Experimental results on atmospheric neutrinos in Super- Kamiokande- I

For the Super-Kamiokande collaboration

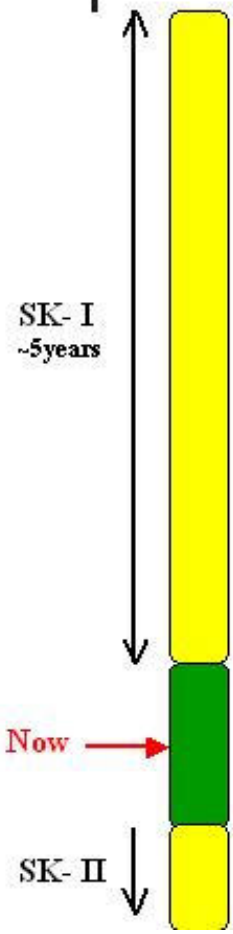
Univ. of Tokyo, Kamioka Observatory
Masato Shiozawa

Super-Kamiokande Collaboration

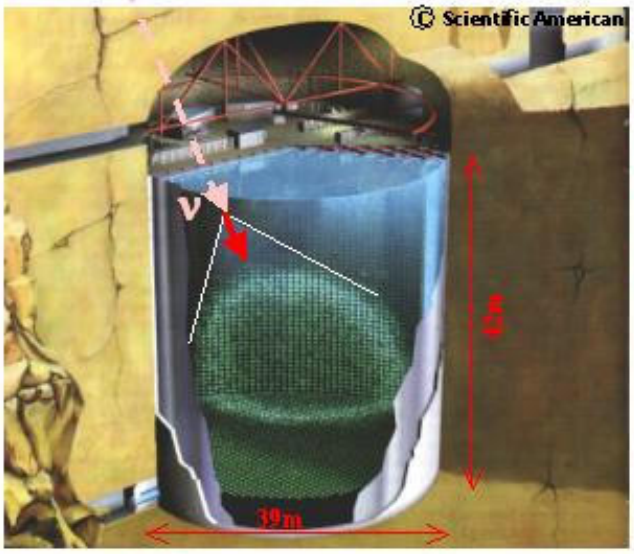
S. Fukuda Y. Fukuda M. Ishitsuka Y. Itow T. Kajita J. Kameda K. Kaneyuki
K. Kobayashi Y. Koshio M. Miura S. Moriyama M. Nakahata S. Nakayama T. Namba
A. Okada N. Sakurai M. Shiozawa Y. Suzuki H. Takeuchi Y. Takeuchi Y. Totsuka
S. Yamada S. Desai M. Earl E. Kearns M.D. Messier J.L. Stone L.R. Sulak C.W. Walter
M. Goldhaber T. Barszczak D. Casper W. Gajewski W.R. Kropp S. Mine D.W. Liu
M.B. Smy H.W. Sobel M.R. Vagins A. Gago K.S. Ganezer W.E. Keig R.W. Ellsworth
S. Tasaka A. Kibayashi J.G. Learned S. Matsuno D. Takemori Y. Hayato T. Ishii
T. Kobayashi T. Maruyama K. Nakamura Y. Obayashi Y. Oyama M. Sakuda
M. Yoshida M. Kohama T. Iwashita A.T. Suzuki A. Ichikawa T. Inagaki I. Kato
T. Nakaya K. Nishikawa T.J. Haines S. Dazeley S. Hatakeyama R. Svoboda
E. Blaufuss M.L. Chen J.A. Goodman G. Guillian G.W. Sullivan D. Turcan
K. Scholberg A. Habig M. Ackermann J. Hill C.K. Jung M. Malek K. Martens
C. Mauger C. McGrew E. Sharkey B. Viren C. Yanagisawa T. Toshito C. Mitsuda
K. Miyano C. Saji T. Shibata Y. Kajiyama Y. Nagashima K. Nitta M. Takita H.I. Kim
S.B. Kim J. Yoo H. Okazawa T. Ishizuka M. Etoh Y. Gando T. Hasegawa K. Inoue
K. Ishihara J. Shirai A. Suzuki M. Koshiba Y. Hatakeyama Y. Ichikawa M. Koike
K. Nishijima H. Ishino M. Morii R. Nishimura Y. Watanabe D. Kielczewska
H.G. Berns S.C. Boyd A.L. Stachyra R.J. Wilkes

122 members

History of Super- Kamiokande



- 1996.4 Start data taking (SK- I)



Water Cherenkov detector

- 1000 m underground
- 50,000 ton (22,500 ton fid.)
- 11,146 20 inch PMTs
- 1,885 anti-counter PMTs

- 2001.7 Stop data taking for detector upgrade
- 2001.11 Accident (6777 inner PMTs, 1100 outer PMTs were destroyed) partial reconstruction of the detector
- 2002.10 resume data taking (SK- II)

Rebuilding Super- Kamiokande

- **Phase-1, SK- II quick restart of K2K**
  - **rebuild SK with 47% inner PMTs by autumn of 2002**
  - **atmospheric ν, proton decay search**
  - **solar ν, SN watch with higher energy threshold**
  - **PMT vessel to avoid chain reaction of explosion**

- **Phase-2, SK- III full detector before the time of commissioning of JHF**

Acrylic + FRP vessel

This talk

Neutrino oscillation study using full SK- I data

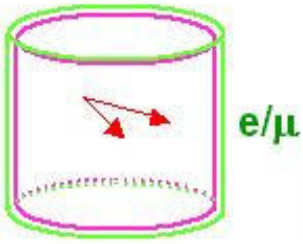
- all data in hand (FC single-ring, FC multi-ring, PC, upward through-going μ, and upward stopping μ)
- expectation by 1dimensional ν flux calculation

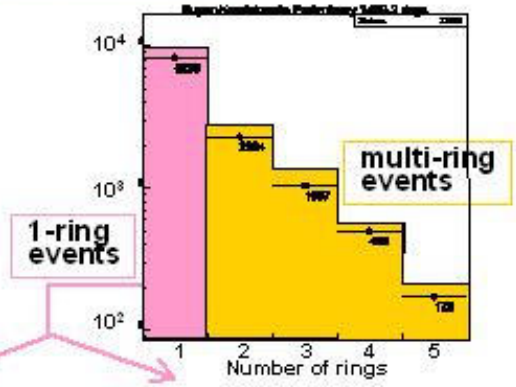
- $\nu_\mu \leftrightarrow \nu_\tau$ two flavor oscillation analyses
- $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$ three flavor oscillation analyses
- Limit on $\nu_\mu \leftrightarrow \nu_s$ admixture
- Test of other hypotheses
  - Test of ν decay hypothesis
  - Test of CPT violation

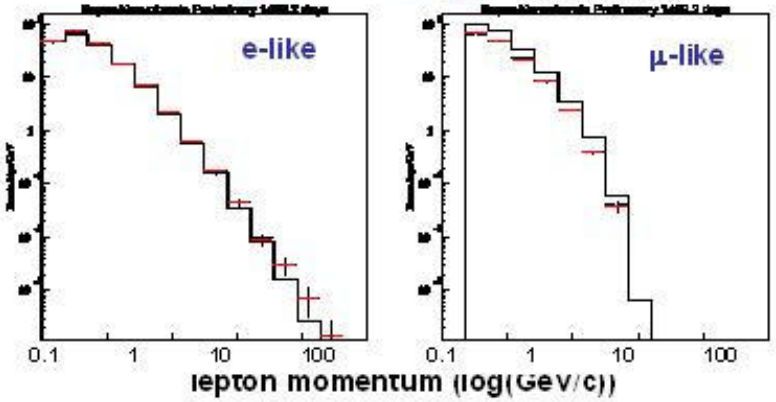
1489 days of contained event data

Contained event
(sub-GeV, multi-GeV sample)

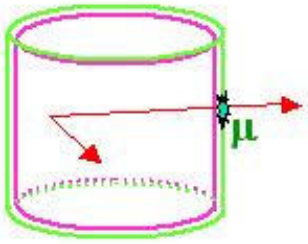
Fully Contained (FC)







Partially Contained (PC)



All are assumed to be μ–like

Summary of contained events

Sub-GeV (Fully Contained)

E_{vis} < 1.33 GeV,
P_e > 100 MeV/c, P_μ > 200 MeV/c

		Data	MC(Honda)
1ring	e-like	3266	3081.0
	μ-like	3181	4703.9
Multi ring		2457	2985.6
	(μ-like)	(225)	(333.9)
Total		8904	10770.5

$$\frac{(\mu/e)_{Data}}{(\mu/e)_{MC}} = 0.638 \begin{matrix}\square 0.016 \\ \square 0.016\end{matrix} \pm 0.050$$

Multi-GeV

Fully Contained (E_{vis} > 1.33 GeV)

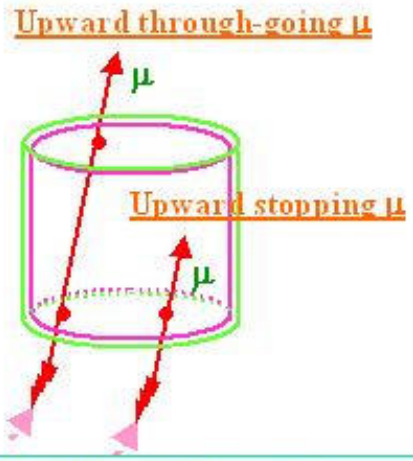
		Data	MC(Honda)
1ring	e-like	772	707.8
	μ-like	664	968.2
Multi ring		1532	1903.5
	(μ-like)	(457)	(719.3)
Total		2968	3579.4

Partially Contained (assigned as μ-like)

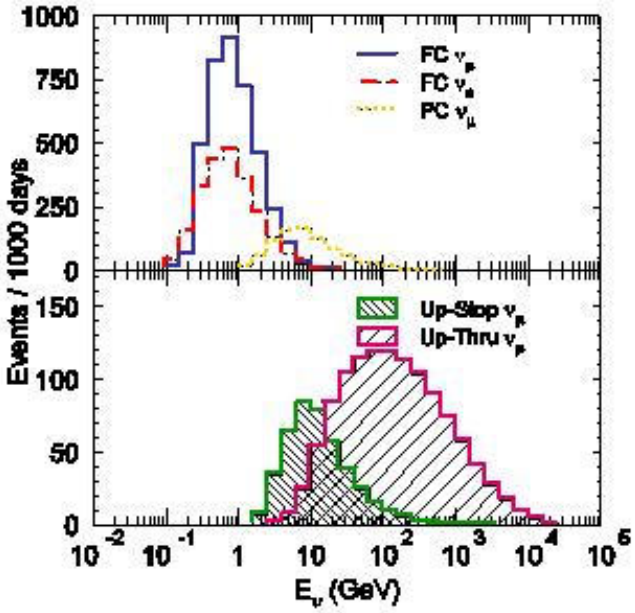
Total	913	1230.0

$$\frac{(\mu/e)_{Data}}{(\mu/e)_{MC}} = 0.658 \begin{matrix}\square 0.030 \\ \square 0.028\end{matrix} \pm 0.078$$

Another technique of atmospheric ν observation



- different energy scale
- different detection technique



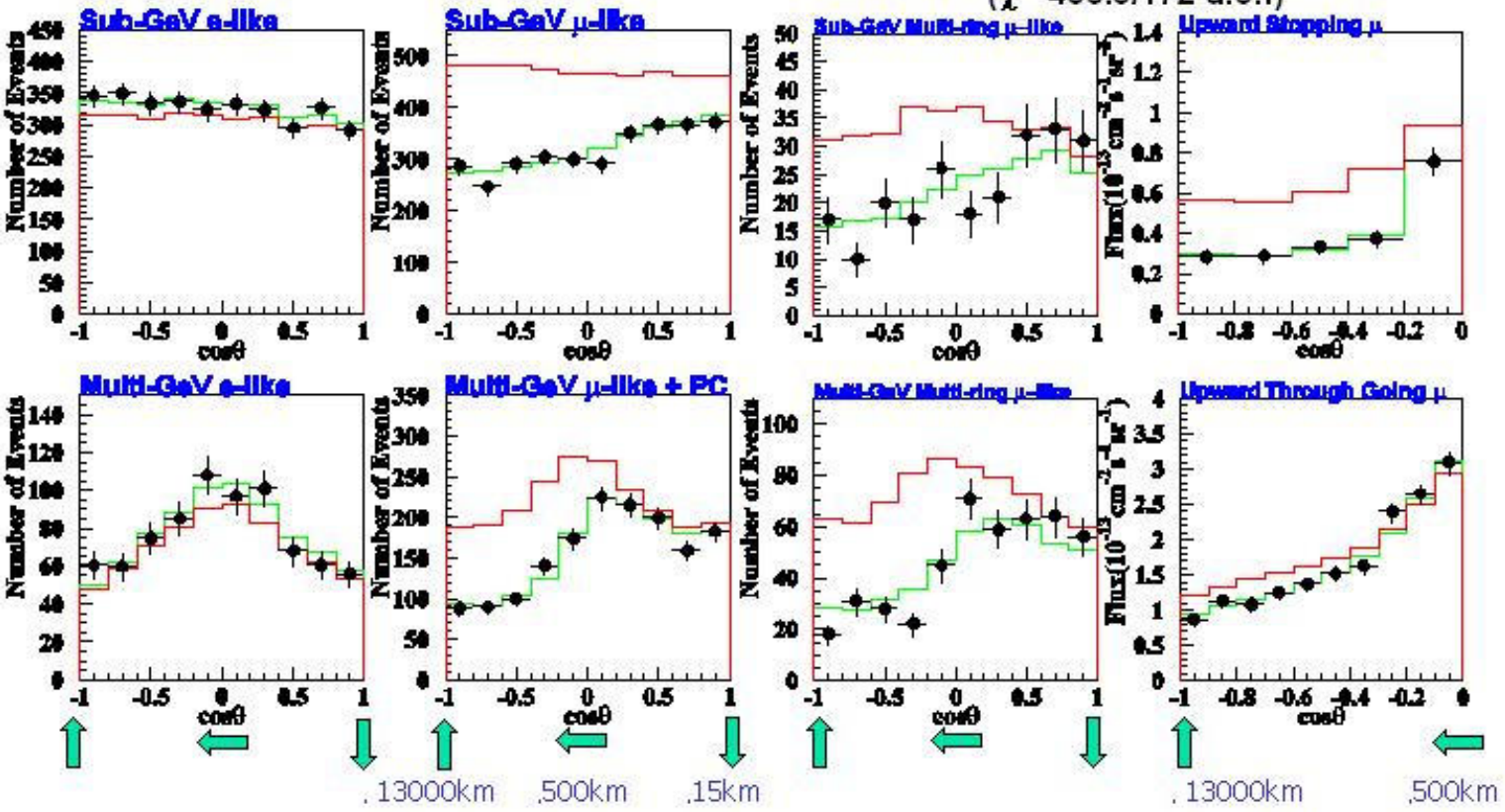
Up through-going μ, 1678days, Obs. 1.7 +- 0.04 +- 0.02 ($\times 10^{-13}$ cm^{-2}s^{-1}sr^{-1})
Exp. 1.97+-0.44

Up stopping μ, 1657days, Obs. 0.41+-0.02+-0.02 ($\times 10^{-13}$ cm^{-2}s^{-1}sr^{-1})
Exp. 0.73+-0.16

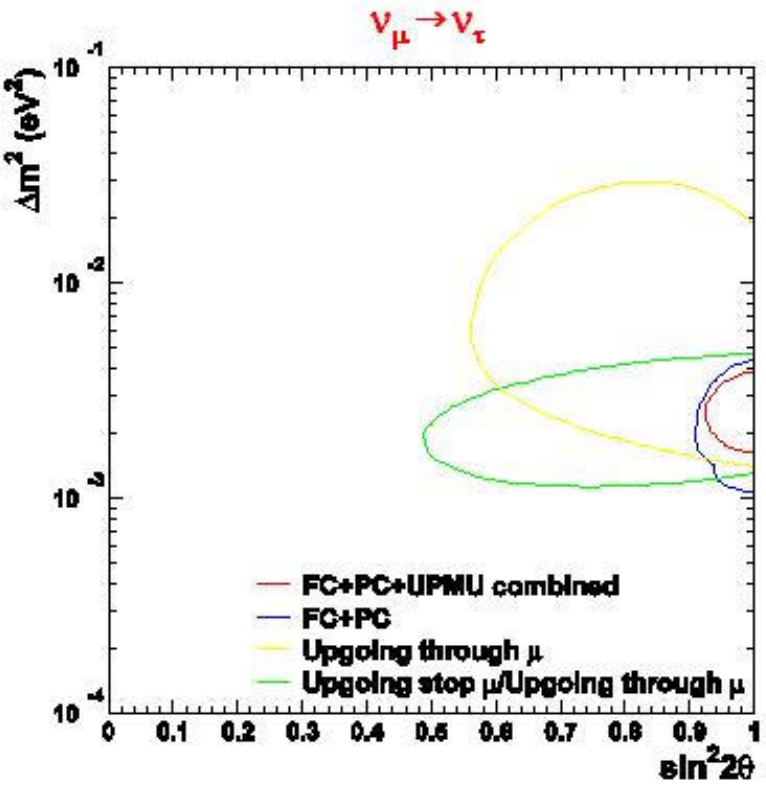
Zenith angle distributions (FC+PC+up-μ)

$\nu_\mu \leftrightarrow \nu_\tau$
2-flavor oscillations

Best fit ($\Delta m^2=2.5\times10^{-3}eV^2$, $\sin^2 2\theta=1.0$
$\chi^2_{min}=163.2/170$ d.o.f)
Null oscillation
($\chi^2=456.5/172$ d.o.f)



Combined allowed regions



$\nu_\mu \leftrightarrow \nu_\tau$ oscillations

Best fit(Δm^2=2.5x10^{-3},$\sin^2 2\theta$=1.0
χ^2_{min}=163.2/170 d.o.f)
No oscillation
(χ^2 =456.5/172 d.o.f)

Δm^2 = (1.6~3.9)x10^{-3}eV^2
$\sin^2 2\theta$ > 0.92 @ 90%CL

□τ detection in atmospheric ν

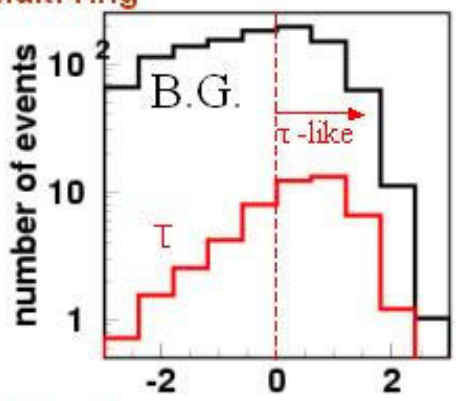
Selection Criteria
- multi-GeV, multi-ring
- most energetic ring is e-like
- log(likelihood) > 1 (single-ring)
  > 0 (multi-ring)

τ likelihood is defined using:
- total energy
- number of rings
- number of decay electrons
- max(Ei)/ΣEi
- distance between ν interaction point and decay-e point
- max(P_μ)
- Pt/Evis$^{3/4}$
- PID likelihood of most energetic ring

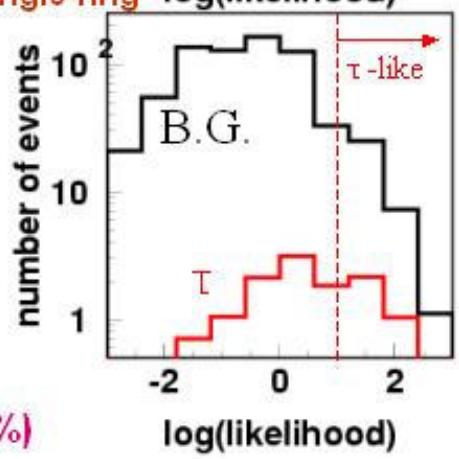
τ–like selection; effτ=44%, S/N=8%

observed τ–like events; 506
MC expectation; CC ν_τ 37 events,
BG 461 events (CCν_e 43.1%, CCν_μ 24.5%, NC 32.4%)

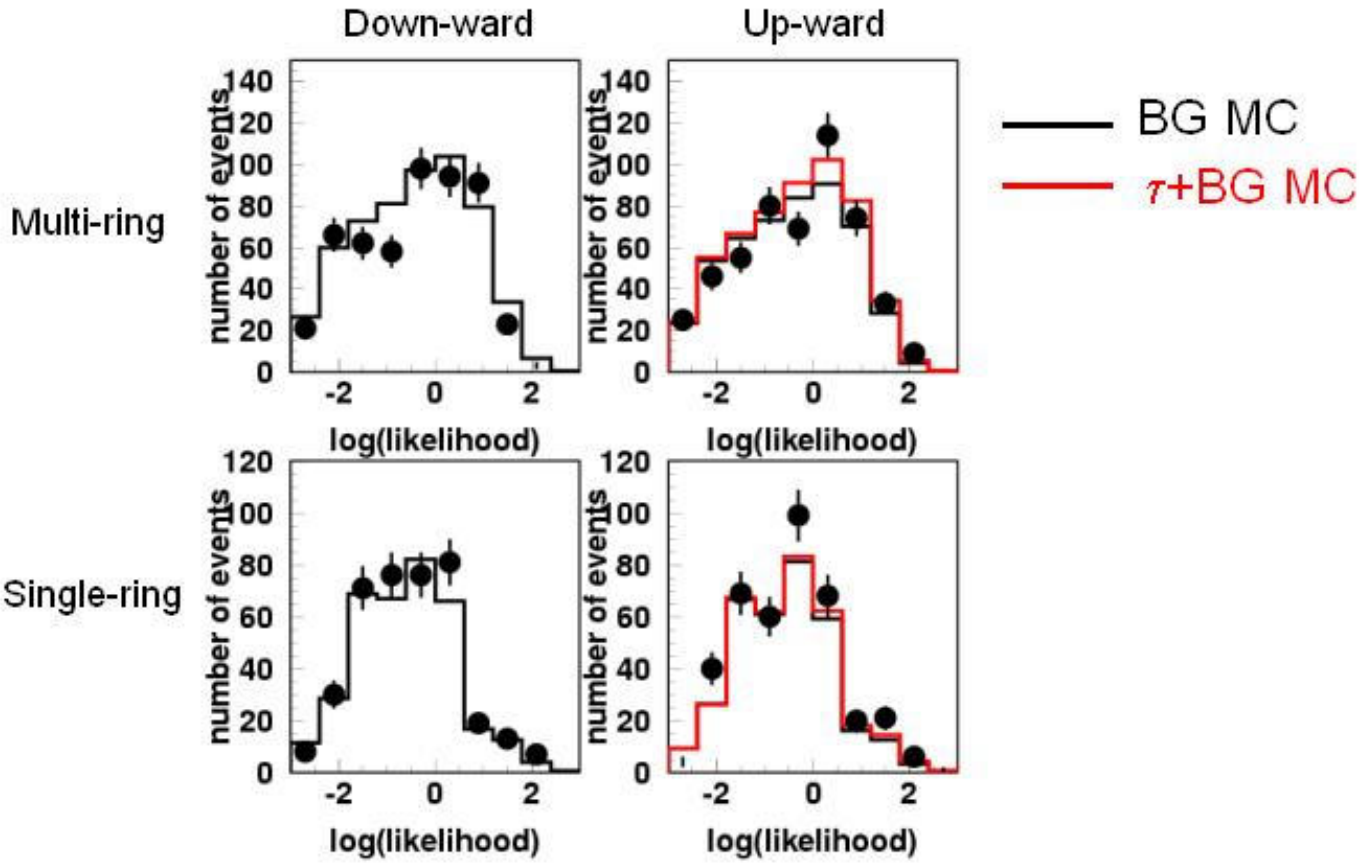
Multi-ring



Single-ring

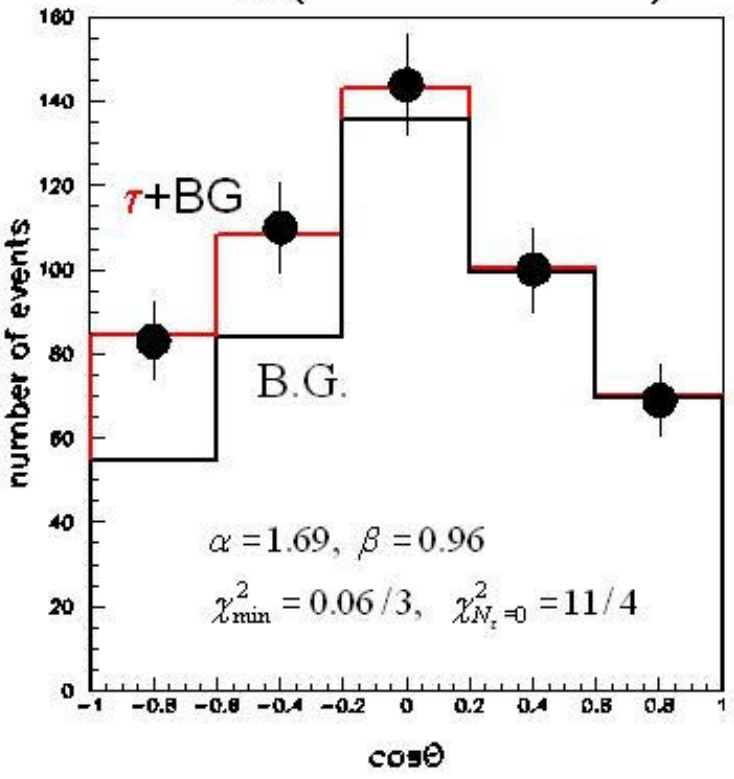


likelihood distributions of data and MC



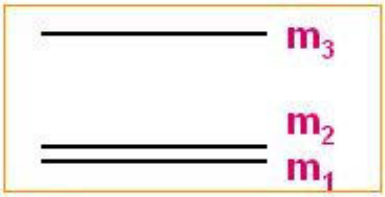
zenith angle dist. of τ-like events

$$\chi^2 = \sum_{\cos\theta}^{5} \left(\frac{N_{data} - \left(\alpha N_{MC}^{\tau} + \beta N_{MC}^{BG}\right)}{\sigma} \right)^2$$



- N^{FC}_{τ}=.αN^{τ}_{MC}/(eff.=0.44)
  =145+-44(stat.)
  +11/-16(sys.)
  N_{exp}=86
- consistent with $\nu_{\mu} \leftrightarrow \nu_{\tau}$
- another analysis gives similar results:
  *analysis-2(neural network)
  N^{FC}_{τ}=99+-39(stat.)
  +-13(Δm^2)
  +0/-16(3-flavor)

Active 3 flavor oscillation analysis



assuming $\Delta m^2_{23} = \Delta m^2_{atm} \sim O(10^{-3})\ eV^2$

$\Delta m^2_{12} = \Delta m^2_{sol} < O(10^{-4})\ eV^2 << \Delta m^2_{atm}$

neutrino oscillations in vacuum are described as;

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta_{13}) \times \sin^2\theta_{23} \times \sin^2(1.27\Delta m^2 L/E)$$

$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4\theta_{13} \times \sin^2(2\theta_{23}) \times \sin^2(1.27\Delta m^2 L/E)$$

$$P(\nu_\tau \rightarrow \nu_e) = \sin^2(2\theta_{13}) \times \cos^2\theta_{23} \times \sin^2(1.27\Delta m^2 L/E)$$

3 parameters; $\Delta m^2 (= m^2_3 - m^2_2)$, θ_{13} ($\sin^2\theta_{13} < 0.026$), θ_{23} ($\sim \pi/4$)

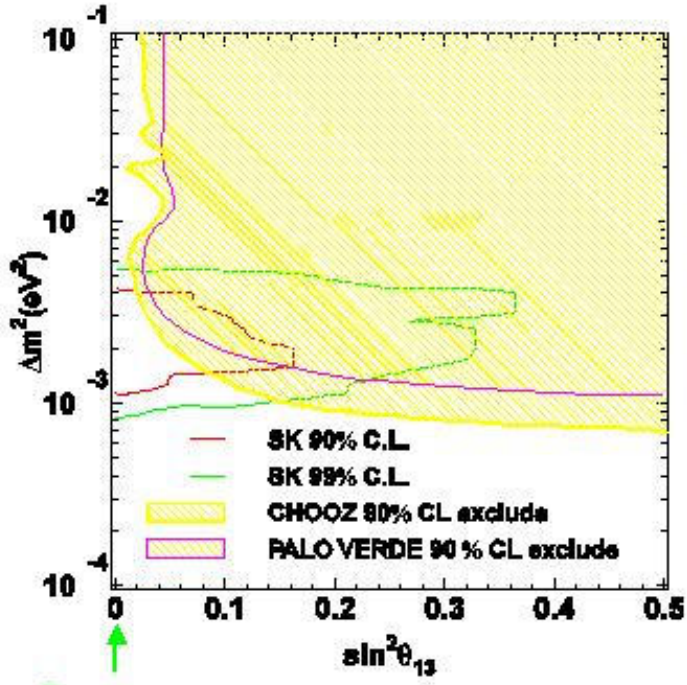
Oscillation effect of ν_e flux is cancelled out @ low energy ($E_\nu < 1$GeV)
However, possible matter effect @ high energy ($E_\nu > 3$ GeV)

nonzero θ_{13}

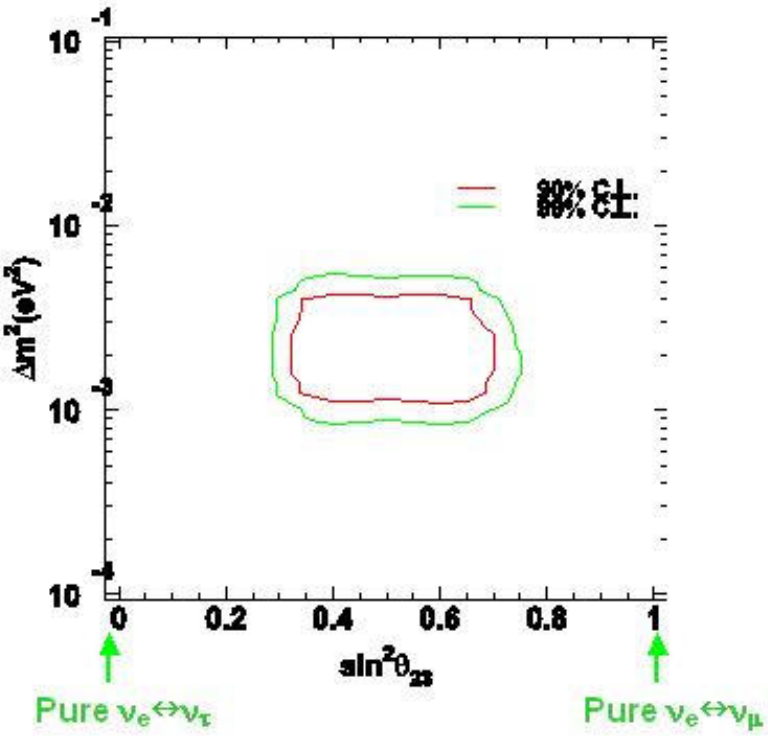
resonance happens at $E_\nu \sim 8$ GeV (Mantle)

$E_\nu \sim 3$ GeV (core) (for $\Delta m^2 = 3 \times 10^{-3} eV^2$)

Allowed region for active 3-flavor oscillations



getting close to CHOOZ's limit on θ_{13}

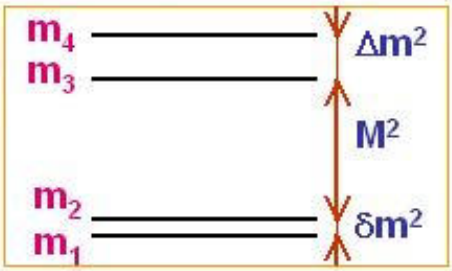


consistent with CHOOZ's excluded region

Limit on sterile ν

analyses following to Fogli, Lisi, Marrone (PRD63,053008)

assuming 3 active ν + 1 sterile ν having
δm^2 (solar) << Δm^2(atm) << M^2(LSND)



simplifies to 3 parameters;
Δm^2(atm), $\sin^2 2\theta$, $\sin^2\xi$

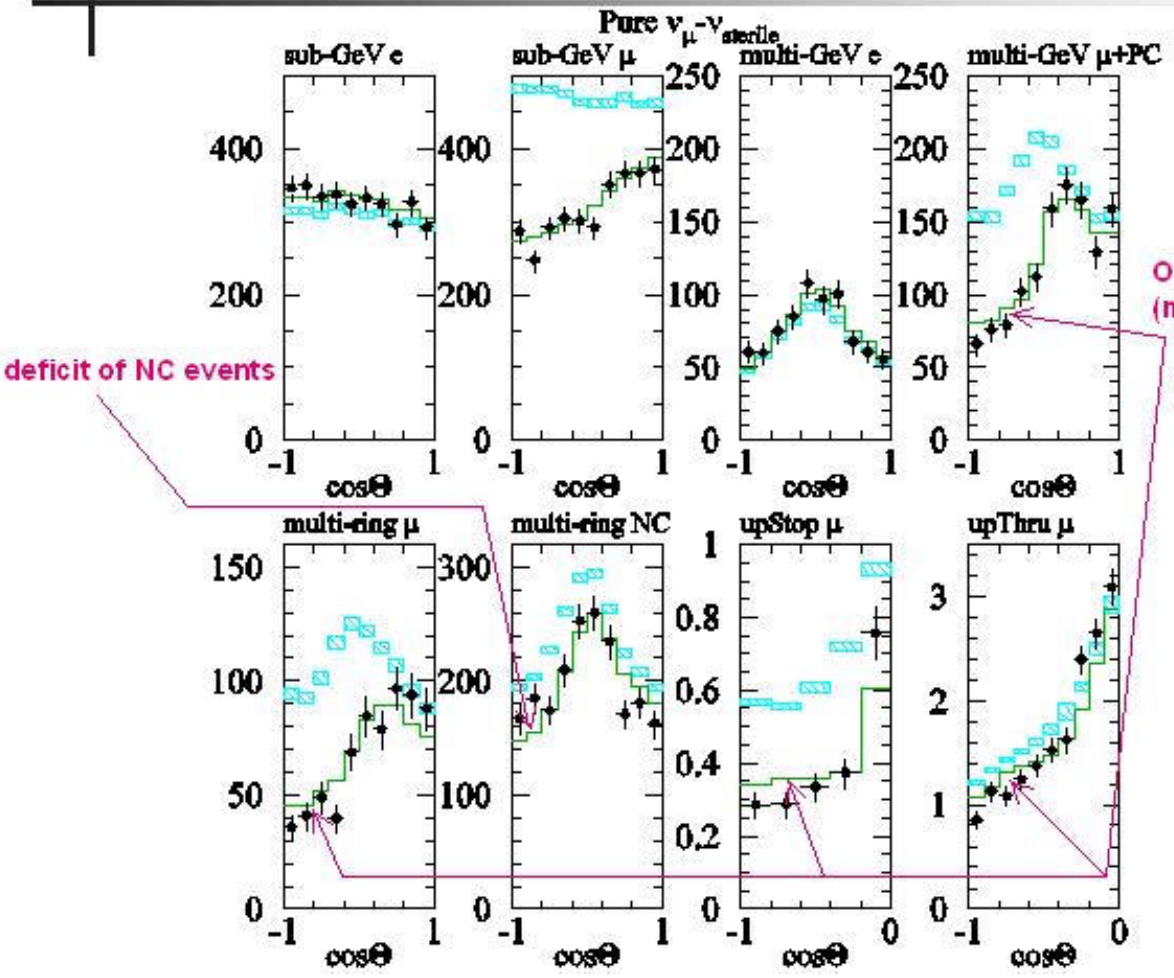
$$\nu_\mu \rightarrow \cos\xi\nu_\tau + \sin\xi\nu_s$$

$\sin^2\xi$=0; pure $\nu_\mu \rightarrow \nu_\tau$
$\sin^2\xi$=1; pure $\nu_\mu \rightarrow \nu_s$

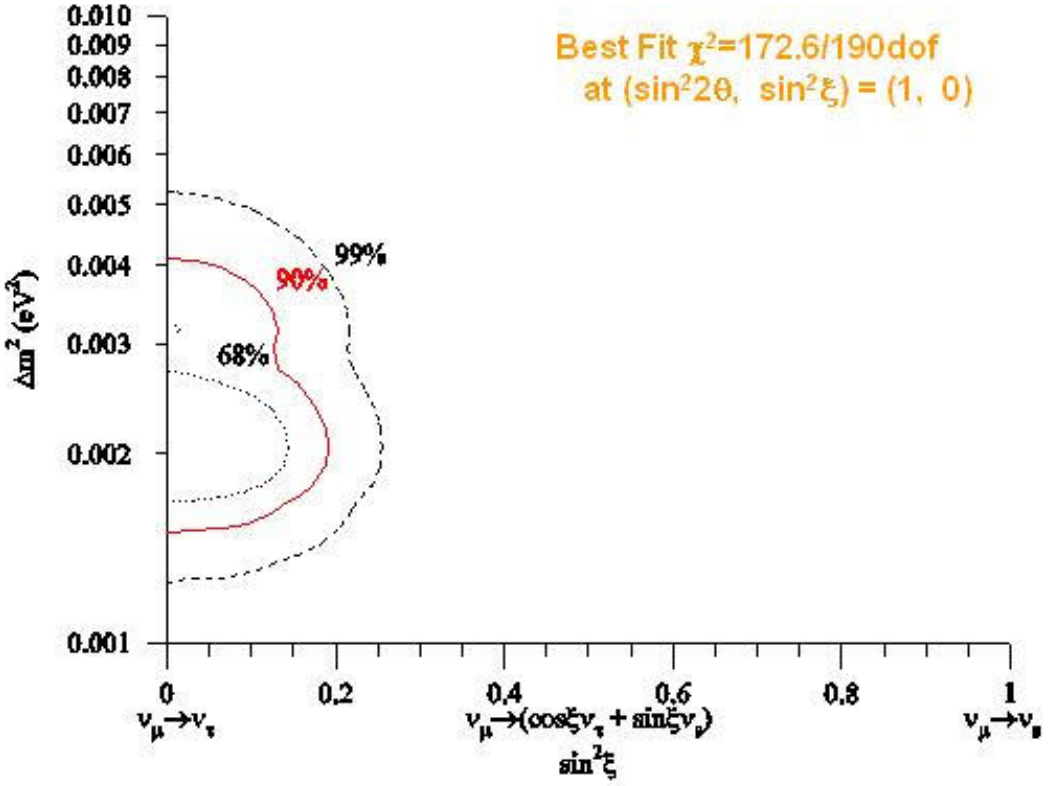
nonzero $\sin^2\xi$

- oscillation suppression happens at multi-GeV region due to matter effect
- deficit of NC events in upward bins is expected

shape of pure $\nu_\mu \leftrightarrow \nu_s$ ($\sin^2\xi$=1)



limit on $\nu_\mu \leftrightarrow \nu_s$ admixture



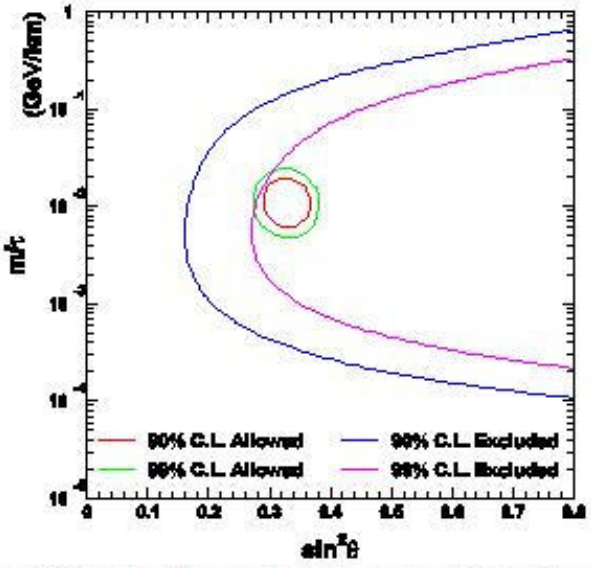
test of other hypotheses

➢ neutrino decay

Survival probability without oscillation($\Delta m^2 \to 0$);

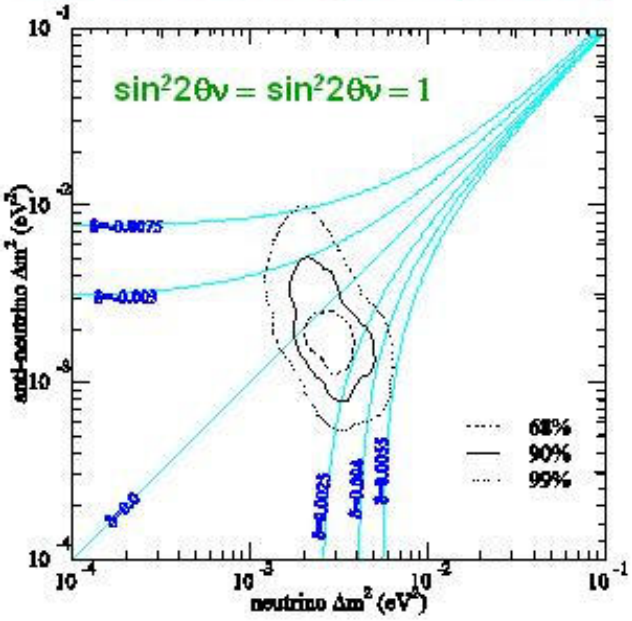
$$P(\nu_\mu \to \nu_\mu) = (\cos^2\vartheta + \sin^2\vartheta \cdot \exp(-\frac{m_3}{2\tau_3}\frac{L}{E}))^2$$

well fits to e,μ data but not to NC sample.



- The 99%CL allowed region by FC 1-ring+PC+up-μ is almost excluded at 99%CL by the NC sample.

➢ $\Delta m^2\nu \neq \Delta m^2\bar{\nu}$ (CPT violation)



- consistent with 0 CPT asymmetry
- limit on $\delta = \Delta m^2\nu - \Delta m^2\bar{\nu}$; $-0.0075 < \delta < 0.0055$

Summary of atmospheric ν observations

- **Atmospheric neutrinos are measured using various techniques in SK- I and analyzed in detail**
  - $\nu_\mu \leftrightarrow \nu_\tau$ 2 flavor oscillations
    - all data are well fitted and agree with each other
    - $\Delta m^2 = 1.6\sim3.9\times10^{-3}$ eV^2, $\sin^2 2\theta > 0.92$ @ 90%CL
    - observed τ–like events also support $\nu_\mu \leftrightarrow \nu_\tau$
  - $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$ 3 flavor oscillations
    - limit on θ_{13} consistent with CHOOZ
  - sterile neutrino admixture
    - ν_s is disfavored as a prominent oscillation partner of ν_μ
    - $\sin^2\xi < 0.19$ @ 90%CL
  - other hypothetical scenarios
    - neutrino decay scenario with $\Delta m^2 \to 0$ is almost excluded at 99%CL
    - consistent with 0 CPT asymmetry; $-0.0075 < \delta = \Delta m^2\nu - \Delta m^2\bar{\nu} < 0.0055$