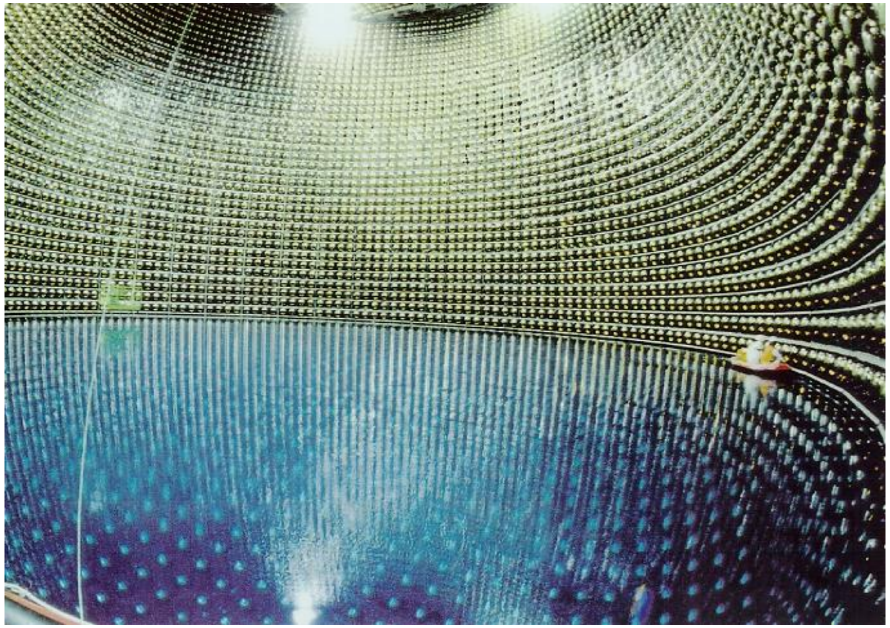

Super–Kamiokande: Atmospheric Neutrinos

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ICHEP, Jul 2002

Introduction

SK

- 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

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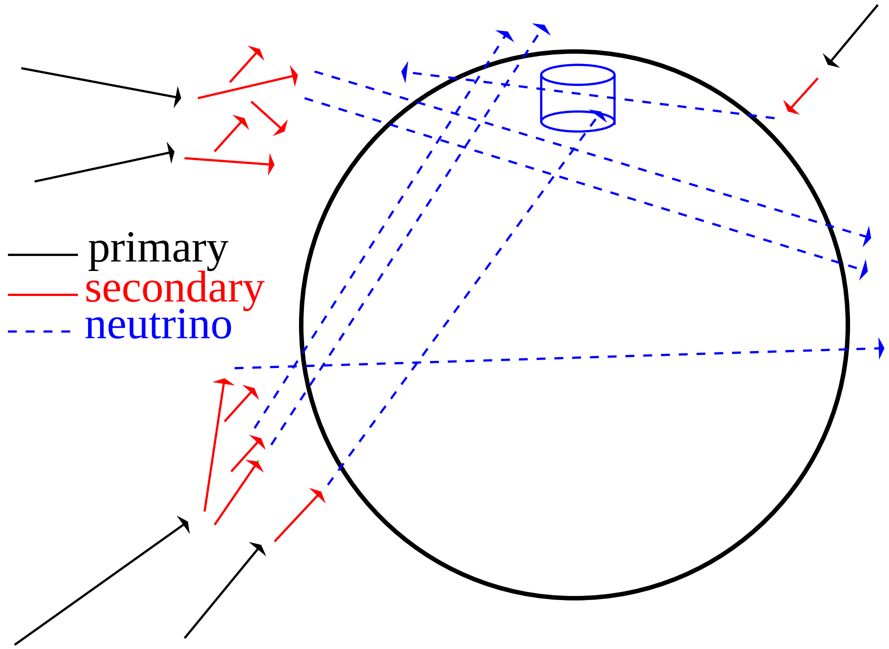
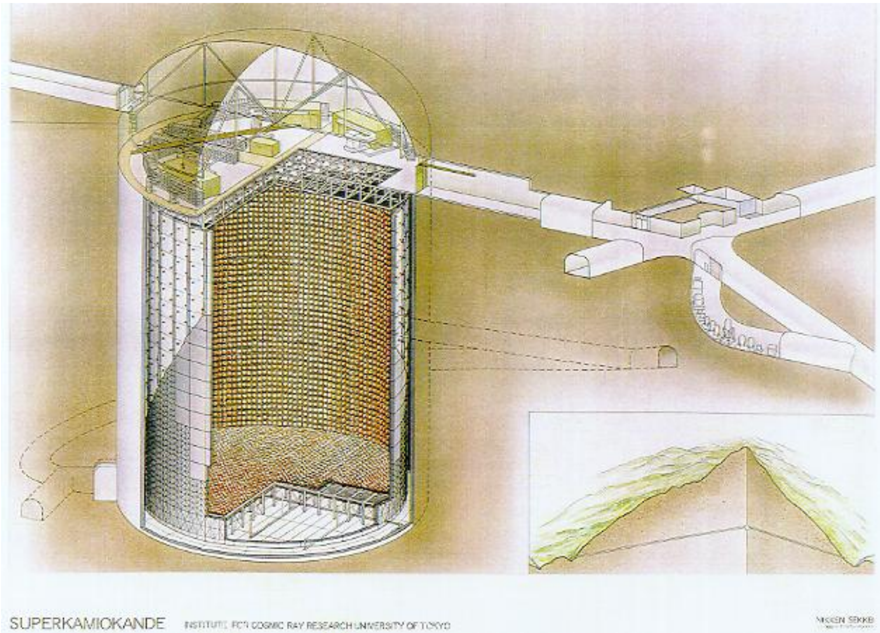


- Primary cosmic-rays + atmospheric nuclei $\rightarrow$ hadronic showers
- Showers $\rightarrow$ many $\pi^{\pm}$
- $\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$
- $\mu^{\pm} \rightarrow e^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_{e}(\bar{\nu}_{e})$
- Expect $\nu_{\mu}/\nu_{e} \sim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

Two-flavor neutrino oscillations.

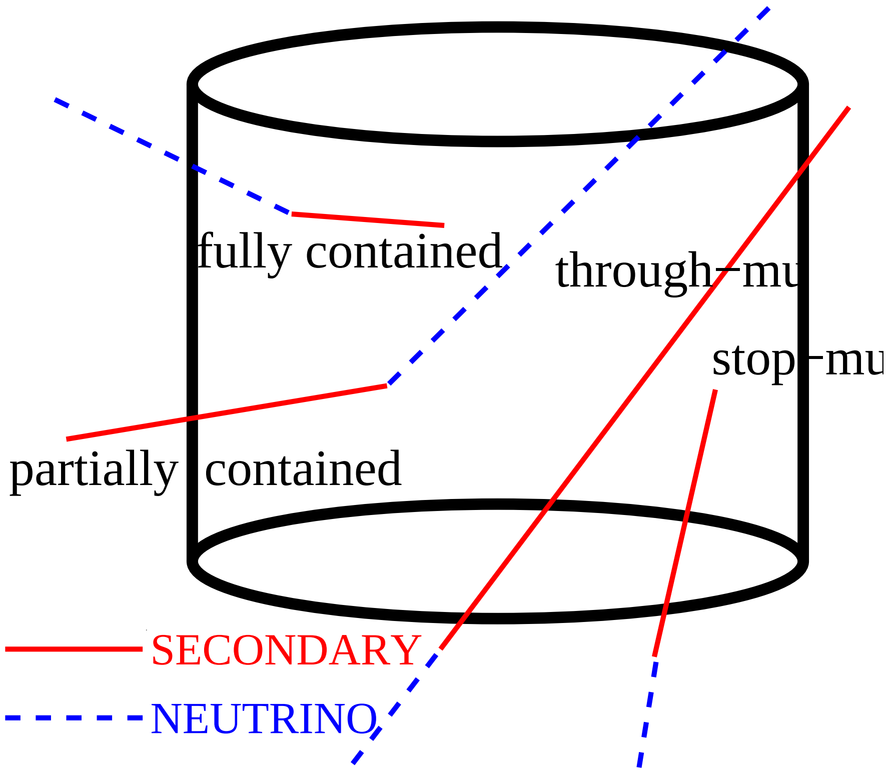
$$P(\nu_{\mu} \rightarrow \nu_{\mu}) = 1 - \sin^2 2\theta \sin^2(1.27 \Delta m^2 \tfrac{L}{E}).$$

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

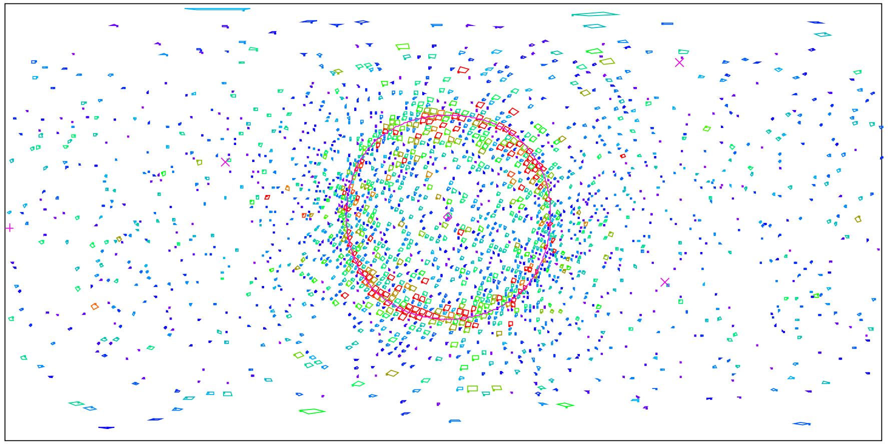


Event type	E_ν
FC (ν_e's and ν_μ's)	$\sim 2\ GeV$
PC ($> 98\%\ \nu_\mu$)	$\sim 10\ GeV$
up-going stopping μ	$\sim 10\ GeV$
up-going through μ	$\sim 100\ GeV$

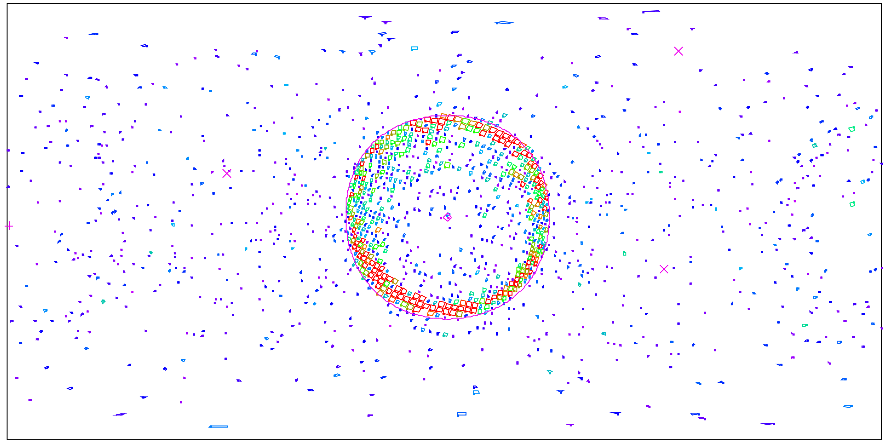
- FC and PC
  $-1 < \cos\theta < 1$
- upward-going μ's
  $-1 < \cos\theta < 0$

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

Evis $< 1.33\ GeV$

$p_e > 100\ MeV/c$

$p_\mu > 200\ MeV/c$

	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

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

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

Multi-GeV and PC Event Summary

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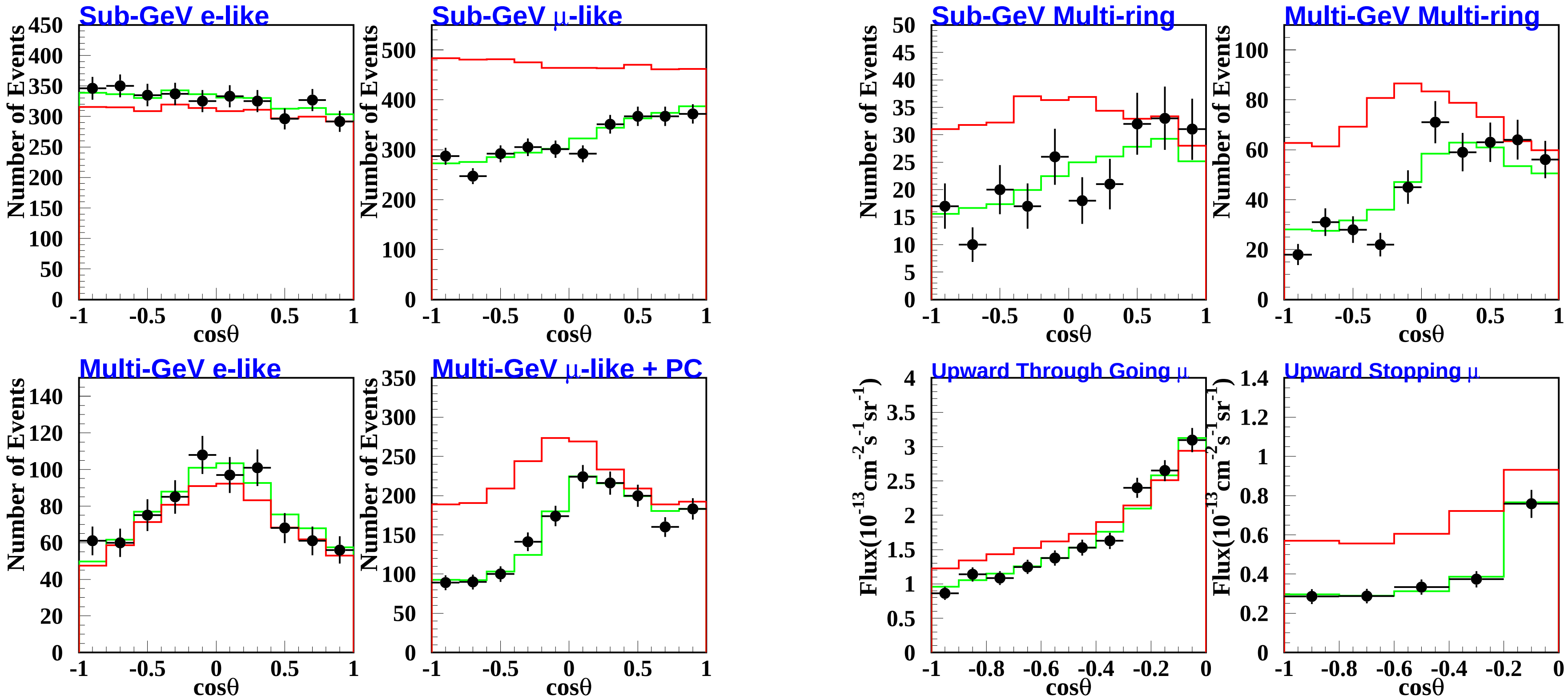
Multi-GeV → Evis $> 1.33\ GeV$

	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

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

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

Zenith Angle Distributions



Null hypothesis

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

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

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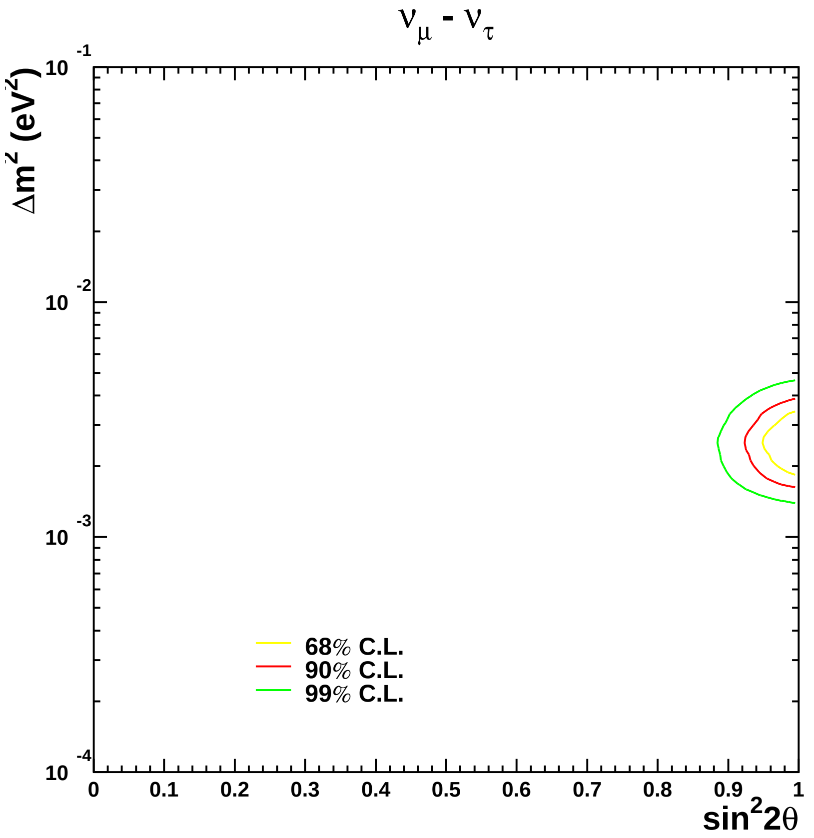

No oscillation

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

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

Best fit:

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

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

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

$\sin^2 2\theta > 0.92$ 90% C.L.

ν_τ Search

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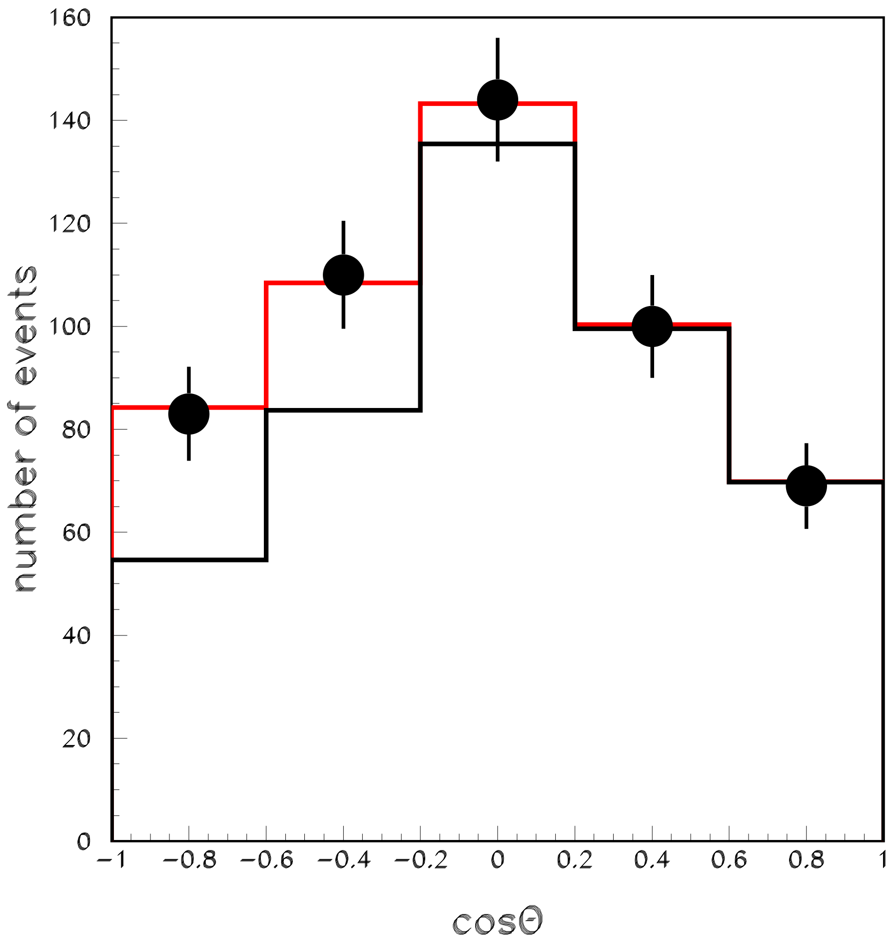

Threshold for $\nu_\tau \rightarrow \tau = 3.5\ GeV$
3 different analyses for τ search

BASIC IDEA

- hadronic decays
- τ heavy - fat events

RESULTS

$145 \pm 44(stat.) + 11/-16(sys.)$

$99 \pm 39(stat.) + 13/-21(sys.)$

Super–Kamiokande is consistent with τ appearance.

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

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

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

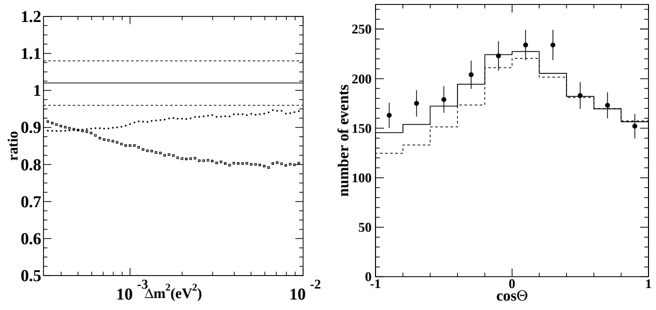
Look beyond single rings to get directional NC sample.
Measure up-down asymmetry (systematic error cancellation).

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

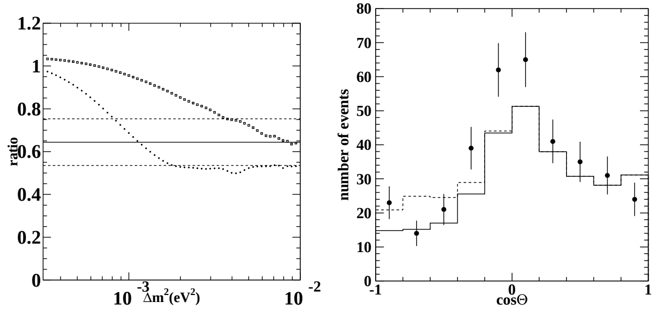
$\nu_\mu \leftrightarrow \nu_s$ vs. $\nu_\mu \leftrightarrow \nu_\tau$

SK

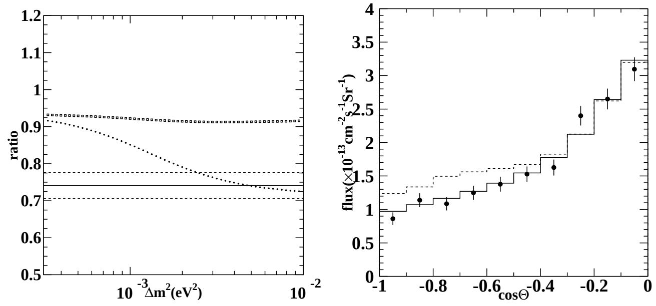
NC enhanced



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

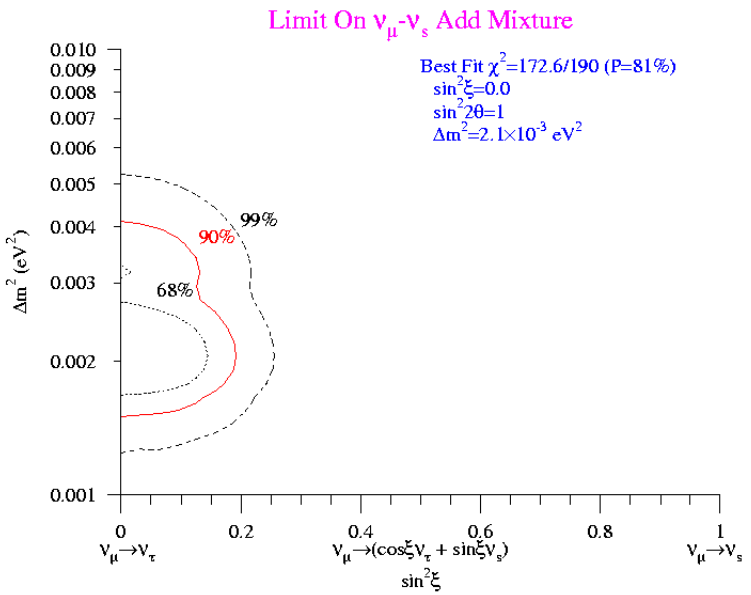
Assume 3 active $+$ 1 sterile neutrino such that $\delta m^2(solar) \ll \Delta m^2(atm) \ll M^2(LSND) \Rightarrow$

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

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

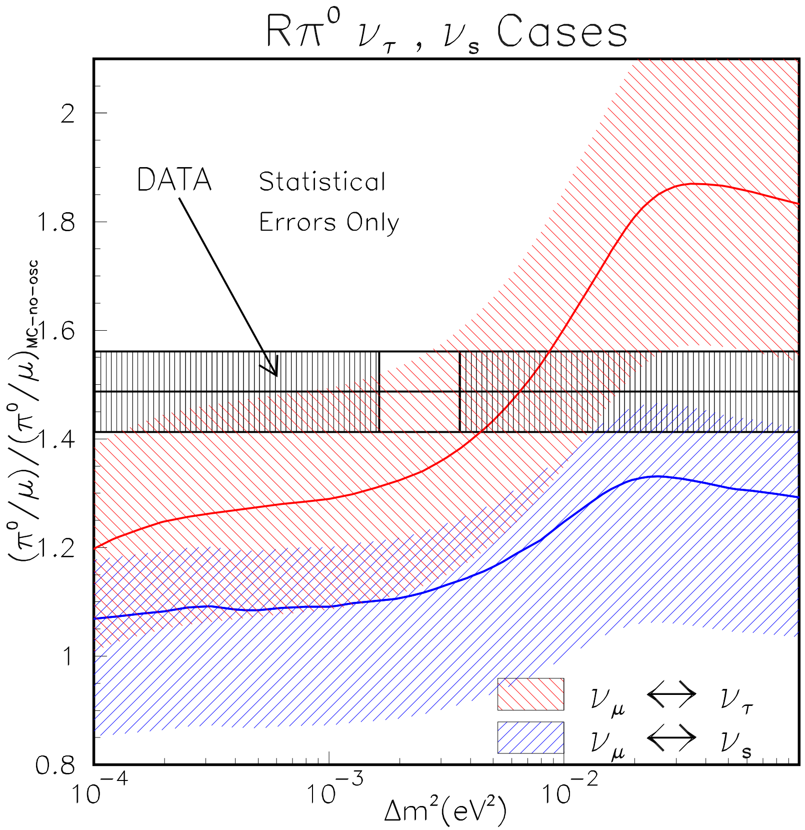
$\sin^2 \xi = 0 \Rightarrow$ pure $\nu_\mu \leftrightarrow \nu_\tau$

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



π^0 Study (Preliminary,1289 days)

SK



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

SK

Assumptions:

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

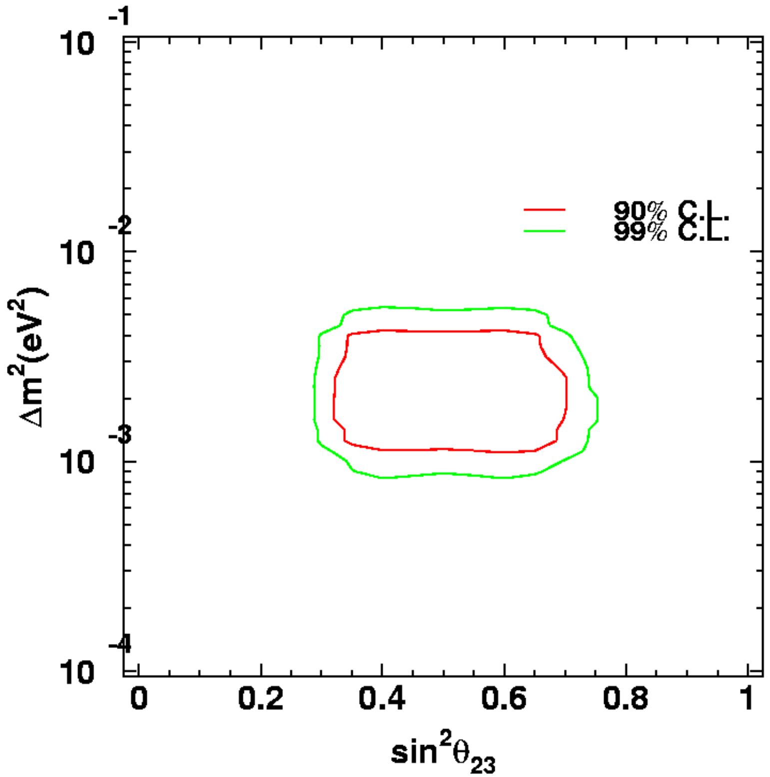
Fit to three parameters: $\Delta m^2_{23}, \theta_{13}, \theta_{23}$

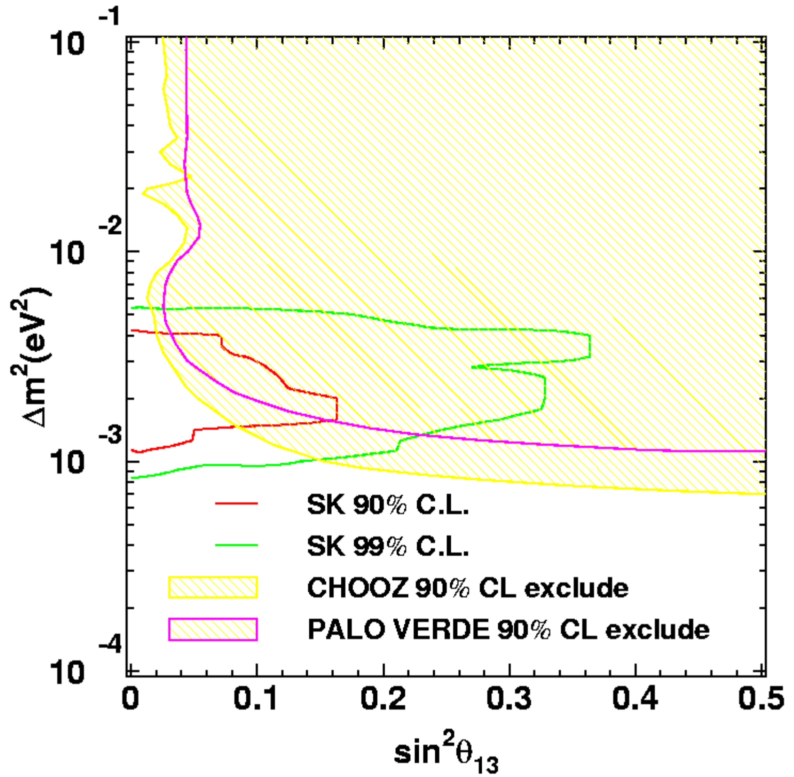
$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta_{13} \times \sin^2 2\theta_{23} \times \sin^2(1.27\Delta m^2 \tfrac{L}{E}).$$

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

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

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


90% C.L.
99% C.L.
$\Delta m^2(eV^2)$
$\sin^2\theta_{23}$


SK 90% C.L.
SK 99% C.L.
CHOOZ 90% CL exclude
PALO VERDE 90% CL exclude
$\Delta m^2(eV^2)$
$\sin^2\theta_{13}$

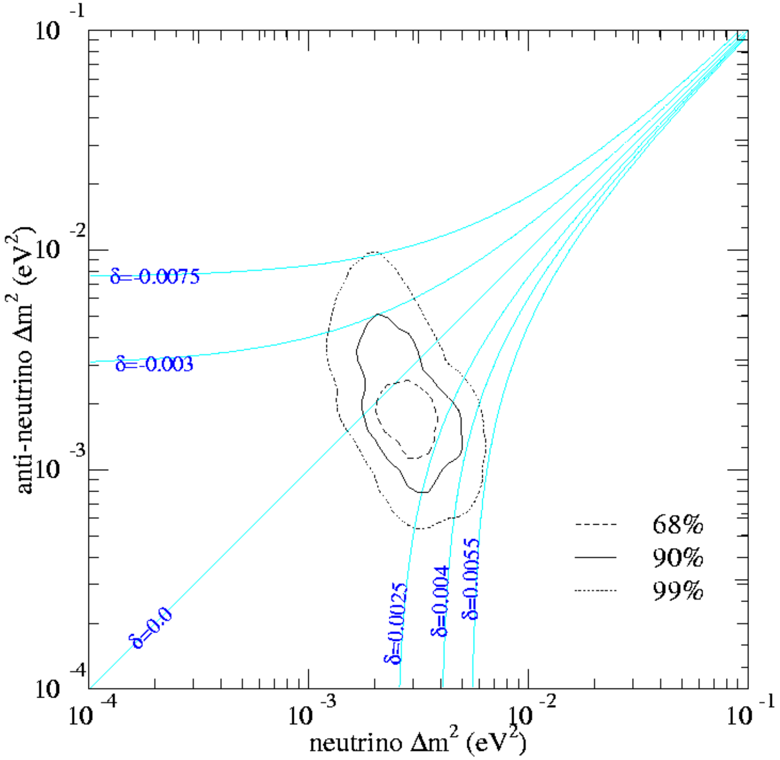
Summary

SK

- $\nu_\mu \leftrightarrow \nu_\tau$
  - 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 CCμ 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

SK



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

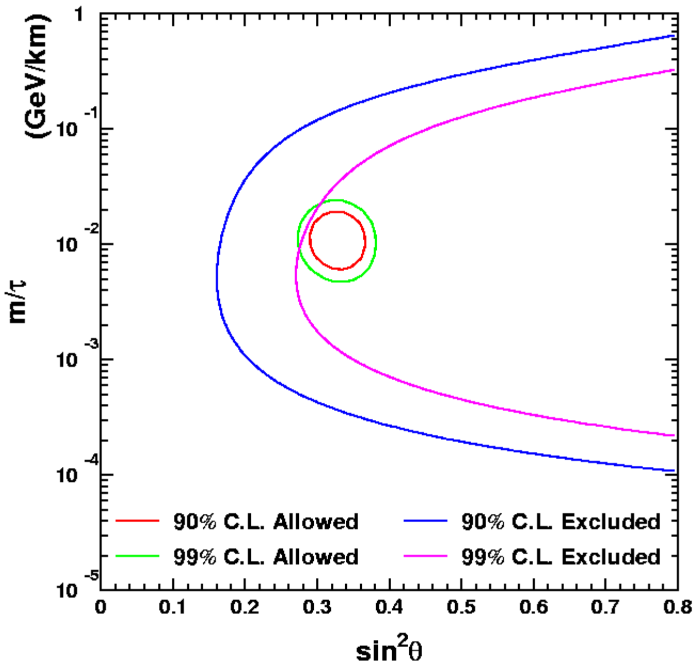
Assume $\sin^2 2\theta = 1$ for neutrinos and anti-neutrinos

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

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

Neutrino Decay

SK



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