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Lecture II

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

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NEUTRINO PHYSICS

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ν-Interactions in SM.

Low energy effective Hamiltonian

$$E^2, q^2 \ll m_W^2 . \qquad G_F/\sqrt{2} = g^2/8m_W^2$$

$$H^{cc}_{eff} = \frac{4G_F}{\sqrt{2}} J^{\dagger}_{\mu L} J_{\mu L} + h.c.$$

$$H^{nc}_{eff} = \frac{G_F}{\sqrt{2}} J^N_\mu J^N_\mu$$

$$J^N_\mu = 2 \sum_i \bar{\psi}_i (T_3 - x_W^2) \psi_i$$

$$= 2 \sum_i \{ g_{iL} \bar{\psi}_{iL} \gamma_\mu \psi_{iL} + g_{iR} \bar{\psi}_{iR} \gamma_\mu \psi_{iR} \}$$

	g_{iL}	g_{iR}
ν	$1/2$	0
e	$-\frac{1}{2} + x_W^2 \approx -1/4$	$x_W^2 \approx 1/4$
u	$\frac{1}{2} - \frac{2}{3} x_W^2 \approx 1/3$	$-\frac{2}{3} x_W^2 \approx -1/6$
d	$-\frac{1}{2} + \frac{2}{3} x_W^2 \approx 5/12$	$\frac{1}{3} x_W^2 \approx 1/12$.

Neutrino Cross-Sections

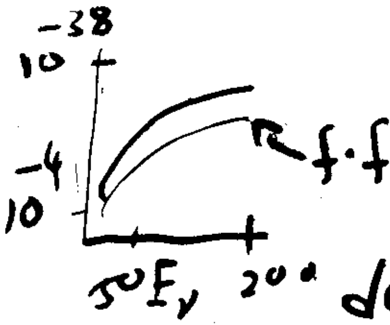
	c
$\nu_e e \to \nu_e e$	1
$\bar{\nu}_e e \to \bar{\nu}_e e$	0.4
$\nu_\mu e \to \nu_\mu e$	0.16
$\bar{\nu}_\mu e \to \bar{\nu}_\mu e$	0.13

$$\sigma \equiv c\left(E_\nu/10\,\text{MeV}\right) 10^{-43}\ \text{cm}^2$$

ν-N

$$H_{eff} \approx \frac{G_F}{\sqrt{2}} |U_{ud}|\, \bar{e}\gamma_\mu(1+\gamma_5)\nu_e \; \bar{p}\gamma_\mu(g_V + g_A\gamma_5)n + h.c.$$

$$\sigma(\bar{\nu}_e p \to e^+ n) = \sigma(\nu_e n \to e^- p)$$
$$= \frac{G_F^2 E_\nu^2}{\pi}\left(1 + 3g_A^2/g_V^2\right)$$
$$\approx 9.2 \cdot 10^{-42}\left(E_\nu/10\,\text{MeV}\right)^2$$



$$\frac{d\sigma}{d(\cos\theta)} \approx 1 - (0.1)\cos\theta$$

$E_\nu >$ few GeV $\longrightarrow$ Deep Inel. Scatt.

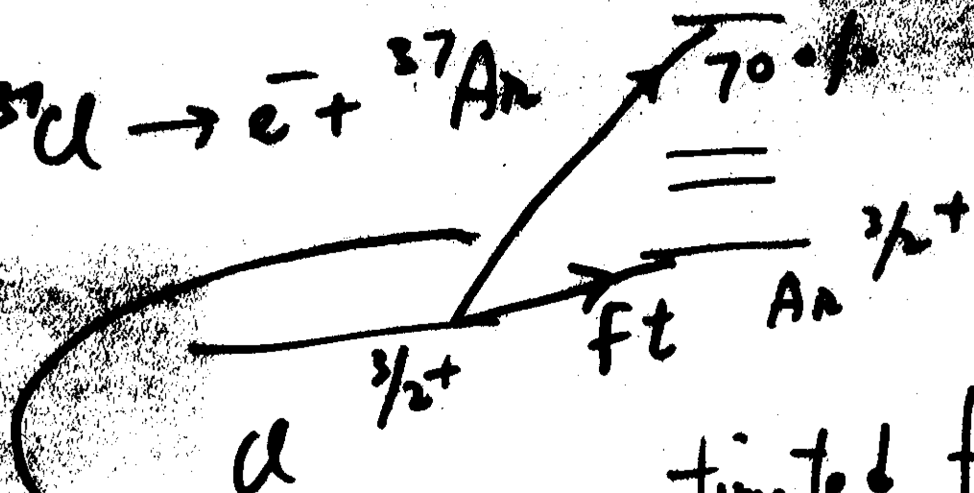
$\nu N \to \nu X$

$$\sigma_\nu \to \frac{G_F^2 m_N E_\nu}{\pi}, \quad \sigma_{\bar{\nu}} \sim \frac{1}{3}\sigma_\nu$$

ν-nucleus scattering

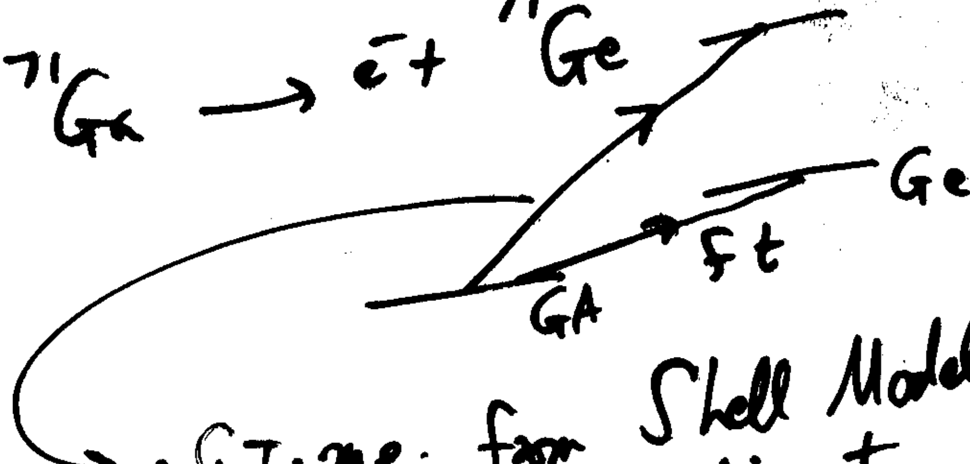
- ν-D scattering $\nu_e D \to p p e^-$
  $\nu_x D \to n p$ [illegible])
  (relate [illegible]

- $\nu_e + {}^{37}Cl \to e^- + {}^{37}Ar$



G.T. m.e. estimated from mirror process $^{37}K \to {}^{37}Ar + e$

- $\nu_e + {}^{71}Ga \to e^- + {}^{71}Ge$



- G.T. m.e. from Shell Model
- " " relation to p–n reaction

Coherent Forward Scattering in matter

$$H_{eff}^{CC} + H_{eff}^{NC} \Rightarrow$$

$$\begin{aligned}
\delta H_{\nu_e} = & \pm \sqrt{2}\, G_F \left(\tfrac{1}{2} + x_W^2\right) n_e \\
& \pm \sqrt{2}\, G_F \left(\tfrac{1}{2} - 2x_W^2\right) n_p \\
& \pm \sqrt{2}\, G_F \left(\tfrac{1}{2}\right) n_n
\end{aligned}$$

$$\begin{aligned}
\delta H_{\nu_\mu} = & \pm \sqrt{2}\, G_F \left(\tfrac{1}{2} + \tfrac{1}{2} x_W^2\right) n_e \\
& \pm \sqrt{2}\, G_F \left(\tfrac{1}{2} - 2x_W^2\right) n_p \\
& \pm \sqrt{2}\, G_F \left(\tfrac{1}{2}\right) n_n
\end{aligned}$$

$\left\{\begin{array}{l} + \longrightarrow \nu \\ - \longrightarrow \bar{\nu} \end{array}\right\}$ {neutral matter $n_e = n_p \approx n_n$}

$$\delta H_{\nu_e} - \delta H_{\nu_\mu} = \pm \sqrt{2}\, G_F\, n_e$$

Atmospheric Neutrinos

<u>Expect:</u> · primary + Air $\to \pi + X$
$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\hookrightarrow \mu\,\nu_\mu$

· @ $h \sim 10-20$ km

· For $E_\mu <$ few GeV $\quad \mu \to e\,\nu_e\,\nu_\mu$

$\Rightarrow \quad \#\nu_\mu / \#\nu_e \approx 2/1. \quad , \quad \bar{\nu}/\nu \sim O(1)$

· low energies ($E <$ few GeV), no θ_z dependence.

· high energies $\#\nu_e \to 0$ & "$\sec\theta$" law sets in.

$$dN_{\nu_\mu} \sim E_\nu^{-2.7}\left[\frac{1}{1+\alpha\cos\theta} + \frac{0.15}{1+\beta\cos\theta} + \cdots\right]$$

$\pi \quad\quad\quad\quad K \quad\quad\quad\quad c, b$

$\alpha = E_\nu/(40\,\text{GeV})$
$\beta = E_\nu/(400\,\text{GeV})$
etc.

· Absolute flux calculations of ν's uncertain by $\sim 20\%$.

· low energy ν_μ/ν_e ratios, many uncertainties cancel $\Rightarrow$ maybe better than 5%

Atmospheric Neutrinos

- Cosmic Ray Primaries
  mostly protons, ~~nuc~~ nuclei
  $(Z \geq 1)$

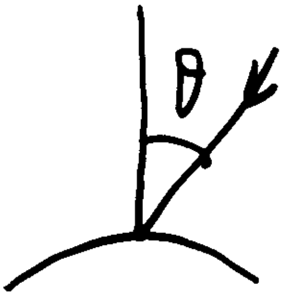
- $p + \text{air} \longrightarrow \pi + \cdots$

  Competition between
  (i) $\pi + \text{air} \longrightarrow X$
  (ii) $\pi \longrightarrow \mu \nu_\mu$

- Most of the action takes place @ few km height

- If $E_\mu <$ few GeV
  then $\mu \rightarrow e \nu_e \nu_\mu$
  (enuf time for this decay before reaching surface).

- Thus for $E_\nu \gtrsim O(\text{GeV})$.
  : $\# \nu \approx \# \bar{\nu}$
  : $\# \nu_\mu / \# \nu_e \approx 2/1$.



Also at these low energies, [redacted] there is [redacted] no zenith angle dependence.

At energies above a few GeV the famous "$\sec\theta$" law takes over, & μ's cannot decay. (Barrett et al.)

Hence $\# \nu_e << \# \nu_\mu$.

& θ dependence is given by:

$$\frac{dN_{\nu_\mu}}{dx} = N_0 E_\nu^{-2.7} \left[\frac{1}{1+(E_{\nu_\mu}/40\,\mathrm{GeV})\cos\theta} + \frac{0.15}{1+(E_{\nu_\mu}/800\,\mathrm{GeV})\cos\theta} + \cdots \right]$$

reflects primary spectrum

π's

K's

charm etc

- As $E_{\nu_\mu} >> 40$ GeV, first term $\sim \sec\theta$.
  Roughly at these energies, in competition between π-decay & π-interaction, decay "wins" at large θ; hence $\# \nu_\mu$ increase at large & go as $\sec\theta$.

- At high energies. $\left(\begin{matrix} \# K^+ > \# K^- \\ \# \nu_\mu > \bar{\nu}_\mu \end{matrix} \right)$

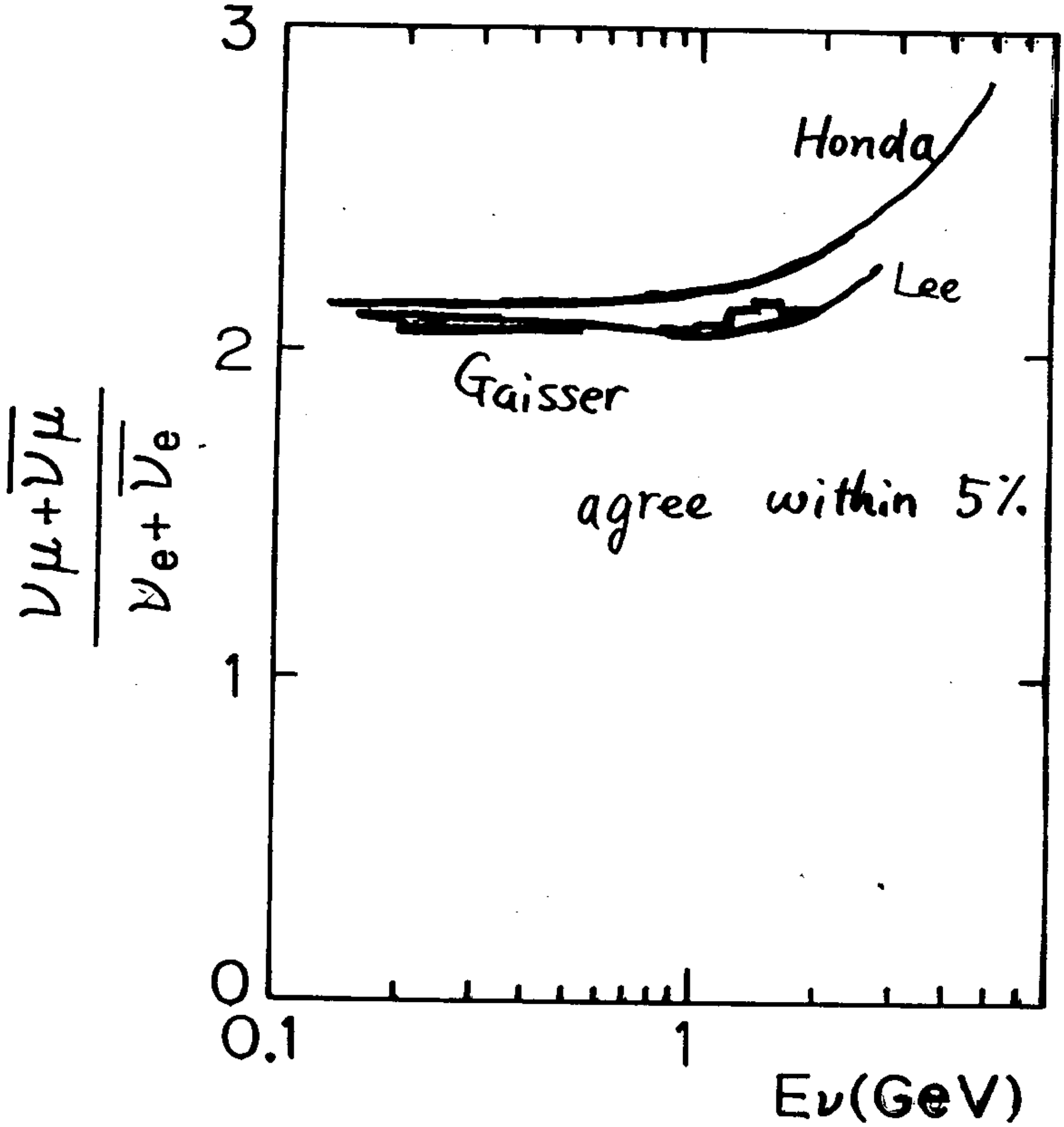
- Charm & beauty lifetimes much shorter than π, K.
  Hence the ν_μ's are "prompt" & do not show the "$\sec\theta$" effect but give a constant term.

In low energy ν_μ, ν_e's in calculating $\#\nu_\mu / \#\nu_e$ many uncertainties cancel & theoretical results uncertain to maybe 5%.

Individual ν_μ, ν_e fluxes (including high energy ν_μ's) uncertain by 20%.

$(``\nu" \equiv \nu + \bar{\nu})$

Zenith angle dependence washed out by magnetic field.



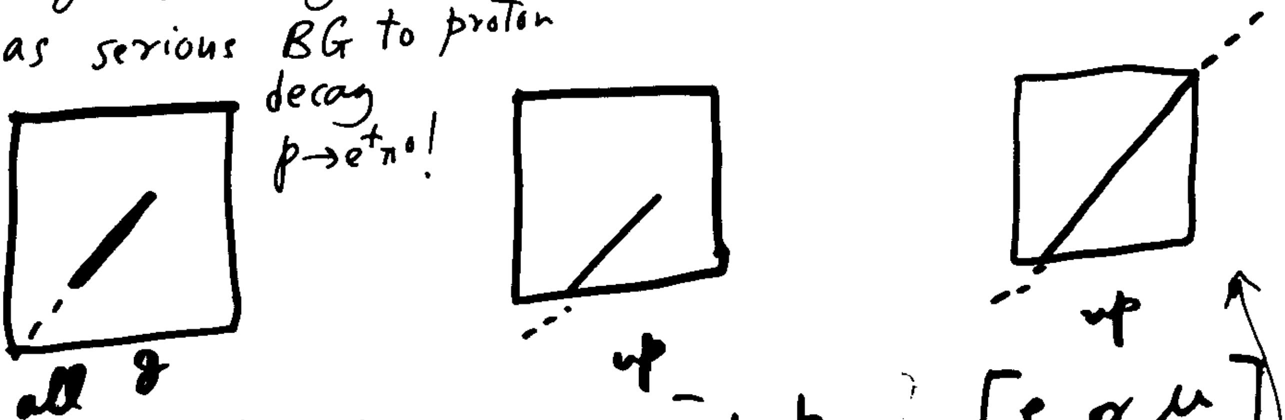
Individual ν_μ, ν_e fluxes uncertain by 20%

Ratio by 5%

In a typical (1 KTON) (water $\hat{c}$) detector ν's make 3 Kinds of events. E.g.

Contained Stopper thrugoing

Originally thought of as serious BG to proton decay $p \to e^+\pi^0$!

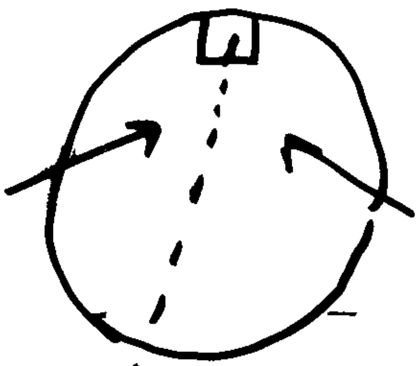


$$\begin{cases} \nu_e + n \longrightarrow e^- + p \\ \nu_\mu + n \longrightarrow \mu^- + p \end{cases}$$

[e or μ tracks]

(downgoing overwhelmed by μBG)

thrugoing = upcoming



all upcoming events

Water $\hat{c}$ Detectors: IMB, Kamiokande, Super Kam.

Others: KGF, Frejus, Baksan, SOUDAN, MACRO

93-0022p

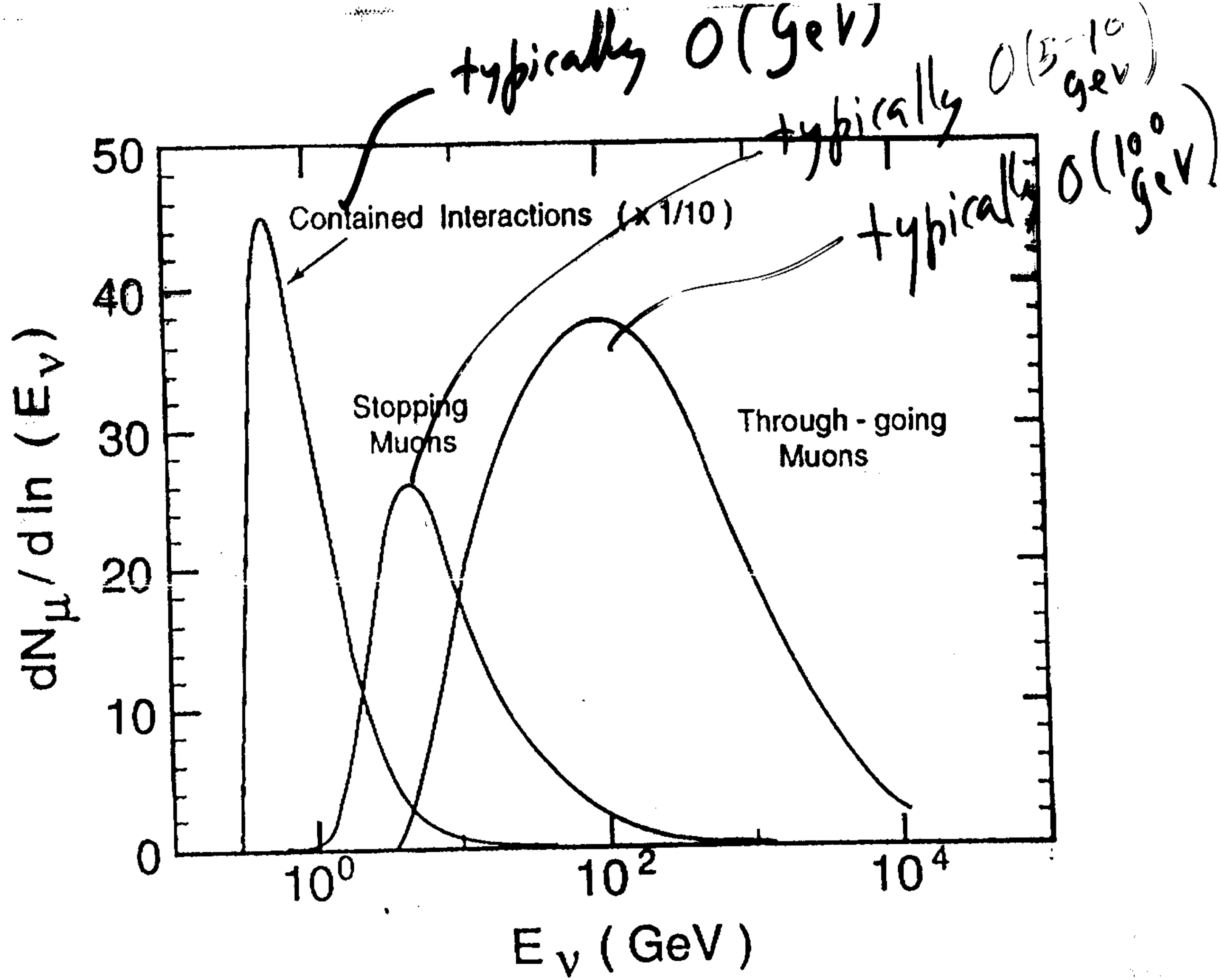
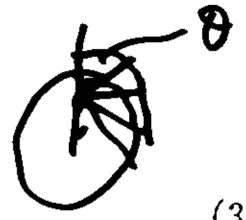


Fig.2

If $\nu_\mu \leftrightarrow \nu_\tau$ oscillations are operative in the low energy atmospheric ν flux, the ν_μ flux will be reduced by a factor of $(1 - P_{\nu_\mu\nu_\tau})$, while the ν_e flux is unaffected. Hence, R becomes

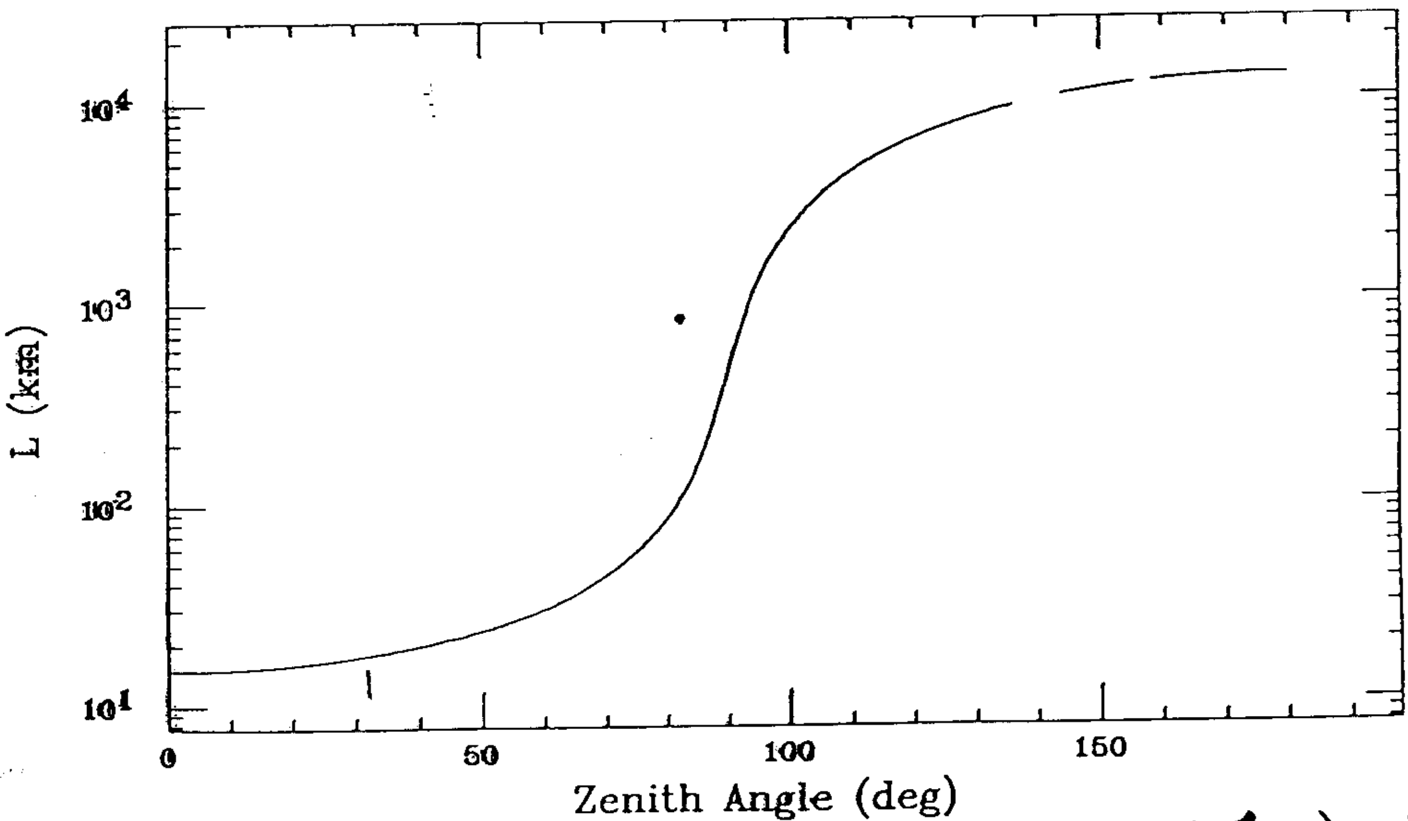


$$\begin{aligned} R_{\nu_\mu\nu_\tau} &= 1 - P_{\nu_\mu\nu_\tau} \\ &= \frac{1}{2}\sin^2 2\theta_{\mu\tau}\left(1 - \cos\frac{2\pi L}{\lambda_{12}}\right) \end{aligned} \tag{3.32}$$

where $\theta_{\mu\tau}$ is the $\nu_\mu\nu_\tau$ vacuum mixing angle and $\lambda_{12} = \frac{4\pi|\mathbf{p}|}{\delta m^2_{12}}$. The neutrino path length L can be described in terms of the zenith angle,[65] ϕ_z, of the event observed in the detector:

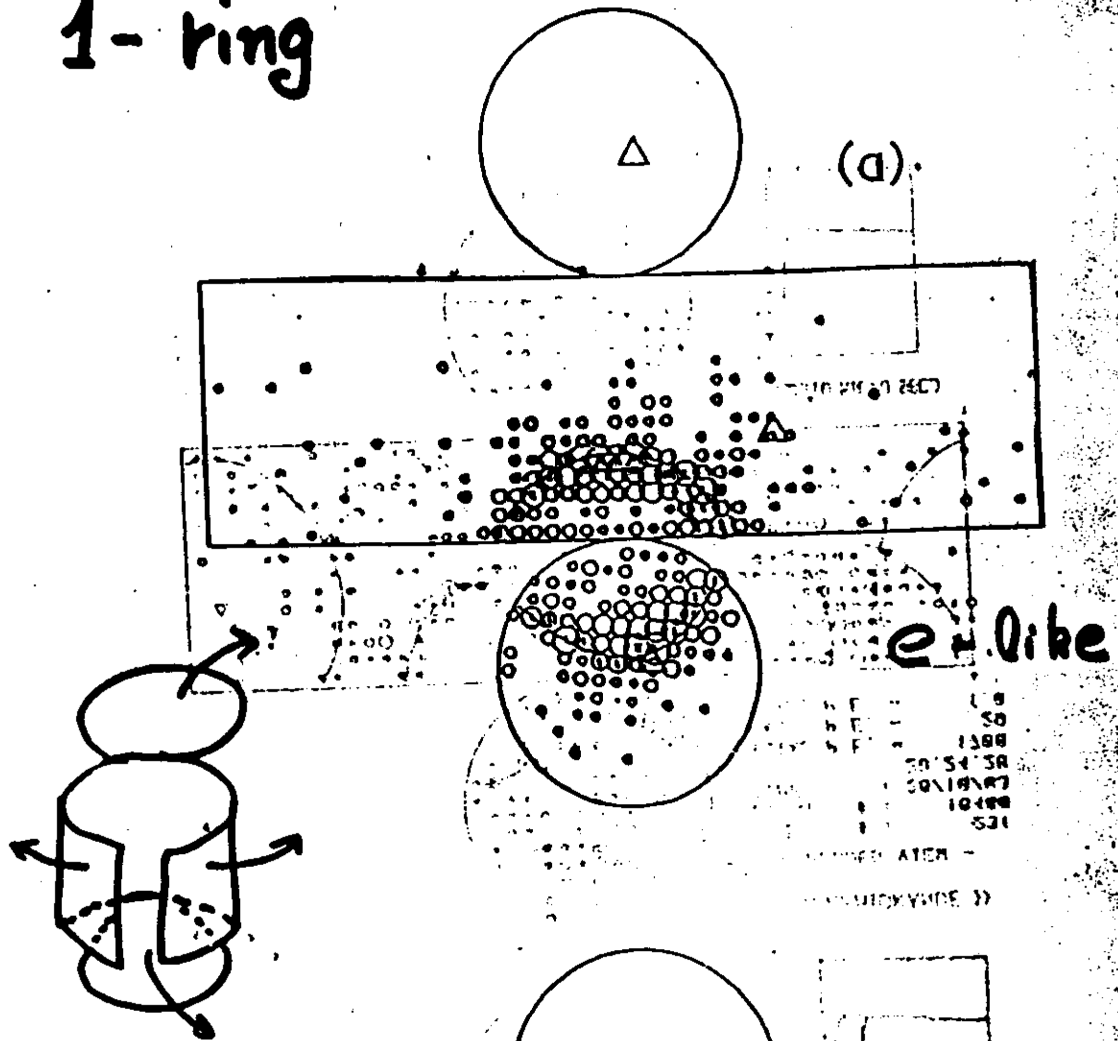
$$L(\phi_z) = R_e\left[\left((1 - h/R_e)^2 - \sin^2\phi_z\right)^{1/2} - \cos\phi_z\right] \tag{3.33}$$

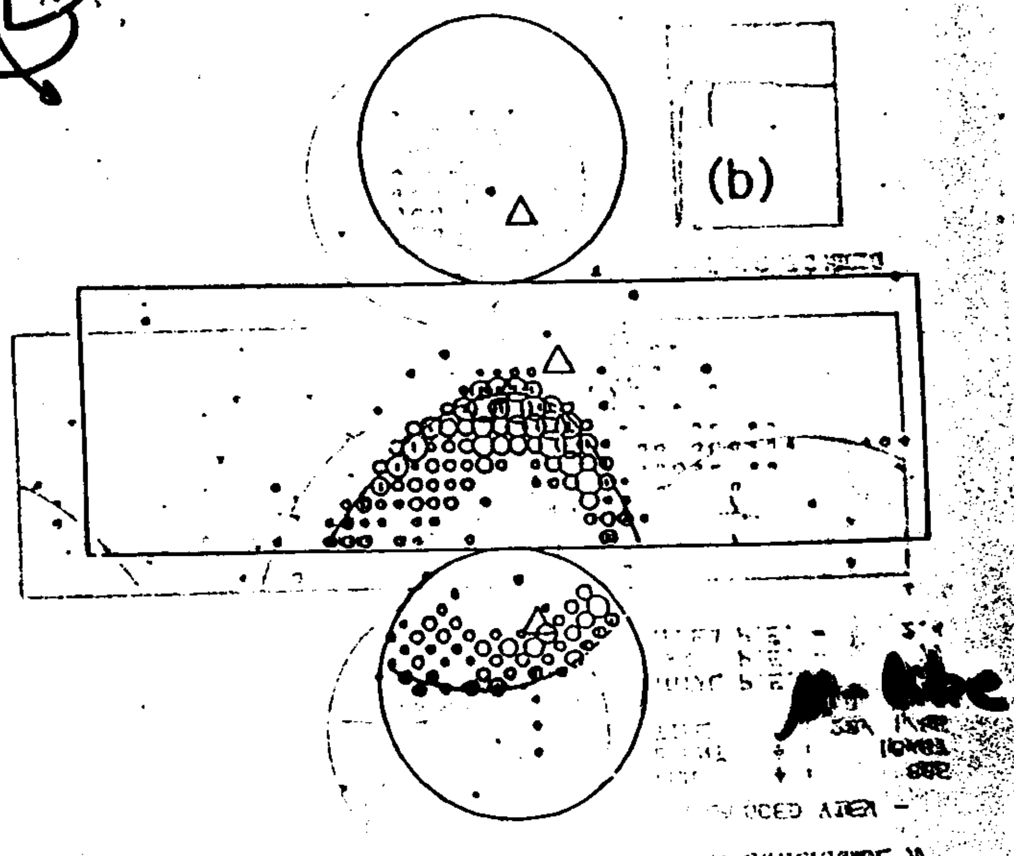
where R_e is the radius of the Earth and h is the atmospheric neutrino production height, which is typically $\sim$ 15 km above sea level (see figure 3.1).



Dependence of θ_z on ~~Height~~ Dist

1- ring





KamioKande

Claimed detection efficiency. (Kamiokande)

e-like	1 pr.	93%	[IMB Similar]
μ-like	1 pr.	88%	

[more multiple scatt.
Cer. Ring more diffuse.]

Events distributed uniformly in FV.

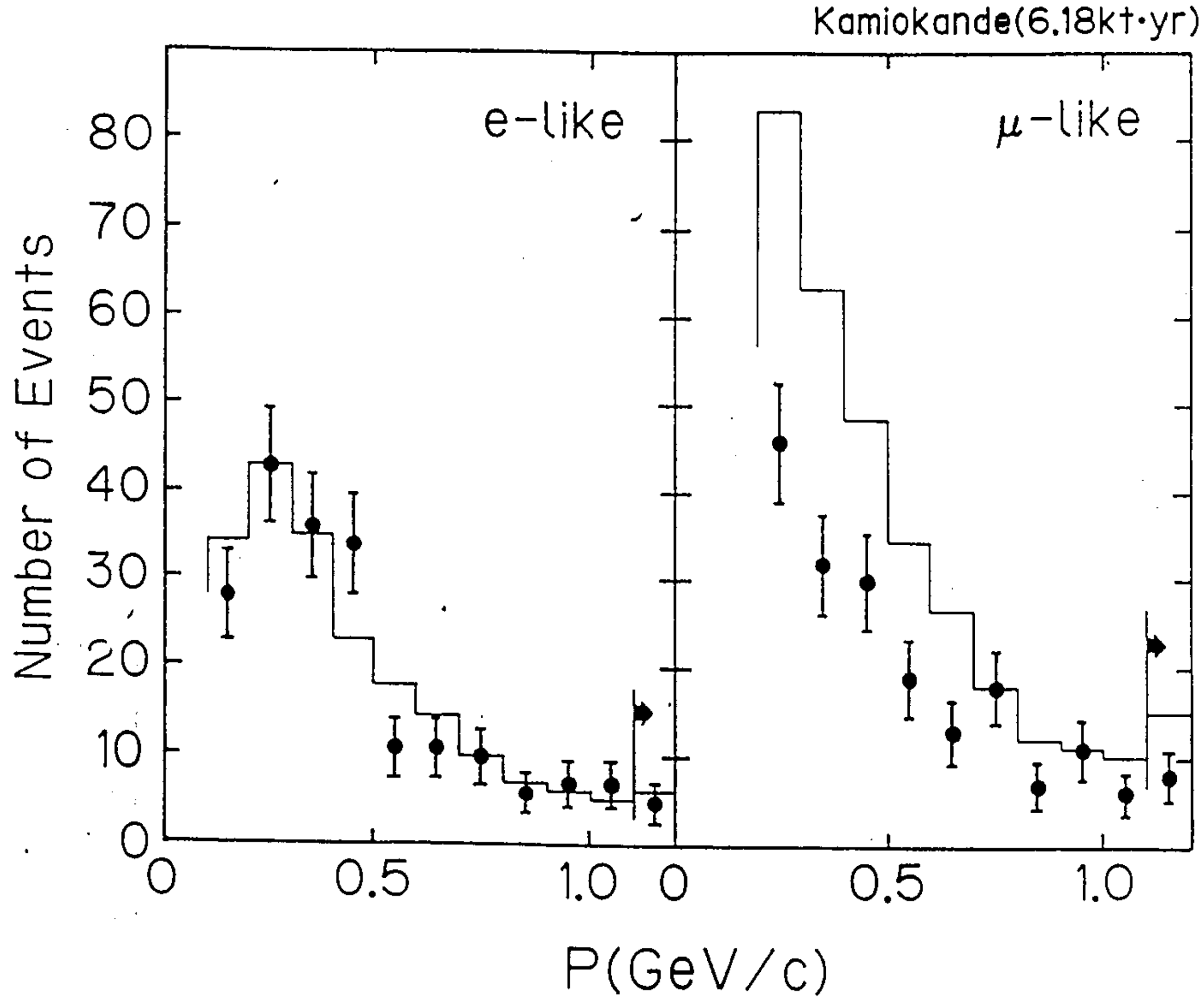
Beleive calculated ν_e, ν_μ fluxes accurate to 20%

Ratio ν_e/ν_μ accurate to 5%.

Energy Range of e/μ 200 - 700 MeV.

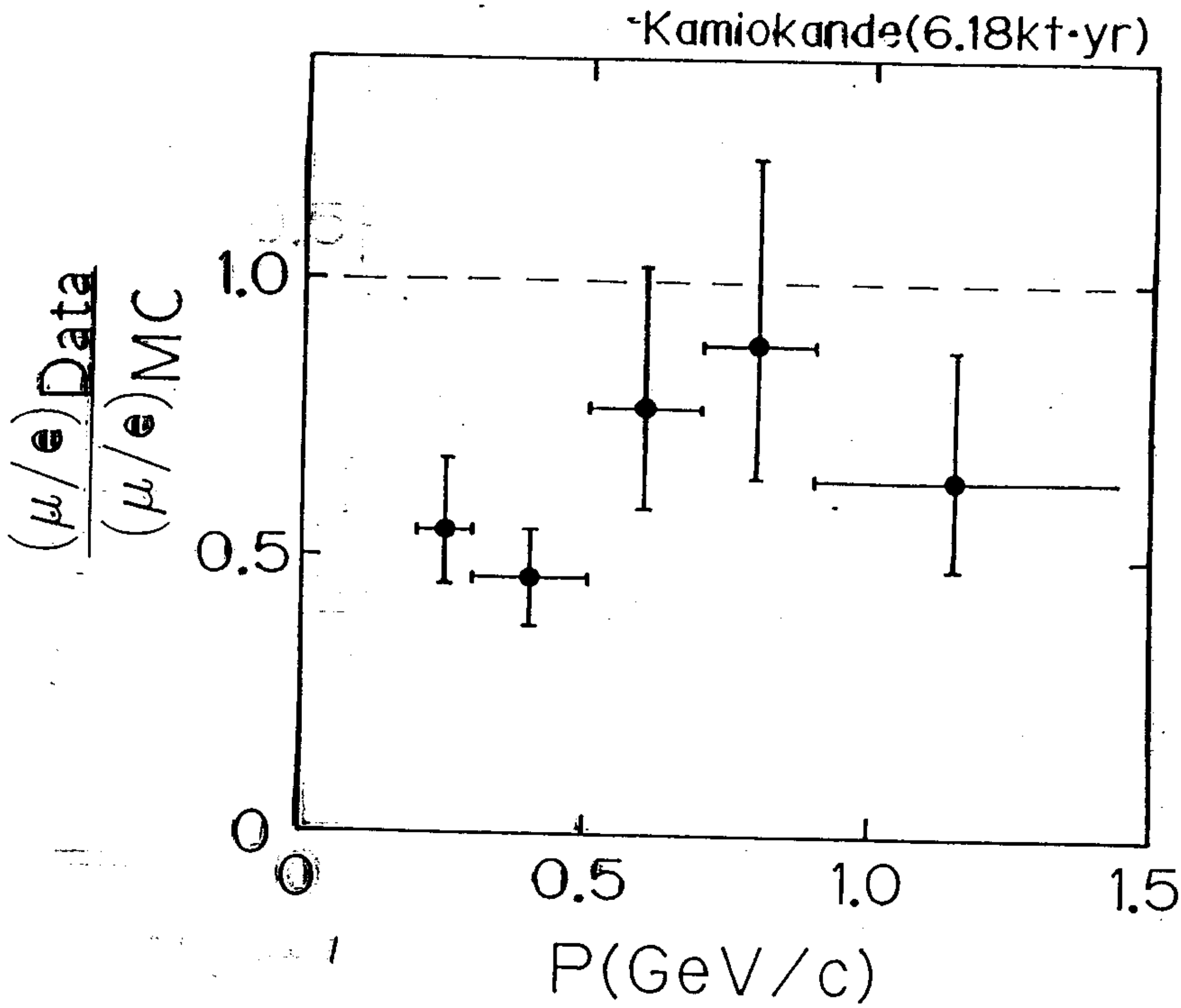
Contained

Momentum spectra of e- and μ-like events.

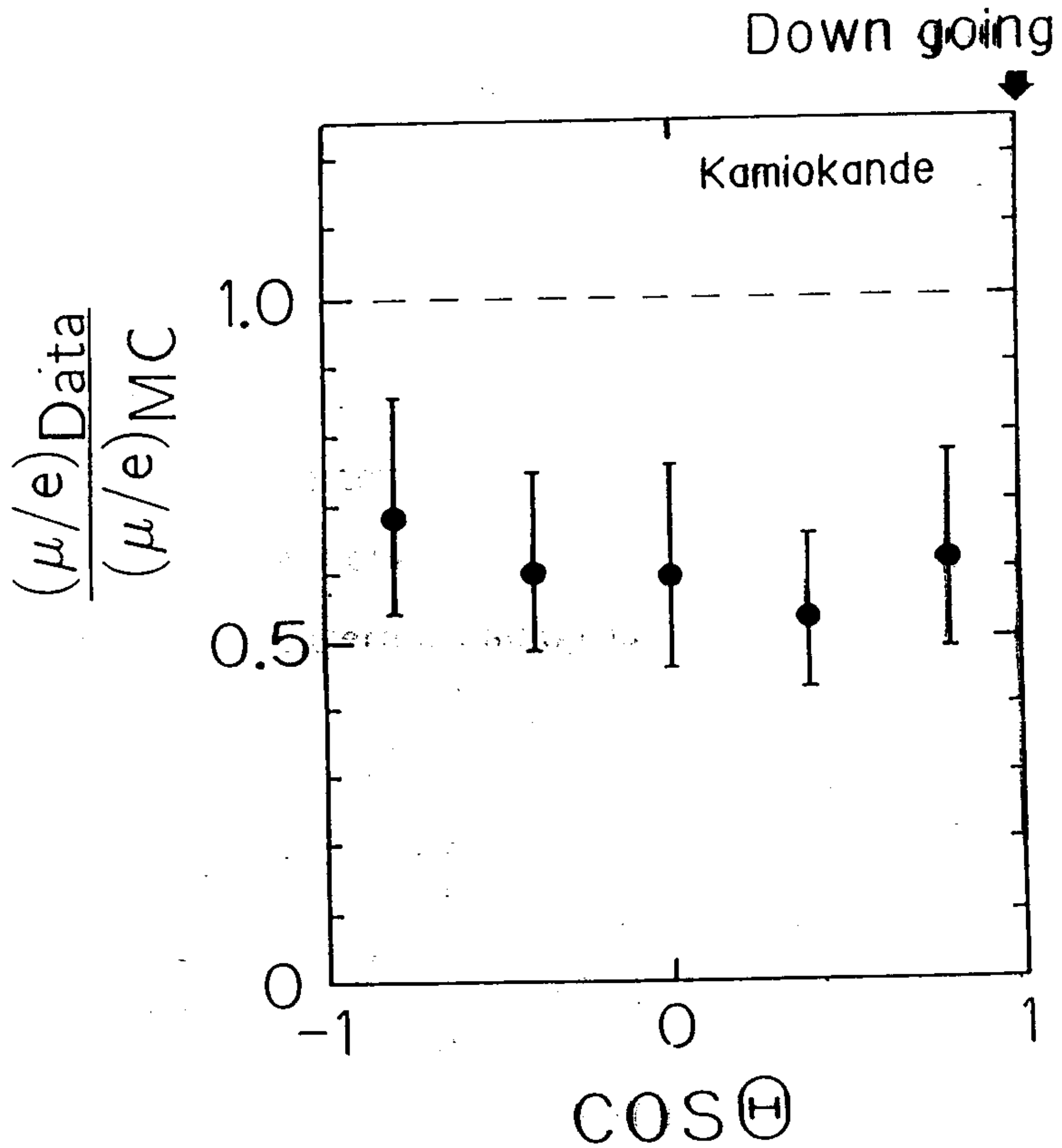


results in PMC

Momentum dependence of $\frac{(\mu/e)_{Data}}{(\mu/e)_{MC}}$



Zenith angle dependence of $\frac{(\mu/e)_{Data}}{(\mu/e)_{MC}}$



$\Longrightarrow$

No strong momentum and zenith angle dependence.

Atmospheric Contained Event
e/μ Anomaly

2.2 Comparison with other experiments

Five underground experiments have reported the atmospheric neutrino observations up to now. Two are the water Cerenkov type experiments of IMB [30] and Kamiokande. The other three are the tracking detectors of NUSEX [31], Frejus [32] and SUDAN-II [33]. All experiments furnish the ability to identify the particle type of e-like or μ-like. Thus, it is possible to compare the R(μ/e) ratios observed in all these experiments. Table 4 lists up the observed and expected event numbers, and R(μ/e).

Table 4: Summary of the low energy ($E_{e,\mu}$ < 1.5GeV/c) atmospheric neutrino data from 5 experiments

Experiment	Data		MC		$\frac{(\mu/e)\text{data}}{(\mu/e)\text{MC}}$
	e	μ	e	μ	
NUSEX	18	32	20.5	36.8	$0.99^{+0.35}_{-0.25}\pm$small
Frejus					
all contained†	57	108	70.6	125.8	$1.06^{+0.19}_{-0.16}\pm0.15$
fully contained	56	66	66.8	90.0	$0.87^{+0.18}_{-0.14}\pm0.12$
SUDAN-II*	13.89	10.95	92	132	$0.55\pm0.29\pm0.10$
IMB-3	325	182	257.3	268.0	$0.54\pm0.05\pm0.12$
Kamiokande	159	151	164.9	260.6	$0.60^{+0.07}_{-0.06}\pm0.05$
p < 500 MeV/c	141	109	138.4	197.1	0.54 ± 0.07
p > 500 MeV/c	57	82	66.6	127.5	$0.75^{+0.14}_{-0.12}$

† fully contained events + partially contained events.
* the event number multiplied by the detection efficiency.

IMB-3 has recently supported smaller R(μ/e) ratio than the MC prediction observed in Kamiokande. On the other hand, two tracking experiments of NUSEX and Frejus show R(μ/e) ~ 1, which means that there is no atmospheric neutrino anomaly as far as these data are concerned. However, statistical significance is not high in the NUSEX data. As for the Frejus data, most of the momentum of observed events are higher than 500 MeV/c, because the event trigger efficiency reaches 50% at 400 MeV/c. Here, one should remember that the atmospheric neutrino anomaly is significant in the low momentum region (< 500 MeV/c) as shown in Fig. 13 and Table 4. Therefore the Frejus result of R(μ/e) $= 0.87^{+0.18}_{-0.16}\pm 0.12$ for fully contained events is not inconsistent with the Kamiokande result of R(μ/e) $= 0.75^{+0.14}_{-0.12}$ for fully contained events with p > 500 MeV/c.

Before 1993 it was sometimes murmured that the atmospheric neutrino anomaly was a unique phenomenon in a water Cerenkov detector. However, in 1993 SUDAN-II has presented its first result on atmospheric neutrinos. The result as shown in Table 4 is consistent with

Atmospheric Neutrinos

Low Energy $E_\nu \sim 0.2$ to 1.2 GeV.

$R = (N_{\nu_\mu} + N_{\bar{\nu}_\mu})/(N_{\nu_e} + N_{\bar{\nu}_e})$ expected to be ~ 2.

# events			
~~5?0~~ 400	Observed: $\hat{c}$ Kam.	$R_{obs}/R_{MC} =$	$0.60 \pm 0.07 \pm 0.05$
507	$\hat{c}$ IMB		$0.54 \pm 0.05 \pm 0.\cancel{0}2$.
1 kT-yr	FeSc SOUDAN - II (trend?)	(~~latest~~) (1996)	~~0.46 ± 0.23~~ ~~0.69 ± 0.21~~ $0.72 \pm 0.16 \pm \ldots$
			$0.87 \pm 0.16 \pm 0.08$
133	FeSc Frejus (contained)		$0.99 \pm^{0.35}_{0.25} \pm$
50	FeSc NUSEX		

- Effect strongest in H_2O $\hat{c}$
- $R_{obs} \sim (0.6)\, R_{exp}$.
- Zenith angle distribution uniform (as expected)

Experiment	kton yr	$R \pm$ stat. $\pm$ sys.
KAMIOKA	6.1	$0.60 \pm 0.06 \pm 0.05$
IMB	7.7	$0.54 \pm 0.05 \pm 0.11$
FREJUS	1.56	$0.87 \pm 0.16 \pm 0.08$
NUSEX	0.40	$0.96 \pm 0.28 \pm 0.00$
SOUDAN	1.52	$0.72 \pm 0.19 \pm 0.07$

Table 1: The atmospheric neutrino ratio $R = (\mu/e)_{DATA}/(\mu/e)_{MC}$ for contained events, from the various underground experiments. A common $\pm 5\%$ contribution to the systematic error, coming from the uncertainty in the predicted flux ratio, has been subtracted from the quoted systematic error where appropriate. A weighted mean of the above results, adding the statistical and systematic errors in quadrature, yields $R = 0.64 \pm 0.06$, where the common $\pm 5\%$ flux-ratio error is now included.

- $R = 0.64 \pm 0.06$

Weighted Mean.

- Effect' Uniform for $E_\nu \sim 0.5$ to 1.2 GeV
- " " in zenith angle

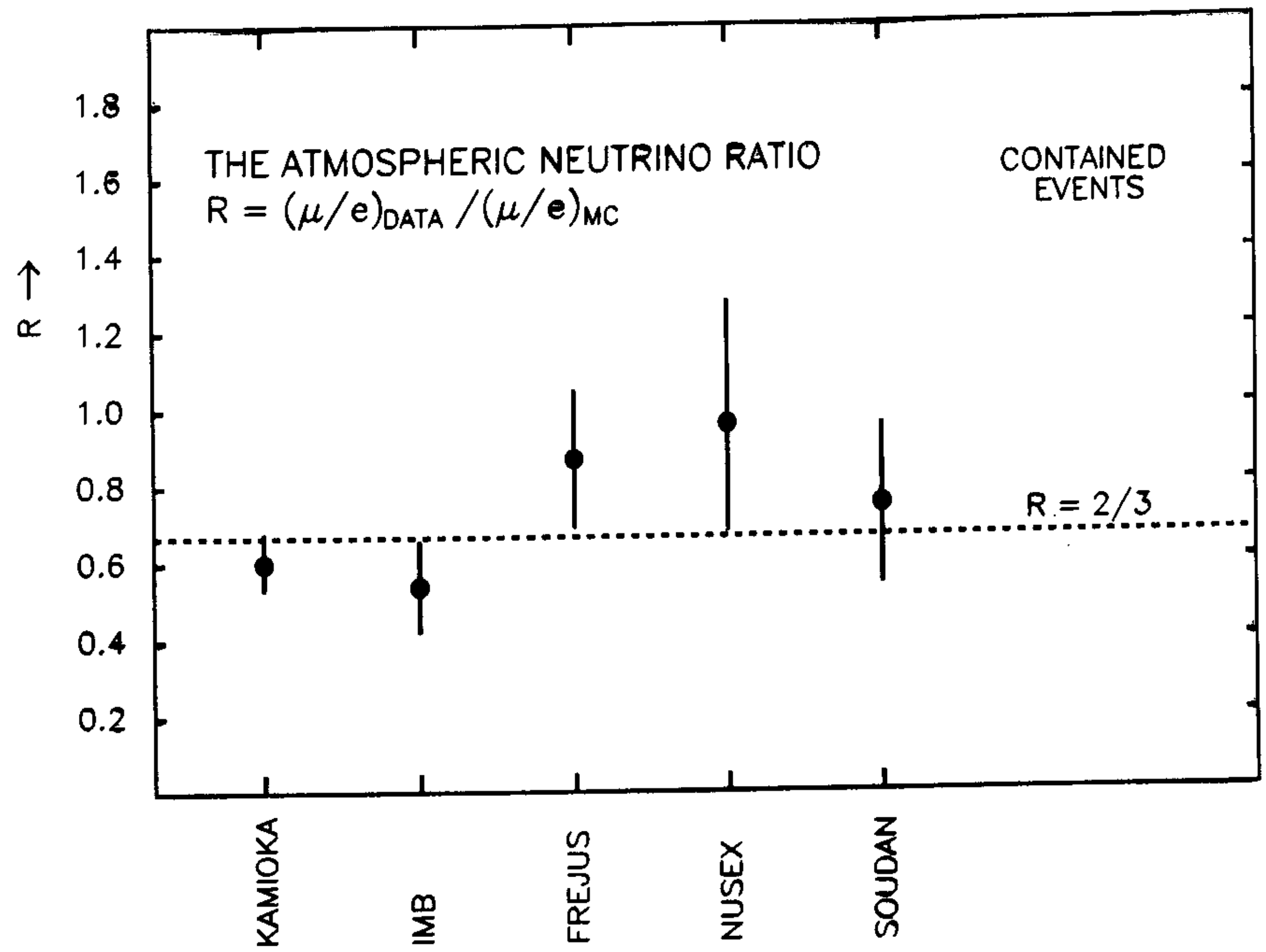

THE ATMOSPHERIC NEUTRINO RATIO
$R = (\mu/e)_{DATA} / (\mu/e)_{MC}$
CONTAINED EVENTS
R →
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
R = 2/3
KAMIOKA
IMB
FREJUS
NUSEX
SOUDAN

Figure 1

[illegible] Results 1997 for R

SuperKam.

(sub-GeV) $\begin{cases} 0.64 \pm 0.04 \pm 0.[illegible] \\ 0.67 \pm 0.05 \pm 0.[illegible] \end{cases}$

Confirmation of Kam.

Live Time 208 days

events $\approx$ 2000.

New Soudan Result:

$$R = 0.67 \pm 0.15 \pm^{0.06}_{0.06}$$

Is the effect real?

Concern	Response
• Water $\hat{c}$ special?	• Now seen in Soudan. II
• e/μ id. problem?	• KEK Beam Test 1994-5.
• ν_e, ν_μ X-sections at low E_ν?	• cannot violate e/μ universality except kinematics.
• If $\pi^+ > \pi^-$, enhance ν_e over $\bar{\nu}_\mu$ ⇒ more "e" (Volkova)	• Very unlikely, need factor of 10 $\bar{\nu}/\nu$
• CR μ ⇒ n near Tank entering in → π^0 → fakes "e" (Ryzshkawa)	• Kamioka plotted events vs. distance from wall, see flat distri.
• Measure μ flux at h = 5-6 miles to normalize ν-fluxes (Perkins)	• Done! (Calgary grp

Conclusion: The effect seems real.

New Physics Solutions for Atmospheric ν_μ/ν_e Anomaly

- A universal ν_e excess. {Bisset JG&L, SP}

  flux $\sim 10^{-3}$ cm^{-2} GeV^{-1} sr^{-1} sec^{-1}.

  if spectrum $\sim E^{-3}$, this gives energy density $\rho_\nu \sim \frac{1}{100} \rho_{CR}$ (safe).

  Galactic Origin? AGN'S?

  Why $\nu_e \gg \nu_\mu$ ($n \to p e \bar{\nu}_e$ or a new particle decay?)

  Can this be ruled out?

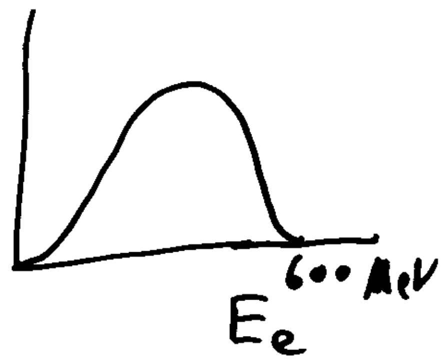
- Universal $\nu_e \equiv \nu_\mu$ excess.

  Tomozawa . . . .

- Proton Decay

  Excess "e" events not due to ν_e's but $P \to e^+ \nu \nu$.

  - Need absolute flux
  - Need "right" spectrum.
  - Anomaly should vanish at $E_e \sim 600$ MeV
  - Need $\tau / B \sim 4 \cdot 10^{31}$ yr



→ Experimental question. Is this true?

- New universal extra-terrestrial BG of ν_e's.
  - Source?
    - $n \to p e^- \nu_e$?
    - $X \to \nu_e \cdots$?

…B 291 (1992) 200–205

Alternative Explanation

PHYSICS LETTERS B

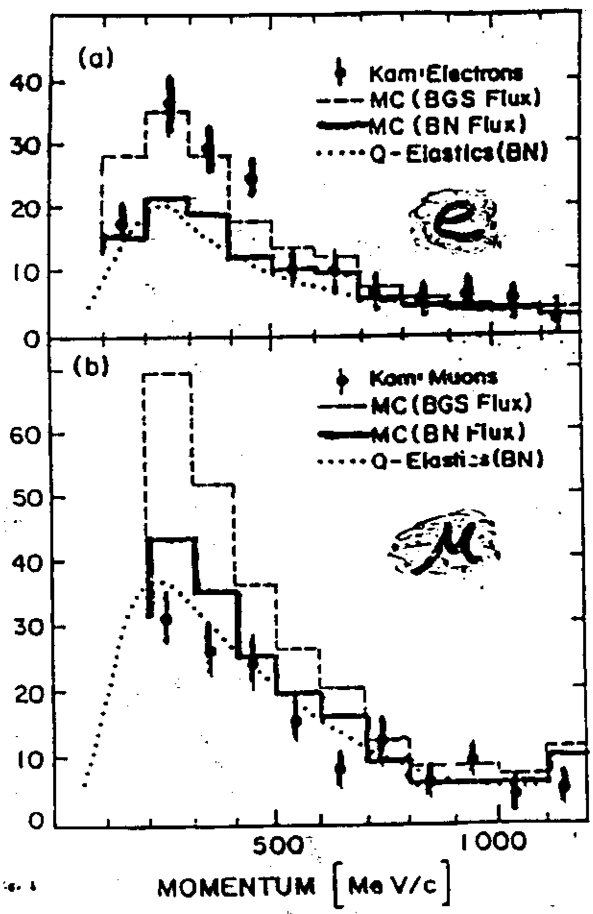
The atmospheric flux ν_μ/ν_e anomaly as manifestation of proton decay $p \to e^+ \nu\nu$

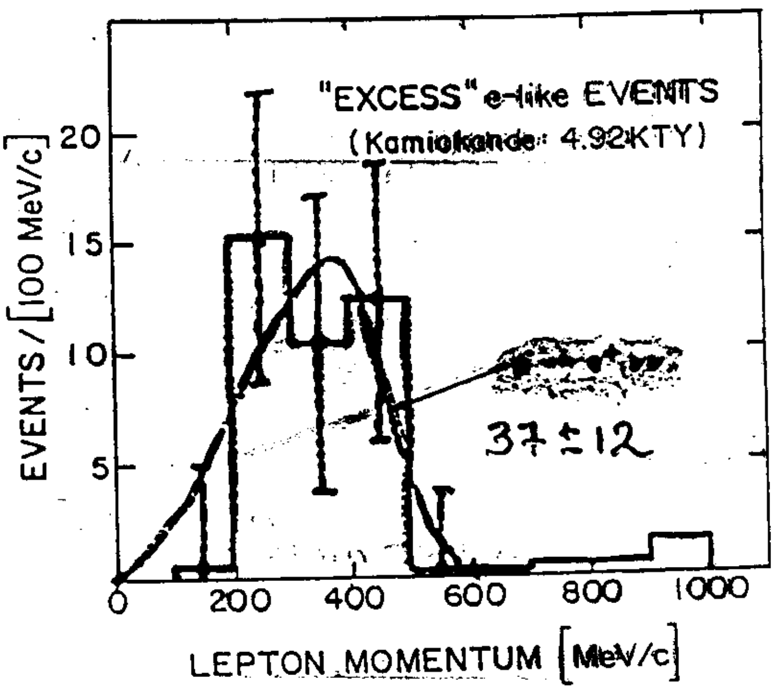
$p \to e^+ \nu\nu$

W.A. Mann, T. Kafka and W. Leeson [1]
Department of Physics, Tufts University, Medford, MA 02155, USA

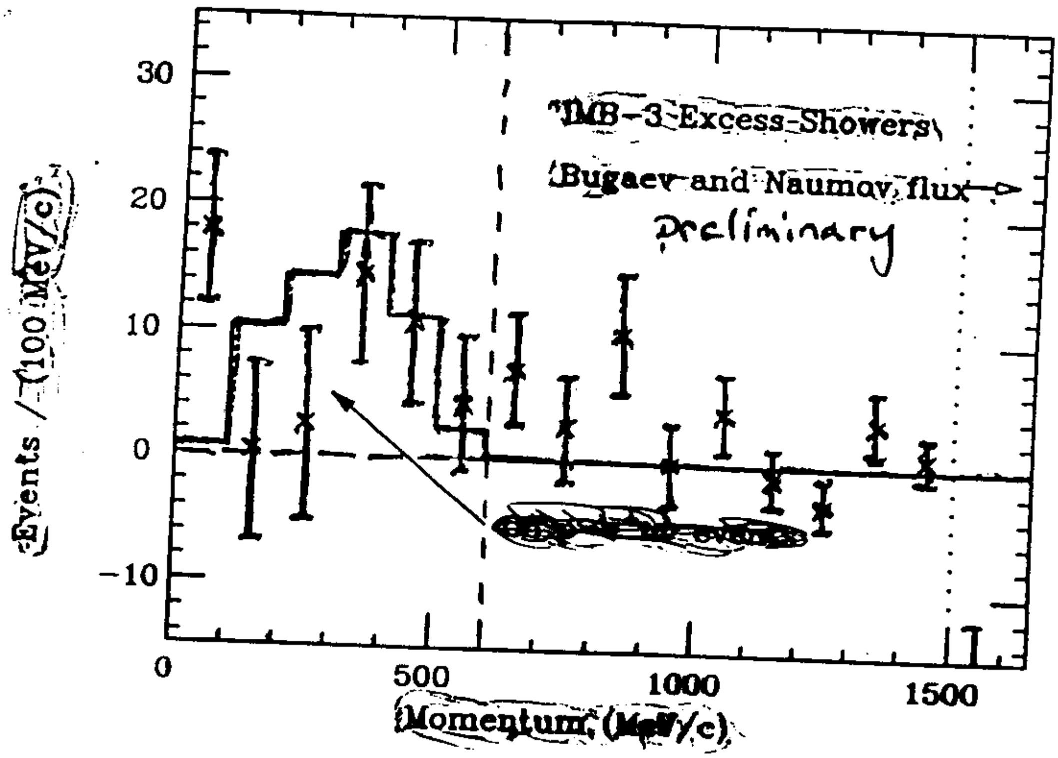
Received 22 June 1992

In a scenario in which absolute fluxes of low energy atmospheric neutrinos are at or below expectations of published calculations, the observed small ν_μ/ν_e ratio is amenable to non-oscillation interpretation. The rate of single-ring, e-like events of 200 to 500 MeV/c in Kamiokande data would appear to be enhanced. The shower momentum spectrum of the event excess is compatible with proton decay $p \to e^+\nu\nu$ with $\tau/B \sim 4 \times 10^{31}$ yr.





$\Rightarrow \tau/B \sim 4 \times 10^{31}$ yr



New Perkins flux
disfavours $p \to e^+ \nu\nu$.

Pati (1984)
Rudaz
Sarkar
O'Donel

Theoretical Aside on $P \to e^+\nu\nu$

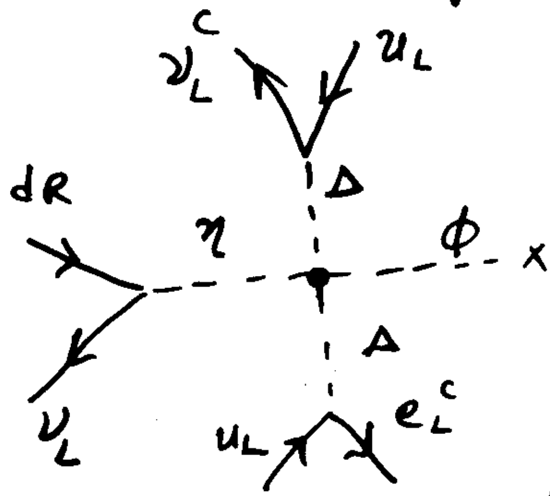
- Simplest Operator: $\frac{g}{M^5}(uud)(\overline{e^+\nu\nu})$

  forbidden by $SU(2) \times U(1)$
  unless a "light" $\underline{\nu_R}$ is added.

- $f/_{M^6} \langle\phi\rangle\, uud\, (\overline{e^+\nu\nu})$ allowed

  need $M \sim 10^5$ GeV.

- Some "light" (few 100 GeV)
  Leptoquarks implied



Δ, η triplet leptoquarks

$m_\Delta \sim 10^5$ GeV

$m_\eta \sim 300$ GeV.

→ tested at LHC . . . .

- Such a spectrum does not occur in minimal $SU(5)$, $SO(10)$ but does in low energy L-R-S theories

Interpretation in terms of Neutrino Oscillations

- Feature : Independent of absolute flux.
- Consider $\nu_\mu - \nu_\tau$ oscillations

Then ν_μ flux modified by

$$N_{\nu_\mu} = N^\circ \left[P_{\nu_\mu \to \nu_\mu} \right]$$
$$= N^\circ \left[1 - \sin^2 2\theta \sin^2\left(\frac{\delta m^2 L}{4 E_\nu} \right) \right]$$

But since $L = L(\theta_{zenith})$

and no dependence on θ_z or L

is seen for $E_\nu \sim 300$ MeV to 1 GeV.

This can only happen if

$$\left\langle \sin^2 \frac{\delta m^2 L}{4E} \right\rangle \approx \text{constant}$$

This happens if $\dfrac{\delta m^2 L}{4E} \gg 1$. [constant $= \frac{1}{2}$]

even for $L \approx h \approx 15-20$ Km

[L varies from 15 Km to 6000 Km !]

Now $$\frac{\delta m^2 L}{4E} \sim 1.23 \frac{\delta m^2 (eV^2)\, L\,(Km)}{E\,(GeV)} \gtrsim 1$$

for $L \lesssim \cancel{20}\ 15$ Km, $E \lesssim 0.3$ GeV.

So $$\delta m^2 \gtrsim \frac{0.3}{1.23 \times 15}\ eV^2$$

or $$\delta m^2 > 0.016\ eV^2$$
$$> 10^{-2}\ eV^2.$$

What about the mixing angle?

Since the effect is large, almost a factor of 2, ~~sin²2θ~~

$$N_{\nu_\mu} \cong 0.6 N^\circ = N^\circ [P_{\mu\mu}]$$

So $P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \approx 0.6$

$$\Rightarrow \quad \underline{\underline{\sin^2 2\theta \approx 0.8}}$$

If oscillations are $\nu_\mu - \nu_e$, slight change.

Because $N_{\nu_\mu} = N_\mu^\circ [\cancel{\ } P_{\mu\mu}] + N_e^\circ P_{\mu e}$

$[N_\mu^\circ / N_e^\circ \equiv \frac{1}{r}]$ $N_{\nu_e} = N_e^\circ [\cancel{\ } P_{ee}] + N_\mu^\circ P_{\mu e}$

~2

$r \sim 1/2$.

& $P_{\mu\mu} = P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta = 1 - P$

$$P_{\mu e} = \frac{1}{2}\sin^2 2\theta = P$$

Then

$$R = \left(\frac{N_{\nu_\mu}}{N_{\nu_e}}\right) \Big/ \left(\frac{N^0_{\nu_\mu}}{N^0_{\nu_e}}\right)$$

$$= \frac{1 - (1-r)P}{1 + (\frac{1}{r} - 1)P}.$$

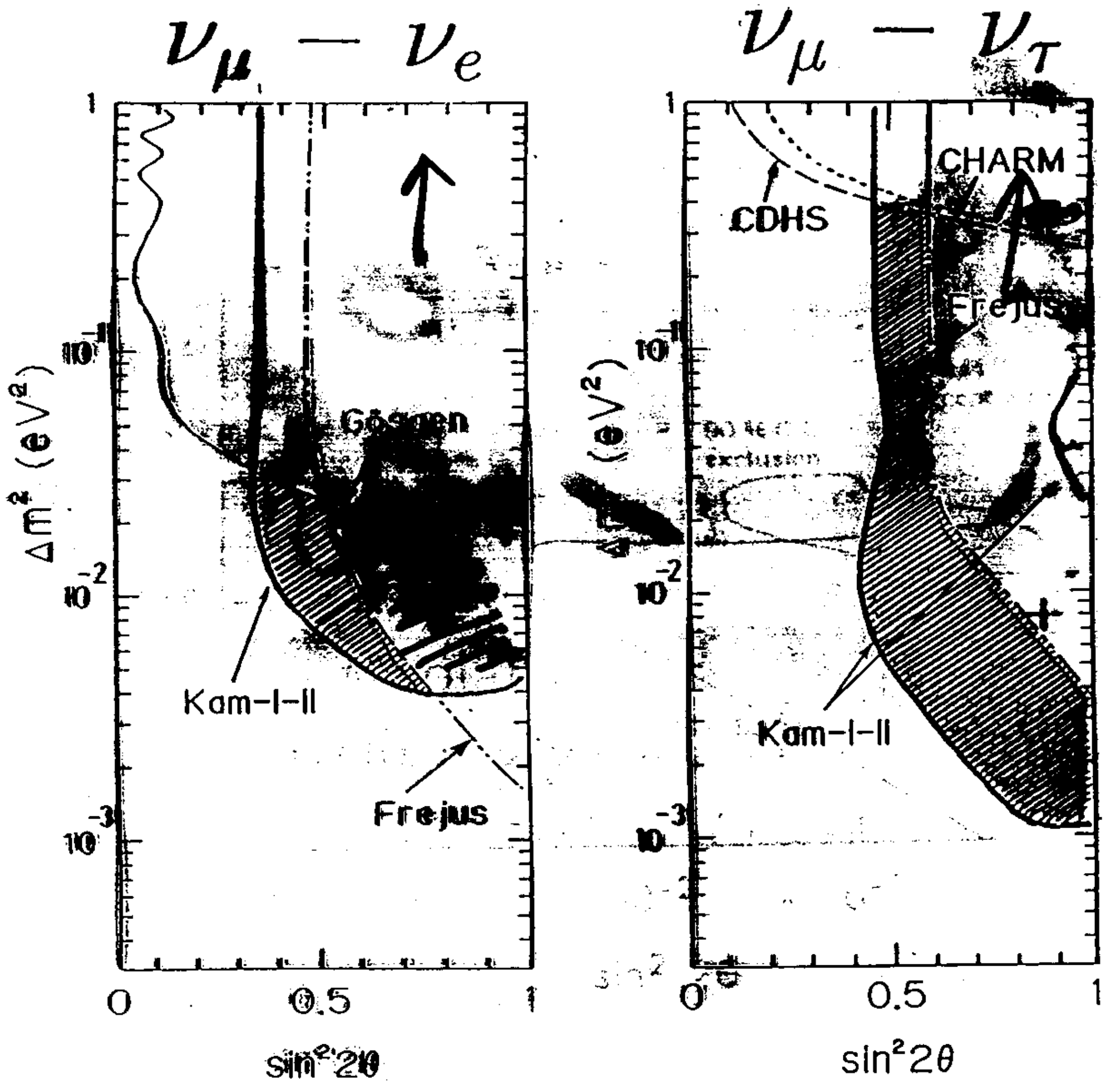
Solve for

$$\sin^2 2\theta = 2P = \frac{2(1-R)}{(\frac{1}{r}-1)R + (1-r)}$$

Find $\sin^2 2\theta \sim 0.6 - 0.7$
for $R \sim 0.5 - 0.6$

Allowed region (90% C.L.)

Kam-I+II (4.92kt·yr)



Fancy Fit by Kamiokande.

If contained event (low energy) anomaly explained by ν_μ osc.; then if scale E_{ν_μ} by factor $\begin{matrix}100\\-200\end{matrix}$

& L by same factor

then <u>same</u> depletion of ν_μ's should be observed.

Hence for upcoming μ-events,
Vertical events should show depletion

Horizontal events $L_{hori} << L_{vert}$

So $\sin^2 \frac{\delta m^2 L}{4E} << 1$, so no depletion!

Unfortunately no conclusion can be drawn NOW from the data.
But possibly consistent with osc (Wait for SuperK!)

Intermediate Energies

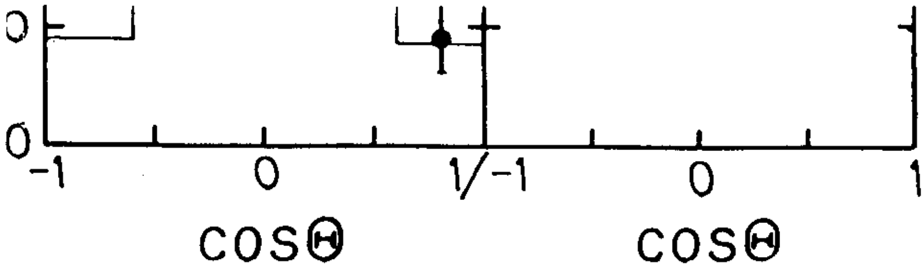
(Stoppers!)

If E_{ν_μ} is in the range 1–10 GeV, there <u>should</u> be some dependence on zenith angle since for higher energies the argument $\frac{\delta m^2 L}{4E}$ of $\sin^2\left(\frac{\delta m^2 L}{4E}\right)$ will decrease and effect of osc. will be smaller.

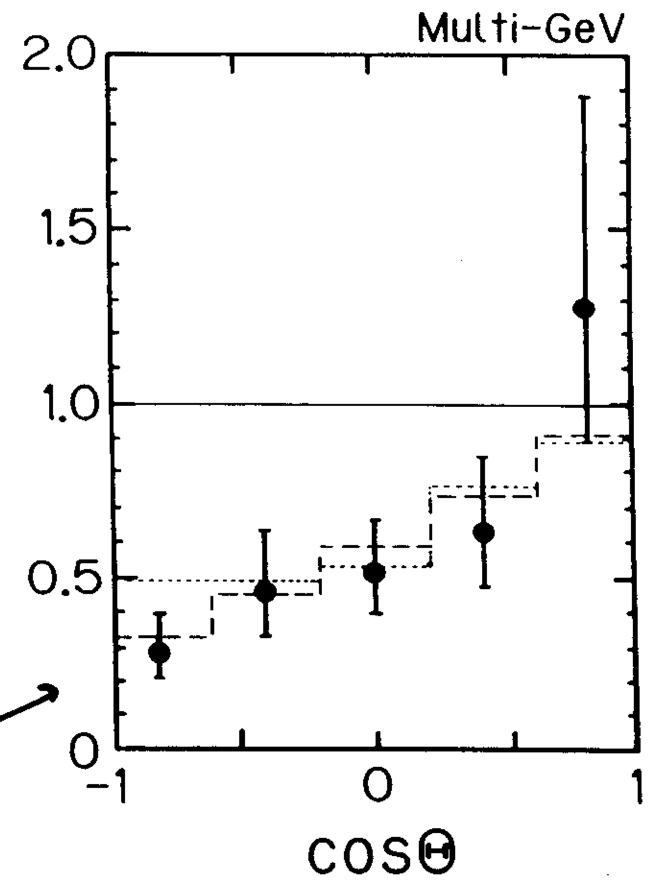
Is this observed.

IMB: No!

Kamiokande: <u>Some Hints!</u>



Zenith-angle distributions for (a) the e-like events and (b) events (the fully-contained and partially-contained events ıbined). The circles with error bars show the data and the ım the MC (without neutrino oscillations). The downward n is given by $\cos\Theta = 1$.



Zenith Angle Dependence in right direction!

L small

L large

Zenith-angle distribution of $(\mu/e)_{data}/(\mu/e)_{MC}$, where : fully-contained and the $\boxed{\text{partially-contained events}}$ are in- The circles with error bars show the data. Also shown expectations from the MC simulations with neutrino os- s for parameter sets (Δm^2, $\sin^2 2\theta$) corresponding to the values to the multi-GeV data for $\nu_\mu \leftrightarrow \nu_e$ ((1.8×10^{-2})), dashes) and $\nu_\mu \leftrightarrow \nu_\tau$ ((1.6×10^{-2} eV^2, 1.0), dots) ons.

Kamioka Results from partially contained events

-like events, and (b) all μ-like events. One

To test for neutrin e- and μ-like (FCe a mapped on (zenith planes, where (cos (5×8) cells. The ran Similarly, the partiall are plotted on a cos into 5-bins. Here we E_{vis} for the partially- E_{vis} is not a good me the partially-containe to draw contours of $\sin^2 2\theta$) plane:

$$\chi^2 = \mathrm{Min.}(\alpha, \beta) \Big(L$$

$$L(\alpha, \beta) = -2 \sum_i \sum_j$$

$$\times \left(X_{ij}(FCe)\right)^{N_{ij}(}$$

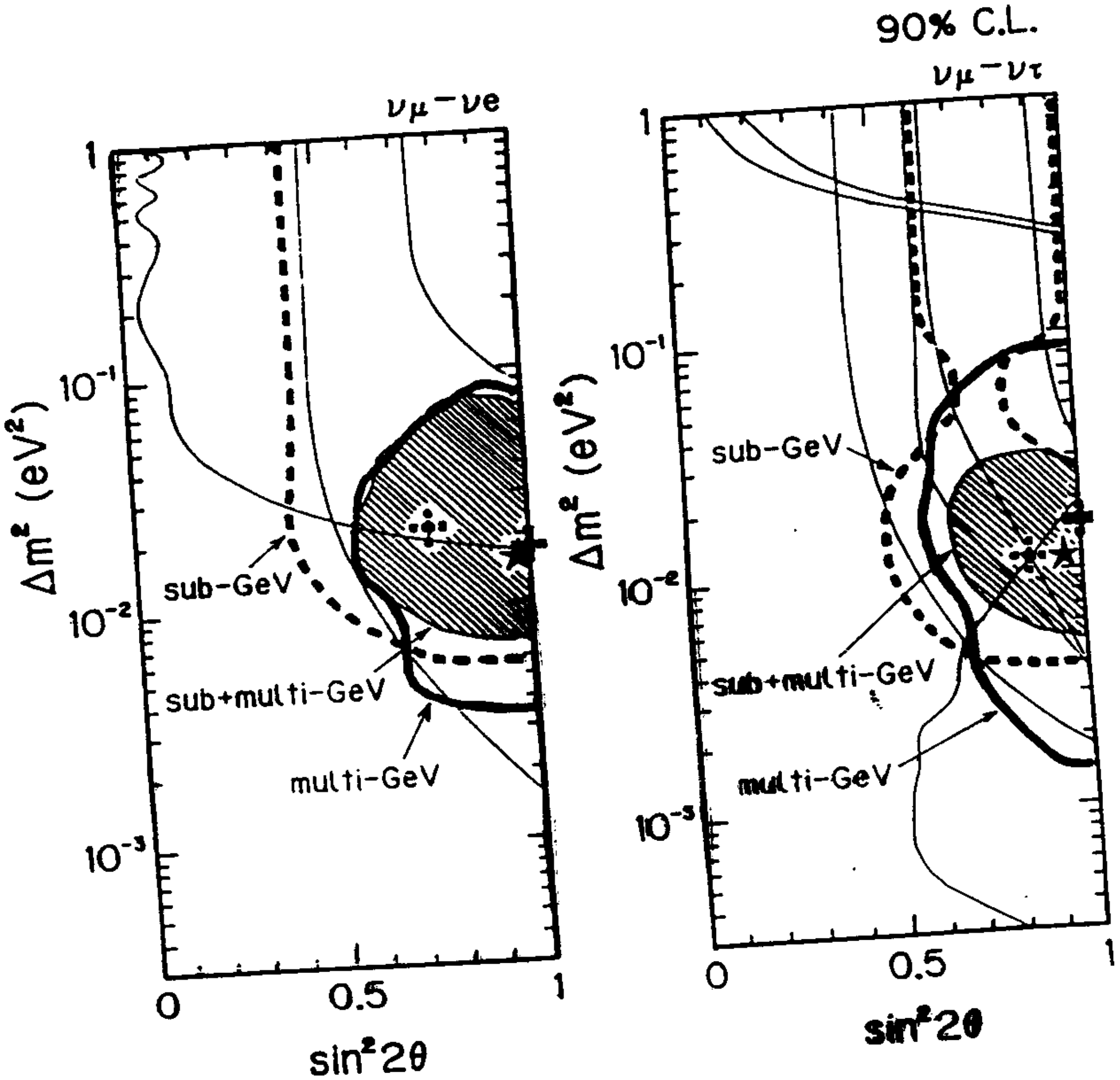
$$+ \ln \left\{ \frac{\left(X_{ij}(FC\mu)\right)^{N}}{} \right.$$

$$+ \ln \left\{ \frac{/ (X_i\ (PC\mu))}{} \right.$$

$$X_{ij}(FCe) = (1 + \alpha)$$

$$X_{ij}(FC\mu) = (1 + \alpha)$$

$$E \sim f e X_i\ (PC\mu) = (1 + \alpha)$$



Fukuda, et. al. Phys. Lett. B (1999)

Higher Energy data set > 1.3 GeV

- $R = 0.57 {}^{+.08}_{-.07} \pm .07$

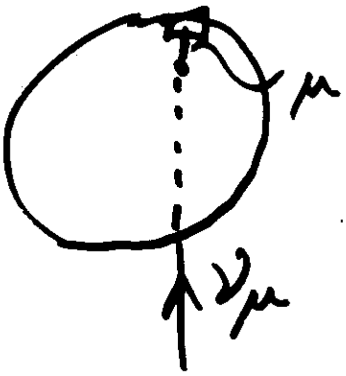
+ Angular analysis

To the extent the zenith angle dependence as seen in multi-GeV events of Kamiokande is real, all explanations except ν-oscillations become unlikely.

But some justified sceptisism - - - - - -

. Wait for data from SuperKamiokande.

Upcoming Muons in U.G.-Detectors



- Throughgoing $E_\nu \sim O(100\ GeV)$
- Stoppers $E_\nu \sim O(10\ GeV)$

- Absolute Fluxes uncertain by 20 %

- Need ν_μ flux, σ_{ν_μ} (H.E.)
  μ Range . . . . .

Data from # events

IMB	~ 600
BAKSAN	~ 400
Kamiokande	~ 350
KGF	~ 100
MACRO	~ 150

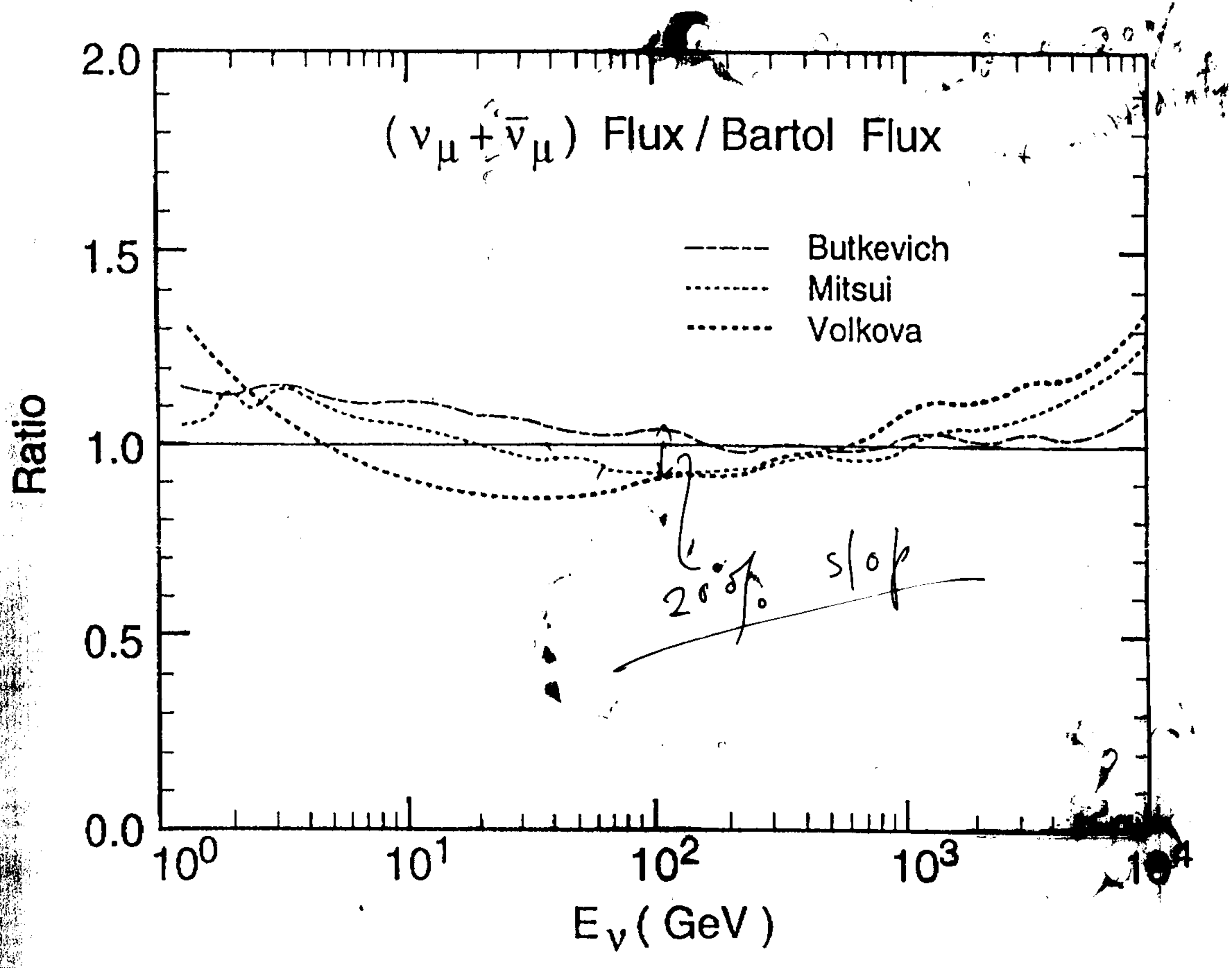
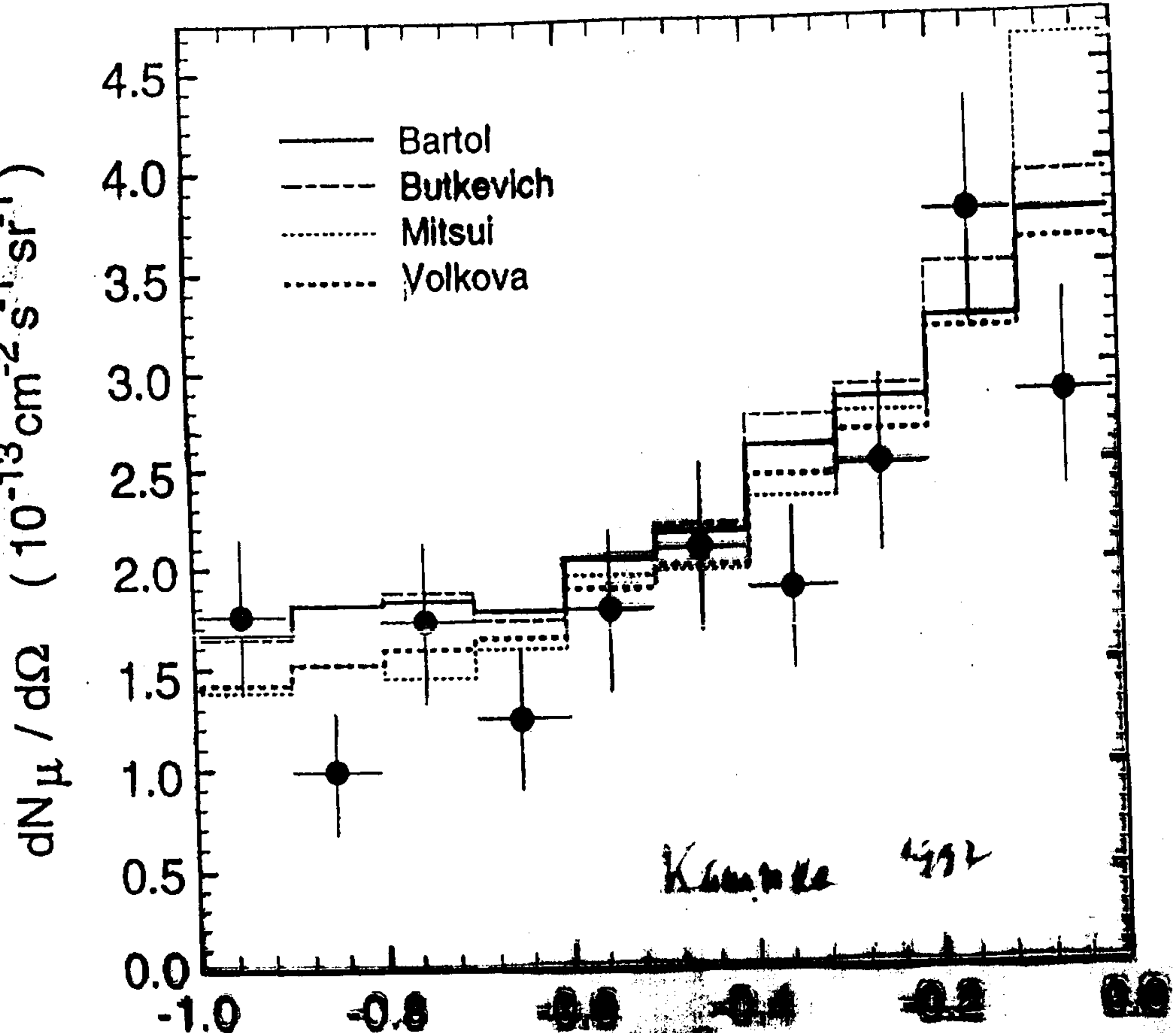


Fig.3b

93-0022L 2



Bartol
Butkevich
Mitsui
Volkova
dNμ / dΩ (10^-13 cm^-2 s^-1 sr^-1)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-1.0
-0.8
-0.6
-0.4
-0.2
0.0

Kamiokande

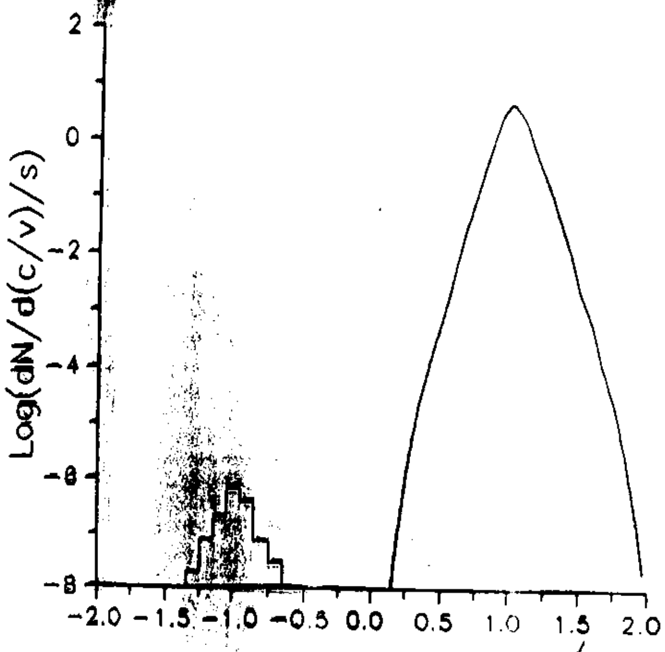


Fig. 2

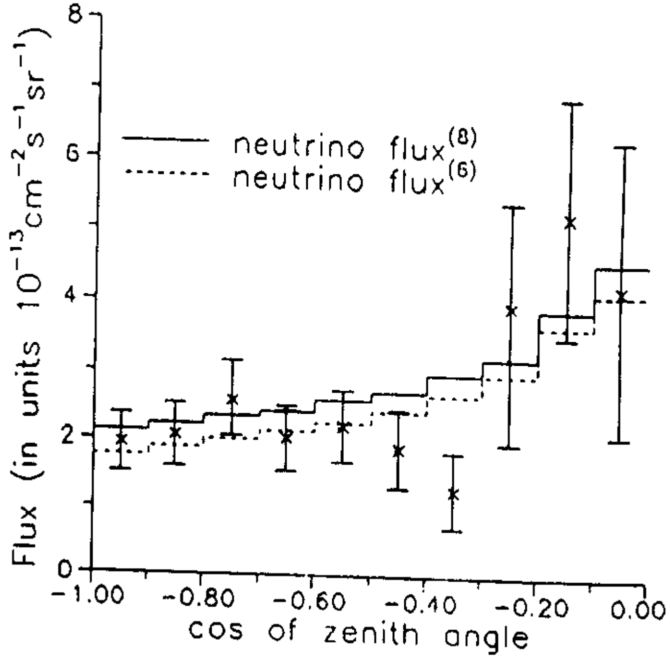


Fig. 3

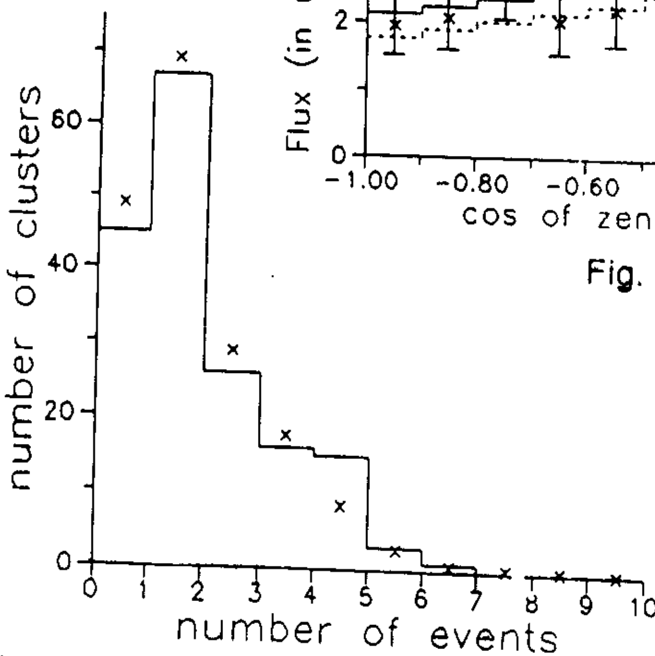


Fig. 4

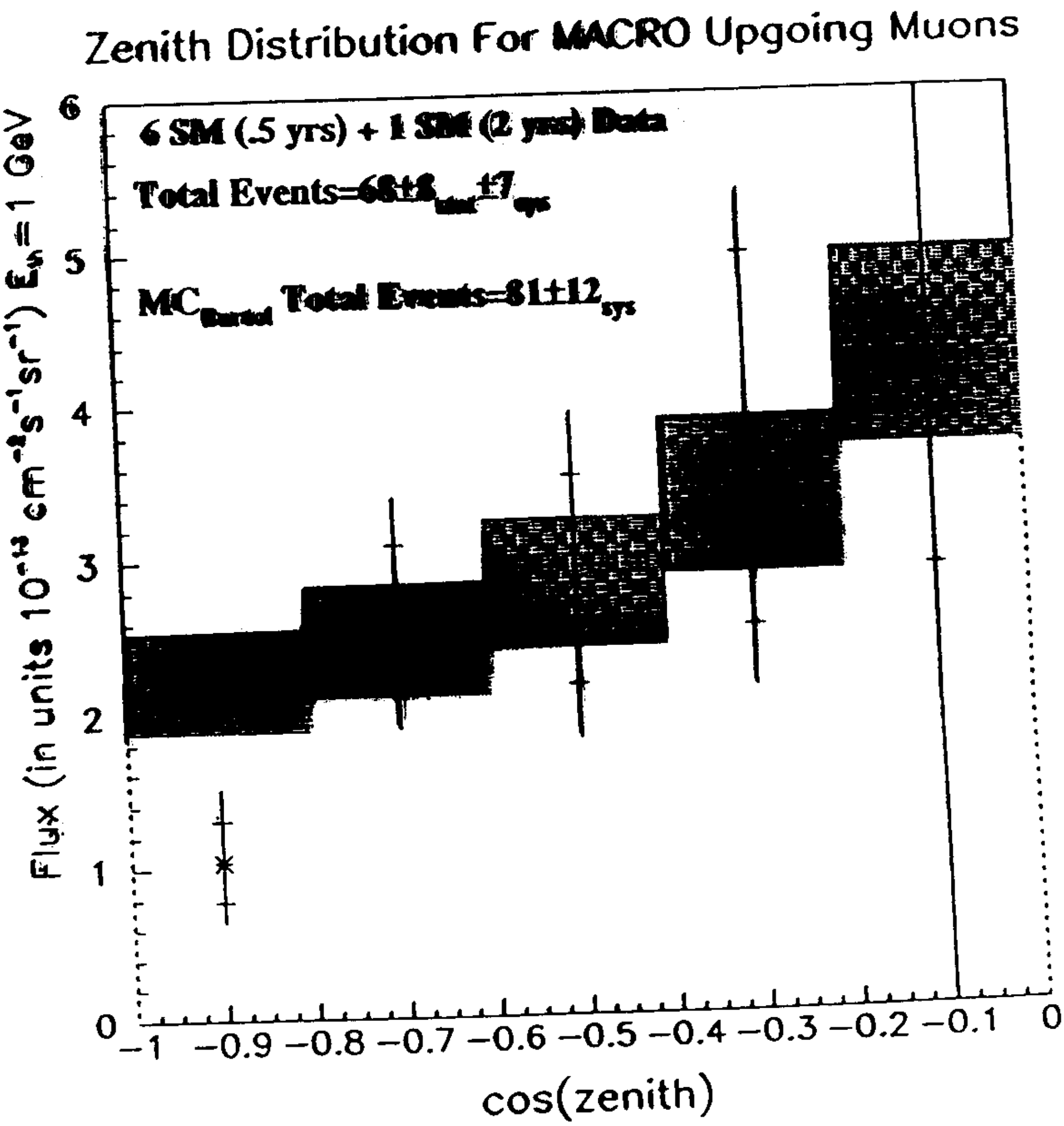
BAKSAN

upcoming thrugoing μ's

tions.

Neutrino Flux	Number of upgoing muons
'Bartol' (1993)	124 ± 15%
Butkevich et al. (1989)	127
Mitsui et al. (1986)	113
Volkova (1980)	112

Lohmann et al. [13] using standard rock. The total systematic un the expected flux of muons at the detector is ±15%.



DATA: 593 ± 24 EVENTS

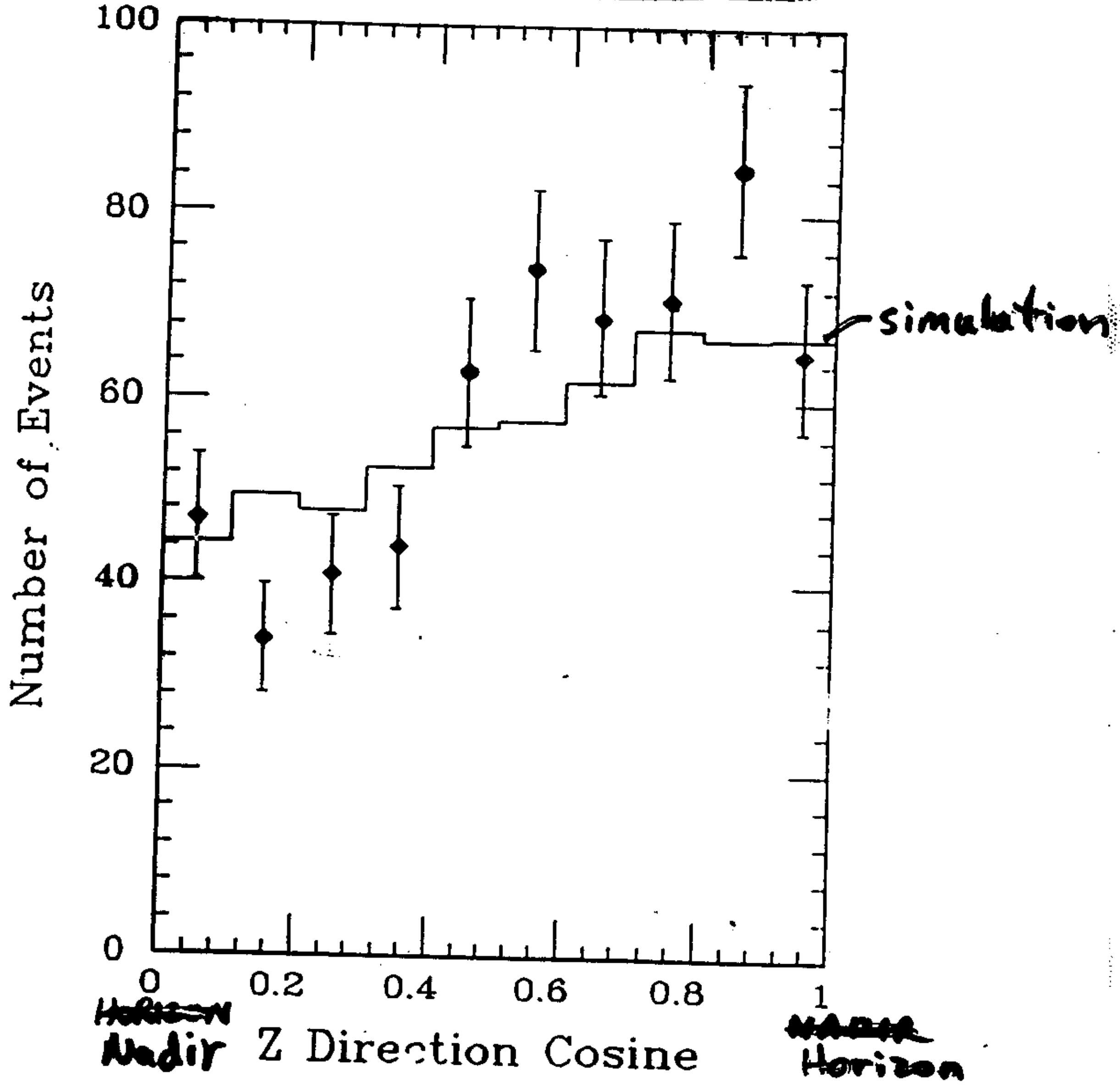
SVOBODA

IMB

MC: (558 − 573) ± 113

← 20%

1273 Days IMB Upward-Going Muons



SIMULATION: EHLQ PARTON DISTRIBUTIONS (u,d,s,c,t,b)
BEZRUKOV & BUGAEV μ PROP.

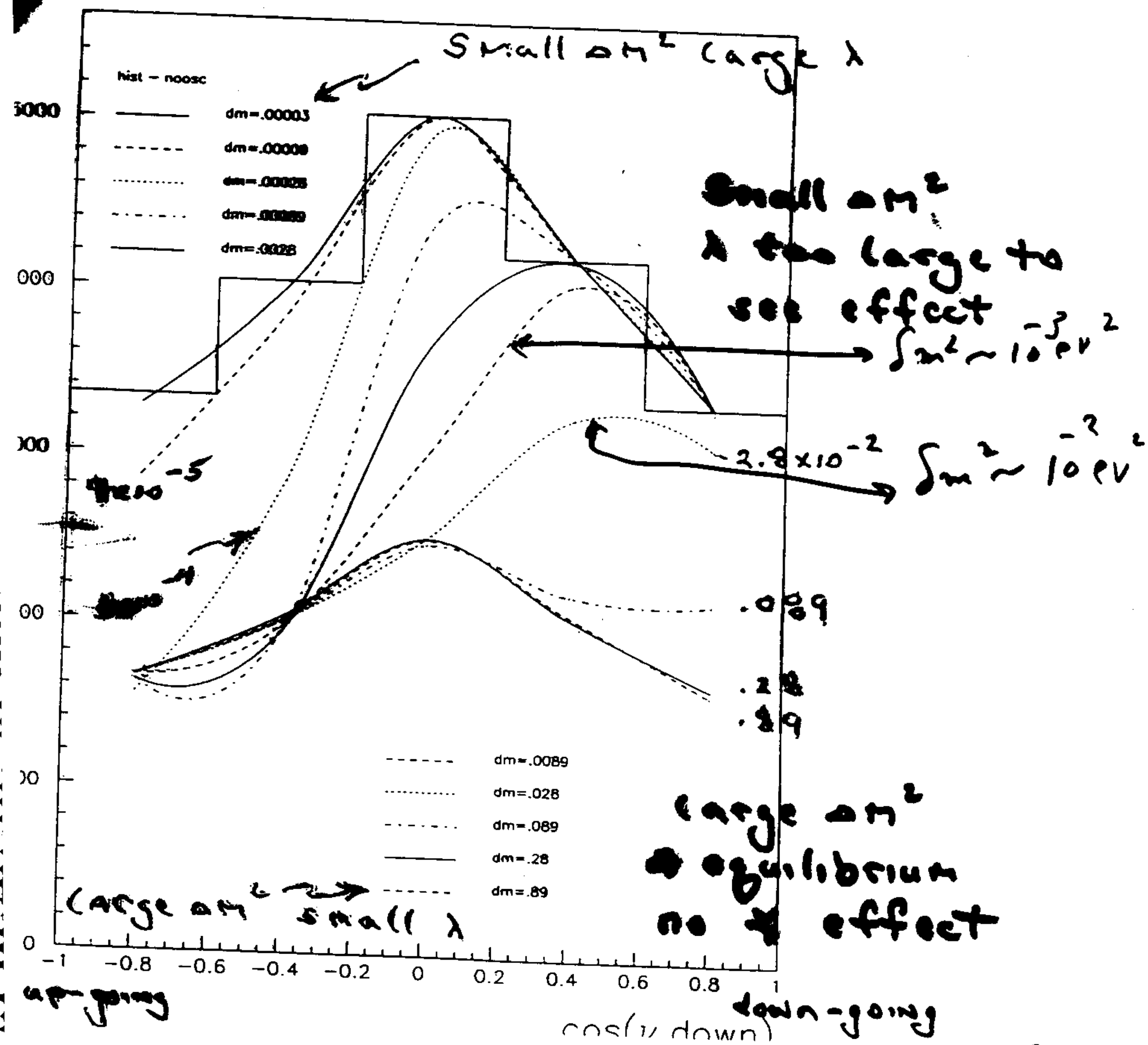
ALSO USED: LOHMANN, et al μ PROP.
Particle Data Book partons (u,d,s,c)
2 different $\nu \sigma_{cc}$ normalizations

Multi 2

SuperK thrugoing μ's

Distortion of θ_z distri. due to mixing fosc.

$\nu_\mu - \nu_\tau$, Kamioka, sin=1   21/07/95 10.39



Future LBL

Tests of Atm. ν Anomaly.

- Refinements
  - SOUDAN
  - Superkam.

- Fermilab → SOUDAN (MINOS).

  $L \sim 730$ KM.

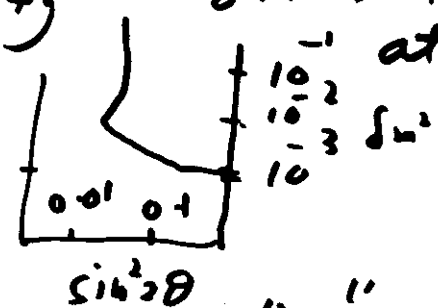
  $\langle E_\nu \rangle \sim 150$ GeV.

  Det. magnet. Fe Pl. ~10KT

  $B \sim 20$KG

  Operate ~ 2000 ?

  Sensitivity $\delta m^2 > 10^{-3} eV^2$ at max. mixing



- events → "μ", "e", "had"

  isolate "τ" events

  statistically via kinem. cuts

- KEK Plans.
  - 50 GeV Proton Accel.
  - ν's to Superkam
  - Near & Intermed. Det

- CERN – LNGS.

Diagnostic Tests for ν Oscillations in contained events in SuperKamiokande Data

or other UG detectors!

J. Learned & S.P.

- Basic Idea:

define asymmetries

$$A_\mu = \frac{N_\mu^{\downarrow} - N_\mu^{\uparrow}}{N_\mu^{\downarrow} + N_\mu^{\uparrow}}$$

$$A_e = \frac{N_e^{\uparrow} - N_e^{\downarrow}}{N_e^{\uparrow} + N_e^{\downarrow}}$$

functions of energy.

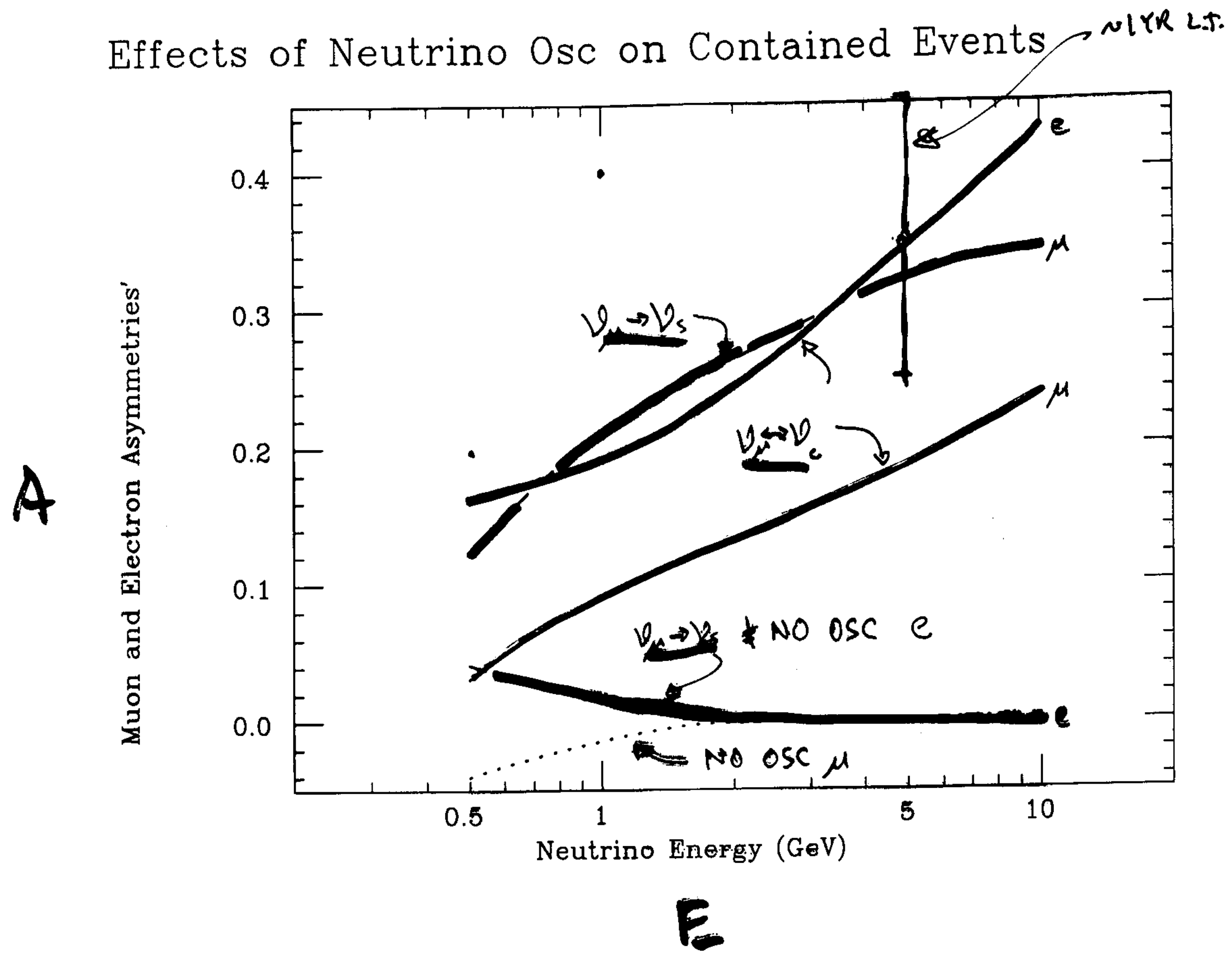
{Note Ae def. opp. A_μ}

- only contained events
- Divide into up & down bins.

Calculation:

- $\phi_\nu(E, \theta)$ from Stanev et al.
- $\sigma_{cc}(\nu)$. (ignore NC or id e/μ)
- assume E_ν too small for τ
- Geom. approx. for eff. vol.
  (Ranges $\sim E$ for μ $\sim \ln E$ for e) for μ, e
- let $\sin^2 2\theta \sim 1$, $\delta m^2 \sim 0.01\,eV^2$
- 1 year running
- ~~Four~~ Five possibities.
  - no osc.
  - $\nu_\mu \longleftrightarrow \nu_e$ osc.
  - $\nu_\mu \to \nu_\tau$ (same as $\nu_\mu \to \nu_{st}$)
  - $\nu_\mu \to \nu_{st}$, $\nu_e \to \nu_{st}'$ (Foot - Volkas)
  - osc. of massless ν's

Effects of Neutrino Osc on Contained Events



Effects of Neutrino Osc on Contained Events