Super-Kamiokande Results and K2K Status

Kenzo NAKAMURA
KEK

NuFact '00
Monterey, California
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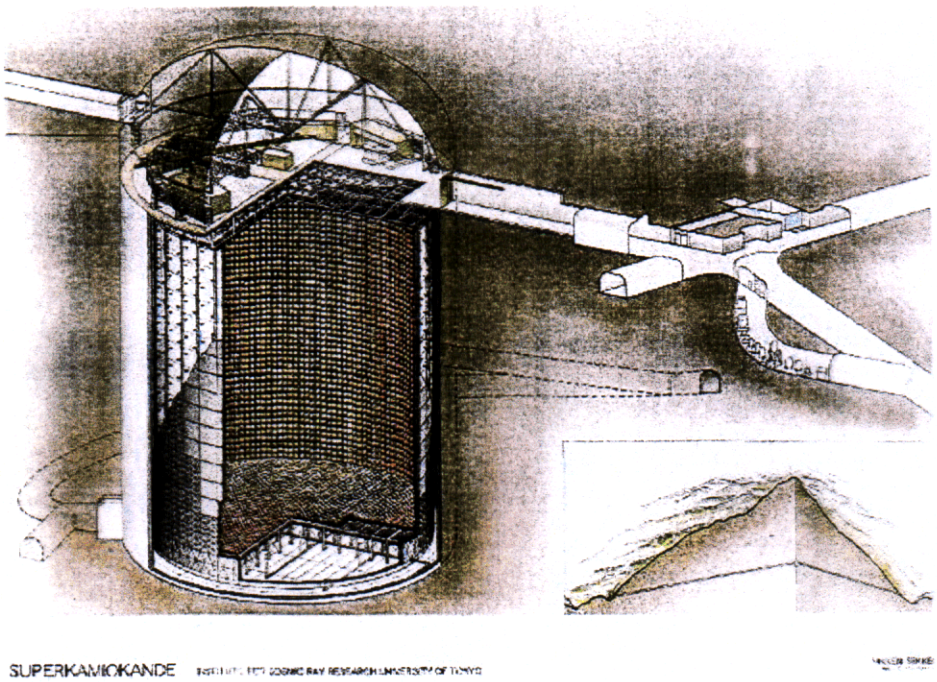
- Introduction
- SK atmospheric-neutrino results
- SK solar-neutrino results
- K2K status

- LOI for a future LBL ν oscillation experiment with a proposed JHF 50 GeV PS

- Conclusions

Super-Kamiokande



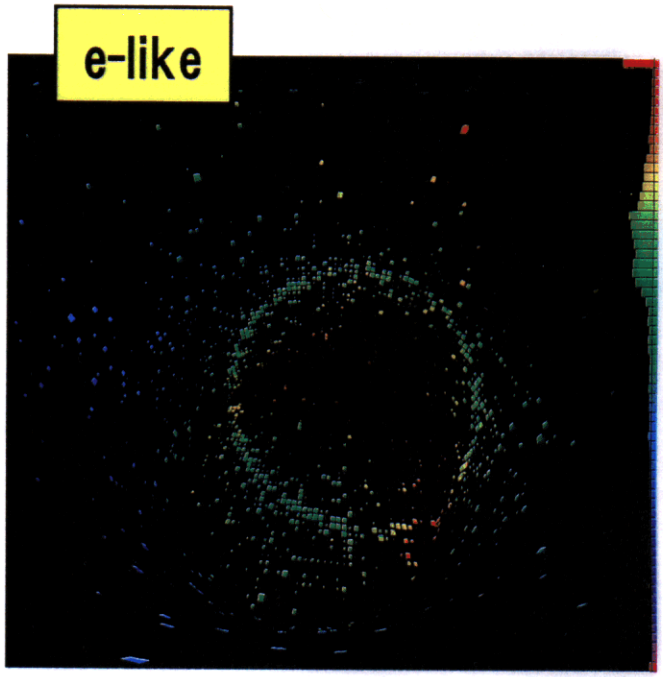
- Giant water Cherenkov detector
  - Total mass: 50,000 tons
  - Fiducial mass: 22,500 tons
  - Location: 1,000 m underground
  - Inner detector: 11,146 PMTs (50-cmϕ)
  - Outer detector: 1,885 PMTs (20-cmϕ)
- Operation since April 1996

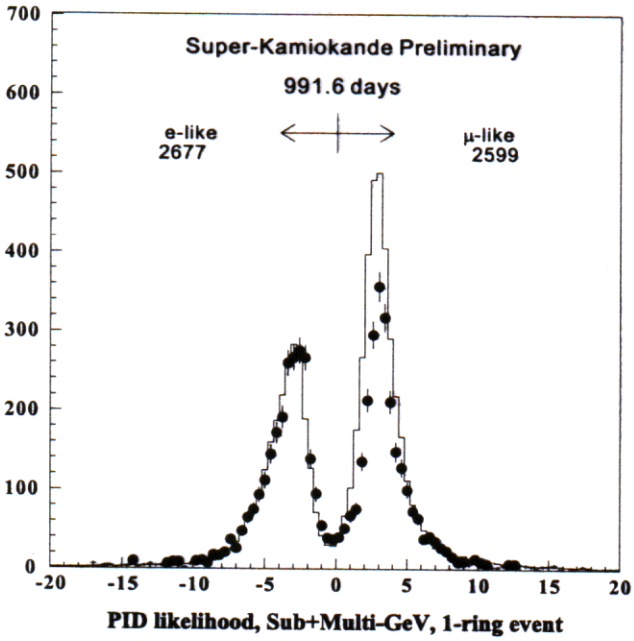
Super-K data

- **Atmospheric-neutrino data**
  - Updated at the Dec-99 Collaboration Meeting
  - Exposure: 61 kton·yr or 992 days
  - Next update: June-00

- **Solar-neutrino data**
  - No update since June-99
    - Now every 6-month update does not give much qualitative improvement of the data
  - Exposure: 825 days
  - Next update: June-00

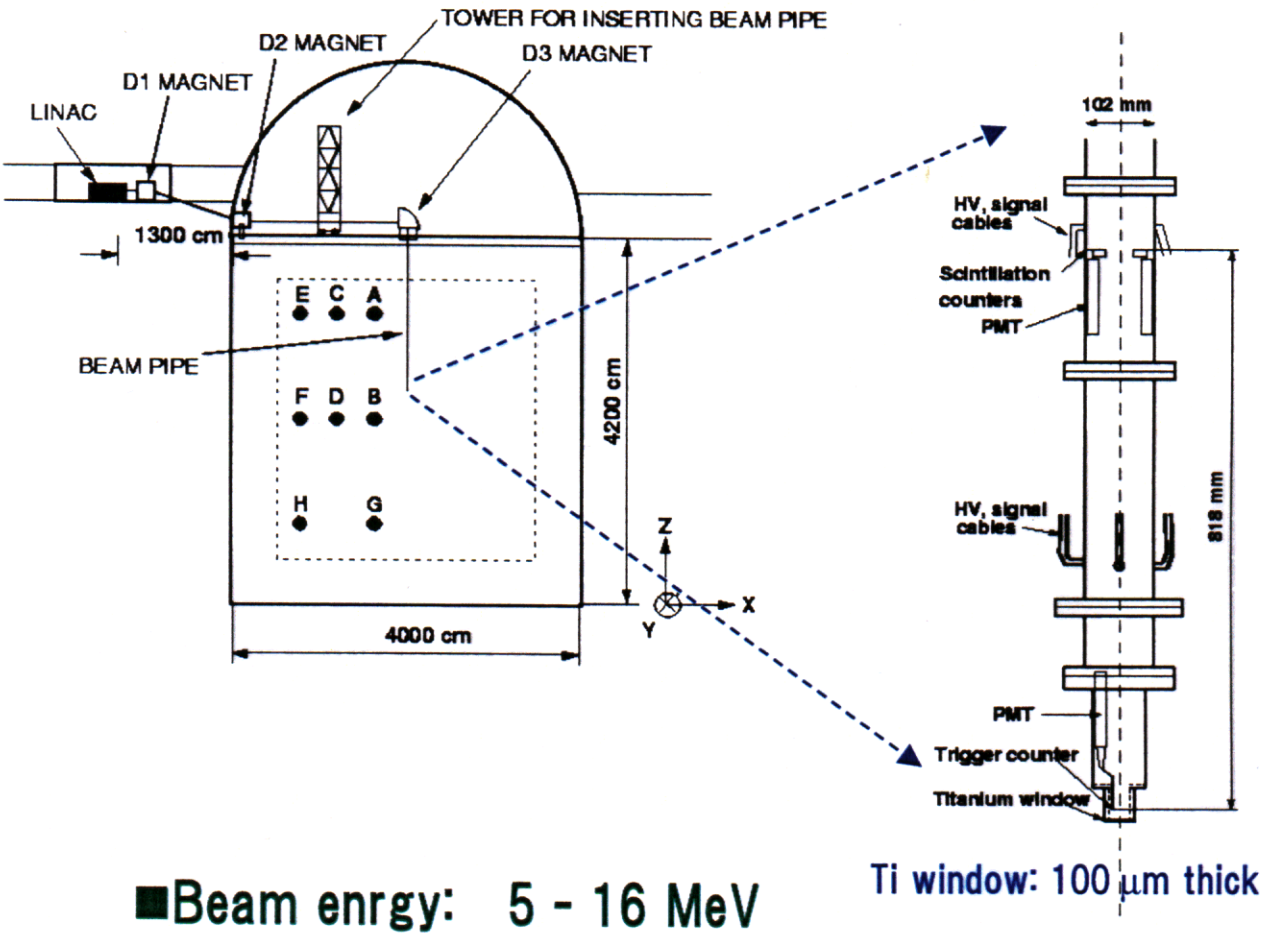
μ/e identification





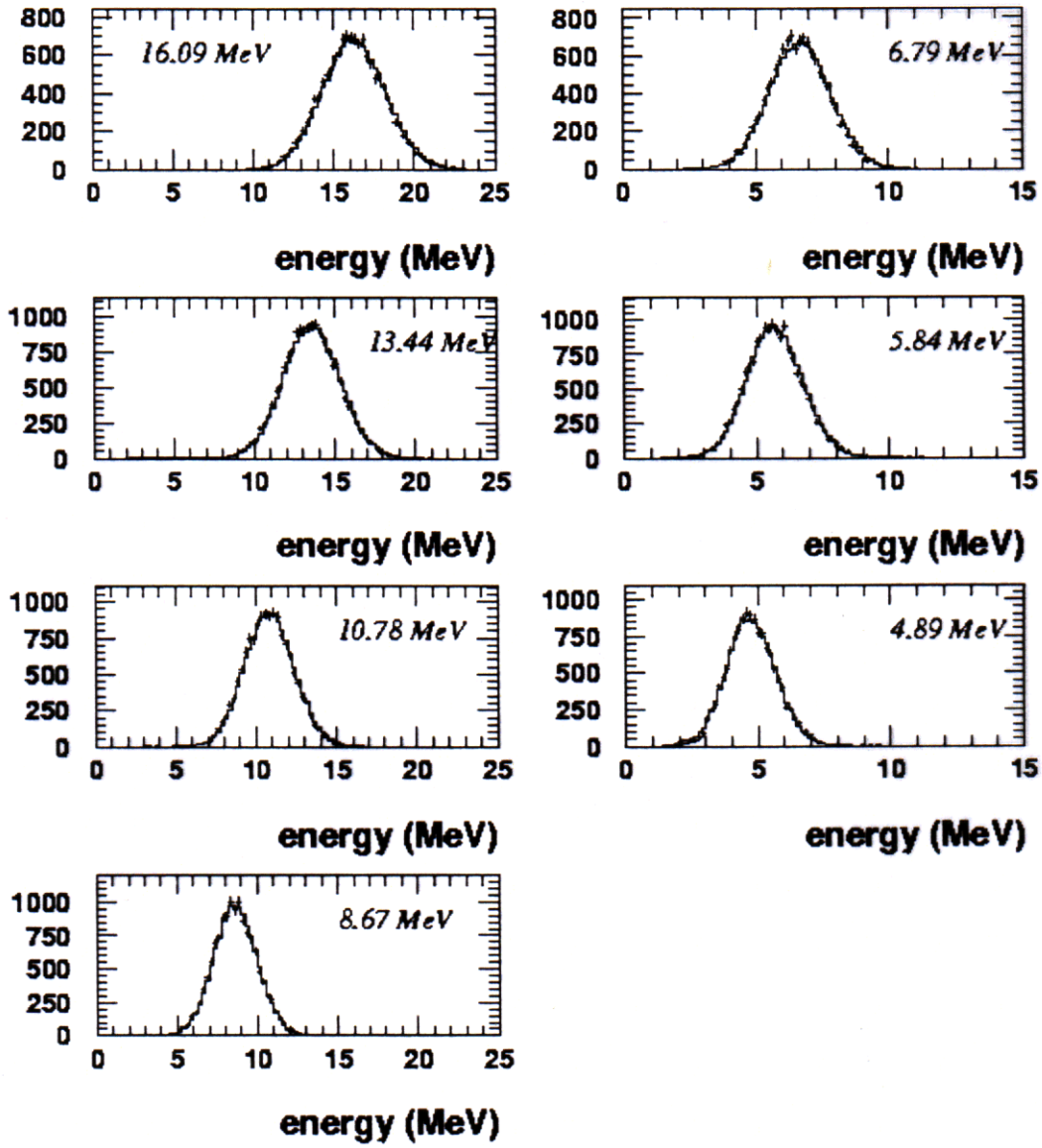
- Likelihood parameter
  - (log-likelihood difference for e and μ hypotheses)
- Validity of the method confirmed by the KEK beam test
- Systematic error to the double ratio R due to miss ID
  - 3% for multi-GeV
  - 2% for sub-GeV

Electron LINAC for calibration



- Beam enrgy: 5 - 16 MeV
- Calibration for
  - Absolute energy scale: < 1%
  - Energy resolution
  - Vertex position resolution
  - Angular resolution

Energy calibration with LINAC

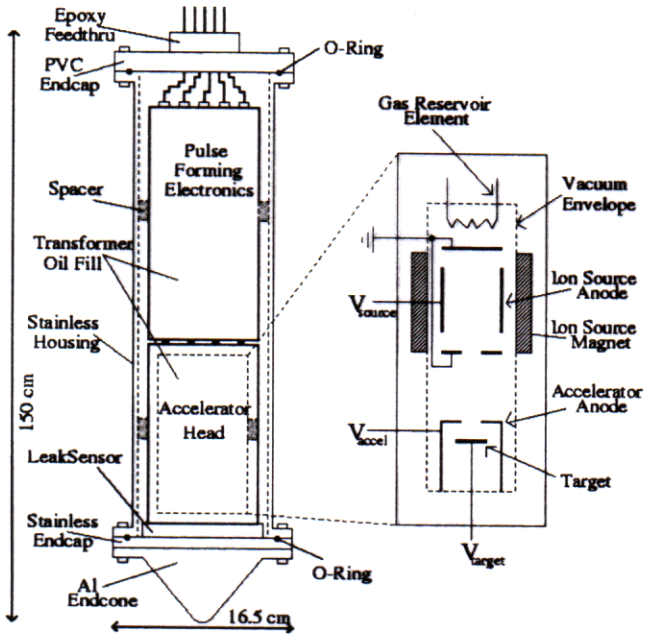


Energy distributions for (x,z) = (-12m, +12m).

Data points are compared to MC.

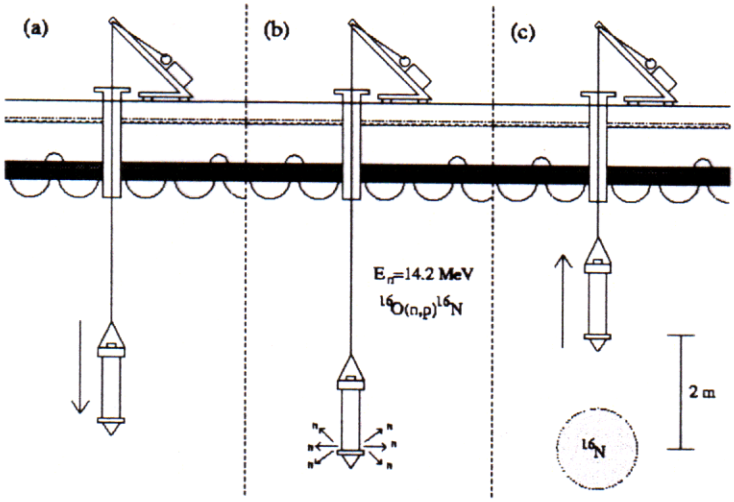
^{16}N calibration with DT generator

- Cross check the absolute energy scale established by LINAC
- Isotropic and different systematic uncertainty



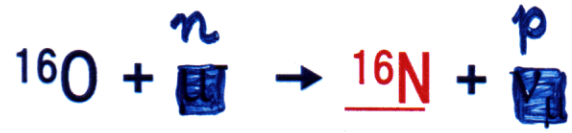
$^{3}H + {}^{2}H \rightarrow {}^{4}He + n$

14.2 MeV

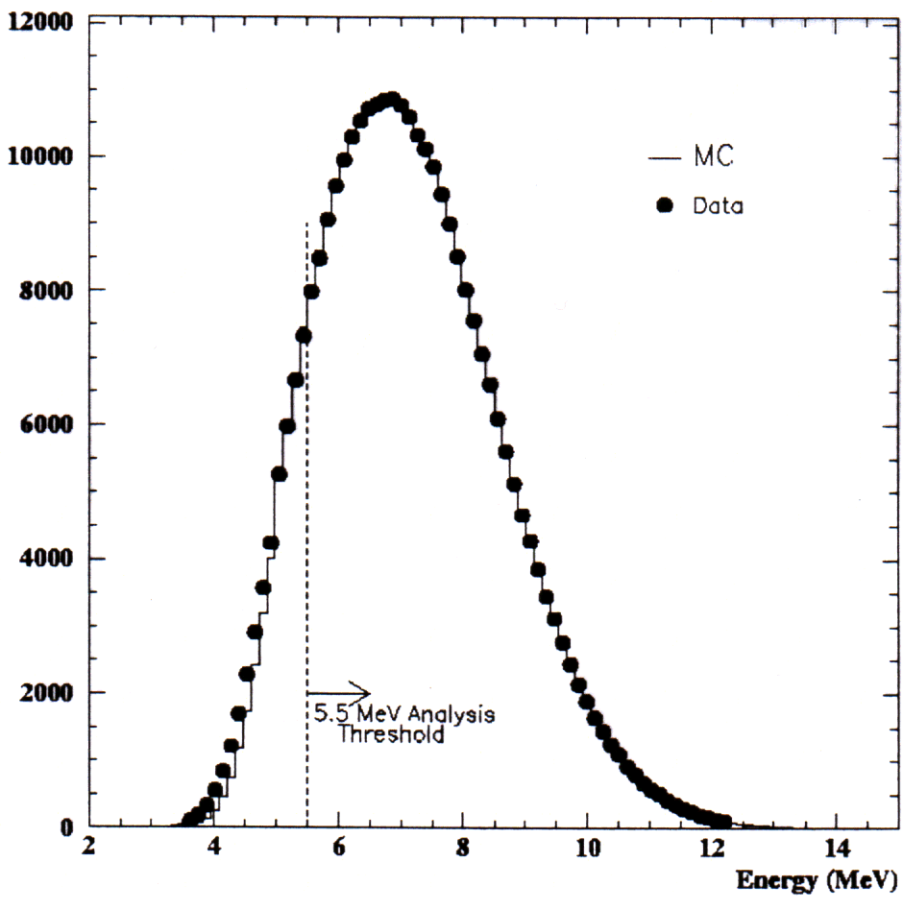


Data-taking method

^{16}N energy calibration

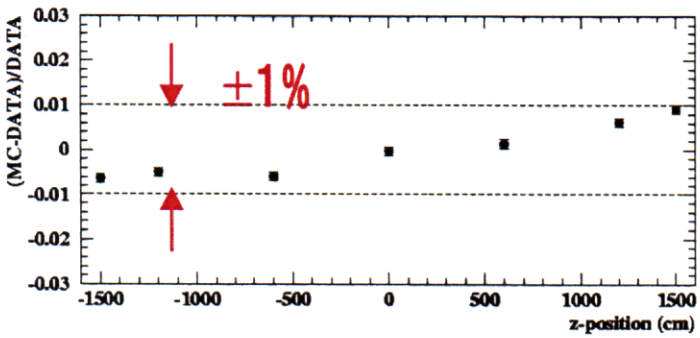


Half life: 7.13 sec

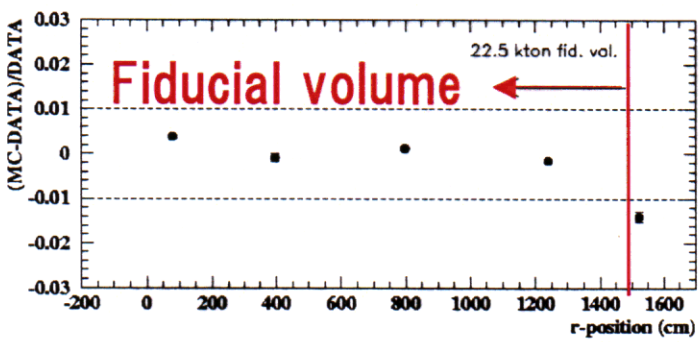


Position-weighted average energy spectrum

^{16}N energy calibration

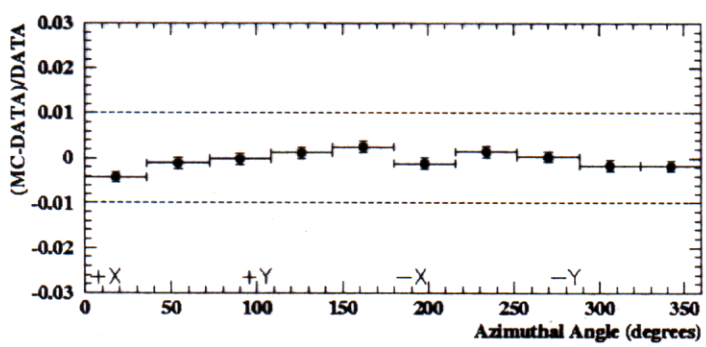


Position dependence of the energy scale



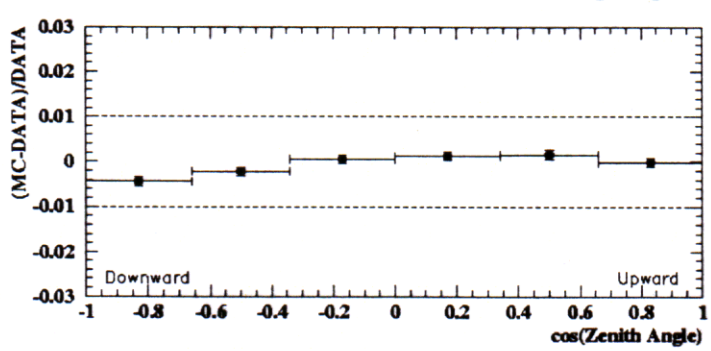
Z

r



Angular dependence of energy scale

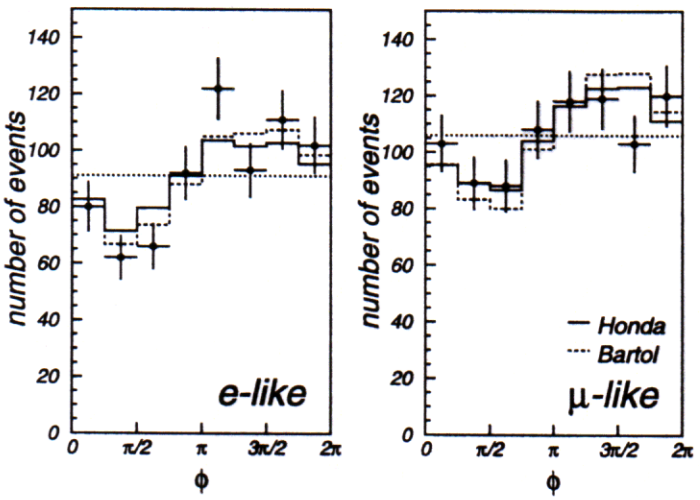
Azimuthal angle

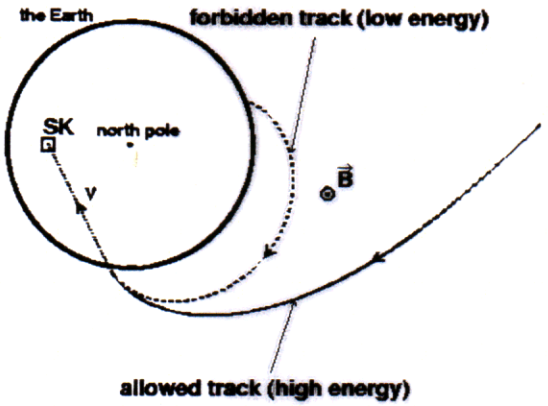


Cos(Zenith angle)

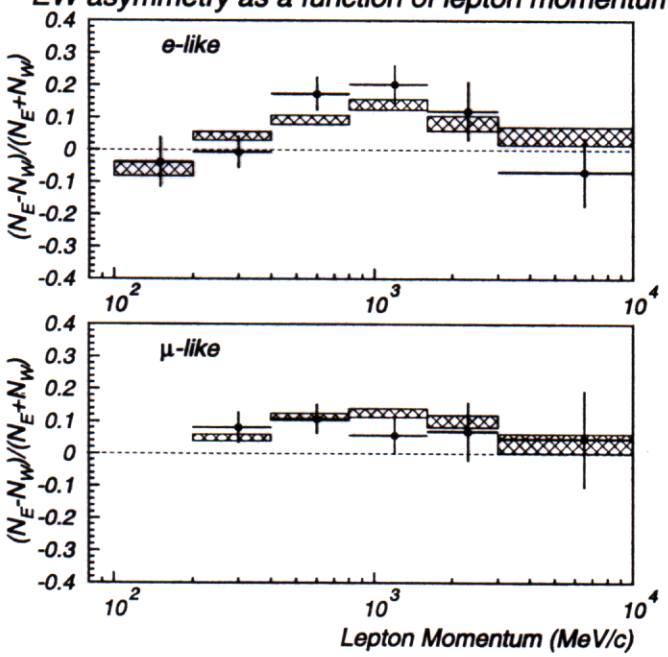
East-west effect

Azimuthal angle distribution





EW asymmetry as a function of lepton momentum



- Primary cosmic rays have positive charge
- So, cutoff energy differs for arrival from East or West
- This causes azimuthal anisotropy
- The obesrved results confirm the validity of Monte Carlo

Sub-GeV, Multi-GeV Event Summary

Sub-GeV event Summary

Evis < 1.33GeV
P_e > 100MeV/c
P_μ > 200MeV/c

	DATA	MC(Honda)	MC(Bartol)
1R	4363	5219.2	5095.0
e-like	2185	2081.8	2049.1
μ-like	2178	3137.4	3045.9
2R	1144	1359.1	1337.2
≥3R	493	652.4	651.0
TOTAL	6000	7230.7	7083.2

$$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = 0.661 \pm \begin{matrix}0.020\\0.020\end{matrix}\ (\text{stat.}) \pm 0.052\ (\text{sys.})\ (\text{Honda})$$

$$= 0.671 \pm \begin{matrix}0.021\\0.020\end{matrix}\ (\text{stat.}) \pm 0.053\ (\text{sys.})\ (\text{Bartol})$$

Multi-GeV event Summary

(1) FC (Evis > 1.33GeV)

	DATA	MC(Honda)	MC(Bartol)
1R	913	1121.3	1139.3
e-like	492	481.3	499.2
μ-like	421	640.0	640.1
2R	368	490.8	502.4
≥3R	659	783.0	817.5
TOTAL	1940	2395.1	2459.2

(2) PC

	DATA	MC(Honda)	MC(Bartol)
TOTAL	563	818.9	864.2

*All events are assumed to be μ-like.
*Fraction of CC ν_μ, $\bar{\nu}_\mu$ events in the PC sample is estimated to be (97-98)%.

$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}}$

FC + PC

$$= 0.660 \pm \begin{matrix}0.038\\0.035\end{matrix}\ (\text{stat.}) \pm 0.078\ (\text{sys.})\ (\text{Honda})$$

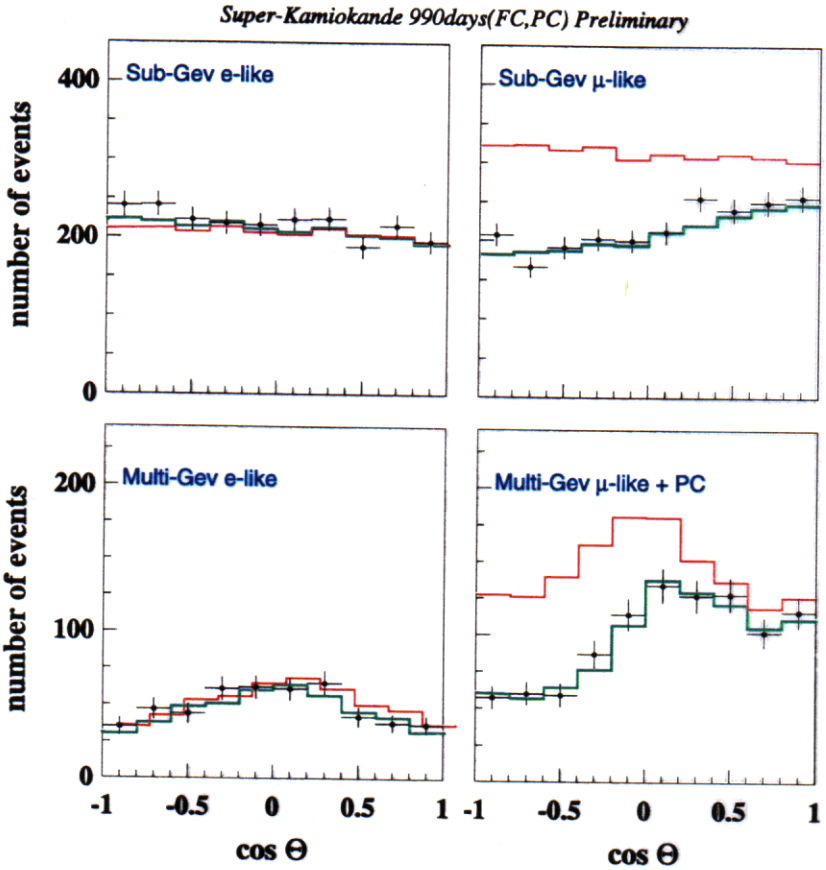
$$= 0.664 \pm \begin{matrix}0.038\\0.036\end{matrix}\ (\text{stat.}) \pm 0.079\ (\text{sys.})\ (\text{Bartol})$$

FC only

$$= 0.643 \pm \begin{matrix}0.044\\0.042\end{matrix}\ (\text{stat.}) \pm 0.094\ (\text{sys.})\ (\text{Honda})$$

$$= 0.667 \pm \begin{matrix}0.046\\0.043\end{matrix}\ (\text{stat.}) \pm 0.098\ (\text{sys.})\ (\text{Bartol})$$

FC+PC
Zenith-angle distributions



Resullt of oscillation analysis (FC+PC)

● Assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillation

Best fit :

χ^2_{min} = 45.3 / 67 d.o.f

at $(\sin^2 2\theta, \Delta m^2) = (1.01 , 2.6\times10^{-3}\ eV^2)$

(Including unphysical region)

χ^2_{min} = 45.4 / 67 d.o.f

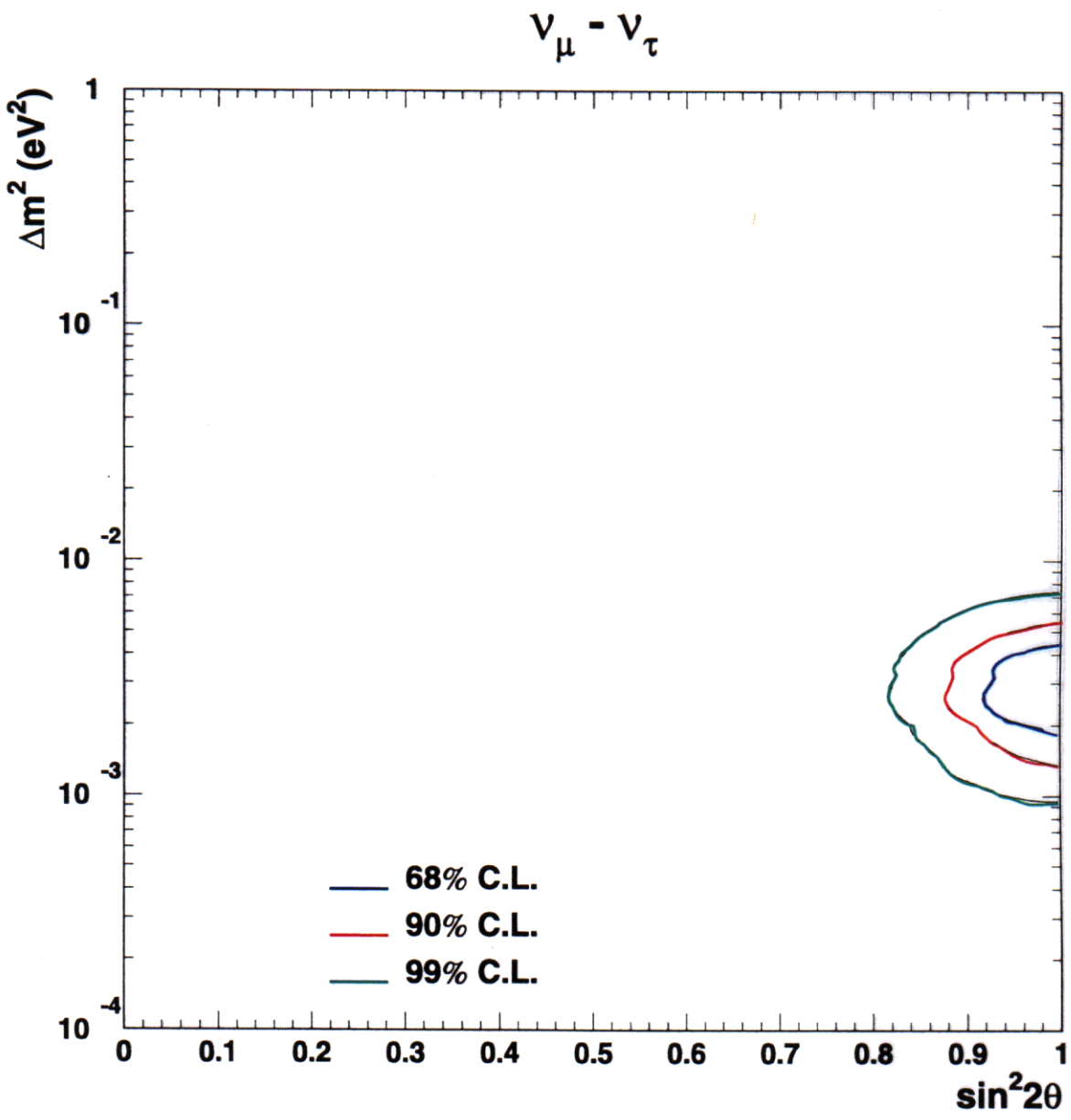
at $(\sin^2 2\theta, \Delta m^2) = (1.00 , 2.6\times10^{-3}\ eV^2)$

(Physical region)

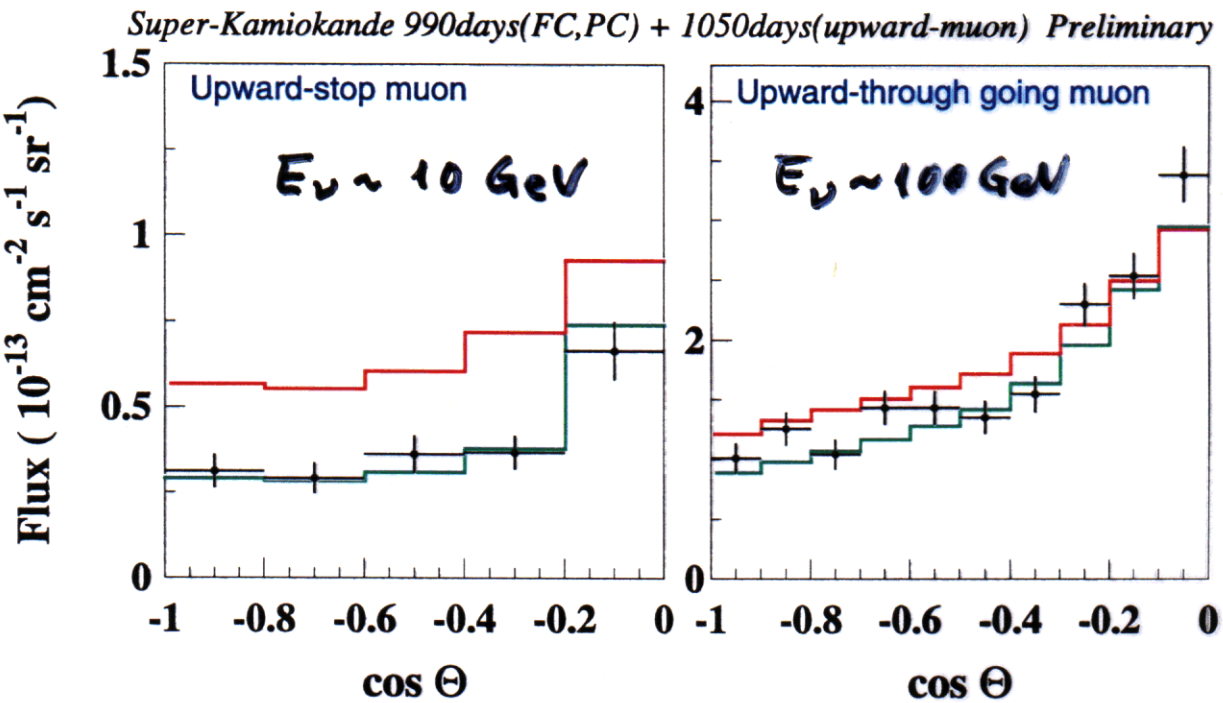
● Assuming null oscillation

χ^2_{min} = 191.0 / 69 d.o.f

Allowed region for FC + PC



Upward-going muons



Result of oscillation analysis (FC+PC+upmu)

- Assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillation

Best fit :

χ^2_{min} = 61.1 / 82 d.o.f

at ($\sin^2 2\theta, \Delta m^2$) = (1.00 , 2.8×10^{-3} eV^2)

(Including unphysical region)

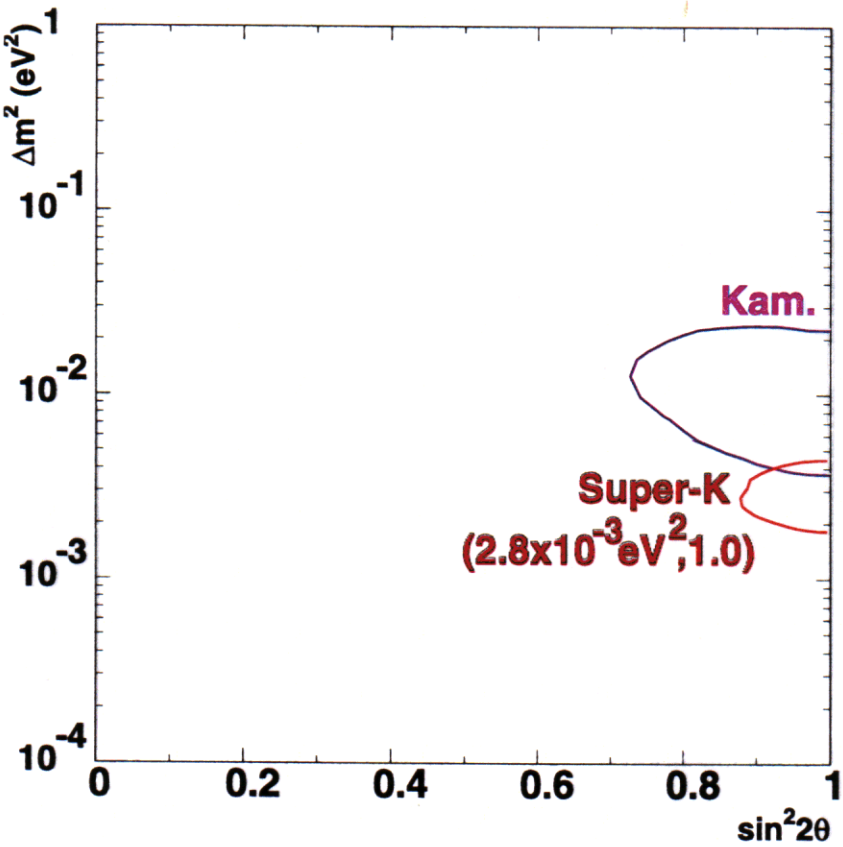
- Assuming null oscillation

χ^2_{min} = 232.5 / 84 d.o.f

Allowed region for FC + PC + up-going μ

Allowed region (FC, PC, up-going μ)

$\nu_\mu \rightarrow \nu_\tau$ 90% C.L.

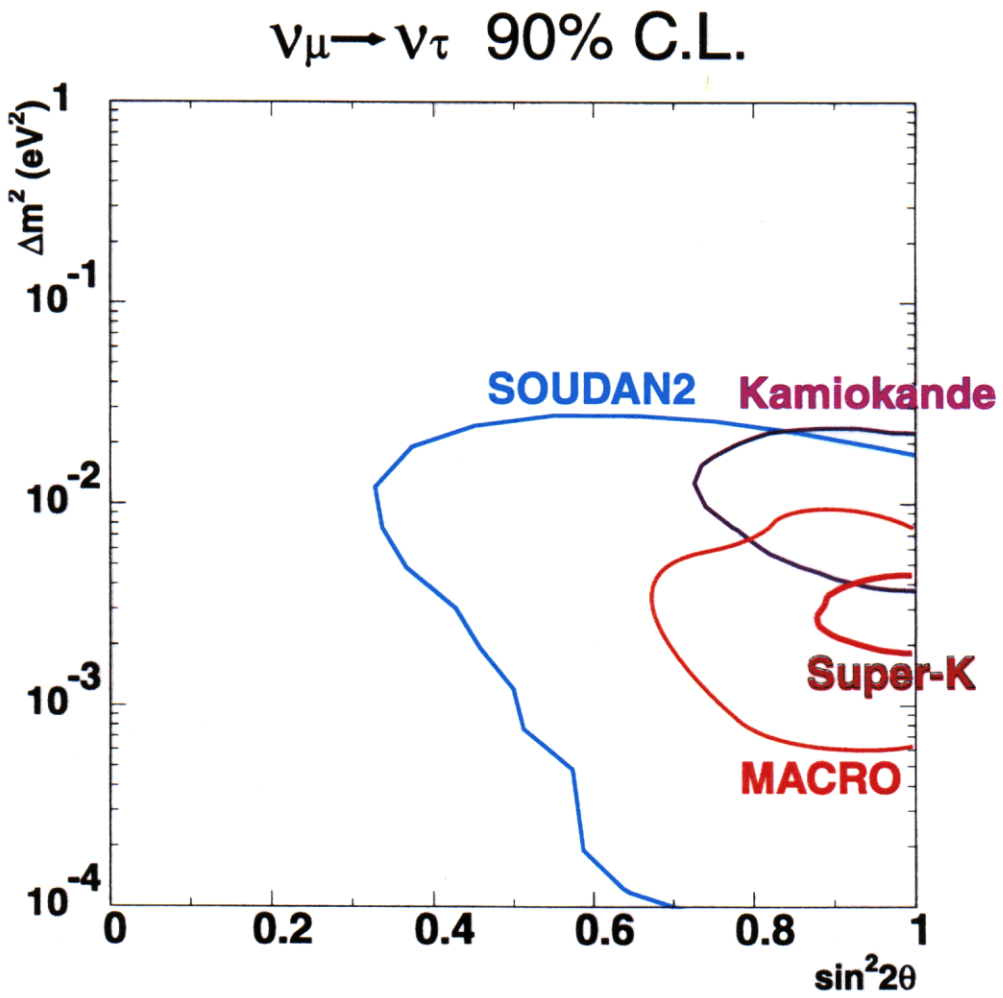


$\Delta m^2 \sim (2 - 5) \times 10^{-3}\ \mathrm{eV}^2$,
$\sin^2 2\theta > 0.88$

(SK 90%C.L. preliminary)

Comparison of allowed regions

Allowed regions



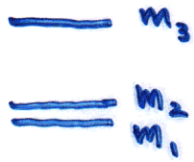
3 flavor oscillation

➤Lepton mixing matrix:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

➤$P(\nu_\beta \to \nu_\alpha) = \delta_{\alpha\beta} - 4\sum_{j<k} U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k} \sin^2(\Delta m^2_{jk} L/4p)$

➤Assuming $m_3^2 >> m_1^2, m_2^2$:



$$\Delta m^2_{13} = \Delta m^2_{23} \equiv \Delta m^2 \ , \ \Delta m^2_{12} = 0$$

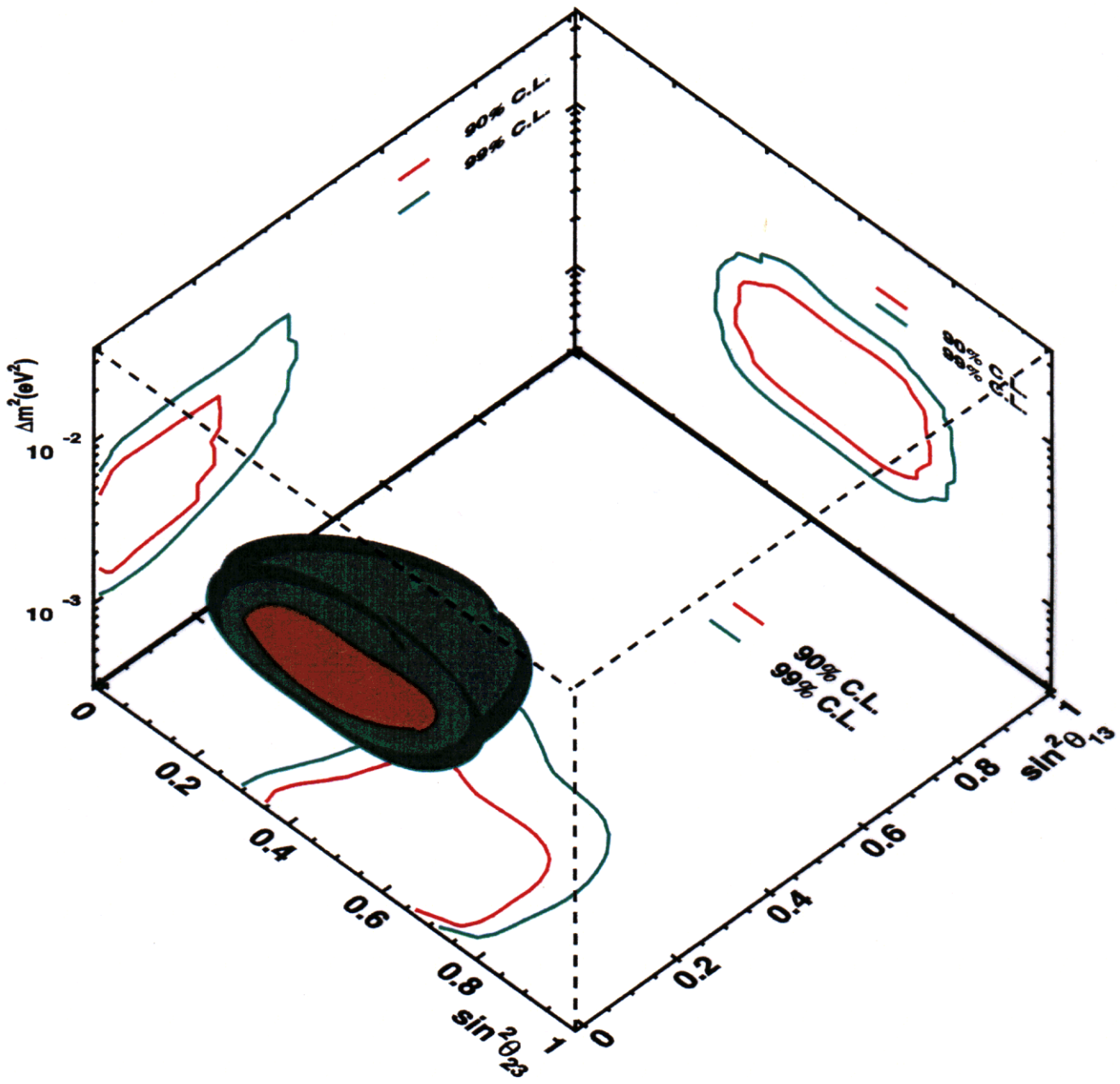
$$P(\nu_\beta \to \nu_\alpha) = 4|U_{\alpha 3}|^2 |U_{\beta 3}|^2 \sin^2(\Delta m^2 L/4p),$$

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4|U_{\alpha 3}|^2 (1-|U_{\alpha 3}|^2) \sin^2(\Delta m^2 L/4p)$$

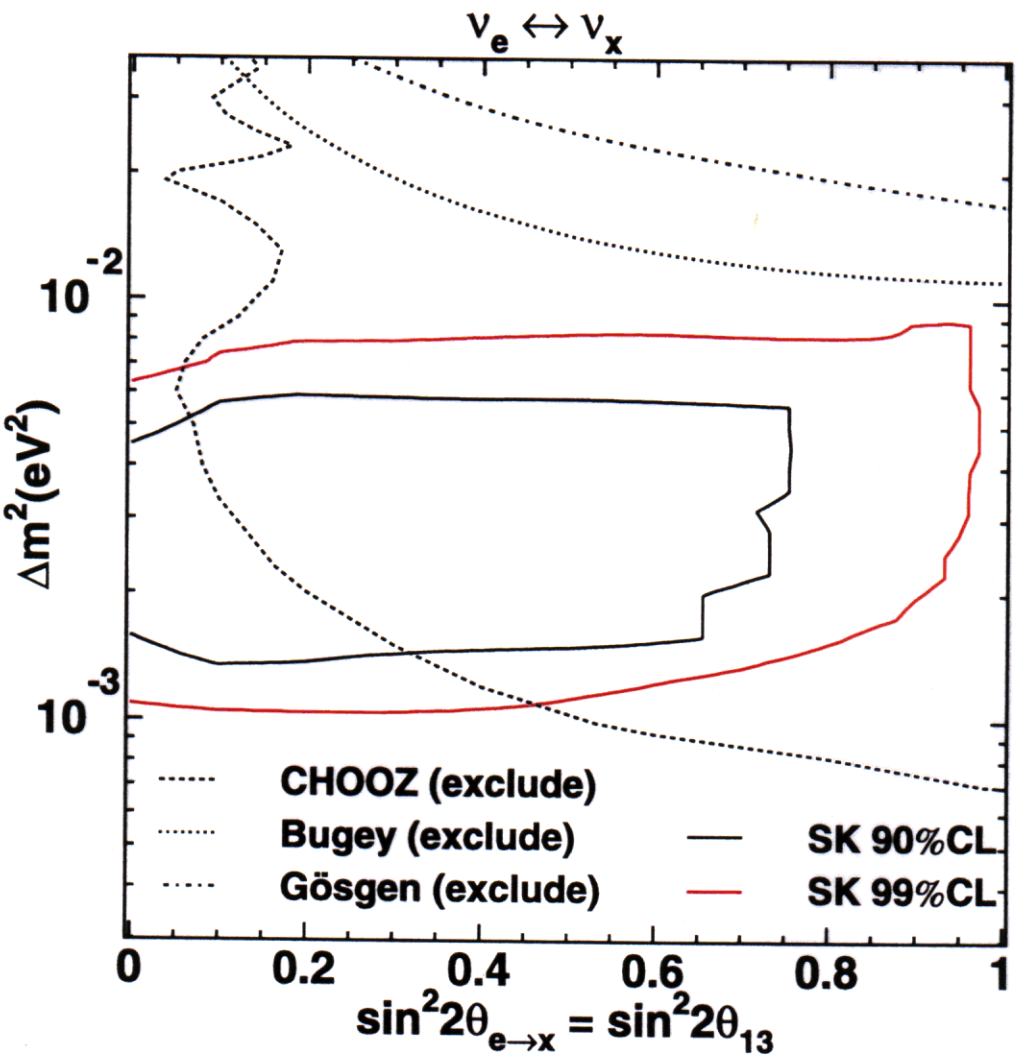
$$(|U_{e3}|^2 = \sin^2\theta_{13} \ , \ |U_{\mu 3}|^2 = \cos^2\theta_{13} \sin^2\theta_{23})$$

☞P can be described only by $(\sin^2\theta_{13} \ , \ \sin^2\theta_{23} \ , \ \Delta m^2)$.

3 flavor analysis for FC + PC



Bounds for $\sin^2 2\theta_{13}$

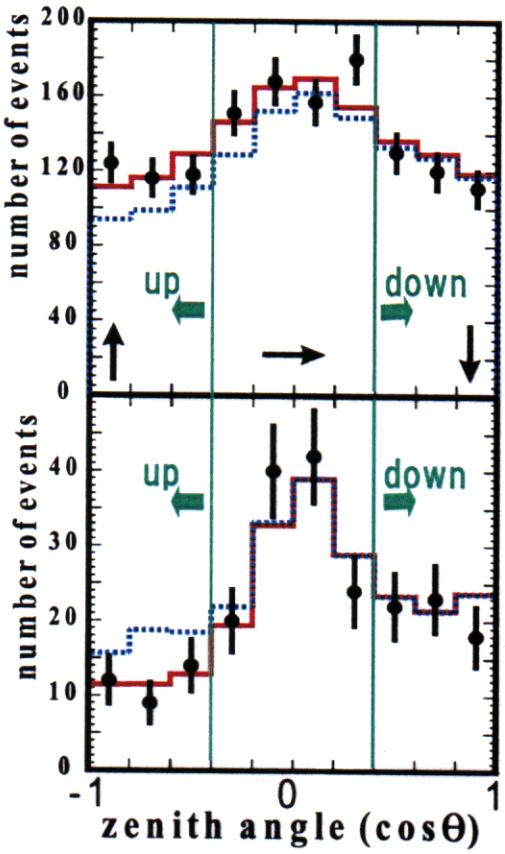


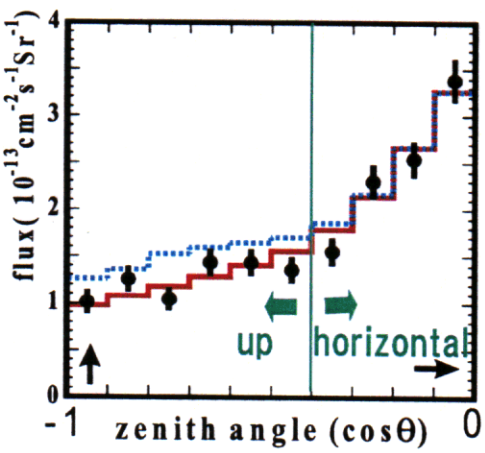
Strategy to discriminate between $\nu_\mu \rightarrow \nu_\tau$ & $\nu_\mu \rightarrow \nu_s$

- ν_s does not interact with matter
  - If $\nu_\mu \rightarrow \nu_\tau$: observe NC events as expected
  - If $\nu_\mu \rightarrow \nu_s$: NC events reduced
- Matter effect
  - $\nu_\mu \rightarrow \nu_\tau$: no matter effect
  - $\nu_\mu \rightarrow \nu_s$: oscillation strongly suppressed for high energy neutrinos by matter effect
    - For $10^{-3} < |\Delta m^2| < 10^{-2}$ eV^2:
      - Matter effect negligible in the sub-GeV region
      - Strong matter effect for $E_\nu > 5 \sim 10$ GeV
- Look at up/down of NC-enriched FC events
- Look at single π^0 events; but large cross section uncertainty
- Look at up/down of high-energy PC events
- Look at vertical/horizontal of upward throughgoing muons

  $E_{median} \sim 100$ GeV

ν_s Sensitive Samples





NC enriched (29%)

- FC Multi-ring
- Max E ring=e-like
- Evis>400MeV

Small matter effect

HE PC

(Eμ>5GeV)

Large Matter effect

Upward throughgoing μ

$\nu_\mu \rightarrow \nu_\tau$

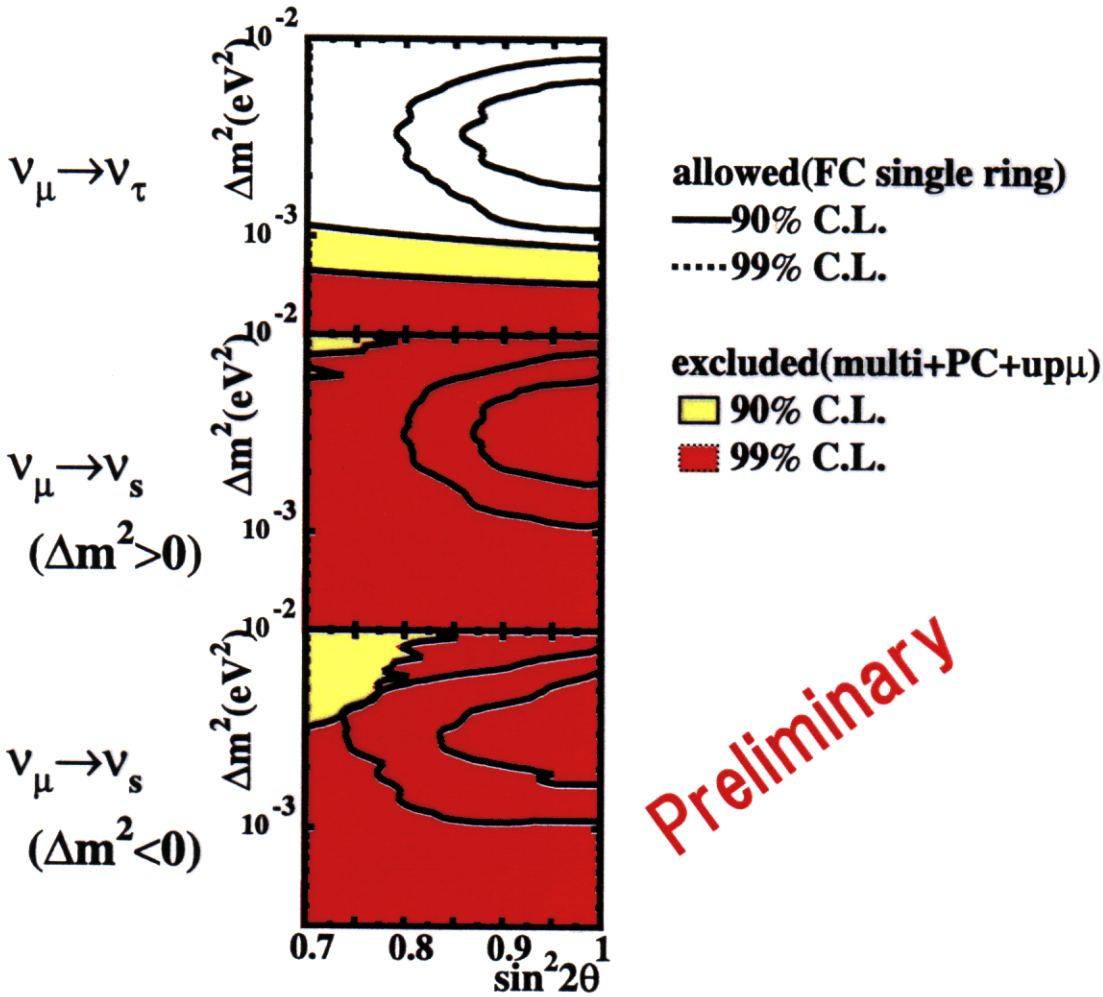
$\nu_\mu \rightarrow \nu_s$

$\Delta m^2 = 3 \times 10^{-3} eV^2$

$\sin^2 2\theta = 1$

ν_τ vs ν_s
Combined Analysis

excluded region from combined analysis(multi+PC+upμ)



$\nu_\mu \rightarrow \nu_s$ oscillation is disfavored
at (almost) 99% C.L.

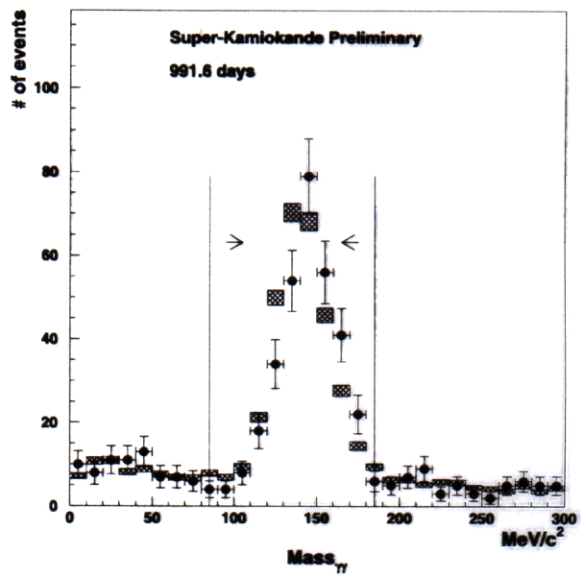
Single π^0

π^0 summary (Preliminary)

live time 991.6 days

Selection criteria for π^0

- 2 rings
- both e-like
- No $\mu \rightarrow e$ decay
- $85\text{MeV/c}^2 < M_{\gamma\gamma} < 185\text{MeV/c}^2$



w/o B.G. sub

observed # of event : 323

expected # of event : 323.4

$$\frac{(\pi^0/e)_{DATA}}{(\pi^0/e)_{MC}} = 0.96 \pm 0.06 \pm 0.01 \pm 0.22$$

data stat. MC stat. sys.

B.G. sub

observed # of event : 275.7

expected # of event : 257.7

$$\frac{(\pi^0/e)_{DATA}}{(\pi^0/e)_{MC}} = 1.02 \pm 0.06 \pm 0.02 \pm 0.24$$

data stat. MC stat. sys.

Single π^0

π^0 MC sample Summary

Charged Current	ν_e	464	' 9.7'%
	ν_μ	170	' 3.6'%
Neutral Current	Δ	1908	40.0%
	coherent π	975	20.5%
	multi π	930	19.5%
	others	318	' 6.7'%
TOTAL		4765	100.0%

systematic error of π^0/e ratio

cross section	20 %
reconstruction tool	7 %
nuclear interaction	7 %
flux	3 %
TOTAL	23 %

- $\nu_\mu \rightarrow \nu_s$ not favored, but not conclusive

Atmospheric neutrino summary

- All the SK atmospheric neutrino data (FC, PC, upward-going μ) are consistent with the $\nu_\mu \rightarrow \nu_\tau$ oscillation.

  90% CL allowed region:

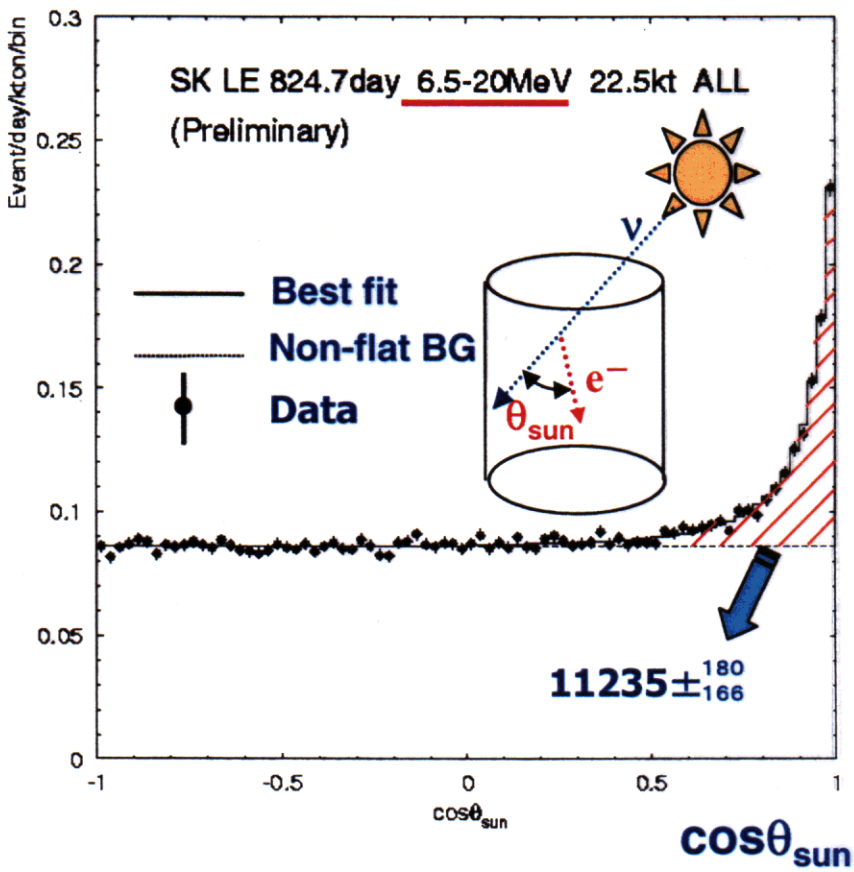
  $2\times10^{-3} < \Delta m^2 < 5\times10^{-3}$ eV^2

  $\sin^2 2\theta > 0.88$

- $\nu_\mu \rightarrow \nu_s$ hypothesis is disfavored at about 99% CL by using NC enriched sample and matter effect.

^{8}B solar-neutrino flux

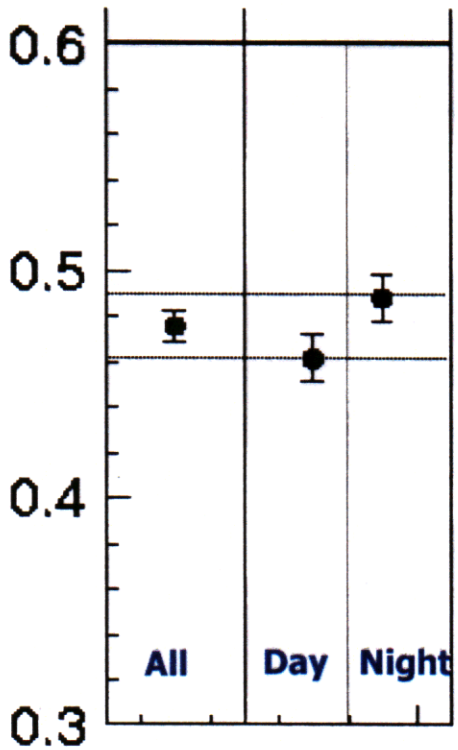
May 31, 1996 ~ April 3, 1999



^{8}B flux : $2.45 \pm 0.04 \pm 0.07$ [x 10^6 /cm^2/sec]

$$\frac{\text{Data}}{\text{SSM(BP98)}} = 0.475\ ^{+0.008}_{-0.007}\ \text{(stat.)} \pm 0.013\ \text{(syst.)}$$

Day & night flux difference



Day 403.2days

$2.37 \pm 0.05(\text{stat.}) \pm {}^{0.07}_{0.06}$ (syst.) [$\times 10^6\ \text{cm}^{-2}\text{s}^{-1}$]

$\frac{\text{Data}}{\text{SSM}} = 0.461 \pm {}^{0.011}_{0.010}$ (stat.) $\pm {}^{0.07}_{0.06}$ (syst.)

Night 421.5days

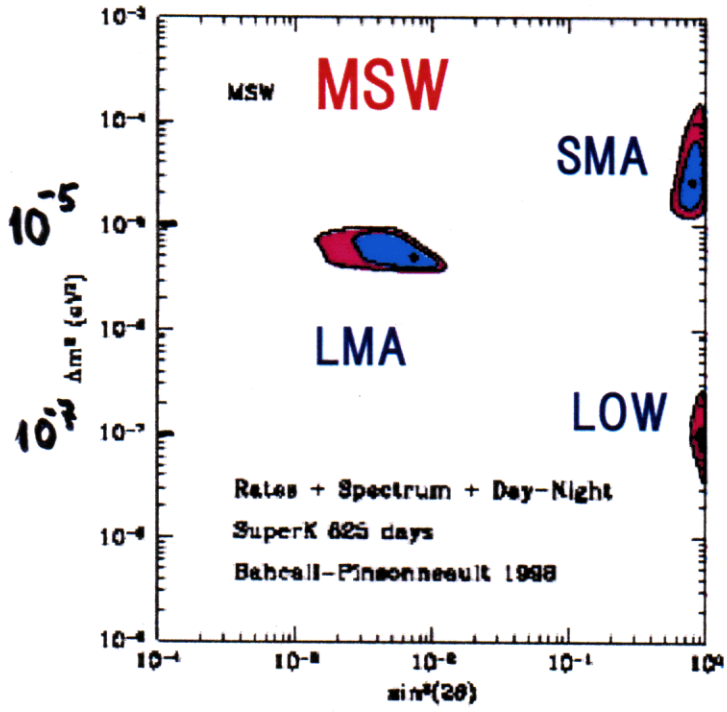
$2.51 \pm {}^{0.06}_{0.05}$ (stat.) ± 0.07 (syst.) [$\times 10^6\ \text{cm}^{-2}\text{s}^{-1}$]

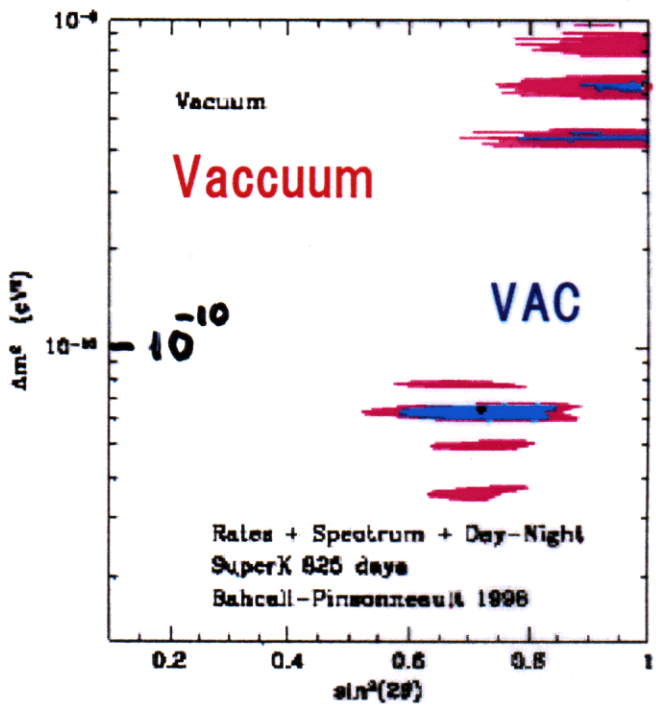
$\frac{\text{Data}}{\text{SSM}} = 0.488 \pm {}^{0.011}_{0.010}$ (stat.) $\pm {}^{0.014}_{0.013}$ (syst.)

$$\frac{\text{N-D}}{(\text{N+D})/2} = 0.065 \pm 0.031(\text{stat.}) \pm 0.013(\text{syst.})$$

- 2σ effect now.
- Should be watched how this will change with statistics.

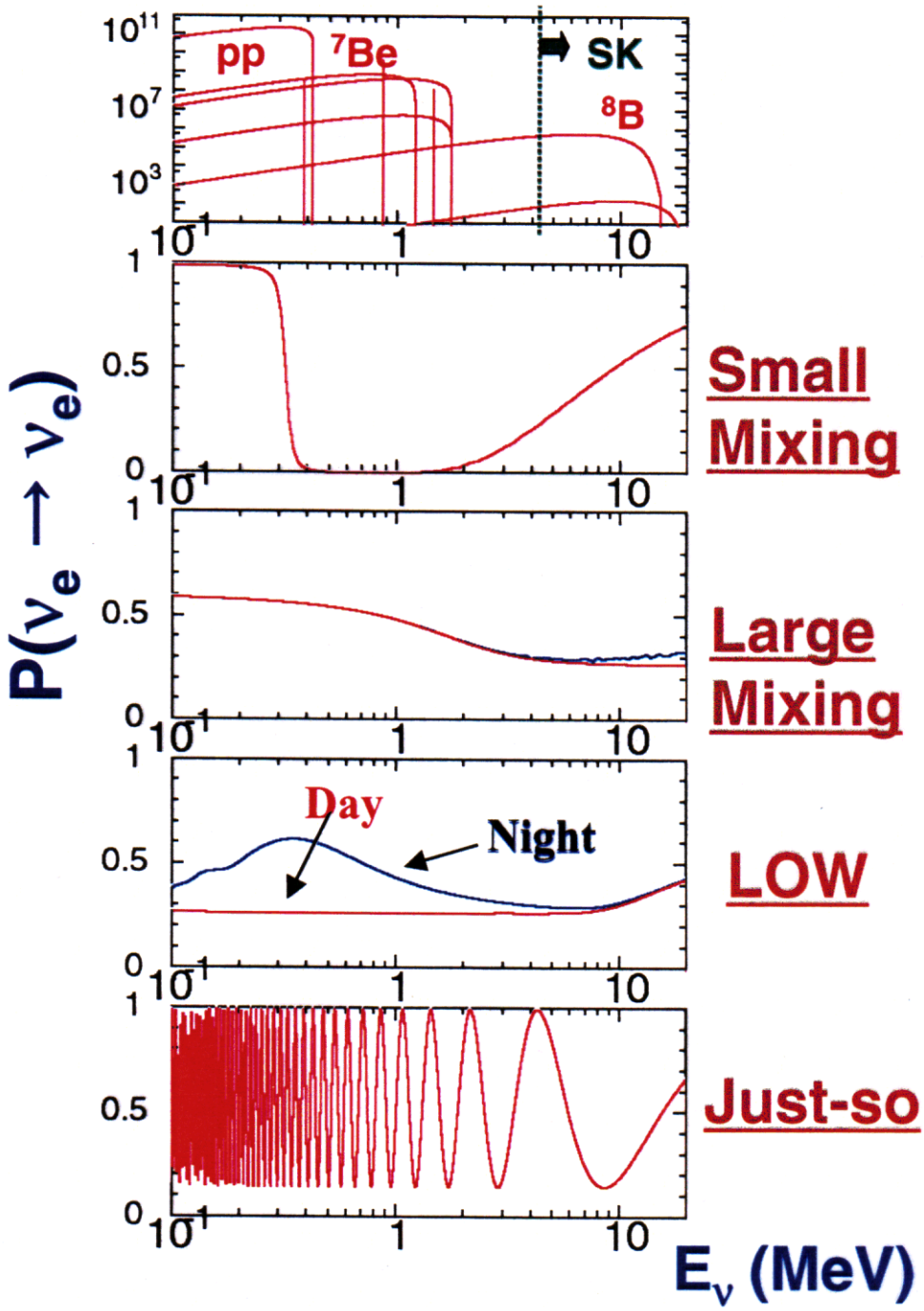
Solutions in the oscillation scenario



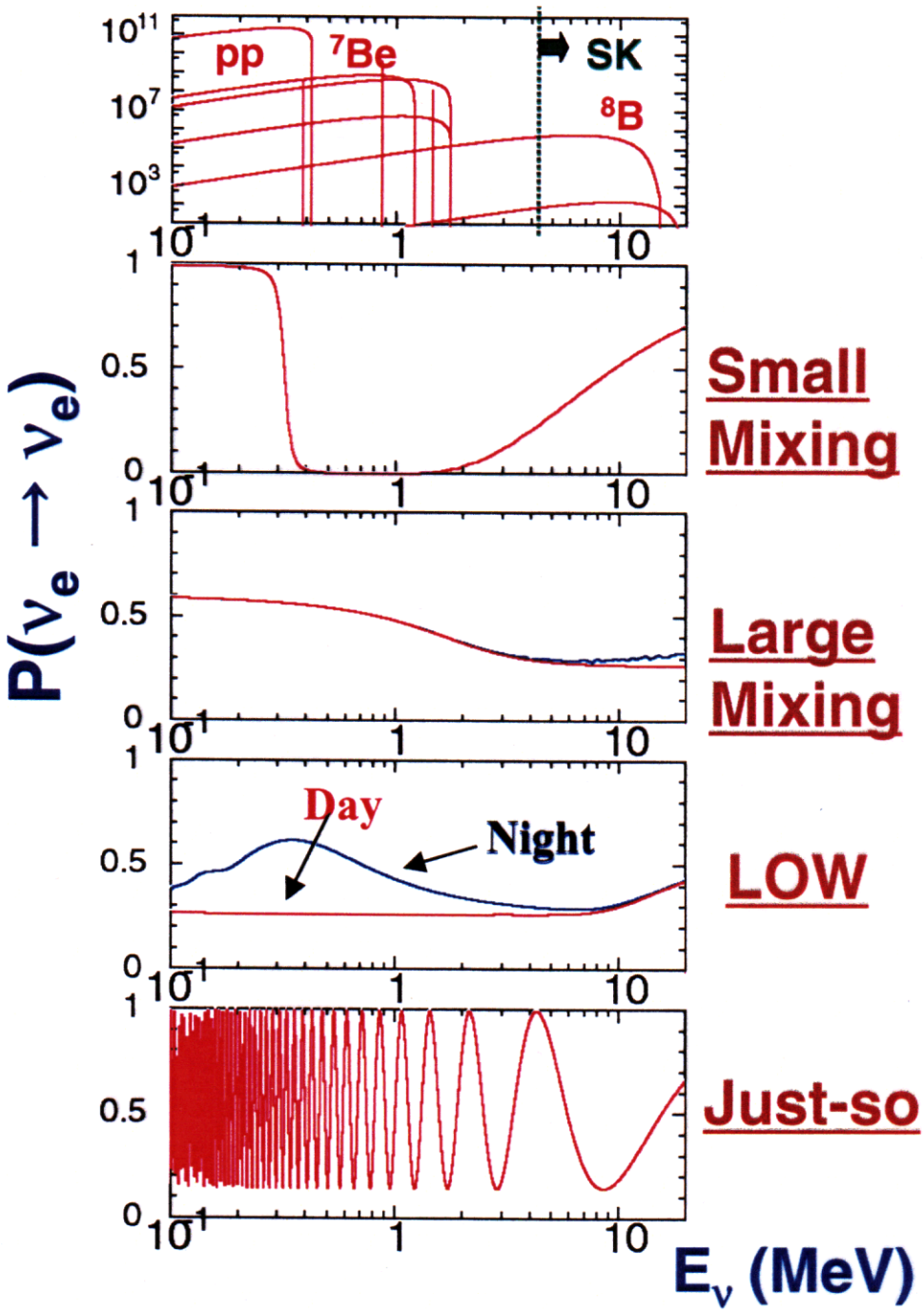


J.N. Bahcall

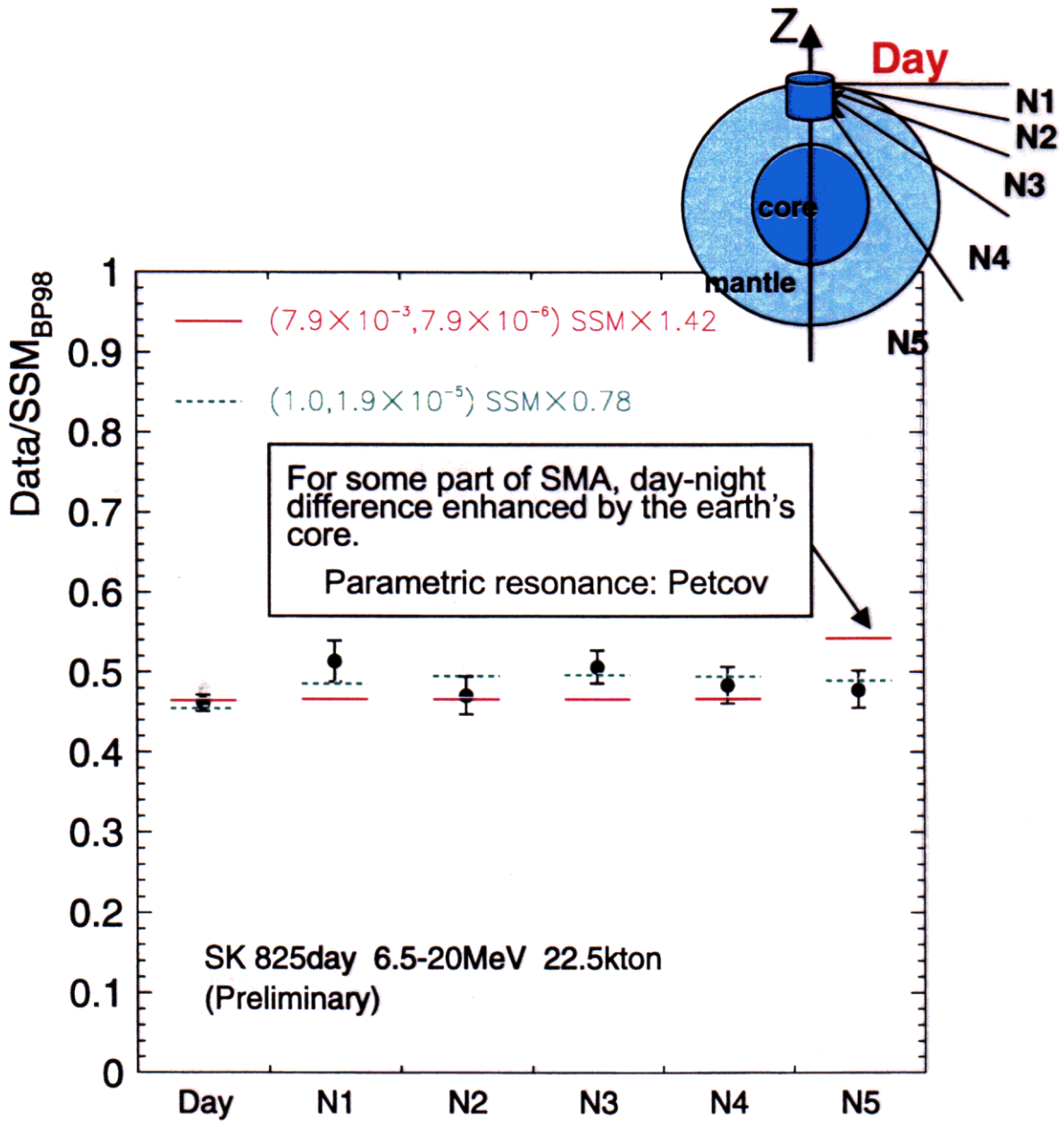
Survival probabilities for various solutions



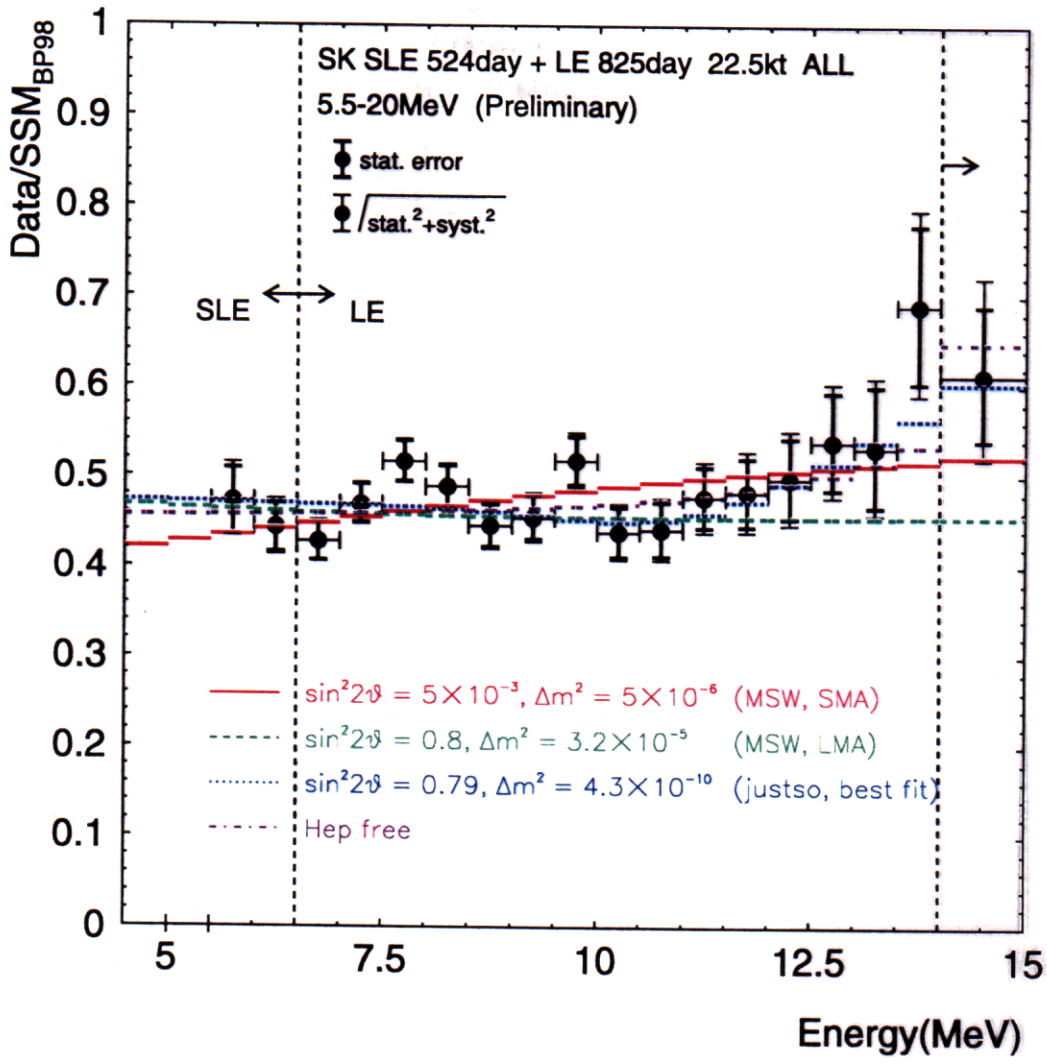
Survival probabilities for various solutions



Day & night fluxes

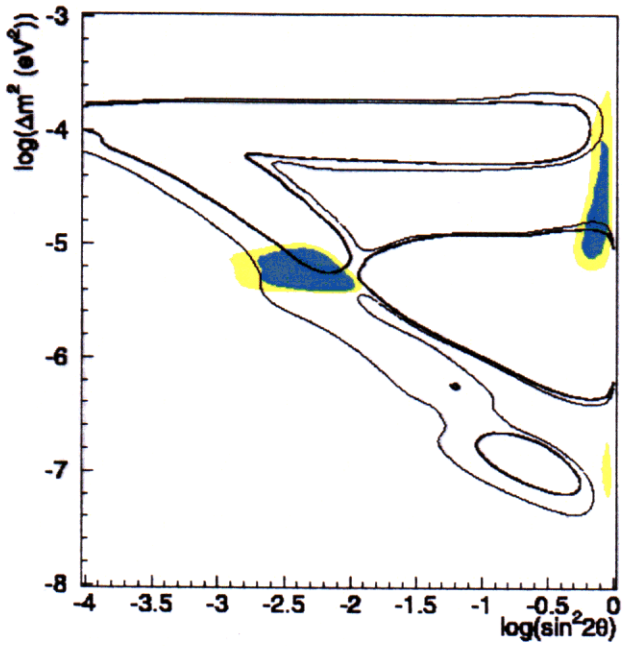


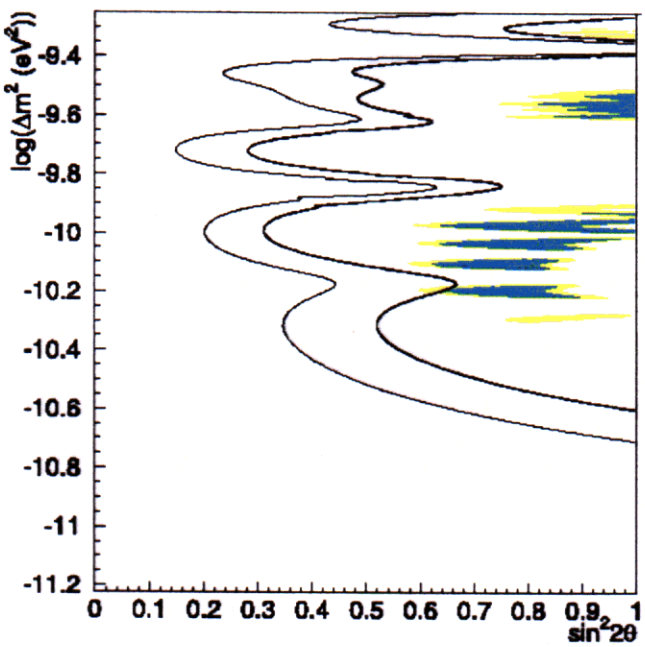
Recoil electron spectrum (Data/SSM)



- Data enhanced at the high energy end
  - Statistics?
  - Energy scale systematics?
    - Explained If energy scale is wrong by 3.6% and resolution by 20% — unlikely
  - hep flux larger than SSM?

hep flux free analysis

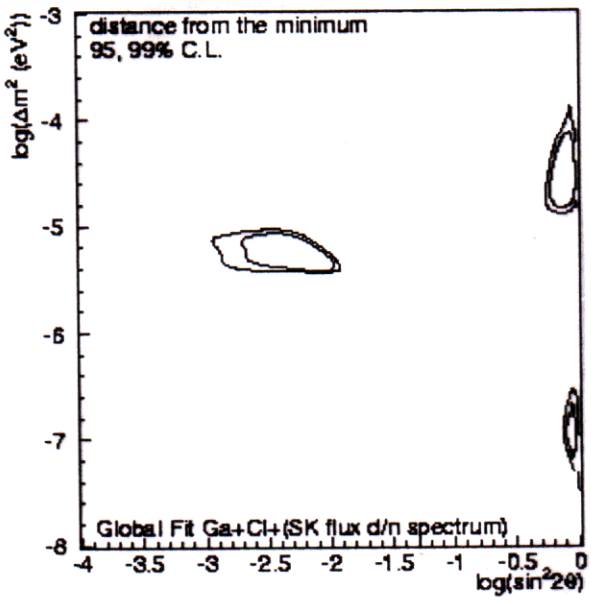


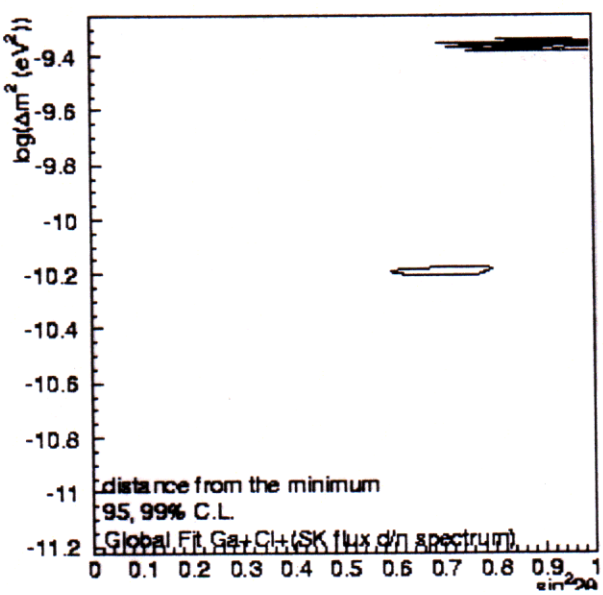


99% CL excluded

95% CL excluded

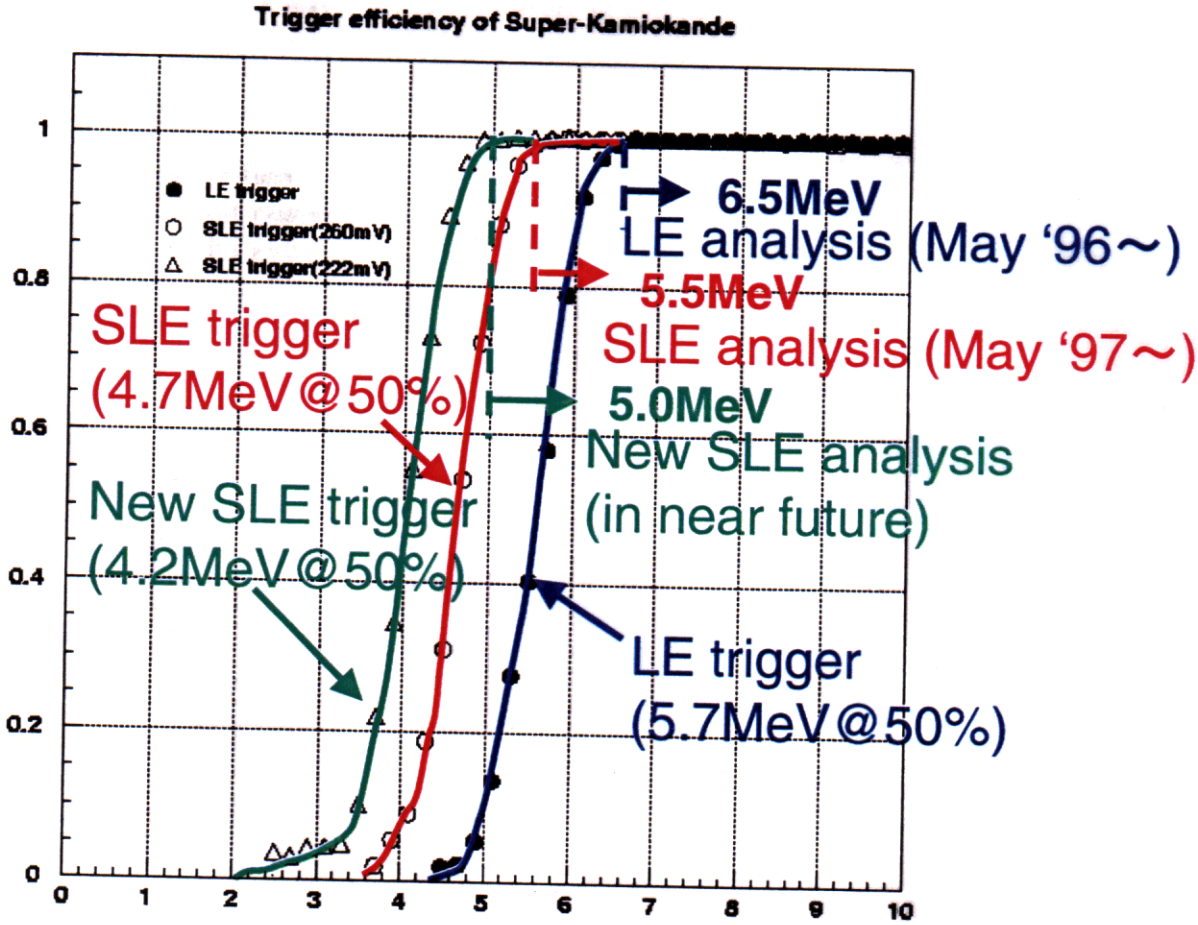
Global analysis



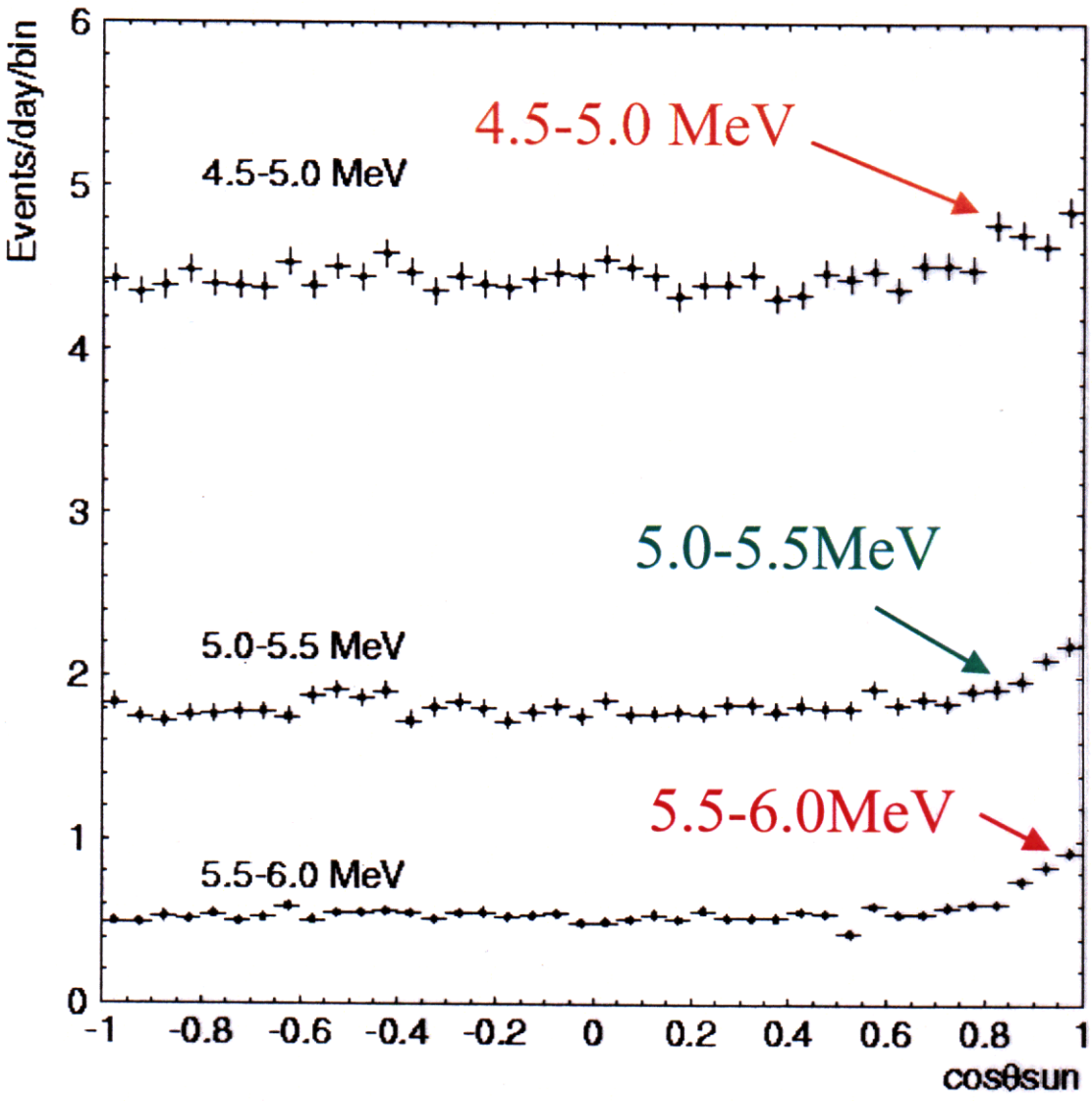


Prospect to lower threshold

- Low energy (LE) trigger
  ≧29 PMT hits / 200nsec (10Hz)
- Super-Low energy (SLE) trigger
  ≧24 PMT hits / 200nsec (120Hz)
- New Super-Low energy trigger (since Sep '99)
  ≧20 PMT hits / 200nsec (550Hz)



Solar neutrino signal at lower energies

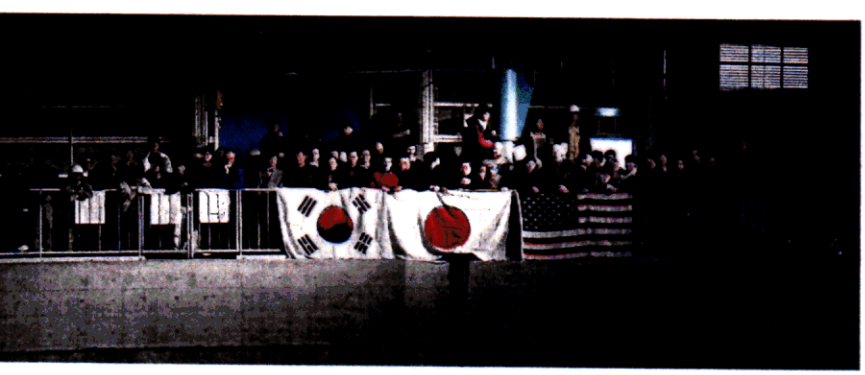


Solar neutrino summary

- ^{8}B solar neutrino flux
  - ~50% of the SSM prediction
  - Day-night flux difference:
    2σ effect now
  - Recoil electron spectrum:
    Enhanced at high energy end?
  - hep-free analysis
    Disfavors vacuum solution?
- Not conclusive yet
- Need to keep watching and wait for SNO:
  - νe scattering: CC + NC
  - Combined with SNO's CC result, possibility to distinguish solutions

K2K

Super Kamiokande

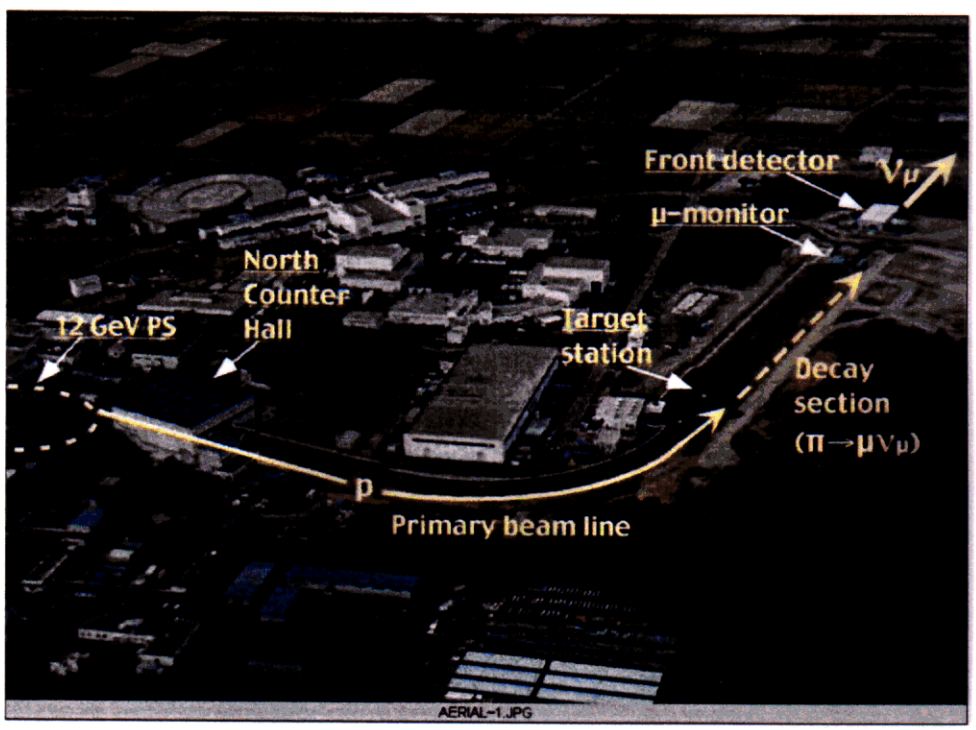


KEK

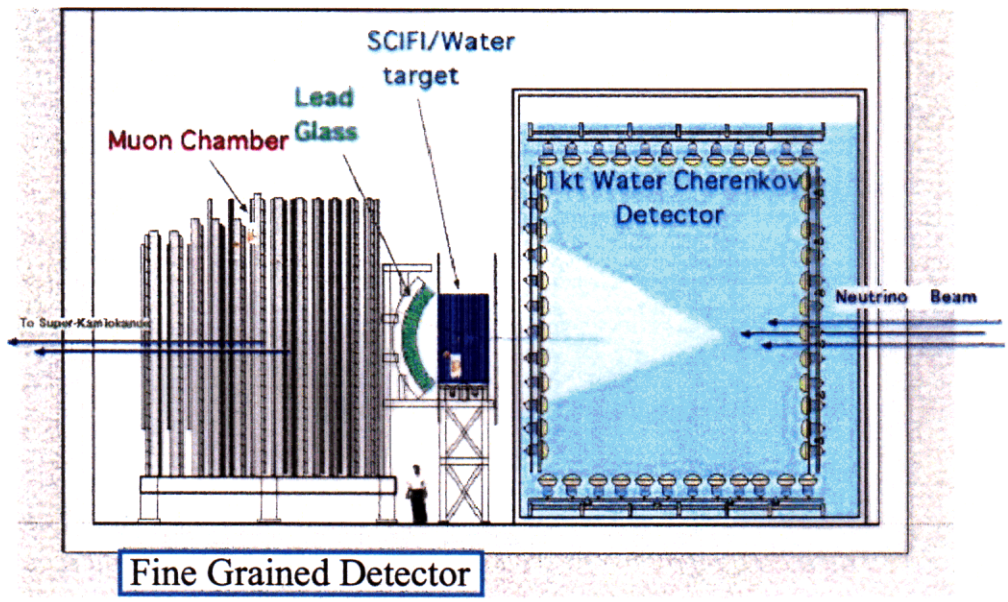
K2K

K2K Experiment

- Accelerator: 12 GeV proton synchrotron
  beam intensity: 6×10^{12} protons/pulse
  repetition: 1 pulse / 2.2 sec
  pulse width: 1 μsec
- Horn-focussed wide-band beam
  Average neutrino energy: 1.4GeV
- Front (near) detector: 300m from the target
- Far detector (Super-Kamiokande):
  250 km from the target
- Goal: 10^{20} protons on target



Near Detector



Purpose

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

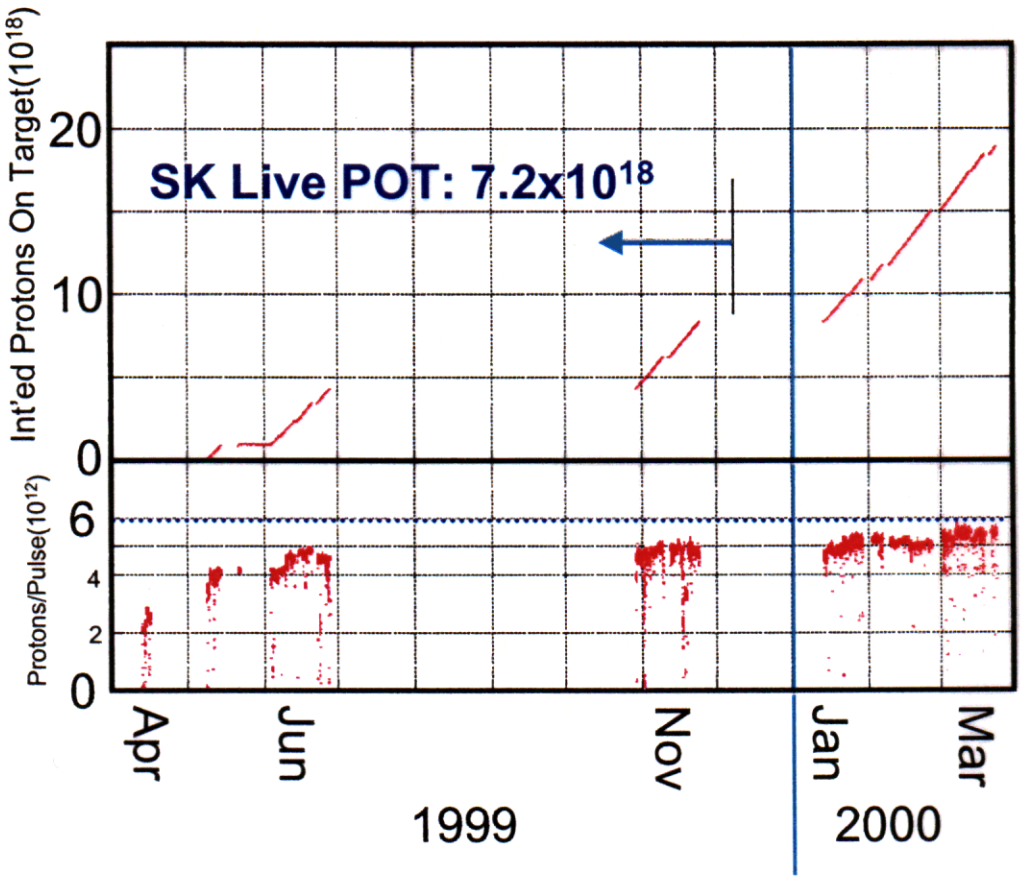
Fine Grained Detector (FGD)

Multi track → study neutrino interaction

1kton water Cherenkov

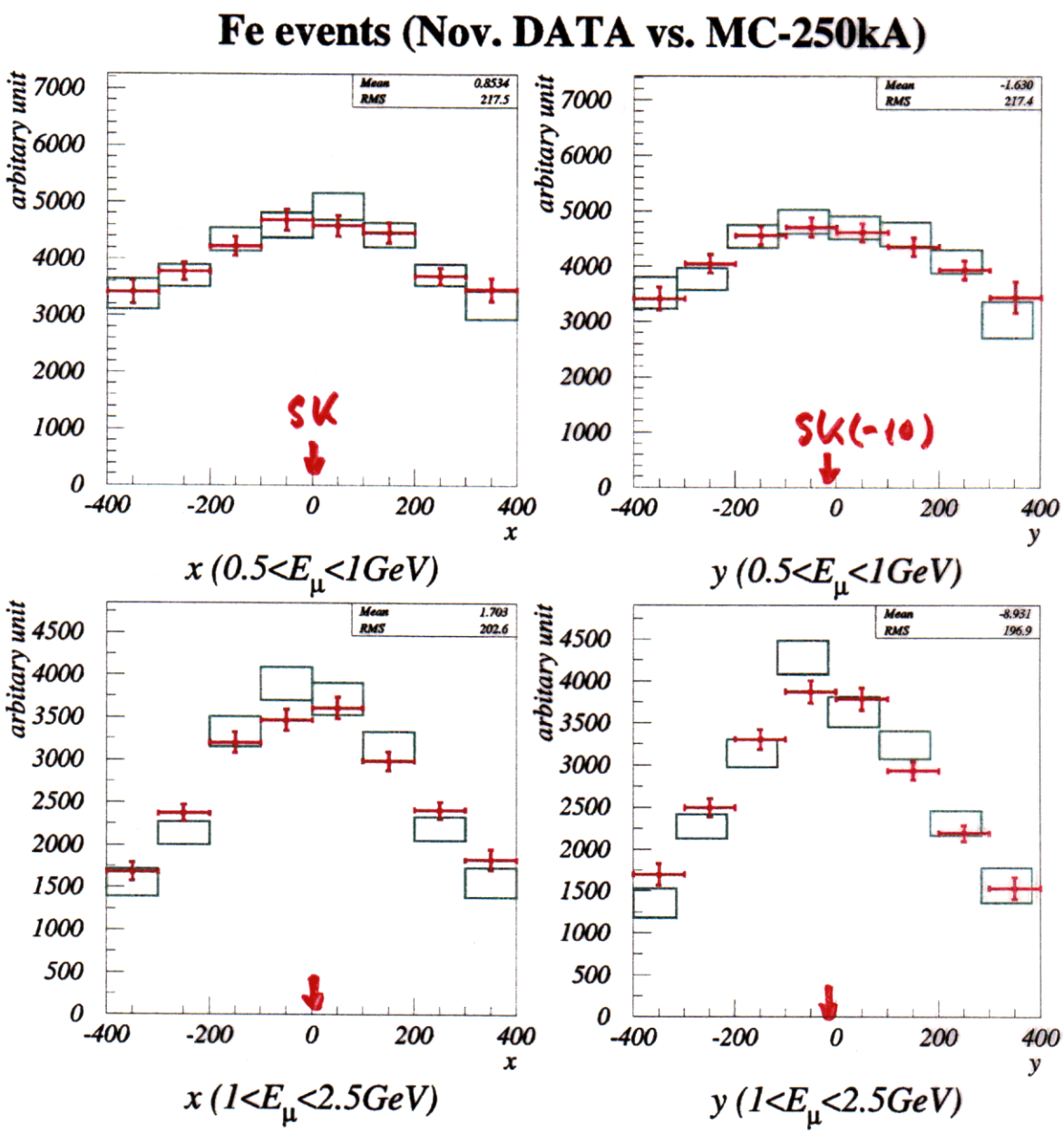
Study systematics of water Cherenkov
NC π^0 cross section

Beam in JFY99



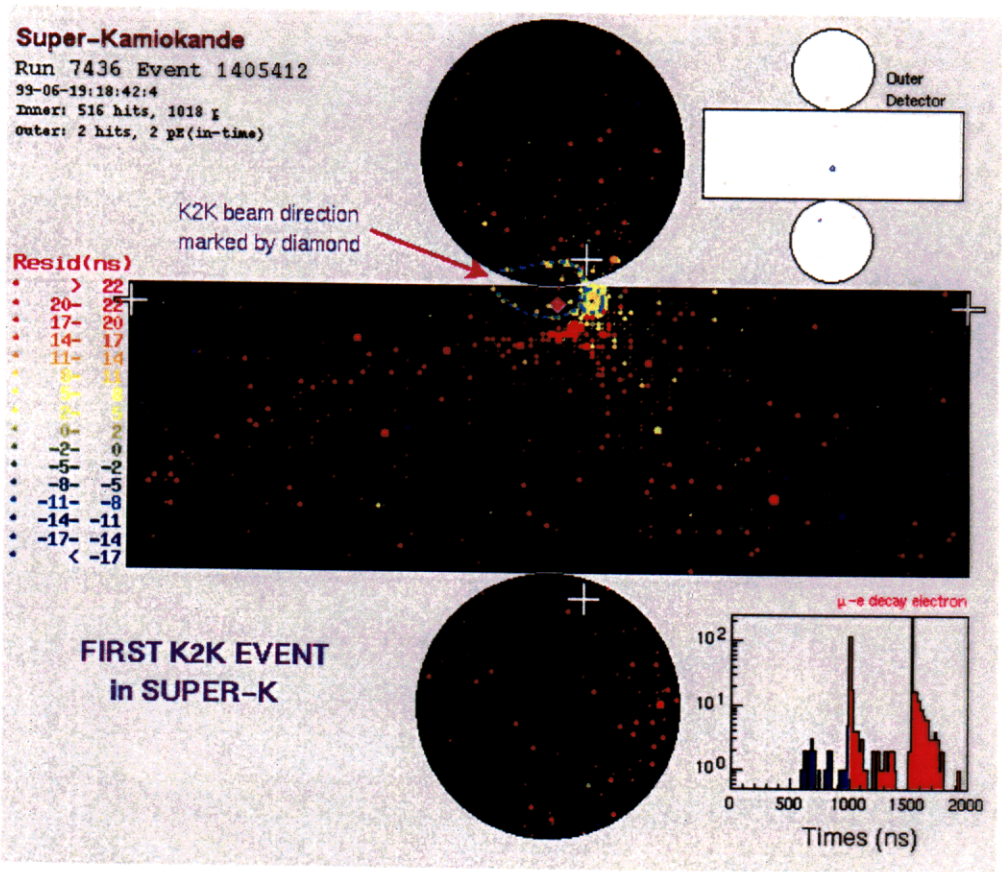
- Design Proton Int. $6x10^{12}$ almost achieved.
- ~$2x10^{19}$POT delivered in FY '99
- $7.2x10^{18}$POT(by Nov '99) used in analysis

Measured neutrino profile at 300m

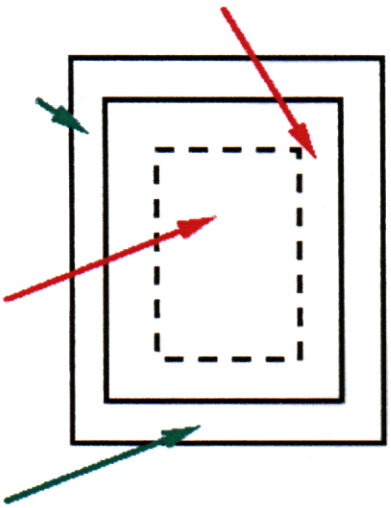


1st FC event

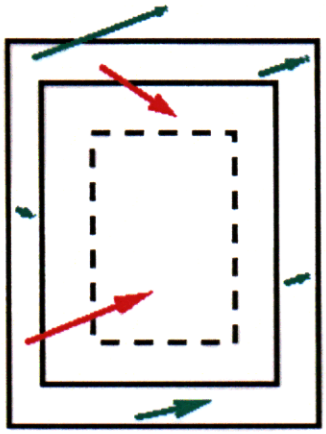
The first event in the 22.5 kton fiducial volume of Super-Kamiokande observed on June 19, 1999



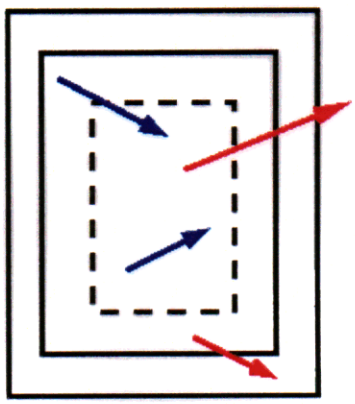
SK event category



Vertex in rock



Vertex in OD



Vertex in ID

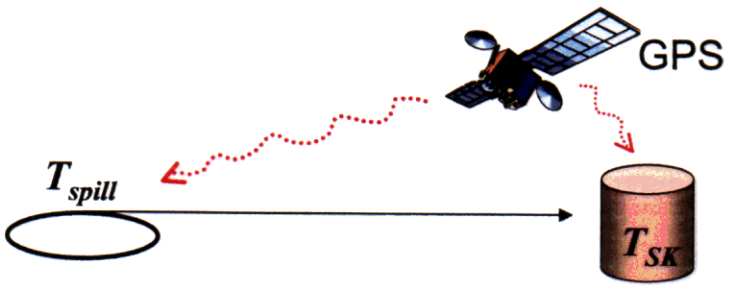
→ Fully contained

- Vertex inside fid. vol.
- Vertex outside fid. vol.

→ OD contained

→ OD crossing

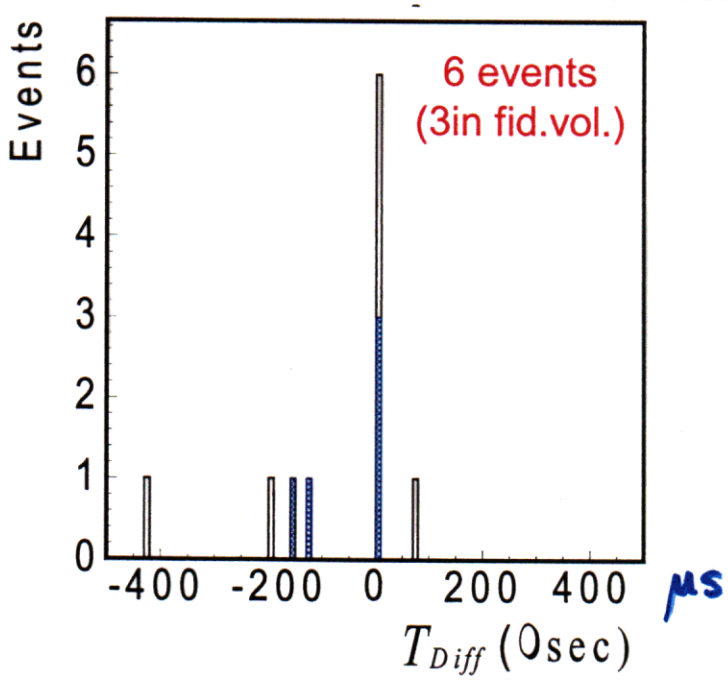
Event time



$$0 \leq T_{\mathrm{Diff}} \equiv T_{SK} - T_{Spill} - \mathrm{TOF} \leq 1\mu\,\mathrm{sec}$$

T_{Spill}, T_{SK}: Abs. time of spill start, SK event measured with GPS
TOF: Time of flight of neutrino from KEK to Kamioka
GPS: Global Positioning System

FC sample observed in June & November,1999



Expected number of events at SK

$N_{SK}(\text{expected}) = N_{KEK}^{obs} \cdot R$

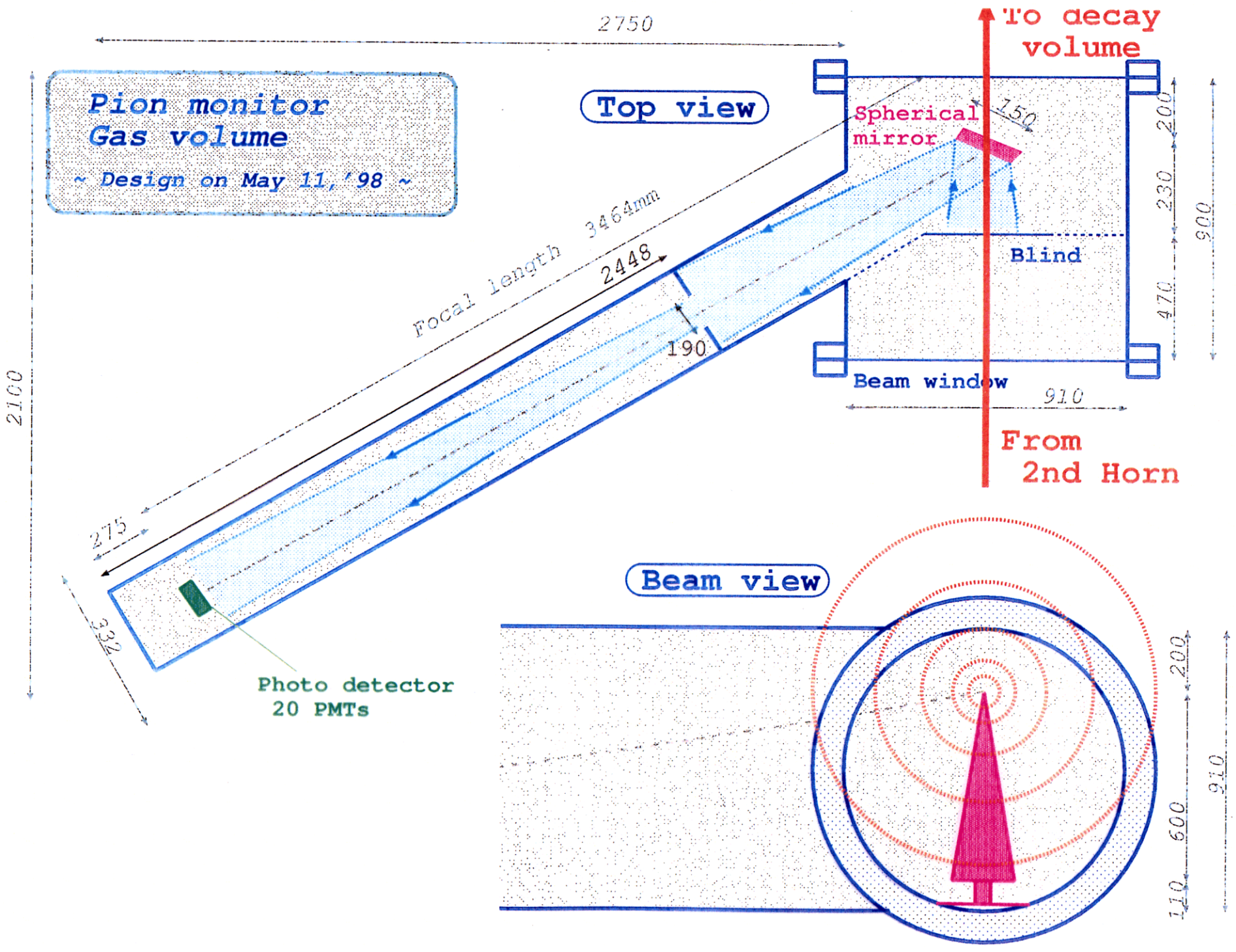
R: Calculated Event Ratio (Far-to-Near Ratio)

$$R = \frac{\int F_{SK}(E_\nu)\,\sigma(E_\nu)\,dE_\nu}{\int F_{KEK}(E_\nu)\,\sigma(E_\nu)\,dE_\nu} \bullet \frac{N_{target}^{SK}}{N_{target}^{KEK}}$$

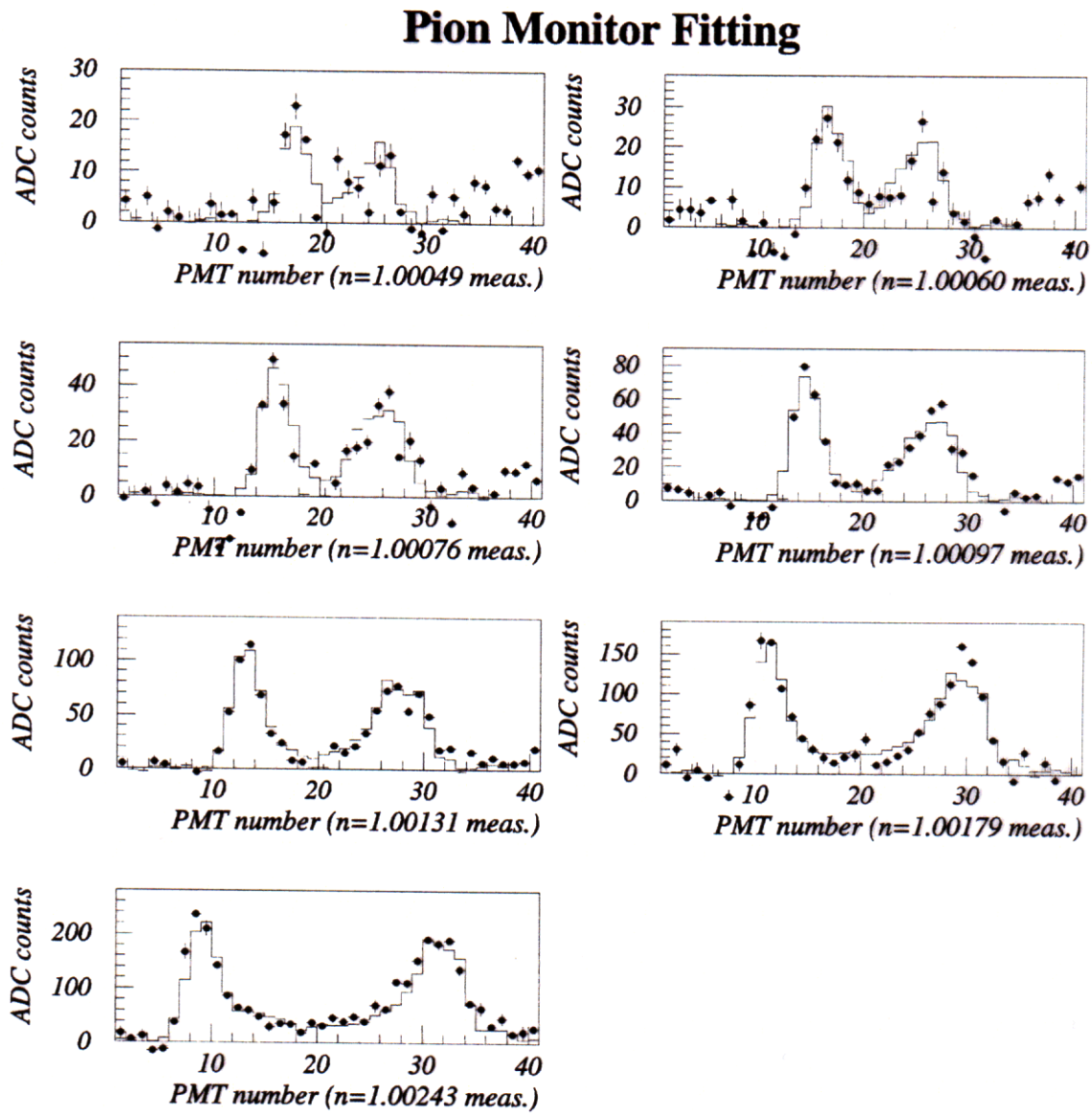
- **Full knowledge of ν_μ flux (ratio) is required.**

Target = water →common cross section

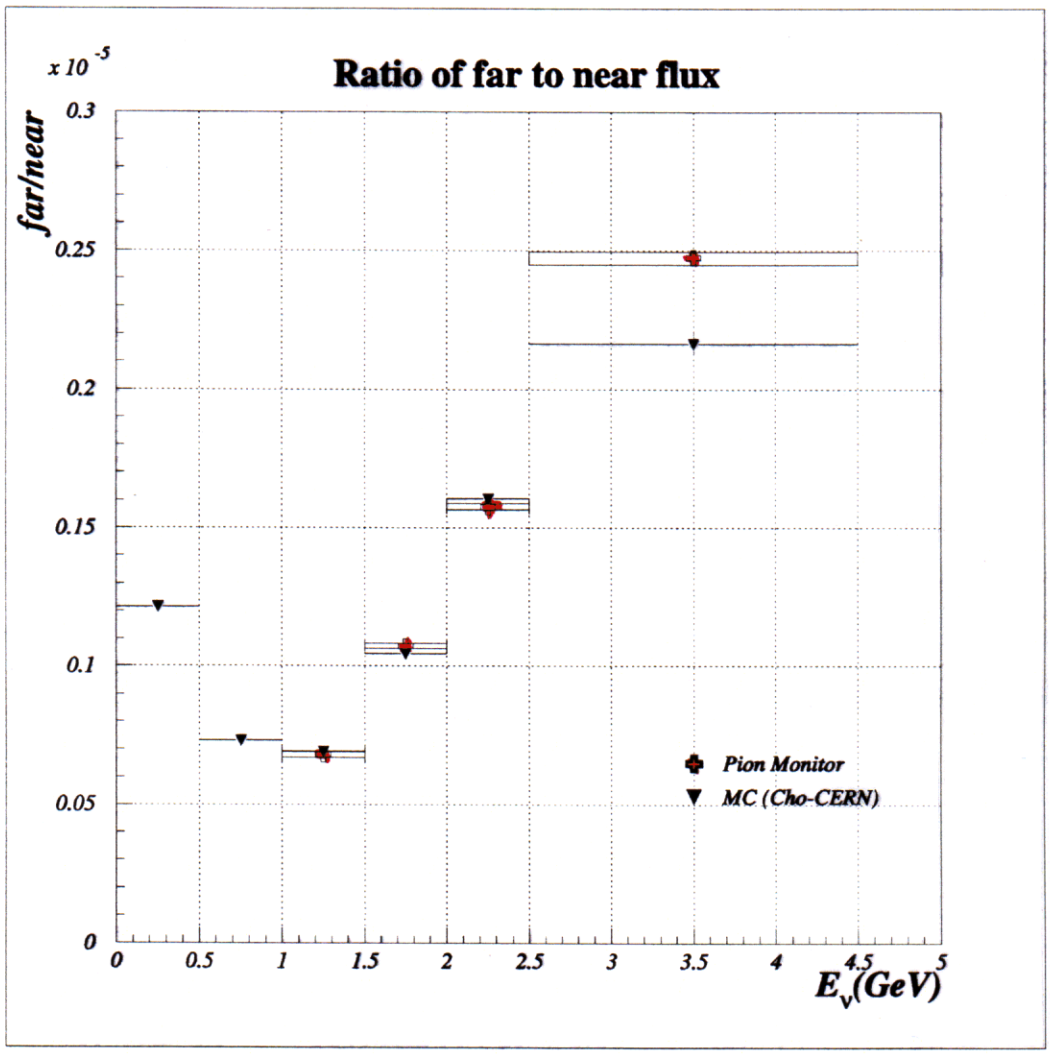
ν_μ Flux ratio (Eν>1GeV) and its systematic uncertainty is independently calculated by π-monitor data. They agree.


Pion monitor
Gas volume
~ Design on May 11, '98 ~
Top view
2750
To decay volume
Spherical mirror
150
200
230
470
900
Blind
Beam window
910
From 2nd Horn
2100
Focal length 3464mm
2448
190
275
332
Photo detector
20 PMTs
Beam view
200
600
110
910

Pion monitor
Fit to the data



Far/near ratio
Pion monitor vs MC



SK events summary

April - November, 1999

$$N_{sk} = N_{1kton} \bullet R \bullet \varepsilon_{sk}$$

N_{1kton} rate

R: Calculated event ratio

*FC (Fully Contained) events

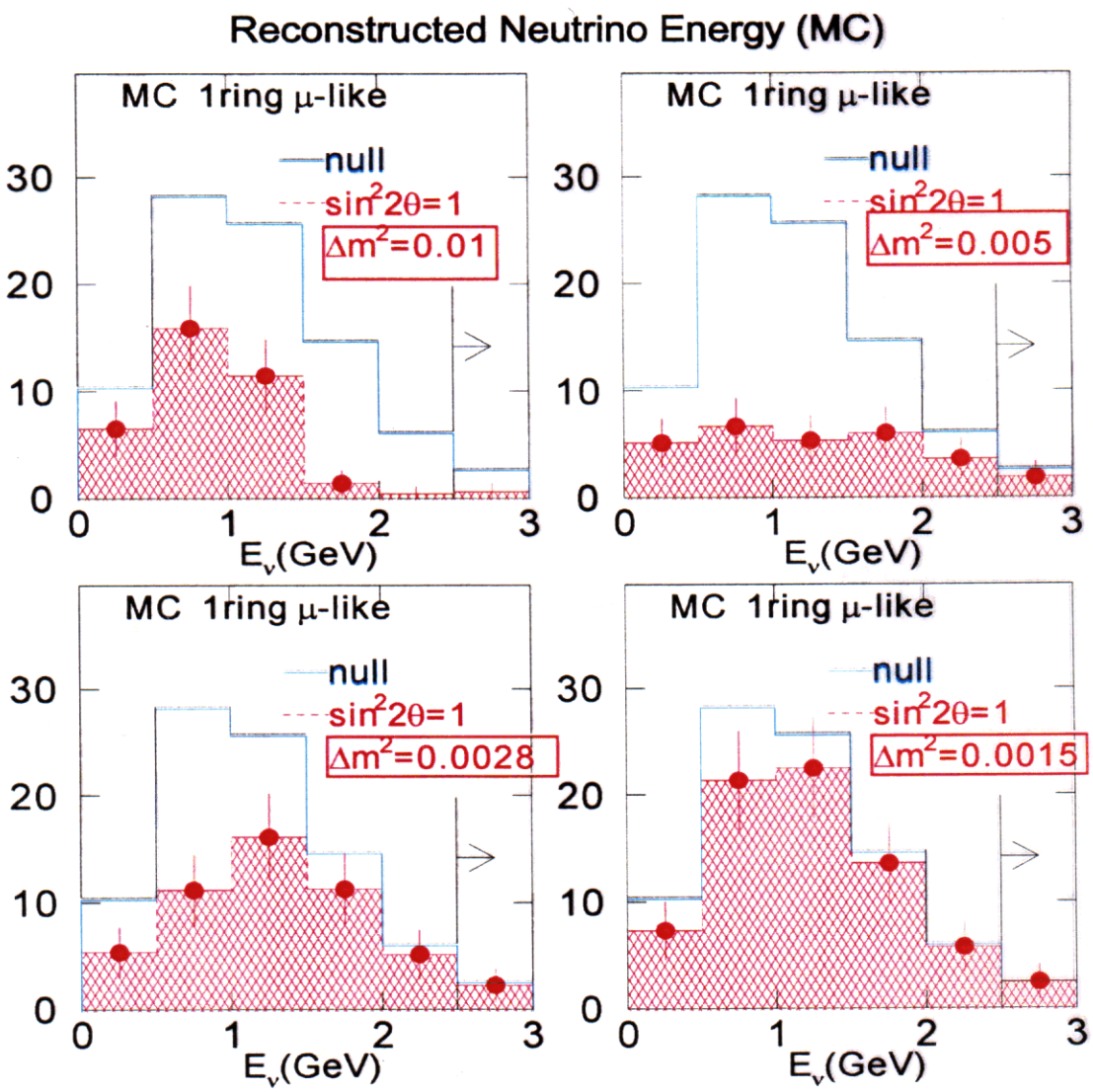
		Expectation			
	Data	No oscillation	$\Delta m^2 = 3\times10^{-3}$	$\Delta m^2 = 5\times10^{-3}$	$\Delta m^2 = 7\times10^{-3}$
FC in fiducial	3	12.3 +1.7 -1.9	8.0	5.4	4.6
out of fiducial	3	5.5 +1.1 -1.2	3.5	2.4	2.1

*OD (Outer Detector) events

	Data	No oscillation	$\Delta m^2 = 3\times10^{-3}$	$\Delta m^2 = 5\times10^{-3}$	$\Delta m^2 = 7\times10^{-3}$
OD Crossing	2	4.2 ±1.6	3.2	2.0	1.3
OD Contained	4	8.7 ±3.3	5.5	3.5	2.9

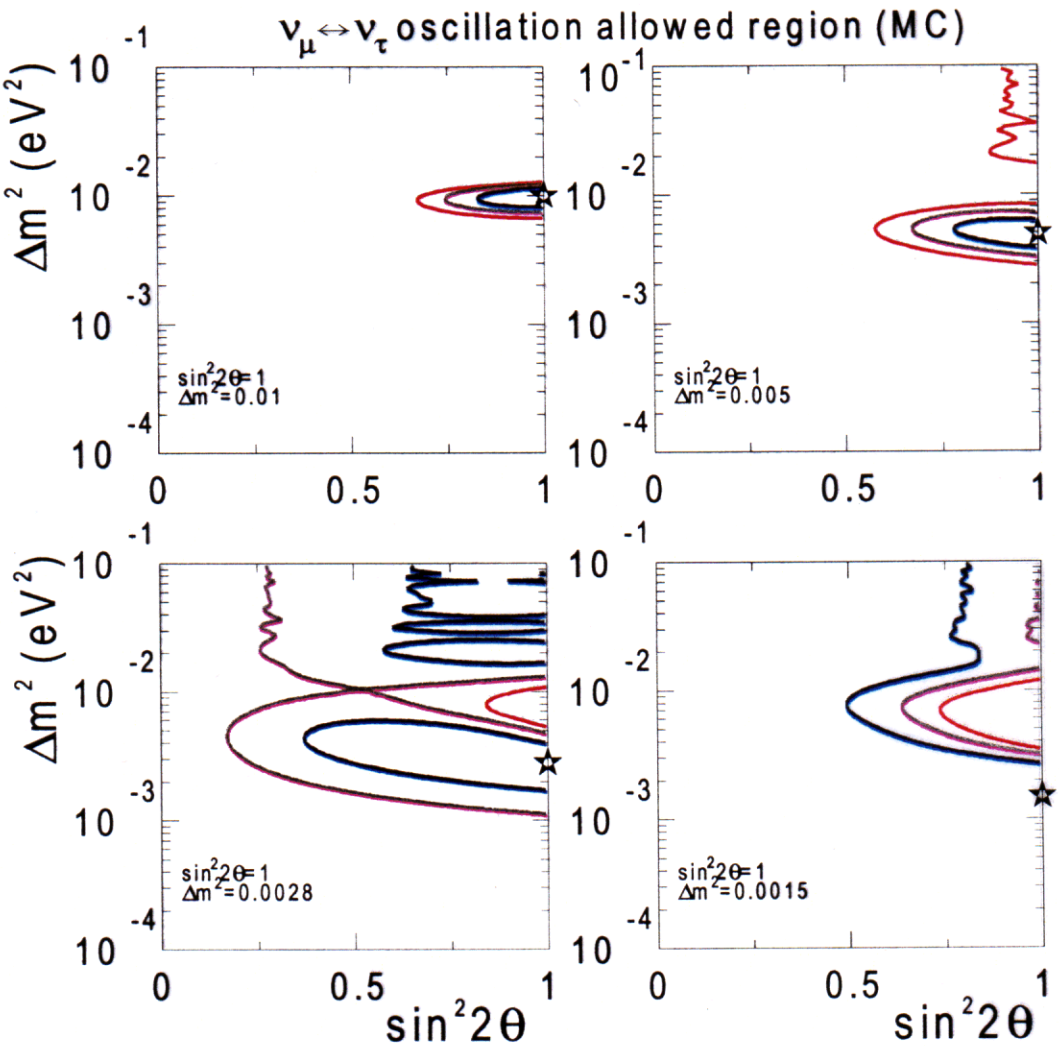
Expected SK events at 10^{20} POT

172 interactions in 22.5ktons
88 μ candidates



Expected Allowed Region

10^{20} POT ~ 5 years



K2K summary

- April – November, 1999
  - 7.2×10^{18} protons on target
  - 6 FC events at SK (3 events have vertex inside the fiducial volume)

    Background < 10^{-3}
  - In addition, 6 OD events were observed

    Backgroud < a few %
- We can accumulate 2×10^{19} pot per year
- ~5 years for 10^{20} pot

LBL ν oscilation experiment at JHF

http://neutrino.kek.jp/jhfnu
http://www-jhf.kek.jp

Letter of Intent:
A Long Baseline Neutrino Oscillation Experiment
using the JHF 50 GeV Proton-Synchrotron
and the Super-Kamiokande Detector

February 3, 2000

—V1.0—

JHF Neutrino Working Group

Y. Itow[1], Y. Obayashi, Y. Totsuka
Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188-8502, Japan

Y. Hayato, H. Ishino, T. Kobayashi[2], K. Nakamura, M. Sakuda
Inst. of Particle and Nuclear Studies, High Energy Accelerator Research Org. (KEK),
Tsukuba, Ibaraki 305-0801, Japan

T. Hara
Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan

T. Nakaya[3], K. Nishikawa[4]
Department of Physics, Kyoto University, Kyoto 606-8502, Japan

T. Hasegawa, K. Ishihara, A. Suzuki
Department of Physics, Tohoku University, Sendai, Miyagi, 980-8578, Japan

[1]Super Kamiokande Contact Person: itow@suketto.icrr.u-tokyo.ac.jp
[2]Neutrino Beam Contact Person: kobayasi@neutrino.kek.jp
[3]Near Detector Contact Person: nakaya@scphys.kyoto-u.ac.jp
[4]Organizer: nishikaw@neutrino.kek.jp

Menu

- Precision measurement of osc. Parameters.
- High intensity 50 GeV proton machine enables experiments with NBB w/ less syst.

- 1year of WBB→ pin points $\Delta m^2(\pm 2x10^{-4}eV^2)$
- ~5years of NBB
  - $d(\sin^2 2\theta_{23}) \sim 0.01$
  - $\sin^2 2\theta_{\mu e} \sim 0.015$
- Existence of ν_s can be tested.

Conclusions

- Super-Kamiokande:
  - Updated atmospheric neutrino and solar neutrino data will be presented at Neutrino 2000.
- K2K:
  - Data up to March 2000 run will be presented at Neutrino 2000.
  - Additional data from May – June 2000 run will be presented at ICHEP 2000.