united nations educational, scientific and cultural organization

international atomic energy agency

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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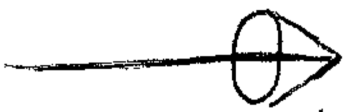
ν98, @Takayama
June 1998

Atmospheric neutrino results from Super-Kamiokande & Kamiokande
— Evidence for ν_μ 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 [Times]

VOL. CXLVII . . . . No. 51,179 — 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.

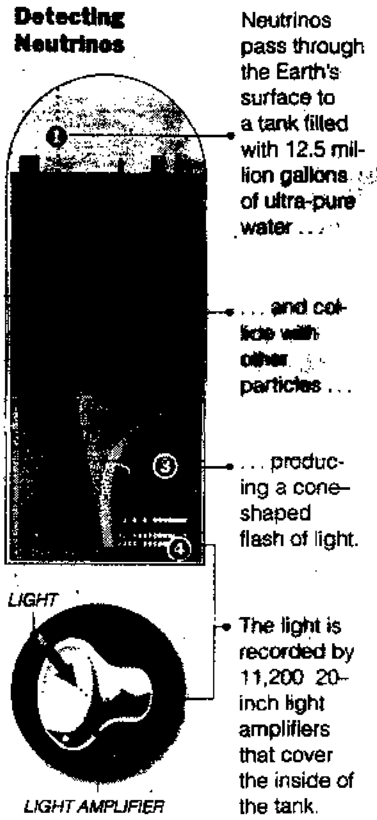
Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence 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 collected 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 [...]

Refugee[s] A Bitte[r]

PADESH, Albania, [...] dent Slobodan Milose[vic] [...] via has unleashed th[e] [...] tary operation in the [...] the end of the war in [...] thousands of ethnic A[...] the border area with [...] reducing their village[s] [...]

At least 10,000 [...] streamed through [...] passes and thousands [...] ing in forests on the o[...] border, according to [...]

Neutrino Physics

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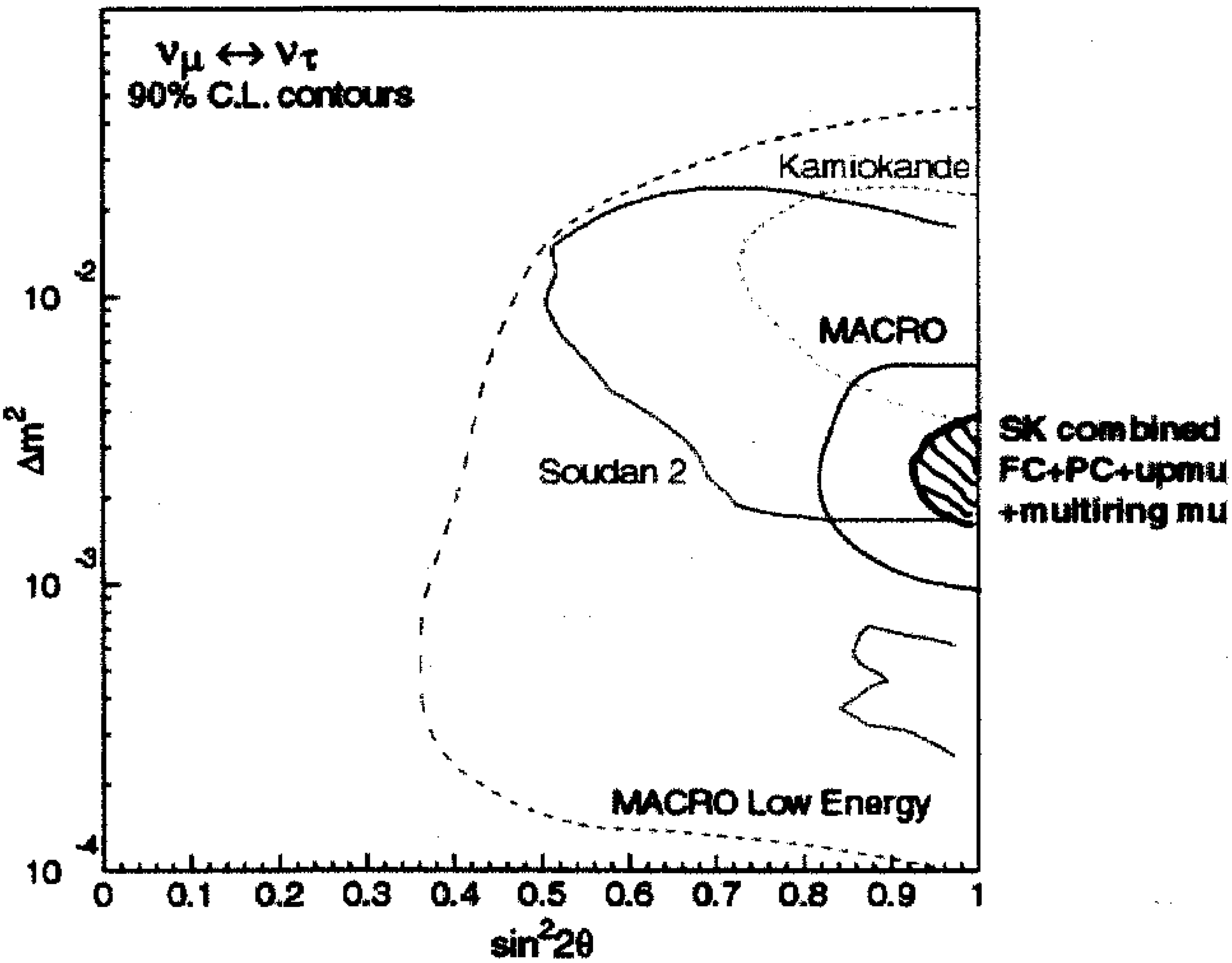
Series Outline:

- Neutrino Oscillations (2 flavors)
  - vacuum (atmospheric ν's, K2K)
  - matter (solar ν's, KAMLAND)
- 3 or more flavors
- θ_{13} and CP or T Violations
- Neutrino Mass, $0\nu\beta\beta$ decay etc

Allowed Regions from Several Experiments



KAMLAND + SOLAR (SNO, SK...)

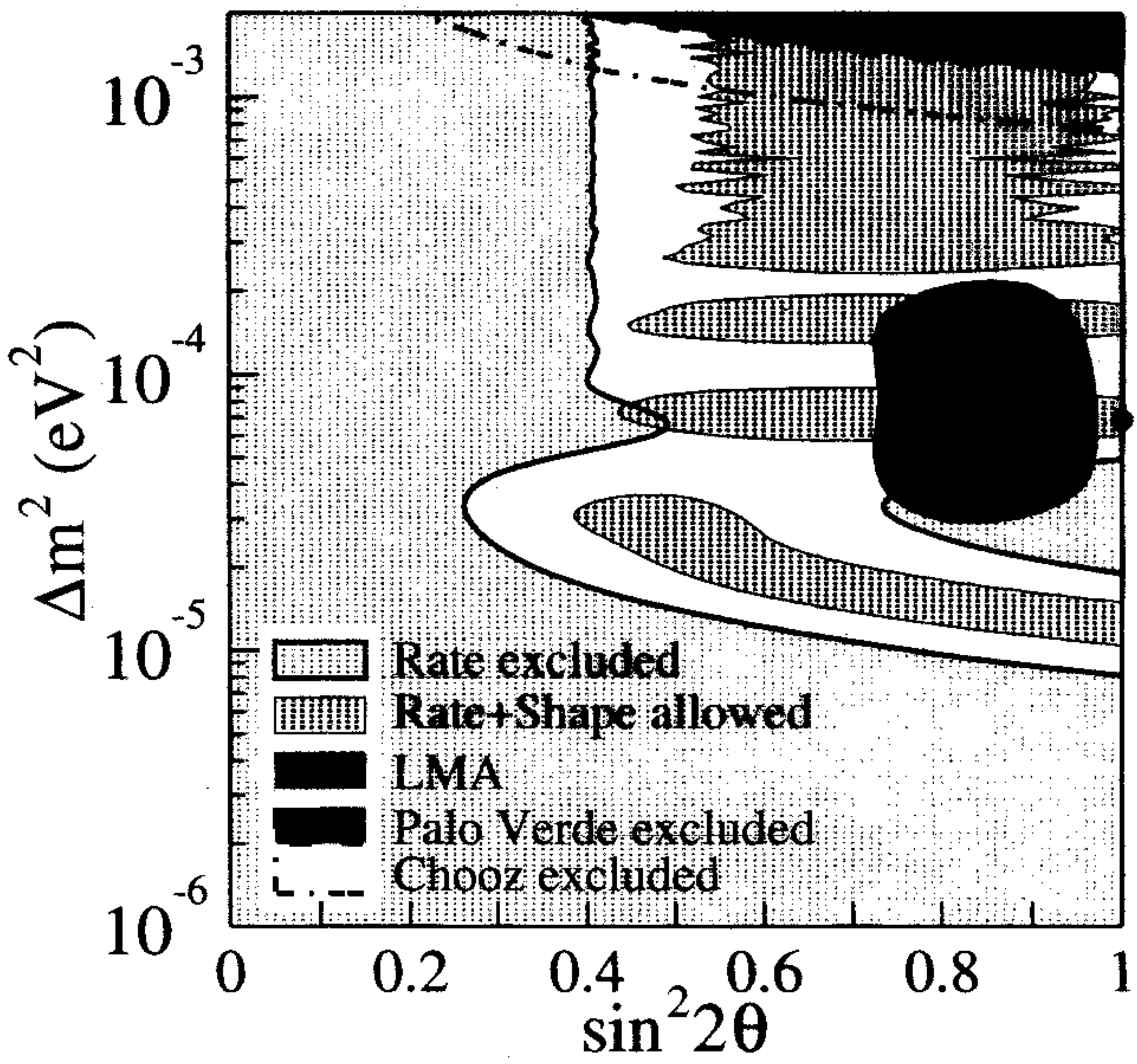


FIG. 6: Allowed regions of neutrino oscillation parameters for the rate analysis and the combined rate and shape analysis from KamLAND at 95% C.L. At the top are the 95% C.L. excluded region from CHOOZ [15] and Palo Verde [16] experiments, respectively. The 95% C.L. allowed region of the 'Large Mixing 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 $\Delta m^2 = 6.9 \times 10^{-5}\mathrm{eV}^2$. All regions look identical under $\theta \leftrightarrow (\pi/2 - \theta)$ except for the LMA region.

Neutrinos (ν)

- very light ($< 10^{-6}\, M_{electron}$)
- weakly interacting
  (pass thru light-years of Pb!)
- electrically neutral
- basic building block of Universe.

The pre-Revolution Neutrino

- Standard Model (Weinberg 1968 / Salam Glashow)

  Neutrino had **zero mass**

  and **no mixing**.

  ν_L , $\overline{\nu}_R$ — cf electron: e_L $\overline{e}_R$, e_R $\overline{e}_L$

  (for Dirac Mass one needs to add ν_R, $\overline{\nu}_L$; Majorana Mass term $\nu\bar{\nu}\phi\phi$ is dimension 5)

- Direct Measurements

  assuming no mixing

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

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

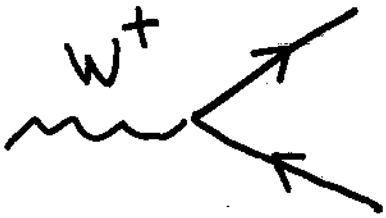
$$M_{\nu_\tau} < 18\,MeV$$

– new indications suggest $M_{\nu_3} \gtrsim \frac{1}{20}\,eV$

Neutrino Oscillations

flavor states:

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



ν_e $\quad \nu_\mu \quad \nu_\tau$ ← left handed

OR OR

e^+ $\quad \mu^+ \quad \tau^+$ ← right handed

mass eigenstates:

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

trivial time evolution (multiplication by phase)

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

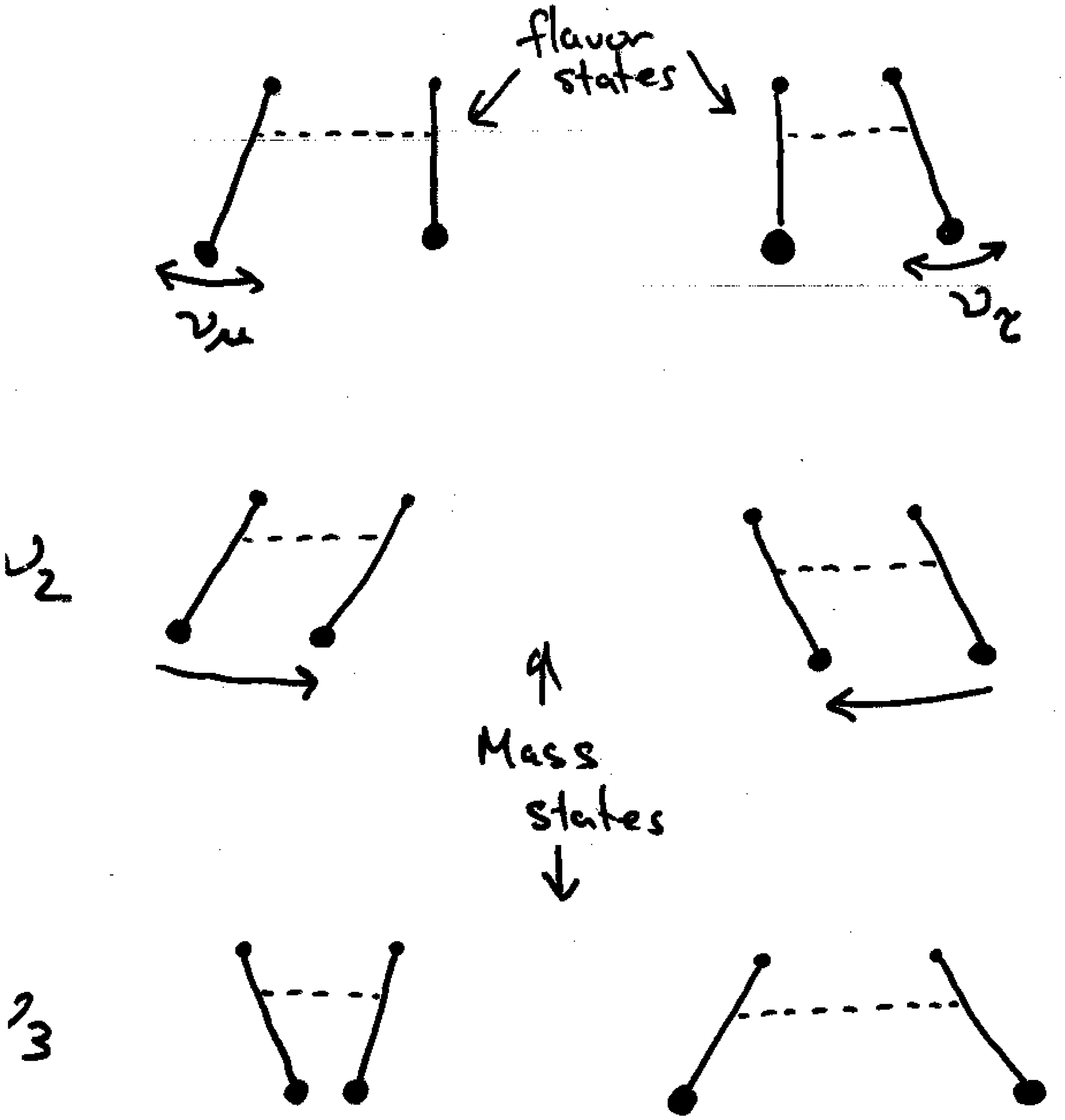
$$= e^{-iE_i t} |\nu_i, 0\rangle$$

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 $\simeq \mathbb{1}$)

related by a Unitary Mixing Matrix

$$\nu_\alpha = \sum_i U^*_{\alpha i} \, \nu_i$$

↑ unitary matrix (PMNS

$\sum_i U^*_{\alpha i} U_{\beta i} = \delta_{\alpha\beta}$ etc

2 x 2 example

$$\begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix}$$

where $\sin\theta \equiv s_\theta$, $\cos\theta \equiv c_\theta$

Suppose we produce a

$$\nu_e = C_\theta \nu_1 + S_\theta \nu_2$$

evolves in time

$$\longrightarrow C_\theta e^{-iE_1 t} \nu_1 + S_\theta e^{-iE_2 t} \nu_2$$

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

$$\cong p + \frac{m_i^2}{2p} + \cdots$$

$$= e^{-ipt} \left(C_\theta e^{-i\frac{m_1^2 t}{2p}} \nu_1 + S_\theta e^{-i\frac{m_2^2 t}{2p}} \nu_2 \right)$$

$$= \left(C_\theta C_\theta e^{-i\frac{m_1^2 t}{2p}} + S_\theta S_\theta e^{-i\frac{m_2^2 t}{2p}} \right) \nu_e$$

$$+ \left(C_\theta (-S_\theta) e^{-i\frac{m_1^2 t}{2p}} + S_\theta C_\theta e^{-i\frac{m_2^2 t}{2p}} \right) \nu_\mu$$

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

$$\underline{\delta m^2 = m_2^2 - m_1^2}$$

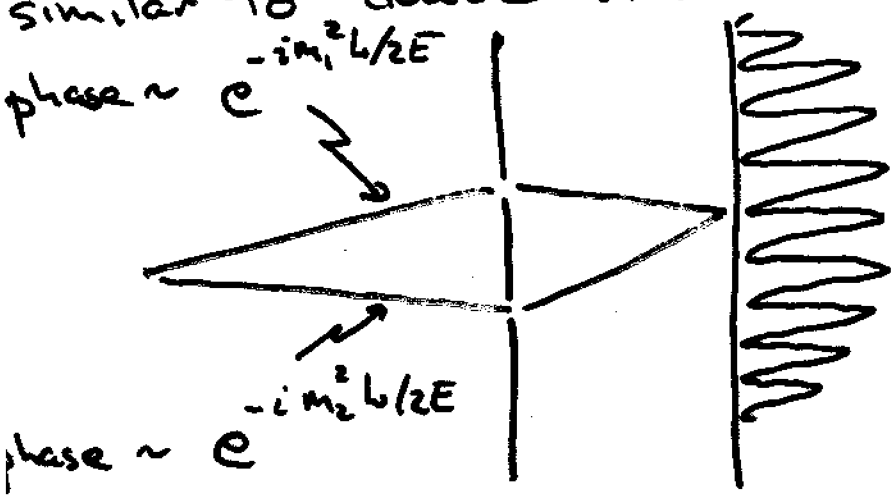
$$P_{e \to \mu} = S_\theta^2 C_\theta^2 \left| e^{-i\frac{(m_2^2 + m_1^2)t}{4p}} \left(e^{-i\frac{\delta m^2 t}{4p}} - e^{+i\frac{\delta m^2 t}{4p}} \right) \right|^2$$

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

use $\left\{ \begin{array}{l} t = L \\ p = E \end{array} \right.$

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

similar to double slit:



Units:

$$\left.\frac{\delta m^2 L}{4E}\right| \longrightarrow \frac{\delta m^2 c^4 . L}{4\hbar c . E}$$

natural units

dimensionless

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

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

L - km   engineering units

E - GeV

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

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

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

$$\left.\frac{\delta m^2 L}{4E}\right|_{\text{natural units}} = 1.2669\ldots \frac{\delta m^2(eV^2)\; L(km)}{E(GeV)}$$

$\downarrow$

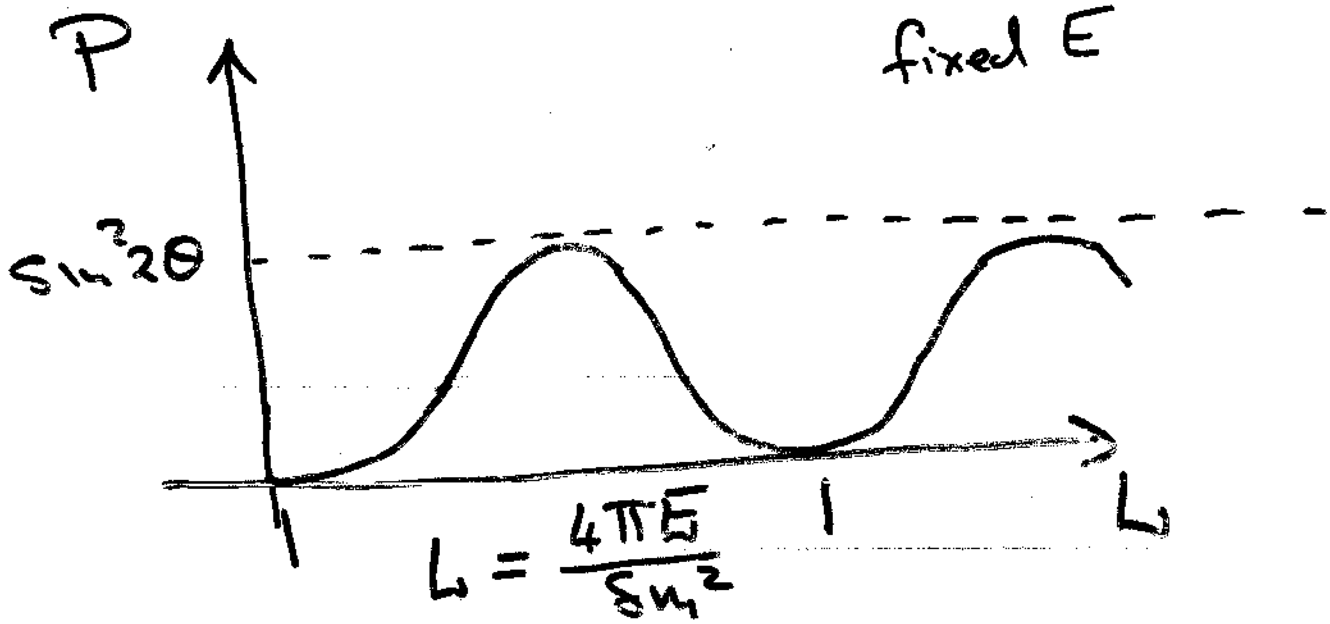
~ 1.27

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

Flavor Transition Probability is

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

fixed E



Oscillation Maximum Occurs at

$$L_{on} = \frac{2\pi E}{\delta m^2}(1+2n) \qquad n = 0, 1, 2, \cdots$$

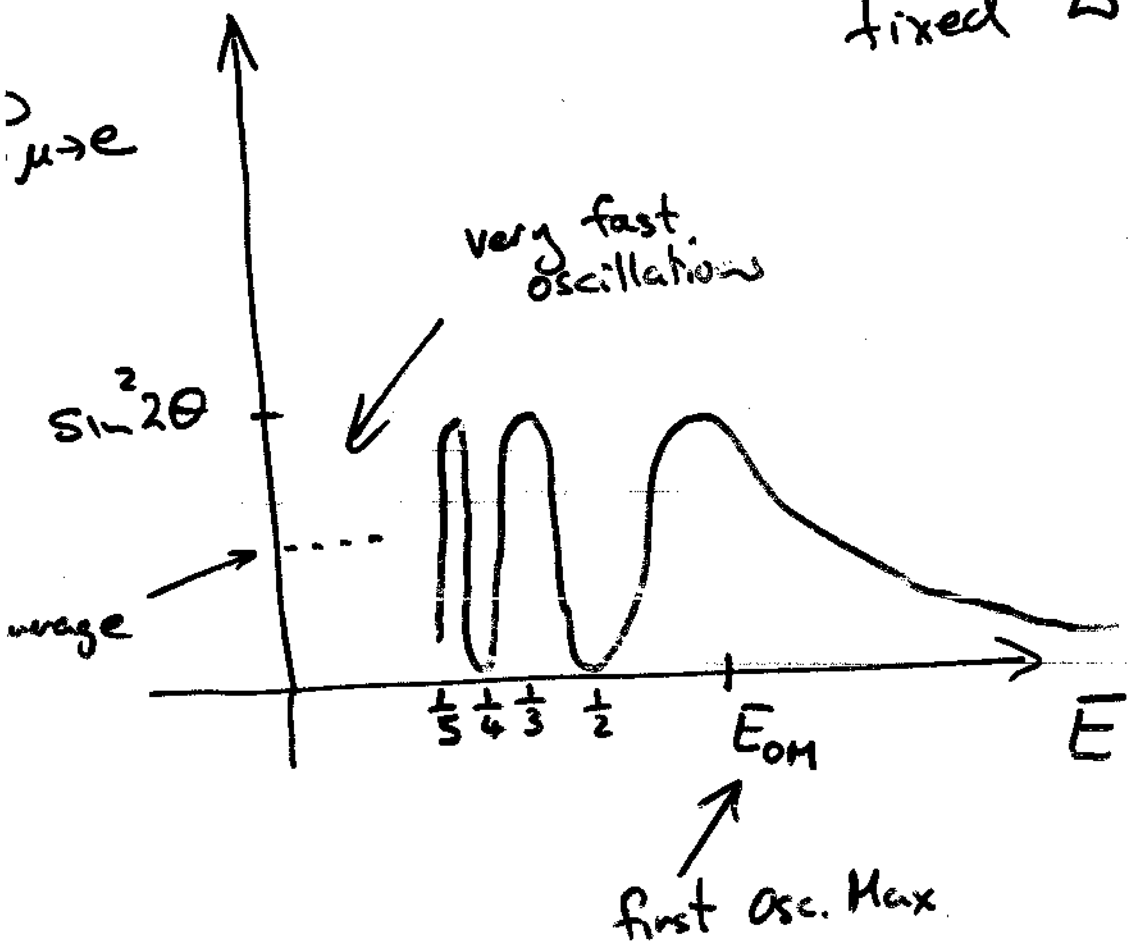
ν_e Survival Probability is

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

small L

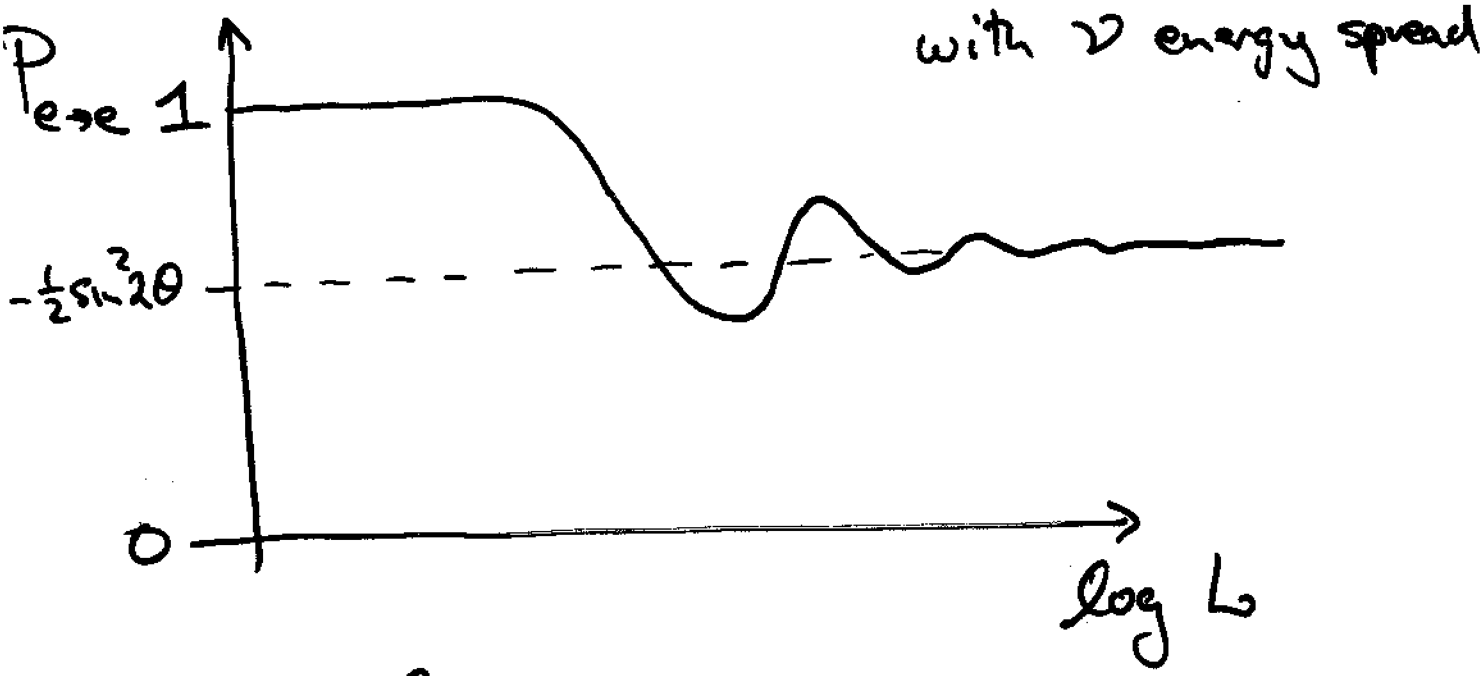
$$P_{e\to e} = 1 - \sin^2 2\theta \left(\frac{\delta m^2 L}{4E}\right)^2 + \mathcal{O}(L^4)$$

fixed L



Peaks at $\frac{1}{(1+2n)} \underbrace{\frac{\delta m^2 L}{2\pi}}_{E_{OM}}$

Zeros at $\frac{1}{2n} \overbrace{\frac{\delta m^2 L}{2\pi}}^{E_{OM}}$



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 δm^2: $\sin^2 \frac{\delta m^2 L}{4E} \sim \frac{1}{2}$

  $$\sin^2 2\theta = 2 P_{min}$$

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

KamLAND:

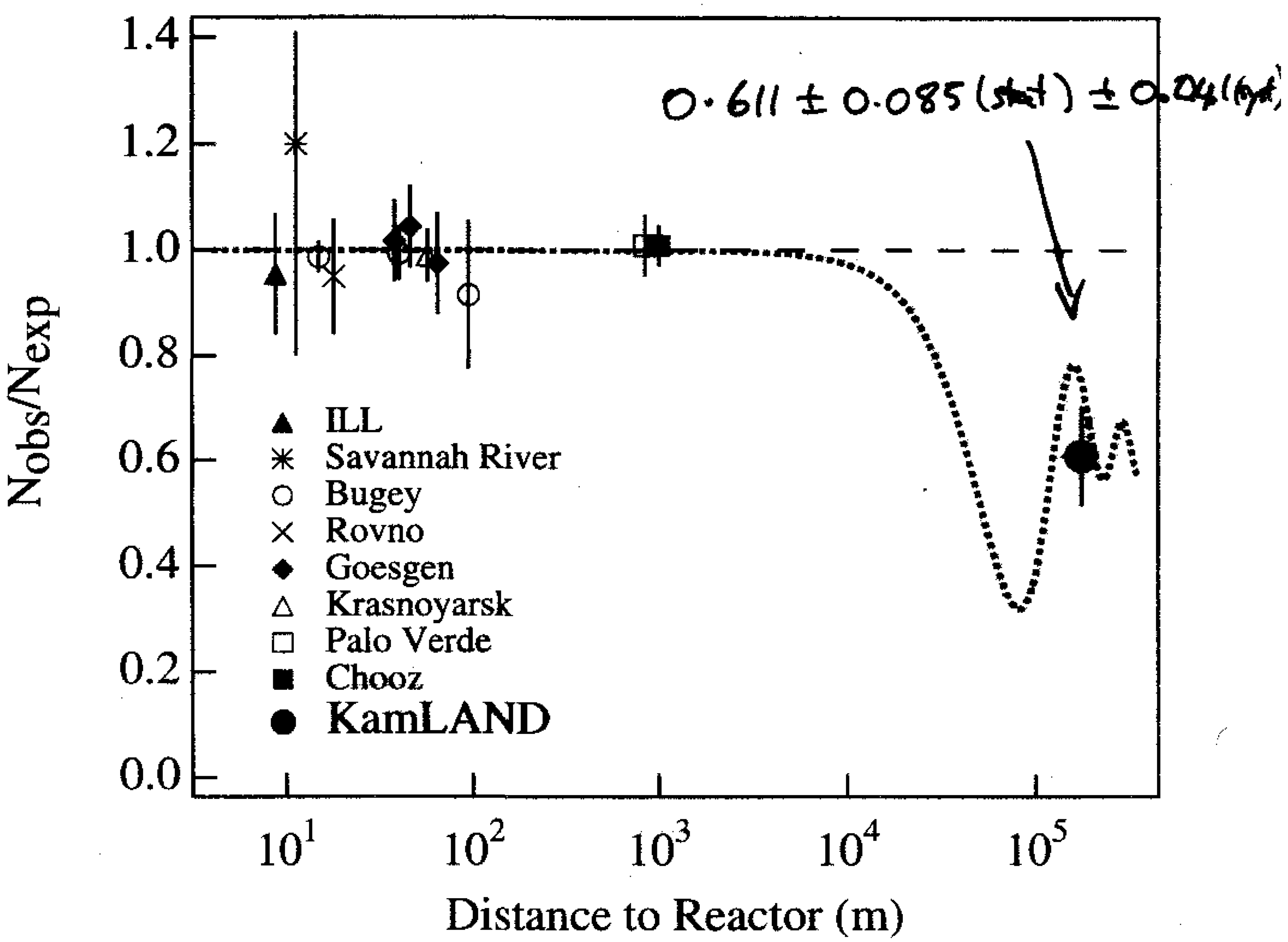
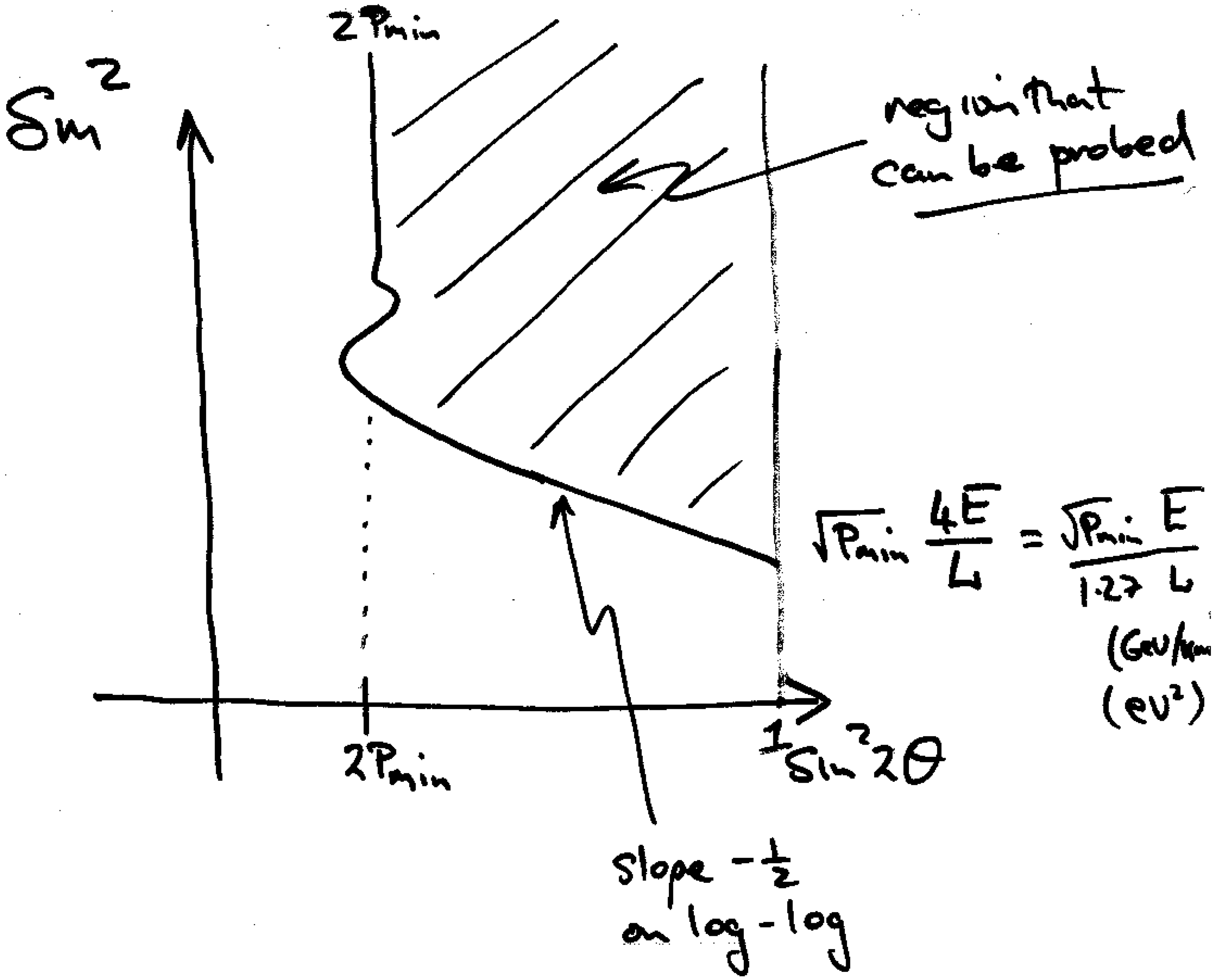


FIG. 4: The ratio of measured to expected $\bar{\nu}_e$ flux from reactor experiments [12]. The solid dot is the KamLAND point plotted at a flux-weighted average distance (the dot size is indicative of the spread in reactor distances). The shaded region indicates the range of flux predictions corresponding 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 $\Delta m^2 = 5.5 \times 10^{-5}$ 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:

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

$P_{min} = 0.2$

$$\sqrt{P_{min}}\,\frac{E}{1.27\,L} \approx 9\times10^{-6}\,\text{eV}^2 \quad \checkmark$$

Why exclude region $\delta m^2 = 2.5\times10^{-3}\,\text{eV}^2$ and $\sin^2 2\theta = 1$?

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

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

---

semi-classical limit

if $\hbar c \to 0$

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

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

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

same as oscillations averaged out

---

equivalent to

Separation of Wave-Packets

e, μ — short, e, μ + oscillations — medium, osc. av. ν_2, ν_1 — very large

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

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

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

$\Delta m^2 = 1\,eV^2 \qquad E = 1\,GeV$

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

if width of wavepacket is macroscopic say 1m then decoherence at 10^{18} m.!

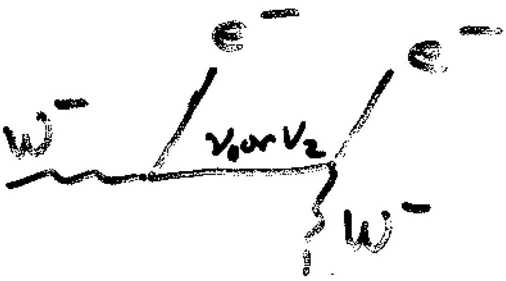
astrophysical distances

PROCESS:	PROBABILITY:
$W^+ \to e^+\nu_1$ or $\mu^+\nu_2$	c_θ^2
$e^+\nu_2$ or $\mu^+\nu_1$	s_θ^2

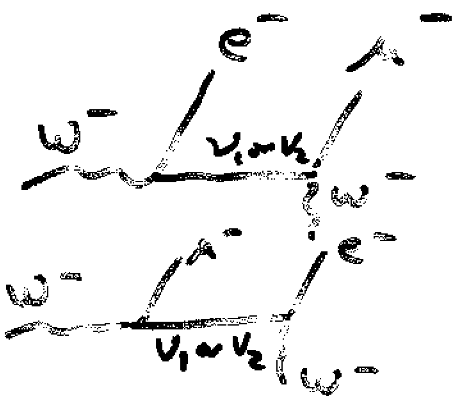
AND

$\nu_1 W^- \to e^- + \cdots$ $\nu_2 W^- \to \mu^- + \cdots$	c_θ^2
$\nu_1 W^- \to \mu^- + \cdots$ $\nu_2 W^- \to e^- + \cdots$	s_θ^2

THEN



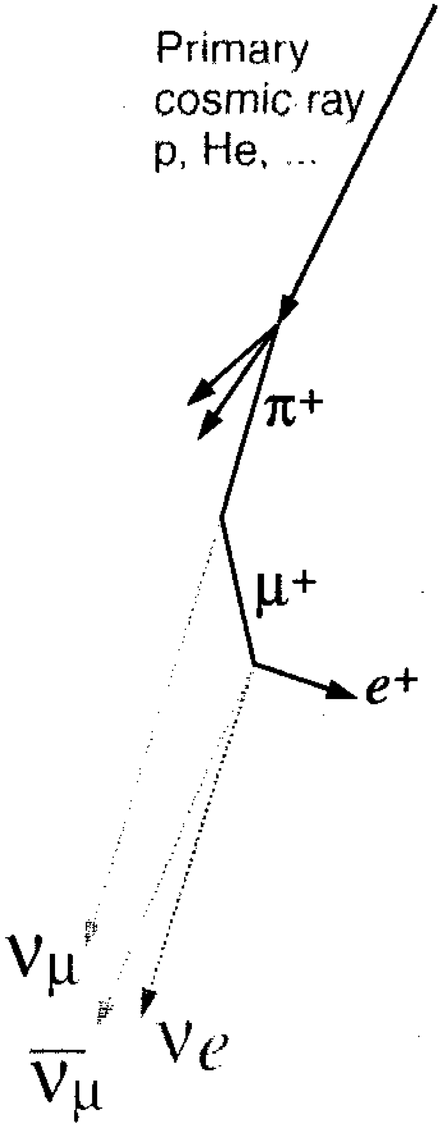
$$P_{\nu_e \to \nu_e} = c_\theta^4 + s_\theta^4$$
$$= 1 - \tfrac{1}{2}\sin^2 2\theta$$



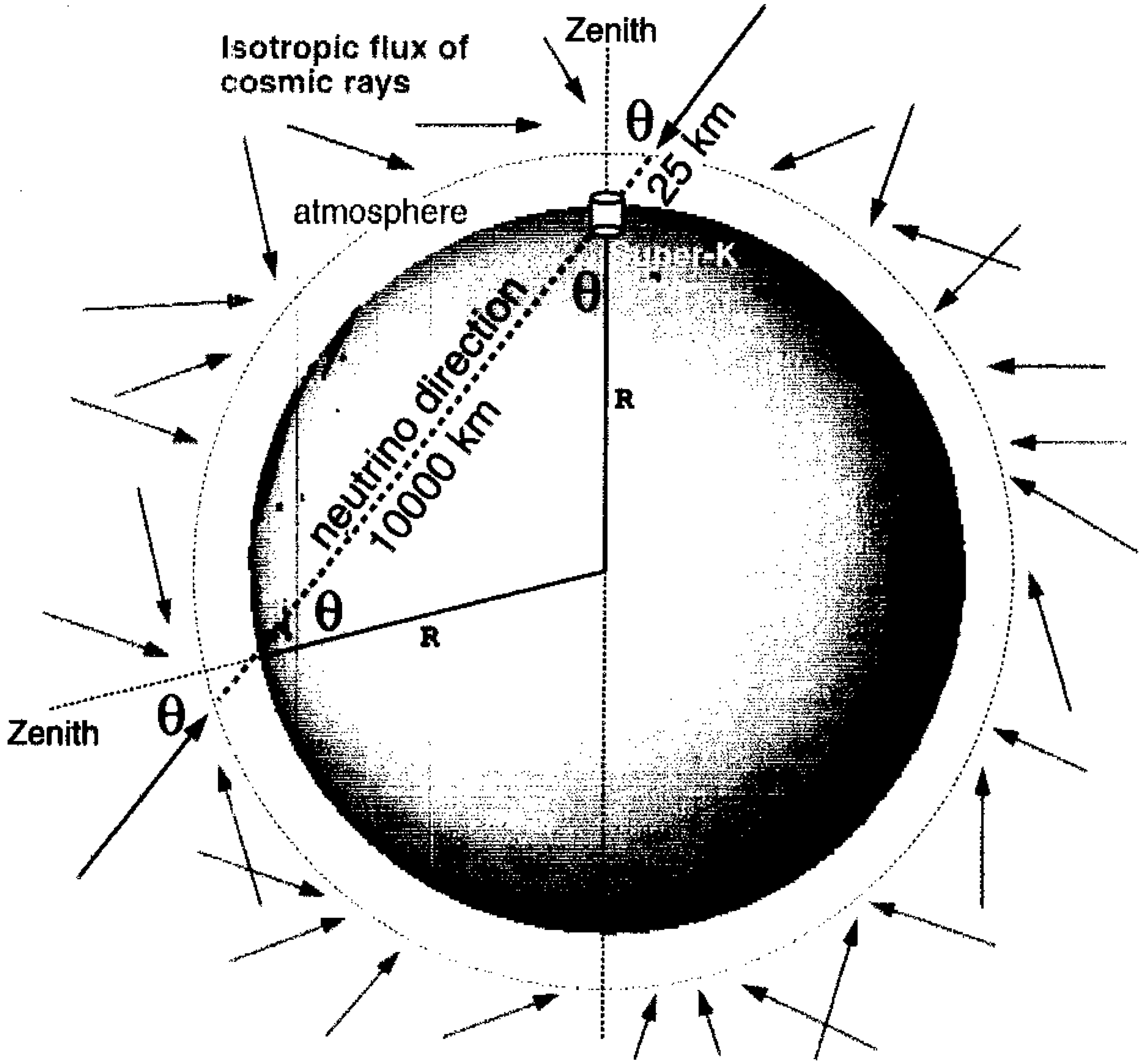
$P_{\nu_e \to \nu_\mu}$ or $P_{\nu_\mu \to \nu_e}$ $= 2 s_\theta^2 c_\theta^2 = \tfrac{1}{2}\sin^2 2\theta$

~~Quarks !!!~~

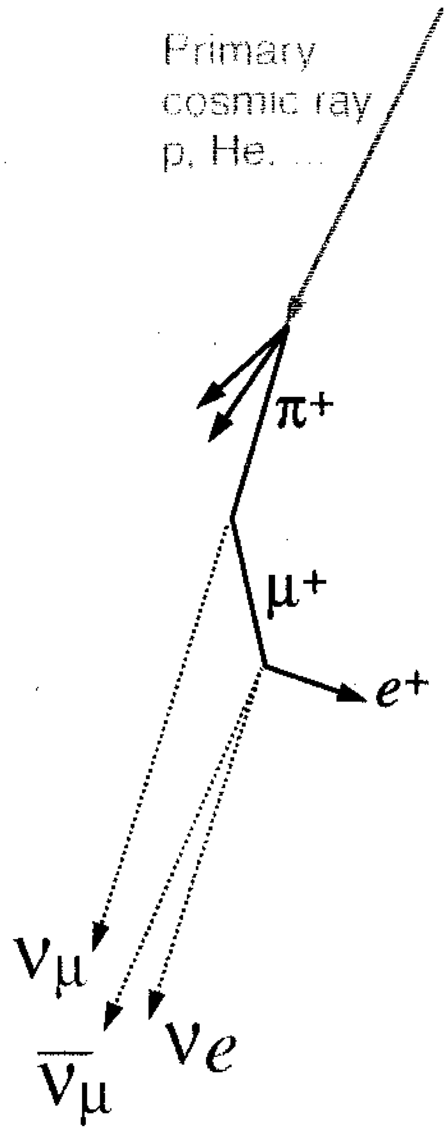
ATMOSPHERIC NEUTRINOS



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



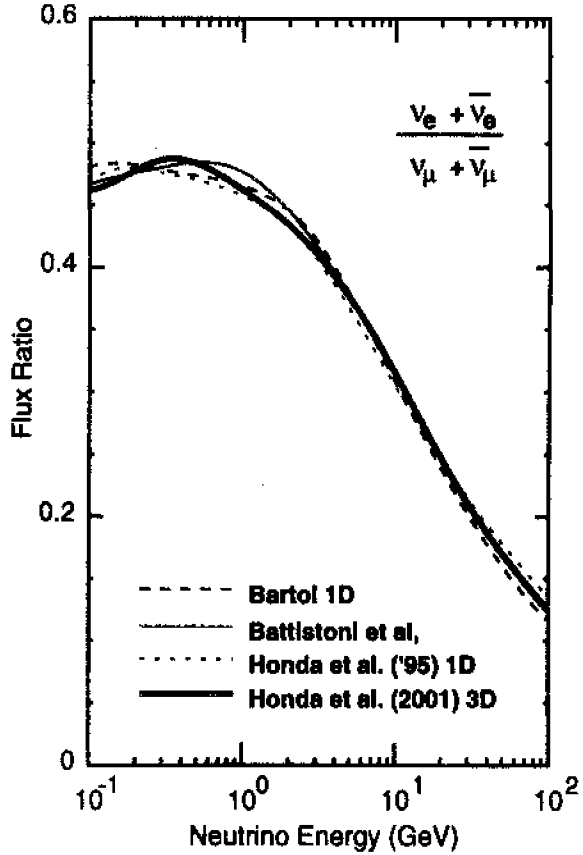
Up-Down Symmetric Flux
(for E_ν > few GeV)



Atmospheric Neutrinos

Flux Ratio of ν_μ to ν_e

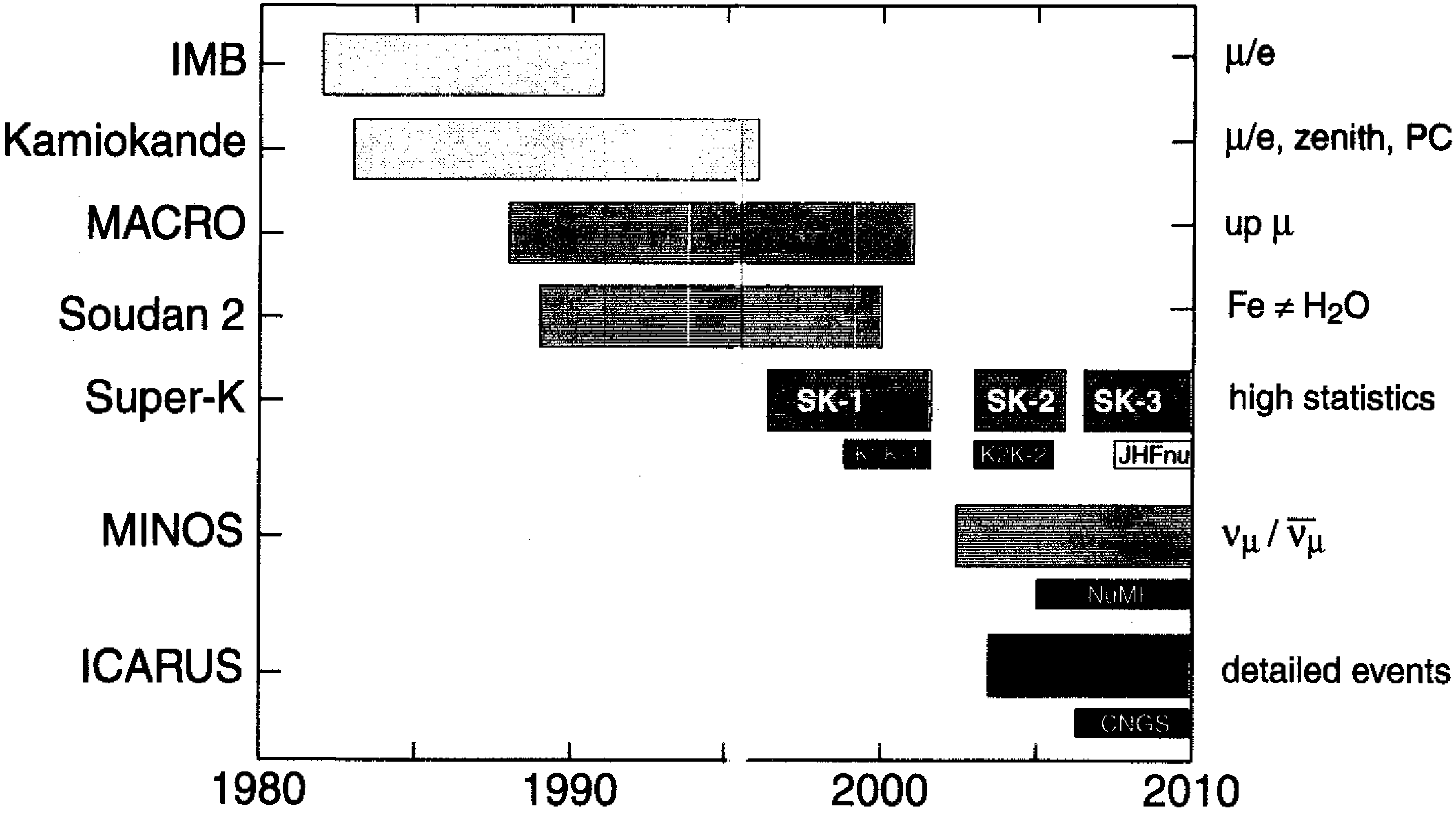
- $\Phi(\nu_\mu)/\Phi(\nu_e)$ ~ 2 below a few GeV
- predicted to ~ 5% over wide range



Gaiser and Honda, Ann.Rev.Nuc.Part.Sci.52(2002)

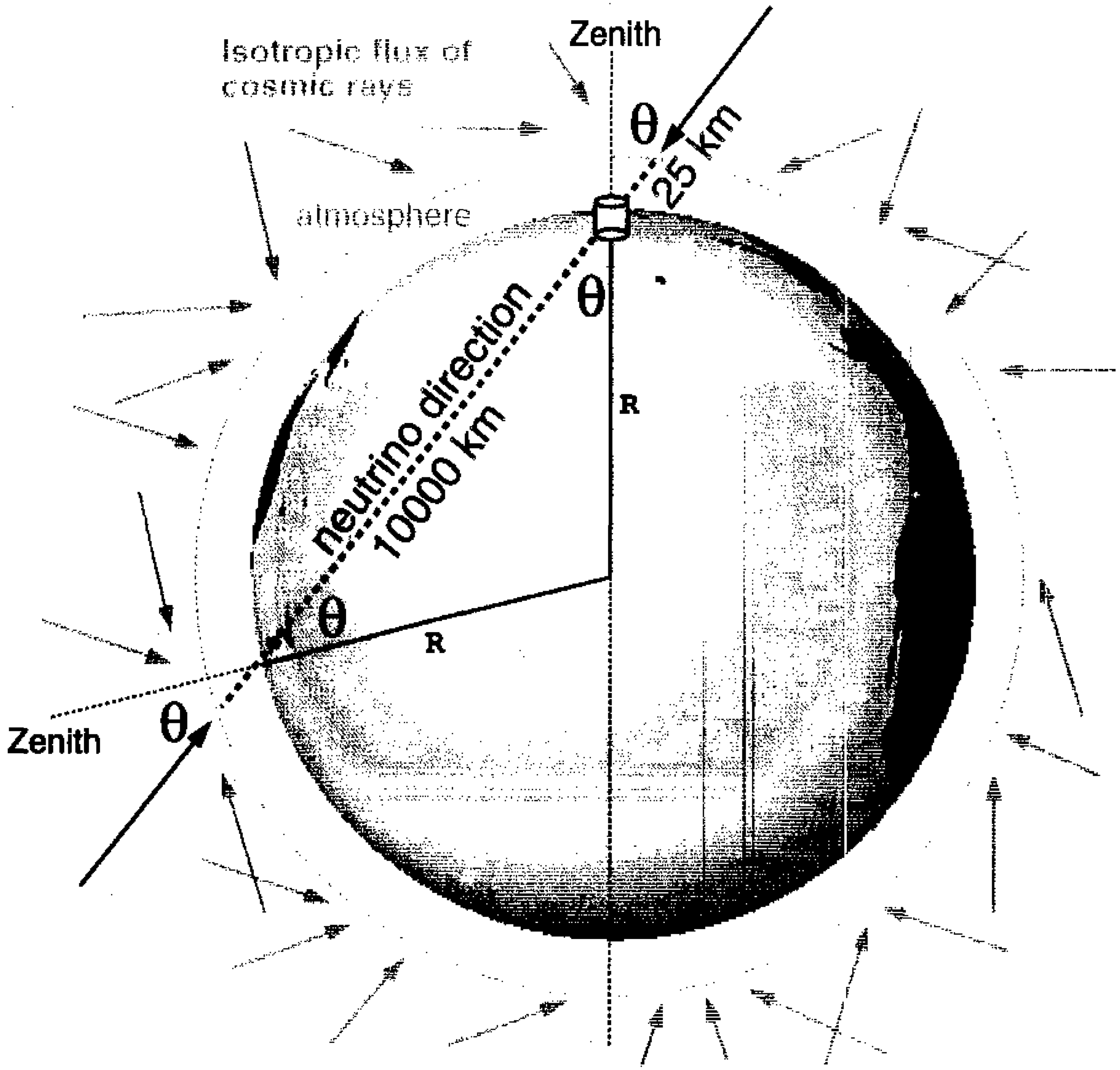
Atmospheric Neutrino Experiments

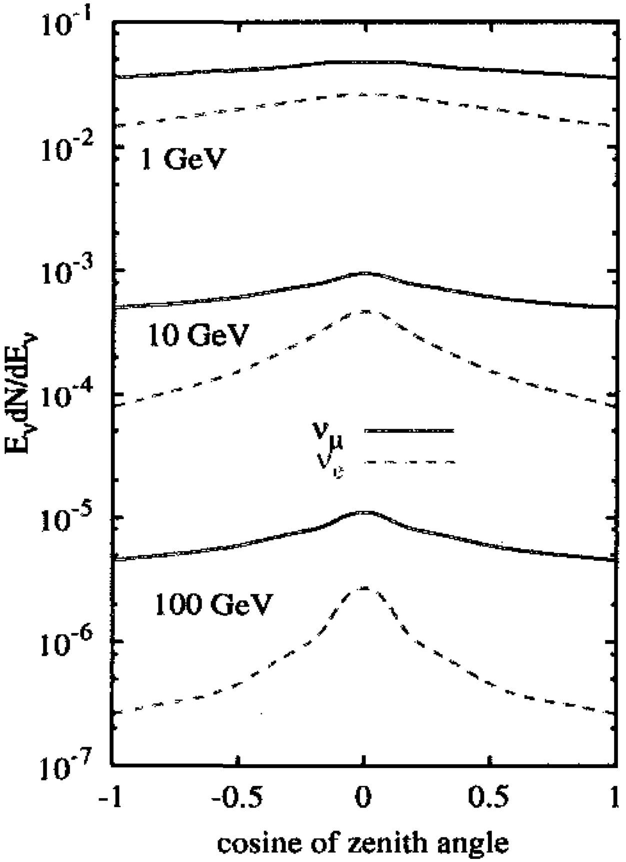
and Long Baseline Neutrino Beams



others: NUSEX, Frejus, Baksan, SNO

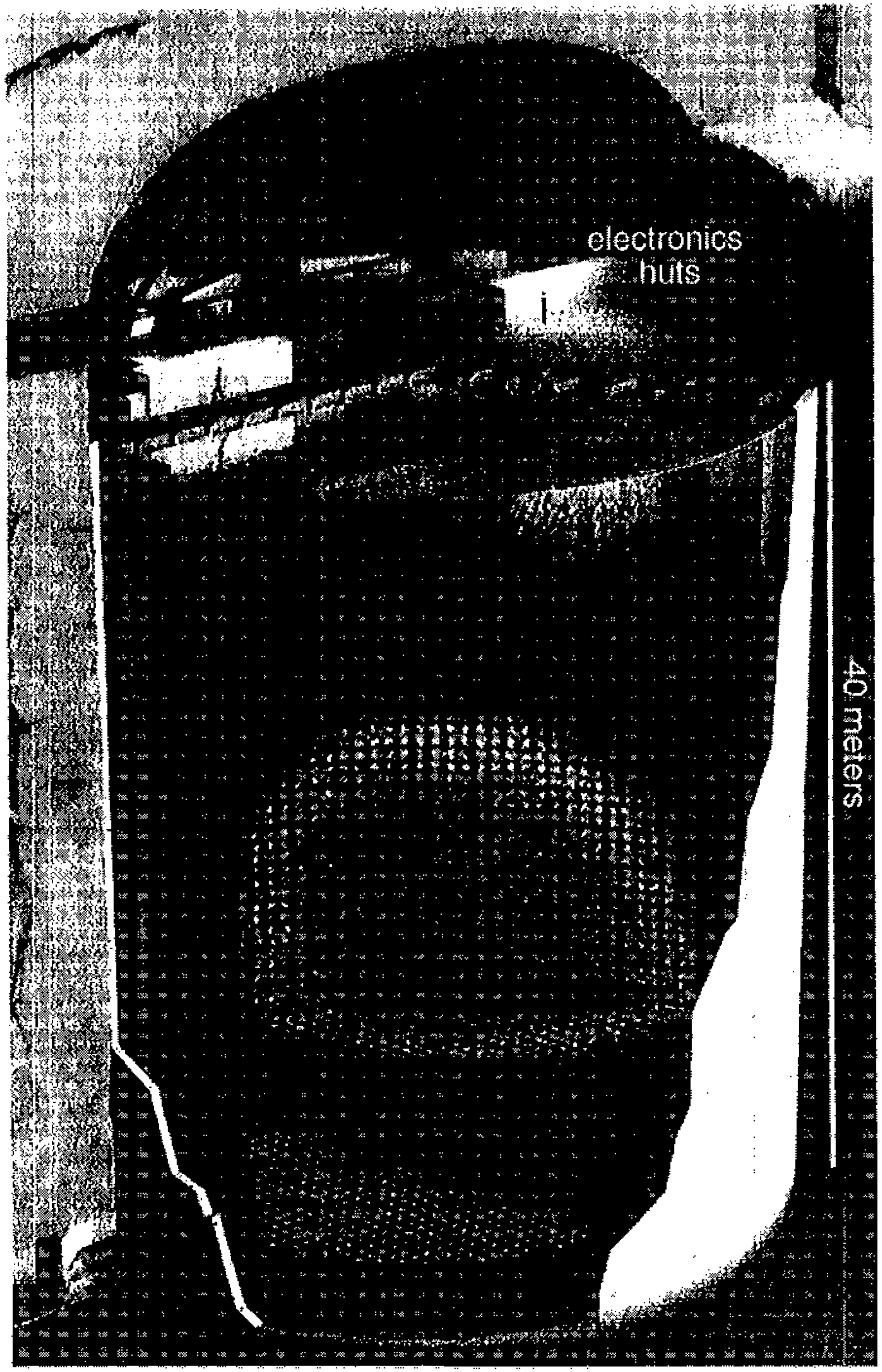
Up-Down Symmetric Flux





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

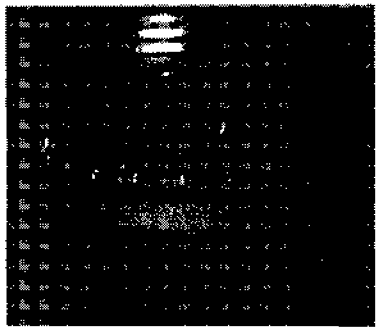
Gaiser and Honda, Ann.Rev.Nuc.Part.Sci.52(2002)



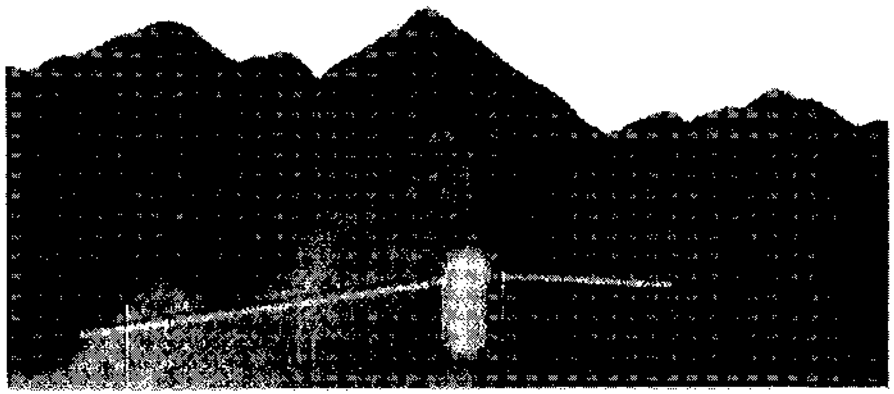
Super-Kamiokande

SK-1 1996 - 2001
- 22.5 kton fiducial mass (2m from wall)
- 11134 50-cm photomultiplier tubes
- 40% photocathode coverage
- 1885 20-cm pmts 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

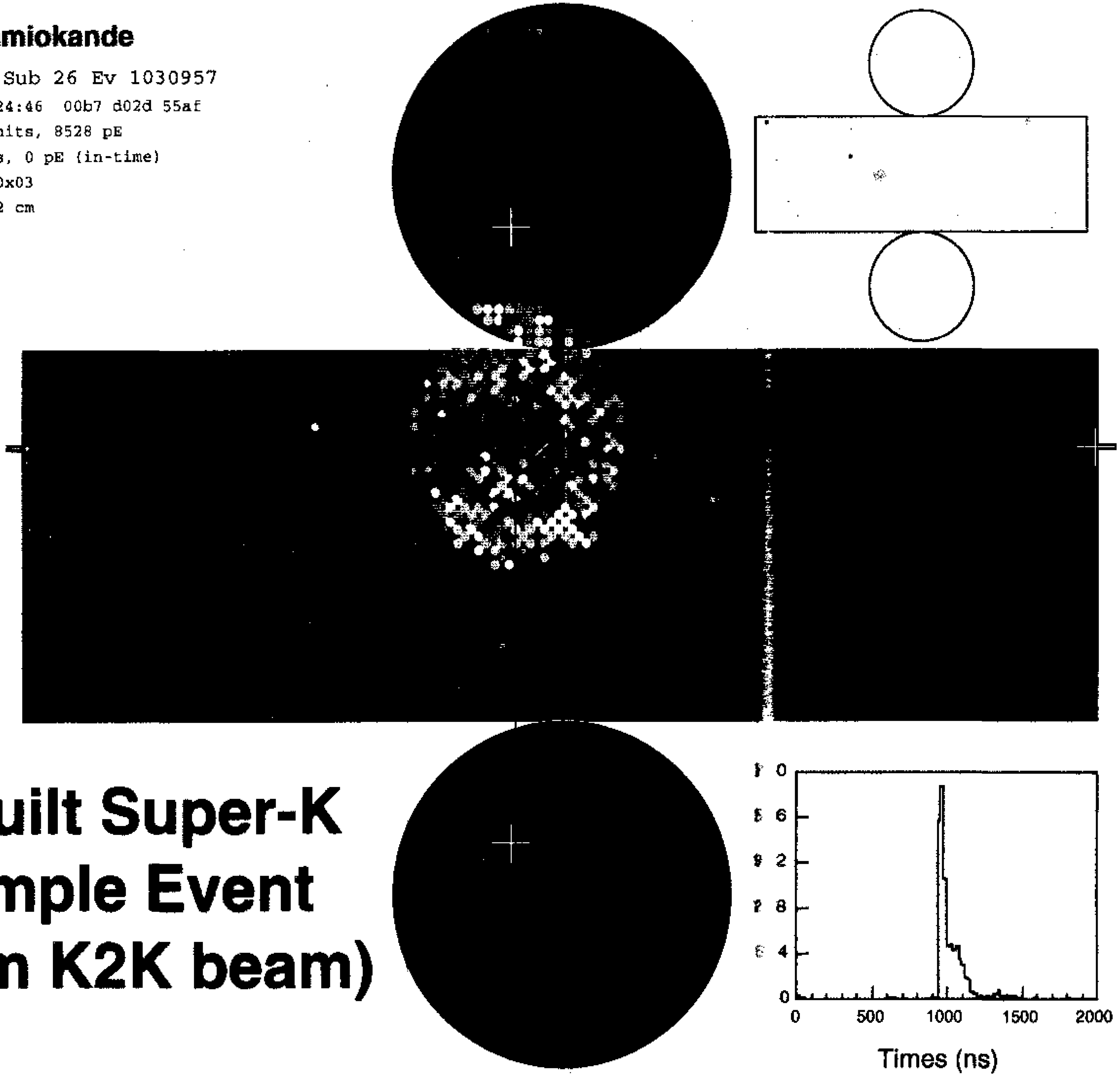


SK-3 2006
- original coverage
to be restored
- JHF ν off-axis beam

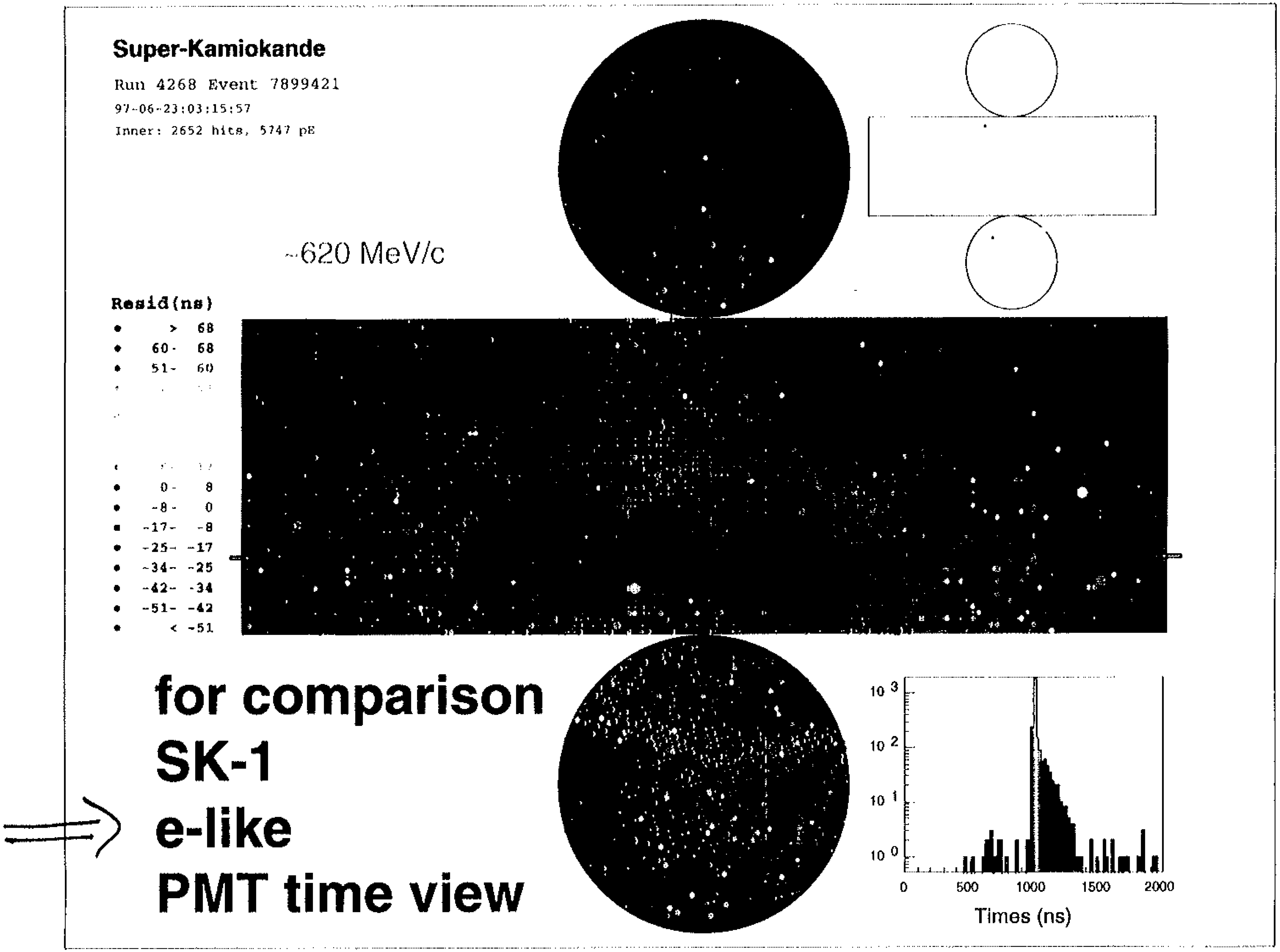


Super-Kamiokande

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



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)
> 68
60- 68
51- 60
0- 8
-8- 0
-17- -8
-25- -17
-34- -25
-42- -34
-51- -42
< -51
for comparison
SK-1
e-like
PMT time view
10 3
10 2
10 1
10 0
0
500
1000
1500
2000
Times (ns)

Measured Double Ratio

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

SK sub-GeV:

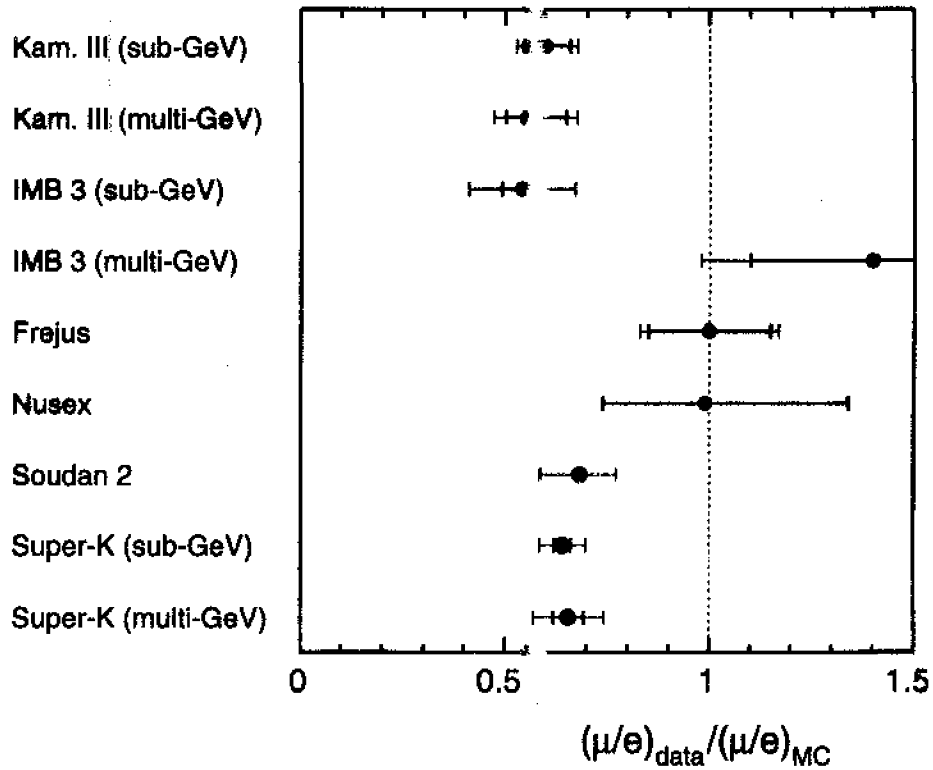
$0.638 \pm 0.016_{stat.} \pm 0.050_{sys.}$

SK multi-GeV:

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

Soudan 2:

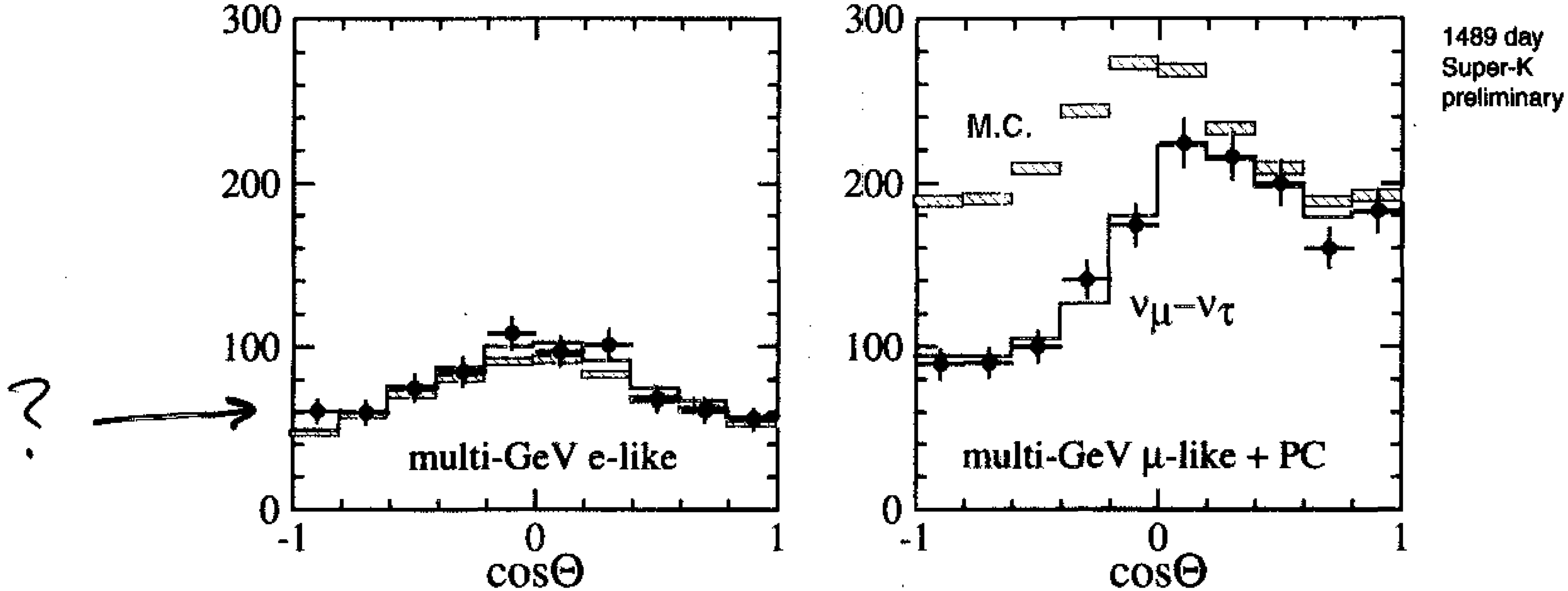
$0.68 \pm 0.12_{total}$



Measured Up-Down Asymmetry

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

> 10σ deviation!



Neutrino travel distance: 12800 6200 700 40 15 km

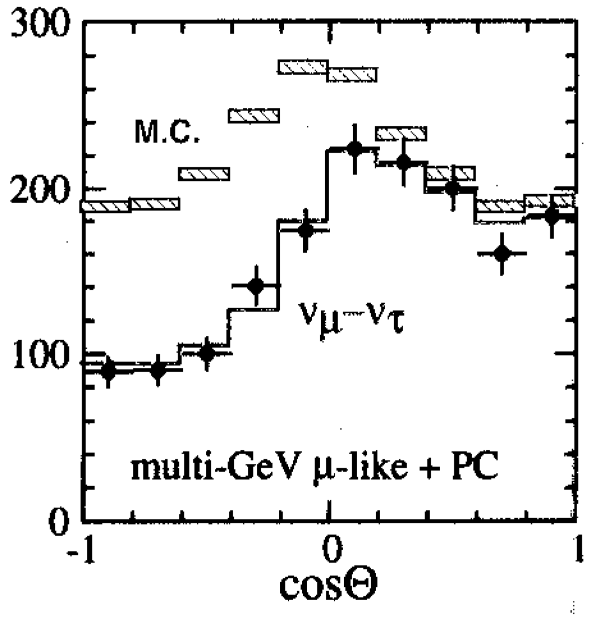
$(\sin^2 2\theta, \Delta m^2) = (1.00, 2.5 \times 10^{-3}\,eV^2)$

$\chi^2 \sim 1$ d.o.f. $\nu_\mu \leftrightarrow \nu_\tau$

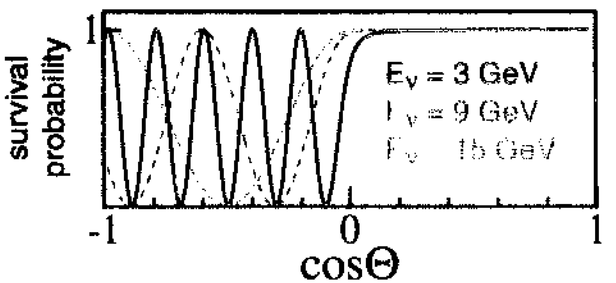
excellent fit.

Interpretation of Neutrino Oscillation

Atmospheric Neutrino Data ... is described by:



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



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

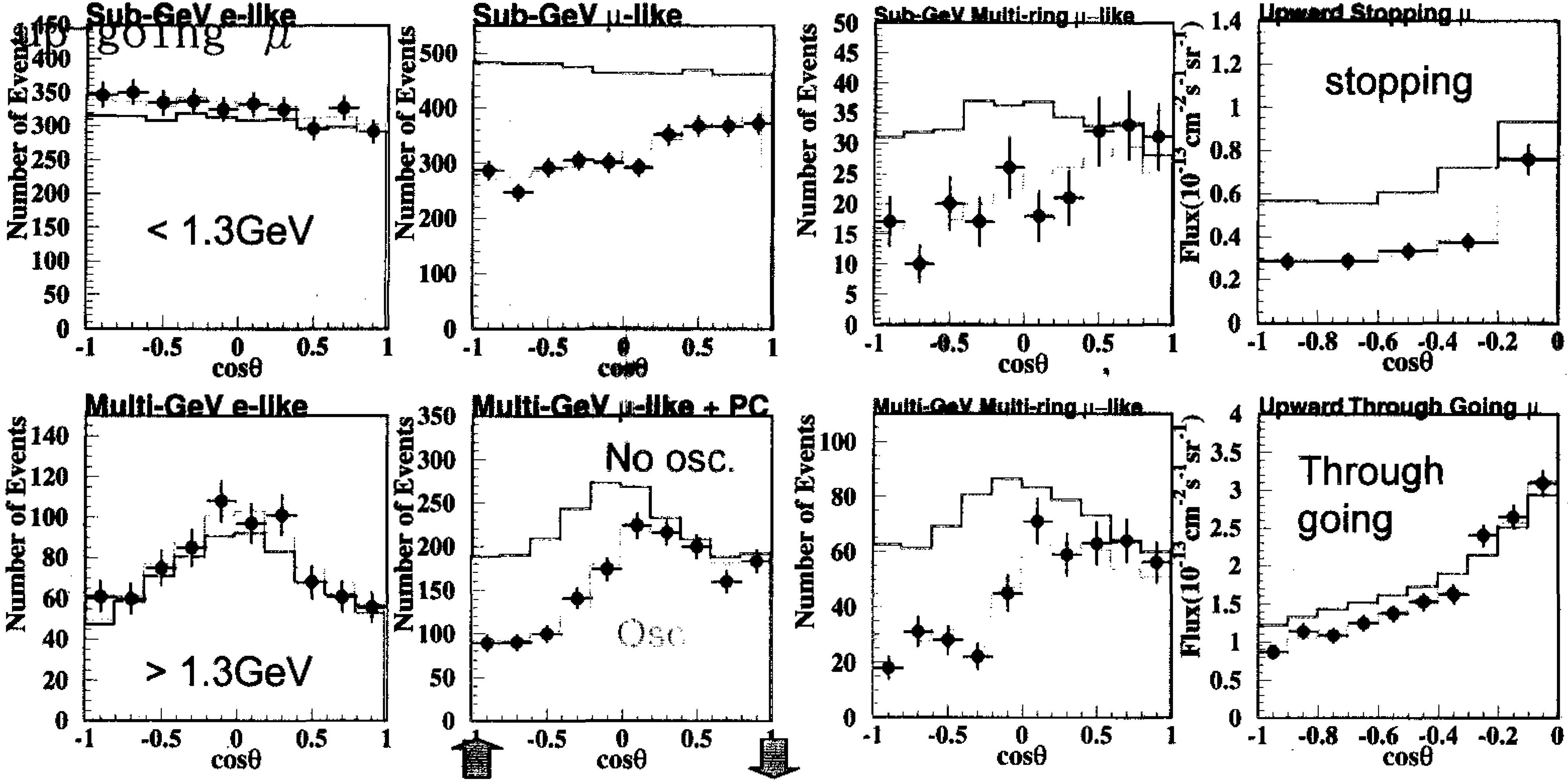
$\Delta m^2 \sim 3 \times 10^{-3}\,eV^2$ $\sin^2 2\theta \sim 1$

SK atmospheric neutrino data

Kajita
Nu Horizons

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

1-ring e-like 1-ring μ-like multi-ring μ-like up going μ



Up-going Down-going

Super-K

II. Atmospheric neutrinos

[redacted]

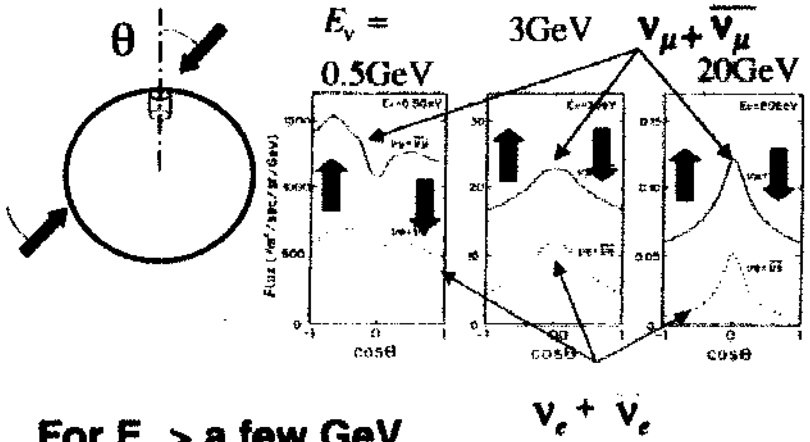
$\nu_\mu + \overline{\nu_\mu}$

$\nu_e + \nu_e$: δ(ratio) ~5%, (δ(flux) ~25%)

$$\Rightarrow \left.\frac{\nu_\mu + \overline{\nu_\mu}}{\nu_e + \overline{\nu_e}}\right|_{Data} \Big/ \left.\frac{\nu_\mu + \overline{\nu_\mu}}{\nu_e + \overline{\nu_e}}\right|_{MC} \neq 1$$

for neutrino oscillations

[redacted]

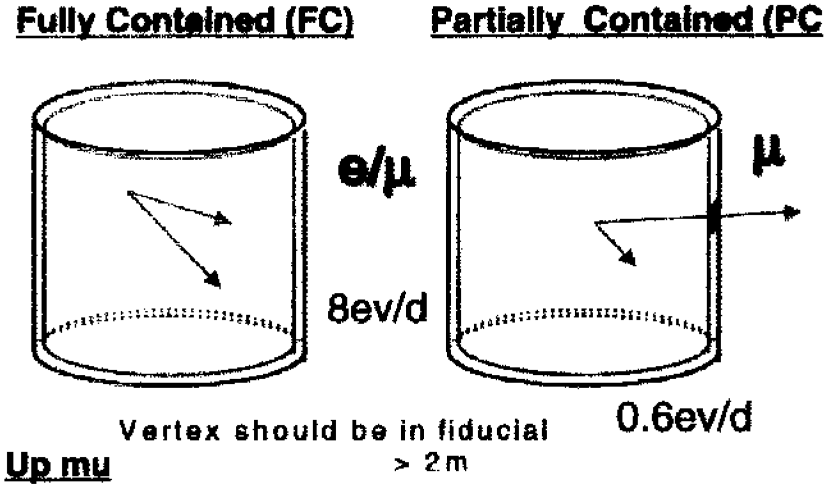


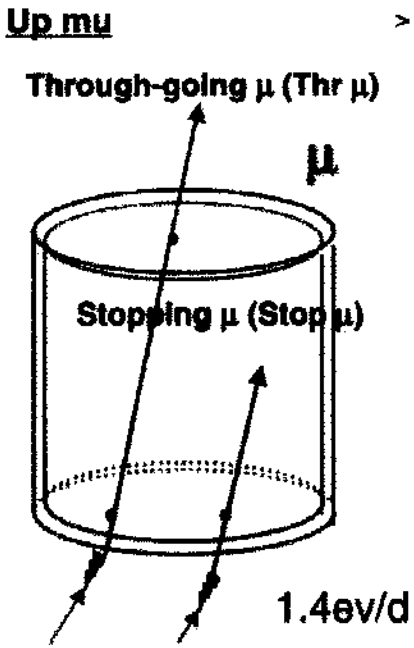
For E_ν > a few GeV,

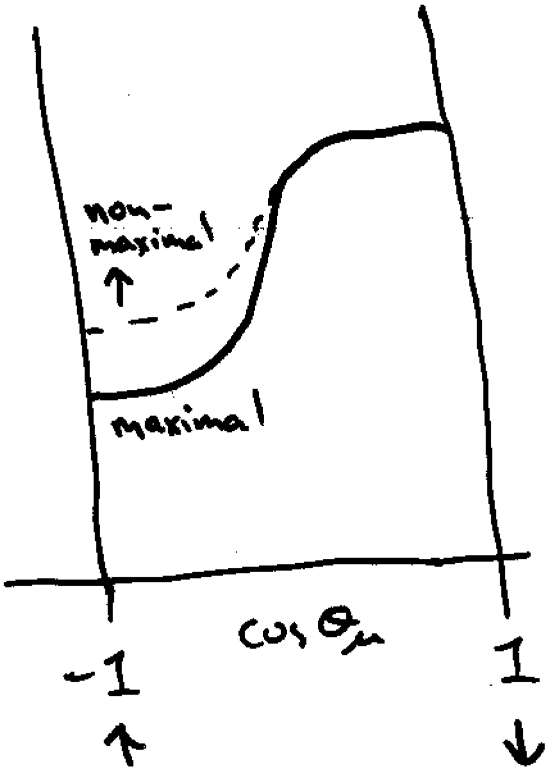
Upward / downward = 1 (within a few %)

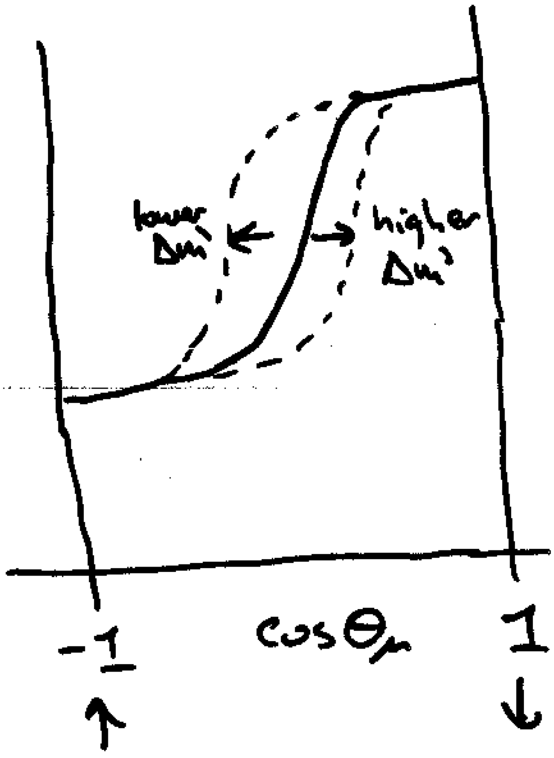
➡ Up/Down asym. for neutrino oscillations

[redacted]

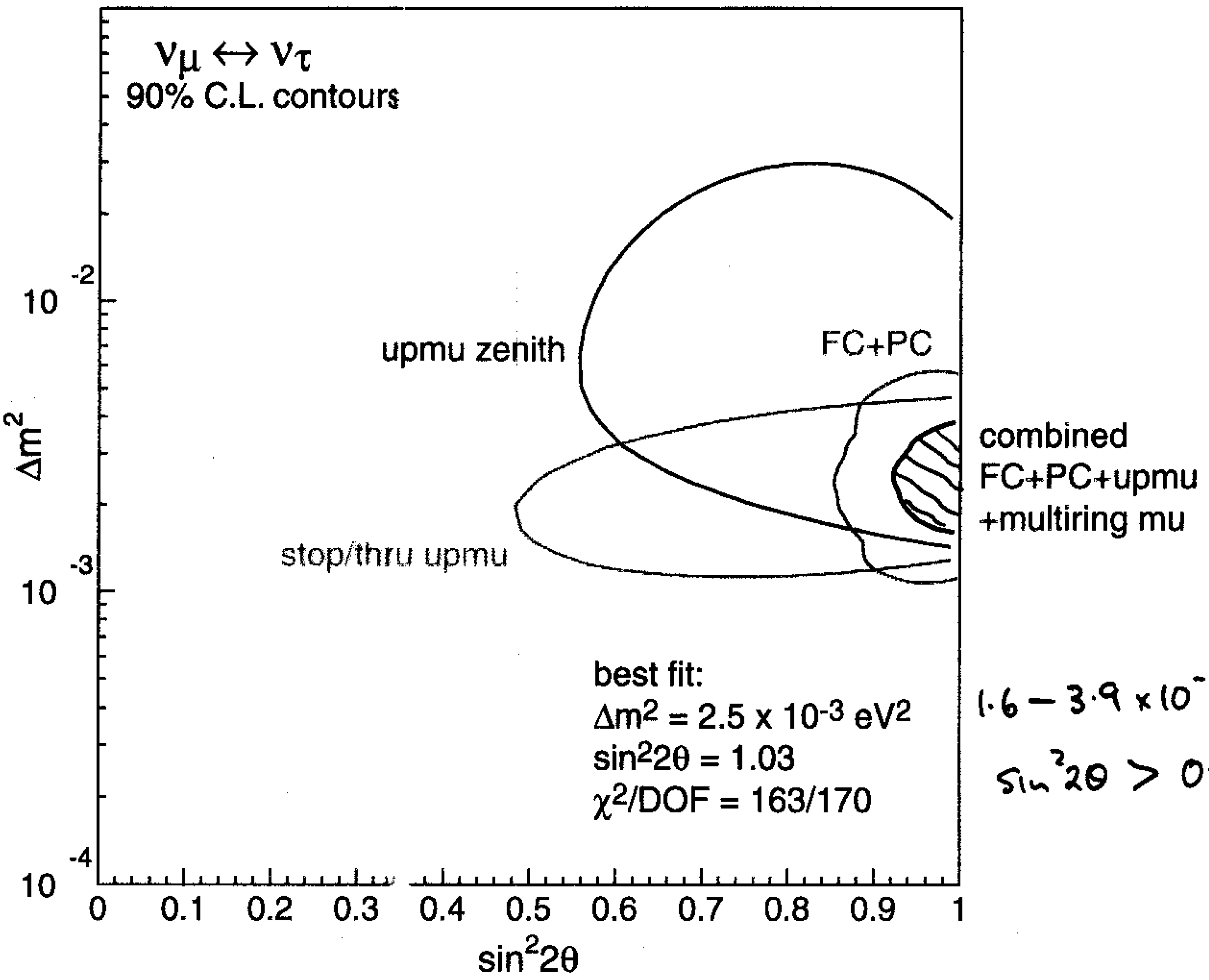





non-
maximal
maximal
cos θμ
-1
1


lower
Δm²
higher
Δm²
cos θμ
-1
1

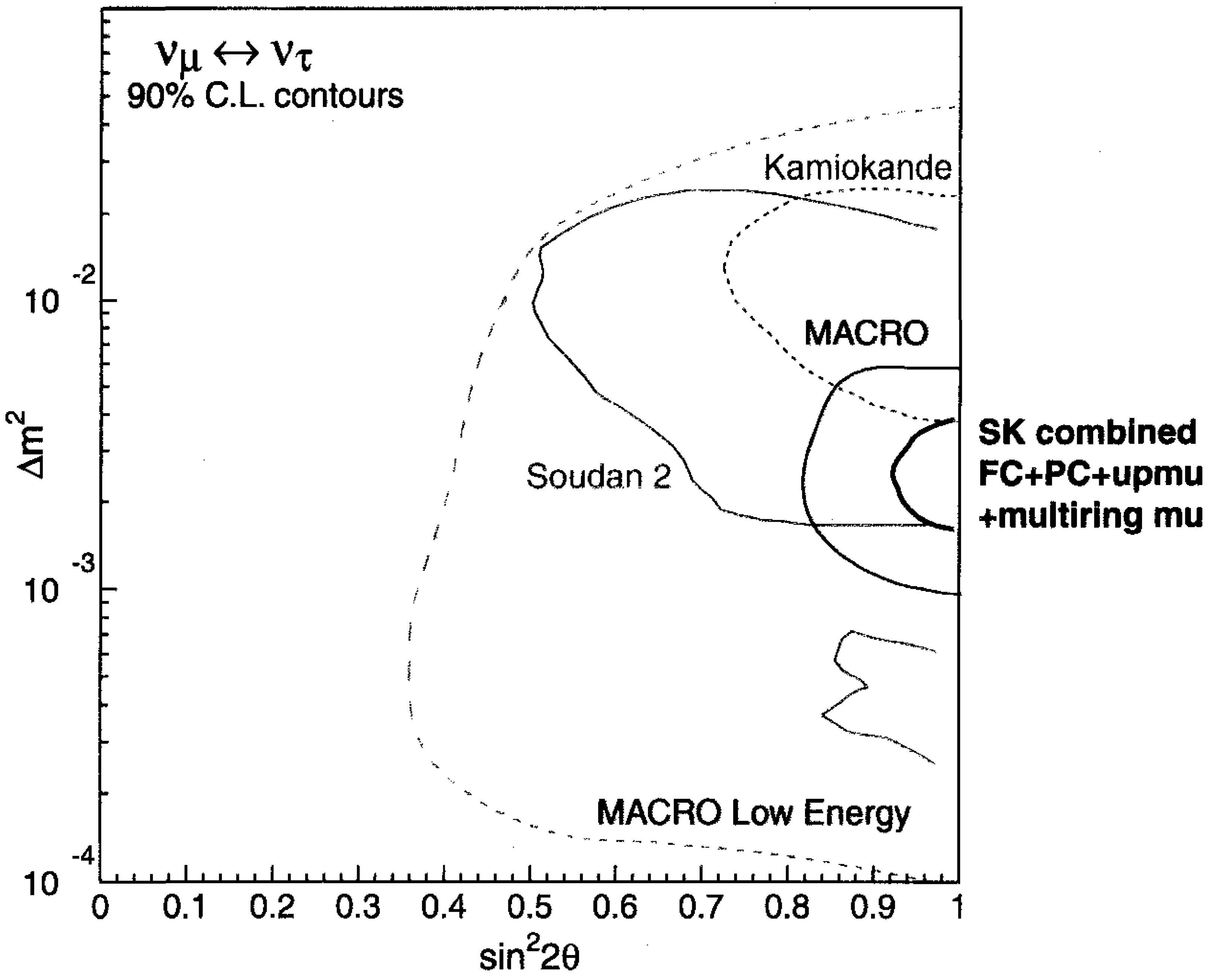
Allowed Regions from Super-K Analyses

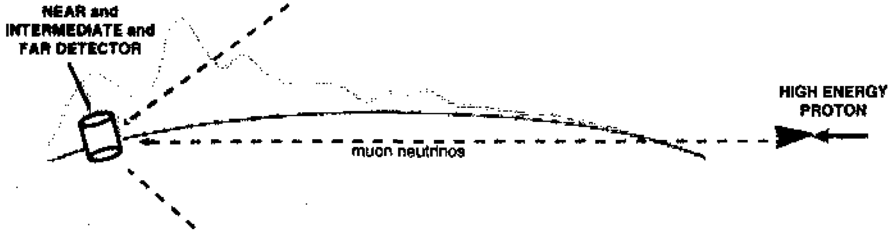


$1.6 - 3.9 \times 10^{-3}$ eV^2

$\sin^2 2\theta > 0.91$

Allowed Regions from Several Experiments



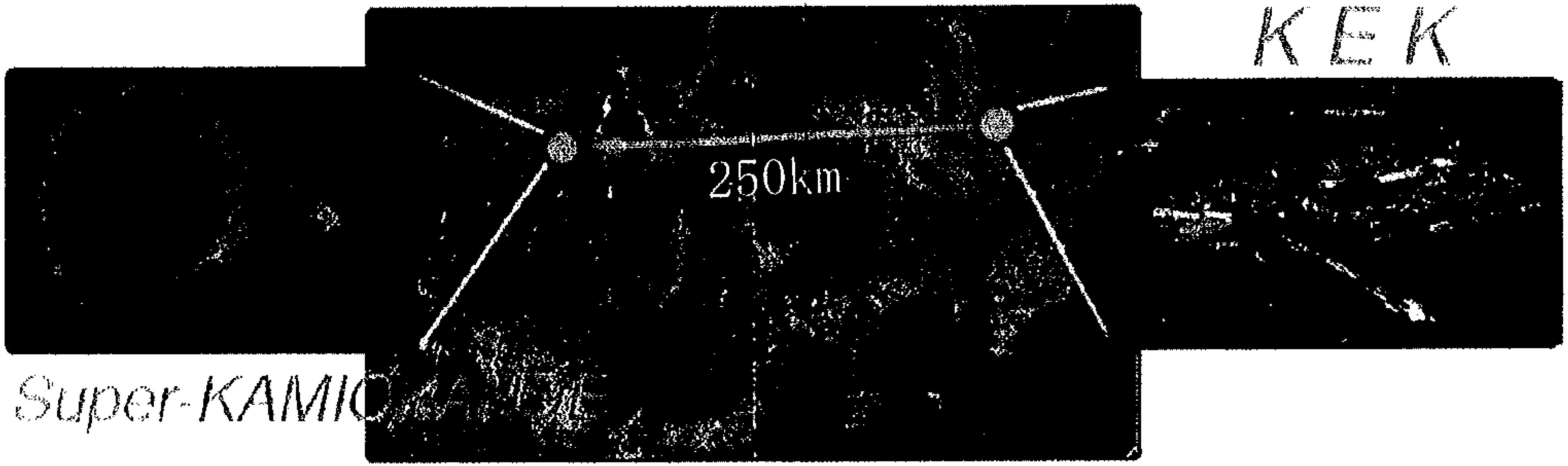


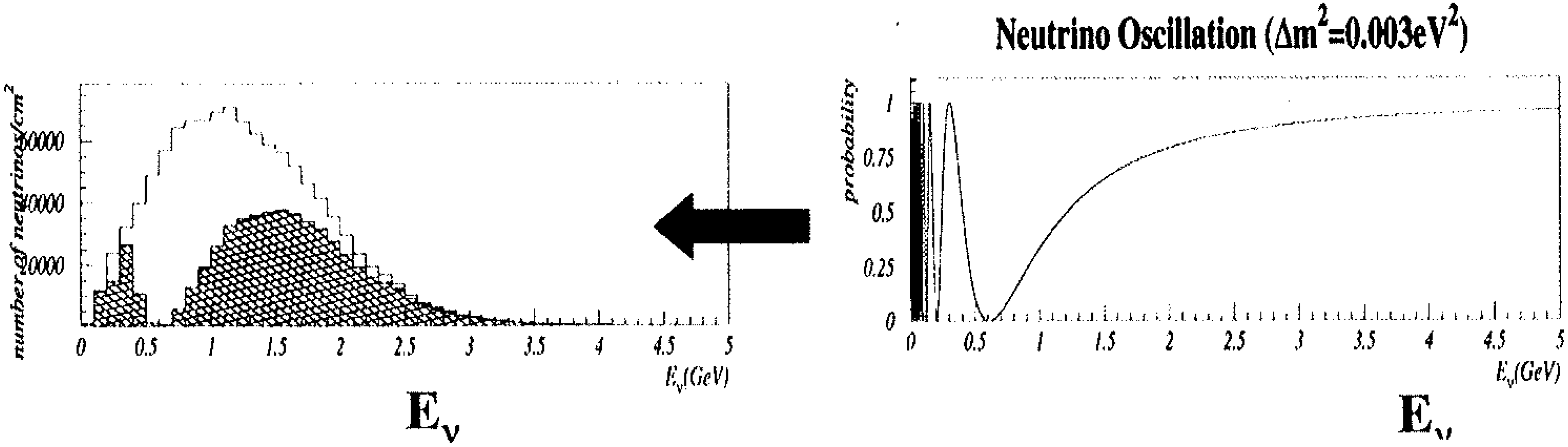
Atmospheric Neutrinos	**Long Baseline Neutrinos**
mixed beam of ν_μ $\overline{\nu}_\mu$ ν_e $\overline{\nu}_e$	nearly pure beam of ν_μ
wide energy band 200 MeV - 1 TeV	narrow energy band, adjustable
continuous flux - free	pulsed flux - expensive
multiple baselines 10 km - 13000 km	fixed baseline 250 / 750 km so far
neutrino direction unknown	neutrino direction known

first solid evidence for neutrino oscillation ...

motivates and suggests design for long baseline experiments

K2K


KEK
250km
Super-KAMIO

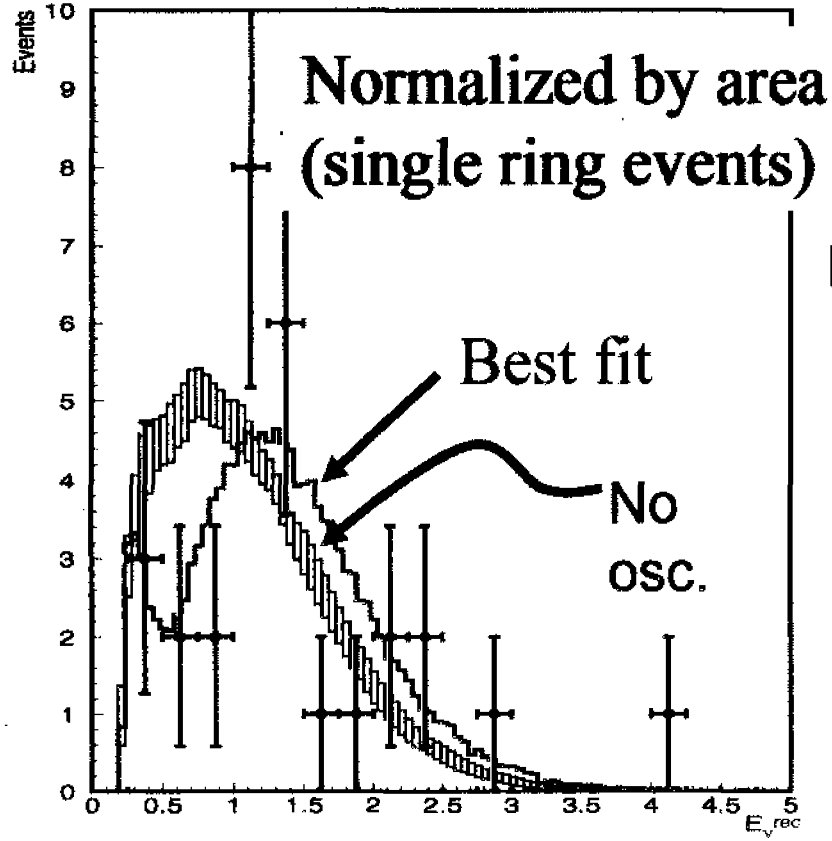

Neutrino Oscillation (Δm^2=0.003eV^2)
probability
E_ν(GeV)
number of neutrinos/cm^2
E_ν
E_ν

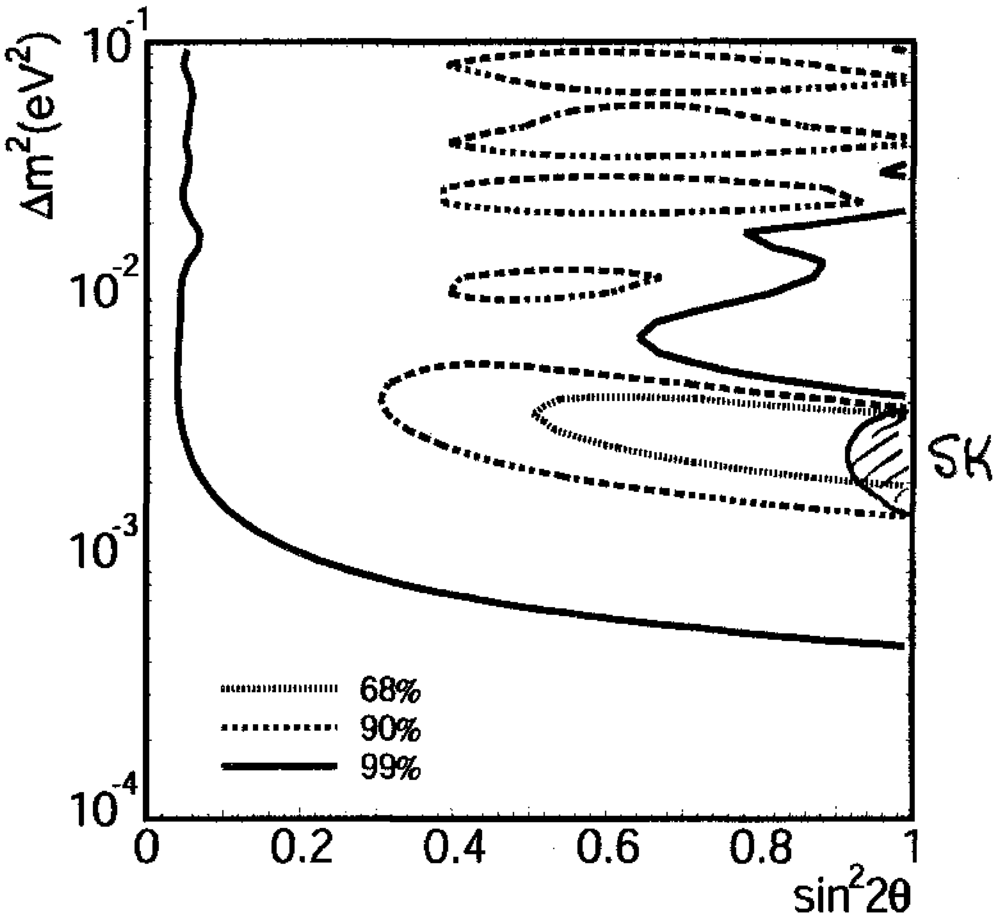
K2K data and oscillation

Data: 1999 – July 2001

N_{SK} (# of event)
56 events observed
80.1+6.2/-5.4 ev. expt'd
null oscillation prob. 1.3%

+



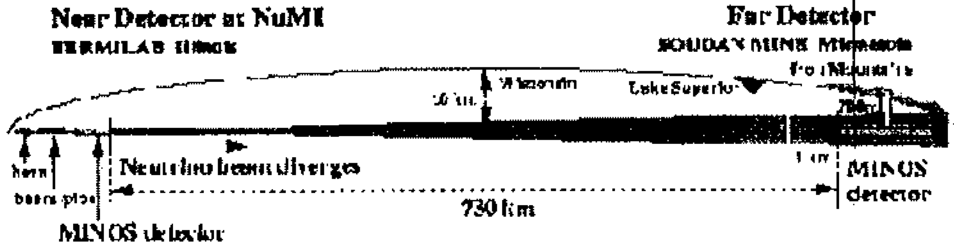


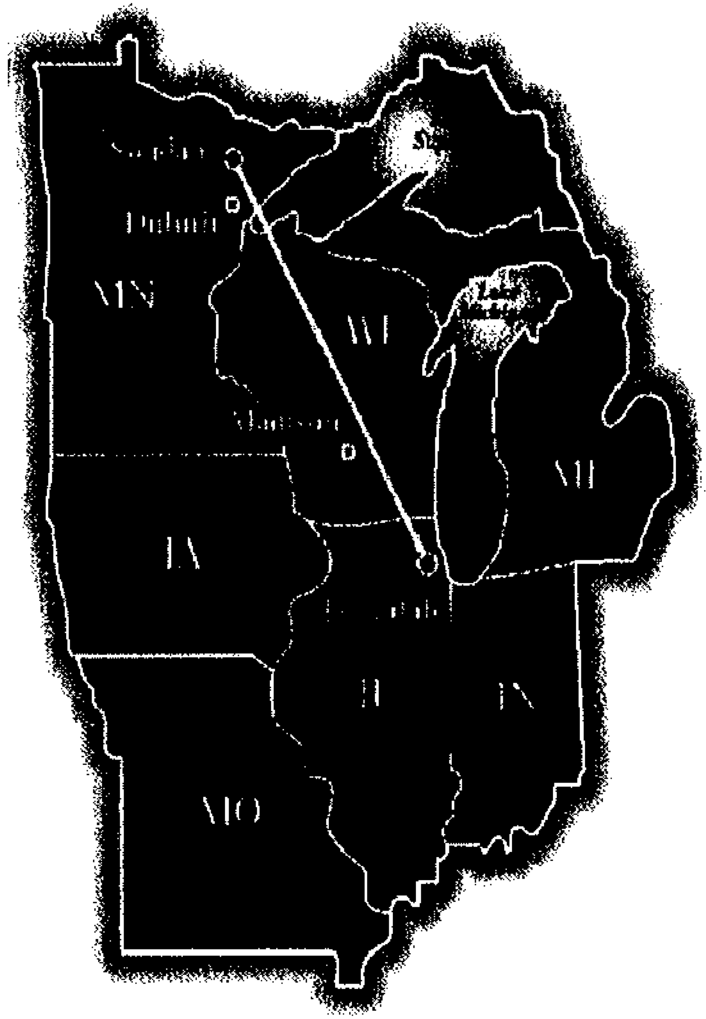
Best fit point ($\sin^2 2\theta$, Δm^2)
= (1.0, $2.8 \times 10^{-3} eV^2$)

Consistent with SK atm.

MINOS

Long-baseline experiment at Fermilab

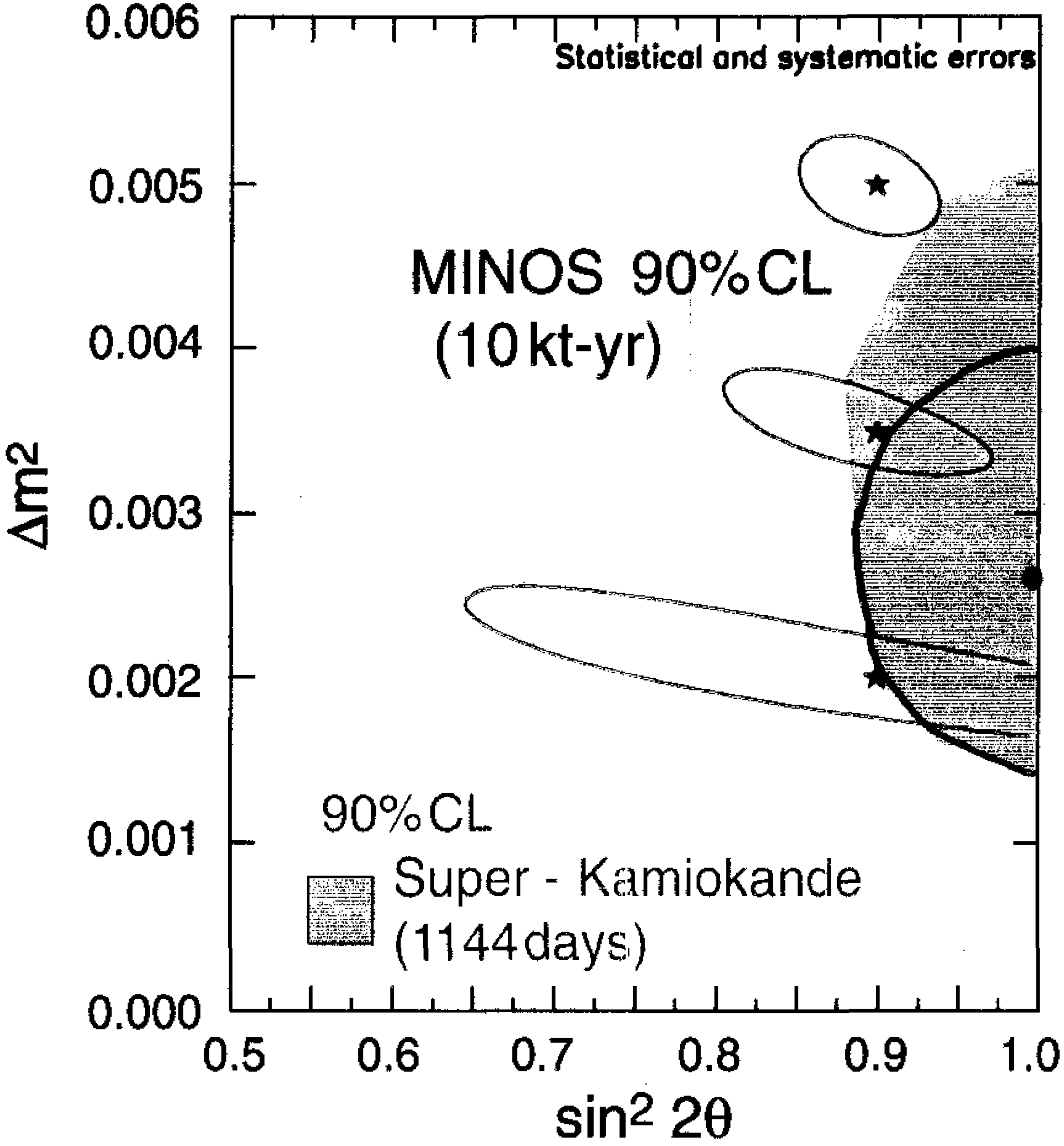




- Beam travels 735 km to Soudan Minnesota
- Sagitta:10 km
- 1km wide at destination

Atmospheric Neutrinos + Long Baseline Neutrinos

Goal: Good Comparison



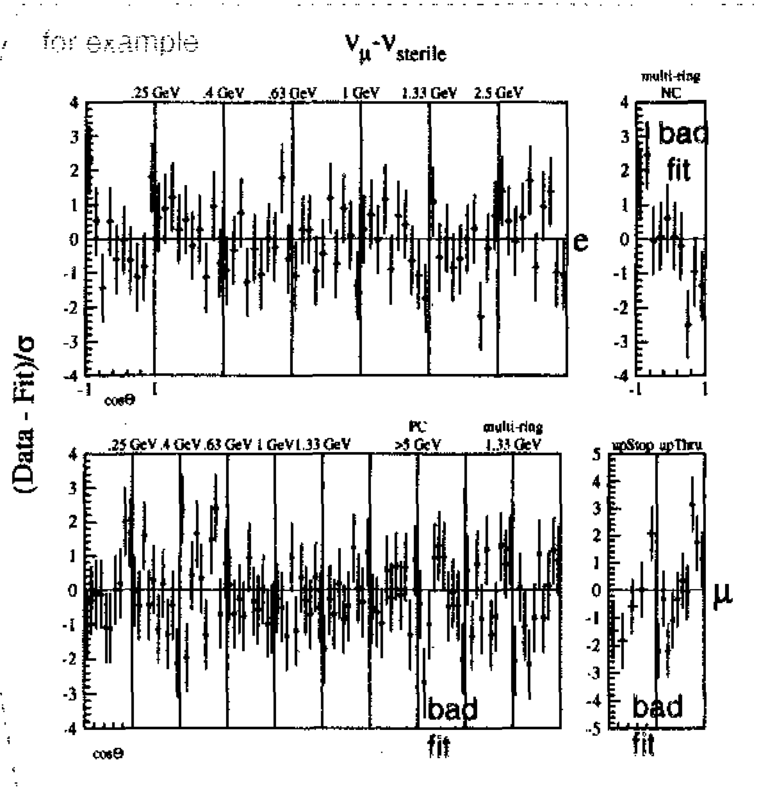
atmospheric neutrino studies will provide as good a target as possible

physics goal: measure non-mximal mixing (if it is true)

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

FC: 10 zenith angle×7 momentum bins
PC: 10 zenith angle bins
upStop 5 zenith angle bins — 195 Bins
upThru 10 zenith angle bins — 190 DOF
multi-Ring μ-like 10 zenith angle bins× 2 momentum bins
multi-Ring NC-like 10 zenith angle bins

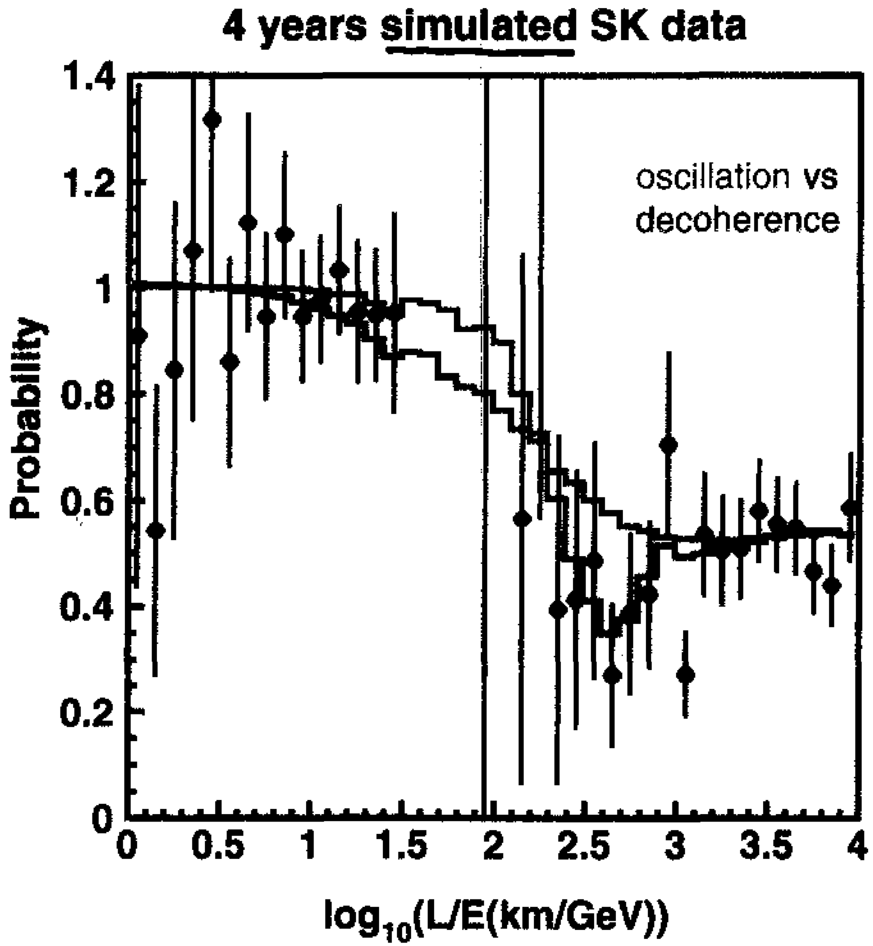
Mode	Best Fit	χ^2	$P(\chi^2)$	$\Delta\chi^2$	σ
ν_μ-ν_τ $\sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$	$\sin^2 2\theta$=1.00 Δm^2=2.1×10^{-3} eV^2	173.8	79%	0.0	0.0
ν_μ-ν_e $\sim\sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$	$\sin^2 2\theta$=0.97 Δm^2=5.1×10^{-3} eV^2	284.3	0.001%	110.5	10.5σ
ν_μ-ν_s $\sim\sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$	$\sin^2 2\theta$=0.98 Δm^2=2.9×10^{-3} eV^2	222.7	5%	48.9	7.0σ
L×E $\sin^2 2\theta \sin^2(\alpha L\times E)$	$\sin^2 2\theta$=0.90 α=5.6×10^{-4}/GeV/km	281.6	0.002%	107.8	10.4σ
ν_μ Decay $\sin^4\theta + \cos^4\theta \exp(-\alpha L/E)$	$\cos^2\theta$=0.50 α=3.7×10^{-3} GeV/km	279.4	0.003%	105.6	10.3σ
ν_μ Decay $(\sin^2\theta + \cos^2\theta e^{-\alpha L/2E})^2$	$\cos^2\theta$=0.33 α=1.2×10^{-3} GeV/km	194.0	41%	20.2	4.5σ
ν_μ Decoherence $0.5\sin^2 2\theta(1-\exp(-(\gamma/E)L/E))$	$\sin^2 2\theta$=0.98 γ=7.3×10^{-3} GeV/km	184.3	64%	10.5	3.2σ
No Oscillations	-	427.4	0%	252.4	15.9σ



matter effects suppress high energy ν_μ-$\nu_{sterile}$ oscillation

neutral current should disappear for $\nu_{sterile}$ oscillation

Super-K can try this analysis too...



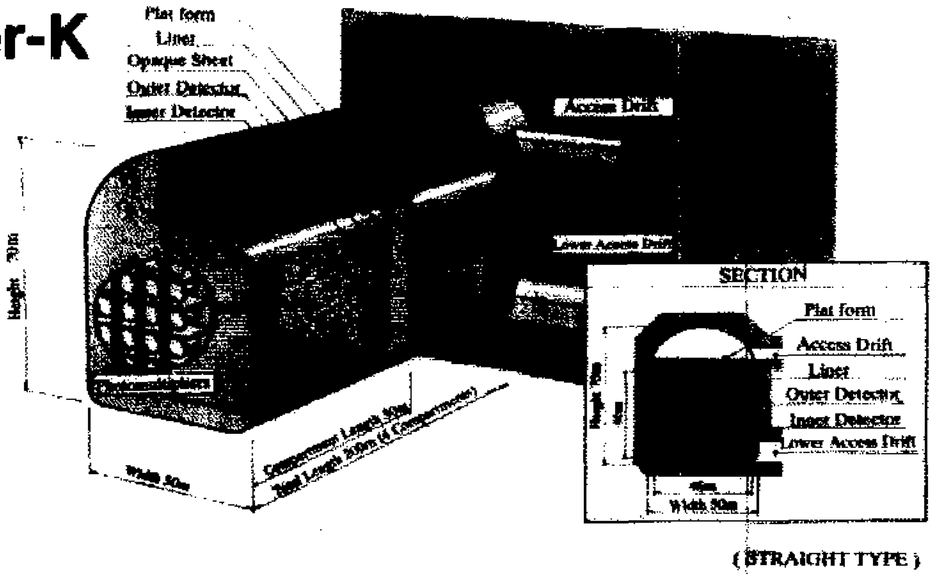
SK-1 may say something at ~2σ
continued running with SK-2 will help.

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

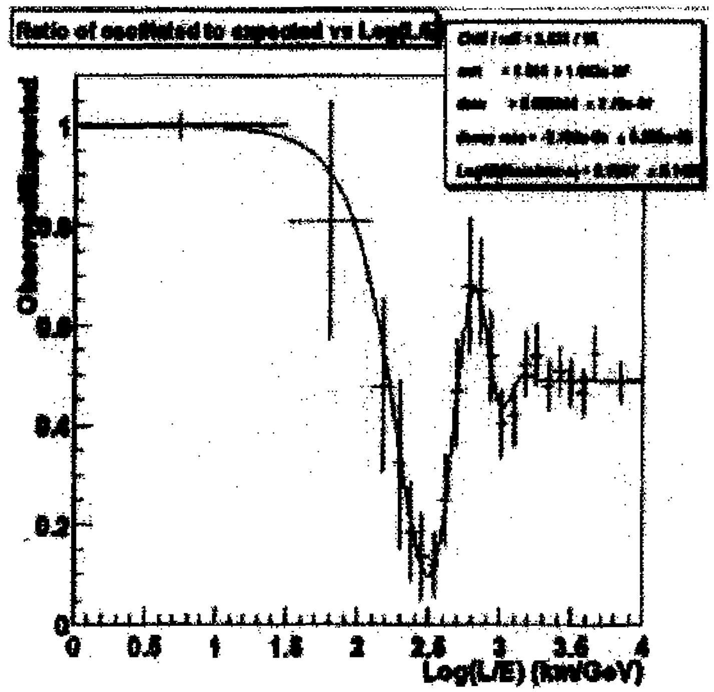
Future Large Water Cherenkov

Hyper-K

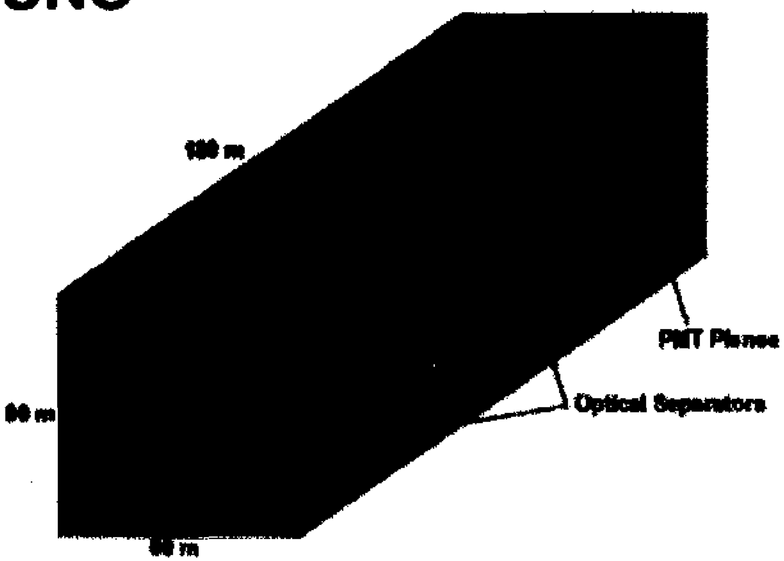

SK



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



UNO



Super-K Tau Appearance Result:

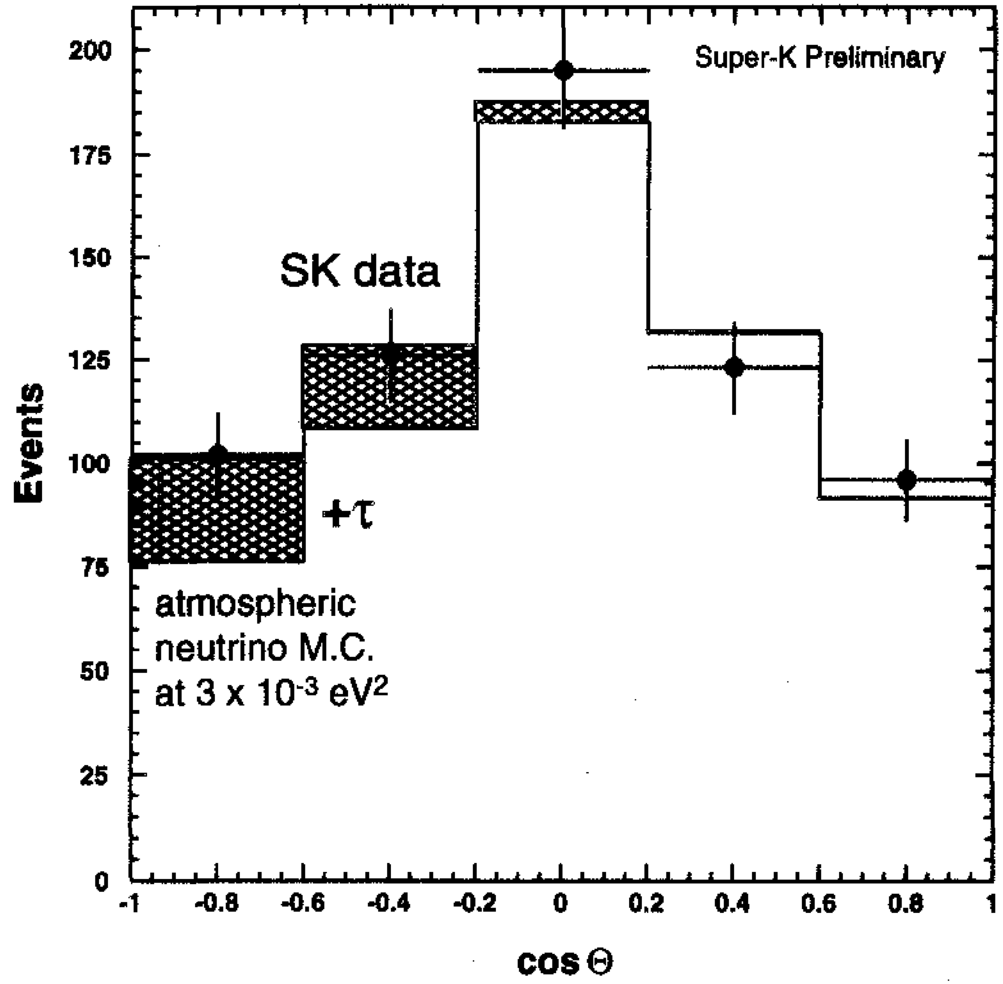
Expected τ-neutrino CC events in SK data sample = 85

Fit to: A x tau appearance
+ B x tau no-appearance
(as a function of cos Θ)

Result (tau events in SK data):
$99 \pm 39 \pm 13 ^{+0}_{-16}$

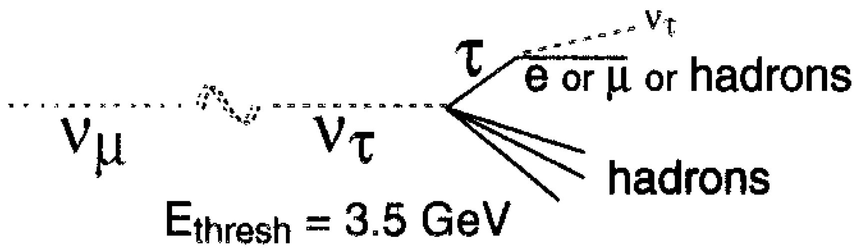
Δm^2 uncertainty — 3-flavor uncertainty

other independent SK analyses give consistent results



SK data is consistent with presence of CC tau neutrino interactions

Tau Appearance Studies

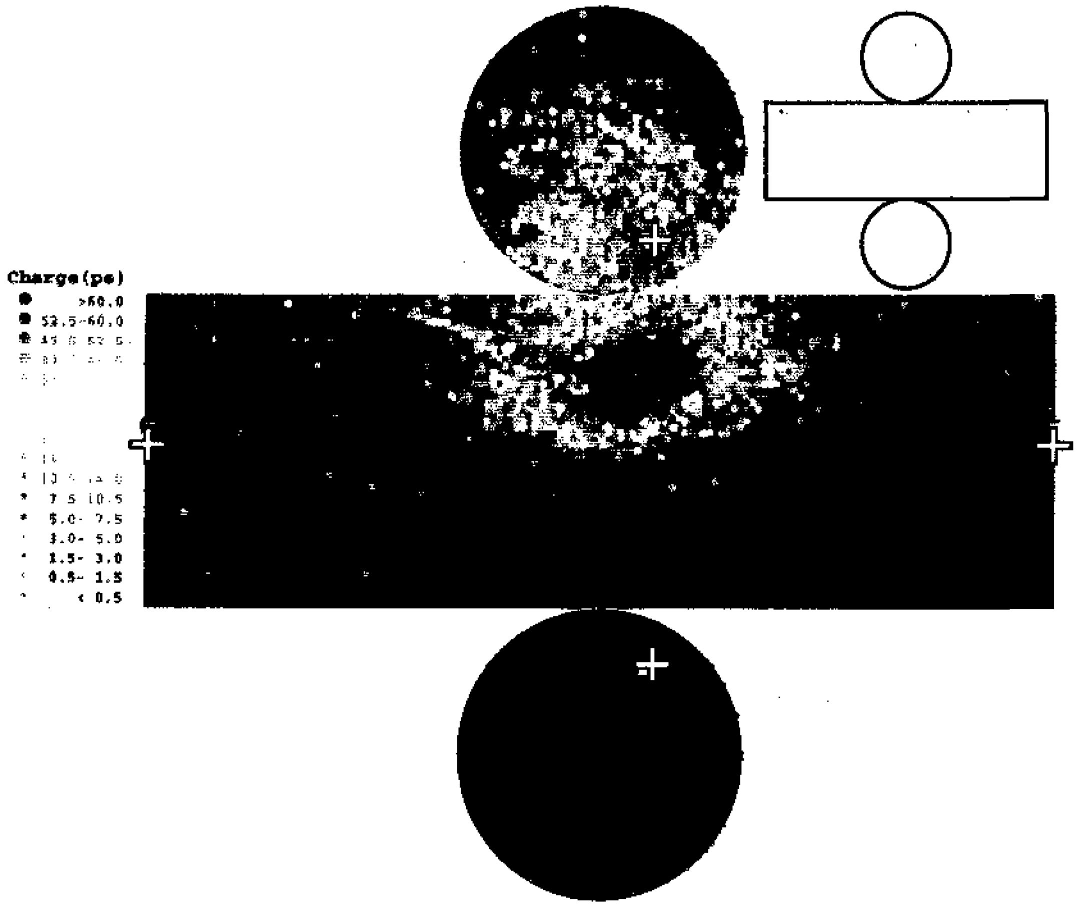


for $\sin^2 2\theta = 1$ and
$\Delta m^2 = 3 \times 10^{-3}$ eV^2,
we expect ~85 events
in the 1489 day SK sample

events have large visible
energy (> 2 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:

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

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta_{atm} \sin^2 \frac{\delta m^2_{atm} L}{4E}$$

$$|\delta m^2_{atm}| \sim 1.6 - 3.9 \times 10^{-3}\ eV^2$$

$$\sin^2 2\theta_{atm} > 0.9 !$$

- K2K (first long (>100 km) ~~long~~ baseline exp) Consistent with Atmospheric ν's.