Results From SuperKamiokande on Atmospheric neutrino and Limits on Matter Instability

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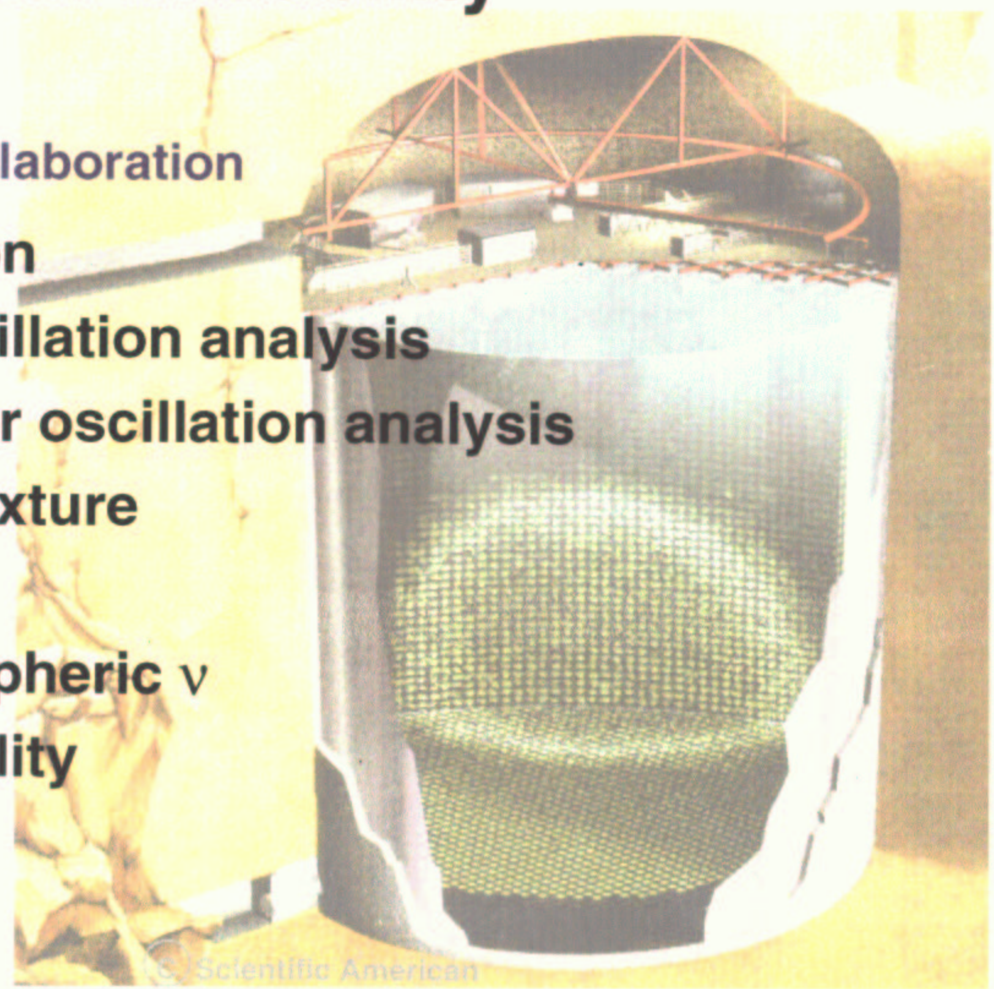
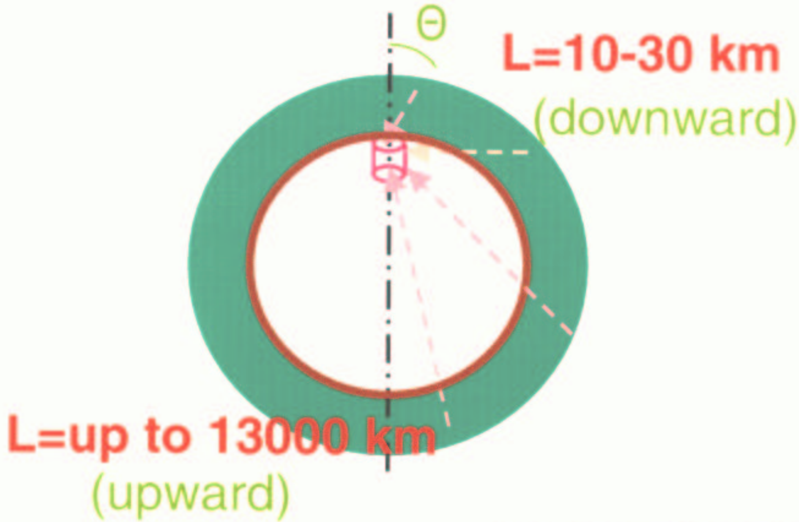
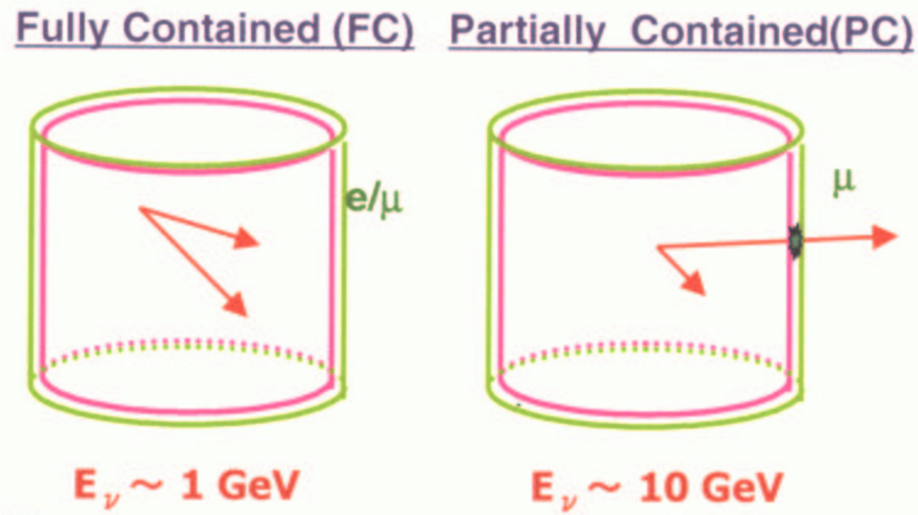
For Super-Kamiokande collaboration

- atmospheric ν oscillation
  - $\nu_\mu \leftrightarrow \nu_\tau$ two flavor oscillation analysis
  - $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$ three flavor oscillation analysis
  - Limit on $\nu_\mu \leftrightarrow \nu_s$ admixture
  - ν decay
  - τ detection in atmospheric ν
- Limits on Matter instability
  - $p \rightarrow e^+\pi^0$
  - $p \rightarrow \nu K^+$

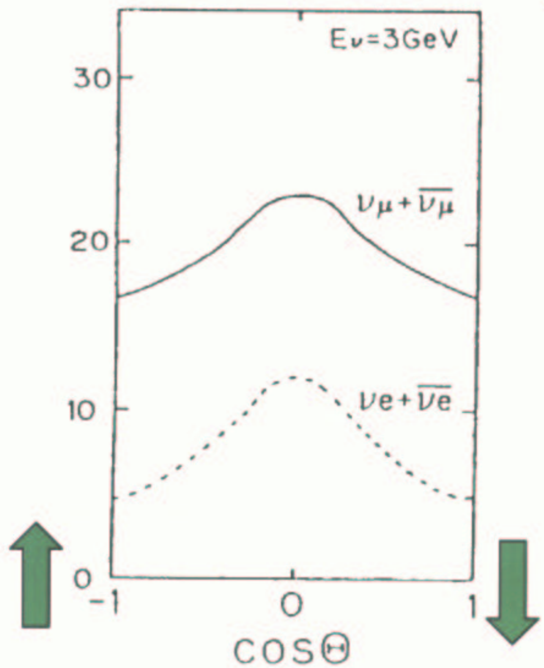


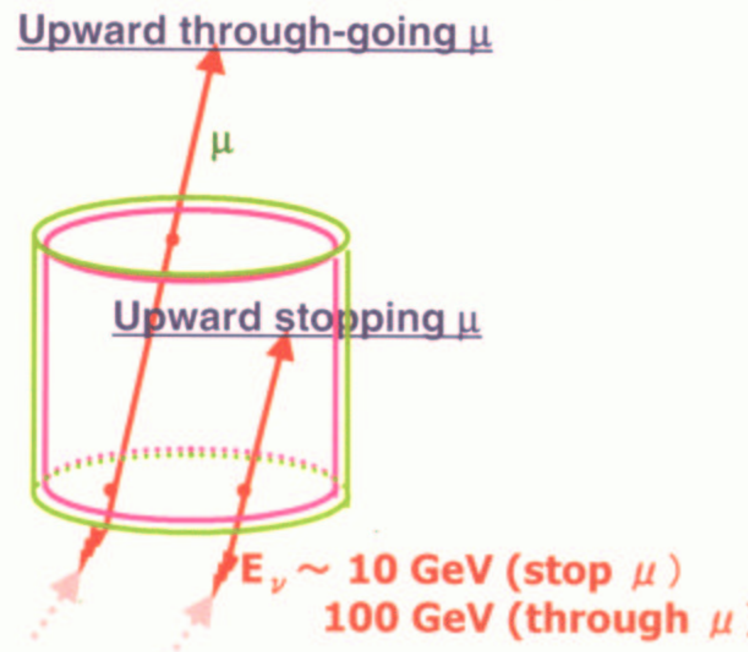
Atmospheric ν & Events Classification





Zenith angle dist. of Atmospheric ν flux





For E$_\nu$ > a few GeV,

Up /down symmetry

Event Summary

Fully & Partially Contained events

Livetime: 1489days

Sub-GeV (Fully Contained)

$E_{vis} < 1.33$ GeV,
$P_e > 100$ MeV/c, $P_\mu > 200$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

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)

	Data	MC(Honda)
Total	913	1230.0

Upward going μ

Up through-going μ, 1678days, Obs. $1.70 \pm 0.04 \pm 0.02$ ($\times 10^{-13} cm^{-2} s^{-1} sr^{-1}$)
Theo. 1.84 ± 0.41(Honda)

Up stopping μ, 1657days, Obs. $0.41 \pm 0.02 \pm 0.02$ ($\times 10^{-13} cm^{-2} s^{-1} sr^{-1}$)
Theo. 0.68 ± 0.15(Honda)

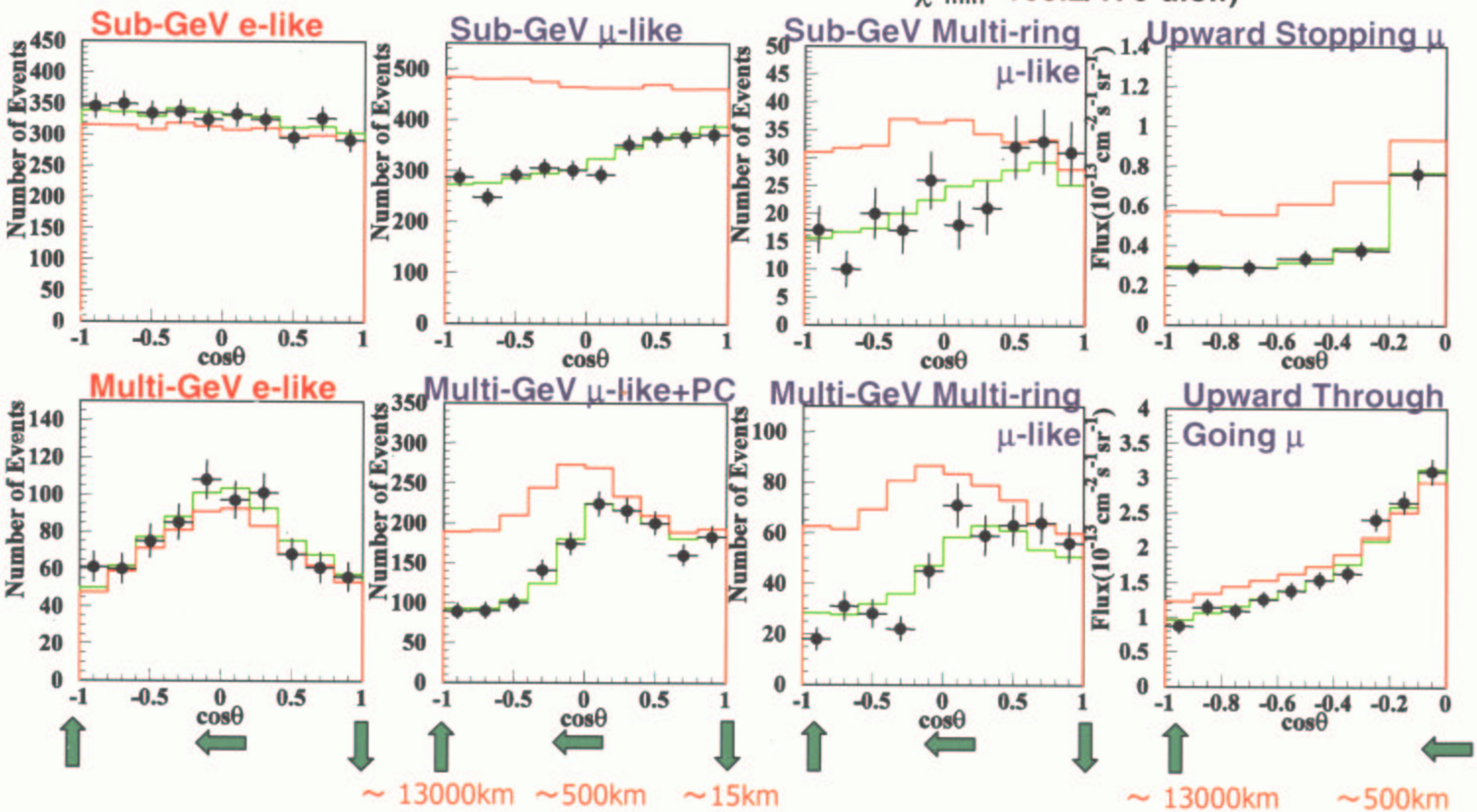
Zenith Angle Distributions

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

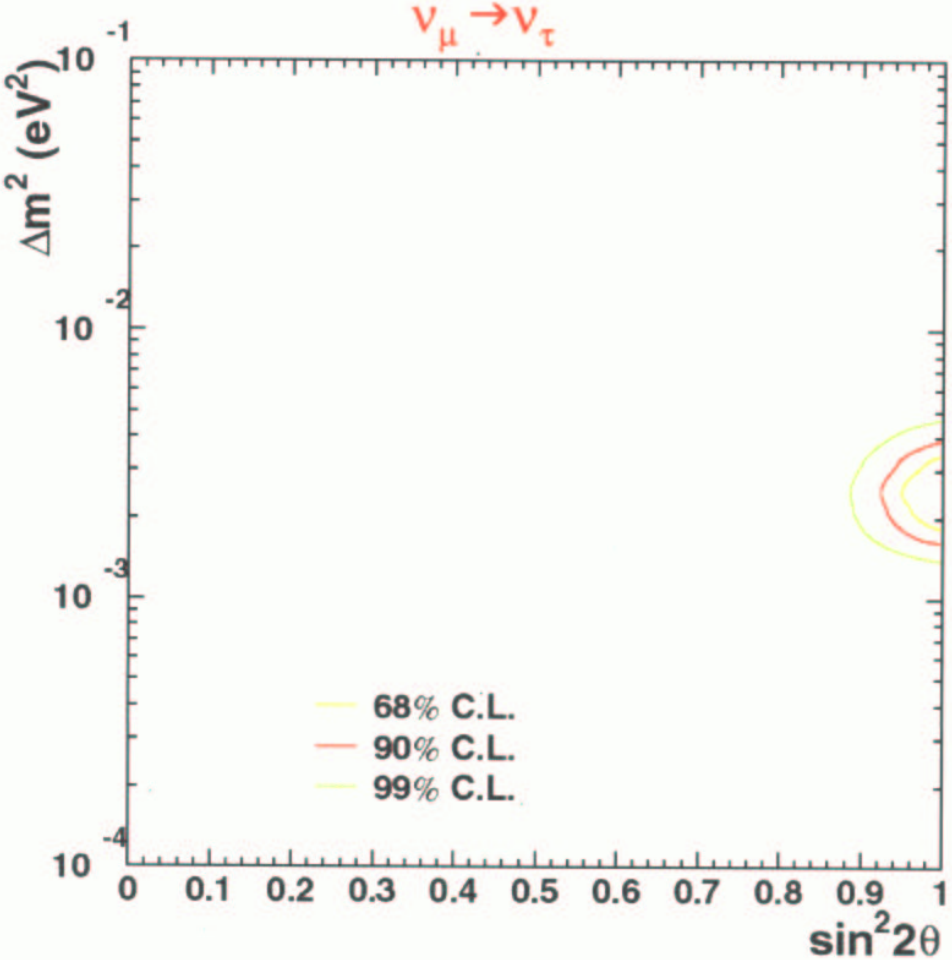
2-flavor oscillations

Null oscillation (χ^2=456.5/172 d.o.f)

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



Allowed Region



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

Best fit

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

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

No oscillation

(χ^2 $= 456.5/172$ d.o.f)

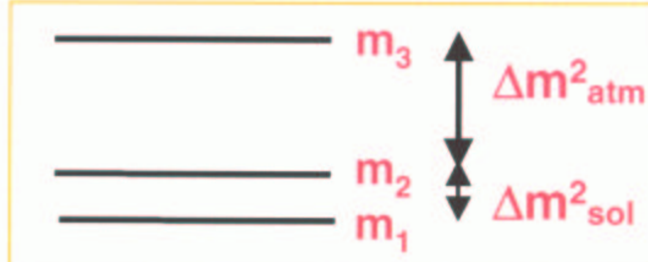
$\Delta m^2 = (1.6 \sim 3.9) \times 10^{-3} eV^2$

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

3-flavor Oscillation Analysis

assuming $\Delta m^2_{23} = \Delta m^2_{atm} > 0(10^{-3})\ eV^2$

$\Delta m^2_{12} = \Delta m^2_{sol} = 0\ eV^2$



neutrino oscillation probabilities are described as;

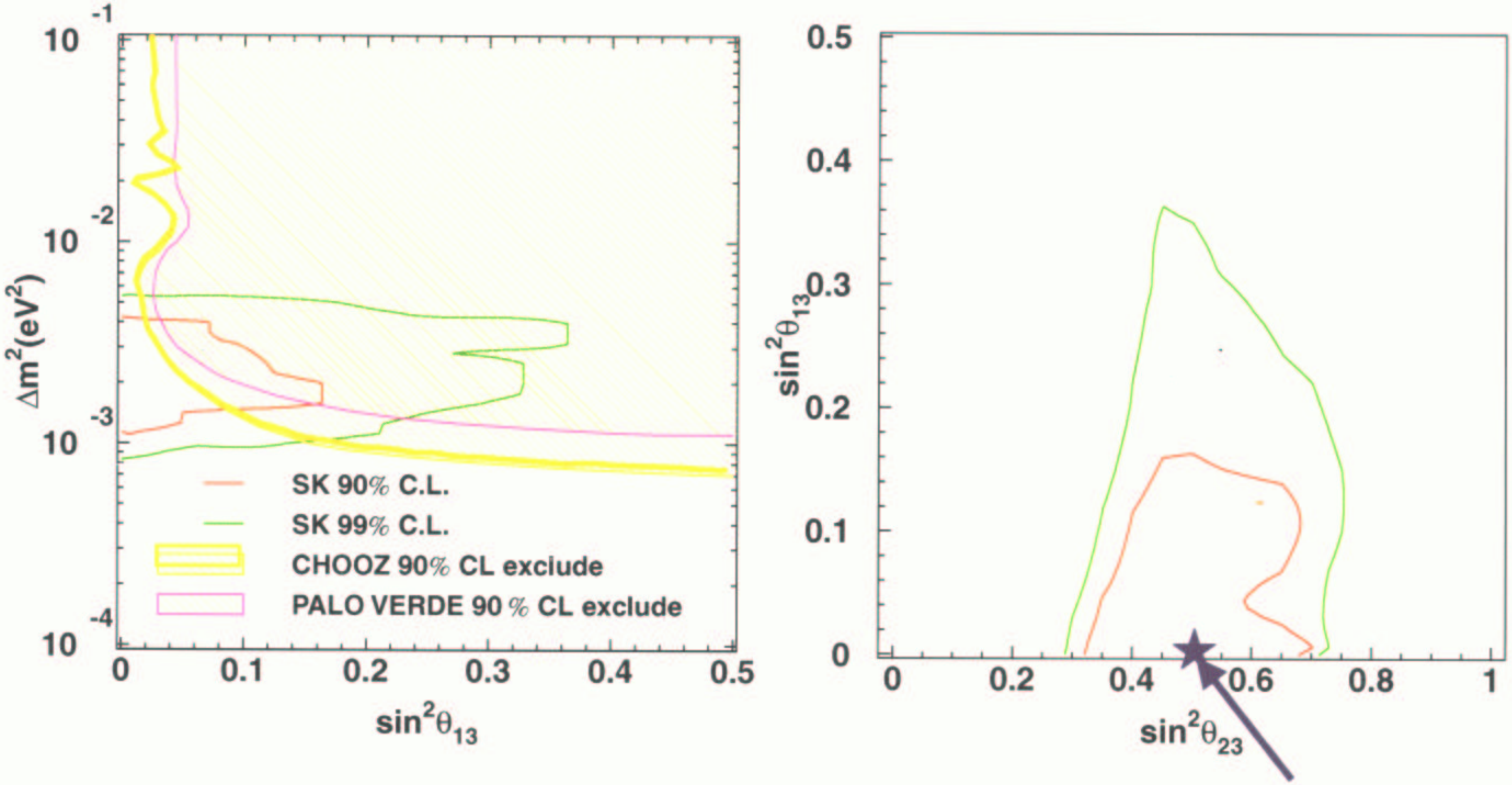
$P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta_{13}) \times \sin^2\theta_{23} \times \sin^2(1.27\Delta m^2 L/E)$

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

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

3 parameters; $\Delta m^2_{23} = \Delta m^2_{13}$, θ_{13}, θ_{23}

Allowed Region For 3-flavor Oscillations



Pure maximal $\nu_\mu \leftrightarrow \nu_\tau$ oscillation

No evidence for non zero θ_{13}

Consistent with pure $\nu_\mu \leftrightarrow \nu_\tau$ oscillations

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

Oscillation Probability is described by 3 parameters;

Δm^2(atm), $\sin^2 2\theta$, $\sin^2\xi$

Admixture state is shown as;

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

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

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

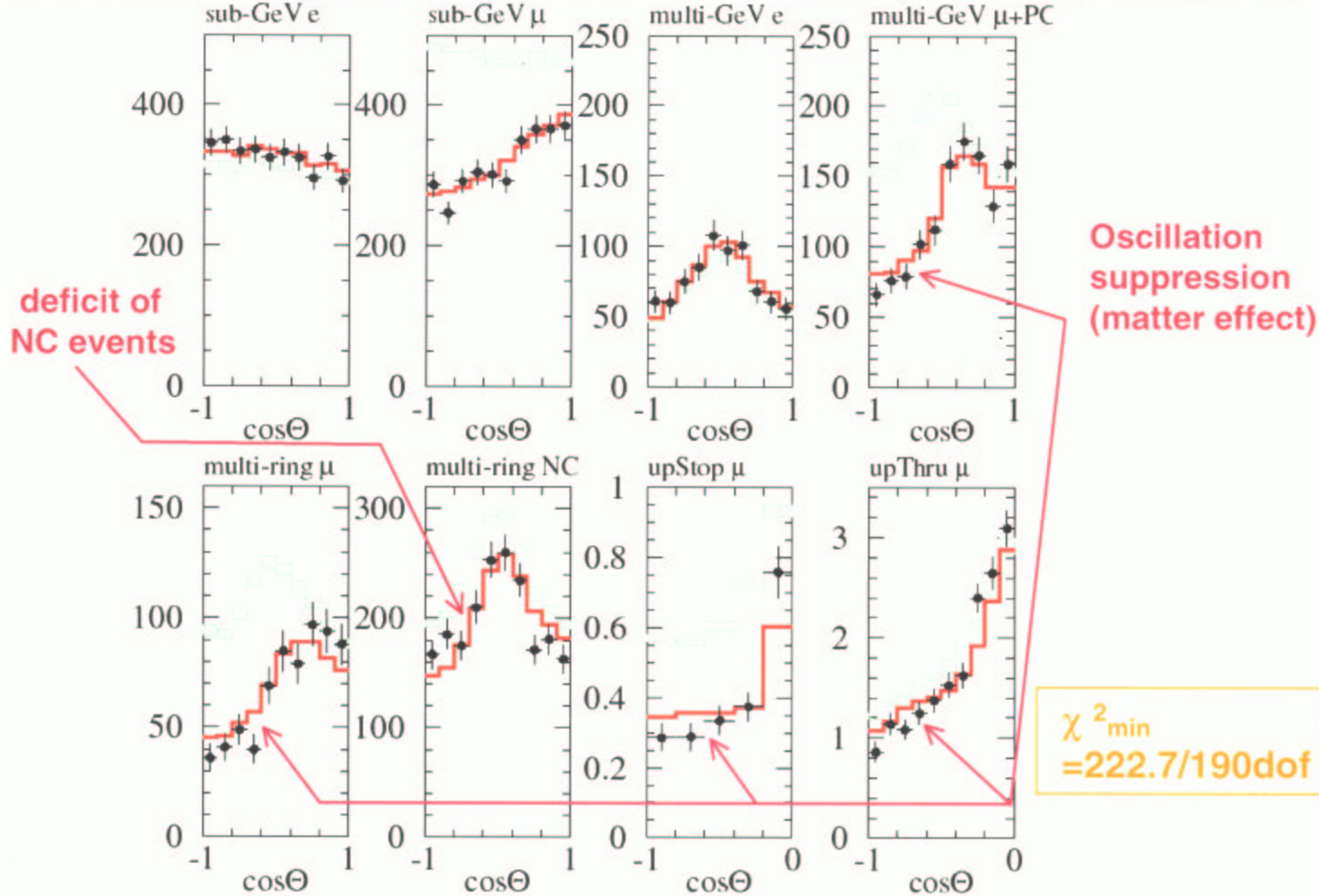
If nonzero $\sin^2\xi$

⇓

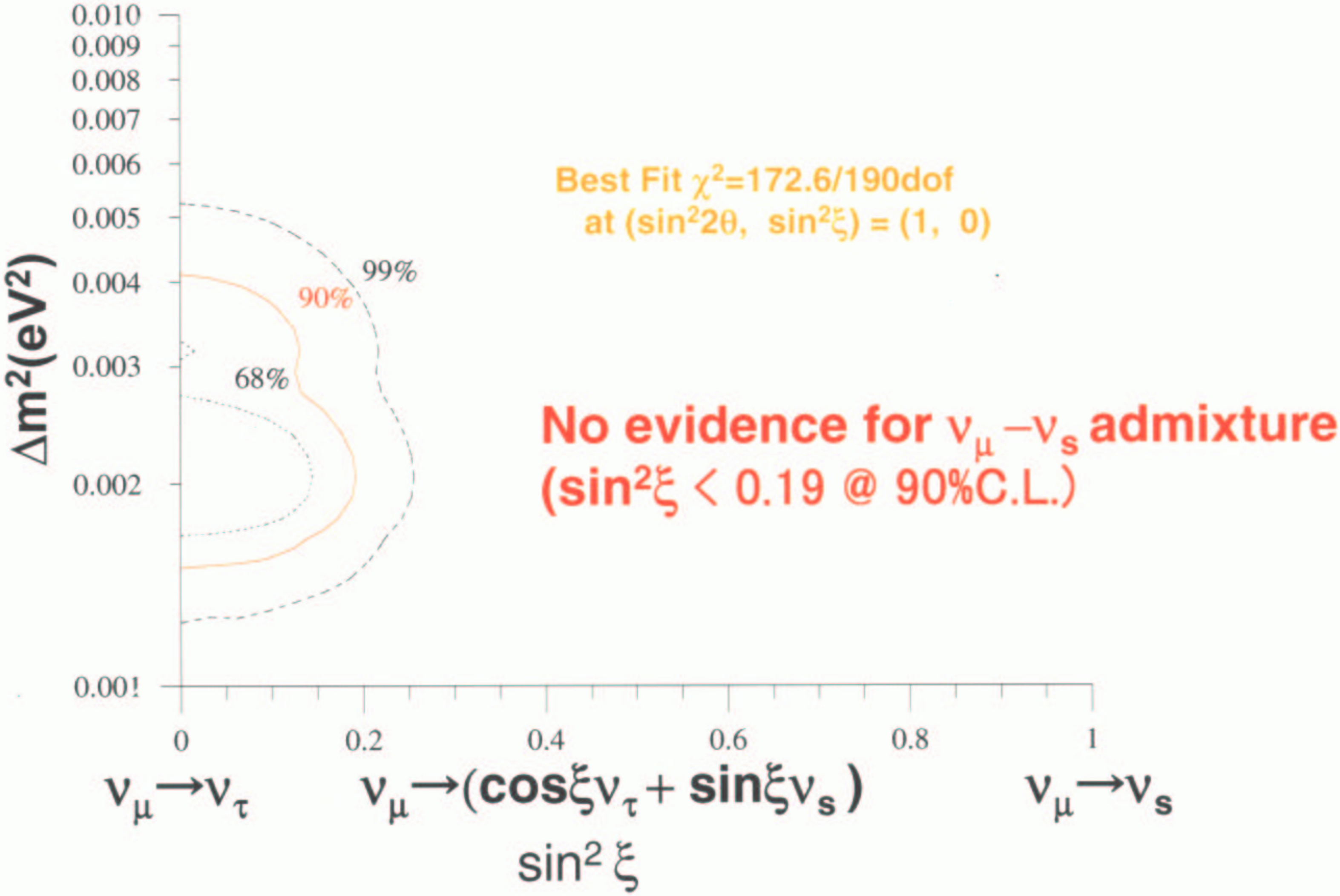
- oscillation suppression happens at multi-GeV region due to matter effect
- deficit of NC events in upward bins is expected

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

Zenith angle distribution for Pure $\nu_\mu \leftrightarrow \nu_s$ ($\sin^2 \xi=1$)



Limit on $\nu_\mu - \nu_s$ Admixture

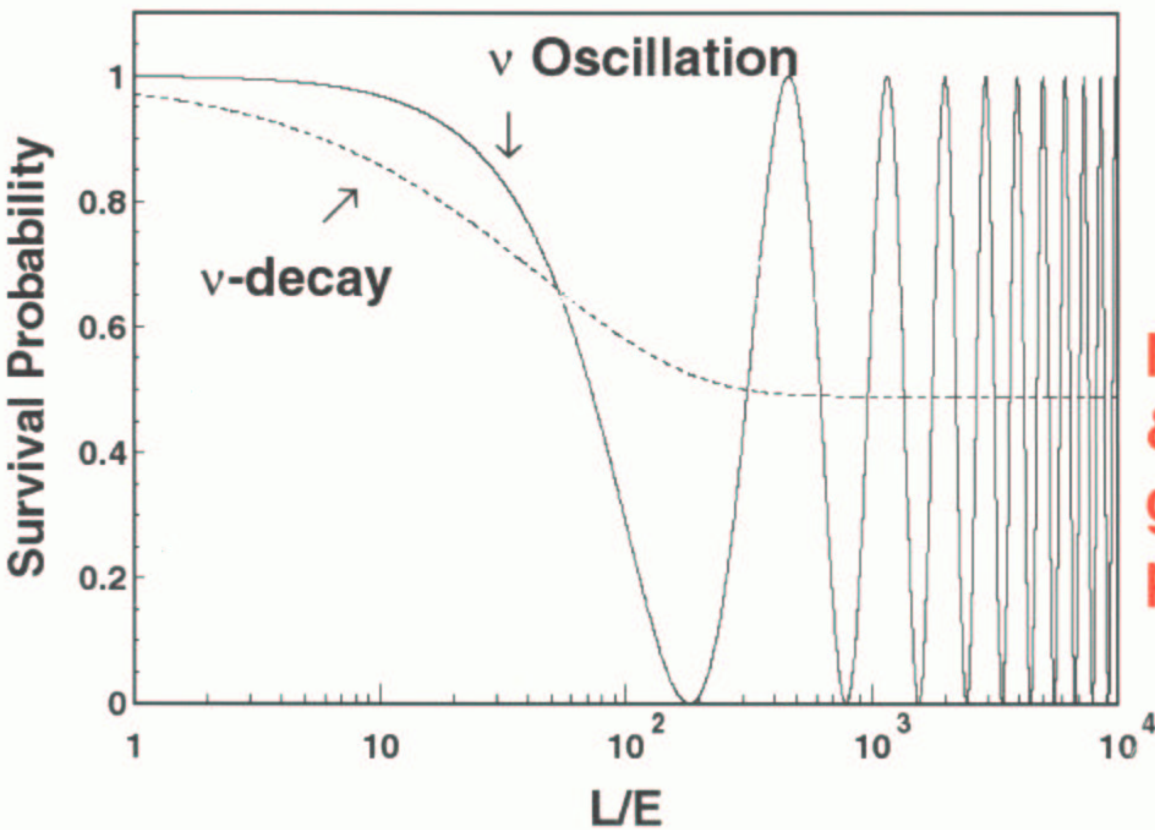


Neutrino Decay

If ν consists of 2 mass eigenstates and decay channel exists ($\nu_3 \Rightarrow$ X(sterile state)) →

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

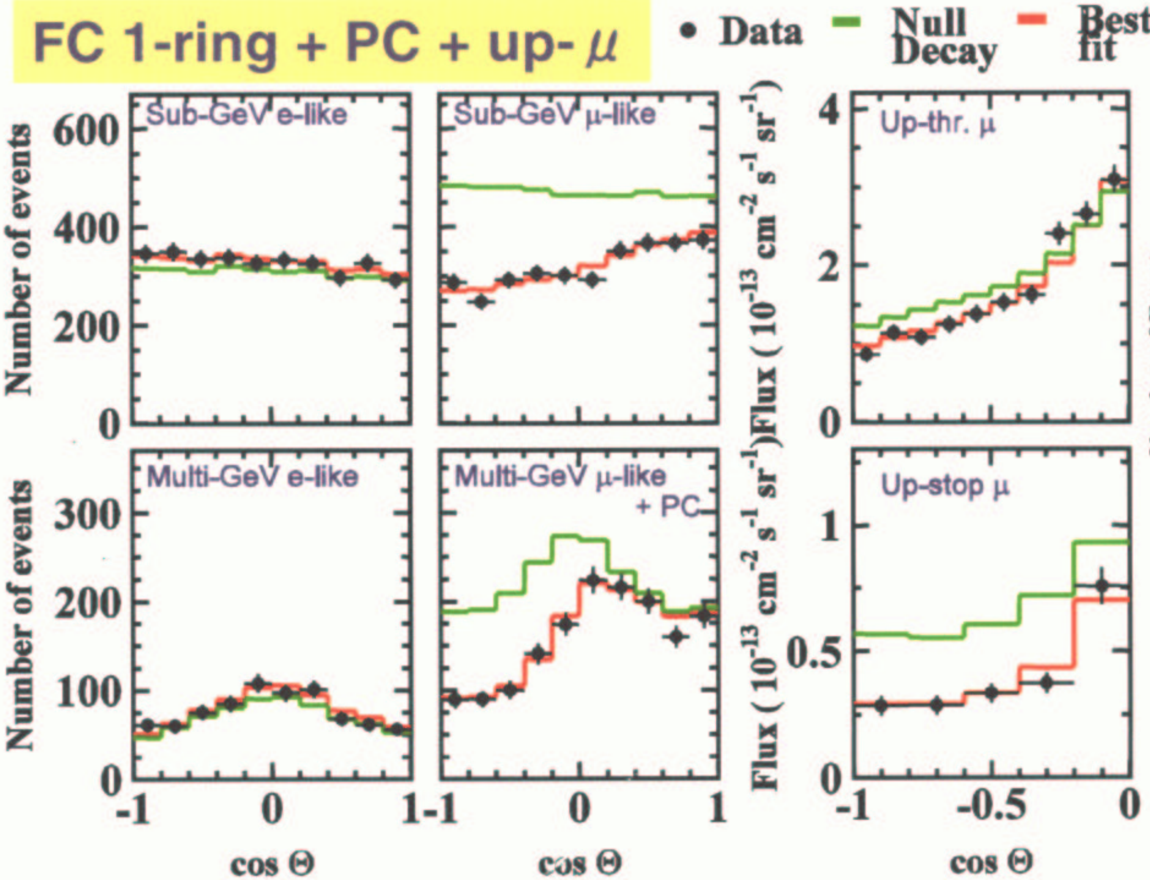
$$P(\nu_\mu \to \nu_\mu) = (\cos^2\vartheta + \sin^2\vartheta \cdot \exp(-\frac{m_3}{2\tau_3}\frac{L}{E}))^2$$



Neutrino decay & Neutrino oscillation give a similar survival probability

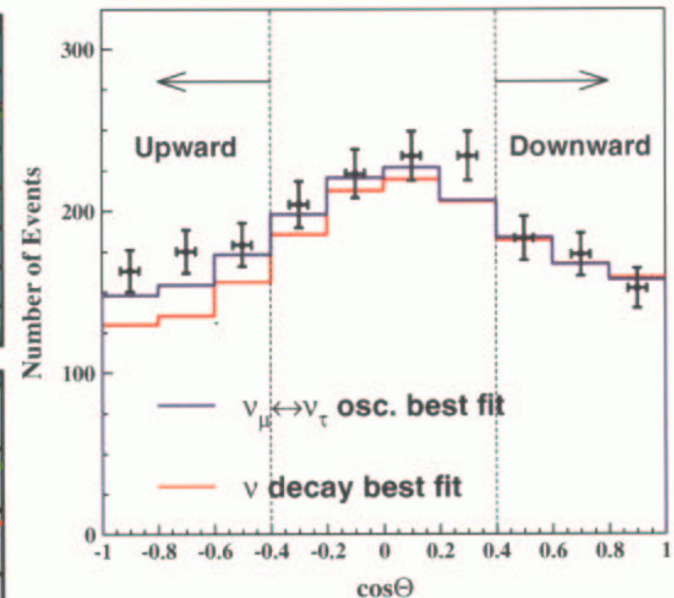
Zenith angle distribution

FC 1-ring + PC + up-μ



FC 1-ring + PC + up-μ data are consistent with neutrino decay scenario

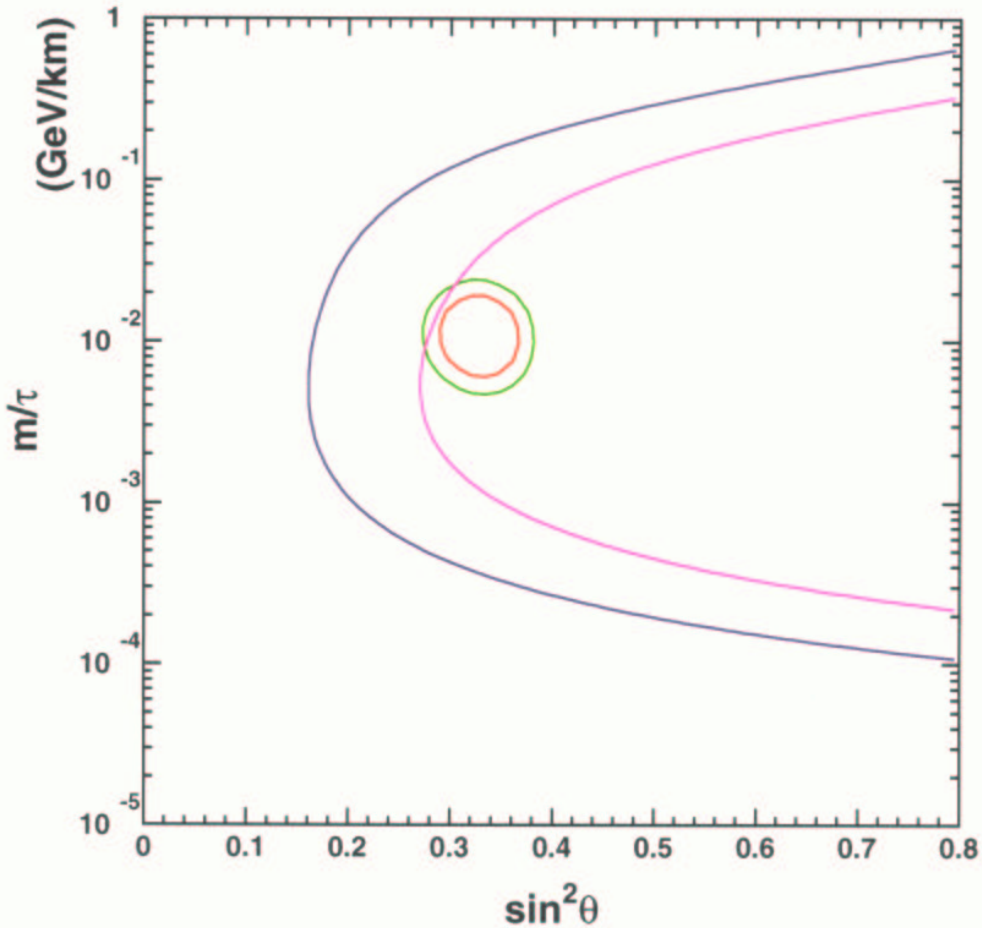
NC sample



Deficit of up-going NC events is expected for ν decay scenario.

But NC sample is not consistent with neutrino decay scenario

Allowed Region



FC 1-ring+PC+up-μ

- 90%C.L Allowed
- 99%C.L Allowed

NC sample

- 90%C.L Excluded
- 99%C.L Excluded

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

τ detection in atmospheric ν

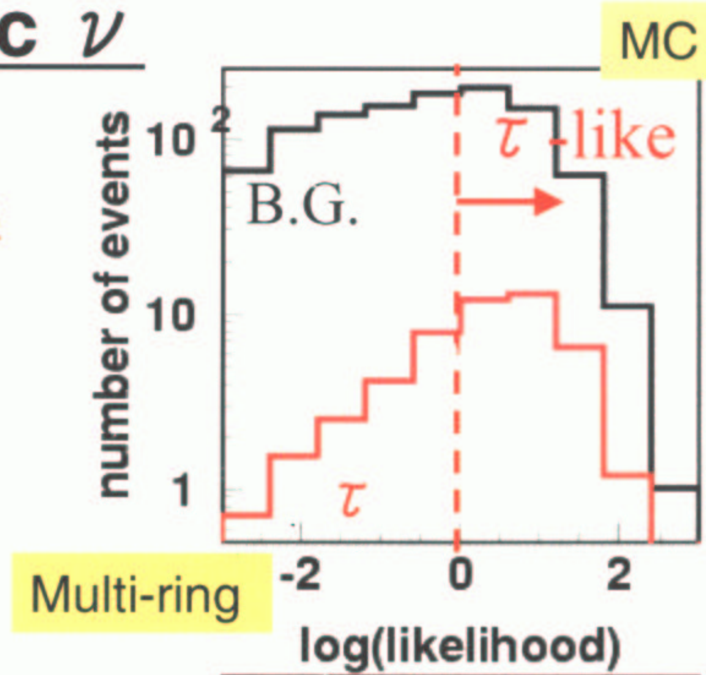
$\nu_\mu \rightarrow \nu_s$ oscillation is disfavored

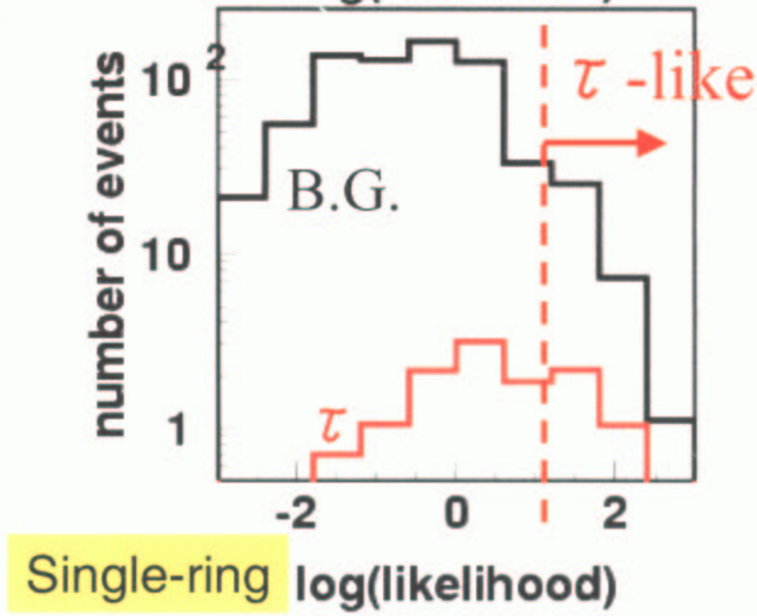
$\nu_\mu \rightarrow \nu_t$ ⇨ CC tau events

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

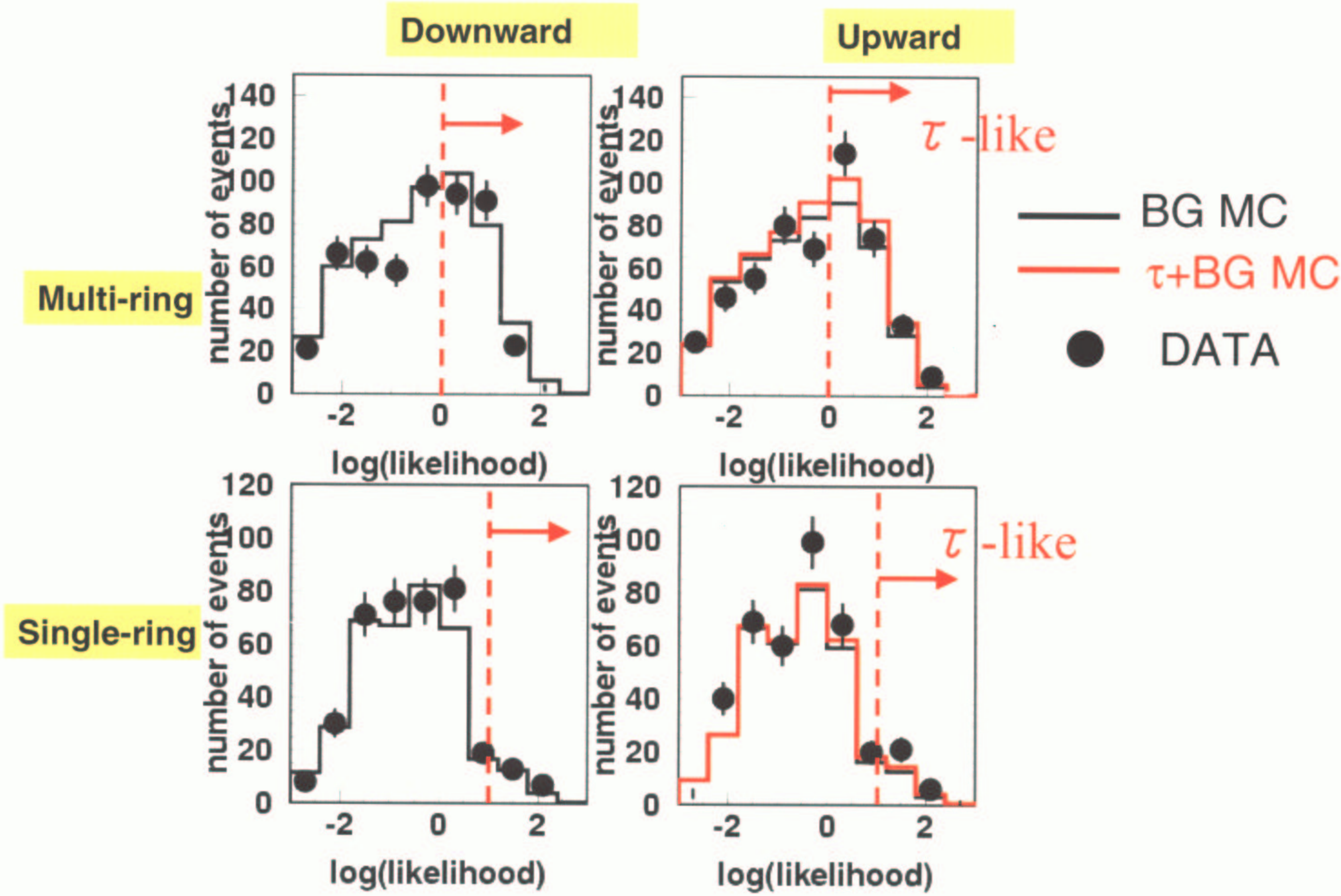
τ likelihood is defined using;
- total energy
- number of rings
- number of decay electrons
- max(Ei)/ Σ Ei
- distance between ν interaction point and decay-e point
- max(P_μ)
- Pt/Evis$^{3/4}$
- PID likelihood of most energetic ring

τ–like selection; effτ=44%, S/N=8%



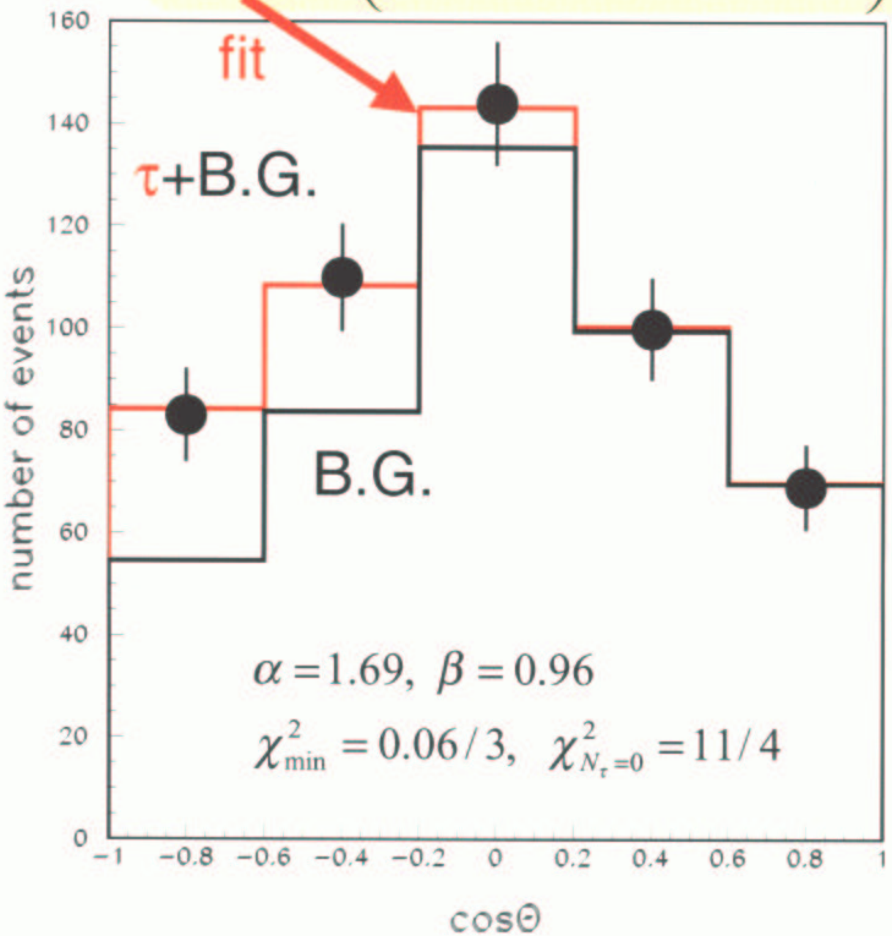


Likelihood Distributions



Zenith Angle Distribution

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



- $N^{FC}_{\tau} = \alpha N^{\tau}_{MC}/(\text{eff.}=0.44)$
  $= 145 \pm 44(\text{stat.})$
  $+11/-16(\text{sys.})$

  $N_{exp}=86$

- consistent with $\nu_\mu \leftrightarrow \nu_\tau$

- another analysis (neural network) gives similar result:

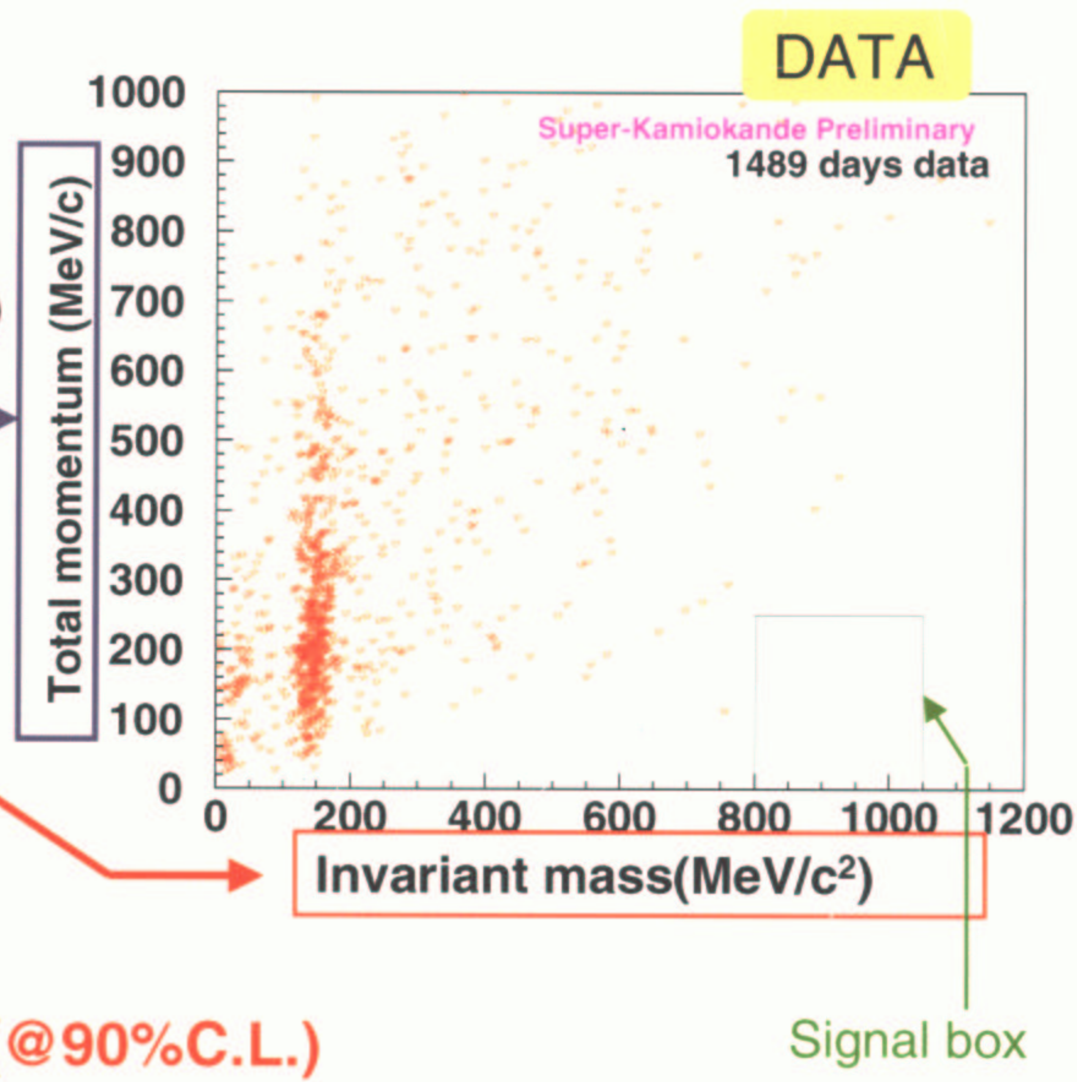
  $N^{FC}_{\tau} = 99 \pm 39(\text{stat.})$

  $+13/-21(\text{syst.})$

Limits on Matter instability

Proton decay($P \rightarrow e^+\pi^0$ mode)

- Selection criteria
  - 2 or 3ring, all ring e-like
  - $85 < M_{\pi 0} < 185 MeV/c^2$(3ring)
  - No decay-e
  - $P_p < 250 MeV/c$
  - $800 < M_p < 1050 MeV/c^2$



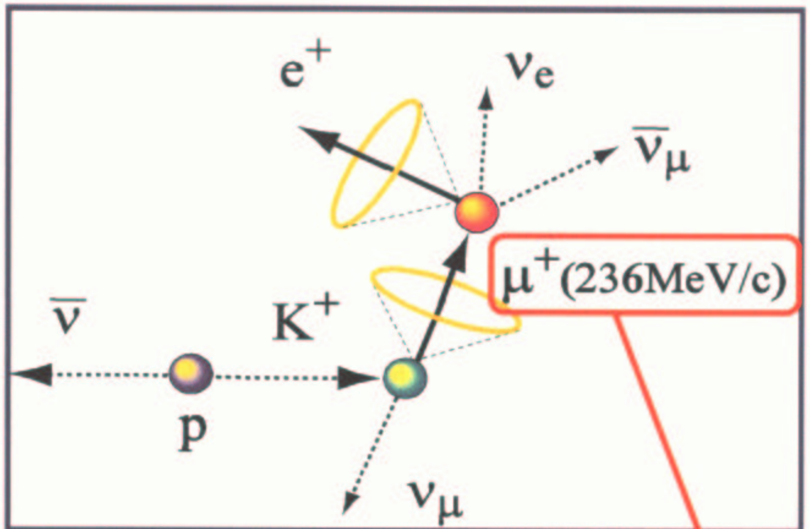
- Result
  - efficiency 43%
  - 0.2 estimated B.G.
  - no candidate
  - $\tau_p / B_{e\pi 0} > 5.7 \times 10^{33}$yrs(@90%C.L.)

Proton decay ($P \to \nu K^+$ mode)

1. $p \to \nu K^+$, $K^+ \to \mu^+ \nu$ spectrum analysis
2. $p \to \nu K^+$, $K^+ \to \mu^+ \nu$ prompt γ search
3. $p \to \nu K^+$, $K^+ \to \pi^+ \pi^0$

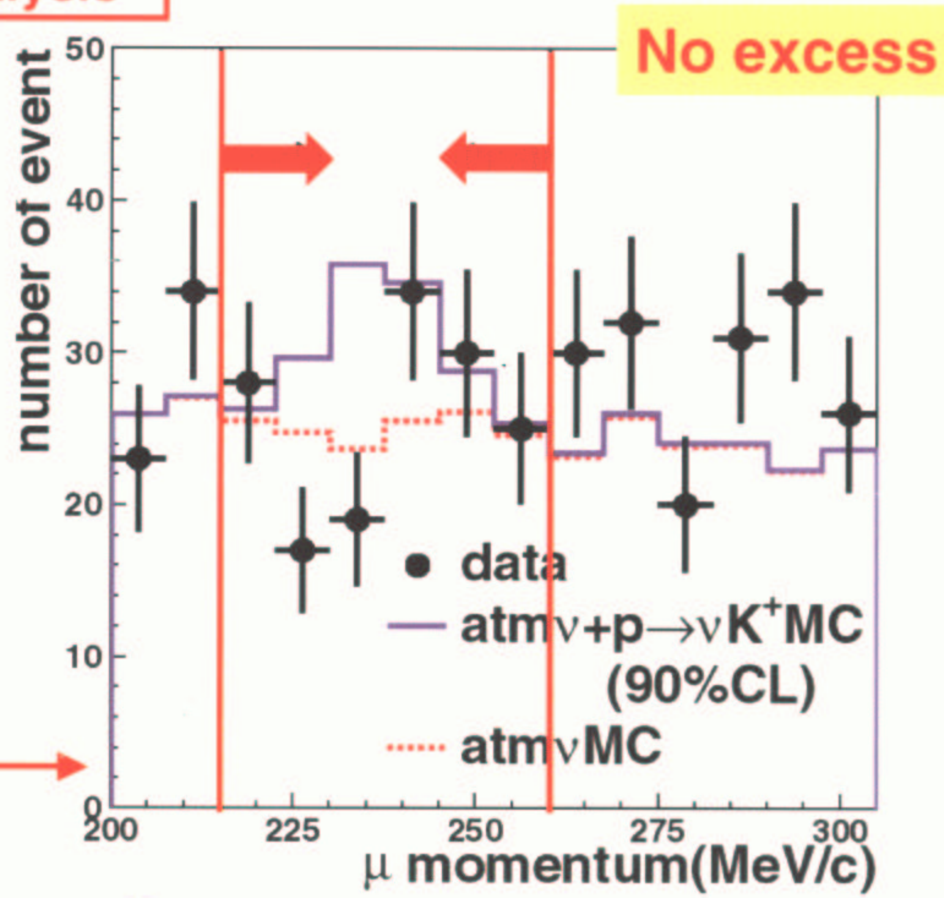
Proton decay ($P \to \nu K^+$ mode)

$p \to \nu K^+$, $K^+ \to \mu^+ \nu$ spectrum analysis



selection criteria

- 1-ring, μ-like
- $215 < p_\mu < 260$ MeV/c
- 1 decay-e
- proton rejection cut
- $N_{\gamma hit} \leq 7$ (No prompt γ hit)

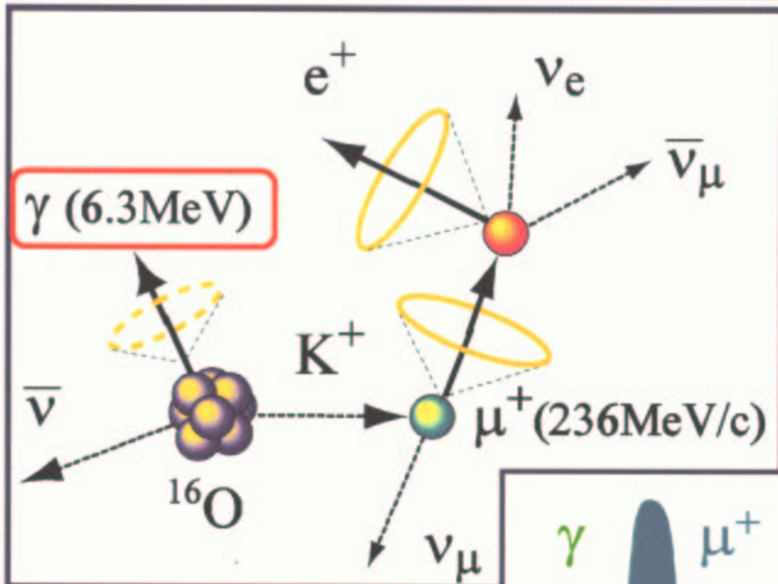


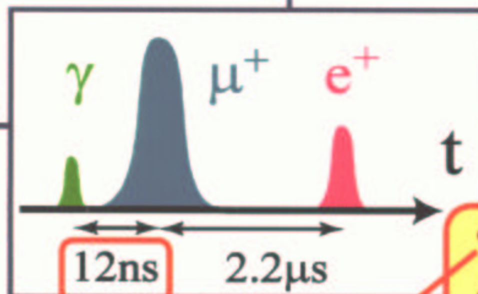
result

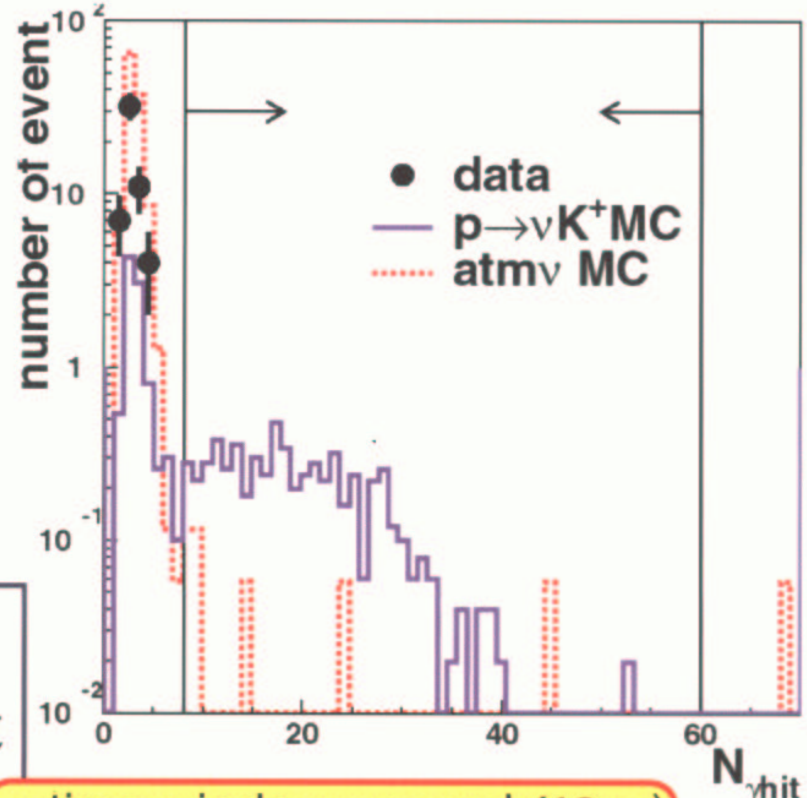
- 33.0% detection efficiency
- no excess

Proton decay ($P \rightarrow \nu K^+$ mode)

$p \rightarrow \nu K^+$, $K^+ \rightarrow \mu^+ \nu$ prompt γ search







selection criteria

- 1ring μ-like
- $215 < P_\mu < 260$ MeV/c
- proton rejection cut
- 1 decay-e
- $7 < N_{\gamma hit} < 60$ (prompt γ)

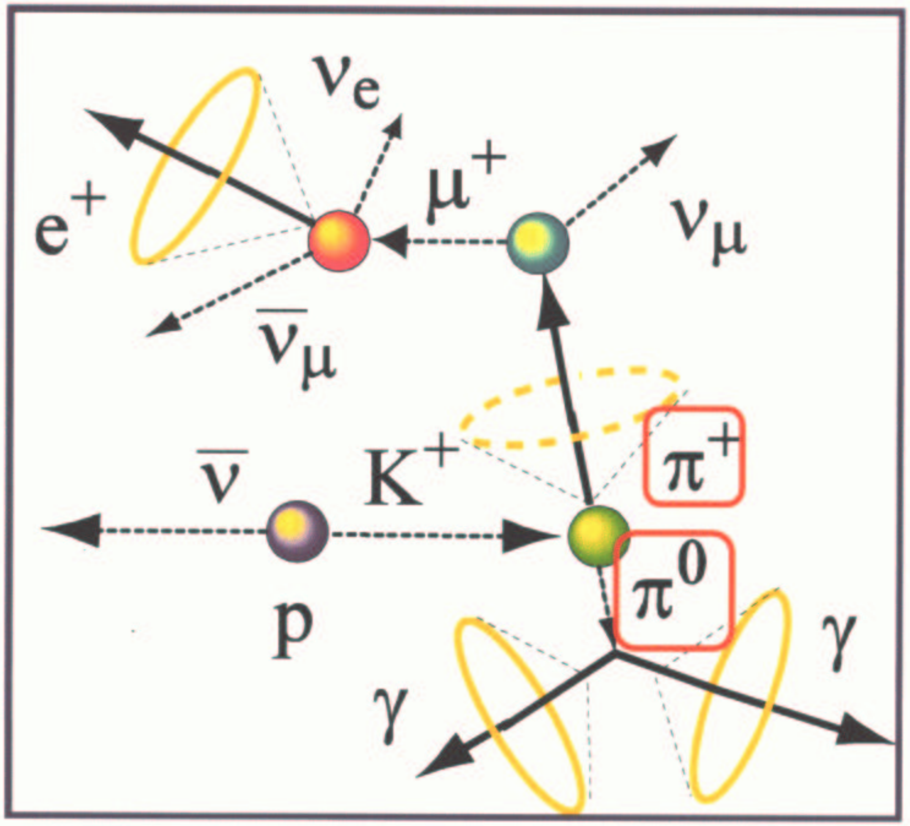
- time window γ search(**12ns**)
- prompt γ signal candidate

result

- 0.3 expected background
- 8.7% detection efficiency
- no candidate event

Proton decay ($P \rightarrow \nu K^+$ mode)

$p \rightarrow \nu K^+$, $K^+ \rightarrow \pi^+ \pi^0$



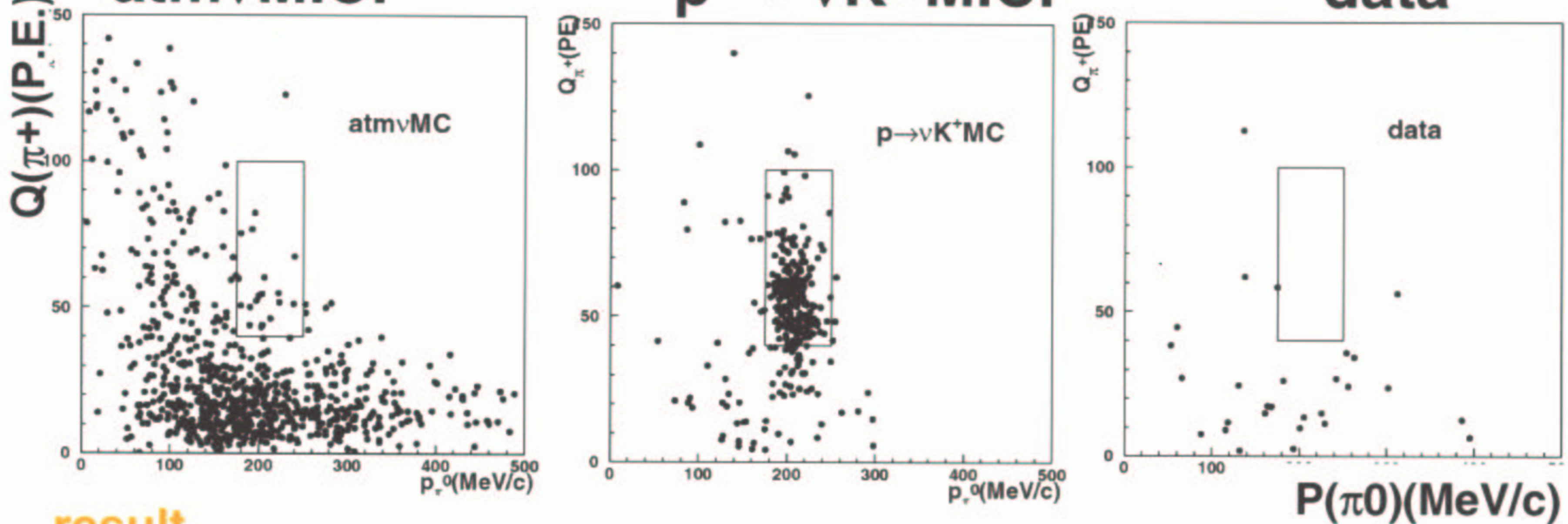
selection criteria

- 2 e-like ring
- 85 < m(π0) < 185MeV/c^2
- 40 < Qπ+ < 100p.e., Qres < 70p.e.
- 175 < P(π0) <250MeV/c
- 1 decay-e

Proton decay (P→νK^+ mode)

$p \to \nu K^+$, $K^+ \to \pi^+ \pi^0$

atmνM.C. | p → νK+-M.C. | data



result

- 0.9 expected background
- 6.5% detection efficiency
- no candidate event

Combined limit(3 methods)

$\tau_p / B_{\nu K+} > 2.0 \times 10^{33}$ yrs(@90%C.L.)

Summary

Detailed studies of neutrino oscillations have been carried out using various types of atmospheric events

- $\nu_\mu \leftrightarrow \nu_\tau$ 2 flavor oscillations
  - $\Delta m^2 = 1.6 \sim 3.9 \times 10^{-3}\ eV^2$, $\sin^2 2\theta > 0.92$ @ 90%CL
- $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$ 3 flavor oscillations
  - No evidence for non zero θ_{13}
- Limit on $\nu_\mu \leftrightarrow \nu_s$ admixture
  - No evidence for $\nu_\mu - \nu_s$ admixture($\sin^2\xi < 0.19$ @ 90%CL)
- ν-decay
  - 99%C.L. allowed region by FC 1-ring+PC+up-μ is almost excluded at 99%C.L. by the NC sample
- Observed τ–like events
  - support $\nu_\mu \leftrightarrow \nu_\tau$

Limits on Matter instability

- $\tau_p/B(e\pi 0) > 5.7 \times 10^{33}$yrs(90%C.L)
- $\tau_p/B(\nu k+) > 2.0 \times 10^{33}$yrs(90%C.L)