Indications of Neutrino Oscillation in the K2K Neutrino Oscillation Experiment

March 10th, 2003
Les Rencontre de Physique de la Vallee d' Aoste,

Taku ISHIDA (KEK IPNS)
for K2K Collaboration

K2K Collaboration

- **JAPAN:** High Energy Accelerator Research Organization (KEK)
Institute for Cosmic Ray Research (ICRR), University 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 November 2002

- **JAPAN:** Hiroshima University
- **EUROPE:** Rome / Saclay / Barcelona / Valencia / Geneva
- **RUSSIA:** Dubna

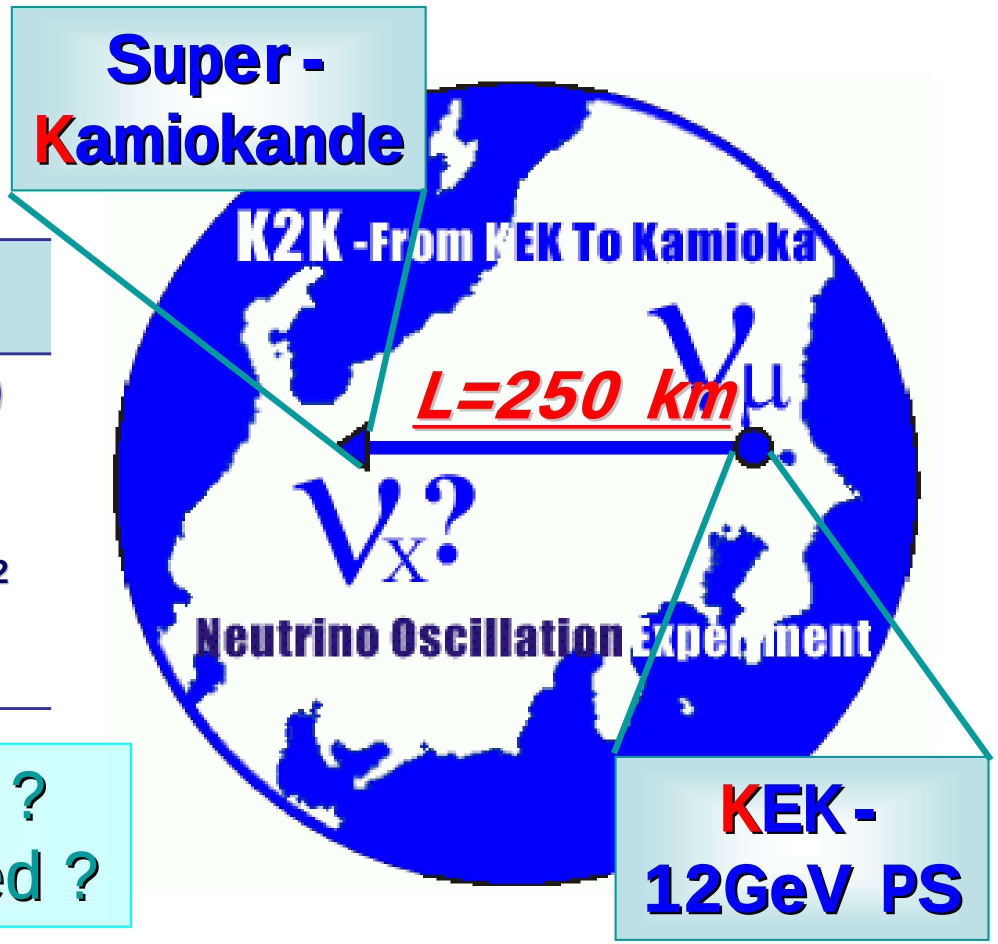
Introduction

- **K2K** is the first accelerator-based long-baseline neutrino oscillation experiment to investigate the neutrino oscillation observed in atmospheric neutrinos.

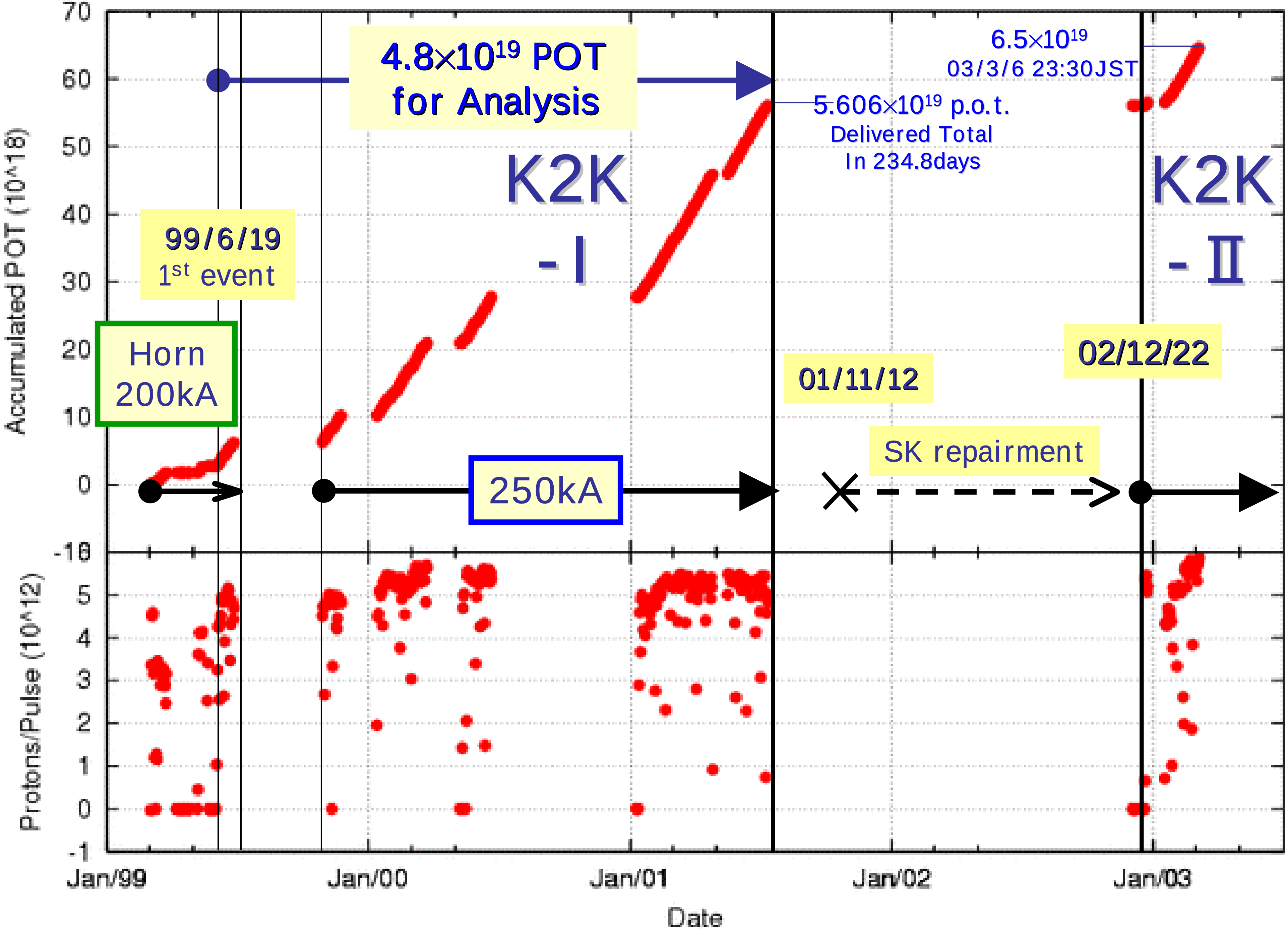
$$P(\nu_\mu \to \nu_X) = Sin^2 2\theta \cdot sin^2(1.27\Delta m^2 L/\underline{E\nu})$$

	Atm.-ν	K2K
L	10~10^4*km*	250*km(fix.)*
Eν	0.1~100GeV	~ 1.3GeV
Δm^2	10^{-1} ~10^{-4}eV^2	> $2 \cdot 10^{-3}$ eV^2
ν_e / ν_μ	50 %	~1%

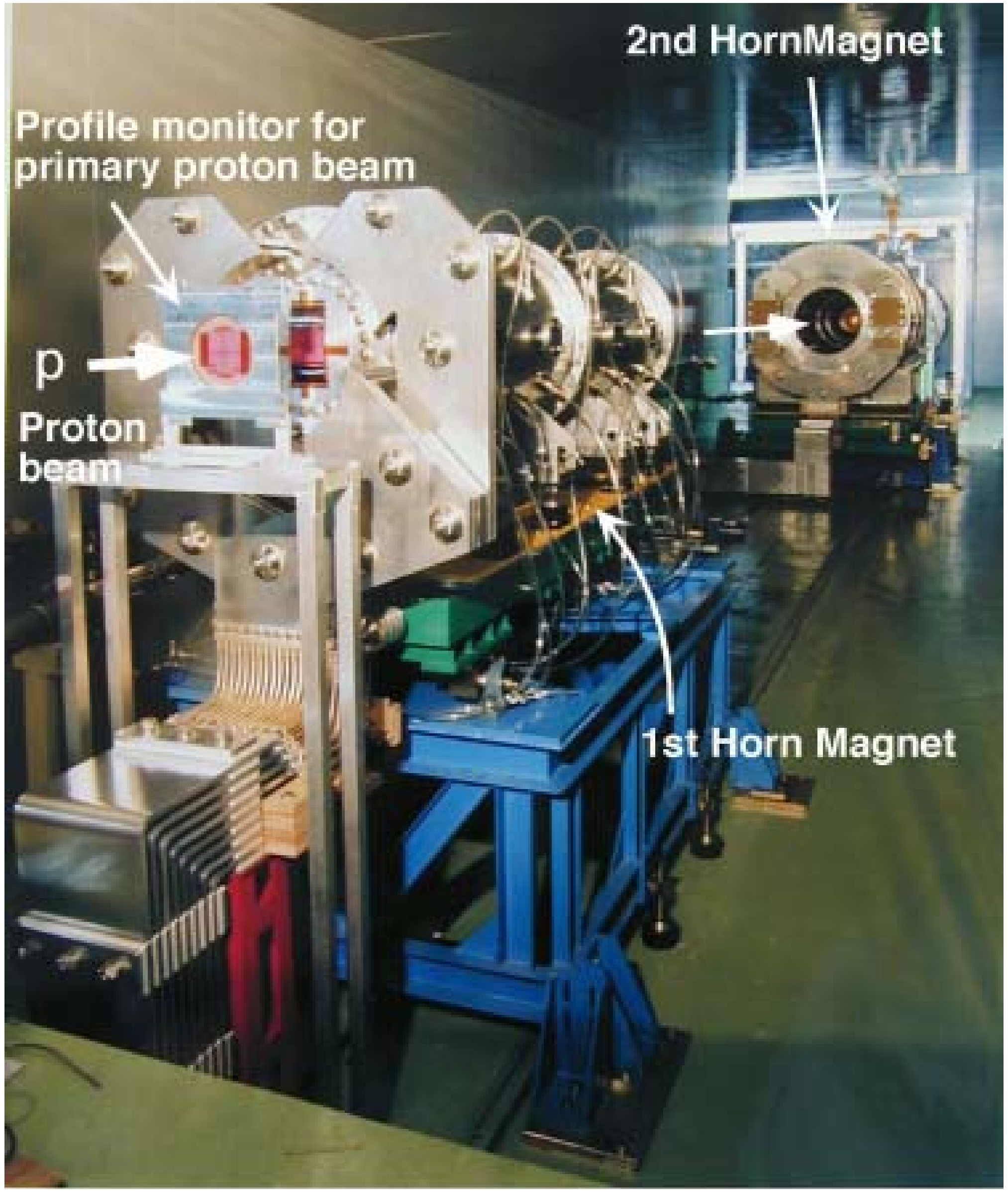
- Do ν_μ events decrease ?
- Is Eν spectrum distorted ?

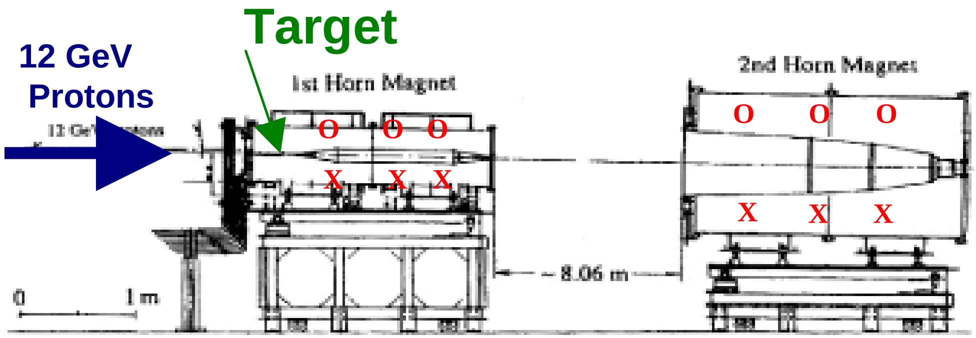


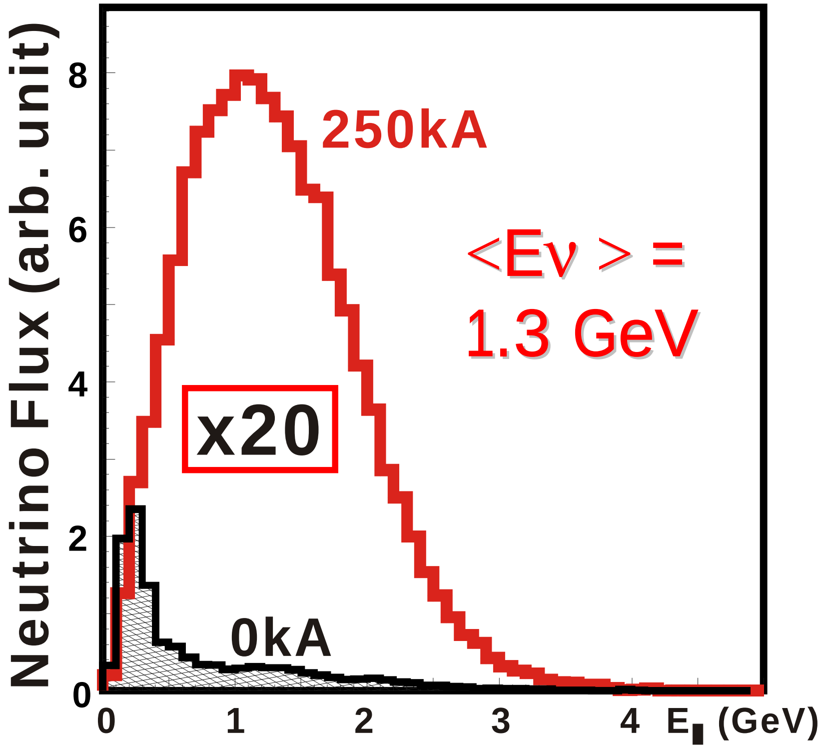
TRISTAN RING
(B-factory)
East
Counter Hall
1.1 μs pulse/2.2s
6~7×10^12 ppp
Al target
DoubleHORNs
π-monitor(pπ,θπ)
Primary Beam-line
12GeV PS
P
Target Station
North
Counter Hall
Decay Section
(200m)
π+ → μ+ + νμ
Muon Pit
Direction(μ)
Front Detectors
Direction(ν)
ν Spectrum/Rate
νμ


4.8×10^19 POT
for Analysis
6.5×10^19
03/3/6 23:30JST
5.606×10^19 p.o.t.
Delivered Total
In 234.8days
K2K
- I
K2K
- II
99/6/19
1st event
Horn
200kA
250kA
01/11/12
02/12/22
SK repairment
Accumulated POT (10^18)
Protons/Pulse (10^12)
Jan/99
Jan/00
Jan/01
Jan/02
Jan/03
Date

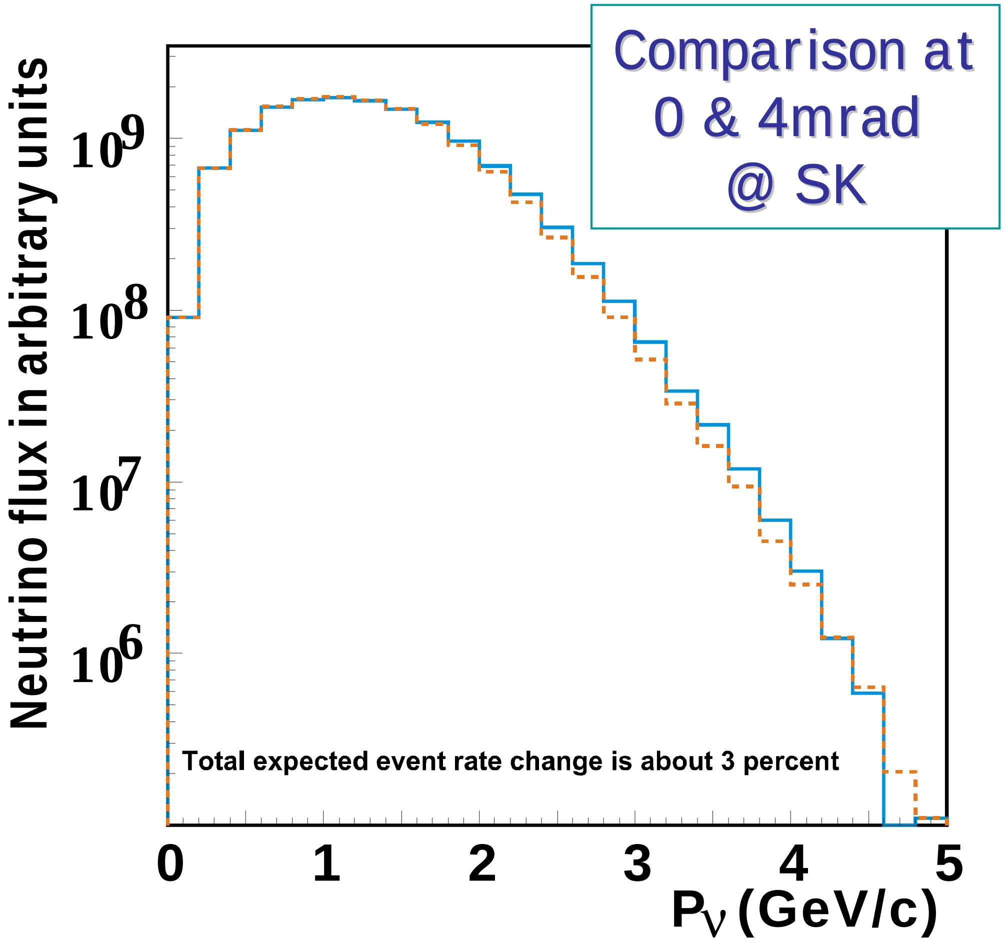
Target (Al) and Two HORNS

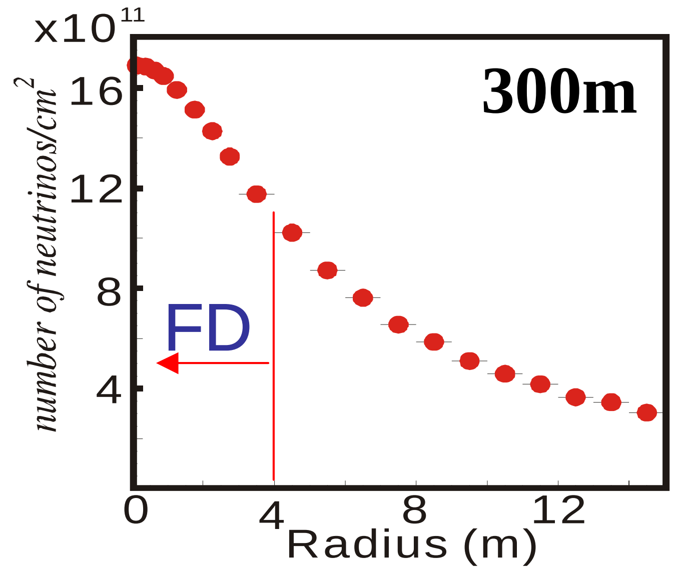


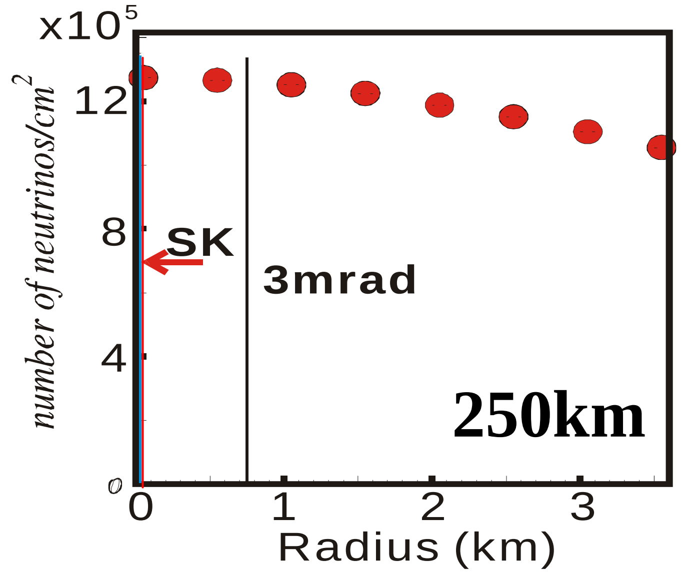




Expected (MC) Neutrino Spectra and Radial Distributions at 300m/250km



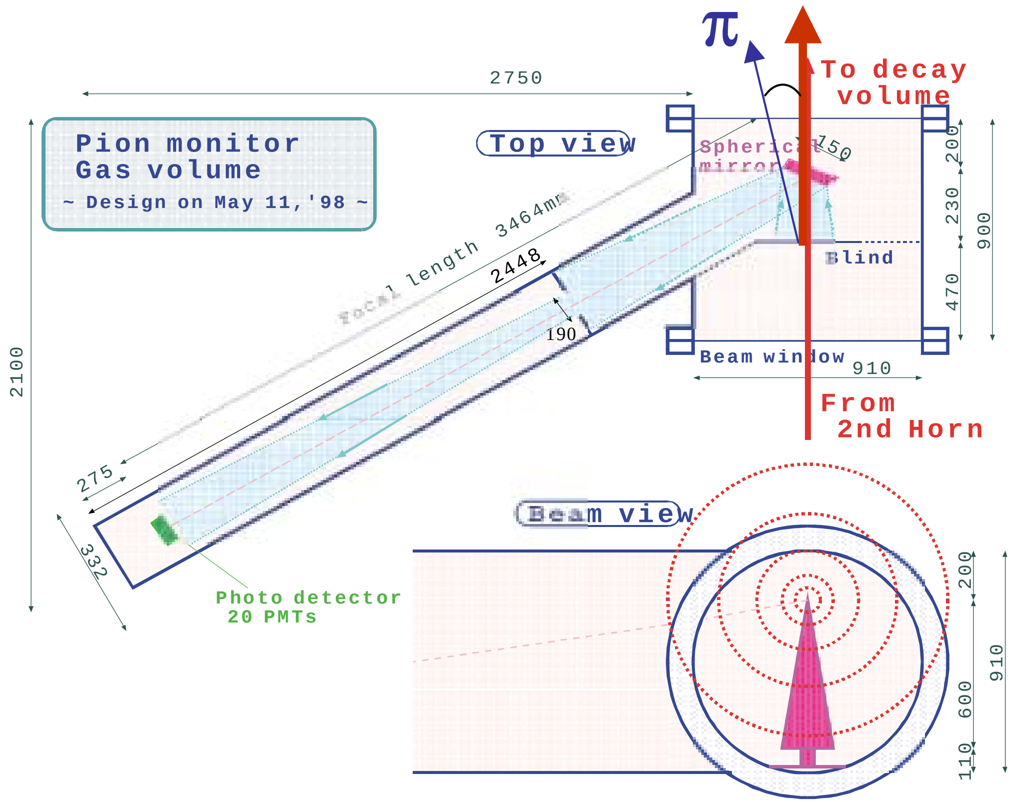


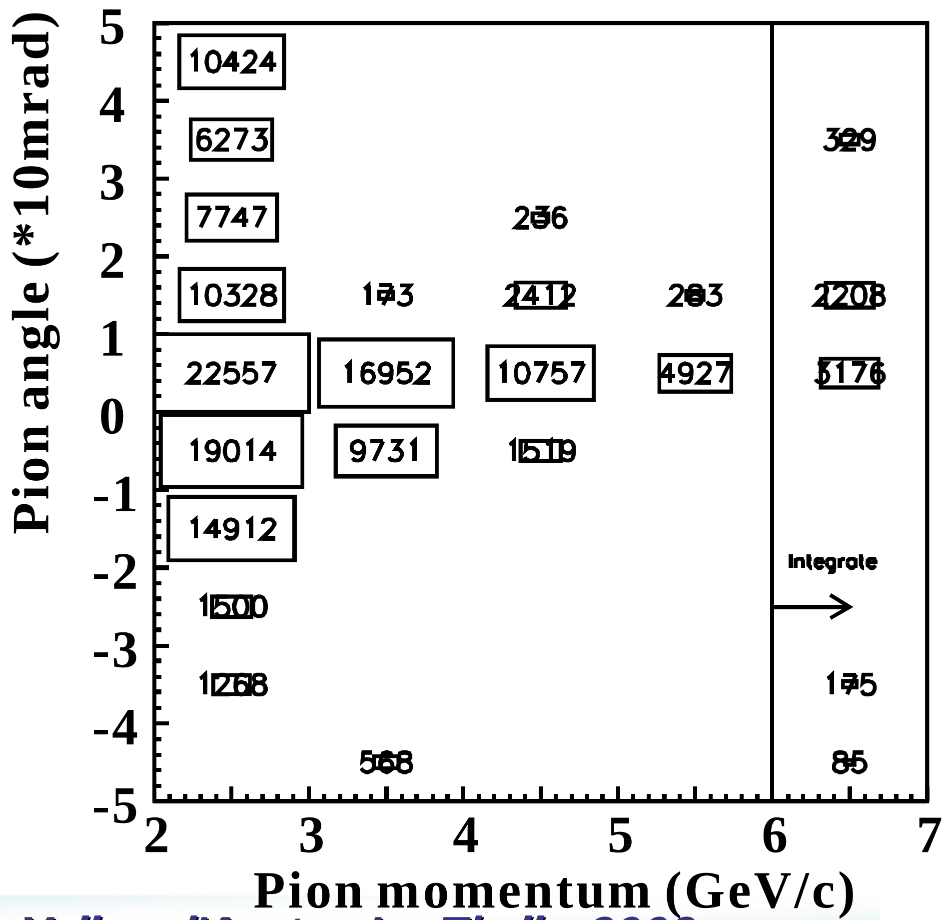


No change in rate and spectrum

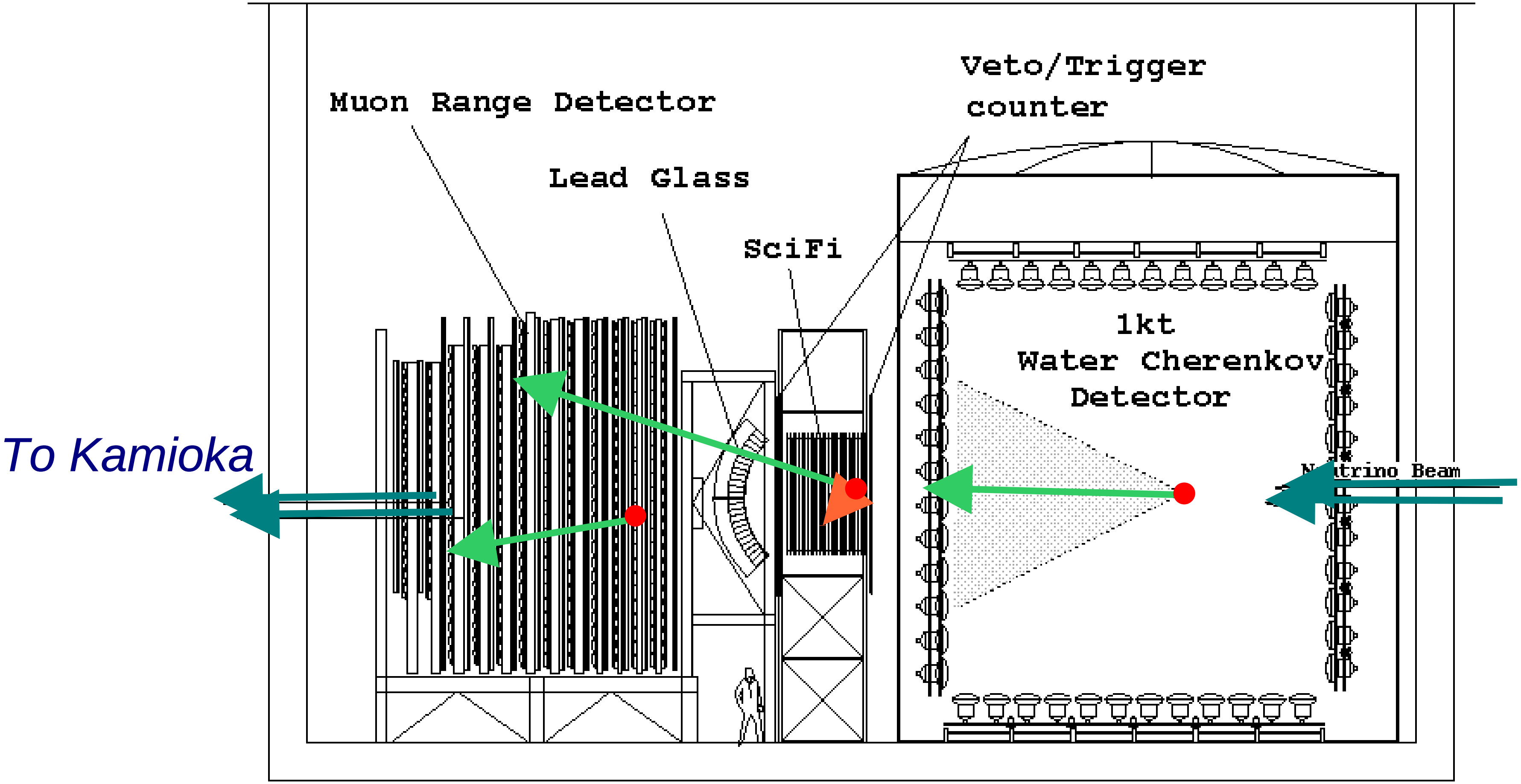
Pion Monitor

- Gas Cherenkov detector: Insensitive to primary protons.
- Measure momentum and angular distribution of pions $N(p_\pi, \theta_\pi)$ just after the 2nd horn (p_π>2GeV/c).
- Near to far extrapolation: F/N(E_ν)



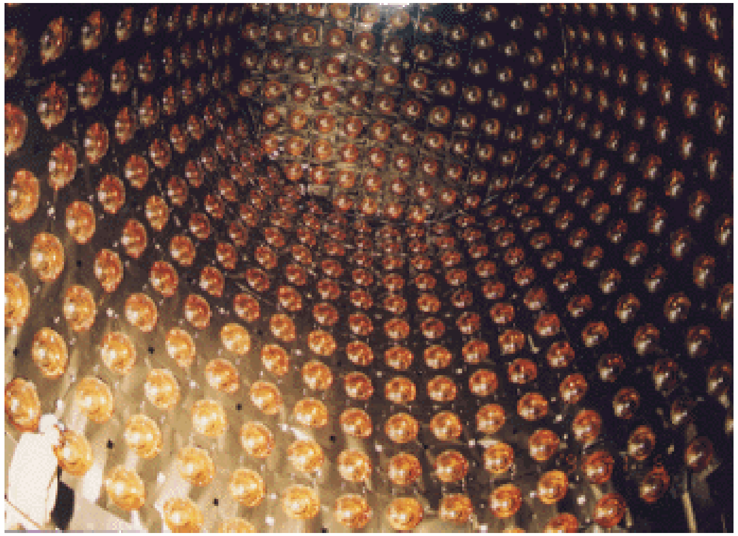


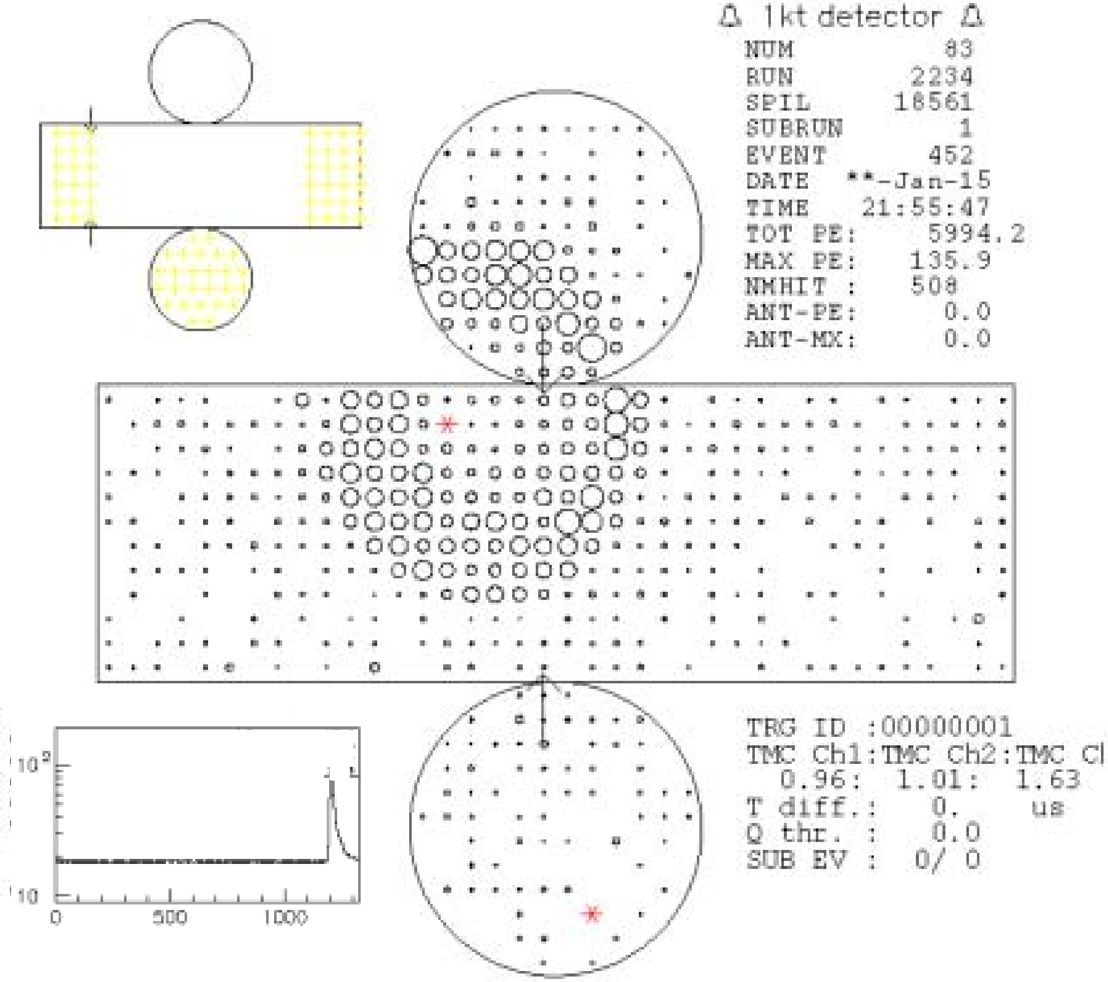
Front neutrino Detectors at KEK



- 1kt Water Cherenkov detector (KT) fiducial: 25 ton H_2O
- Water target/Scintillating fiber tracker (SciFi) 5.9 ton H_2O
- Muon range detector(MRD) 700 ton Iron
- Lead glass detector (LG)

Water Cherenkov Detector (1kt)

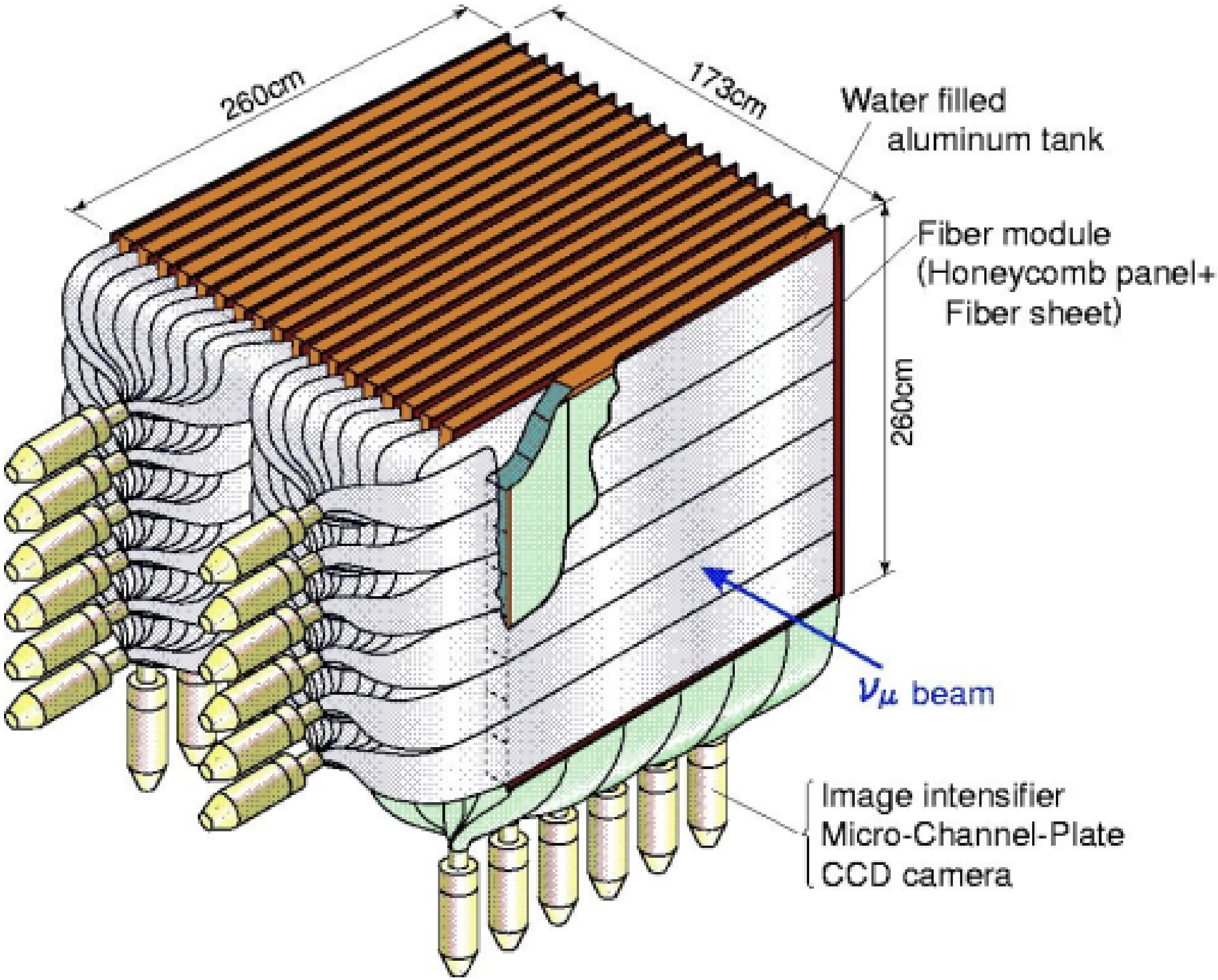




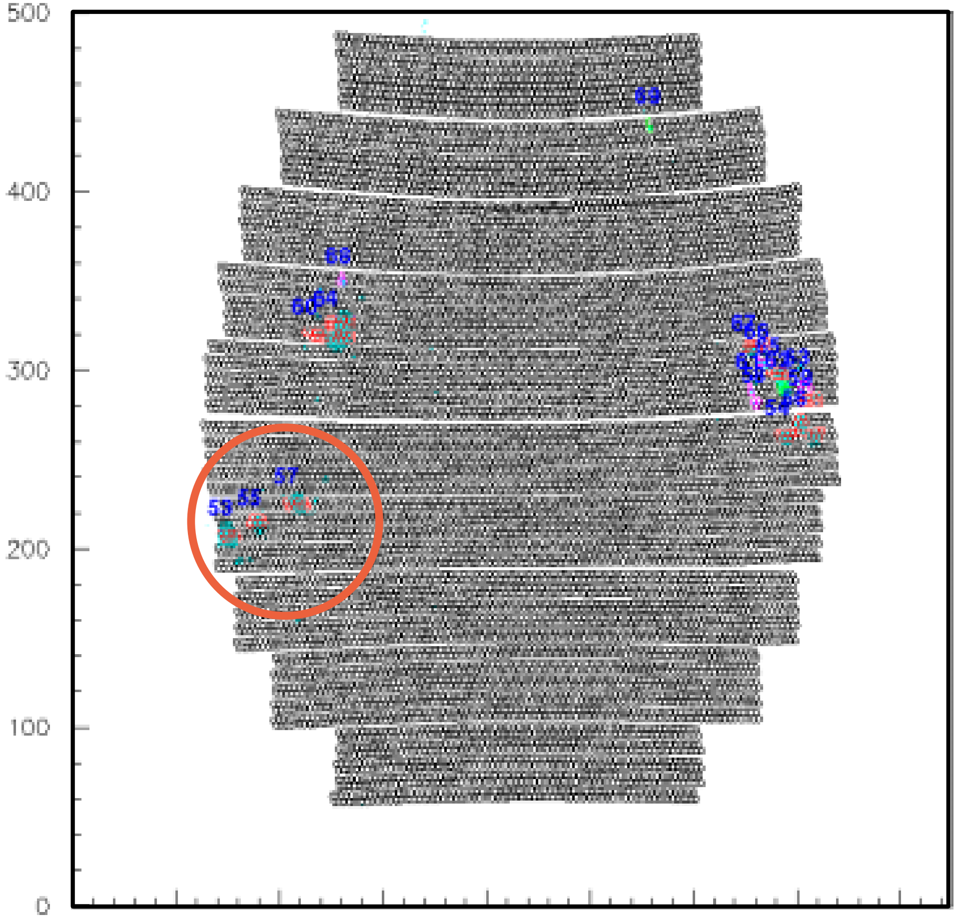
Typical 1R event

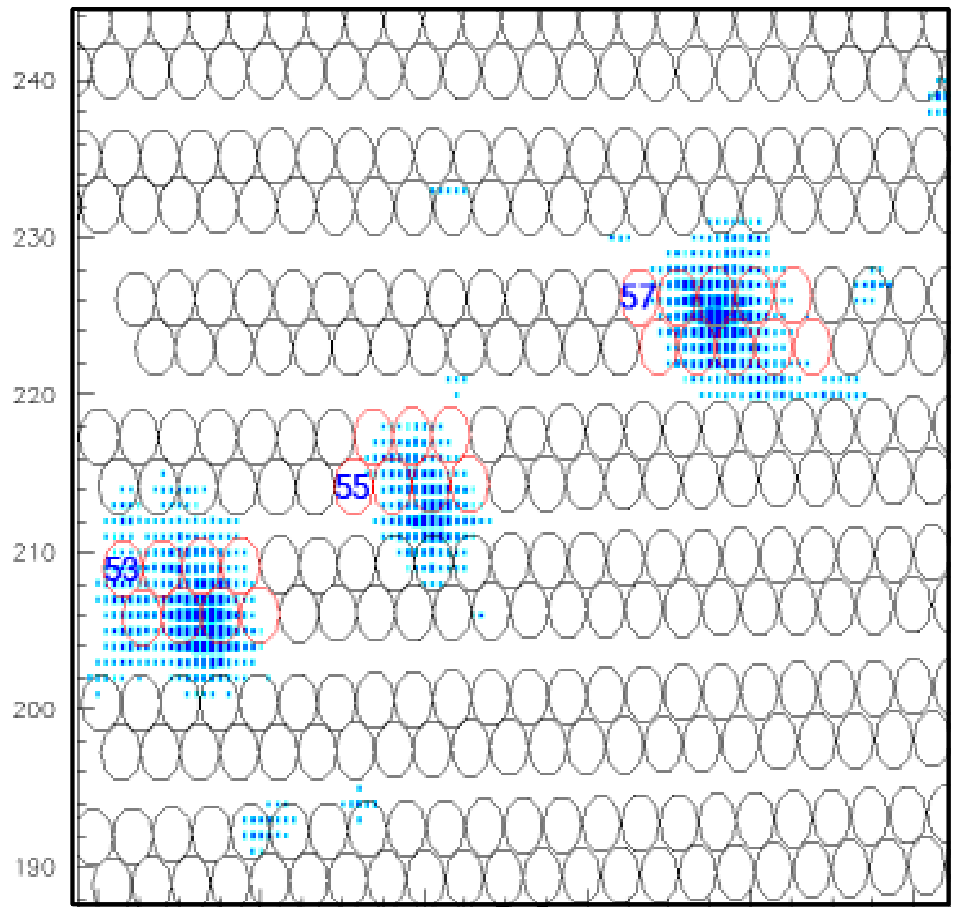
- A miniture of Super-Kamiokande detector with 1/50 volume
- 680 20" PMTs with 70cm spacing (same as SK)
- Inner Volume : 496 tons
  Fiducial Volume : 25.1 tons
  (r=2m sylindrical volume along beam)

Scintillating Fiber(SciFi) Tracker



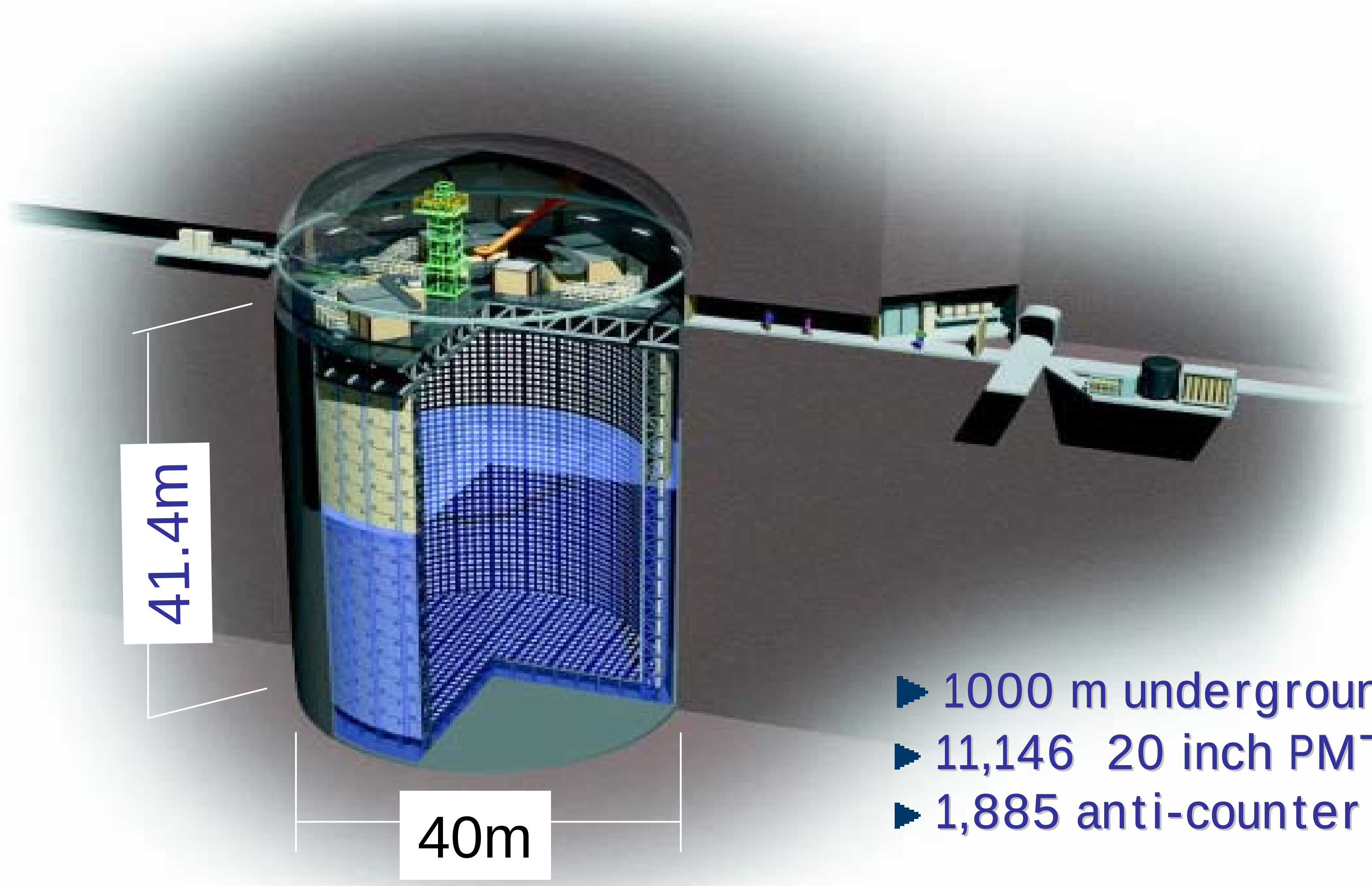
Typical CCD Pixel Image





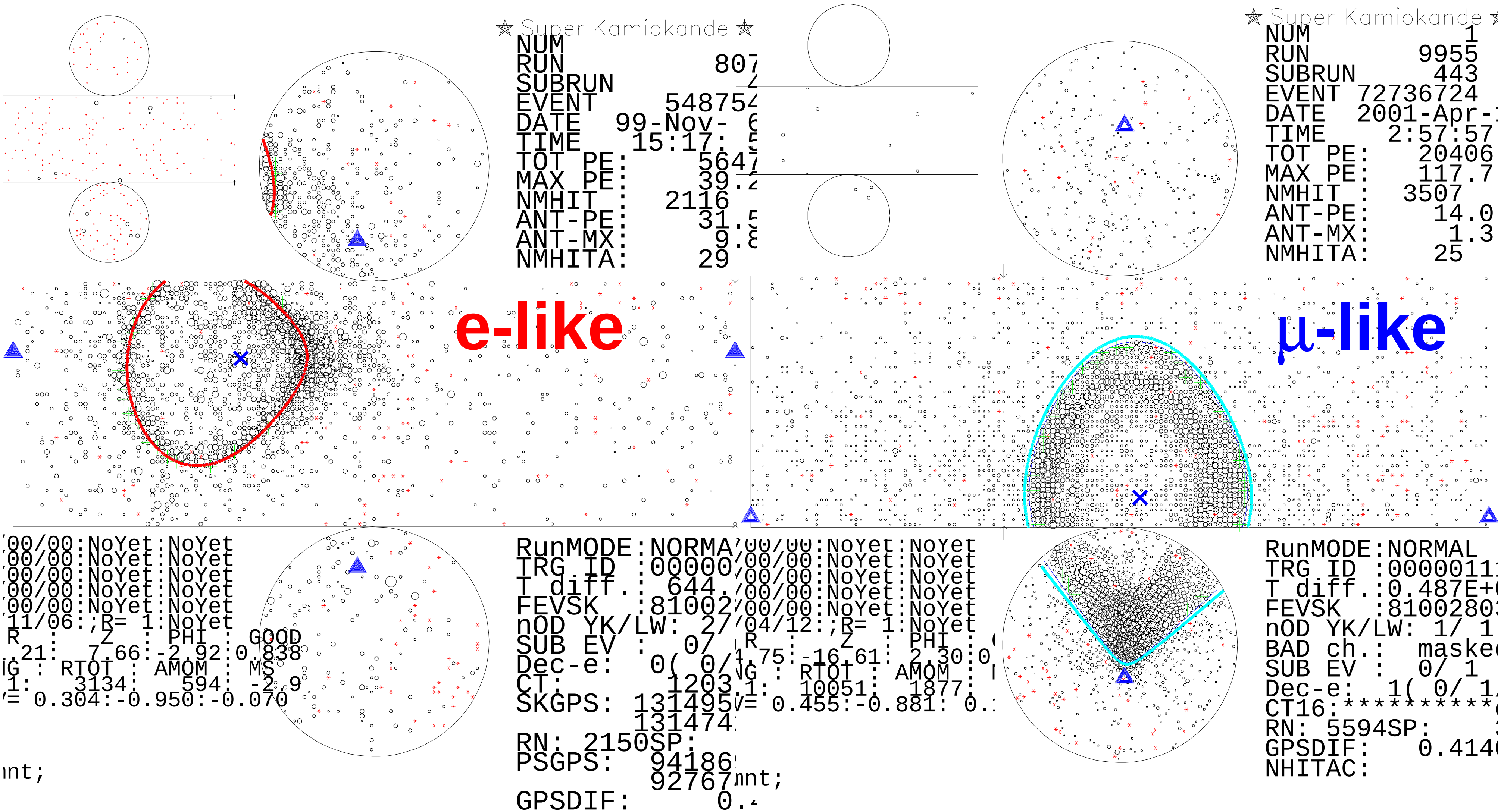
Super-Kamiokande (April 1996 commissioned)

- 50,000 ton water Cherenkov detector (22.5 kton fiducial volume)
- Optically separated INNER and OUTER detector

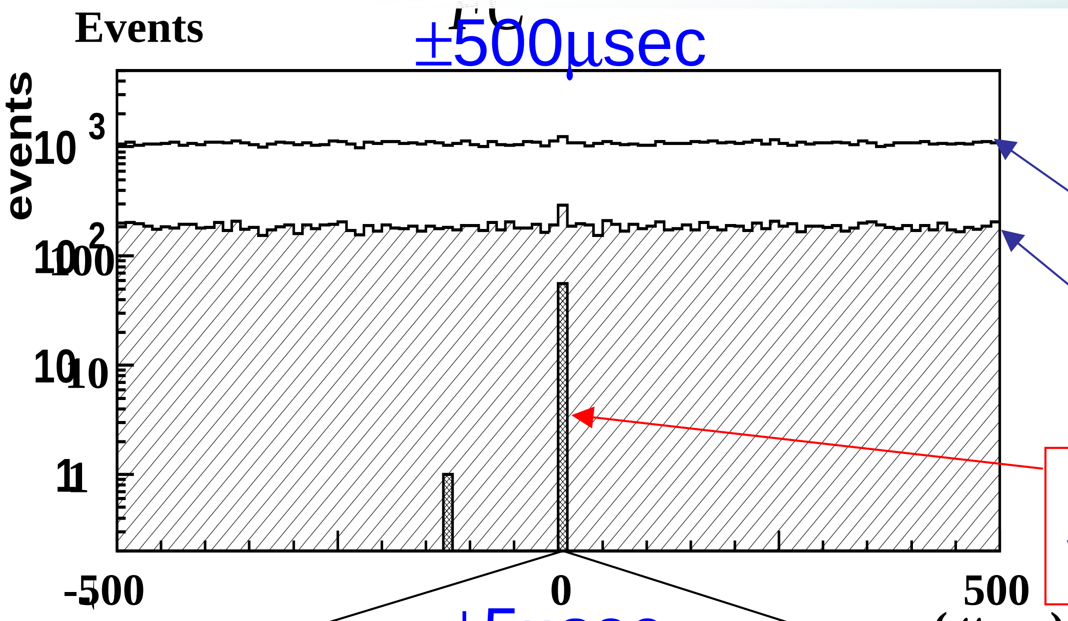


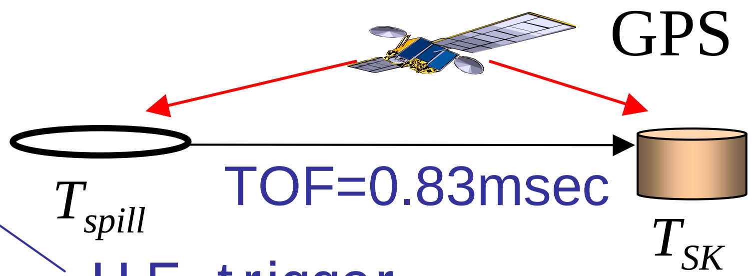
- 1000 m underground
- 11,146 20 inch PMTs
- 1,885 anti-counter PMTs

e-like and μ-like events



Super-K Event Selection by GPS

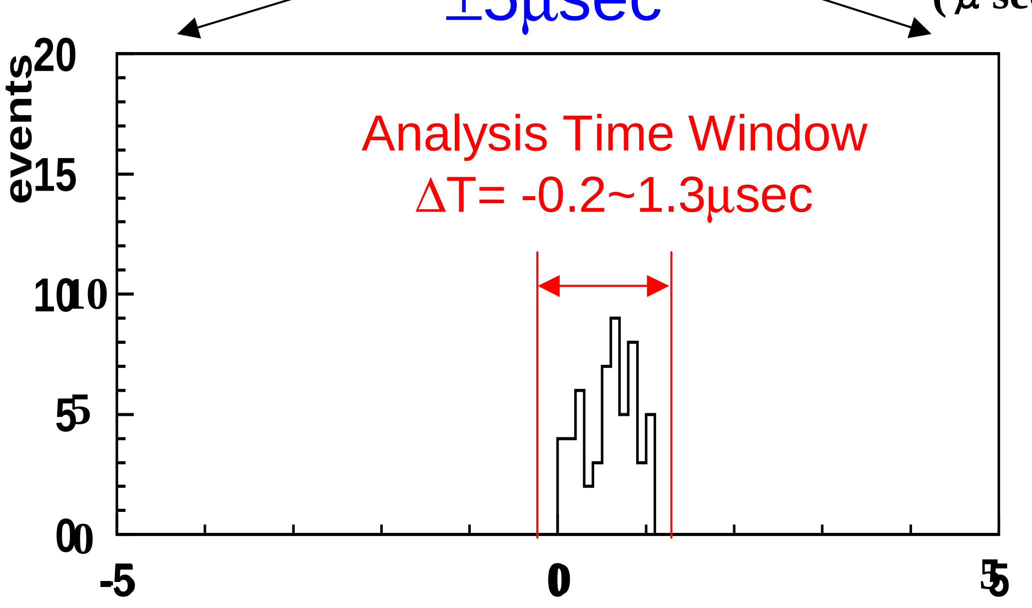




H.E. trigger

Not a Decay Electron Event

No Activity in Outer Detector (FC)
Vertex is in Fiducial Volume (FV)



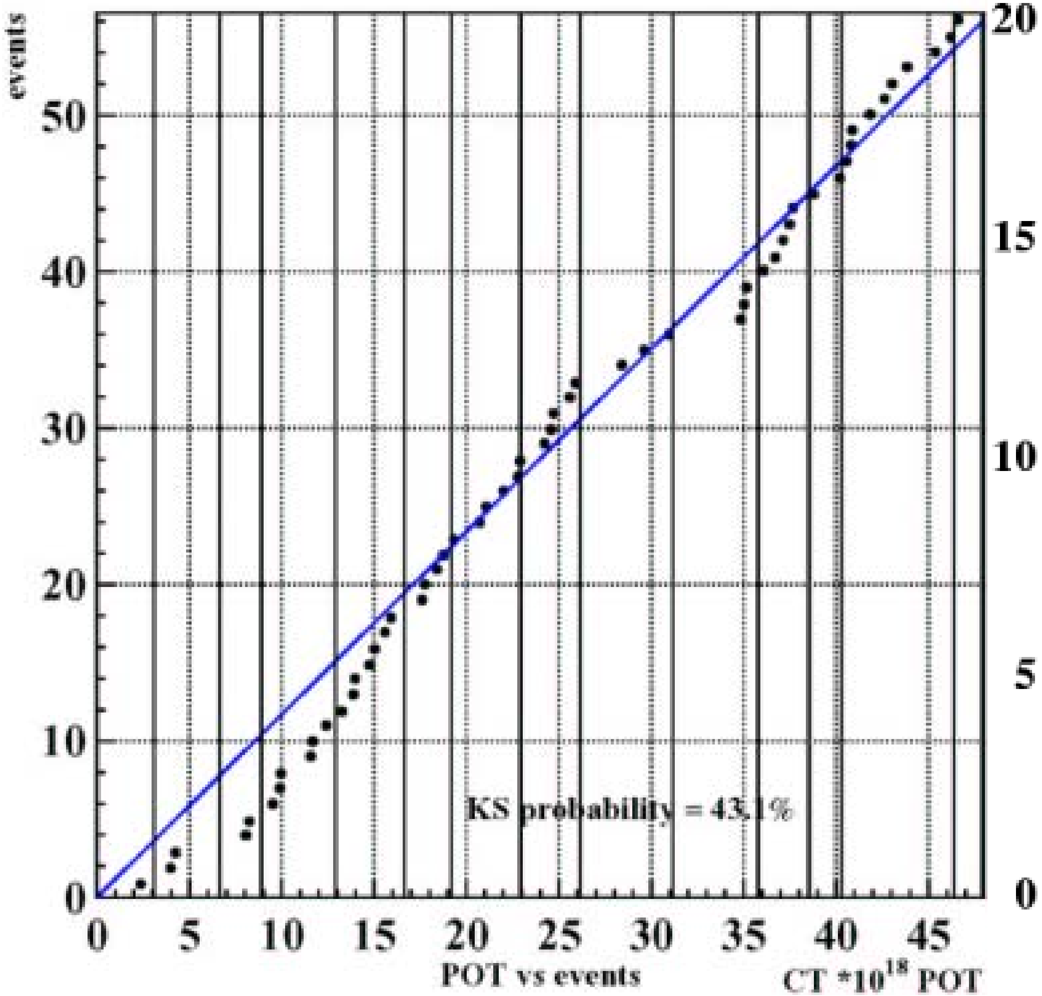
56 FCFV Events

where

- 1 Ring = 32
  - μ-like 30 / e-like 2
- Multi-Ring = 24

(Expected atm.ν B.G. ~10^{-3}/1.5μs)

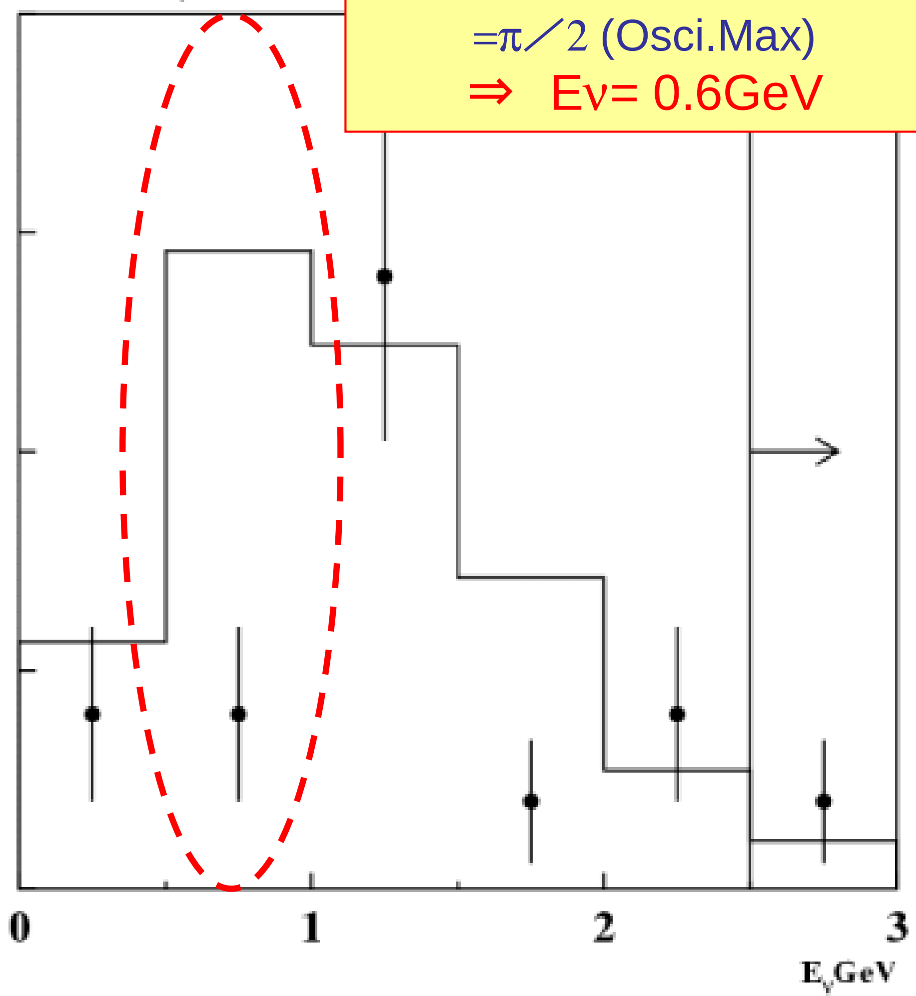
Event v.s. POT dist.



KS test probability: **43%**

Eνrec of FCFV-1Rμlike

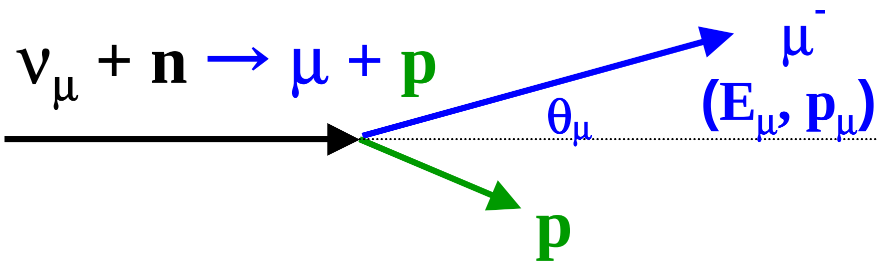
1.27・**0.003**eV^2・250km／Eν
=π／2 (Osci.Max)
⇒ Eν= 0.6GeV



29 1R events with HC250kA

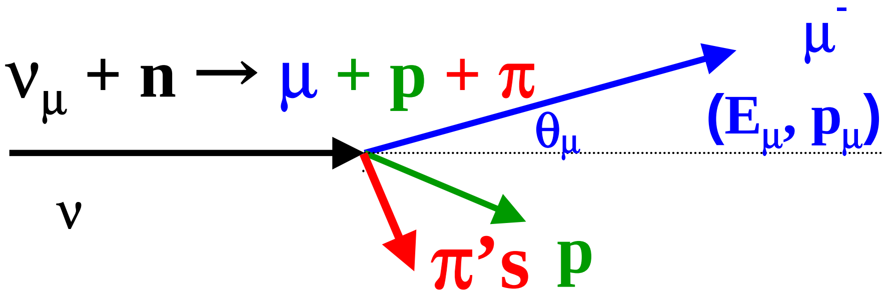
Neutrino Energy Reconstruction

CC quasi elastic (QE)



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

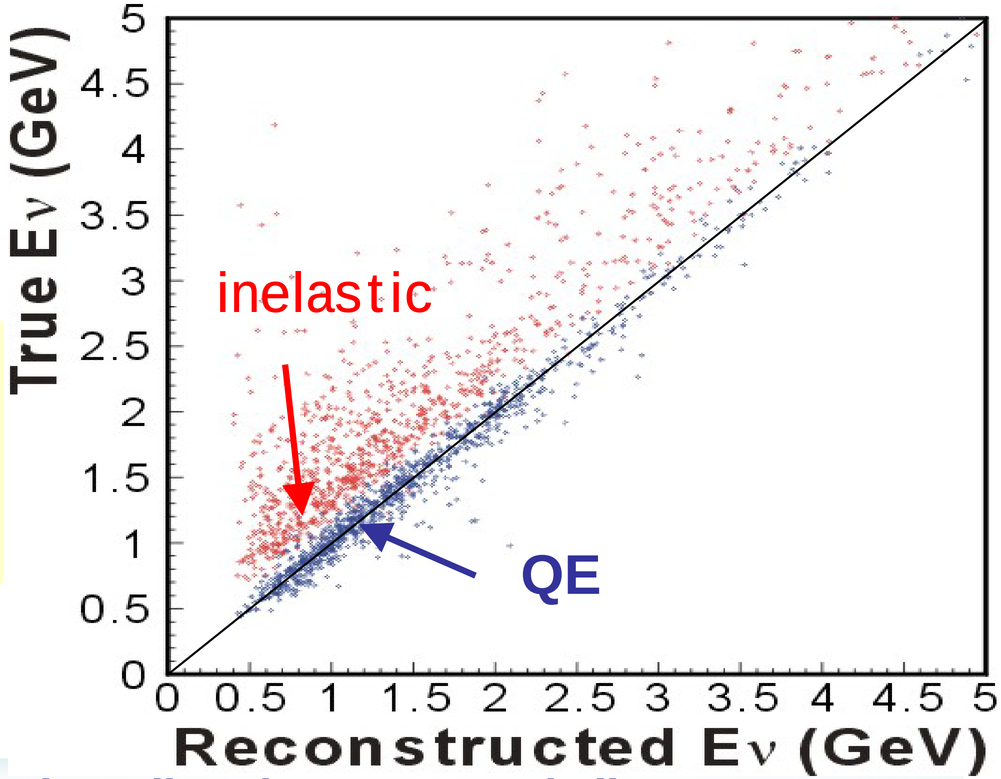
CC inelastic



Rate(Eν,Near) → <u>φ(Eν,Near)</u>

↑

σ(QE), σ(nonQE)



Oscillation Analysis

Super-K

? ($sin^2 2\theta$, Δm^2) ?

Expectation
#ν and $E_\nu^{rec.}$

Observation
#ν(56), E_ν^{rec}(29)

Far/Near Ratio
(beam MC & π mon.)

FD @ KEK

Measurement
$\Phi(E_\nu)$, nQE/QE

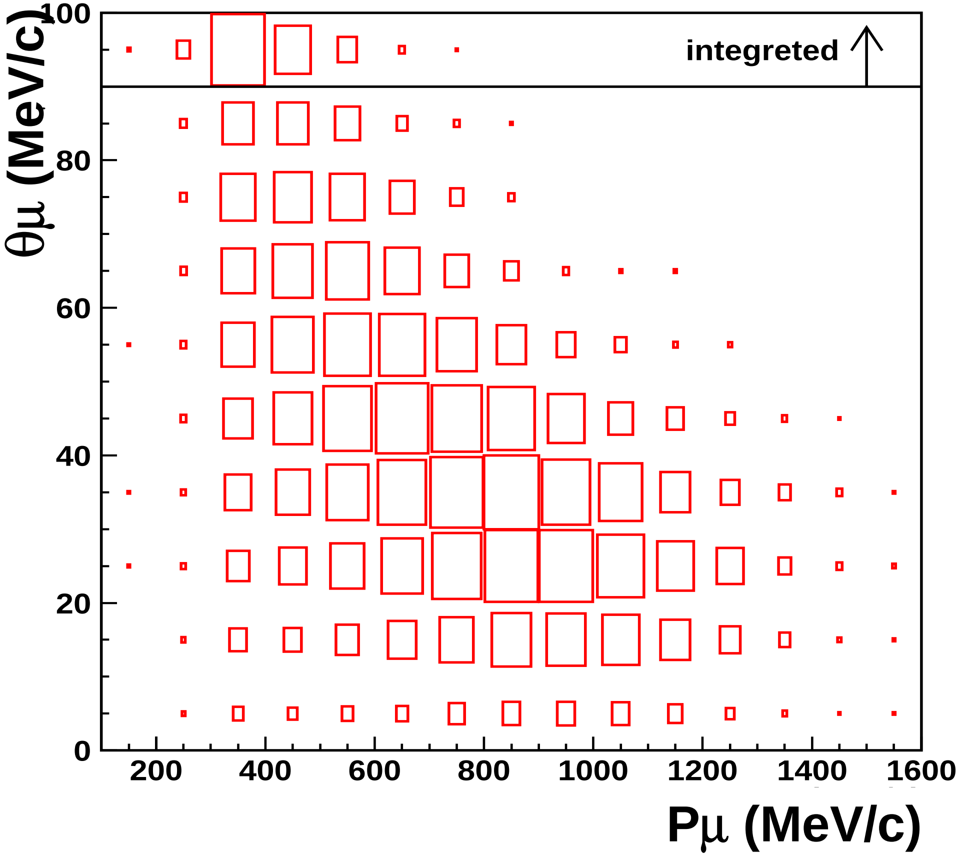
Observation
#ν, p_μ and θ_μ

ν interaction MC
ν Flux and Spectrum

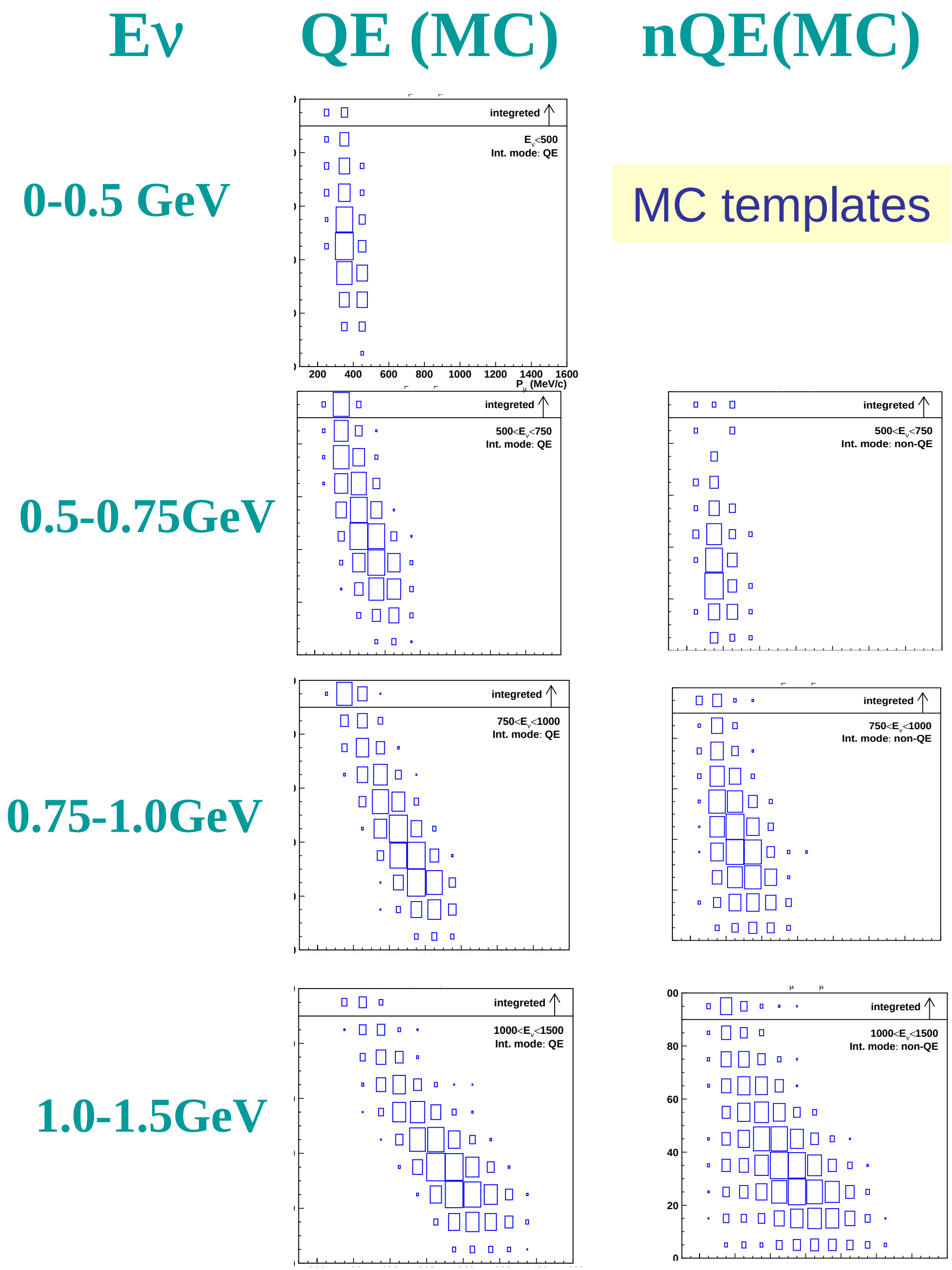
FD @ KEK

$(p_\mu, \theta_\mu) \rightarrow \phi(E\nu)$, nQE/QE

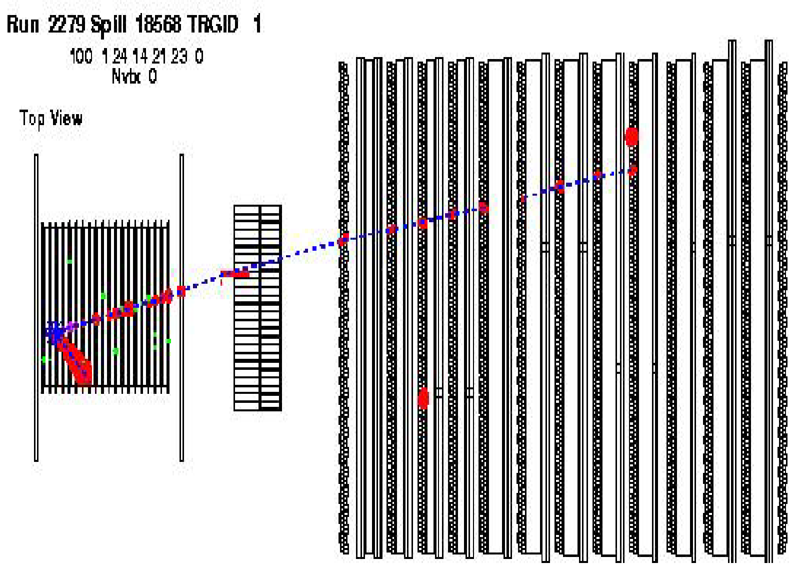
(1) KT 1Rμ-like ~36,000 events



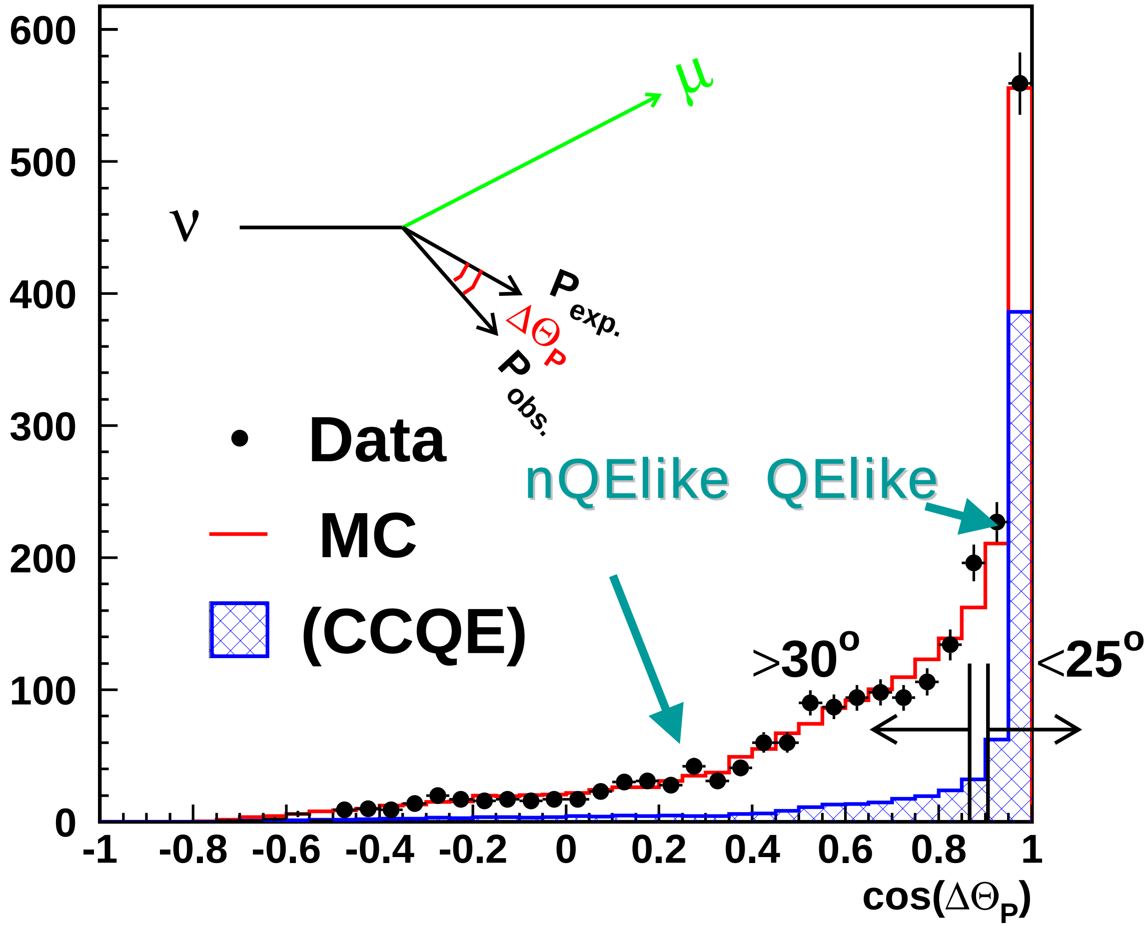
- ν flux $\phi_{near}(E\nu)$ (8 bins)
- ν interaction (nQE/QE)



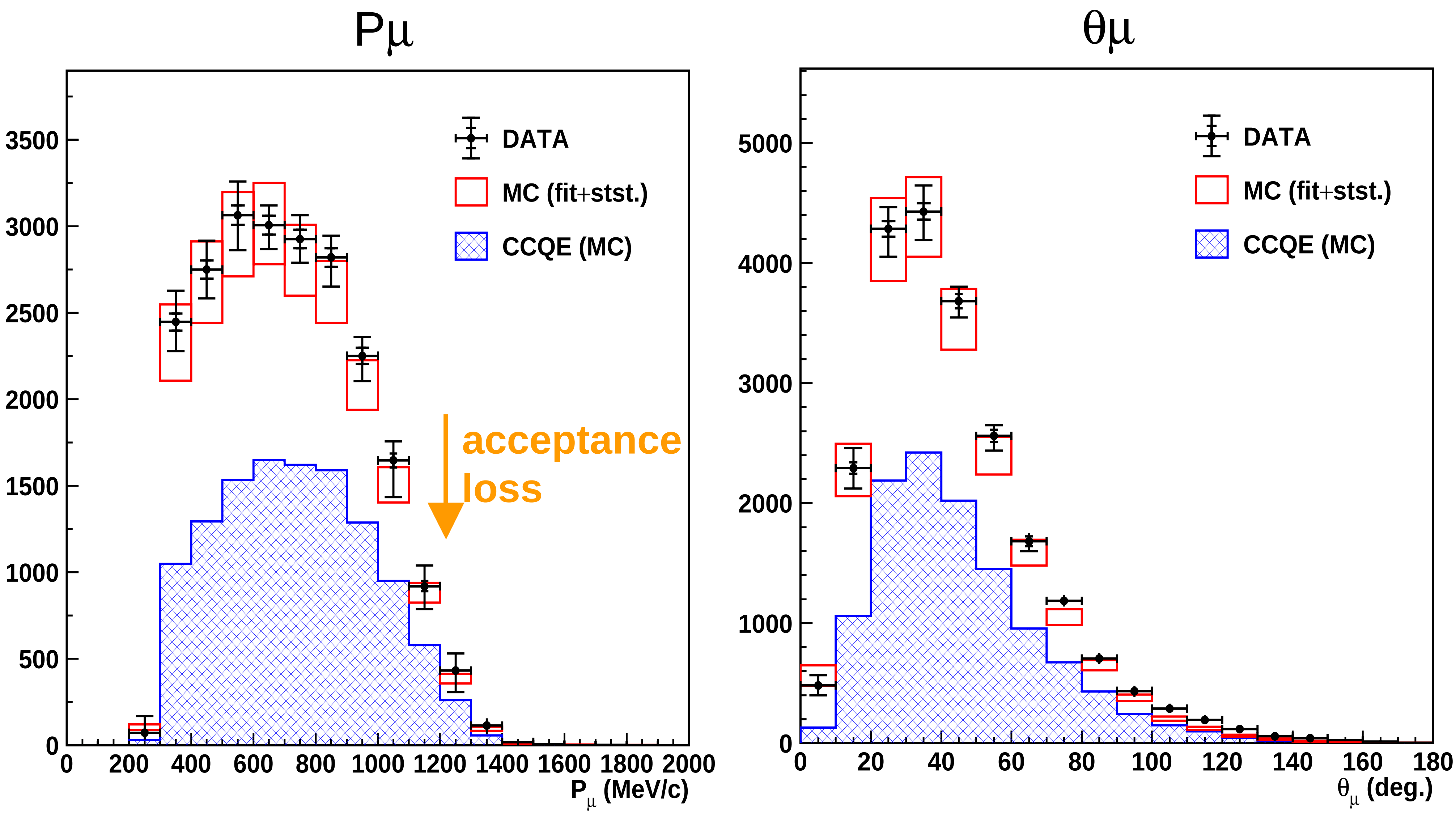
QE and nQE in SciFi 2-track events



(2) 1-track
5,951events/44points
(3) 2-track ($\Delta\Theta_P \leq 25^o$)
761events/40points
(4) 2-track ($\Delta\Theta_P \geq 30^o$)
1,291events/40points
124 data points
~ 8,000 events in total.
R(non-QE/QE) is constrained by (3) / (2)
Δ R < 10%



(1) KT (p_μ, θ_μ) distribution using ϕ_{fit}, QE/nQE_{fit}



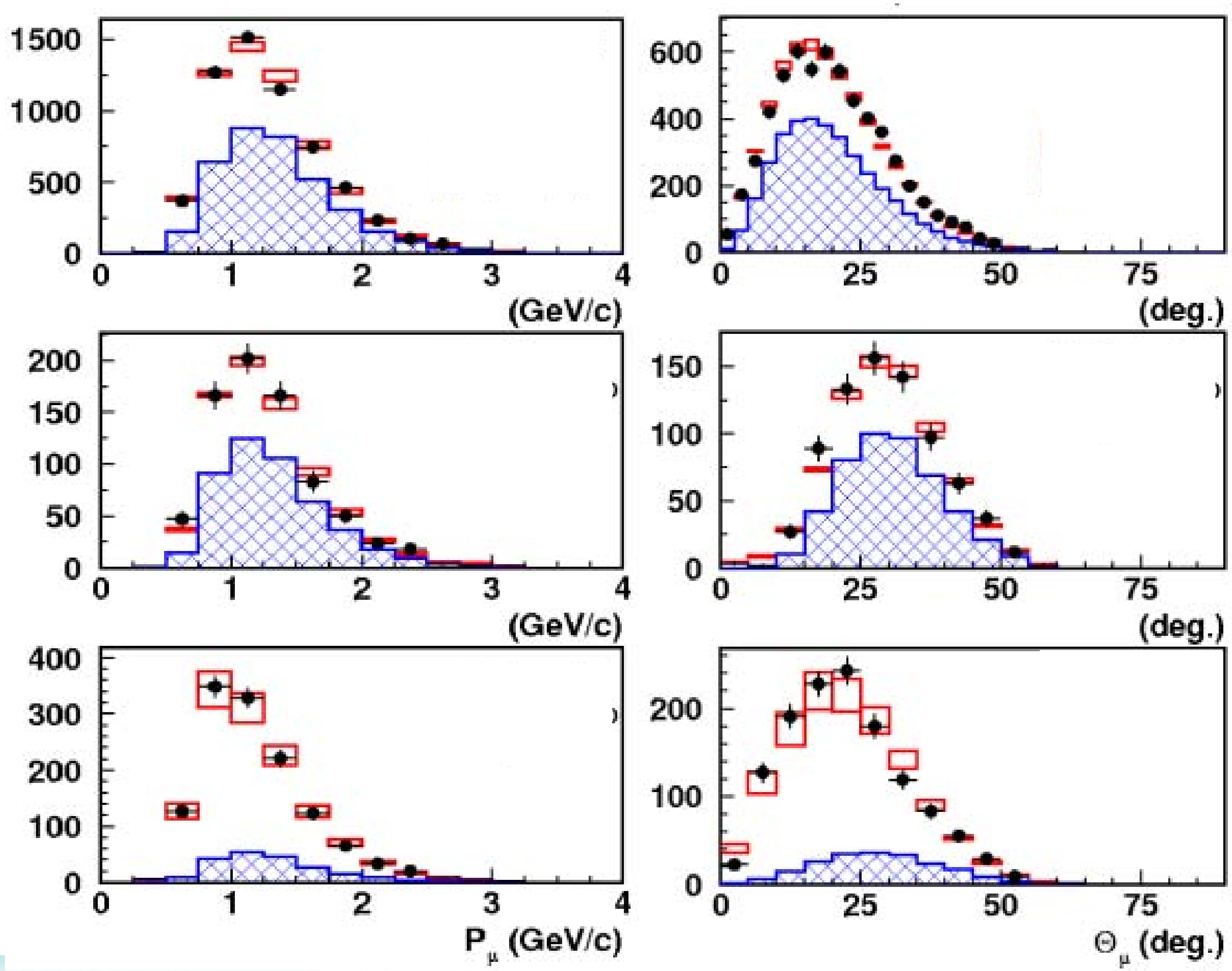
SciFi (p_μ,θ_μ) distributions

P_μ Θ_μ

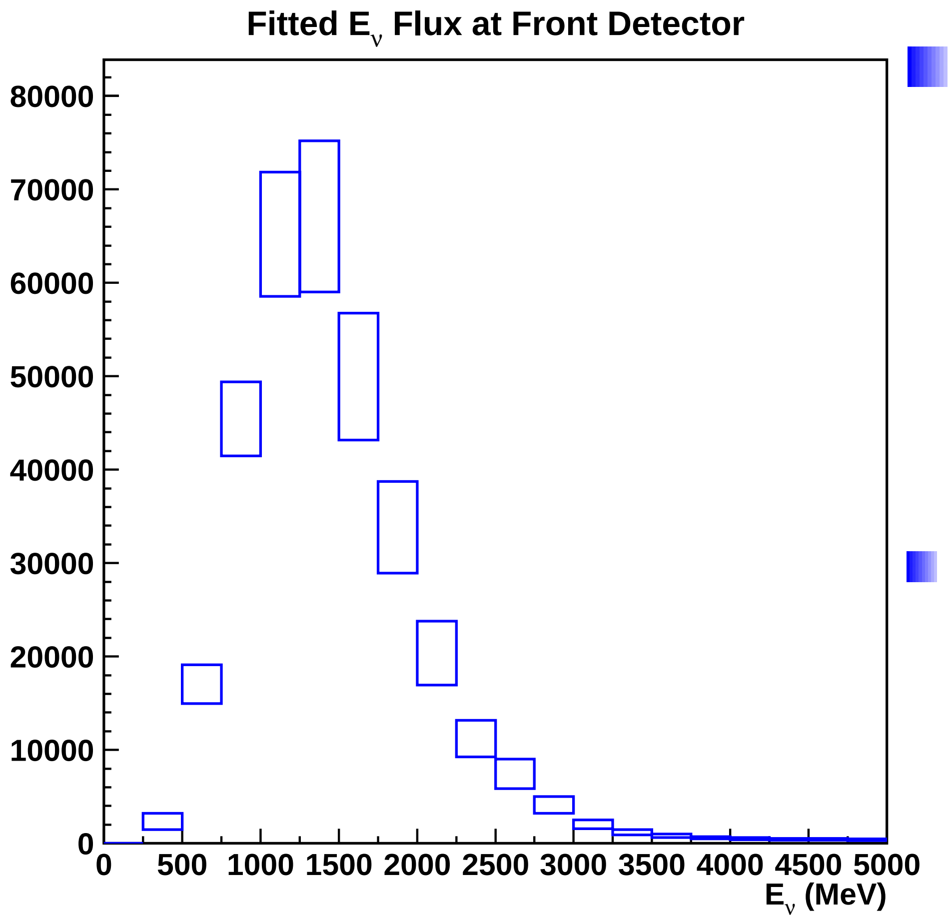
(2) 1-track

(3) 2-track $\Delta\Theta_P \leq 25^o$

(4) 2-track $\Delta\Theta_P \geq 30^o$



Fit result of Neutrino Flux at KEK Site



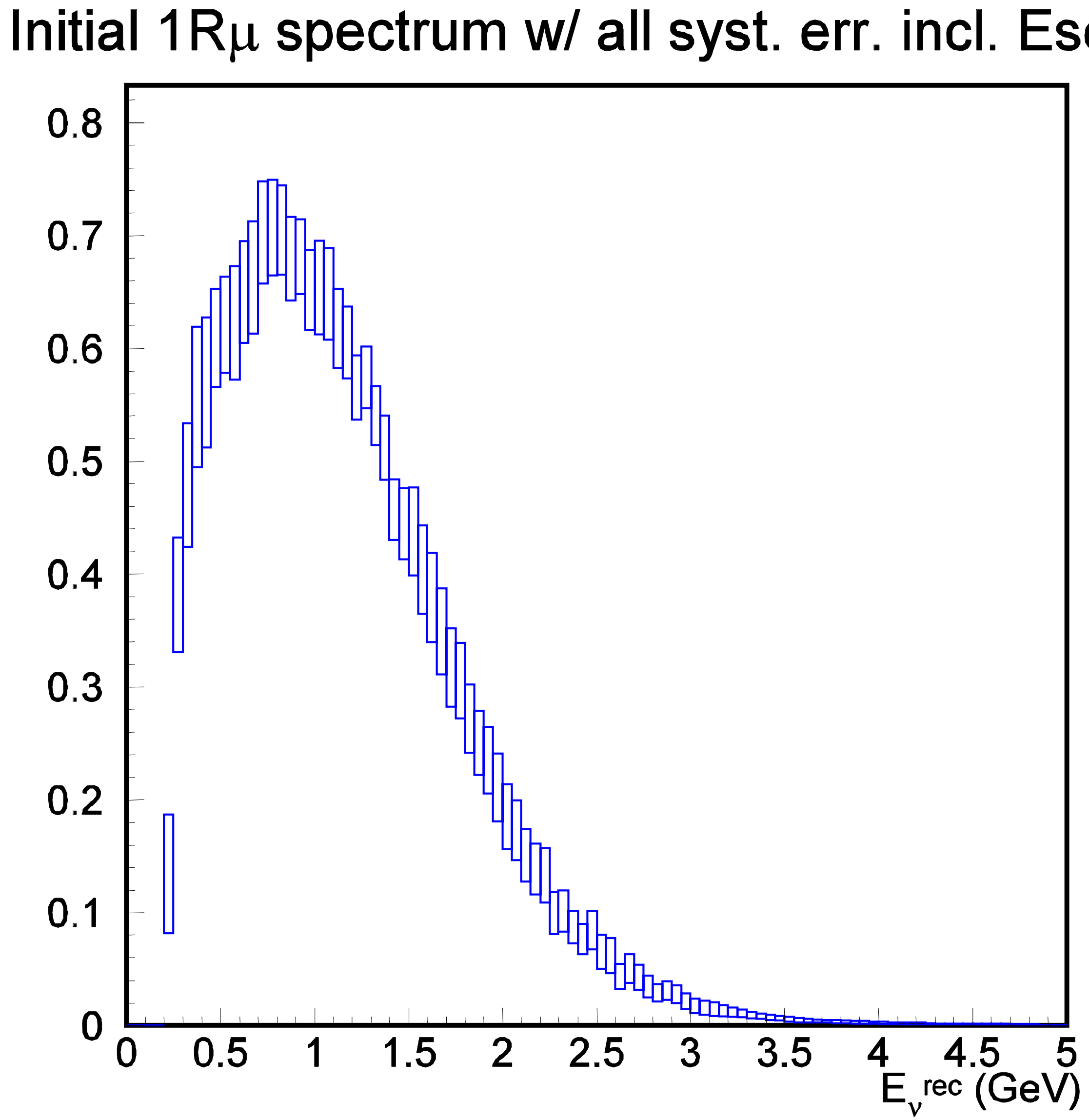
E_ν (MeV)

- **χ^2=227 for 194 *d.o.f***
  - **Φ1 ($E\nu <$ 500) = 1.3 $\pm$ 0.5**
  - **Φ2 (500$\leq E\nu <$ 750) = 1.02 $\pm$ 0.12**
  - **Φ3 (750$\leq E\nu <$1000) = 1.01 $\pm$ 0.09**
  - **Φ4 (1500$\leq E\nu <$2000) = 0.95 $\pm$ 0.07**
  - **Φ5 (2000$\leq E\nu <$2500) = 0.96 $\pm$ 0.08**
  - **Φ5 (2500$\leq E\nu <$3000) = 1.18 $\pm$ 0.19**
  - **Φ6 (3000$\leq E\nu$) = 1.07$\pm$ 0.20**

- **nQE/QE = 0.93 $\pm$ 0.20 (0.06)**

  Error is assigned based on the disagreement between SciFi and KT results.
  - **KT only: nQE/QE=0.73**
  - **SciFi only: nQE/QE=1.09**

Super-K: Expected E_ν^{rec} spectrum for $1R\mu$



Maximum likelihood fit with $(\sin^2 2\theta, \Delta m^2)$

Likelihood

$$L_{tot} = L_{norm} \cdot L_{shape} \cdot L_{syst}$$

Term for # of FCFV events

$$L_{norm} = Poisson(N_{obs}, N_{\exp'ed}(\Delta m^2, \sin^2 2\theta, f_{\mathrm{syst}}))$$

N_{obs}: Observed number of FCFV events (56)

$$N_{\exp'ed}(\Delta m^2, \sin^2 2\theta, f_{\mathrm{syst}}) = N_{KT}^{obs} \cdot \frac{N_{SK}^{MC}(\Delta m^2, \sin^2 2\theta, f_{\mathrm{syst}})}{N_{KT}^{MC}(f_{\mathrm{syst}})}$$

(exp'ed # of FCFV events)

Term for E_ν^{rec} distribution for 1Rμ events

$$L_{shape} \equiv \prod_{i=1}^{29} P(E_i^{rec}; \Delta m^2, \sin^2 2\theta, f_{\mathrm{syst}})$$

P: normalized E_ν^{rec} distribution for 1Rμ events estimated by MC simulation

Systematic parameters

$$L_{syst} \equiv \exp\left(-\Delta f^{T}_{\Phi,nQE} \cdot M^{-1}_{FD} \cdot \Delta f_{\Phi,nQE} / 2\right)$$
$$\times \exp\left(-\Delta f^{T}_{F/N} \cdot M^{-1}_{F/N} \cdot \Delta f_{F/N} / 2\right)$$
$$\times \exp\left(-\Delta f^{T}_{\varepsilon SK} \cdot M^{-1}_{\varepsilon SK} \cdot \Delta f_{\varepsilon SK} / 2\right)$$
$$\times \exp\left(-\Delta f^{2}_{n6} / 2\sigma^{2}_{n6}\right)$$
$$\times \exp\left(-\Delta f^{2}_{n11} / 2\sigma^{2}_{n11}\right)$$
$$\times \exp\left(-\Delta f^{2}_{Esk} / 2\sigma^{2}_{Esk}\right)$$

$$\Delta f = f - f_{cent}$$

- M_{FD}, M_{π}, $M_{\varepsilon \mathrm{SK}}$: error matrices(spec+nQE/QE, far/near, ε_{SK})

  σ_{n6}: norm. err. for Jun99 (=+0.80–0.68 evts)

  σ_{n11}:norm. err. for Nov99~ (=5.34% dominated by KT/SK fid. vol. err.)

  σ_{Esk}: SK energy scale error (3%)

Expected number of FCFV events w/o oscillation

Generate many sets of random numbers for f_{syst} which distribute according to the error matrices

Calculate

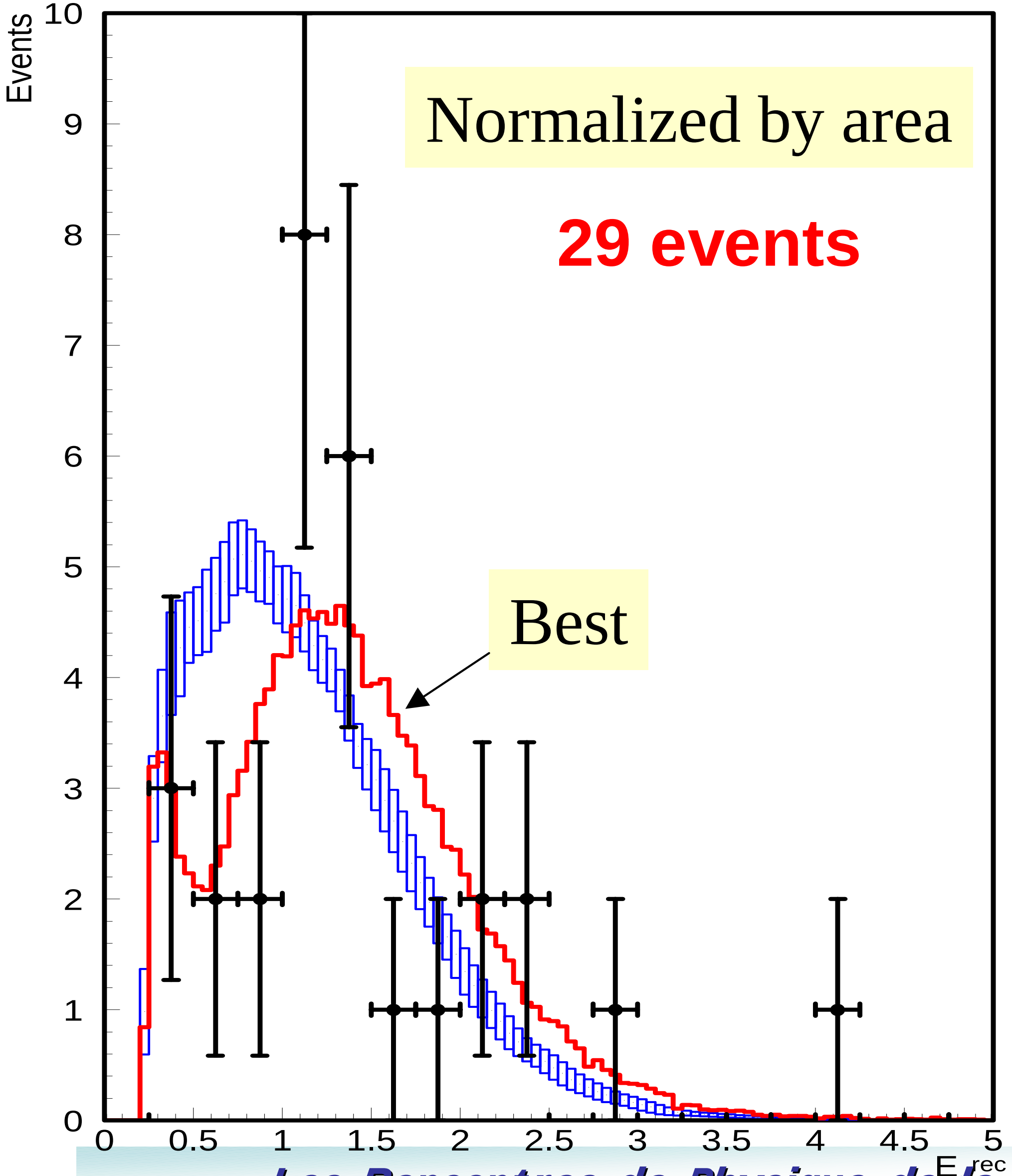
$$N_{\mathrm{exp'ed}}(\Delta m^2, \sin^2 2\theta, f_{syst})$$

for each set w/ $\sin^2 2\theta = 0$

$$80.1^{+6.2}_{-5.4} \text{ events}$$

Jun99	Total	+1.0% –0.85%
Nov99~	Spectrum	+0.56% –0.63%
	nQE/QE	+0.47% –1.1%
	Far/Near	+4.9% –5.0%
	Norm	5.0%
Total		**+7.7% –6.7%**

Best fit 1Rμ spectrum & Nsk



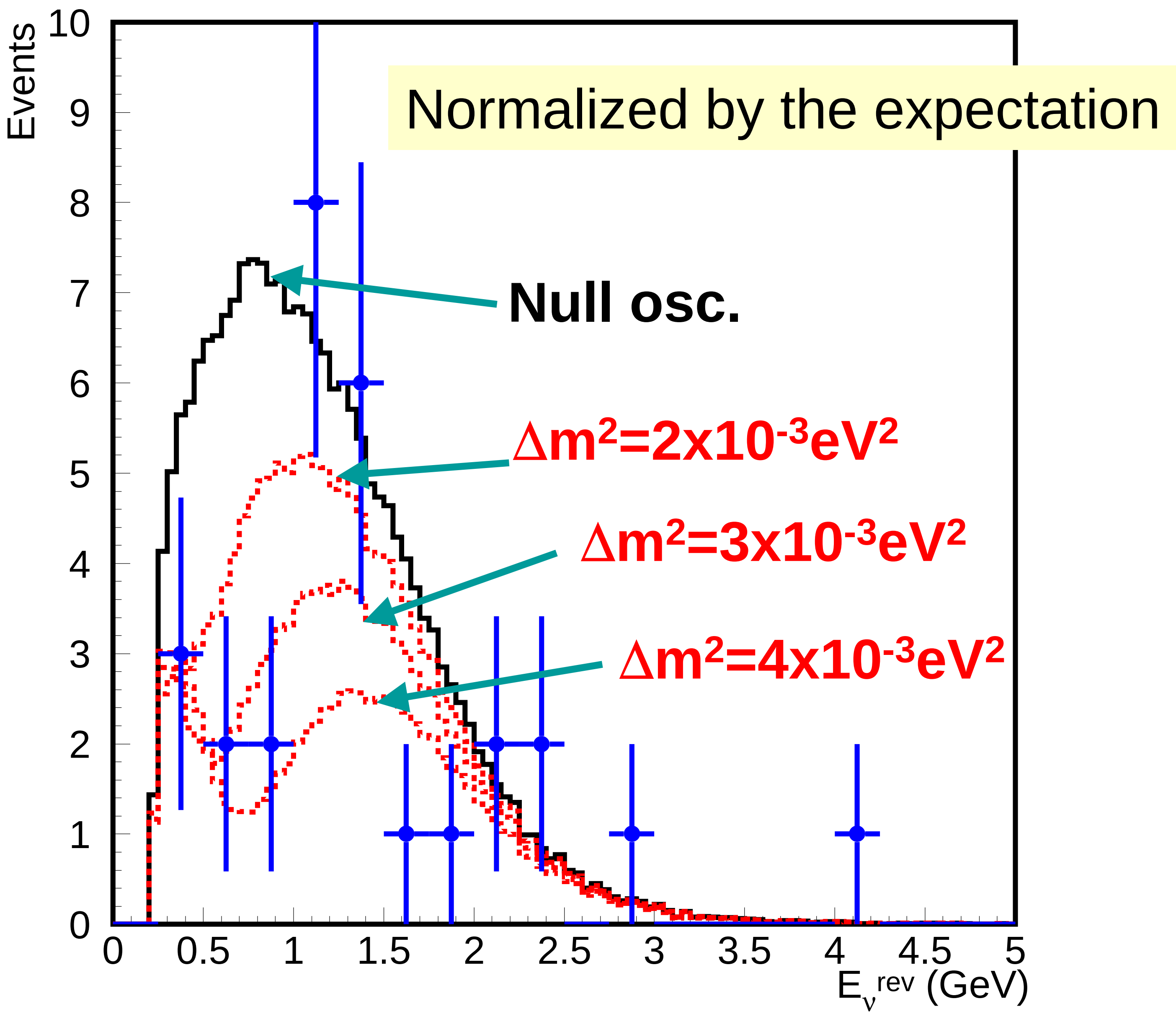
Best fit point ($\sin^2 2\theta$, Δm^2) = (1.0, 2.8×10^{-3}eV^2)

KS test prob.(shape): 79%

N_{SK}=54.2 (Obs.=56)

Very good agreement Shape & N_{SK}

1Rμ spectrum with Δm^2



Result

Null Oscillation Probability

	analysis-1	analysis-2
N_{SK} only	1.3%	0.7%
Shape only	15.7%	14.3%
N_{SK}+Shape	0.7%	0.4%

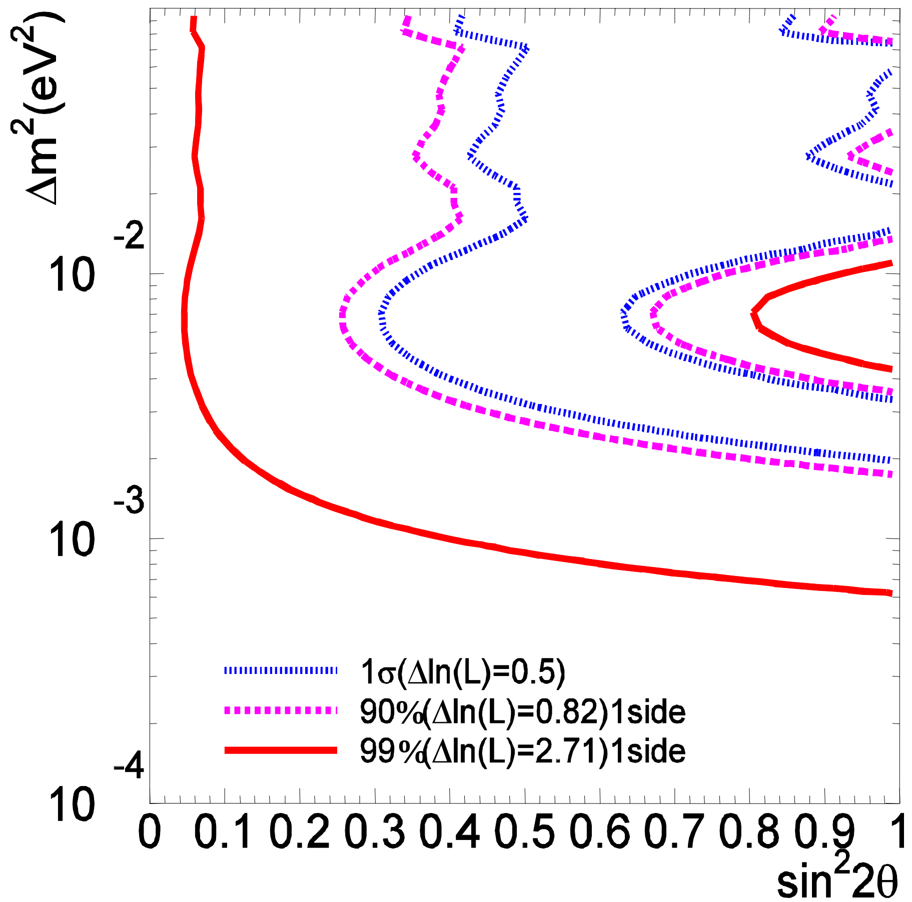
Best fit ($\sin^2 2\theta$, Δm^2)

	analysis-1	analysis-2
Shape only	(1.0, 3.0×10^{-3}eV^2)	(1.0, 3.2×10^{-3}eV^2)
N_{SK} +Shape	(1.0, 2.8×10^{-3}eV^2)	(1.0, 2.7×10^{-3}eV^2)

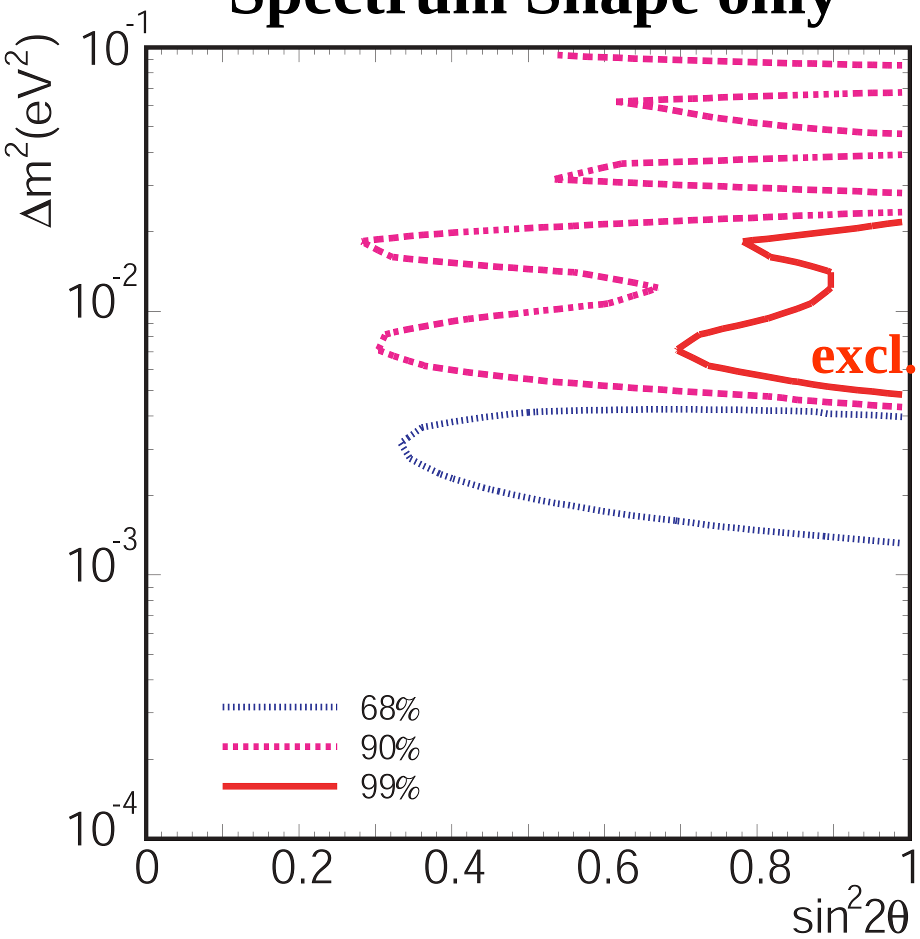
Both Shape and N_{SK} +Shape indicate consistent parameter region

Allowed regions

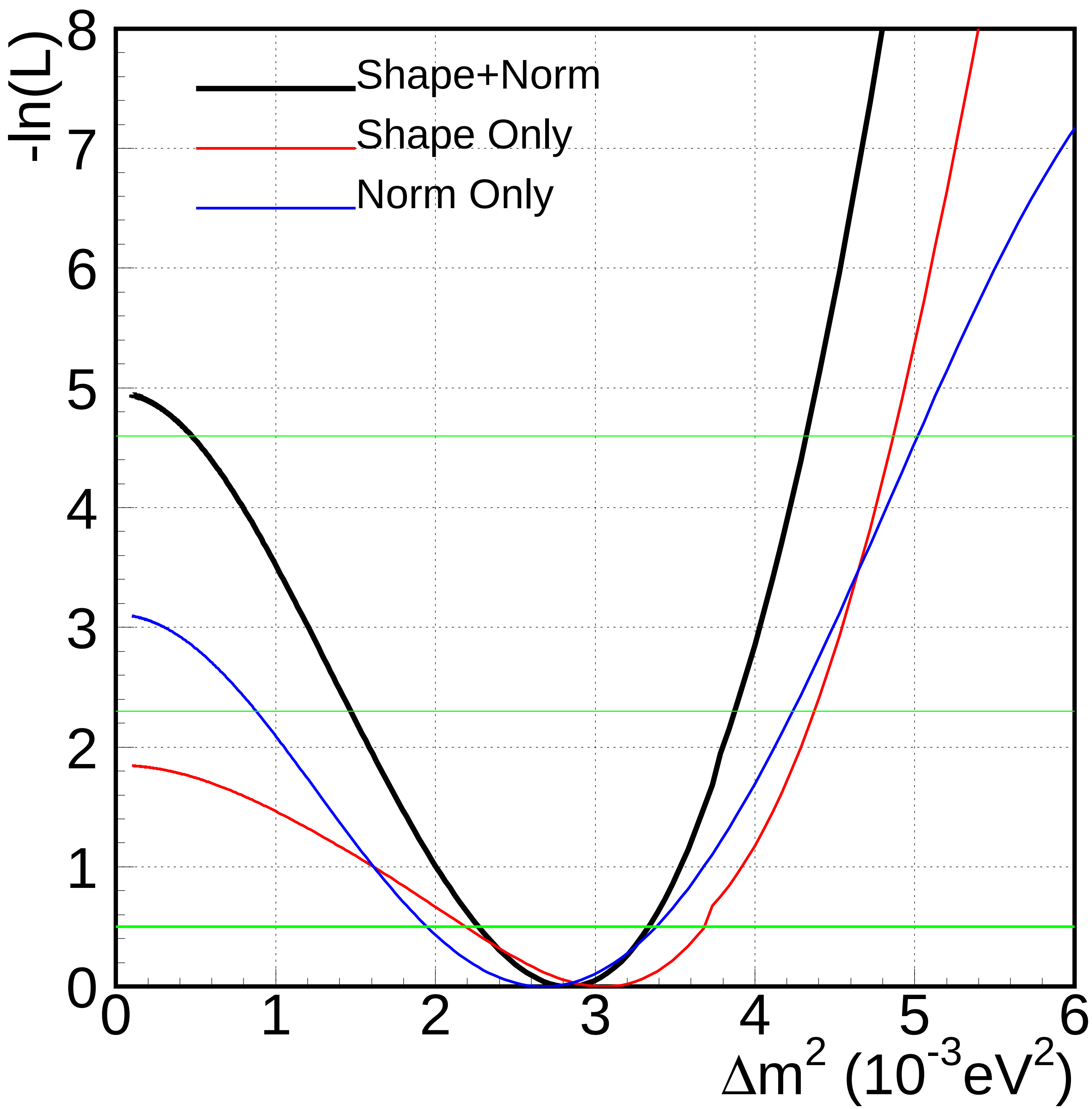
Total no. of Events only



Spectrum Shape only

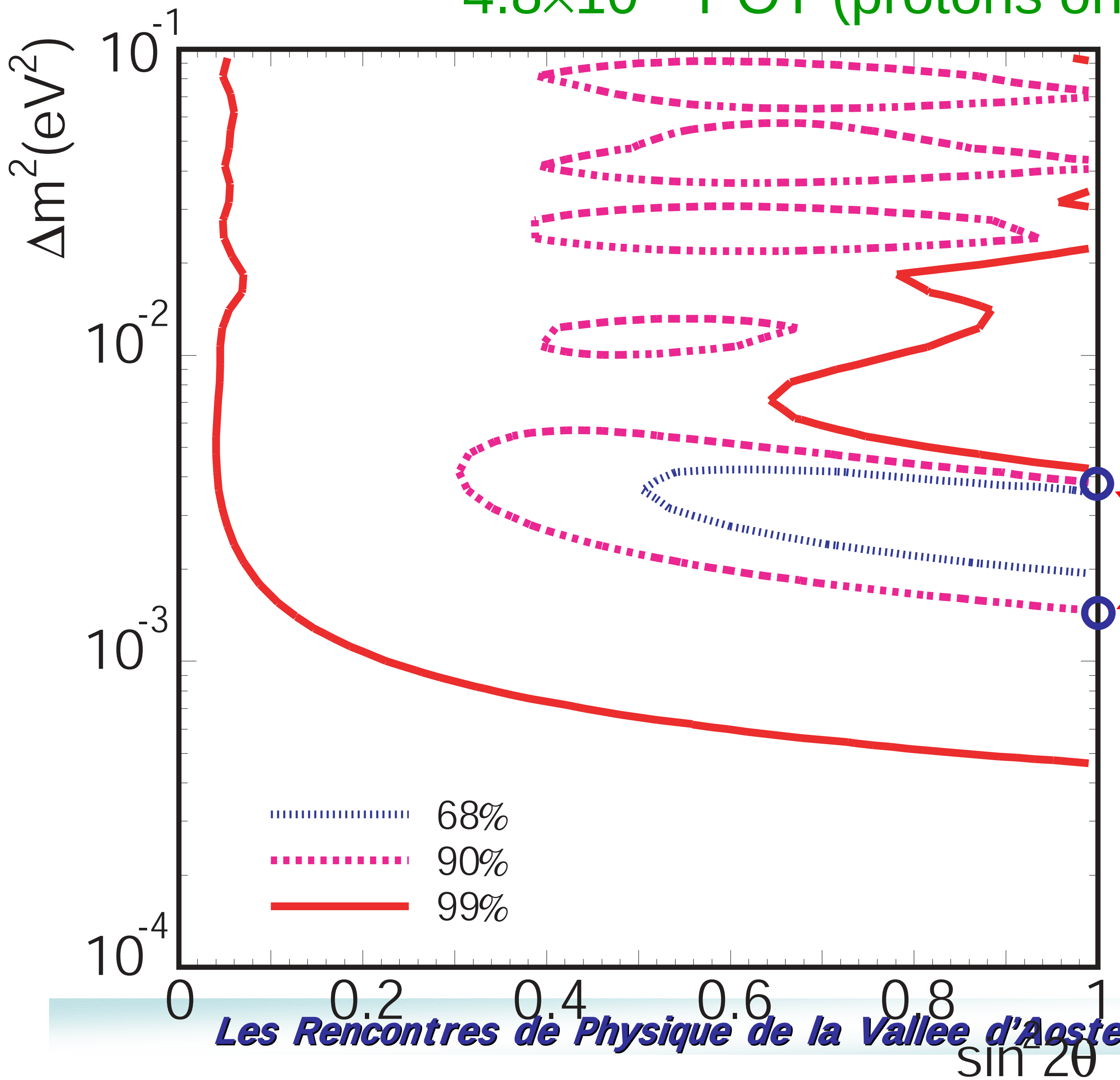


Both indicate consistent Δm^2 region


-ln(L)
Shape+Norm
Shape Only
Norm Only
0
1
2
3
4
5
6
7
8
0
1
2
3
4
5
6
Δm^2 (10^{-3}eV^2)

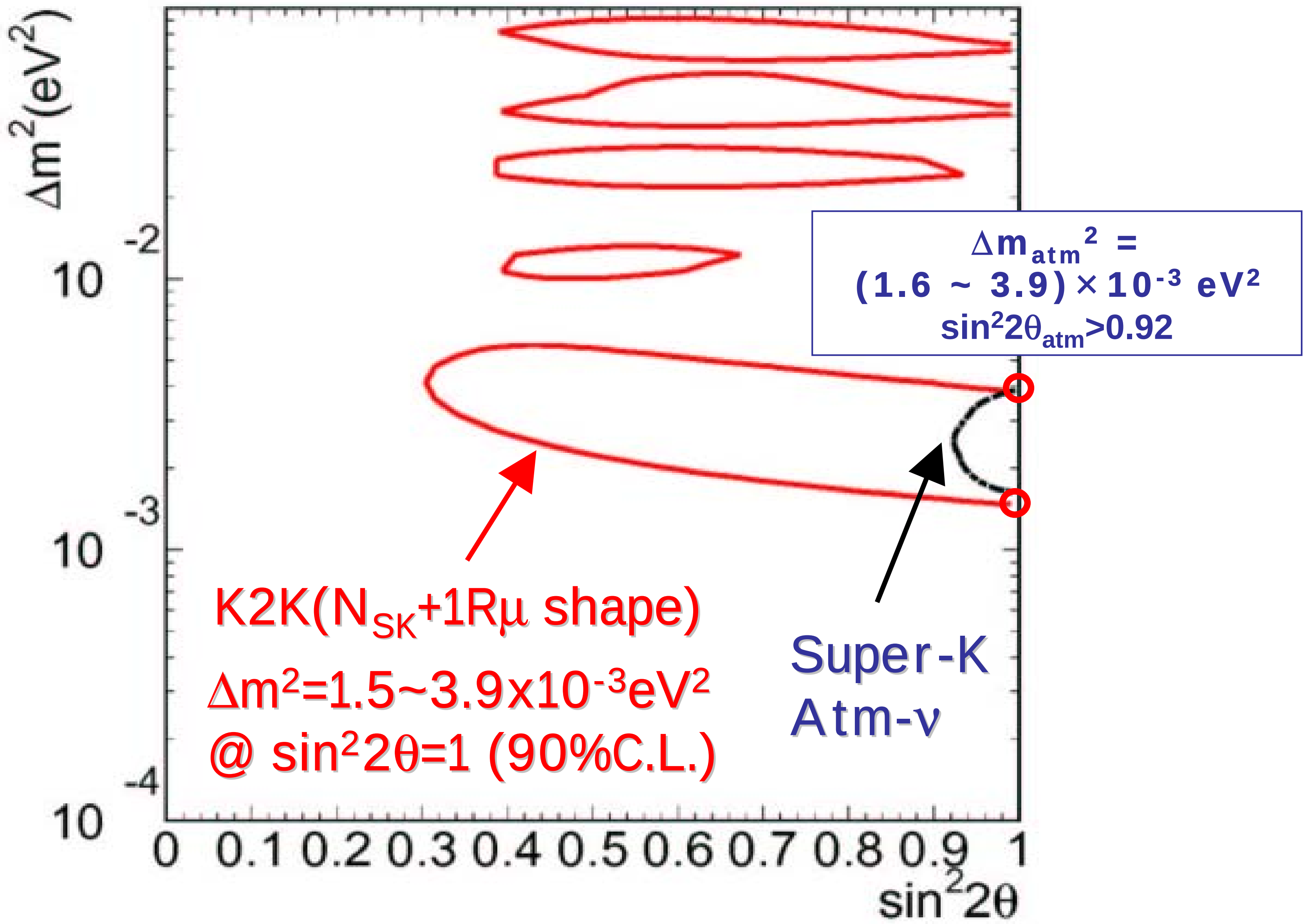
Allowed region (Shape+Norm)

4.8×10^{19} POT (protons on target)



Δm^2= $1.5\sim3.9\times10^{-3}eV^2$ @ $\sin^2 2\theta=1$ @90%CL

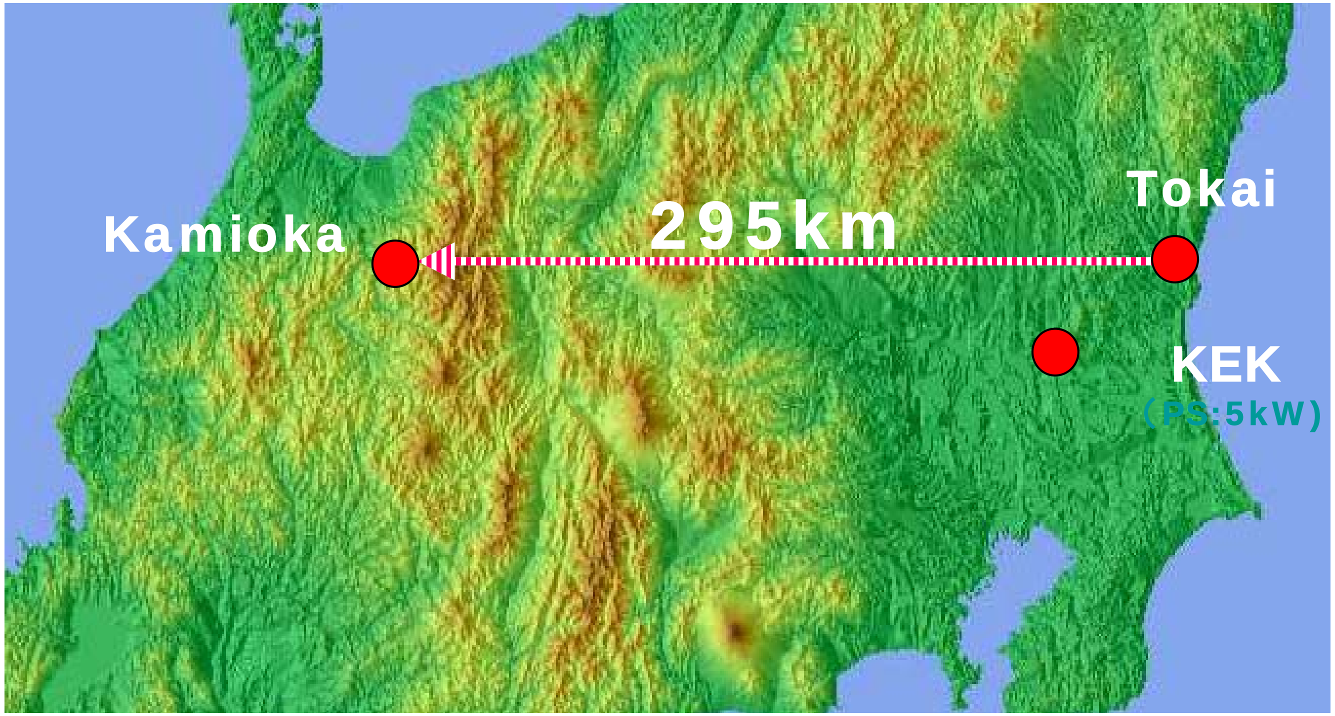
90%CL Allowed Regions of K2K and SK atm-ν



Conclusion

- K2K Oscillation analysis on June99 ~July01 data(K2K-I)
  1. Null oscillation probability is less than 1%.
  2. Both SK rate reduction and E_ν^{rec} shape indicate consistent oscillation parameters region.
  3. Δm^2=1.5~3.9x10^{-3}eV^2 for $\sin^2 2\theta$=1 @ 90%CL
  4. $\sin^2 2\theta$, Δm^2 are consistent with atmospheric neutrino results
- Data taking has been resumed successfully (2002/12/22~, K2K-II).
- Goal is to accumulate 10^{20} protons on target, Twice as large as this data sample.

JHF-Kamioka ν Project



- ***JHF 50GeV PS → Super-Kamiokande***

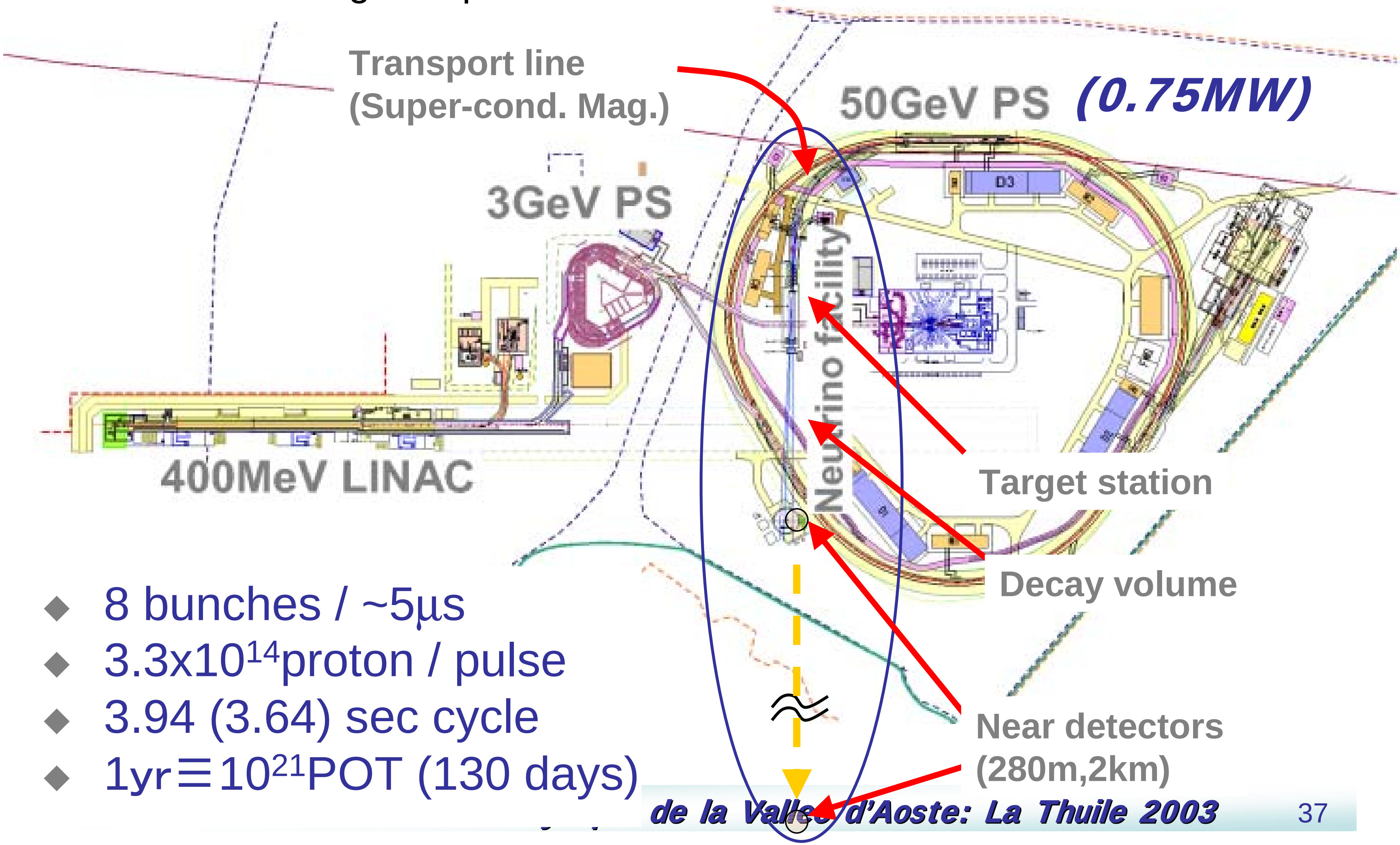
  (0.75MW) (22.5kt fid.)

  - × ~100 of K2K
  - $\nu_\mu \to \nu_x$ disapp. / $\nu_\mu \to \nu_e$ **app.** / NC

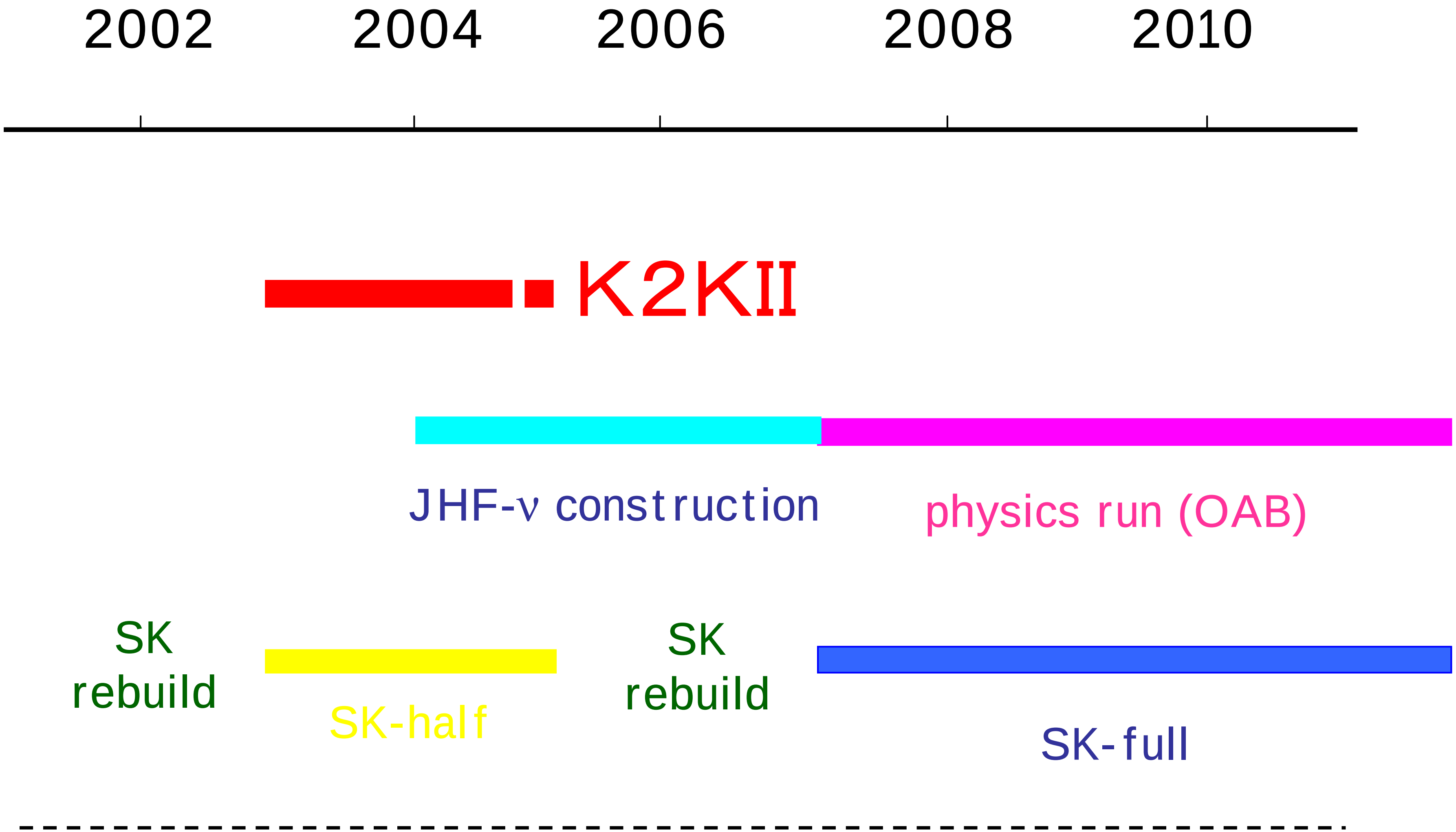
JHF Facility

Const.：2001～2006 (approved)

（ν beam-line： budget request submitted）



- 8 bunches / ~5μs
- 3.3×10^{14}proton / pulse
- 3.94 (3.64) sec cycle
- 1yr≡10^{21}POT (130 days)


2002
2004
2006
2008
2010
K2KII
JHF-ν construction
physics run (OAB)
SK
rebuild
SK-half
SK
rebuild
SK-full