Neutrino Oscillations Experiments at Fermilab

ICHEP2000
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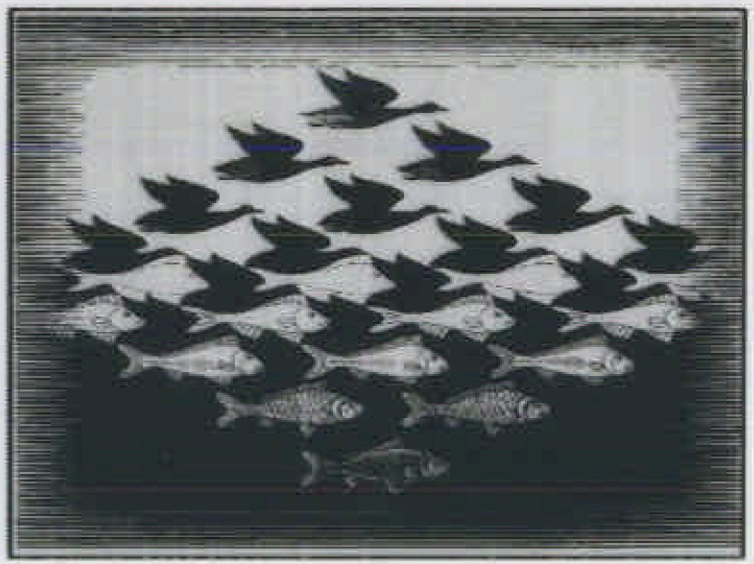
Outline

- Current Burning Questions
- Experiments to address them
  - MiniBOONE
  - NUMI/MINOS



Neutrino Oscillations: a Tool to Measure Masses

- Theoretically, it is natural to expect neutrinos to have mass
  - Not required to be massless by any symmetry such as gauge invariance
  - All other fermions are massive
- Neutrinos can have Dirac (M_D) and/or Majorana (M_M) mass terms
  - See-saw mechanism
    - 4-state Dirac neutrino with mass M_D ($\sim m_q$ or m_l) gets split into two 2-state Majorana neutrinos (ν, N)
    - Lepton number violation!

$$m_\nu = M_D^2 / M_N = small \qquad m_N = M_M = large$$

- **Direct measurements can probe masses above ~1eV**
- **Only neutrino oscillations can probe $m_\nu < 1$ eV**

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 $\bar{\nu}_e + p \to n + e^+$

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

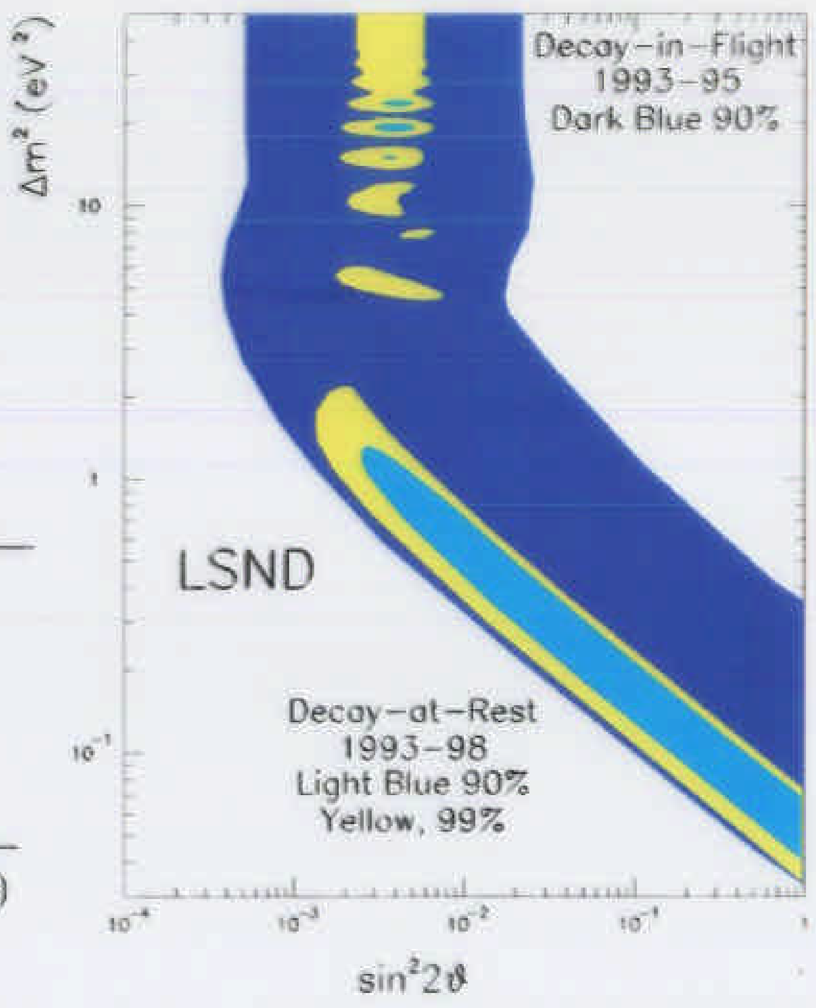
stopped $\pi^+ \to \nu_\mu \mu^+$
$\hookrightarrow e^+ \bar{\nu}_\mu \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$

Excess: 83.3 ± 21.2 ± 12.0 events

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

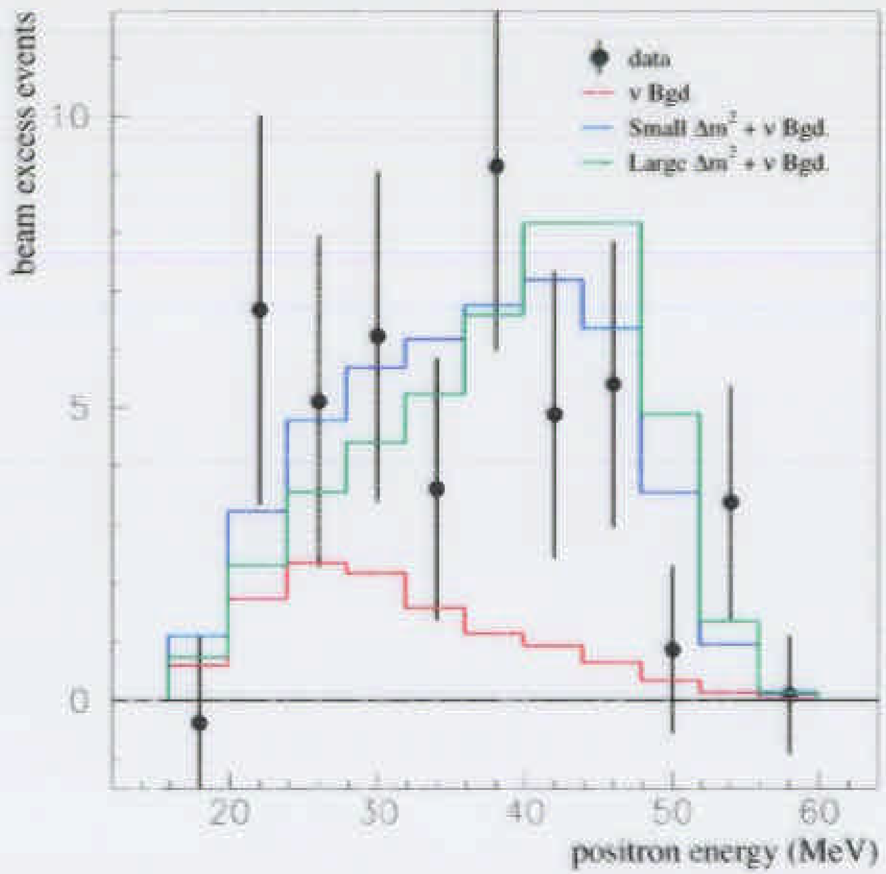
$\pi^+ \to \nu_\mu \mu^+$ $\nu_\mu \to \nu_e$

Excess: 18.1 ± 6.6 ± 4.0 events

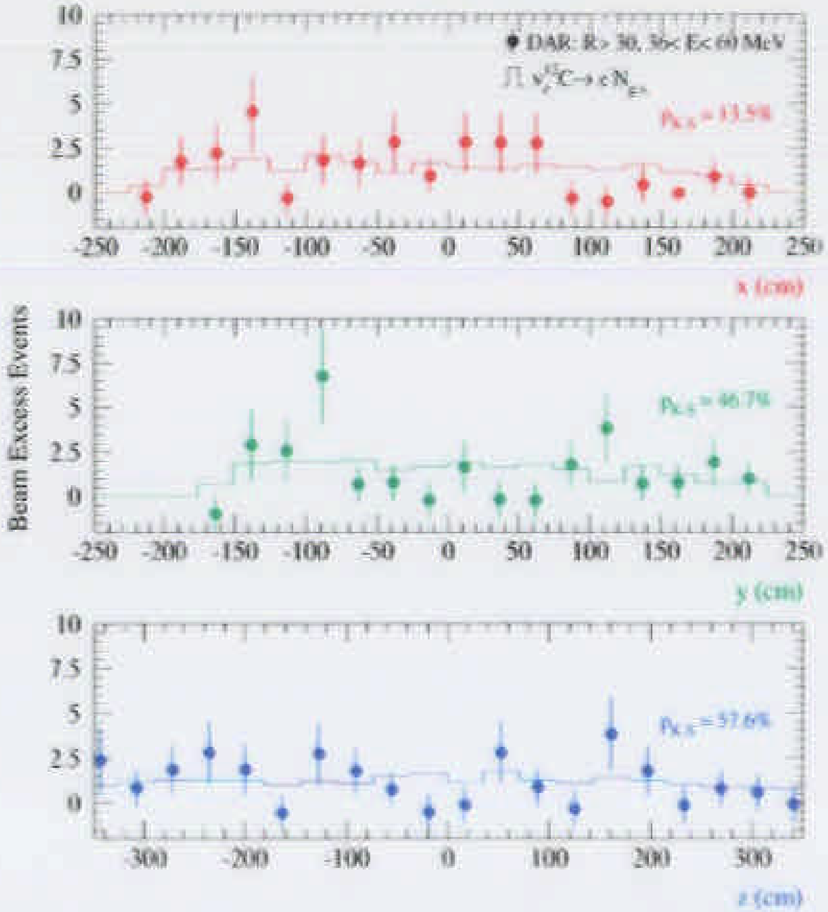


LSND Excess ν_e Events

- Excess ν_e events have much higher energy than backgrounds

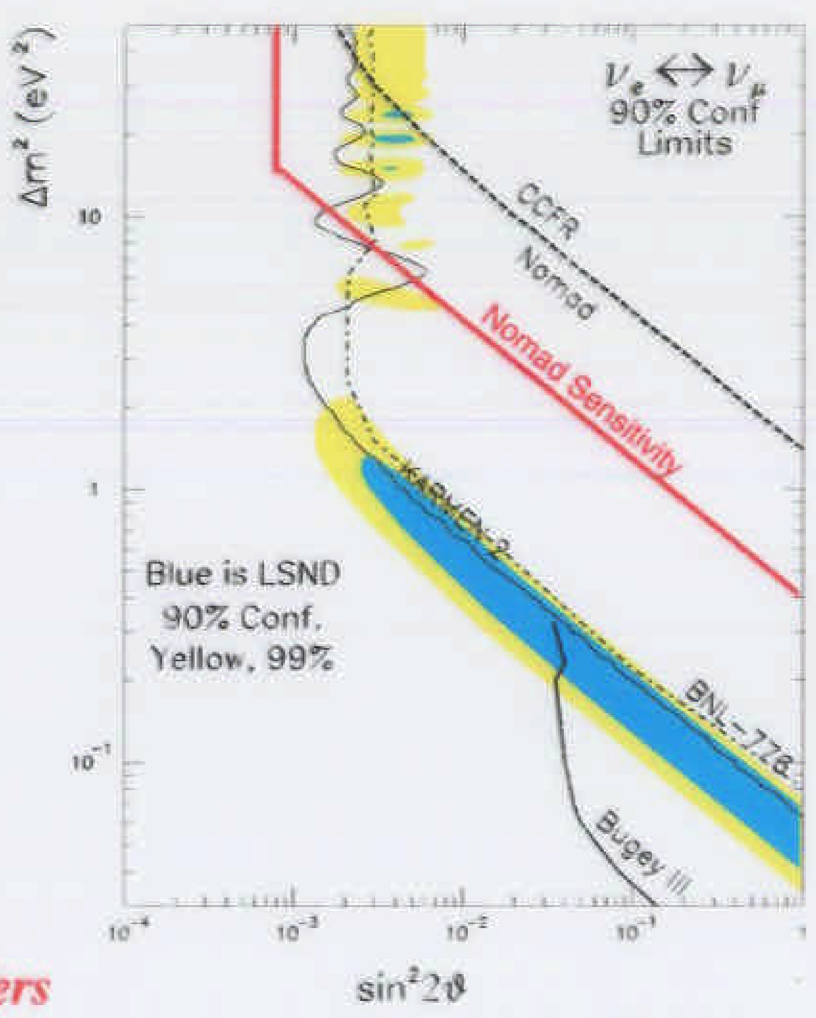


- Spatial distribution in detector is consistent with $\nu_e\, ^{12}C \rightarrow e^- N_{g.s.}$ events



LSND Puzzle

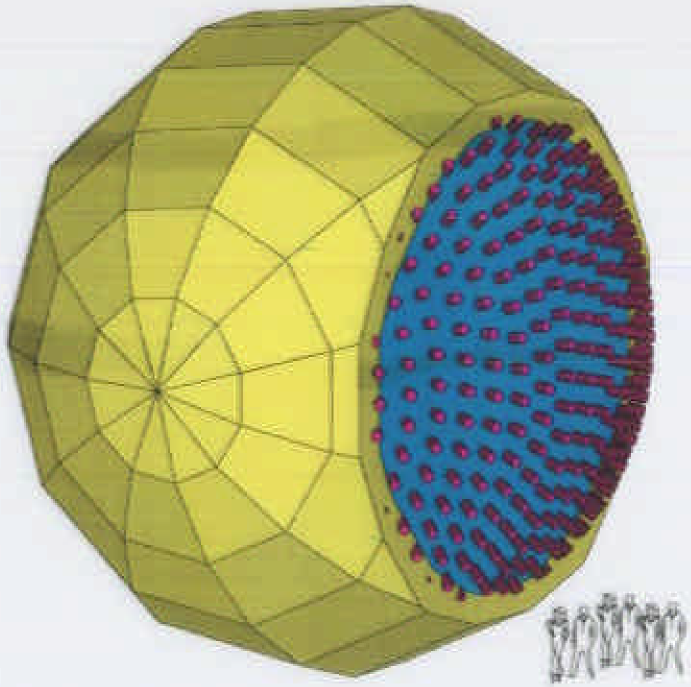
- Are we witnessing $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations?
- neutrino CCFR, Nomad, and Bugey exps. rule out high and low Δm^2 region
- Karmen experiment :
  Sees no indication of oscillation but is not incompatible:
  - Expected 8 events
  - Observed 7.8 ± 0.5 events



Need decisive experiment to check LSND result and measure parameters if oscillations $\Rightarrow$ **MiniBooNE**

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

- Use protons from the 8 GeV booster
  $\Rightarrow$ Neutrino Beam $<E_\nu>\sim$ 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.)



Particle Identification in the MiniBOONE Experiment

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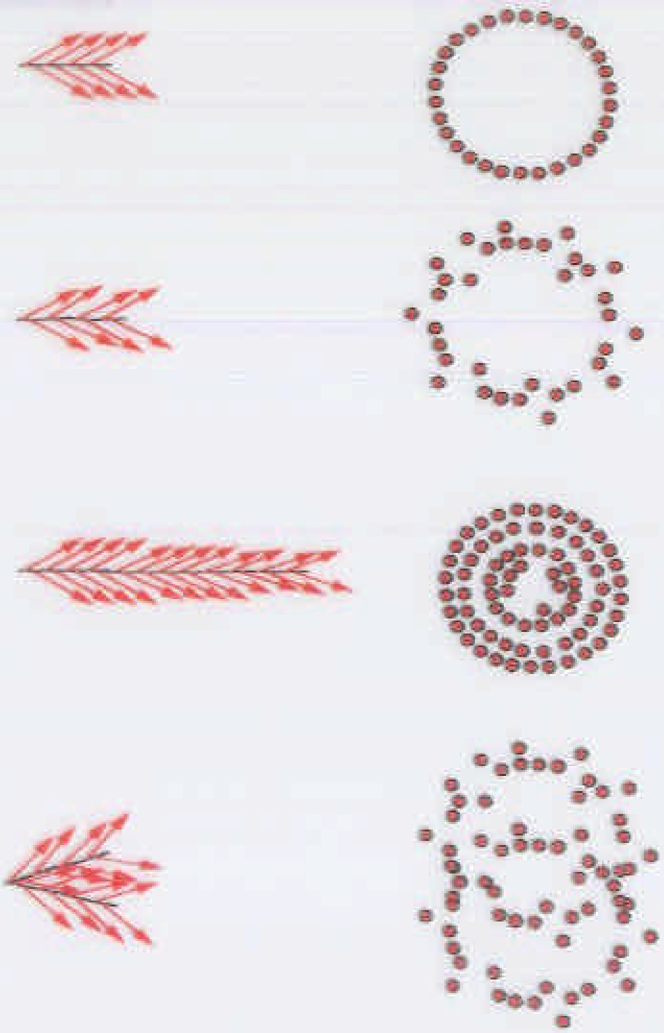
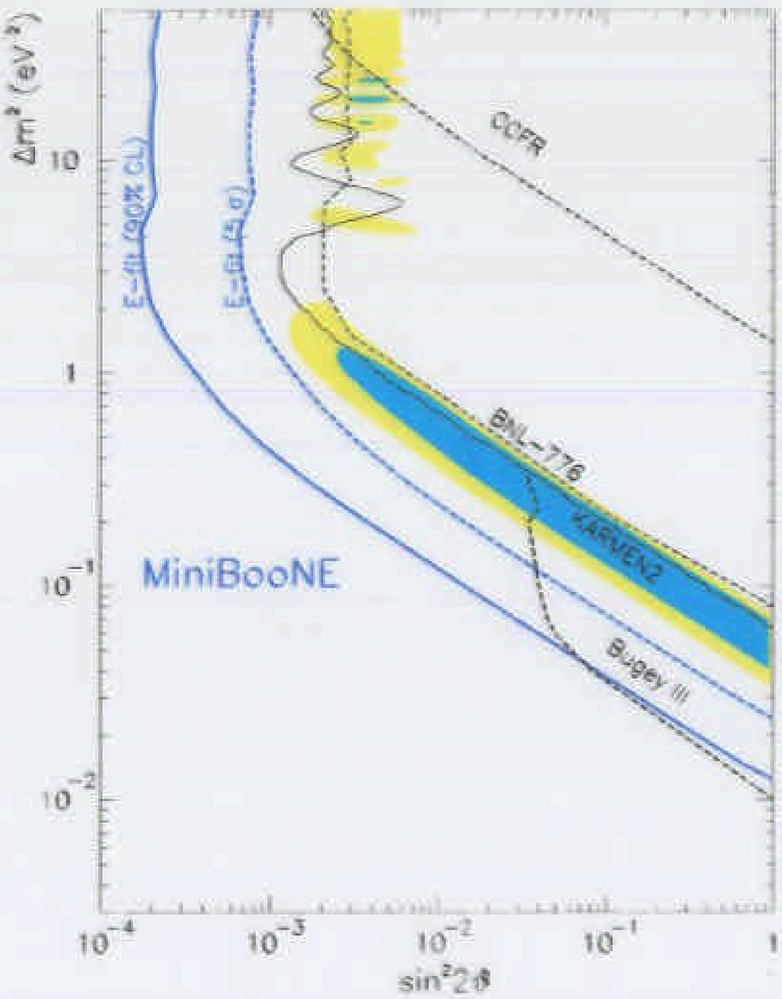
Cerenkov Light...

From side | Ring



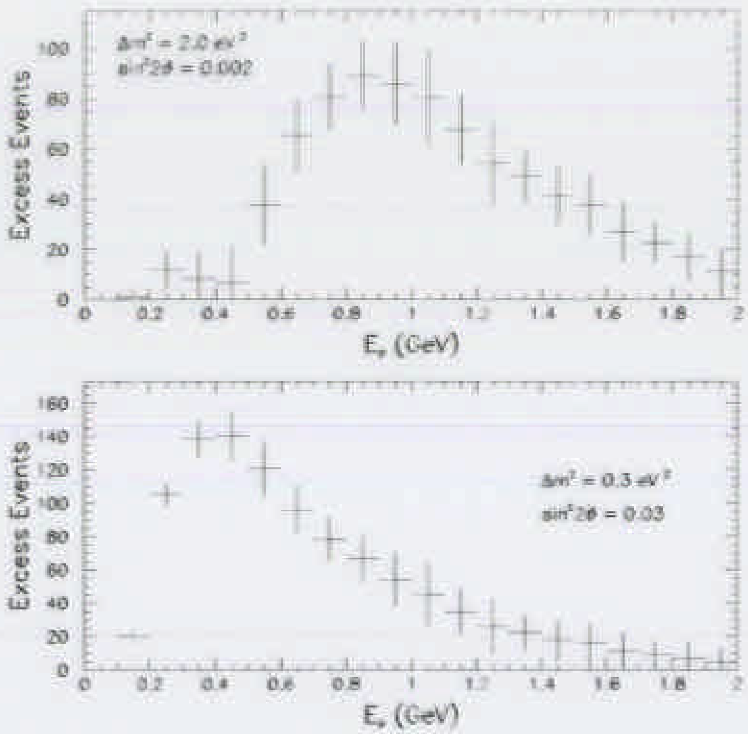
short track, no multiple scattering	Sharp Ring
electrons: short track, mult. scat., brems.	Fuzzy Ring
muons: long track, slows down	Sharp Outer Ring with Fuzzy Inner Region
neutral pions: 2 electron-like tracks	Two Fuzzy Rings

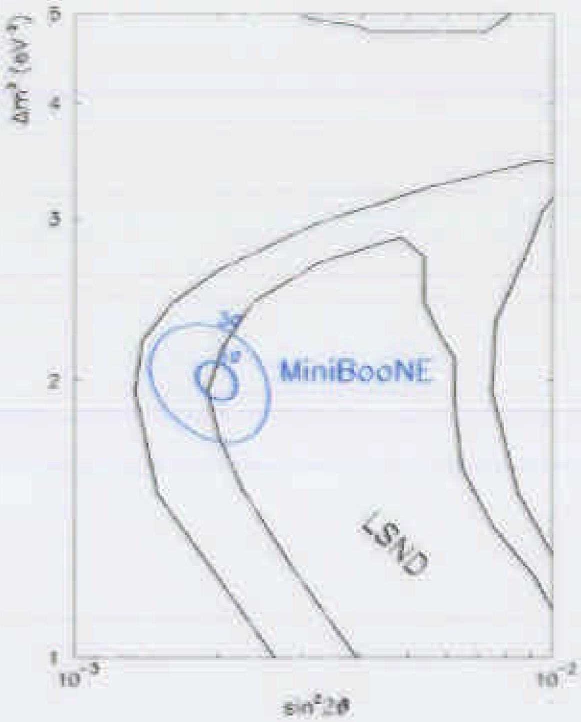
MiniBooNE Rates and Sensitivity



- 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 $\rightarrow$ >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

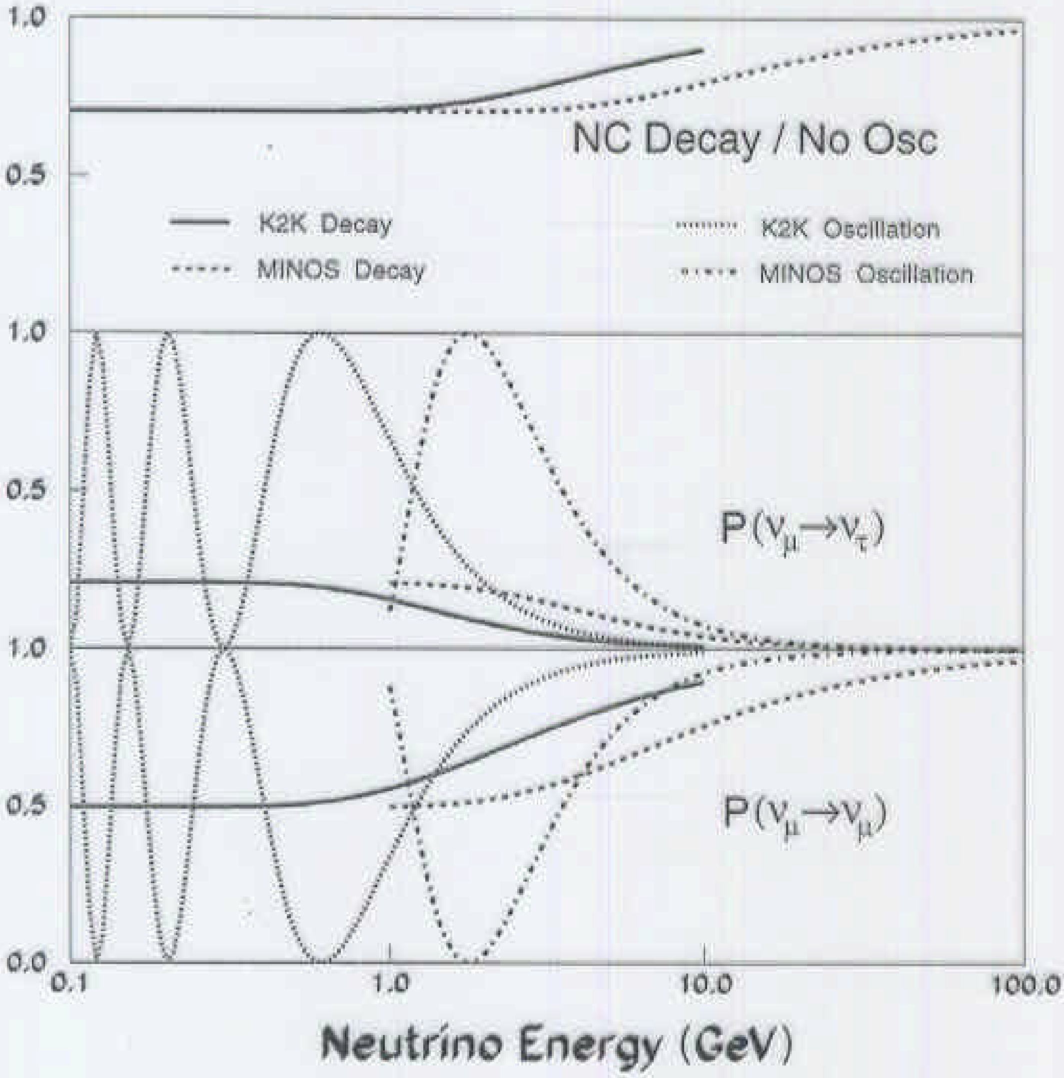
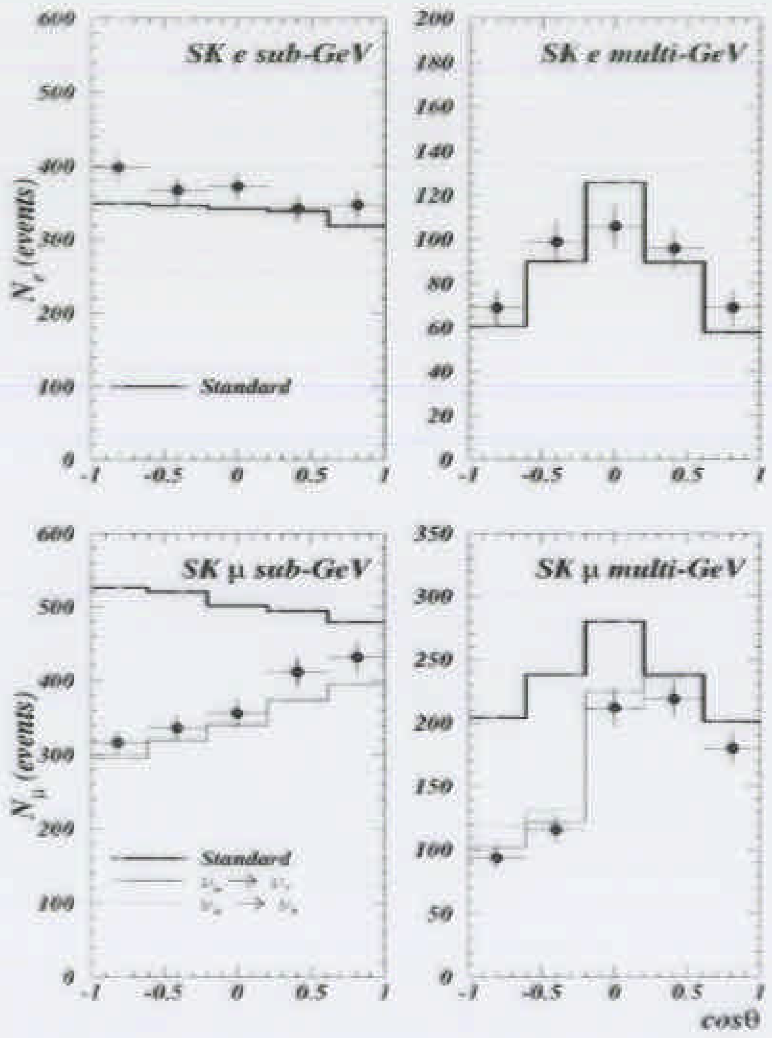


FIGURE 3. Long-baseline expectations for the K2K and MINOS long-baseline experiments from the decay model and the ν_μ-ν_τ oscillation model. The upper panel gives the neutral current predictions compared to no oscillations (or ν_μ-ν_τ oscillations).

Results from Super-K Experiment



- ν_μ flux reduced by about 50% for long flight path
- if it is a result of the neutrino oscillations, then :
  - the dominant mode is numu to nutau
  - mixing angle is very large
  - Δm^2 : $1.5\times10^{-3} \le \Delta m^2 \le 8\times10^{-3}$ GeV^2

? Is this deficit due to oscillations? Decays? Extra dimensions?

? If oscillations:

¿ what is the value of Δm^2

¿ what is a possible admixture of ν_e

¿ what is a possible admixture of $\nu_{sterile}$

¿ are ν_τ really there

Three-Generation Neutrino Oscillation Formalism

- For 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 will be oscillations between all the neutrino flavors with amplitudes given by mixing angles.

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

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

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

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

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

The MINOS Beamline

Two Detector Neutrino Oscillation Experiment (Start 2003)

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

Two detector experiment: Oscillation case

Near Detector

"short" $S_n = \Phi_n (\sigma^{NC} + \varepsilon\sigma^{CC})$

"long" $L_n = \Phi_n (1-\varepsilon)\, \sigma^{CC}$

Far Detector

$S_f = \Phi_f (\sigma^{NC} + \varepsilon\sigma^{CC} + \eta\xi\sigma^{CC})$ ← appearance

$L_f = \Phi_f (1-\varepsilon)(1-\xi)\sigma^{CC}$ ← disappearance

Possible suppression of CC cross section of oscillated neutrinos

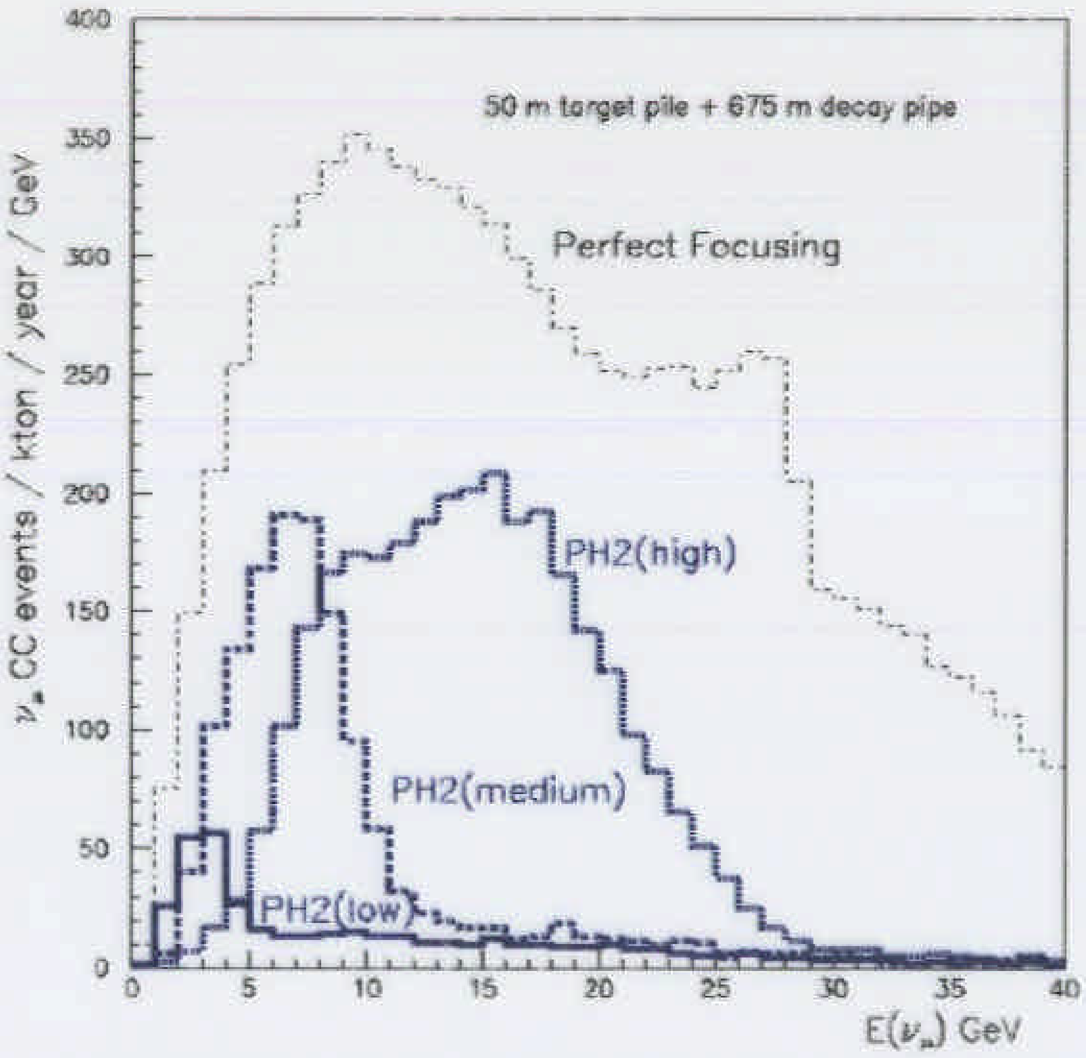
Combined: appearance x disappearance experiment => good sensitivity

$$R = \frac{\frac{S_f}{L_f}}{\frac{S_n}{L_n}} = \frac{1}{1-\xi}\left(1 + \frac{\eta\xi \frac{\sigma^{CC}}{\sigma^{NC}}}{1+\varepsilon\frac{\sigma^{CC}}{\sigma^{NC}}}\right)$$

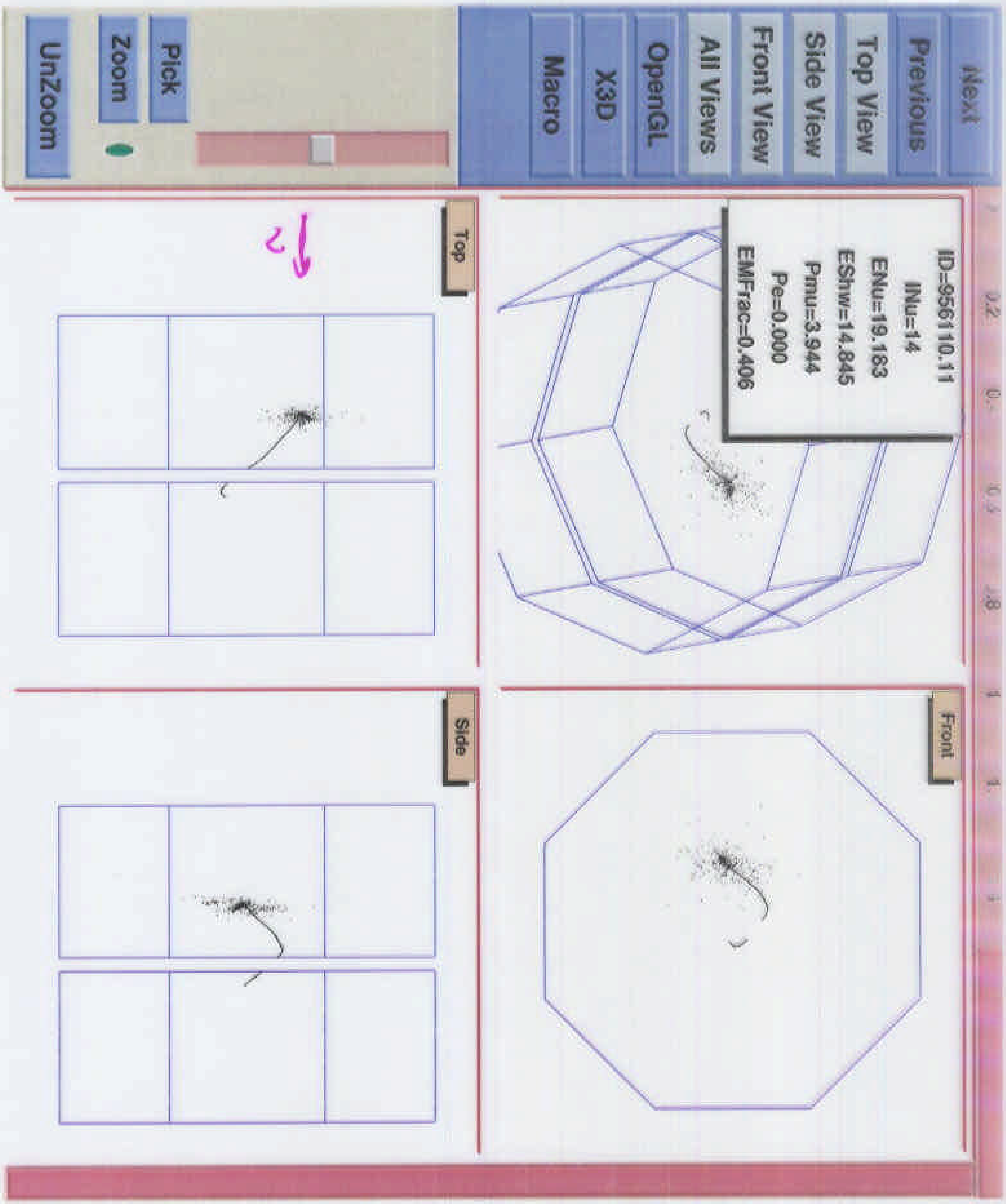
Most of flux and systematic errors cancel

$$1 = R^{\nu_\mu \to \nu_{sterile}} \le R^{\nu_\mu \to \nu_\tau} \le R^{\nu_\mu \to \nu_e}$$

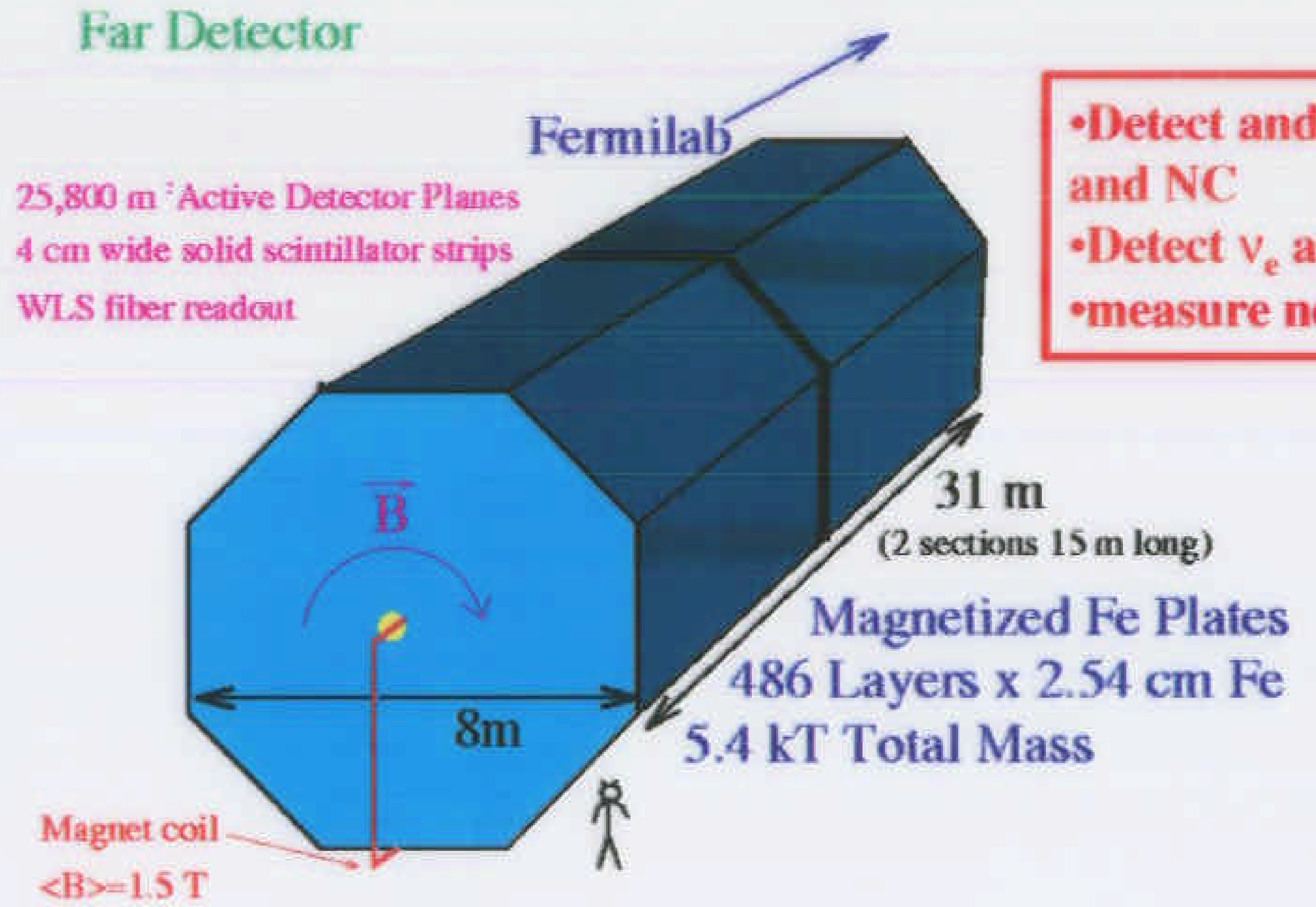
NuMI: Flexible Neutrino Beam



- CC Events Rates in Minos 5kt detector:
  - High 16,000/yr
  - Medium 7,000/yr
  - Low 2,500/yr


Next
Previous
Top View
Side View
Front View
All Views
OpenGL
X3D
Macro
Pick
Zoom
UnZoom
ID=956110.11
INu=14
ENu=19.183
EShw=14.845
Pmu=3.944
Pe=0.000
EMFrac=0.406
Top
Side
Front

MINOS Far Detector



- Detect and identify ν_μ CC and NC
- Detect ν_e and ν_τ NC/CC
- measure neutrino energy

Oscillation effects observable at MINOS

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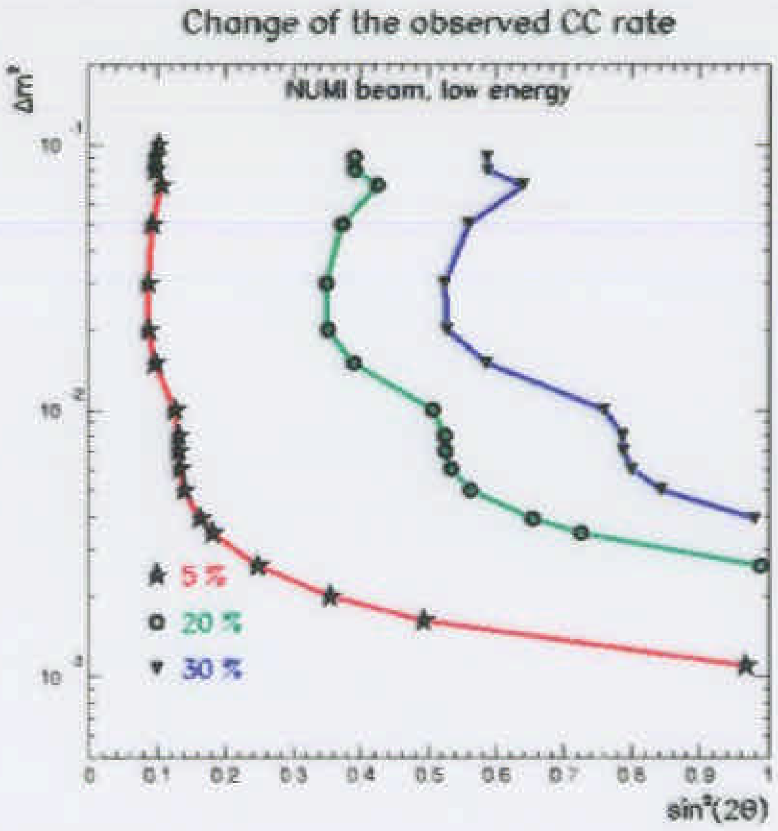
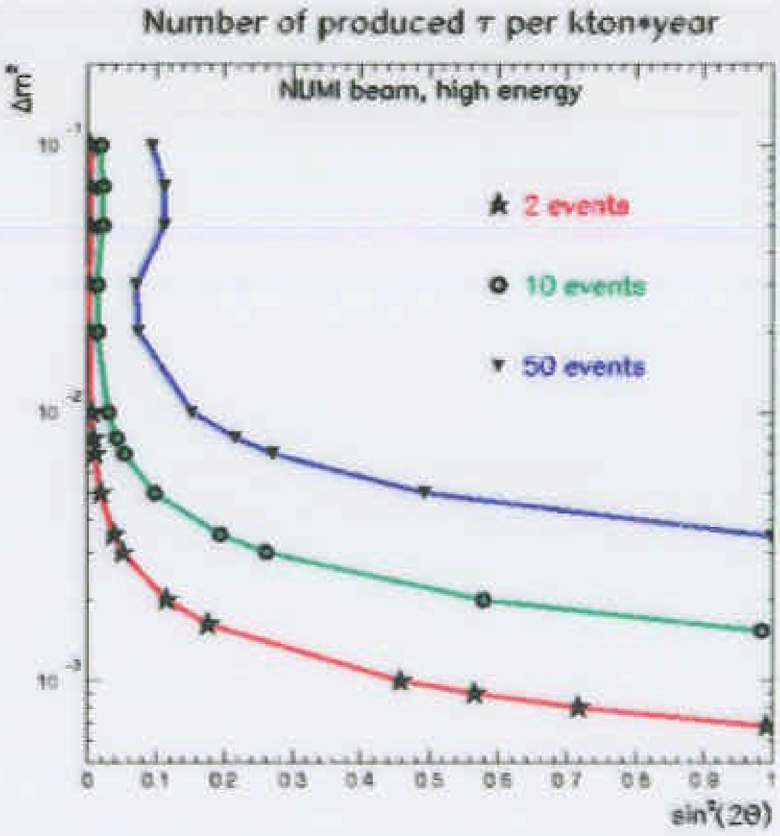
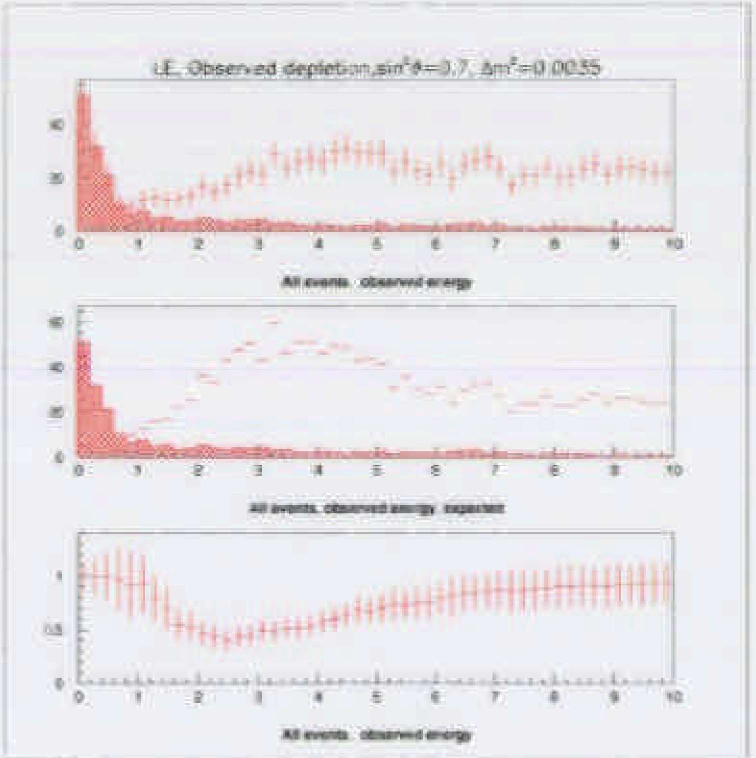
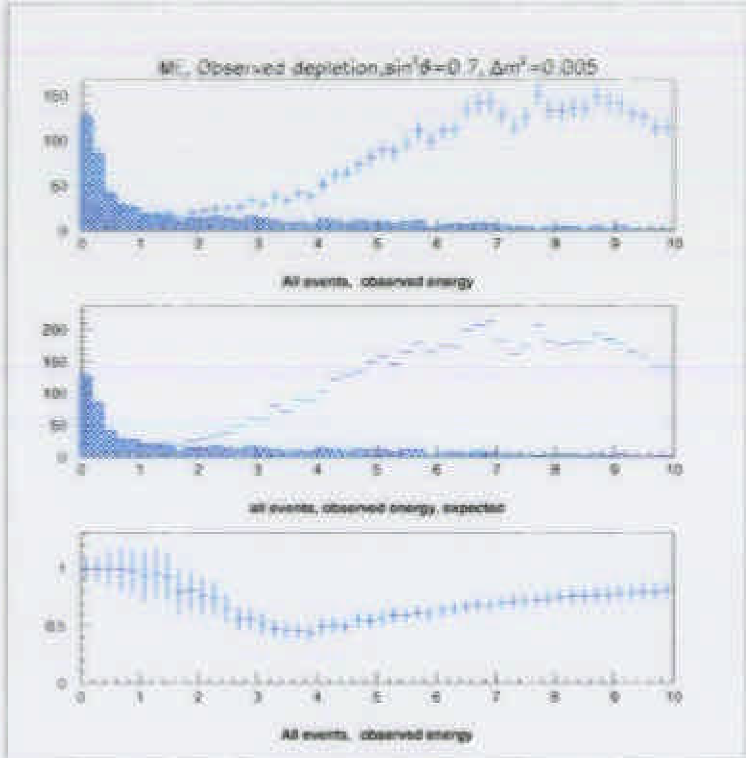




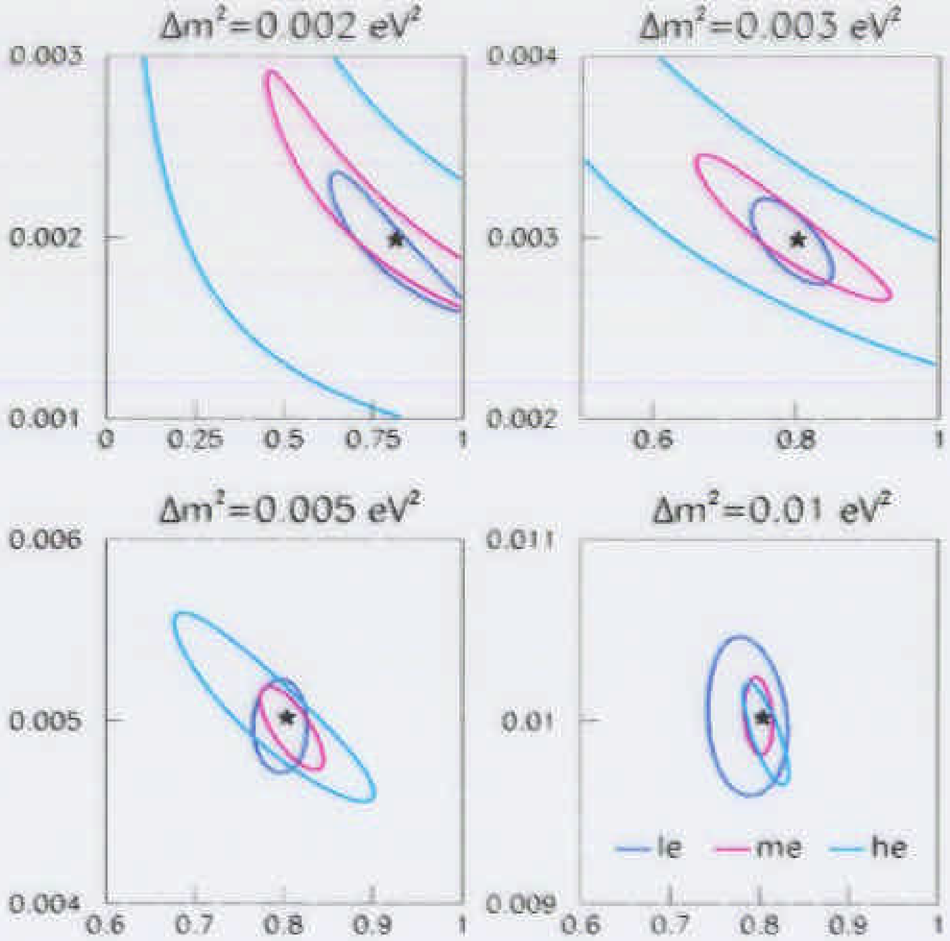
Oscillations or Decays? or Other?





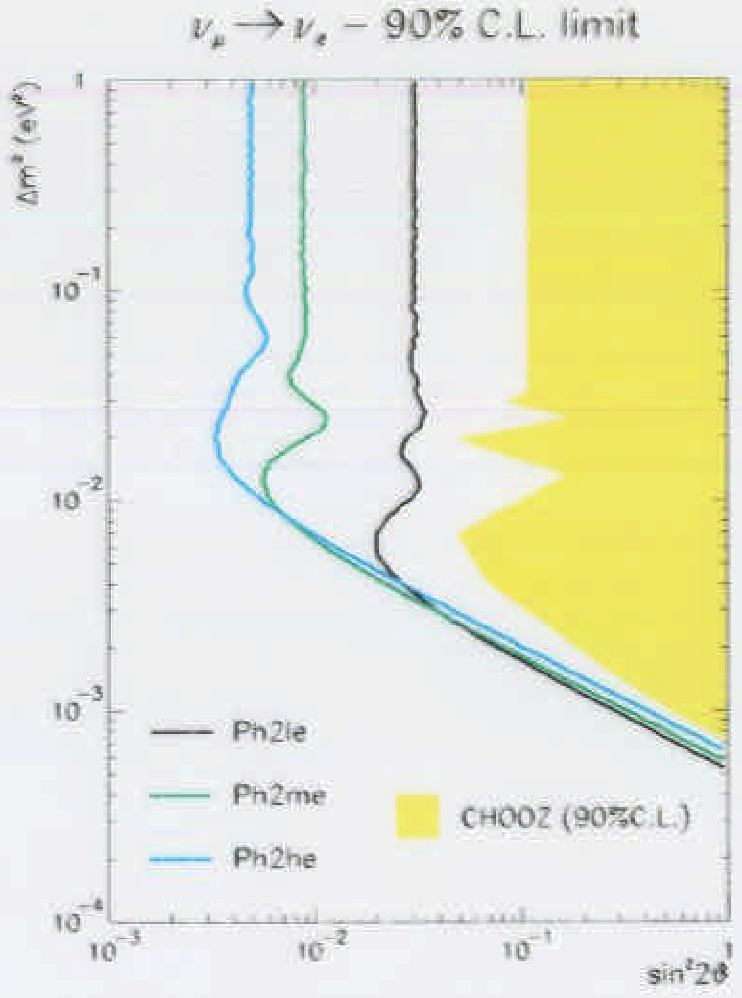
Observed energy distribution of ν_μ CC interactions provide a measure of the ν_μ survival probability as a function of E_ν

Measuring the Oscillation Parameters



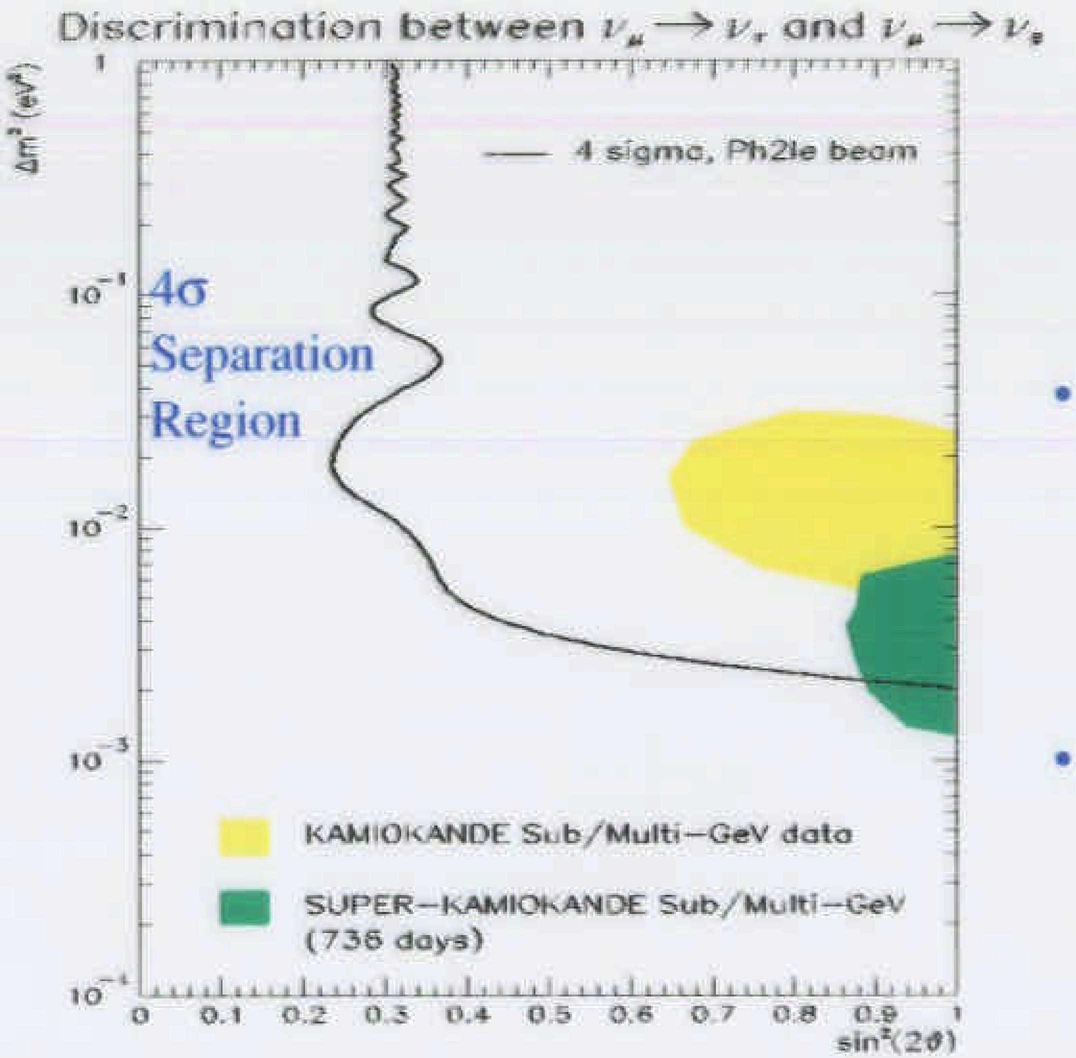
Expected errors from the fit to the energy distribution of ν_μ CC events

Limits on ν_μ to ν_e Oscillations



Sample of ν_e candidates defined using topological cuts

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 ν_μ , CC production of τ's will look like NC ~80% of the time

  CC/NC down

- For ν_μ sterile , both CC and NC will be suppressed.

  CC/NC stays ~ constant

On the Importance of the Near Detector

- ν_μ disappearance:
  - ν energy and radial distribution => constraint on the far detector flux
  - beam pointing
- NC/CC:
  - 'short/long' ratio including cuts, efficiencies and smearing
- ν_e appearance:
  - measure intrinsic ν_e component of the beam
  - measure background of mis-identified NC events
- ν_τ appearance:
  - measure background of mis-identified NC events
- **Very high statistics (700,000 times higher than in the Far Detector)**

NUMI/MINOS Schedule

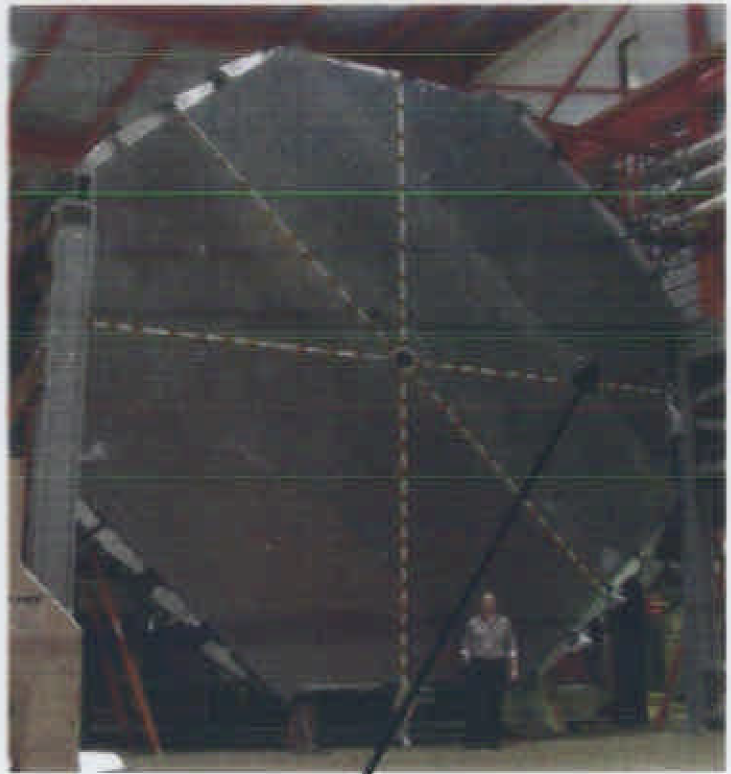
- Detector Hall construction in Minnesota (now - 2001)
- Beam Tunnel construction at Fermilab (2000 - 2002)
- Far/Near Detector construction (2001 - 2003)
- Start data run (2003 - 2004)

MINOS Steel Plane Prototype

Soudan Excavation in Progress

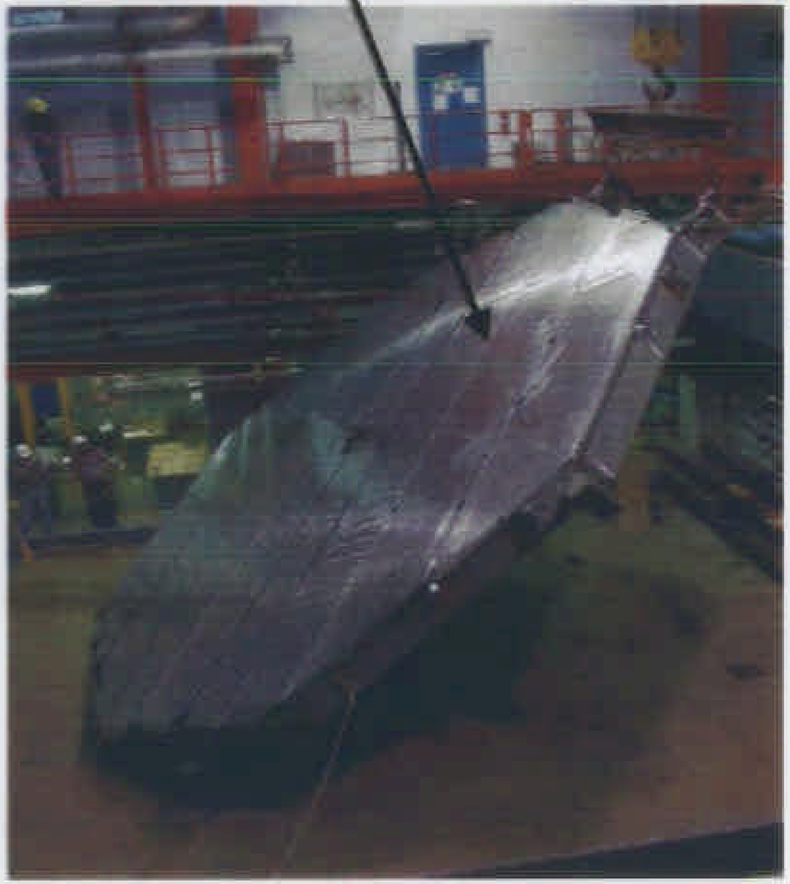
To be completed this year!

Minos 4-Plane Prototype

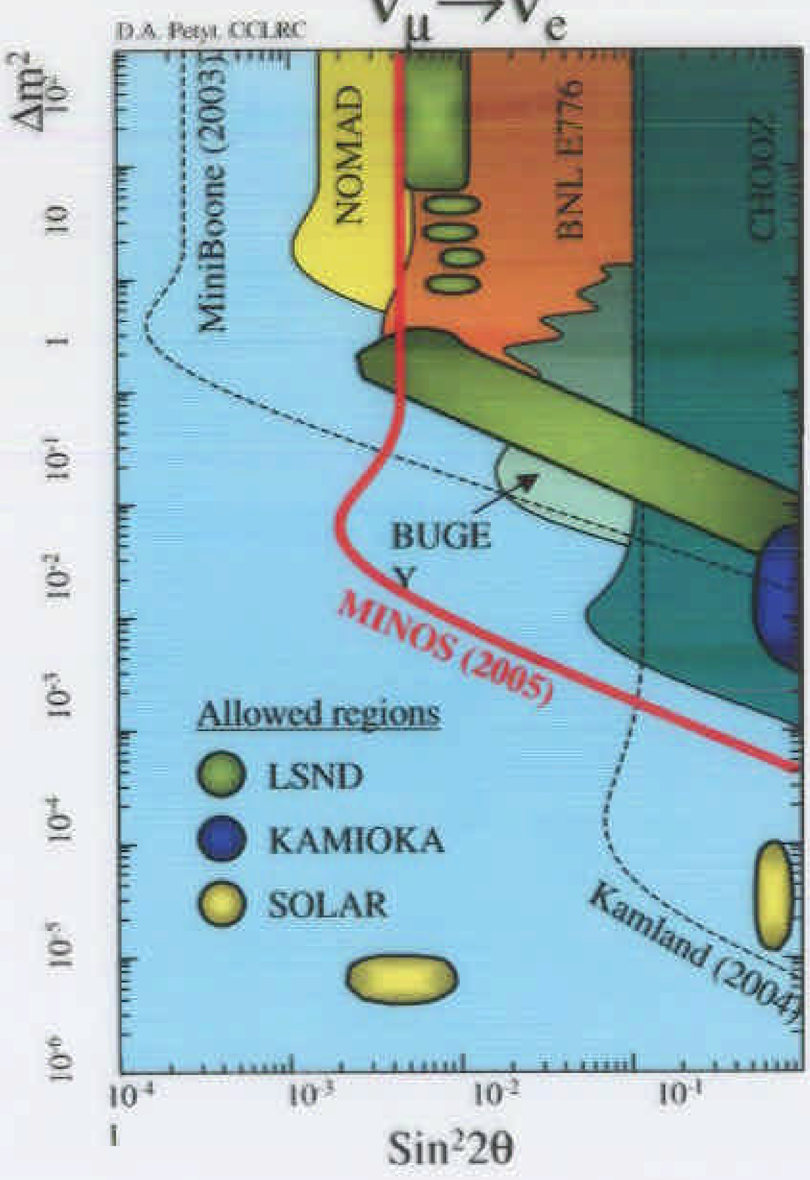


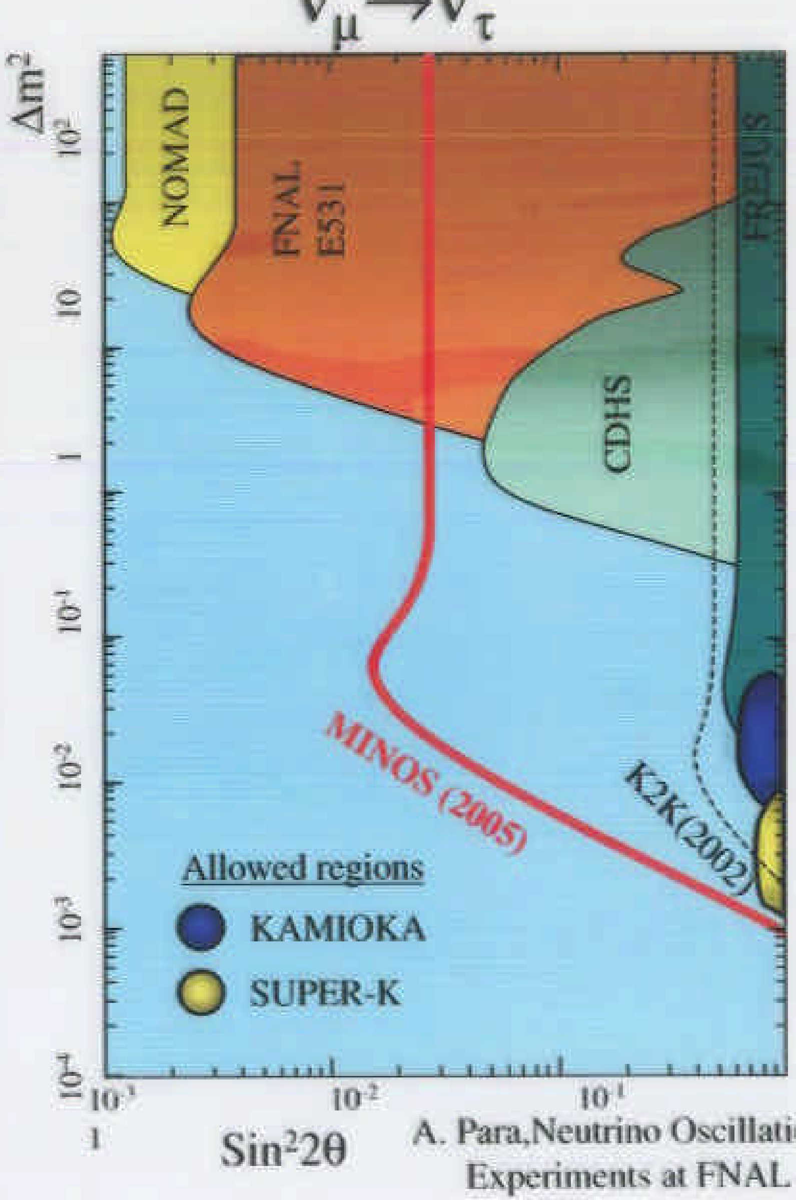
flux coils for field measurement

4 planes, 3 equipped with scintillator modules



What the (near) future holds





MINOS Physics Measurements

- Obtain firm evidence for oscillations:
  (Near/Far comparison reduces systematic uncertainties)
  - CC interaction rate and energy distribution
  - NC/CC rate ratio and energy distribution
- Measurement of oscillation parameters, Δm^2, $\sin^2 2\theta$
  - CC energy distribution
- Determination of the oscillation mode(s)
  - NC/CC rate measurements: a tool to discriminate against $\nu_{sterile}$
  - Identification of ν_e by topological criteria
  - Identification of ν_τ by its exclusive decay modes (works best if Δm^2 is relatively high)