EXOTIC EXPLANATIONS FOR NEUTRINO ANOMALIES

{Neutrino Anomalies without Oscillations}

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2/99

What is Exotic?

<u>Acc. Webster's</u>

exotic: 1. foreign

2. • having the charm or fascination of the unfamiliar

- strangely beautiful
- enticing.

At one time ν-oscillations would have been "exotic". Today they are mundane.

Explanations which follow will be "strange"

& "unfamiliar"

but perhaps <u>not</u> "charming" & "enticing".

So may be not "exotic" but "weird" or "bizarre"

Observed Neutrino Anomalies

- LSND : $\bar{\nu}_\mu \to \bar{\nu}_e$ & $\nu_\mu \to \nu_e$

  $P \sim 3 \cdot 10^{-3}$

  osc. interp. $\nu_\mu \leftrightarrow \nu_e$, $\delta m^2 \sim 0.2$ to $3\,eV^2$

  $\sin^2 2\theta \sim .04 - 3 \cdot 10^{-3}$

- SOLAR :
  - $P(\nu_e \to \nu_e) \neq 1$
  - P different for ^8B, ^7Be, pp etc.
  - spectrum distorted? (Not clear how much $^3He\,p$...?)

  osc. interp. $\nu_e \to \nu_x$, $(\delta m^2 \sim 10^{-5} - 10^{-6}\,eV^2$ or $10^{-10}\,eV^2)$

  $(\sin^2 2\theta \sim 5 \cdot 10^{-3}$ or $\sim 1)$

- ATM :
  - $P(\nu_\mu \to \nu_\mu) \neq 1$
  - L/E dependence
  - $(P(\nu_e \to \nu_e) \approx 1$.

  osc. interp. $\nu_\mu \to \nu_x$ $(x = \tau$ or st.$)$ $\delta m^2 \sim (0.5 - 8)\, 10^{-3}\,eV^2$

- KARMEN : Decay?
- Tritium End Point?

Simultaneous Explanation of all 3 anomalies.

- 4 ν's = 3 flavor + 1 sterile
  - $\nu_e - \nu_{st}$ for sun OR
  - $\nu_\mu - \nu_{st}$ for ATM.
- 6 ν's = 3 pseudo-Dirac ν's.
  - $\nu_e - \nu^1_{st}$ for sun AND
  - $\nu_\mu - \nu^2_{st}$ for ATM
- 2 explained by oscillations & 1 by new physics. Several possibities.
- All 3 explained by new physics without oscillations.

Caveat: Non-oscillatory scenarios will, generally, involve $m_{\nu_i} \neq 0$, mixings etc., not be elegant nor economical.

LSND. Consider $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ DAR.

If in addition $\mu^+ \to e^+ \bar{\nu}_e X$ (B.R. $\sim 3 \cdot 10^{-3}$)
that would explain LSND observ.

What can X be?

$X \equiv \nu_\mu$? NO. $\mu \bar{e} \leftrightarrow \bar{\mu} e$ Too large

$X \equiv \nu_e$? NO. Too Large FCNC
e.g. $Z \to \mu \bar{e}$.

$X \equiv \nu_\tau$? No Too large $\tau \to \mu e e$

$X \equiv \bar{\nu}_\alpha$
$X \equiv \nu_{sterile}$ } ?

Models?

Not Easy.

P. Herczeg
Y. Grossman & Bergman.

Exptl. Test: → { Rate Constant
No L/E dependence

New Physics at Detector?
e.g. $\bar{\nu}_\mu p \to n e^+$?
Not Possible ⇒ Too large $\pi^+ \to e^+ \nu$.

L. Johnson & D. McKay.

SOLAR

. $m_{\nu_i} \to 0$

. FCNC & NUDNC.

e.g.
FCNC $\to$ $\varepsilon \frac{4G_F}{\sqrt{2}} \left\{ \bar{\nu}_{eL} \gamma_\mu \nu_{\tau L} \, \bar{q}_L \gamma_\mu q_L + h.c. \right\}$

NUNC $\to$ $\varepsilon' \frac{4G_F}{\sqrt{2}} \left\{ (\bar{\nu}_{eL} \gamma_\mu \nu_{eL} - \bar{\nu}_{\tau L} \gamma_\mu \nu_{\tau L}) \, \bar{q} \gamma_\mu q_L \right\}$

$\nu_e e$. c.c. $\frac{4G_F}{\sqrt{2}} \bar{\nu}_{eL} \gamma_\mu \nu_{eL} \, \bar{e}_L \gamma_\mu e_L.$

Then ν_e, ν_τ propagation in matter:

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \alpha + \beta & \gamma \\ \gamma & -\beta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\tau \end{pmatrix}$$

where $\alpha = G_F N_e$, $\beta = \varepsilon' G_F N_q$

& $\gamma = \varepsilon G_F N_q.$

MSW Resonance @ $\alpha + \beta + \beta = 0$

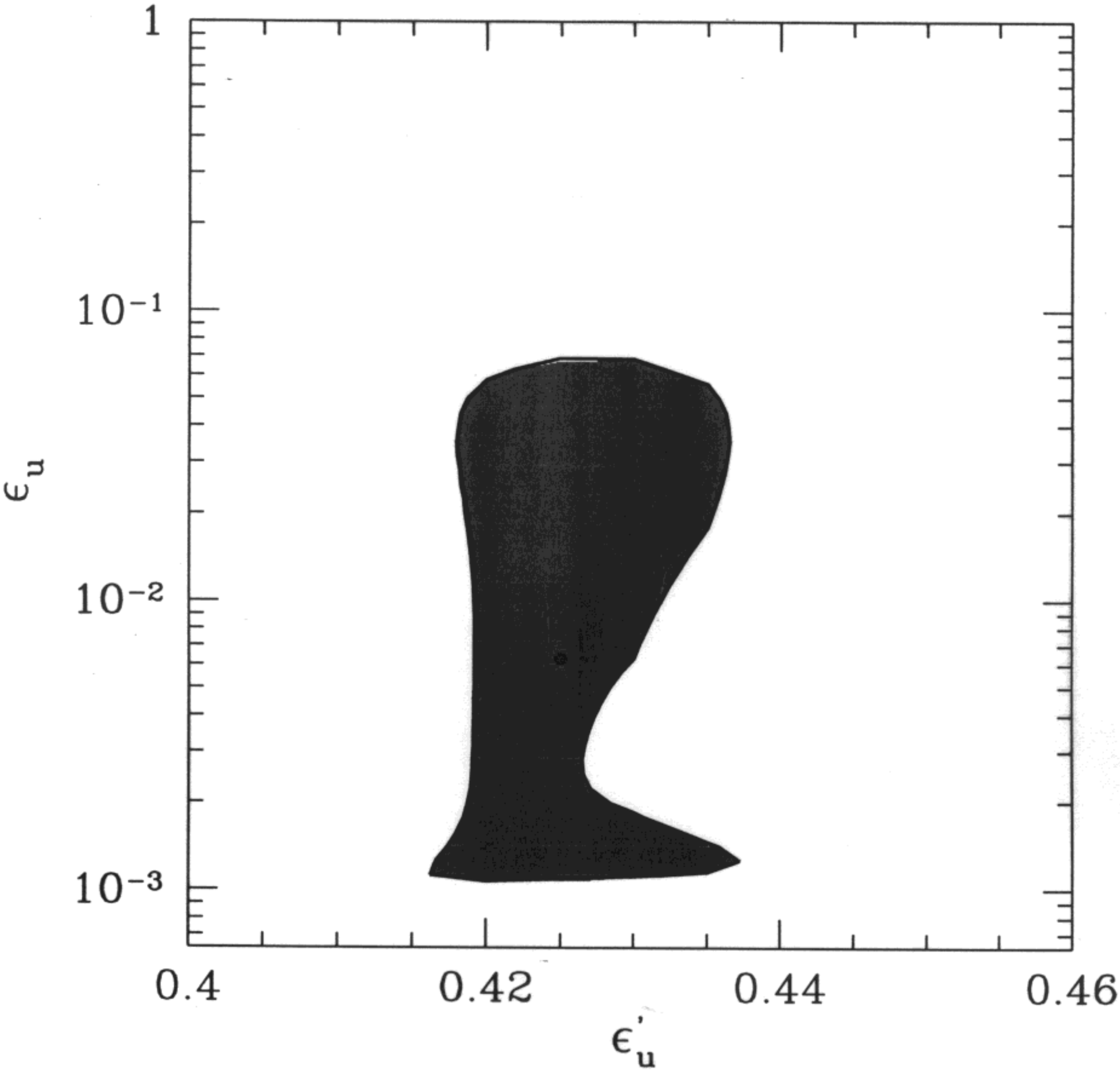
$$\Rightarrow \varepsilon' = \frac{1}{2} N_e / N_q.$$

$\chi^2_{min} \sim 3$ Babu, Grossman, Krastev 6

$\rightarrow 1$ if ^8B free (w.i.p.)

d.o.f. $1 \rightarrow 2$ if SAGE & Gallex

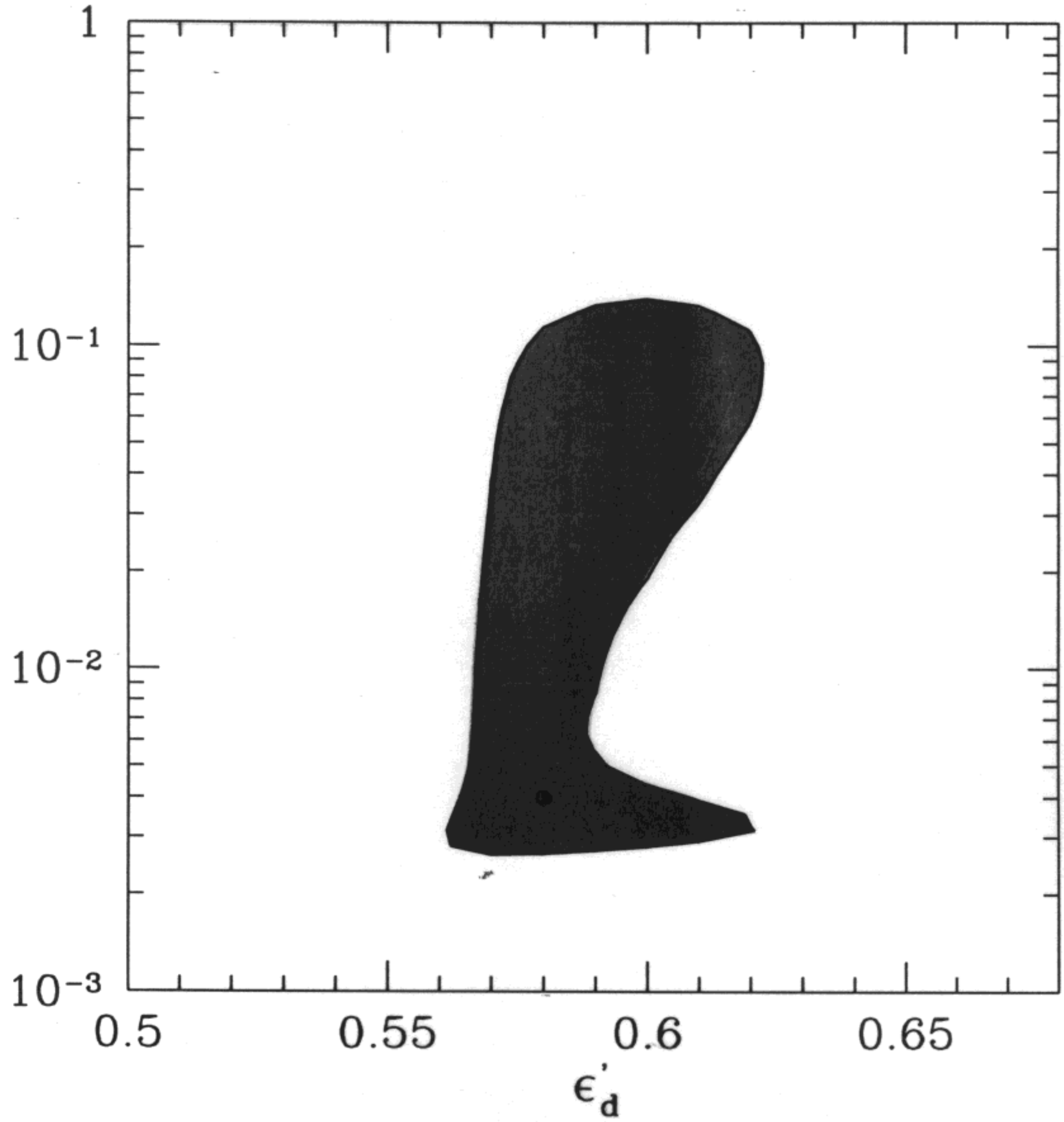
Only rates used.



$\chi^2_{min} \sim 3 \to 1$ if ^8B free

BGK

6a



· Such couplings arise in SUSY $\not{R}$

<u>Features</u> · No energy dependence.

· different suppression

for ^8B, ^7Be, PP obtained since production regions diff. & Resonance point depends on densities.

· Resonance in both ν & $\bar{\nu}$.

· Resemble Large Angle MSW.

· except that day night effect is energy indep.

Valle et al.
Do the same thing for Atm. ν's thru earth
Can Test in LBL

Guzzo, Masiero, Petcov
Roulet
Barger, Philips, Whisnant
Krastev, Bahcall.
Brooijmans → extend to 3 families & account for ATM as well.
V. Poor fits.
Babu, Grossman & Krastev (99)

for 90, 95 and 99 % C. L., respectively.

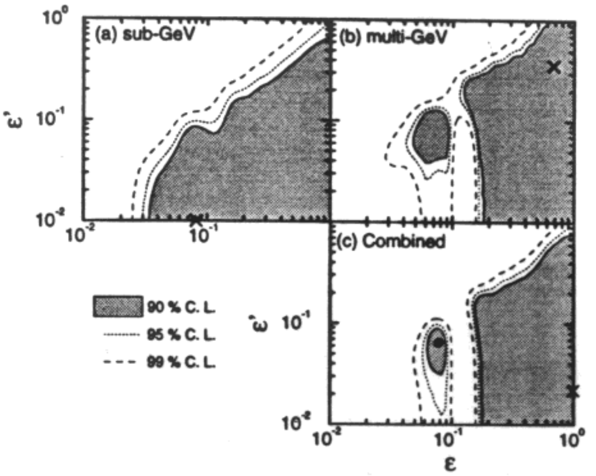


FIG. 1. Allowed region for ϵ_ν and ϵ'_ν for SuperKamiokande (a) sub-GeV (b) multi-GeV and (c) combined events in the massless-neutrino scenario. The best fit points for each case is indicated by the crosses.

In the parameter region we have considered, i.e., ϵ and ϵ' in the interval [0.01, 1.0], we found that $\chi^2_{min} = 6.3$ and 6.4 for the sub-GeV and multi-GeV samples (8 d. o. f. corresponding to 10 data points minus two free parameters). These minima are obtained for $(\epsilon, \epsilon') = (0.08, 0.01)$ and $(0.68, 0.36)$, respectively, as indicated by the crosses in Fig. 1. For the combined case, $\chi^2_{min} = 14.7$ (18 d.o.f) for $(\epsilon, \epsilon') = (0.99, 0.02)$. In the combined case the local best fit point ($\chi^2 = 16.9$ for $(\epsilon, \epsilon') = (0.08, 0.07)$) in the "island" determined by the 90 % C. L. curve it is also indicated by a filled circle. This point is interesting because it still generates a good fit to the data, while the value for the FC parameter ϵ is relatively small. We find also that the χ^2 is relatively flat along the ϵ' axis around the best fit point.

In Fig. 2 we give the expected zenith angle distribution of μ-like sub-GeV events (a) and multi-GeV events (b) evaluated with our Monte Carlo program for the best fit points determined above. Our results clearly indicate an excellent fit for the μ-like events showing that they are highly depleted at $\cos\theta = -1$ with respect to the SM prediction in the absence of oscillation or FC neutrino-matter interactions. Note that, except for the assumption that the FC ν_μ-matter interaction involves d-quarks, our result is quite general, since we have not explicitly considered any particular model as the origin of the FC neutrino-matter interaction. We also note that we only present the results for μ-like events because e-like events are not affected by our $\nu_\mu \to \nu_\tau$ transition.

What can we say about the required strength of the neutrino-matter interaction in order to obtain a good fit of the observed data? From our results and Eq.(3) we see that for masses $m \approx 200$ GeV we need at least $g_{\tau f} \cdot g_{\mu f} \sim 0.1$ for the the mixing term ϵ. Similarly our best fit ϵ' value implies $|g_{\tau f}|^2 - |g_{\mu f}|^2 \sim 0.1$. While these values are relatively large, they are both weak-strength couplings. Moreover they are consistent with present experimental bounds, for example from universality of the weak interaction which is manifestly violated by Eq.(1).

For the purpose of showing this explicitly we consider for the moment the supersymmetric model with broken R-parity as our theoretical context [20]. In this case the FC ν_μ-matter interactions are mediated by a scalar b-type quark, $\tilde{b}$, the supersymmetric partner of the bottom quark, so that we need only to check the couplings where a d-quark and a μ- or τ-neutrino is involved, i.e $g_{id} = \lambda'_{i31}$, where λ'_{ijk} are the coupling constants in the broken R-parity superpotential $\lambda'_{ijk} L_i Q_j D^c_k$, and L, Q and D are standard superfields. Constraints on the magnitude of such FC interactions in broken R-parity models have been given in [24]. The most stringent limit to the values of the relevant FC quantities comes from the experimental bound BR$(\tau^- \to \rho^0 + \mu^-) < 6.3 \times 10^{-6}$ [25] which implies that $|\lambda'_{331}\lambda'_{231}| < 1.2 \times 10^{-3} \times (m(\tilde{t})/100 \text{ GeV})^2$. As a result we find $\epsilon < 1.8 \times 10^{-3} m^2(\tilde{t})/m^2(\tilde{b}_L)$ at 90 % C. L. Since the $\tilde{t}$ squark is a mixing of both left and right scalars, the above limit on the ratio of stop to sbottom mass is actually milder. Precision tests of the standard electroweak model imply that, individually these couplings are less constrained: $\lambda'_{231} < 0.22\,(m(\tilde{t})/100$ GeV) at 2-σ level while $\lambda'_{331} < 0.48\,(m(\tilde{t})/100$ GeV) at 1-σ level [24,26]. This corresponds to a limit on $\epsilon' < 0.35\, m^2(\tilde{t})/m^2(\tilde{b}_L)$ at 1-σ. We therefore see that the required strength of FC ν_μ-matter interaction is consistent with present data. One should note that broken R-parity sypersymmetric models typically lead to neutrino masses which could be large. One may suppress

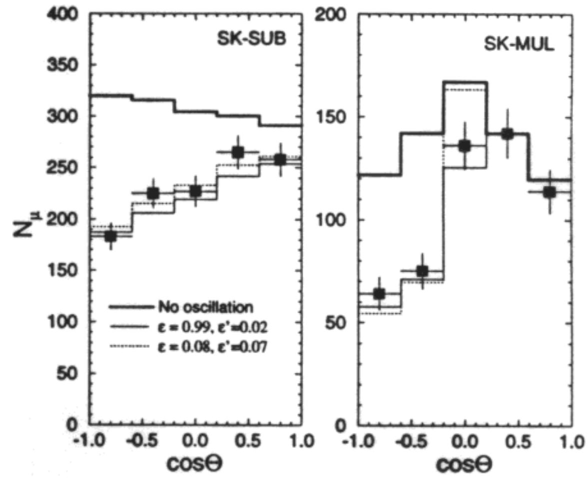


FIG. 2. Best-fit zenith angle distributions in the massless-neutrino FC scenario (thin-solid, dotted lines) versus no-oscillation hypothesis (thick-solid line). The SuperKamiokande data are indicated by the crosses.

7.

Gonzalez-Garcia et al. But poor fit to up thru mu's. Lipari & Lusignoli

ATMOSPHERIC

(1) $\nu_\mu - \nu_\tau$ mixing w. $\delta m^2 \sim O(eV^2)$, $\sin^2 2\theta \sim 1$

$\Rightarrow R \sim 0.6$, no oscill. (avg).

skip this one!

· To account for L/E depend: invent new $\nu_\tau q$ interaction. (Ma-Roy '97)

$$\propto \frac{4G_F}{\sqrt{2}} \bar{\nu}_{\tau_L} \gamma_\mu \nu_{\tau_L} \bar{q}_L \gamma_\mu q_L$$

· Get matter-effect in $\nu_\mu - \nu_\tau$ prop.

$$i\frac{d}{dt}\begin{pmatrix}\nu_\mu \\ \nu_\tau\end{pmatrix} = \begin{pmatrix}0 & A \\ A & B+C\end{pmatrix}\begin{pmatrix}\nu_\mu \\ \nu_\tau\end{pmatrix}.$$

$$A = \frac{\delta m^2 \sin 2\theta_0}{4E} \qquad B = \frac{\delta m^2}{2E}\cos 2\theta_0$$

$$\& \; C = \alpha G_F N_q$$

MSW Resonance when $B+C=0$ (for either ν or $\bar{\nu}$).

$E < 1\,GeV \rightarrow$ no Resonance

$E > 1\,GeV \rightarrow$ Resonance Possible.

Then $P_{\mu\mu} \neq P_{\bar{\mu}\bar{\mu}}$, also $\phi_{\nu_\mu} \neq \phi_{\bar{\nu}_\mu}$ & $\sigma_{\nu_\mu} \neq \sigma_{\bar{\nu}_\mu}$

Since exptly only an average $\bar{P}_{\mu\mu}$ observed (weighted) $\Rightarrow$

$$\hat{P} \sim \frac{3r P + \bar{P}}{3r + 1}$$

$\left(r = \Phi / \bar{\Phi}, \text{ assume } \bar{\sigma}/\sigma \approx 1/3 \right)$

- With no matter effects $\hat{P} = P = \bar{P}$
- With m.e. e.g. possible to get $\hat{P} \sim 0.4$ (up)
  $\hat{P} \sim 0.6$ (down)
- Detailed L/E distri. not calculate
- Model possibly in trouble since α needed is v. large $\sim O(10)$
  $\Rightarrow$ ν_τ N.C. x-section boosted by 100, No sign of such anomalous showers in Super-K
- SNO should see huge effects from $\nu_e \to \nu_\tau + D \to n + p + \nu_\tau$
  huge x-section

E. Ma & P. Roy

Neutrino Decay For ATMOSPHERIC ν Observations

Barger, Learned, Weiler, S.P.

- $\nu_H \longrightarrow \bar{\nu}_L' + \chi$ (χ = Boson, $m \approx 0$) ($m_H \neq 0$)
- mass & mixing present in general. ($\nu_L \equiv \nu_L'$ or $\not\equiv \nu_L'$)
- $\nu_\mu = \cos\theta\, \nu_H + \sin\theta\, \nu_L$
- $P_{\mu\mu} = \sin^4\theta + \cos^4\theta \exp(-\alpha L/E)$
  $+ 2\sin^2\theta\cos^2\theta \cos(\delta m^2 L/2E) \exp(-\alpha L/2E)$

$\alpha = m_H/\tau_H \longrightarrow$ rest frame lifetime

if δm^2 "large" ($> 0.1\ eV^2$)

(A) $P_{\mu\mu} \simeq \sin^4\theta + \cos^4\theta \exp(-\alpha L/E)$

if δm^2 "v. small" ($< 10^{-4}\ eV^2$)

(B) $P_{\mu\mu} \approx \left(\sin^2\theta + \cos^2\theta \exp\left(-\frac{\alpha L}{2E}\right)\right)^2$

Fit (A) & (B) to Super-K data to fix θ & α.

For (8A) fit ~ $\theta \sim 20^\circ$, $\alpha \sim 1\,\text{GeV}/D_E$

$D_E \sim 12{,}800$ Km (Earth Diameter)

$= \gamma c \tau_H$ @ $1\,\text{GeV}$

For coupling $g\,\bar{\nu}_H \nu_L \chi$

$$\tau_H = \frac{16\pi}{g^2} \frac{m_H^3}{\delta m^2 (m_H + m_L)^2}$$

$$\rightarrow \quad g^2 \delta m^2 \sim (2-7)\,10^{-4}\ \text{eV}^2$$

From K − π Decays $\Rightarrow g^2 < 2.4 \cdot 10^{-4}$

$$\Rightarrow \quad \underline{\delta m^2 > 0.73\ \text{eV}^2}.$$

Hence if δm^2 in Decay $\equiv \delta m^2$ in Osc (A)

$\delta m^2_{osc} > 0.1\ \text{eV}^2 \Rightarrow$ <u>Choose Option</u>.

If δm^2 in Decay $\not\equiv \delta m^2$ in Osc.

δm^2_{osc} can be v.small

$\Rightarrow$ Option (B) is viable.

Can account for all anomalies w. 3 flavors

Choose $$U = \begin{pmatrix} 1 & 0.02 & 0.04 \\ -0.05 & 0.93 & 0.36 \\ \varepsilon & -0.36 & 0.93^2 \end{pmatrix}$$

CDHS $\Downarrow$

$$\mathcal{O}(1)\, eV^2 > \delta m^2_{32} \gtrsim 0.73\ eV^2 \qquad \delta m^2_{31} \sim 0.5 \cdot 10^{-5}\ eV^2$$

Solar: SMA MSW

LSND: $P_{\mu e} \sim 10^{-3}$.

Models: . Dirac ν's $\overline{\nu^c_{R_3}}\, \nu_{R_2}\, \chi$

χ has $I = 0$, $L = -2$.

. Potential problems

w. BBN $N^{\nu}_{eff} \sim 4 - 4.5$

w. SN χ escape quickly.

. Majorana ν's $\overline{\nu^c_{L_3}}\, \nu_{L_2}\, J$.

. $J \sim$ singlet + triplet. Safe (BBN & SN).

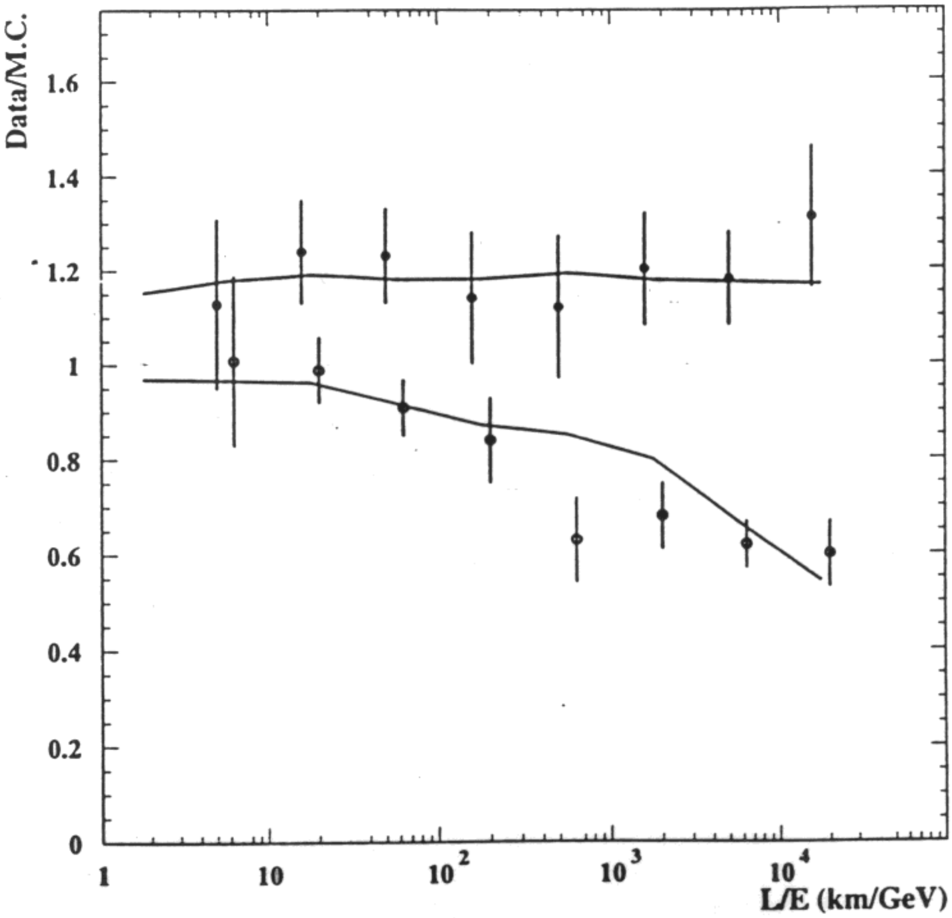
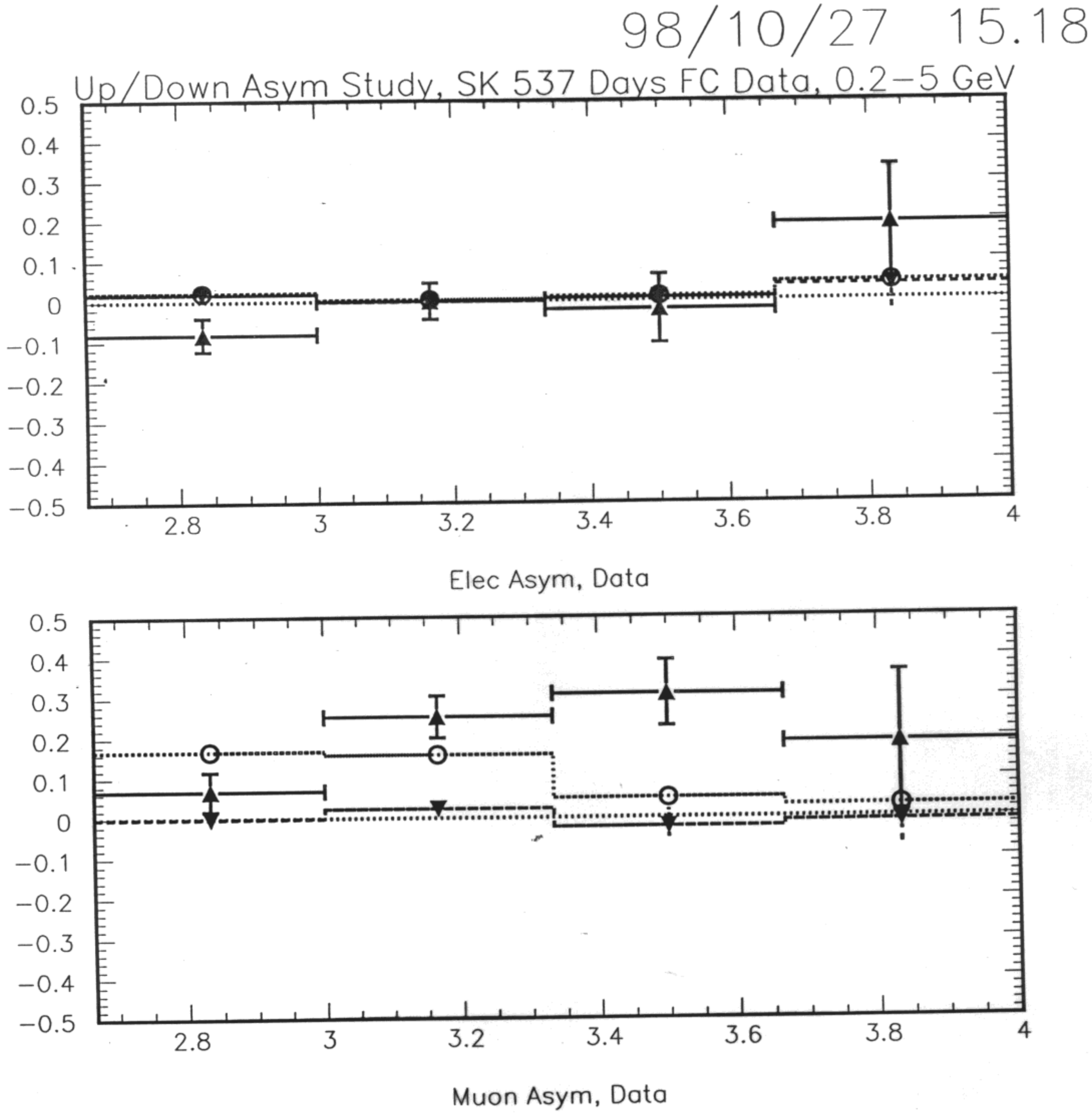


FIG. 1. The Super-Kamiokande data/expectations as a function of L/E, for electron events (upper) and muon events (lower). Our model normalized to the electron flux total is shown by the lines, indicating an acceptable fit for decaying muon neutrinos.

A

χ^2/d.o.f. 9/8


98/10/27 15.18
Up/Down Asym Study, SK 537 Days FC Data, 0.2–5 GeV
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
2.8
3
3.2
3.4
3.6
3.8
4
Elec Asym, Data
Muon Asym, Data

χ^2/d.o.f. 9/4

A

Fogli, Lisi, Marrone, Scioscia. (15

Lipari, Lusignoli

FIGURES

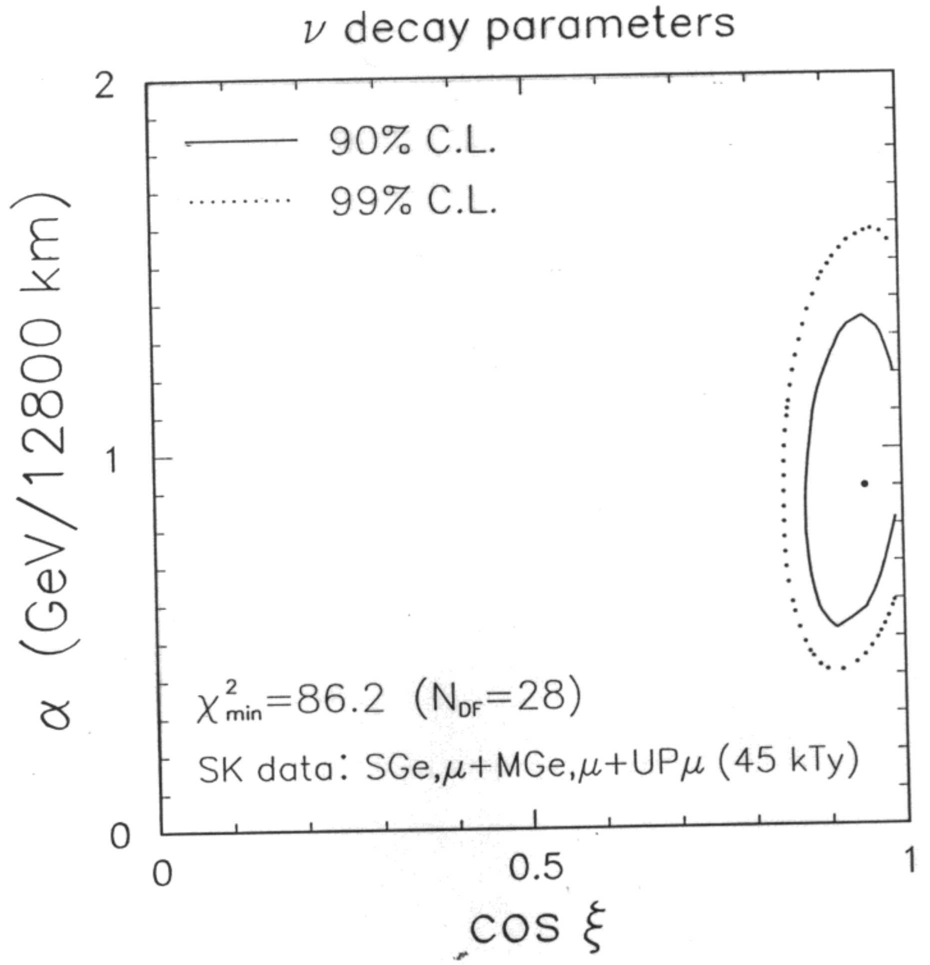


FIG. 1. Fit to the Super-Kamiokande data (45 kTy, 30 data points) in the plane of the neutrino decay parameters $\cos\xi = \langle\nu_\mu|\nu_d\rangle$ and $\alpha = m_d/\tau_d$. The solid and dotted lines are defined by $\chi^2 - \chi^2_{\rm min} = 4.61$ and 9.21, corresponding to 90% and 99% C.L. for two variables. The analysis favors $\alpha \sim 1$ GeV$/D_\oplus$ and large $\cos\xi$. However, even at the best fit point there is poor agreement between data and theory ($\chi^2_{\rm min}/N_{\rm DF} = 86.2/28 = 3.1$), indicating that ν decay is not a viable explanation of the Super-Kamiokande observations.

Fogli, Lisi, Marrone, Sciosia

hep-ph/9902267

Similar Results: Lipari Lusignoli

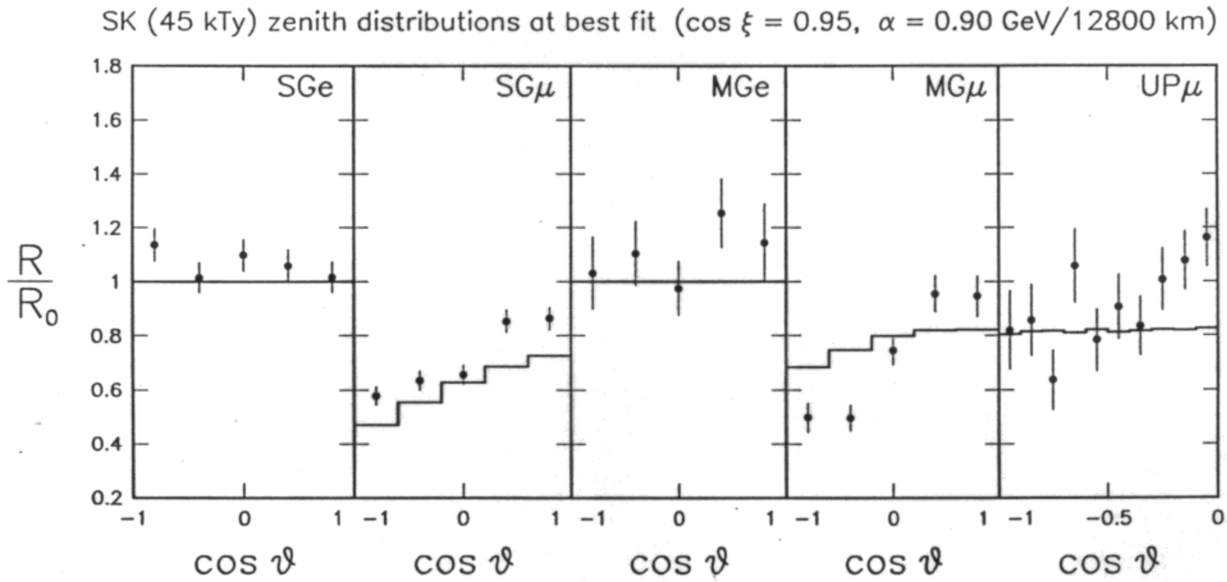


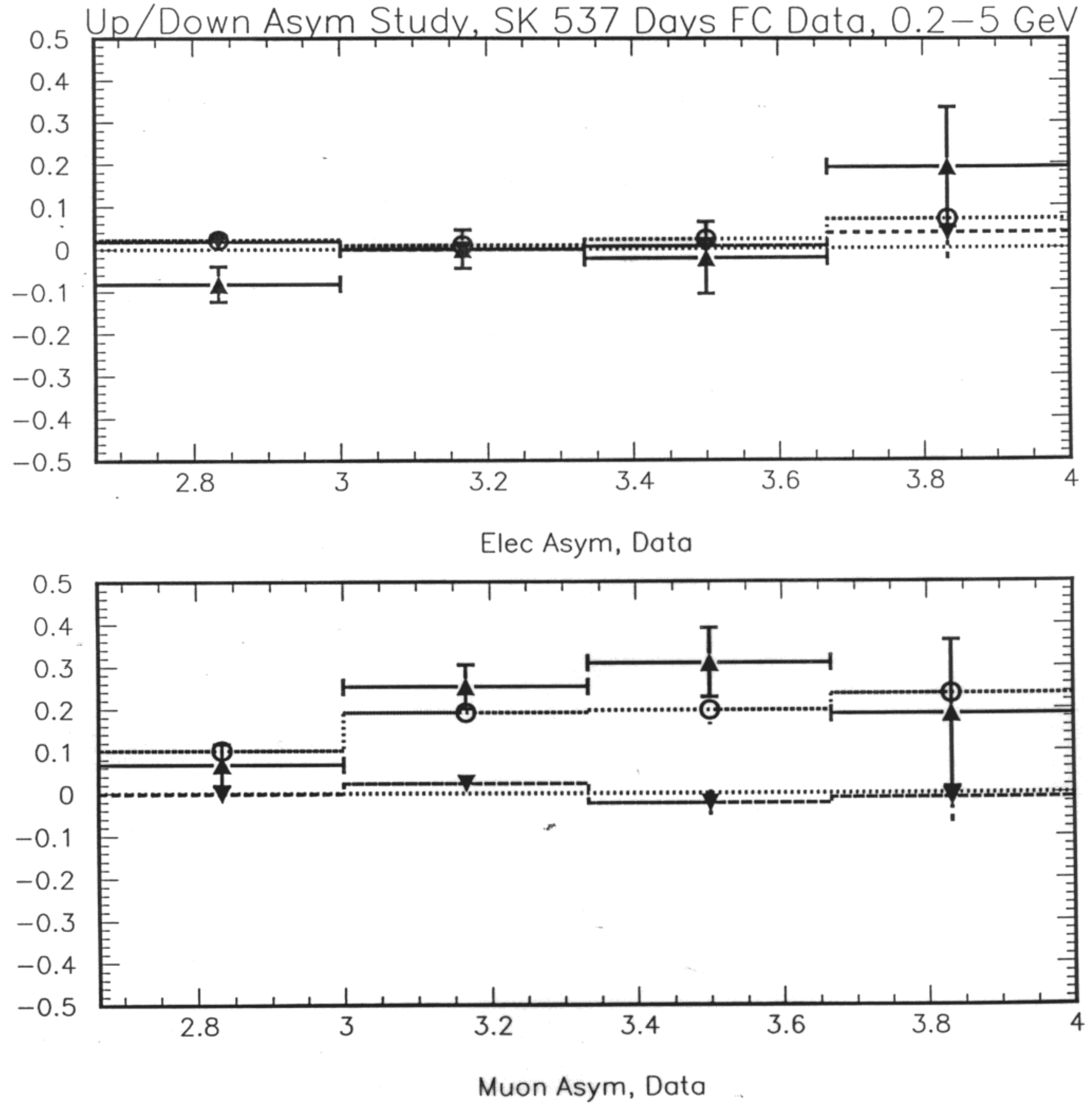
FIG. 2. Zenith angle distributions of Super-Kamiokande sub-GeV e-like and μ-like events (SGe and SGμ), multi-GeV e-like and μ-like events (MGe and MGμ), and upward-going muons (UPμ). Data: dots with $\pm 1\sigma$ statistical error bars. Theory (ν decay best fit): solid curves. In each bin, both theoretical and experimental rates R are normalized to their standard (no decay) expectations R_0. The solid curves do not appear to reproduce the muon data pattern.

As E increases ν's dont decay

difficult to fit HE μ's.

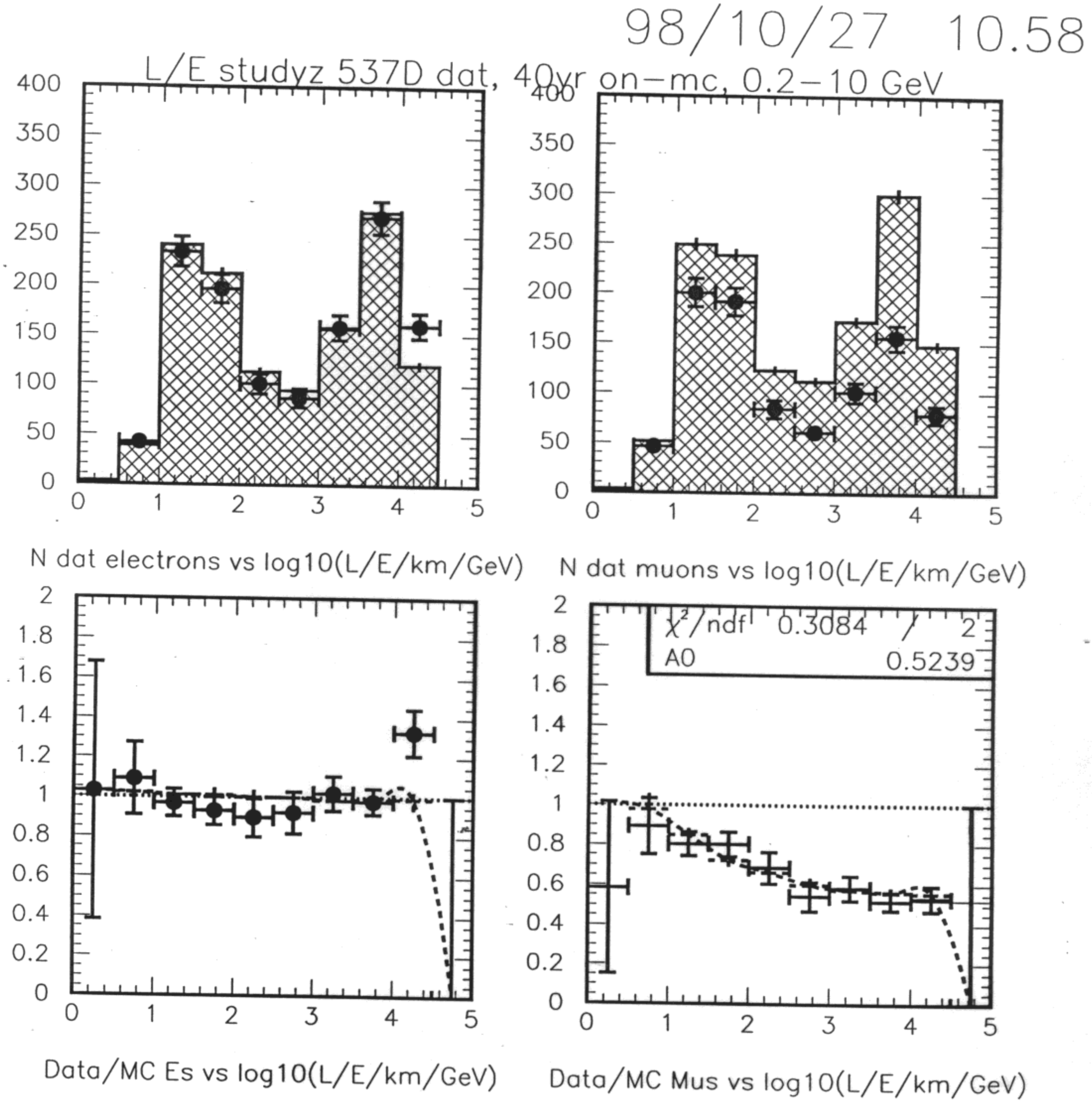
Model B fits all Atm. data (17)

98/10/27 11.05



Learned et al.

B



Learned et al.

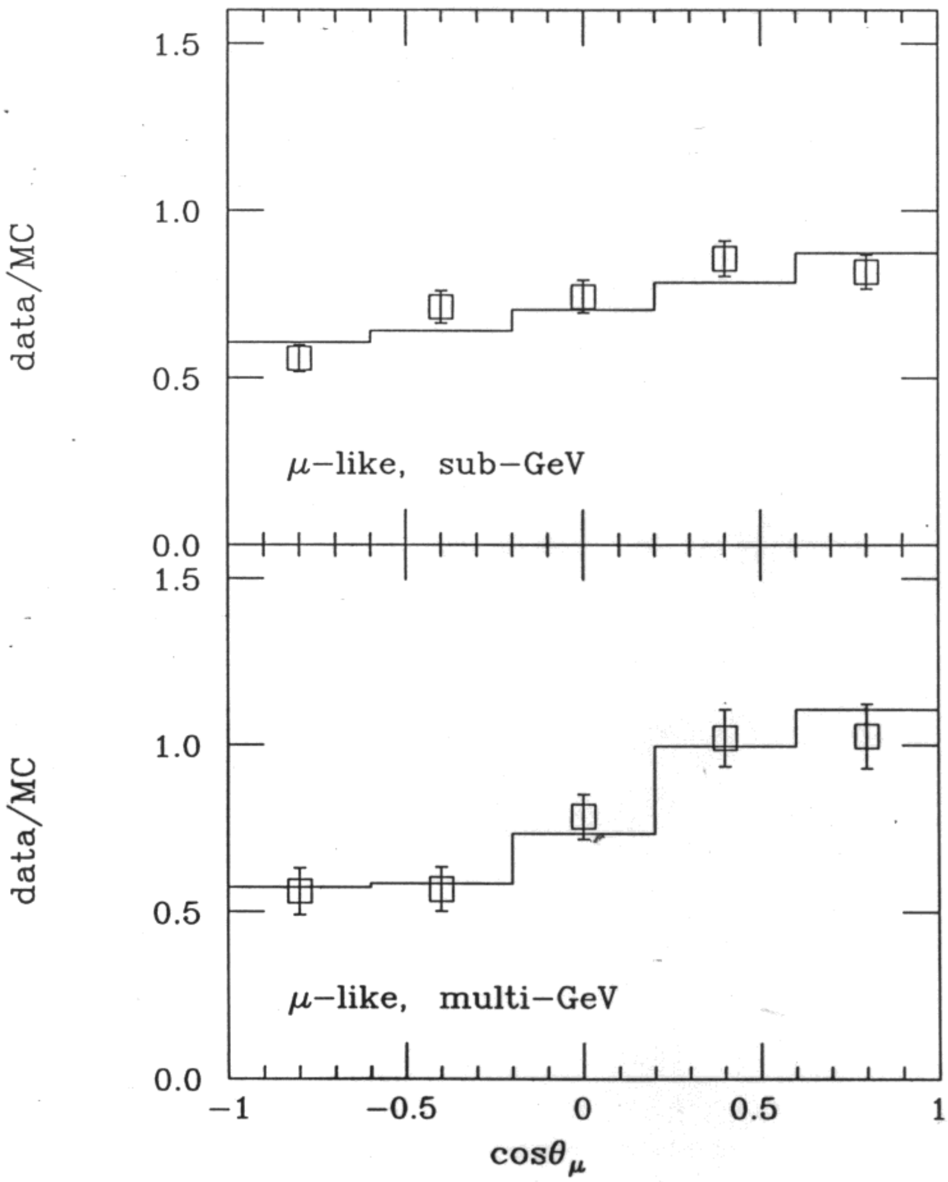
B

Model B

Lipari, Lusignoli

$\chi^2 \sim 33.7$ for 32 d.o.f

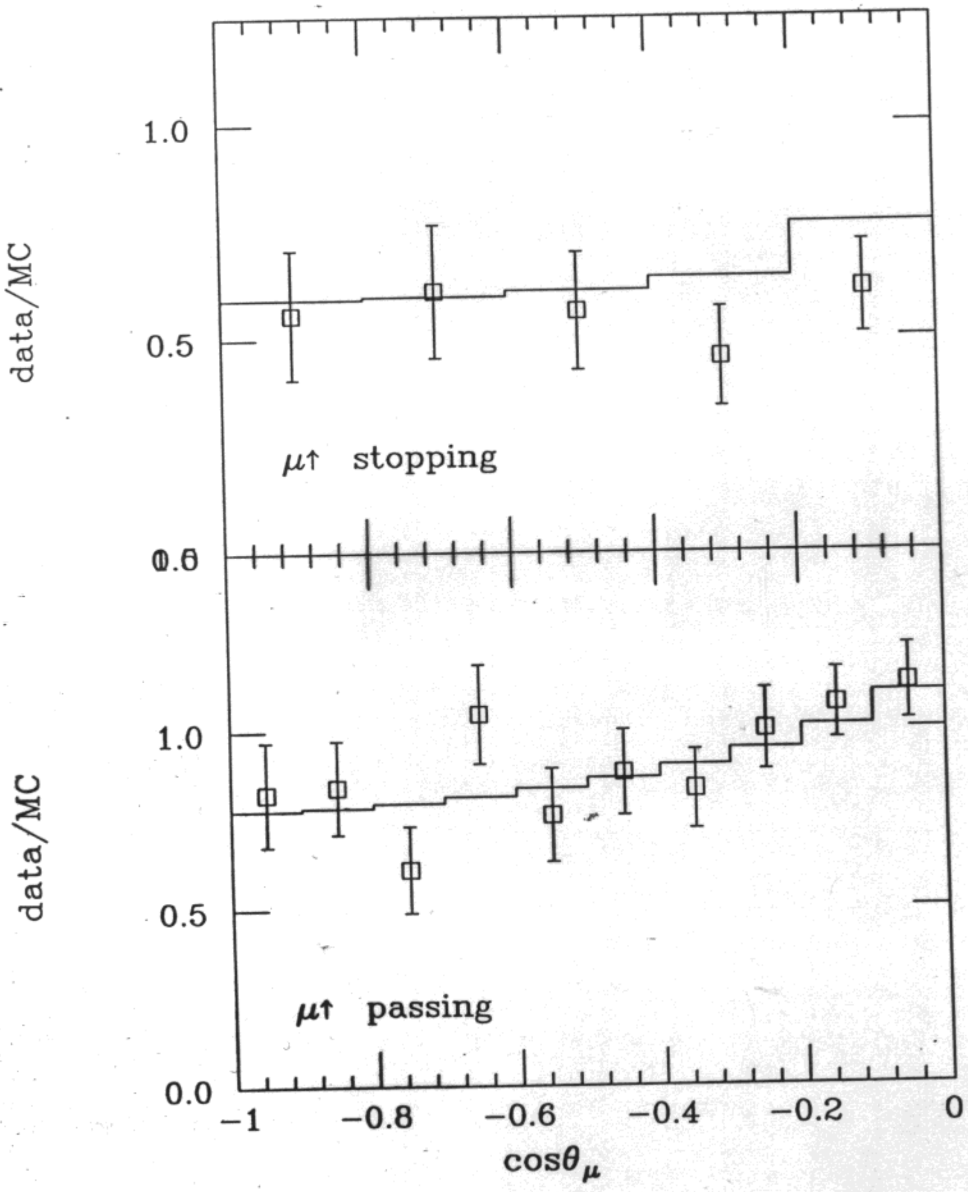
$\cos^2\theta \sim 0.3$ $\alpha = 63$ km/GeV



B

Lipari, Lusignoli

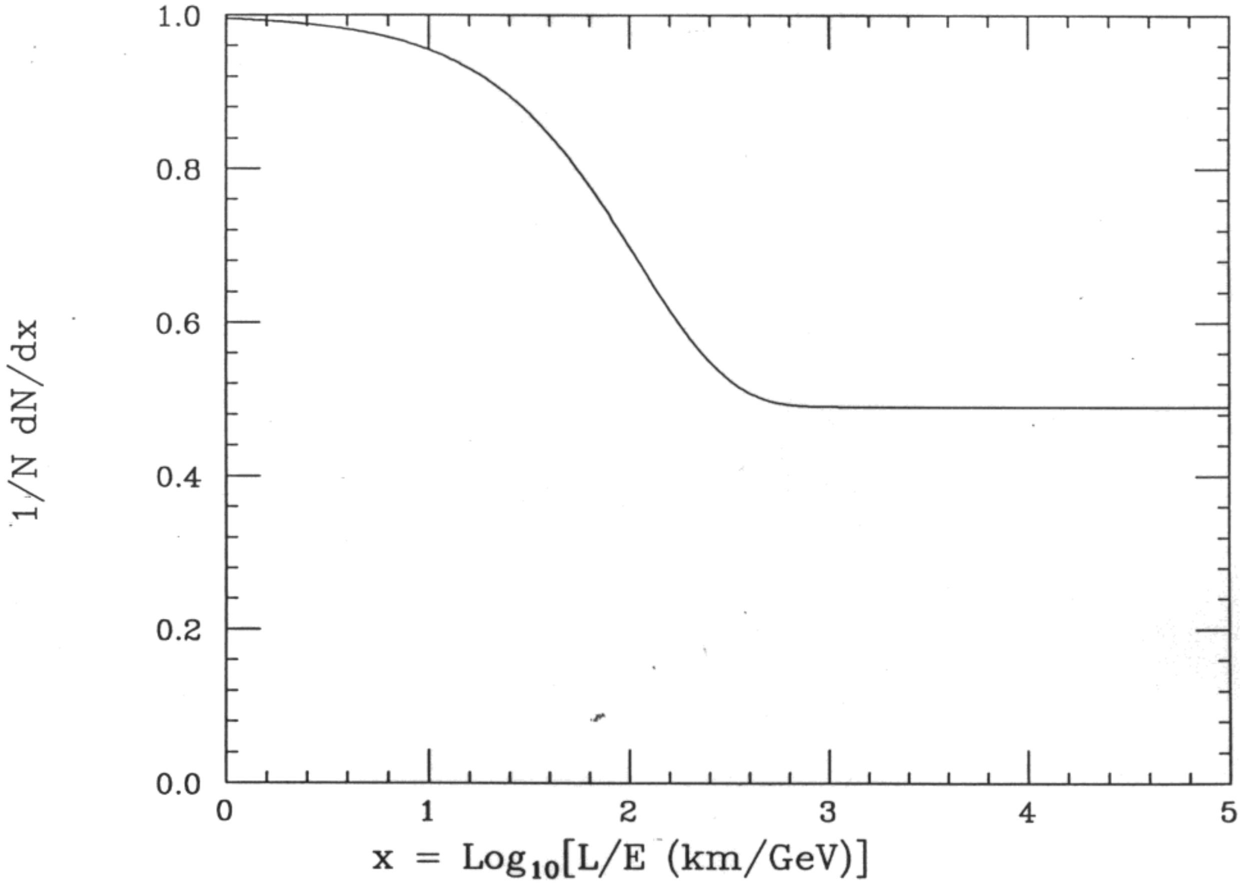
(20



B

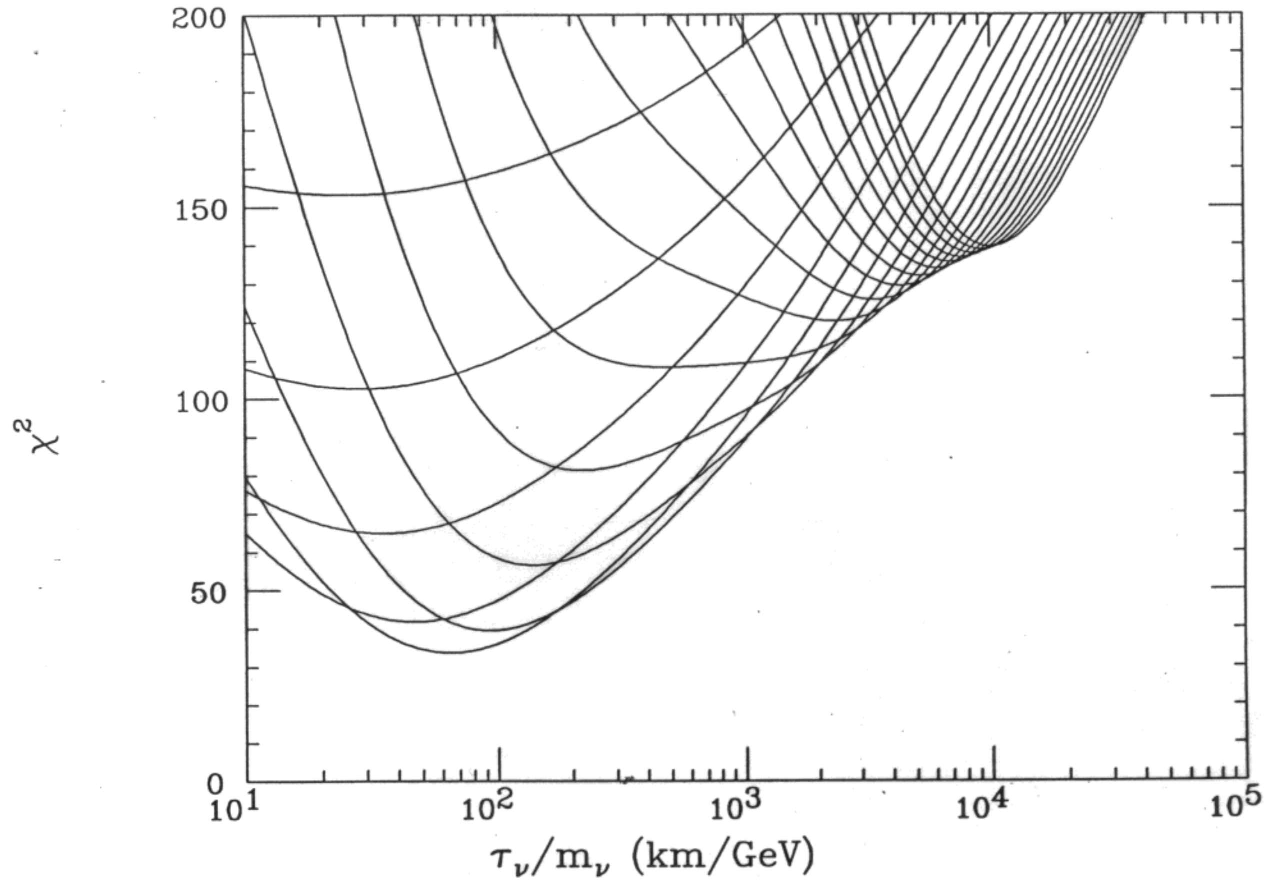
(21)

Lipari, Lusignoli



(B)

Lipari, Lusignoli



B

- No conflict with existing non-radiative τ_{ν_μ} bounds (few km/GeV)

- No FCNC e.g. $\mu \to e x$ induced.

<u>Tests</u>: • Eventually Super-K to distinguish Pure Osc. function from pure decay function of L/E ?

- LBL expectations Different from osc

	Osc.	Decay (A)	Decay (B)
$P_{\mu\mu}$	50%	80 %	50 %
$P_{\mu\tau}$	50%	20 %	20 %

- Flavor Mixes of ν's from SN, AGN, GRB's affected differently.
  → Implications for ν Telescopes.

- No $0\nu\beta\beta$.

Flavor Mix of ν's from AGN's etc.

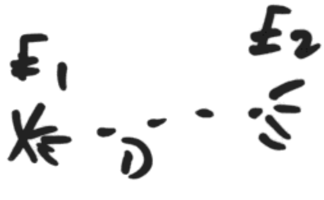
- Production : Beam Dump $\rightarrow$ $\nu_\mu : \nu_e : \nu_\tau \sim 2 : 1 : \varepsilon$ $(\varepsilon << 1)$
- Propagation Matrix : $P = \begin{pmatrix} P_{\mu\mu} & P_{\mu e} & P_{\mu\tau} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix}$

  depends on U_{mix} & δm_{ij}^2.
- For Example $U = \begin{pmatrix} 1/\sqrt{2} & -1/\sqrt{2} & 0 \\ 1/2 & 1/2 & -1/\sqrt{2} \\ 1/2 & 1/2 & 1/\sqrt{2} \end{pmatrix}$

$\Rightarrow$ Flavor Mix @ Earth is $\nu_\mu : \nu_e : \nu_\tau \simeq 1 : 1 : 1.$

- KM3, $E_\nu \sim$ few PeV

  measure Flavor Mix :
  - μ's
  - e's via Glashow Resonant events (@ 6.4 PeV)
  - τ's by Double Bang Events.



$\left(\begin{matrix} D \sim 100\,m \\ E_2 > E_1 \end{matrix} \right)$.

Check on ν mixing matrix.

[Learned & S.P.]

SOLAR NEUTRINO DECAY?

(old idea: {Bahcall, Frautschi, Cabibbo, (1972)} {Tennakone, S.P.}

Acker & S.P.

- $\nu_e \to \nu' + \chi$
- Model A

  $\chi^2_{min} \sim 15$, $U_{e1} = 0.6$, $\tau_\nu (10\,MeV) \sim 27$ sec.

- Model B

  $\chi^2_{min} \sim 11$, $U_{e1} \sim 0.6$, $\tau_\nu \sim 6$ sec.

- ν_e Decay can <u>not</u> account for data @ 99% C.L.

- Confirms conclusion in '93 (by A.A. & S.P.) with newer data & newer decay models.

ATMOSPHERIC ③ Decoherence.

due to ν_μ inter. en-route to detector

e.g. • ν - B.G. v. large.

• new flavor sensitive inter. in extra dim.

• Q.M. viol.

In this case ν_μ survival prob. given by

$$P_{\mu\mu}(t) = \frac{1}{2}\left[1 + \cos 2\theta\, e^{-t/\tau}\right]$$

$$1/\tau = D(E) \sin 2\theta \sqrt{1 - \frac{\sin^2 2\theta}{4}}$$

Rough fit to Super-K L/E obtained

$$\tau \sim 10^{-2}\,s, \quad \sin 2\theta \lesssim 0.4.$$

$$[\delta m^2 \sin 2\theta >> 10^{-3}\,eV^2].$$

[Grossman & Worah] $\quad t/\tau \longrightarrow L/L_0 \quad (L_0 \sim 3000\,km)$

Proposal of Eichler & Seidov
(hep-ph/9810372).

· Survival Probability $P_{\alpha\alpha}$:

$$P_{\alpha\alpha} = \cos^2\theta \exp(-L/L_0) + \sin^2\theta$$

$$L_0 = \frac{1}{\alpha} L_P E_P^2 / E^2$$

$P \to$ Planck

$\alpha \sim O(1/100)$

$$\to P_{\alpha\alpha} = \cos^2\theta \exp[-\beta L E^2] + \sin^2\theta$$

$L_P E_P^2 \sim 4$ (km-GeV^2) $\quad \beta = \alpha / L_P E_P^2$

Physical Origin? Speculative:

· absorption by scattering on "foam"?

· $\sigma \propto E^2$? (only at low E?).

- Possible Good fit to Solar ν data.
- V. Poor fit to Atmospheric Data
- Flavor Dependence?

<u>Conclusion</u>: Even if ν's have masses & do mix, observed ν-anomalies may NOT be due to oscillations, but due to other exotic new physics.

These possibilities are testable (sometimes) & should be ruled out (by experiments).