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LETTER OF INTENT FOR AN EXPERIMENT TO IMPROVE LIMITS FOR $\nu_\mu \leftrightarrow \nu_\tau$ NEUTRINO OSCILLATIONS

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RATIONALE

H. Harari [1] and other theorists have presented the striking hypothesis that the tau neutrino, if massive, is the only known particle which could provide sufficient mass to close the universe. He and others employ a see-saw mechanism which in the simplest version relates masses of the leptons to quark masses in the same generation as follows:

$$M_{\nu_e} : M_{\nu_\mu} : M_{\nu_\tau} = \frac{m_u^2}{M} : \frac{m_c^2}{M} : \frac{m_t^2}{M} \tag{1}$$

where m_q are the respective up, charm and top quark masses and M is a very massive decoupled neutrino. Thus, the ν_μ could be 6×10^4 times heavier than ν_e, and in turn the ν_τ could be 6×10^3 times heavier than ν_μ, for a 100 GeV top mass. If the top quark mass is 100 GeV, a tau-neutrino mass in the range 10-60 eV, sufficient to close the universe, could be generated and still maintain $\nu_e \leftrightarrow \nu_\mu$ oscillations in the 10^{-4} to 10^{-7} eV^2 range required by the MSW [2], [3] solution to the solar neutrino problem. The see-saw mechanism has been employed in many more complicated scenarios, most of which also indicate that the tau neutrino would be by far the most massive of the known neutrinos.

By assuming that lepton mixing angles are comparable to K-M matrix quark mixing angles, Harari infers that $\sin^2(2\alpha)$ must be larger than 4×10^{-4}, though as pointed out by Marciano [4] if Harari's ansatz is taken too literally, $\sin^2(2\alpha)$ should be approximately 10^{-2} and mixing already should have been found.

The present world limits for oscillation are given in Figure 1. These limits are determined by Fermilab experiment E531 [5] and the CERN CDHSW experiment [6]. Oscillations with a coupling greater than 0.5×10^{-2} have been ruled out for δM^2 greater than 20 eV^2. We discuss here the preliminary design of an experiment that could access 20 times smaller couplings in the mixing parameter and 5 times smaller δM^2, as shown in Figure 7.

Because this new experiment would have excellent muon identification and topological identification of charm, it also appears possible to make a definitive measurement both of the "slow rescaling" of charm production and of the strange sea, which contribute large systematic errors to the determination of $\sin^2(\theta_W)$ as derived from deep-inelastic neutrino scattering measurements. $\text{Sin}^2(\theta_W)$ is closely related to the ratio of neutral to charged current interactions. Extraction of $\sin^2(\theta_W)$ is performed using a parton model which assumes that all quarks are produced at full strength, which is not true for heavy charm quarks. The slow onset of charm production has been parameterized in terms of the charm quark mass, with ensuing errors of ± 0.4 GeV/c^2. Observing approximately 600 D^o mesons near threshhold in neutrino interactions could improve systematic errors on this mass by a factor of four, and provides a test of the validity of the slow scaling correction. Assuming its validity, an overall improvement of 1.5 to 2 could be made in the total world-wide error of $\sin^2(\theta_W)$ as derived from deep inelastic neutrino scattering [7].

Measuring the background from charm production in neutrino and anti-neutrino interactions also would yield a sensitive determination of the strange sea as a byproduct. This possibility currently is under investigation.

EXPERIMENTAL DESIGN

We have made a preliminary design of an experiment which could increase the sensitivity for detecting oscillations by a factor of 20 over that of E531. This increase is due to four factors:

- Obtaining 60 times more interactions by increasing emulsion target mass and using a rapid-cycling high-intensity low-energy neutrino beam.
- Minimizing background by increasing muon detection efficiency and scanning only for single-prong tau decays.
- Minimizing the number of events to be scanned by rejecting all events containing muons.

- Minimizing emulsion analysis time by incorporating the automatic scanning and measuring techniques developed for Fermilab Experiment E653.

The new experiment consists of a hybrid emulsion-electronic spectrometer as described in Figures 2a, 2b, 2c, and the Appendix. Multiple layers of emulsion are incorporated to enhance rate; scintillating fiber planes and straw tube drift chambers are used to provide tracking between layers of emulsion. A magnetic field of approximately one Tesla is provided to obtain the sign and P_T of tau-lepton single-prong decays and to aid in vertex reconstruction. The magnet shown is the existing 15 foot bubble-chamber magnet, which is about to be placed on surplus. Scintillating fiber planes placed immediately downstream of the emulsion layers provide excellent two-track separation, while straws furnish 100μ spatial resolution for momentum determination and extrapolation into the emulsion. Momenta for tracks below 6 GeV/c could be measured to better than 15% using chambers between adjacent planes of emulsion, and this range could be increased to 29 GeV/c if the track penetrates through an additional emulsion plane into the adjacent set of chambers. The momentum range could be doubled for a select subset of tracks by incorporating higher precision measurements made in emulsion.

The emulsion and tracking systems reside within a "cave" of electromagnetic and hadron calorimeters. Tau candidates occurring in events with an electron or muon coming from the interaction vertex cannot constitute evidence for a tau charged-current interaction and must be rejected. Electrons would be identified by observing a charged track which showers in the electromagnetic calorimeters, and muons by observation of scintillator pulse heights along candidate paths in the highly segmented hadron calorimeters.

Under study is the possibility that candidates for tau neutrino charged-current interactions populating kinematical regions which are unphysical for producing the heavy tau lepton can be eliminated by cutting on the measured values for the conventional neutrino variables x and y. These variables for such tau candidate events can be derived by coupling direct measurements of charged hadron momenta (from tracking) and neutral hadron momenta (from calorimetry) with a precision emulsion measurement of the initial tau candidate direction. Studies of charm scaling or the strange sea also would require measurement of x and y for ordinary muonic charged-current neutrino and anti-neutrino interactions in which a charm particle is produced.

A typical tau neutrino emulsion interaction is shown schematically in Figure 3. The primary vertex is located by scanning back along emulsion tracks which match those found by the electronic spectrometer, as was done in E531. Once an event has been located in the emulsion, the slopes of charged emulsion tracks coming from the primary can be measured using the automatic technique developed at Nagoya University and presently adopted by several other institutions in Japan.

Because of the relatively large mass of the tau, it is produced at rather small laboratory angles: 98% of real taus will be at angles of less than 15 degrees. A "follow-down" procedure searching for "kinks" will be performed on all primary emulsion tracks whose angles are less than 15 degrees, and whose slopes do not match those of any electronic detector track. A 2.5 millimeter follow-down suffices, since the typical decay length is $\gamma c\tau$, where $c\tau$ is 90 microns and γ's are of order 5. Only "muon-less" kinks with a P_T greater than 0.1 GeV/c would be recorded by emulsion scanners; taus decay 69% of the time into muonless single-prong "kinks" while most of the background is multiprong. The ability to present electronic track and P_T information on-line to emulsion scanners was developed during E-653, a previous hybrid emulsion experiment.

NEUTRINO BEAM AND ESTIMATED YIELDS

Neutrino beam

The layout of the proposed neutrino beam line is shown in Figure 4; much of the civil construction already exists. Note that the 400 meter decay pipe is followed by 120 meters of iron, sufficient to completely range out 150 GeV muons. A small experimental hall with perhaps 500 square meters of floor space is shown downstream of the steel. A high-intensity neutrino beam design relying on a double-horn focussing system has been developed by L. Stutte [8]. The spectrum of neutrino interactions for the proposed 150 GeV beam is given in Figure 5a; it peaks around 9 GeV. The number of charged-current interactions per 10^{13} protons and a 1 meter $\times$ 1 meter neutrino target made from 180 liters of emulsion is 0.054 (corresponding to a total yield of 0.072 interactions). An offline cut on visible energy corresponding to 11 to 60 Gev in beam energy will retain 57% of these interactions while enriching the potential tau sample.

Yield of events

The calculated ratio of ν_τ to ν_μ total charged-current cross-sections is shown in Figure 5b. Both muon and tau channels include the quasi-elastic channels $\nu + n \rightarrow \mu, \tau + p$ and $\nu + p \rightarrow \mu, \tau + \Delta^{++}$ which are significant at the low-energy end of the spectrum. The cross-section ratio averaged over the accepted range of beam energy is 0.50, compared with 0.53 for the higher-energy beam used in E531. While the ν_τ to ν_μ cross-section ratio is smaller in the Fermilab 150 GeV beam than for the 400 GeV wide-band beam at CERN, the effect of this reduction on interaction rates is compensated by the associated machine cycle-time decrease from 14 seconds to 4 seconds. Yields based on 2.6 x 10^6 pulses at 2 x 10^{13} protons per pulse and 180 liters of emulsion are itemized and compared in Table I with the summed 350 GeV and 400 Gev running of E531. The 150 GeV numbers are consistent with an 8 month run averaging 85 hours per week of useful beam.

TABLE I
COMPARISON OF E-531 AND PROPOSED 150 GEV RUNNING

ITEM	E531	150 GeV
# PULSES	1 X10^6	2.6 X 10^6
PROTONS/PULSE	1.3 X 10^{13}	2.0 X 10^{13}
AMT. EMULSION	23 liters	180 liters
FIDUCIAL VOL.	80%	90%
INT. (NC + CC)†	3,386	185,000
INT. WITH TAGGED μ^-	1,870	132,000
INT. WITH PRIMARY τ's	0	?

† The neutrino interaction yields of Table I include corrections for requiring that the neutrino energy lie between 11.5 and 60 GeV (57%), fiducial volume acceptance (90%), and event triggering and finding efficiency (95%).

BACKGROUNDS

Candidates for charged current interactions of tau neutrinos consist of events with no primary muon or electron which have a high P_T negative kink track with a production angle less than 15 degrees. Possible sources of background consist of tau neutrinos coming from the primary proton beam dump, ordinary interacting tracks which scatter without leaving evidence for nuclear breakup in the emulsion, charged hyperon and kaon decays, and a variety of cases containing single prong decays of charm particles.

The cave geometry of the calorimeters creates high efficiencies for detecting muons and electrons from the primary vertex over a wide range of angles and energies. Muon efficiency is presented as a function of neutrino energy in Figure 5c for μ^- from all charged-current neutrino events (solid curve) and for μ^+ from antineutrino-produced anticharm (dashed curve). The high μ^- efficiency is important in reducing the number of events to be scanned in the emulsion; it is achieved by identifying muons with momenta greater than 1.0 GeV/c and angles less than 45 degrees. The μ^+ efficiency is essential for reducing the background of kinks from anticharm decays found in the emulsion, and requires muon identification at momenta down to 0.8 GeV/c and out to 60 degrees for a small number of events.

Note that a small percentage of pions will penetrate the range material without interacting and will be identified as muons. This results in a slight lowering of the detection efficiency for real tau decays, but has little impact on the experiment. Misidentifying a small percentage of pions as muons is acceptable if all real muons are rejected.

Neutrons emanating from neutrino interactions in the shield wall, calorimeters, magnet coils and other massive targets also constitute a potential source of background which (though negligible for E531) is under consideration for the more sensitive experiment herein discussed. This study is still in process and results will be included in an updated letter of intent provided for the Aspen PAC meeting this summer.

Tau neutrinos from the proton dump

A simple calculation, while not overly precise, indicates that the number of interactions due to real tau neutrinos coming from the proton beam dump is not a serious source of background, due in part to the low energy of the beam. The ratio of ν_τ to ν_μ production is given by:

$$\begin{aligned}(\nu_\tau/\nu_\mu) &= (C/\pi)(D_s/C)(D_s \to \tau/\pi \to \mu)(\nu_\tau accept./\nu_\mu accept.) \qquad (2)\\ &= (<10^{-4})(0.1)(0.02/0.17)(<0.1) \quad < \quad \text{few} \times 10^{-7}\end{aligned}$$

where the first term on the right-hand side is the per-event ratio of charm with $x_F \geq 0.3$ to the high-momentum pion yield at 150 GeV, and the second is the fraction of D_s to all charm. The numerator of the third term assumes that 2% of D_s particles decay into $(\tau + \nu_\tau)$, while the denominator includes the fact that in the allowed drift space approximately 17% of pions decay. The last term indicates that ν_μ are produced in a more forward direction than ν_τ, hence have a larger acceptance.

Other non-charm backgrounds

Non-charm backgrounds in the emulsion target can come from secondary interactions and decays of strange particles. The probability that a track would suffer a secondary single-prong "kink" interaction with no dark tracks from nuclear breakup and occurring within 2.5 millimeters of production is approximately 1 x 10^{-4}. Since perhaps 2 tracks per interaction have sufficient energy, only 36% of tracks are negative, 0.02 have a $P_T > 0.2$ GeV/c and only a third of all events have no evidence for a muon from the primary interaction, this background is reduced below 10^{-6} per event [9]. Note that precise emulsion information about the kink angle can be coupled by computer to momentum determinations of electronic spectrometer tracks, providing a determination of the kink P_T "on-line" to emulsion scanners.

In the absence of P_T cuts, strange decay backgrounds from Σ^-, Ξ^- and K^- are 1.5 x 10^{-5}, less than 1.5 x 10^{-5} and 5 x 10^{-6}, respectively. The P_T distributions for these particles as well as for tau leptons are given in Figure 6. A P_T cut of 0.2 GeV/c would eliminate all hyperon decays and most of the kaon decays while leaving 85% of the taus. Currently, it is our belief that we would employ the same 0.125 GeV/c P_T cut used in E-531 analysis, but it is comforting to know that a slightly larger cut could reduce all non-charm background below the 10^{-6} level.

Backgrounds from charm production

There are three types of charm background events: single and associated charm coming from neutrino interactions and anti-charm coming from interactions of anti-neutrinos. The first two sources are negligible. Single charged charm generated by neutrinos is positive, whereas a tau lepton coming from a charged-current interaction would be negative. In a low-energy neutrino beam, the per-event charm yield is approximately 3.5%, the primary muon will be found in 95% of interactions and any single charged charm produced will have the wrong sign. At these low neutrino energies, associated production of charm is extremely small. However, all events containing tau candidates would be scanned for a second vertex with an efficiency experimentally determined to be in excess of 80%. We estimate that the combined background from these first two sources would be less than 10^{-6}.

The dominant contribution to background therefore comes from anti-neutrino interactions in which a negative charm single-prong decay occurs and the primary charged-current muon or electron is missed. It is assumed that the ratio of $\overline{\nu}_\mu$ to ν_μ interactions is 4%, as in E531. The muon antineutrino charged-current background may then be calculated as follows:

$$BG = \left(\frac{\overline{\nu}}{\nu+\overline{\nu}}\right)\left(\frac{C^-}{C^- + C^o}\right)(BR \to 1P, no\ \mu)(Eff)\cdot\left(\frac{\overline{\nu}\to C}{\overline{\nu}\to all}\right)(Miss\ \mu) \quad (3)$$

$$= (0.04)(0.4)(0.45)(0.7)\cdot(0.00159)$$

$$= 0.80 \text{ x } 10^{-5}$$

where the terms on the right are, respectively, the ratio of anti-neutrino to total interactions, the fraction of anticharm which is charged, the muonless "kink" branching ratio, the kink-finding efficiency, and the product of the fraction of anti-neutrino interactions producing charm and the probability of missing the muon, averaged over the beam spectrum. Note that there is negligible anti-Λ_c production in a low-energy antineutrino beam. If we assume that the relative yield of $\overline{\nu}_e$ is the same as the measured value of 1.5% for ν_e interactions in E531, and add this to (3), the overall antineutrino background increases to 1.10×10^{-5}.

The summed background from all sources is estimated to be 1.2×10^{-5}. Note that all sources of background are inherently measurable. For example, one could scan a subset of non-muon tracks for several centimeters in emulsion. The number of kink interactions and strange decays per unit length would be roughly uniform over this distance, whereas all real τ decays would occur in the first few millimeters of path. Muon inefficiencies could be estimated reliably by comparing results in this experiment with charged-current distributions measured by others. The crucial number of anti-charm particles produced in $\overline{\nu}$ interactions could be determined by searching for their decays in events with a primary μ^+. It is imperative that background levels be demonstrated through measurement, as a positive oscillation signal would consist solely of an excess of short-decay-length kinks with large P_T's.

Number of events to be scanned

Emulsion scanning would be performed for all neutral-current events, plus the 5% of charged-current events without identified muons. This is 53×10^3 events, or approximately 28% of all interactions. As discussed previously, scanning would consist first of primary vertex location by scanning upstream through the emulsion along one of the higher-momentum tracks from an interaction, then kink-searching by following 2.5 mm downstream along all charged tracks from the primary interaction with angles less than 15 degrees. Developing 180 liters of emulsion would take approximately 6 months, while scanning the required number of interactions would take two years. After perhaps 10% of the emulsion is developed, such operations in principle could proceed concurrently.

CORRECTIONS TO THE RAW DATA

The raw ratio of (found ν_τ / found charged-current interactions) is subject to a sizable correction before one can infer the actual fractional ν_τ interaction rate.

$$R = R_{raw} \times (CORRECTION) \tag{4}$$

$$CORRECTION = \left(\int K(E_\nu)N(E_\nu)dE_\nu\right)^{-1} \tag{5}$$

where $N(E_\nu)$ is the neutrino energy spectrum and

$$K(E_\nu) = \int \left(\frac{\sigma_\tau}{\sigma_\mu}\right)\left(\frac{\varepsilon_\tau}{\varepsilon_\mu}\right)\left(\frac{A_\tau}{A_\mu}\right)(\Sigma\, B_i S_i)dx\, dy\, dP_T \tag{6}$$

The σ term is the ratio of ν_τ to ν_μ neutrino cross-sections, the ε term is the ratio of triggering efficiencies, the A term is the ratio of τ to μ acceptances and the final term is a sum over the product of τ decay-mode branching ratios and the emulsion finding efficiencies for that mode. Since most of the factors are slowly varying, they can be removed from the integral without introducing significant error. The product of average ratios for triggering efficiency, acceptances, the kink detection efficiency and the "muon-less" kink branching ratio is $(1.0)(1.0)(0.7)(0.68) = 0.48$. After these factors are brought outside the integral, the correction reduces to an integral over the σ_τ/σ_μ ratio which is displayed as a function of neutrino energy in Figure 5b [10]. The value of this integral for the proposed 150 GeV beam is 0.502 resulting in an overall correction value of 4.15.

ESTIMATED OSCILLATION LIMITS

If zero ν_τ interactions are seen over a background of 139,000 $\times$ $(1.2 \times 10^{-5}) =$ 1.67, the 90% C.L. on the signal (observed events = expected background) is 3.7 events over a denominator of 122,000 found charged-current interactions:

$$R = \left(\frac{3.7}{122,000}\right) \times (4.15) = 1.25 \times 10^{-4} \tag{7}$$

R may be interpreted in terms of a two-parameter representation of neutrino oscillations between two neutrino species:

$$R = \sin^2(2\alpha) \int \rho(\frac{L}{E}) \sin^2(1.27\delta M^2 \frac{L}{E}) d\frac{L}{E} \tag{8}$$

where ρ gives the flux of neutrinos in terms of the variable (L/E), L is the neutrino flight path in meters, E the neutrino energy in MeV and δM^2 is the difference of the squared neutrino masses in (eV)^2. For large δM^2 the oscillation length is small compared to the variation in neutrino flight length, and the (L/E) integral has an approximate value of 0.5. Thus, the sensitivity in $\sin^2(2\alpha)$ is 2.5 x 10^{-4} at the 90% CL. The usual plot of $\sin^2(2\alpha)$ sensitivity versus δM^2 is given in Figure 7. If the actual experiment were to have statistics decreased over those proposed in this discussion, the $\sin^2(2\alpha)$ limit would increase inversely as the statistics while the δM^2 limit would increase inversely as the square root of the statistics.

TIME SCHEDULE

This document contains the basic ideas for the oscillation experiment, but plans are evolving rapidly. A significantly improved letter will be available in time for the Aspen meeting this summer, and a full proposal will be submitted to the October, 1989 meeting of the PAC. Time constraints are set by the CERN CHARM group, which expects to perform an oscillation experiment in their existing neutrino beam by the end of 1993.

PRELIMINARY COST ESTIMATES

Precise cost estimates clearly are beyond the scope of a letter of intent. Further, costs involved in construction of the beam and experimental hall, as well as in moving the 15 foot bubble chamber magnet, can best be made by Fermilab and have not been included. However, it is important to make preliminary estimates which indicate that costs for constructing and operating the proposed detection apparatus would be comparable to that for typical fixed target experiments.

1. The cost for purchasing 200 liters of Fuji emulsion plus constructing and developing modules is approximately 210 million yen, or $1.6 million, exclusive of labor. Funds would have to be made available from several sources in Japan as well as from the Japan-U.S. agreement for high energy physics.

2. The estimated cost for constructing 12,000 channels of straw-tube tracking @$50/channel (including both hardware and electronics) is $600K.

3. Construction of scintillating fibers (as discussed in the appendix) is currently the focus of research, development and design. Hence, the cost estimate of $600K for a full system can be trusted only to perhaps $\pm$ 30%.

4. A Fermilab gas-mixing system, together with an associated gas shed and alarm system, would be required; those provided for E653 would be adequate and would cost approximately $90 K.

5. 10 tons of stiffened lead @$2K per ton, total $40 K.

6. 300 tons of nonmagnetic calorimeter metal @ $1000 per ton, total $300K.

7. Approximately 6,000 scintillator strips equipped with wave-shifter light guides which couple them to 2000 photomultiplier tubes must be purchased. Ohio State University is performing a similar task for 40,000 scintillator strips balanced to 1% as part of the United States contribution to the ZEUS calorimeter. Based on this experience, it is estimated that the SCSN-38 scintillators together with light guides would cost $350K exclusive of installation costs, while the 2000 Hamamatsu 580 photomultiplier tubes with bases, cables and power supplies would cost $500K. The total would be $850K.

8. The mechanical structure supporting all apparatus must be precisely aligned and yet must allow rapid partial disassembly to access tracking and emulsion apparatus during operation. Further, it must be strong enough not to be shaken apart during a possible magnet quench. Its cost is difficult to estimate, but cannot be less than $100K, and would require several months of mechanical engineering support from Fermilab during design and construction.

9. The experiment has a low rate of data collection and requires a minimal data acquisition system and on-line computer. It is estimated that the entire PREP plus "home-built" costs would be less than $400K.

10. Off-line computing needs also would be minimal, and could be handled at the associated universities.

11. Operating costs @ $15K per operating month for 1 year would total $180K, and could be spread among experimental collaborators.

The total estimated cost, exclusive of the beam line and experimental hall, is \$4.8 million. Increasing this number by 15% to cover estimated indirect costs on non-equipment items and adding an additional 25% for contingency gives a final number of \$6.9 million, with a funding profile which could span 3 to 4 fiscal years.

REQUESTED ACTION BY PAC

Discussions by the PAC of the quality of the physics versus estimated cost, as well as criticism of the experimental methodology, would be most helpful in constructing a final proposal.

References

[1] H. Harari, Phys. Lett. B216, 413 (1989).

[2] L. Wolfenstein, Phys. Rev. D17, 2369 (1978).

[3] S. P. Mikheyev and A. Yu. Smirnov, Sov. J. Nucl. Phys. 42, 913 (1985).

[4] W. Marciano, rapporteur's talk at Conference on New Directions in Neutrino Physics, Fermilab, (1988).

[5] N. Ushida, *et al.*, Phys. Rev. Lett. **57**, 2897 (1986).

[6] F. Dydak, *et al.*, Phys. Lett. **134B**, 281 (1984).

[7] The above statements are based on calculations by R. Brock.

[8] Future Options for Fermilab Fixed Target Beams, p. 65.

[9] The estimate of secondary interaction kink background was derived from old emulsion papers which exhibit some disagreement, and the P_T cut may not be quite as effective as claimed. Nagoya University collaborators therefore plan to make a re-measurement this summer in an exposure to a pion beam at KEK.

[10] A. Gauthier, Ph.D. thesis, The Ohio State University, 84 (1987). Results were corrected slightly to include better estimates of the contribution from quasi-elastic scattering.

APPENDIX

BRIEF DISCUSSION OF EMULSION AND SCINTILLATING FIBER DESIGN

Emulsion

The emulsion will be grouped into 6 modules, as shown in figures 2a and 2b. Each 1 meter × 1 meter × 3 cm module will be composed of twenty five 1 meter × 1 meter × 1.2 millimeter emulsion sheets mounted perpendicularly to the beam, as shown in figure 2c. Individual sheets will be comprised of 560 micron thick layers of emulsion attached on either side of an 80 micron plastic sheet.

After exposure, each sheet will be cut into 5 cm × 5 cm squares, and squares with the same beam-view location from succeeding sheets will be mounted on a 25 cm × 25 cm plastic plate prior to developing. This geometry makes it possible to follow downstream along tracks from an interaction without changing viewing plates. The large size of the squares should keep edge loss effects below 5%. The cost of emulsion is 10^6 yen per liter (the current rate of exchange is 130 yen per dollar). An extra 20% must be added to take into account both the cost of developing and an estimated 10% emulsion loss during module construction. The cost of refurbishing existing pouring and developing laboratories is not included.

The above design is an extension of the design used in Fermilab experiment E653. The similarity makes it possible to estimate the time (typically 10 minutes) for finding a production vertex in the emulsion, and the time (typically 3 minutes/track) for kink searching along those emulsion tracks at the production vertex which cannot be matched to any track in the electronic spectrometer. Typically 4 interactions per hour can be measured on each of ten existing automatic scanning stations. Assuming a usage of 25 hours per week per station leads to 50,000 interactions scanned per year, a rate 3 times higher than for the complicated hadronic production events of E653. To be conservative, it is assumed that scanning for the experiment would take 2 years.

Scintillating Fibers

X and Y-view scintillating fiber layers will be placed immediately downstream of each emulsion module in order to resolve closely-spaced tracks. Fiber bundles with dimensions 1 mm × 2 cm × 2 meters have been built by Kyowa Gas Company of Japan at an approximate cost of 80 yen per centimeter of length. These fiber bundles are composed of arrays 5 fibers deep by 100 fibers wide. Each fiber has a square cross-section of 200 micron × 200 micron, has a 1 meter attenuation length, and yields 2 photo-electrons per millimeter of path for traversing minimum-ionizing charged tracks. A 20 fiber-layer sheet 4 millimeters in thickness would give (after attenuation) roughly 4 hits per passing track. Each layer would have 10^5 fibers, and 12 layers sum to 1.2×10^6 channels.

Ten centimeter diameter image intensifier tubes are under development by Hamamatsu Corporation. Each will have optical fiber windows with 200 micron $\times$ 200 micron resolution at the window and a typical quantum efficiency of 10% at 450 nanometers. Image demagnification will be 1/4, which is matched to the 50 micron resolution of the first microchannel plate. Each microchannel plate has a total of 8×10^5 channels. The estimated cost per tube is approximately 3×10^6 yen. The present readout CCD costs 3×10^5 yen, and has 493×768 pixels, for a total of 3.8×10^5 cells.

Extensive R & D must be performed to increase both attenuation length and the number of photo-electrons. Mounting, magnetic shielding and readout electronics must be designed. Present cost estimates for the fiber system must be considered approximate.

FIGURE CAPTIONS

FIGURE 1: δM^2 vs $\sin^2(2\alpha)$ plane showing the limits for $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillation; the regions to the right of the curves are excluded at the 90% confidence level.

FIGURE 2: a) Plan view of experiment; b) Elevation view of layout of experiment; c) Detail of emulsion and scintillating fibers which indicates how tower geometry will be created in order to speed scanning.

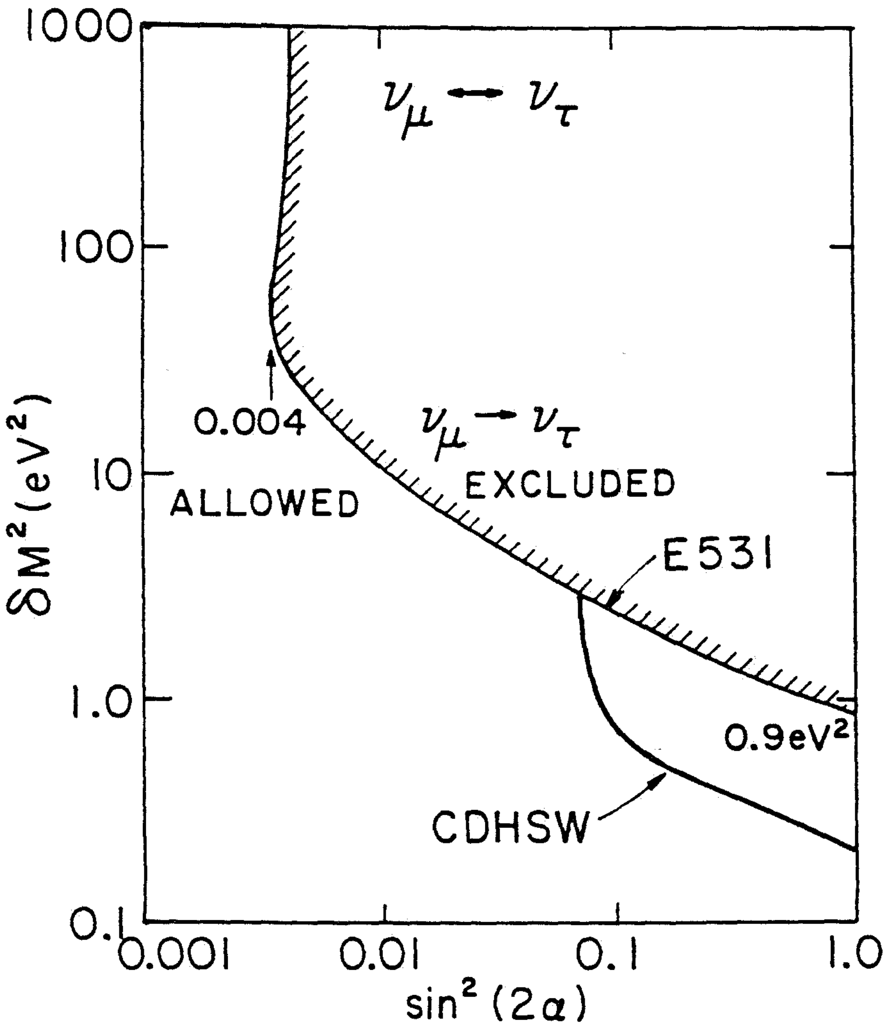
FIGURE 3: Schematic picture of a ν_τ interaction. Note the heavily-ionizing tracks from nuclear breakup, the absence of an identified muon from the interaction vertex and a short decay-length "kink" with a large P_T.

FIGURE 4: Layout of proposed neutrino beam line showing the location of the proposed oscillation experiment.

FIGURE 5: a) Charged-current event rate for the 150 GeV high-flux neutrino beam. The calculation assumes a 400 meter decay pipe, 120 meter shield and a double-horn focussing system.
b) The ratio of ν_τ/ν_μ cross-sections displayed as a function of incident neutrino energy. These curves have been corrected for the contributions of quasi-elastic and Δ^{++} production processes.
c) Average muon detection efficiency as a function of neutrino energy for μ^- from all charged current events (solid), and for μ^+ from anticharm production by antineutrinos (dashed); note the suppressed zero.

FIGURE 6: P_T distributions for (a) hyperon, (b) charged kaon and (c) τ lepton decays. Note that all hyperon and most of the kaon decays could be eliminated with a P_T cut of 0.2 GeV/c, whereas 85% of τ decays would survive.

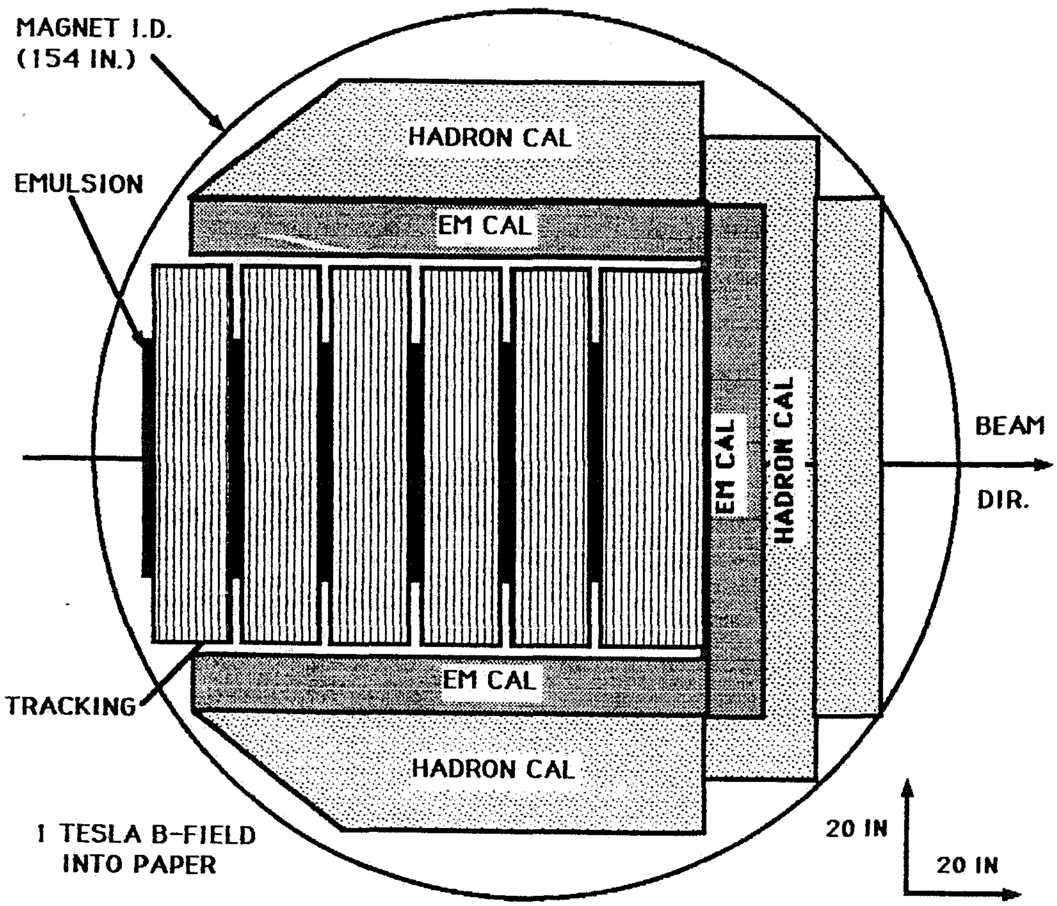
FIGURE 7: δM^2 versus $\sin^2(2\alpha)$ plane showing the previous limits for $\nu_\mu \rightarrow \nu_\tau$ oscillation superposed on improved limits which could be obtained from the new experiment.



$$R(\nu_\mu \leftrightarrow \nu_\tau) = \sin^2(2\alpha) \underbrace{\int \rho(\eta) \sin^2(1.27\,\delta M^2 \eta)\, d\eta}_{\approx \frac{1}{2} \text{ FOR LARGE } \delta M^2}$$

$$\eta = L/E$$

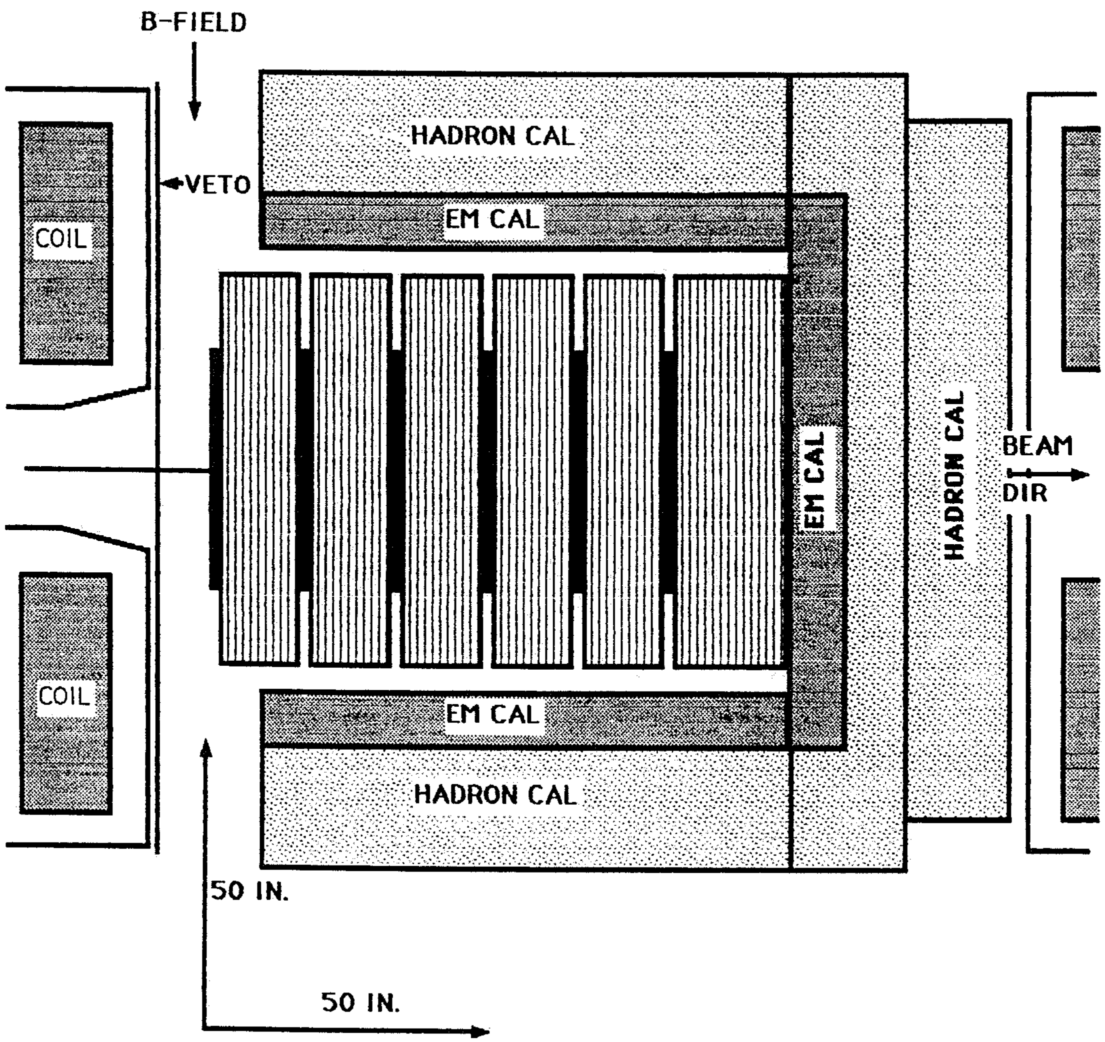
FIGURE 1: δM^2 vs $\sin^2(2\alpha)$ plane showing the limits for $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillation; the regions to the right of the curves are excluded at the 90% confidence level.



SCINTILLATOR COUNTERS DOWNSTREAM OF ALL EMULSION MODULES AND IN ALL CALORIMETERS NOT SHOWN. MOST MUONS IDENTIFIED BY RANGE AND P.H. IN THE CALORIMETERS. RANGE WALL DOWNSTREAM OF COILS FOR CENTRAL HIGH-ENERGY MUONS NOT SHOWN.

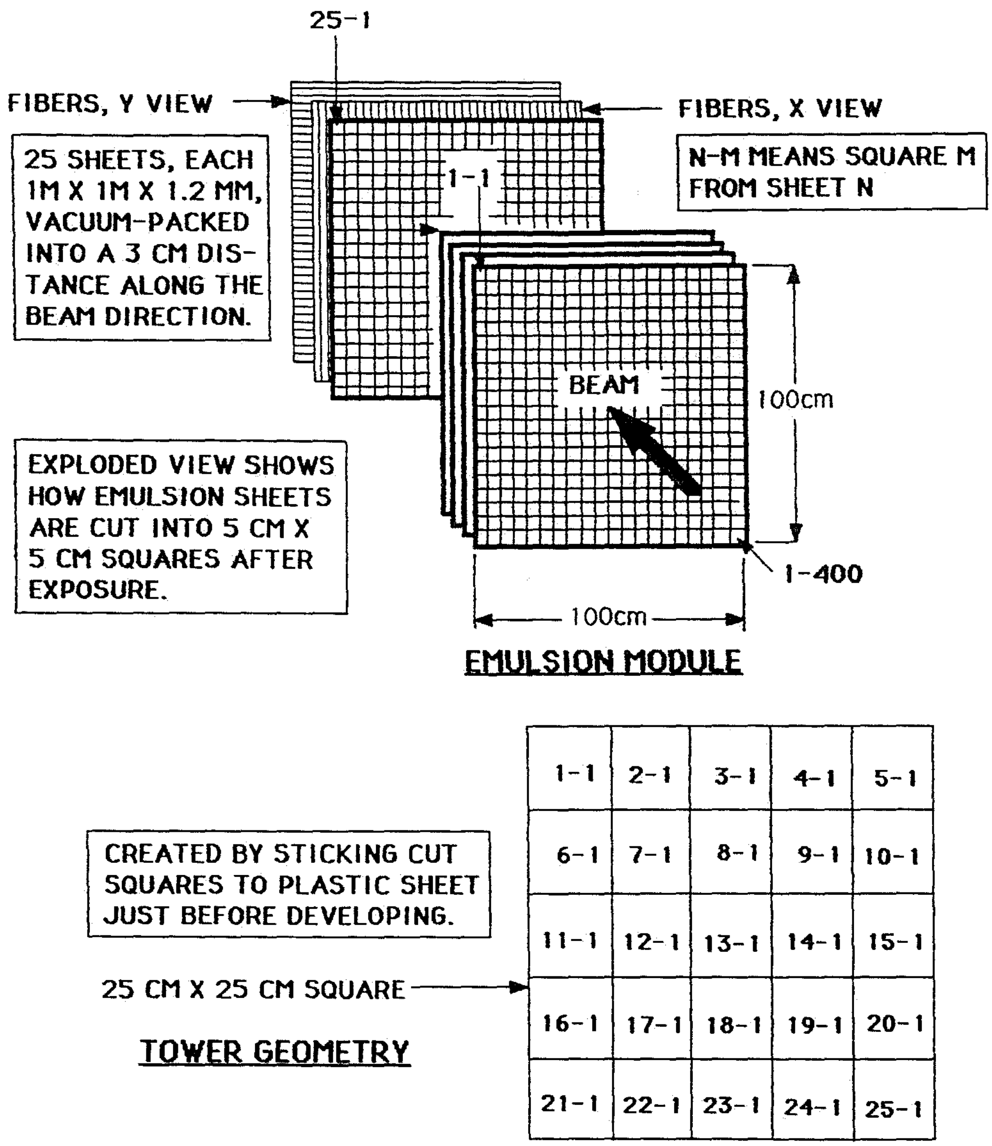
NEUTRINO OSCILLATION EXPERIMENT
PLAN VIEW

FIGURE 2a



NEUTRINO OSCILLATION EXPERIMENT
ELEVATION VIEW

FIGURE 2b



EMULSION PLUS SCINT. FIBER MODULE

FIGURE 2c

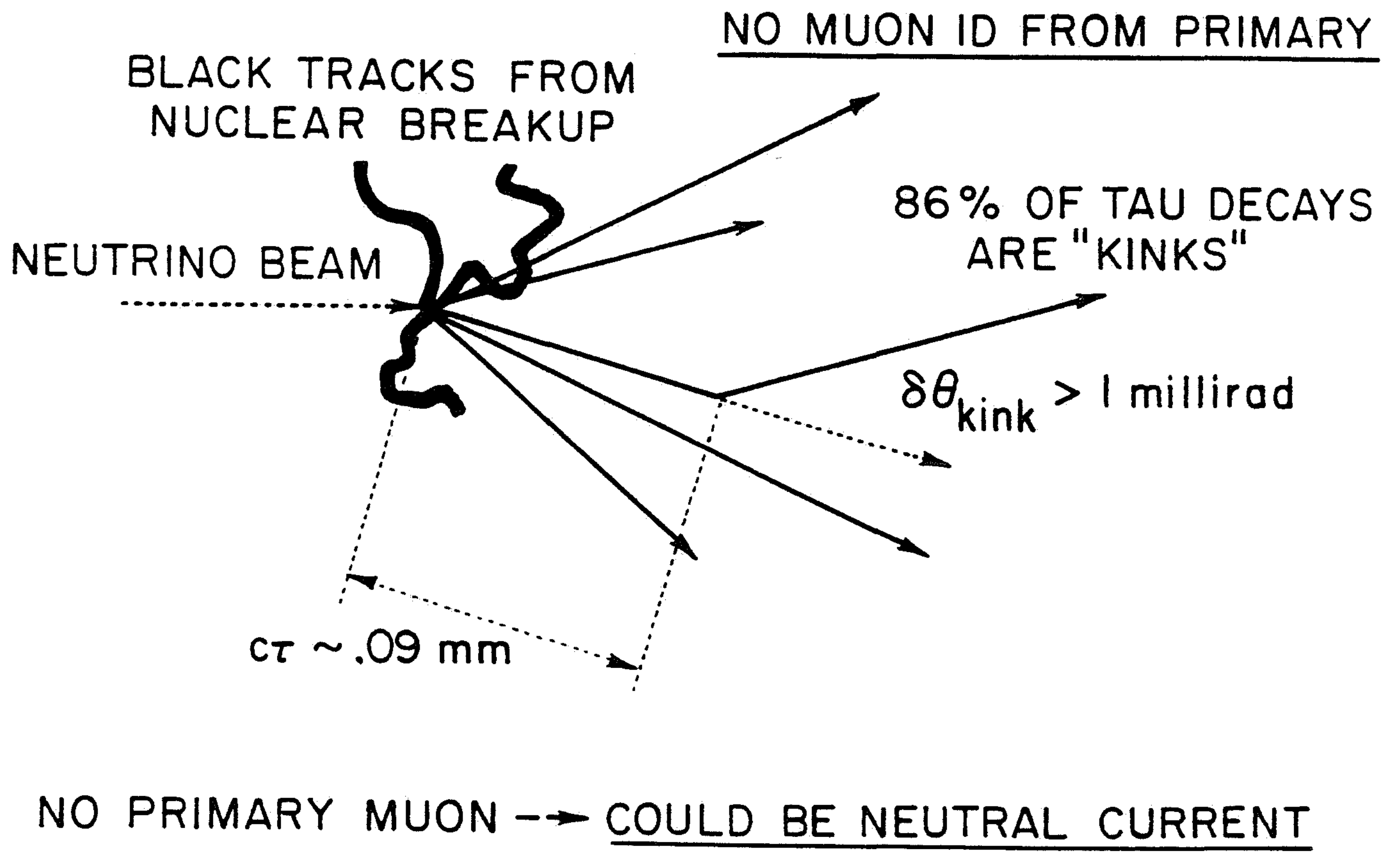


FIGURE 3: Schematic picture of a ν_τ interaction. Note the heavily-ionizing tracks from nuclear breakup, the absence of an identified muon from the interaction vertex and a short decay-length "kink" with a large P_T.

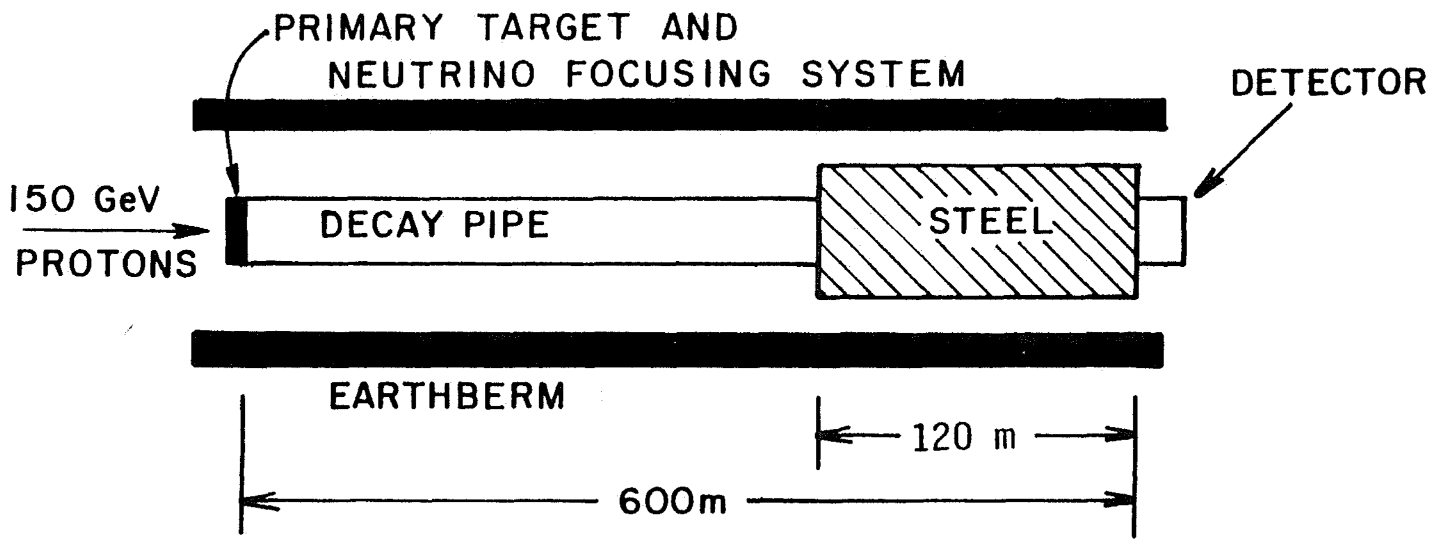


FIGURE 4: Layout of proposed neutrino beam line showing the location of the proposed oscillation experiment.

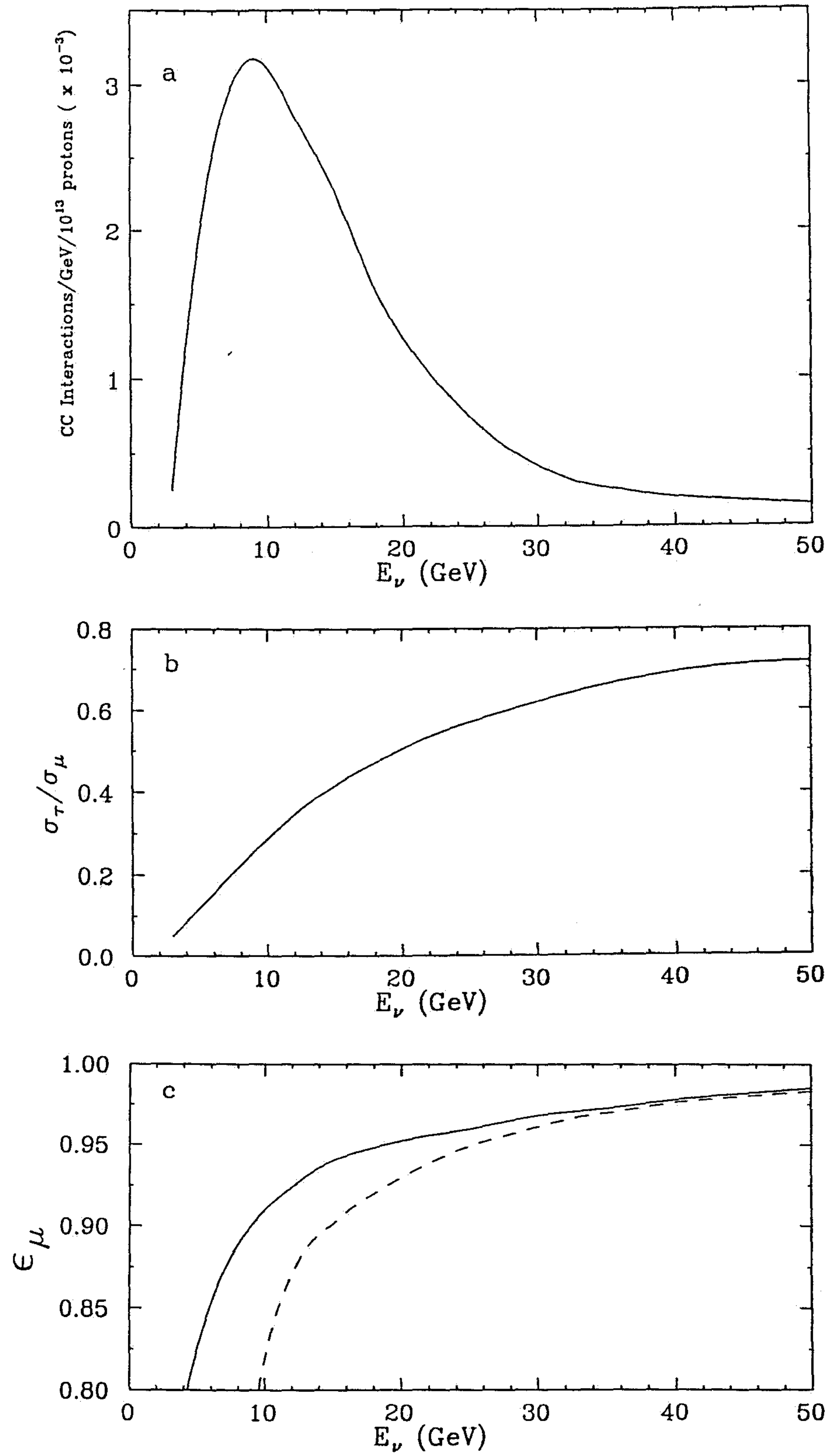


FIGURE 5: a) Charged-current event rate for the 150 GeV high-flux neutrino beam. The calculation assumes a 400 meter decay pipe, 120 meter shield and a double-horn focussing system.
b) The ratio of ν_τ/ν_μ cross-sections displayed as a function of incident neutrino energy. These curves have been corrected for the contributions of quasi-elastic and Δ^{++} production processes.
c) Average muon detection efficiency as a function of neutrino energy for μ^- from all charged current events (solid), and for μ^+ from anticharm production by antineutrinos (dashed); note the suppressed zero.

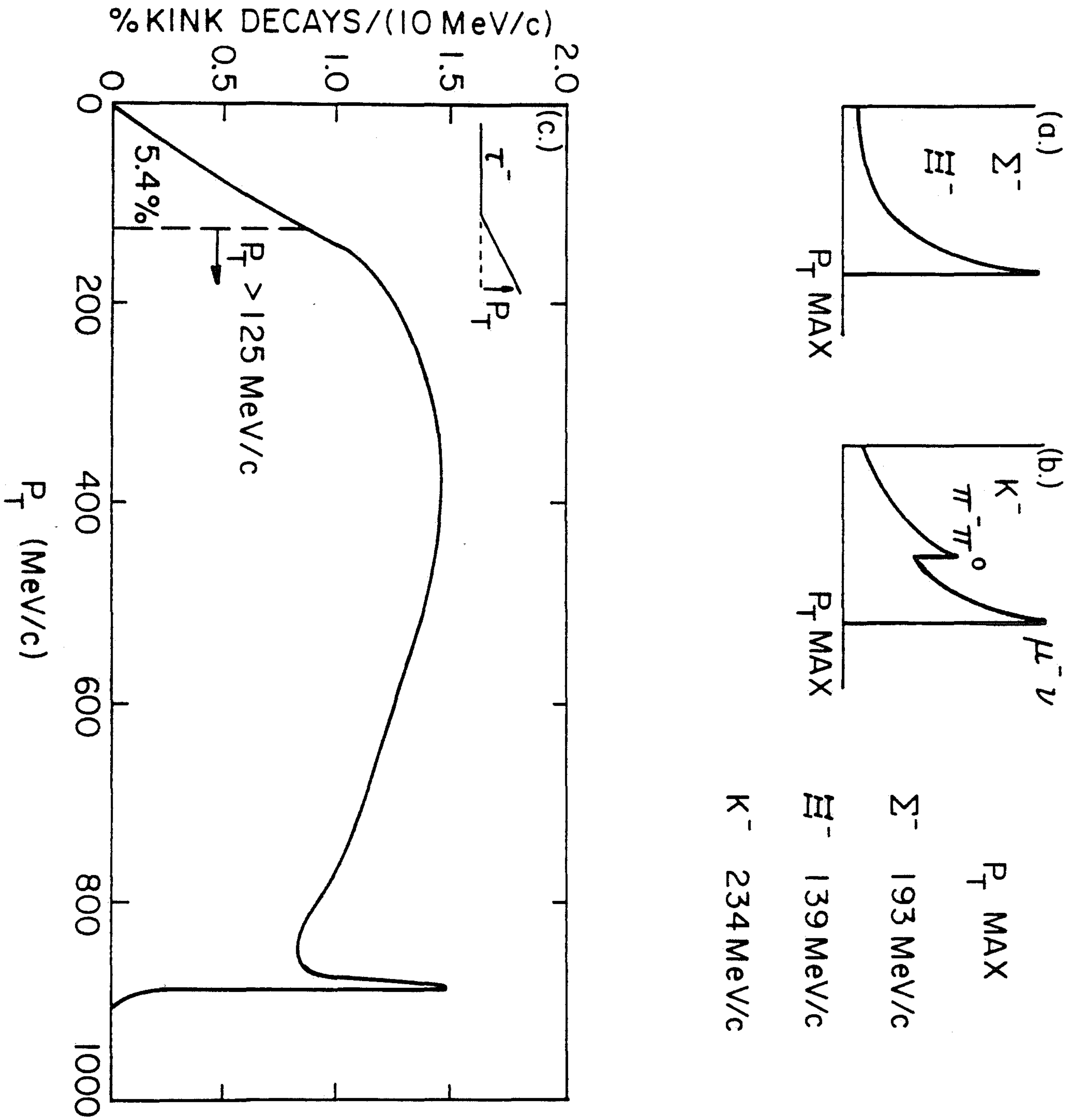


FIGURE 6: P_T distributions for (a) hyperon, (b) charged kaon and (c) τ lepton decays. Note that all hyperon and most of the kaon decays could be eliminated with a P_T cut of 0.2 GeV/c, whereas 85% of τ decays would survive.

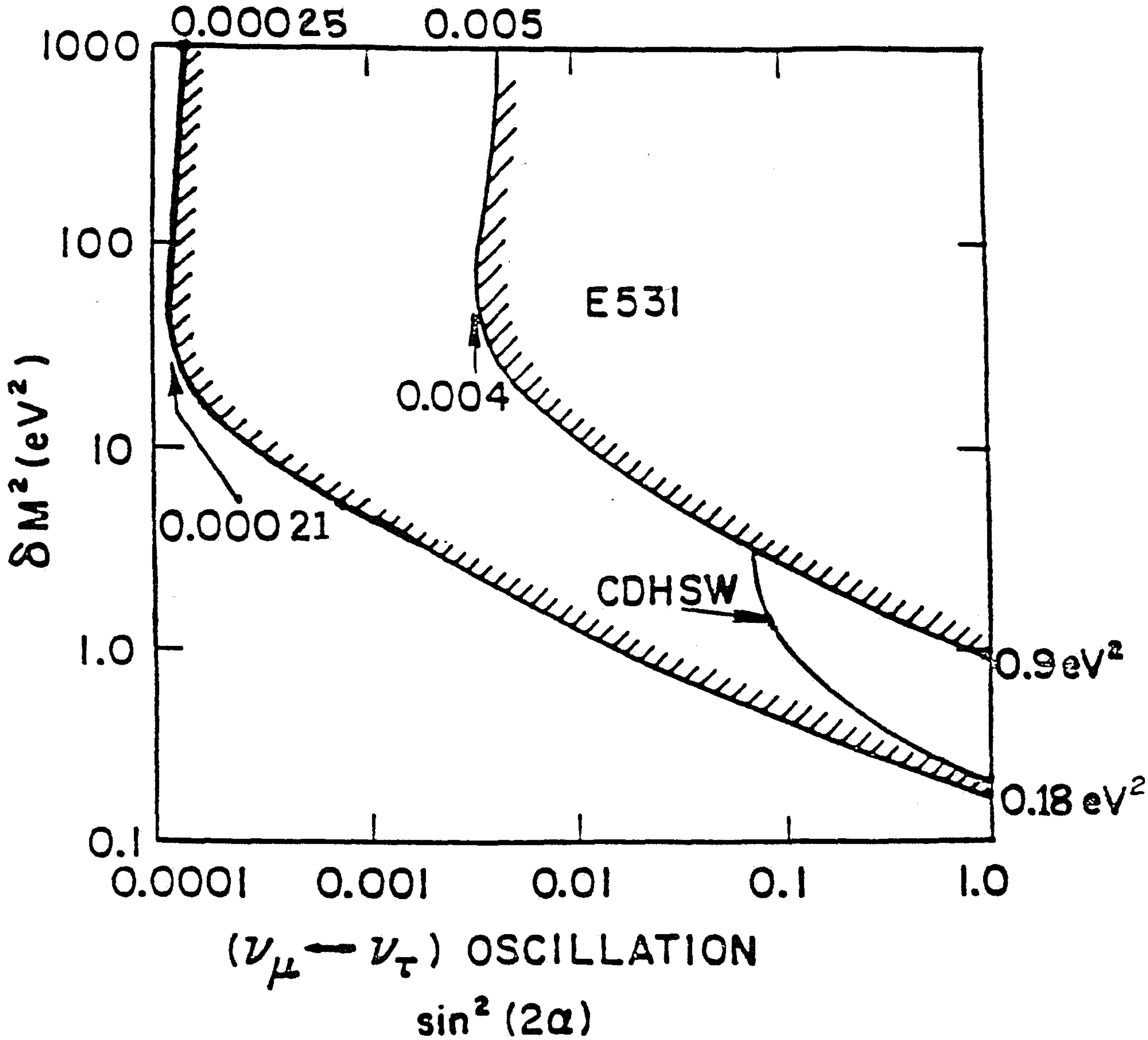


FIGURE 7: δM^2 versus $\sin^2(2\alpha)$ plane showing the previous limits for $\nu_\mu \rightarrow \nu_\tau$ oscillation superposed on improved limits which could be obtained from the new experiment.

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0/

LETTER OF INTENT FOR AN EXPERIMENT TO IMPROVE LIMITS FOR $\nu_\mu \leftrightarrow \nu_\tau$ NEUTRINO OSCILLATIONS

R. J. Lipton
Carnegie-Mellon University
and
R. J. Stefanski
Fermilab
and
K. Niwa
Nagoya University
and
H. Fukushima
Kobe University
and
S. G. Frederiksen, N. W. Reay, K. Reibel, R. A. Sidwell and N. R. Stanton
The Ohio State University
and
M. Teranaka
Osaka City University

COST ESTIMATES, ETC.
AVAILABLE
IN UPDATED LETTER!
- BUT TODAY -
INTRO TO CONCEPT

NEUTRINO OSCILLATIONS

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

$$\text{RATE} \sim \sin^2(2\alpha)\ \sin^2\left(1.27\frac{L}{E}\delta m^2\right)$$

MOTIVATION

MASSIVE NEUTRINOS

CAN CLOSE

UNIVERSE

SEE-SAW MECHANISM

$$M_{\nu e} : M_{\nu\mu} : M_{\nu\tau} = \frac{m_u^2}{M} : \frac{m_c^2}{M} : \frac{m_t^2}{M}$$

10^4 10^4

HARARI: ONLY INDICATOR, AS STRICT SU(5) GUTS, & EVEN $M_{\nu\tau} \ll 1$

MEANS

$$\delta m^2 = M_{\nu\tau}^2$$

HARARI ANSATZ

α ~ KM ANGLES

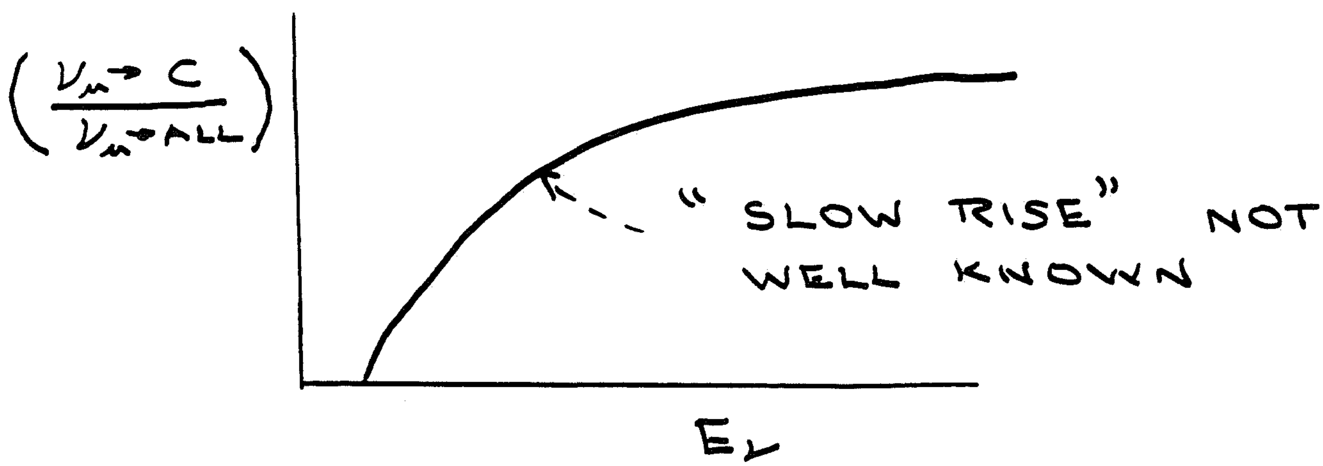
MEANS

$$\sin^2(2\alpha) > 4 \times 10^{-4}$$

GET MORE THAN OSC.

MUST STUDY BKGNDS:

$$\nu_\mu \to c X \mu^- \qquad \bar{\nu}_\mu \to \bar{c} X \mu^+$$



$$M_c \sim 1.5 \pm 0.4 \ GeV/c^2 \Rightarrow \delta M_c \sim 0.1$$

$$\left(\frac{NC}{CC}\right)_\nu = \rho^2 \left(\frac{1}{2} - \sin^2\Theta_W + \frac{20}{27} \sin^4 \Theta_W \right)$$

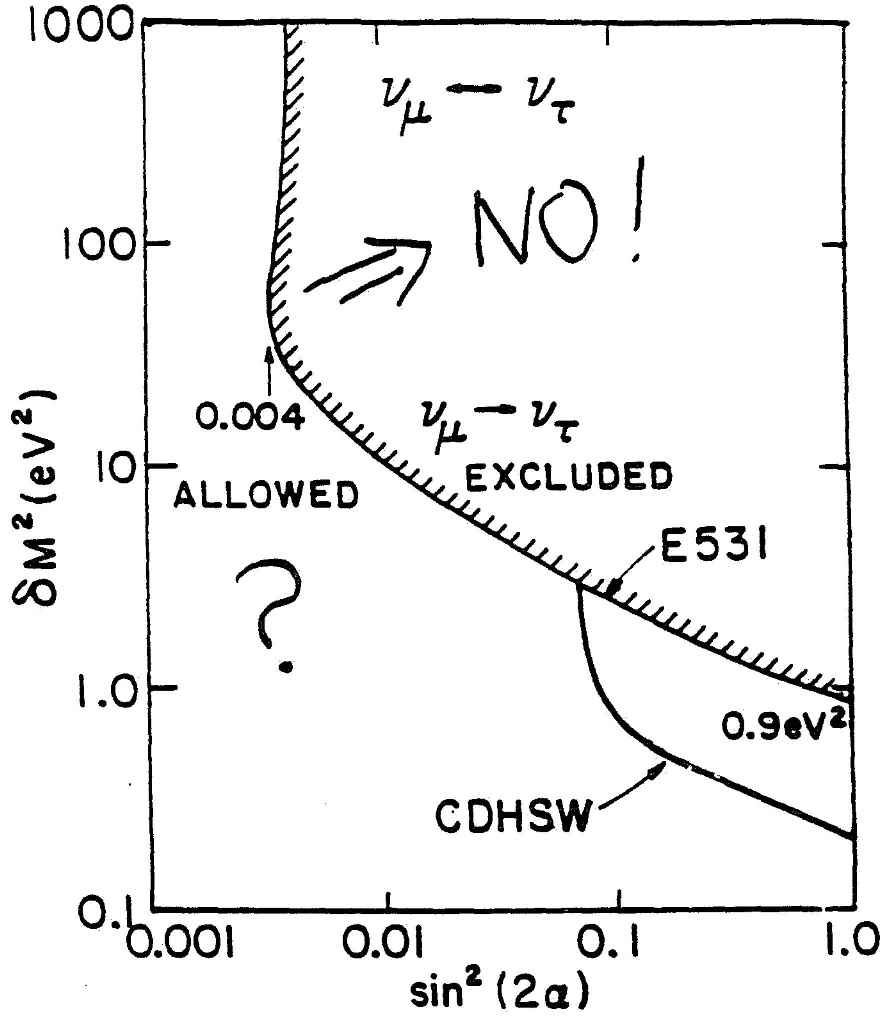
CORRECT CC UPWARD

?? IS CHARM CORR. O.K.??

IF SO, $\delta(\sin^2\Theta_W) \to 1\frac{1}{2}$-2X BETTER

— R. BROCK —

ALSO, MAKE DIRECT MEASUREMENT OF STRANGE SEA.

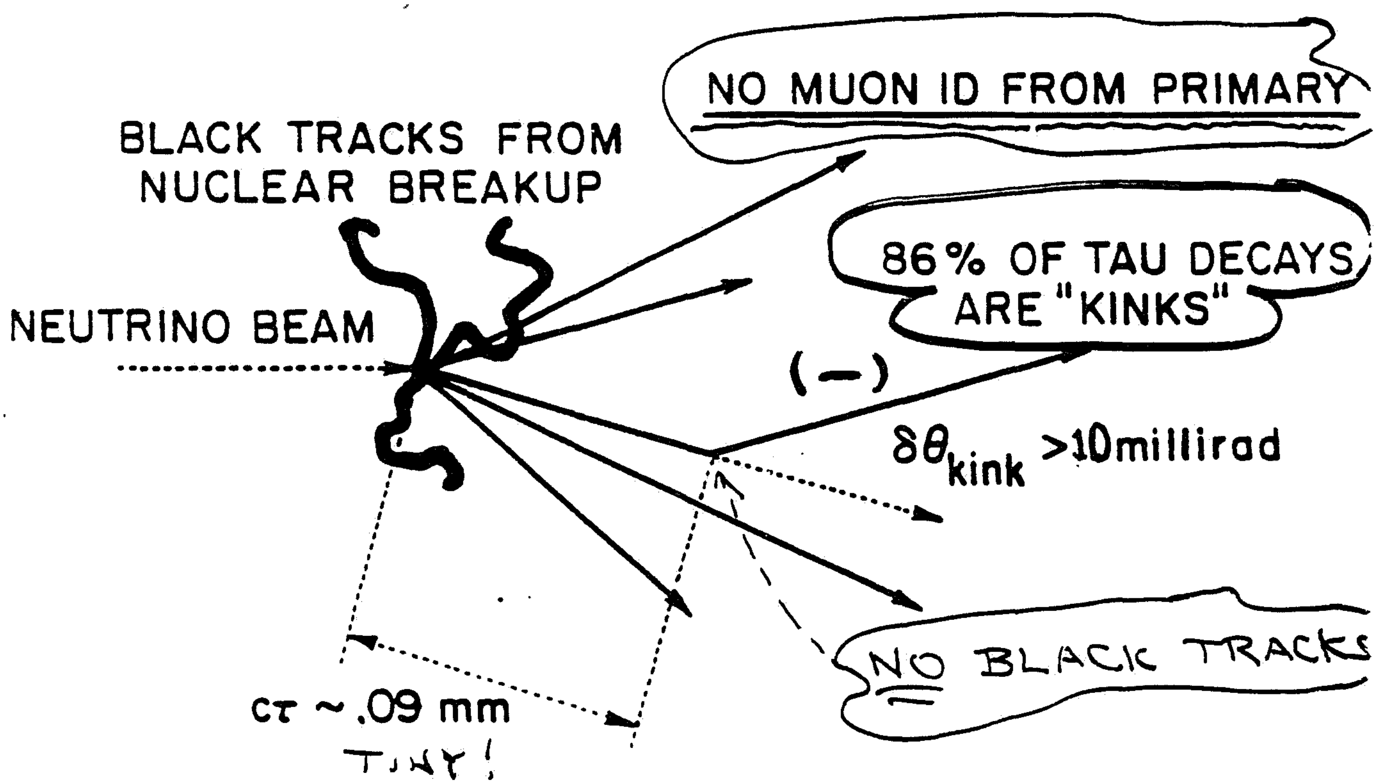


$$R(\nu_\mu \leftrightarrow \nu_\tau) = \sin^2(2\alpha) \underbrace{\int \rho(\eta) \sin^2(1.27\,\delta M^2 \eta)\, d\eta}_{\approx \frac{1}{2} \text{ FOR LARGE } \delta M^2}$$

$\eta = L/E$

PRESENT LIMITS

ν_τ + EMULSION → τ^- X



NO PRIMARY MUON → COULD BE NEUTRAL CURRENT

4 KEY POINTS

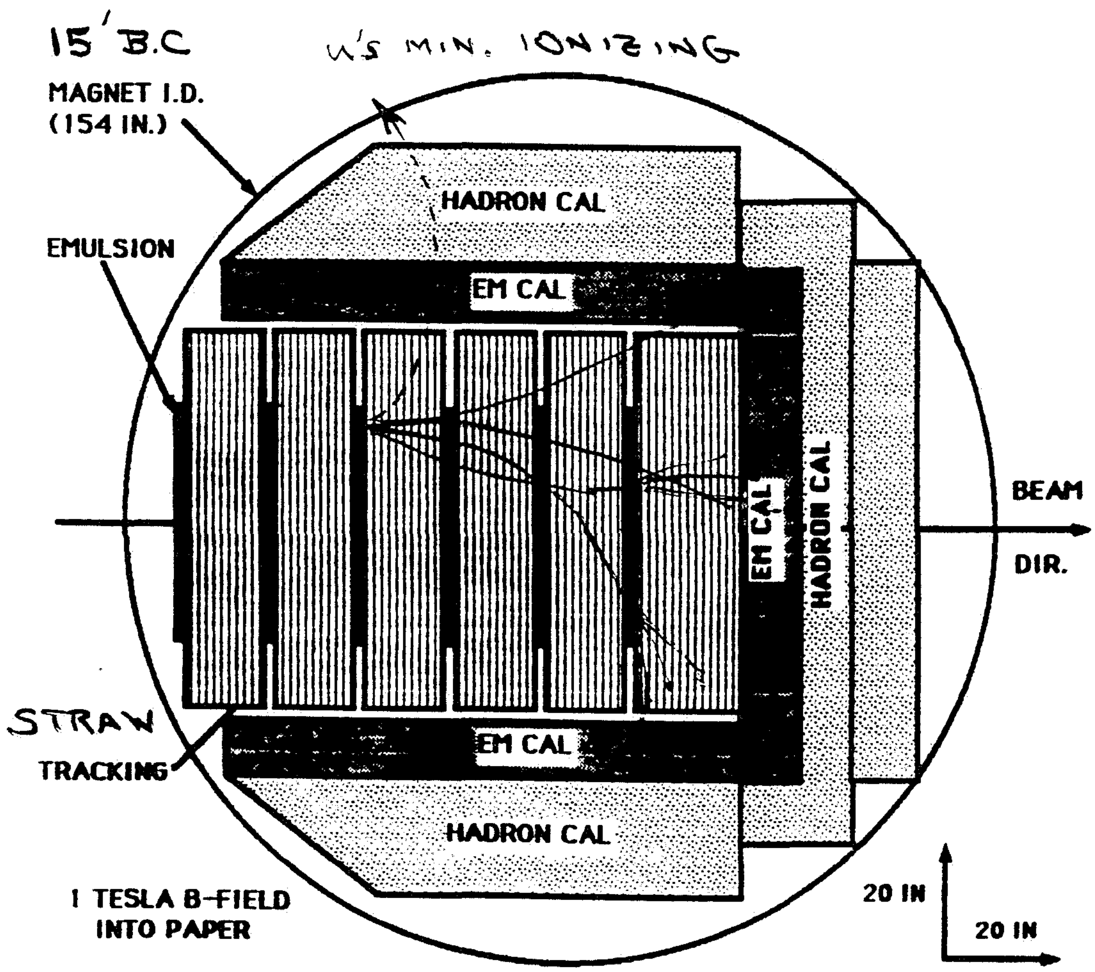
1) NEED GOOD μ, e DETECTION
2) MUST SEE SECONDARY INT.
3) MUST SEE PARENT DIRECTION (P_T CUT)
4) MUST WORK WITH "KINKS" NEED "VISUAL" MEDIUM.

E531: $\sin^2 2\alpha < \frac{1}{2}\%$ (90% CL.

PROPOSED: $\sin^2 2\alpha \lesssim 2\frac{1}{2} \times 10^{-4}$

IMPROVEMENTS

- 60× <u>MORE</u> INT.
  Rapid-cycling beam!
  10× <u>MORE</u> Emulsion!
- 70% → ≳ 90% μ Effic
- SCAN <u>ONLY</u> MUONLESS EVENTS
- USE <u>FAST</u> AUTOMATIC SCANNING



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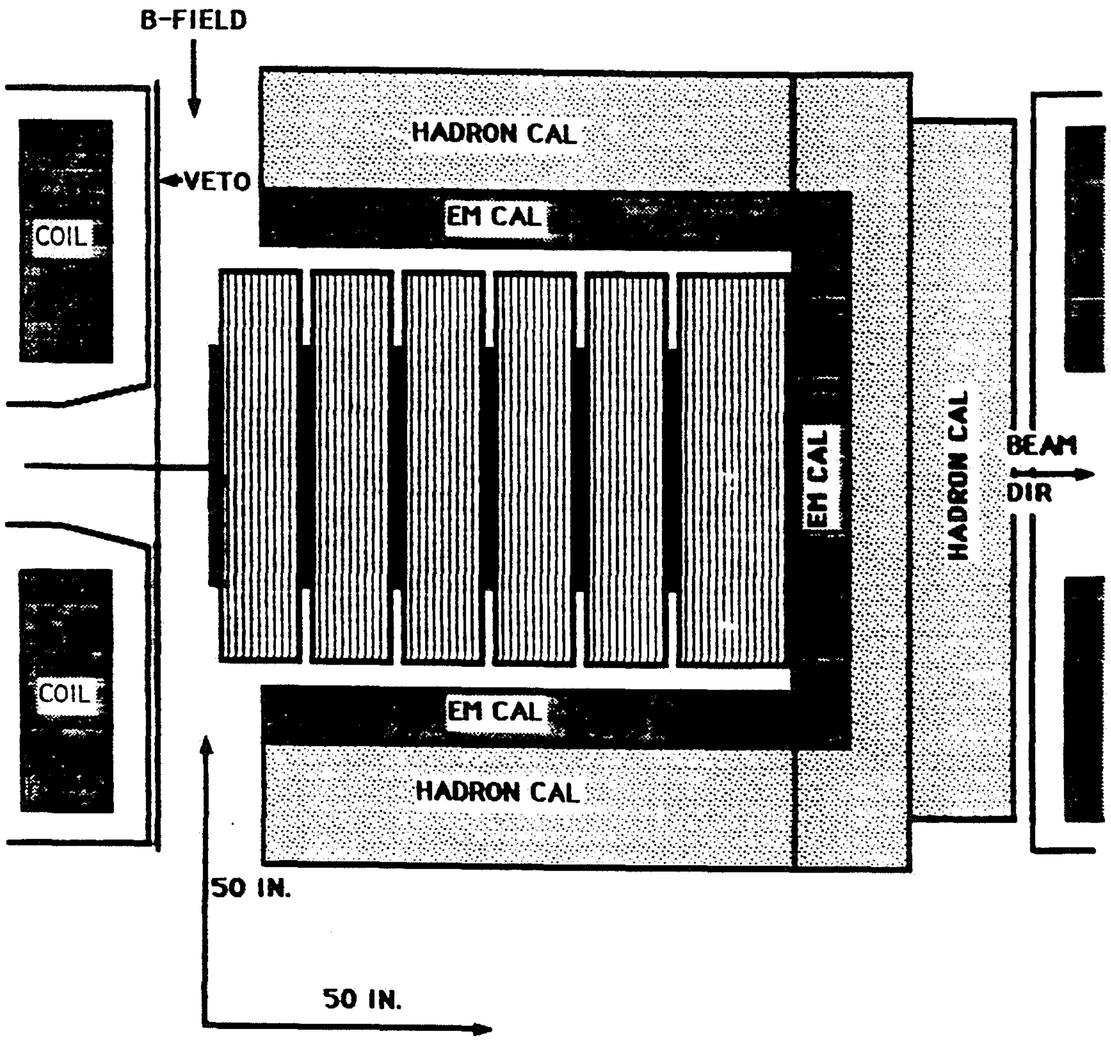
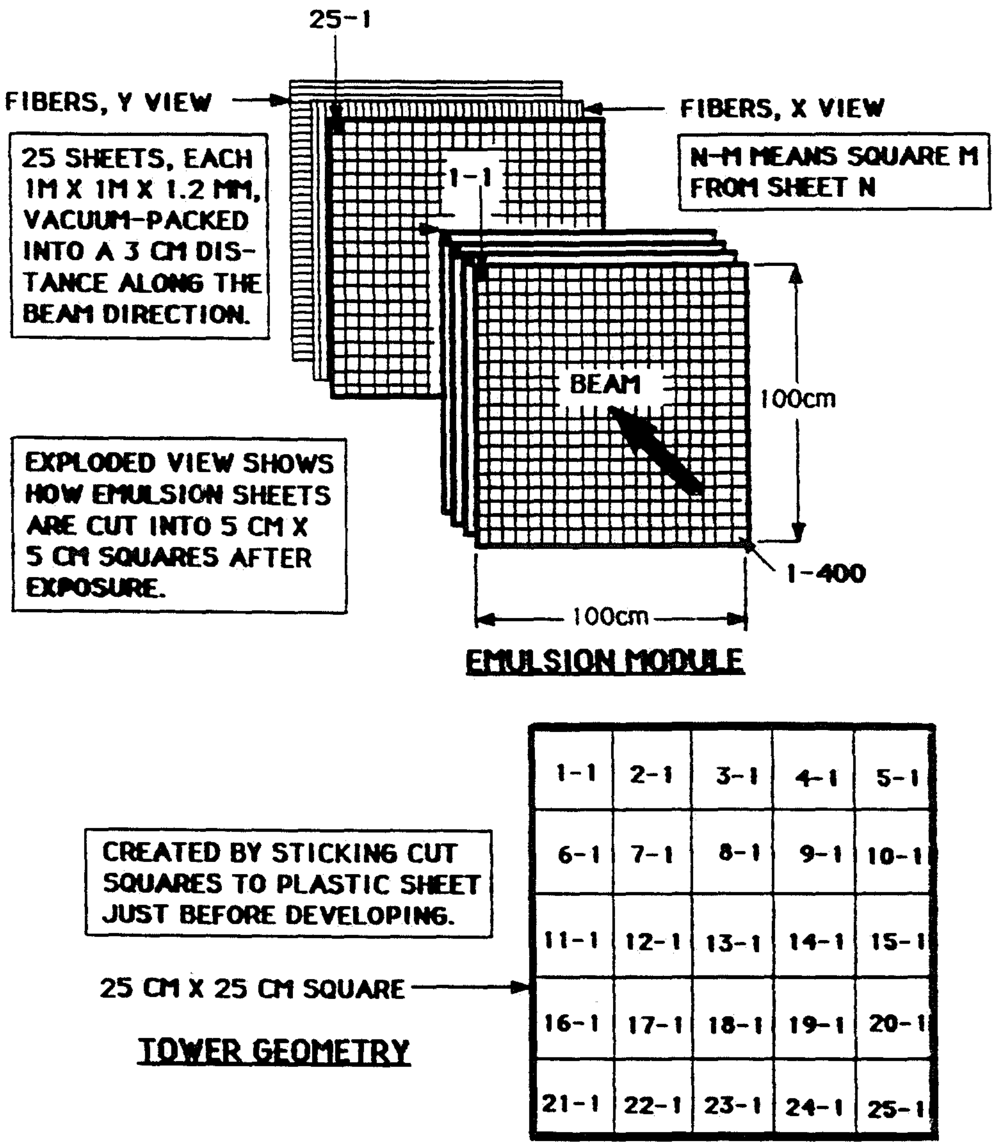
NEUTRINO OSCILLATION EXPERIMENT
PLAN VIEW

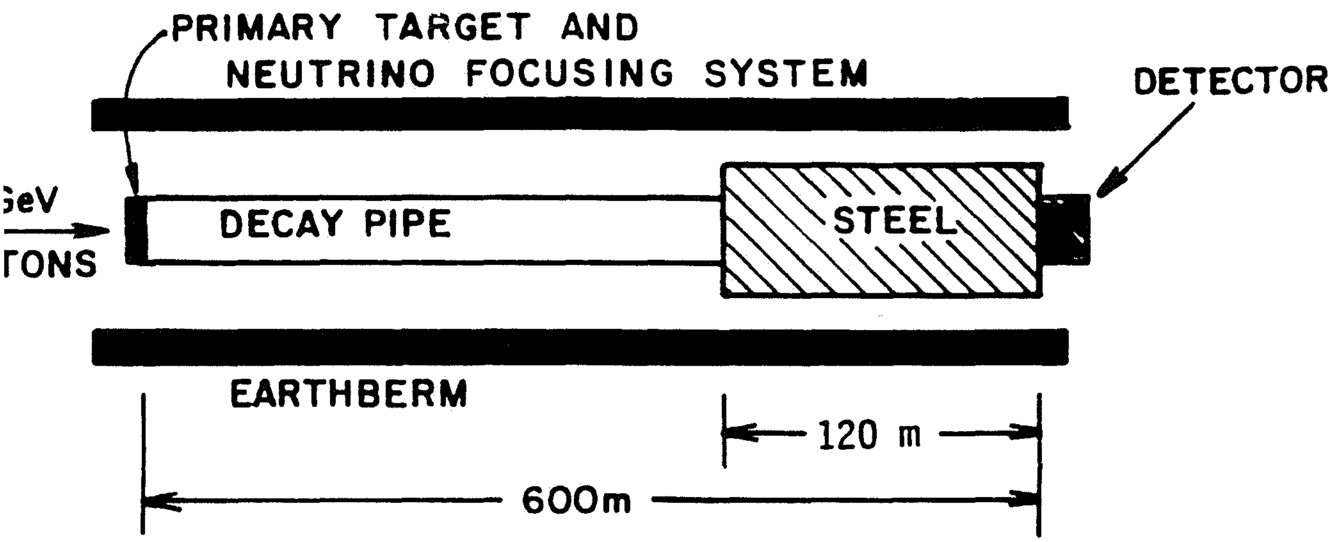
ELECTRONIC EMULSION B.C.



NEUTRINO OSCILLATION EXPERIMENT
ELEVATION VIEW

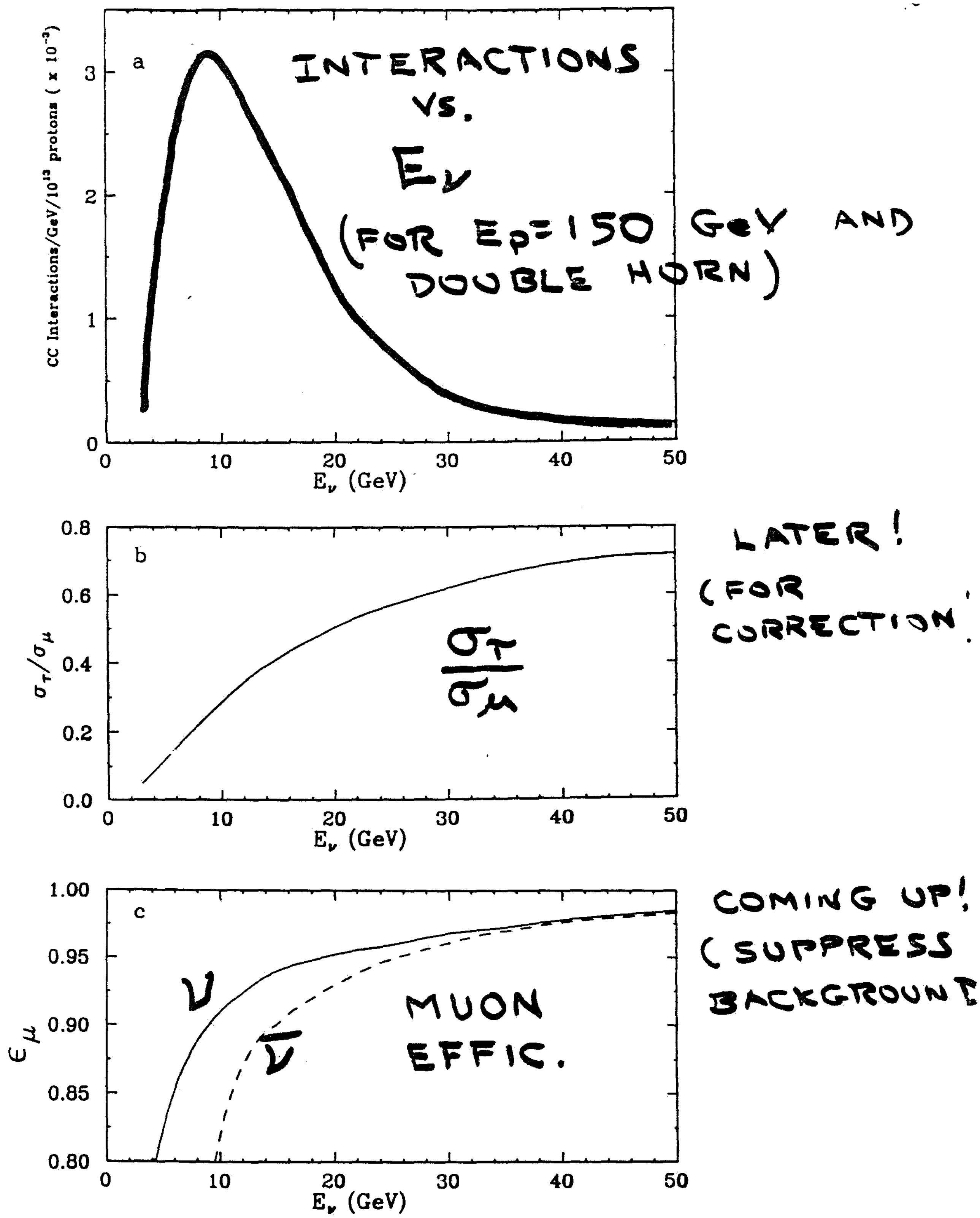


EMULSION PLUS SCINT. FIBER MODULE



A LOT EXISTS, BUT NEED

1) DOUBLE HORN (L. STUTTE)
2) SOME DIGGING
3) BUILDING FOR DETECTOR
4) MOVE 15' MAGNET



a
INTERACTIONS vs. E_ν
(FOR E_p=150 GeV AND DOUBLE HORN)
CC Interactions/GeV/10^{13} protons (x 10^{-3})
E_ν (GeV)
b
LATER! (FOR CORRECTION)
σ_τ/σ_μ
E_ν (GeV)
c
COMING UP! (SUPPRESS BACKGROUND)
ν
$\bar{\nu}$
MUON EFFIC.
ϵ_μ
E_ν (GeV)

BACKGROUNDS

STRANGE DECAYS $< 10^{-6}$

ν_τ FROM DUMP $< 10^{-6} \times 1-3$

ν_μ + EM -> μ^- + CHARM + X $< 10^{-6}$

ν_μ + EM -> $C\bar{C}$ + X $< 10^{-6}$

BIG BACKGROUND

"D^-"

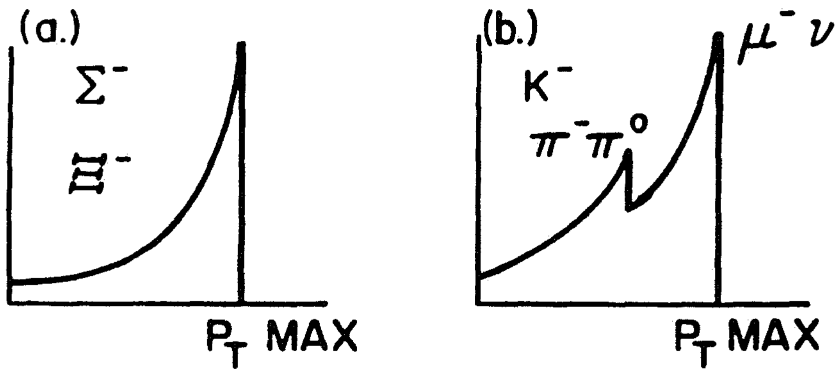
$\bar{\nu}_\mu$ + EM -> μ^+ + ANTICHARM + X

↳ MISS MUON ↳ KINK (−)

$\sim 0.8 \times 10^{-5}$

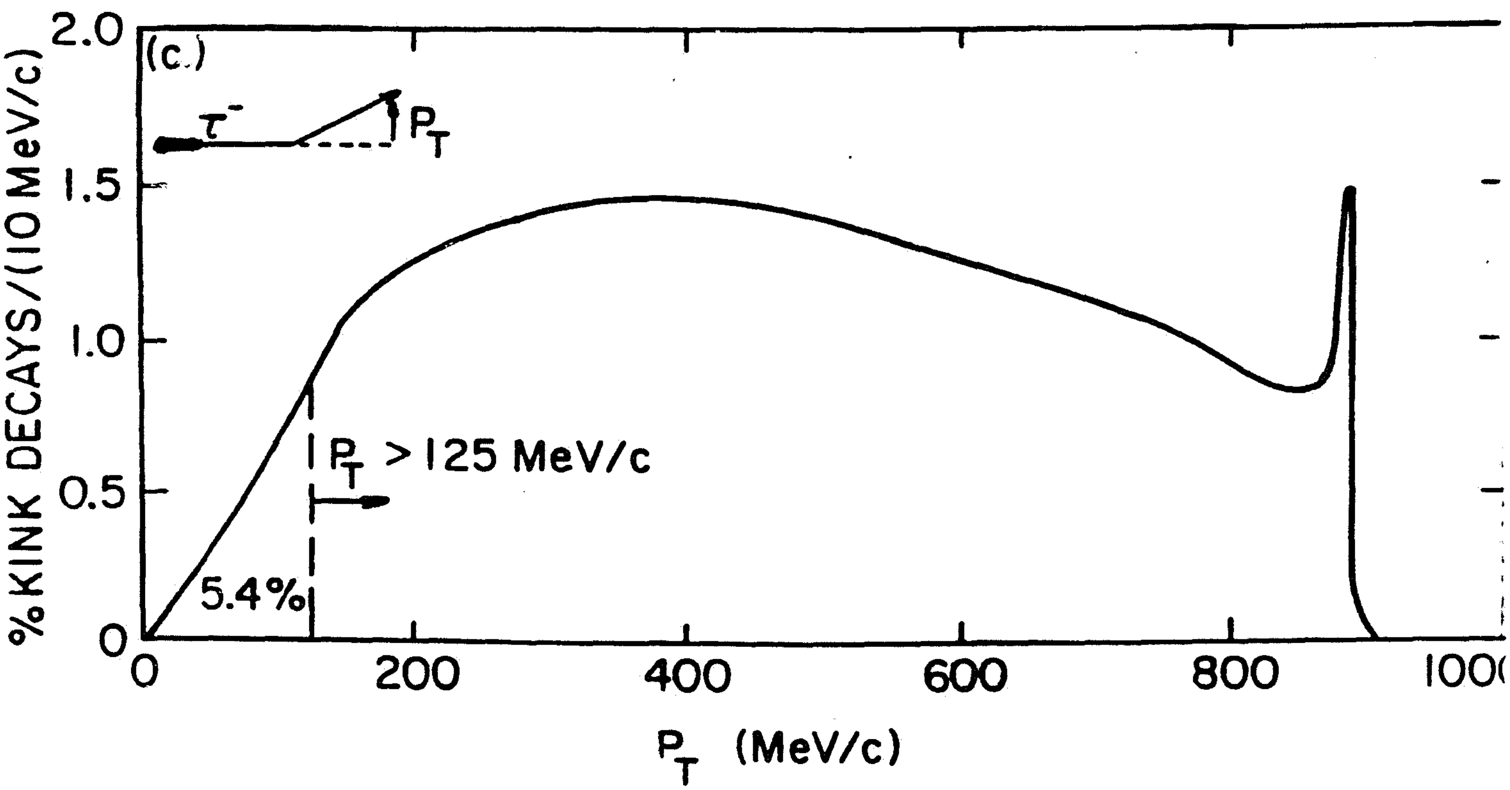
ABOVE PLUS $\bar{\nu}_e \to \bar{c}$ SUM TO

1.2×10^{-5}



	P_T MAX
Σ^-	193 MeV/c
Ξ^-	139 MeV/c
K^-	234 MeV/c

P_T CUTS CAN ELIMINATE STRANGE DECAYS



ALL BACKGROUNDS ARE MEASURABLE

TAU DECAYS ARE SHORT BUT STRANGE DECAYS UNIFORM OVER CENTIMETERS
(ALSO SECONDARY INT.)

THE YIELD OF SINGLE AND DOUBLE CHARM FROM ν AND $\bar{\nu}$ WILL BE MEASURED

IMPROVE $\sin^2\theta_W$

MUON EFFICIENCY WILL BE MEASURED

RATES

180 LITERS OF EMULSION

5×10^{19} PROTONS (150 GeV)

1 F.T. RUN @ 2×10^{13} / PULSE.

122,000 C.C. FOUND IN SOFTWARE

SCAN 53,000 EVENTS
(2 YEARS)

EXPECT 1.7 BKGND.

CORRECTIONS

$$R = R_{RAW} \times (\text{CORR})$$

$$(\text{CORR}) = \left(\int K(E_\nu) N(E_\nu)\, dE_\nu \right)^{-1}$$

$$K(E_\nu) = \int \left(\frac{\sigma_\tau}{\sigma_\mu}\right)\left(\frac{\varepsilon_\tau}{\varepsilon_\mu}\right)\left(\frac{A_\tau}{A_\mu}\right)\left(\Sigma B_i S_i\right) dx\, dy\, d$$

$$\left(\frac{\varepsilon_\tau}{\varepsilon_\mu}\right)\left(\frac{A_\tau}{A_\mu}\right)(B_i S_i) = (1.0)(1.0)(.68)(.7)$$

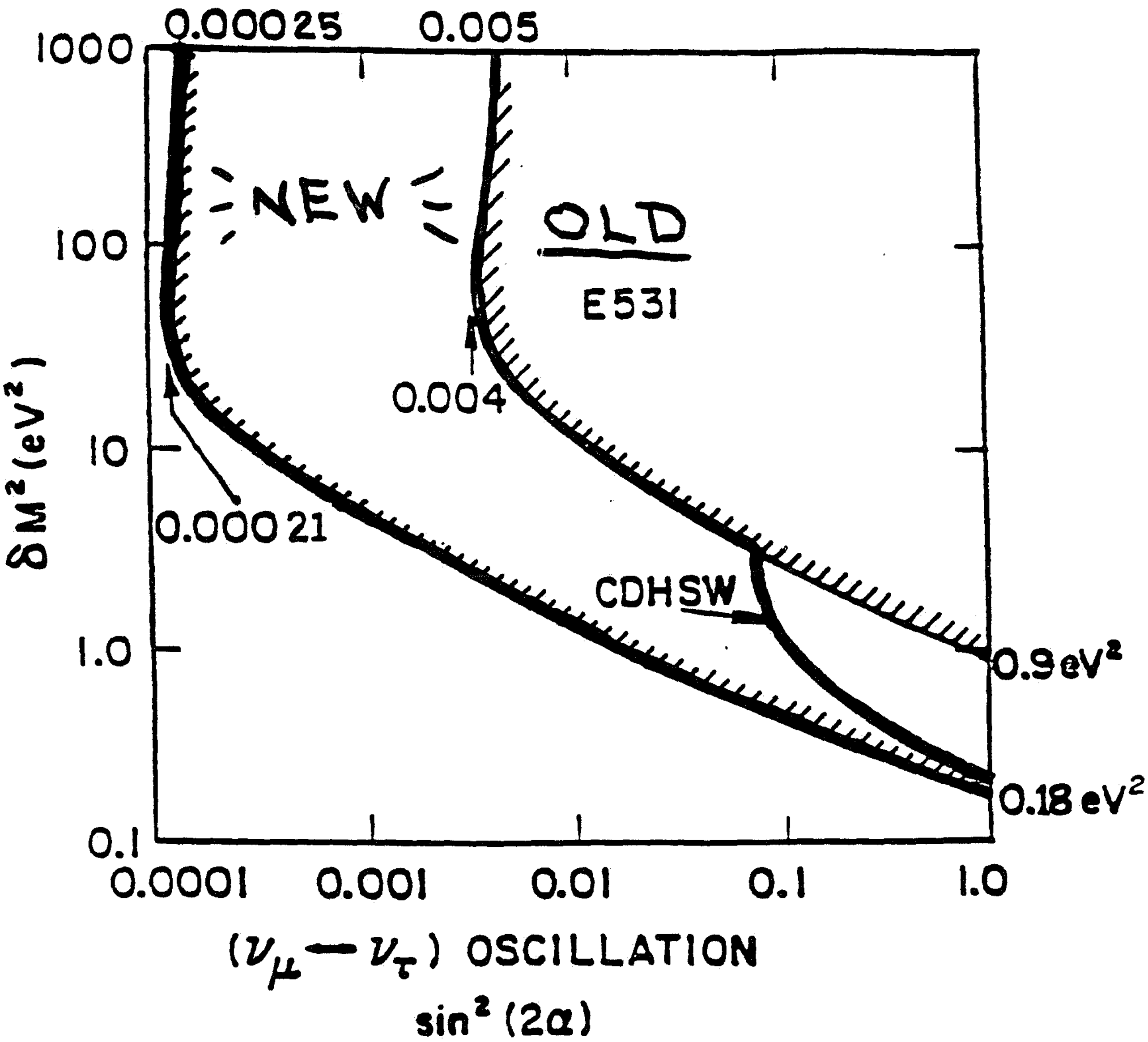
$$(\text{CORR}) = 4.15$$

FOR BIG δm^2, $\frac{1}{2}\nu_\tau$, $\frac{1}{2}\nu_\mu$

$$R = R_{RAW} \times (8.3)$$

IF 0 EV. OVER BKGND OF 1.7

$$R = \left(\frac{3.7}{122{,}000}\right) \times 8.3 = \boxed{2.5 \times 10^{-4}}$$


0.00025
0.005
1000
100
10
1.0
0.1
NEW
OLD
E531
0.004
0.00021
CDHSW
0.9 eV²
0.18 eV²
δM² (eV²)
0.0001
0.001
0.01
0.1
1.0
(ν_μ — ν_τ) OSCILLATION
sin² (2α)

– IN PROCESS –

1) M.C. NEUTRON BKGND

2) M.C. "TRICKS"

   a) ϕ CUT BETWEEN $\Sigma \vec{P}_{HADRON}$ AND KINK DIRECTION.

   b) 2-BODY JACOBIAN PEAK IN MISSING MASS.

3) MEASURE Hi P_T KINKS IN SECONDARY INT. AT KEK.

4) COMPLETE DESIGN, FULL M.C. SIMULATION.

5) PROPOSAL FOR NOVEMBER PAC

(EXPECT CERN COMPETITIO IN '93)

PAC INPUT ON PHYSICS & DESIGN

+

<u>KEEPING</u> 15' MAGNET

ARE IMPORTANT!

— THANKS FOR LISTENING