

Super- Kamiokande: Atmospheric Neutrinos

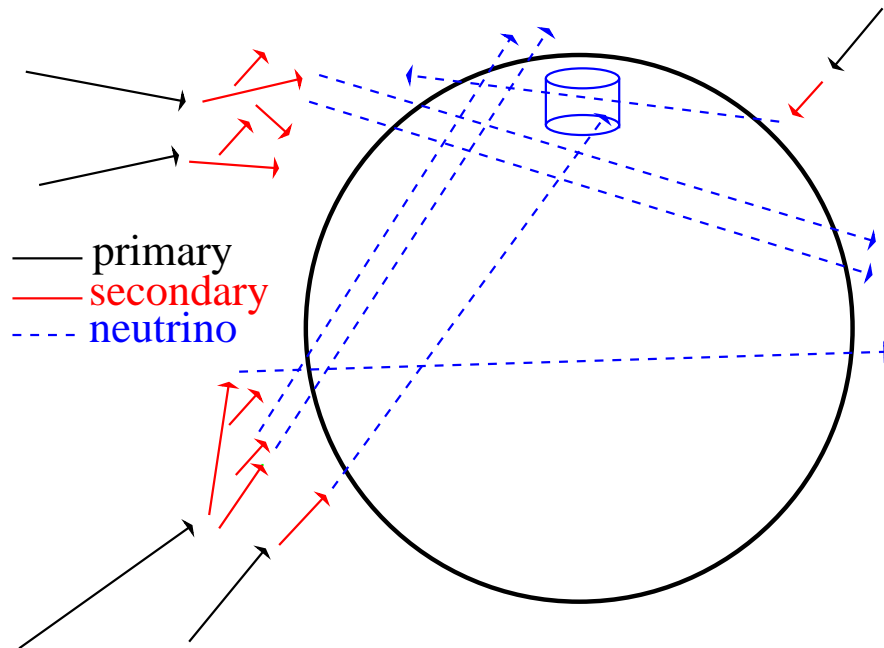
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ICHEP, Jul 2002

Introduction



- Origin of Atmospheric Neutrinos
- Neutrino Oscillation
- Full SK I - 1489 days
- $\nu_{\mu} \leftrightarrow \nu_{\tau}$
- Search for ν_{τ}
- $\nu_{\mu} \leftrightarrow \nu_{\tau}$ VS. $\nu_{\mu} \leftrightarrow \nu_s$
- Sterile Neutrino Admixture
- Three Active Flavor Oscillations

Origin of Atmospheric Neutrinos

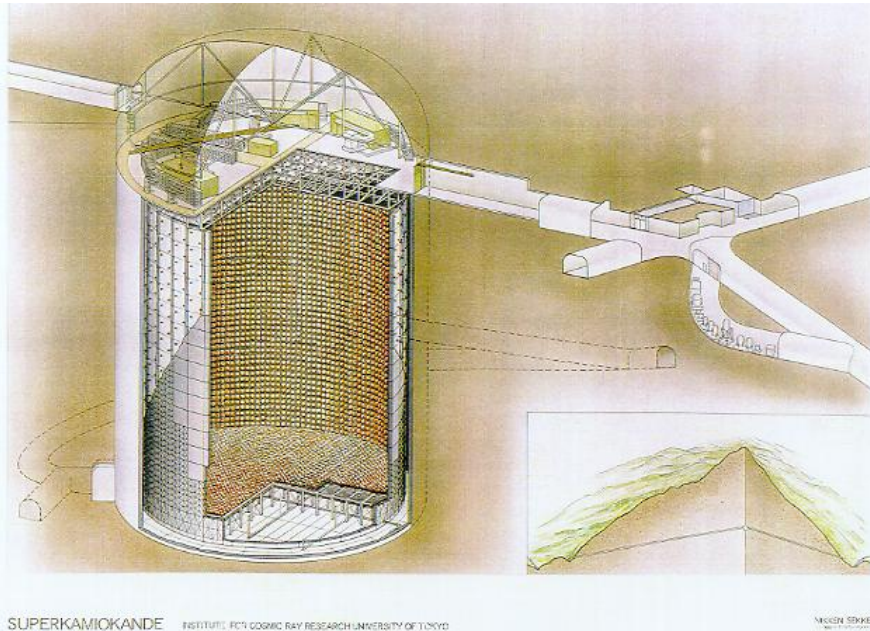


- Primary cosmic-rays + atmospheric nuclei \rightarrow hadronic showers
- Showers \rightarrow many π^\pm
- $\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$
- $\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$
- Expect $\nu_\mu/\nu_e \sim 2$
- Absolute flux uncertainty 20% \Rightarrow measure $\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}$

Two-flavor neutrino oscillations.

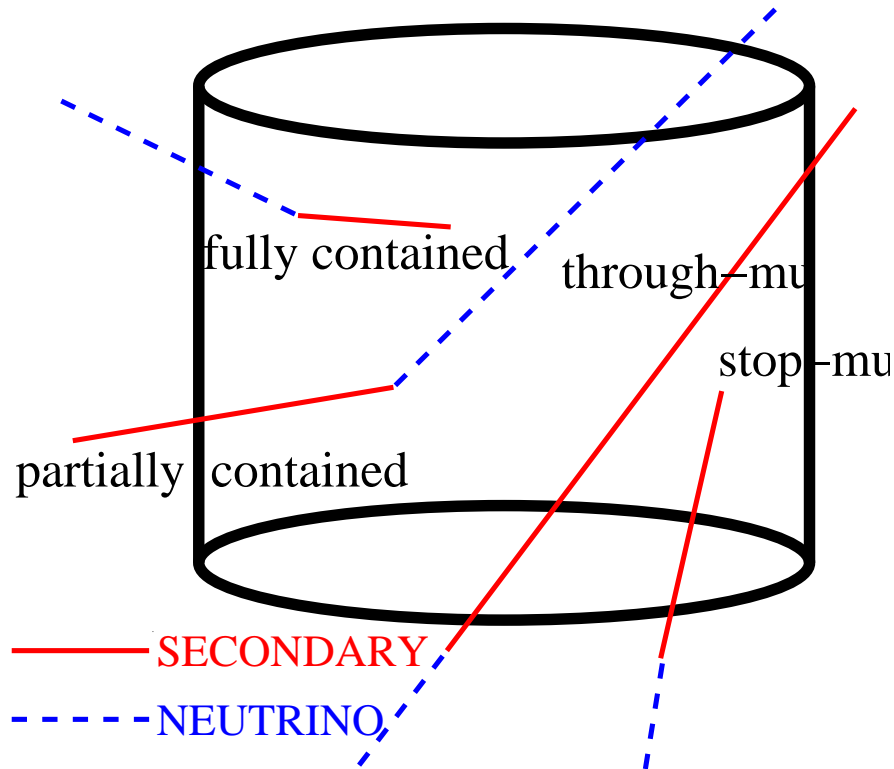
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.27 \Delta m^2 \frac{L}{E}).$$

Super-Kamiokande



- zinc mine Kamioka, Japan
- 1000 m rock overburden
2700 meters water equivalent
- 50 kton water Cherenkov detector
- 22.5 kton fiducial volume
- 11,146 inner photo-multiplier tubes (PMTs)
- 1885 outer photo-multiplier tubes (PMTs)
- cosmic-ray μ rate 2.7 per second

SK Atmospheric ν Detection



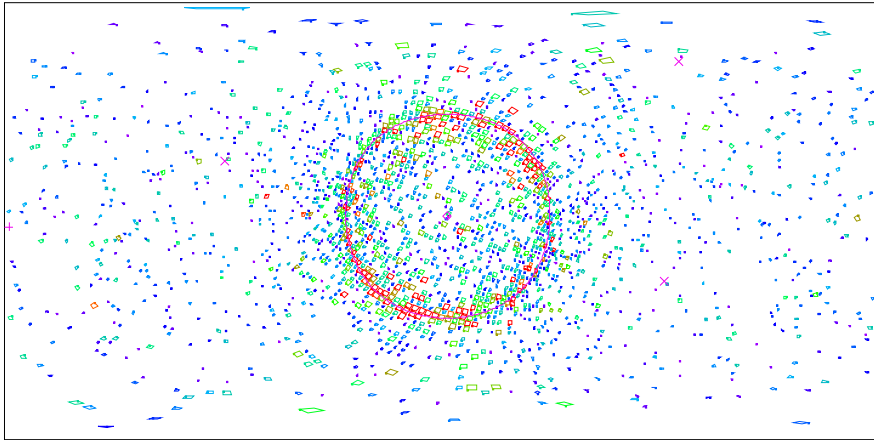
Event type	E_ν
FC (ν_e 's and ν_μ 's)	$\sim 2 \text{ GeV}$
PC ($> 98\% \nu_\mu$)	$\sim 10 \text{ GeV}$
up-going stopping μ	$\sim 10 \text{ GeV}$
up-going through μ	$\sim 100 \text{ GeV}$

- FC and PC
 $-1 < \cos \theta < 1$
- upward-going μ 's
 $-1 < \cos \theta < 0$

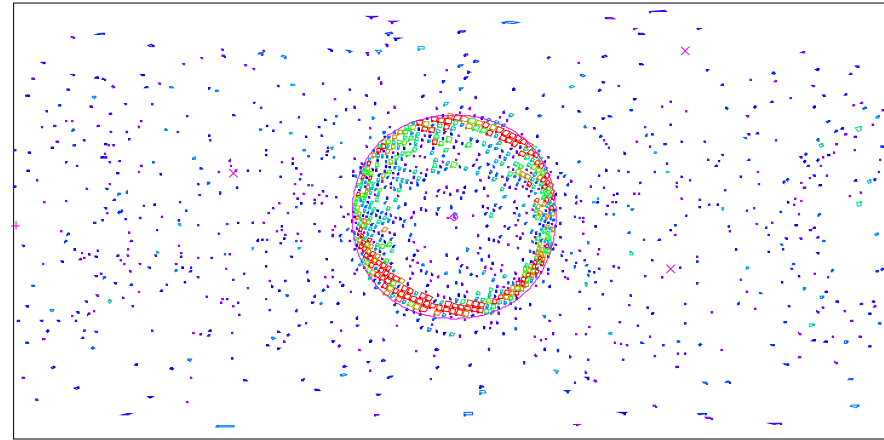
Reconstruction



Electron-like



Muon-like



For FC and PC events, we measure:

- position
- number of rings
- momentum of each ring
- particle ID (μ -like or e -like)

Sub-GeV Event Summary



$E_{vis} < 1.33 \text{ GeV}$
 $p_e > 100 \text{ MeV}/c$
 $p_\mu > 200 \text{ MeV}/c$

	DATA	MC(Honda)	MC(Bartol)
1 Ring e -like	3266	3081.0	3032.1
1 Ring μ -like	3181	4703.9	4564.6
Multi-Ring	2457	2985.6	2952.6
Total	8904	10770.5	10549.2

$$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = 0.638 \pm 0.016(stat.) \pm 0.050(sys.) \text{ (Honda).}$$

$$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = 0.647 \pm 0.016(stat.) \pm 0.051(sys.) \text{ (Bartol).}$$

Multi-GeV and PC Event Summary



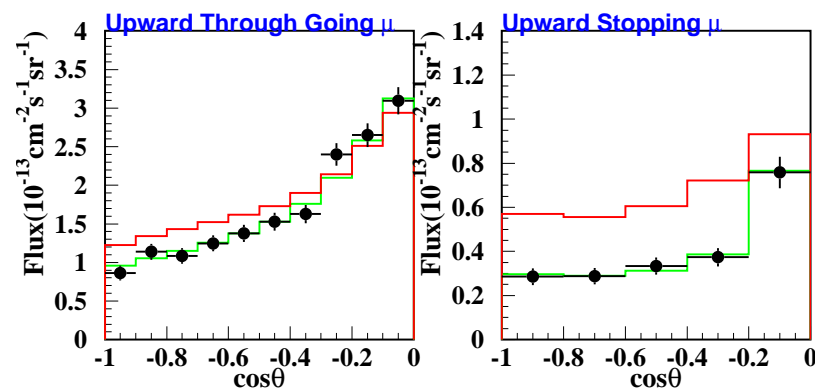
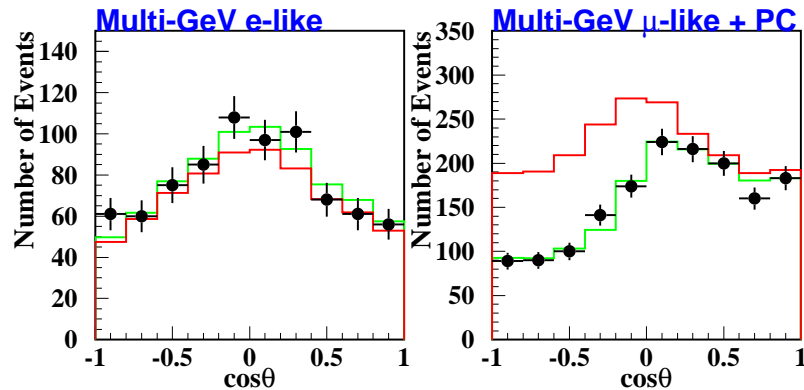
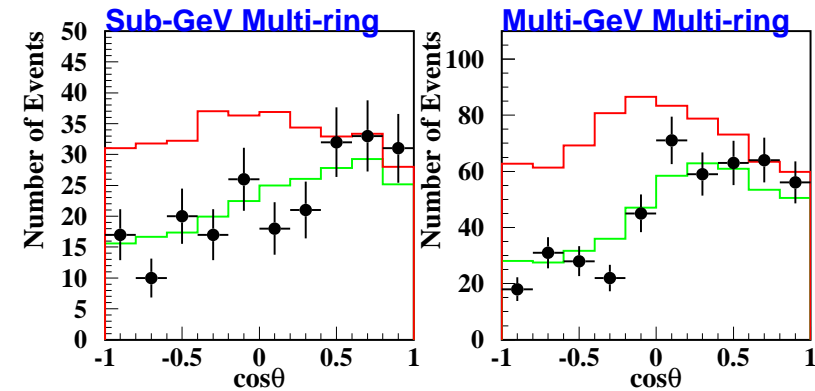
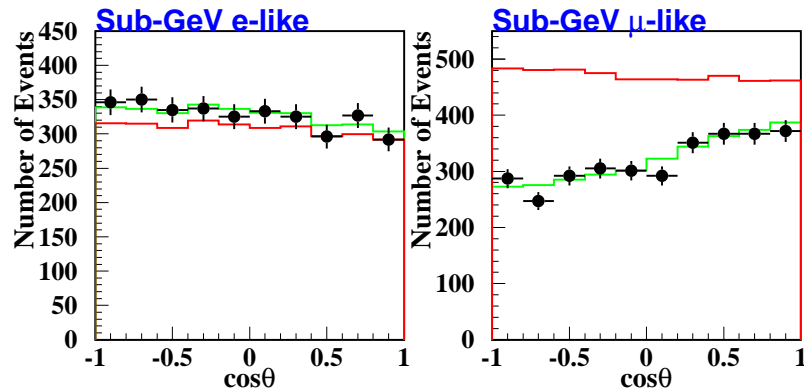
Multi-GeV \rightarrow Evis > 1.33 GeV

	DATA	MC(Honda)	MC(Bartol)
1 Ring e -like	772	707.8	734.2
1 Ring μ -like	664	968.2	967.8
Multi-Ring	1532	1903.5	1972.3
Total (Multi-GeV)	2968	3579.4	3674.3
PC (assumed μ -like)	913	1230.0	1297.5

$$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = 0.658 \pm \frac{0.030}{0.028} (stat.) \pm 0.050 (sys.) \text{ (Honda).}$$

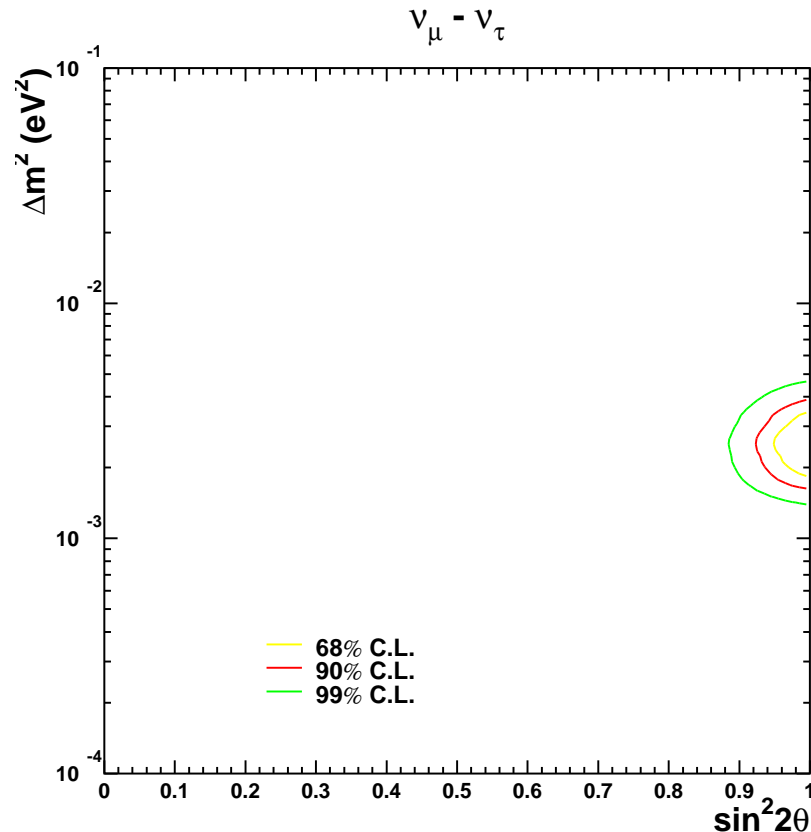
$$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = 0.662 \pm \frac{0.030}{0.028} (stat.) \pm 0.050 (sys.) \text{ (Bartol).}$$

Zenith Angle Distributions



Null hypothesis
 $\nu_\mu \leftrightarrow \nu_\tau$ fit to these data

$\nu_\mu \leftrightarrow \nu_\tau$ Oscillation



No oscillation

$$\chi_{min}^2 = 456.5/170 \text{ d.o.f.})$$

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

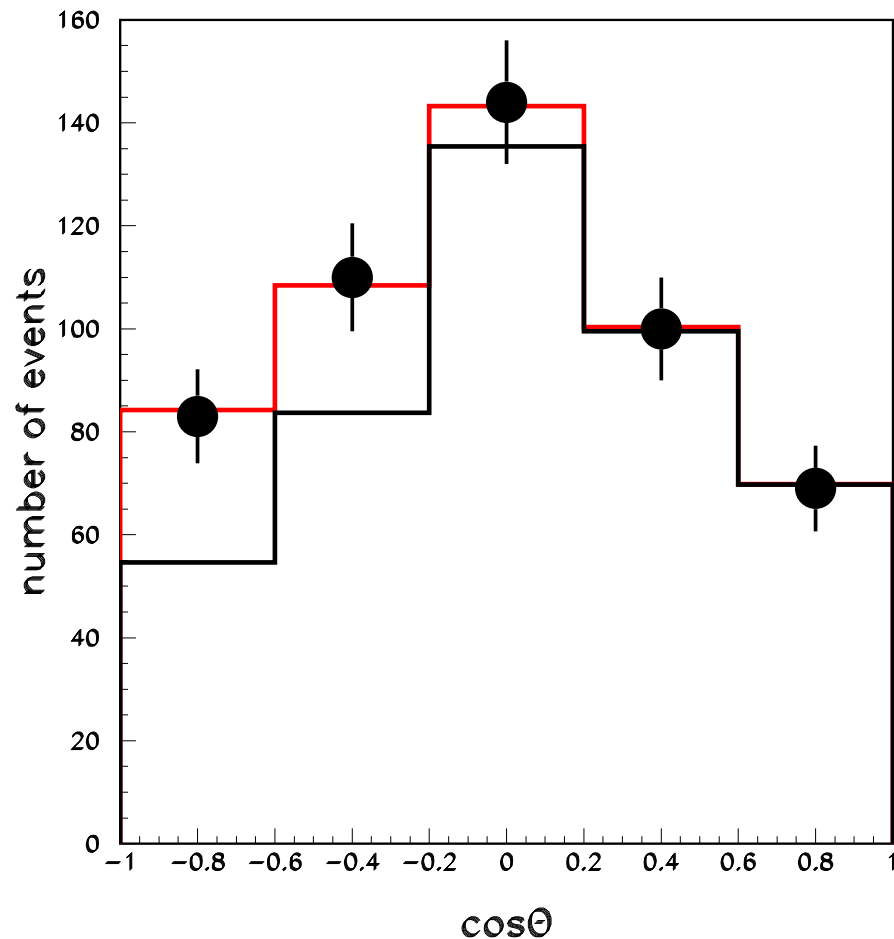
Best fit:

$$\Delta m^2 = 2.5 \times 10^{-3} eV^2, \sin^2 2\theta = 1.0$$

$$\chi_{min}^2 = 163.2/170 \text{ d.o.f.})$$

$$\Delta m^2 \in 1.6 \sim 3.9 \times 10^{-3} eV^2$$

$$\sin^2 2\theta > 0.92 \quad 90\% \text{ C.L.}$$



Threshold for $\nu_\tau \rightarrow \tau = 3.5 \text{ GeV}$
3 different analyses for τ search

BASIC IDEA

- hadronic decays
- τ heavy - fat events

RESULTS

$145 \pm 44(\text{stat.}) + 11/ - 16(\text{sys.})$
 $99 \pm 39(\text{stat.}) + 13/ - 21(\text{sys.})$

Super-Kamiokande is consistent with τ appearance.

$$\nu_\mu \leftrightarrow \nu_s \text{ VS. } \nu_\mu \leftrightarrow \nu_\tau$$



ν_s does not interact with matter (definition)

If pure $\nu_\mu \leftrightarrow \nu_s$ is correct,

- NC events reduced
- Matter effects suppress oscillation at high E_{ν_μ}

$$P(\nu_\mu \rightarrow \nu_s) = \frac{\sin^2 2\theta_v}{R} \times \sin^2\left(\pi \frac{L\Delta m^2}{4\pi E_\nu \sqrt{R}}\right), \text{ where}$$

$$R = \left(\mp \frac{\sqrt{2}G_F N_n E_\nu}{\Delta m^2} - \cos 2\theta\right)^2 + \sin^2 2\theta$$

Look beyond single rings to get directional NC sample.

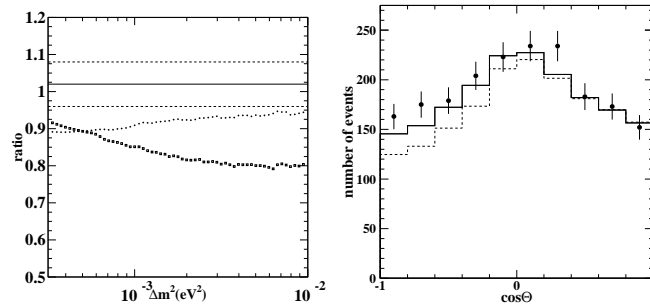
Measure up-down asymmetry (systematic error cancellation).

- Multi-Ring NC enhanced sample ($\sim 30\%$ NC)
- PC sample $E_{vis} > 5 \text{ GeV} \rightarrow E_\nu \sim 20 \text{ GeV}$
- Through- μ sample $E_\nu \sim 100 \text{ GeV}$

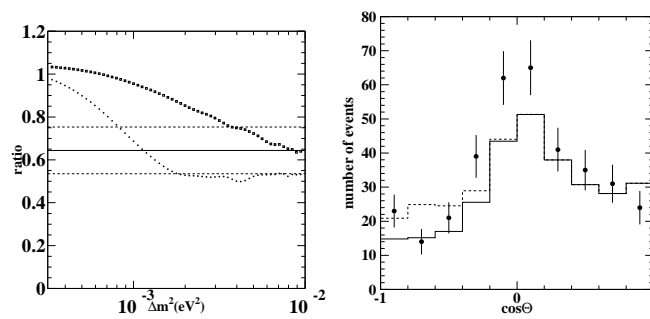
$\nu_\mu \leftrightarrow \nu_s$ VS. $\nu_\mu \leftrightarrow \nu_\tau$



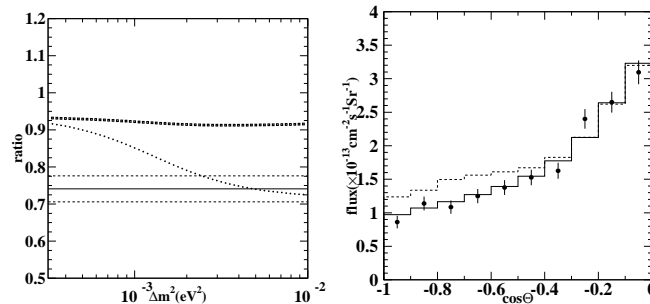
NC enhanced



PC



up- μ



When combined with single ring oscillation result, pure $\nu_\mu \leftrightarrow \nu_s$ is ruled out at the 99% C.L.

Limit on Sterile Admixture



Analysis follows Fogli, Lisi,
Marrone (PRD63) (2001)
053008

Assume 3 active + 1 sterile
neutrino such that

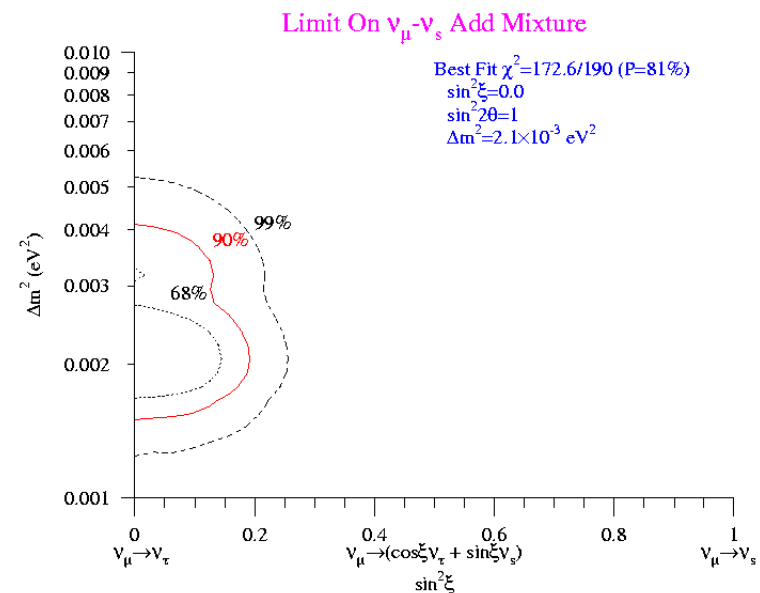
$$\delta m^2(\text{solar}) \ll \Delta m^2(\text{atm}) \ll M^2(\text{LSND}) \Rightarrow$$

simply to 3 quantities: Δm^2 ,
 $\sin^2 2\theta$, $\sin^2 \xi$

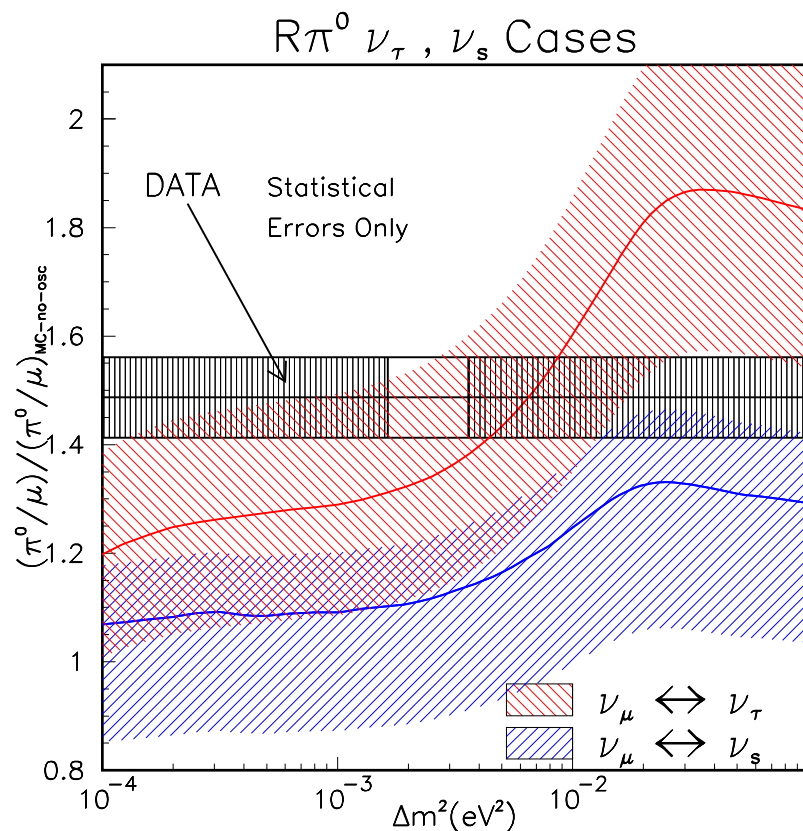
$$\nu_\mu \rightarrow \cos\xi \nu_\tau + \sin\xi \nu_s$$

$$\sin^2 \xi = 0 \Rightarrow \text{pure } \nu_\mu \leftrightarrow \nu_\tau$$

$$\sin^2 \xi = 1 \Rightarrow \text{pure } \nu_\mu \leftrightarrow \nu_s$$



π^0 Study (Preliminary, 1289 days)



Recent results from K2K have made possible $\nu_\mu \leftrightarrow \nu_s$ studies using the NC π^0 sample.

- define double ratio:
$$R_{\pi^0} \equiv \frac{(\pi^0/\mu)_{data}}{(\pi^0/\mu)_{MC}}$$
- for each oscillation scenario, make predictions
- compare data with the predictions

$$R_{\pi^0} = 1.49 \pm 0.08 \pm 0.22$$

$\nu_\mu \leftrightarrow \nu_\tau$ prediction is 1.34
 $\nu_\mu \leftrightarrow \nu_s$ prediction is 1.12

SK R_{π^0} more consistent with $\nu_\mu \leftrightarrow \nu_\tau$.

3 Active Flavor Oscillations



Assumptions:

- $\Delta m_{13}^2 \approx \Delta m_{23}^2 = \Delta m_{atm}^2$
- $\Delta m_{12}^2 = m_{sol}^2 \ll \Delta m_{23}^2, \Delta m_{13}^2$

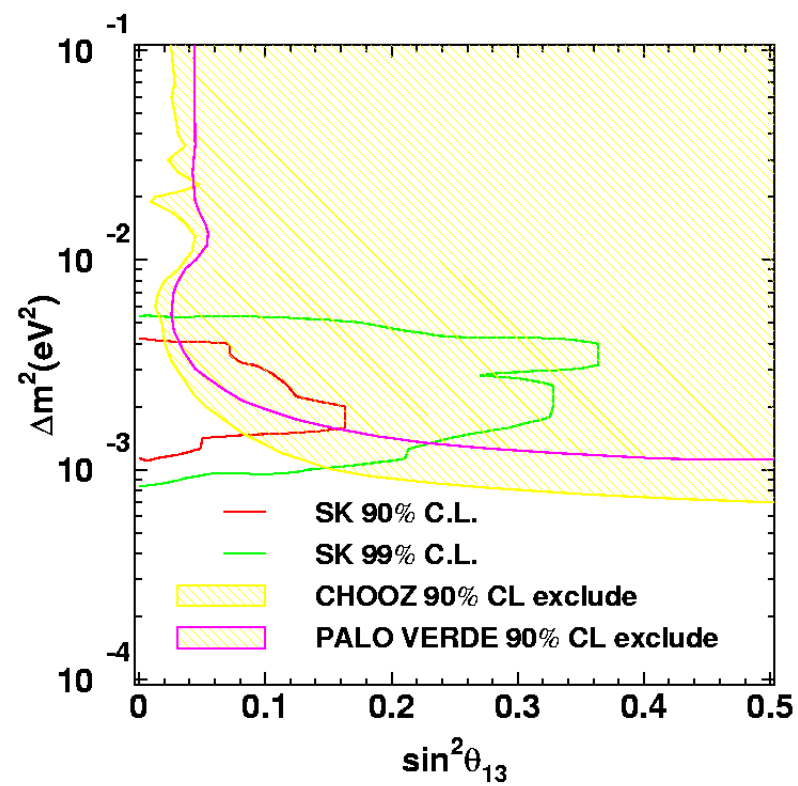
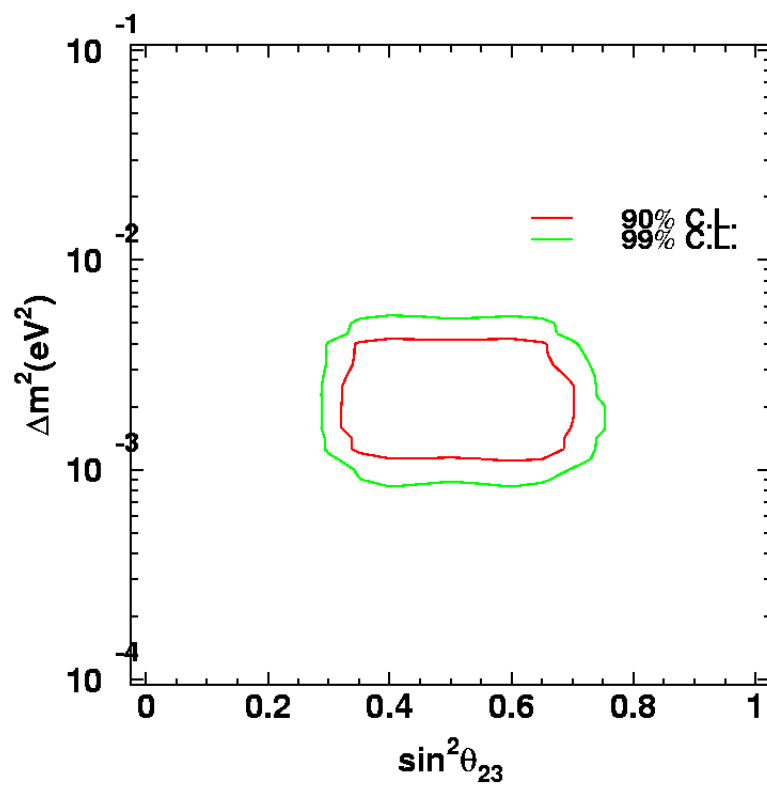
Fit to three parameters: $\Delta m_{23}^2, \theta_{13}, \theta_{23}$

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

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

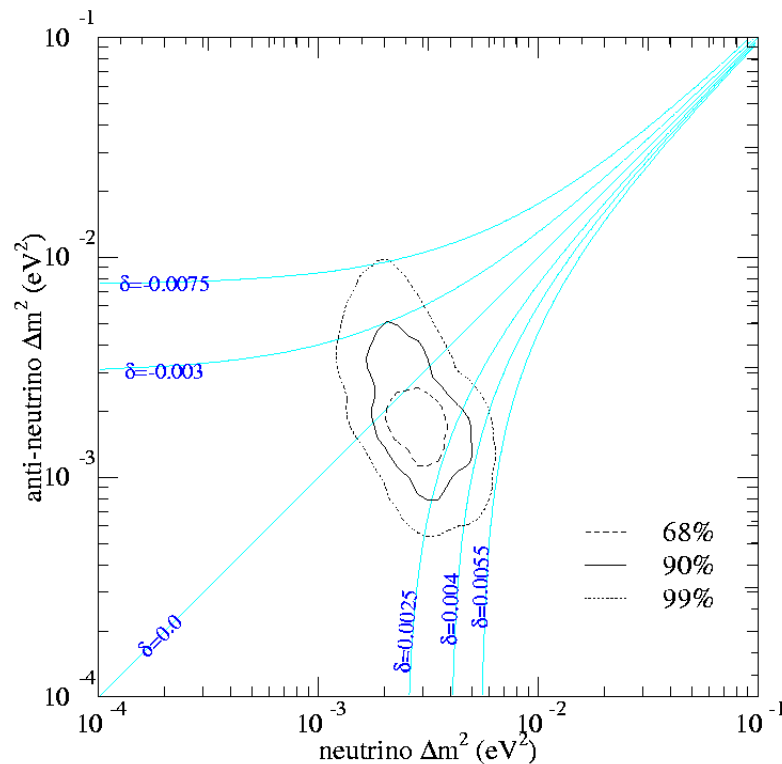
$$P(\nu_\tau \rightarrow \nu_e) = \sin^2 2\theta_{13} \times \cos^2 2\theta_{23} \times \sin^2(1.27\Delta m^2 \frac{L}{E}).$$

For $E_\nu > 3 \text{ GeV}$, matter effect can enhance oscillations (θ_{13})



- $\nu_\mu \leftrightarrow \nu_\tau$
 - SK data consistent with each other
 - Best Fit $\Delta m^2 = 2.5 \times 10^{-3} eV^2, \sin^2 2\theta = 1.0$
 $\Delta m^2 \in 1.6 \sim 3.9 \times 10^{-3} eV^2 \sin^2 2\theta > 0.92$ 90% C.L.
 - Search for ν_τ - consistent with τ appearance
- $\nu_\mu \leftrightarrow \nu_\tau$ VS. $\nu_\mu \leftrightarrow \nu_s$
 - NC and CC_μ zenith angles: pure $\nu_\mu \leftrightarrow \nu_s$ disfavored 99% C.L.
 - $\nu_\mu \leftrightarrow \nu_s$ admixture $\sin^2 \xi < 0.19$ 90% C.L.
 - NC-rate (R_{π^0}) pure $\nu_\mu \leftrightarrow \nu_s$ disfavored 90% C.L.
- Three Active Flavor Oscillations
 - Consistent with maximal $\nu_\mu \leftrightarrow \nu_\tau$
 - Small θ_{13} allowed - consistent with CHOOZ, Palo Verde

CPT Violation



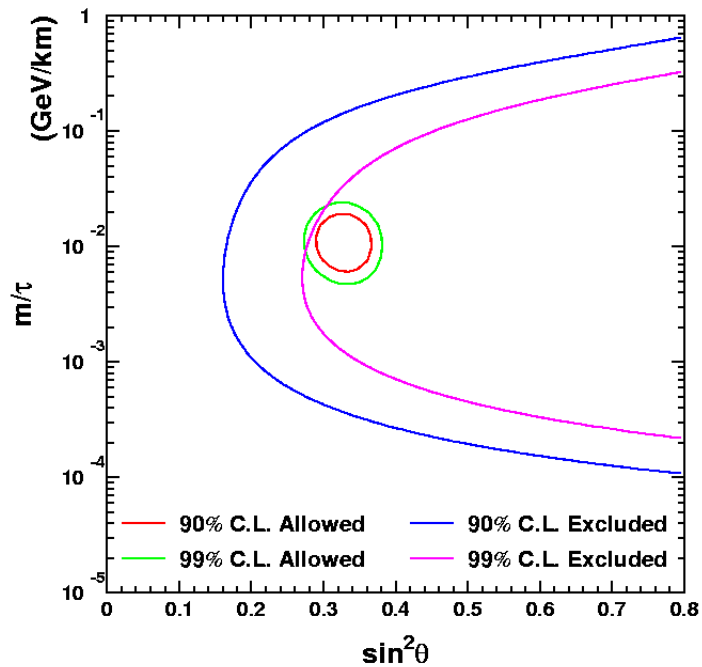
If CPT violated $\delta = \Delta m_{\nu}^2 - \Delta m_{\bar{\nu}}^2 \neq 0$

Assume $\sin^2 2\theta = 1$ for neutrinos and anti-neutrinos

Best fit($\nu, \bar{\nu}$): $\delta = (2.8, 1.9) \times 10^{-3} eV^2$

Consistent with 0 CPT asymmetry ($-0.0075 < \delta < 0.0055 eV^2$)

Neutrino Decay



Consider $\Delta m^2 \rightarrow 0$ case

$$P(\nu_\mu \rightarrow \nu_\mu) = (\cos^2 \theta + (\sin^2 \theta \times \exp(-\frac{m}{2\tau} \frac{L}{E})))^2$$

FC 1-ring+PC+up- μ fit well

NC enhanced sample does not fit well