ATMOSPHERIC NEUTRINOS

Y. Totsuka

- ~~Brief History~~

$$R = \frac{(N\mu/Ne)_{data}}{(N\mu/Ne)_{MC}}$$

Zenith Angle Distribution

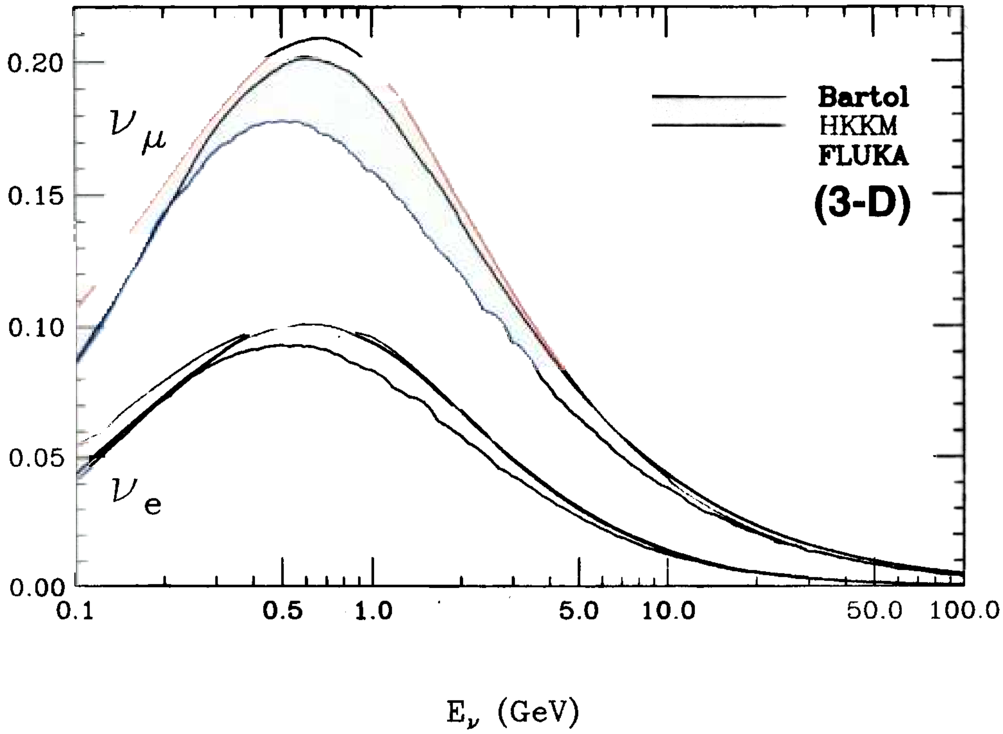
- **Evidence for $\nu_\mu \rightarrow \nu_\tau$ Oscillation**
- **Comment on 3-Dimensional Flux Calculation**
- **2 flavor $\nu_\mu \rightarrow \nu_s$**
- ν Decay
- ~~Future~~
- Conclusion

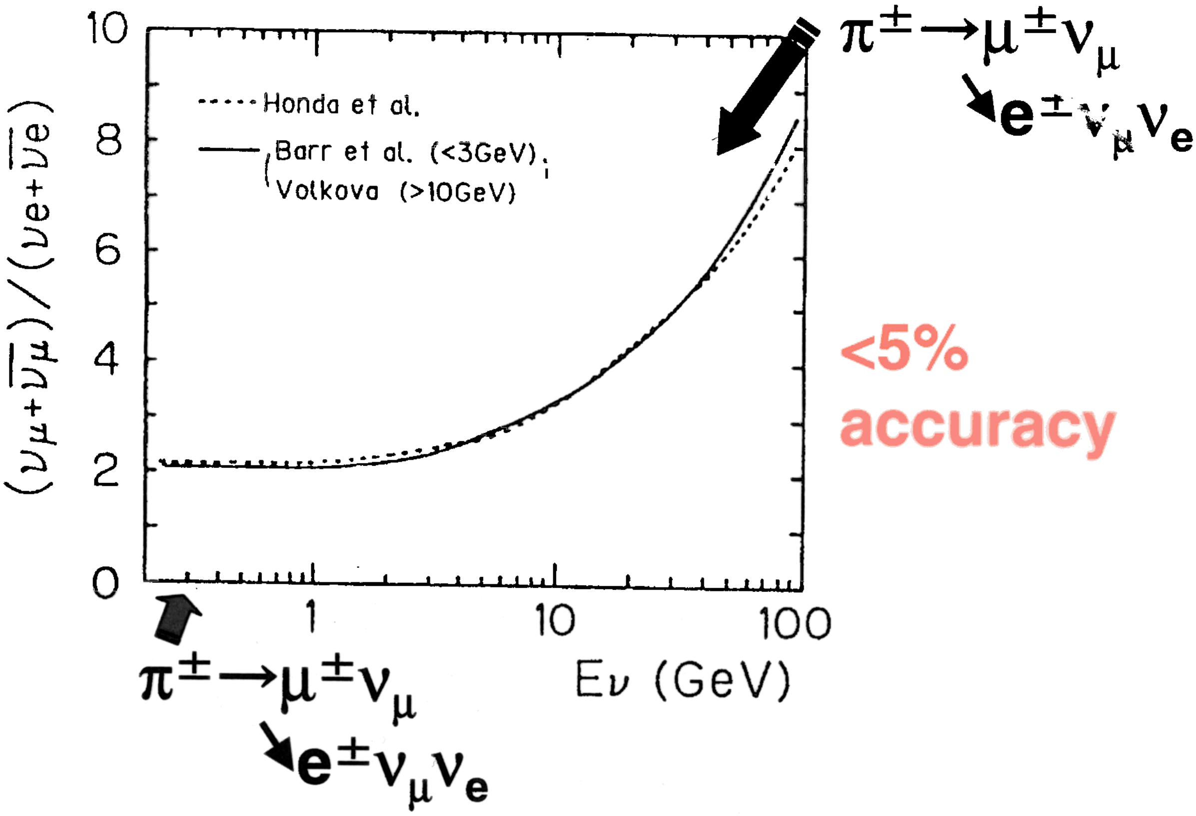
Brief History

- Atmospheric neutrinos were the serious background for proton decay searches which were active in the 1980's.
- Study of atmospheric neutrinos had to be made carefully to purify proton decay candidates.
- Anomaly was found:
  - Kamiokande; small (μ/e) ratio (1988)
  - Frejus, NUSEX; no anomaly (1989-1995)
  - IMB; supported Kamiokande (1991)
  - Kamiokande; asymmetric zenith-angle distribution for high energy μ (1994)
  - Super-K; evidence for atm-ν oscillation (1998)
  - MACRO, Soudan 2; confirmed Super-K
- Who imagined that atmospheric neutrinos would have precious information on neutrino properties?

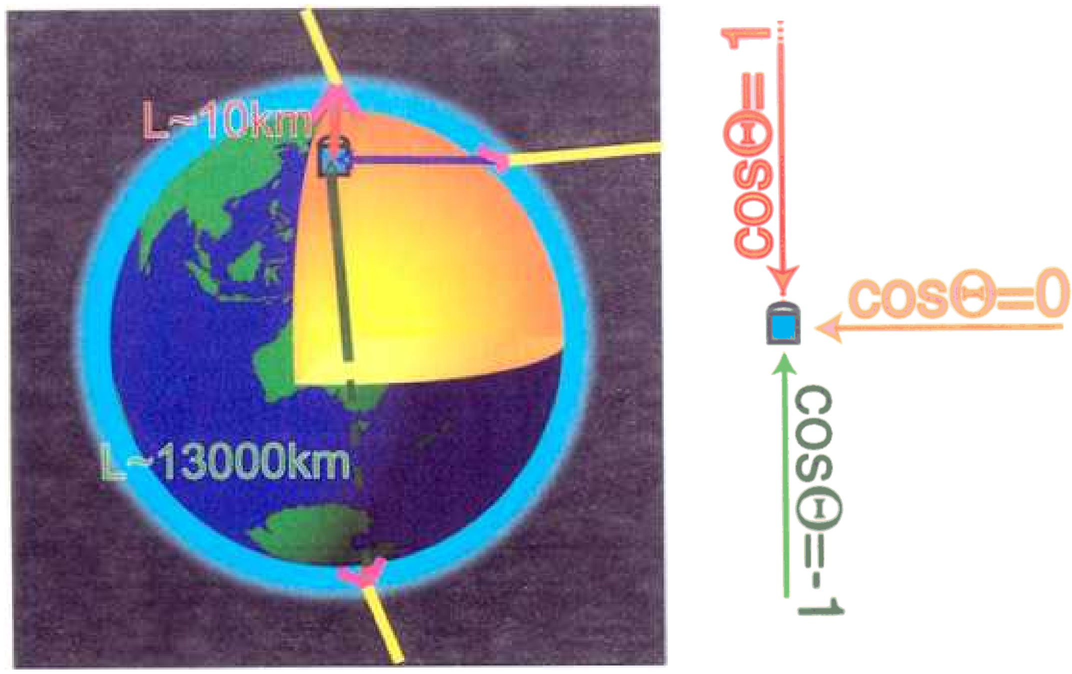
Atmospheric neutrino spectrum

MODEL dependence of ENERGY spectrum (P.Lipari)

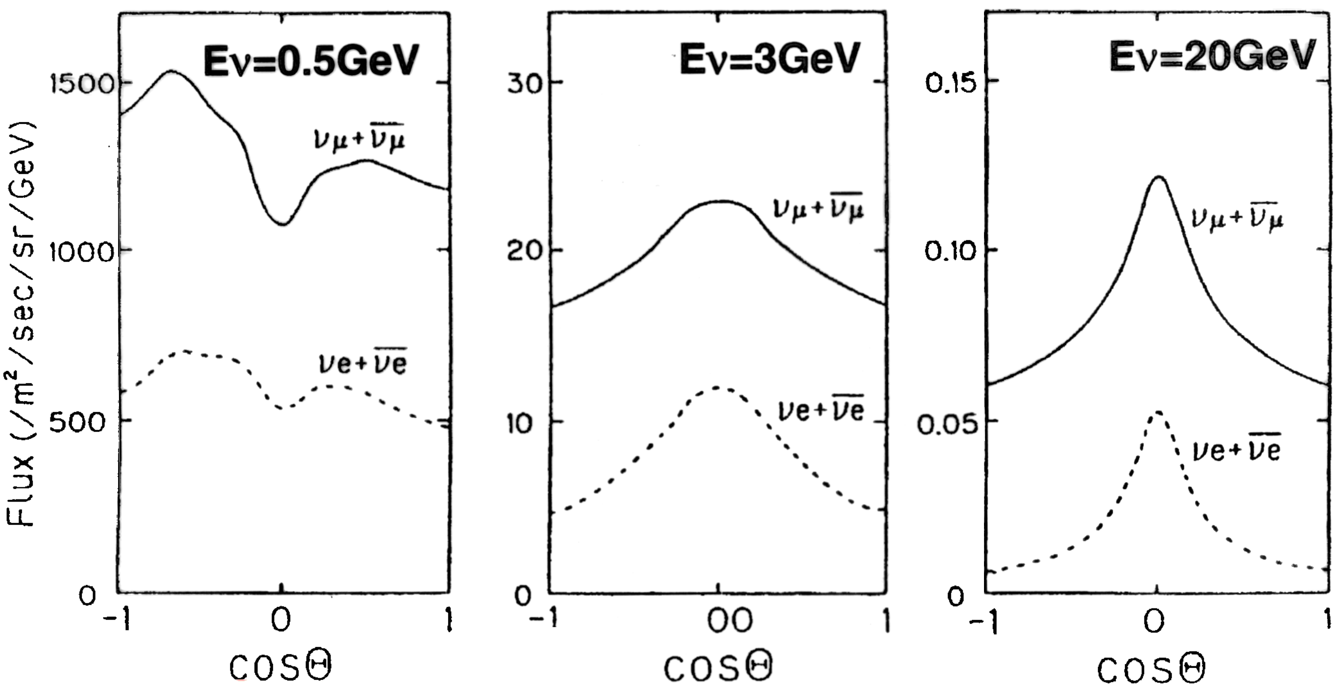




Zenith angle distribution(1D)



Calculated zenith angle distribution

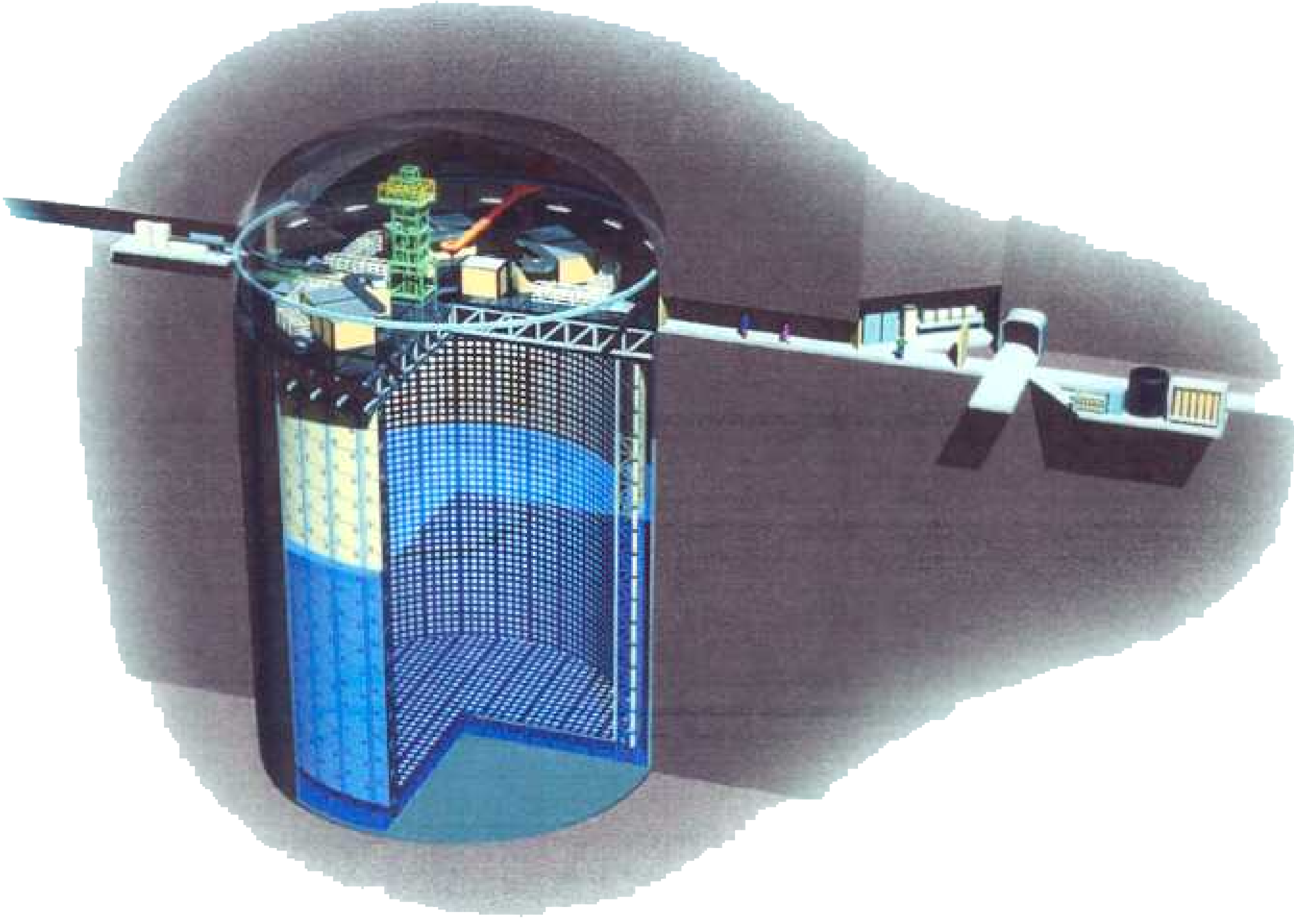


For E_ν > a few GeV,

Upward / downward = 1 (within a few %)

Up/Down asymmetry for neutrino oscillations

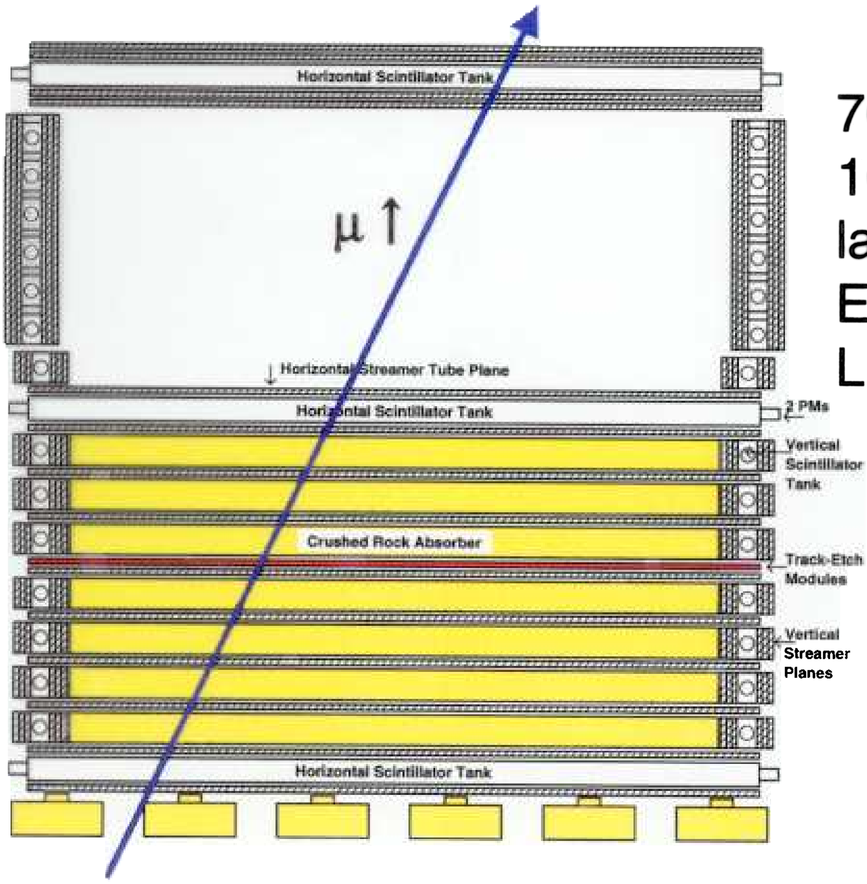
Super-Kamiokande Detector



50,000 ton water Cherenkov detector (22.5 kton fiducial volume)

Livetime (exposure): 1289 days (79.3 kt·yr)

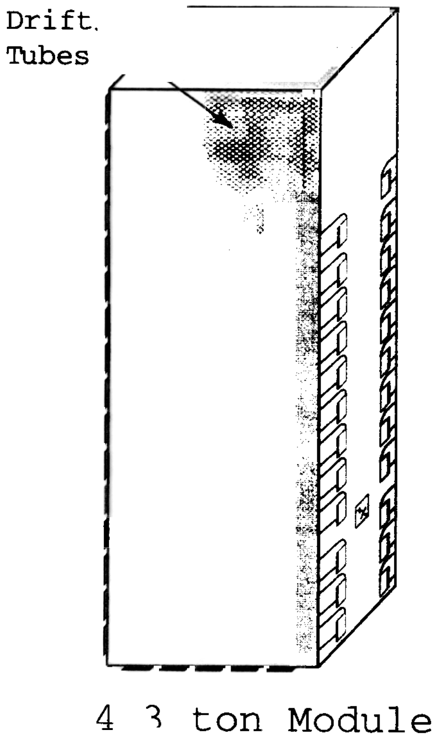
MACRO



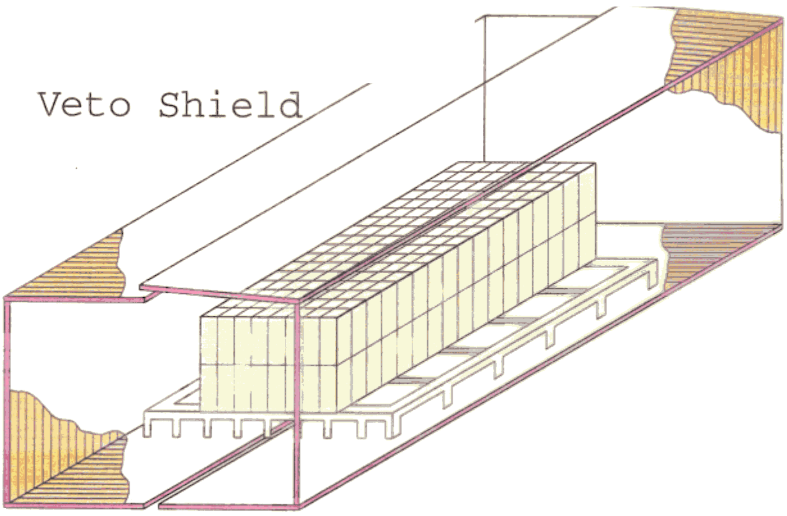
76.6m x 12m x 9.3m
10 streamer tube layers
E^{μ}_{min} = 1GeV
Livetime = 6.16 yrs

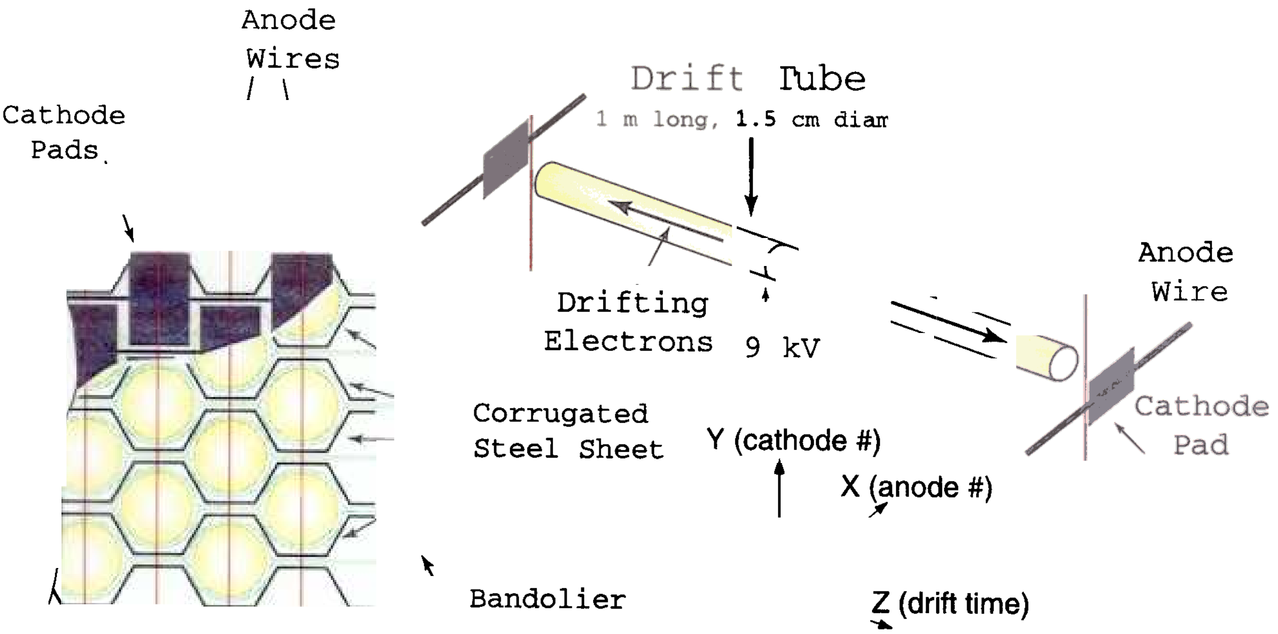
Soudan 2

- 963 ton Fe + drift tubes with dE/dx measurement capability
- Exposure: 5.1 kt·yr



224 1m x 1m x 2.7 m honeycomb lattice geometry modules surrounded by a 1700 m^2 proportional counter veto shield.

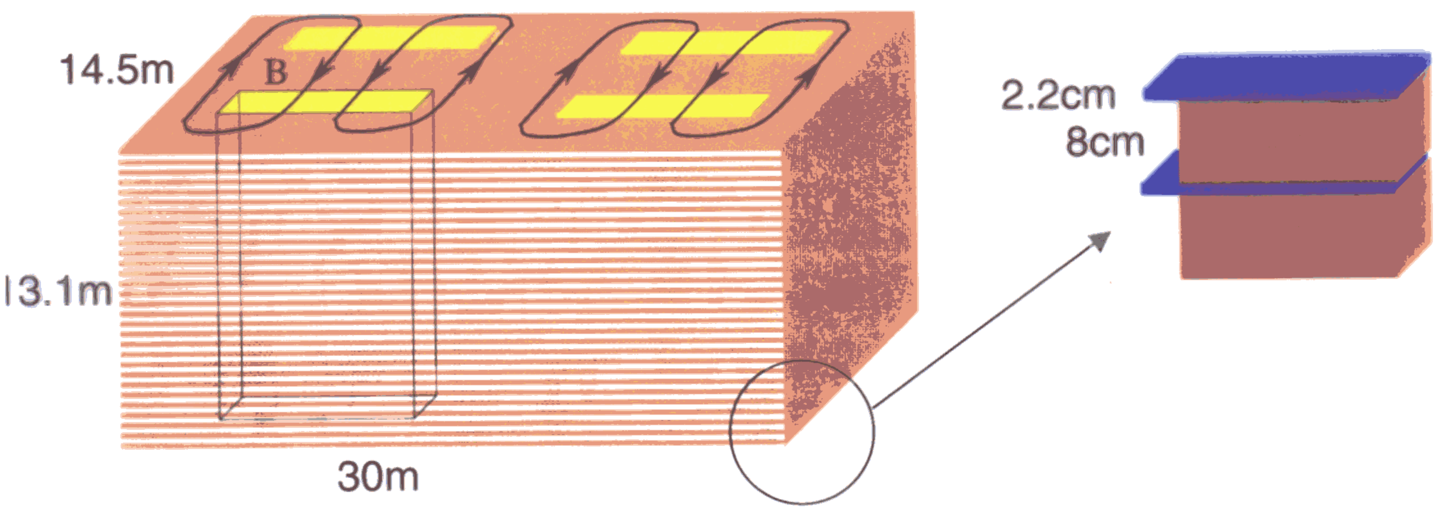




The MONOLITH Detector (future)

Large mass ~ 35 kton
Magnetized Fe spectrometer B = 1.3 Tesla
Space resolution ~ 1 cm (rms on X-Y coordinates)
Time resolution ~ 1 ns (for up/down discrimination)
Momentum resolution σ_p/p ~ 20% from track curvature for PC muons
~ 6% from range for FC muons
Hadron E resolution $\sigma_{E_h}/E_h \sim 90\%/\sqrt{E_h[GeV]} \oplus 30\%$

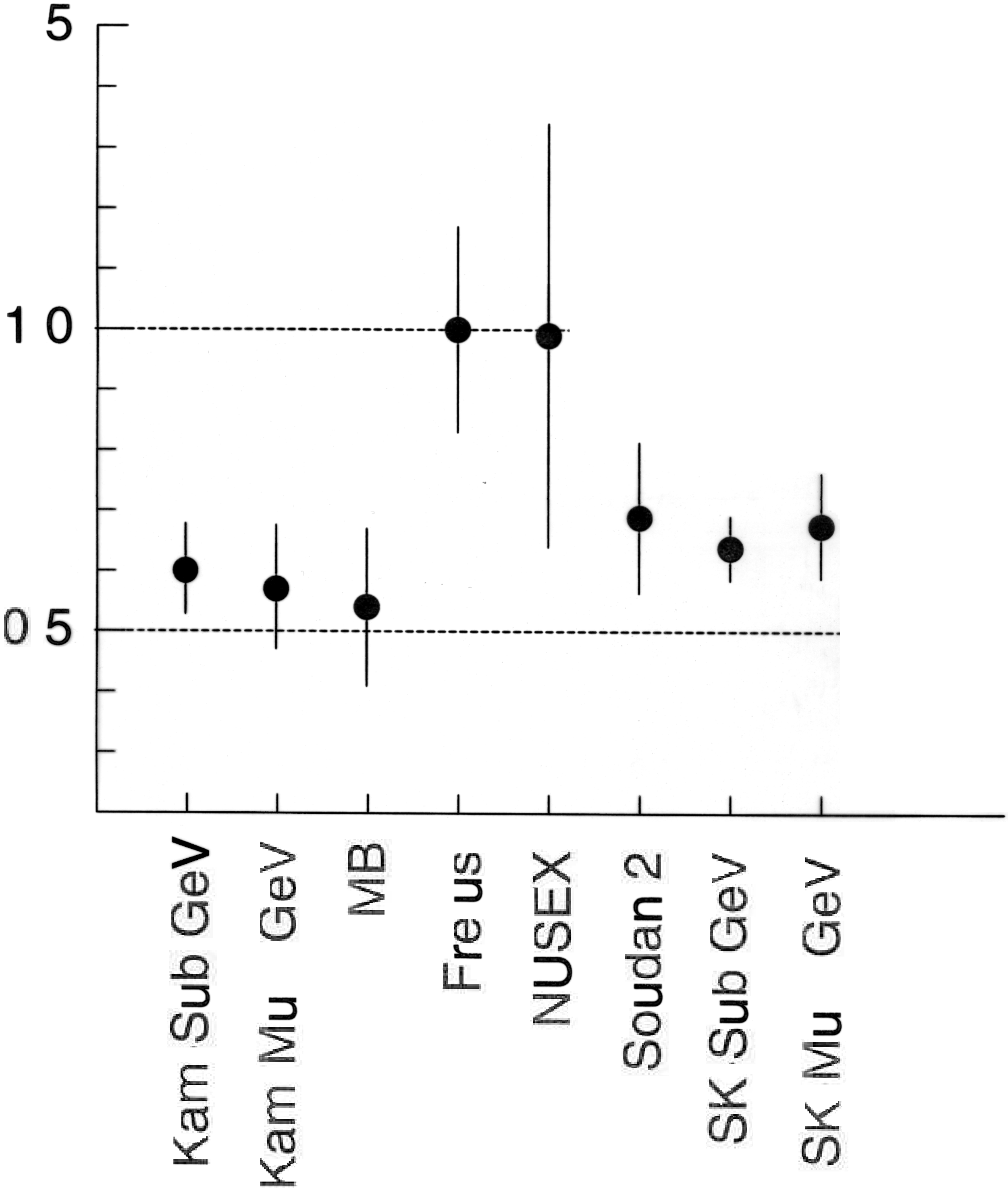
$8.0 \times 3000 \times 1450\ cm^3 \times 7.87\ g/cm^3 = 285$ ton/plane
130 planes



~54000 m^2 of detector : Glass RPC
~1500 m^2 of external veto: Scintillator Counters

Courtsey: G.C.Trinchero

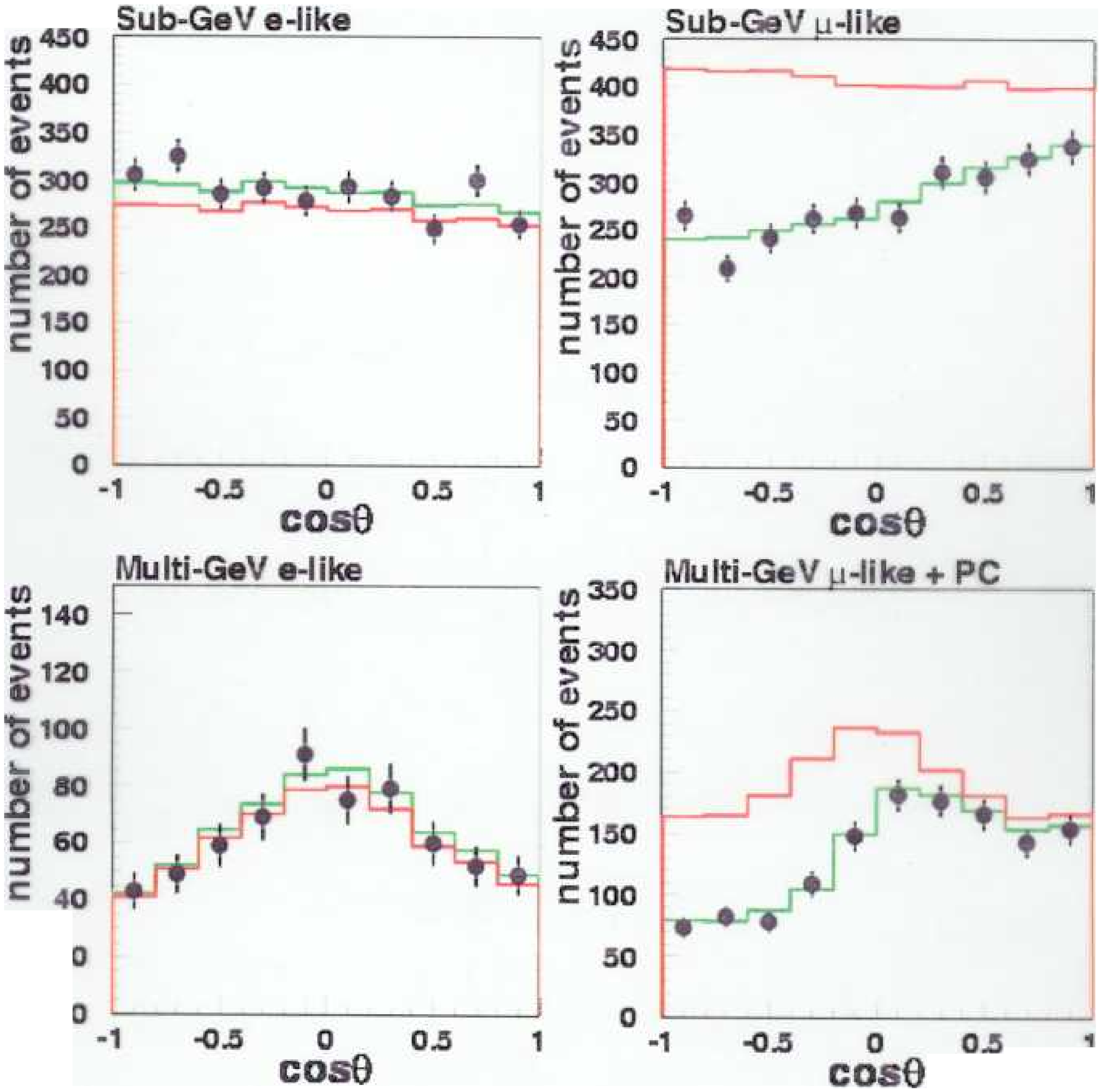
$$R = \frac{(N\mu/Ne)_{data}}{(N\mu/Ne)_{MC}}$$



Zenith Angle Distribution (Super-K)-I

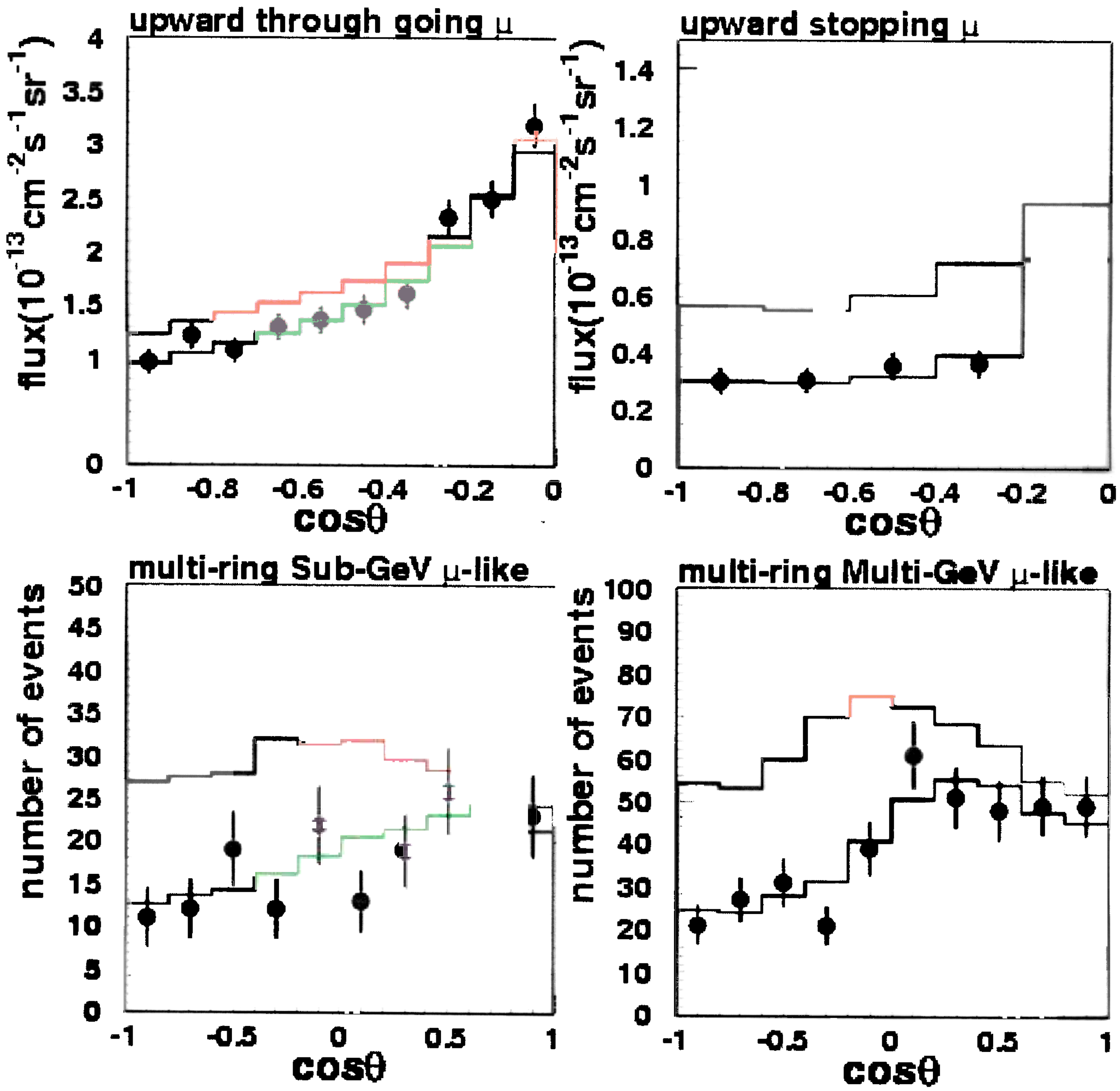
No oscillation

Best fit ($\Delta m^2 = 2.5\times10^{-3}$eV^2, $\sin^2 2\theta = 1.00$)



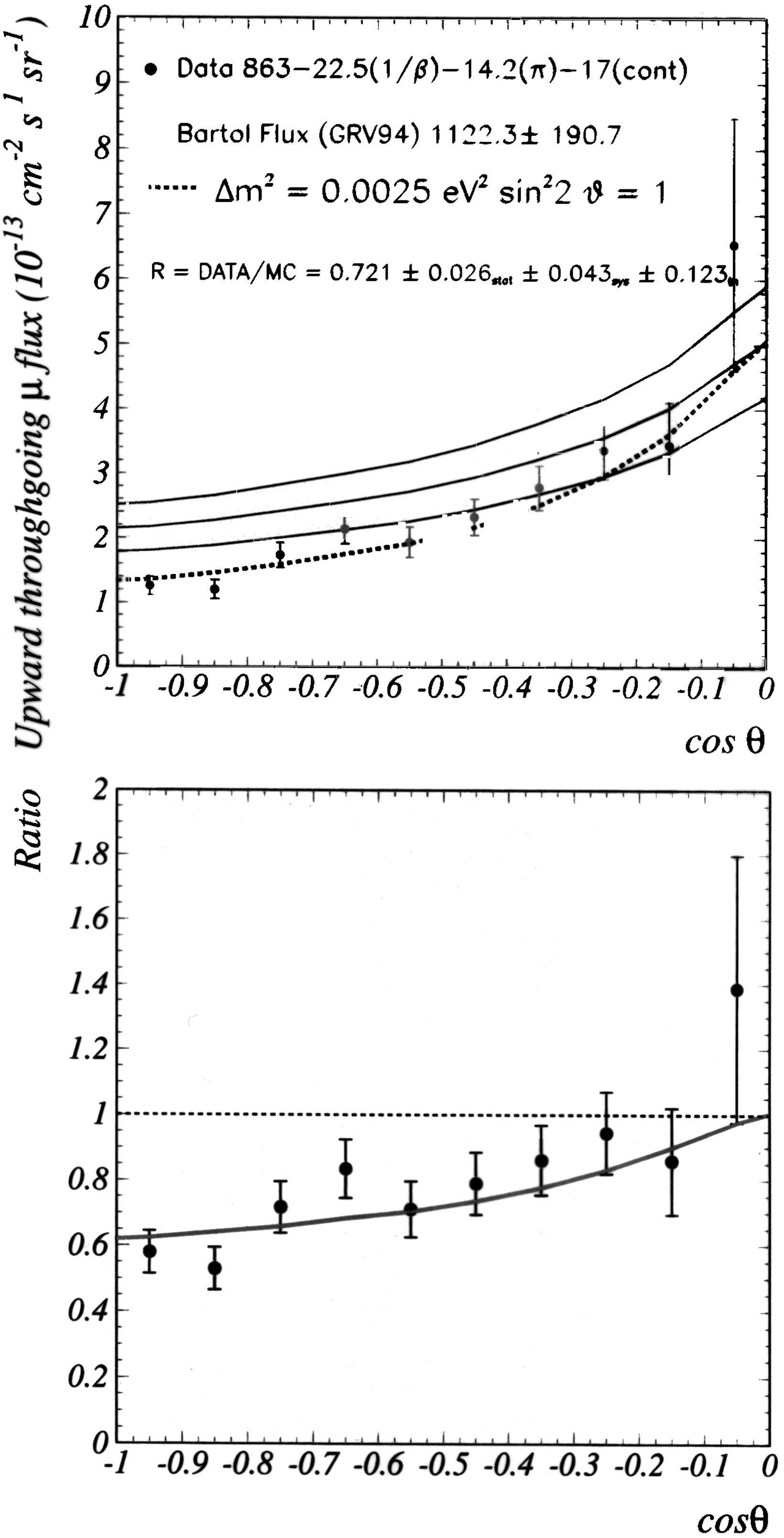
Zenith Angle Distribution (Super-K)-II

No oscillation
Best fit ($\Delta m^2=2.5\times10^{-3}eV^2$, $\sin^2 2\theta=1.00$)



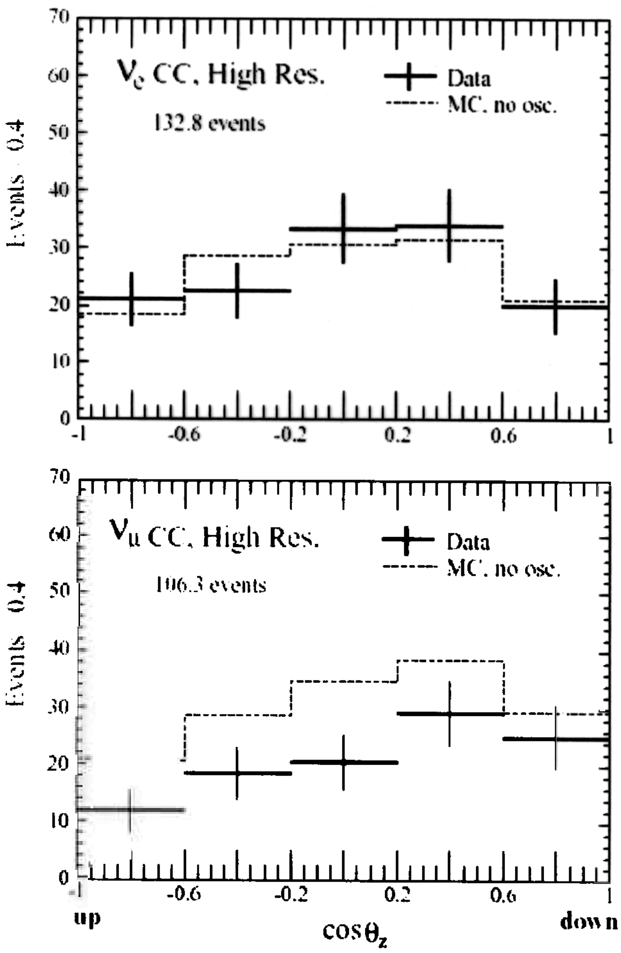
Zenith Angle Distribution (MACRO)

Thru-μ ↑ (809 events)

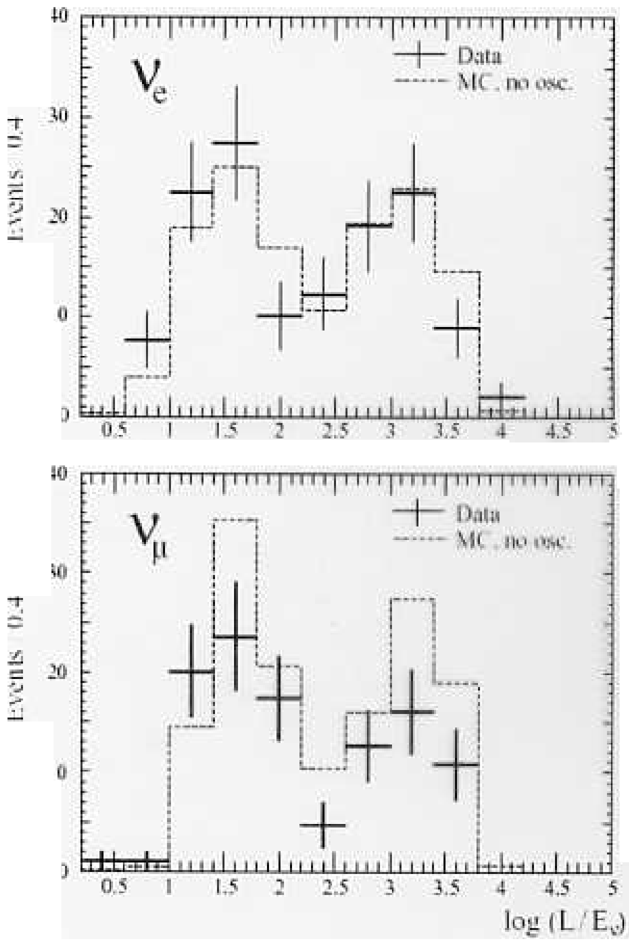


Zenith Angle Distribution (Soudan 2)

HiRes events (106.3±14.7 ν_μ, 132.8±13.4 ν_e)



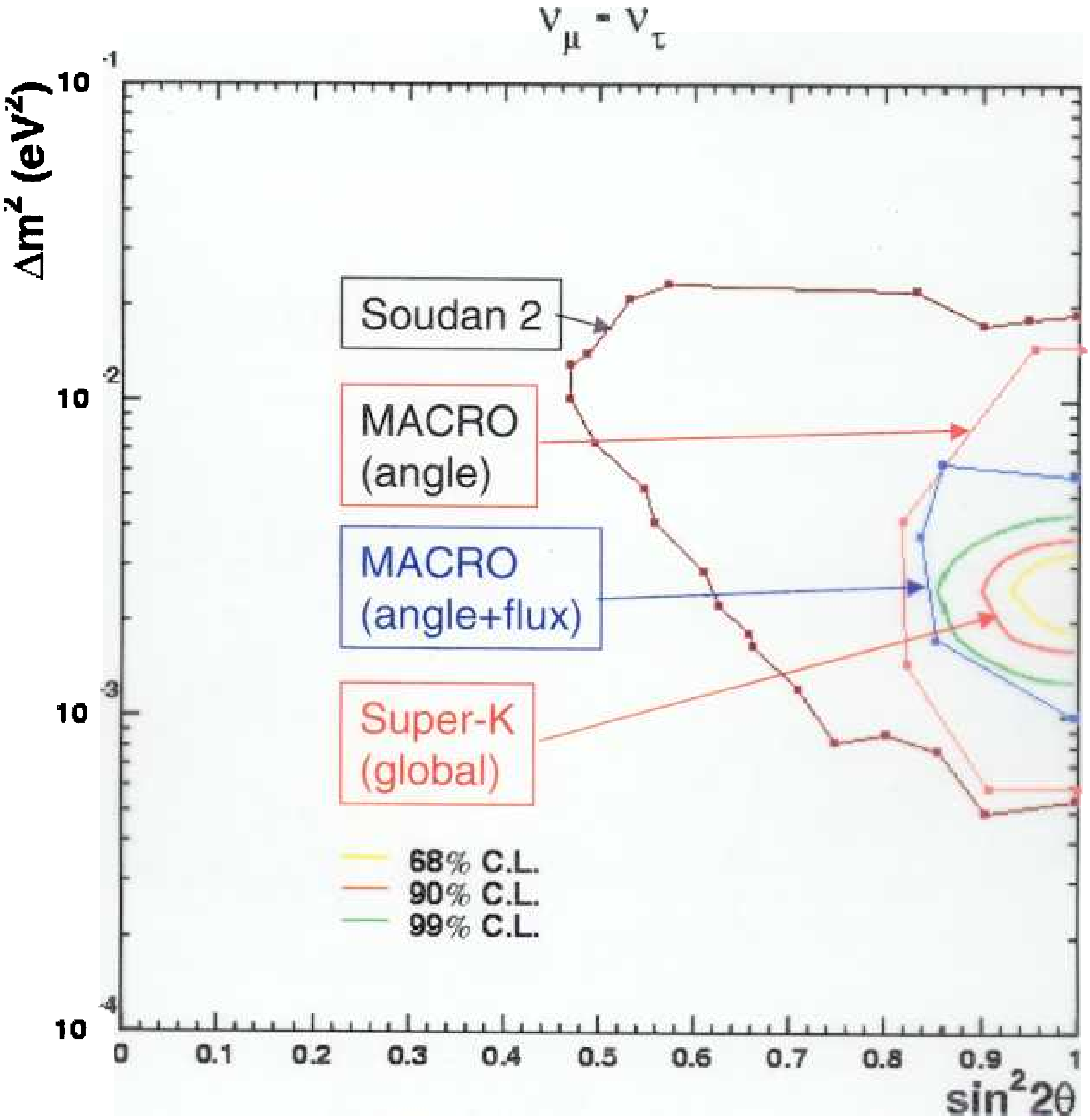
cos Θ



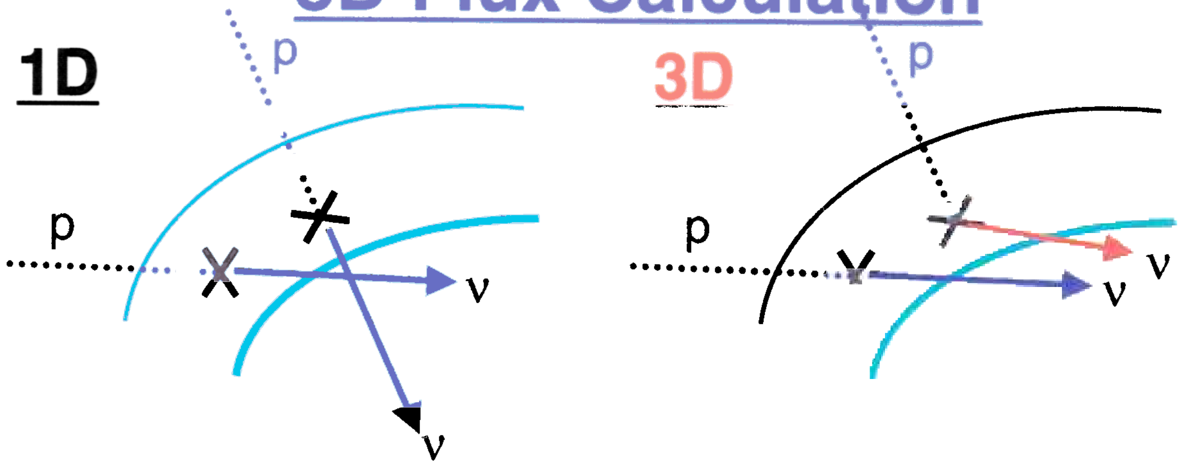
log(L/Eν)

Evidence for Neutrino Oscillations

Allowed regions (90% CL)

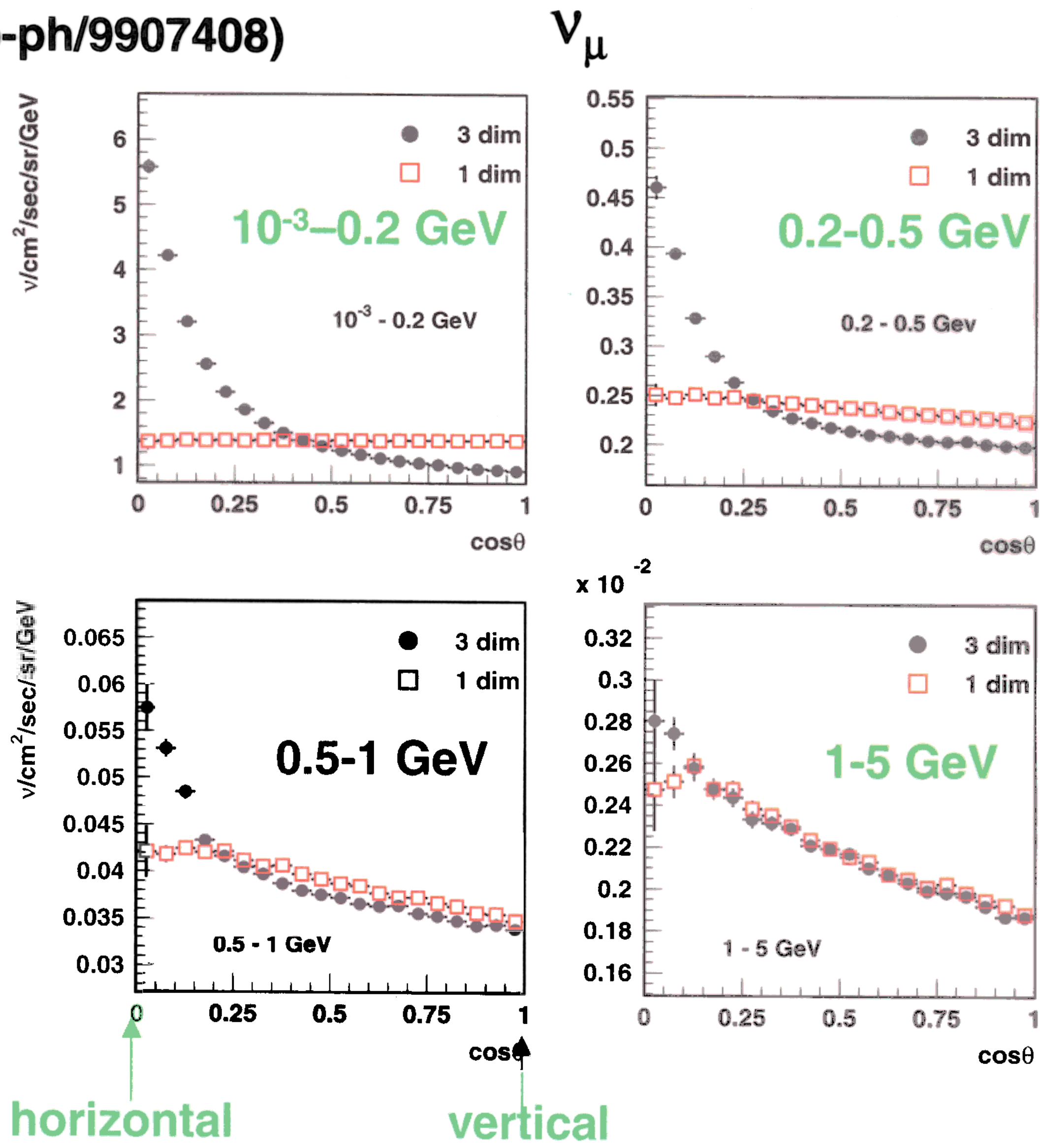


3D Flux Calculation



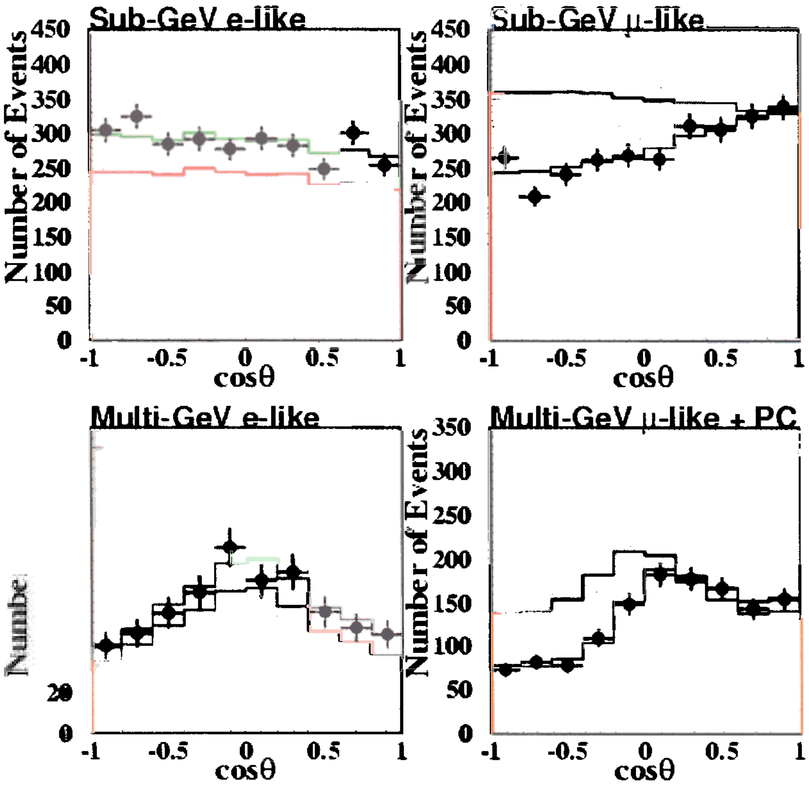
3D calculation by G.Battistoni et al.

(hep-ph/9907408)

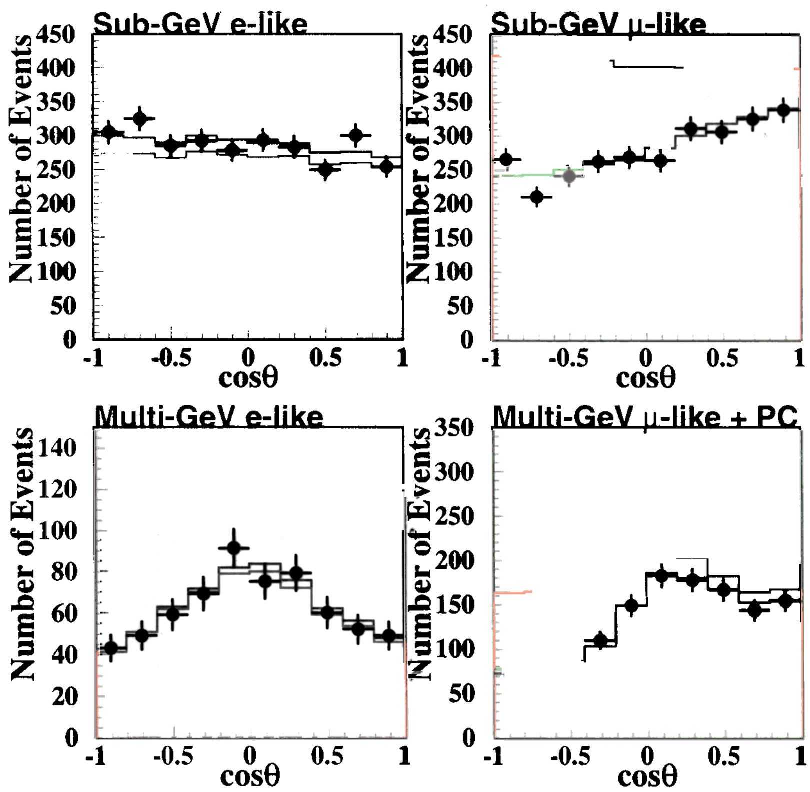


Zenith angle distr. with 3D calculation

1289 days (79.3 kt·yrs)



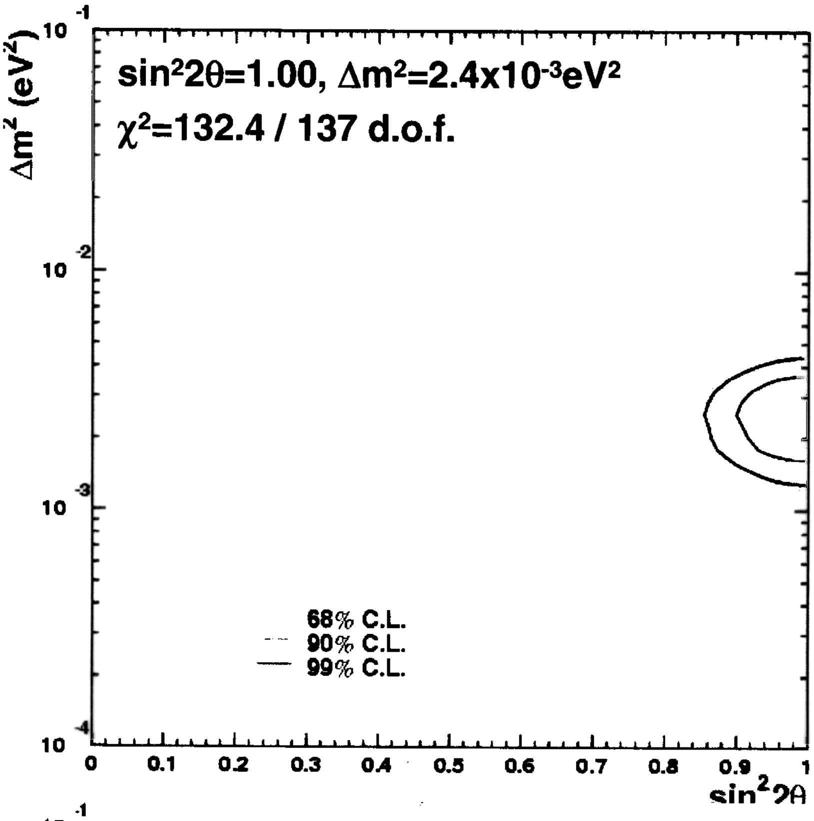
3-D
Problem in absolute flux?

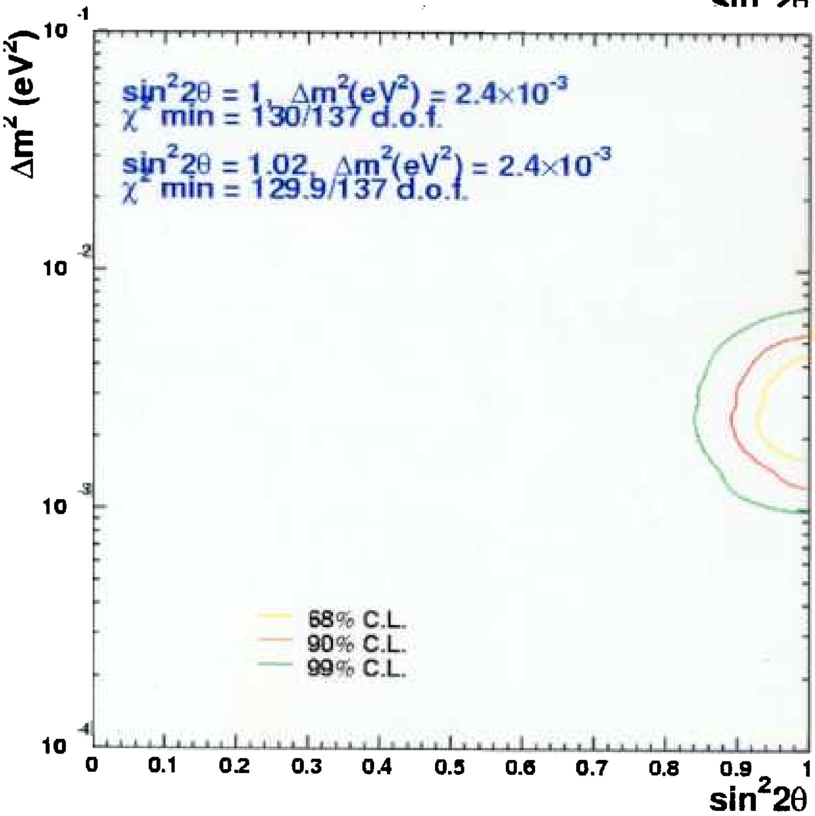


1-D

1D vs 3D for Super-K FC+PC Data

$\nu_\mu \rightarrow \nu_\tau$ 79.3 kt·yrs





Evidence for oscillation is robust

2 flavor $\nu_\mu \rightarrow \nu_{sterile}$ (matter in earth)

Using matter effect and enriched NC sample

$\nu_\mu \rightarrow \nu_\tau$: No matter effect

$\nu_\mu \rightarrow \nu_s$: With matter effect

Neutrino oscillation in matter:

$$\begin{pmatrix} \nu_\mu \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

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

$$\zeta = -\sqrt{2}\, G_F n_n E_\nu / \Delta m^2$$

For $\sin^2 2\theta = \sim 1$ $\quad \sin^2 2\theta_m \sim \dfrac{1}{\zeta^2 + 1}$

And for E_ν = 30~100 GeV ➡ $\zeta \gg 1$ and

$\sin^2 2\theta_m \ll 1$

Suppression !

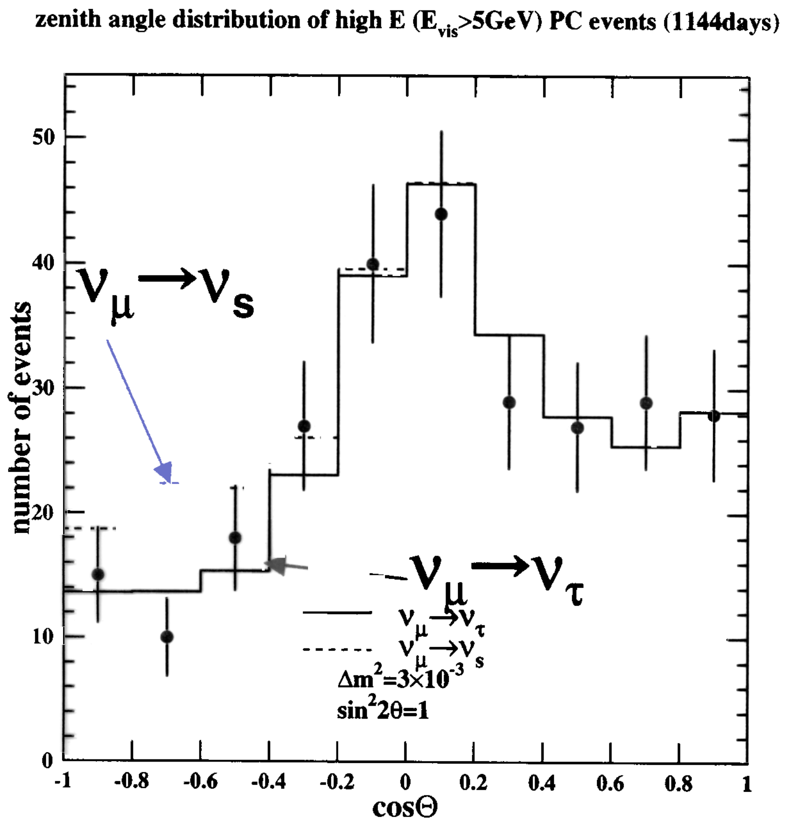
Strategy:

Obtain allowed region using lower energy events (fully contained sample)

Then,

Test zenith angle of NC enriched events, high energy PC and through-going muon events.

Zenith angle of high energy PC events



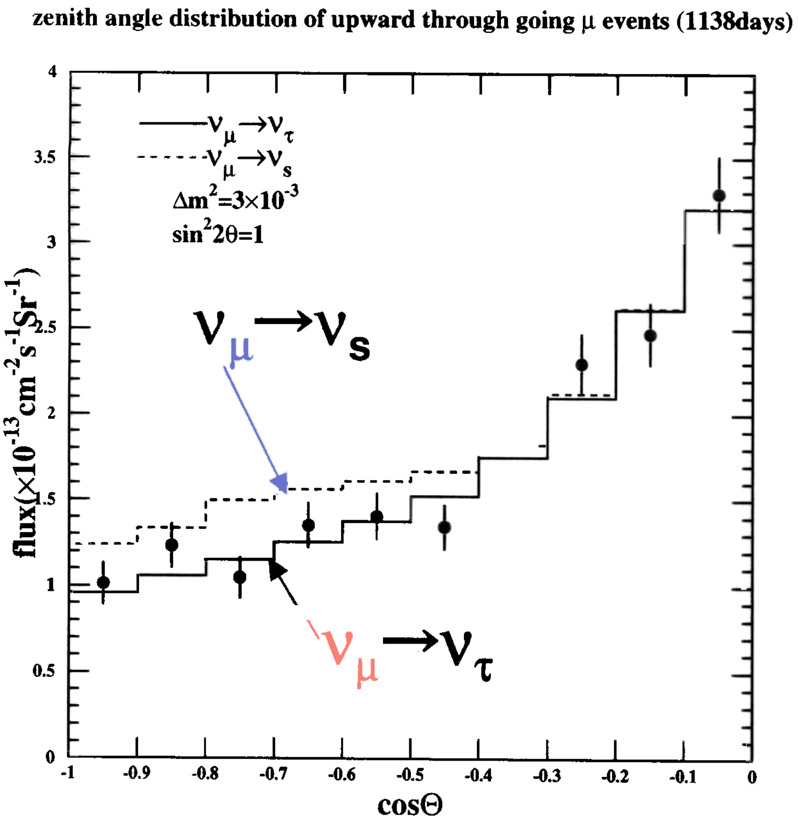
> 45000 p.e.
(E> ~ 5 GeV)

<E>=~25 GeV

$\Delta m^2 = 3 \times 10^{-3} eV^2$

$\sin^2 2\theta = 1$

Zenith angle of upward-going muon



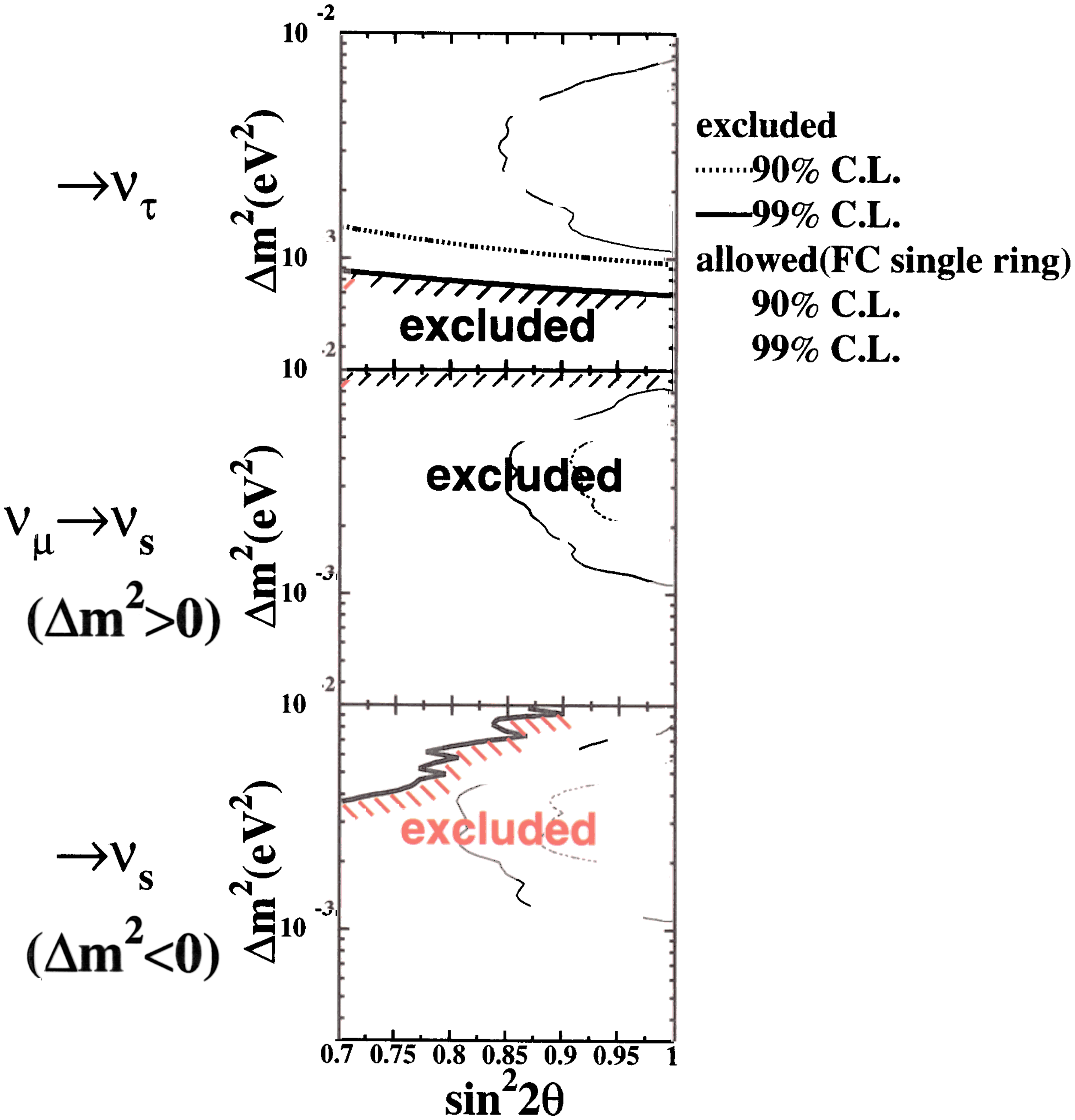
$\Delta m^2 = 3 \times 10^{-3} eV^2$

$\sin^2 2\theta = 1$

Allowed vs. excluded regions

combine NC enriched, high E PC and up muons

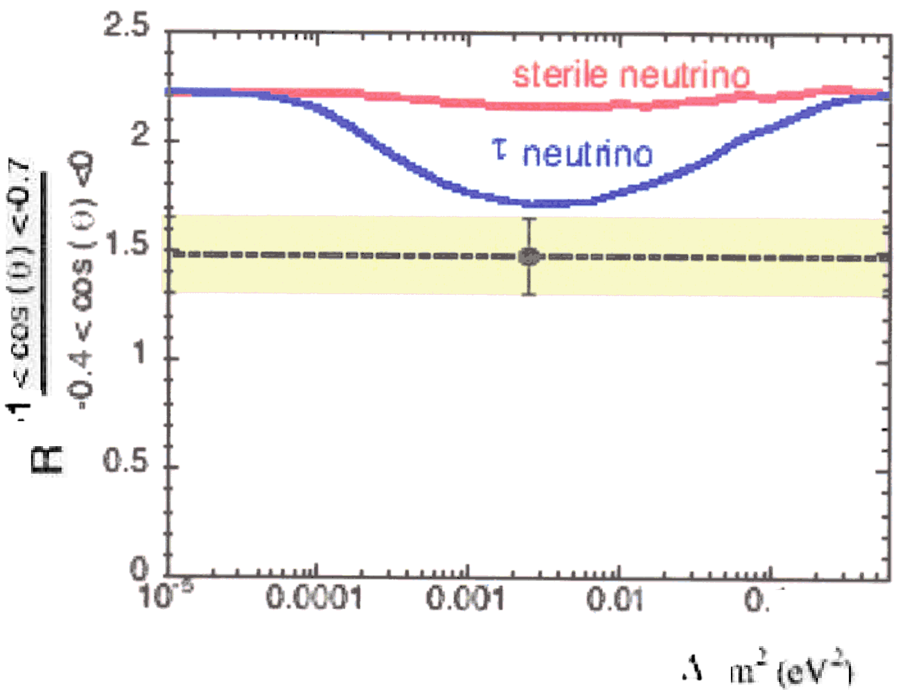
excluded region from combined analysis(multi+PC+upμ)



$\nu_\mu\to\nu_s$ is excluded with 99 % C.L.

Sterile Neutrinos (MACRO)

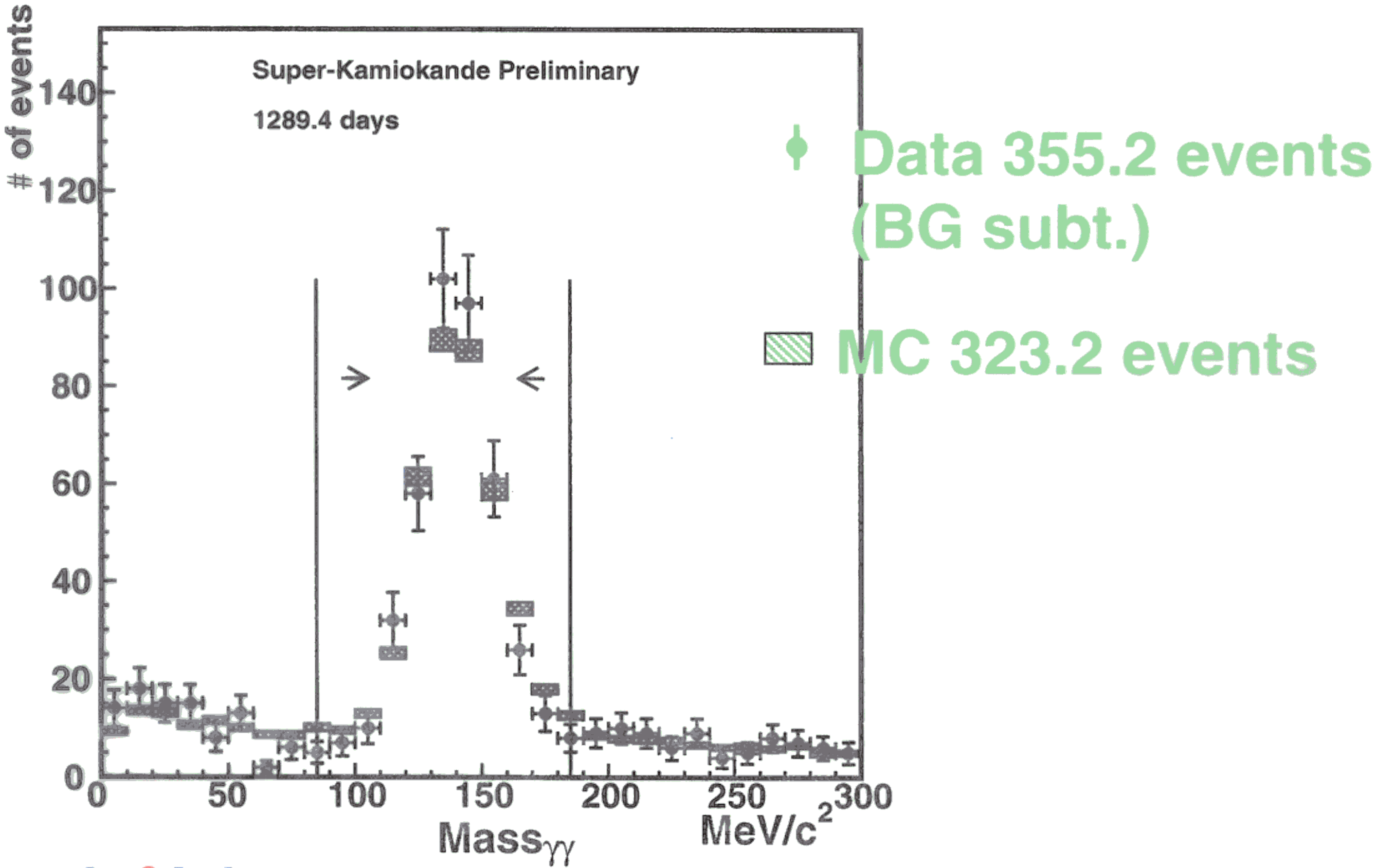
For $\mu\uparrow$



$\nu_\mu \rightarrow \nu_s$ oscillations (for any mixing) are excluded at ~99% CL compared to the $\nu_\mu \rightarrow \nu_\tau$ channel with maximum mixing (ICRC2001 1069)

2 flavor $\nu_\mu \rightarrow \nu_{sterile}$ (π^0 method)

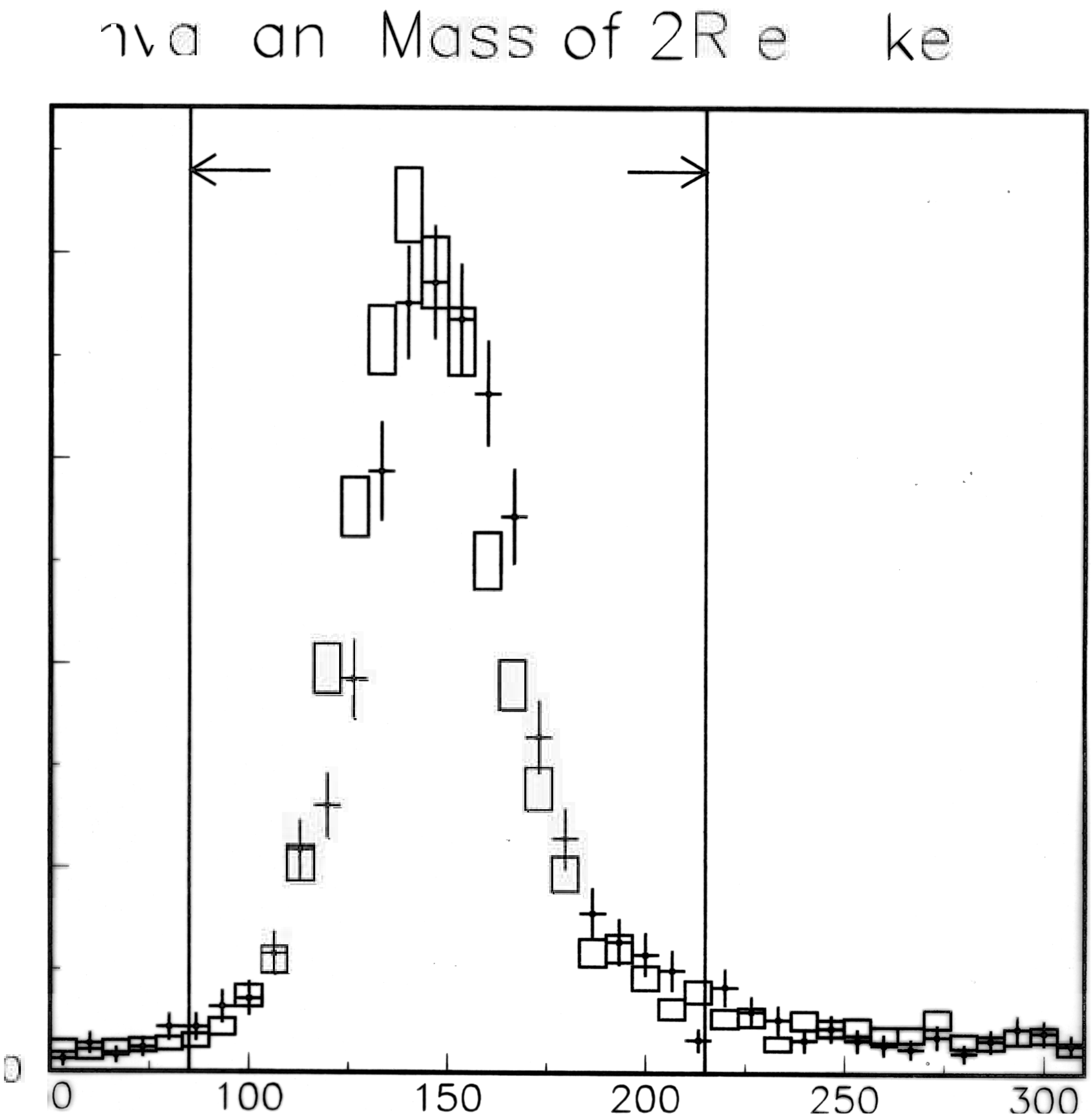
$$\frac{(\pi^0/\mu)_{Data}}{(\pi^0/\mu)_{MC}} \begin{cases} > 1 & \text{for } \nu_\mu \rightarrow \nu_\tau \\ \sim 1 & \text{for } \nu_\mu \rightarrow \nu_s \end{cases}$$



$$\frac{(\pi^0/\mu)_{Data}}{(\pi^0/\mu)_{MC}} = 1.49 \pm 0.08(\text{stat.}) \pm 0.11(\text{sys.})$$

Experimental only

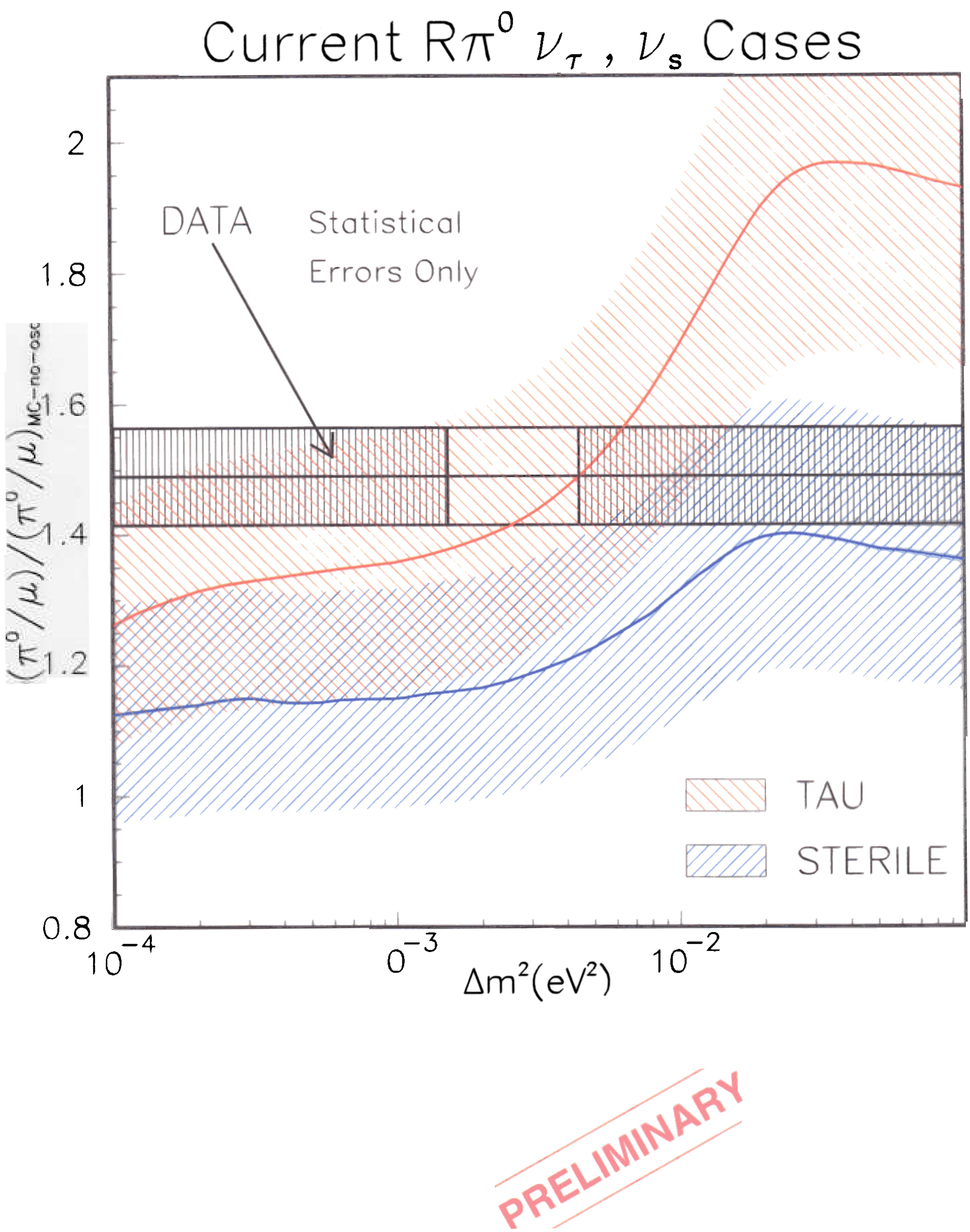
π^0 info from K2K 1kt



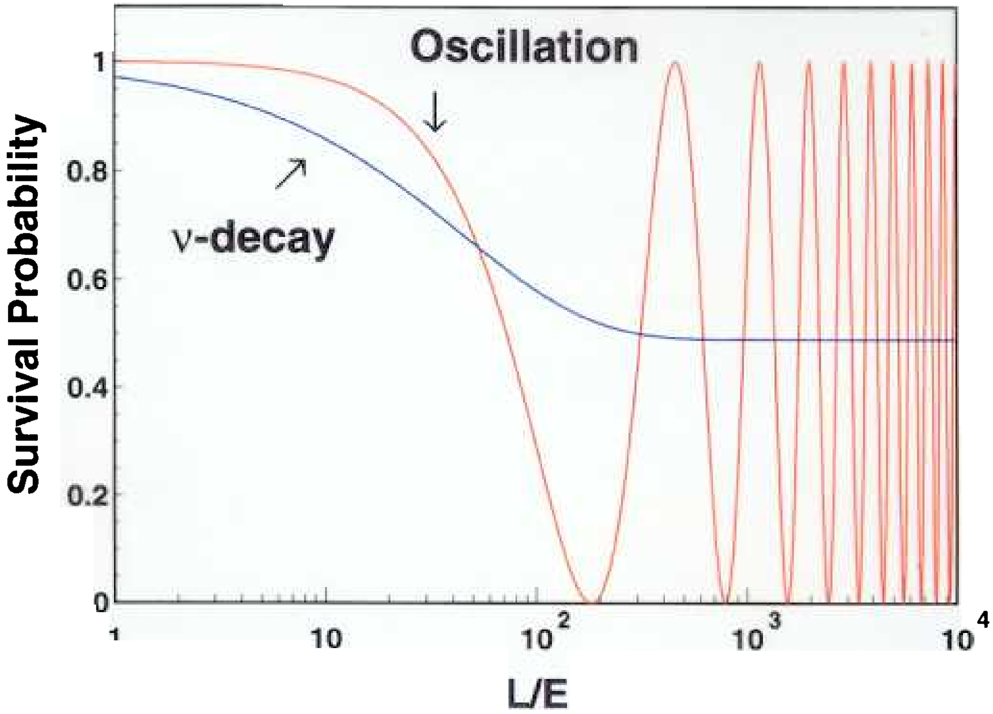
$$\frac{\left(\frac{\pi^0}{\text{FC-}\mu}\right)_{\text{data}}}{\left(\frac{\pi^0}{\text{FC-}\mu}\right)_{\text{MC}}} \quad 0.99 \pm 0.03 \pm 0.1$$

PRELIMINARY

$(\pi^0/\mu)_{data}$ vs $(\pi^0/\mu)_{MC\text{-}no\text{-}osc}$



Neutrino decay



V.Barger etal., PLB462(1999)109 assumed that neutrinos oscillate and decay via $\nu_2 \rightarrow \bar{\nu}_4 X$ with small θ_{14} which is already ruled out from solar neutrinos. However the following equation is general even for ν_3 decay.

$$P(\nu_\mu \rightarrow \nu_\mu) = \cos^4\theta + \sin^4\theta \exp\left(-\frac{m_3}{\tau_3}\frac{L}{E}\right)$$

$$+ 0.5\sin^2 2\theta \exp\left(-\frac{m_3}{2\tau_3}\frac{L}{E}\right)\cos\left(\frac{\Delta m^2 L}{2E}\right)$$

$\lambda_{dcy} >> \lambda_{osc}$ was already ruled out.

Consider $\lambda_{dcy} << \lambda_{osc}$

Where $\lambda_{dcy} = \dfrac{\tau_3 E}{m_3}$, $\lambda_{osc} = \dfrac{4\pi E}{\Delta m^2}$

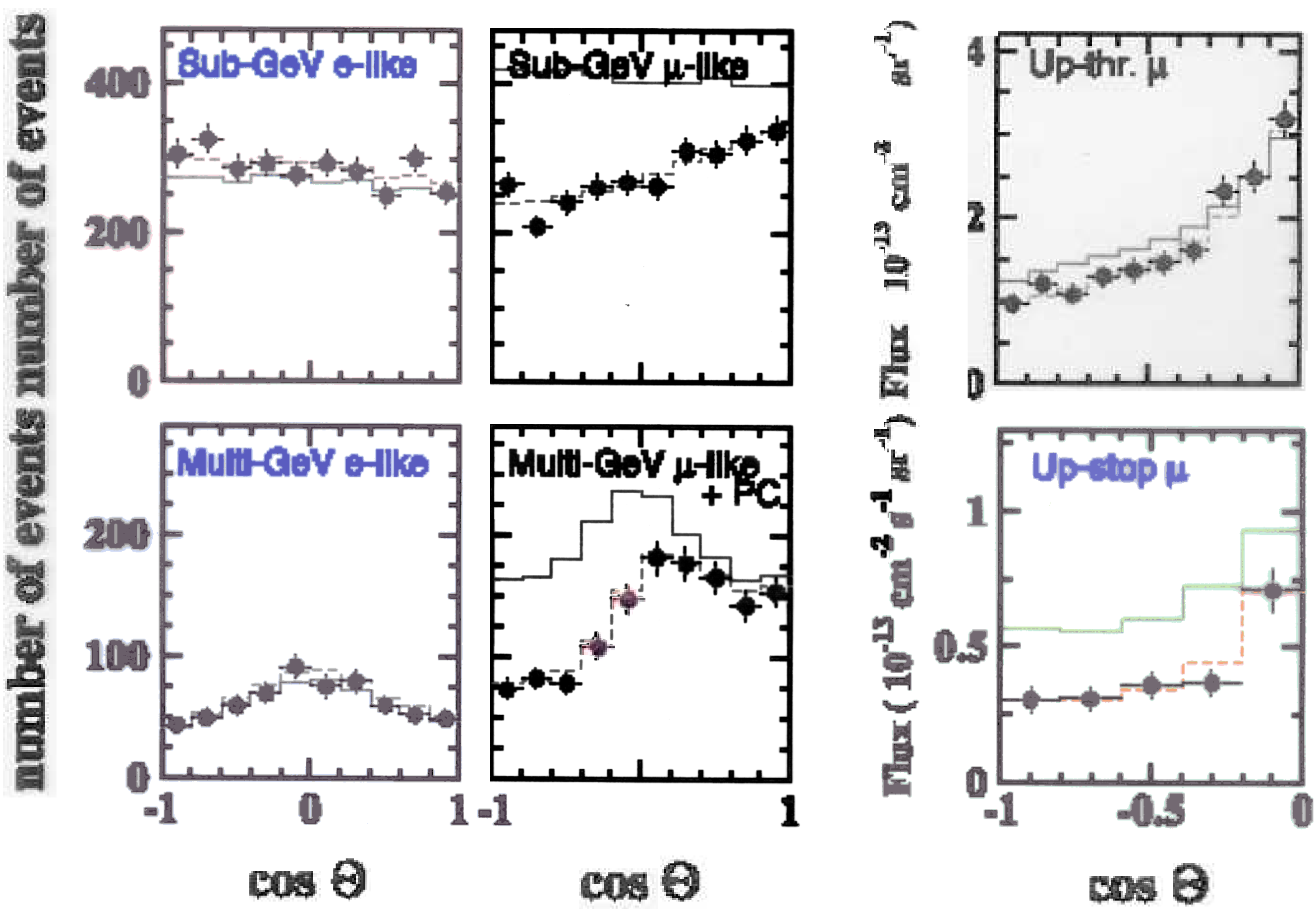
λ dcy $\ll$ λ osc

For $\Delta m^2 \to 0$,

χ^2 = 47.1/153 dof

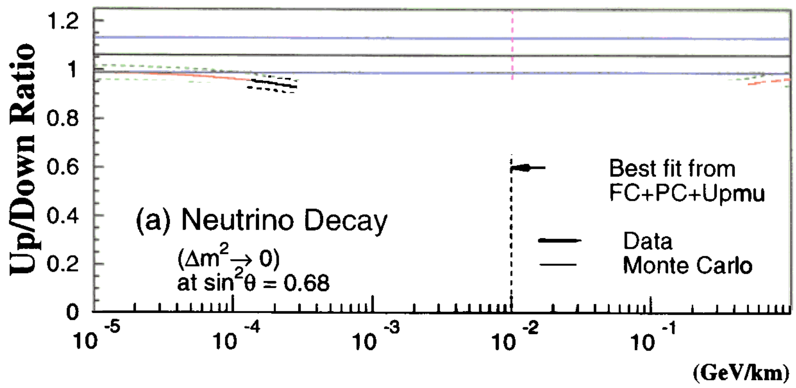
at $(\sin^2\theta, m_3/\tau_3)$ = (0.68, 0.01 (GeV/km))

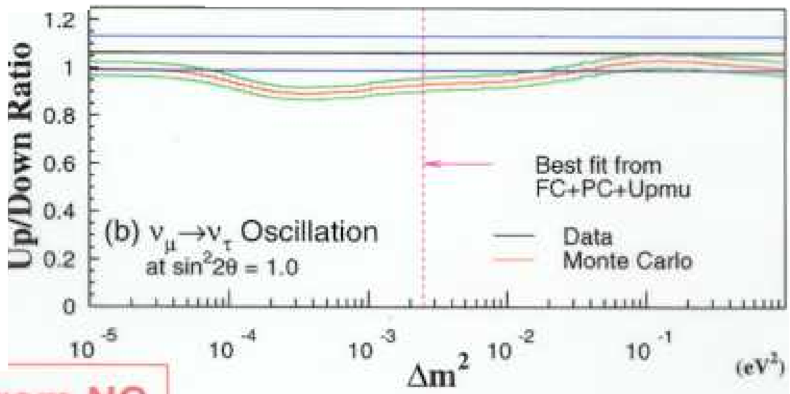
Good fit



Up/down of NC enriched events (short λ_{dcy})

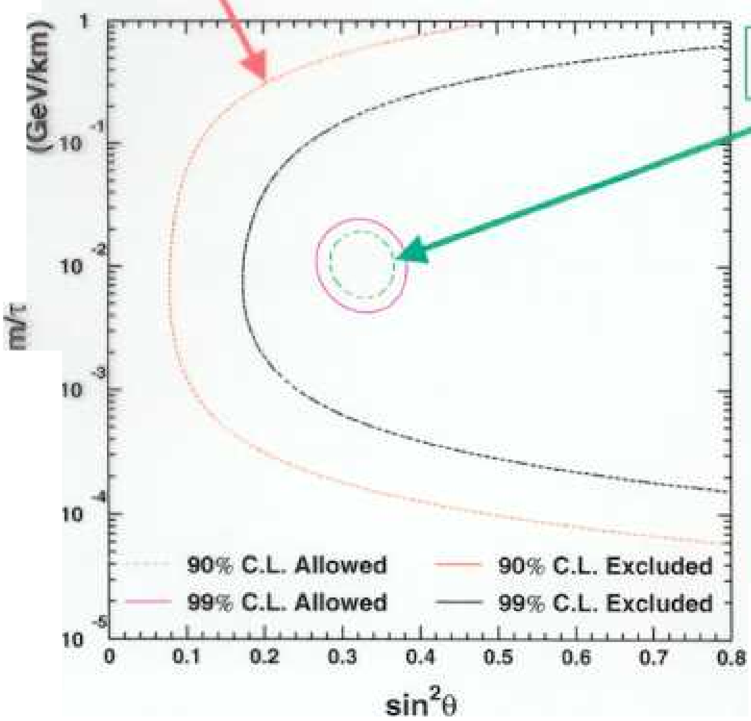
FC, Nring>1, Evis>400MeV, Brightest ring = e-like





Excluded from NC

Allowed from FC+PC+Upmu



The case of

$\lambda_{dcy} \ll \lambda_{osc}$

is ruled out

Conclusion

- (Almost) final results from MACRO and Soudan 2 have confirmed the atmospheric neutrino anomaly

  Neutrino oscillation $\nu_\mu \rightarrow \nu_\tau$ explains all the observations

  2 component oscillation $\nu_\mu \rightarrow \nu_s$ is disfavored at > 99% CL

  Neutrino decay is disfavored at > 99%CL for $\lambda_{dcay} \gg \lambda_{osc}$ or $\lambda_{dcay} \ll \lambda_{osc}$

  3-D flux calculation does not change evidence for neutrino oscillation

  Accelerator experiments (and Monolith) will soon confirm the oscillation $\nu_\mu \rightarrow \nu_\tau$ of atmospheric neutrinos and measure the underlying parameters precisely

- More study is needed for a possible electron excess