The study of atmospheric neutrinos with Super-Kamiokande

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The Super-Kamiokande Collaboration

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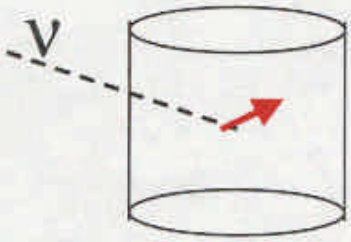
This Talk

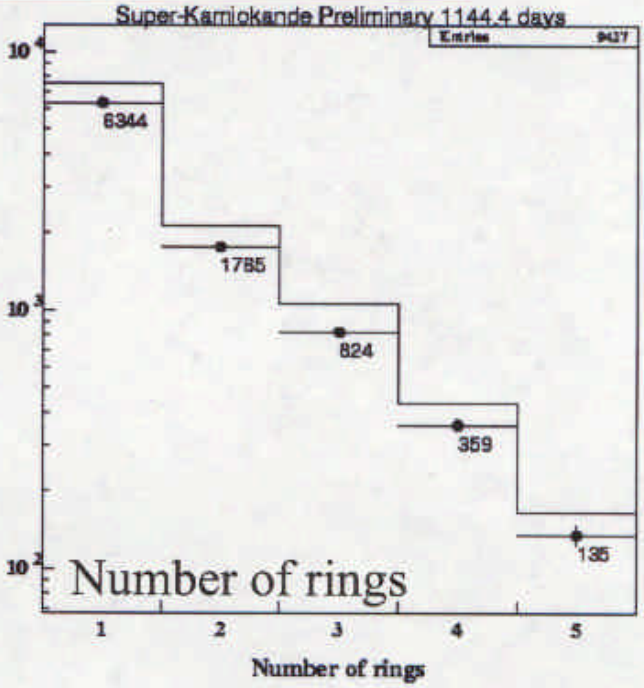
- Updated results from 1144 days of SuperK atmospheric neutrino data
- Neutrino flavor content compared with expectations
- Zenith angle distribution of data and expected distributions
  - More data ➔ 10 bin plots
- Neutrino oscillation interpretation
  - First indications from 3-D flux calculations
  - Three flavor analysis
  - Limits on $\nu_\mu \longrightarrow \nu_S$ oscillation
- Simple limit on more exotic models
- Future

1144 live day sample

70.5 kton years

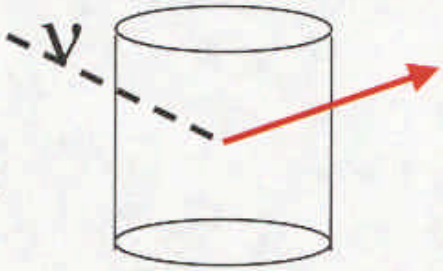
Fully Contained
events: E_{vis}> 30 MeV
>2 meters from wall





	Data	MC
1R	6344	7547.9
2R	1765	2135.0
>2R	1318	1656.6
Total	9427	11339.4
events/day	8.2	9.9

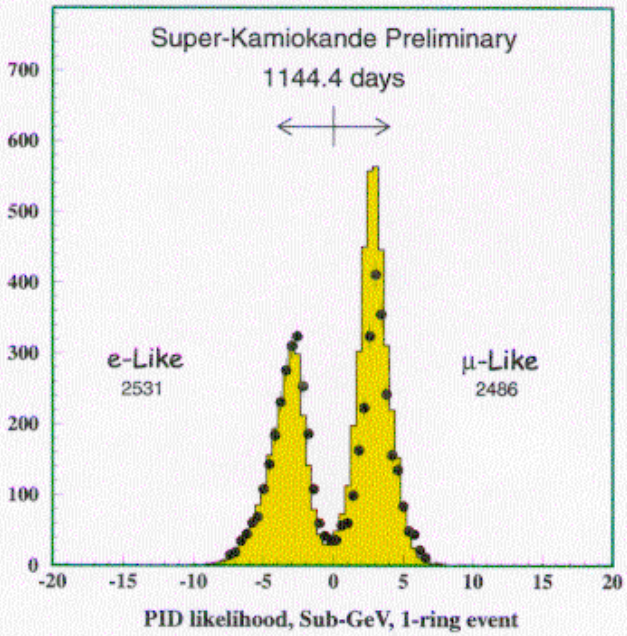
Partially Contained events:

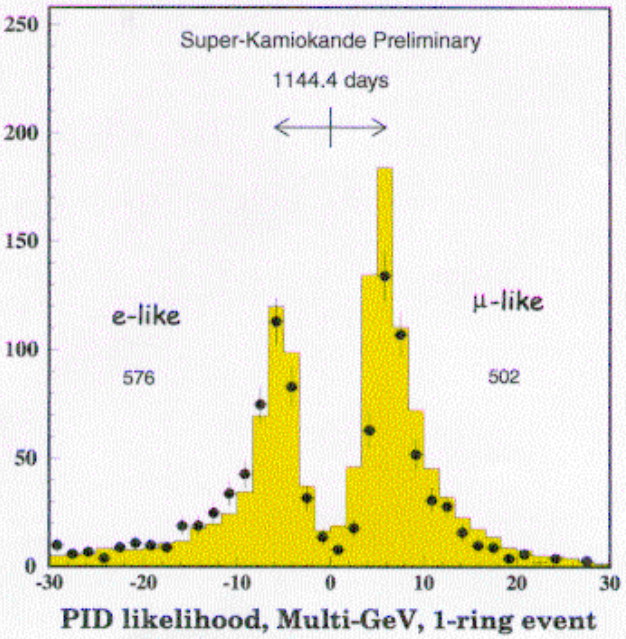


	Data	MC
Total	665	945.1
events/day	0.58	0.83

Particle Identification

Based on likelihood of shape around Cerenkov ring.





Electron-like:

e, γ, π^0

Muon-like:

$\mu, \pi^{+/-}$

Mis-ID Prob.:

MC, CC events

0.8 +/- 0.1%

Cosmic-ray μ:

0.4 +/- 0.1%

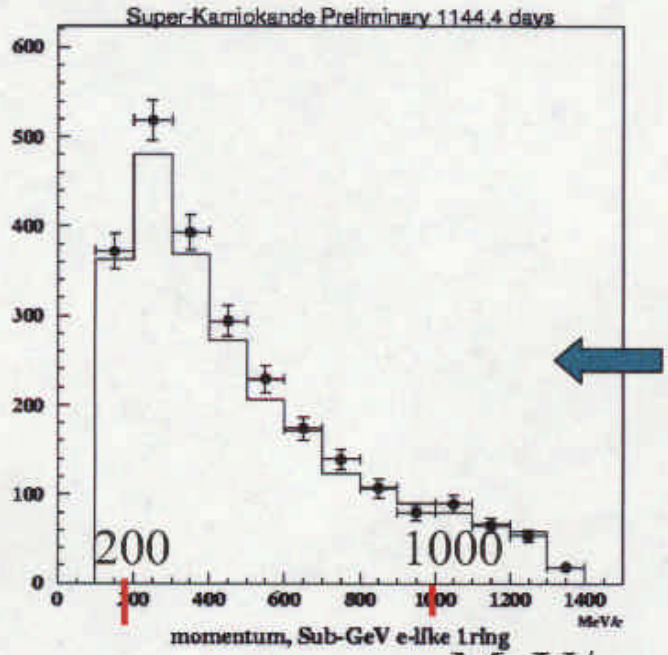
Michel e's:

1.8 +/- 0.5%

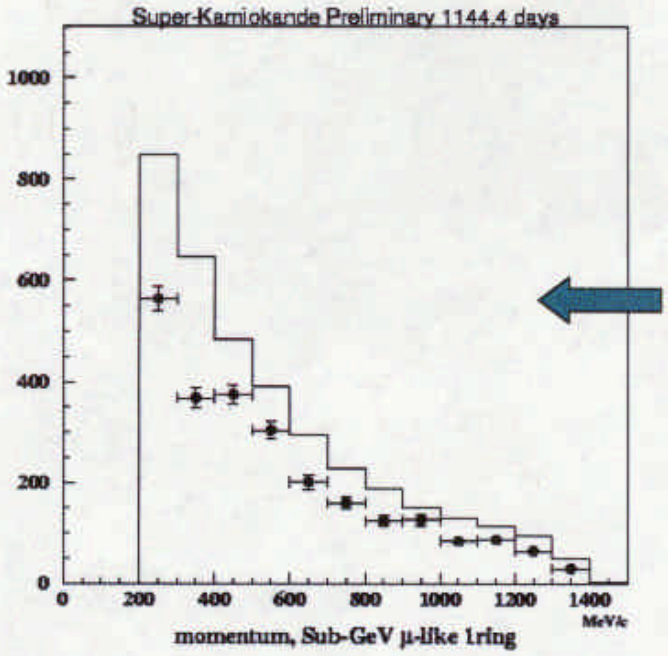
1-ring events sub-Gev Sample

1144 day sample

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

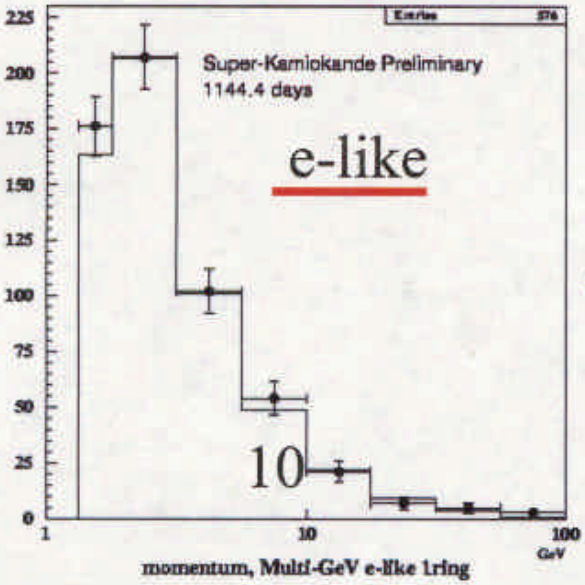


e-like
MC (Honda)
66% ν_e CC Q.E.
21% ν_e CC not Q.E.
1.3% ν_μ CC
9.8% NC



μ-like
MC (Honda)
72% ν_μ CC Q.E.
24% ν_μ CC not Q.E.
0.3% ν_e CC
4.2% NC

1-ring Multi-GeV 1144 days

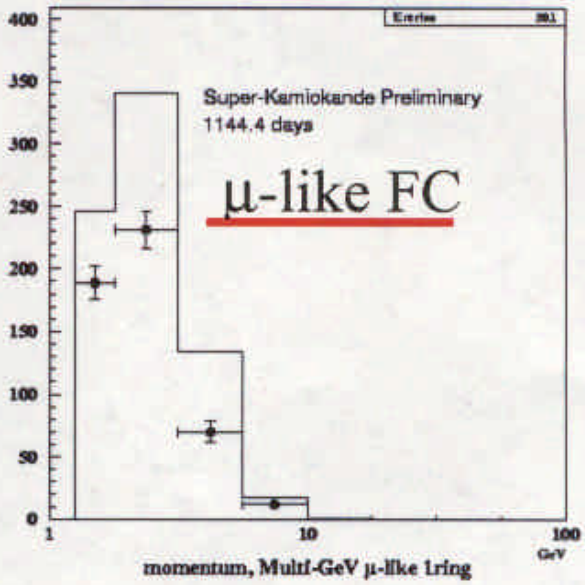


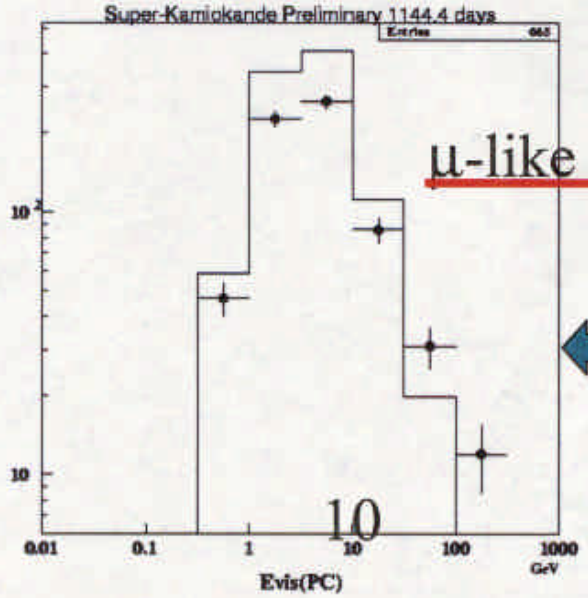
$E_{VIS} > 1.33$ GeV

MC (Honda)
38% ν_e CC Q.E.
46% ν_e CC not Q.E.
7.1% ν_μ CC
8.6% NC

GeV/c

MC (Honda)
54% ν_μ CC Q.E.
45% ν_μ CC not Q.E.
0.6% ν_e CC
0.4% NC





MC (Honda)
17% ν_μ CC Q.E.
81% ν_μ CC not Q.E.
1.9% ν_e CC
0.9% NC

$$R = \frac{(\nu_\mu/\nu_e)DATA}{(\nu_\mu/\nu_e)M.C.}$$

1144 day sample

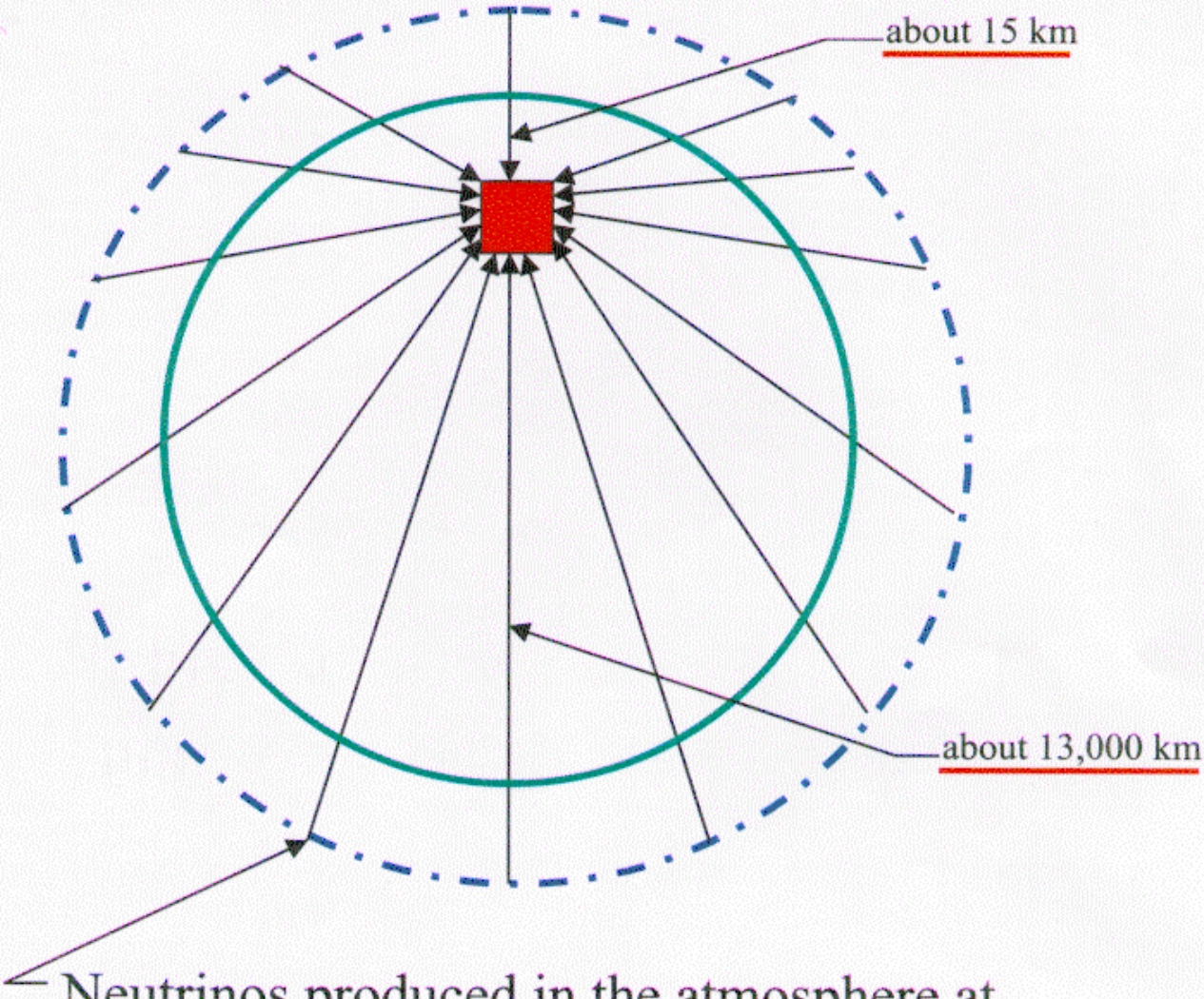
Sub-GeV	Data	MC (Honda)	MC (Bartol)
Total	6902	8345.0	8174.7
1-Ring	5017	6023.5	5880.1
e-like	2531	2402.6	2364.9
μ-like	2486	3620.9	3515.2

R=0.652 +/- 0.019 +/- 0.051 Honda
R=0.661 +/- 0.019 +/- 0.052 Bartol

Multi-GeV	Data	MC (Honda)	MC (Bartol)
Total	2276	2764.2	2838.2
1-Ring FC	1078	1294.1	1314.8
e-like	576	555.4	576.1
μ-like	502	738.7	738.7
PC μ	665	945.1	997.4

R= 0.668 +/- 0.034 +/- 0.079 Honda
R= 0.672 +/- 0.034 +/- 0.080 Bartol

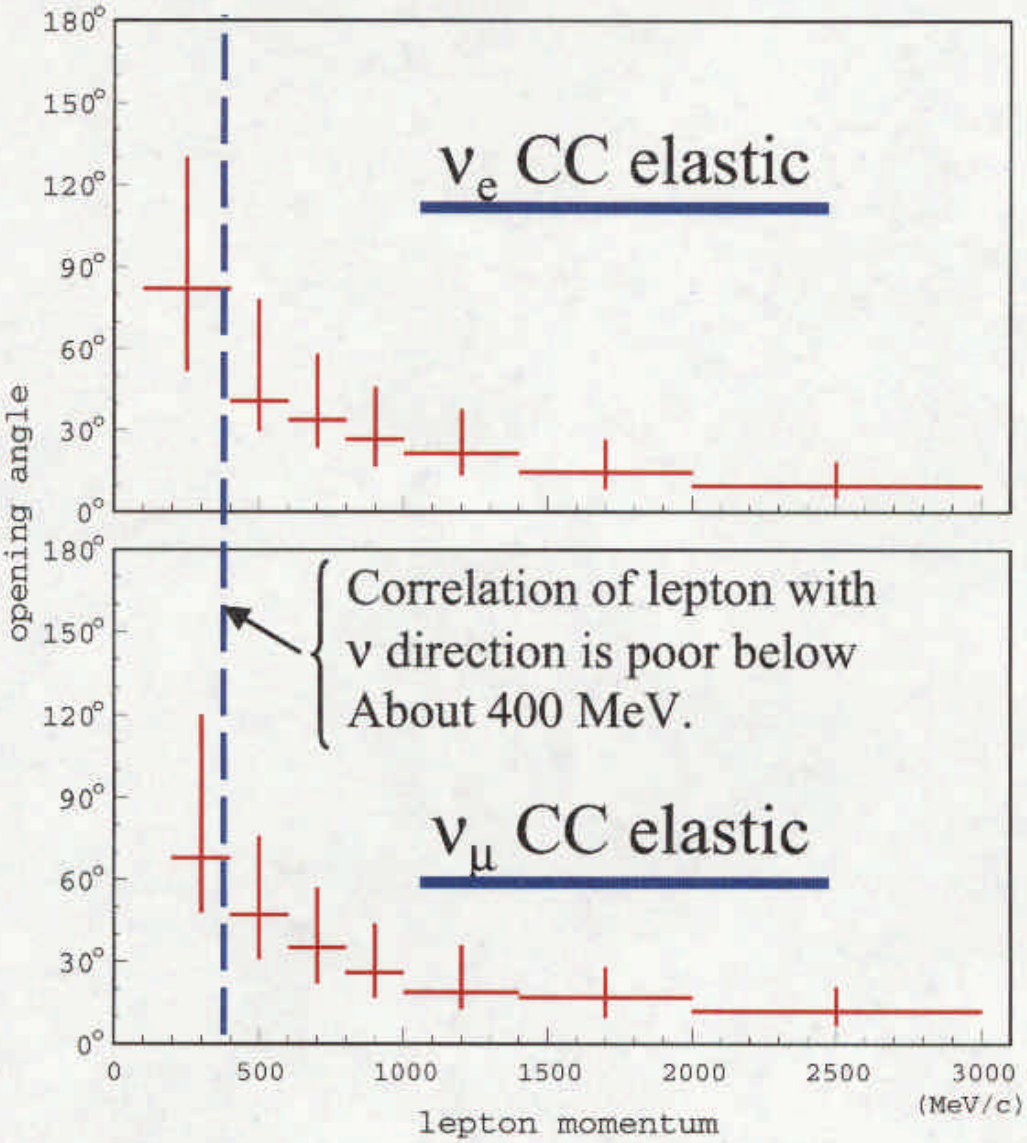
Study Angular Distributions of ν_μ and ν_e with Super-Kamiokande



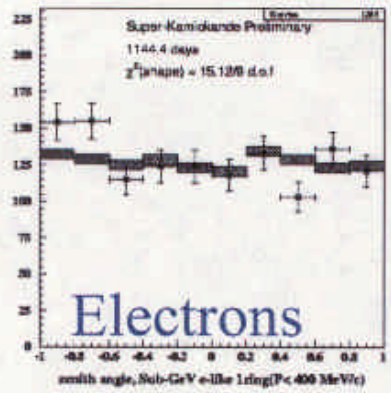
Neutrinos produced in the atmosphere at ~15 km altitude...

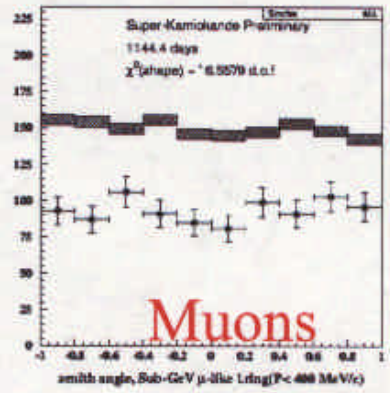
travel through the earth and interact in the detector.

ν – Lepton angular correlation

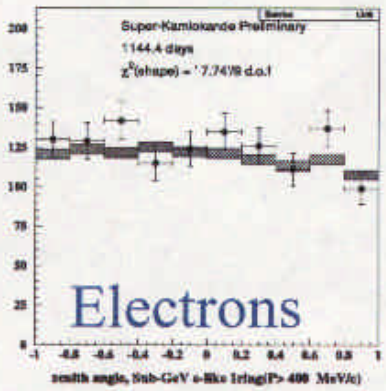


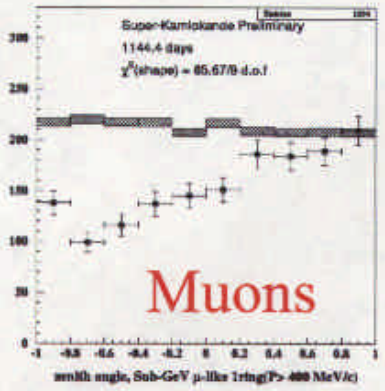
What do we see?



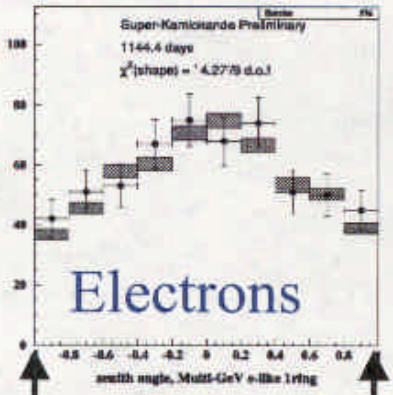


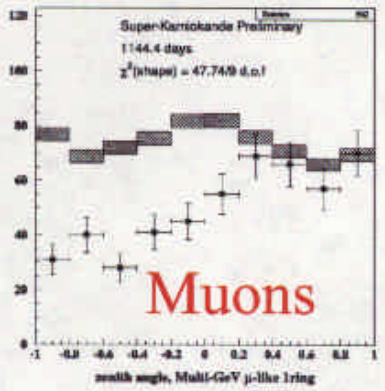
Sub-GeV
E < 400 MeV





Sub-GeV
E > 400 MeV
E < 1.33 GeV

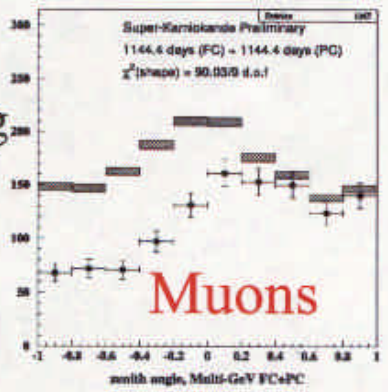




Multi-GeV
E > 1.33 GeV

Up-going

Down-going

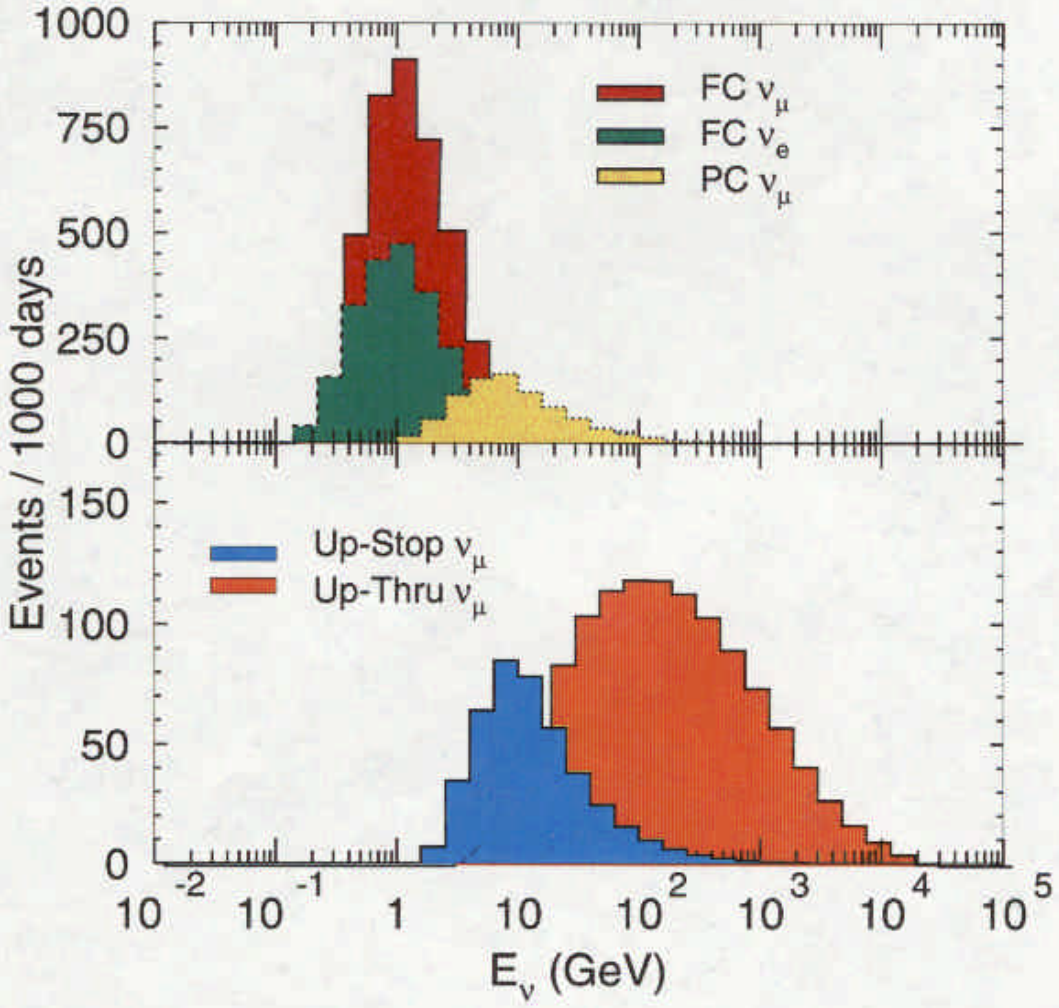


FC+PC events
E > 1.33 GeV

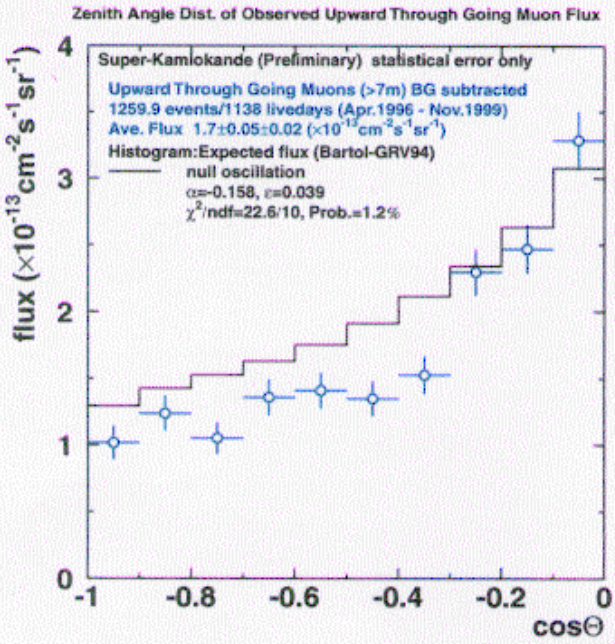
Supporting evidence

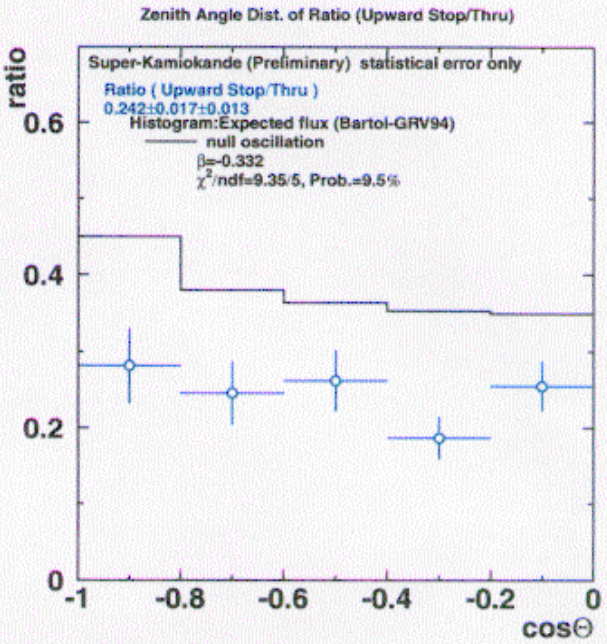
Look at other aspects of atmospheric neutrinos to see if there is supporting evidence for the effect.

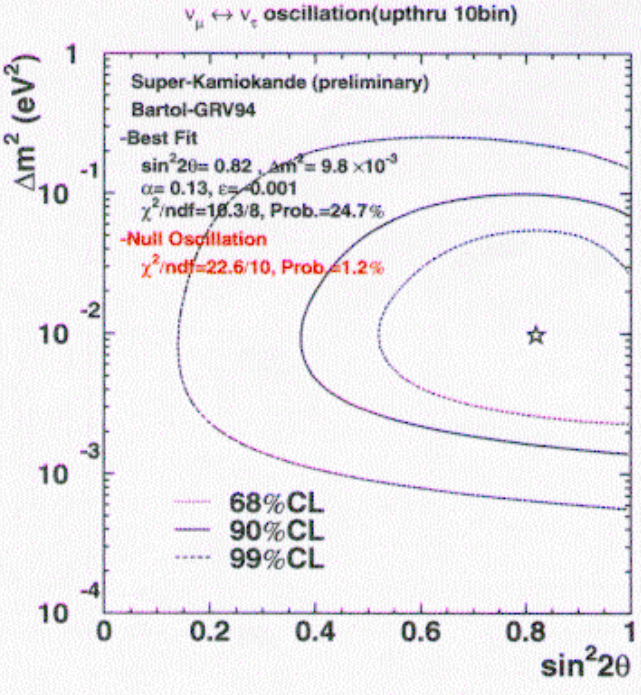
- Upward-going neutrino induced muons.
  - Those that enter and exit the detector.
  - Those that stop in the detector.
- Different systematics, Different energy range.

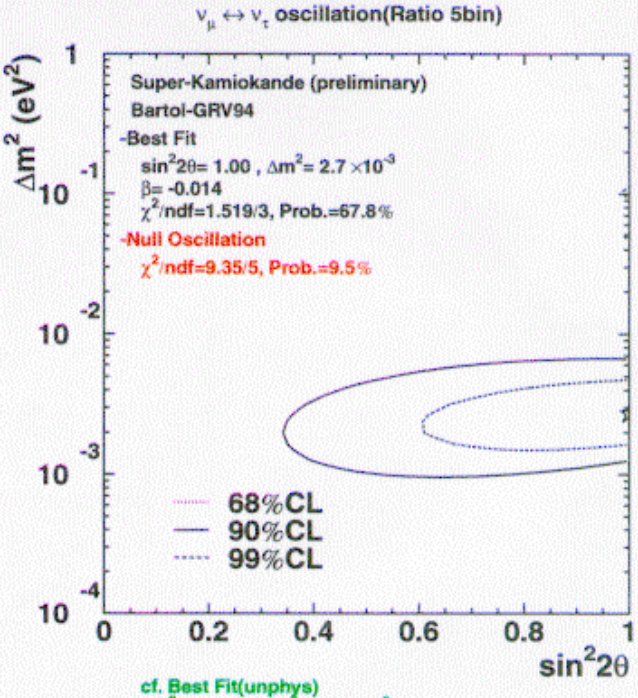


Upward-going muon data

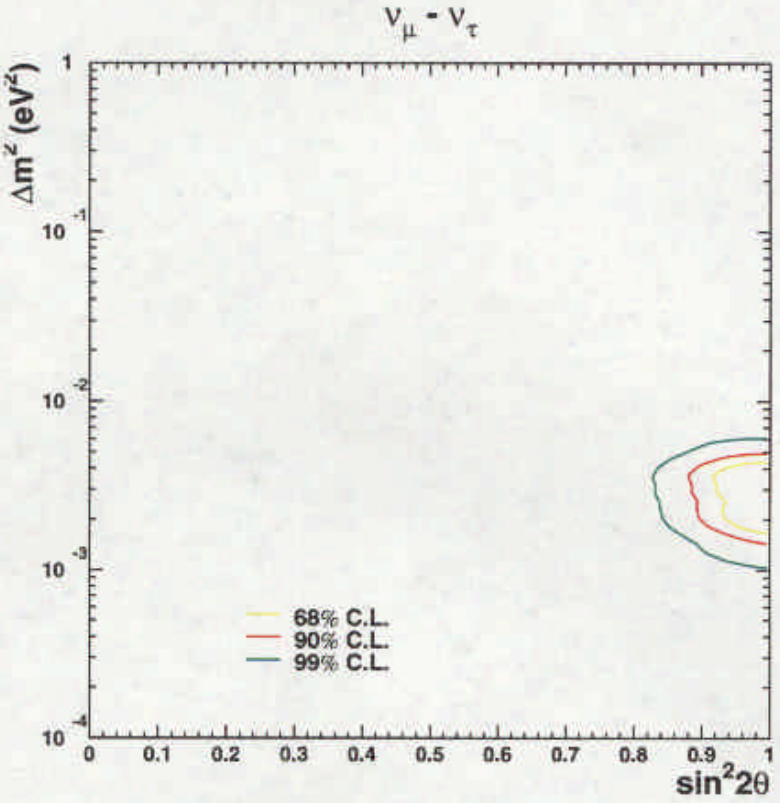








Result of combined fit FC,PC,UpMu



Result of Oscillation Analysis (FC + PC + Upmu)

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

Best fit :

χ^2_{min} = 135.3 / 152 d.o.f

at $(\sin^2 2\theta, \Delta m^2) = (1.01 , 3.2\times10^{-3}\ eV^2)$

(Including unphysical region)

χ^2_{min} = 135.4 / 152 d.o.f

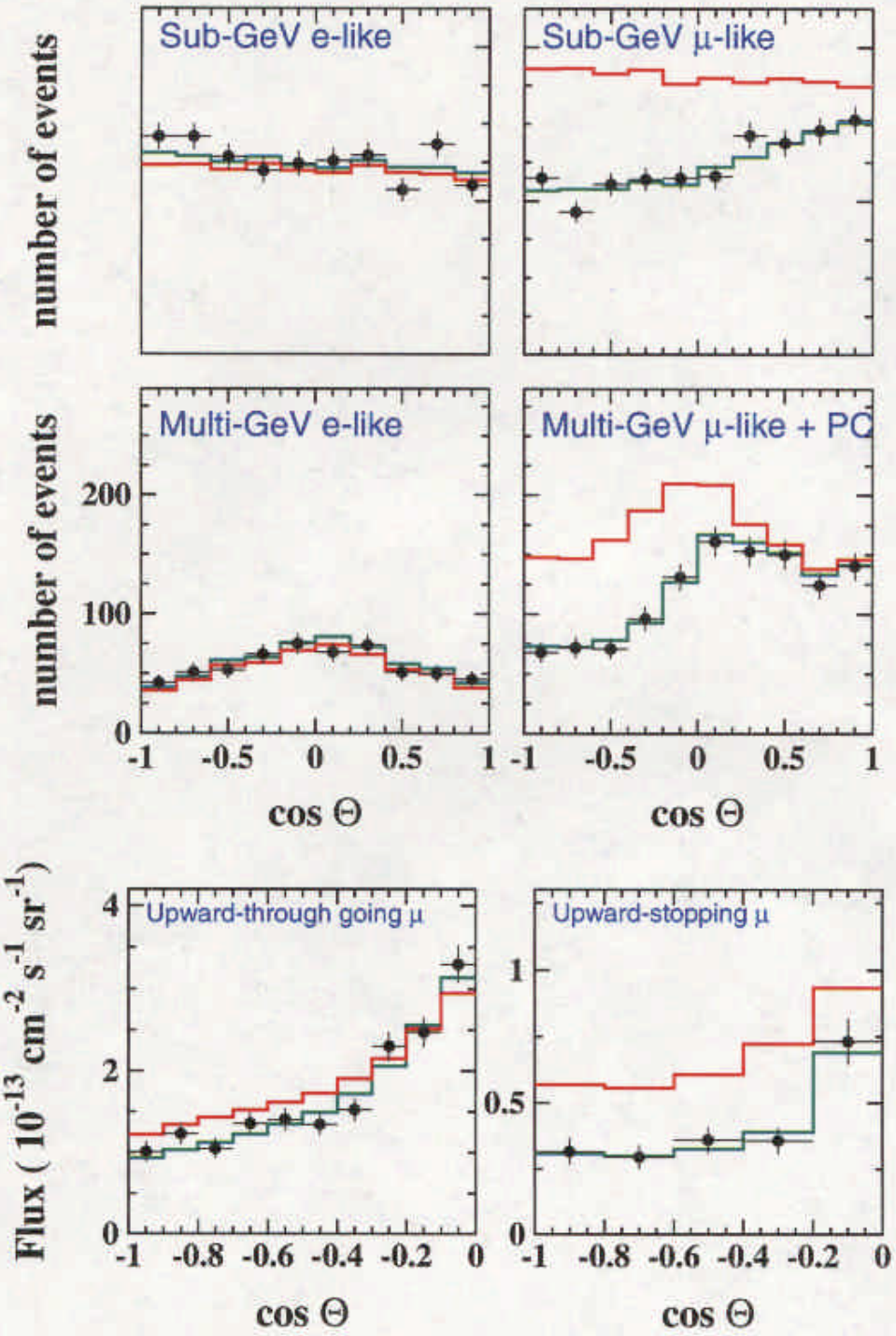
at $(\sin^2 2\theta, \Delta m^2) = (1.00 , 3.2\times10^{-3}\ eV^2)$

(Physical region)

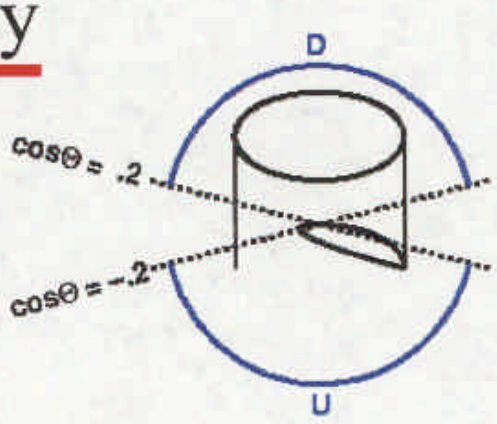
- Assuming null oscillation

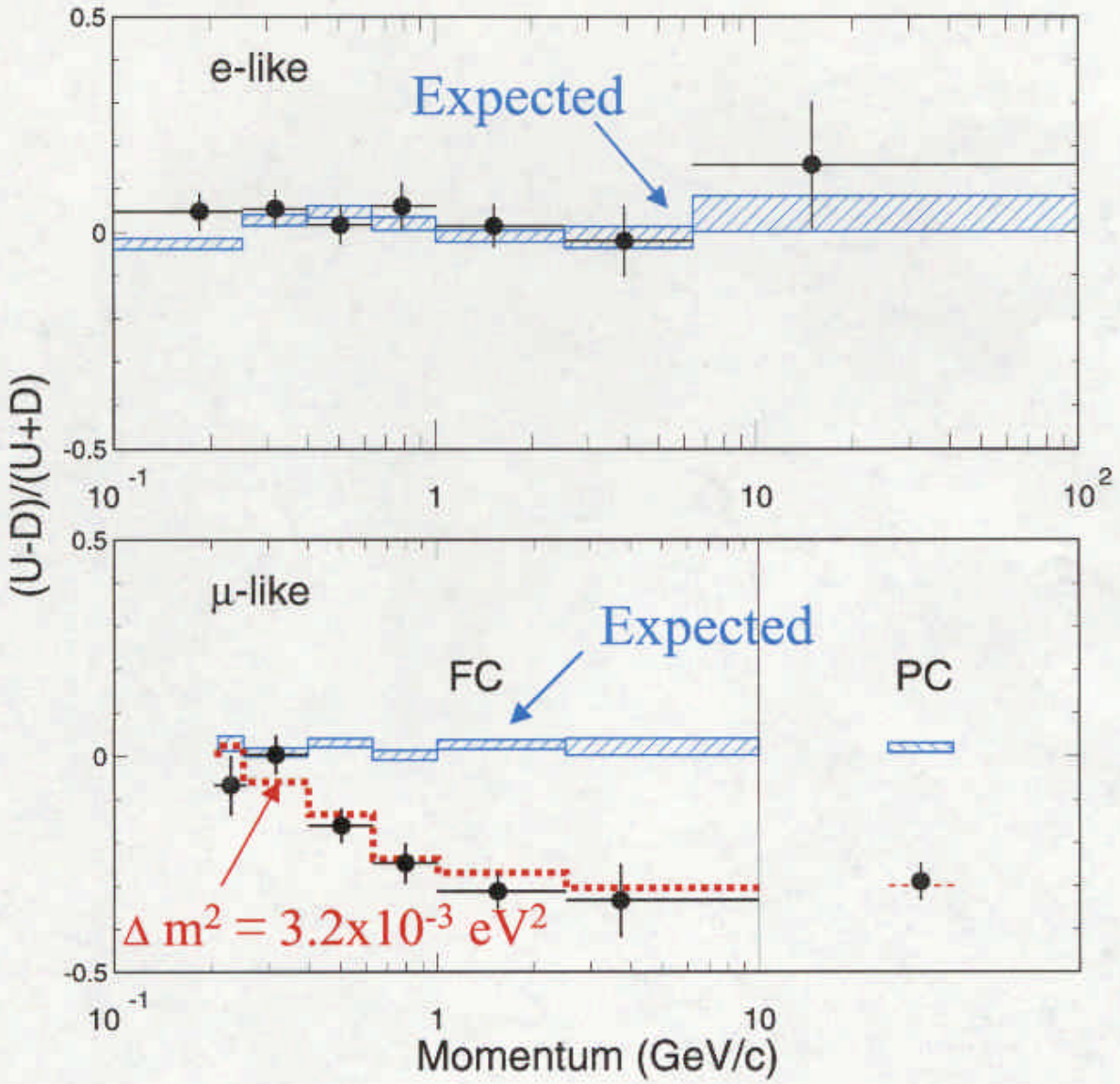
$\chi^2 = _{min}$ = 316.2 / 154 d.o.f

Zenith distributions with combined fit

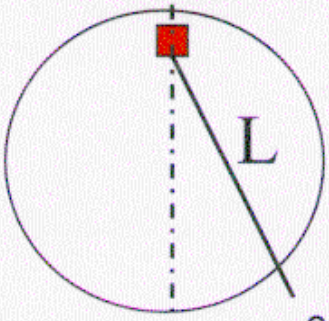


Up-Down Asymmetry vs. Momentum



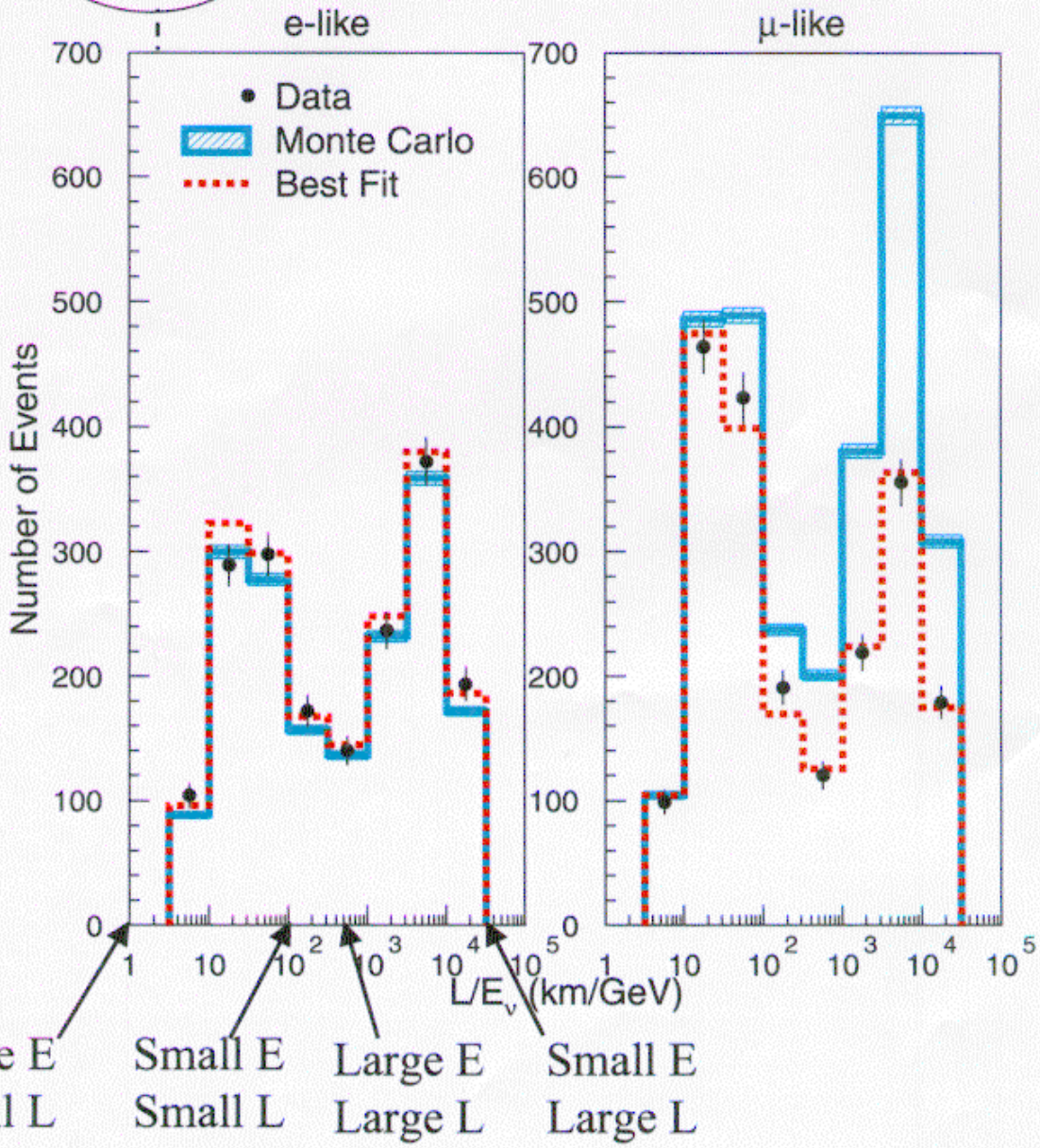


Bin data as a function of L/E_ν



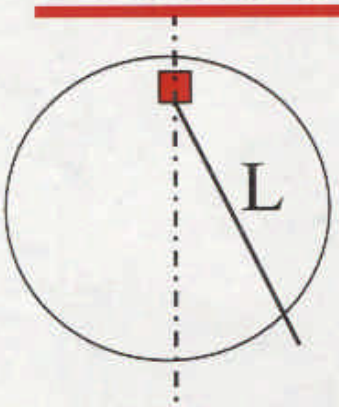
$$P_{\nu\nu'} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E_\nu)$$

Use P > 400 Mev/c

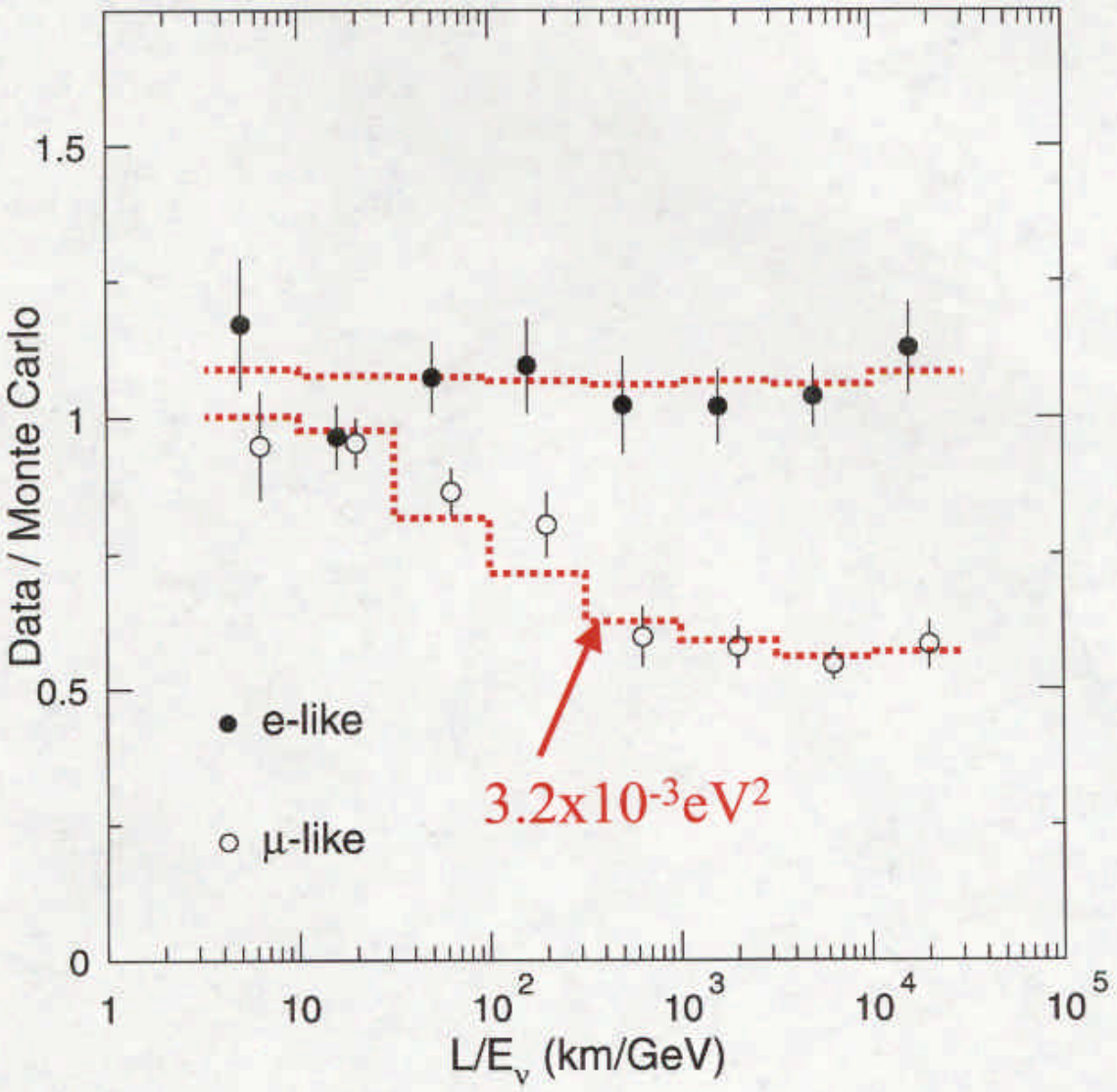


Large E Small L | Small E Small L | Large E Large L | Small E Large L

Bin data as a function of L/E_ν



$$P_{\nu\nu'} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E_\nu)$$



Probability of more exotic oscillation models

Test $\nu_\mu \longrightarrow \nu_\tau$ oscillation with:

$P(\nu_\mu \longrightarrow \nu_\tau) = \sin^2 2\theta \sin^2(\beta L^* E^n)$

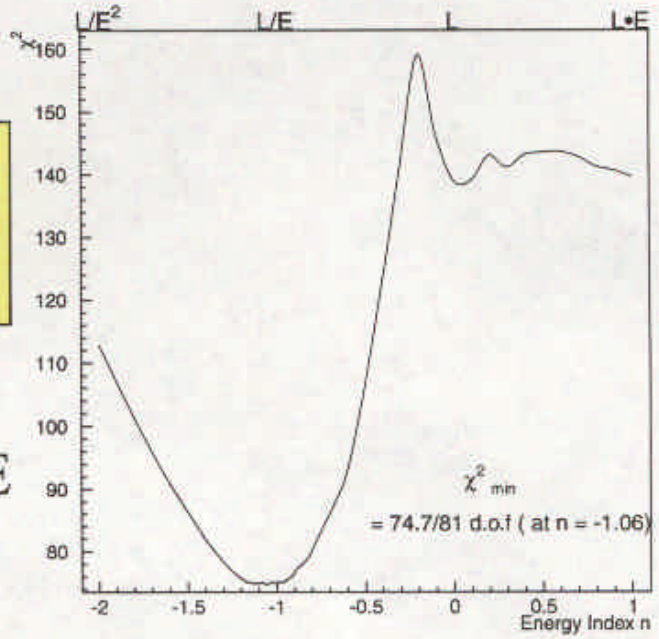
where θ, β, n : parameters

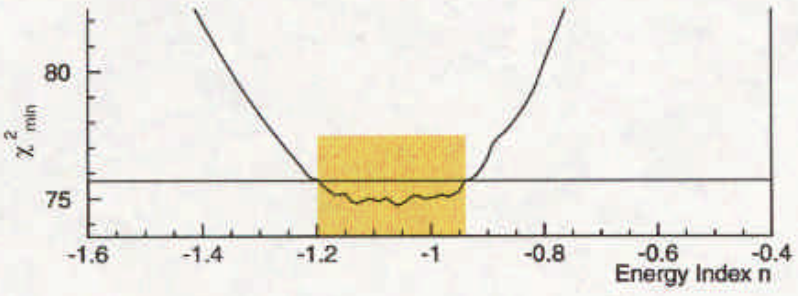
Use FC,PC,UpMu data

Vary $\sin^2 2\theta$ from 0.7 to 1.3

Vary index n from –2.0 to 1.0

L/E^2 L^*E

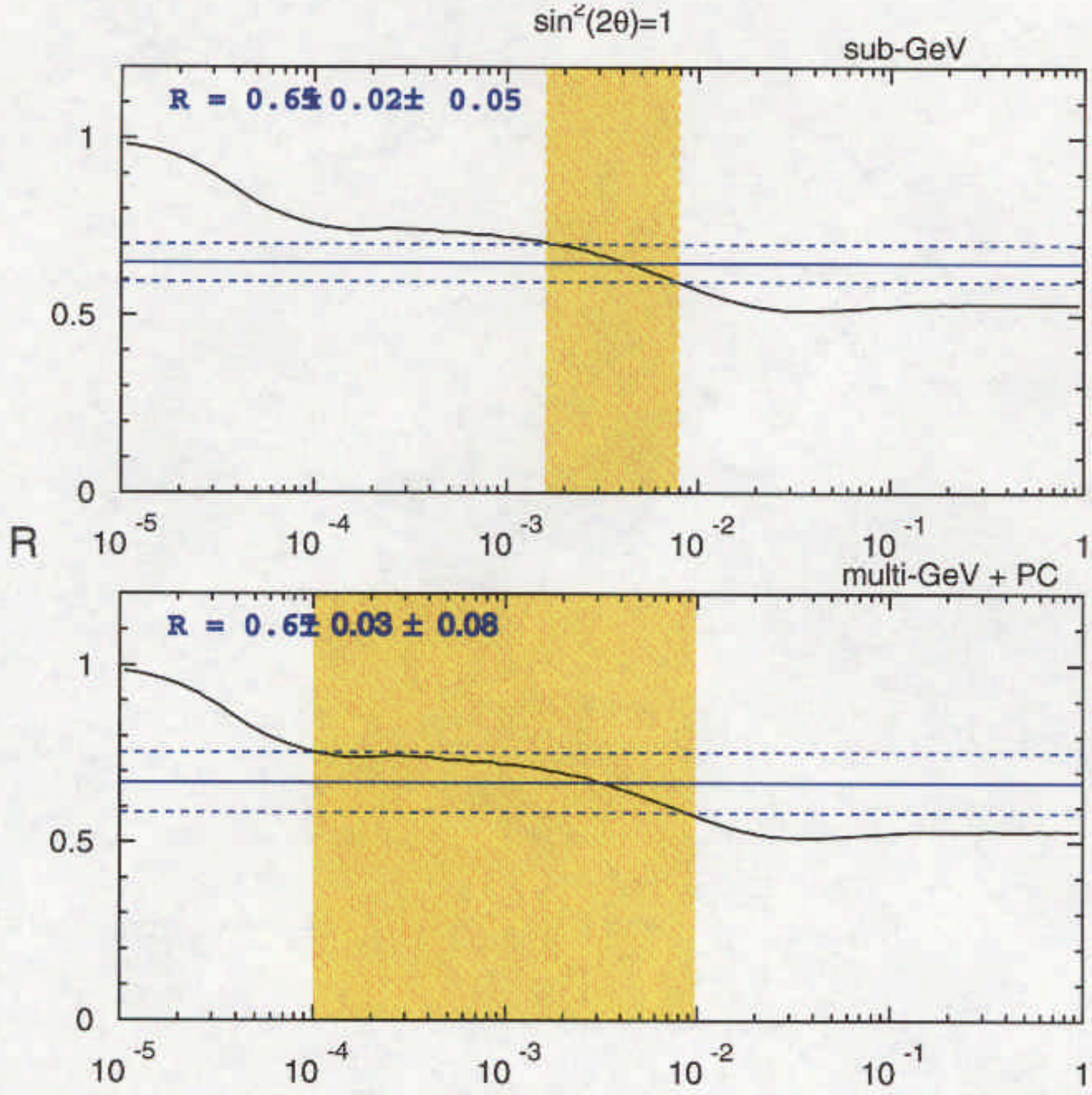




Magnified view

n = -1.06 +/- 0.14

Consistency of ν_μ/ν_e ratios with zenith angle results

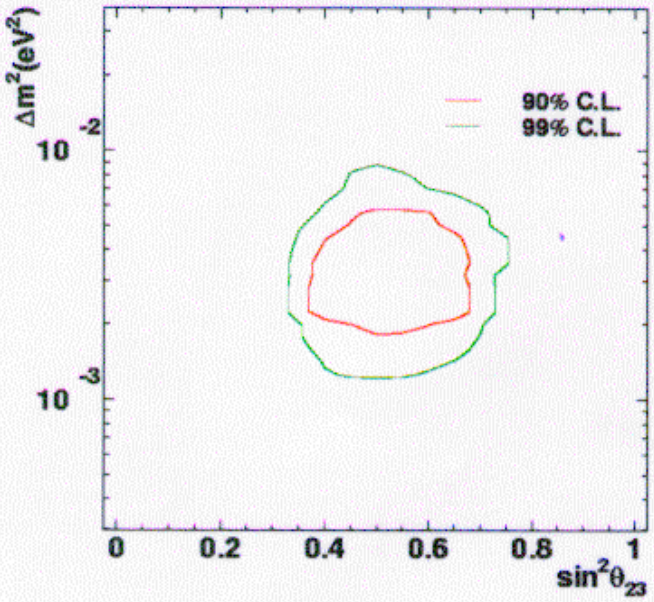


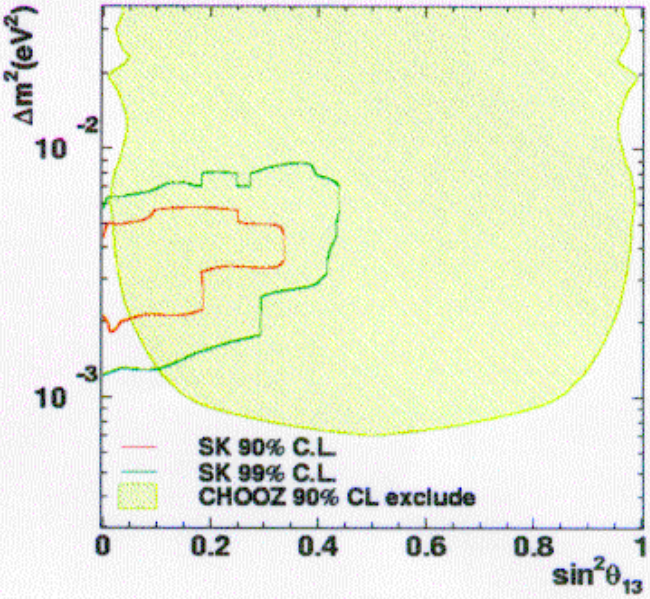
Three flavor oscillation analysis

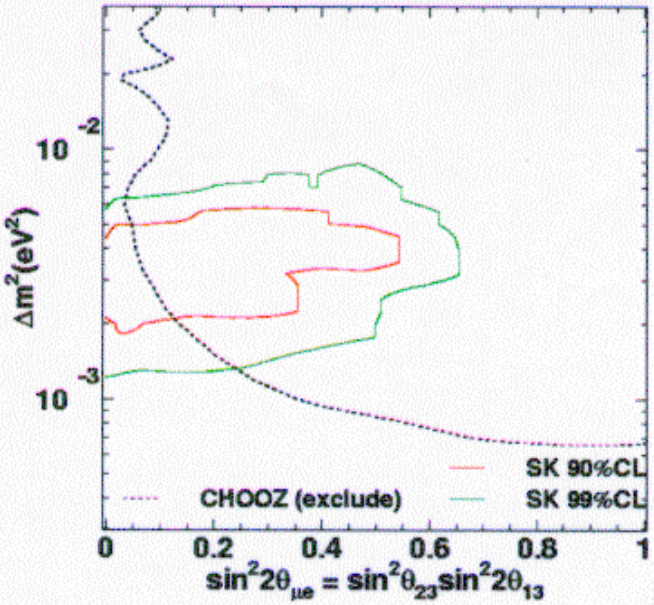
Assume $m_1 = m_2 \ll m_3$

We have only 3 free parameters:

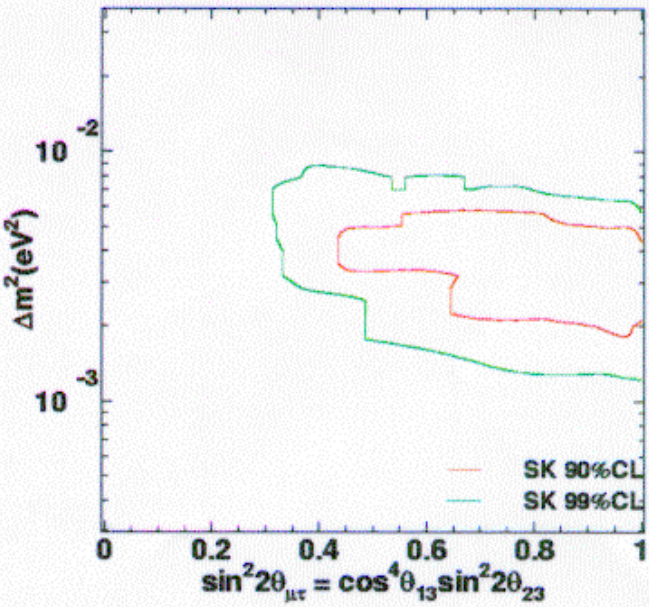
- $\delta m^2 = m_3^2 - m_1^2$
- mixing: $\sin^2\theta_{13}$
  $\sin^2\theta_{23}$







$\nu_\mu \longrightarrow \nu_e$



$\nu_\mu \longrightarrow \nu_\tau$

Limits on $\nu_\mu \rightarrow \nu_{sterile}$ oscillation

1. Compare rate of neutral current interactions with charged current interactions.

   Tau neutrino interactions suppressed by tau threshold, but NC are not.

   Sterile neutrinos don't produce CC or NC.

2. Use matter *suppression* of ν_s oscillation at large E_ν

$$P(\upsilon_a \rightarrow \upsilon_b) = \sin^2 2\theta \sin^2(1.27\,\Delta m^2[eV^2]\,L[km]/E[GeV])$$

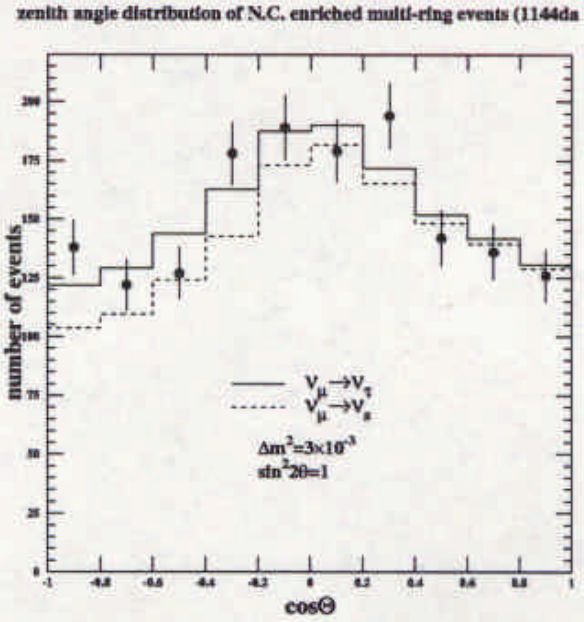
$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{|\zeta - \cos 2\theta|^2 + \sin^2 2\theta}$$

$$L_m = \frac{L}{\sqrt{[\zeta - \cos 2\theta]^2 + \sin^2 2\theta}}$$

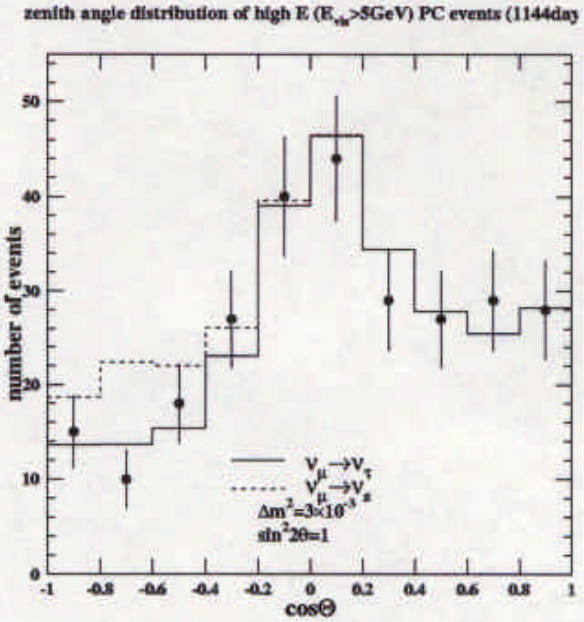
where: $\zeta = \dfrac{2EV_{ab}}{\Delta m^2}$

For high energies ξ term drives $\sin^2 2\theta$
And L_m to zero implying NO oscillation.

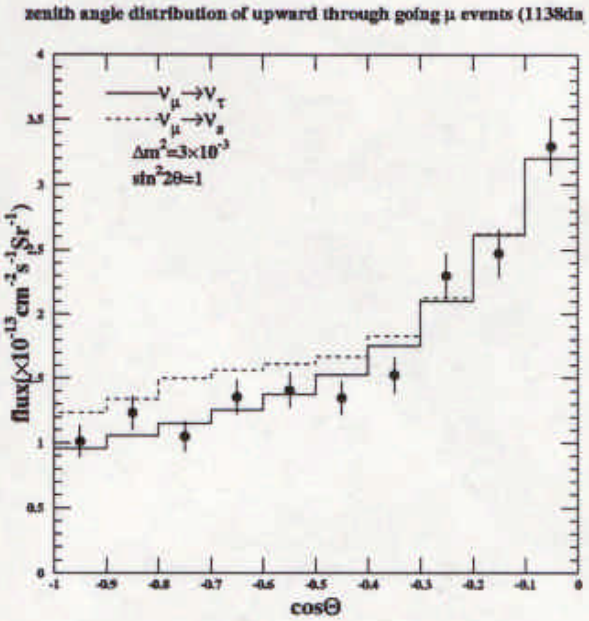
Zenith angle distributions



NC enriched multi-ring events

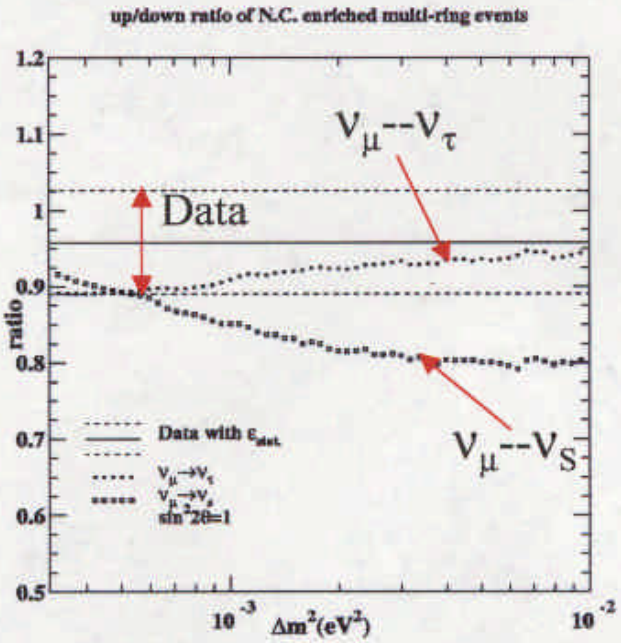


E_{vis}> 5 GeV PC events

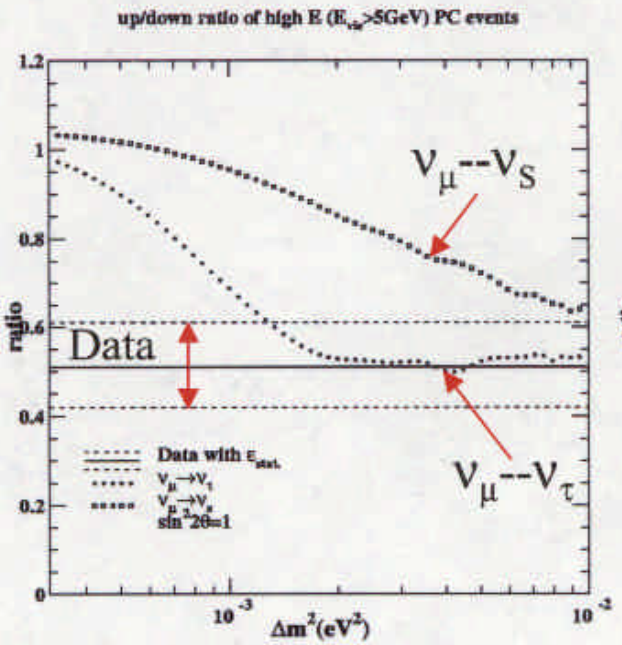


Up mu events

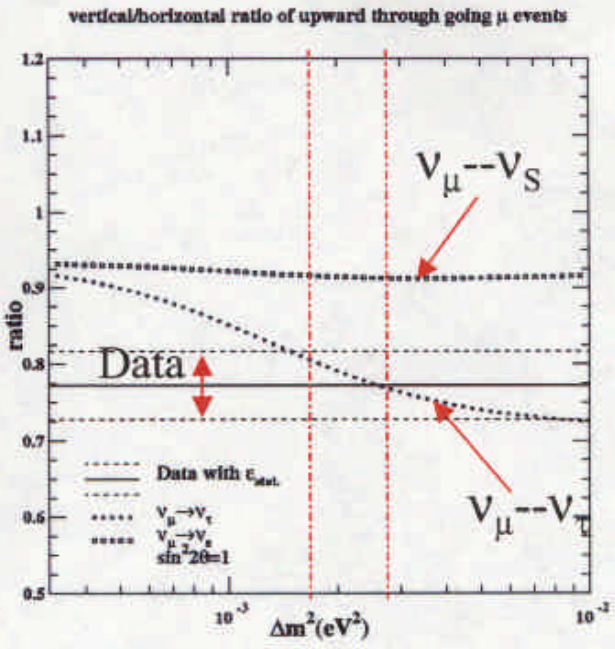
Ratios



Up/Down ratio
NC enriched multi-ring

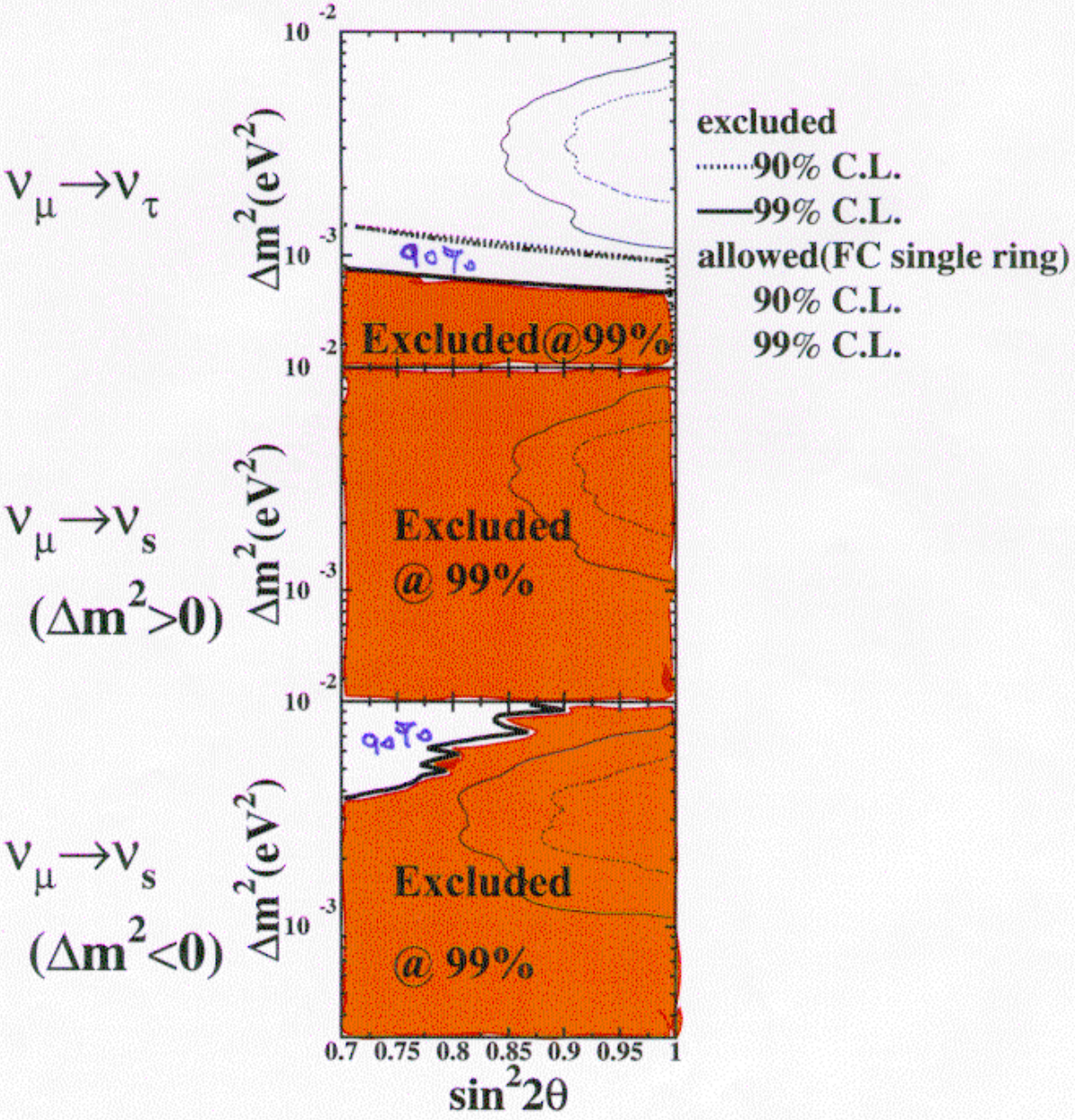


Up/Down ratio
High Energy PC



Vertical/Horizontal Ratio
up muons

Excluded regions from combined analysis (multi+PC+UpMu)



Conclusions

- We observe an anomalous ratio of ν_μ/ν_e in the atmospheric neutrinos.
- An angular asymmetry is observed in Sub-GeV and Multi-GeV samples.
- A $\nu_\mu \longrightarrow \nu_\tau$ hypothesis fits both R<1 and Angular asymmetry.
  - Oscillations $\nu_\mu \rightarrow \nu_\tau$ are dominant

    $1.5\times10^{-3} < \Delta m^2 < 5\times10^{-3}$ eV^2
    $\sin^2 2\theta > .88$ (90% CL)
  - Small contribution of $\nu_\mu \rightarrow \nu_e$ oscillations is not excluded
  - Oscillations $\nu_\mu \rightarrow \nu_s$ are excluded at 99% CL
  - Models leading to other than L/E dependence are disfavored.
- More data and analysis to come:
  - Search for ν_τ appearance
  - Long baseline accelerator experiment --- K2K started March 1999 (see Nakamura talk this conference).