I. Introduction

A. Neutrino oscillation results from solar and atmospheric neutrino data.

In the last few years, questions concerning the masses of the light, standard model neutrinos and the degree to which they mix have received increasing attention. The situation is summarized in Fig. 1 in which are plotted both the solar neutrino results and also the most recent atmospheric neutrino results interpreted in the framework of neutrino oscillations.

In one current interpretation the results from solar neutrino detectors [1] suggest that the disappearance of electron type neutrinos (ν_e) may be due to resonant neutrino oscillations in the matter of the Sun, and that the ν_e and the neutrino type into which it oscillates, possibly ν_μ, have small, $\leq 10^{-2}$ eV, mass. In addition, recent results on atmospheric neutrinos from the Kamiokande and IMB imaging water Cherenkov detectors suggest that the observed disappearance of muon type neutrinos (ν_μ) may be due to vacuum neutrino oscillations, and that the mass of the neutrino into which the ν_μ oscillates, possibly the ν_τ, lies in the interval from 10^{-2} to $O(1)$ eV [2].

A second scenario explains the solar neutrino deficit via $\nu_e \leftrightarrow \nu_s$, where both the ν_e and the sterile neutrino ν_s are much lighter ($\Delta m^2_{es} \sim 10^{-5} eV^2$) than the ν_μ and ν_τ [3]. The mass difference of ν_μ and ν_τ, as indicated by the atmospheric neutrino results, $5 \times 10^{-3} \lesssim \Delta m^2_{\mu\tau} \lesssim 3 \times 10^{-2} eV^2$, allows both ν_μ and ν_τ masses to be approximately equal and of the order of a few eV. This scenario is motivated in part by the need for an admixture (20–40%) of hot dark matter—roughly 7 eV worth—relative to the total, which would be consistent with the cosmic background radiation fluctuations, galaxy position and cluster correlations and large scale velocity flows.

We emphasize that the experiment discussed here, AGS E889, is important in either scenario, as will be discussed in detail in what follows.

Confirmation or repudiation of the solar neutrino results will be forthcoming in the next few years as the new solar neutrino detectors now under construction come into operation [4]. The experimental prospects for exploitation of the atmospheric neutrino results is, however, less clear. The present data sample is based on approximately 15 kiloton-years and more data continue to be acquired. A larger statistical sample will be of value, but the inherent limitation in the interpretation of the data is in the normalization which rests largely on a calculation of the expected atmospheric neutrino flux ratio ν_μ/ν_e and the interactions of the ν_μ and ν_e in the detectors. In certain salient respects the calculation is less suspect than usual, e.g., the absolute magnitude and constitution of the primary cosmic ray flux cancel out of the ν_μ/ν_e ratio, and all extant calculations yield the same value for the ratio within 5% uncertainty as seen in Table 1. Furthermore, the model used to describe the interactions of ν_μ ($\bar{\nu}_\mu$) and $\nu_e(\bar{\nu}_e)$ with ^{16}O is unlikely either to be seriously incorrect or to require corrections that might explain the effect, as shown in Table 2 and described in reference [5].

Fig. 2 shows a comparison of the $\cos\theta_Z$ distributions of the sub-GeV and multi-GeV atmospheric neutrino data [6], which indicates for the first time an energy dependence consistent with a neutrino oscillation interpretation of the totality of the data; the parameter regions allowed for the channels $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\mu \leftrightarrow \nu_\tau$ are shown in Fig. 3. This result will be extended and exploited with high statistics in the data forthcoming from Superkamiokande. In short, while scepticism remains, no source of error in the atmospheric neutrino data or its interpretation has been uncovered. Nevertheless, the normalization of the data, i.e., the predicted ratio of muon to electron events necessary for comparison with the observed ratio, remains a semi-empirical calculation, and prevents a definitive conclusion on neutrino mass and mixing from being reached.

Attempts in other, smaller detectors, i.e., the Fréjus and Soudan [7] iron plate-chamber detectors of approximately 1 kiloton total mass, to reproduce the results from the imaging water Cherenkov detectors have been statistically inconclusive, in part because of small mass and relatively short exposures. Fréjus claims no discrepancy similar to that in Table 2 within approximately 2σ while the central value of the μ/e ratio from Soudan is consistent with the average value in Table 2 but at present only 2σ away from unity.

The range of Δm^2 and $\sin^2 2\theta$ obtained from the atmospheric neutrino data does, however, suggest that a properly designed, long baseline neutrino oscillation experiment carried out with relatively low energy ν_μ from an accelerator over a reasonable distance would definitively answer the questions relating to the observed ν_μ disappearance in the atmospheric neutrino data. Such an experiment would eliminate the normalization problem in the atmospheric neutrino observations and conclusively confirm or deny the occurrence of neutrino oscillations in a $\Delta m^2 - \sin^2 2\theta$ region which would include all of the region indicated by the atmospheric neutrino data in Fig. 3 and some beyond. Of equal importance, a single long baseline accelerator experiment with several detectors would provide sufficient control of possible systematic errors to ensure a convincing result and to allow a quite small region of the $\Delta m^2 - \sin^2 2\theta$ space to be specified as the result of the experiment.

At present, there are two data-taking accelerator experiments in the world, Karmen and LSND, directed toward a small part of the $\Delta m^2 - \sin^2 2\theta$ region indicated by the atmospheric neutrinos [8]. These experiments, which look for $\nu_\mu \rightarrow \nu_e(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ oscillations expect to cover the interval $\Delta m^2 \gtrsim 0.1 eV^2$ and $\sin^2 2\theta \geq 10^{-2}$, i.e., a part of the allowed interval delineated by the atmospheric neutrino data (see below).

For completeness, we note that two neutrino oscillation experiments, Chorus and Nomad, directed primarily toward the oscillation channel $\nu_\mu \leftrightarrow \nu_\tau$ have been operating at CERN [9]. These are similar in concept and in plan to an earlier experiment at Fermilab [10] in that they seek to observe τ leptons produced by ν_τ from oscillations. The region in the $\Delta m^2 - \sin^2 2\theta$ space of vacuum oscillations that the past and future Fermilab and present CERN experiments will explore is shown in Fig. 4, which indicates, first, that they have no overlap with the region specified by the atmospheric neutrino result in Fig. 3, and consequently none with the experiment proposed here; and, second, that these experiments and the AGS experiment described here will together explore practically the entire region of the neutrino oscillation space in which a tau neutrino mass might be of such magnitude as to be influential as dark matter in the universe.

Before concluding this introductory section, we note that there is additional information in Fig. 1 from the atmospheric neutrino observations beside that from the data described earlier and shown in Table 2. The cross hatched area marked "KAM allowed" showing the implications of the atmospheric neutrino data for neutrino oscillations is the result of studies of atmospheric ν_μ– and ν_e–induced events in the Kamiokande and IMB detectors that are completely or partially contained, which ensures that the momentum of each produced μ and e is measured or approximated along with particle identification, and gives high probability that no other particles with velocities above the Cherenkov radiation threshold are present. The virtue of this method is that the observed ratio of muon single (Cherenkov) ring events to electron single ring events can be directly compared to the corresponding calculated ratio based on estimates of the atmospheric flux ratio $\phi(\nu_\mu)/\phi(\nu_e)$, as stated above. In calculating the flux ratio $\phi(\nu_\mu)/\phi(\nu_e)$, absolute knowledge of certain factors that enter the calculation is unnecessary, e.g., the absolute value of the primary components of the cosmic rays that impinge on the earth's atmosphere cancels out of the ratio $\phi(\nu_\mu)/\phi(\nu_e)$. As a consequence, the ratio $\phi(\nu_\mu)/\phi(\nu_e)$ is thought to be known within an uncertainty of less than 5% (Table 1), while the absolute values of $\phi(\nu_\mu)$ and $\phi(\nu_e)$ are not estimated to better than about 30%. The uncertainty in the predicted ratio of atmospheric ν_μ–induced events to atmospheric ν_e–induced events includes the 5% uncertainty in the incident flux ratio as well as other possible systematic uncertainties (Table 2 and reference [5]), the total of which amount to a systematic error of the order of 10%. References [2], and [5], give a more complete explanation of the contained event data.

The additional information from atmospheric neutrino studies comes from observations of upward-going muons produced in the rock or salt surrounding the Kamiokande and IMB detectors by the atmospheric ν_μ flux. There is little background from cosmic ray muons in the upward-going sample. Most of the upward-going muons, which are the products of neutrinos of average energy roughly 100 GeV, pass through the detectors, but about 20% of the upward-going muons are produced in reactions of neutrinos of average energy about 10 GeV and stop in the detectors. To use the through-going upward muon intensity alone as a means to search for neutrino oscillations requires that the neutrino flux in the interval 10 to 1000 GeV be calculated absolutely and that absolute neutrino cross sections with matter in that energy region be estimated accurately. These introduce uncertainties in the upward through-going muon flux calculations of about 20% and lead to corresponding uncertainties in the neutrino oscillation parameters $\Delta m^2 - \sin^2 2\theta$ [11]. The ratio of upward stopping muons to upward through-going muons is, however, less ambiguous, principally because uncertainties in absolute scale approximately cancel [10]. That ratio provides the excluded region in Fig. 1 marked "IMB atmos. upward muons (stopping/thru)" [12].

References

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Reference	Method	Interaction model	R_ν
Barr, Gaisser, Stanev	M.C.	Parametrized data	0.48
Lee and Koh	M.C.	”	0.48
Honda, Kasahara, et al.	M.C.	NUCRIN + LUND	0.46
Kawasaki and Mizuta	analytic	Aanalytic parametrization	0.49

Table 1: *The calculated ratio* $R_\nu = \phi(\nu_e + \bar{\nu}_e)/\phi(\nu_\mu + \bar{\nu}_\mu)$ *obtained from neutrino flux calculations in the cited references for the interval* $0.1 \lesssim E_\nu \lesssim 1.5 GeV$. *There is a small energy dependence of* R_ν *above the energy interval specified. From T.K. Gaisser in Proc. Conf. on Long Baseline Neutrino Oscillations (Fermilab, Nov. 17-21, 1991)(ed. M. Goodman) p. 111.*

Detector	$R(\mu/e)_{meas}$	$R(\mu/e)_{calc}$	$R(\mu/e)^{meas}_{calc}$	P_e MeV/c	P_μ MeV/c
IMB	0.531 ± 0.0535	0.987	0.54 ± 0.054	> 100	> 300
(LEE FLUX)	0.849 ± 0.0936	1.884	0.45 ± 0.050	> 300	> 300
	0.829 ± 0.108	1.871	0.44 ± 0.058	> 400	> 400
	0.764 ± 0.123	1.798	0.43 ± 0.068	> 500	> 500
KAM	0.671 ± 0.0895	1.051	0.64 ± 0.085	> 100	> 300
(LEE FLUX)	1.093 ± 0.163	1.836	0.60 ± 0.089	> 300	> 300
(Gaisser Flux)	0.671 ± 0.0895	1.067	0.63 ± 0.084	> 100	> 300
	1.093 ± 0.163	1.860	0.59 ± 0.088	> 300	> 300

Table 2: *Ratios of muon and electron events from the IMB and Kamiokande detectors for different momentum thresholds and different neutrino flux calculations. The upper limit of momentum interval in all entries is 900 MeV/c.* $R_{meas}(\mu/e)$, $R_{calc}(\mu/e)$, *and* $R^{meas}_{calc}(\mu/e)$ *are, respectively, the measured, calculated, and measured over calculated ratios. For assignments of systematic errors, see the original papers. From Reference [5].*

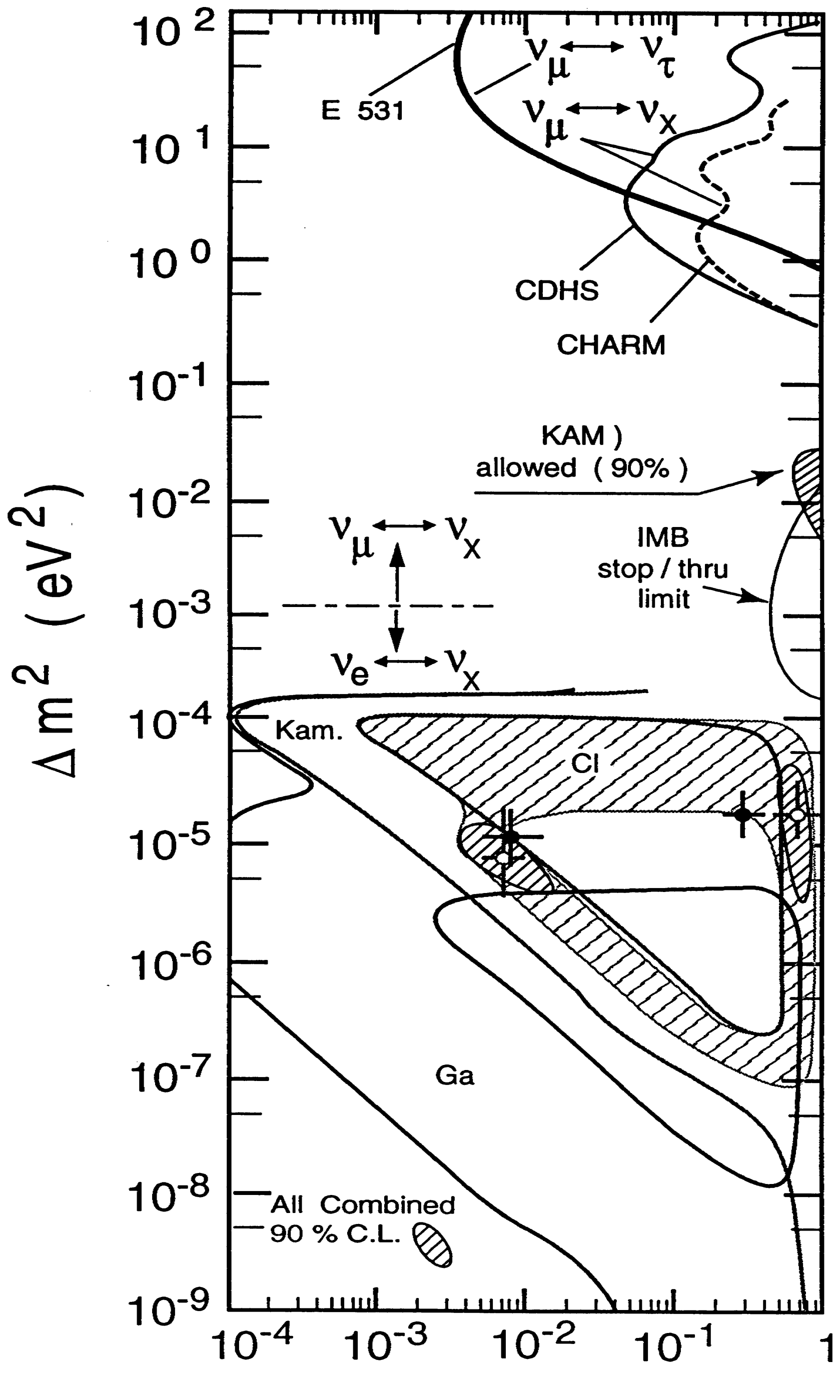
Figure Captions

Figure 1a. Summary of all available data for the neutrino oscillation channels $\nu_\mu \to \nu_x$ and $\nu_e \to \nu_x$ bearing on the $\Delta m^2 - \sin^2 2\theta$ region shown. The shaded areas are allowed for neutrino oscillations. The solar neutrino data which yield the allowed region below $\Delta m^2 \approx 10^{-4} eV^2$ are described in reference [1], the reference to E531 is [7]. The data in the upper half of the plot including the atmospheric neutrino data are from [2] and references therein. (b). Another representation of the totality of neutrino oscillation data, from the last citation in reference 2, also includes all data and is based on the assumption that 3-fold neutrino oscillations are taking place.

Figure 2. Plots of $\cos\theta_Z$ from the sub-GeV and multi-GeV data of Kamiokande, from Phys. Lett. B335, 237 (1994).

Figure 3. Plots of Δm^2 vs $\sin^2 2\theta$ for $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\mu \leftrightarrow \nu_\tau$, showing allowed regions cross hatched, from Phys. Lett. B 335, 237 (1994).

Figure 4. The cross hatched region shows $\Delta m^2 - \sin^2 2\theta$ for $\nu_\mu \leftrightarrow \nu_\tau$ accessible to two approved CERN experiments [9] and a proposed Fermilab experiment [10].



$\nu_\mu \leftrightarrow \nu_\tau$
$\nu_\mu \leftrightarrow \nu_x$
E 531
CDHS
CHARM
KAM)
allowed (90%)
IMB
stop / thru
limit
$\nu_\mu \leftrightarrow \nu_x$
$\nu_e \leftrightarrow \nu_x$
Kam.
Cl
Ga
All Combined
90 % C.L.
Δm^2 (eV^2)
$\sin^2 2\theta$

Figure 1a

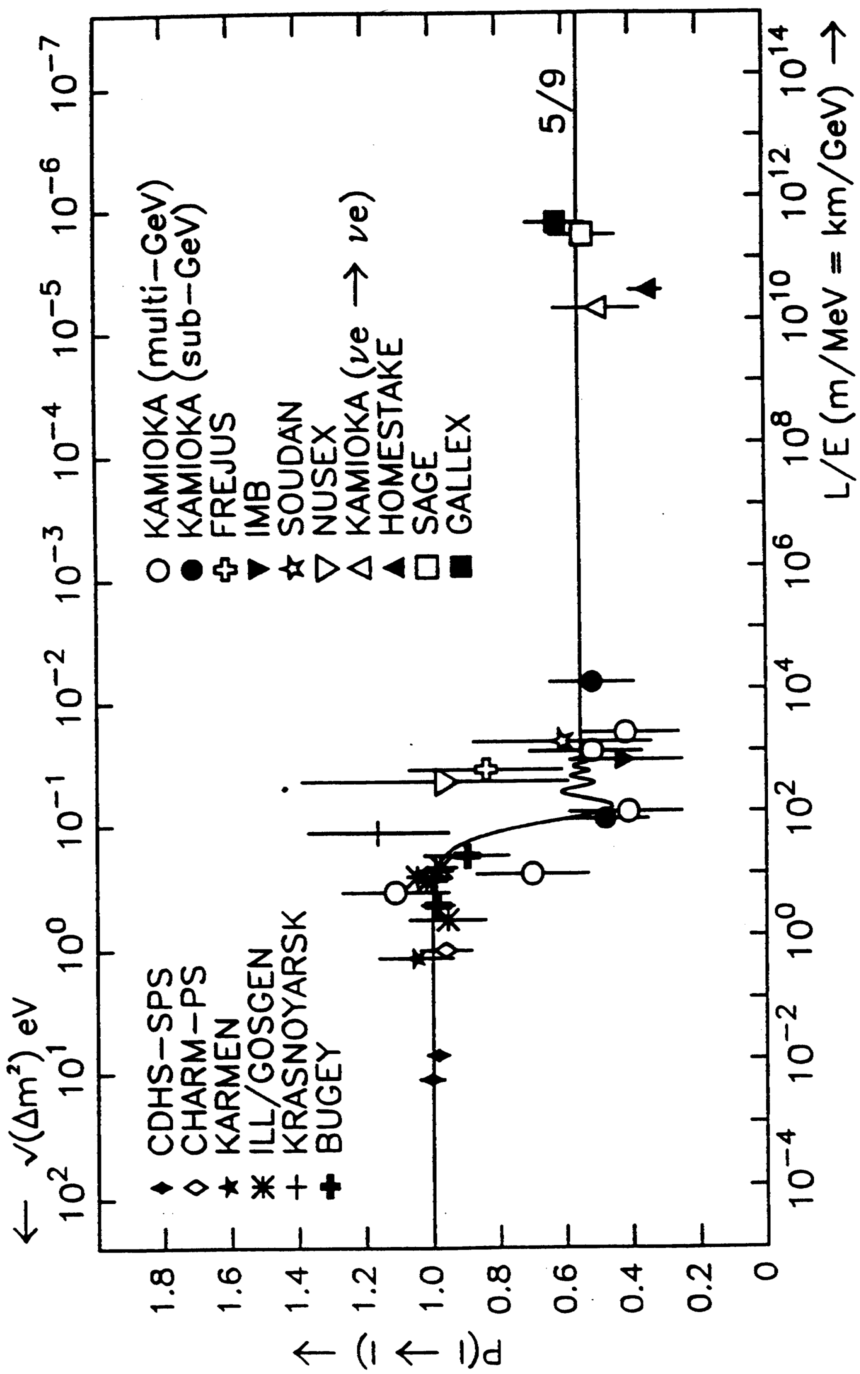
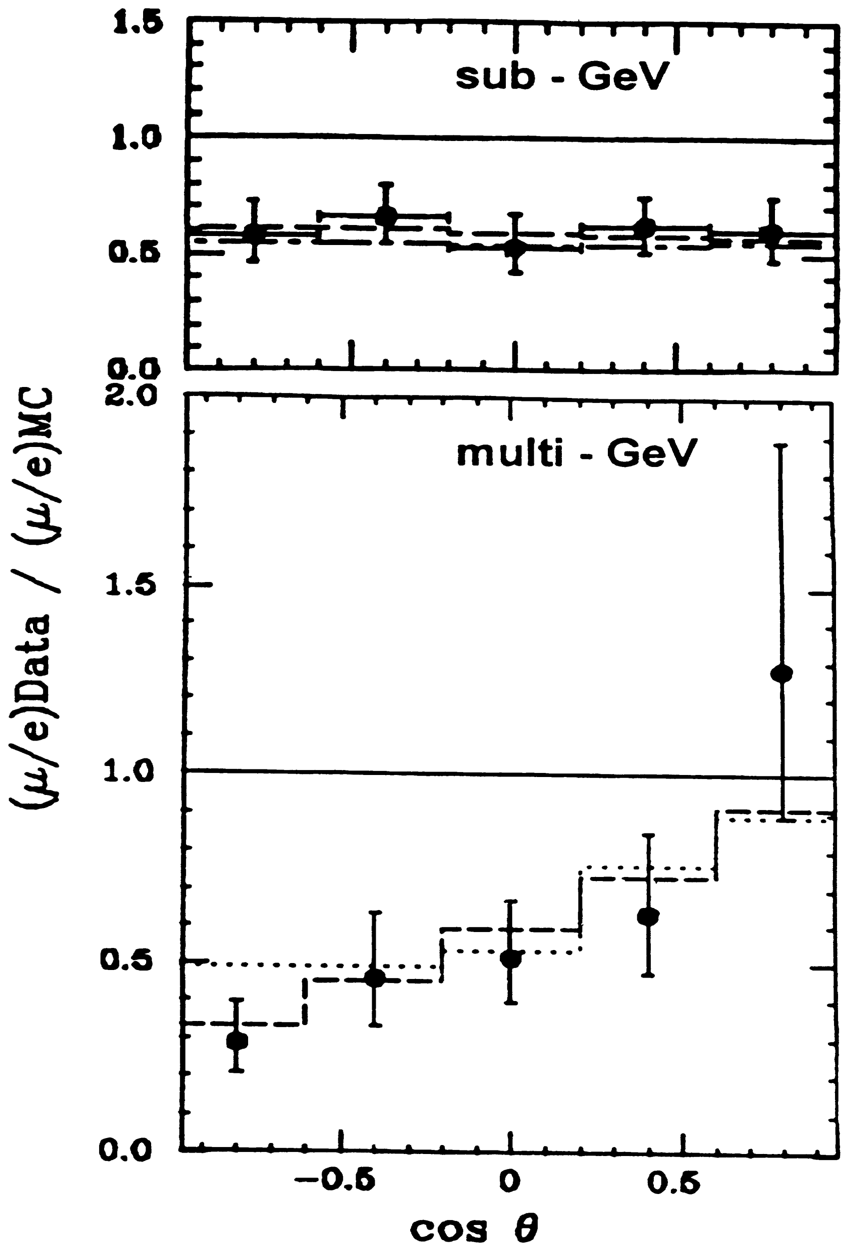


Figure 1b. From P.F. Harrison, et al., RAL-94-125 (1994)



sub - GeV
multi - GeV
(μ/e)Data / (μ/e)MC
cos θ
1.5
1.0
0.5
0.0
2.0
1.5
1.0
0.5
0.0
−0.5
0
0.5

Figure 2

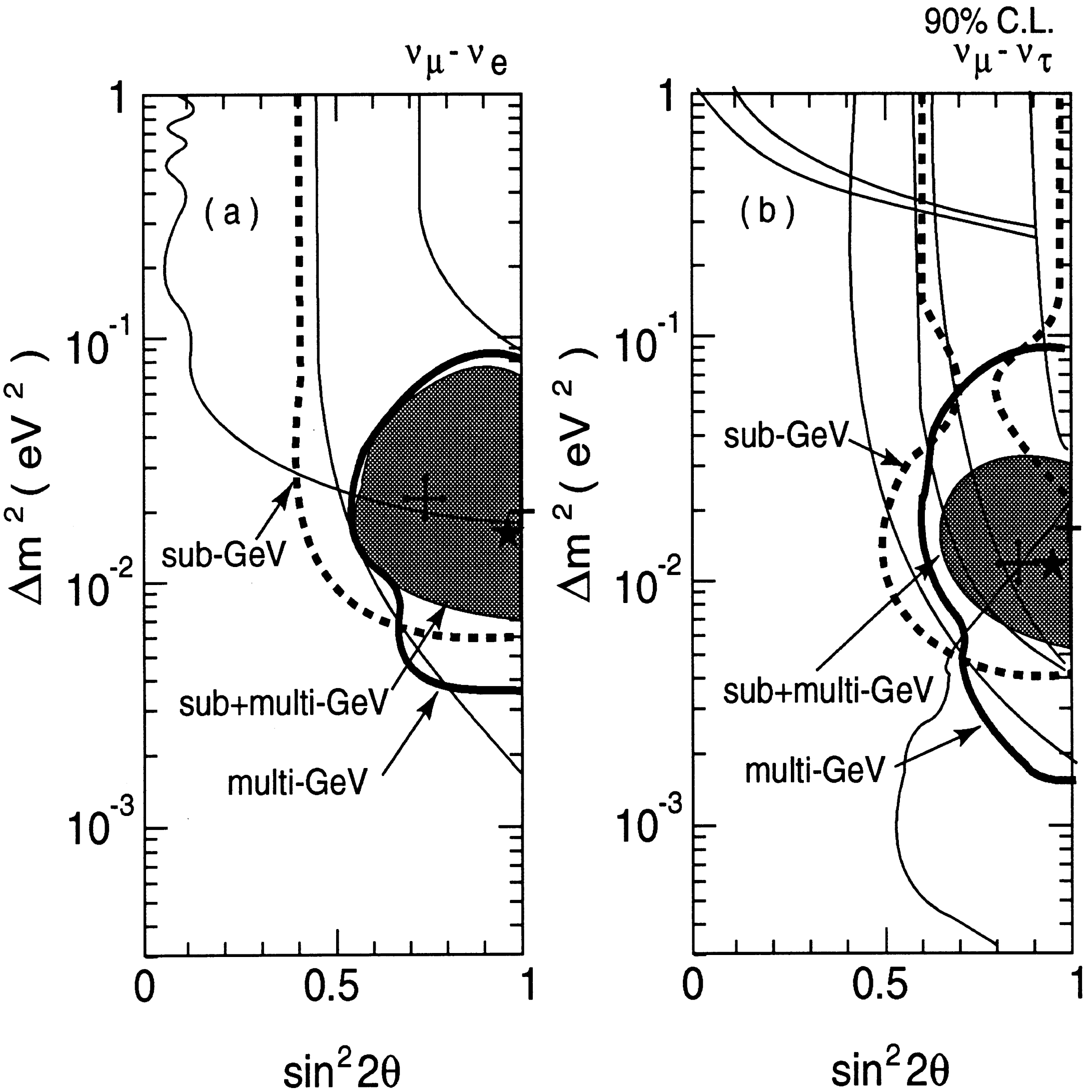


Figure 3. From KAM Collab., Phy. Lett. B335, 237 (1994)

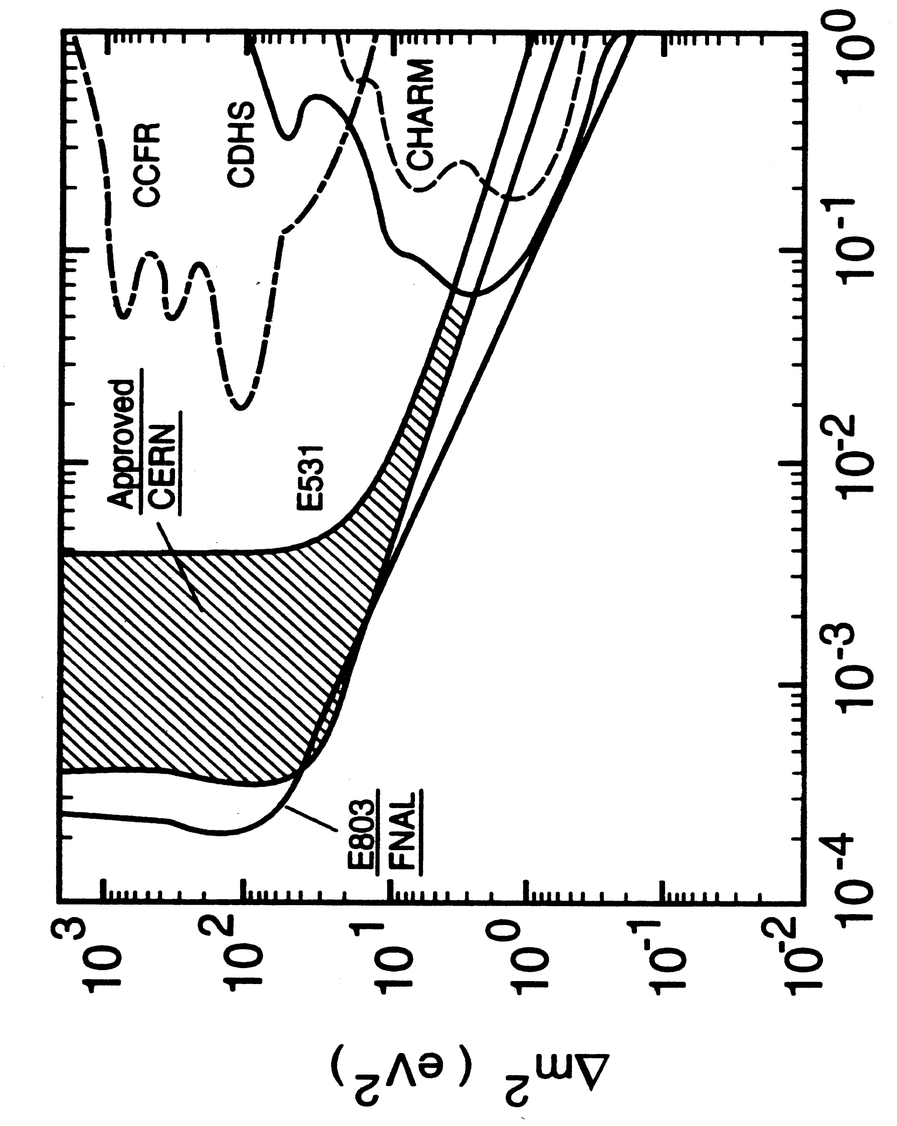

CCFR
CDHS
CHARM
E531
Approved
CERN
E803
FNAL
Δm^2 (eV^2)
$\sin^2 2\theta_{\mu\tau}$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0

Figure 4