



the

**abdus salam**  
international centre for theoretical physics

**SMR.1508 - 2**

***SUMMER SCHOOL ON PARTICLE PHYSICS***

**16 June - 4 July 2003**

**NEUTRINO PHYSICS**

**Lecture 1**

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Batavia, IL  
U.S.A.**



V98,  $\odot$  Takayan  
June 1998

# Atmospheric neutrino results from Super-Kamiokande & Kamiokande

— Evidence for  $\nu_\mu$  oscillations —



T. Kajita

Kamioka observatory, Univ. of Tokyo

for the { Kamiokande  
Super-Kamiokande } Collaborations

"All the News  
That's Fit to Print"

# The New York

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FRIDAY, JUNE 5, 1998

## Mass Found in Elusive Particle; Universe May Never Be the Same

### Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that much of the mass of the universe is in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

Others said the newly detected but as yet unmeasured mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collect-



### And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

The New York Times

ed by the detector except the existence of neutrino mass had been essentially ruled out.

Dr. Yoji Totsuka, leader of the coalition and director of the Kamioka Neutrino Observatory where the underground detector is situated, 30 miles north of here in the Japan Alps, acknowledged that his group's announcement was "very strong," but said, "We have investigated all

Continued on Page A14

## OKLAHOMA BLAST BRINGS LIFE TERM FOR TERRY NICHOLS

### 'ENEMY OF CONSTITUTION'

### Judge Denounces Conspiracy and Hears From the Victims of a Terrifying Ordeal

By JO THOMAS

DENVER, June 4 — Calling him "an enemy of the Constitution," a Federal judge today sentenced Terry L. Nichols to life in prison without the possibility of parole for conspiring to bomb the Oklahoma City Federal Building, the deadliest terrorist attack ever on American soil.

In passing sentence after hearing from survivors of the blast and relatives of some of the 168 people who died in it, the judge, Richard P. Matsch of Federal District Court, said, "This was not a murder case."

He added: "It is a crime and the victims have spoken eloquently here. But it is not a crime as to them so much as it is a crime against the Constitution of the United States. That's the victim."

Last December, Mr. Nichols was convicted of conspiring with Timothy J. McVeigh to use a weapon of mass destruction in the April 19, 1995, bombing of the Alfred P. Murrah Federal Building, but was acquitted of Federal murder charges in the deaths of eight Federal agents who died. Mr. Nichols was found guilty of involuntary manslaughter in those deaths and today was given the maximum sentence of six years in prison for each, to run concurrently with his life sentence. He was also acquitted of actually committing the bombing.

While the conspiracy charge carried a possible death sentence, the jurors need to vote unanimously for such punishment, and they could not do so. The sentencing then fell to Judge Matsch.

Mr. McVeigh was convicted on all counts in an earlier trial and was sentenced to death.



Bajram Curri, in no Yugoslavia in three

## Refugees A Bitte

PADESH, Albania, and Slobodan Milosevic has unleashed military operation in the end of the war in thousands of ethnic A the border area with reducing their villages.

At least 10,000 streamed through passes and thousands in forests on the border according to

# Neutrino Physics

Stephen Parke

Fermilab

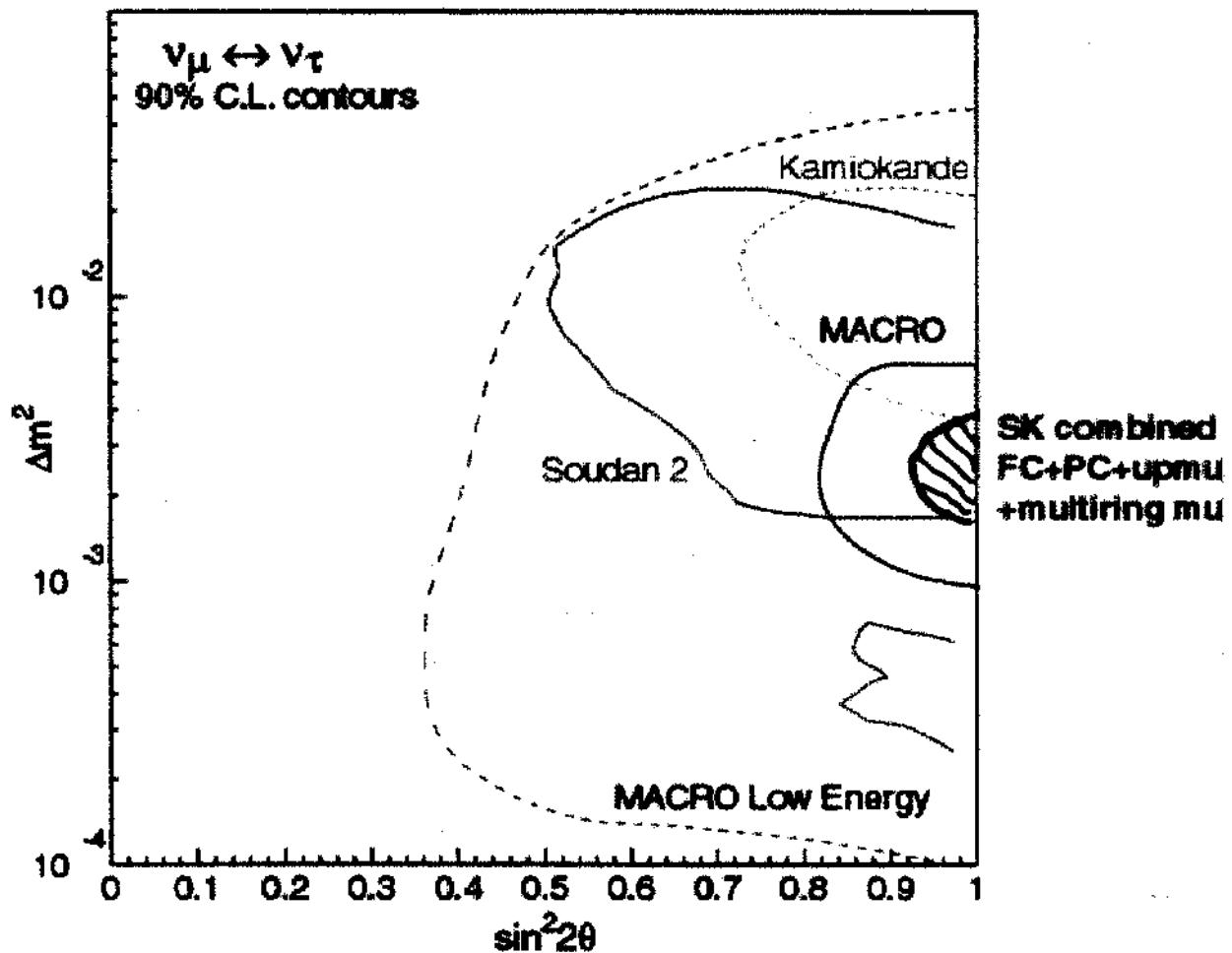
parke@fnal.gov

Series Outline: <http://theory.fnal.gov/people/parke>

- ☒ Neutrino Oscillations (2 flavors)
  - Vacuum (atmospheric  $\nu$ 's )  
K2K
  - matter ( solar  $\nu$ 's )  
KAMLAND
- ☒ 3 or more flavors
- ☒  $\theta_{13}$  and CP or T Violations
- ☒ Neutrino Mass, ~~☒~~  $\beta\beta$  decay etc

First Back Next Sync Video

## Allowed Regions from Several Experiments



KAMLAND + SOLAR (SNO, SK...)

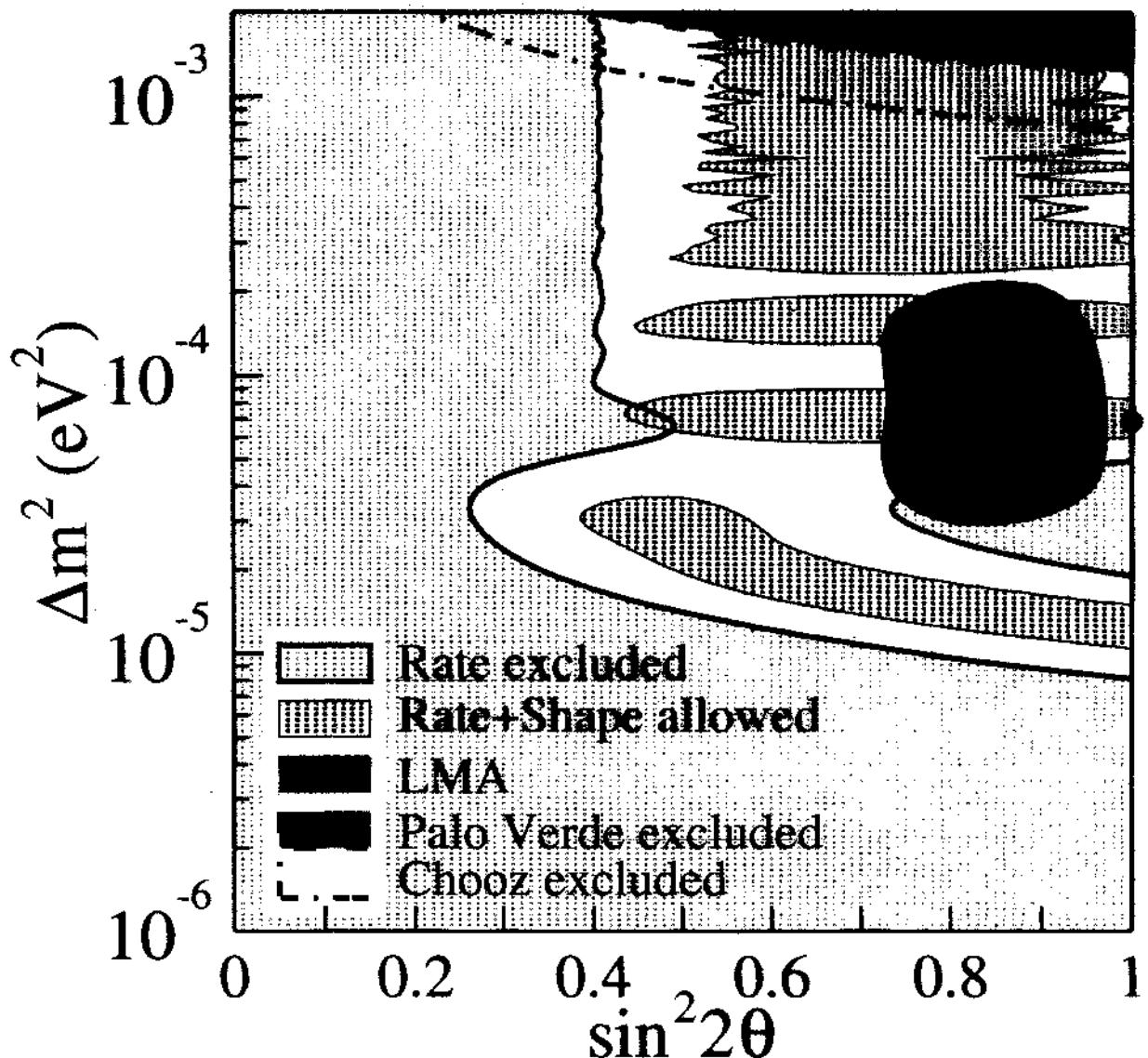


FIG. 6: Allowed regions of neutrino oscillation parameters for the rate analysis and the combined rate and shape analysis from KamLAND at 95% C.L. At the top are the 95% C.L. excluded region from CHOOZ [15] and Palo Verde [16] experiments, respectively. The 95% C.L. allowed region of the ‘Large Mixing Angle’ (LMA) solution of solar neutrino experiments [13] is also shown. The thick dot indicates the best fit to the KamLAND data in the physical region:  $\sin^2 2\theta = 1.0$  and  $\Delta m^2 = 6.9 \times 10^{-5} eV^2$ . All regions look identical under  $\theta \leftrightarrow (\pi/2 - \theta)$  except for the LMA region.

# Neutrinos ( $\nu$ )

- very light ( $< 10^{-6}$  M<sub>electron</sub>)
- weakly interacting  
(pass thru light-years of Pb)
- electrically neutral
- basic building block of Universe.

## The pre-Revolutionary Neutrino

- Standard Model (Weinberg 1968)

Salam Glashow

Neutrino had zero mass

and no mixing.

$$\nu_L, \bar{\nu}_R$$

{ cf electron  
 $e_L \quad \bar{e}_R$   
 $e_R \quad \bar{e}_L$

- for Dirac Mass one needs to add  $\nu_R, \bar{\nu}_L$   
× Majorana Mass term  $\nu \bar{\nu} \phi \phi$  is dimension 5

- Direct Measurements

assuming no mixing

$$M_{\nu_e} < 3 \text{ eV}$$

$$M_{\nu_\mu} < 190 \text{ keV}$$

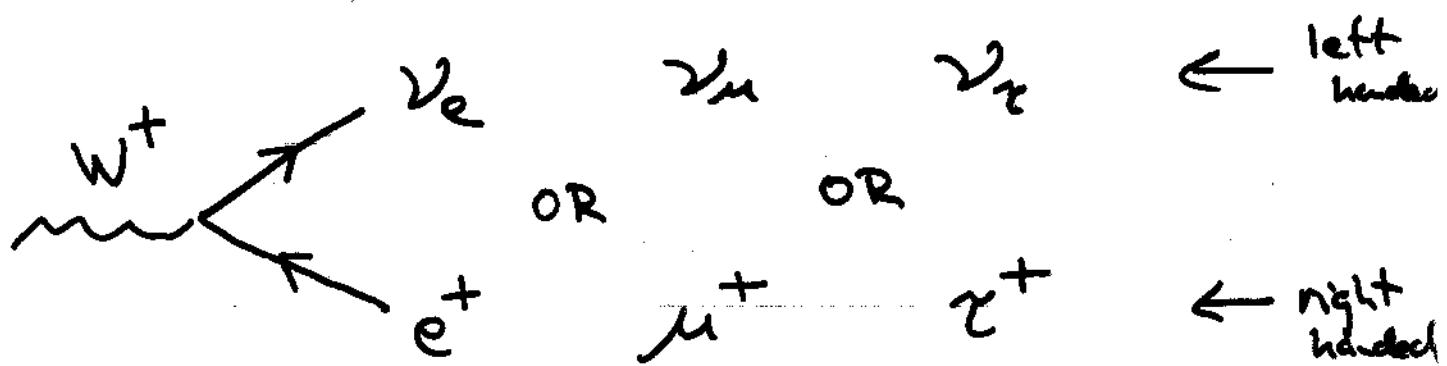
$$M_{\nu_\tau} < 18 \text{ MeV}$$

- new indications suggest  $M_{\nu_3} \gtrsim \frac{1}{20} \text{ eV}$

# Neutrino Oscillations

flavor states:

$$\nu_\alpha = \nu_e, \nu_\mu, \nu_\tau (\nu_s \dots)$$



mass eigenstates:

$$\nu_i = \nu_1, \nu_2, \nu_3, \dots$$

trivial time evolution (multiplication by phase)

$$|\nu_i, t\rangle = e^{-iHt} |\nu_i, 0\rangle$$

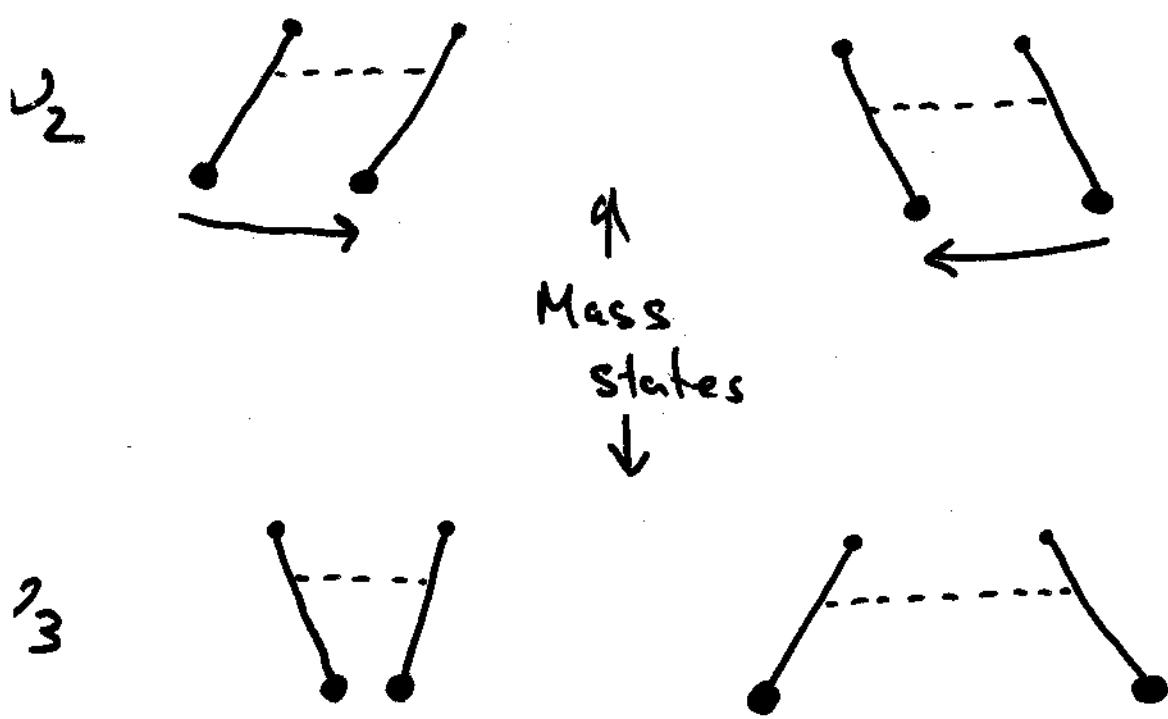
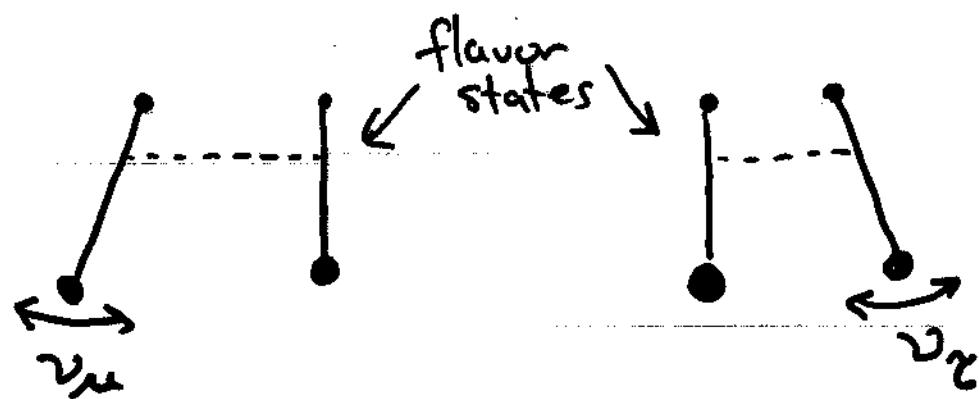
$$= e^{-iE_it} |\nu_i, 0\rangle$$

If Neutrinos have Mass then

flavor states  $\not\equiv$  Mass states

then neutrinos can oscillate:

Mechanical Analogue:



If neutrinos have mass then

flavor states  $\neq$  mass eigenstates

(quarks!!! CKM  $\approx 1$ )

Mixing  
related by a Unitary Matrix

$$\tilde{\nu}_\alpha = \sum_i U_{\alpha i}^* \nu_i$$

↑  
unitary matrix (PMNS)  
 $\sum_i U_{\alpha i}^* U_{\beta i} = \delta_{\alpha \beta}$  etc

2x2 example

$$\begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}$$

$$\sin \theta \equiv s_\theta$$

where  $\cos \theta \equiv c_\theta$

Suppose we produce a

$$\psi_e = C_0 \psi_1 + S_0 \psi_2$$

evolves in time

$$\rightarrow C_0 e^{-iE_1 t} \psi_1 + S_0 e^{-iE_2 t} \psi_2$$

now  $E_i = \sqrt{p^2 + m_i^2}$  with  $p \gg m_i$

$$\approx p + \frac{m_i^2}{2p} + \dots$$

$$= e^{-ip\vec{t}'} \left( C_0 e^{-i\frac{m_1^2}{2p} t} \psi_1 + S_0 e^{-i\frac{m_2^2}{2p} t} \psi_2 \right)$$

$$= \left( C_0 C_0 e^{-i\frac{m_1^2}{2p} t} + S_0 S_0 e^{-i\frac{m_2^2}{2p} t} \right) \psi_e$$

$$+ \left( C_0 (-S_0) e^{-i\frac{m_1^2}{2p} t} + S_0 C_0 e^{-i\frac{m_2^2}{2p} t} \right) \psi_u$$

$$P_{\nu_e \rightarrow \nu_\mu} = S_\theta^2 C_\theta^2 \left| e^{-i \frac{m_2^2 t}{2p}} - e^{-i \frac{m_1^2 t}{2p}} \right|^2$$

$$\underline{S_m^2 = M_2^2 - M_1^2}$$

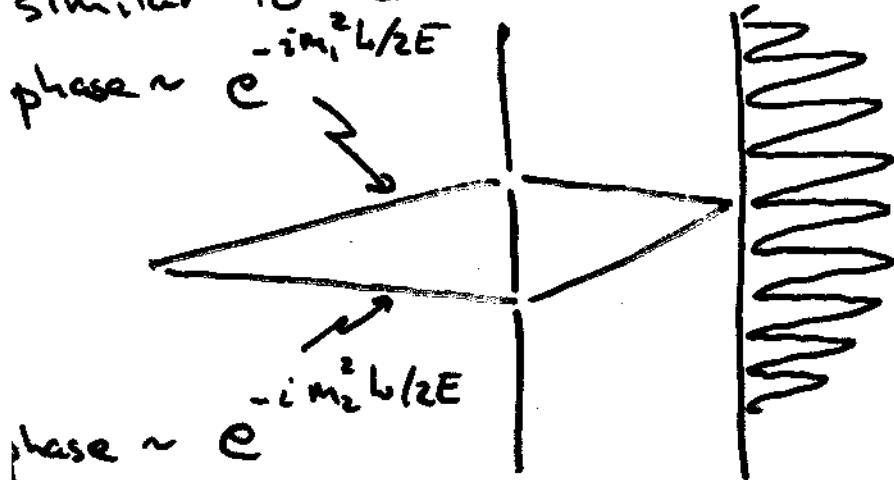
$$P_{e \rightarrow \mu} = S_\theta^2 C_\theta^2 \left| e^{-i \frac{(m_2^2 + m_1^2)t}{4p}} \left( e^{-i \frac{S_m^2 t}{4p}} - e^{+i \frac{S_m^2 t}{4p}} \right) \right|^2$$

use  
 $\begin{cases} t=L \\ p=E \end{cases}$

$$= 4 S_\theta^2 C_\theta^2 \sin^2 \frac{S_m^2 t}{4p}$$

$$P_{\nu_e \rightarrow \nu_\mu} = \sin^2 2\theta \sin^2 \frac{S_m^2 L}{4E}$$

similar to double slit:



Units:

$$\frac{\delta m^2 L}{4E} \quad | \quad \rightarrow \quad \frac{\delta m^2 c^4 \cdot L}{4\hbar c \cdot E}$$

natural units

dimensionless

$$\left( \frac{Et}{\pi} = \frac{E\hbar c}{\pi c} = \frac{EL}{\pi c} \right)$$

$$(\delta m^2 c^4) - eV^2$$

$$L = \text{km}$$

engineering units

$$E = \text{GeV}$$

$$\frac{eV^2 \text{ km}}{\text{GeV}} = \frac{eV^2 10^{18} \text{ fm}}{10^9 \text{ eV}}$$

$$= 10^3 \text{ MeV.fm}$$

$$\hbar c = 197 \text{ MeV.fm}$$

$$\frac{\delta m^2 L}{4E} \quad | \quad = 1.2669... \quad \frac{\delta m^2 (eV^2) L (\text{km})}{E (\text{GeV})}$$

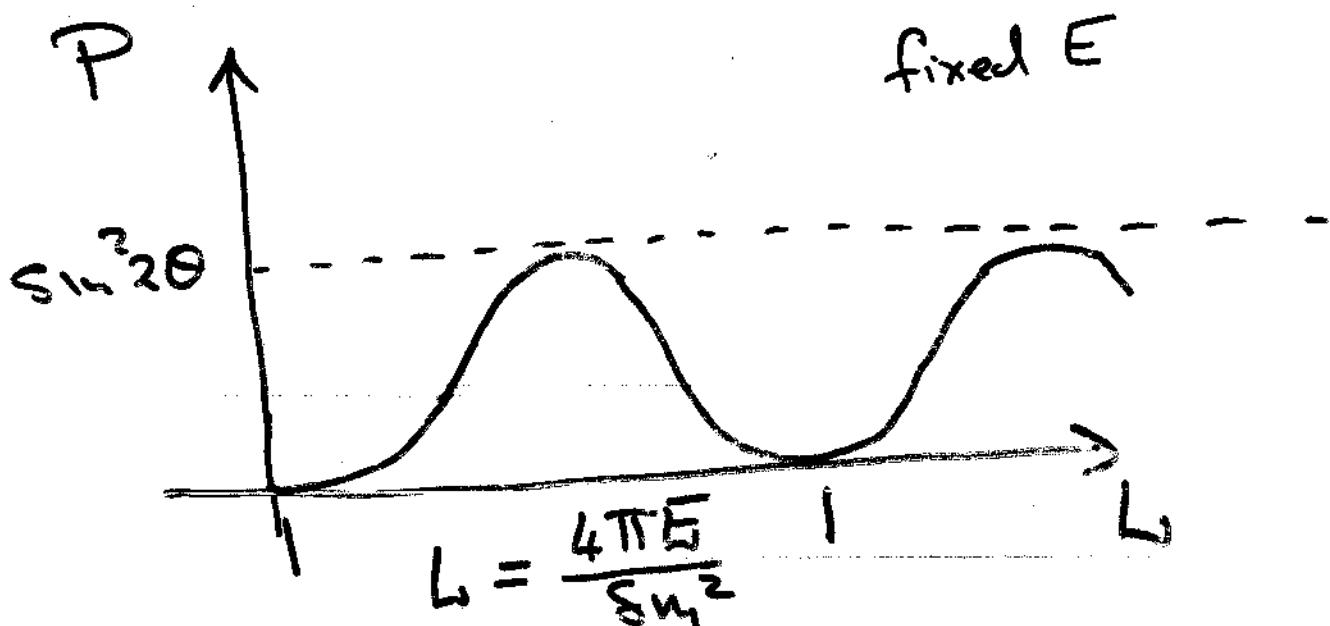
↓

$$\sim 1.27 \quad \left( \frac{1}{4} \rightarrow 1.27 \right)$$

natural  
units

Flavor Transition Probability is

$$P_{e \rightarrow \mu} = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$



Oscillation Maximum Occurs at

$$L_{\text{on}} = \frac{2\pi E}{8m^2} (1+2n)$$

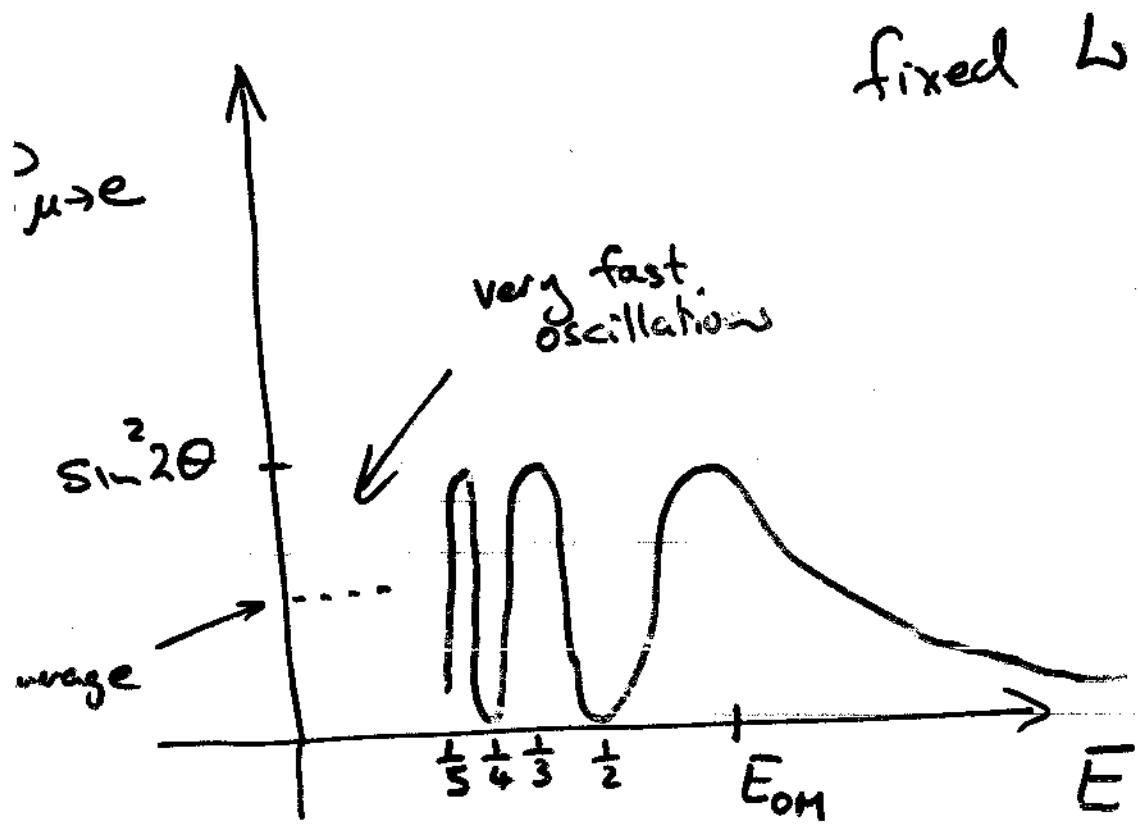
$n=0, 1, 2, \dots$

$\nu_e$  Survival Probability is

$$P_{e \rightarrow e} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

small  $L$

$$P_{e \rightarrow e} = 1 - \sin^2 2\theta \left( \frac{\Delta m^2 L}{4E} \right)^2 + \mathcal{O}(L^4)$$



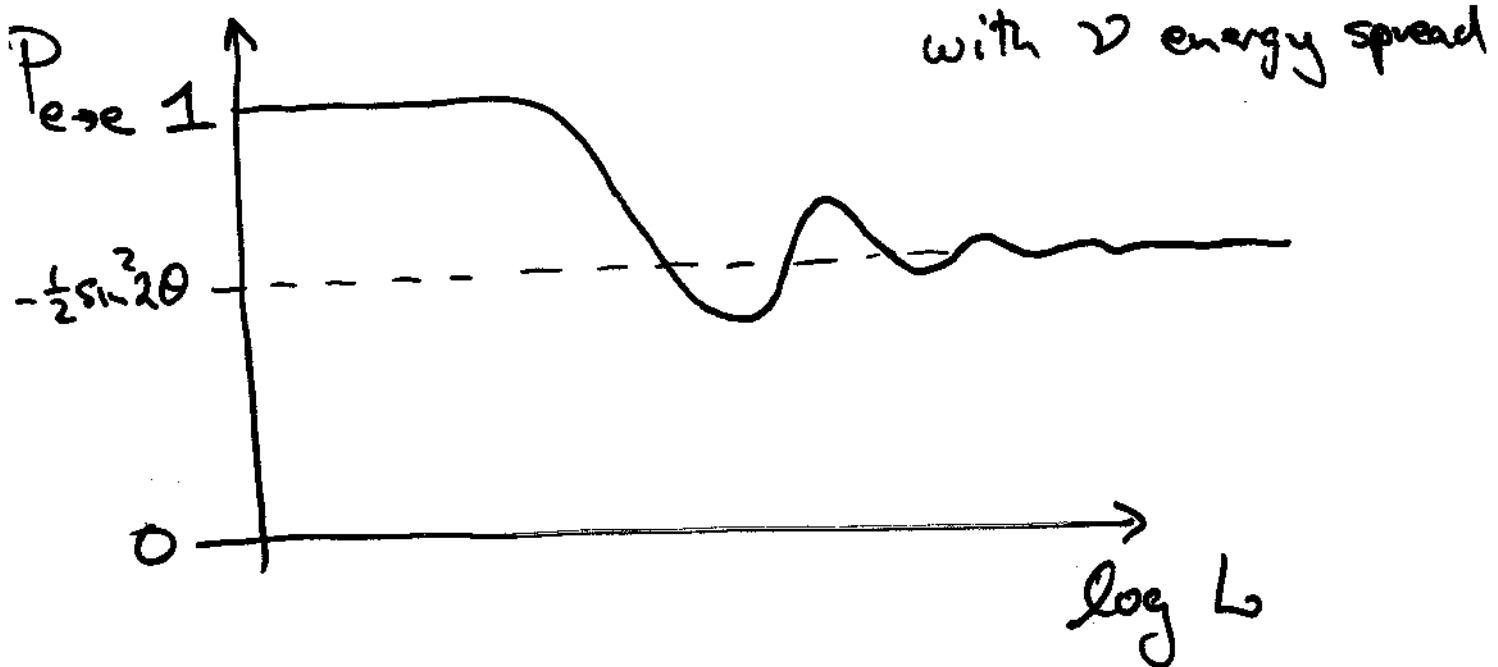
Peaks at

$$\frac{1}{(1+2n)} \quad \frac{\sin^2 L}{2\pi}$$

$$E_{0M}$$

Zeros at

$$\frac{1}{2n} \quad \frac{\sin^2 L}{2\pi}$$



KamLAND fig.

Suppose  $P_{\min}$  is the smallest transition probability an experiment can possibly see:  
What does the curve in  $(\delta m^2, \sin^2 2\theta)$  space look like of

$$P_{\min} = \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4E}$$

- at large  $\delta m^2$ :  $\sin^2 \frac{\delta m^2 L}{4E} \sim \frac{1}{2}$   
 $\sin^2 2\theta = 2 P_{\min}$
- Osc. Max  $L = \frac{2\pi E}{\delta m^2} \rightarrow \sin^2 2\theta = P_{\min}$
- $\sin^2 2\theta = 1$   $\delta m^2 = \sqrt{P_{\min}} \frac{4E}{L}$

# KamLAND:

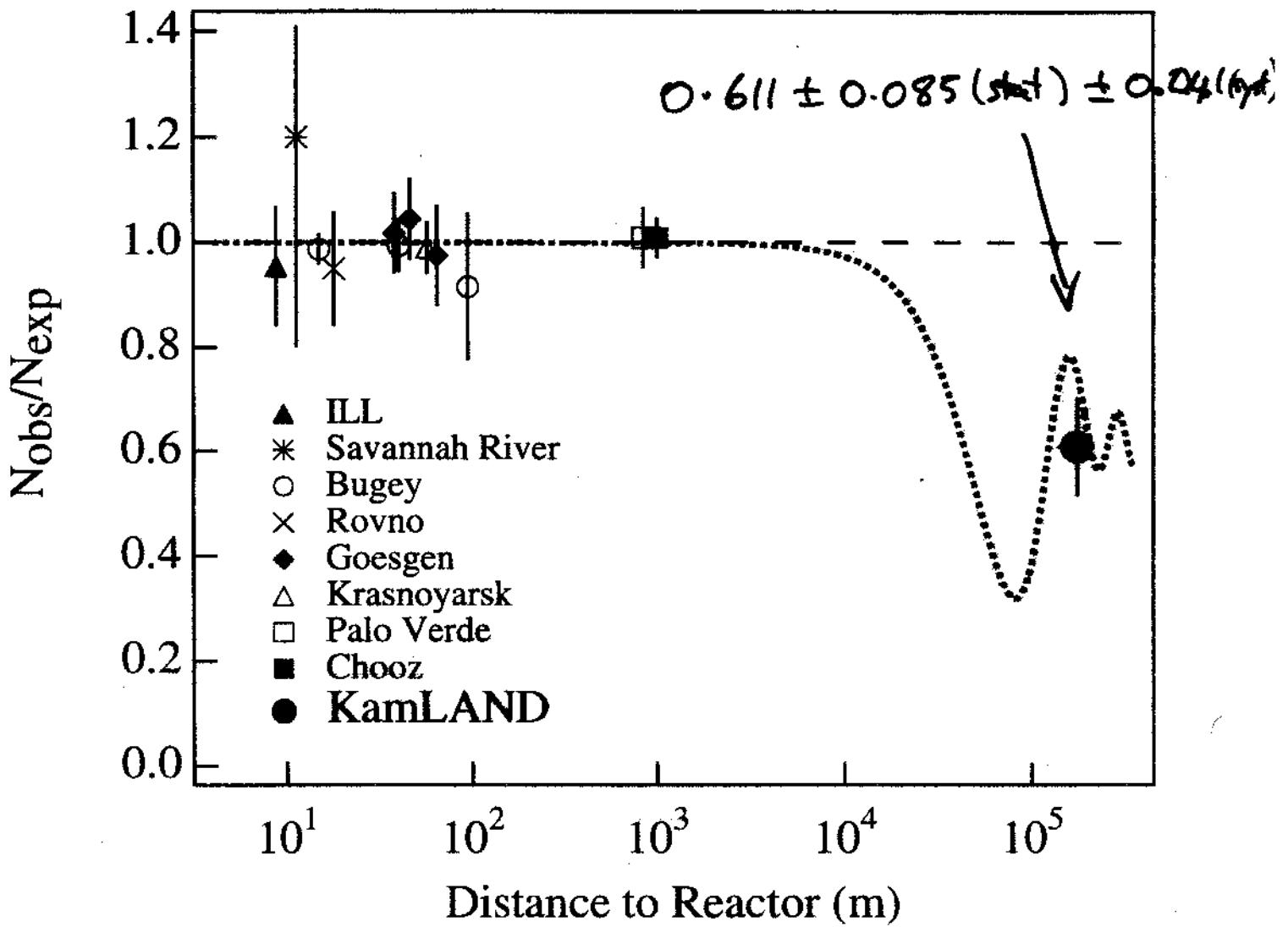
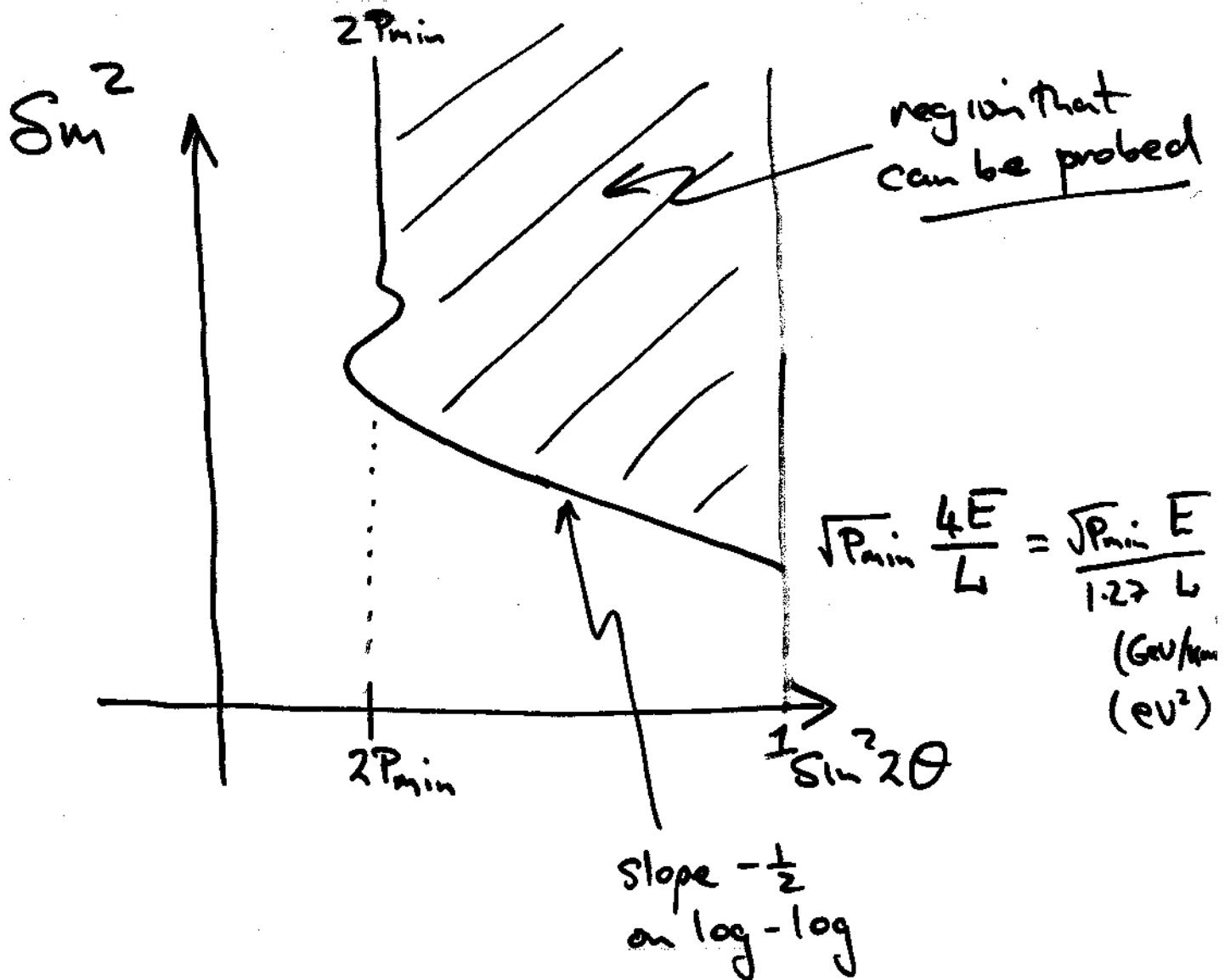


FIG. 4: The ratio of measured to expected  $\bar{\nu}_e$  flux from reactor experiments [12]. The solid dot is the KamLAND point plotted at a flux-weighted average distance (the dot size is indicative of the spread in reactor distances). The shaded region indicates the range of flux predictions corresponding to the 95% C.L. LMA region found in a global analysis of the solar neutrino data [13]. The dotted curve corresponds to  $\sin^2 2\theta = 0.833$  and  $\Delta m^2 = 5.5 \times 10^{-5} \text{ eV}^2$  [13] and is representative of recent best-fit LMA predictions while the dashed curve shows the case of small mixing angles (or no oscillation).



KamLAND:

$$\langle E \rangle \sim 3 \text{ MeV} \quad \langle L \rangle \sim 200 \text{ km}$$

$$P_{min} = 0.2$$

$$\sqrt{P_{min}} \frac{E}{1.27 L} \approx 9 \times 10^{-6} \text{ eV}^2$$

Why exclude region  $S_m^2 = 2.5 \times 10^{-3} \text{ eV}^2$  and  $\sin^2 2\theta = 1$ ?

$$P_{\nu_e \rightarrow \nu_e} = 1 - \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4E}$$

$$P_{\nu_e \rightarrow \nu_\mu} = \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4E}$$

semi-classical limit

if  $\hbar c \rightarrow 0$

$$\sin^2 \frac{\delta m^2 L}{4E} = \sin^2 \frac{\delta m^2 L}{4\hbar c E} = \frac{1}{2}$$

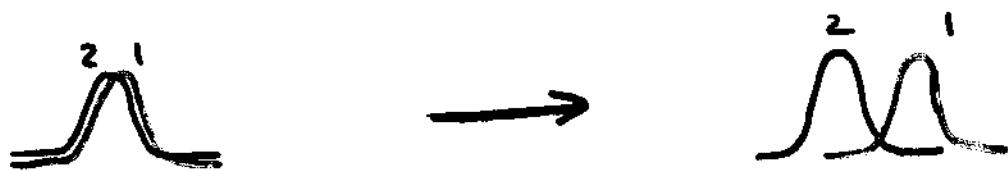
$$P_{\nu_e \rightarrow \nu_e} = 1 - \frac{1}{2} \sin^2 2\theta$$

$$P_{\nu_e \rightarrow \nu_\mu} = \frac{1}{2} \sin^2 2\theta$$

same as oscillations averaged out

equivalent to

# Separation of Wave-Packets



$e, \mu$        $e, \mu$       osc.av.  
 - short , + oscillations      medium  
 very large  $\epsilon$

$$\frac{1}{\gamma^2} = 1 - \beta^2$$

$$\beta_1^2 - \beta_2^2 = \left(1 - \frac{m_1^2}{E^2}\right) - \left(1 - \frac{m_2^2}{E^2}\right) = \frac{\Delta m^2}{E^2}$$

$$\Delta\beta = \beta_1 - \beta_2 = \frac{\Delta m^2}{2E^2} \quad \text{since } \beta_1 \approx \beta_2 \approx 1$$

$$\Delta m^2 = 1 \text{ eV}^2 \quad E = 1 \text{ GeV}$$

$$\Delta\beta = \left(\frac{1}{10^9}\right)^2 = 10^{-18}$$

if width of wavepacket is macroscopic  
 say 1m then decoherence at  $10^{18} \text{ m.}$   
 astrophysical distances

PROCESS:

$$W^+ \rightarrow e^+ \nu_1 \text{ or } \mu^+ \nu_2$$

$$c_\theta^2$$

$$e^+ \nu_2 \text{ or } \mu^+ \nu_1$$

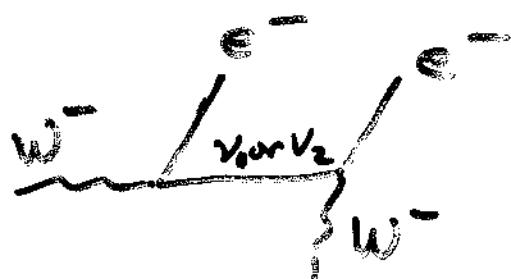
$$s_\theta^2$$

AND

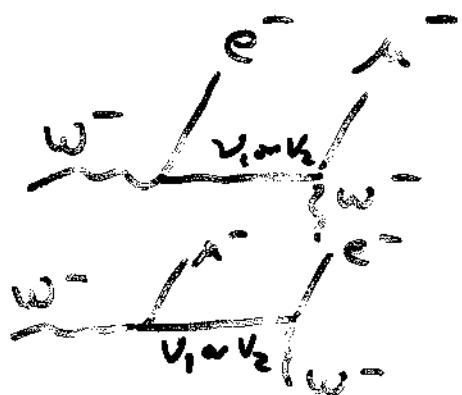
$$\begin{aligned} \nu_1 W^- &\rightarrow \bar{e}^- + \dots \\ \nu_2 W^- &\rightarrow \bar{\mu}^- + \dots \end{aligned} \quad \left. \right\} c_\theta^2$$

$$\begin{aligned} \nu_1 W^- &\rightarrow \bar{\mu}^- + \dots \\ \nu_2 W^- &\rightarrow \bar{e}^- + \dots \end{aligned} \quad \left. \right\} s_\theta^2$$

THEN



$$\begin{aligned} P_{\nu_e \rightarrow \nu_e} &= C_\theta^4 + S_\theta^4 \\ &= 1 - \frac{1}{2} \sin^2 2\theta \end{aligned}$$

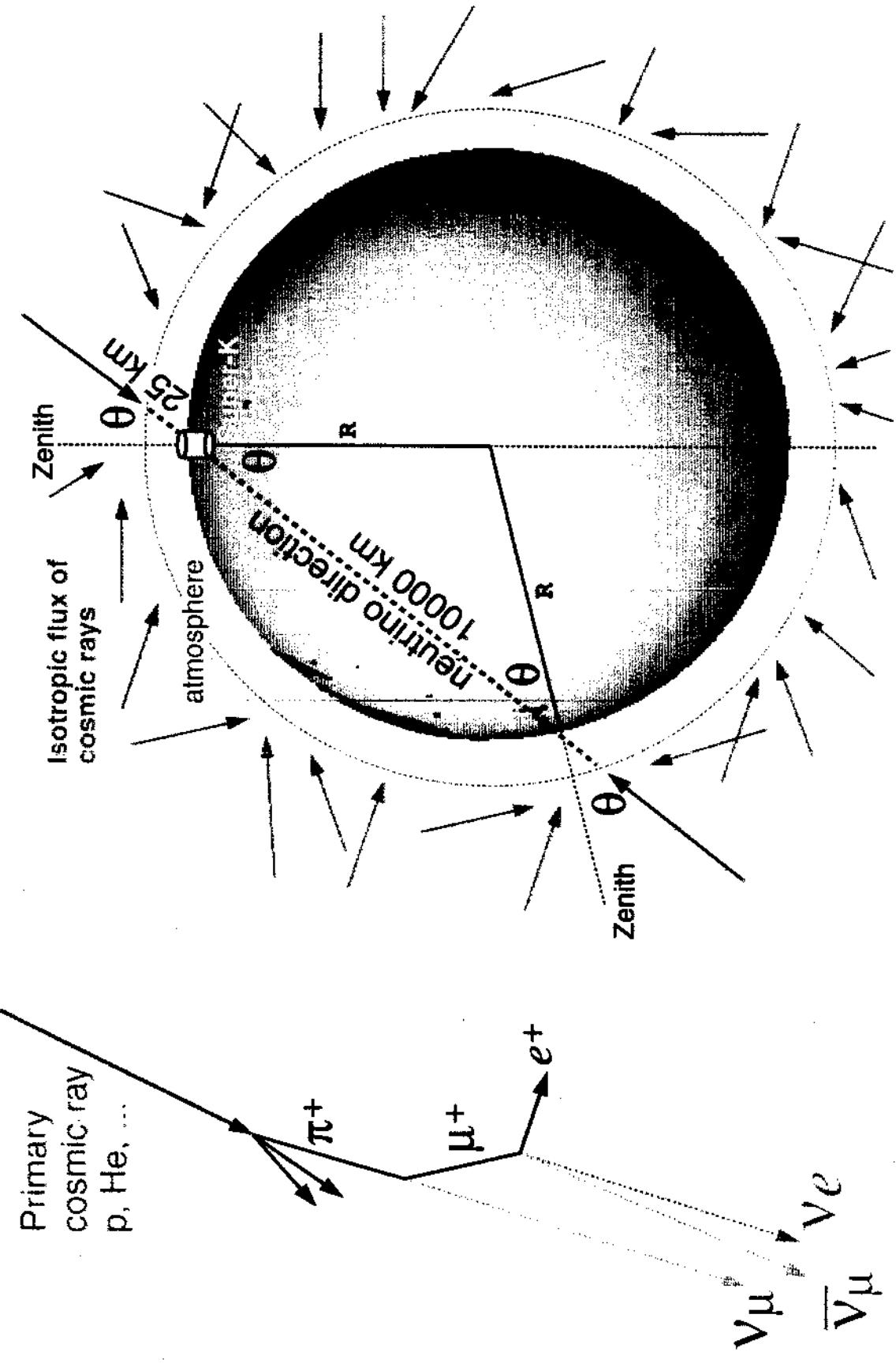


$$P_{\nu_e \rightarrow \nu_\mu} = 2 S_\theta^2 C_\theta^2 = \frac{1}{2} \sin^2 2\theta$$

$$P_{\nu_\mu \rightarrow \nu_e}$$

Quarks !!!

# ATMOSPHERIC NEUTRINOS

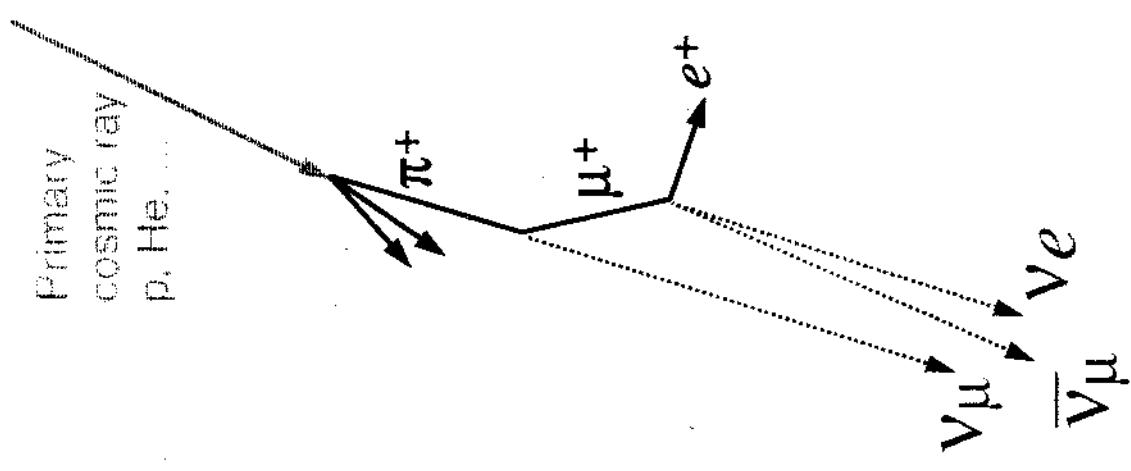
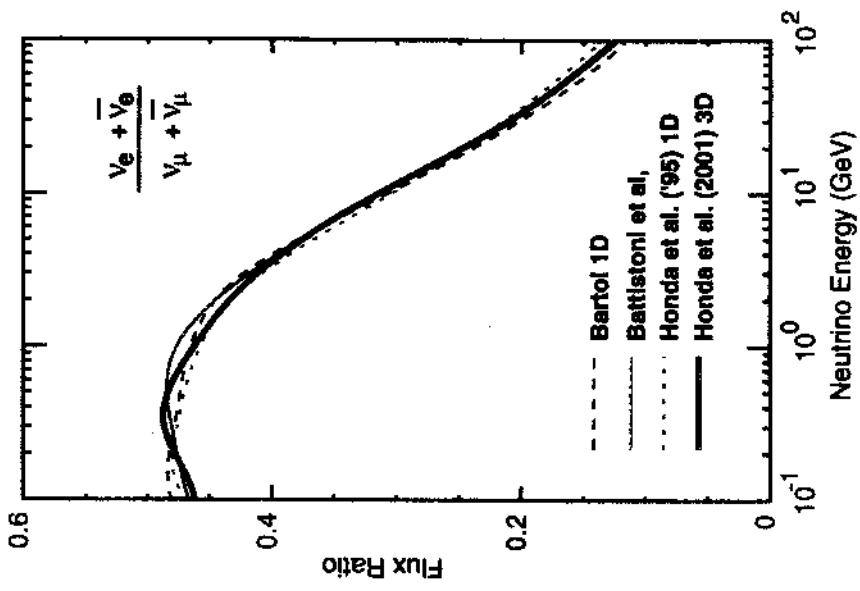


**Ratio of  $\nu_\mu/\nu_e \sim 2$**   
 (for  $E_\nu <$  few GeV)

**Up-Down Symmetric Flux**  
 (for  $E_\nu >$  few GeV)

# Flux Ratio of $\nu_\mu$ to $\nu_e$

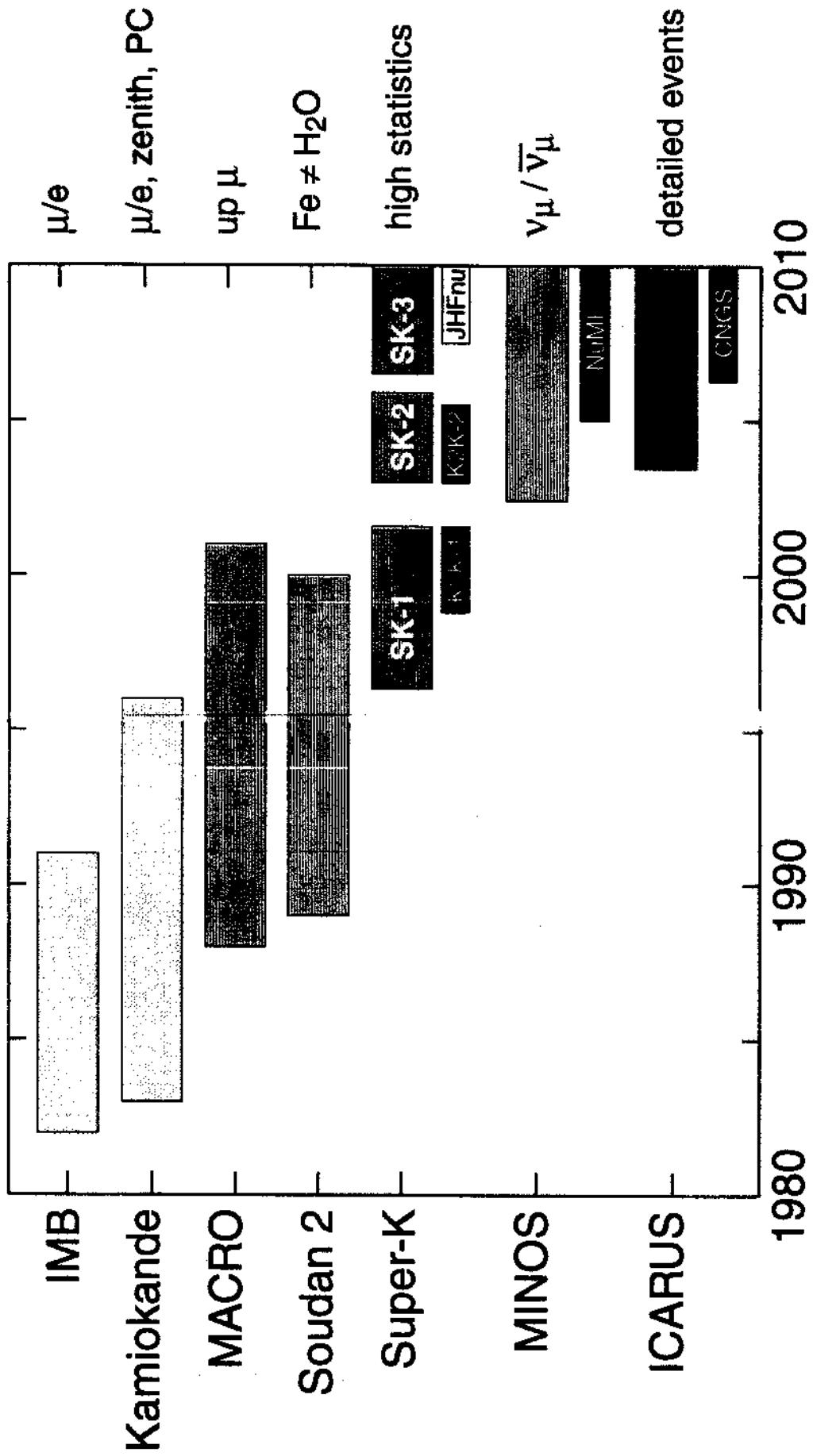
- $\Phi(\nu_\mu)/\Phi(\nu_e) \sim 2$  below a few GeV
- predicted to  $\sim 5\%$  over wide range



Atmospheric Neutrinos

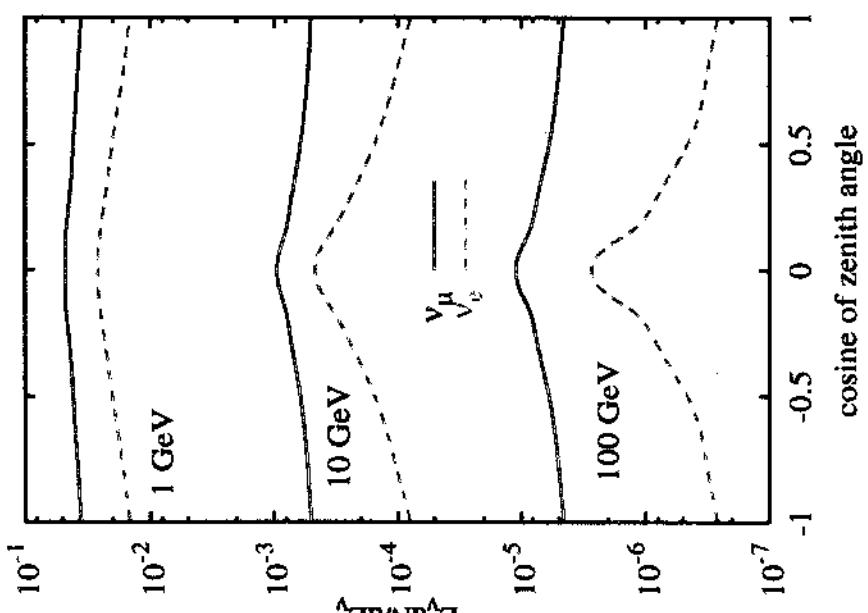
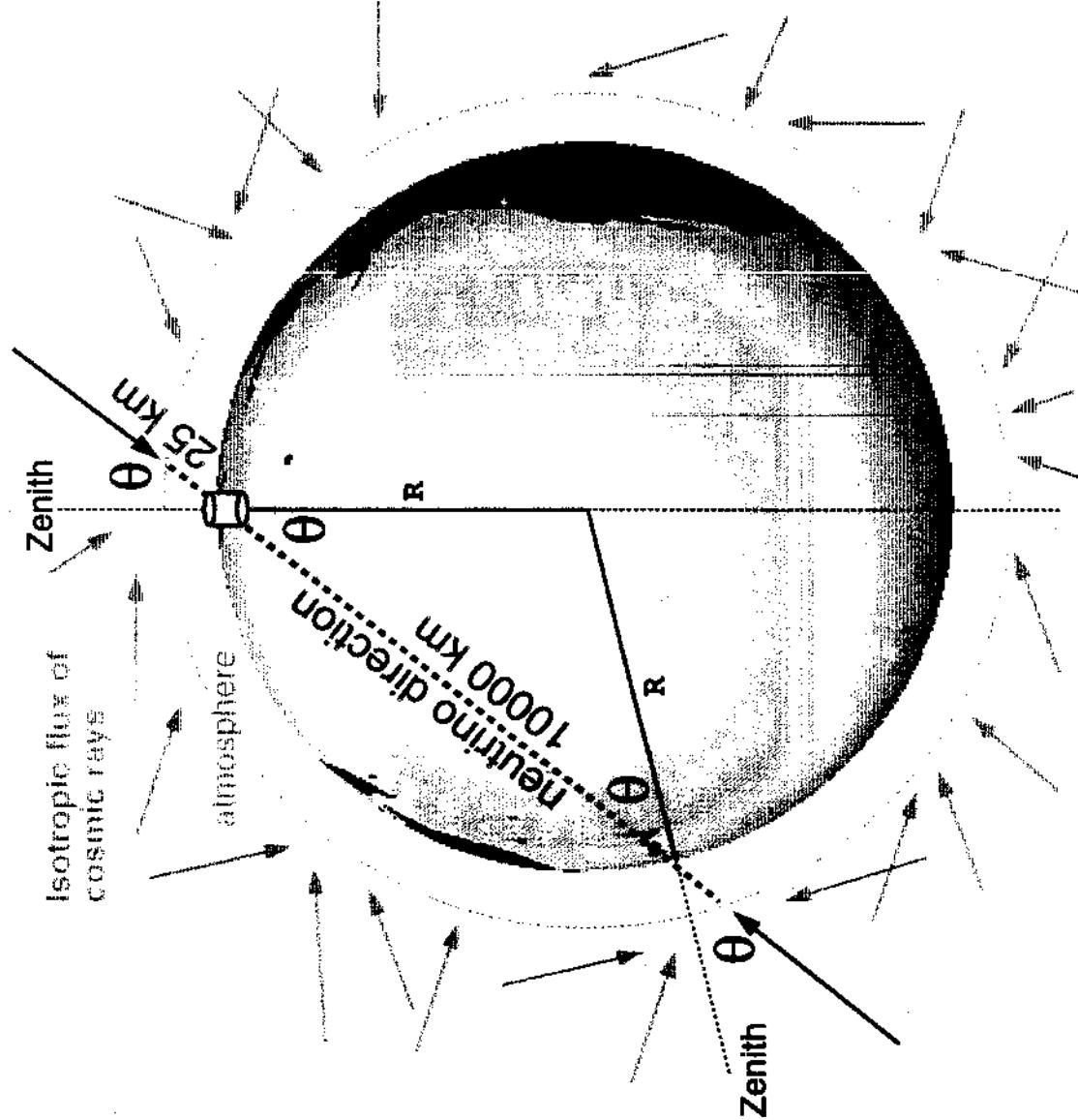
# Atmospheric Neutrino Experiments

and Long Baseline Neutrino Beams



Others: NUSEX, Trejus, Baksan, SNO

# Up-Down Symmetric Flux



- above a few GeV - no geomagnetic effect
- enhancement at horizon due to pion survival

# Super-Kamiokande

## SK-1 1996 - 2001

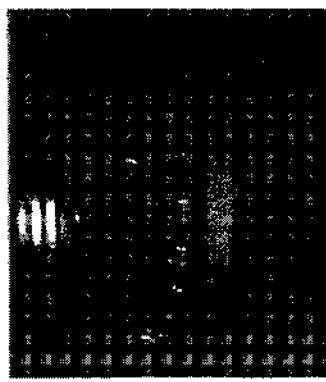
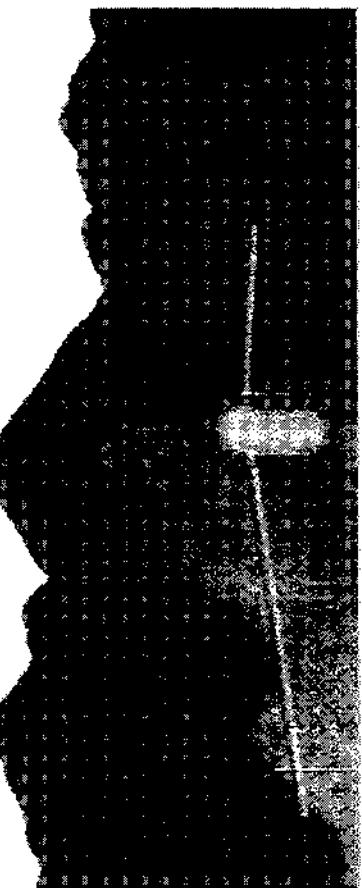
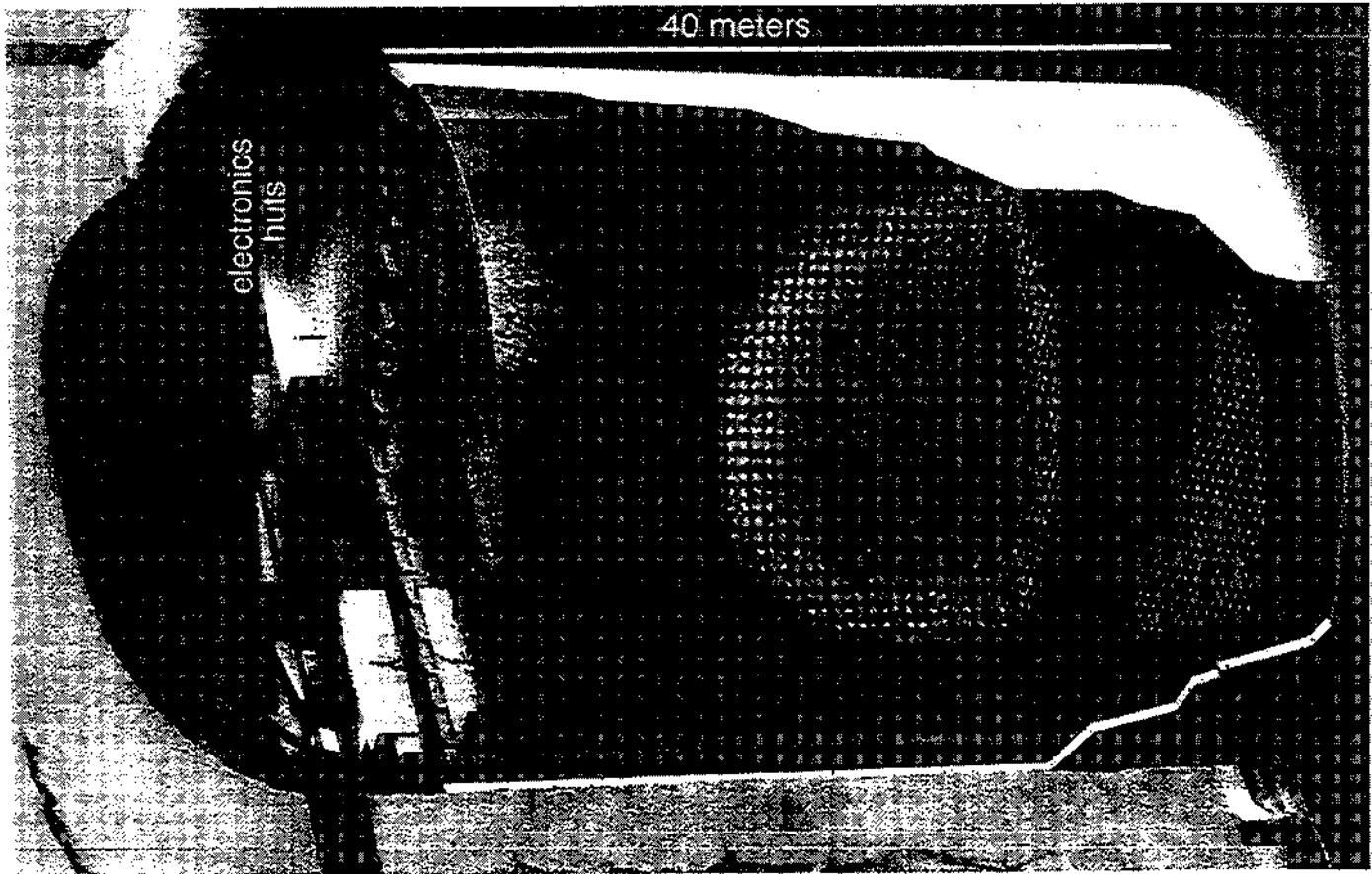
- 22.5 kton fiducial mass (2m from wall)
- 11134 50-cm photomultiplier tubes
- 40% photocathode coverage
- 1885 20-cm pmnts in outer detector

## SK-2 2003 - 2006 (estimated)

- 5183 PMTs, mostly recovered from accident
- ~20% coverage with acrylic shields →
- outer detector fully restored
- K2K beam resumed

## SK-3 2006

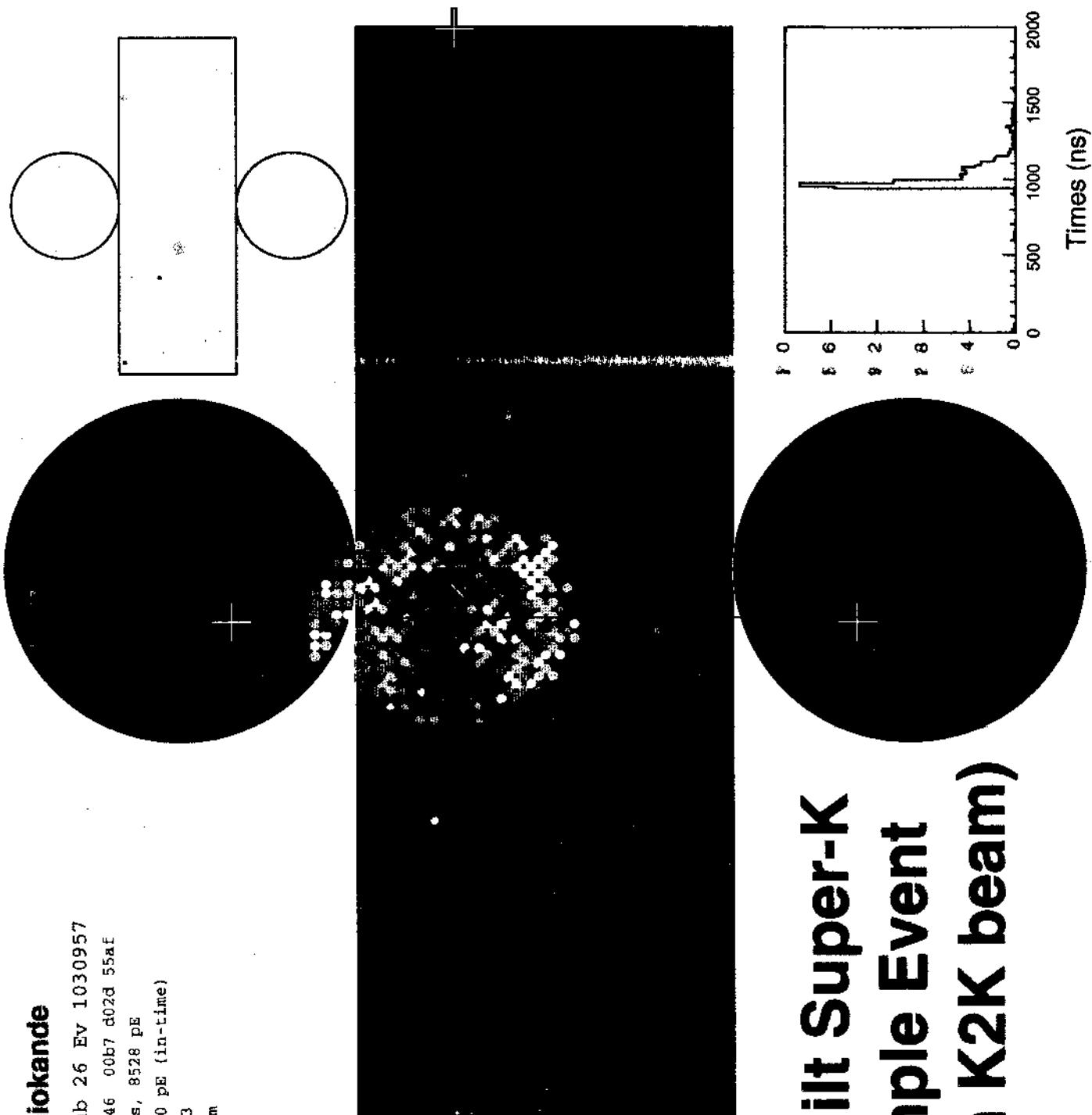
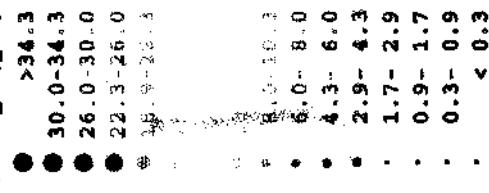
- original coverage to be restored
- JHF v off-axis beam



## Super-Kamiokande

Run 21703 Sub 26 Ev 1030957  
03-02-08:19:24:46 00b7 d02d 55af  
Inner: 1289 hits, 8528 pE  
Outer: 2 hits, 0 pE (in-time)  
Trigger ID: 0x03  
D wall: 945.2 cm

### charge (pe)



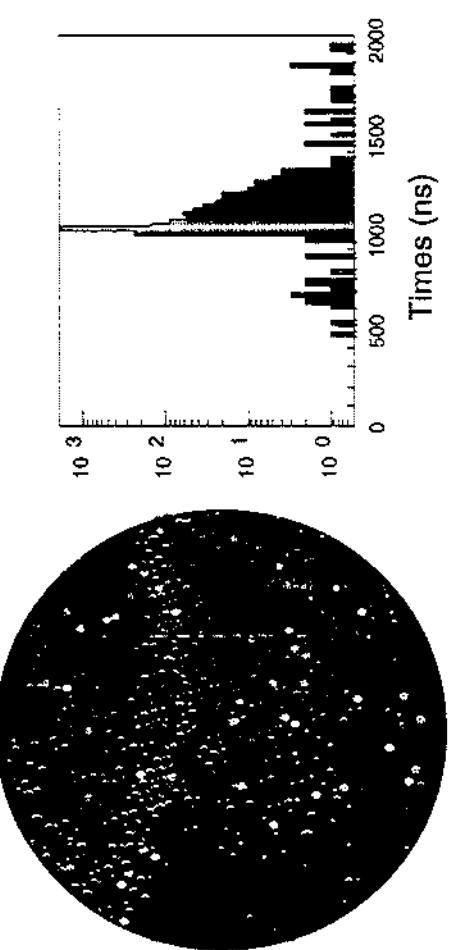
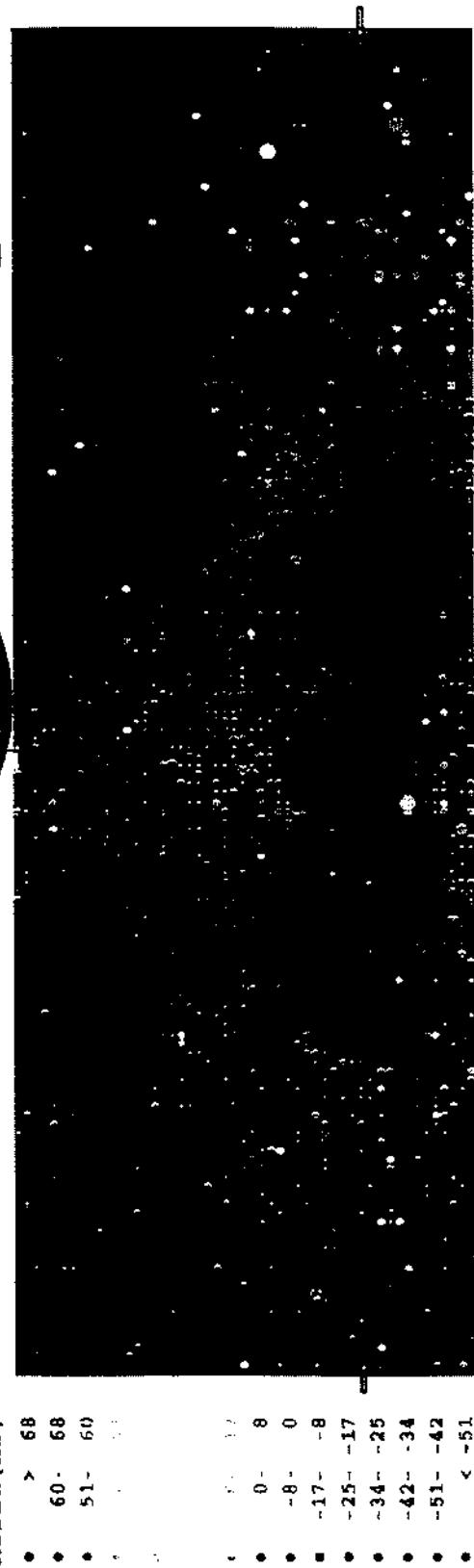
# Rebuilt Super-K Example Event (from K2K beam)

## Super-Kamiokande

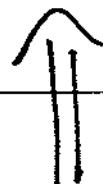
Run 4268 Event 7899421  
97-06-23:03:15:57  
Inner: 2652 hits, 5747 PE

~620 MeV/c

Resid(ns)



for comparison  
**SK-1**  
**e-like**  
**PMT time view**



# Measured Double Ratio

$$\frac{(N_\mu/N_e)_{\text{DATA}}}{(N_\mu/N_e)_{\text{M.C.}}}$$

**SK sub-GeV:**

$$0.638 \pm 0.016 \pm 0.050_{\text{stat.}}$$

Kam. III (sub-GeV)

Kam. III (multi-GeV)

IMB 3 (sub-GeV)

IMB 3 (multi-GeV)

**SK multi-GeV:**

$$0.658 \pm 0.030 \pm 0.078_{\text{stat.}}$$

Frejus

Nusex

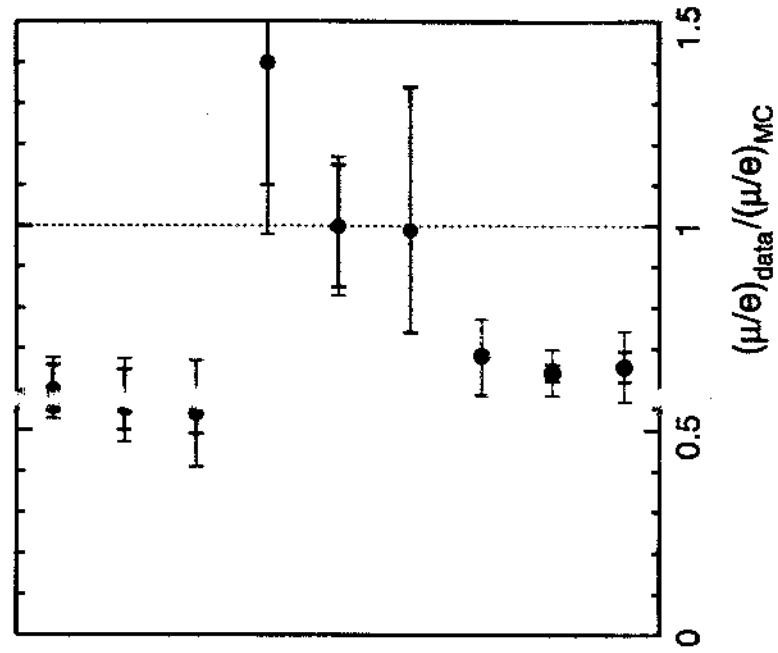
Soudan 2

Super-K (sub-GeV)

Super-K (multi-GeV)

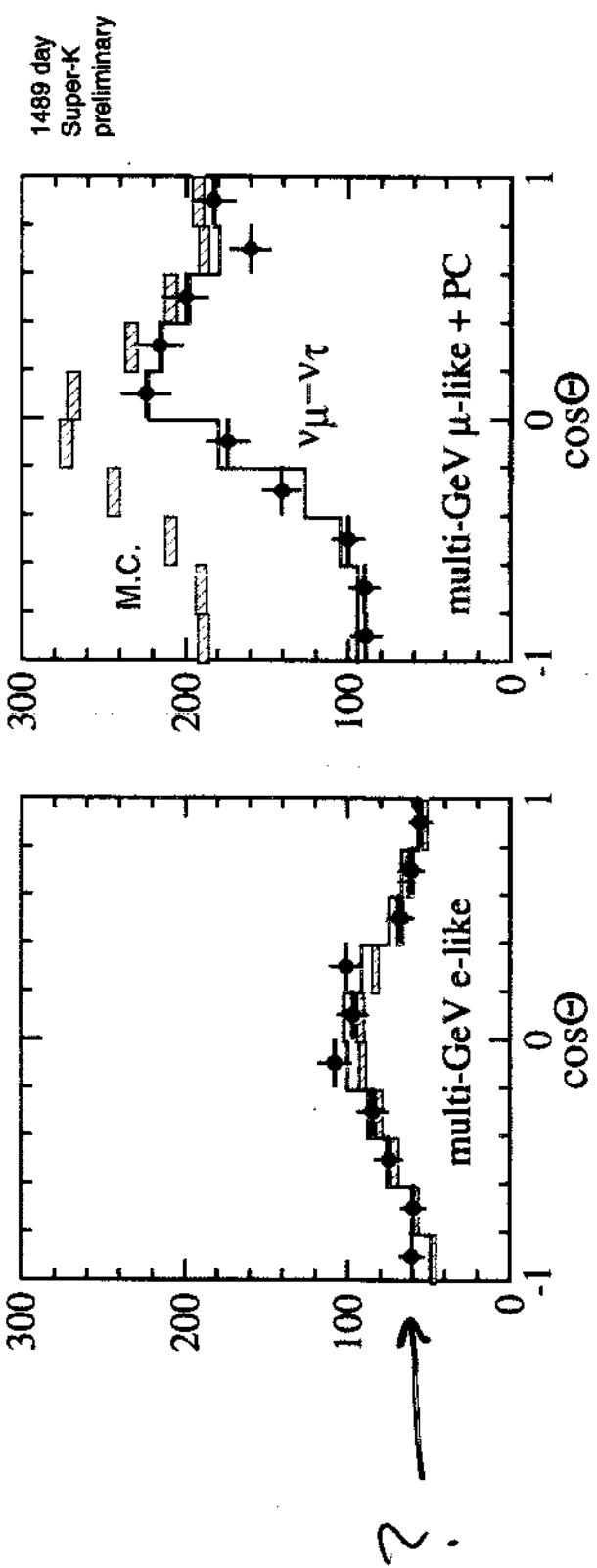
**Soudan 2:**

$$0.68 \pm 0.12_{\text{total}}$$



# Measured Up-Down Asymmetry

$$\text{SK multi-GeV: } \left( \frac{N_{\text{UP}} - N_{\text{DOWN}}}{N_{\text{UP}} + N_{\text{DOWN}}} \right)_{\mu\text{-like}} = -0.288 \pm 0.028 \pm 0.004_{\text{stat. sys.}} > 10\sigma \text{ deviation!}$$



Neutrino travel distance: 12800 6200 700 40 15 km

$$(\sin^2 2\theta, \Delta m^2) = (1.00, 2.5 \times 10^{-3} \text{ eV}^2)$$

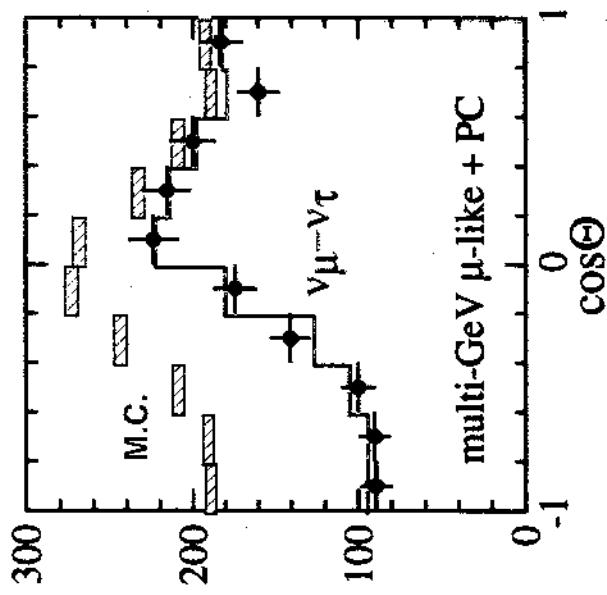
$$\chi^2 \sim 1 \text{ d.o.f. } \nu_e \leftrightarrow \bar{\nu}_e$$

overall fit.

# Interpretation of Neutrino Oscillation

Atmospheric Neutrino Data ...

is described by:

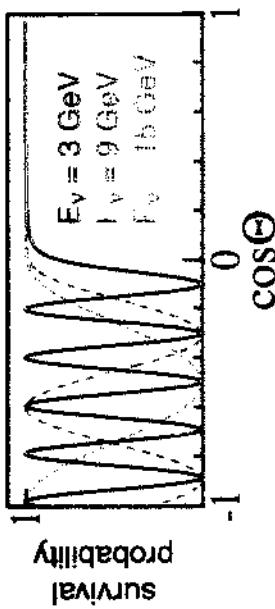


Two flavor neutrino oscillations

$$P(\nu_\mu - \nu_\tau) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right)$$

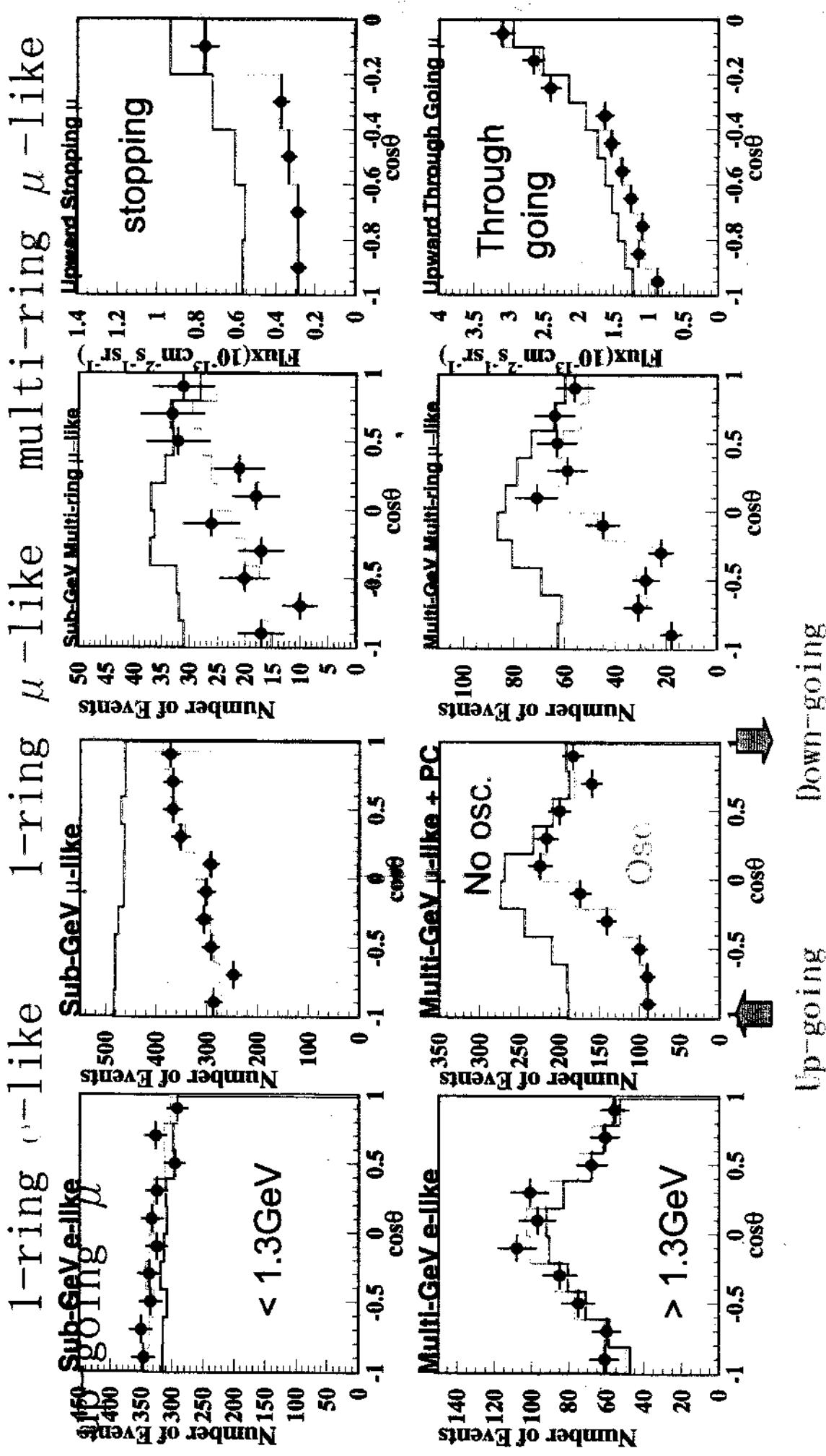
with oscillation parameters of  
 $\Delta m^2 \sim 3 \times 10^{-3} \text{ eV}^2$     $\sin^2 2\theta \sim 1$

12800   6200   700   40   15 km  
Neutrino travel distance ( $L$ )



# SK atmospheric neutrino data

1489day FC+PC data + 1678day upward going muon data



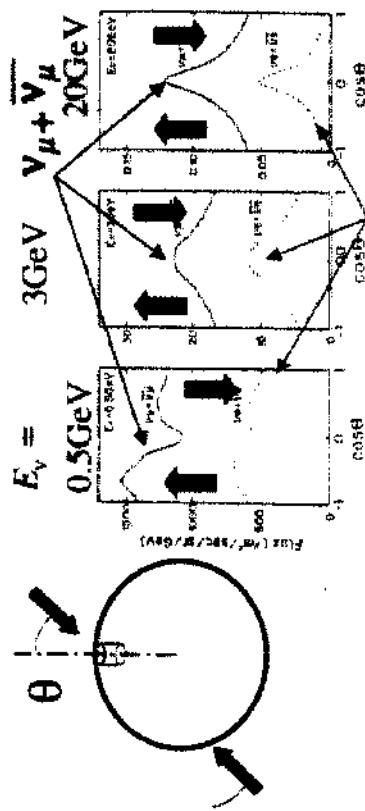
# Super-K

## II. Atmospheric neutrinos

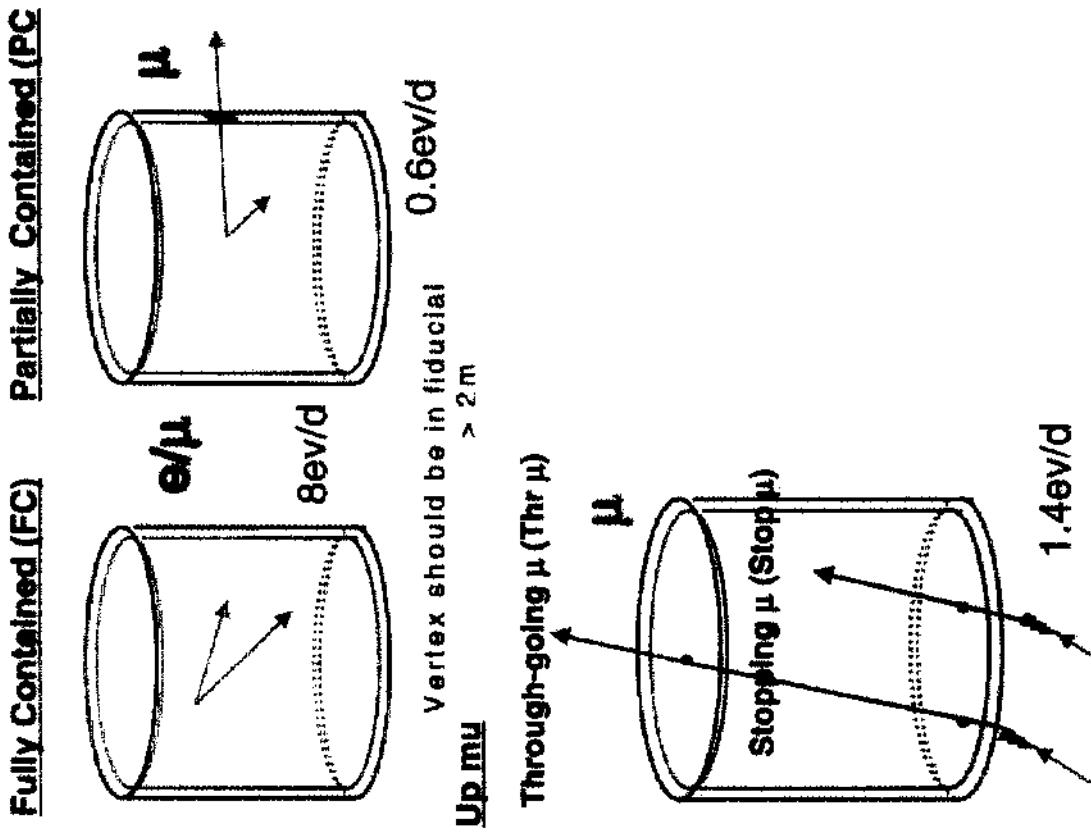
$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} : \delta(\text{ratio}) \sim 5\%, (\delta(\text{flux}) \sim 25\%)$$

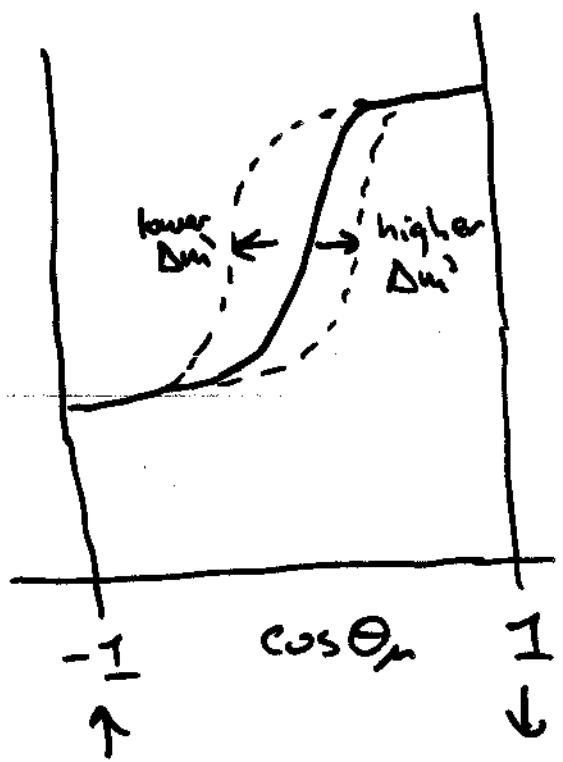
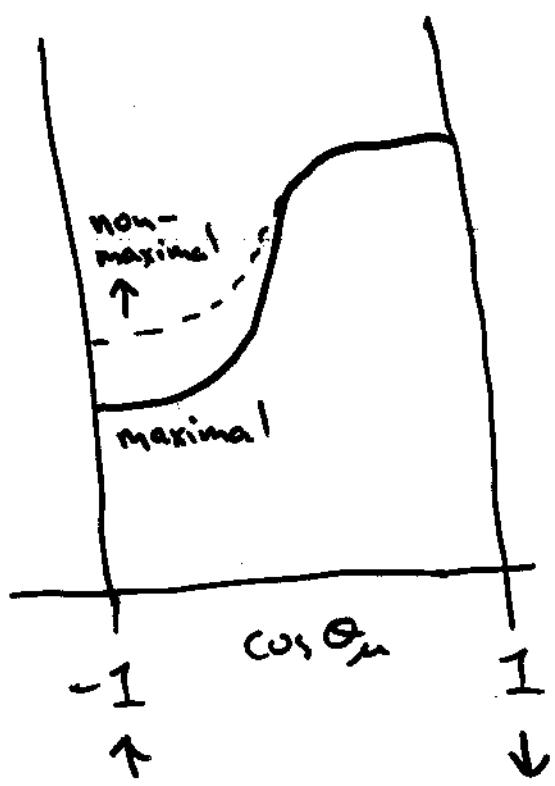
$$\rightarrow \left| \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \right| \text{ Data} / \left| \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \right| \text{ MC} \neq 1$$

for neutrino oscillations

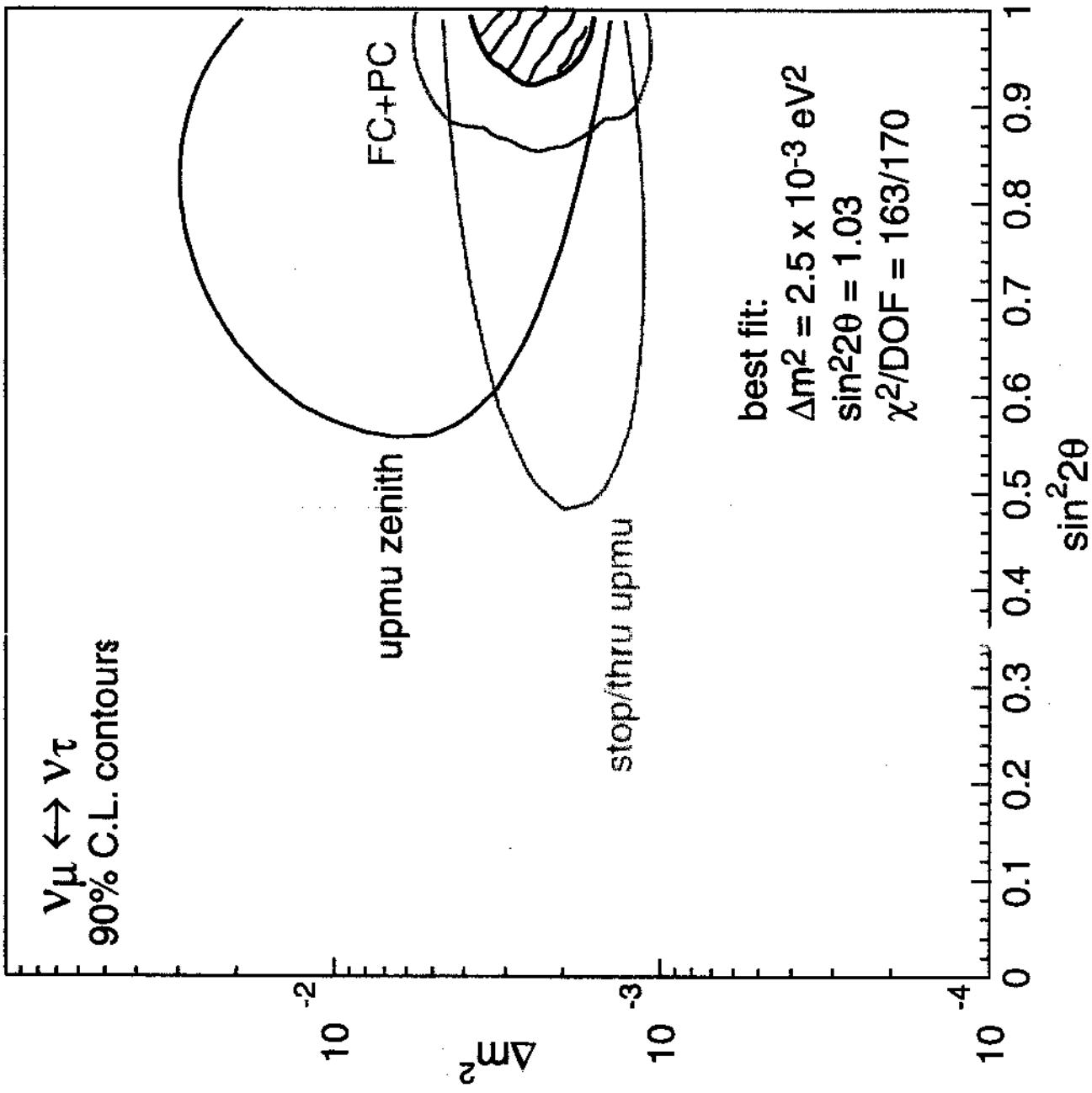


For  $E_\nu > \text{a few GeV}$ ,  
Upward / downward = 1 (within a few %)  
Up/Down asym. for neutrino oscillations

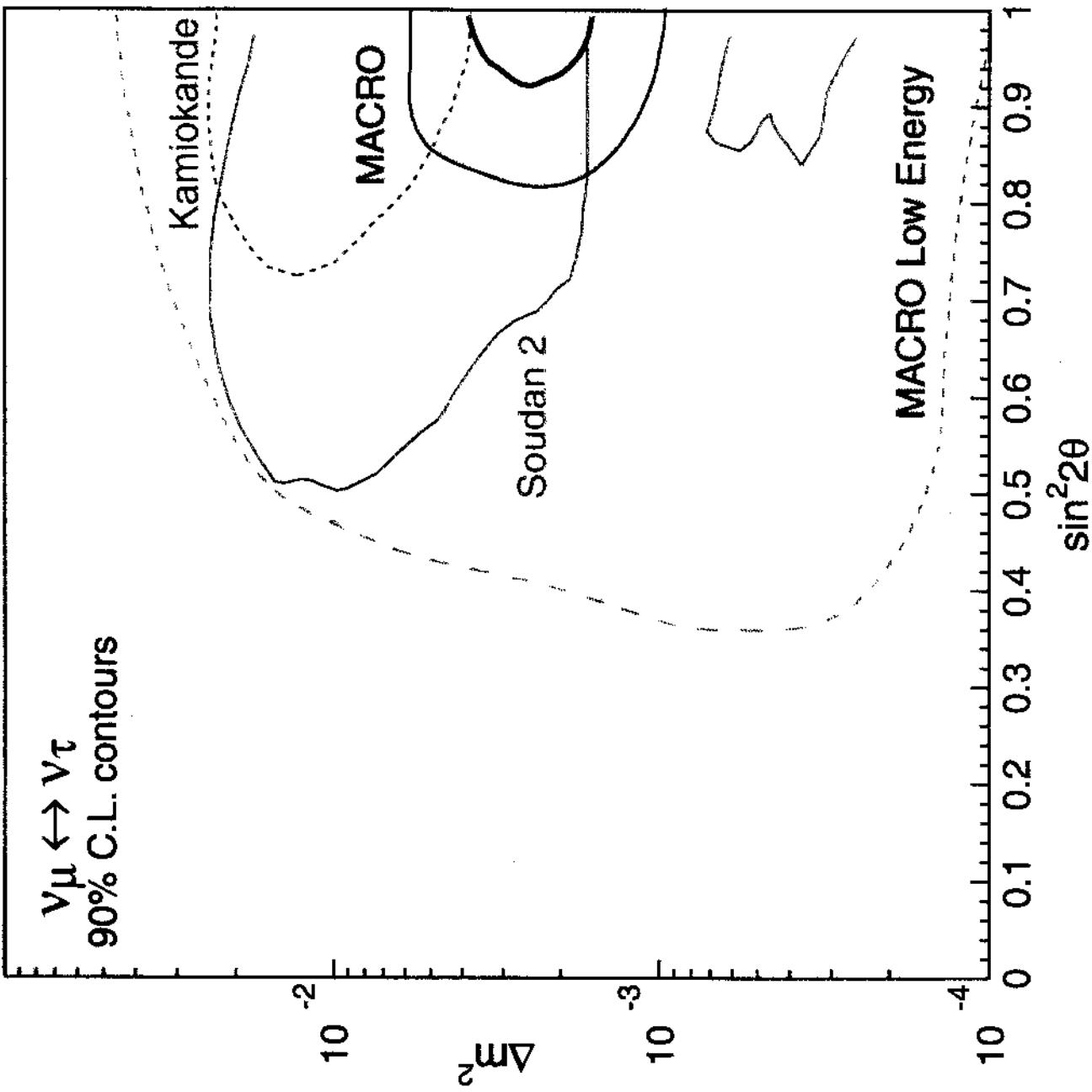




# Allowed Regions from Super-K Analyses



# Allowed Regions from Several Experiments





## Atmospheric Neutrinos

## Long Baseline Neutrinos

mixed beam of  $\nu_\mu \bar{\nu}_\mu \nu_e \bar{\nu}_e$

wide energy band 200 MeV - 1 TeV

continuous flux - free

multiple baselines 10 km - 13000 km

neutrino direction unknown

nearly pure beam of  $\nu_\mu$

narrow energy band, adjustable

pulsed flux - expensive

fixed baseline 250 / 750 km so far

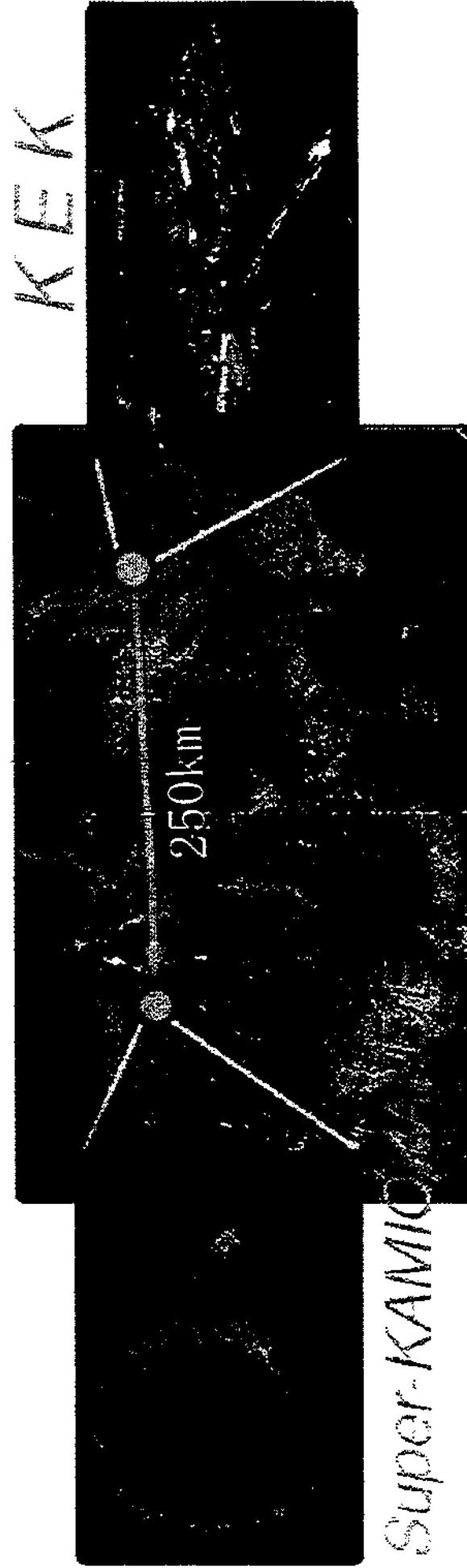
neutrino direction known

**first solid evidence for  
neutrino oscillation ...**

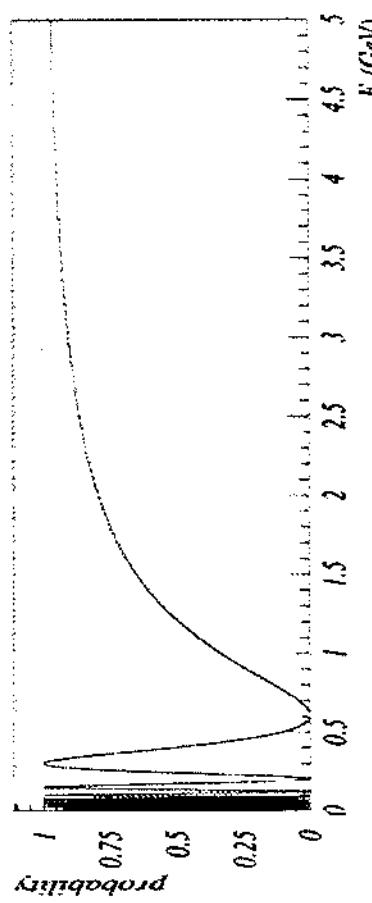


**motivates and  
suggests design for  
long baseline experiments**

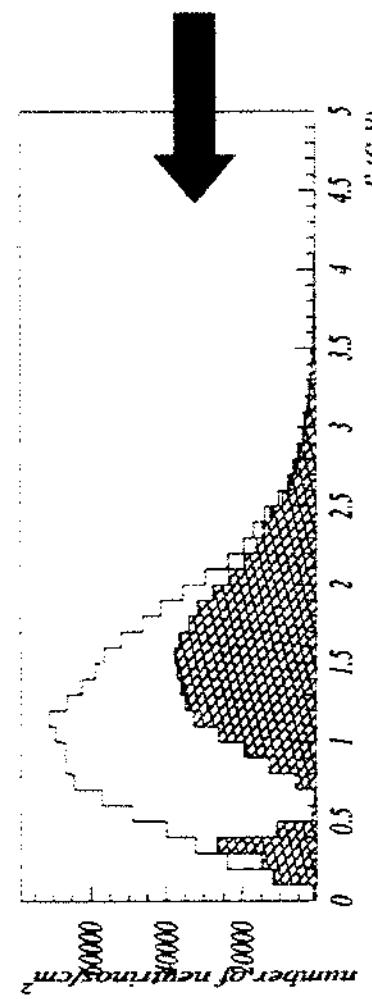
# K2K



Neutrino Oscillation ( $\Delta m^2 = 0.003 \text{ eV}^2$ )



$E_\nu$

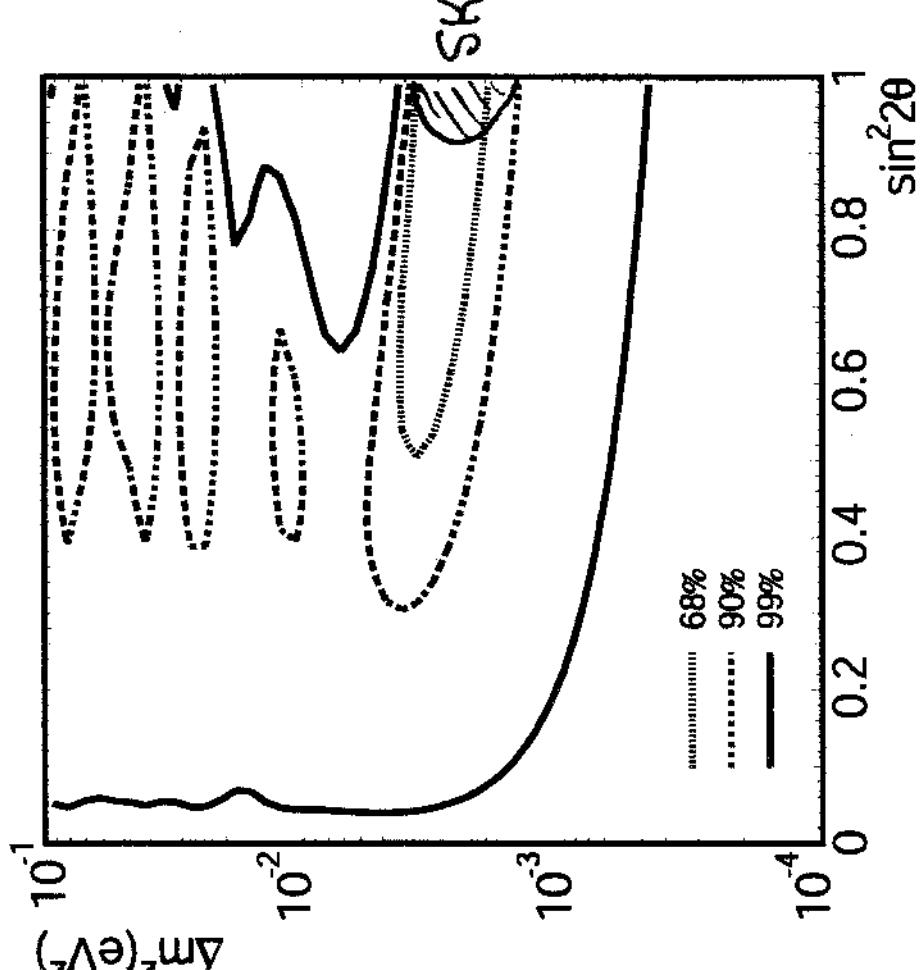
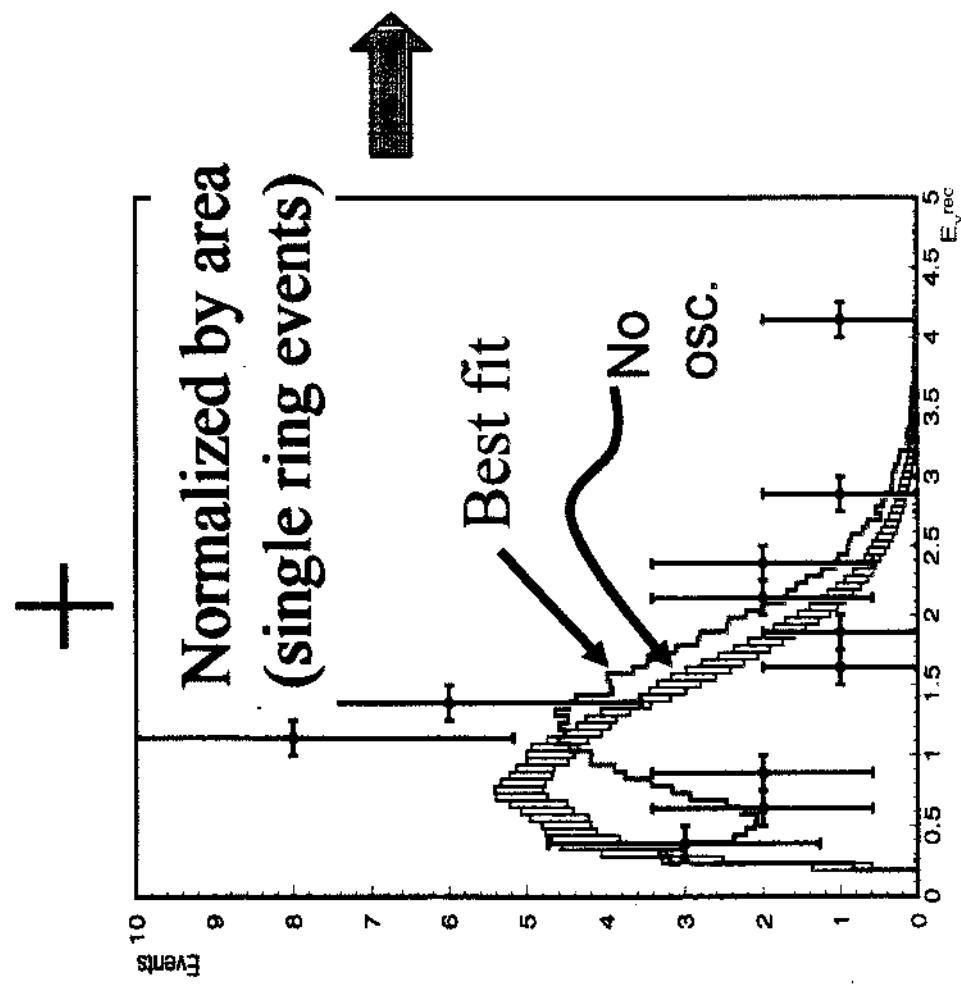


$E_\nu$

# K2K data and oscillation

Data: 1999 – July 2001

N<sub>SK</sub> (# of event)  
**56 events observed**  
**80.1+6.2/-5.4 ev. expt'd**  
null oscillation prob. 1.3%

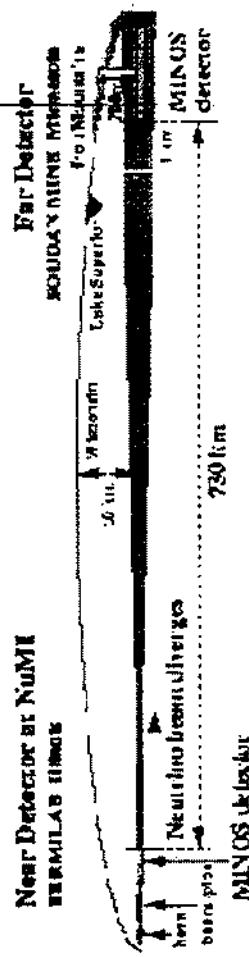


**Best fit point ( $\sin^2 2\theta, \Delta m^2$ )**  
 $= (1.0, 2.8 \times 10^{-3} \text{ eV}^2)$   
Consistent with SK atm.

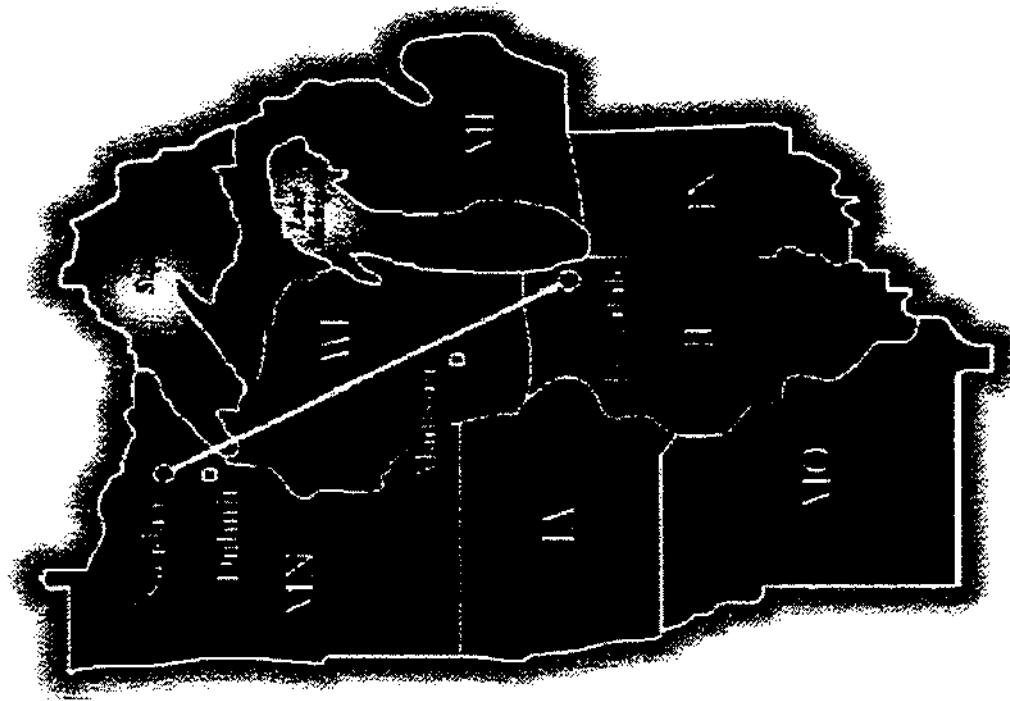


# MINOS

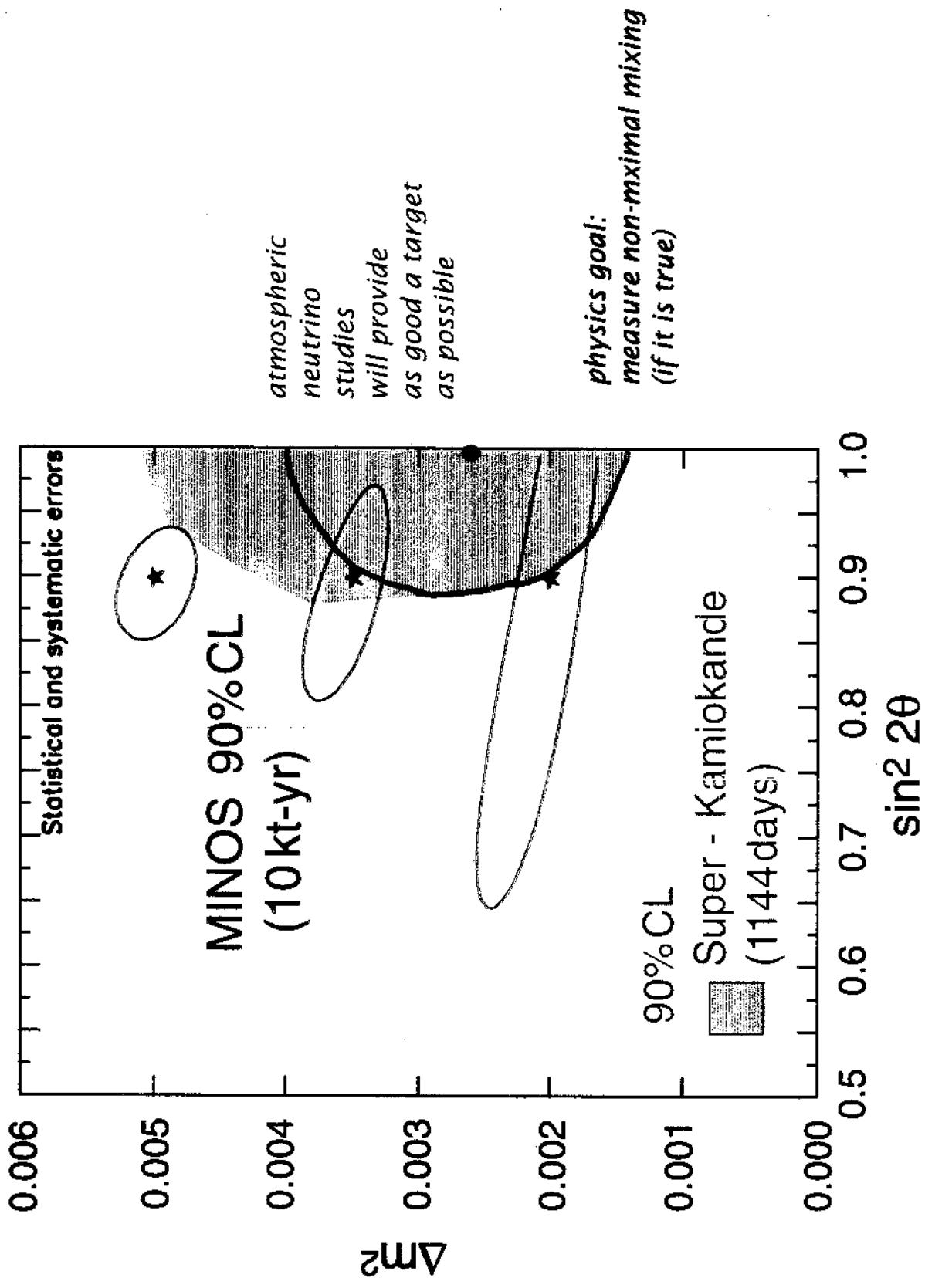
Long-baseline experiment at Fermilab



- Beam travels 735 km to Soudan Minnesota
- Sagitta: 10 km
- 1 km wide at destination



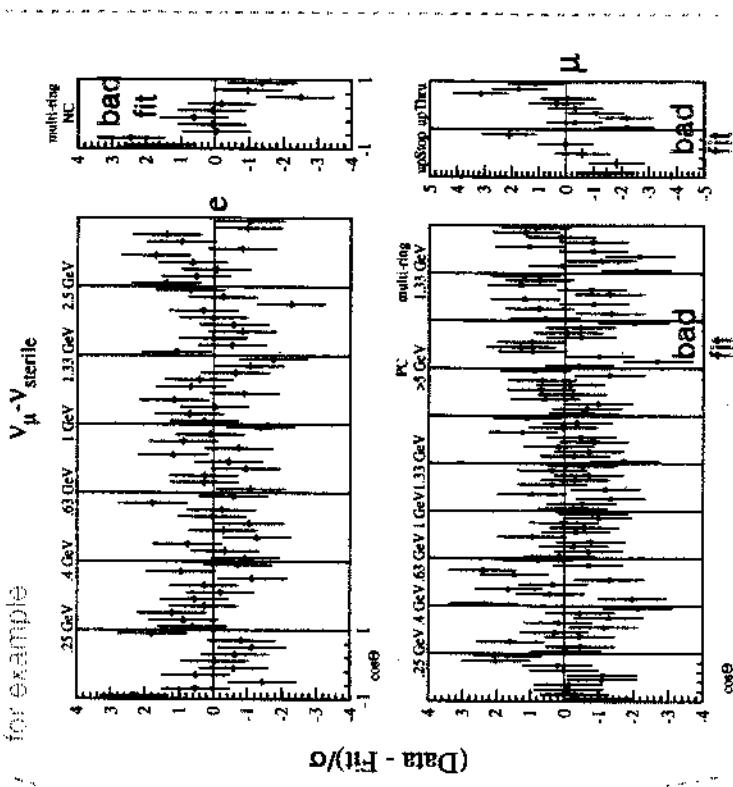
# Atmospheric Neutrinos + Long Baseline Neutrinos Goal: Good Comparison



# Check SK data against alternatives to $\nu_\mu - \nu_\tau$

FC: 10 zenith angle×7 momentum bins  
 PC: 10 zenith angle bins  
 up Step 5 zenith angle bins  
 up Thru 10 zenith angle bins  
 multi-Ring  $\mu$ -like 10 zenith angle bins×2 momentum bins  
 multi-Ring NC-like 10 zenith angle bins

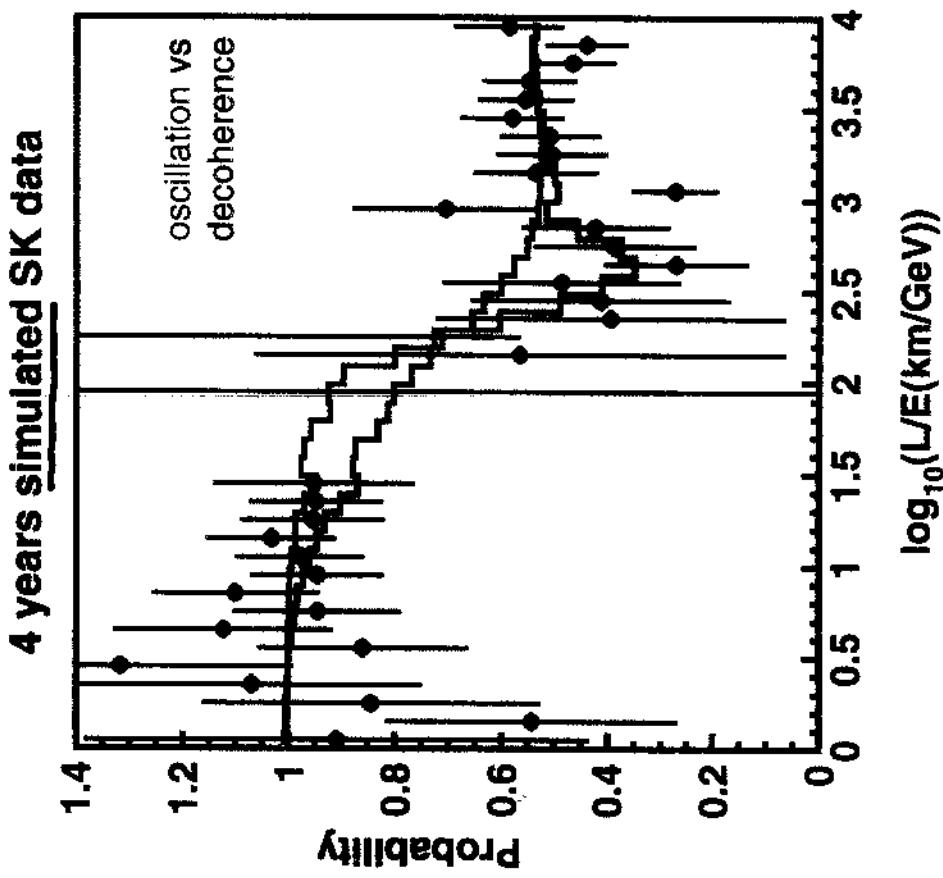
| Mode   | Best Fit                                       | $\chi^2$ | P( $\chi^2$ ) | $\Delta\chi^2$ | $\sigma$      |
|--|--|----------|---------------|----------------|---------------|
| $\nu_\mu - \nu_\tau$<br>$\sin^2 2\theta = 1.00$  | $\sin^2 2\theta = 1.00$                        | 173.8    | 79%           | 0.0            | 0.0           |
| $\sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$<br>$\Delta m^2 = 2.1 \times 10^{-3} \text{ eV}^2$                           | $\Delta m^2 = 2.1 \times 10^{-3} \text{ eV}^2$ | 284.3    | 0.001%        | 110.5          | 10.5 $\sigma$ |
| $\nu_\mu - \nu_e$<br>$\sim \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$<br>$\Delta m^2 = 5.1 \times 10^{-3} \text{ eV}^2$ | $\Delta m^2 = 5.1 \times 10^{-3} \text{ eV}^2$ | 222.7    | 5%            | 48.9           | 7.0 $\sigma$  |
| $\nu_\mu - \nu_s$<br>$\sim \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$<br>$\Delta m^2 = 2.9 \times 10^{-3} \text{ eV}^2$ | $\sin^2 2\theta = 0.98$                        | 281.6    | 0.002%        | 107.8          | 10.4 $\sigma$ |
| $L \times E$<br>$\sin^2 2\theta \sin^2(\alpha L \times E)$<br>$\alpha = 5.6 \times 10^{-4} / \text{GeV/km}$              | $\cos^2 \theta = 0.50$                         | 279.4    | 0.003%        | 105.6          | 10.3 $\sigma$ |
| $\nu_\mu$ Decay<br>$\sin^4 \theta + \cos^4 \theta \exp(-\alpha L/E)$   | $\alpha = 3.7 \times 10^{-3} \text{ GeV/km}$   | 194.0    | 41%           | 20.2           | 4.5 $\sigma$  |
| $\nu_\mu$ Decay<br>$(\sin^2 \theta + \cos^2 \theta e^{-\alpha L/2E})^2$  | $\sin^2 2\theta = 0.98$                        | 184.3    | 64%           | 10.5           | 3.2 $\sigma$  |
| $\nu_\mu$ Decoherence<br>$0.5 \sin^2 2\theta (1 - \exp(-(\gamma E)L/E)) \gamma = 7.3 \times 10^{-3} \text{ GeV/km}$      |  | 427.4    | 0%            | 252.4          | 15.9 $\sigma$ |
| No Oscillations  |  |          |               |                |               |



matter effects suppress high energy  
 $\nu_\mu$ -sterile oscillation  
 neutral current should disappear  
 $\nu_\mu$ -sterile oscillation

neutral current oscillation  
 for  $\nu$  sterile oscillation

# Super-K can try this analysis too...

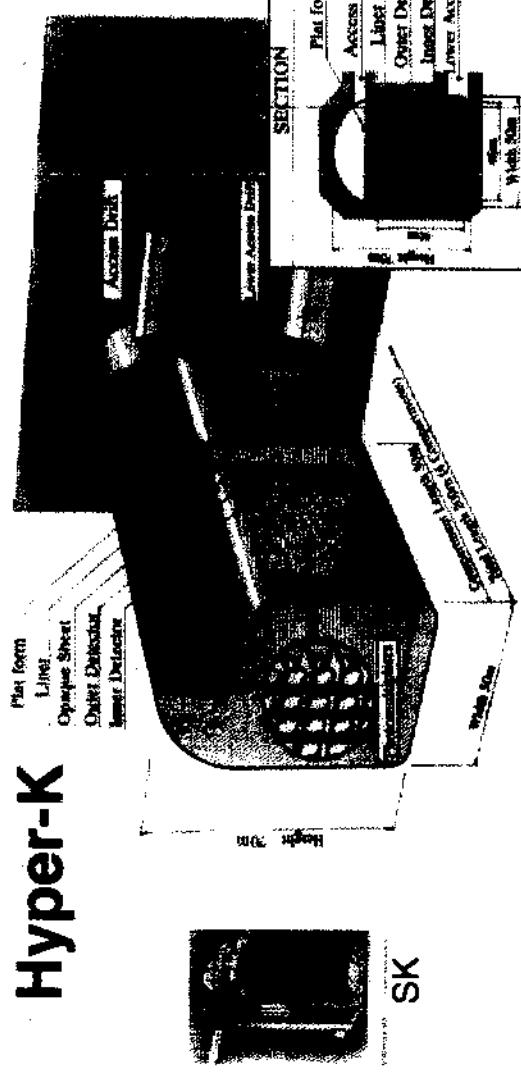


SK-1 may say something at  $\sim 2\sigma$   
continued running with SK-2 will help.

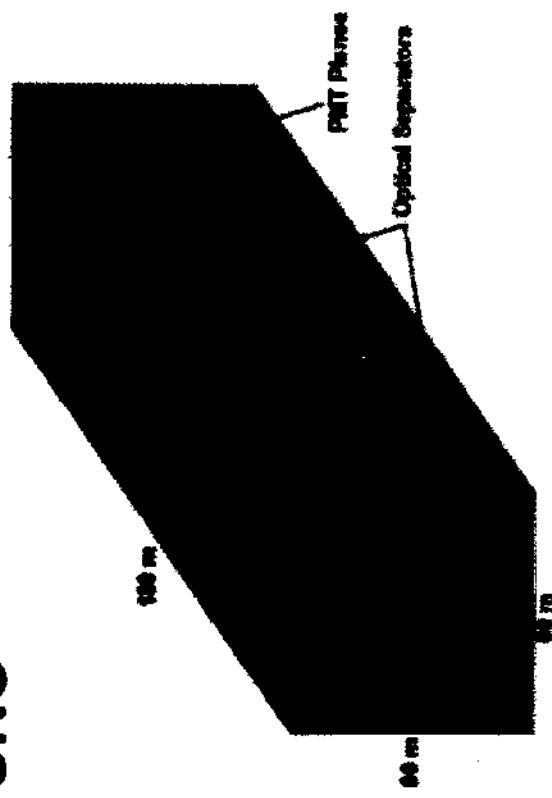
$$P = \exp(-\gamma L/\epsilon) + \frac{1}{2} \sin^2 2\theta (1 - \exp(-\gamma L/\epsilon))$$

# Future Large Water Cherenkov

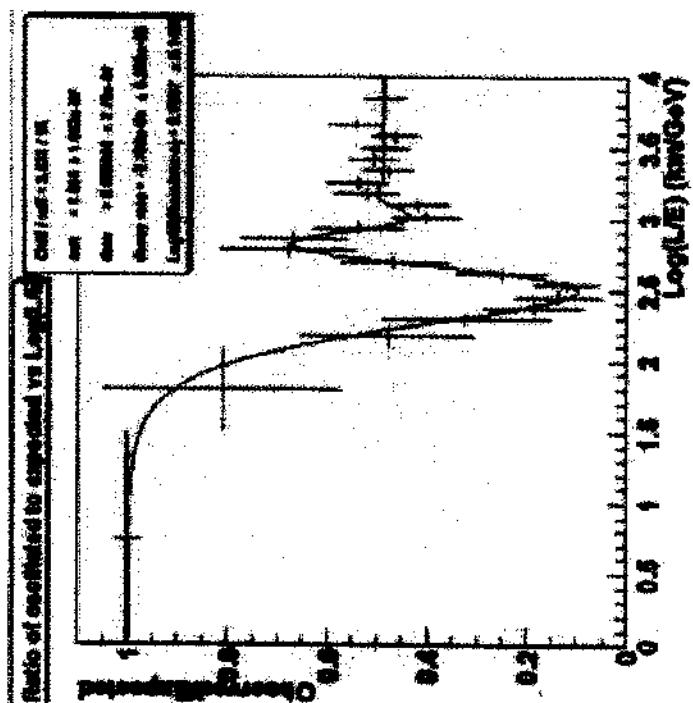
## Hyper-K



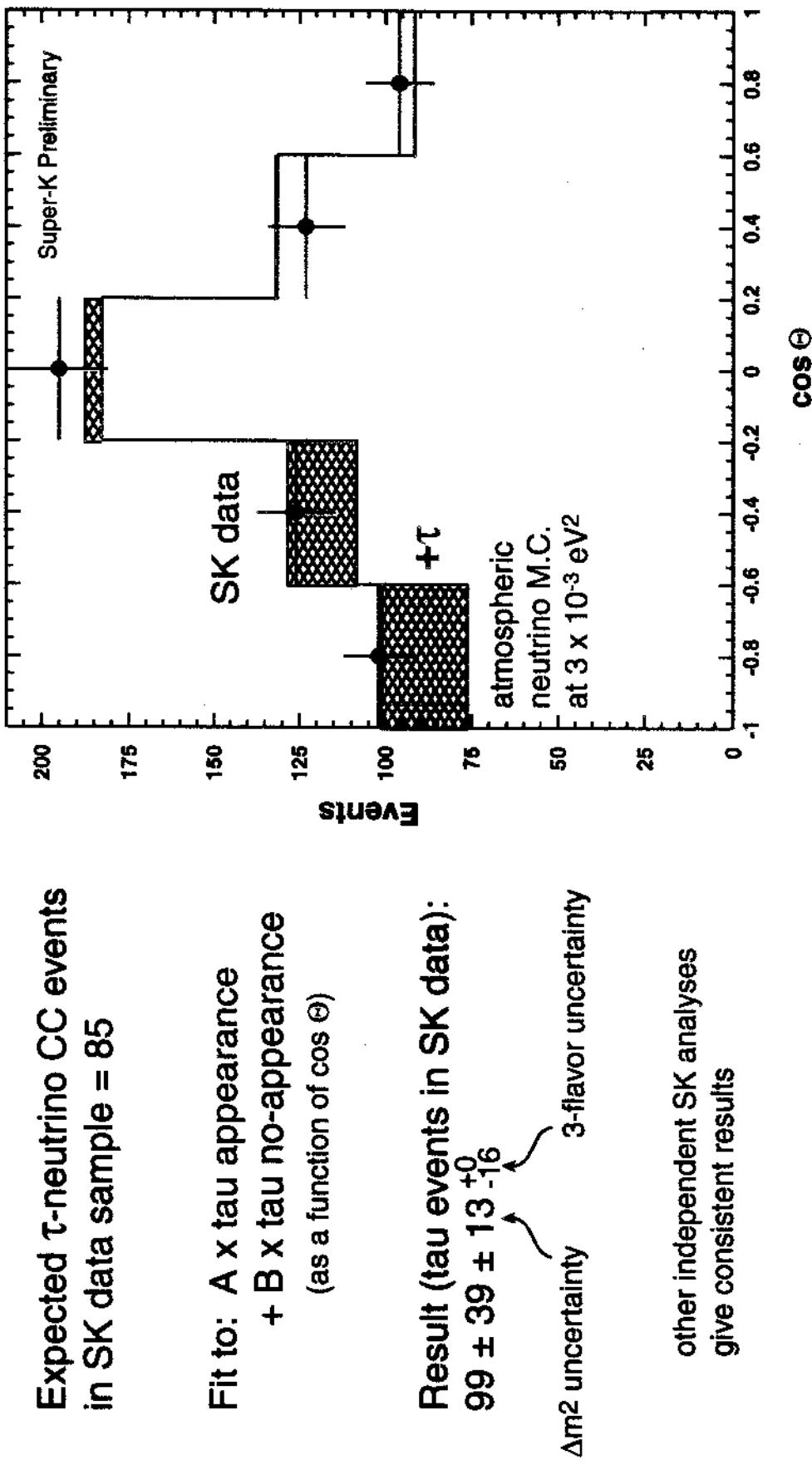
UNO



*Can contain high energy muons  
because of large size ... allowing  
good L and E measurement*

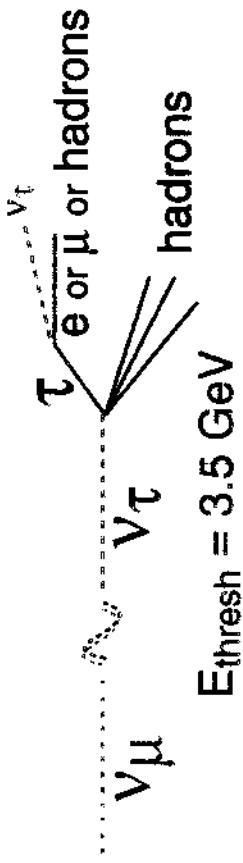


# Super-K Tau Appearance Result:



SK data is consistent with presence of CC tau neutrino interactions

# Tau Appearance Studies

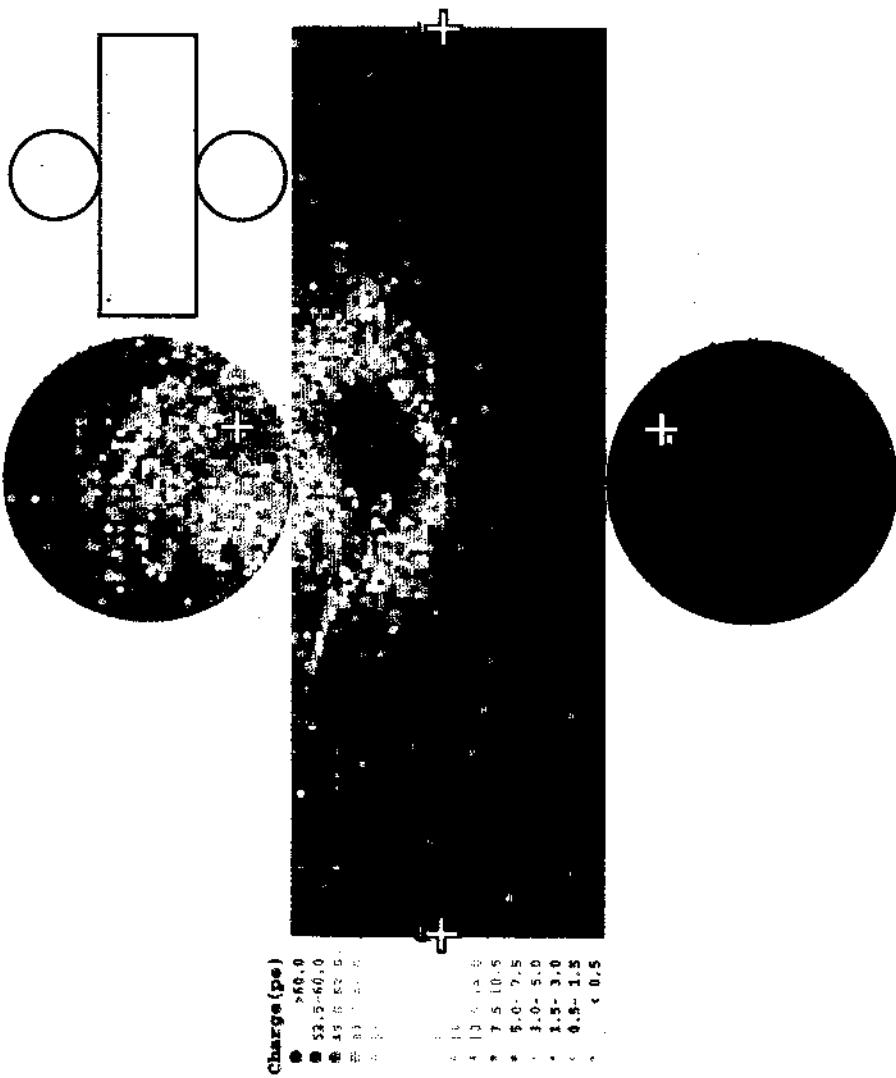


for  $\sin^2 2\theta = 1$  and  
 $\Delta m^2 = 3 \times 10^{-3} \text{ eV}^2$ ,  
we expect  $\sim 85$  events  
in the 1489 day SK sample

events have large visible  
energy ( $> 2 \text{ GeV}$ )

multiple rings  
(not all may be reconstructed)

over threshold,  
only upward-going neutrinos  
have sufficient oscillation length



generally speaking... rather difficult events to exclusively identify

## Atmospheric Neutrinos

- Compelling Evidence for Neutrino Oscillations:

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

$$P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2 2\theta_{\text{atm}} \sin^2 \frac{\Delta m_{\text{atm}}^2 L}{4E}$$

$$|\Delta m_{\text{atm}}^2| \approx 1.6 - 3.9 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta_{\text{atm}} > 0.91$$

- K2K (first long ( $> 100 \text{ km}$ ) ~~long baseline~~<sup>exp</sup>)  
Consistent with Atmospheric  $\nu_S$ .