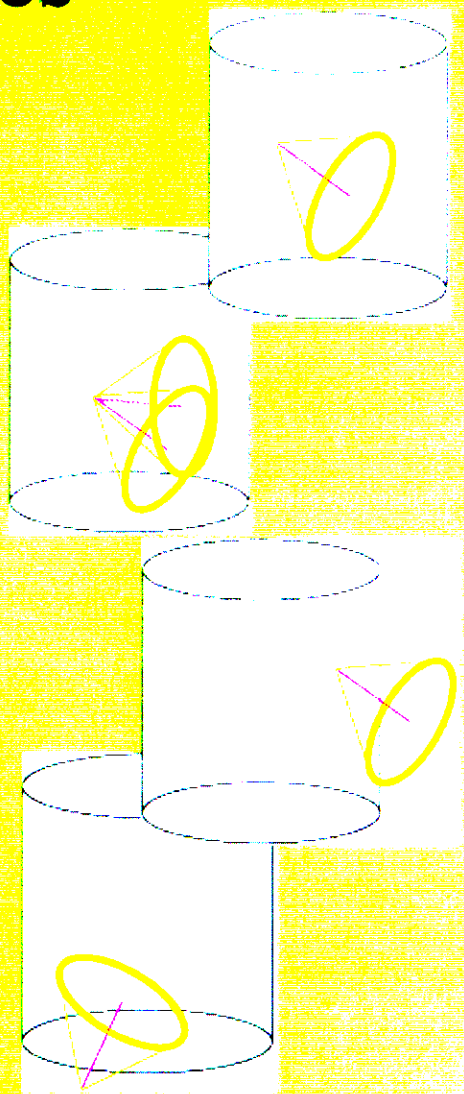
Atmospheric Neutrinos

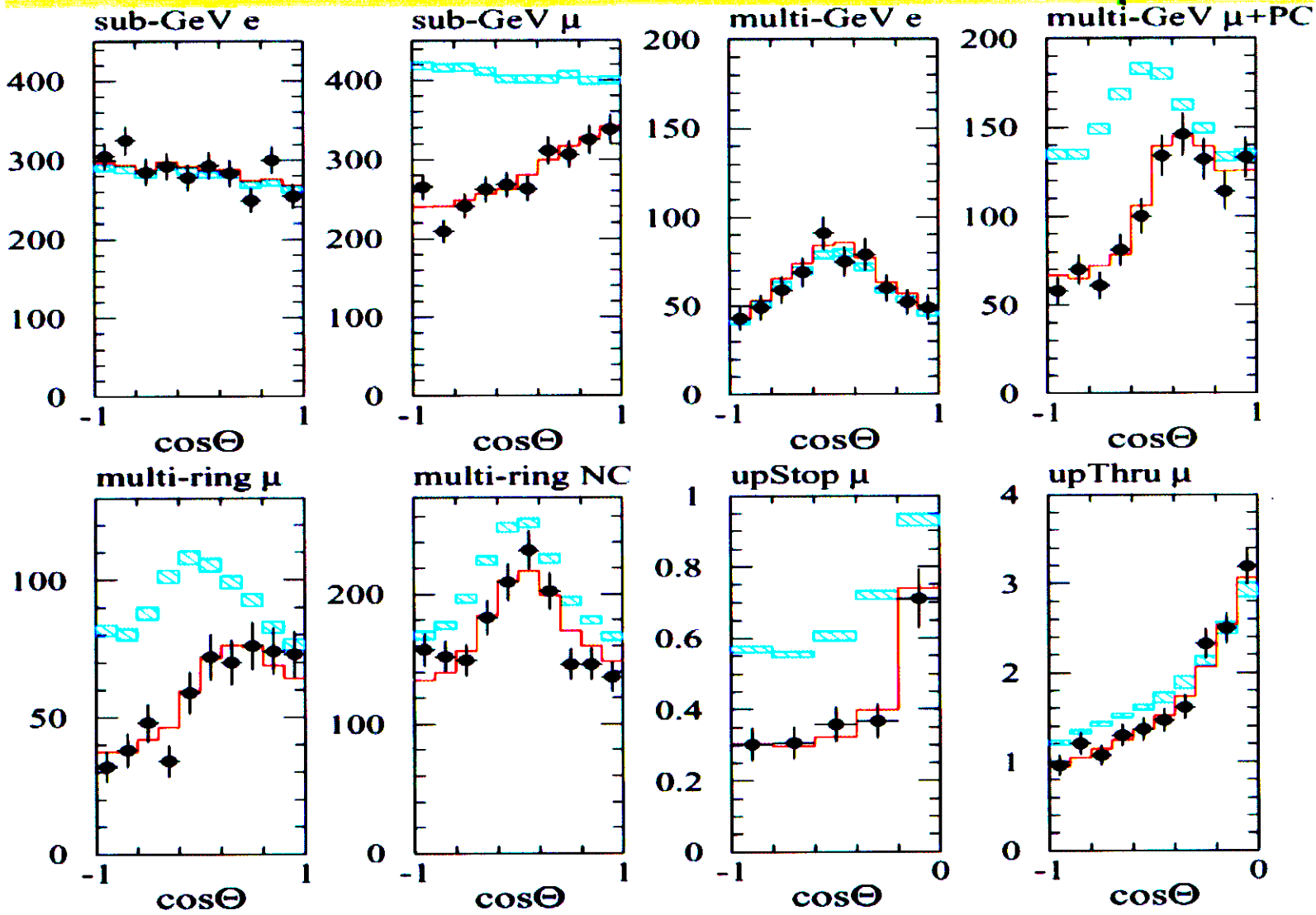
SUPERKAMIOKANDE

Data Samples

- Fully contained (FC) events have determined energy and PID: no OD activity allowed
- Multi-ring (fully contained) events: μ-like or neutral-current (e.g. π^0s) enhanced (NC)
- Partially contained (PC) events are assumed μs, no precise energy: only exiting particles allowed
- Upward-going muons (from rock): stopping (lower energy) or through-going (higher energy)



Data and Oscillation Best Fit ($\nu_\mu - \nu_\tau$)

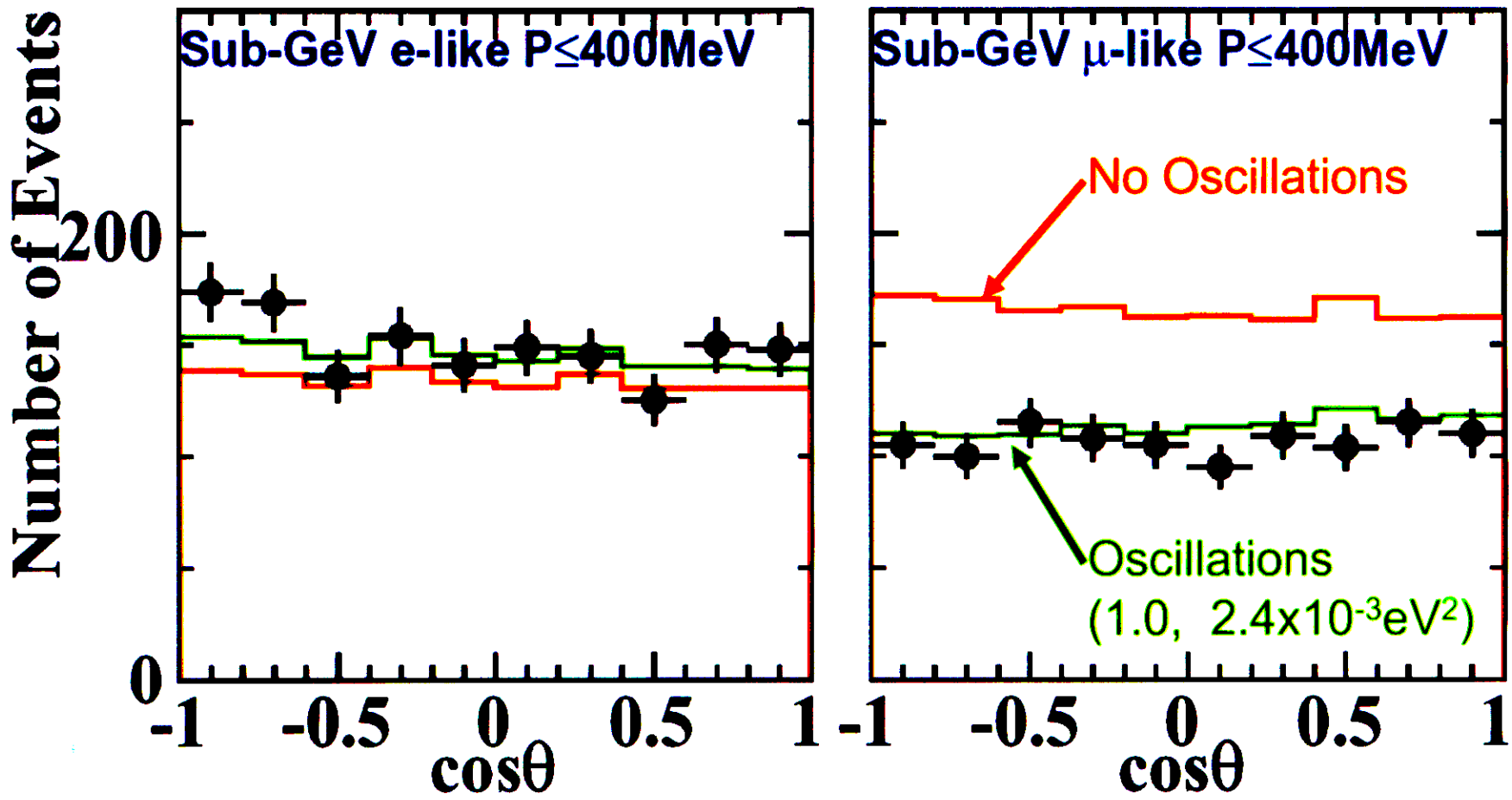


$E_{vis} < 1.4$ GeV - Single Ring

1289 days

Low Energy Sample

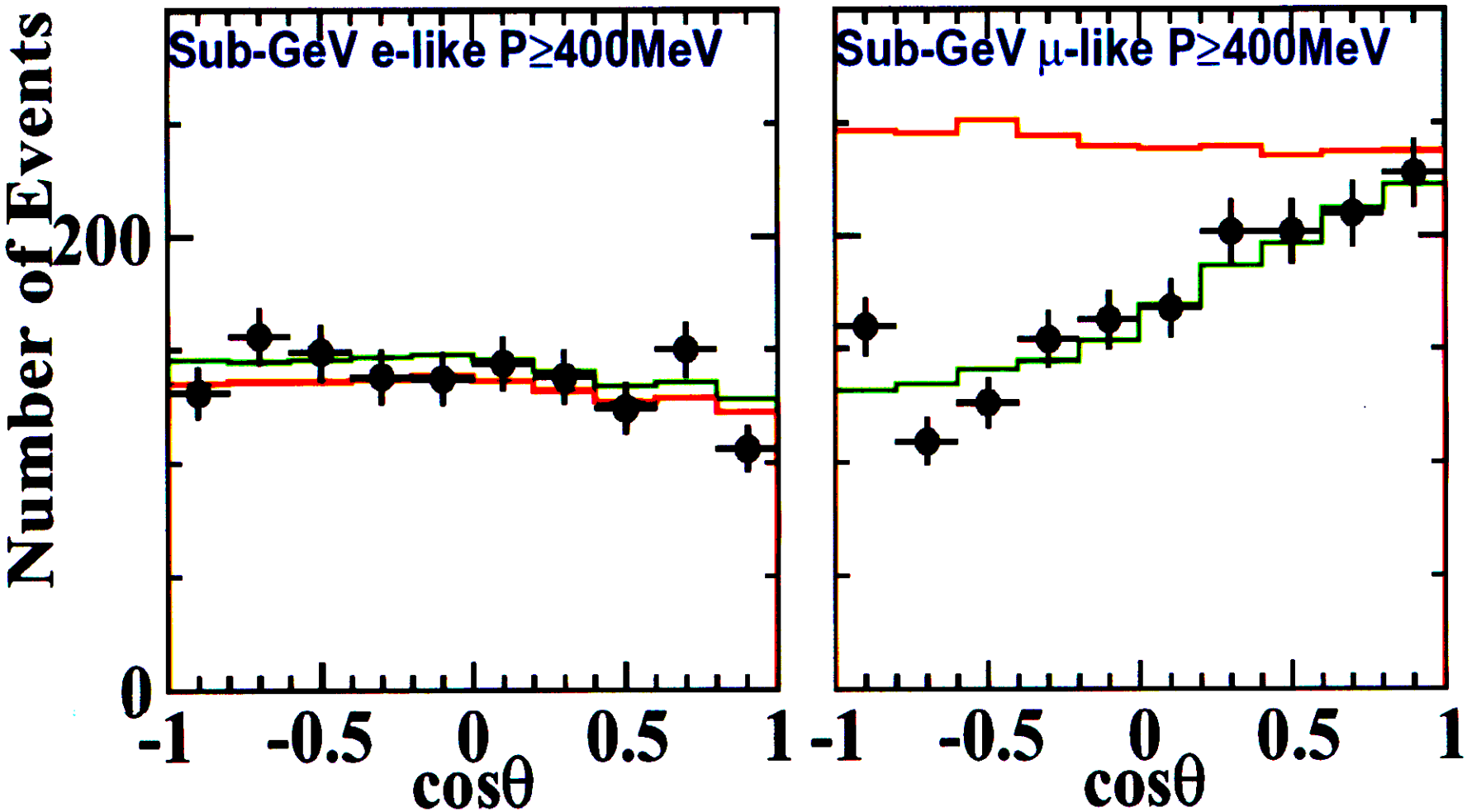
22.5 Kton fiducial



Global χ^{2min} = 132.4 / 137 d.o.f for ν_μ to ν_τ

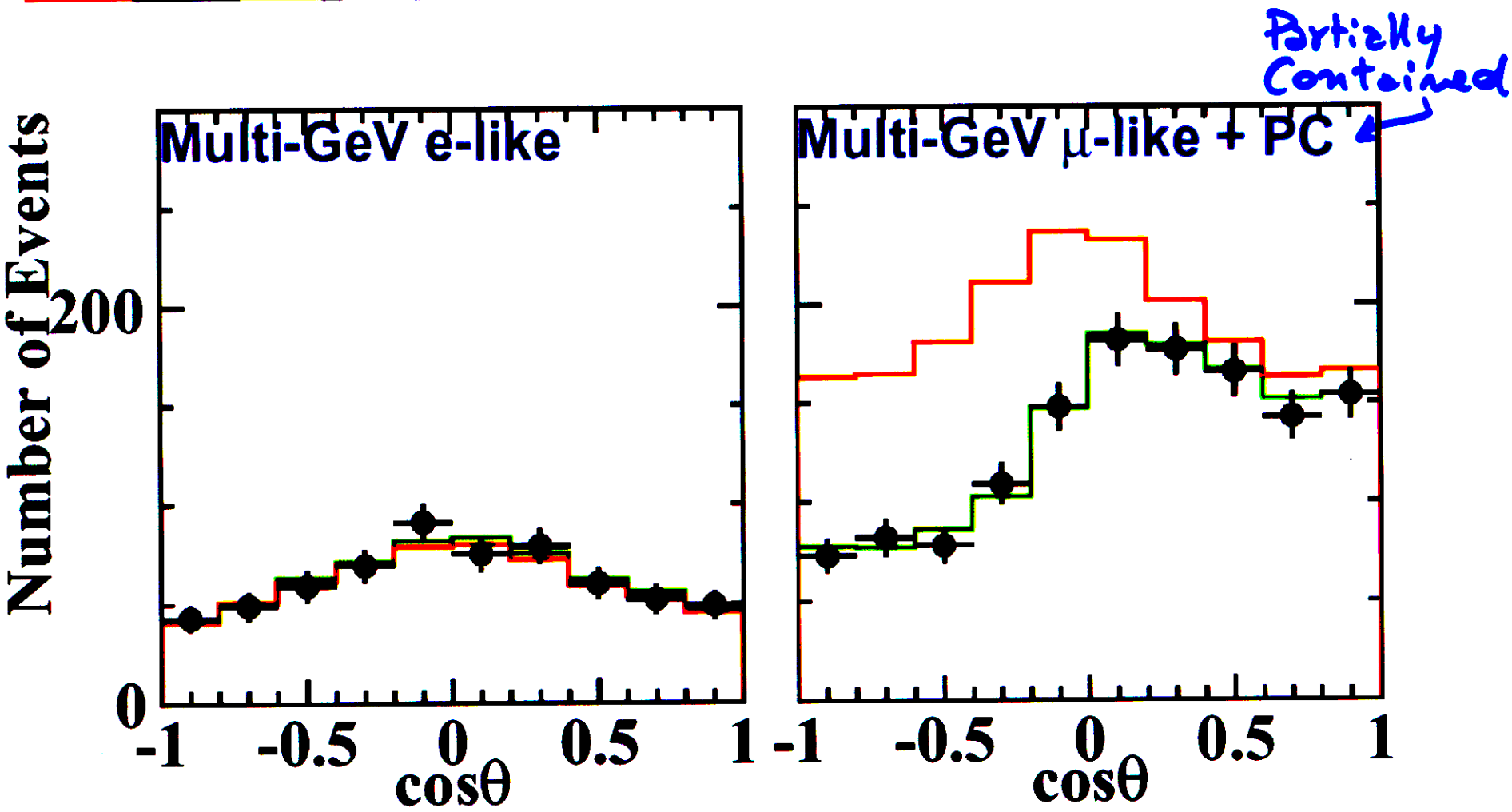
at $(\sin^2 2\theta, \Delta m^2) = (1.00, 2.4\times10^{-3}\ eV^2)$

Moderate Energy Sample

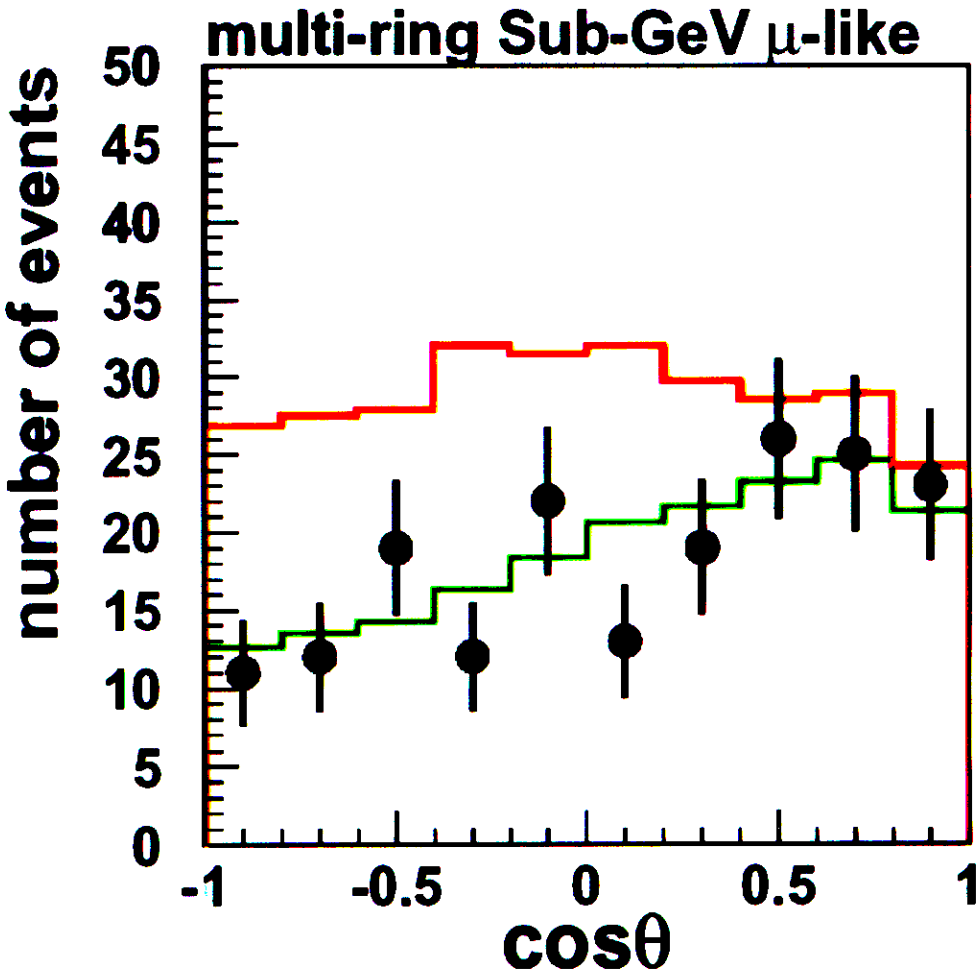


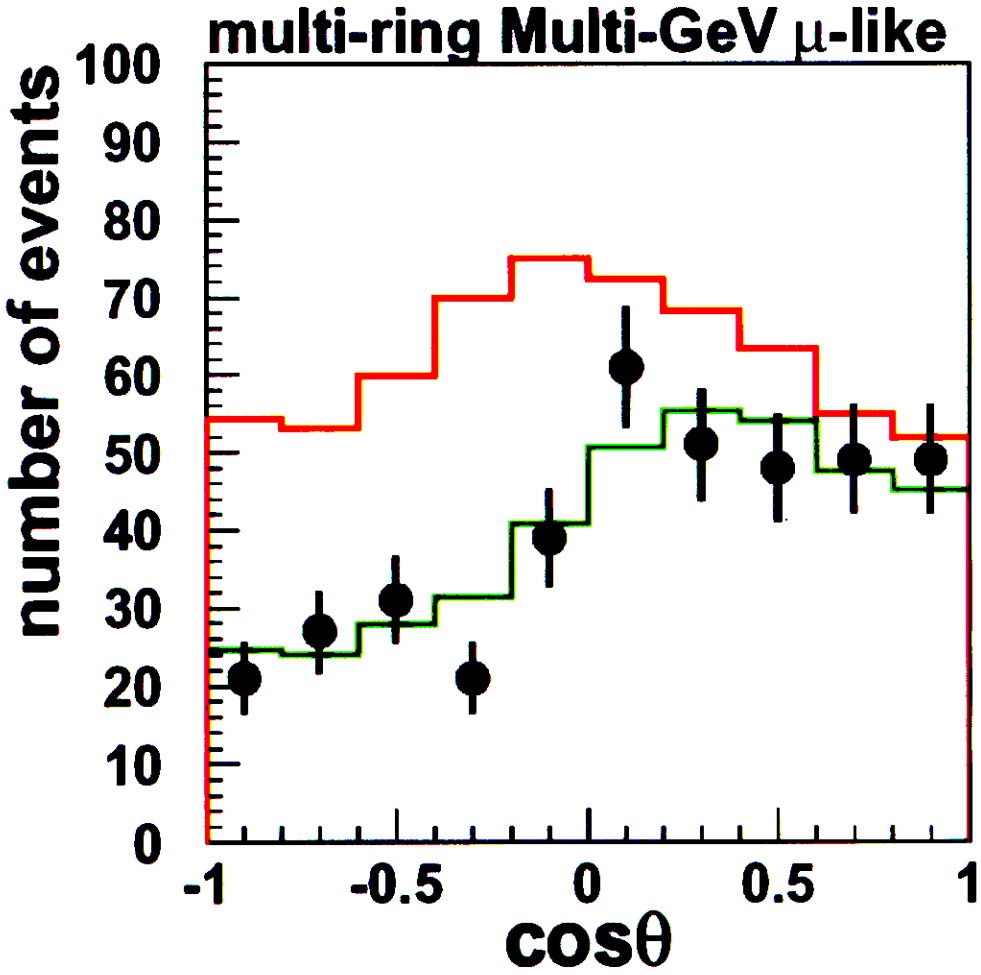
$E_{vis} > 1.4$ GeV - Single Ring

Multi-GeV Sample

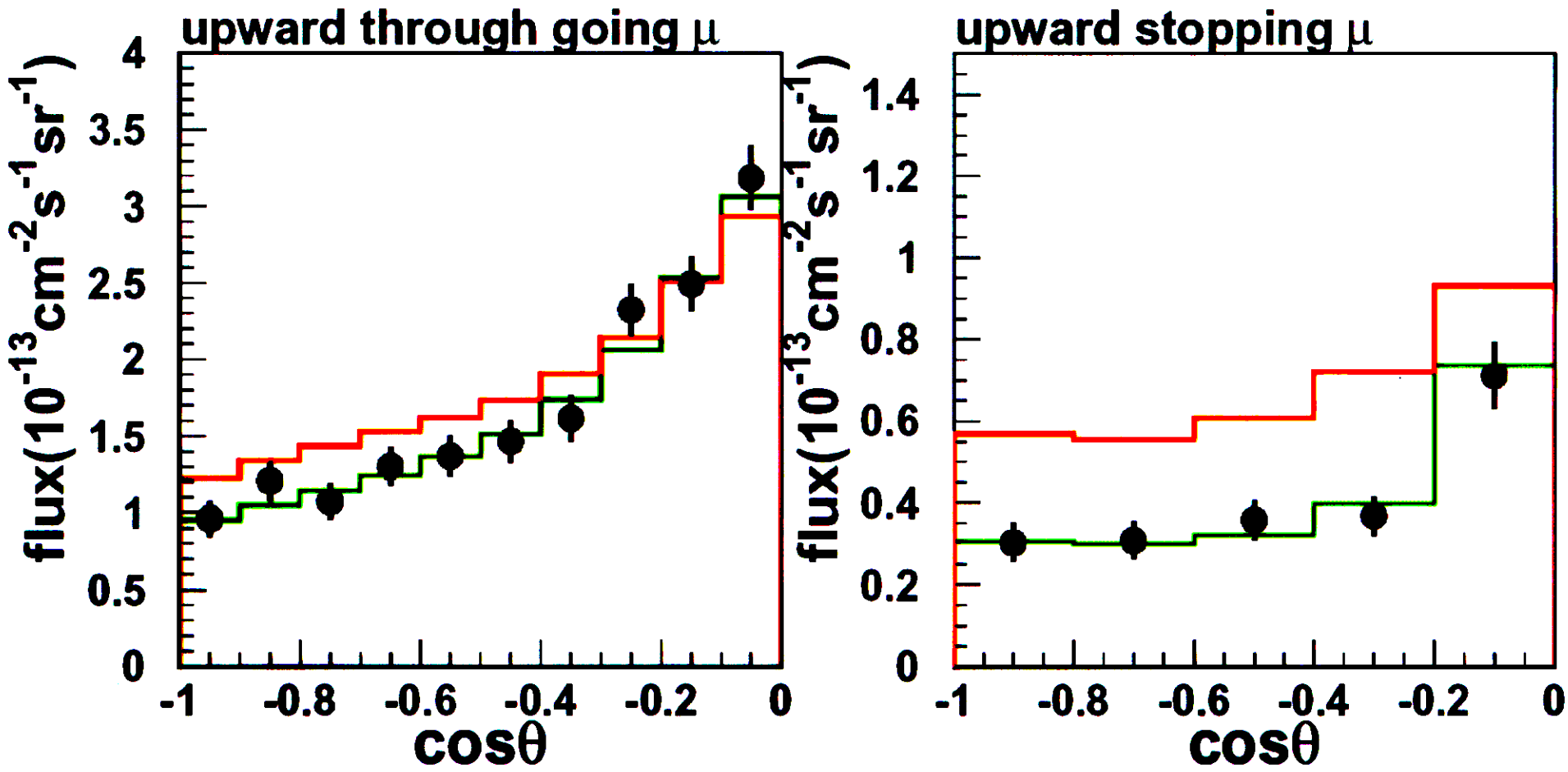


Multi-Ring Events

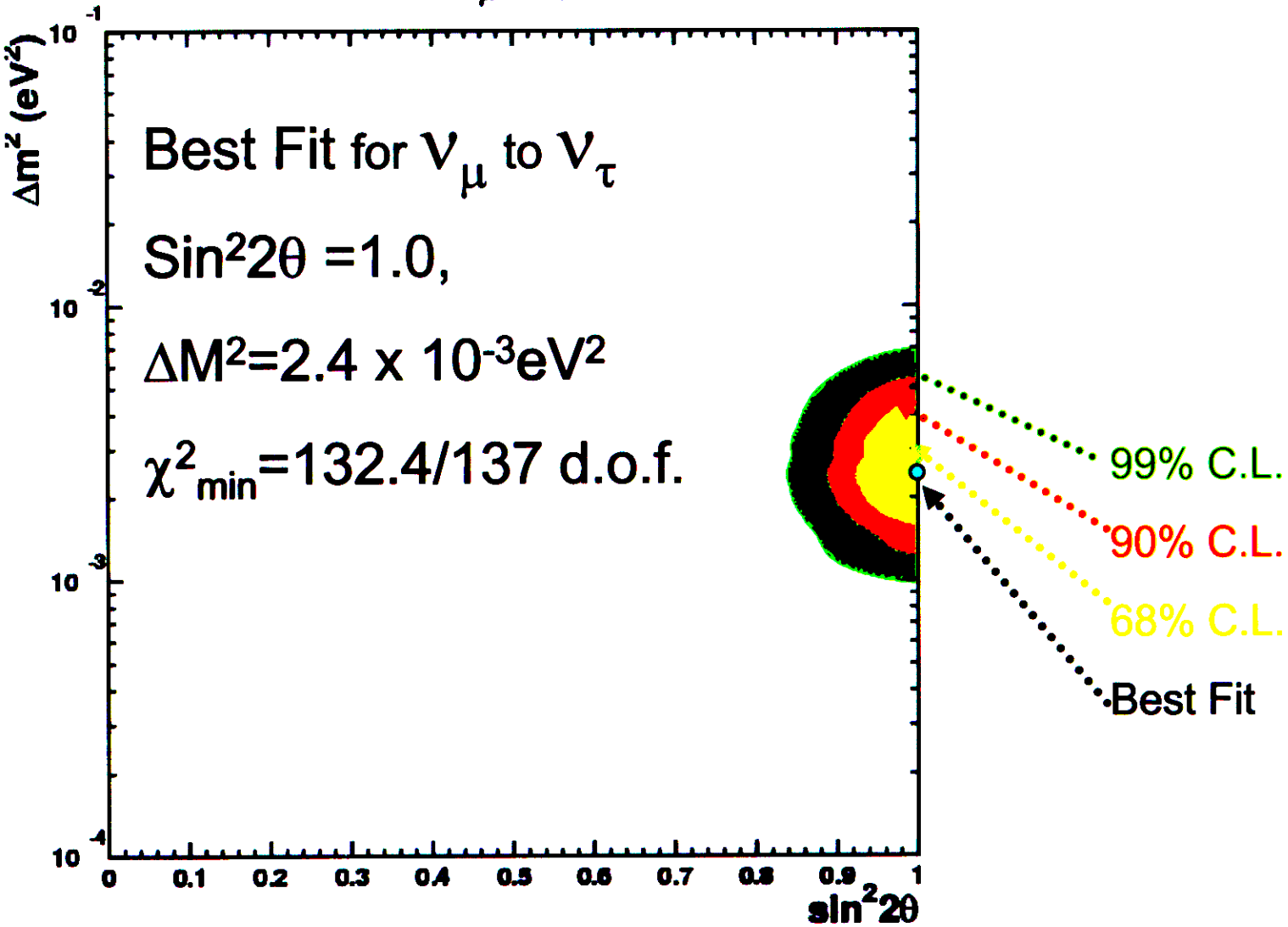




Upward Going Muons

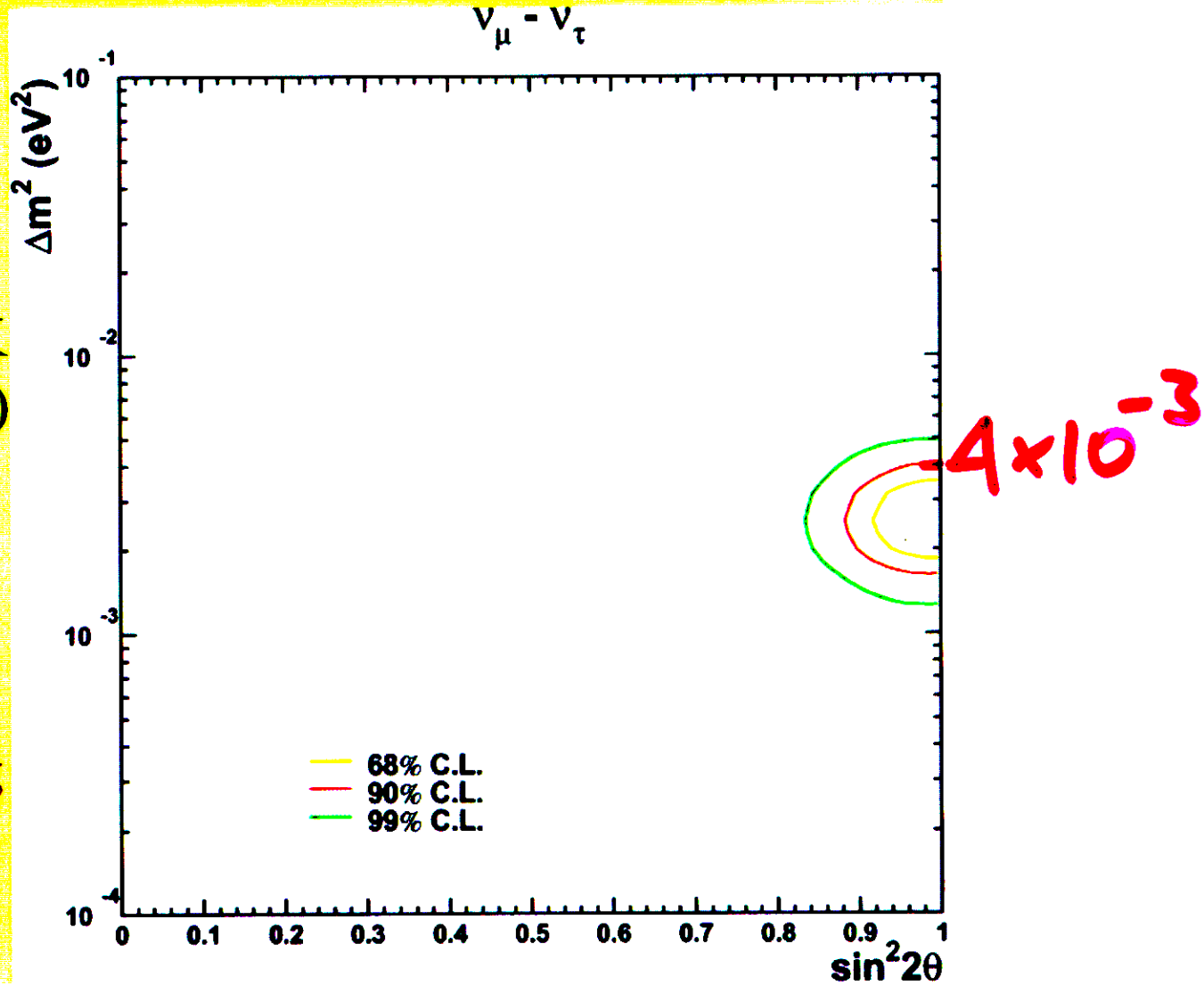


SK : Summary of Atmospheric Results



Atmospheric Allowed Region

- Disappearance of μ-type, no appearance of e-type: $\nu_\mu - \nu_\tau$
- Uses all Super-K data sets (1290d) FC, PC, up μ and multi-ring
- Very good χ^2 (175.0/190)
- Maximal mixing



Michael Smy, UC Irvine

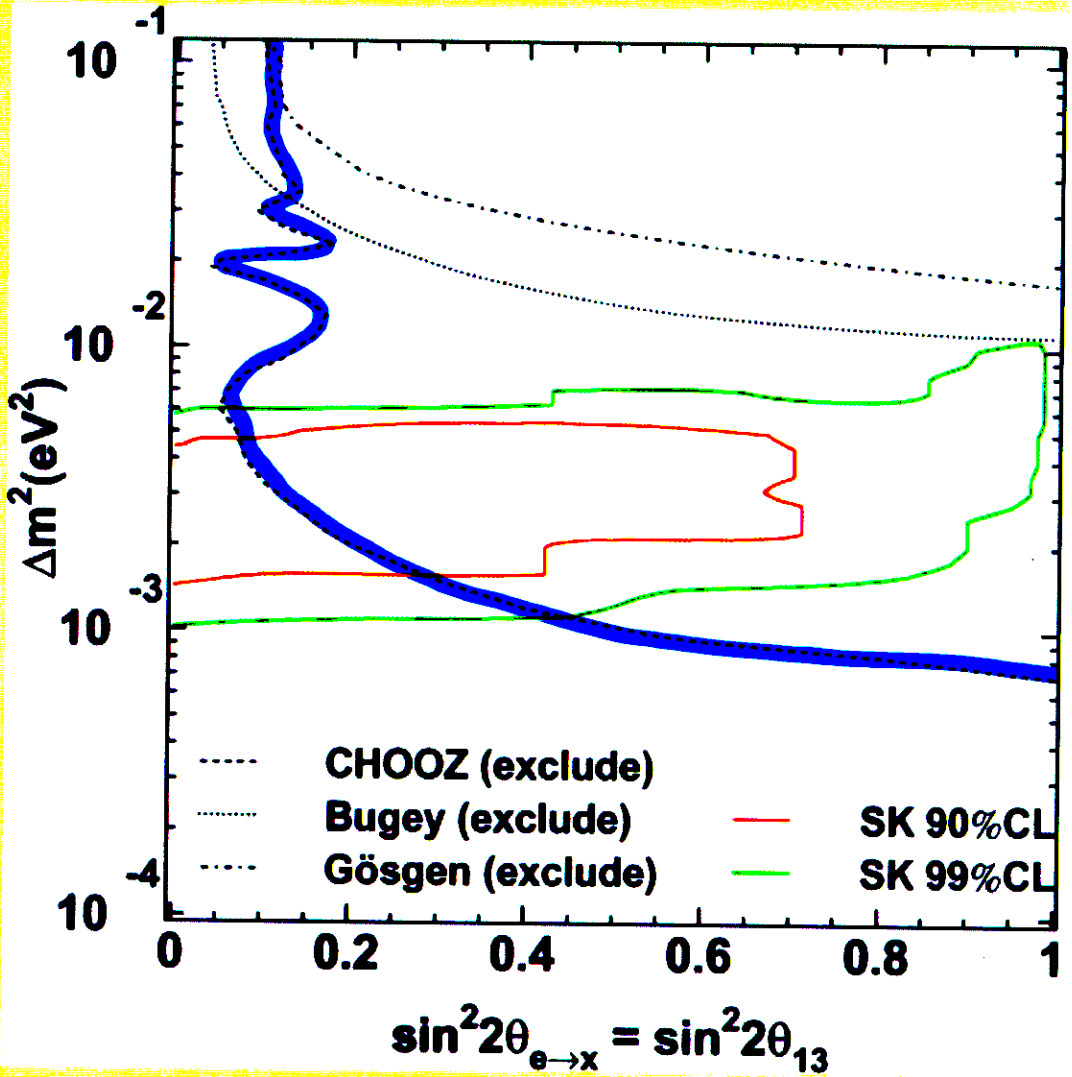
Nature of atmospheric Oscillation

	Mode	Best fit	$\Delta\chi 2$	σ
1)	ν_μ-ν_τ	$\sin^2 2\theta=1.00$; $\Delta m^2=2.5\times10^{-3}eV^2$	0.0	0.0
	ν_μ-ν_e	$\sin^2 2\theta=0.97$; $\Delta m^2=5.0\times10^{-3}eV^2$	79.3	8.9
	ν_μ-ν_s	$\sin^2 2\theta=0.96$; $\Delta m^2=3.6\times10^{-3}eV^2$	19.0	4.4
	LxE	$\sin^2 2\theta=0.90$; $\alpha=5.3\times10^{-4}$	67.1	8.2
	ν_μ Decay	$\cos^2\theta=0.47$; $\alpha=3.0\times10^{-3}eV^2$	81.1	9.0
2)	ν_μ Decay to ν_s	$\cos^2\theta=0.33$; $\alpha=1.1\times10^{-2}eV^2$	14.1	3.8

REACTOR } + CP cons

Limits on θ_{13}

- CHOOZ limit by far the best
- SK allowed area contributes in low Δm^2 region
- Favor for ν_μ–ν_τ, disfavor ν_μ–ν_e
- No hint for electron appearance



Michael Smy, UC Irvine

Reactor $\bar{\nu}_e$

Atm $\nu_e + \bar{\nu}_e/3$

CHOOZ LIMIT

$$\mathrm{sen}^2 2\theta_{13} < 0.1$$

$$4\theta_{13}^2 \lesssim 0.1$$

$$\theta_{13} \lesssim \sqrt{\frac{0.1}{4}} = 0.16 \text{ rad}$$

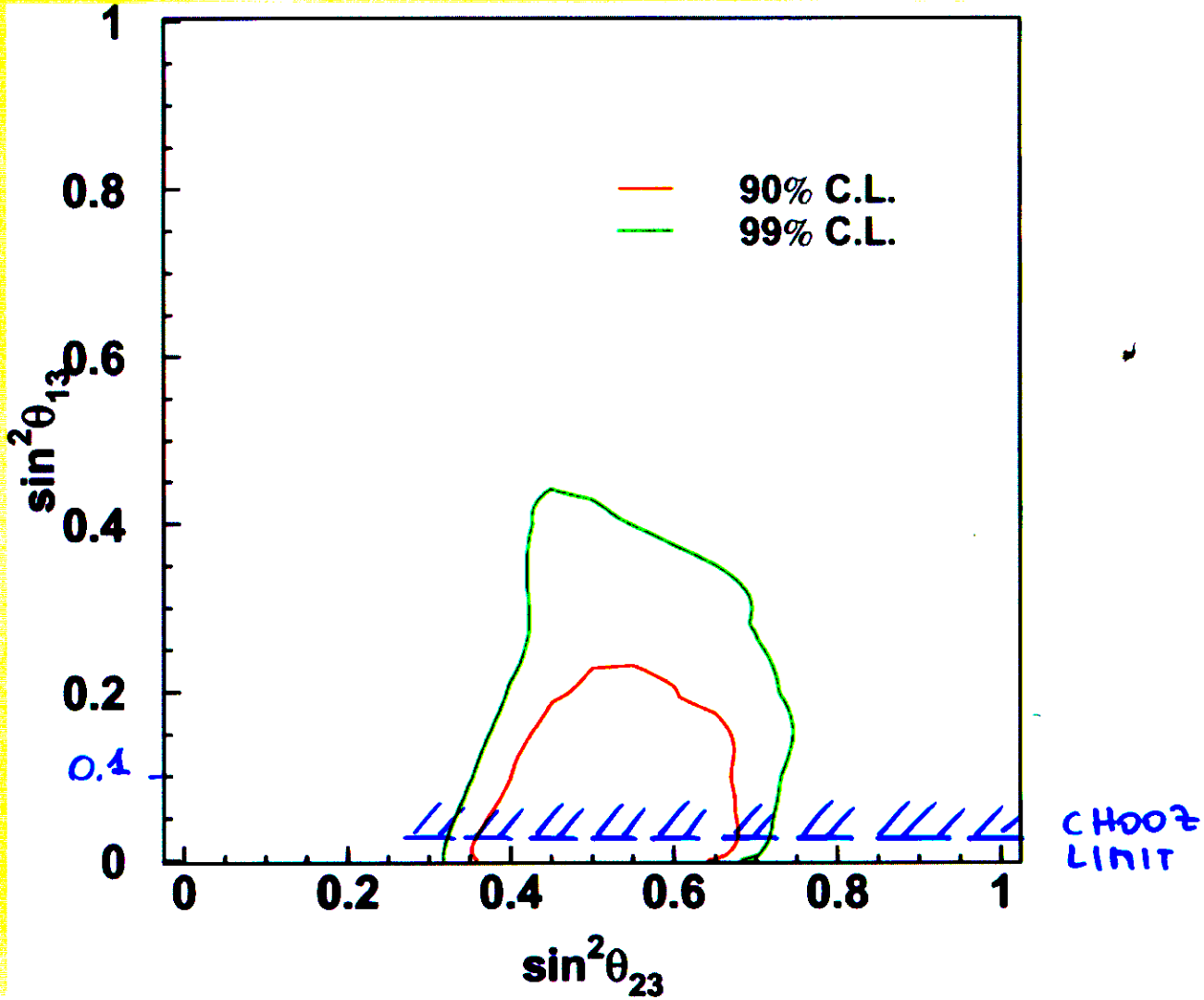
$$(9^\circ)$$

$$\sin\theta_{13} \leq 0.16 \text{ rad}$$

$$\sin^2\theta_{13} \leq 0.02$$

θ_{13} Versus θ_{23}

- Maximal mixing in the dominant mode (ν_μ–ν_τ)
- Zero mixing in the subdominant mode (ν_μ–ν_e)
- About 30 to 40% e-type fraction (90% C.L.) allowed



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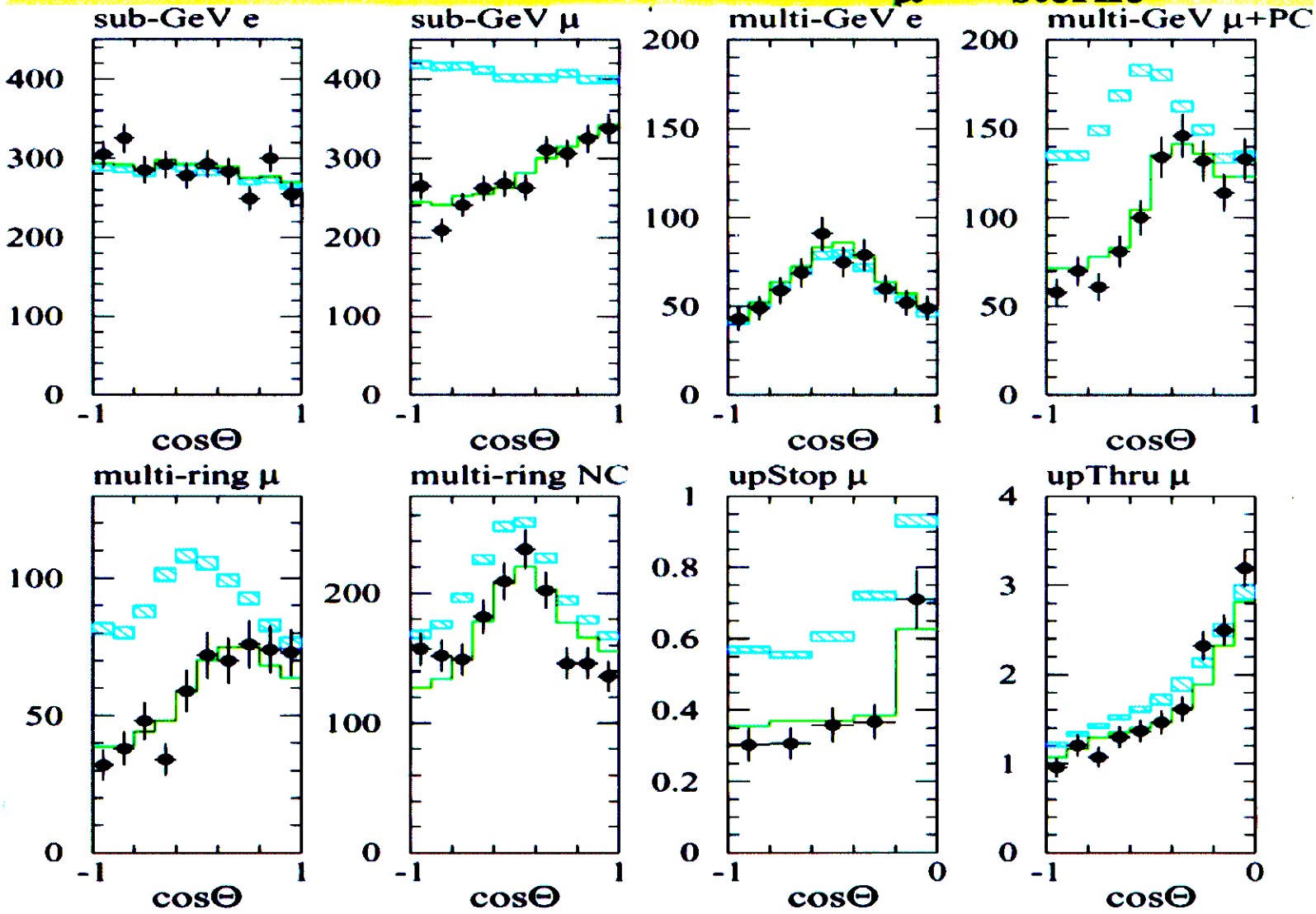
N.B $\sin^2\theta$ not $\sin^2 2\theta$ or θ^2 vs $4\theta^2$

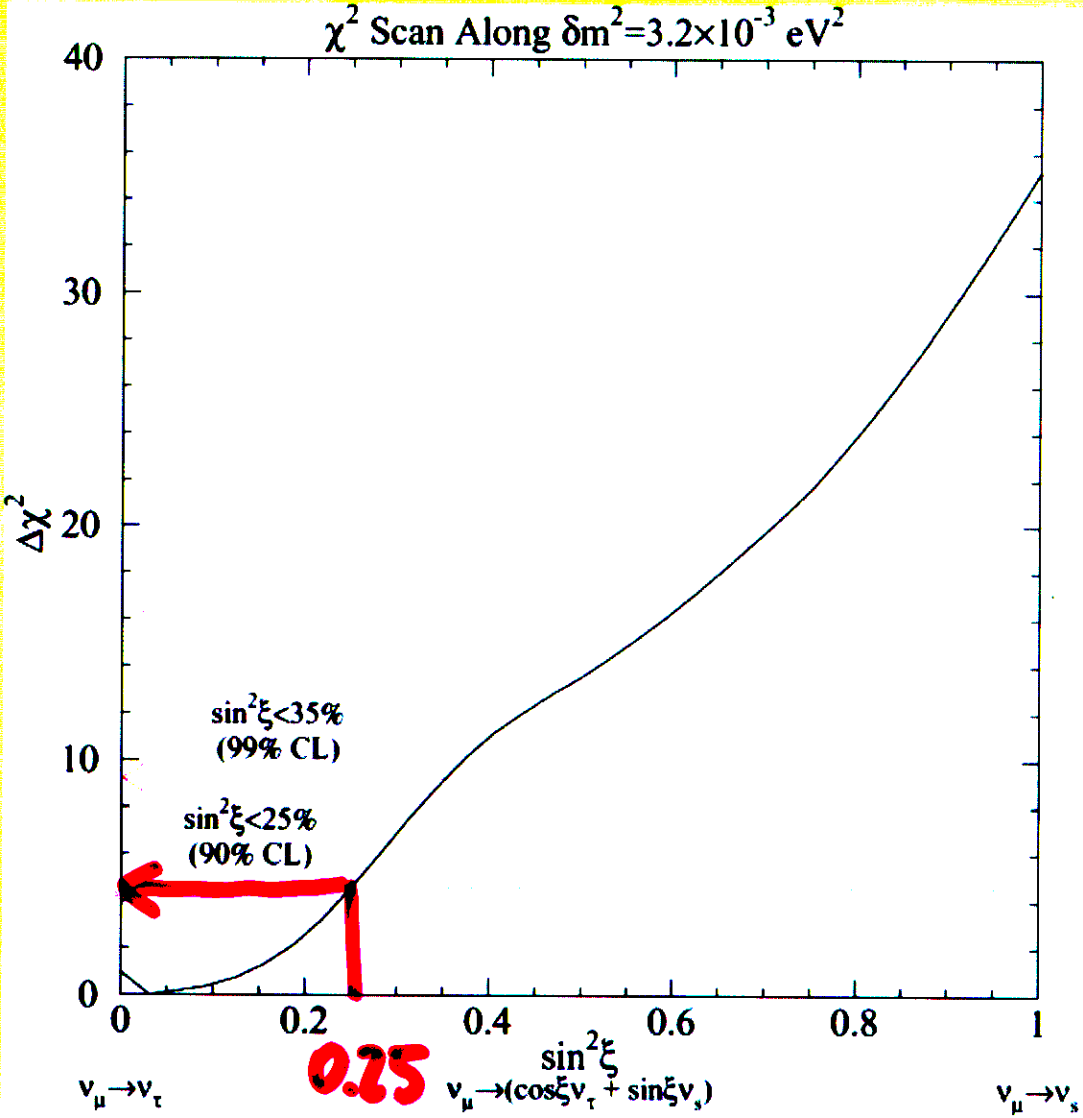
Oscillation Best Fit ($\nu_\mu - \nu_{sterile}$)



$\sin^2\xi$

Limit on Sterile Content

- Consistent with pure ν_μ–ν_τ
- Sterile Content Limit of 25% (90% C.L.) is based on 2 d.o.f.
- Pure ν_μ–$\nu_{sterile}$ don't fit well the NC multi-ring and the up-μ samples



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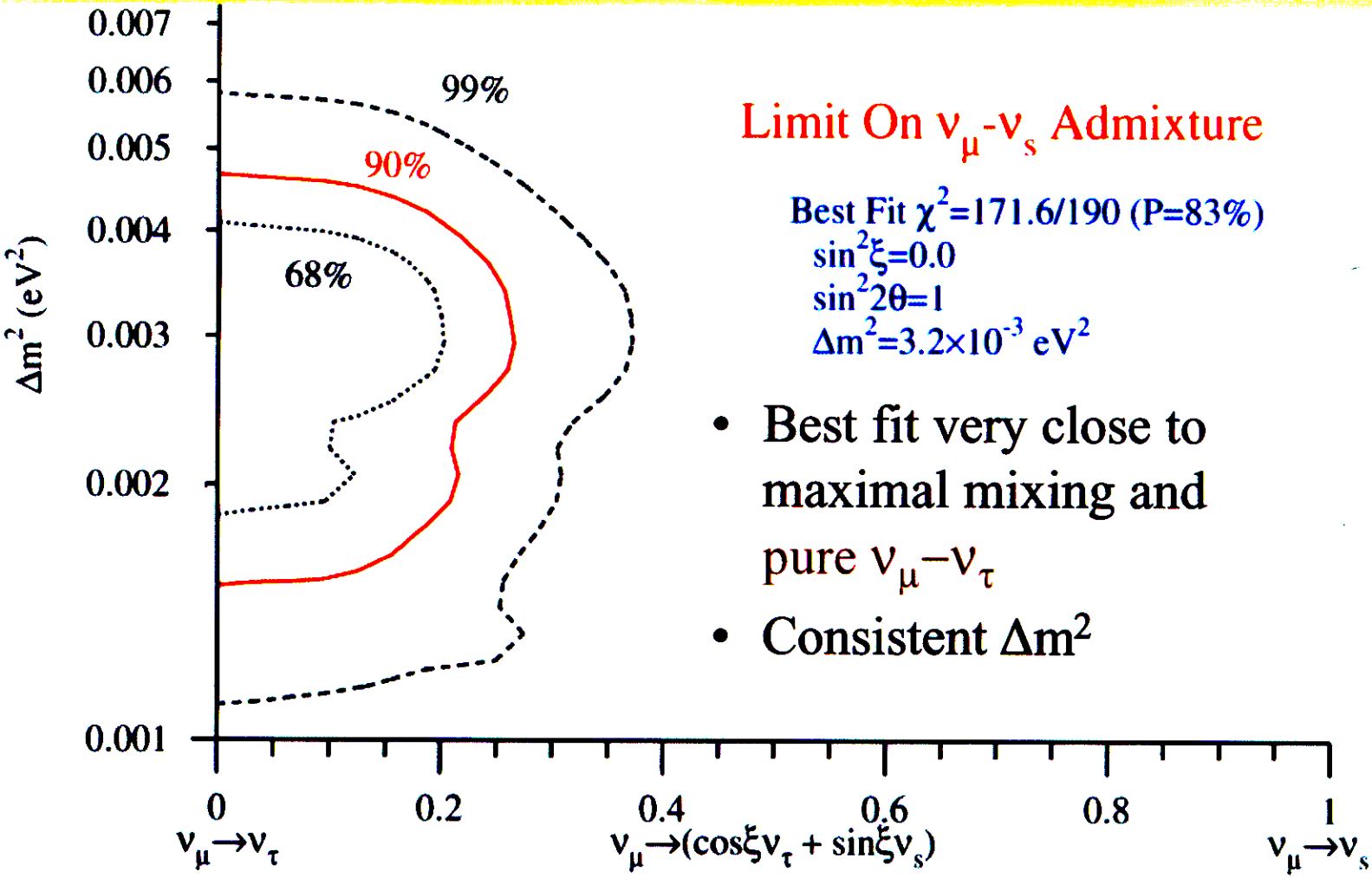
Limit on Sterile Content



Limit On ν_μ-ν_s Admixture

Best Fit χ^2=171.6/190 (P=83%)
$\sin^2\xi$=0.0
$\sin^2 2\theta$=1
Δm^2=3.2×10^{-3} eV^2

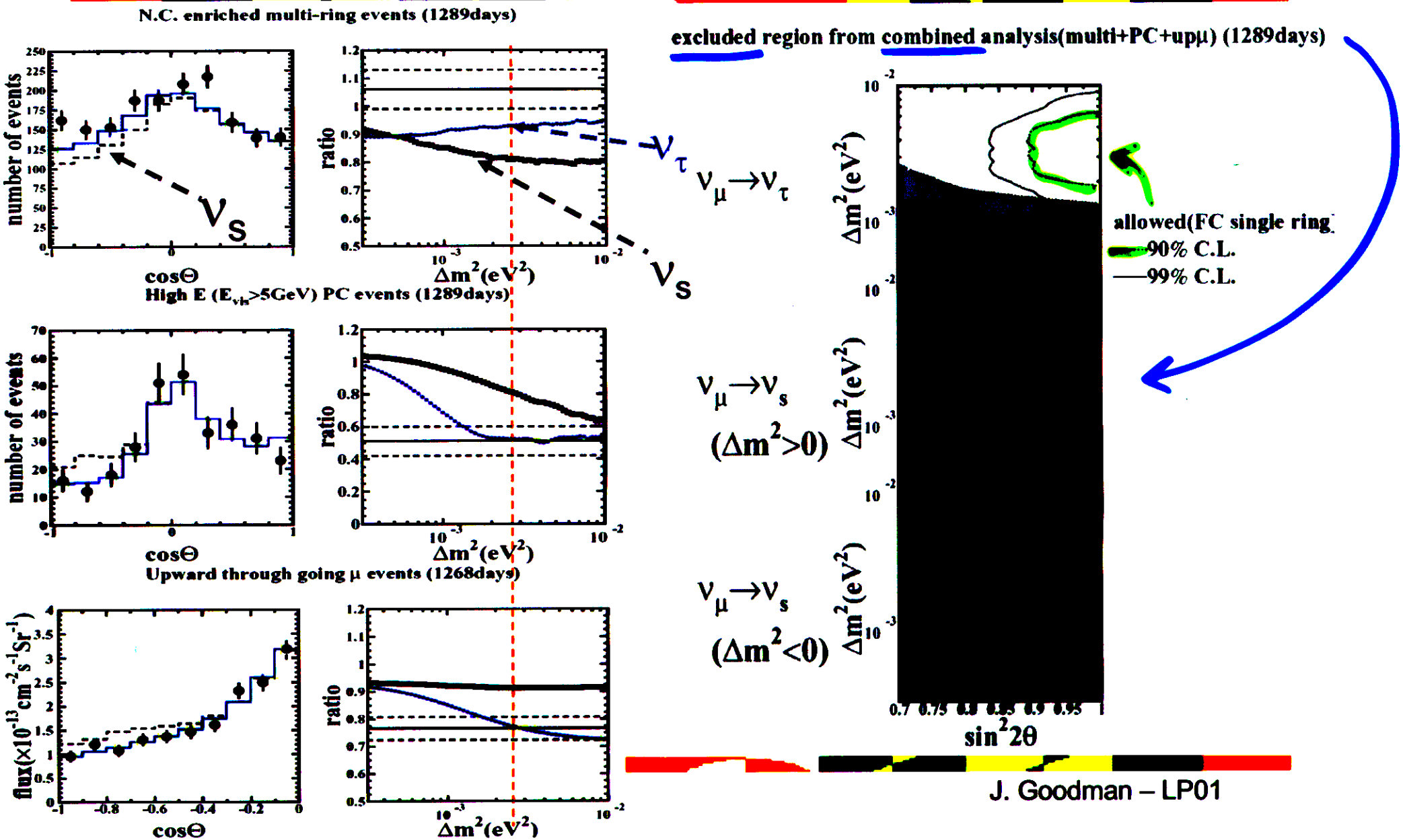
- Best fit very close to maximal mixing and pure $\nu_\mu - \nu_\tau$
- Consistent Δm^2

$\sin^2\xi$

fraction of sterile content

Michael Smy, UC Irvine

SK: Tau vs Sterile Neutrino Analysis



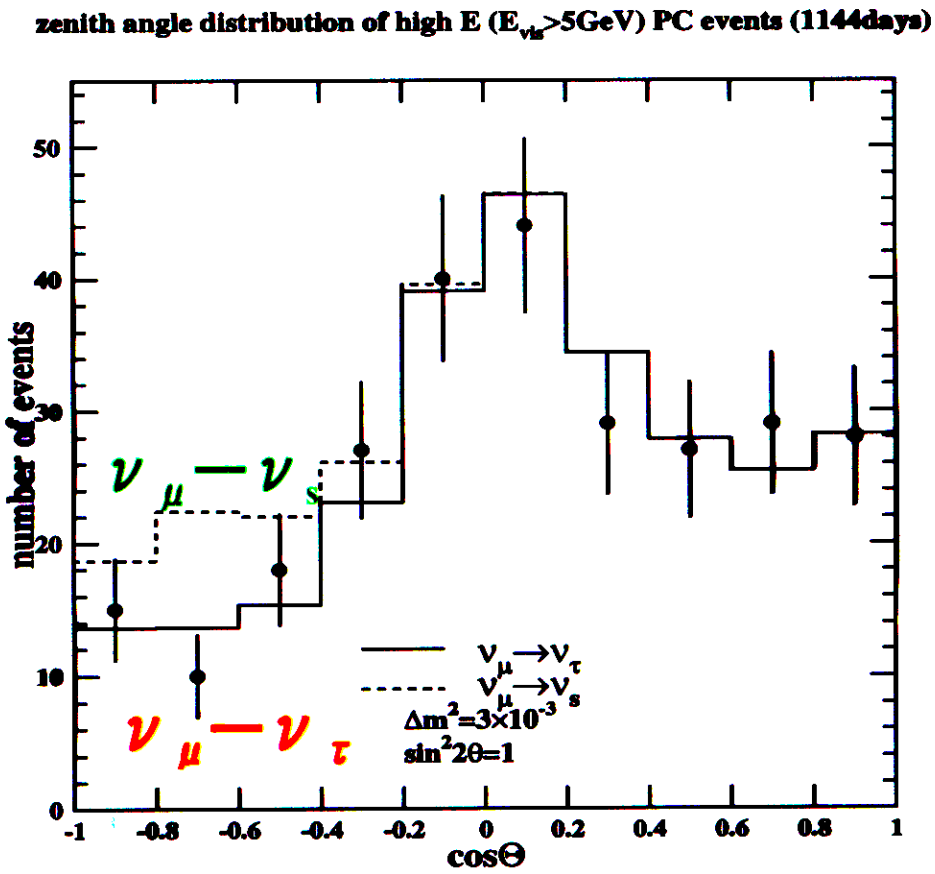
J. Goodman – LP01

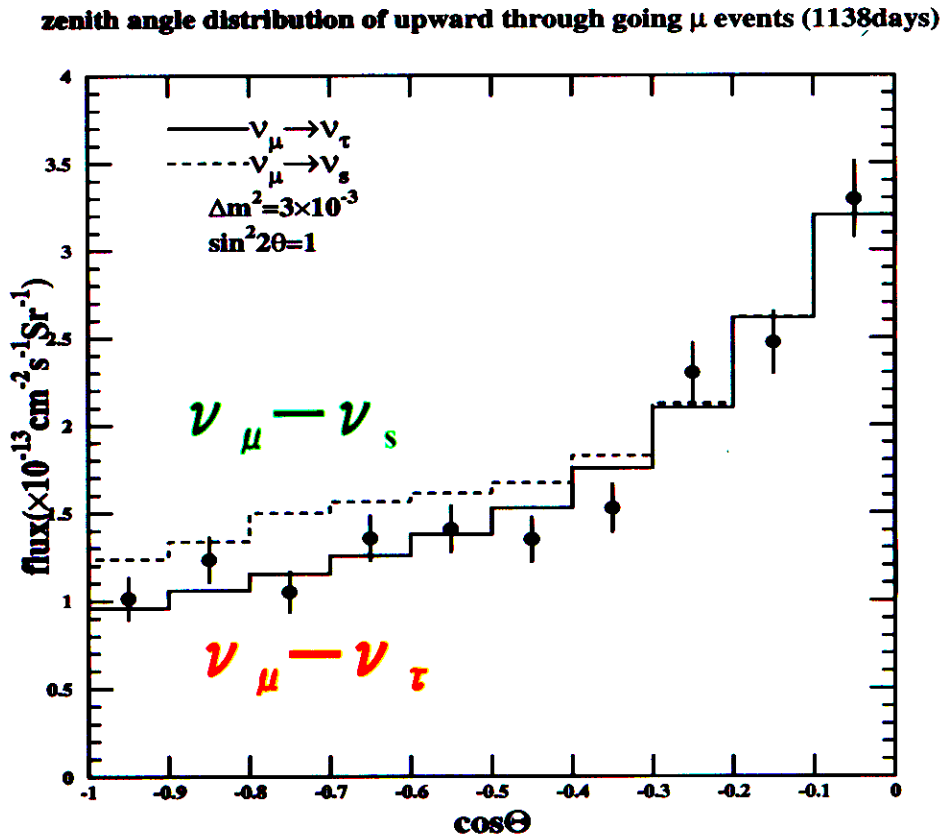
matter effect in the earth

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\left(\frac{2VE_\nu}{\Delta m^2} - \cos 2\theta\right)^2 + \sin^2 2\theta}$$

$\sin^2 2\theta \sim 1$, $E_\nu > 20$GeV

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

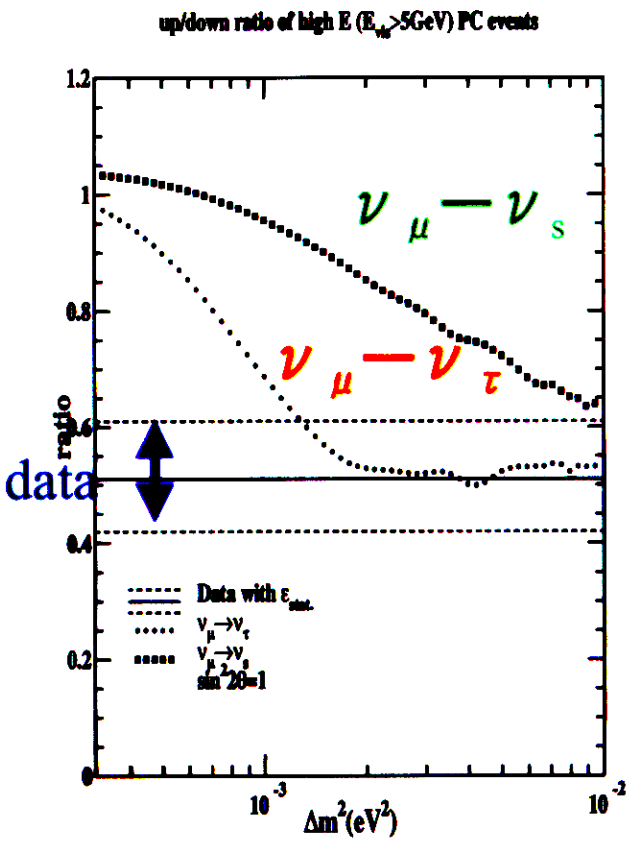


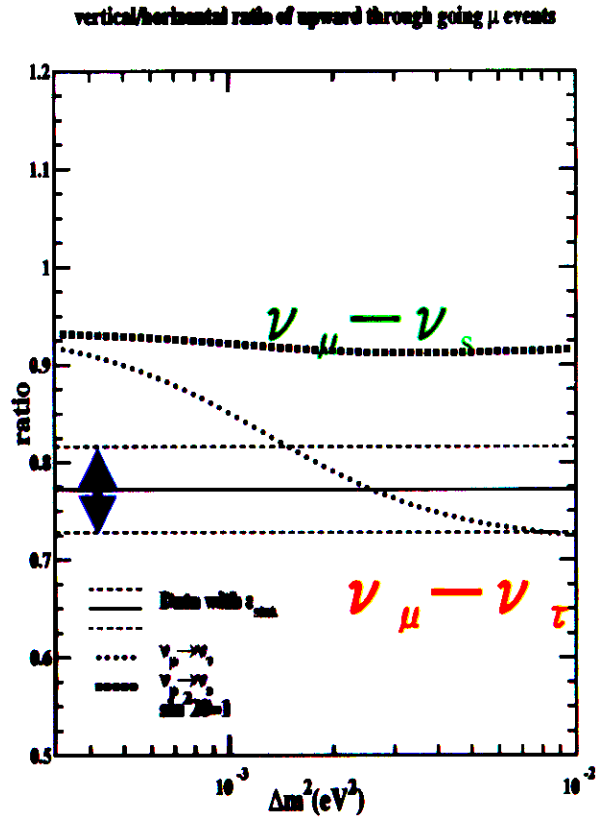


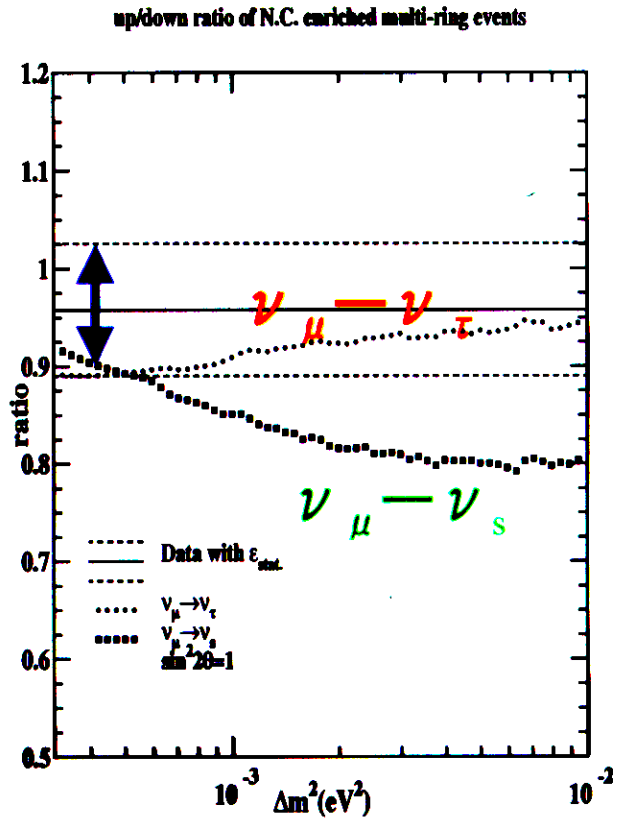
PC, Evis>5GeV
<E ν >~25GeV
up/down ratio

up through going μ
<E ν >~100GeV
vertical/horizontal ratio

$\nu_\mu - \nu_\tau$ v.s. $\nu_\mu - \nu_s$





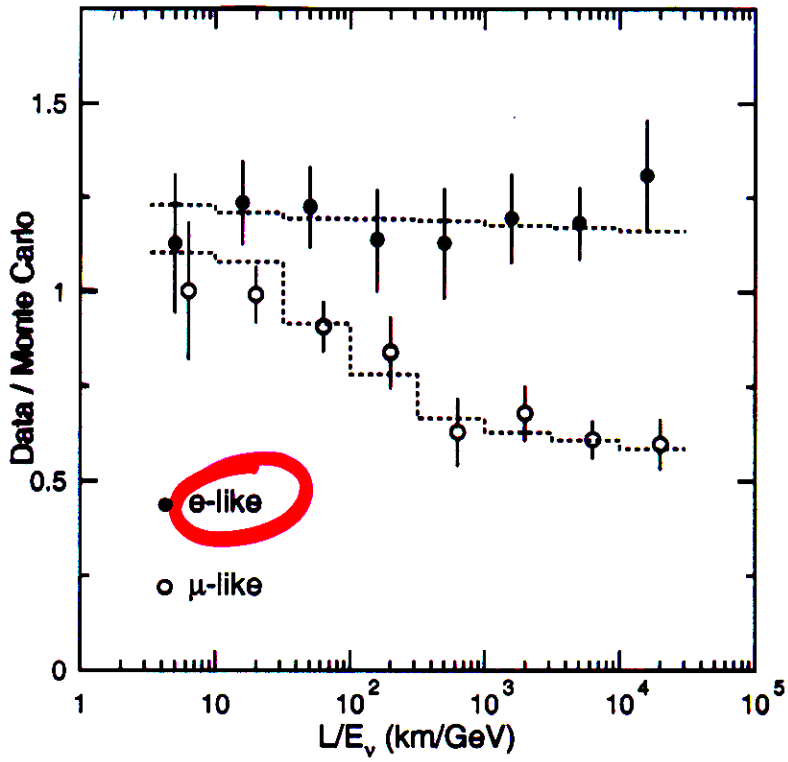


high energy PC up/down ratio

up through μ vertical/horizontal ratio

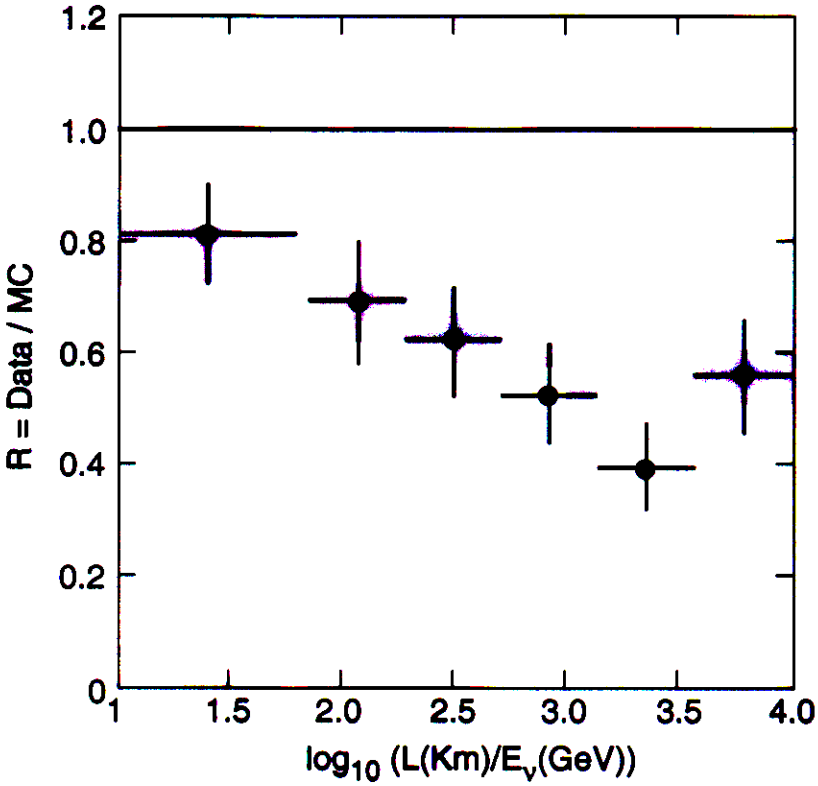
NC enrigh multi ring event up/down ratio

SuperKamiokande



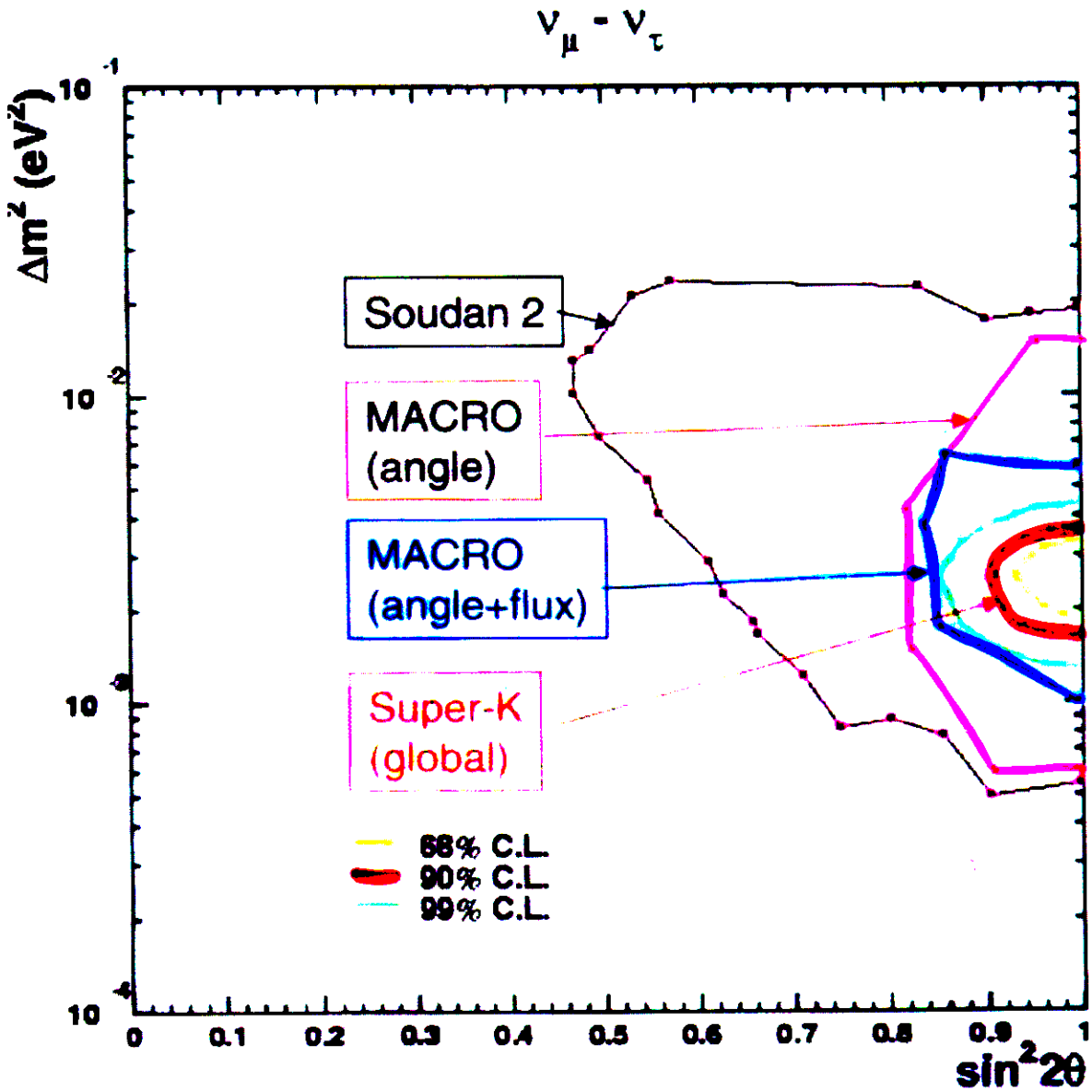
← ~20% electron excess

MACRO



Evidence for Neutrino Oscillations

Allowed regions (90% CL)



Y. Totsuka @ TAUP 2001

K2K *Results* (@NORIOND 2002)

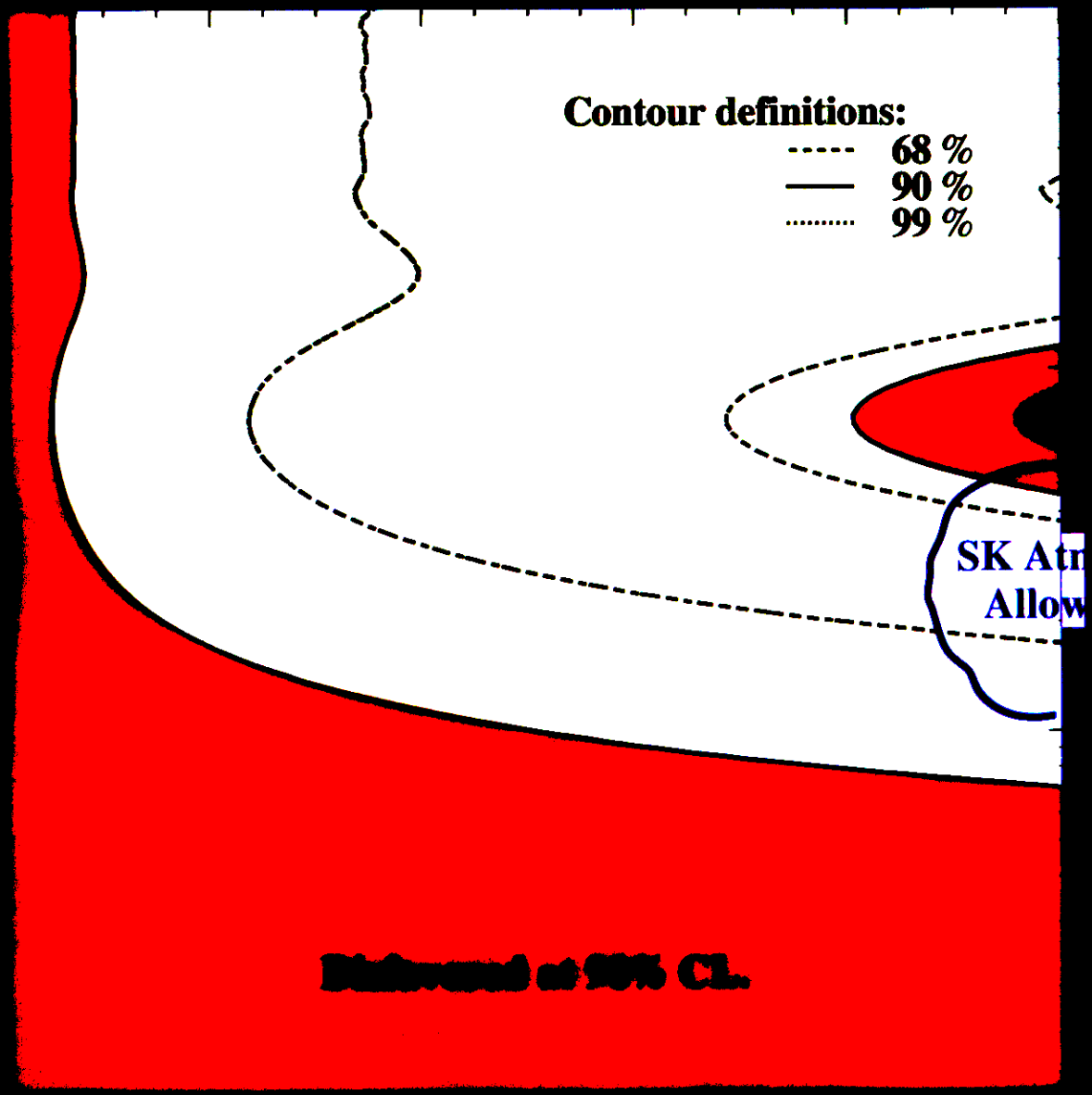
$\sin^2 2\theta = 1.0$

Event Category	Observed	Expected	$\Delta m^2 = 3 \times 10^{-3}\ eV^2$
Single Ring μ-like	30	44.0±6.8	24.4
Single Ring *e*-like	2	4.4 ±1.7	3.7
Multi Ring	24	32.2±5.3	24.3
TOTAL	56	$80.6\ ^{+7.3}_{-8.0}$	52.4

Dominant Systematic Errors are an uncertainty of far-near ratio (~7%) and an uncertainty of 1kt fiducial volume (~4%).

The provability of null oscillation scenario is **only 3%** .
(It was 10% in the last year).

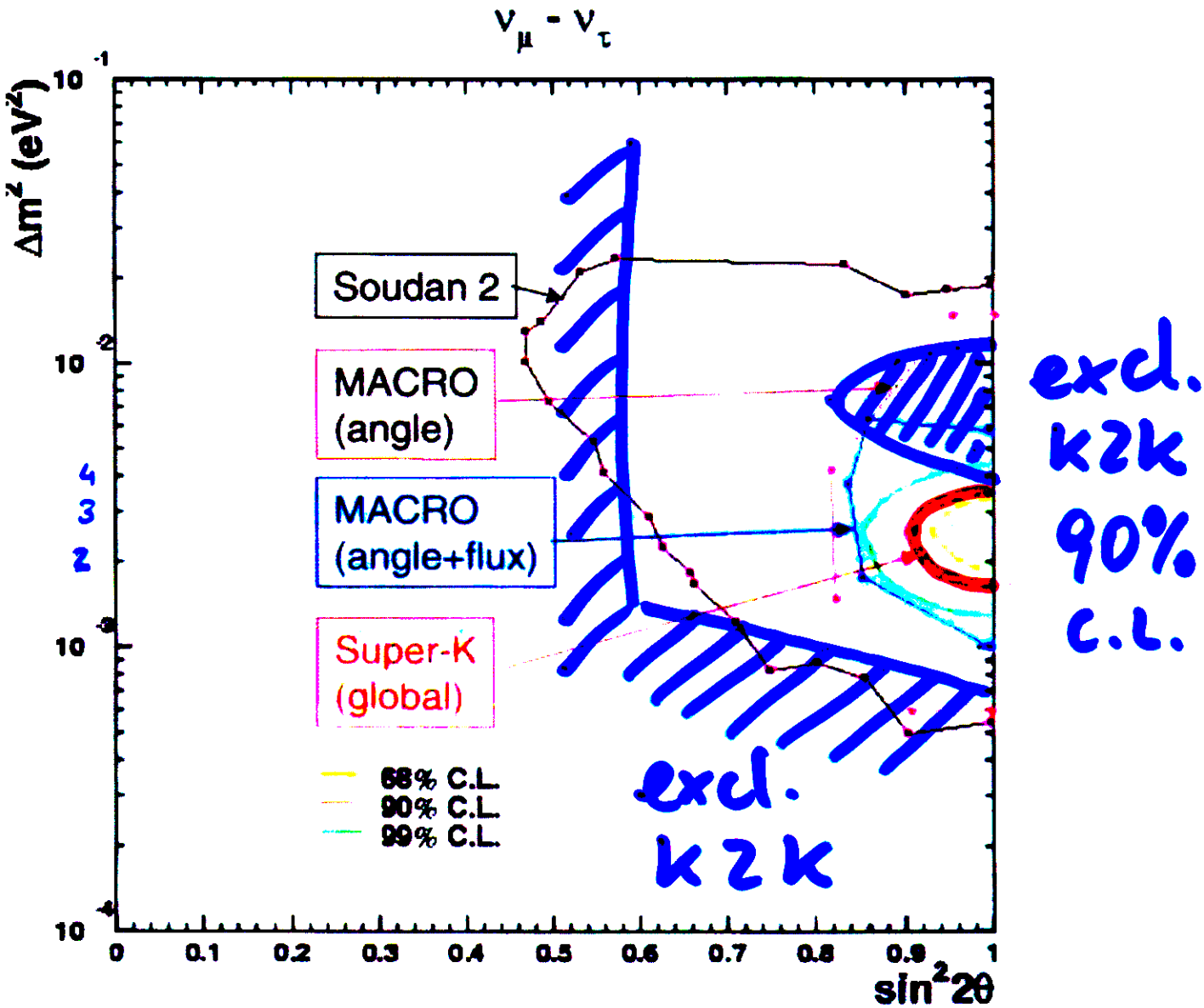
K2K oscillation contour



ALL ATM exp + K2K

Evidence for Neutrino Oscillations

Allowed regions (90% CL)



K2K allowed region @ NORIOND 2002

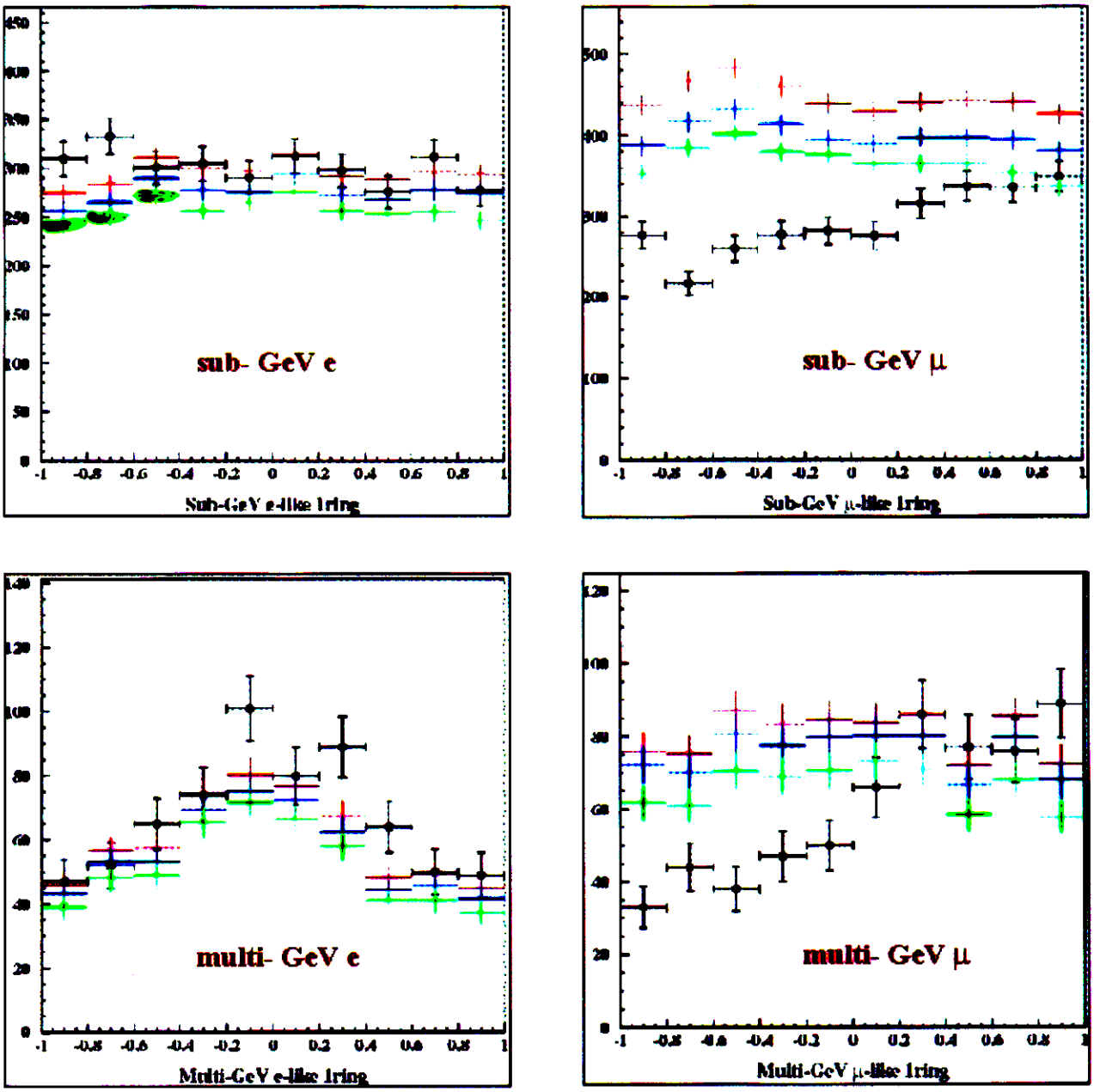
all ATM exp + REACTOR exp

What does it mean?

- Atmospheric problem is due to neutrino flavor oscillation
- μ-type neutrinos oscillate predominantly into τ-type neutrinos, no sterile neutrino needed
- A hint of appearance of τ-type neutrinos ($< 2\sigma$)
- The mixing is large, possibly maximal
- The Δm^2 is a few times $10^{-3} eV^2$
- No hint of positive θ_{13}, set limit

Neutrini Atmosferici di Super-Kamiokande

Dati SK punti neri, calcolo FLUKA punti verdi, calcoli di Honda *etal* vecchi/nuovi punti rossi/blu.



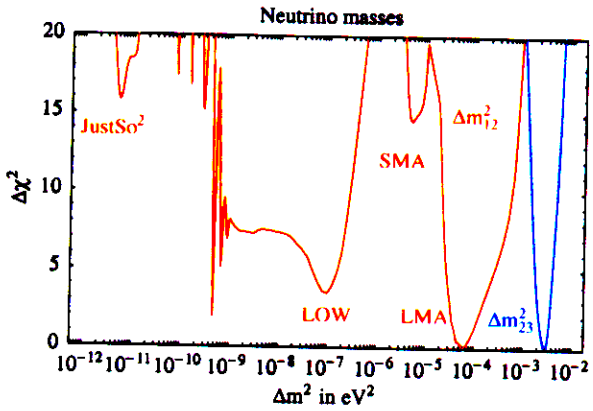
Da M Shiozawa, trasparenza preparata per il meeting AMS a Trento (Oct 01). In quella occasione, G Battistoni ha osservato che i calcoli più aggiornati rinforzano (anzichè indebolire) l'indicazione di un eccesso di 'elettroni' nei dati di SK.

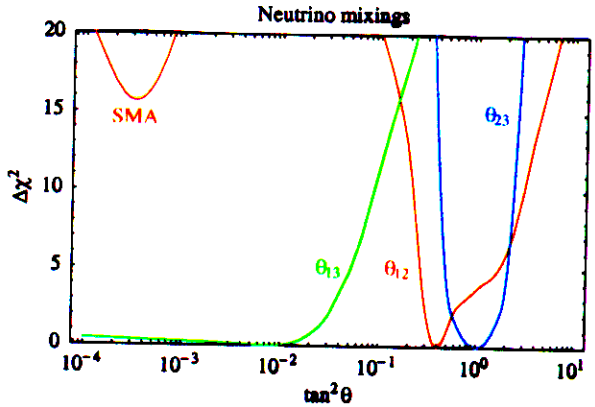
F. Vissani @ PD 2002

A. Strumia et al (unpublished)

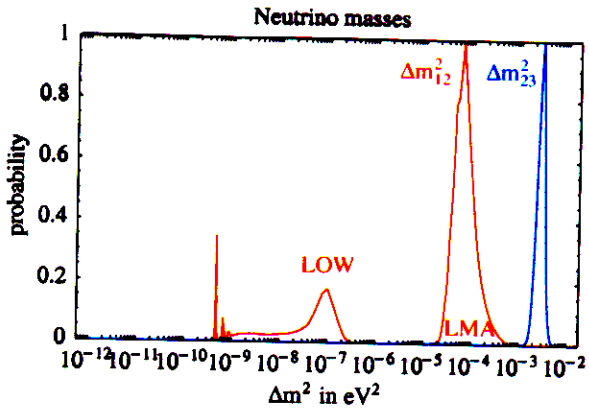
All we know from oscillations

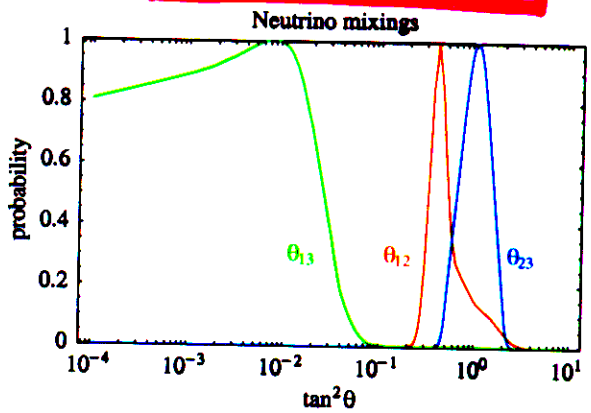
We can summarize all we know today on the parameters of massive neutrinos with $\Delta\chi^2$ plots:





These can be converted into probabilities as $\boxed{P = \exp(-\Delta\chi^2/2)}$:





Guide to colors:

Red: "solar" parameters

Blue: "atmospheric" parameters

Green: "reactor" parameters

F. Vissani @ PD 2002

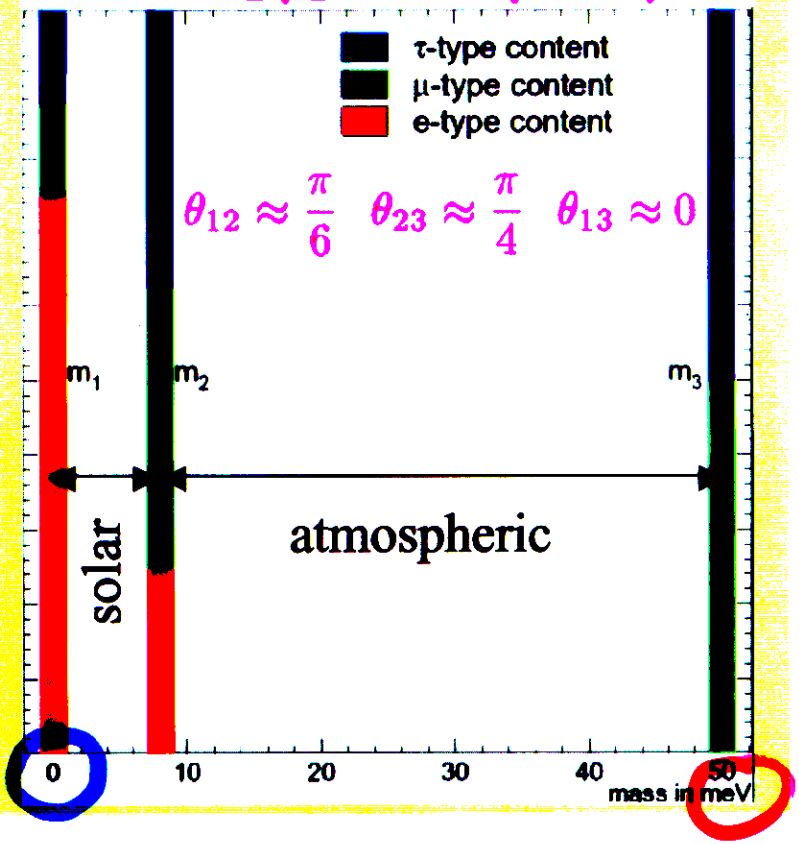
All ATM + SOLAR + REACTOR exp

What does it all mean?

- Prefer large mixing
- 3 neutrinos are enough: no hint anywhere in SK for sterile neutrinos
- $\Delta m^2_{atm}=0.0025 eV^2$
- $\Delta m^2_{solar}=0.00006 eV^2$
- Mass scheme (right):
  - Assume $m_1=0$
  - Assume $\theta_{13}=0$
  - Neglect CP phase

!!!

$$U \approx \begin{pmatrix} \frac{\sqrt{3}}{2} & \frac{1}{2} & 0 \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{2\sqrt{2}} & -\frac{1}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$



!!!

Michael Smy, UC Irvine

milliElectronVolt is the NEW mass scale

if this is the case

($m_\nu \sim 10^{-3}$ eV)

the UNIVERSE is 90% filled with useless neutrinos!

(still LSND to be confirmed/disproved

NUTEV to be understood)

THE STANDARD SCENARIO (3 ν flavor oscillations) IS NOT COMPLETE !!!

@ Pheno 2002, april 20

- 2D position of 10^8 galaxies
- redshifts of 10^6 "
- " 10^5 quasars

Why do we care?

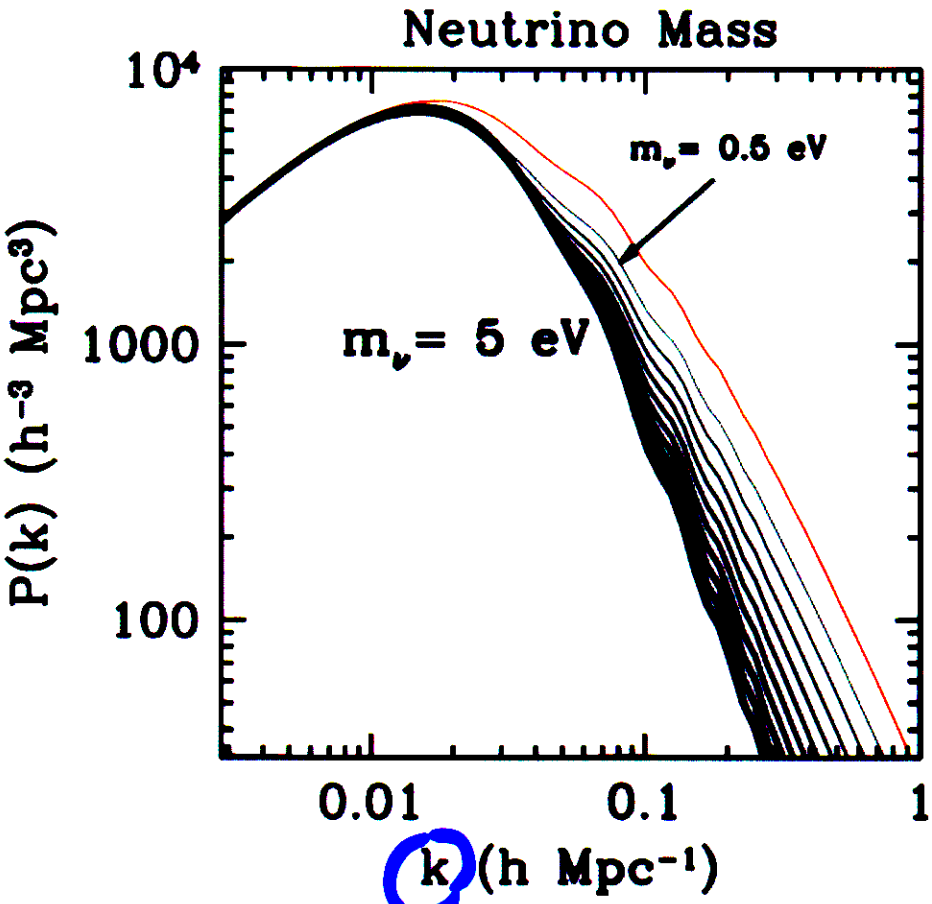
- Shape of Power spectrum depends on cosmological parameters
- Can check modern cosmology: $\Omega_m = 0.3; h = 0.7; \Omega_b = 0.04; \Omega_{\text{total}} = 1$
- Learn about: neutrino mass; Dark matter and Dark energy; inflation

$\Rightarrow \quad m_{\nu,tot} \lesssim 2\ \text{eV} \quad (95\%\ \text{cl})$

"A new limit on the total ν mass from 2dF Galaxy Redshift Survey"

• astro-ph/0204152

P(k) ≡ Power spectrum

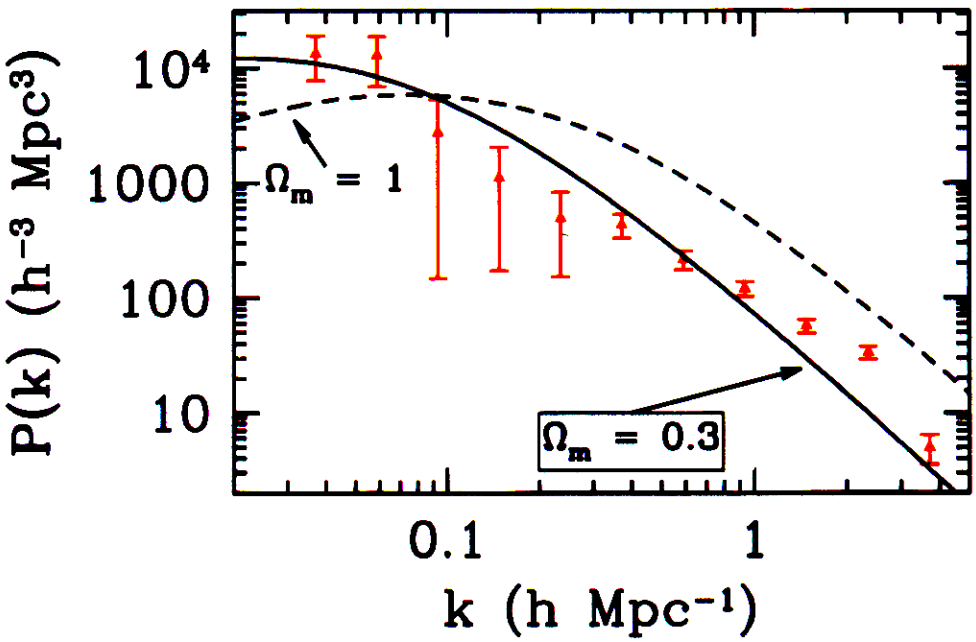


comoving wavenumber

- ν's are relativistic at equality
- Freestream out of overdense regions
- Current limits range from 2 – 5 eV

Angular Correlation Function

SDSS Results 2002

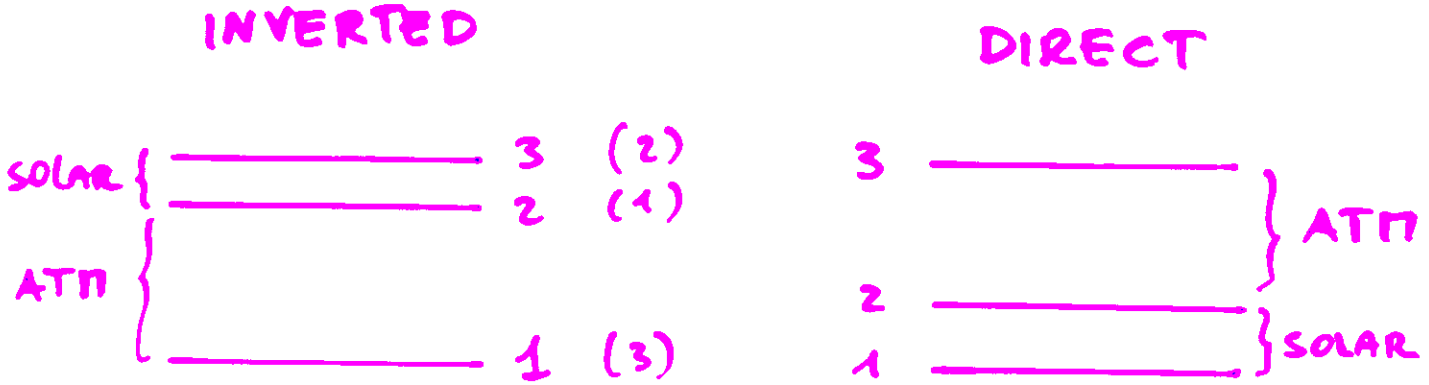


Dodelson et al. 2002

- Based on 5% of photoetric data
- Extensive tests for systematics
- sCDM ruled out at $3-4\sigma$!!!

hierarchy vs cosmology

m_1 gives the ABSOLUTE SCALE



m_1 is <u>not</u> determined from osc. exp.

hierarchy :

$|m_1| \ll |m_2| \sim |m_3|$

inverted

because $\delta m^2_{32} = \delta m^2_{\odot}$

$\Downarrow$

$m_1 \sim 0$

$|m_1| \sim |m_2| \ll |m_3|$

direct

because $\delta m^2_{32} = \delta m^2_{atm}$

$\Downarrow$

$m_2 \sim m_1 \sim 0$

degeneracy :

$m_i \sim O(eV) \quad \forall i$