Accelerator-Based Neutrino Oscillation Experiments

- **Outline**
  - Basics
  - Early experiments
  - CHORUS / NOMAD
  - LSND / KARMEN / MiniBooNE
  - K2K / MINOS / Gran Sasso
  - Neutrino Factories

Basics: Oscillations

- Neutrinos are produced by the weak interaction in weak interaction eigenstates: ν_e, ν_μ, ν_τ
- There is no reason for these eigenstates to be identical to the mass eigenstates: ν_1, ν_2, ν_3
- They are related by a unitary transformation:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- This has come to be known as the Maki-Nakagawa-Sakata matrix after the physicists who in 1962 first wrote down a Cabibbo-like matrix for neutrinos.

Basics: Two ν Oscillations

- The mass eigenstates propagate as $e^{-iEt/\hbar}$. Thus, different masses develop different phases with time, resulting in oscillations in the weak eigenstates:
- If we consider only 2 states, then

$$\nu_\alpha = \nu_1 \cos\theta + \nu_2 \sin\theta$$

$$\nu_\beta = -\nu_1 \sin\theta + \nu_2 \cos\theta$$

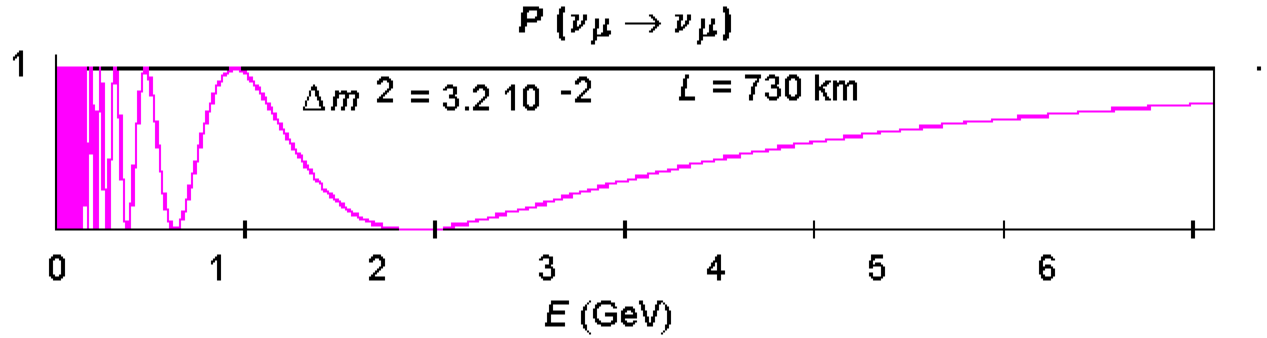
and

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right), \text{ where}$$

$$\Delta m^2 \equiv (m_1^2 - m_2^2) \text{ is in } (\text{eV}/c^2)^2, L \text{ is in km, and } E \text{ is in GeV.}$$

Basics: *L / E* Dependence

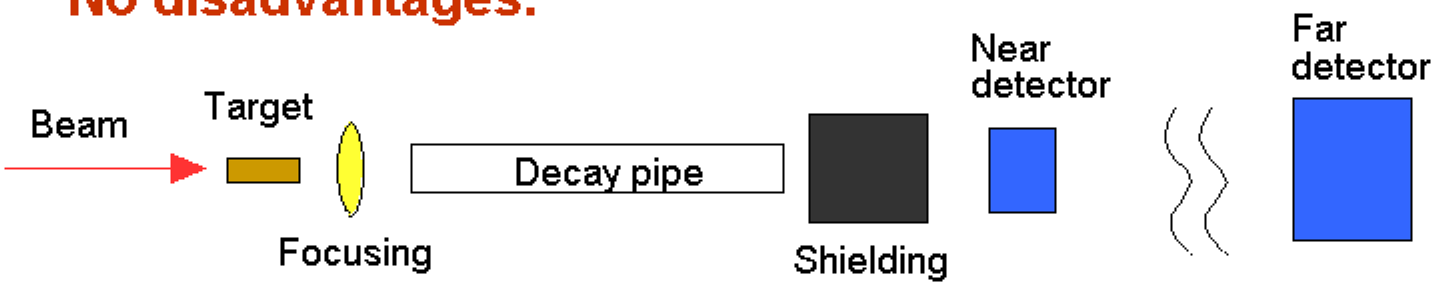
- In this case there are only two parameters to be measured: $\sin^2(2\theta)$, which determines the size of the oscillation, and Δm^2 in $\sin^2(1.27\,\Delta m^2 L/E)$, which determines the dependence of the oscillation on L/E .
- For $\Delta m^2 << L/E$, $P \rightarrow \sin^2(2\theta)(1.27\,\Delta m^2 L/E)^2$
- For $\Delta m^2 >> L/E$, $P \rightarrow \sin^2(2\theta)(1/2)$
- Maximum sensitivity to both parameters at $E/L \cong 0.81\,\Delta m^2$



Basics: Types of Experiments

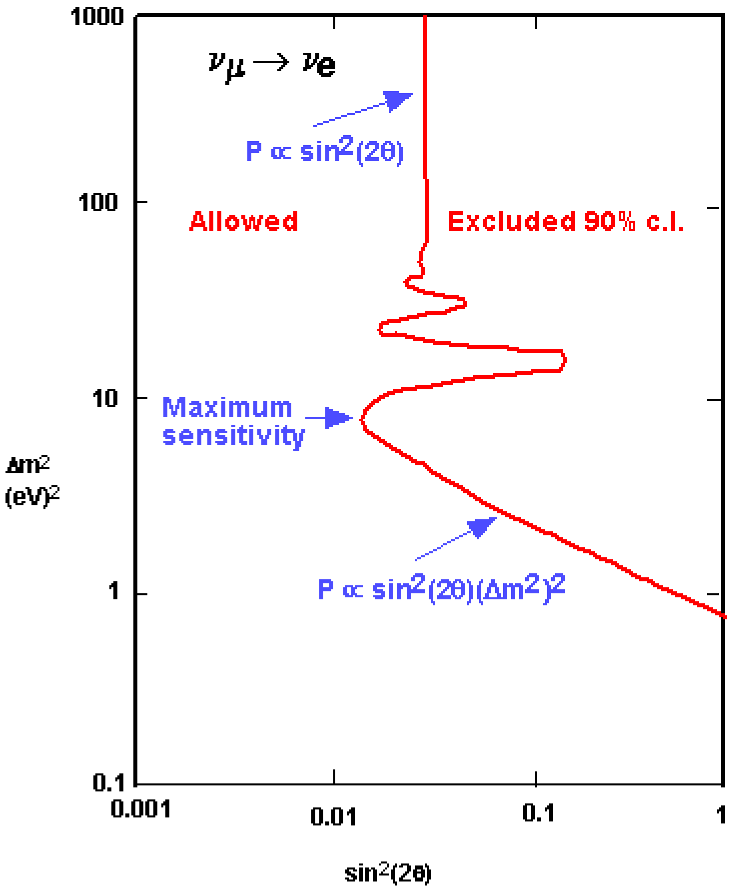
- Disappearance or appearance
  - **Disappearance: Sum of all oscillations including those to sterile neutrinos**
  - **Appearance: Specific channel, in general capable of greater sensitivity to $\sin^2(2\theta)$**
- One or Two detectors
  - **One detector: Expectations must be calculated**
  - **Two detectors: Expectations taken from near detector.**

No disadvantages.

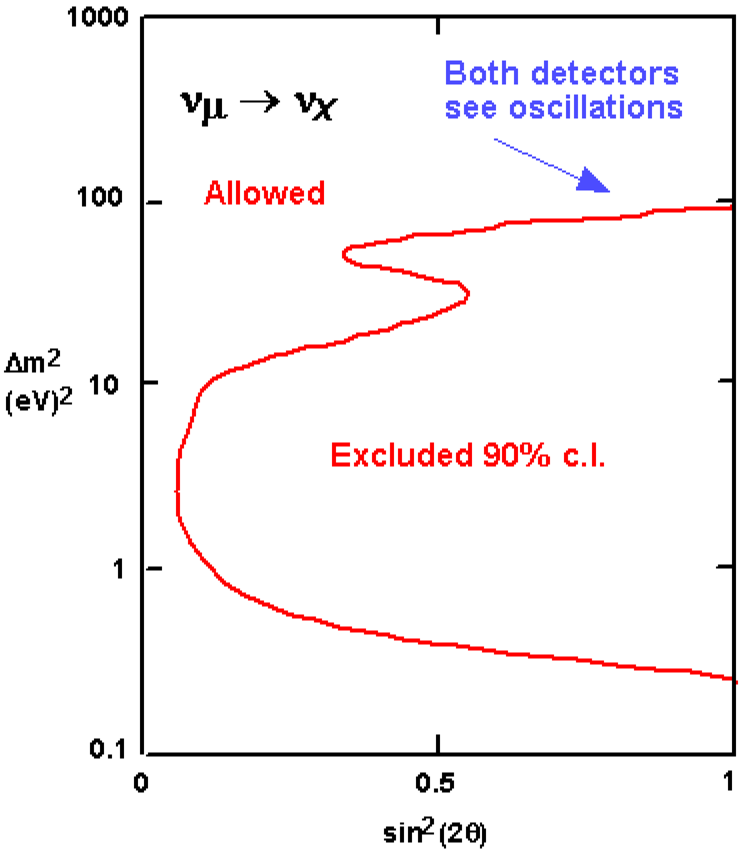


Basics: Exclusion Plots

1981 Fermilab Bubble Chamber Experiment



1983 CERN 2 Detector Counter Experiment



Basics: 3 Neutrino Mixing

- Increasingly, we need to consider 3 neutrino mixing.
- A 3x3 unitary matrix has 4 independent parameters, three angles and a complex phase. We take these to be $\theta_{12}, \theta_{13}, \theta_{23}$ and δ. Then

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

where $c_{ij} \equiv \cos(\theta_{ij})$ and $s_{ij} \equiv \sin(\theta_{ij})$.

Basics: 3 Neutrino Mixing

- With 3 neutrinos, a CP violation term enters, but it will not be important in our discussion until we discuss neutrino factories.

$$P(\nu_\alpha \to \nu_\beta) = P_{CP+}(\nu_\alpha \to \nu_\beta) + P_{CP-}(\nu_\alpha \to \nu_\beta), \text{ where}$$

$$P_{CP+}(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}) \sin^2\left(\frac{1.27\,\Delta m^2_{ij} L}{E}\right)$$

$$P_{CP-}(\nu_\alpha \to \nu_\beta) = 2\sum_{i>j} \mathrm{Im}(U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}) \sin\left(\frac{2.54\,\Delta m^2_{ij} L}{E}\right), \text{ where}$$

$$\Delta m^2_{ij} \equiv (m^2_i - m^2_j) \text{ is in } (\mathrm{eV}/c^2)^2, L \text{ is in km, and } E \text{ is in GeV.}$$

$$\text{N.B.:}\quad P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\beta \to \bar{\nu}_\alpha) = P_{CP+}(\nu_\alpha \to \nu_\beta) + P_{CP-}(\nu_\alpha \to \nu_\beta)$$

$$\text{and } P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = P(\nu_\beta \to \nu_\alpha) = P_{CP+}(\nu_\alpha \to \nu_\beta) - P_{CP-}(\nu_\alpha \to \nu_\beta)$$

Why Accelerator Experiments?

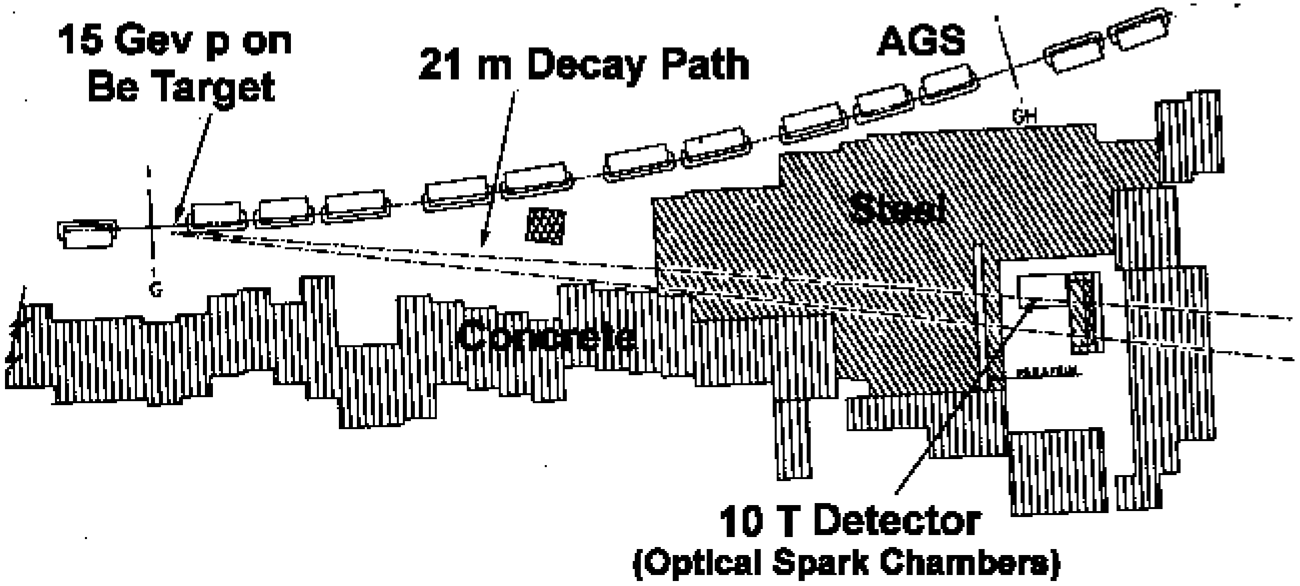
Source	Neutrino types	Mode	Advantage
Solar	ν_e	Disappearance	Great distance
Atmospheric	Mixture of ν_e $\bar{\nu}_e$ ν_μ $\bar{\nu}_\mu$	Mostly disappearance	Variable distance
Reactor	$\bar{\nu}_e$	Disappearance	Low energy
Accelerator π^+/K^+	Mostly ν_μ	Either	Control of energy and baseline
Accelerator μ^-	ν_μ and $\bar{\nu}_e$		

Where Do We Stand?

- Solar favored solution (LMA):
  - $2 \times 10^{-5} < \Delta m^2 < 10^{-4}\ (\mathrm{eV}/c^2)^2$
  - $\sin^2(2\theta) > 0.6$
  - Sterile neutrino disfavored at 95% c.l.
- Atmospheric favored solution:
  - $1.5 \times 10^{-3} < \Delta m^2 < 5 \times 10^{-3}\ (\mathrm{eV}/c^2)^2$
  - $\sin^2(2\theta) > 0.9$
  - $\nu_\mu \to \nu_\tau$ favored at 99% c.l.
- LSND experiment
  - $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation with $\Delta m^2 > 0.2\ (\mathrm{eV}/c^2)^2$
- All three of these results cannot be correct!

The First Accelerator Neutrino Experiment

- The first accelerators with intense enough beams to create neutrino beams were the CERN PS (1959) and the Brookhaven AGS (1960).
- In 1962, L. Lederman, M. Schwartz, and J. Steinberger, et al. Perform the first accelerator neutrino experiment at the AGS.



The First Accelerator Neutrino Experiment

- 34 single muon events, 5 consistent with cosmic ray background
- 6 “shower” events, consistent with neutron, misidentified muon, and beam ν_e backgrounds
- Experimenter’s conclusion: There are two types of neutrinos. (The possibility of neutrino oscillations suggested by Pontecorvo 5 years later in 1967.)
- Average E_ν ~ 1 GeV; average L ~ 24 m
- We would say today that the experiment excluded $\nu_\mu \to \nu_e$ oscillations at the 90% c.l. for
  - $\Delta m^2 > 15\ (\mathrm{eV}/c^2)^2$ for $\sin^2(2\theta) = 1$
  - $\sin^2(2\theta) > 0.4$ for high Δm^2

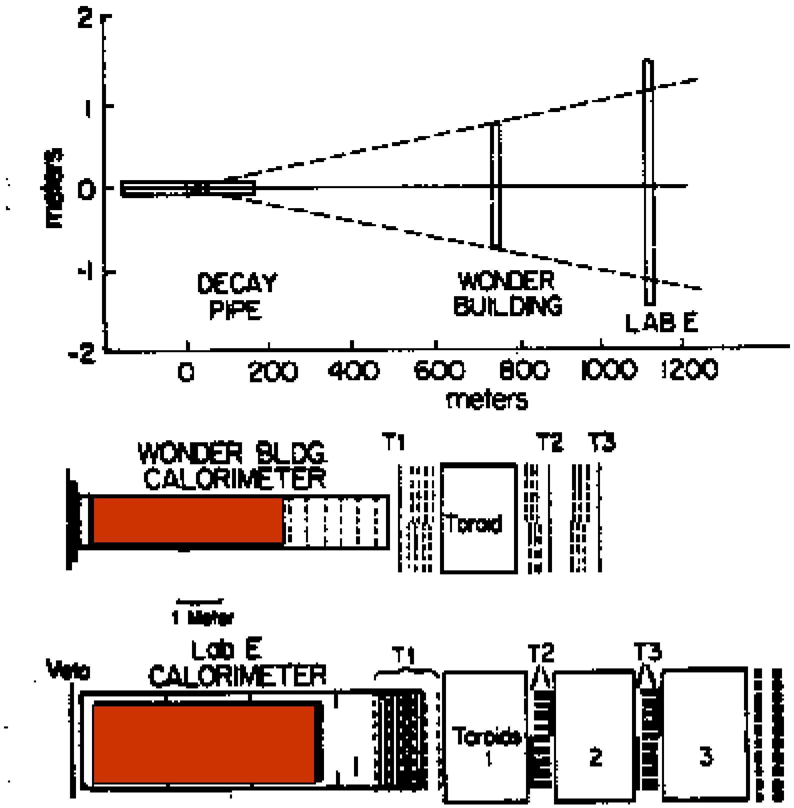
Early Experiments

- First round of dedicated neutrino oscillation experiments were done in the 1980's.
- Three types:
  - ν_μ disappearance

    First two-detector experiments
  - $\nu_\mu \varnothing \nu_e$ appearance
  - $\nu_\mu \varnothing \nu_\tau$ appearance

Early Experiments: CCFR ν_μ Disappearance

- **Detectors at 700 and 1100 m**



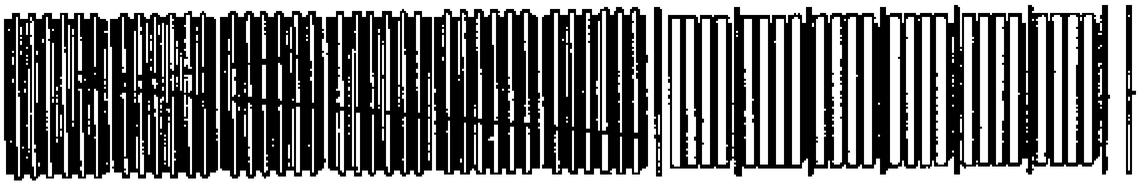
🟥 Fiducial region

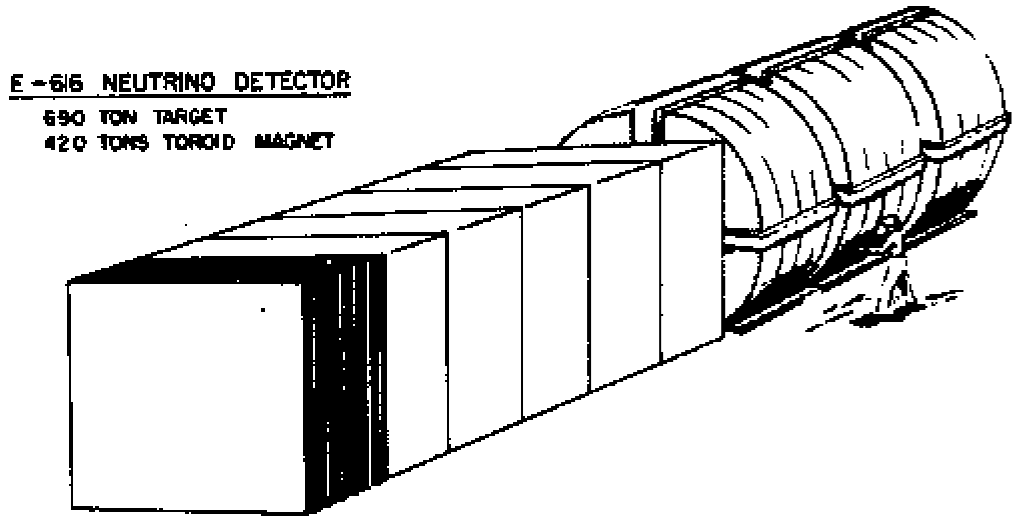
108 T
scintillators every 10 cm
chambers every 30 cm

444 T (fiducial)
scintillators every 10 cm
chambers every 20 cm

Early Experiments: CCFR ν_μ Disappearance

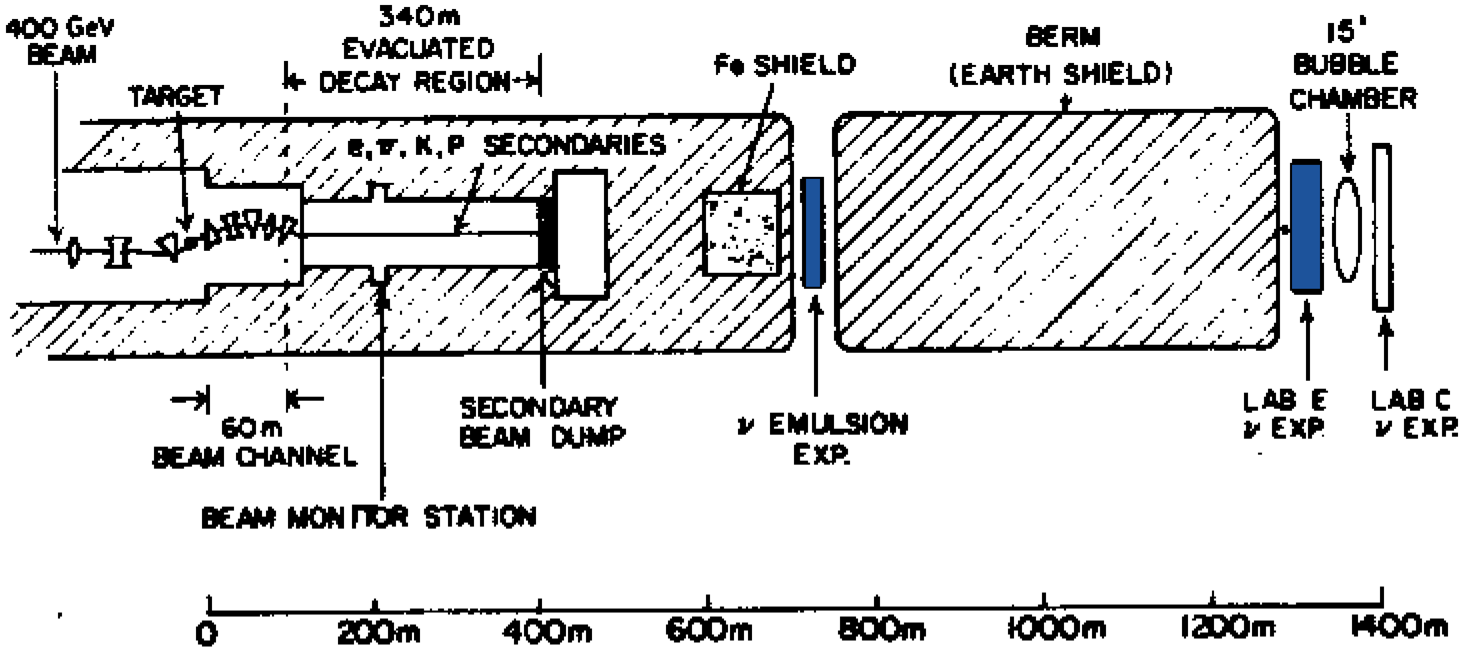
- Typical coarse detector





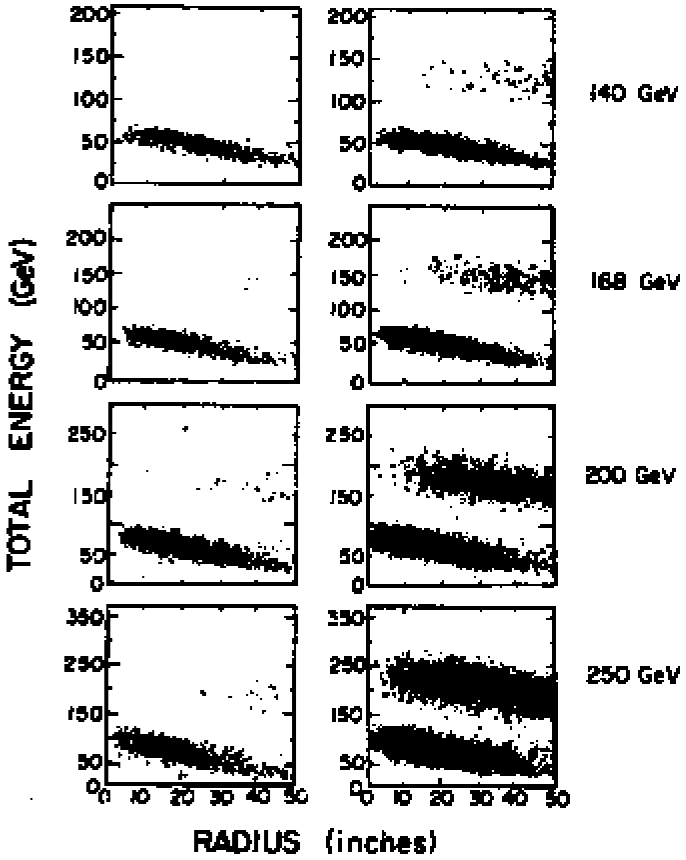
Early Experiments: CCFR ν_μ Disappearance

- Dichromatic beam at 100, 140, 165, 200 and 250 GeV/*c* π and K



Early Experiments: CCFR ν_μ Disappearance

- Dichromatic radius vs. energy

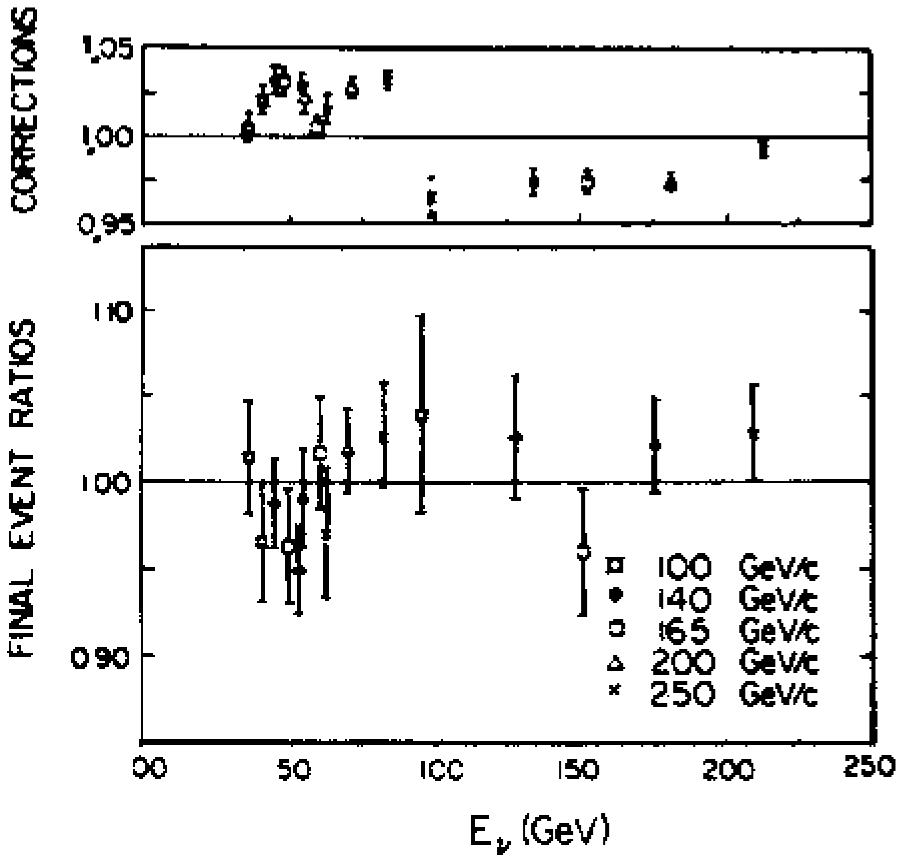


π Ø $\mu\nu$ and K Ø $\mu\nu$ are 2-body decays, so angle and energy are completely correlated.

Energy was determined from the radius!

Early Experiments: CCFR ν_μ Disappearance

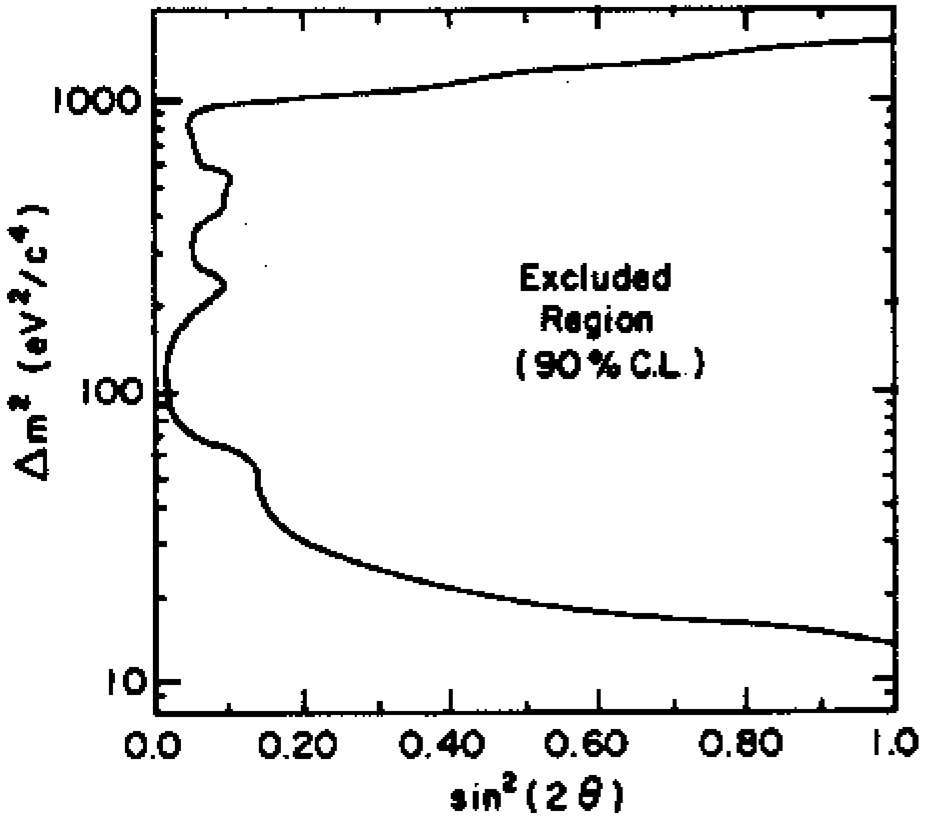
- Corrections and results



Monte Carlo corrections typically 3%

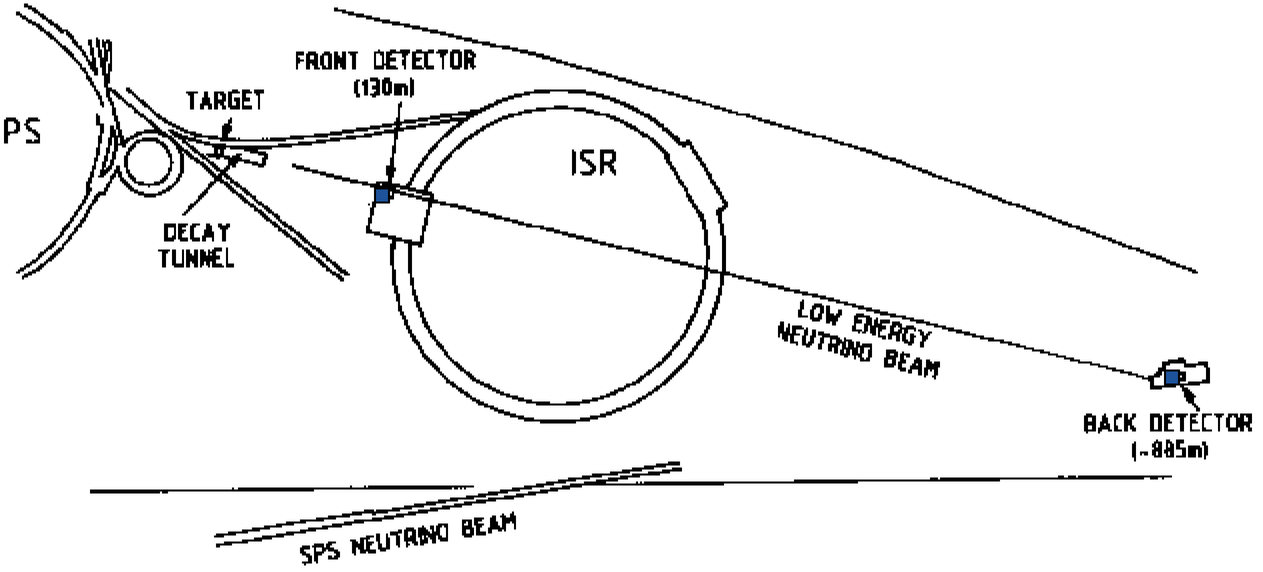
Early Experiments: CCFR ν_μ Disappearance

- **Exclusion plot**



Early Experiments: CDHS and CHARM ν_μ Disappearance

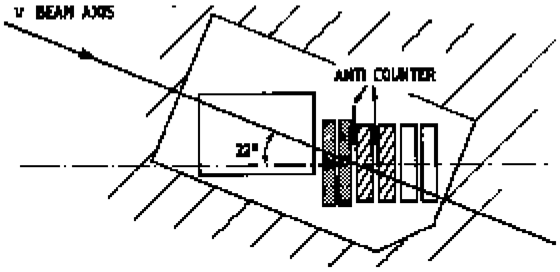
- CERN low energy ν beam (19.2 GeV *p*)
  - Detectors at 130 m and 900 m
  - Bare target beam with average E = 3 GeV



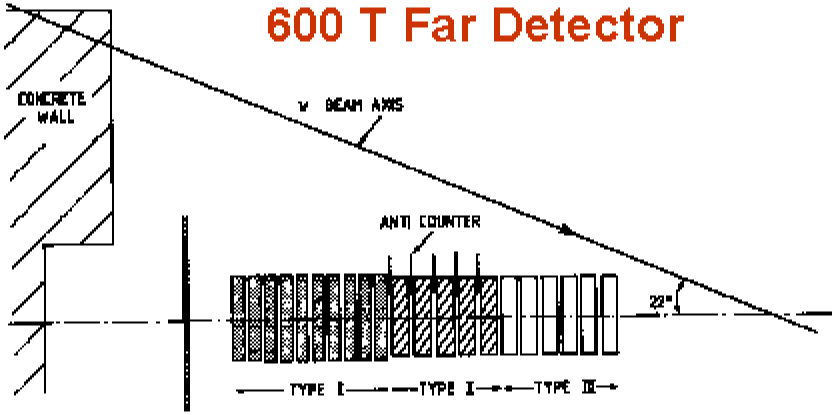
Early Experiments: CDHS ν_μ Disappearance

- **Detectors:**

100 T Near Detector



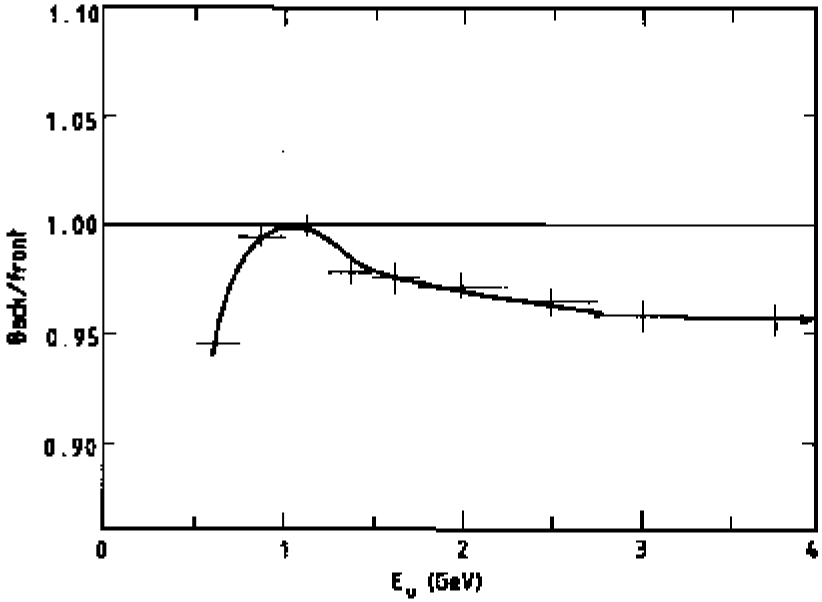
600 T Far Detector



Type I: 2.5 cm Fe
Type II: 5 cm Fe
Type III: 15 cm Fe

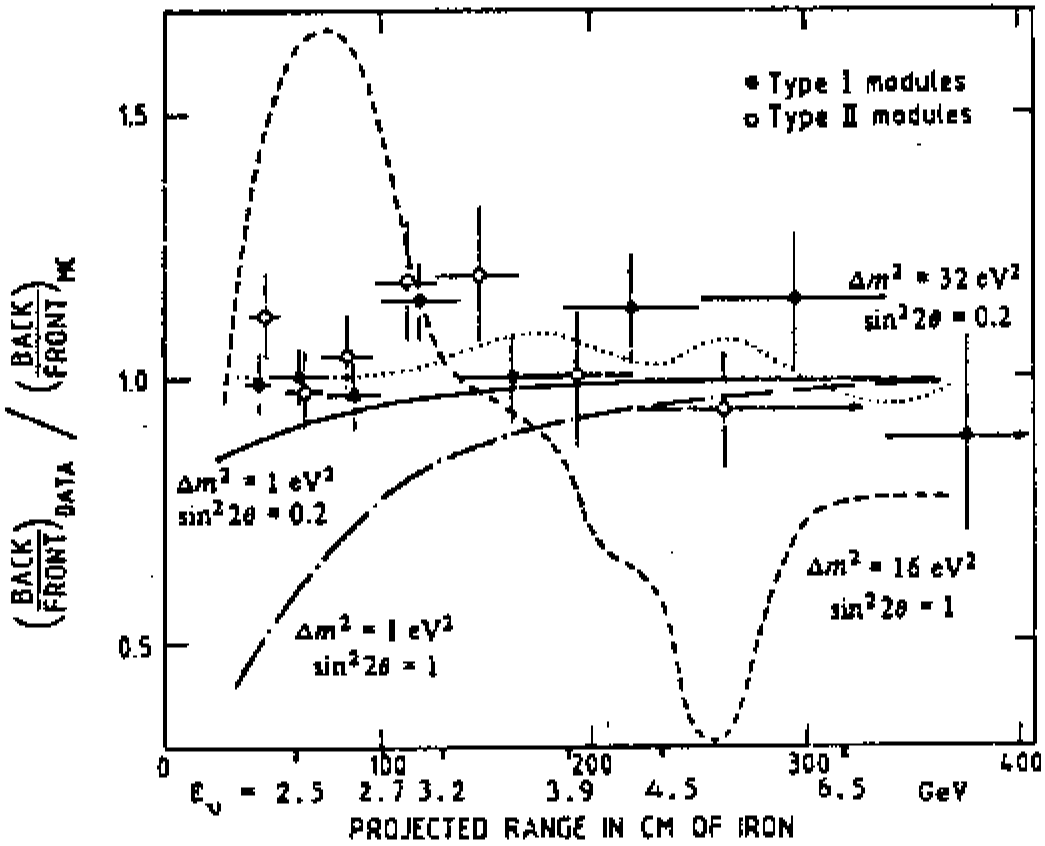
Early Experiments: CDHS ν_μ Disappearance

- **Corrections:**
  - Bare target to get approximate L^{-2} scaling
  - Event length used to estimate energy
  - Remaining corrections 5% or less



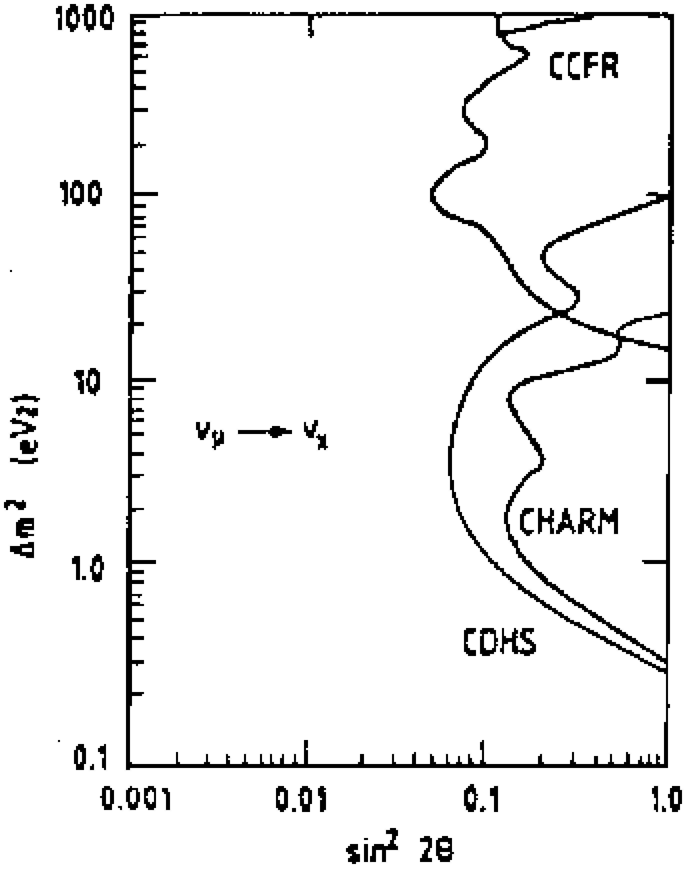
Early Experiments: CDHS ν_μ Disappearance

- **Results**



Early Experiments: ν_μ Disappearance

- **Exclusion plot**



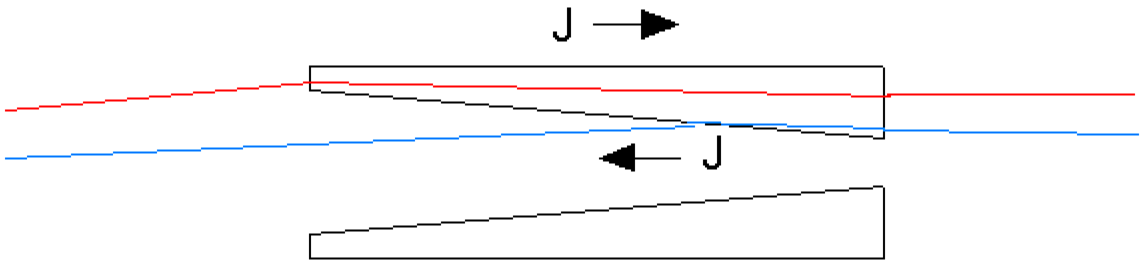
Due to systematic effects, it is difficult to do much better than this in $\sin^2(2\theta)$.

Early Experiments: $\nu_\mu \rightarrow \nu_e$ Appearance

- Many neutrino experiments in the 1980s looked for excess electrons in their data samples.
- Backgrounds from
  - ν_es in the beam from K_{e3} and μ decays (usually about 1%)
  - Misidentified electrons from π_0 photons and charged pions

Early Experiments: BNL E776 $\nu_\mu \rightarrow \nu_e$ Appearance

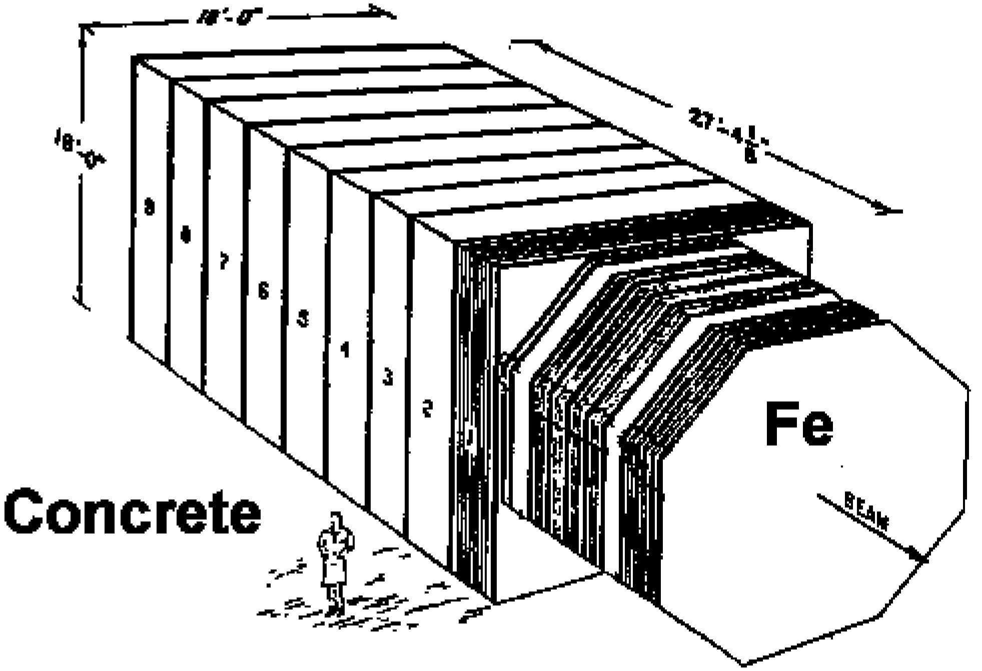
- Most sensitive experiment was Brookhaven E-776
  - Detector 1 km from the target. (Proposed as a two detector experiment, the near detector and half the far detector were not funded.)
  - Wide band beam focused with a magnetic horn



  - Typical E_ν = 1.4 GeV

Early Experiments: BNL E776 Detector

- Detector was a finely segmented EM calorimeter and a muon spectrometer. The EM calorimeter was 230 T of 1 in concrete plates interleaved with proportional drift tubes and scintillators.



Early Experiments: BNL E776 $\nu_\mu \rightarrow \nu_e$ Appearance

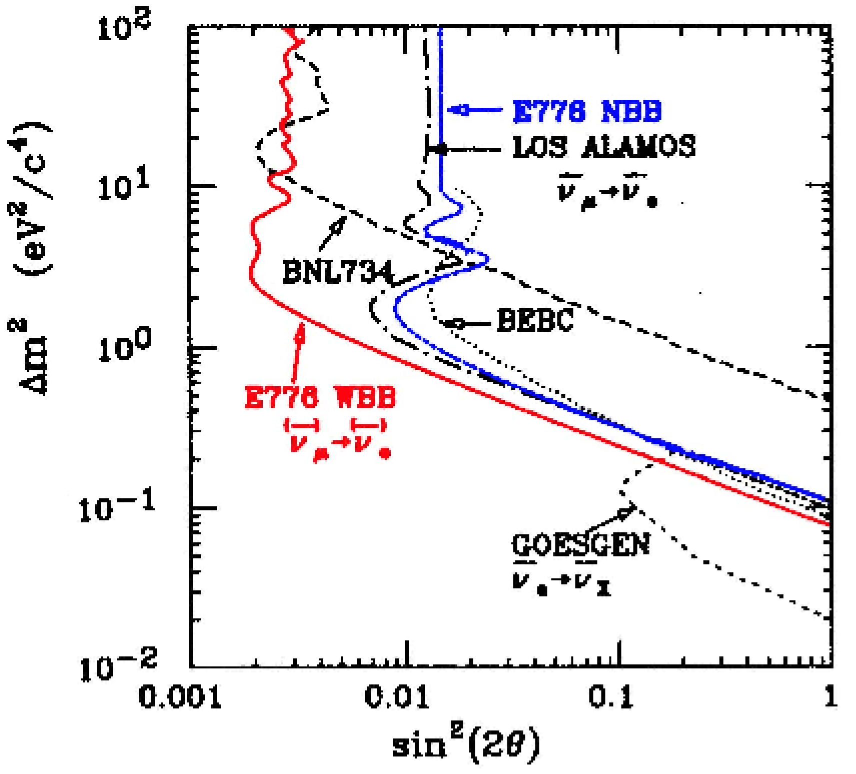
- Results (2 months of running in 1986)
  - 136 e^- like events with 131 ± 30 background expected
  - 47 e^+ like events with 62 ± 18 background expected
  - Excluded at 90% c.l.

$$\Delta m^2 > 0.075\ (\mathrm{eV}/c^2)^2$$

for $\sin^2(2\theta) = 1$

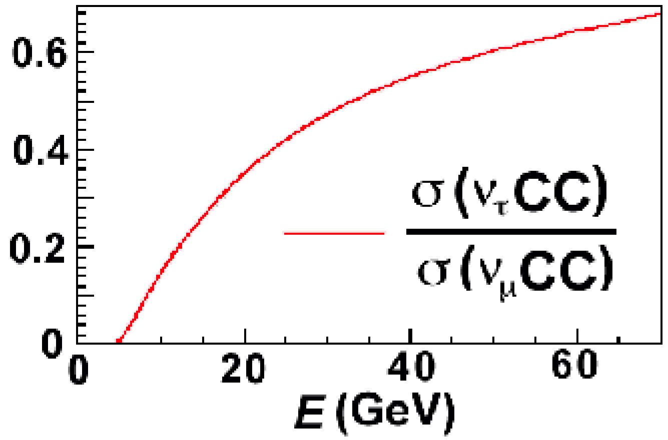
$$\sin^2(2\theta) > 0.003$$

for high Δm^2



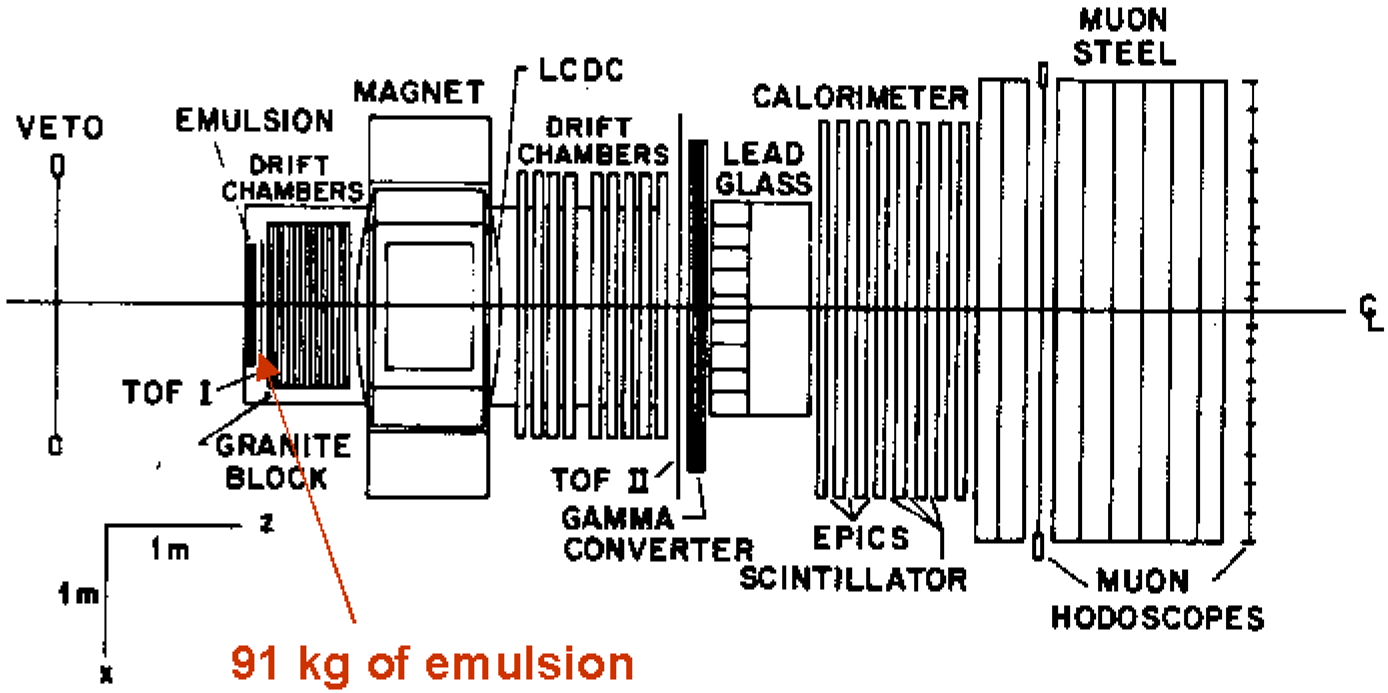
Early Experiments: $\nu_\mu \rightarrow \nu_\tau$ Appearance

- Considerations
  - Indirect: If ν_μ disappears and ν_e does not appear and neutral currents are normal, then $\nu_\mu \rightarrow \nu_\tau$.
    Limitation: Cannot probe small $\sin^2(2\theta)$.
  - Direct: Observe ν_τ through $\nu_\tau N \rightarrow \tau X$.
    Limitation: Must have E_ν well above τ threshold. (Threshold is at 3.5 GeV, but E_ν must be in the 10-20 GeV range to produce substantial numbers of τs due to threshold effects.)
  - Simplest direct method is to t



Early Experiments: FNAL E531 $\nu_\mu \rightarrow \nu_\tau$ Appearance

- Detector is an average of 750 m from the neutrino production point



91 kg of emulsion

Early Experiments: FNAL E531 $\nu_\mu \rightarrow \nu_\tau$ Appearance

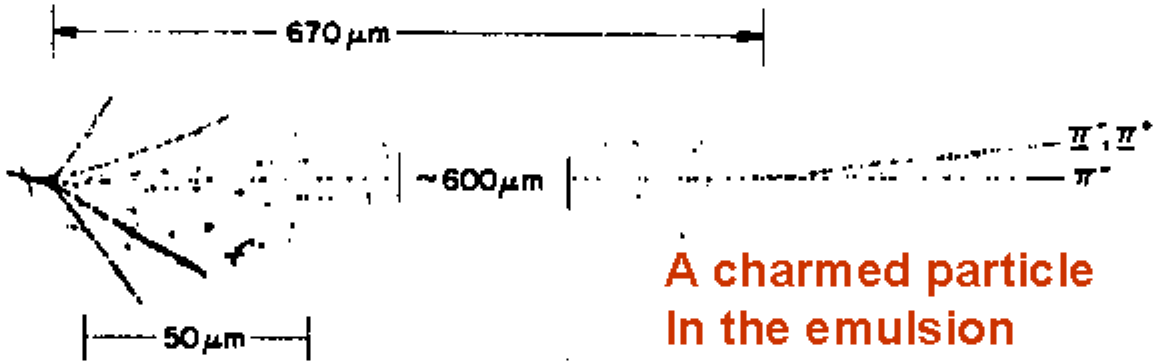
- Analysis
  - Look for short tracks with kinks

    104 events with $p_t > 125$ MeV/c (suppress scattering)

    25 events with negative particle (suppress charm)

    3 events without muon (suppress charm)

    0 events with $p > 2.5$ GeV/c (95% of τs have this)



A charmed particle
In the emulsion

Early Experiments: FNAL E531 $\nu_\mu \to \nu_\tau$ Appearance

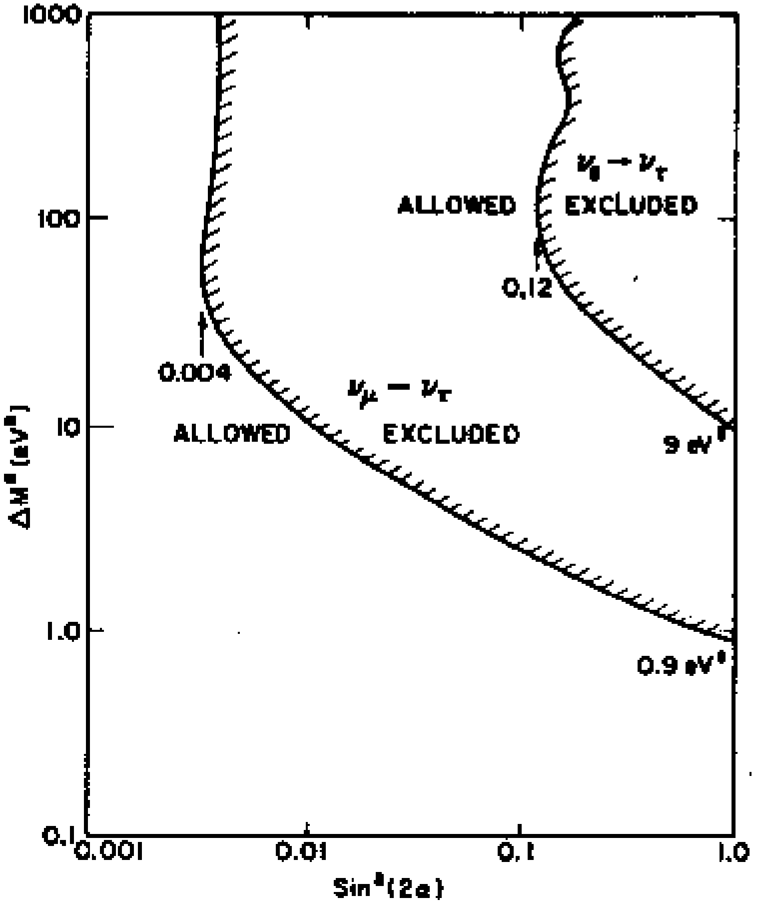
- Exclusion at 90% c.l.

$$\Delta m^2 > 0.9\ (\mathrm{eV}/c^2)^2$$

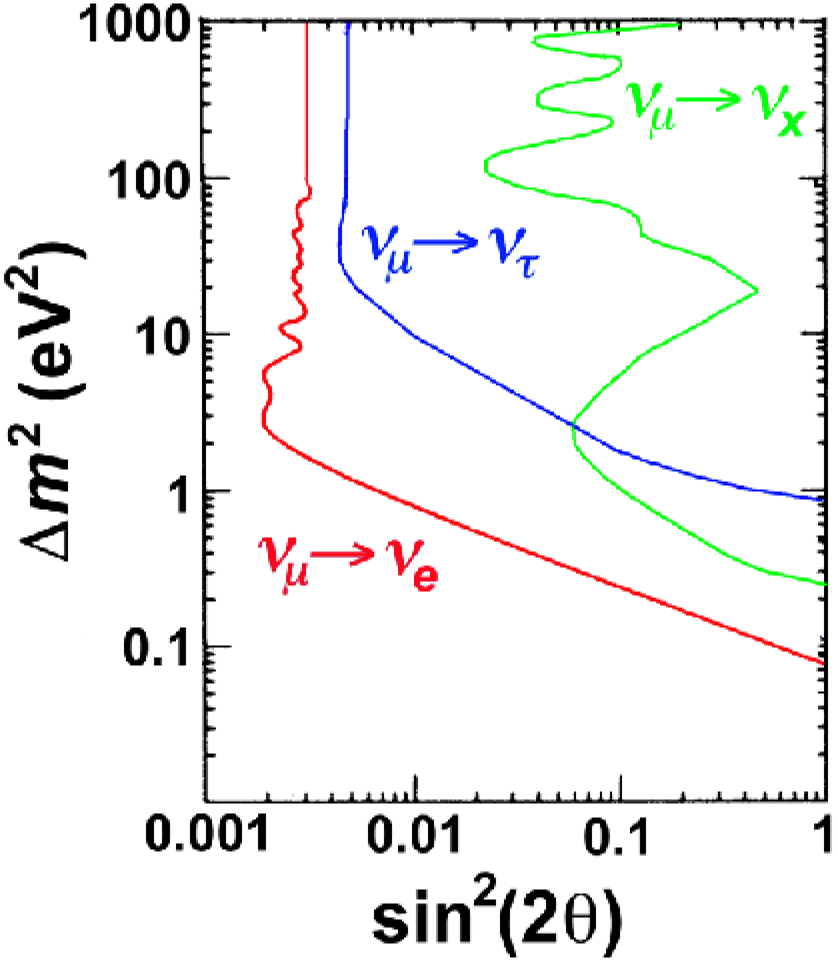
for $\sin^2(2\theta) = 1$

$$\sin^2(2\theta) > 0.005$$

for high Δm^2



Early Experiments: Summary



CHORUS/NOMAD Experiments

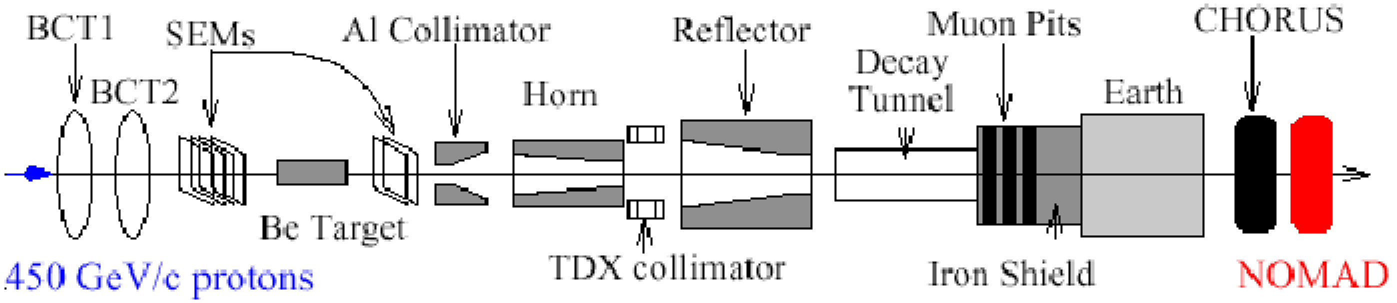
- The search for $\nu_\mu \varnothing \nu_\tau$ oscillations in the Δm^2 range of 10 to 1000 $(\mathrm{eV}/c^2)^2$ became particularly attractive in the early 1990's due to
  - COBE results on the anisotropy of the cosmic microwave background coupled with measurements on the clustering of galaxies, which seemed to require hot dark matter.
  - Numerology associated with the seesaw mechanism:

$$m(\nu_\alpha) = \frac{(m^f_\alpha)^2}{M} \Rightarrow \frac{m(\nu_\tau)}{m(\nu_\mu)} = \left(\frac{m(t)}{m(c)}\right)^2$$

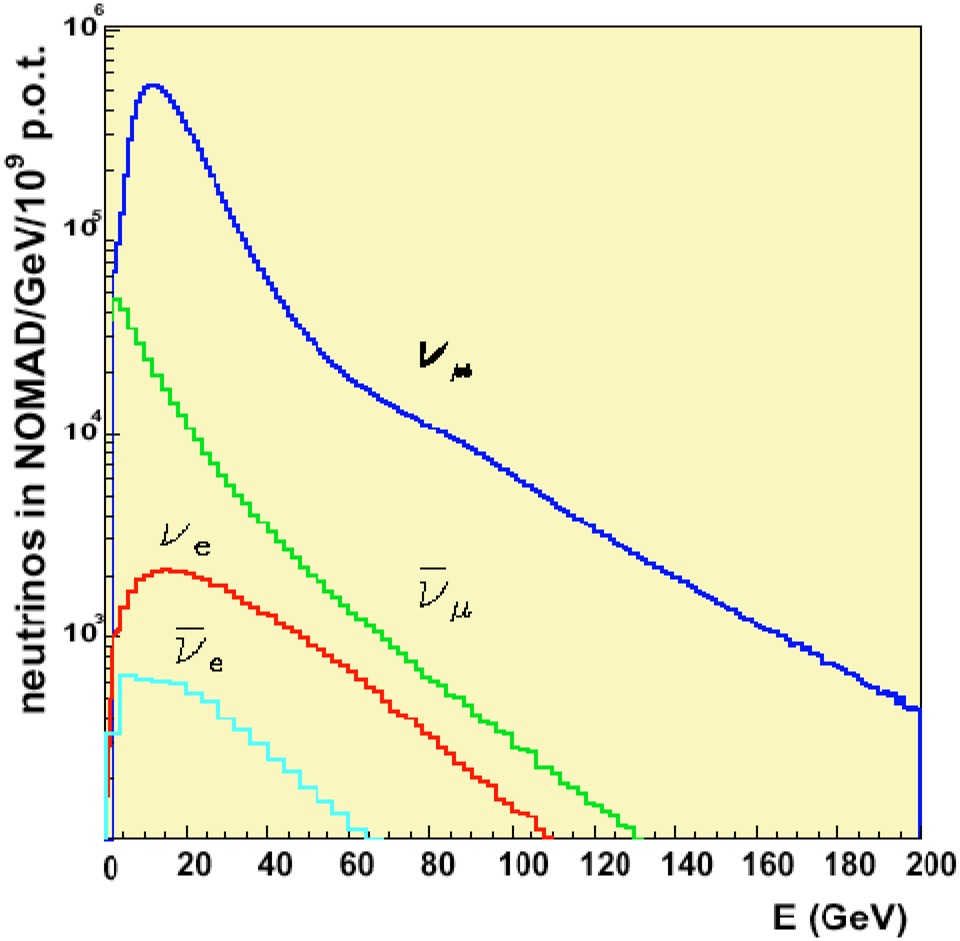
gives ν_τ masses in this range if the ν_μ mass is associated with solar matter oscillations.

CHORUS/NOMAD Experiments

- Two CERN experiments, CHORUS and NOMAD, had the goal of increase the sensitivity in $\sin^2(2\theta)$ by an order of magnitude over what had been achieved by E531.
- CHORUS used the “traditional” method of taking a picture of the ν_τs in emulsion. Same basic design as E531, but with 770 kg of emulsion.
- NOMAD sought to identify ν_τs solely by kinematic criteria.
- Both experiments in the CERN 450 GeV SpS beam about 600 m from the average decay point.



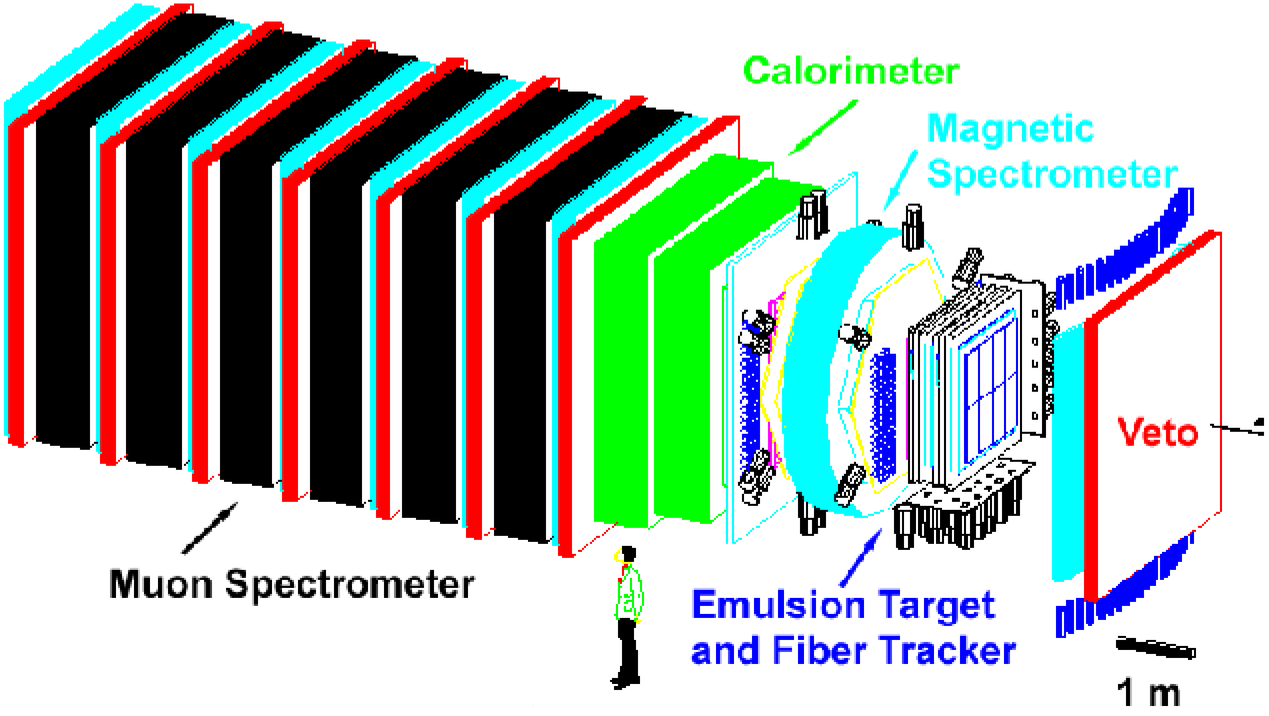
CHORUS/NOMAD Experiments Beam



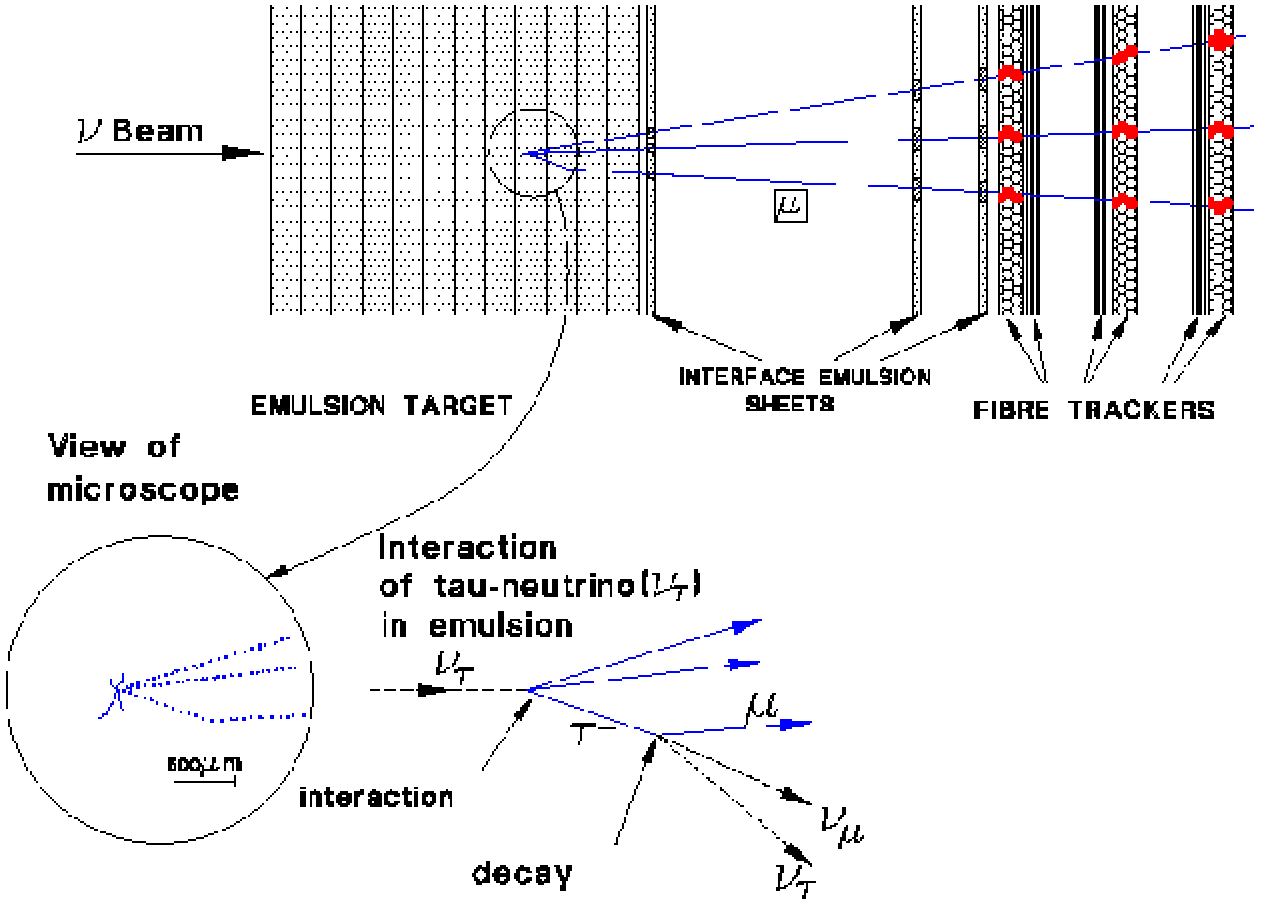
Average ν_μ energy = 24 GeV

Average ν_μ interaction energy = 43 GeV

CHORUS Detector



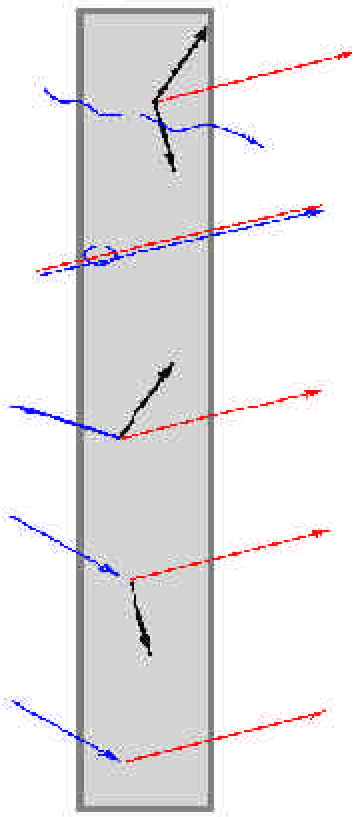
CHORUS Emulsion Target



CHORUS Scanning

	1 μ	0 μ
Events scanned	355 k	85 k
Vertices located	144 k	20 k
Events selected for eye-scan	11 k	2 k
Kink candidates after eye-scan	0	0

CHORUS Manual Scanning



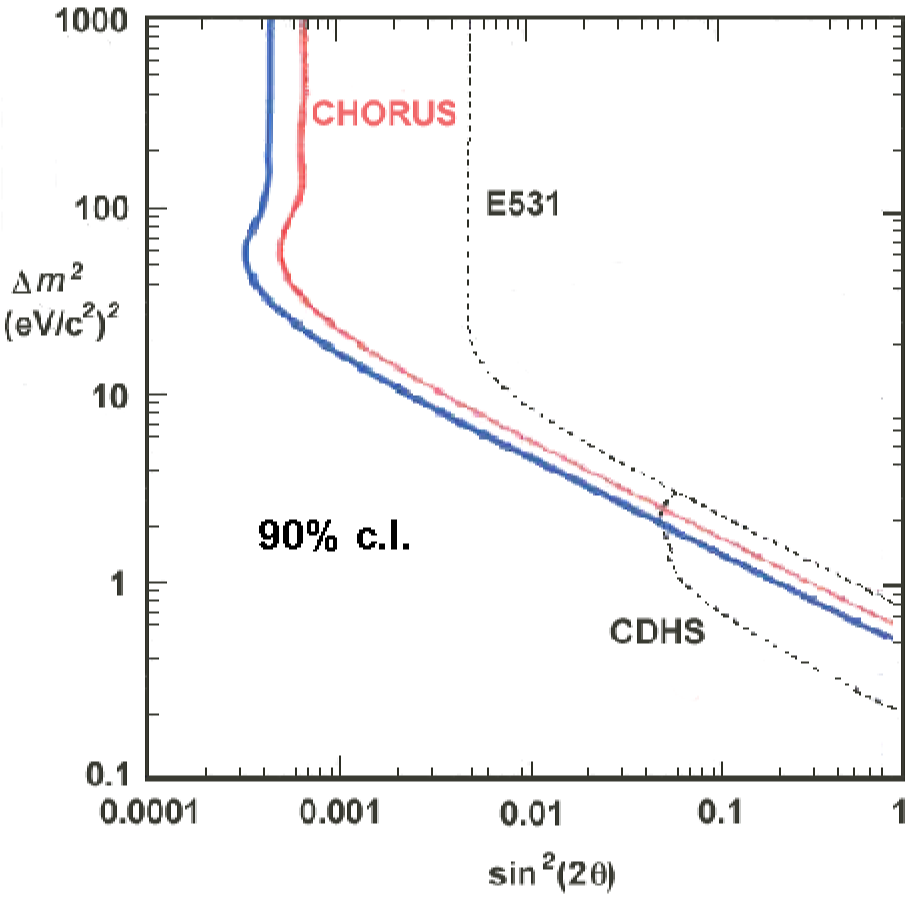
Low momentum background track	~78%
Parent=Daughter No angle difference	~5%
Backward-going nuclear fragment	~13%
Hadron interaction	~3%
Decay (Kink)	~1%

P_t > 250 MeV/c to eliminate π/K decays reduces this to 0

CHORUS Backgrounds

	$1\ \mu$	$0\ \mu$
Charm from $\bar{\nu}$ with missed lepton $\bar{\nu}N \rightarrow D^- X \ell^+;\quad D^- \rightarrow \mu^- / h^- +$ neutrals	0.11	0.02
Charm from ν with wrong charge	neg	0.3
Associated charm production in NC	neg	neg
Hadronic white kinks (scattering with no recoil or nuclear breakup)	neg	0.8
Prompt beam ν_τ	neg	neg
Total background	**0.11**	**1.1**

CHORUS Exclusion Plot



Red and blue curves correspond to different statistical treatments.

With additional scanning, CHORUS expects to reach a sensitivity of 10^{-4}.