Neutrino Oscillation Experiments with Accelerator Produced Neutrino Beams

- Outline
  - Framework and Current Situation
  - Accelerator and Reactor Osc. Experiments Probing:
    - Solar Neutrino
    - Atmospheric Neutrino
    - LSND $\nu_\mu \rightarrow \nu_e$ Region
  - Brief comments on muon storage ring ν–Factory
    (See A. Sessler talk on muon storage rings)

M. Shaevitz
ICFA Seminar Talk
October 5, 1999

Neutrino Oscillation Formalism

- Most analyses assume 2-generation mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_e \end{pmatrix} \qquad P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L / E) \qquad \Delta m^2 = m_1^2 - m_2^2$$

- But we have 3-generations: ν_e , ν_μ, and ν_τ (and maybe even more ….. the sterile neutrino ν_s's)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

← CKM-like Mixing Matrix for Leptons

(In this 3-generation model, there are 3 Δm^2's but only two are independent.)

$$\Delta m_{12}^2 = m_1^2 - m_2^2 \quad , \quad \Delta m_{23}^2 = m_2^2 - m_3^2 \quad , \quad \Delta m_{31}^2 = m_3^2 - m_1^2$$

- At each Δm^2, there can be oscillations between all the neutrino flavors with different mixing angle combinations.

For example: (3 sets of 3 equations like these)

$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2(1.27 \Delta m_{32}^2 L / E_\nu)$$

$$P(\nu_\mu \to \nu_e) = \cos^2\theta_{13} \sin^2 2\theta_{13} \sin^2(1.27 \Delta m_{32}^2 L / E_\nu)$$

$$P(\nu_e \to \nu_\tau) = \cos^2\theta_{13} \sin^2 2\theta_{13} \sin^2(1.27 \Delta m_{32}^2 L / E_\nu)$$

← $\nu_\mu \to \nu_e$ at the same Δm^2 as $\nu_\mu \to \nu_\tau$

CP Violation in Neutrino Oscillations

- Disappearance measurements cannot see CP violation effect

$$P(\nu_\mu \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$$

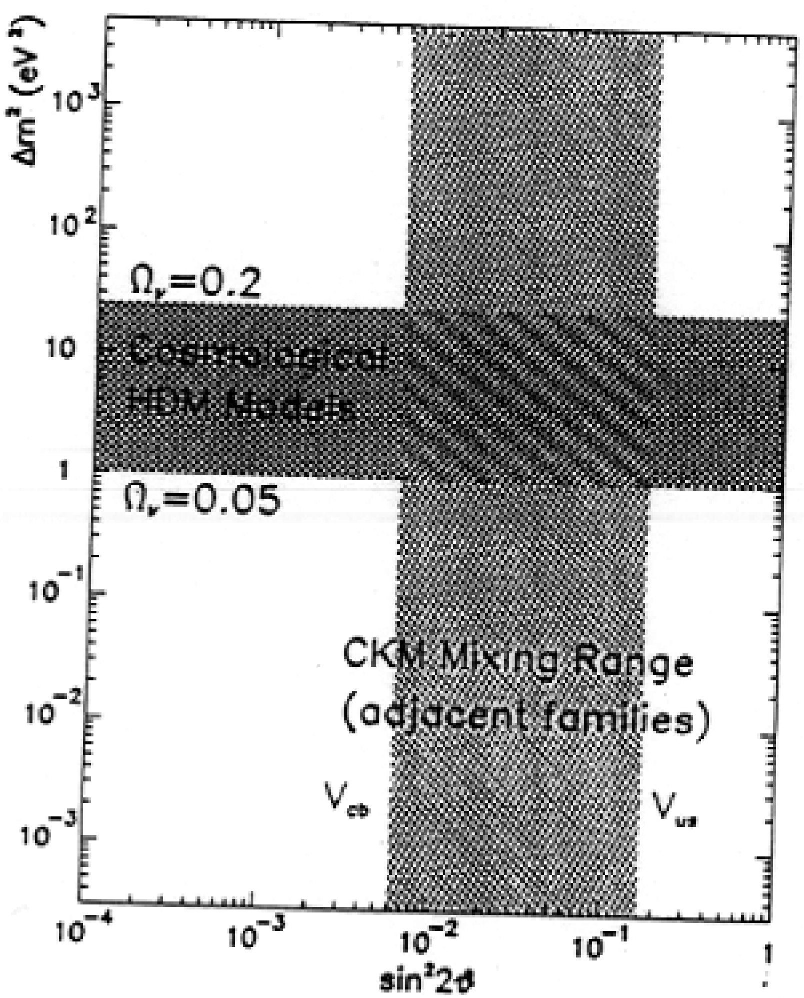
- Very, very hard to see CP violation effects in exclusive (appearance) measurements. (From B. Kayser)
  - Only can see CP violation effects if an experiment is sensitive to oscillations involving at least three types of neutrinos.

    $$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 4\,\mathrm{Im}(U_{\mu 1} U^*_{e1} U^*_{\mu 1} U_{e1})(s_{12} + s_{23} + s_{31})$$

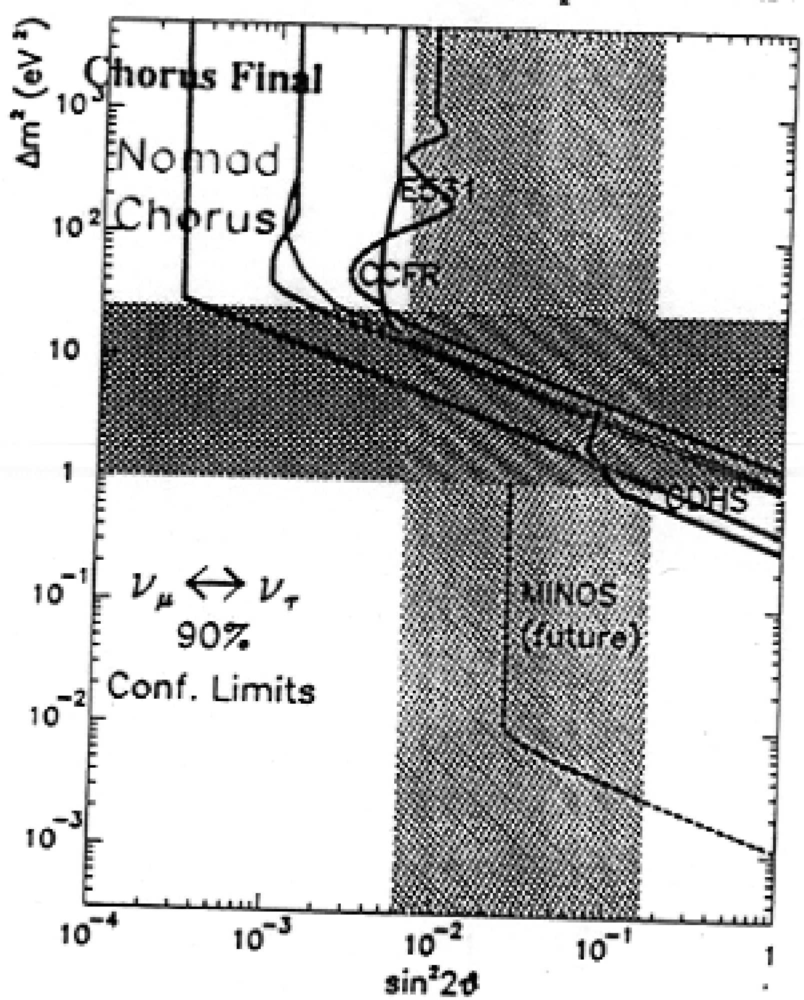
    where $s_{ij} = \sin(\delta m^2_{ij} L/2E)$ and $\delta m^2_{ij} = m_i^2 - m_j^2$
  - All the terms (s_{12}, s_{13}, s_{23}) must not be <<1 or effectively becomes only two component oscillation
    - For example, if $s_{12} \approx 0$ then $s_{13} \approx -s_{23} \Rightarrow s_{12} + s_{31} + s_{23} \approx 0$

$\Rightarrow$ **To see CP violation must be sensitive to solar neutrino $\Delta m^2 \approx 10^{-4} - 10^{-10}$ eV^2**

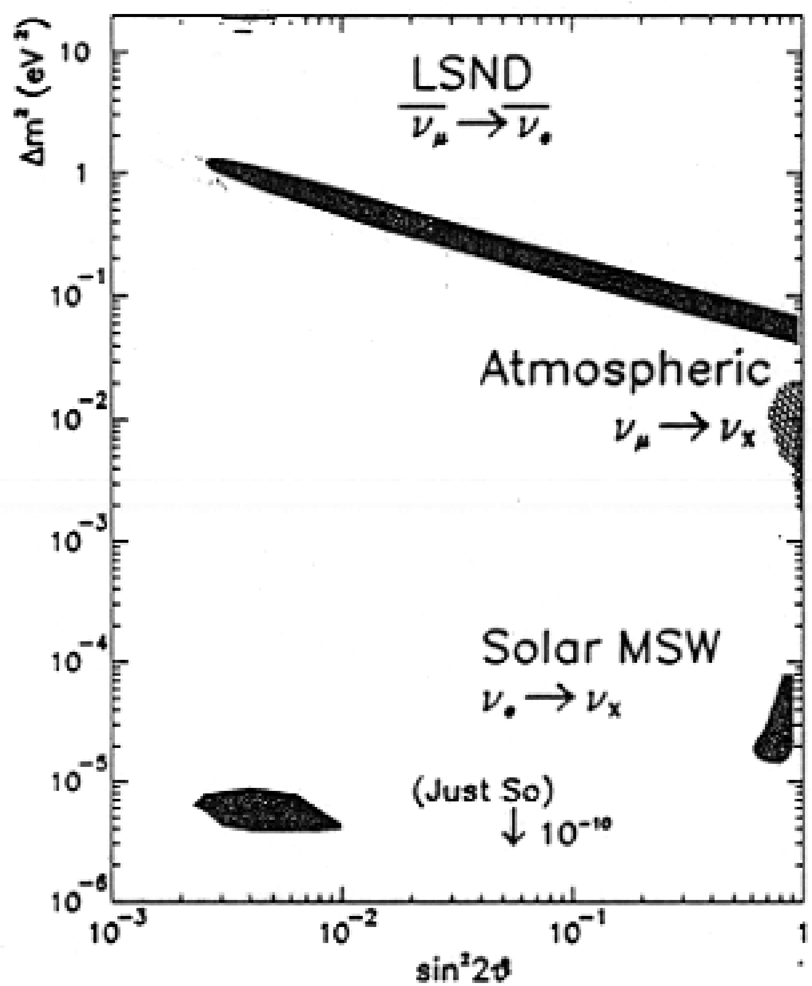
Phenomenological Guidance



Chorus and Nomad Exps. at CERN

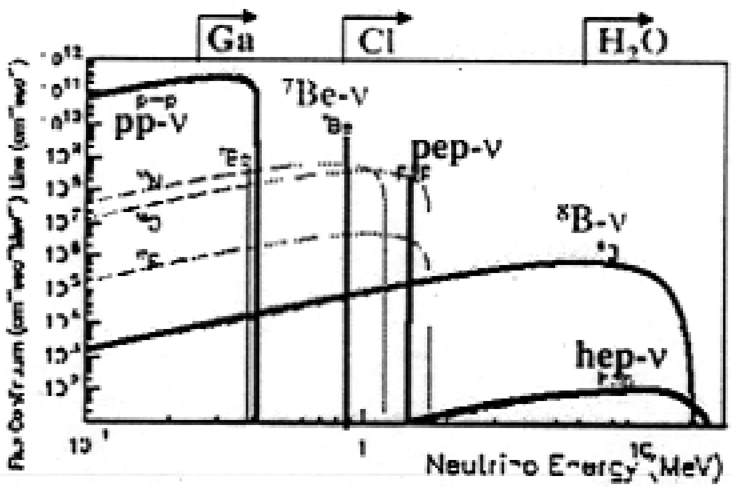


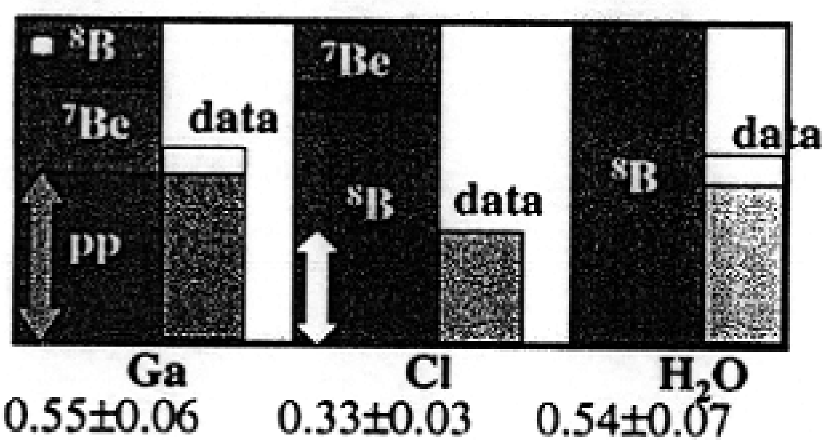
Three Indications of Neutrino Oscillations



- Questions:
  - Are all three indications really neutrino oscillations? (If so then need fourth ν_s)
    - Need to see oscillatory behavior in E_ν or L
    - Need 4σ measurements not 90% CL
  - Determine which flavors are oscillating
  - Which solar solution if any is correct?
  - Measure oscillation parameters $\pm\Delta m^2$, $\sin^2 2\theta$
  - Measure full lepton flavor mixing matrix

Solar Neutrino Studies



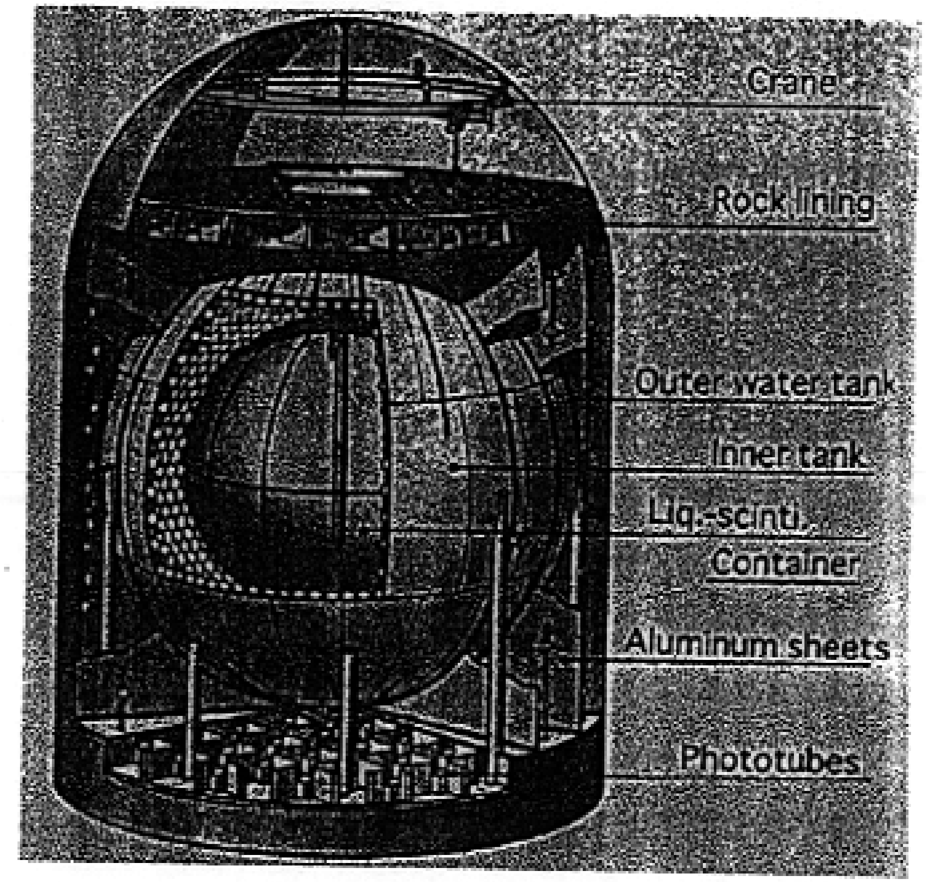


Future Studies:

- Super-Kamiodande
  - Increased statistics
  - Lower Threshold to 4.5MeV
- SNO
  - CC(9ev/day)/NC(3ev/day)
    - Flux Indep. or $\nu_e \rightarrow \nu_s$
    - CC: E spectrum and D/N
- Borexino
  - Good statistics measurement of ^{7}Be ν's (55ev/day)
  - Seasonal variation if Vac. Osc.
- KamLAND (Reactor Exp.)
  - LMA region (700 events/yr)

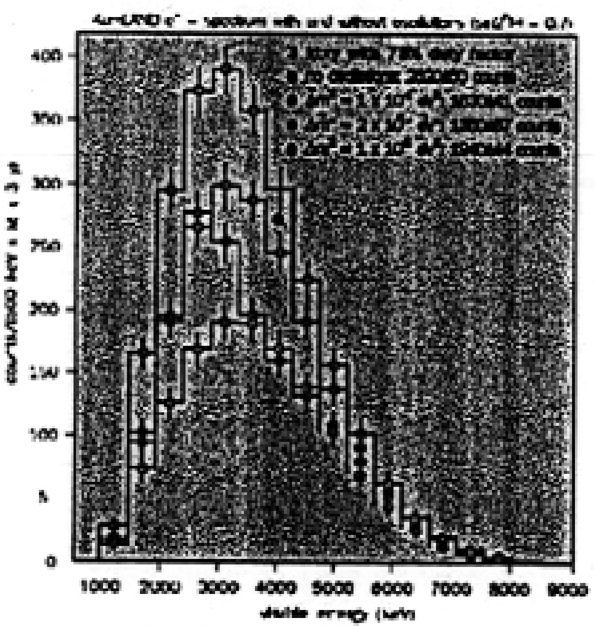
KamLAND
(Kamioka Liquid scintillator Anti-Neutrino Detector)

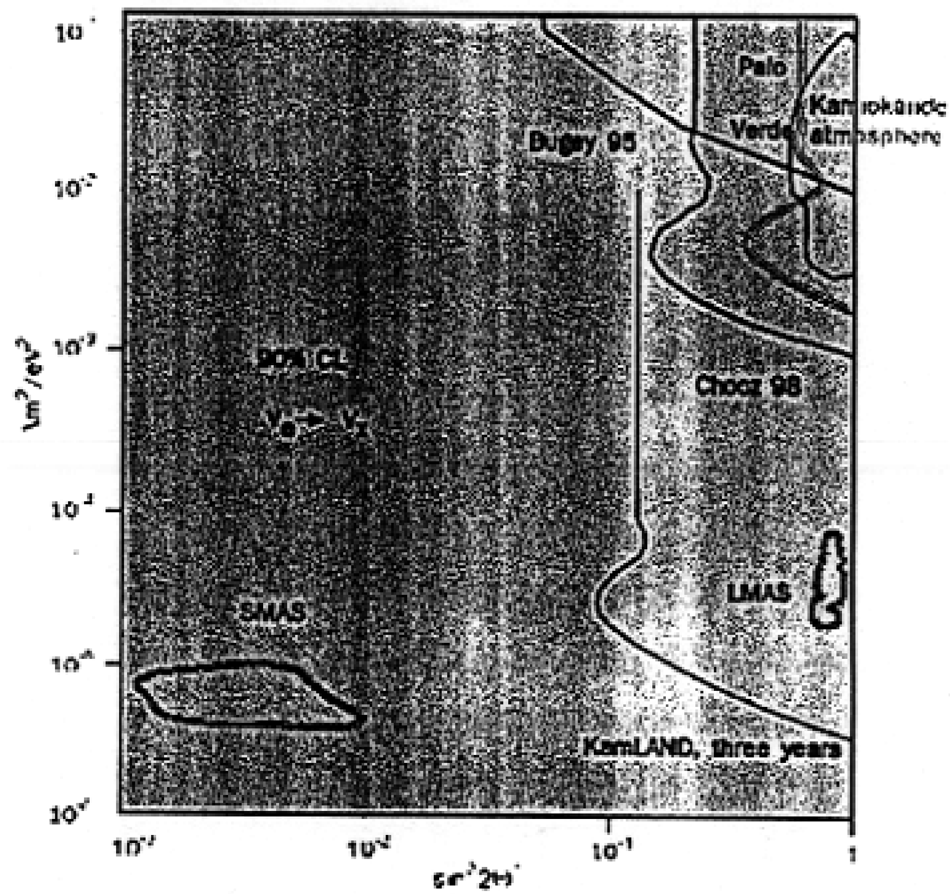
- First attempt to study the solar neutrino puzzle "in the laboratory"
  - Start Data in 2001
- Neutrino Source:
  - Japan's 51 nuclear power reactors
- Distance/Energy:
  - ~150-200 km / ~1 MeV $\Rightarrow \Delta m^2 \approx 10^{-5}$ eV^2
- Detector:
  - 13m-diameter spherical balloon filled with liquid scintillator and PMT's



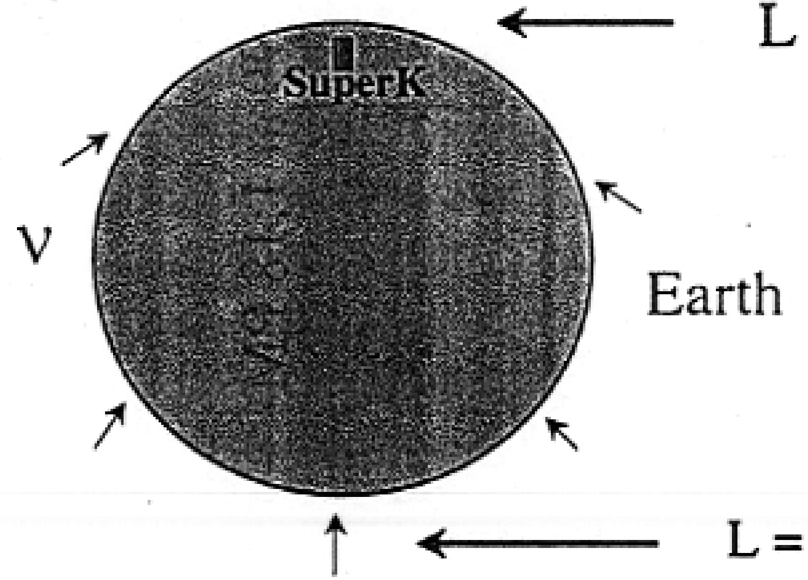
KamLAND Expected Sensitivity

- Expected rate:
  - 700 antineutrinos detected per year with no oscillations.





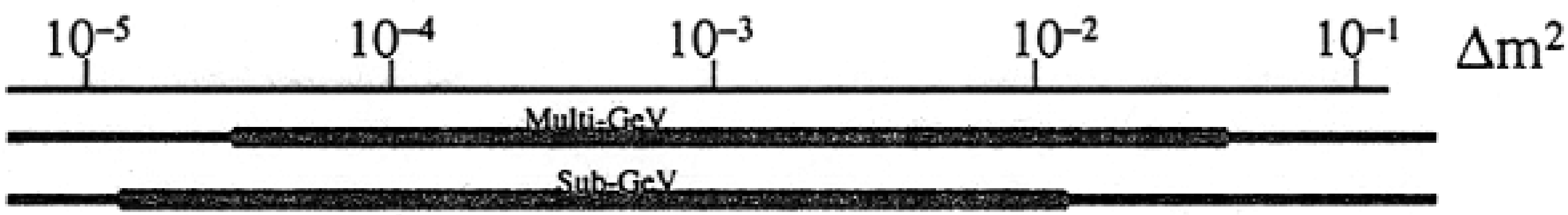
Atmospheric Neutrino Oscillation Sensitivity



L = 20 km, Oscillations if $\Delta m^2 > 10^{-2} eV^2$

$E_\nu \sim$ 300 MeV - 2 GeV

L = 10^4 km, Oscillations if $\Delta m^2 >$ few x 10^{-5} eV^2



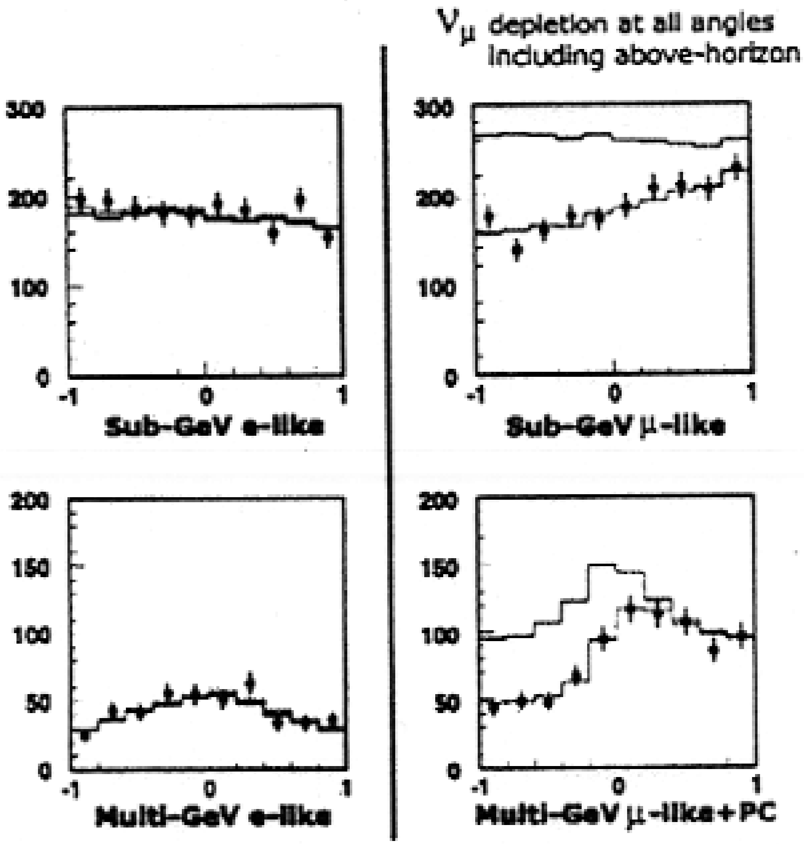
No oscillations	Zenith angle dependence	Oscillations for all angles
R = 1.0	0.5 < R < 1.0	R = 0.5 if $\sin^2 2\theta = 1$

Recent Super-K Results (848 days = 52 kton-yrs)

Zenith Angle - 10 bins:

No Osc.

$\nu_\mu \rightarrow \nu_\tau$

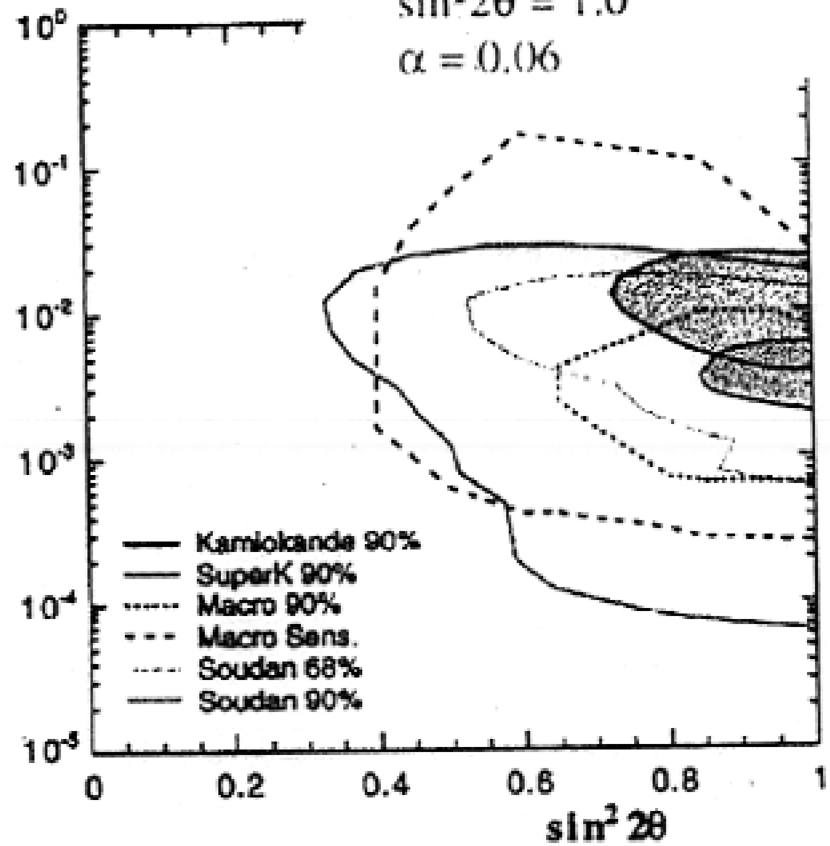


SuperK Best Fit:

$\Delta m^2 = 3.5\times10^{-3}\ eV^2$

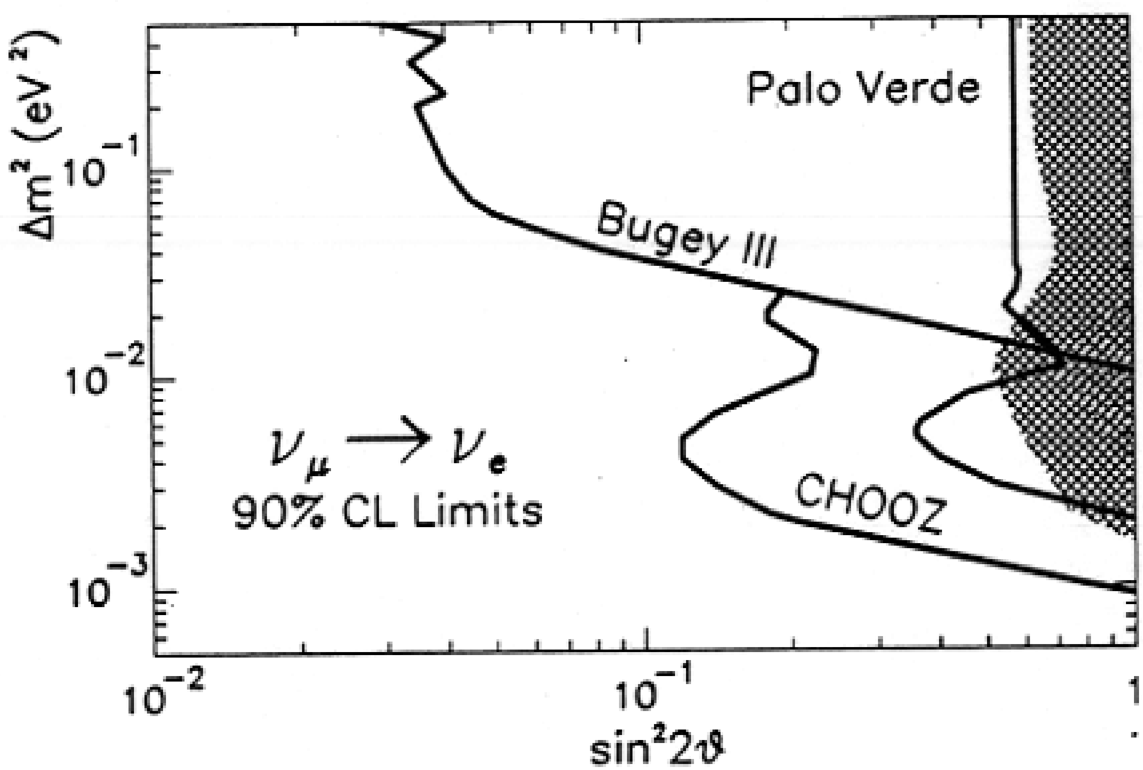
$\sin^2 2\theta = 1.0$

$\alpha = 0.06$



Reactor Experiments Limit Atmospheric $\nu_\mu \rightarrow \nu_e$ Possibilities

- CHOOZ, Bugey, and Palo Verde Reactor Experiments
  - $\langle E_\nu \rangle \sim 3$ MeV and $L \sim 1$ km $\Rightarrow$ $\Delta m^2 \approx 3\times10^{-3}$ eV^2

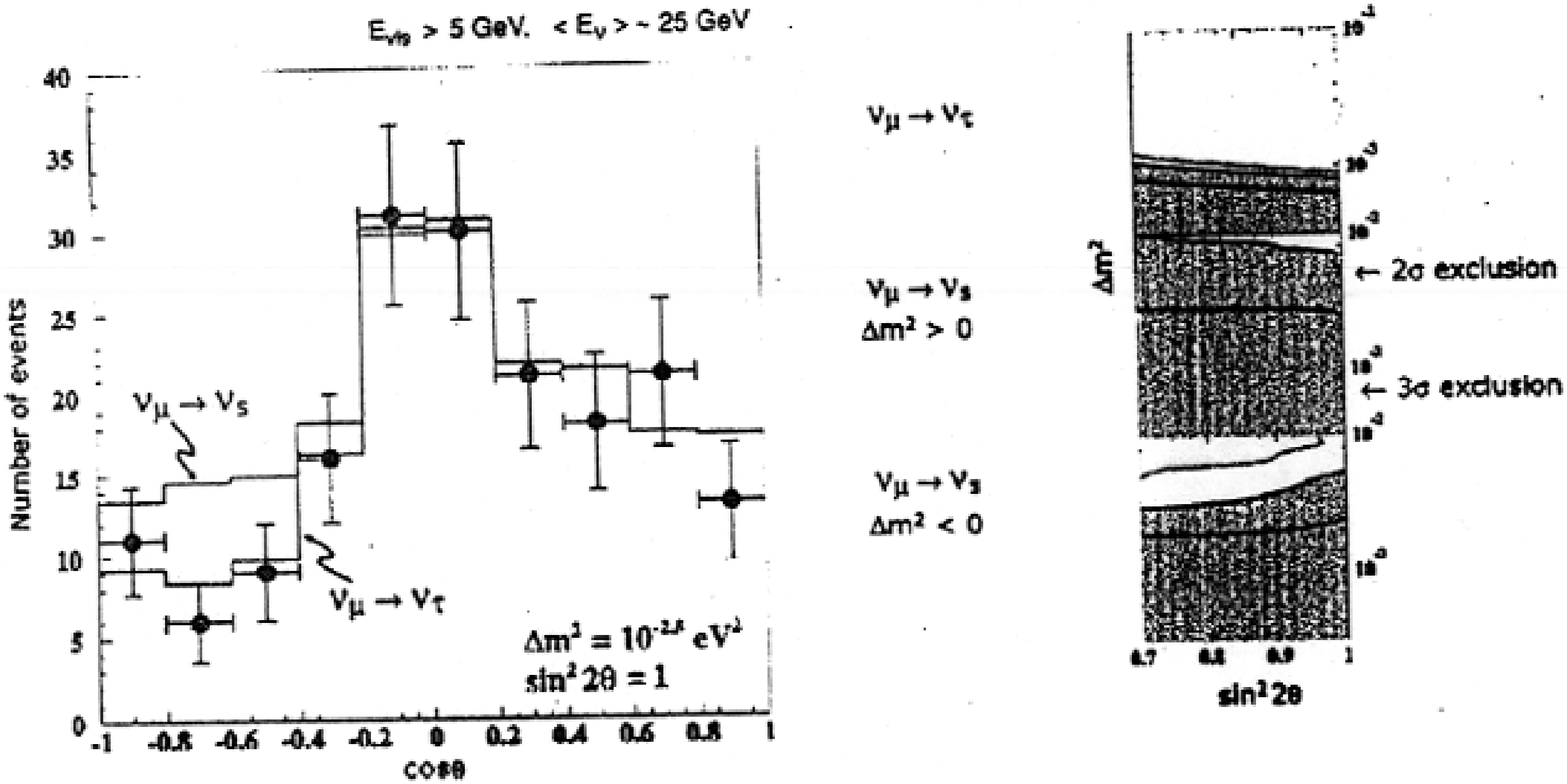


What flavors are oscillating?

- Dominant $\nu_\mu \rightarrow \nu_e$:
  - Ruled out by CHOOZ reactor ν experiment
  - Sub-dominant osc. possible at the $\sin^2 2\theta < 0.10$ level
    Could SuperK be seeing mixture of $\nu_\mu \rightarrow \nu_e$ at 10^{-4} eV^2 and $\nu_\mu \rightarrow \nu_\tau$ at 10^{-1} eV^2
- Dominant $\nu_\mu \rightarrow \nu_\tau$:
  - Try to isolate the ν_τ events?
    - Super-K (Soudan) has ~ 47 (4) CC ν_τ's in their sample but these are hard to isolate from NC events
- Dominant $\nu_\mu \rightarrow \nu_{sterile}$:
  - $\nu_{sterile}$ has no coupling to $Z^0 \Rightarrow$ Look for $\nu N \rightarrow \nu N \pi^0$ $\Leftarrow$ (Not easy)
    - Super-K π^0 - like (~NC/CC) double ratio (Data/MC)
      Current value is $1.11 \pm 0.06 \pm 0.26$
      (expect 1.00 for ν_τ and ~0.8 for $\nu_{sterile}$).
  - $\nu_{sterile}$ will have matter effects at $\cos\theta = -1$ $\Leftarrow$ (Δm^2 dependent)

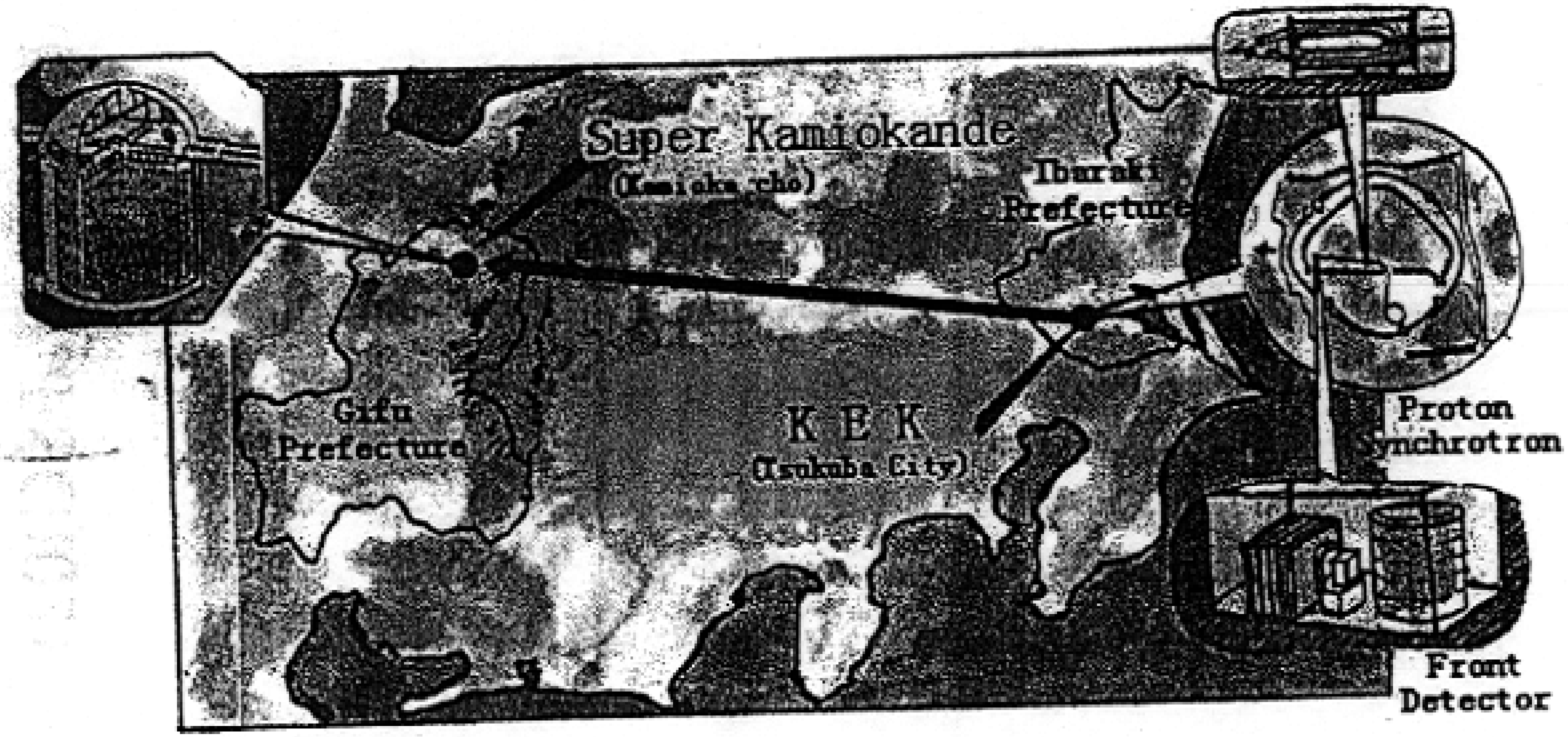
Matter Effect Analysis in SuperK

- Interactions with matter in earth effect $\nu_\mu \rightarrow \nu_{sterile}$ oscillations since $\nu_{sterile}$ has no NC interactions with quarks.



KEK to SuperK (K2K) Experiment

- Low energy, $\langle E_\nu \rangle$=1.4 GeV, beam sent from KEK to SuperK (250 km)
- Several front detectors at 100m and beam monitors



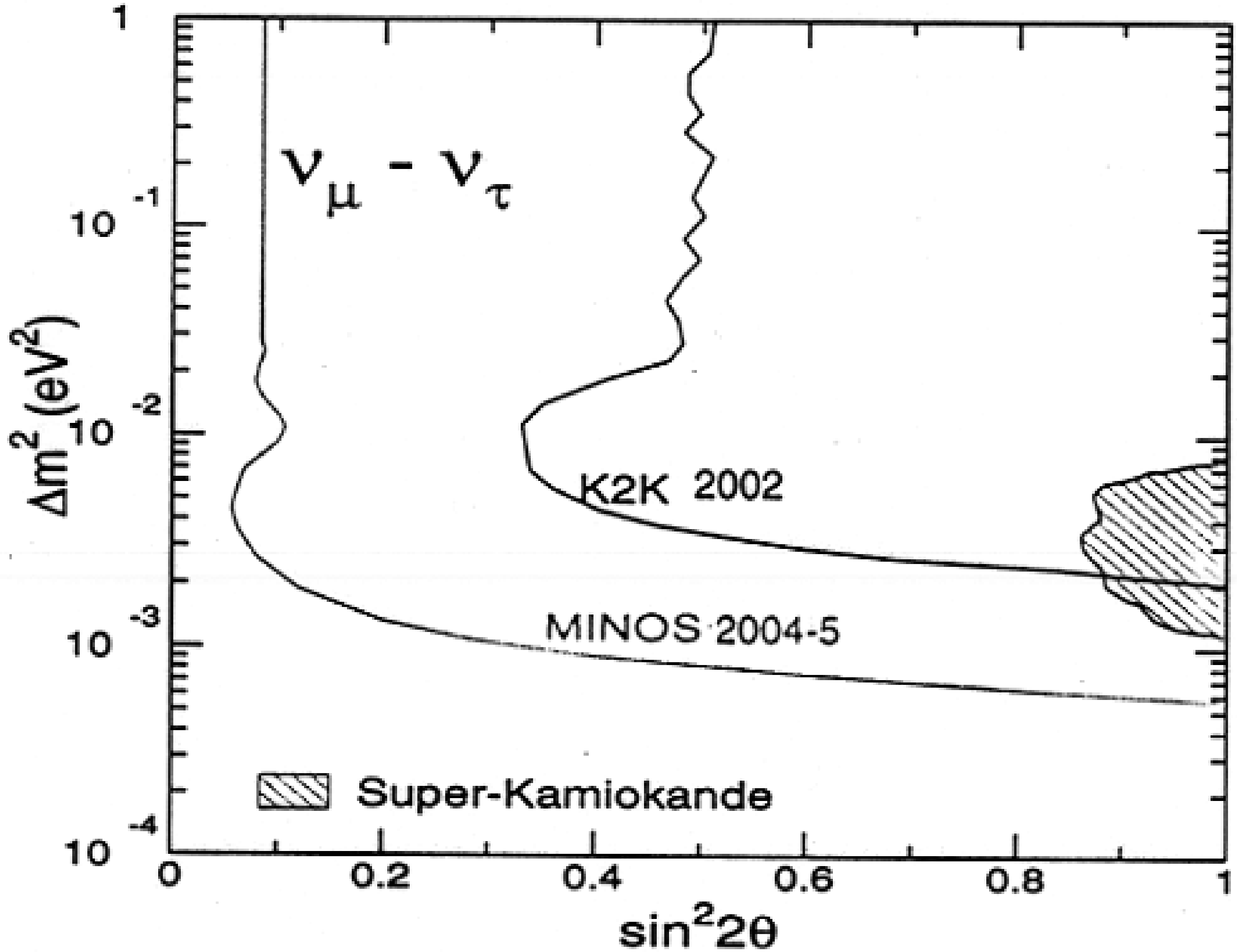
K2K Expectations and Status

- Expected Event Rates for 3yrs (~10^{20}pot):

	Fine-Grained Near	1 kt H_2O Near	Super-K
ν_μ CC	126,700	408,000	345
ν_μ NC	44,900	144,000	120
single π^0	9,200	29,500	25
ν_e CC	1,250	4,000	4

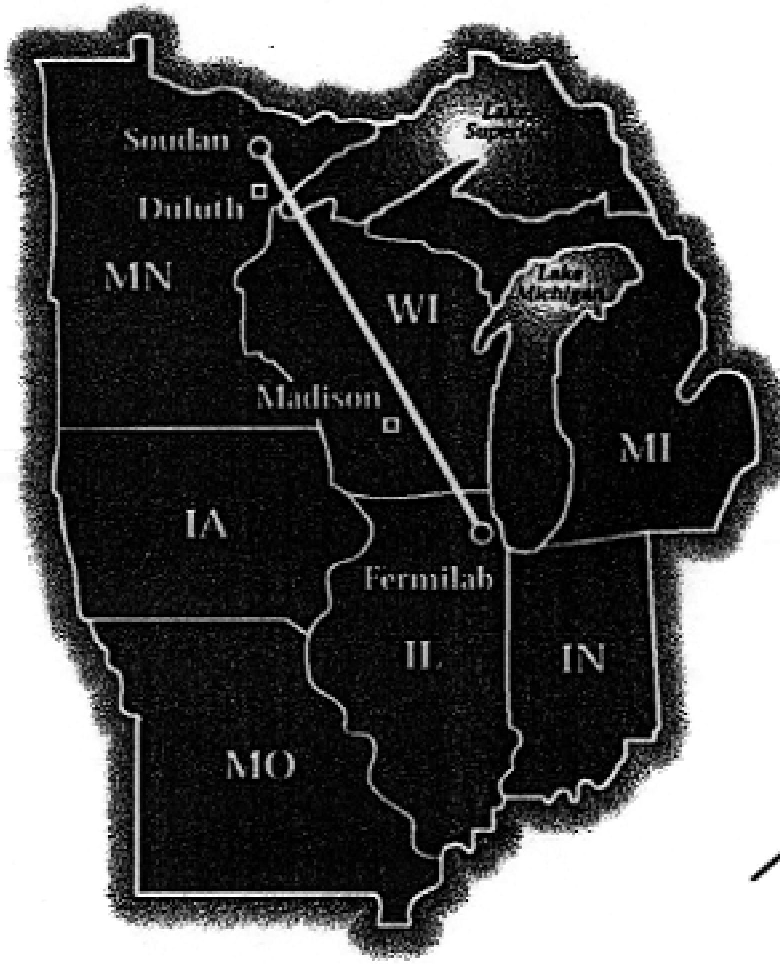
- Current Status:
  - Ran for 20 days.
    - Rate in front detectors close to expectation (10% low)
    - Observed four events in SuperK within 1μs
      One in fid.vol. with low energy
    - Expected five events in fid. vol. with no oscillations

K2K and MINOS Sensitivities



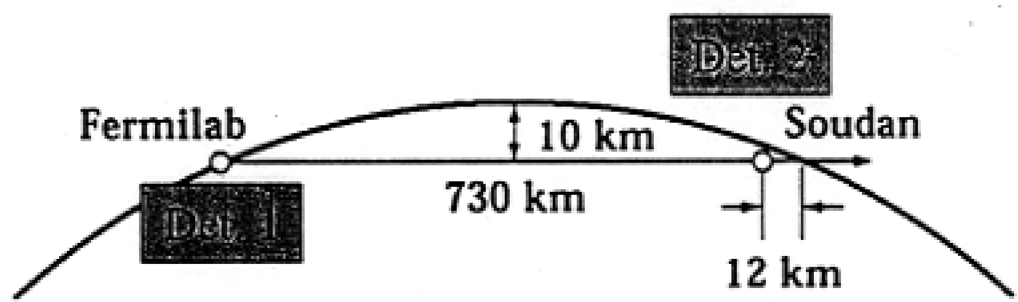
- **Only 90% CL regions ⇒ Need 4σ to 5σ**

The MINOS Beamline

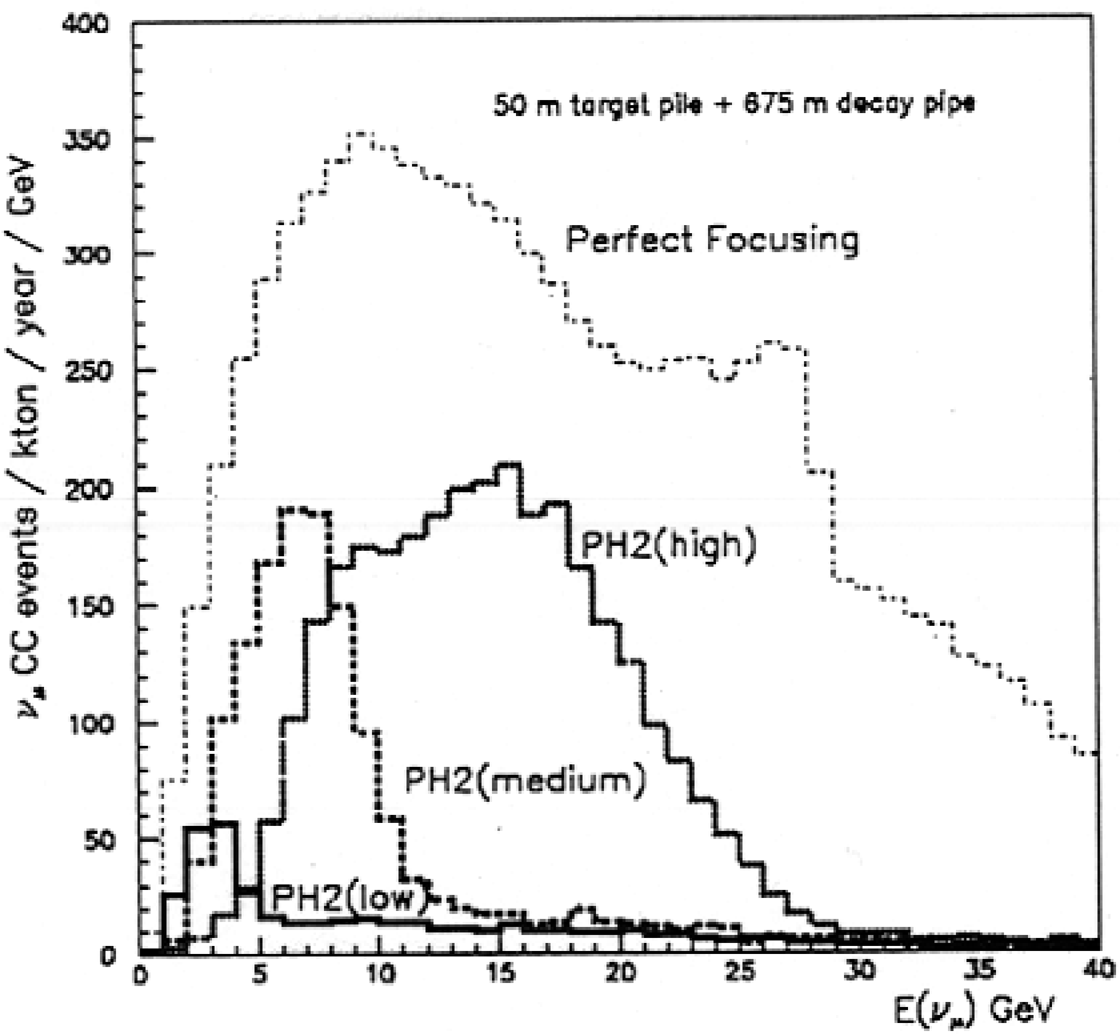


Two Detector Neutrino Oscillation Experiment (Start 2004)

- Far Detector (5.4 ktons) :
  - 8m diameter by 1" steel plates
  - 4cm wide solid scintillator strips
  - Steel magnetized at 1.5 T



NuMI Beam Options

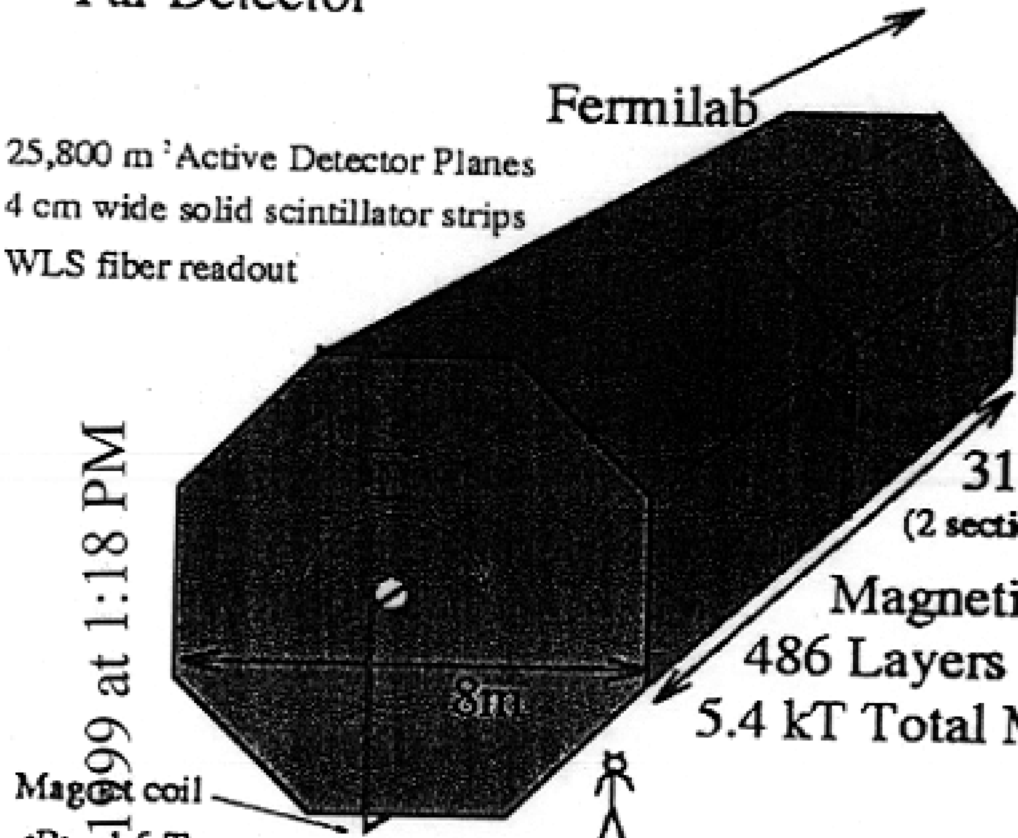


- CC Events Rates in Minos 5kt detector:
  - High 10,000/yr
  - Medium 5,000/yr
  - Low 700/yr

MINOS Far Detector

Far Detector

25,800 m ²Active Detector Planes
4 cm wide solid scintillator strips
WLS fiber readout

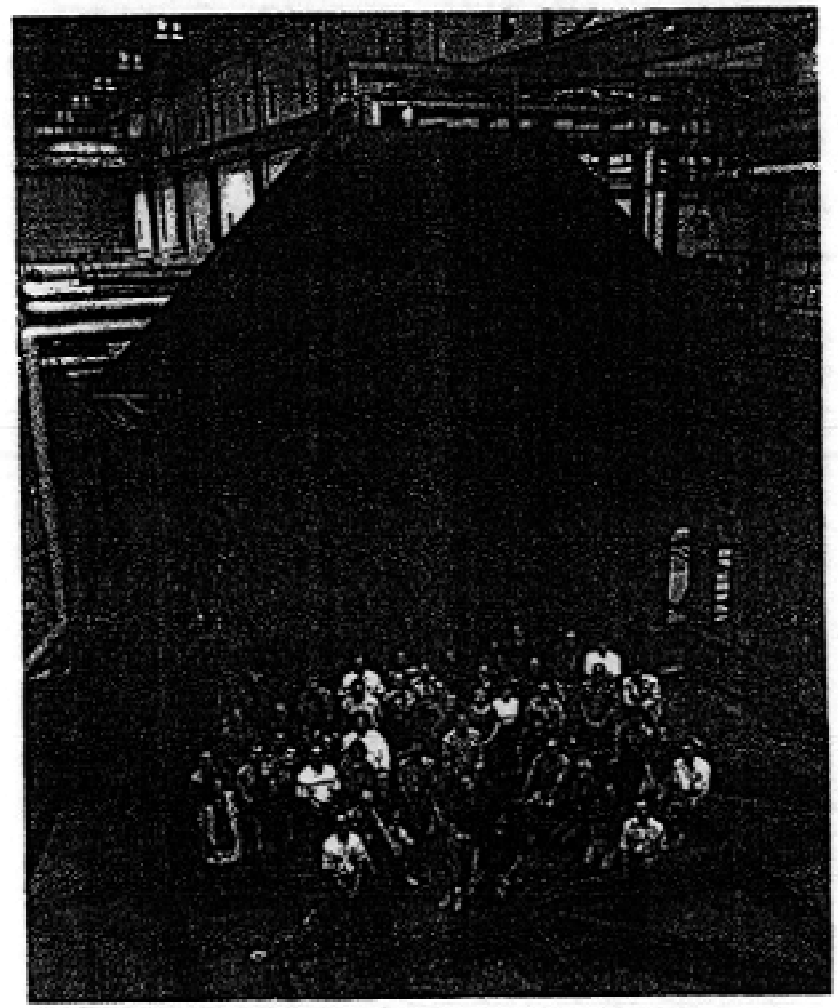


Magnetized Fe Plates
486 Layers x 2.54 cm Fe
5.4 kT Total Mass

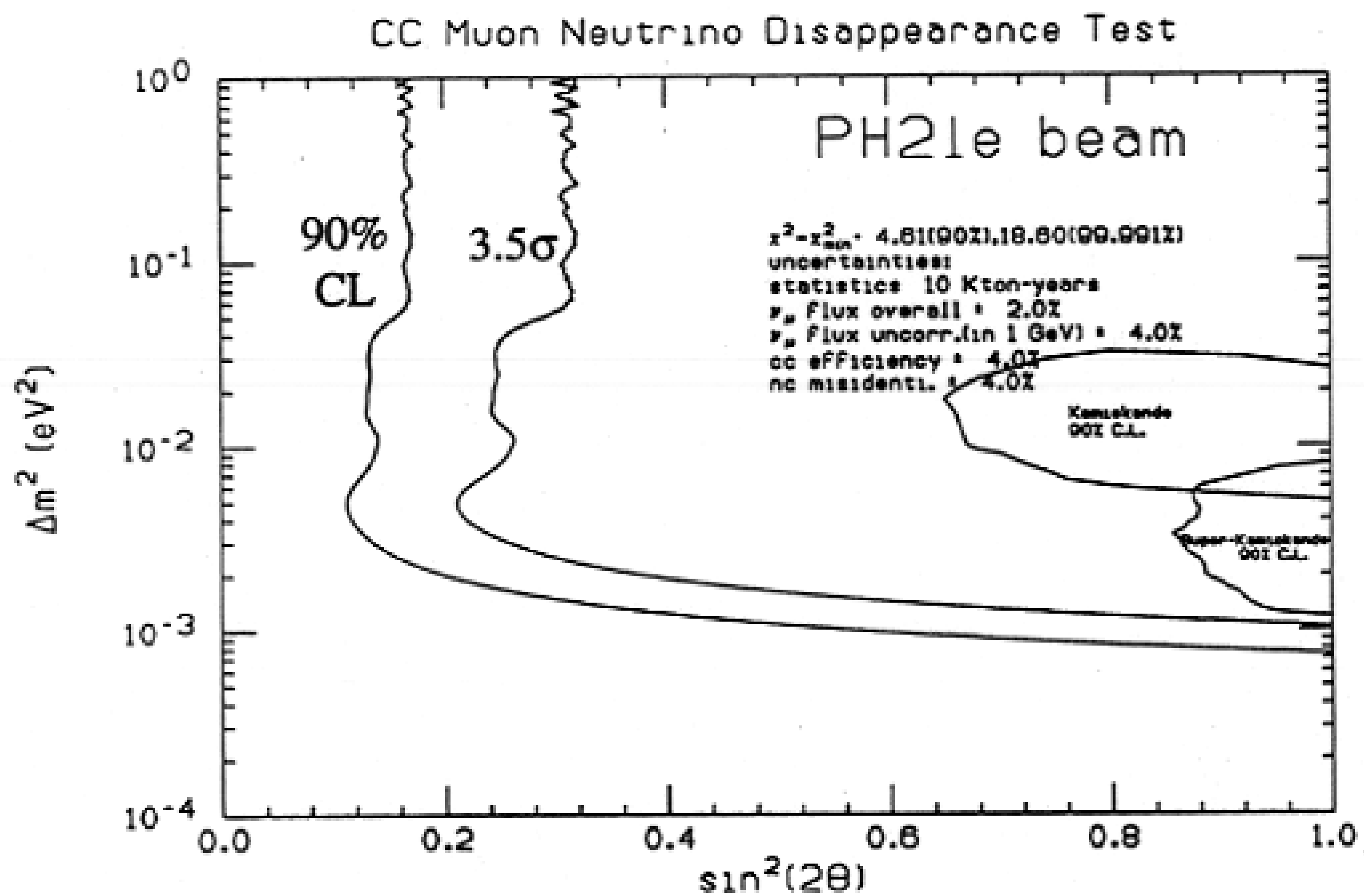
Schedule

- Detector Hall construction in Minnesota (now - 2001)
- Beam Tunnel construction at Fermilab (2000 - 2002)
- Far Detector construction (2001 - 2003)
- Start data run (2003 - 2004)

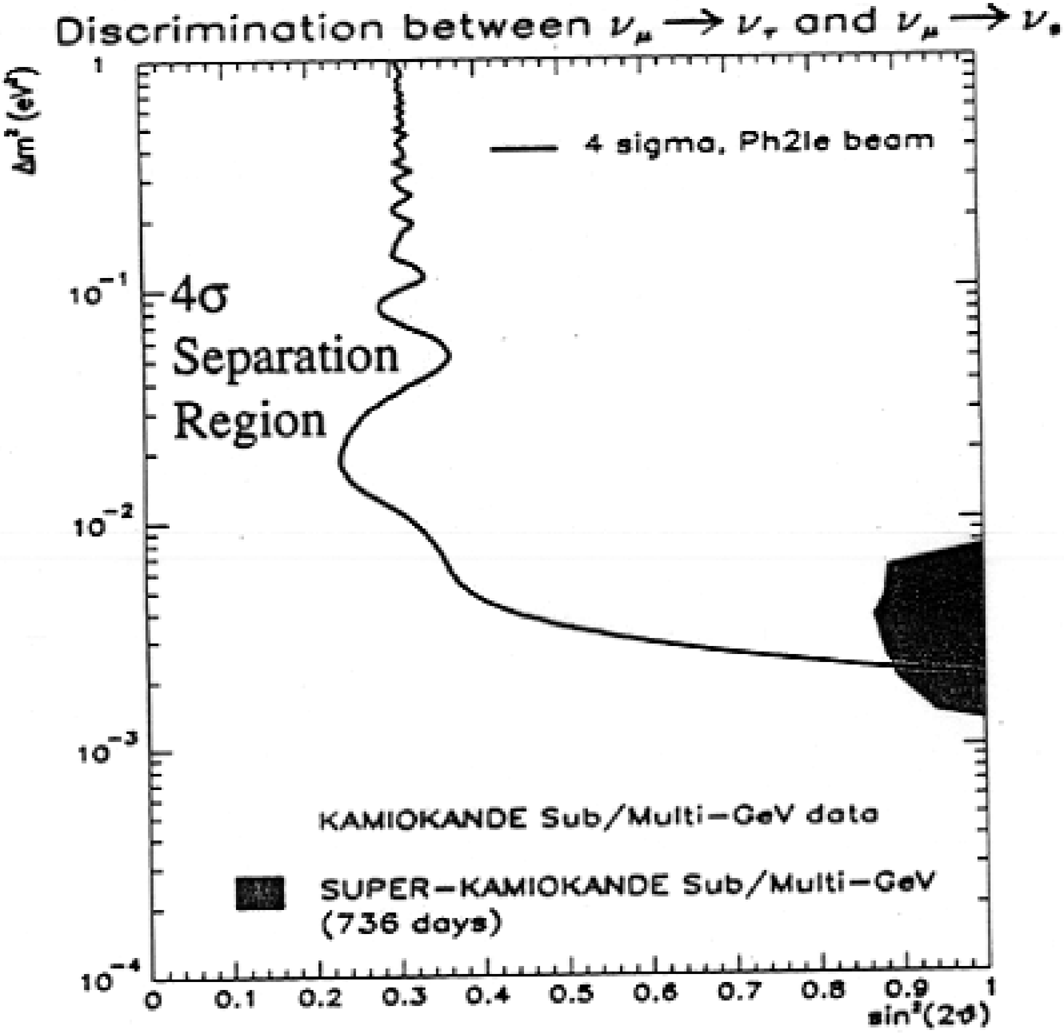
MINOS Steel Plane Prototype



MINOS Δm^2 Sensitivity



MINOS Oscillation Mode Sensitivity
(Discriminate $\nu_\mu \rightarrow \nu_\tau$ vs. $\nu_\mu \rightarrow \nu_{sterile}$)



- Use CC/NC Ratio to distinguish between oscillations to ν_τ or $\nu_{sterile}$
- For $\nu_\mu \rightarrow \nu_\tau$, CC production of τ's will look like NC ~80% of the time

  CC/NC → down
- For $\nu_\mu \rightarrow \nu_{sterile}$, both CC and NC will be suppressed.

  CC/NC stays ~ constant

Is the Next Step a ν_τ Appearance Experiments?

- Will MINOS and/or SuperK decisively determine oscillation mode corresponding to the atmospheric deficit?

- If not, then may need to observe ν_τ directly
  - ***MINOS: Hybrid Emulsion Detector***
  - ***CERN to Gran Sasso Program***

- These new detectors may also be able to probe $\nu_\mu \rightarrow \nu_e$ at low Δm^2 and low $\sin^2 2\theta$
  - Sensitive to other elements of the lepton mixing matrix

ν_τ Appearance Experiments

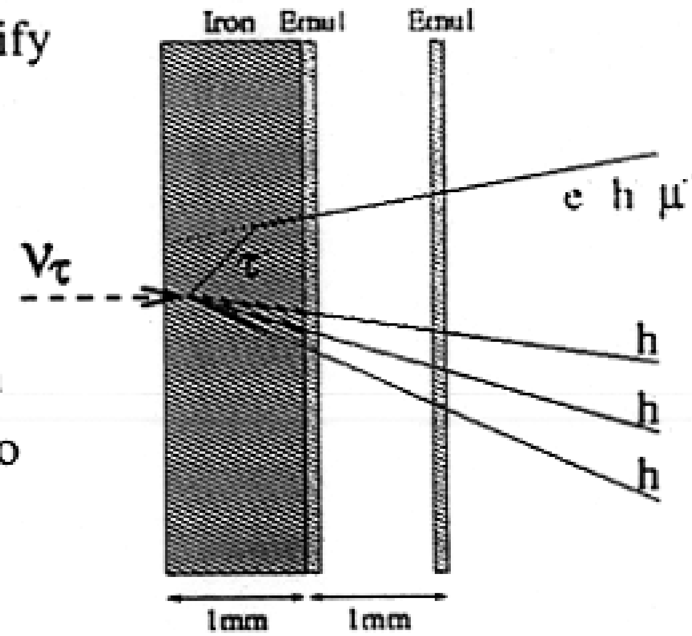
ICANOE

MINOS (HED)	NOE	ICARUS	Opera
~ 1 kt	8 kt	2.4 - 30 kt	0.8 kt
Hybrid	Fine grain	LAr TPC	Pb or Fe
Emulsion	calorimeter	τ ID	Emulsion

Cern to Gran Sasso ν Osc. Program (CNGS)

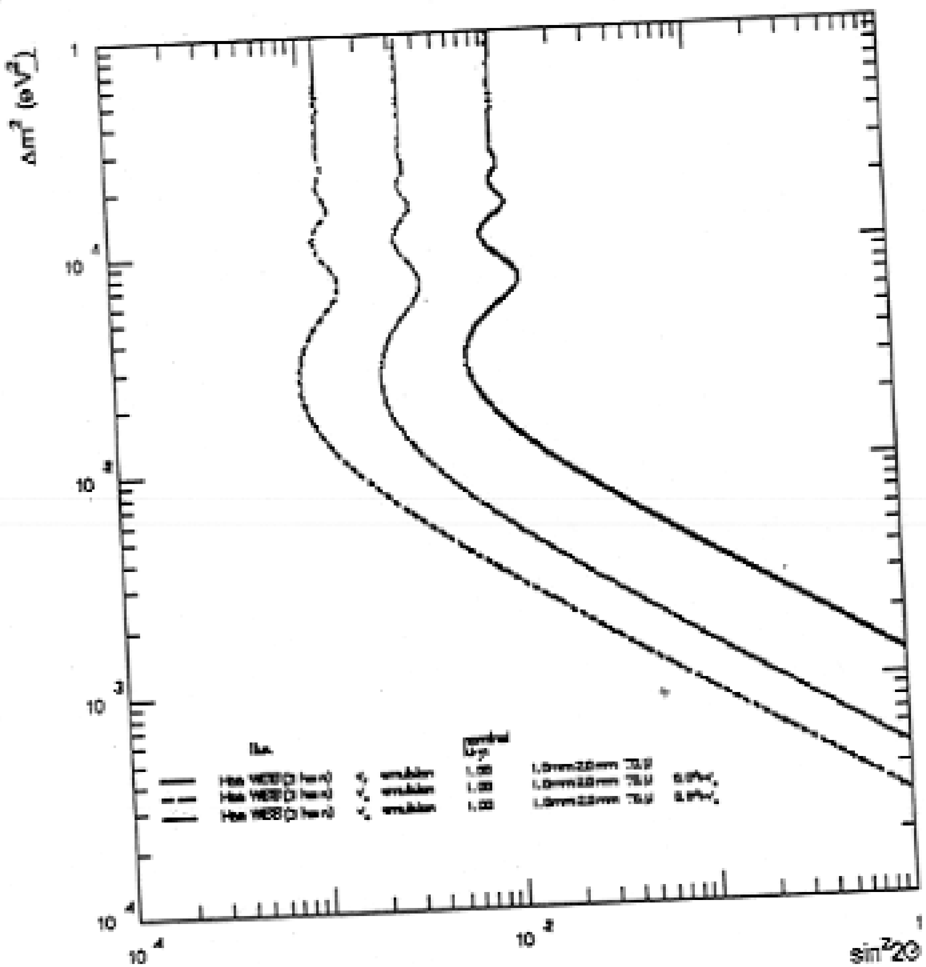
MINOS Hybrid Emulsion Detector

- Emulsion (combined with scintillator or chambers)
  - Emulsion may be only practical medium to identify ν_τ interactions on an individual event basis
  - Unambiguous determination of the oscillation into ν_τ
- Problems/challenges:
  - Need to reach large fiducial mass of order 1 kton
  - Finding and scanning events in emulsion needs to be automated



- Fermilab considering this addition to MINOS
  - Physics case to be reviewed in Nov.
    - ⇒ R&D program with goal of detector in 2005

Emulsion Detector Sensitivity



1 kt-yr Exposure
High energy beam

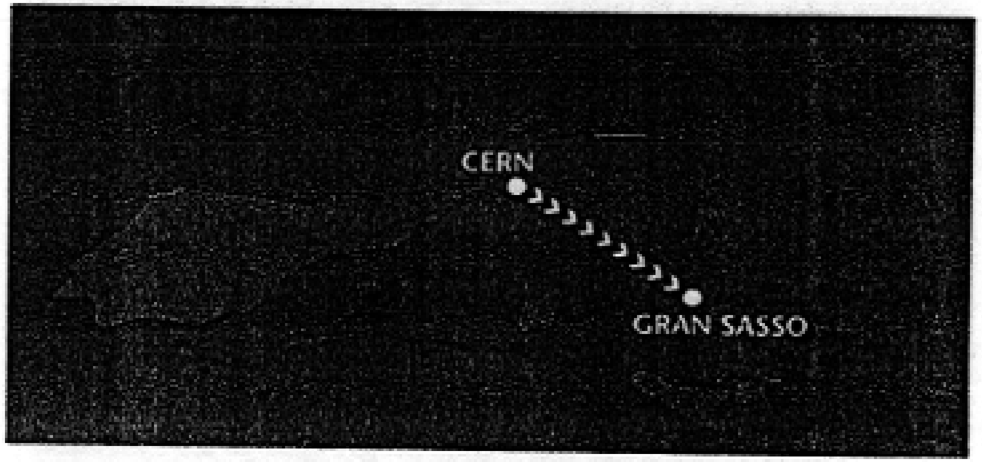
—— $\nu_\mu \rightarrow \nu_\tau$

...... $\nu_\mu \rightarrow \nu_e$ (0.6% ν_e)

- - - $\nu_\mu \rightarrow \nu_e$ (no ν_e)

1mm thick lead
2mm thick spacer

CERN to Gran Sasso ν Osc. Program (CNGS)

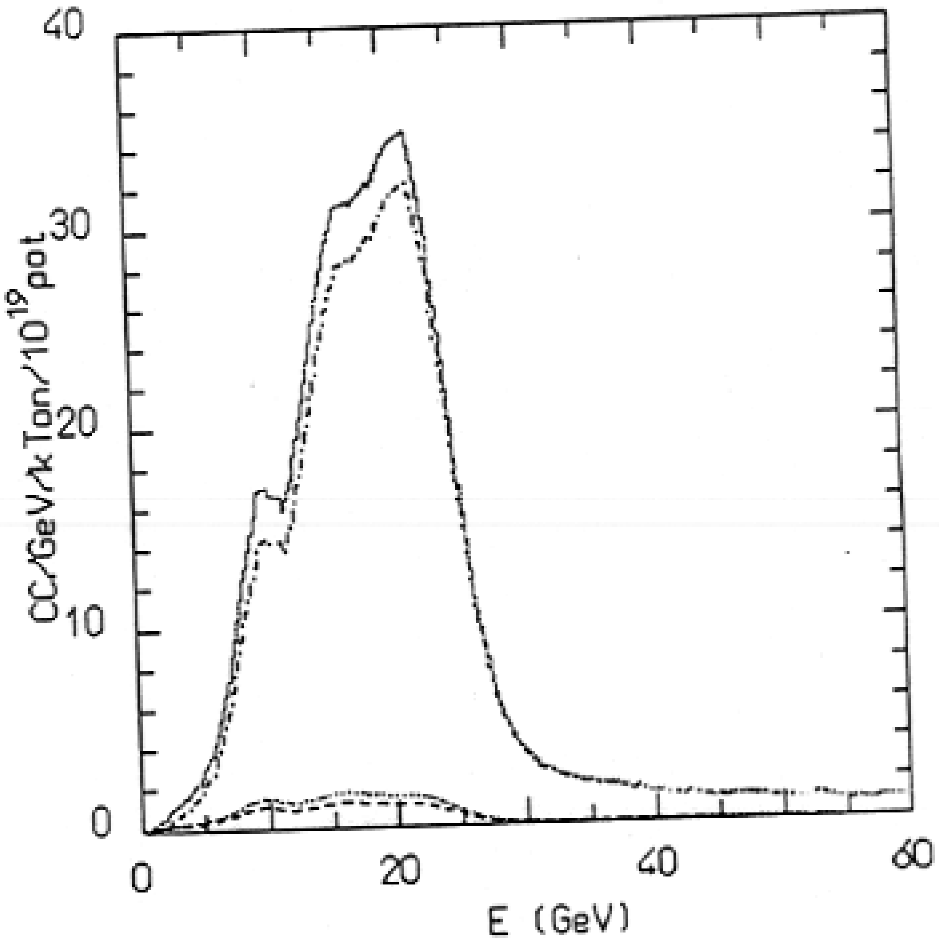


- The possibility of a neutrino beam from CERN to Gran Sasso is also being considered
  - Unlikely that a near detector hall would be built
- Emphasis on appearance experiments with ν_τ and ν_e identification
  - ***Opera Experiment***: Emulsion detector (similar to MINOS HED)
  - ***ICANOE Experiment***: Liquid argon plus fine grain calorimetry
- Formal Decision expected in December

CERN to Gran Sasso Beam

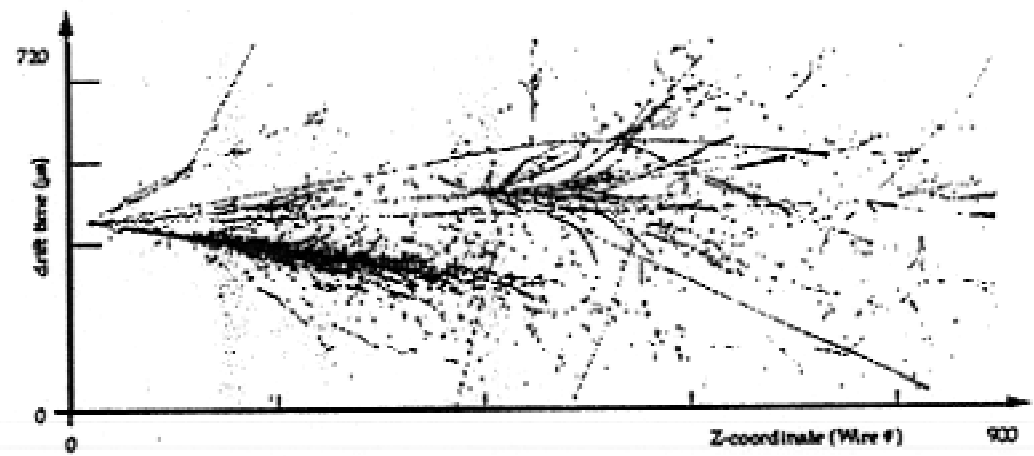
- Uses 400 GeV protons on target:
  - $\langle E_\nu \rangle \approx 17$ GeV
  - Distance ≈ 750 km
  - $\sim 4.5 \times 10^{19}$ protons on target/yr
- Event rate at Gran Sasso:
  - ν_μ CC: 2450 events/kton/yr
  - ν_μ NC: 823 events/kton/yr
  - ν_e's (0.8%) : 21 events/kton/yr

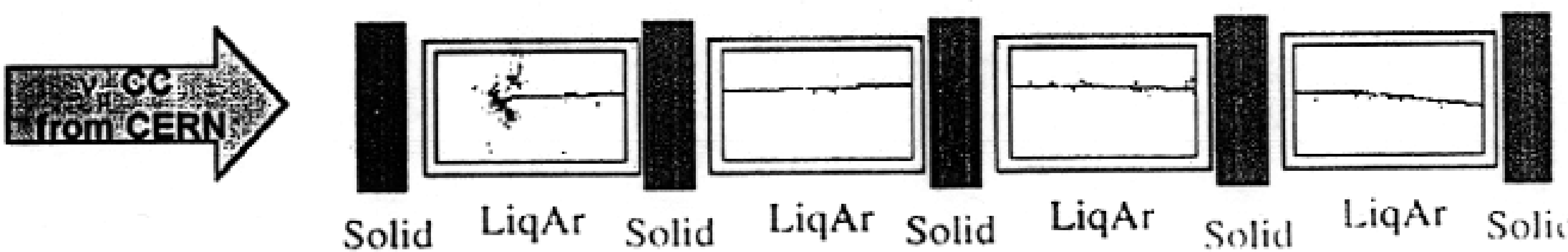
  ⇒ **Similar to MINOS beam**



ICANOE (ICARUS-NOE) Experiment

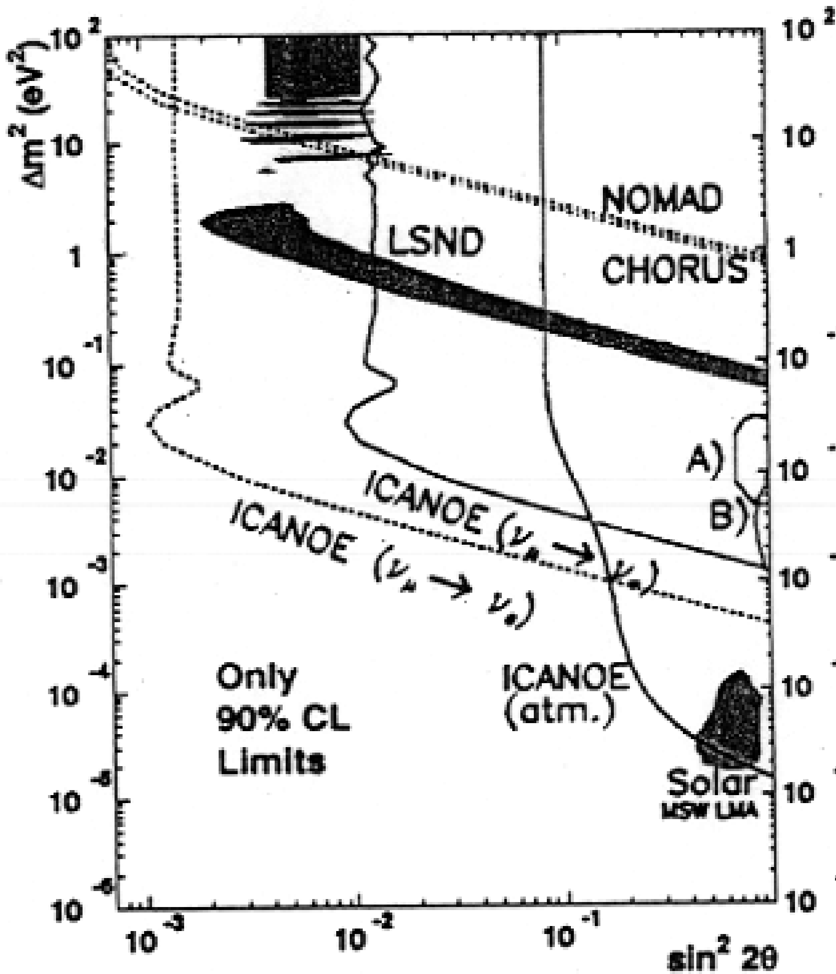
- Merging of liquid argon calorimeter with magnetized fine grain solid calorimeter
  - Liq Ar: 4 @ 1250 = 5000 tons
  - Solid: 4 @ 625 = 2500 tons
- Detect and identify all neutrino species





ICANOE Oscillation Sensitivity

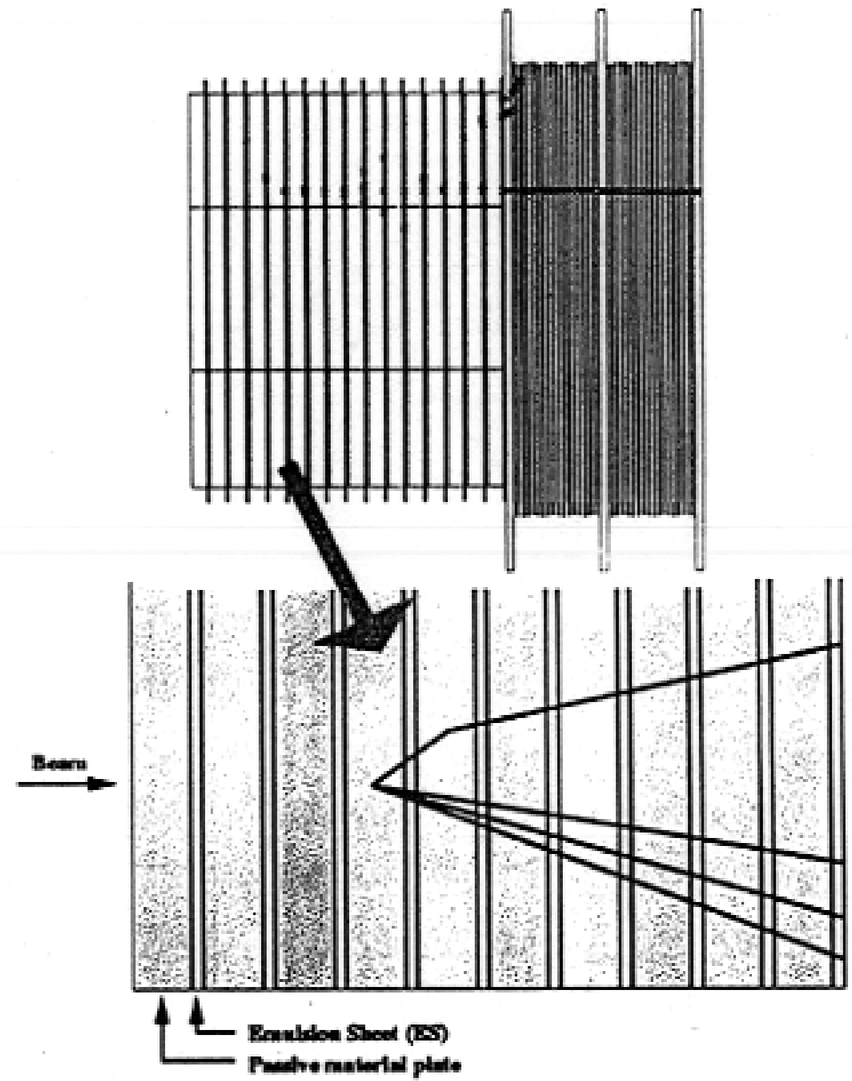
- CERN-NGS neutrinos
  - ν_τ appearance search
    - Fine grain detector
    - Kinematical selection
  - ν_e appearance search
    - Good electron ID
    - Bkgnd from beam ν_e and $\nu_\mu \rightarrow \nu_\tau \rightarrow \tau \rightarrow e$
- Atmospheric neutrinos
  - Isotropic detector
  - Good angular and energy resolution for investigating osc. effects
  - Can reach Solar LMA region for low E_ν and $\cos\theta_Z = -1$



OPERA Hybrid Emulsion Experiment

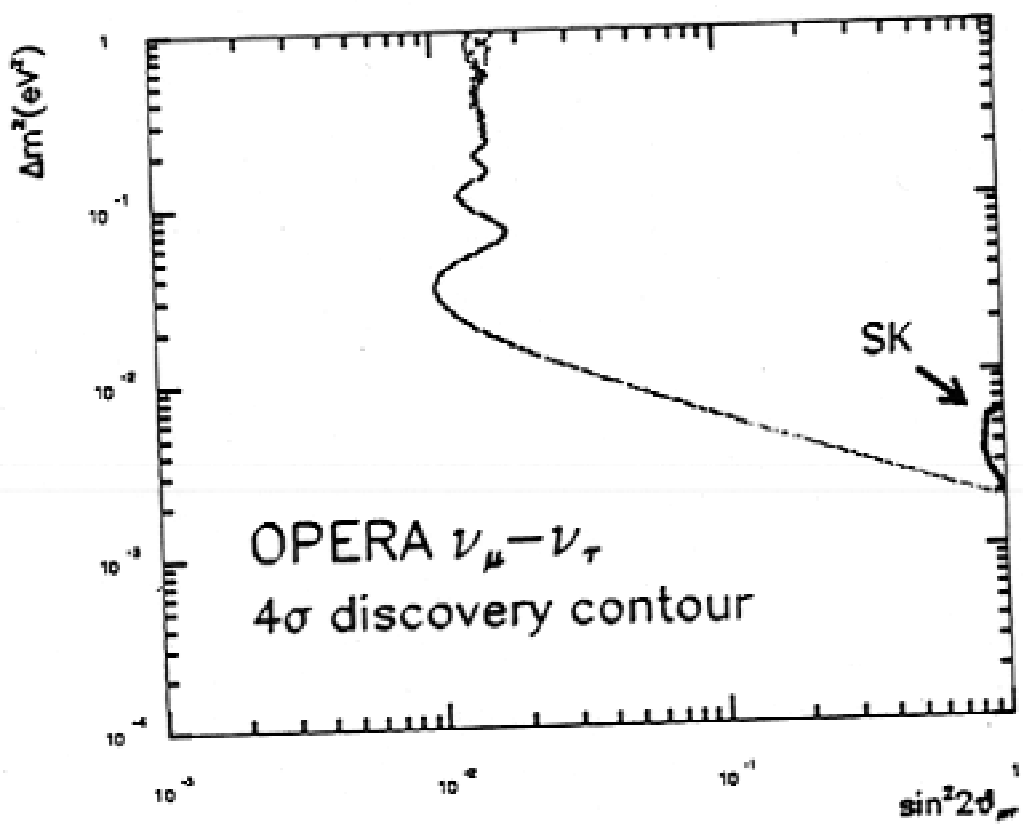
(Oscillation Project with Emulsion-tRacking Apparatus)

- Emulsion bricks interspersed with electronics trackers (like MINOS HED proposal)
  - Trackers determine bricks with neutrino events
  - Use automated scanning to find and measure events in emulsion
  - Look for indications of τ-decay kink
- Goal: 1.5 kton hybrid target
  - ~ 3,600 ν_μ CC events/yr × efficiency
  - ~ 45 ν_τ events/yr × efficiency @ $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2
    - efficiency: 2 - 10 % ?



OPERA Sensitivity

- Very low background
  - Can confirm oscillations with few events
- For five year exposure (2.25×10^{20} pot)
  - ~ 20 $\nu_\mu \rightarrow \nu_\tau$ osc. events @ $\Delta m^2 = 3.5\times10^{-3}$ eV^2
  - ~ 0.5 events background



LSND Experiment at LANL

- Neutrino source from stopped π^+'s in the proton beam stop.
  - 1mA, 800 MeV protons
  - Cerenkov detector: 167 tons @ 30 m
  - π^+ decay chain gives no $\bar{\nu}_e$ $\langle E_\nu \rangle \approx 40$ MeV
  - Look for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

"Decay-at-rest" Analysis (ν's from beamstop)

stopped $\pi^+ \rightarrow \nu_\mu \mu^+$

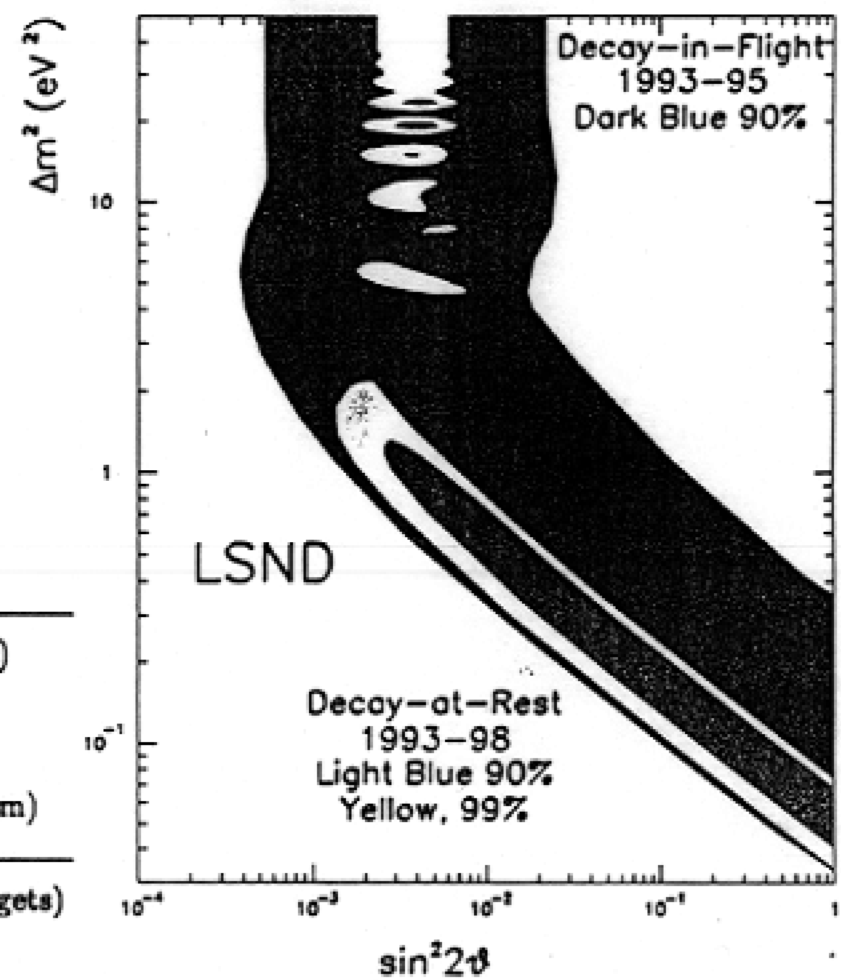
$\hookrightarrow e^+ \bar{\nu}_\mu \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Excess: 39.5 ± 8.8 events (1993-1998, prelim)

"Decay-in-flight" Analysis (stop + upstream targets)

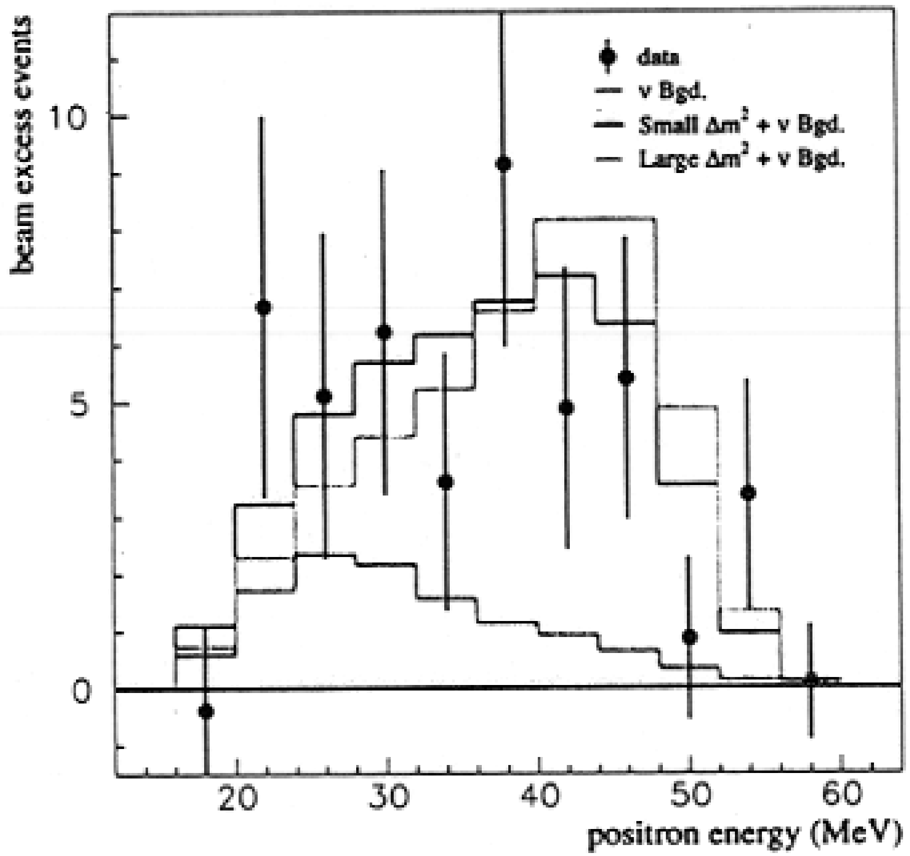
$\pi^+ \rightarrow \nu_\mu \mu^+$ $\nu_\mu \rightarrow \nu_e$

Excess: 18.1 ± 6.6 ± 4.0 events (1993-1995)

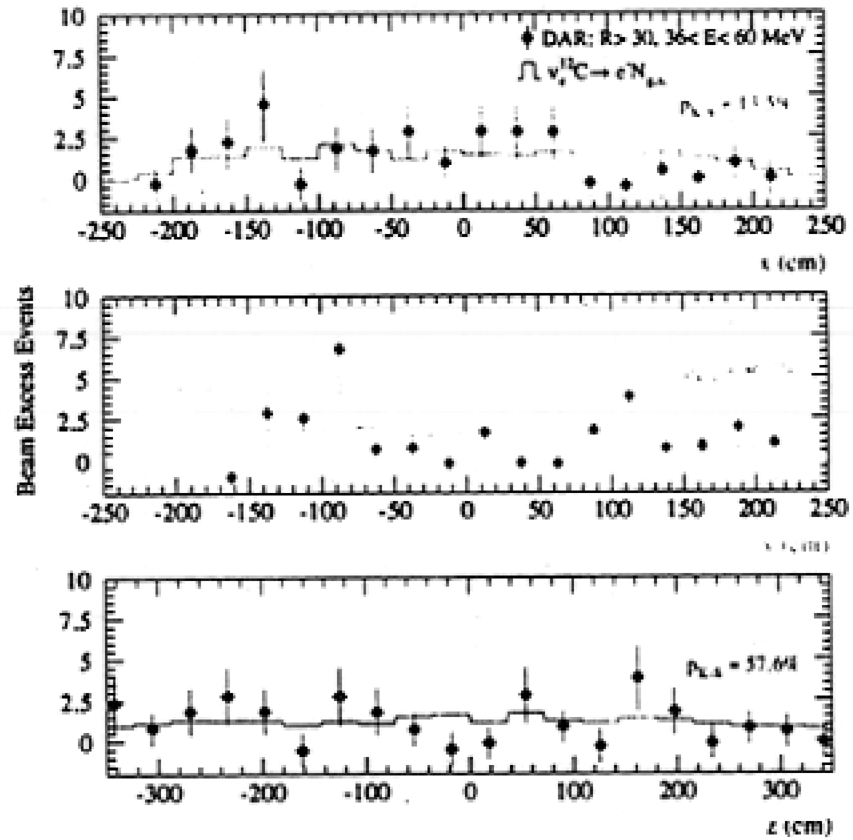


Distributions of Excess ν_e Events

- Excess ν_e events have much higher energy than backgrounds

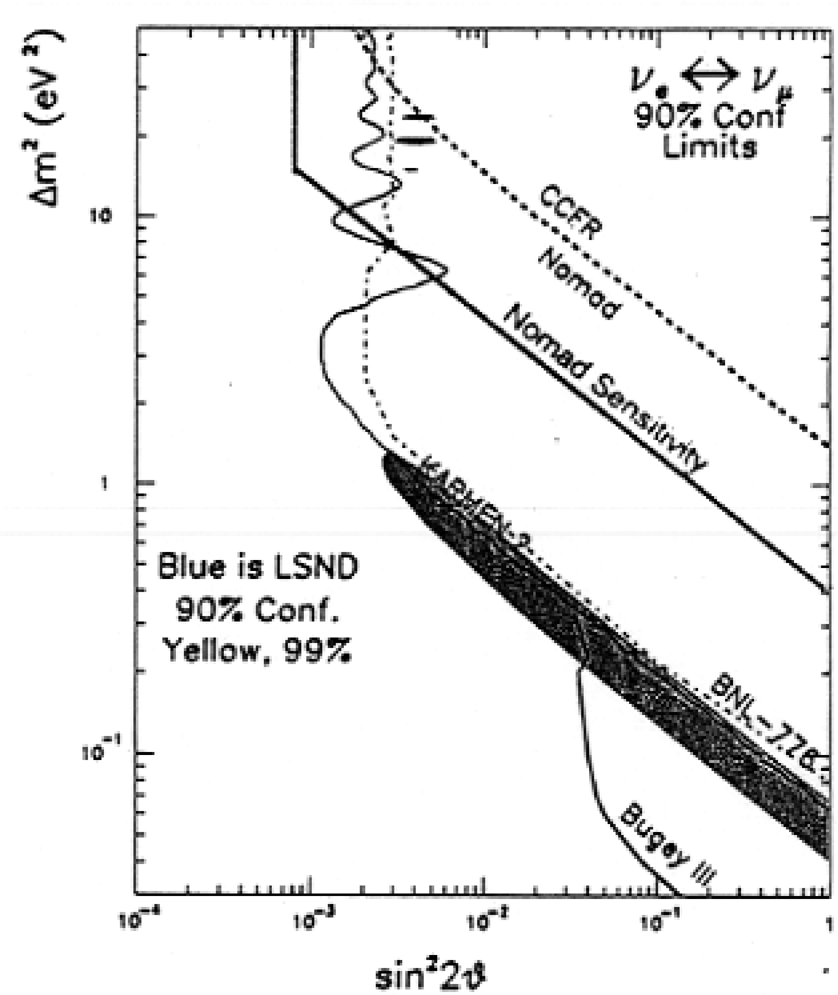


- Spatial distribution in detector is consistent with $\nu_e\,^{12}C \rightarrow e^- N_{g.s.}$ events



Restrictions from Other Experiments

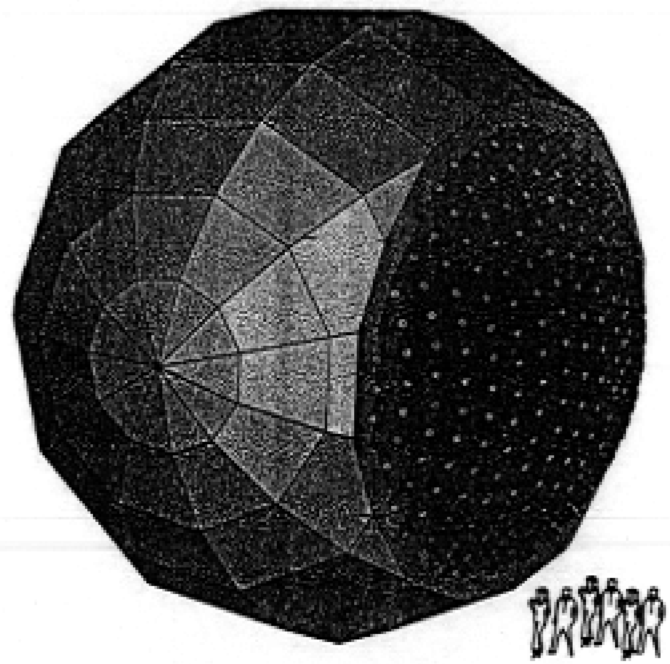
- CCFR and Nomad rule out high Δm^2 region
- Bugey Reactor experiment rules out high $\sin^2 2\theta$ and requires $\Delta m^2 > 0.2$ eV^2
- Karmen experiment :
  - Similar to LSND stopped π^+ beam (200 μa) but closer distance (18m)
  - Sees no indication of oscillation but is not incompatible:
    - Expected 8 events
    - Observed 7.8 ± 0.5 events



Need decisive experiment to check LSND result and measure parameters if oscillations ⇒ MiniBooNE

MiniBooNE ($\nu_\mu \rightarrow \nu_e$) Experiment at Fermilab

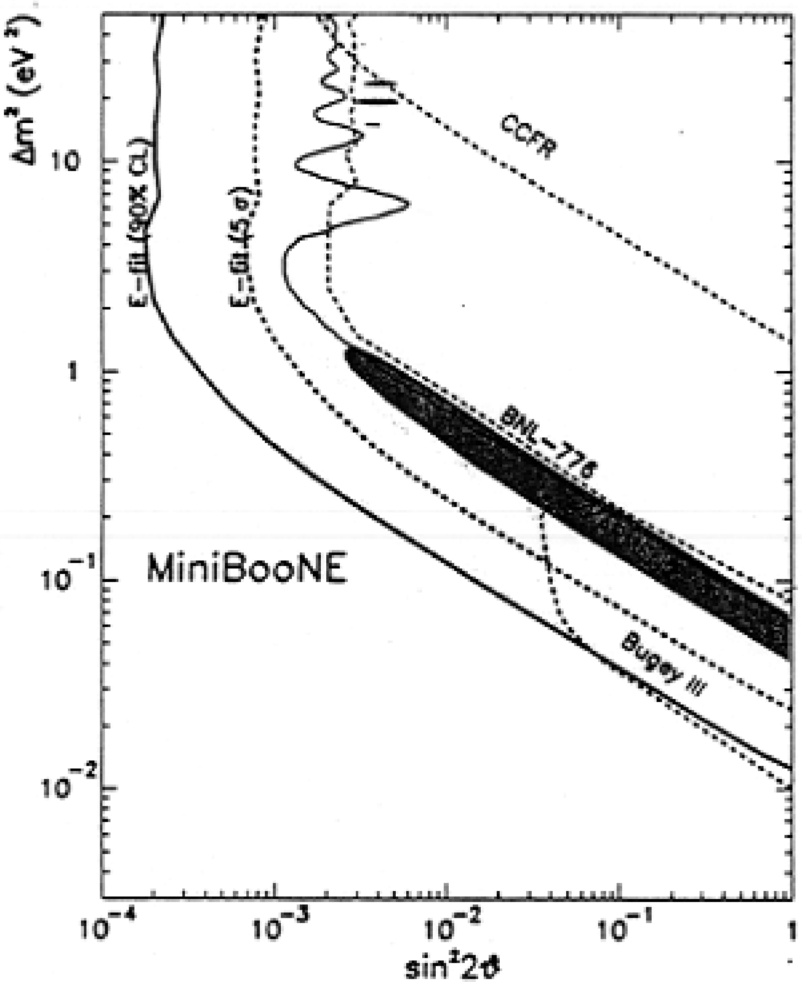
- Use protons from the 8 GeV booster
  ⇒ Neutrino Beam $\langle E_\nu \rangle \sim 1$ GeV
- Detector
  - 12 m sphere filled with mineral oil and PMTs
  - Located at 500m from neutrino source.
  - ~1000 event signal if LSND is verified
  - Expected significance 15 - 44 σ
  - If signal observed, add second detector at appropriate distance (MiniBooNE → BooNE Exp.)



Status:

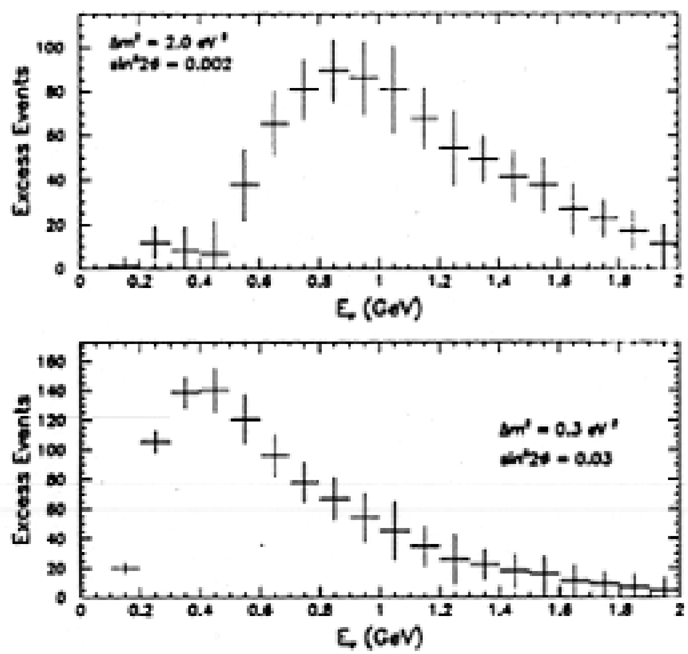
- Detector Tank Bid Accepted
- Beam/Target Station design being completed
- Beam and Detector complete end of 2001
- Data Run 2002+

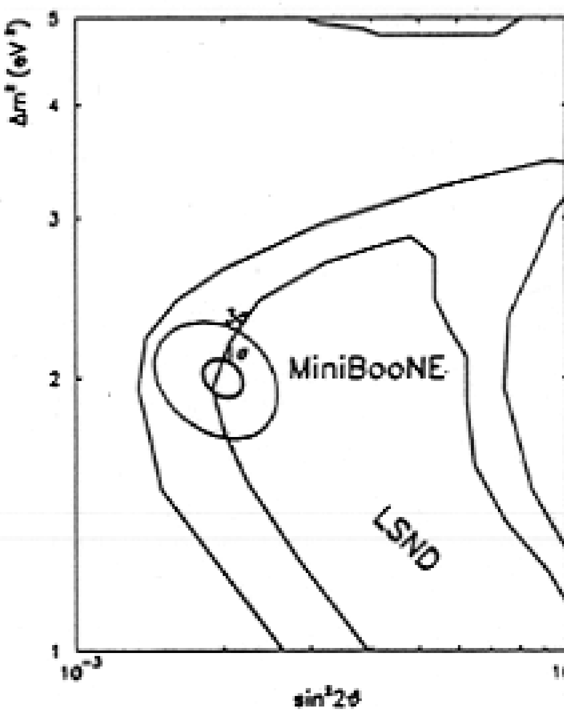
MiniBooNE Rates and Sensitivity



- Expected events/yr
  - 500,000 ν_μ CC quasi-elastic
  - 1275 ν_e from μ decays
  - 425 ν_e from K decays
- Decisive investigation of LSND region
  - LSND → >5σ signal in MiniBooNE
  - Osc. signal has different energy than intrinsic ν_e
  - Experimental determinations of all backgrounds.

MiniBooNE: Oscillation Parameter Measurements





Two signal examples:

Δm_0^2	$\sin^2 2\theta_0$	$\delta(\Delta m^2)$	$\delta(\sin^2 2\theta)$	Signal Signif.
0.3 (eV^2)	0.03	0.10 (eV^2)	0.02	44 σ
2.0 (eV^2)	0.002	0.10 (eV^2)	0.0002	15 σ

Muon Storage Ring ν–Factory

More detail in talk by A. Sessler

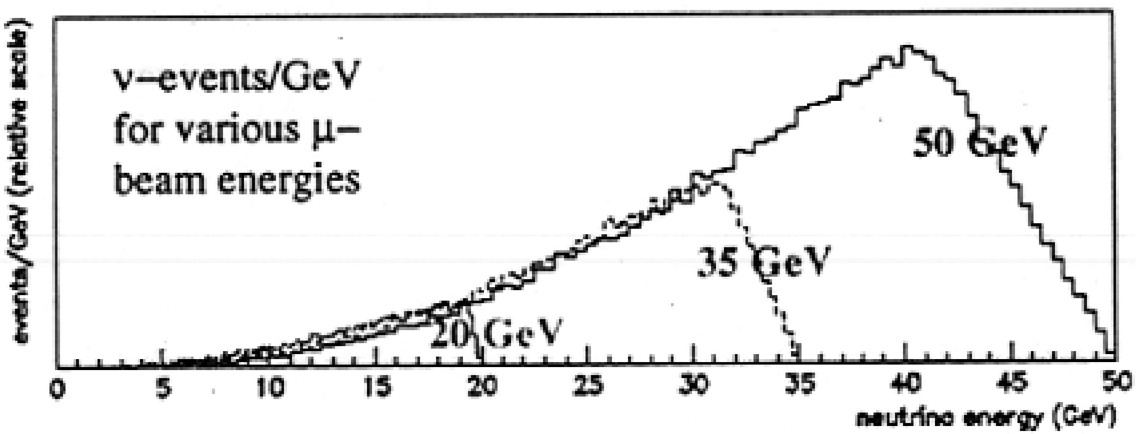
- Muon storage ring could provide a super intense neutrino beam at energies above τ threshold.
  - High intensity would allow studies of ν_τ oscillations and other oscillations at low mixing angles.
- Flavor composition/energy selectable and well understood:

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e \quad \text{or} \quad \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

- Highly collimated beam
  - Very long baseline experiments possible
- Physics opportunities
  - Map out different flavor oscillations
  - Start to see earth matter effects
  - Reach solar neutrino region with accelerator beams
  - Maybe even CP violation effects ??

ν - Factory Beam and Detector Parameters

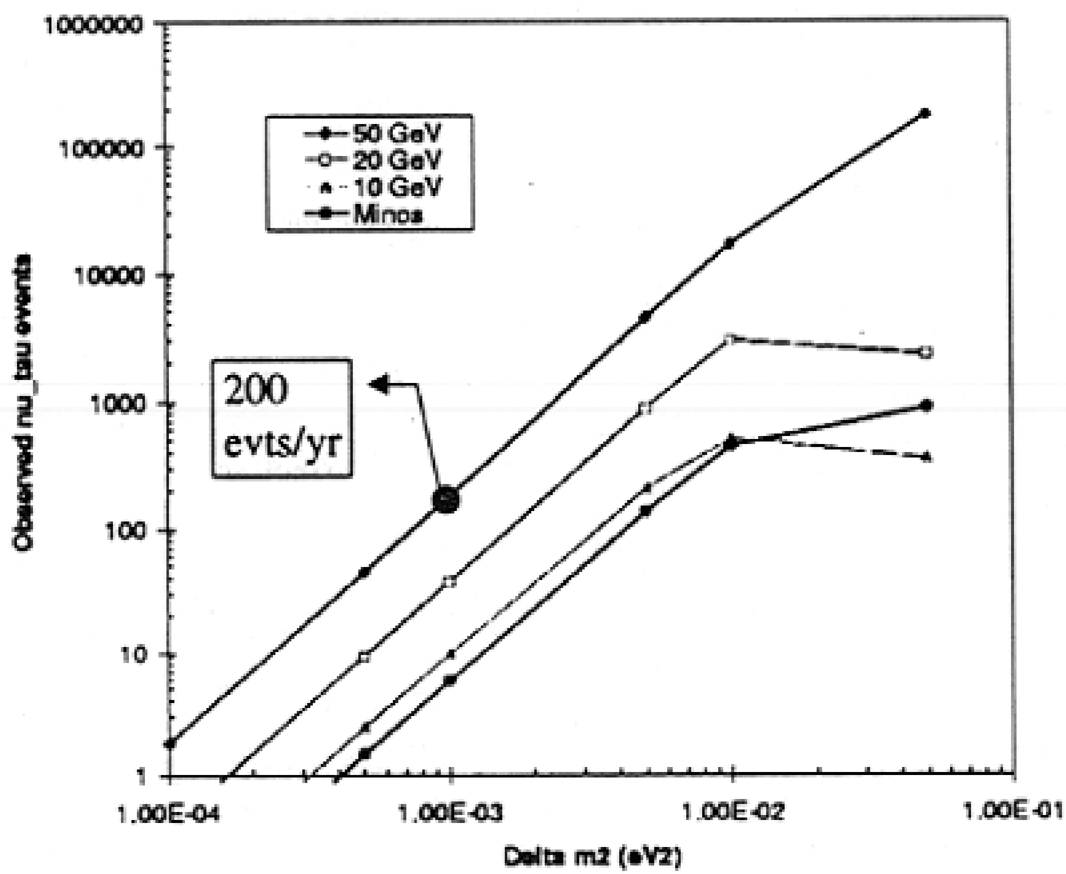
- High Rate Beam:
  - 10^{20} - 10^{21} muon decays /yr
  - ν rates higher than conventional beams for $E_{storage} > \sim 20$ GeV
  - Rate in detector $\propto E^3 \Rightarrow$ High storage ring energy ~ 50 GeV



- Detector:
  - Large: $\geq$ 10 kton
  - Need at least $\mu^{\pm}$ identification (with beam flavor constraints)
    - Better to also have $e^{\pm}$ and $\tau^{\pm}$ identification

ν_τ Appearance Rates in a ν–Factory Beam

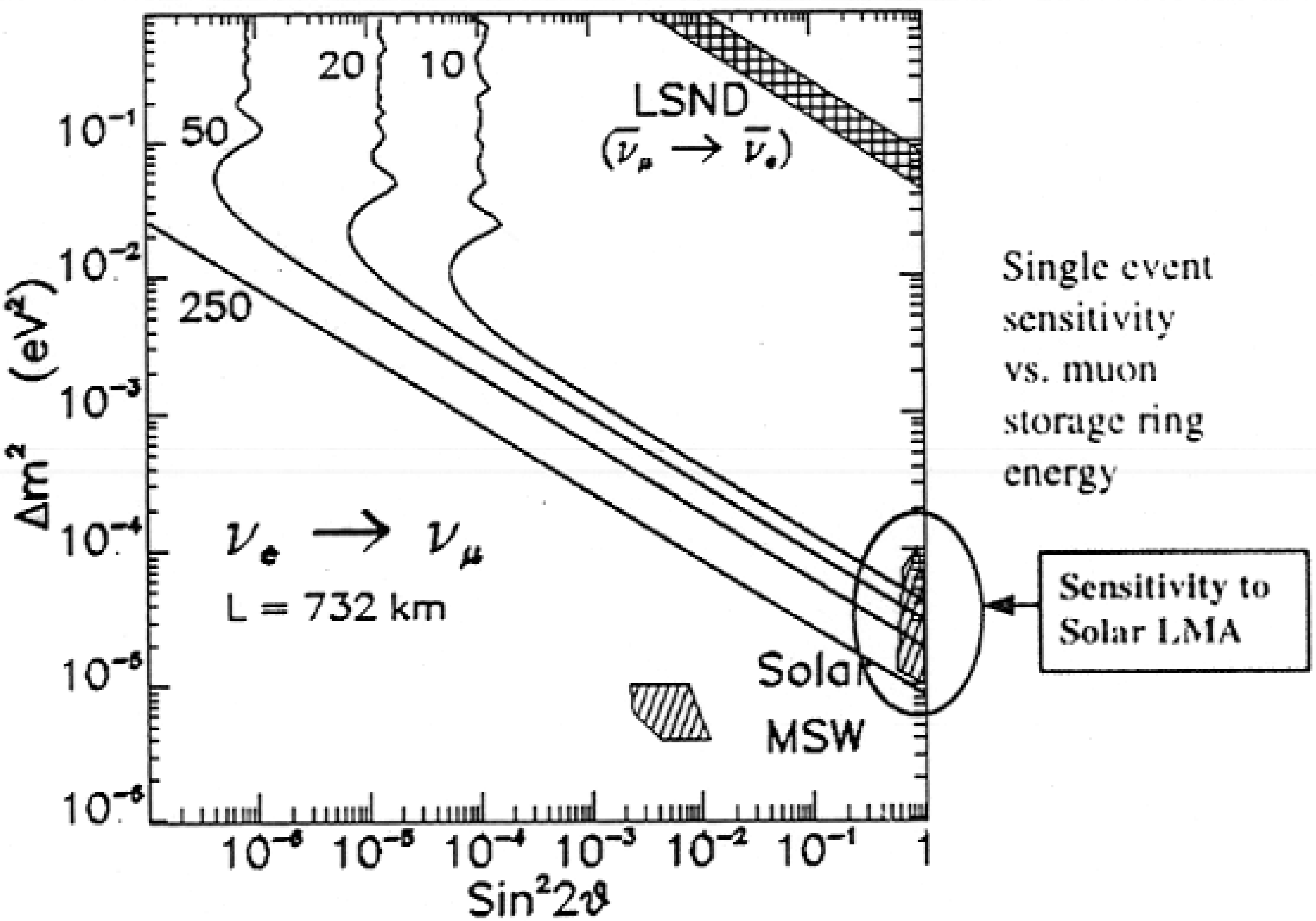
$\nu_\mu \rightarrow \nu_\tau$ events/2kton - yr



Comparison of ν-Factory rates for muon storage rings of various energies. (MINOS is also shown.)

- 1kton emulsion detector at 730km for 2 yrs. (Perfect efficiency)
- Assuming $\nu_\mu \rightarrow \nu_\tau$ oscillations with $\sin^2 2\theta = 1.0$

Low Δm^2 Sensitivity of ν–Beams



Summary

- Much more information in next five years