

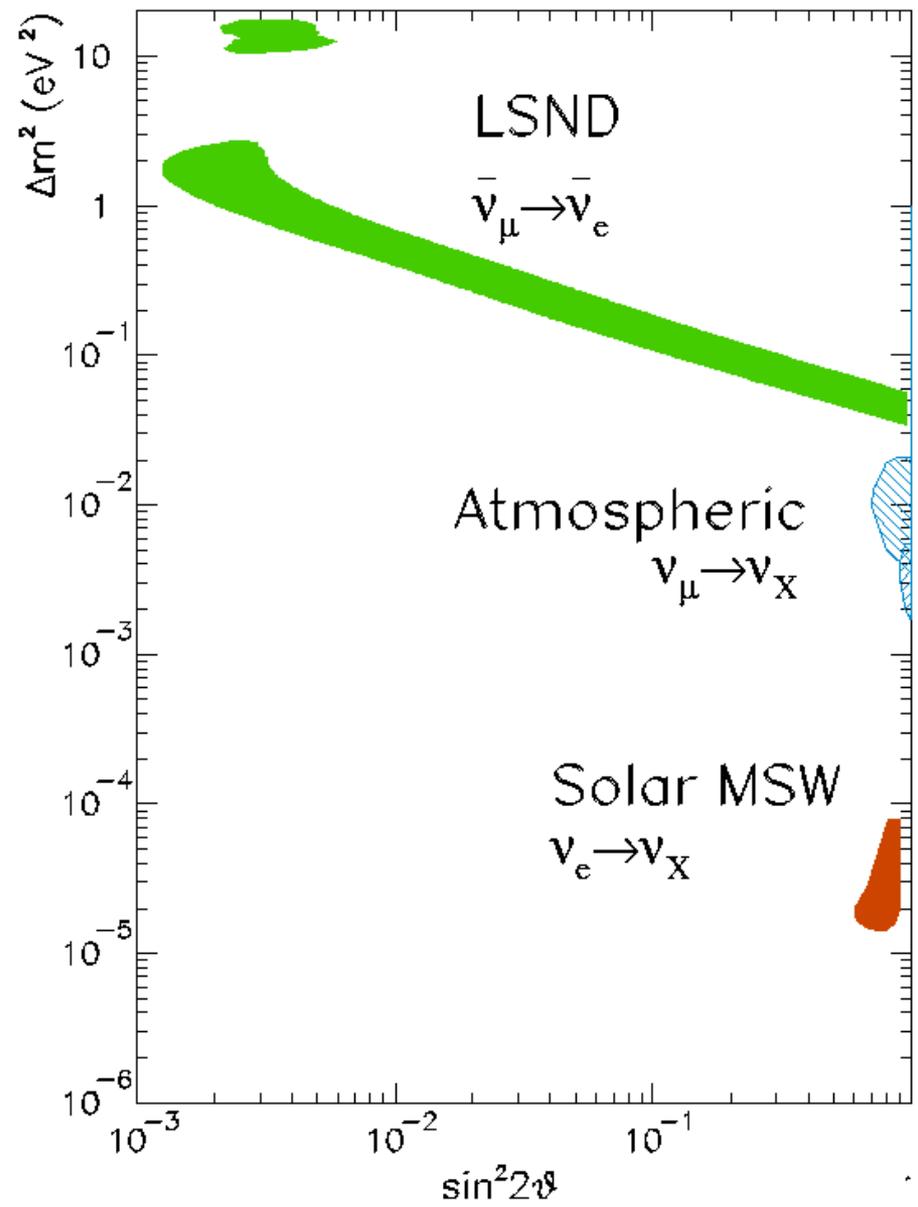
Neutrino Oscillation Program

Michael Shaevitz (Columbia / Fermilab)

- Current Status of neutrino mass and oscillations
- Status of NuMI/MINOS Experiment
- Status of the MiniBooNE Experiment

Current Neutrino Oscillation Signals

- Three Positive Signals
 - Solar Neutrinos
 - Atmospheric Neutrinos
 - LSND : Low-E Accelerator Neutrinos



Solar Neutrino Experiments (Observe Rate of ν_e from the Sun)

Rate measurement

- Homestake (US)
- SAGE (Russia)
- Gallex+GNO (Italy)
- Super-K (Japan) H_2O
- **SNO (Canada) D_2O**

Reaction

- $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
- $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
- $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
- $\nu_x + e^- \rightarrow \nu_x + e^-$
- $\nu_e + d \rightarrow p + p + e^-$
- $\nu_x + d \rightarrow n + p + \nu_x$

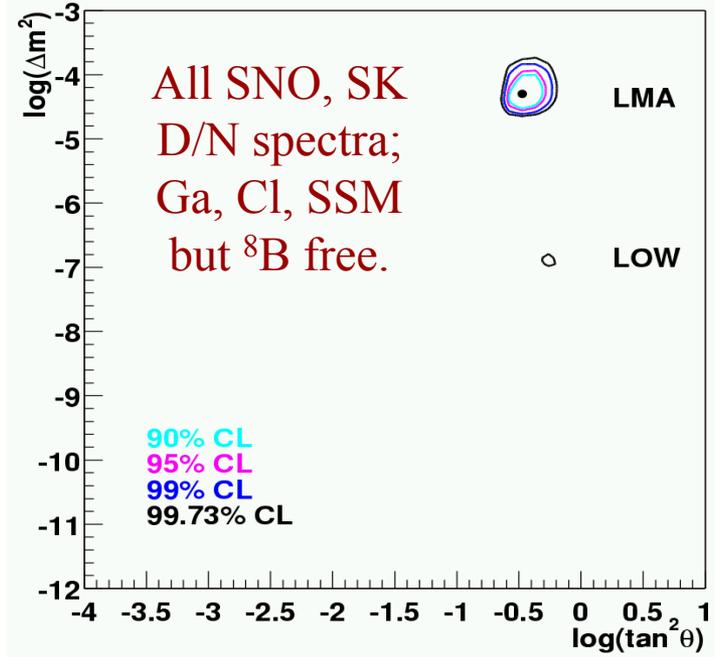
Obs / Theory

- 0.34 ± 0.03
- 0.59 ± 0.06
- 0.58 ± 0.05
- 0.46 ± 0.02
- 0.35 ± 0.03
- 1.01 ± 0.23**

Recent SNO measurement is strong indication of oscillations of electron neutrinos into ν_μ or ν_τ types

Combination of experiments is very restrictive

$\Delta m^2 = 5 \times 10^{-5} eV^2, \sin^2 2\theta = 0.8$

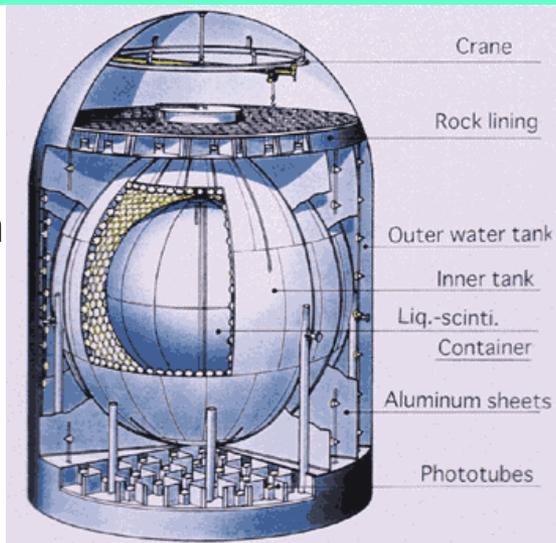


Upcoming Tests of Solar Oscillations

Kamland

Reactor neutrino exp. in solar region

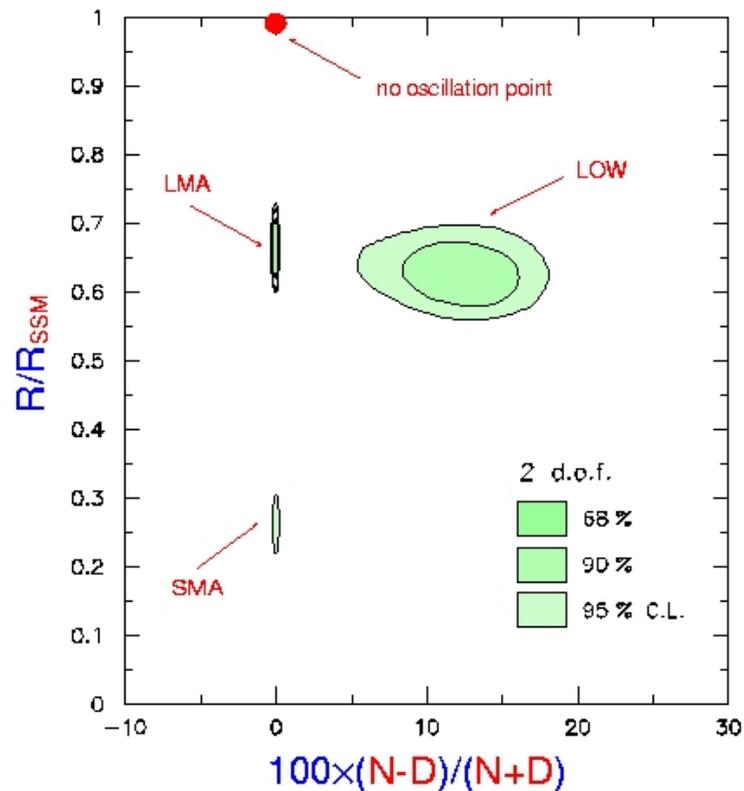
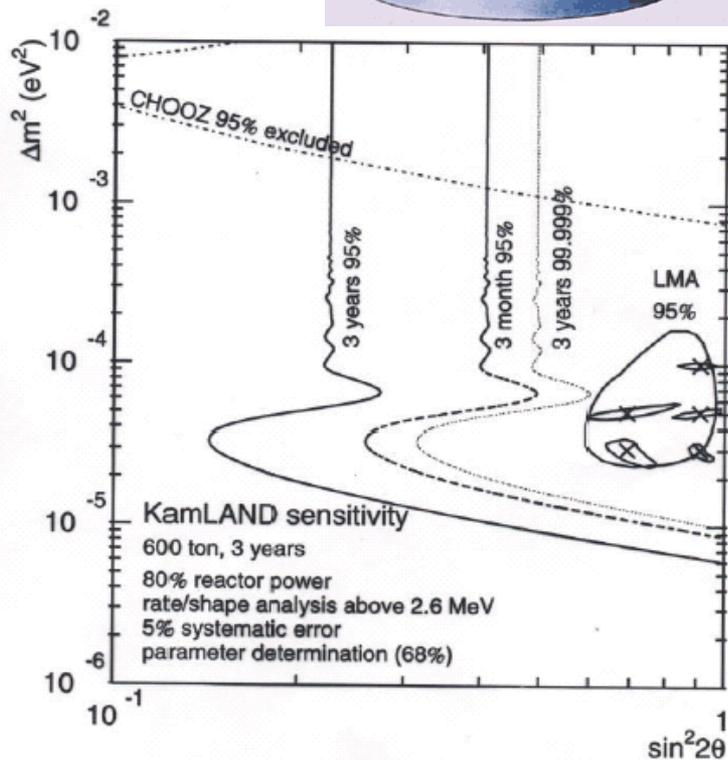
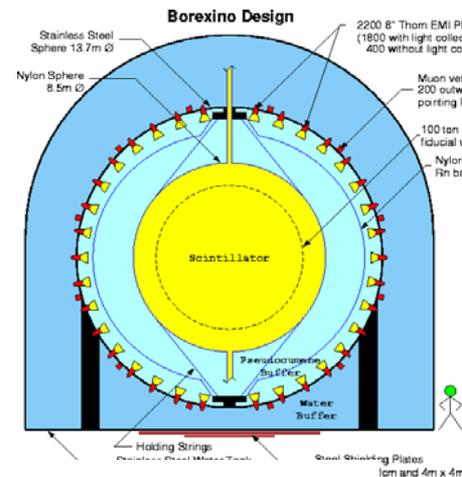
$\bar{\nu}_e$ from reactors (L~170km)



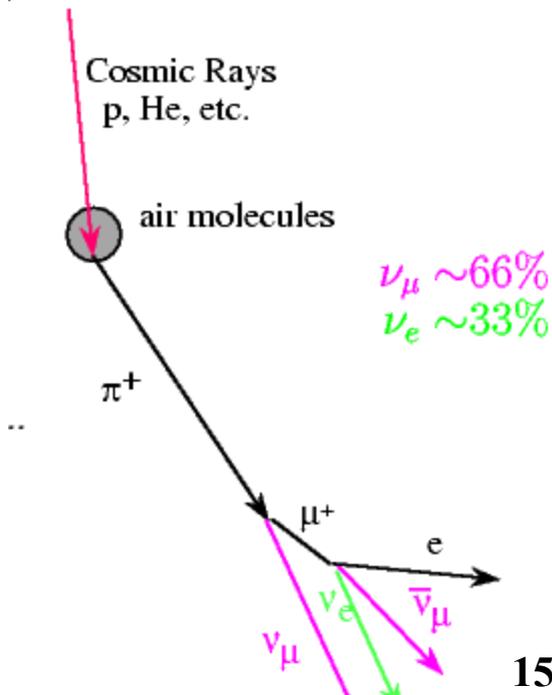
Borexino

Go after ${}^7\text{Be}$ ν 's

- 300 ton liquid scintillator
- 2200 8-inch phototubes



Atmospheric Neutrino Oscillations

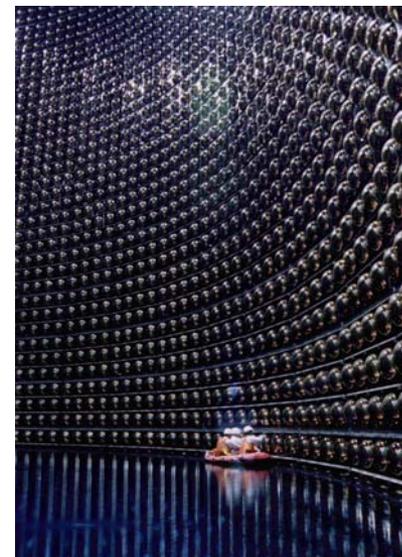


- Super-Kamiokande in Japan sees a ν_μ deficit with zenith angle

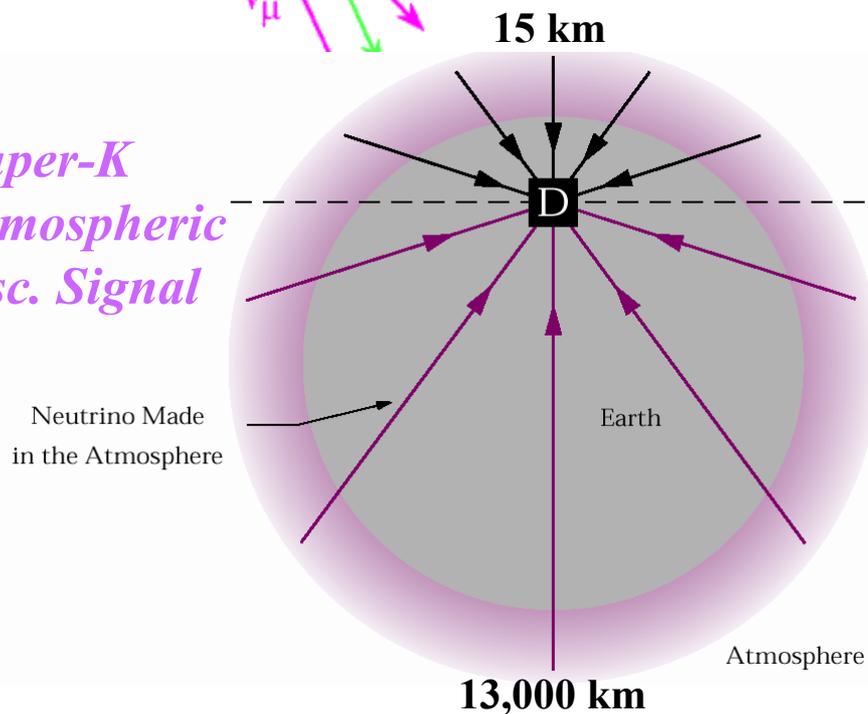
Best fit:

$$\Delta m^2 = 2.4 \times 10^{-3} \text{eV}^2$$

$$\sin^2 2\theta = 1.0$$



*Super-K
Atmospheric
Osc. Signal*



*Now need better experiments
⇒ K2K and NuMI/Minos*

- Definitive proof of oscillations
- Better parameter measurements

K2K (KEK to Super-K) Experiment

Best fit parameters
($\sin^2 2\theta, \Delta m^2$)

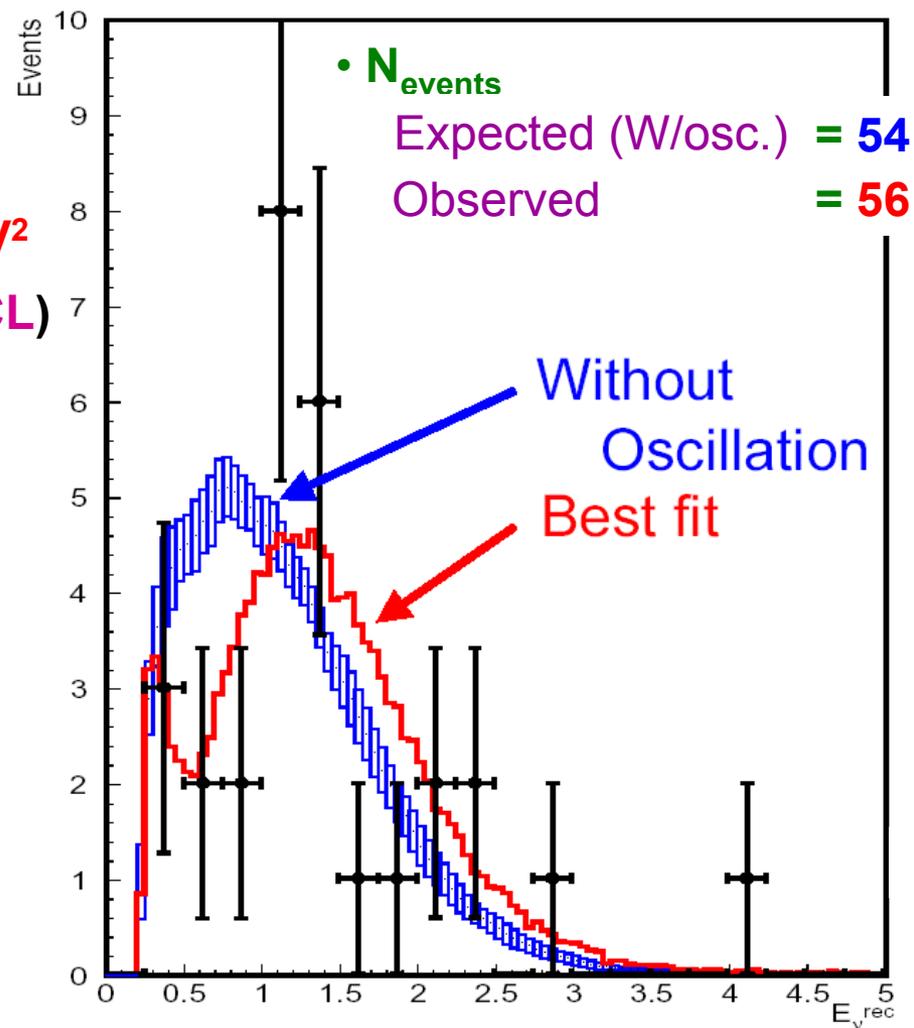
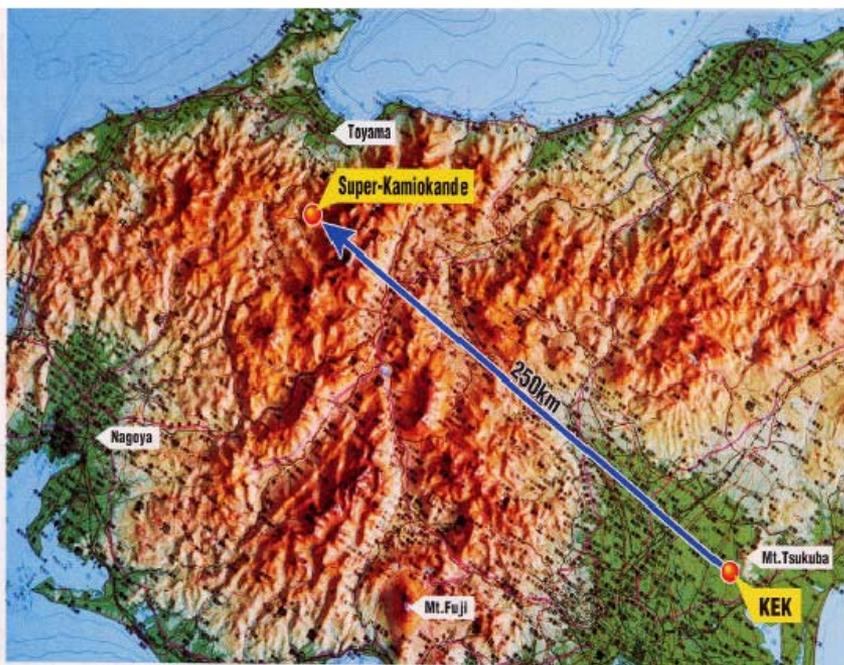
$$=(1.0, 2.8 \times 10^{-3} \text{ eV}^2)$$

- ν_μ (99%) beam
- $\langle E_\nu \rangle \sim 1.3 \text{ GeV}$
- Near detector
@ 300m
- Far detector:
Super Kamiokande (SK)
@ 250km

K2K 1999-2001 data:

$$\Delta m^2 = 1.5 \sim 3.9 \times 10^{-3} \text{ eV}^2$$

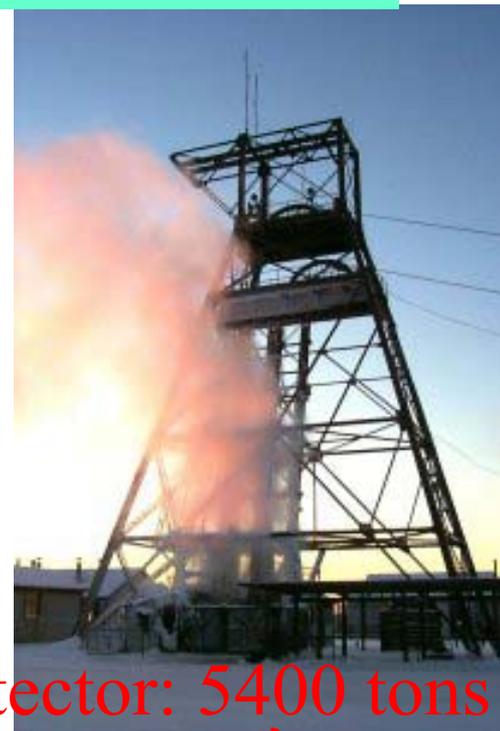
$$\text{@ } \sin^2 2\theta = 1 \text{ (90\% CL)}$$



The NuMI/MINOS Experiment

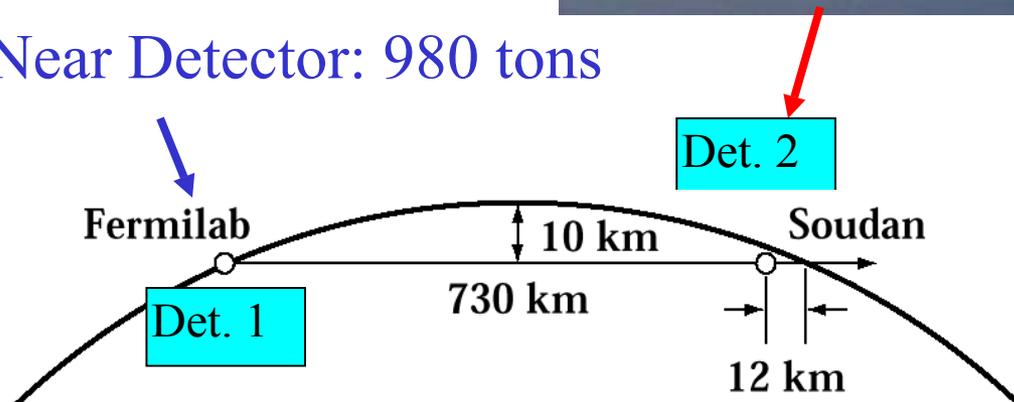


Two Detector Neutrino Oscillation Experiment



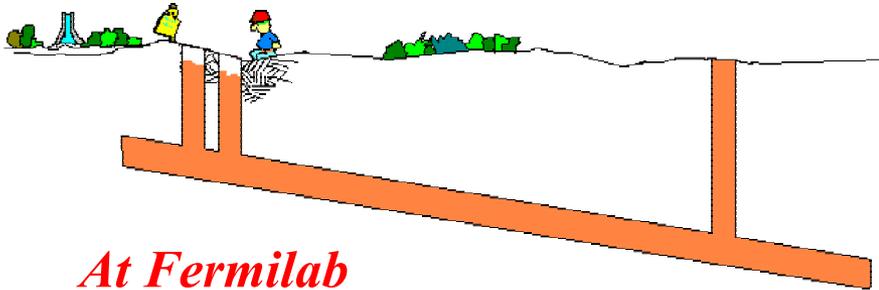
Far Detector: 5400 tons

Near Detector: 980 tons



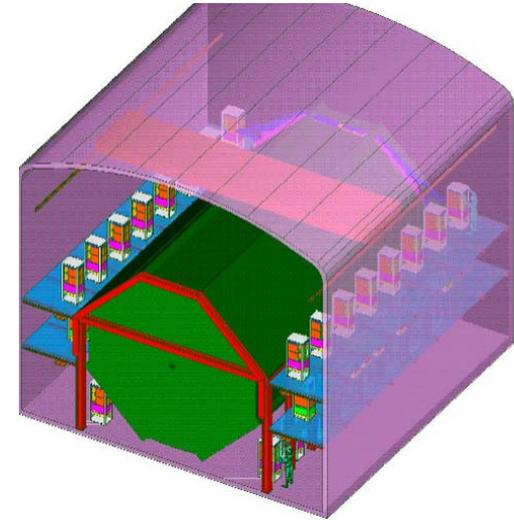
NuMI/Minos Project

*In an old iron mine
(State Park)
Soudan, Minnesota*



*At Fermilab
in Illinois*

*Large Project: \$170M for
beam and two detectors*



Task Name	2002				2003				2004				2005				2006				20		
	Q4	Q1	Q2	Q3	Q4	Q1																	
Fermilab underground civil construction	█																						
Outfitting of NuMI Facility at Fermilab						█																	
Installation of Beam line Components										█													
Far Detector Installation	█																						
Near Detector Installation										█													
Start Commissioning																							
Start operation of Experiment																							
DOE - CD4																							

(Calendar year)

Start early 2005

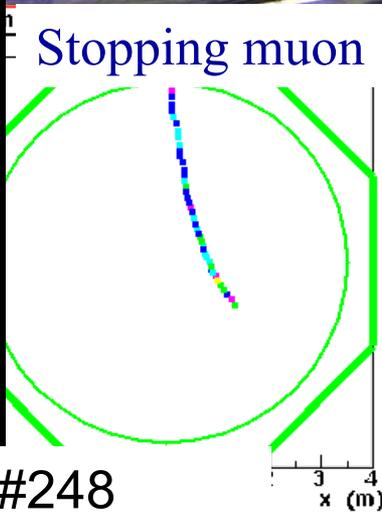
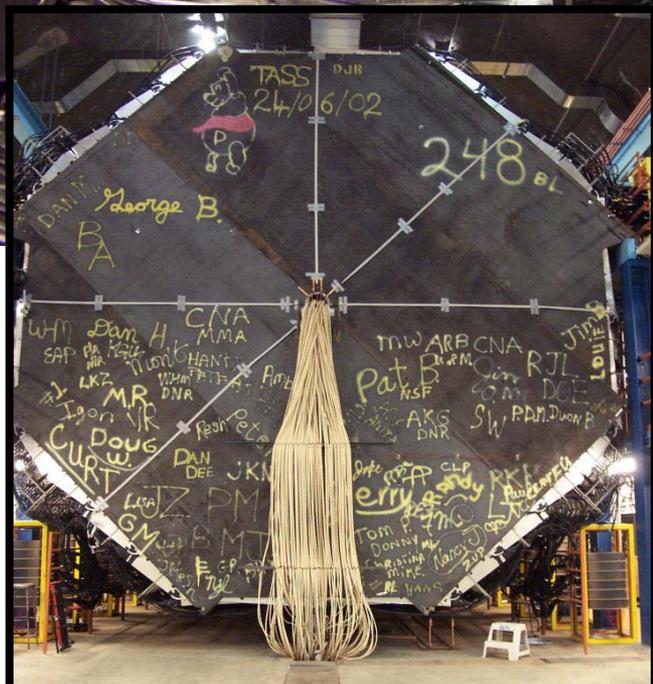


NuMI/MINOS: Progress

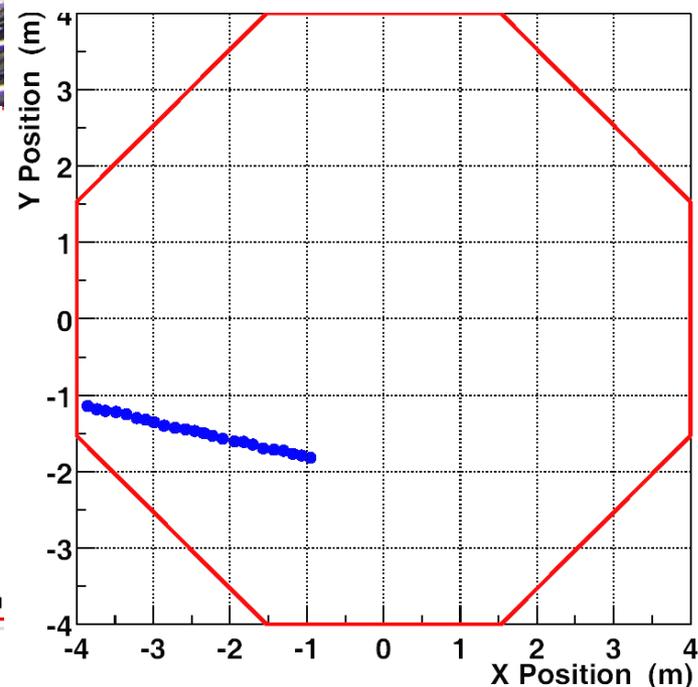
Completion schedule has been constant since new baseline developed in July 2001
⇒ Start operations of NuMI/Minos experiment is Feb., 2005

- Civil Construction
 - NuMI facility at Fermilab
 - TBM Excavation completed Dec '01
 - Decay pipe installation w/concrete shielding complete July '02
 - Outfitting Proposals under evaluation July '02
 - MINOS hall at Soudan
 - Outfitting completed July '01
- Beamline Components
 - Fabrication of focusing horns underway
 - Design & engineering >80% completed
- MINOS Detector
 - Erected 1st Far detector plane July '01
 - First neutrino interaction observed in Far detector planes Apr '01
 - 50% (~248 planes) of Far detector complete and commissioned July '02

MINOS Far Detector in Minnesota



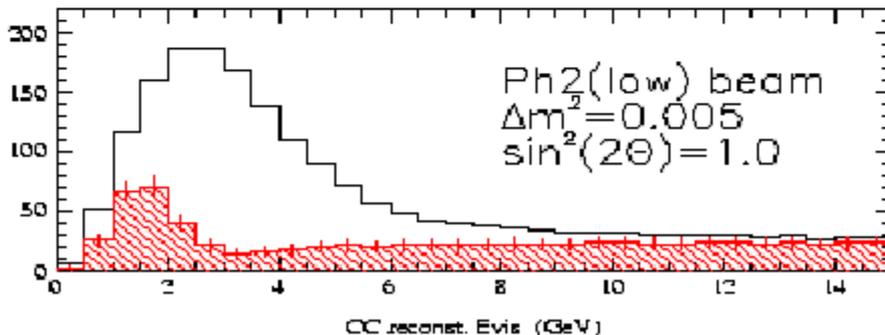
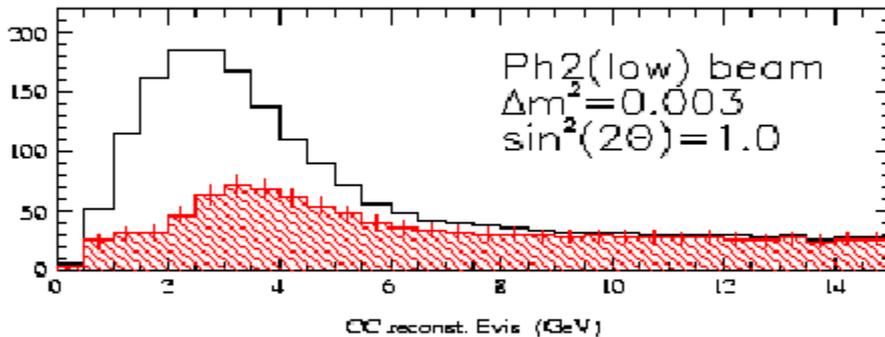
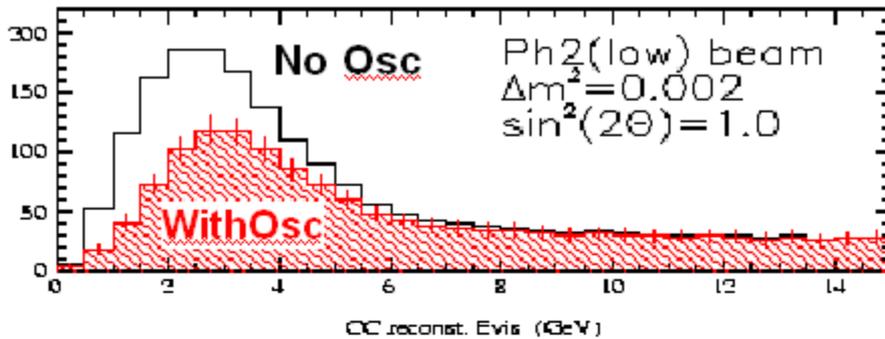
The First Atmosph. Neutrino Event in MINOS (March 23, 2002)



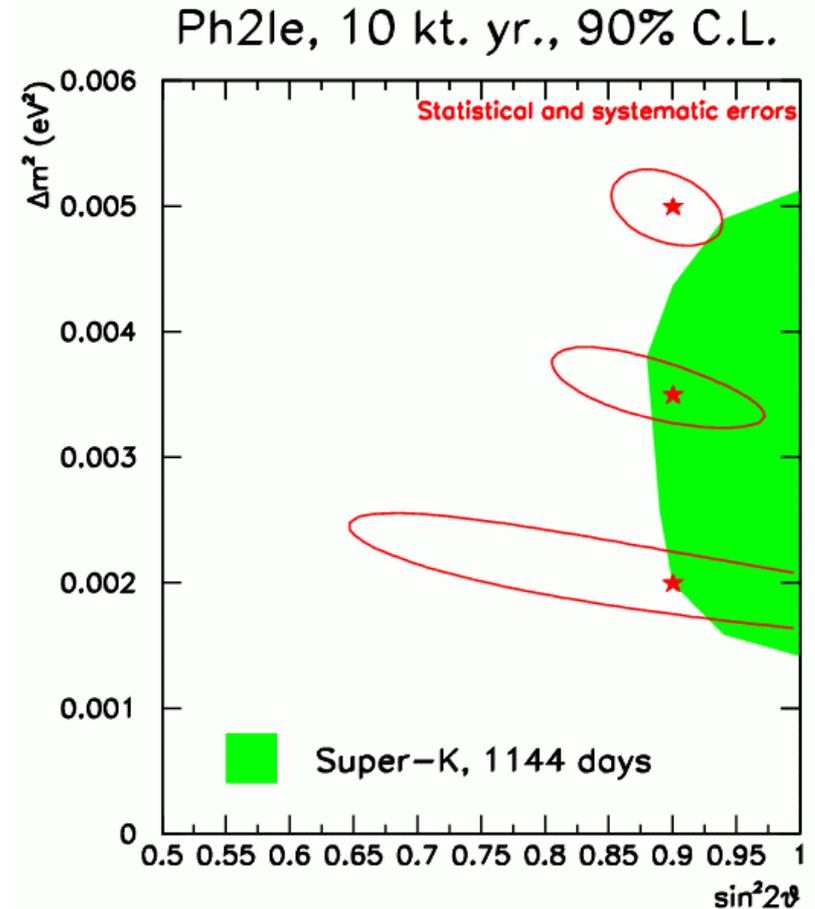
Far Detector Installation Plane #248
50% complete and magnet energized!!

MINOS Oscillation Sensitivity

Minos will see the oscillatory behavior



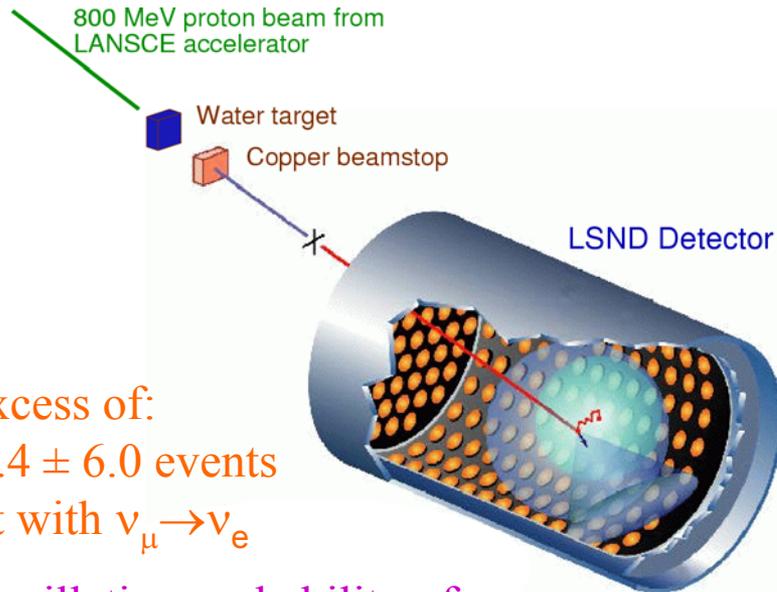
Minos can measure Δm^2 and $\sin^2 2\theta$ over the complete Super-K region



10 kt-yr Exposure
(~1400 CC events/yr)

The LSND Signal Region

- LSND (Liq. Scint. Neutrino Detector) at Los Alamos saw evidence for oscillations in the high Δm^2 region



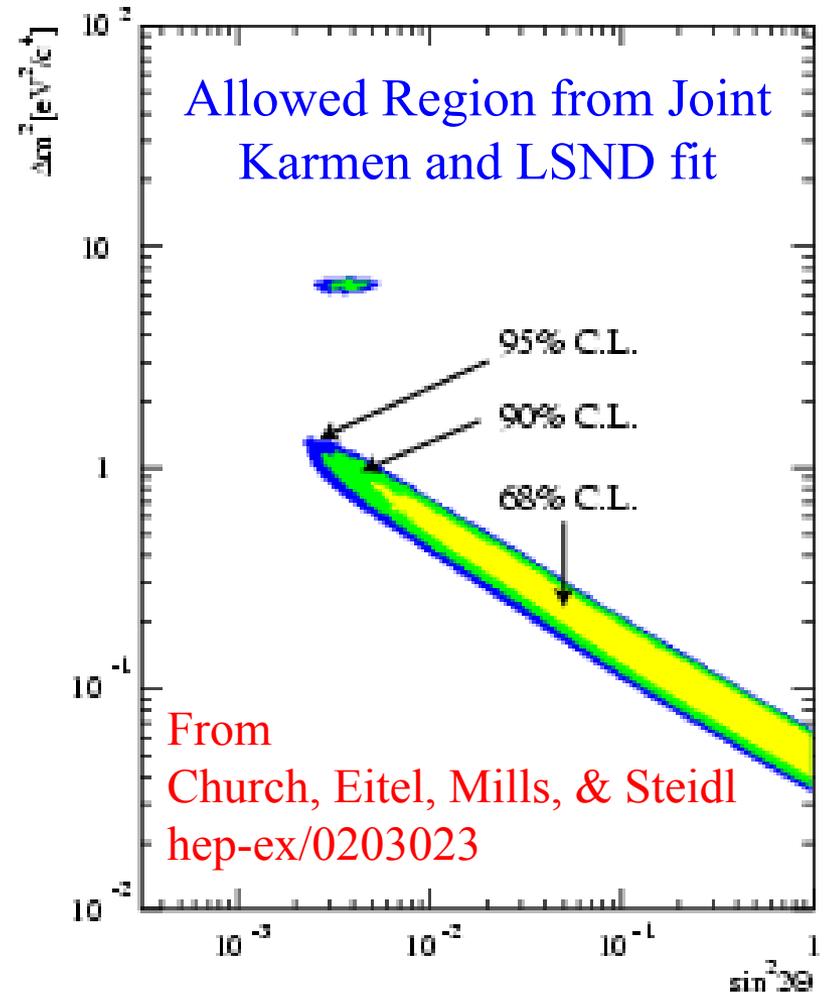
Saw an excess of:
 $87.9 \pm 22.4 \pm 6.0$ events
 consistent with $\nu_\mu \rightarrow \nu_e$

With an oscillation probability of
 $(0.264 \pm 0.067 \pm 0.045)\%$.

3.3σ evidence for oscillation.

This signal could have a major impact on field

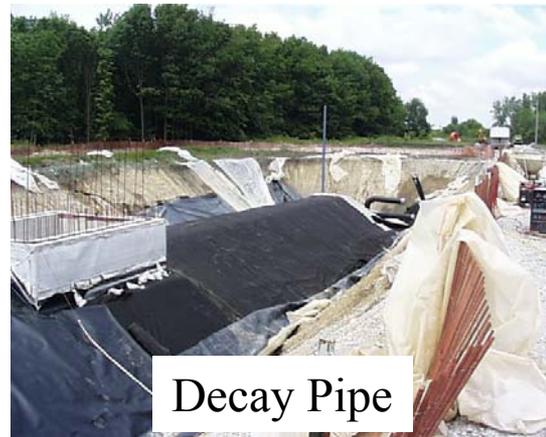
\Rightarrow *Need a definitive measurement in this region* \Rightarrow *MiniBooNE*



MiniBooNE Neutrino Experiment at Fermilab

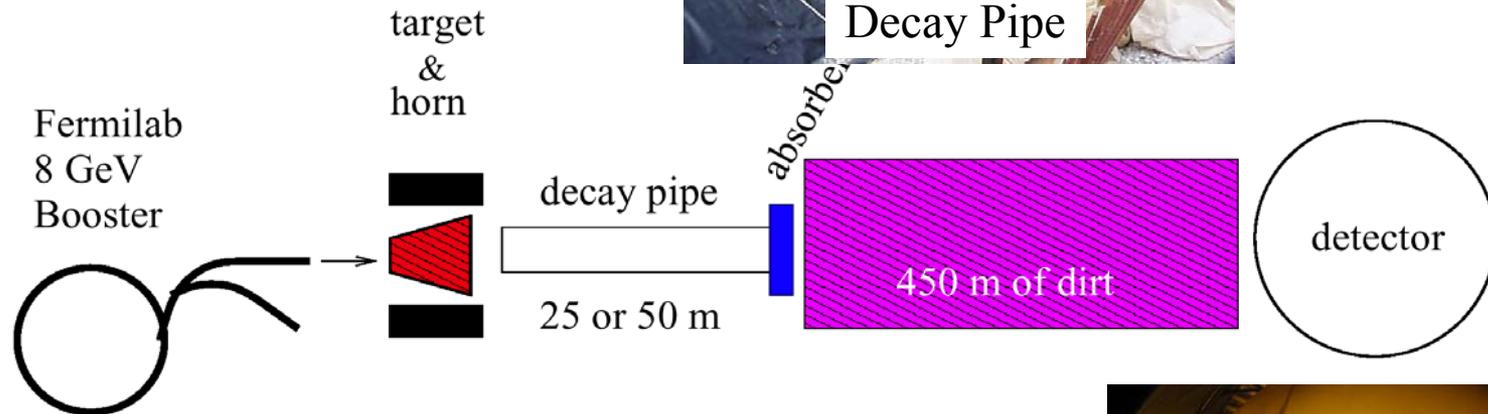


8 GeV Beam Transport



Decay Pipe

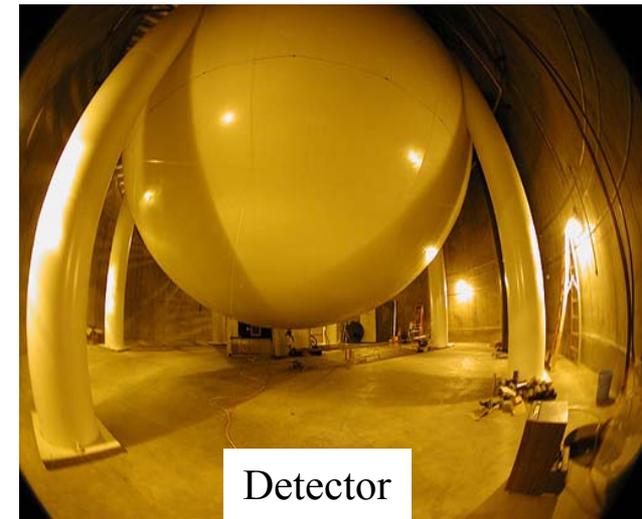
Variable decay pipe length (2 absorbers @ 50m and 25m)



One magnetic Horn, with Be target

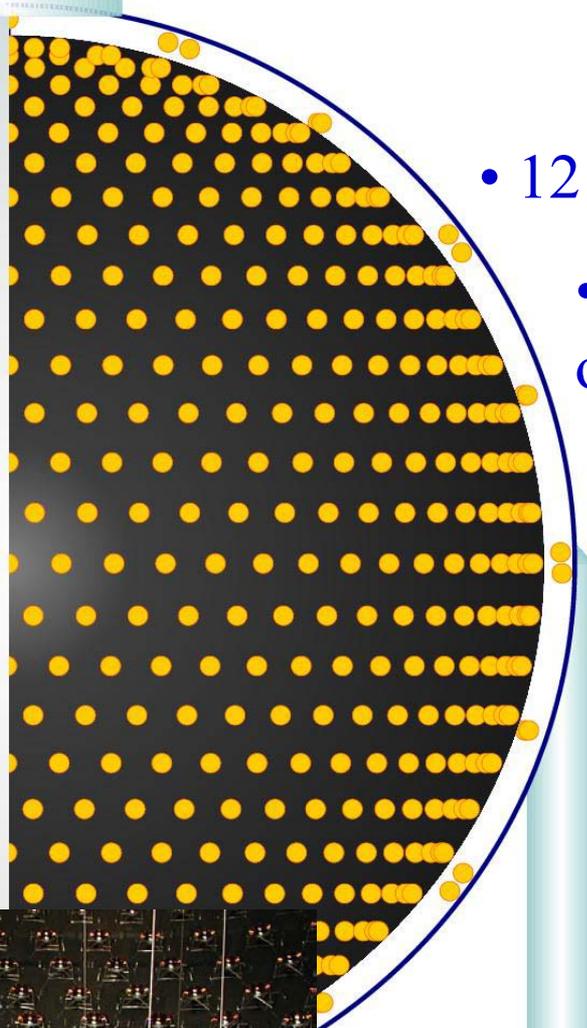
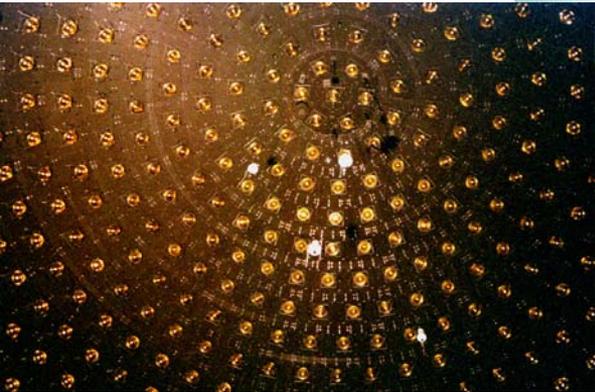


Magnetic Horn

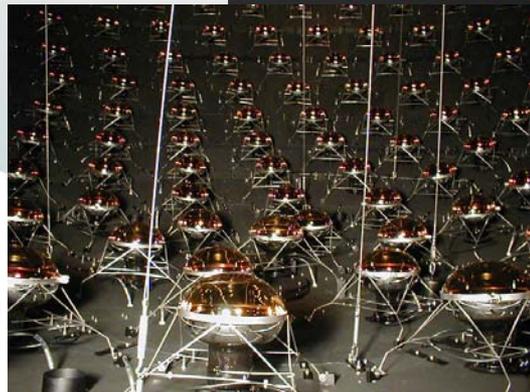
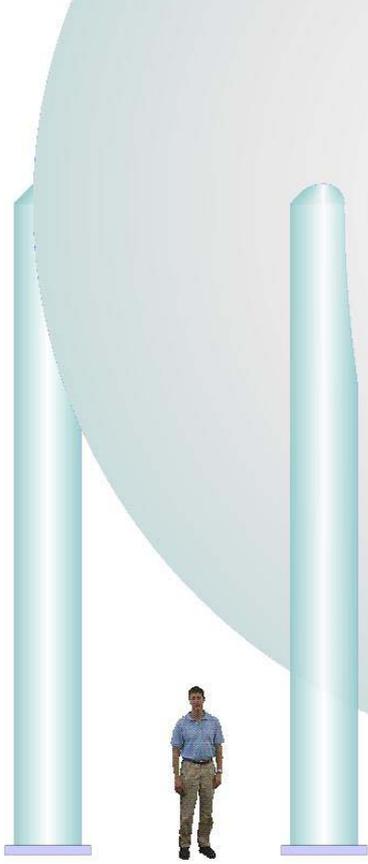


Detector

The MiniBooNE Detector

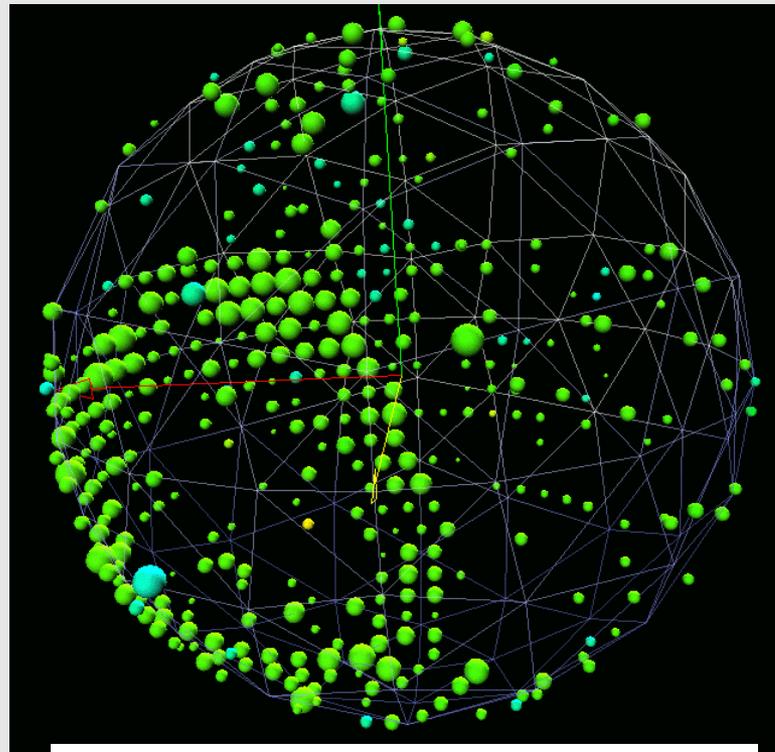
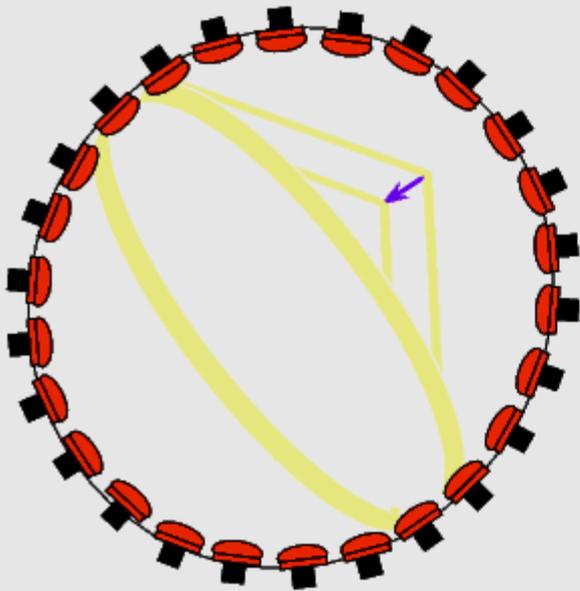


- 12 meter diameter sphere
- Filled with 950,000 liters of undoped mineral oil
- Light tight inner region with 1280 photomultiplier tubes
- Outer veto region with 241 PMTs.
- **Oscillation Search Method:**
Look for ν_e events in a pure ν_μ beam



Particle Identification By Phototube Hit Pattern

- Charged particles produce Čerenkov and scintillation photons as they go through the oil
 - Pattern of phototube hits tells the particle type



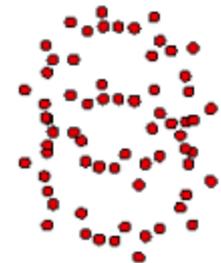
MiniBooNE Cosmic Ray Data Event



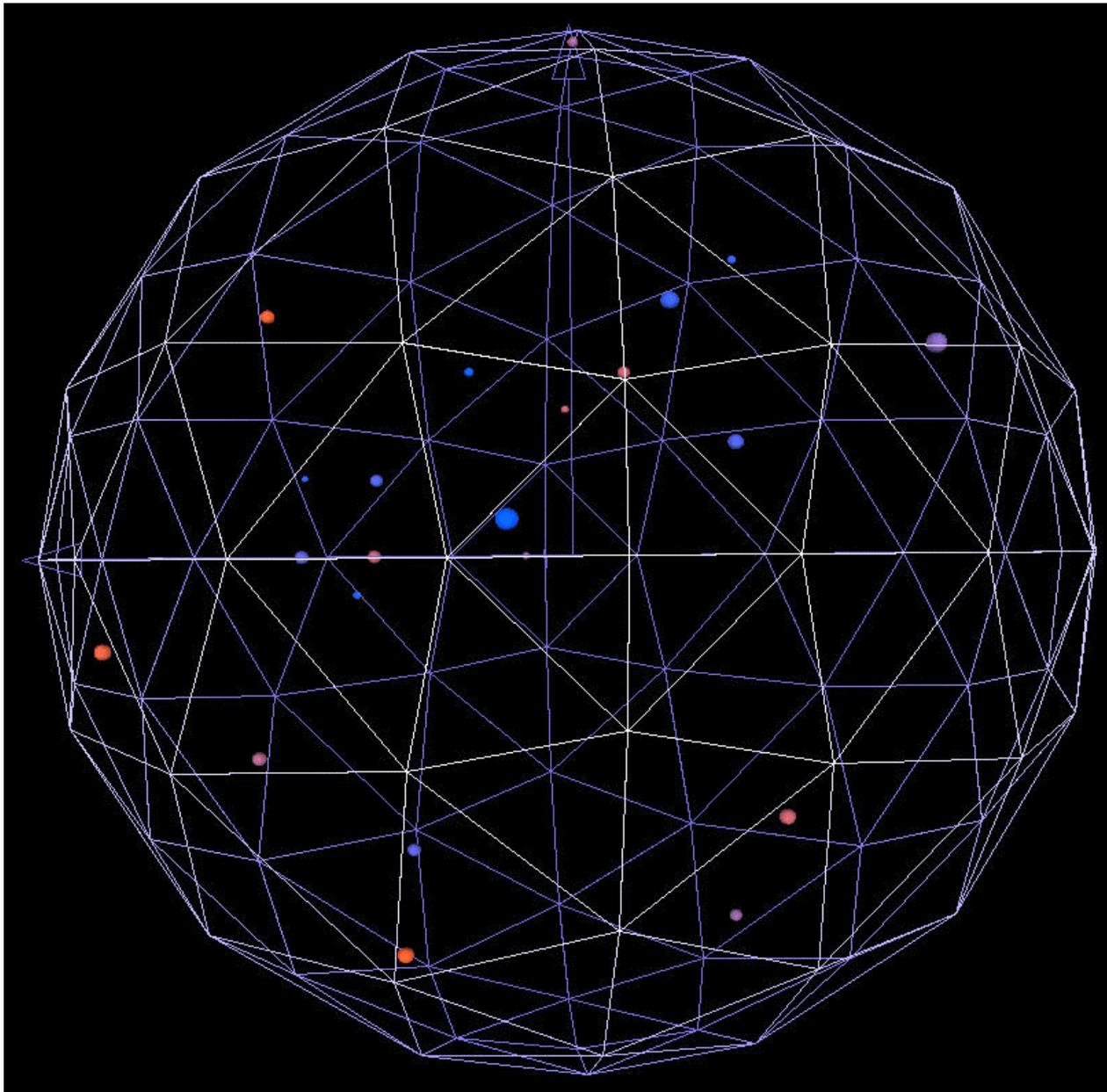
e^-



μ



π^0

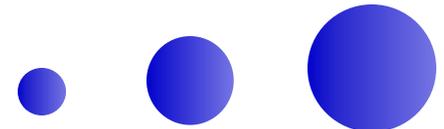


Muon Decay Candidate

Animation

Each frame is 25 ns
with 10 ns steps.

Charge (Size)



Time (Color)

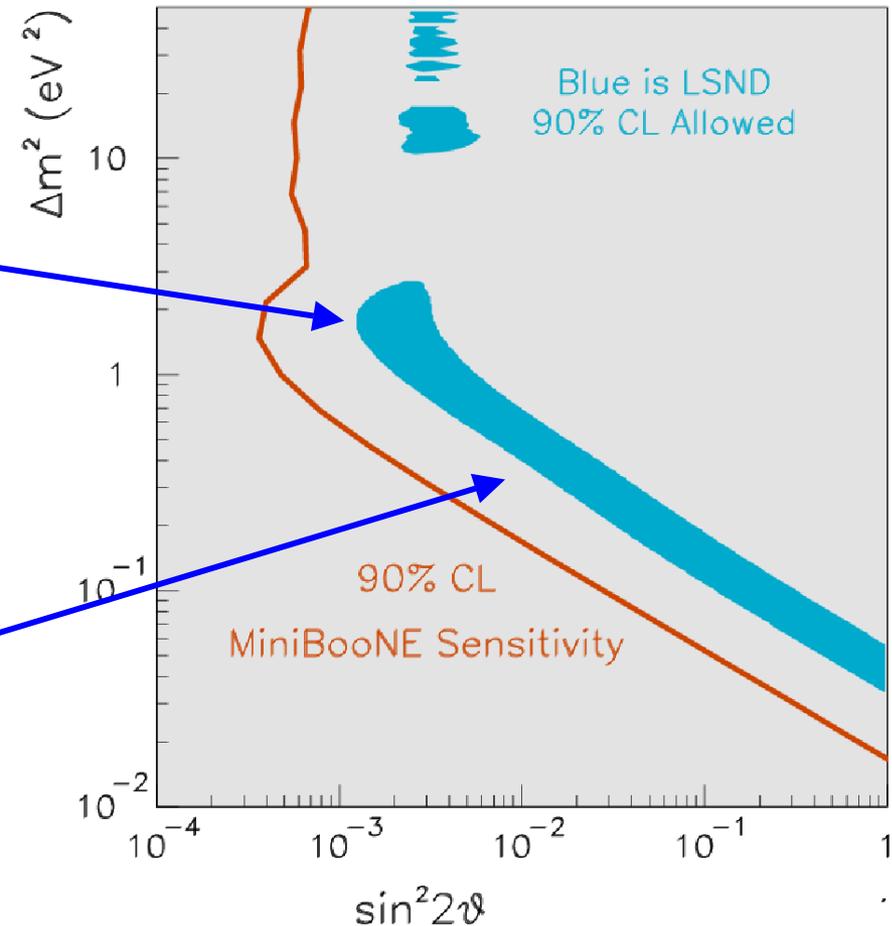
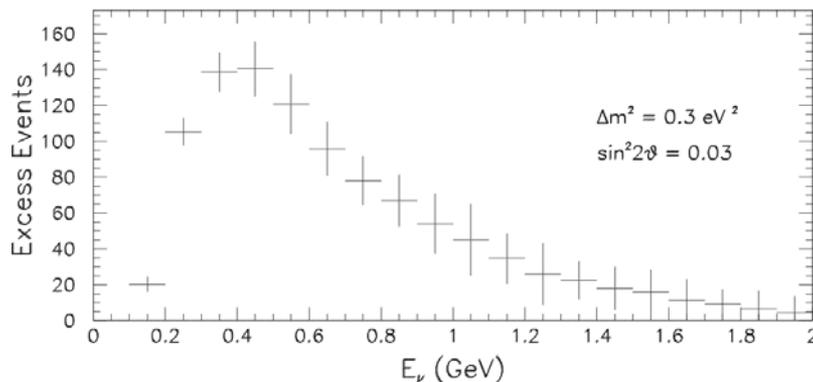
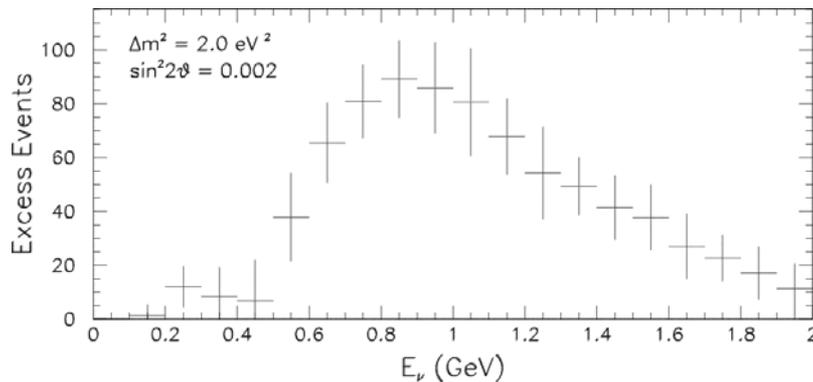


MiniBooNE About to Start Running (mid-August)

With two years of running MiniBooNE will completely include or exclude the entire LSND signal region at the 5σ level.

Expected events

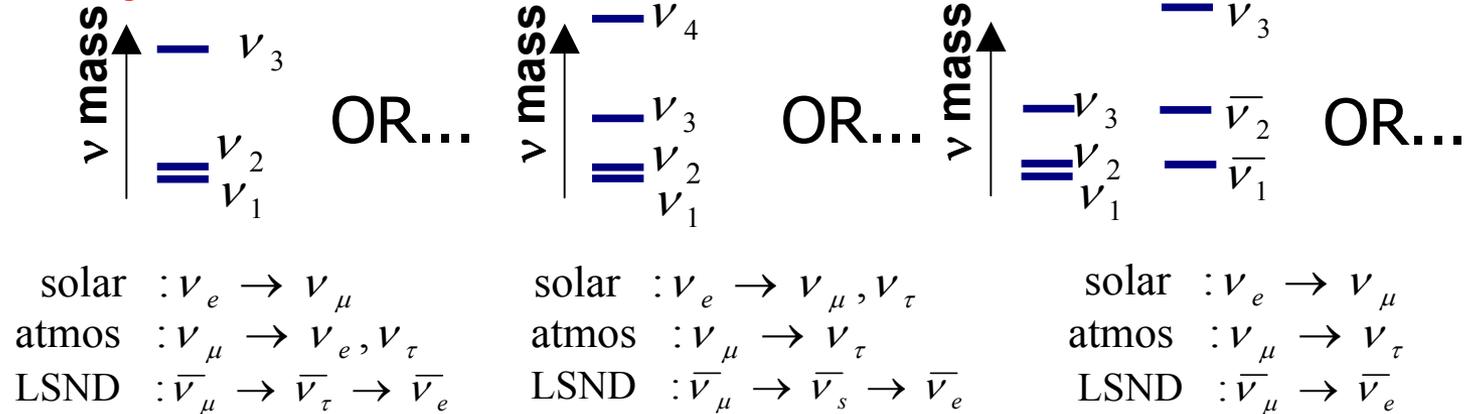
- 500,000 ν_μ CC quasi-elastic
- **~ 1000 ν_e if LSND correct**



Implications for the Particle Physics

- If MiniBooNE sees $\nu_\mu \rightarrow \nu_e$ signal \Rightarrow *Need extension of theory*

Only 3 active ν : **3 active+1 sterile ν :** **CPT violation:**



- Neutrino mixing and CP violation \Rightarrow *Window on New Physics***

Neutrino Mixing Matrix

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

$$\begin{pmatrix} \text{big} & \text{big} & \text{small?} \\ \text{big} & \text{big} & \text{big} \\ \text{big} & \text{big} & \text{big} \end{pmatrix}$$



- Explanation of Matter – Antimatter Asymmetry in Universe**

- Why is ν mass so small !?!**

Quark Mixing Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} \text{big} & \text{small} & \text{very tiny} \\ \text{small} & \text{big} & \text{tiny} \\ \text{tiny} & \text{tiny} & \text{big} \end{pmatrix}$$

Future Possibilities: Matter Effects and CP Violation

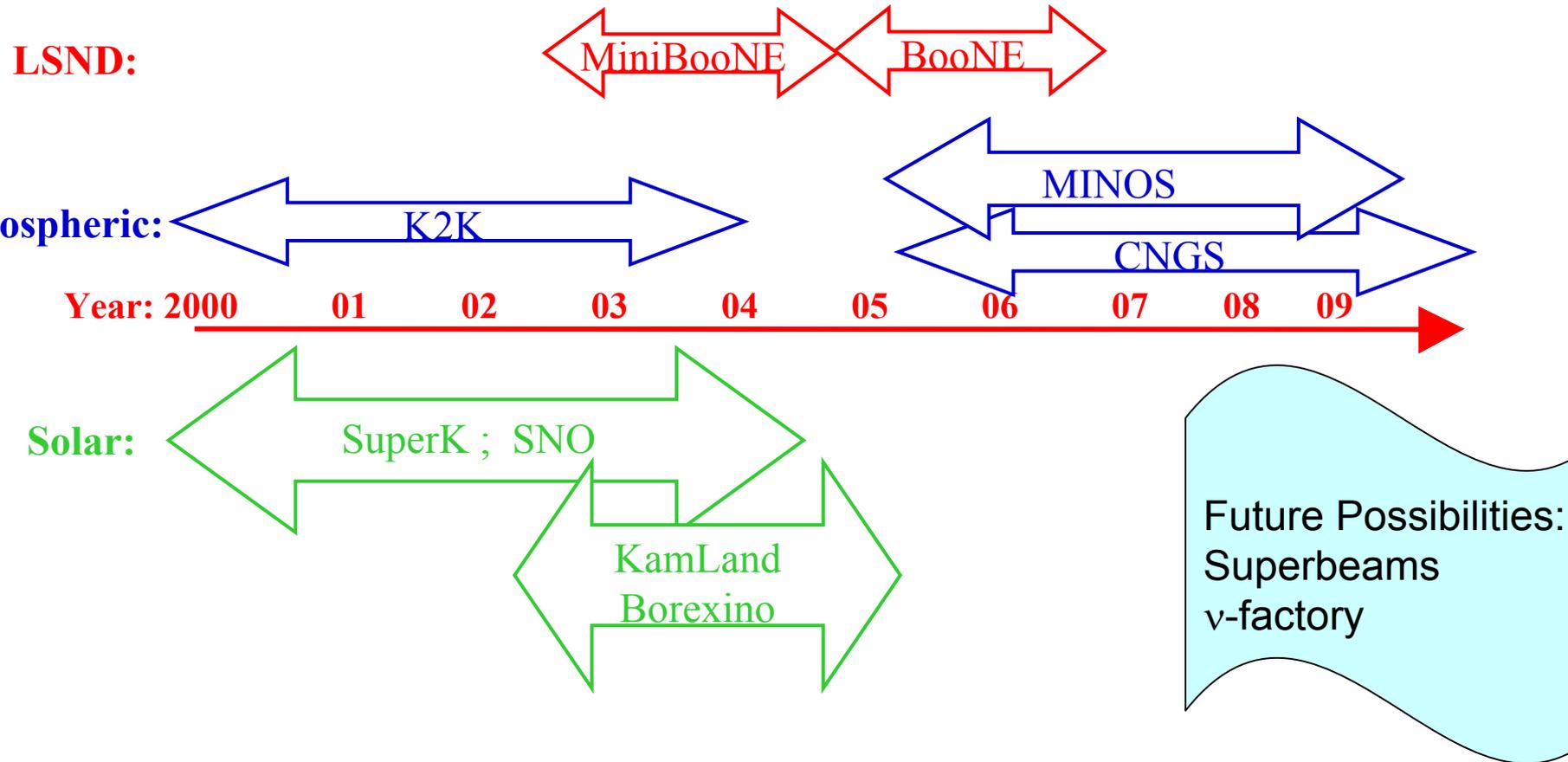
Roadmap for neutrino oscillations beyond current program:

- Stage 1 – Constrain / measure θ_{13}
 - NuMI / MINOS on-axis probes $\sin^2 2\theta_{13} > 0.06$ @ 90%CL
 - NuMI(JHF) offaxis could go down to $\sin^2 2\theta_{13} > 0.01$ @ 90%CL

- Stage 2 – Measure CP violation and sign of Δm_{23}^2 with conventional beams
 - Must have $\sin^2 2\theta_{13} > 0.01$
 - Need to measure $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
 - Need increased rate (especially for $\bar{\nu}$'s) \Rightarrow **Need High Intensity Proton Driver**

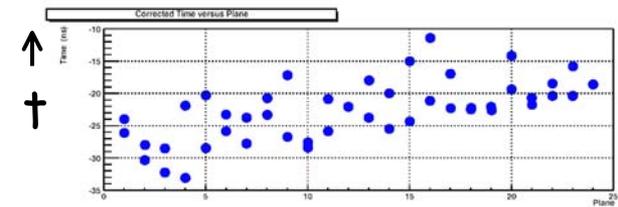
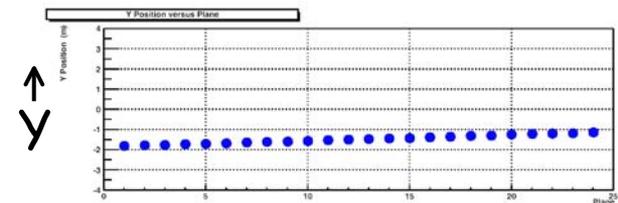
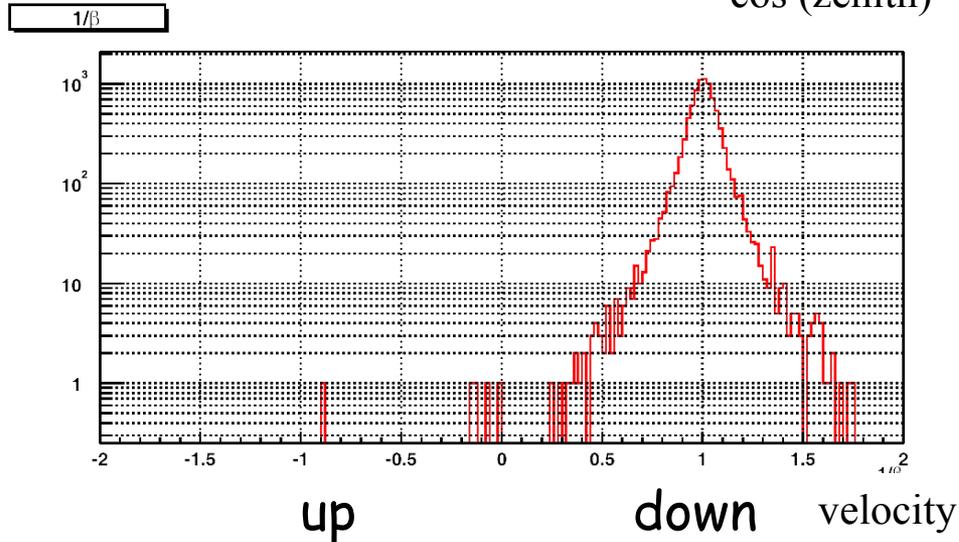
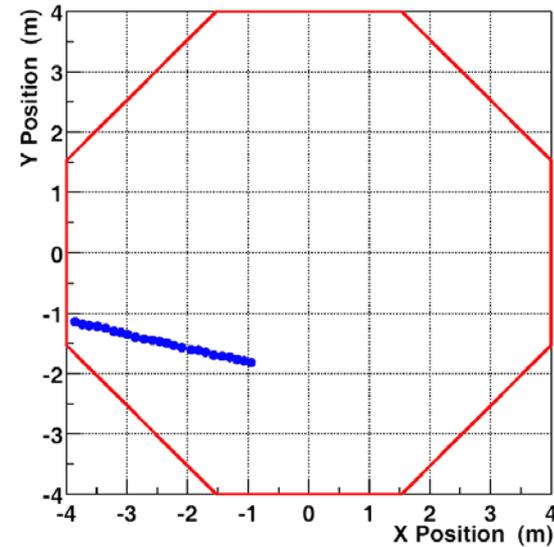
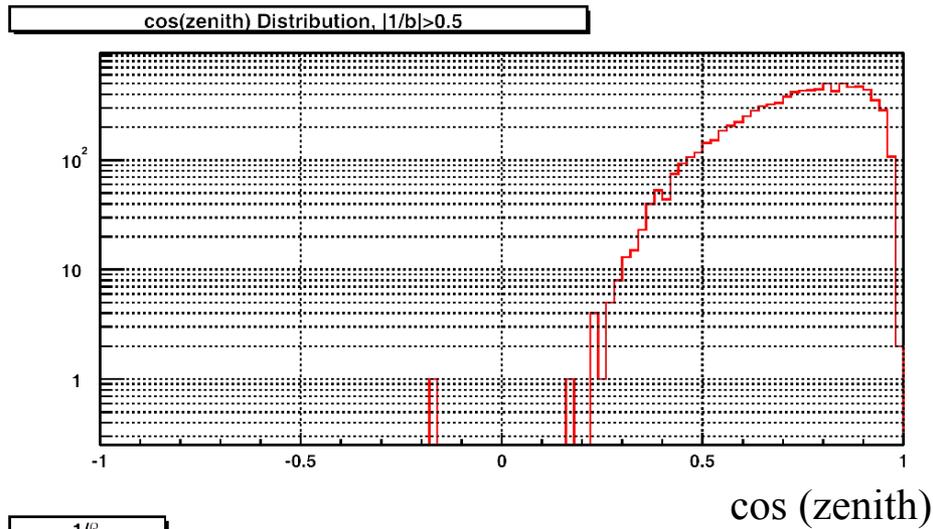
- Stage 3 – Measurements with *Neutrino Factory*
 - Map out CP violation with precision for $\sin^2 2\theta_{13} > 0.01$
 - Probe $\nu_\mu \rightarrow \nu_e$ transitions down to $\sin^2 2\theta_{13} > 0.001$

Oscillation Experiment Timeline



Exciting Times for Neutrino Experimentation over the next decade !!

The First Neutrino Event in MINOS (March 23, 2002)



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