From Here to a Neutrino Factory: Neutrino Oscillations Now and Again

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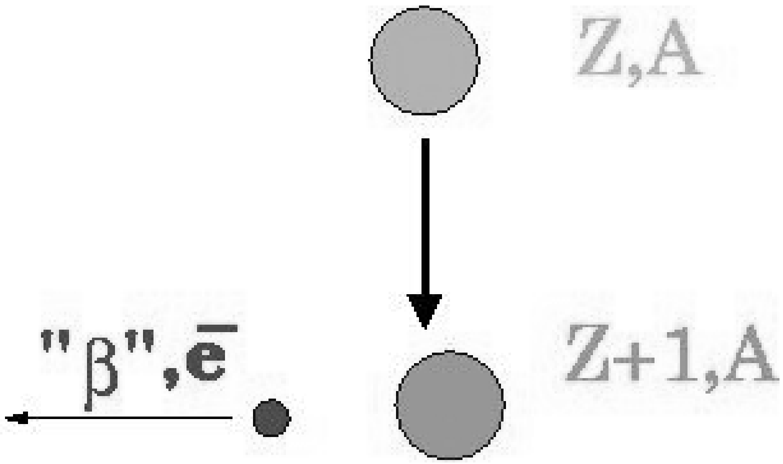
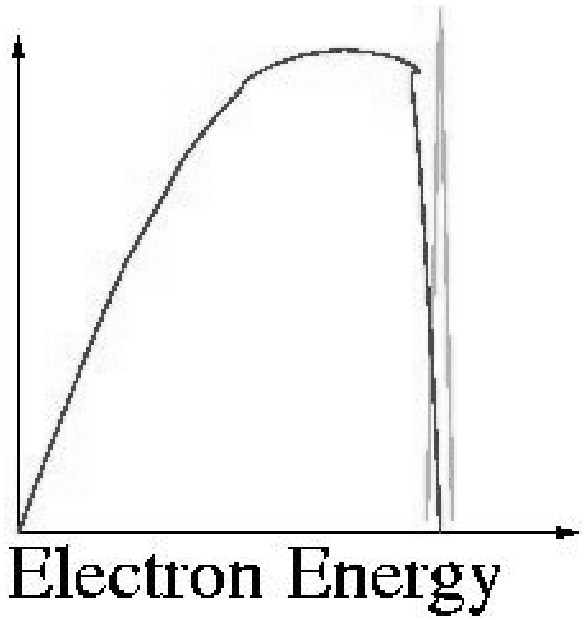
Outline of this Talk

- History of Neutrino Physics
- Neutrino Oscillation Signals
- Current Round of Experiments
- What will be left to measure?
- “Superbeams”
- Neutrino Factory

The First Energy Crisis

- Studies of beta decay around 1914 saw:
  - Energy was not being conserved!





- Two body reaction, electron energy should be fixed…
- Where did the other energy go?
- Spin statistics didn't work: how can ½ integer spin particle become two ½ integer particles?

An Unlikely Solution…

- In letter from Pauli to conference in Tubingen dated 4 December, 1930:
  - I have hit upon a desperate remedy to save the “exchange theorm” of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin ½
- Chadwick finds solution to spin statistics problem in 1934, steals name
- Fermi suggests “neutrino” (ν) particle to solve energy conservation problem: calculates interaction rate: need $2.5\text{x}10^{20}$cm of water to see one ν interact!

Weak Interactions

- Current-current interaction
:

$$\mathrm{H}_{w} = \frac{G_F}{\sqrt{2}} J^{\mu} J_{\mu}$$

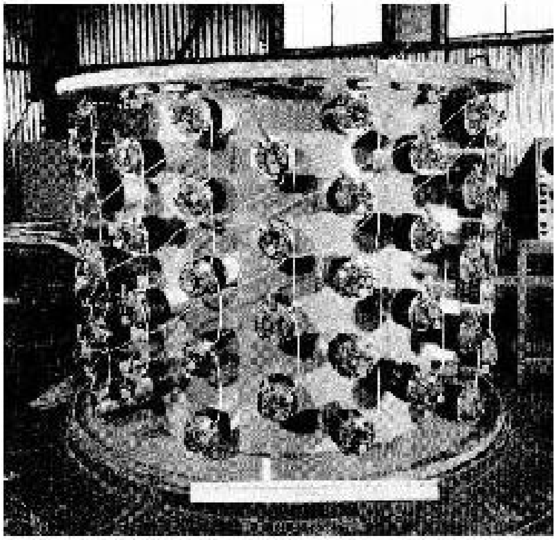
- Fermi 1934. Paper rejected by 'Nature' because "it contained speculations too remote from reality to be of interest to the reader"
- Modern version:

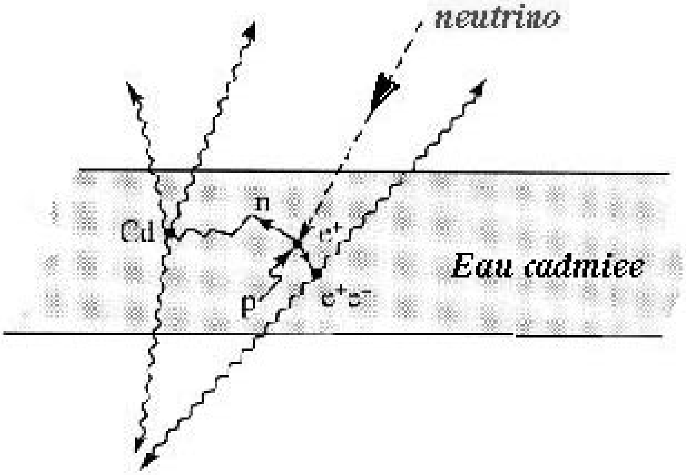
$$H_{weak} = \frac{G_F}{\sqrt{2}} \left[\bar{l} \gamma_{\mu} (1 - \gamma_5) \nu \right] \left[\bar{f} \gamma^{\mu} (V - A\gamma_5) f \right] + h.c.$$

- $P_L = 1/2(1-\gamma_5)$ is a projection operator onto left-handed states for fermions and right-handed states for antifermions
- Only left handed ferminos and right handed anti-fermions participate in weak interactions: Parity violation

Discovery of the Neutrino

- Alternate Technology: 10^{20} neutrinos, few cm of water!





- See ν $\bar{p}$ to e^+ n
- Reines and Cowan, 1954-1957, 1 ton detector
- Nobel Prize, 1995

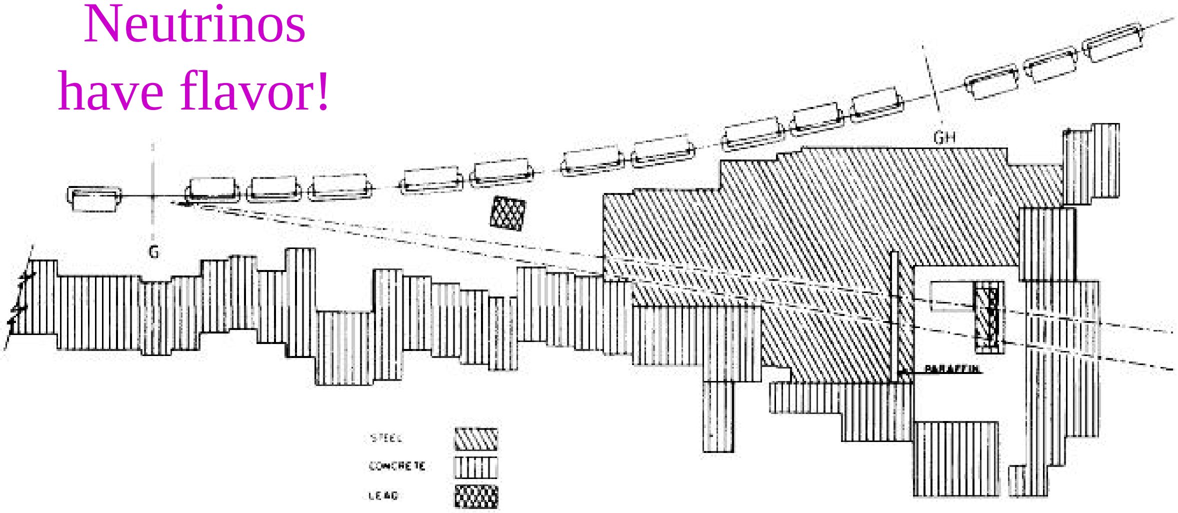
Neutrinos from Nearby Fission Reactor

- Observed 1 event every few minutes
- Very hard—need a lot of shielding,
- need to know backgrounds from cosmic rays

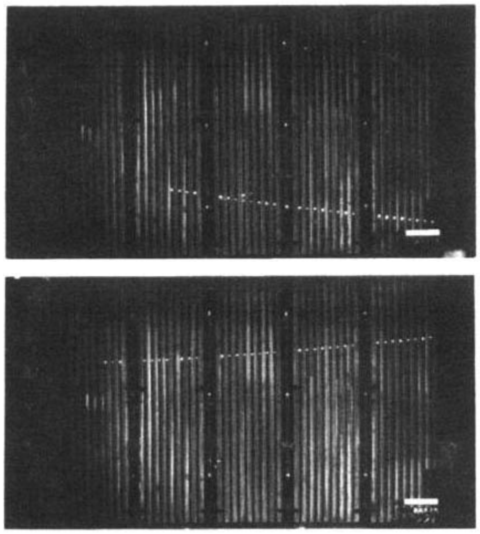
2 kinds of Neutrinos

- Pions decay to muons, but again, energy was missing –must be a neutrino…
- But if $\mu^- \rightarrow e^- \nu\nu$ then $\mu^- \rightarrow e^- \gamma$ too unless…
- First Decay-in-flight ν beam BNL AGS
- 15BeV protons on Be Target
- 21m decay region,13.5m Fe Shield, 1 Ton Detector

Neutrinos have flavor!

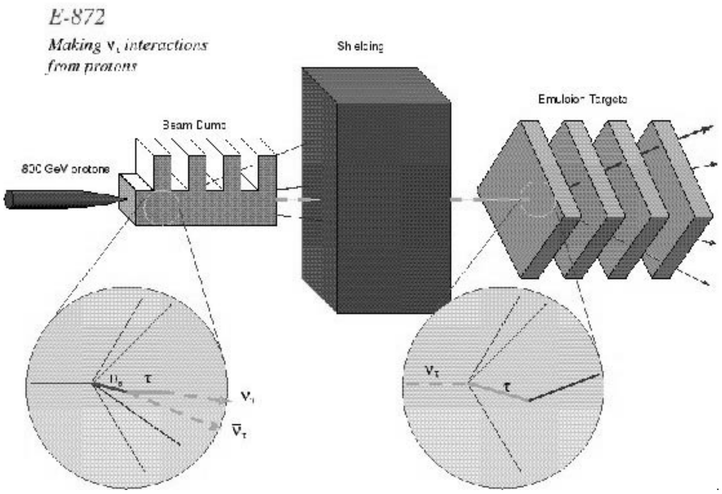


- 3.5x10^{17} POT
- 34 single-μ events
- 5 background
- NO e-like events!
- PRL: 1960, NP: 1988
- Lederman, Swartz, Steinberger

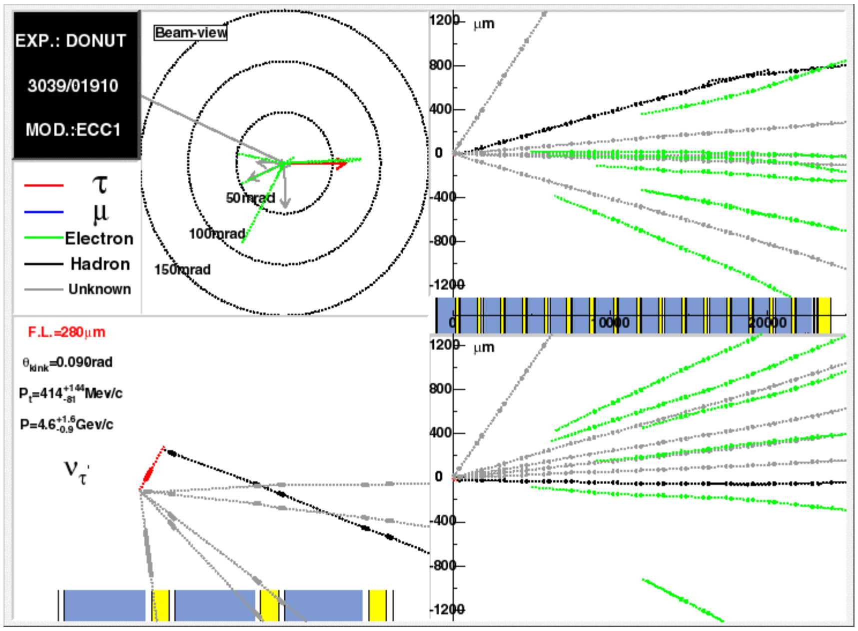


The Third (and last?) Neutrino

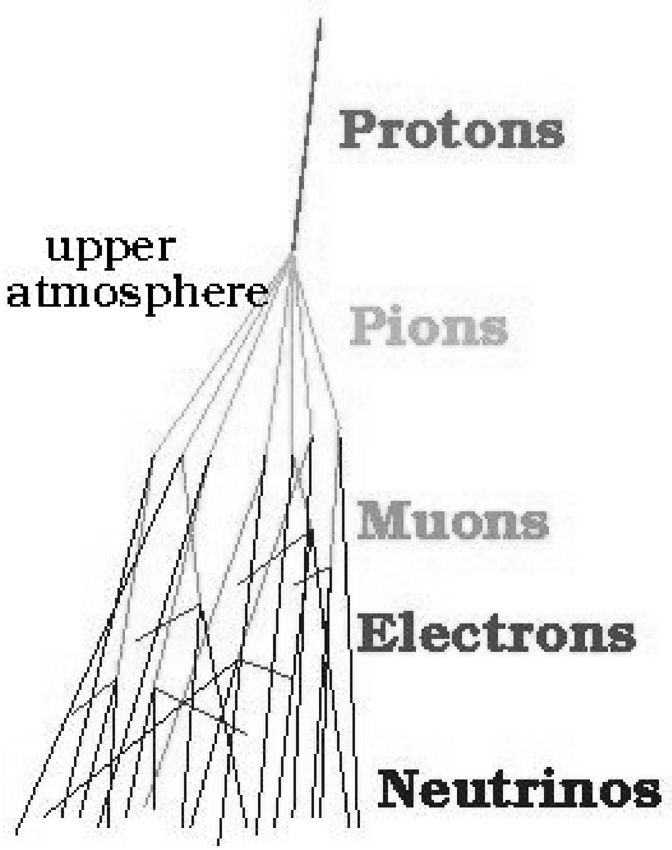
- There are three generations of charged leptons: e, μ, τ
- Three neutrinos should also exist!
- DONUT Experiment at FNAL: 1997-98
- Making a beam of ν_τ is hard! Want only D_s's to decay

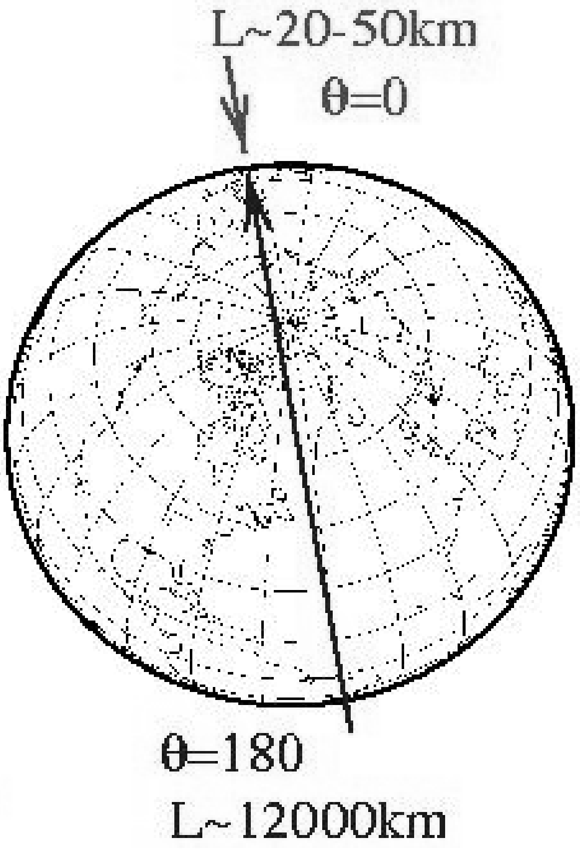


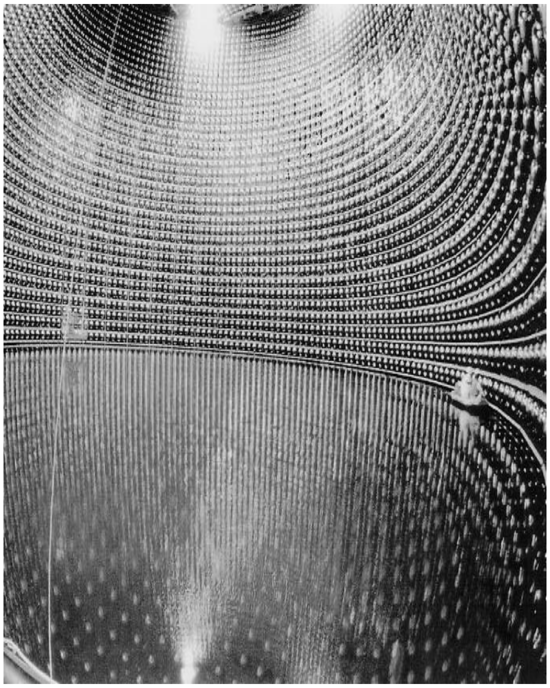
- Seeing τ decay is also hard: need very sensitive detector
- 4 events seen, expect 0.34 background



Neutrinos from the Atmosphere



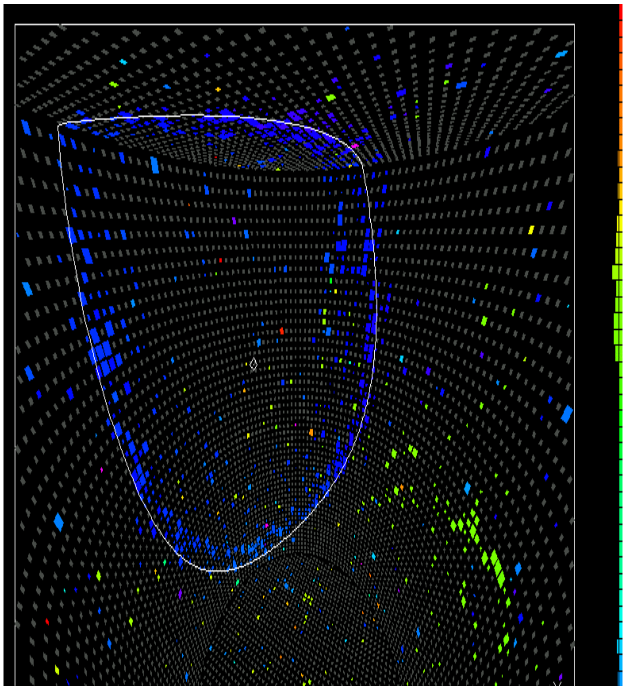


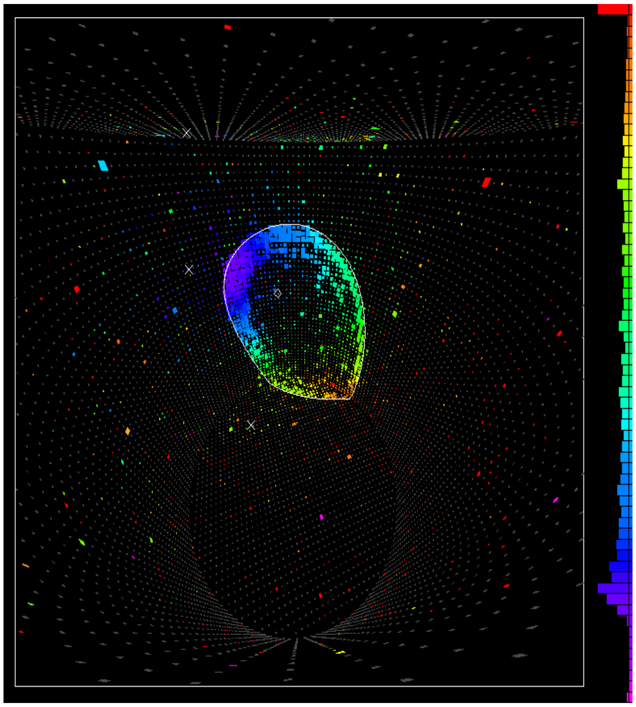


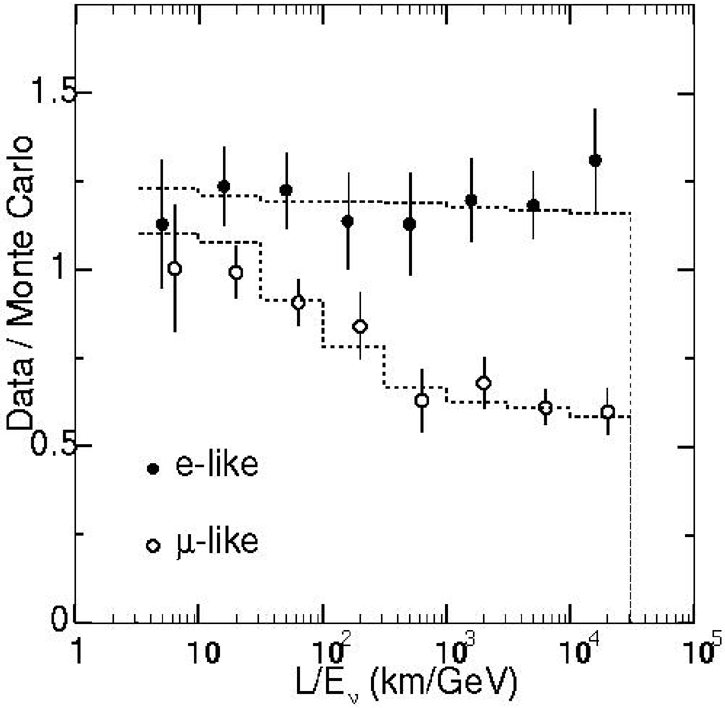
- SuperKamiokande
- 50 Kton H_20 tank
- 11K photomultiplier tubes on ‘inner tank’
- 2K PMT’s ‘outer shield’
- Kamioka mine under mountain

Super Kamiokande Results

$\upsilon_e N \rightarrow e^- X$ $\upsilon_\mu N \rightarrow \mu^- X$



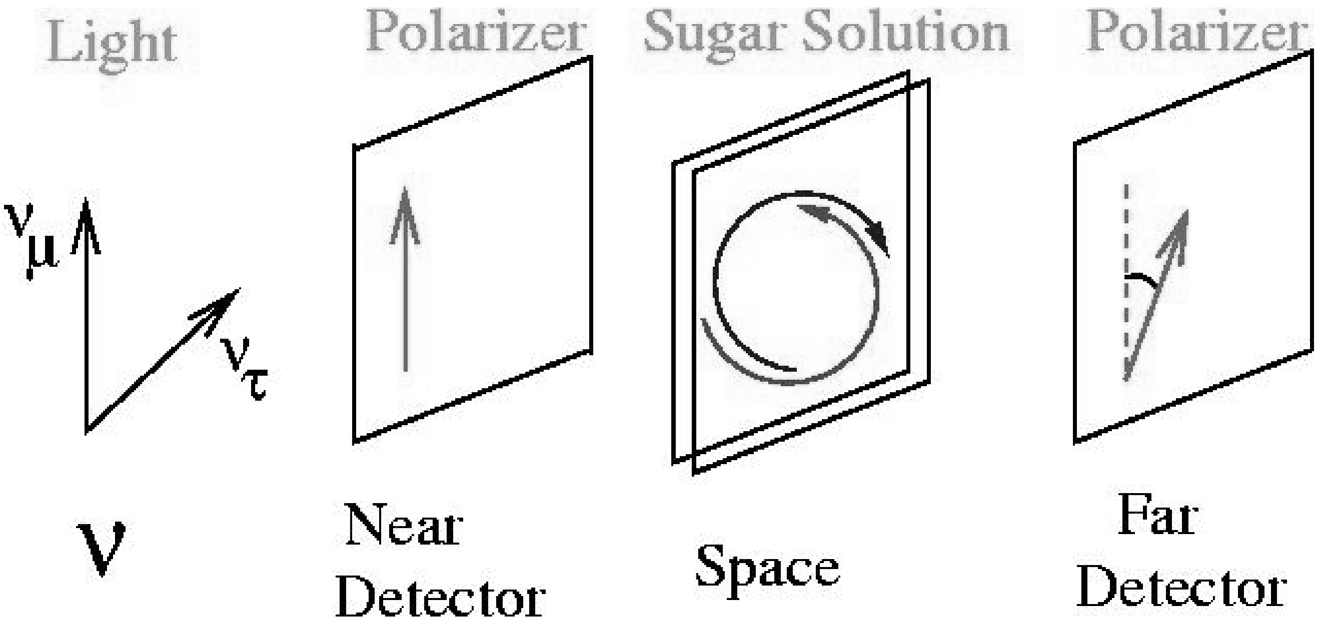




- $\nu_\mu : \nu_e$ flux: 2:1
- Many Baselines
- Many Energies
- One Detector
- ν_μ disappearing but NOT becoming ν_e

Optics Analogy

(stolen mercilessly from Joe Boudreau)



- Consider an optical beam: two polarization directions, vertical (ν_μ), and horizontal (ν_τ)
- Know that you're in mostly horizontal state from near detector
- Imagine space as a sugar solution filter: helicity of sugar means that left handed polarization has a different speed than right handed polarization

$$\nu_\mu = \frac{\nu_1 + \nu_2}{\sqrt{2}} \qquad \nu_\tau = \frac{\nu_2 - \nu_1}{\sqrt{2}}$$

Can be

written as….

$$\nu_1 = \frac{\nu_\mu + \nu_\tau}{\sqrt{2}} \qquad \nu_2 = \frac{\nu_\tau - \nu_\mu}{\sqrt{2}}$$

- Send beam in as ν_μ after passing through space IF the two components travel at different speeds, then there will be a phase difference
- See if your far detector (polarizer) measures fewer ν_μ than your near detector predicts

Neutrino Oscillations

- If we postulate:
  - « Neutrinos have (different) mass

    so different masses travel at different velocities!
  - « The ***Weak Eigenstates*** are a mixture of ***Mass Eigenstates***

    ν_μ is not all ν_1, or all ν_2

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Then a pure ν_μ beam at t=0, will develop a $\nu_{(\text{not } \mu)}$ component with time.

The Probability for Oscillations...

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

Oscillation Formula Parameters

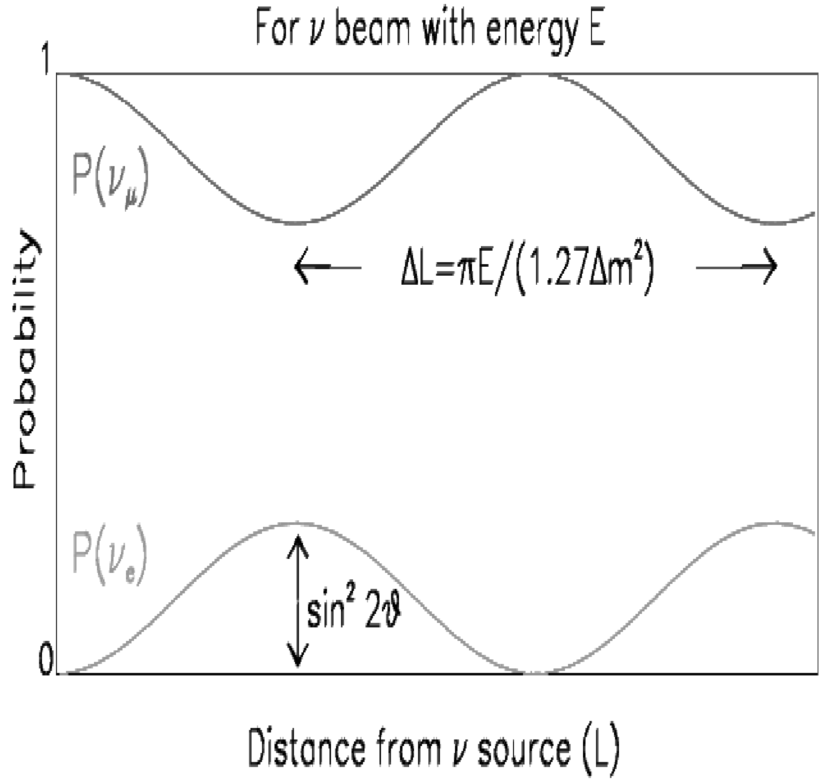
$$P_{oscillations} = \sin^2 2\theta \times \sin^2\left(1.27\frac{\Delta m^2(eV^2)L(km)}{E(GeV)}\right)$$

…Depends Upon Two Experimental Parameters:

- L – The distance from the ν source to detector (km)
- E – The energy of the neutrinos (GeV)

…And Two Fundamental Parameters:

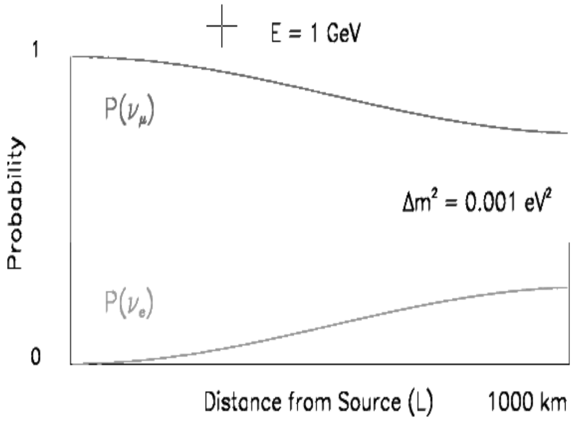
- $\Delta m^2 = m_1^2 - m_2^2 \quad (eV^2)$
- $\sin^2 2\theta$

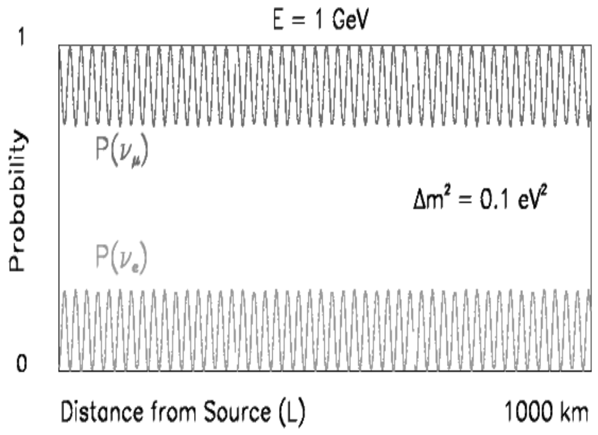


Oscillation Phenomenology

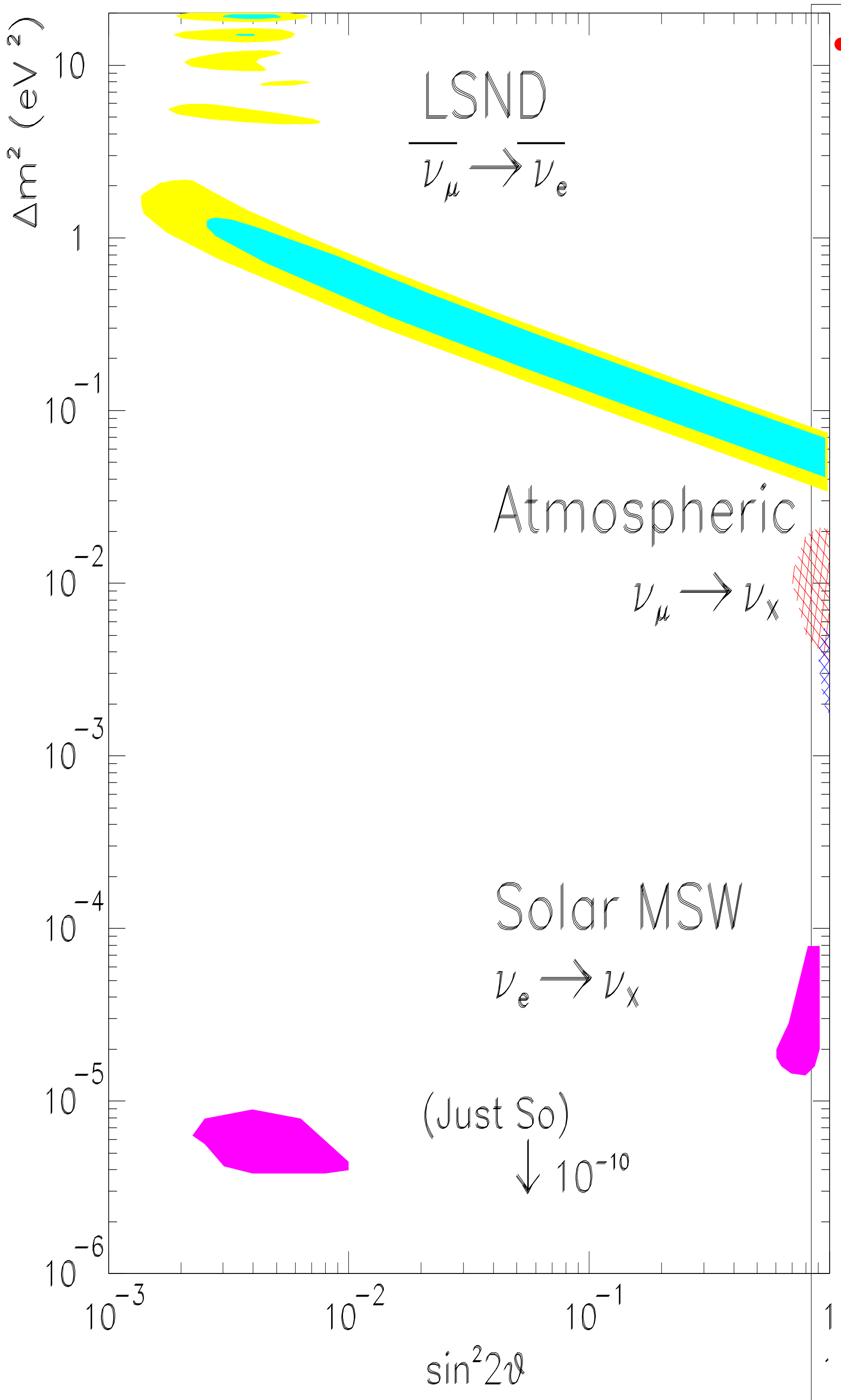
- Two types of oscillation searches:
  - ***Appearance Experiment:***
    Look for appearance of ν_e or ν_τ in a pure ν_μ beam vs. L and E
    - Need to know the backgrounds
  - ***Disappearance Experiment:***
    Look for a change in ν_μ flux as a function of L and E
    - Need to know the flux and cross sections

- $P_{osc} = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$ sets the details of search
  - Mixing angle $\sin^2 2\theta$ sets the needed statistics





Three Indications of Oscillations



- Open questions:
  - Are all three indications really neutrino oscillations?
    - Need to see oscillatory behavior in E_ν or L
    - Need measurements with well understood systematics
  - Determine which flavors are oscillating
  - Which solar solution, if any is correct?
  - Measure oscillation parameters Δm^2, $\sin^2 2\theta$
  - Measure full lepton flavor mixing matrix

We’ve come a long way since the 60’s…

120 GeV protons hit target

π^+ produced at wide range of angles

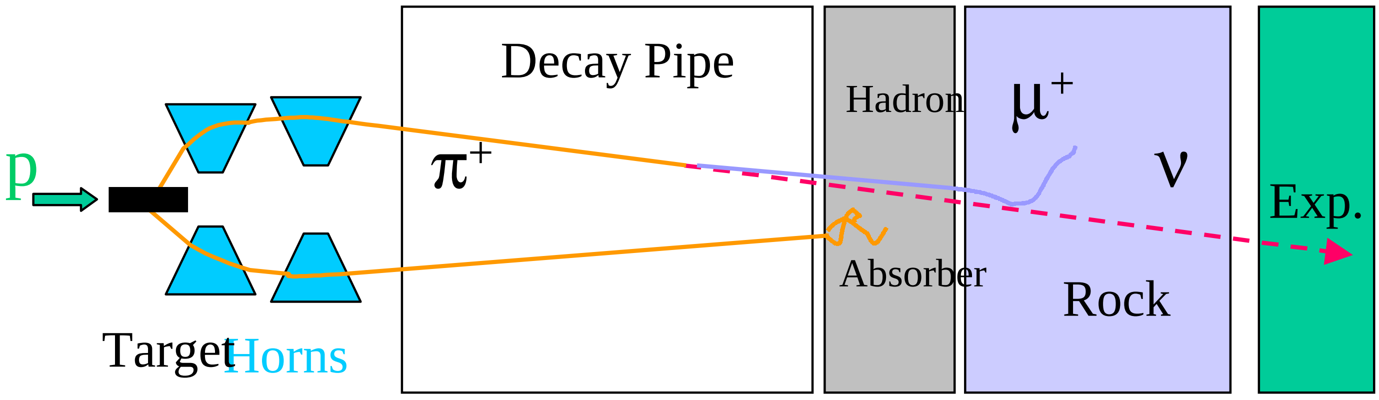
Magnetic horns to focus π^+

π^+ decay to $\mu^+\nu$ in evacuated pipe

Left-over hadrons shower in Abs.

Rock shield ranges out μ^+

ν beam goes through earth



Proton Energy: 8 times higher

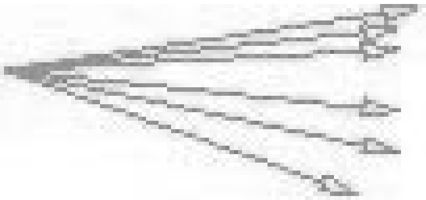
Protons on Target: 2000 more

Decay Region: 35 times longer

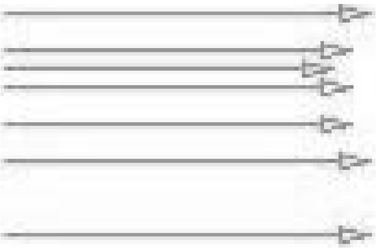
All pointing at a 58mrad (2.5°) from horizontal!

Focusing Pions: letting them decay is not enough!

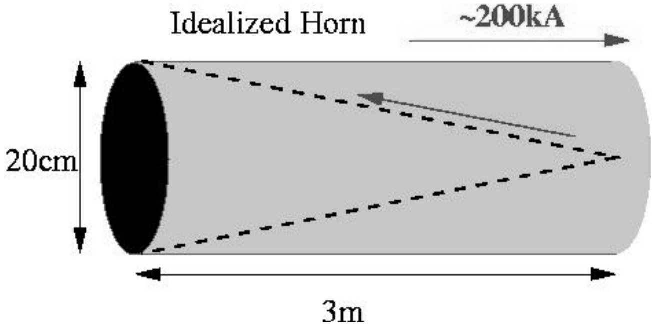
FROM

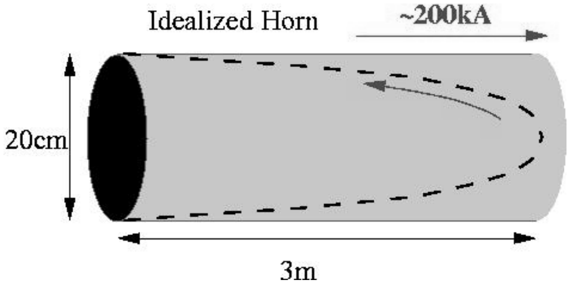


TO



- Particles get produced at target with roughly constant p_t, and a steeply falling distribution of p
- Horn: a 2-layered sheet conductor
- No current inside inner conductor, no current outside outer conductor
- Between conductors, toroidal field proportional to 1/r



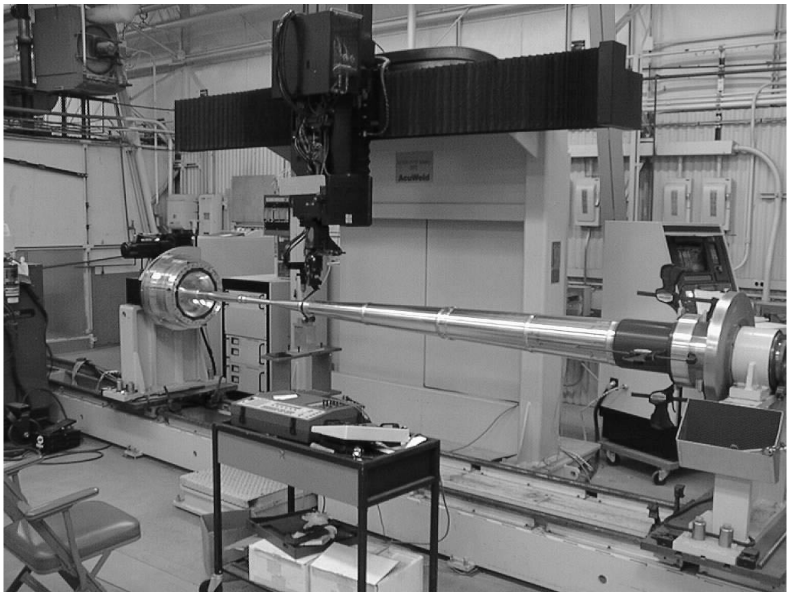


$$\delta p_t \approx \frac{e\mu_0 I}{2\pi c r} \times \frac{r l}{r_{outer}}$$

$$\delta p_t \approx \frac{e\mu_0 I}{2\pi c r} \times \frac{r^2 l}{r_{outer}^2} \approx p_{tune}\theta$$

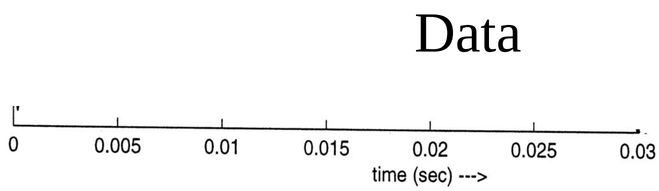
- For wide energy band, want to give all momentum particles the same pt kick: conical horn!
- For narrow energy band, want to focus all pions of a given momentum: want p_t kick to be proportional to r

NUMI Horn Tests

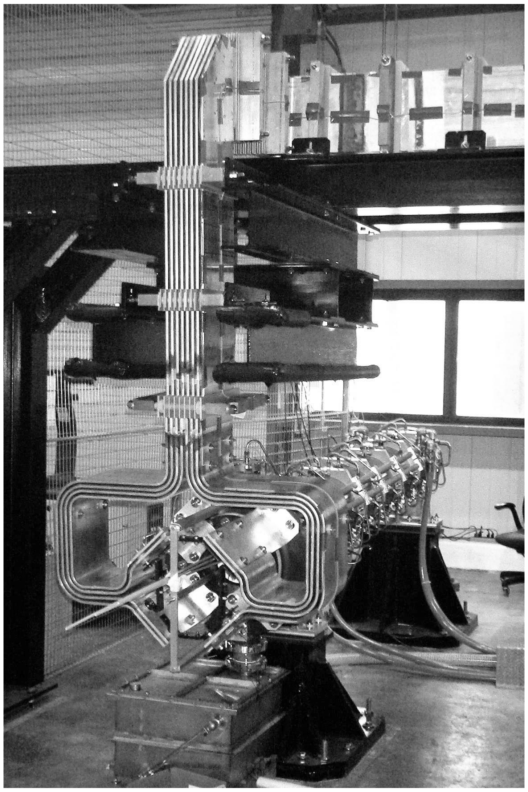


Already seen 6Million Pulses—
2/3 NUMI year

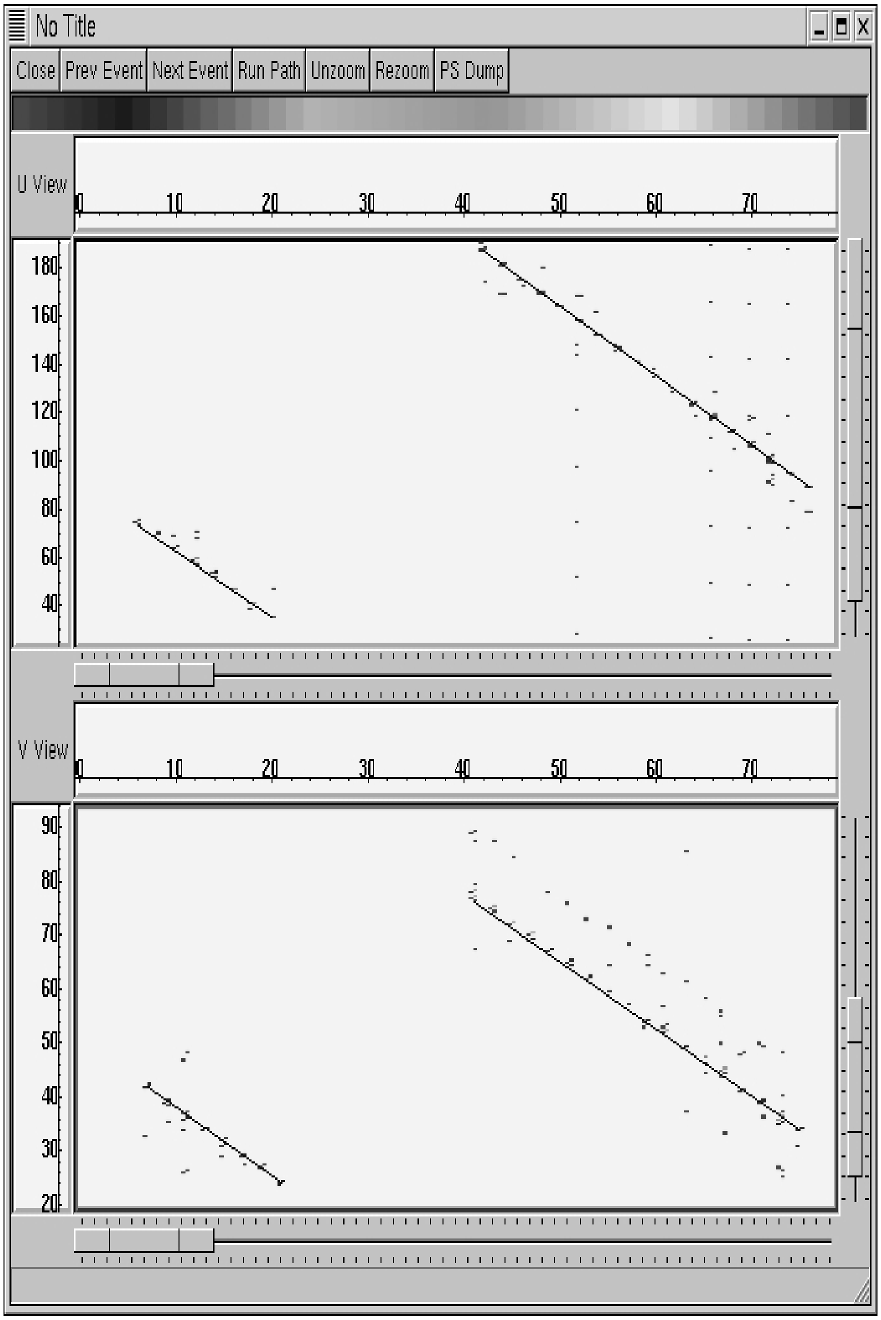
- B~1/r as close as we can measure (0.1%!)
- 1.5T at max
- B<30Gauss in center



55µm, 1.17kHz: Data,
71 µm, 1.19KHz ANSYS
Frank Nezrick



Double Cosmic-Ray Muon in MINOS Far Detector



Color shows pulse size

Scintillator strip number →

'u' view

'v' view

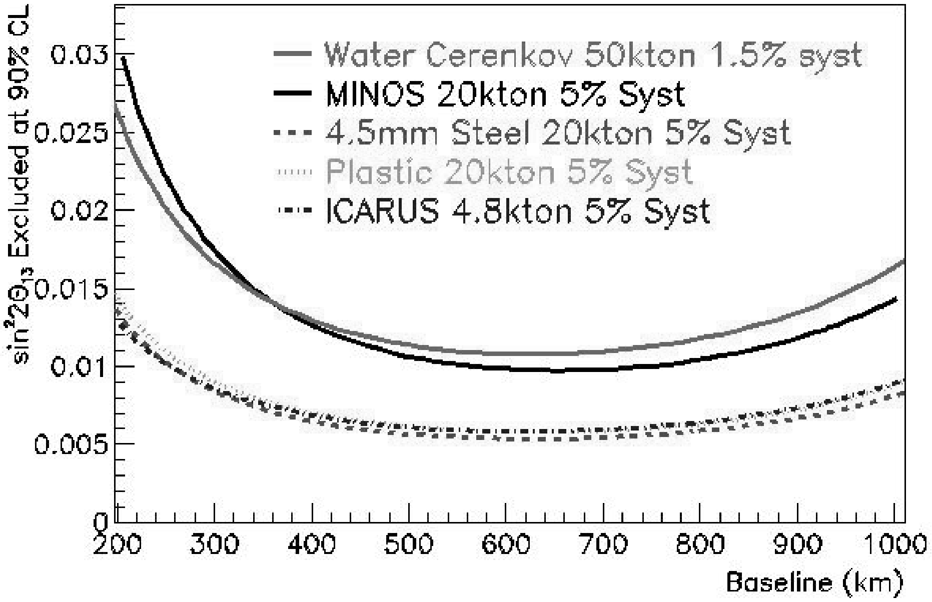
Lines are from fits by track reconstruction software

Detector plane number (1-76) →

How well could this do?

- Need to optimize:
  - « Baseline –have a wide range for any one angle!
  - « Detector—many options being considered

    (Signal and Bckgnd efficiency, and how massive?)
- Electron appearance requirements
  - « Good segmentation
    - * Identify outgoing electrons
  - « Good energy resolution
    - * Separate ν_e and NC events
  - « Particle identification

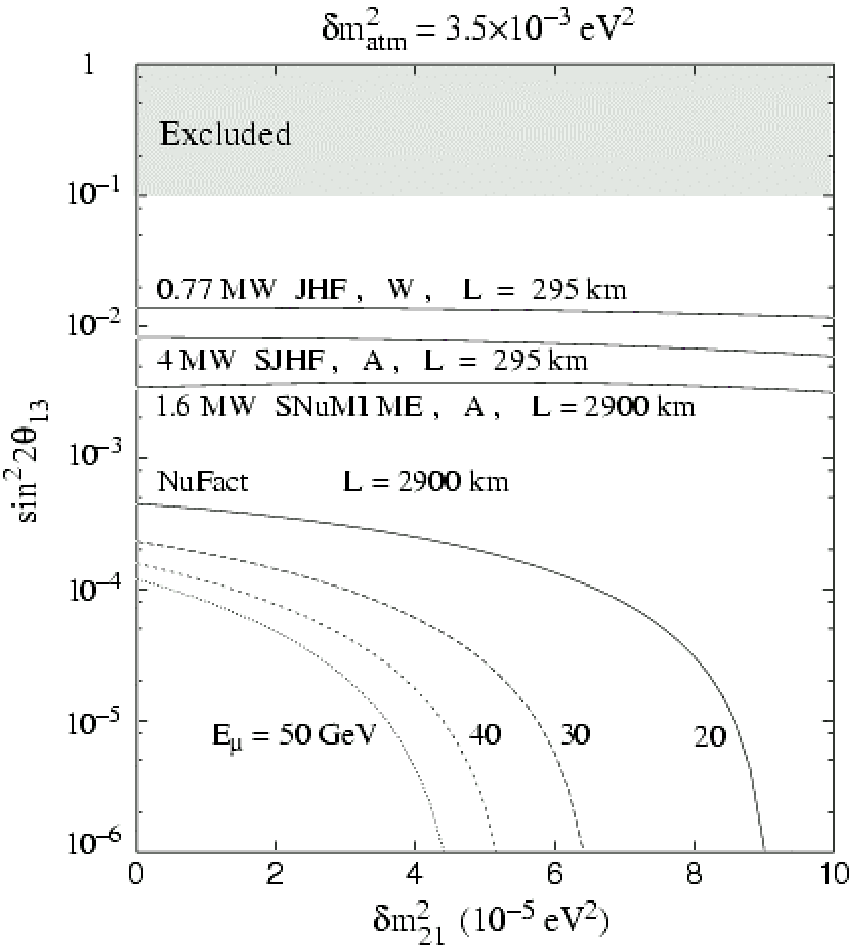


Conclusion from preliminary studies: can do a factor of 10 better than current limits!

Upgradable program

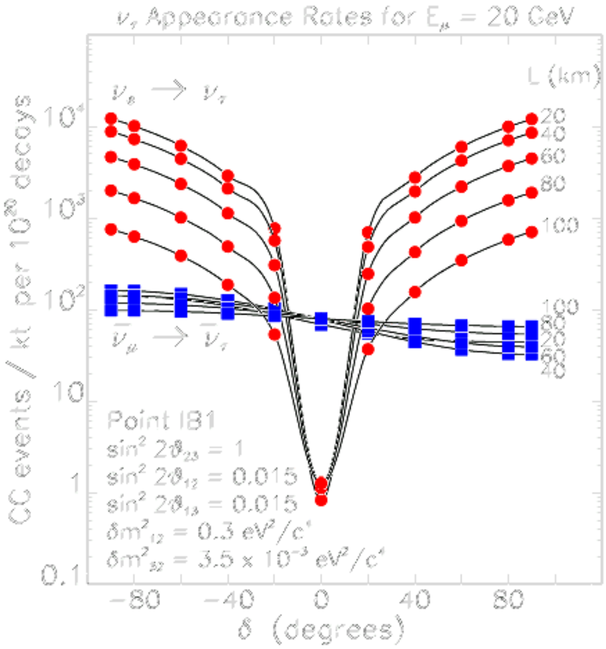
Can make anti-neutrino beams too!

Neutrino Factory Reach



Factor of 10 better
Than JHF upgrade!
If LMA and Θ_{13} small,
Might even see signs
of solar mass scale!
Larger parameter
space accessible for
CP studies
(hep-ph/010352)

If LSND confirmed:
Look for ν_τ
appearance at shorter
Baselines—CP
studies galore!
(hep-ph/010352)



Conclusions

- Lesson to be learned from history: measurements can and will surprise you!
  - (nb: if LSND is due to oscillations, things look even more bizarre than I've shown here…)
- This is an exciting time to be doing neutrino physics
- There are lots of challenges ahead
  - Need detectors to tell ν_e from ν_μ events
  - Need more neutrinos please!
- Longer Term: Neutrino factories can push this field from its discovery phase to precision phase!