



# **Future Accelerator-based Neutrino Facilities**

**Argonne Workshop on  
Trends in Neutrino Physics  
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# Outline

- **Current Experiment**
  - K2K
- **Planned Experiments**
  - MINOS
  - Gran Sasso
- **Superbeams**
  - NuMI Off-Axis
  - J-PARC
  - Brookhaven
- **Background-free Techniques**
  - Beta Beams
  - Neutrino Factories



# Sterile Neutrino Assumption

- I will assume that MiniBooNE will not confirm LSND (because present data strongly disfavor sterile neutrinos that would be compatible with LSND).
  - However, if it does confirm:
    - Further short baseline experiments
    - 2+2: Search for sterile neutrino oscillations in long baseline experiments
    - 3+1: Long baseline experiments decouple



# Formalism

- Weak and mass eigenstates related by 3 angles and one complex phase:

$$|\nu_\ell\rangle = U|\nu_h\rangle, \quad \text{where } (c_{ij} \equiv \cos \theta_{ij}, \quad s_{ij} \equiv \sin \theta_{ij})$$

$$U = \begin{pmatrix} 1 & 0 & 0 & c_{13} & 0 & s_{13}e^{i\phi} & c_{12} & s_{12} & 0 \\ 0 & c_{23} & s_{23} & 0 & 1 & 0 & s_{12} & c_{12} & 0 \\ 0 & -s_{23} & c_{23} & -s_{13}e^{i\phi} & 0 & c_{13} & 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\phi} \\ s_{12}c_{23} & c_{12}c_{23} & s_{12}s_{23}s_{13}e^{i\phi} & c_{12}c_{23} & s_{12}s_{23}s_{13}e^{i\phi} & s_{23}c_{13} \\ s_{12}s_{23} & -c_{12}c_{23}s_{13}e^{i\phi} & -c_{12}s_{23} & -c_{12}s_{23} & s_{12}c_{23}s_{13}e^{i\phi} & c_{23}c_{13} \end{pmatrix}$$



# Vacuum Oscillations

- Matter effects: In vacuum,

$$i\hbar \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = H \begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix}, \quad H = \begin{pmatrix} \frac{\Delta m^2}{4E} \cos 2\theta & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & -\frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix}$$

$$P(\nu_e \rightarrow \nu_x) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right)$$

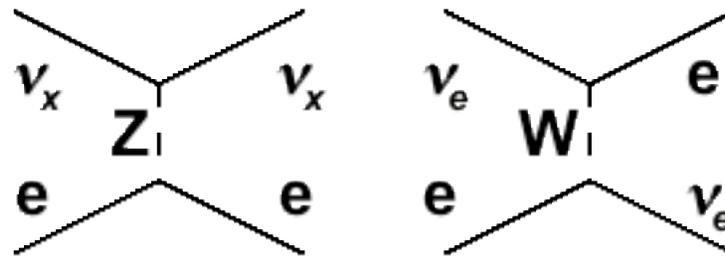
$$\Delta m_{ij}^2 \equiv (m_i^2 - m_j^2) \text{ is in } (\text{eV} / c^2)^2,$$

$L$  is in km, and  $E$  is in GeV



# Matter Oscillations

- Matter effects: In matter  $\nu_e$ 's interact differently than  $\nu_x$ 's.

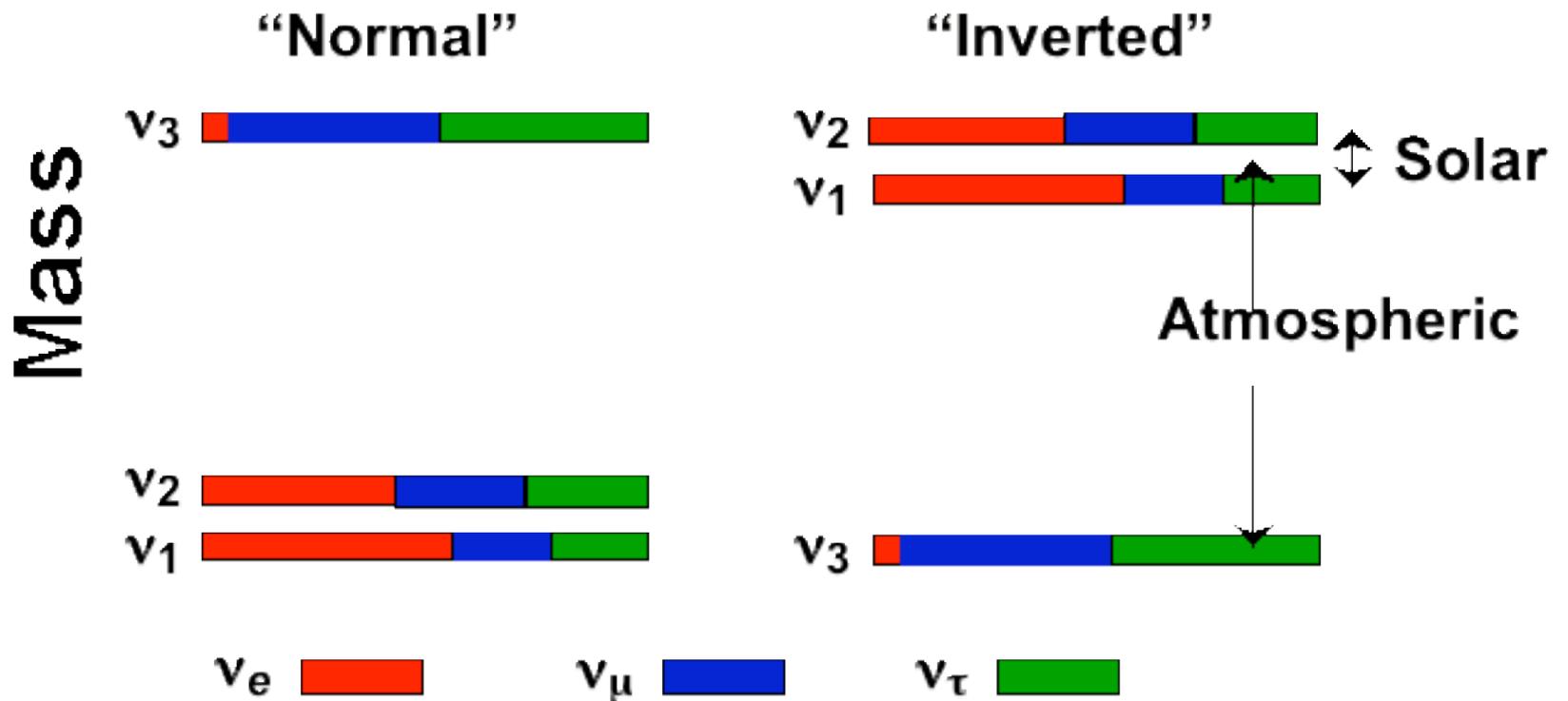


$$H = \begin{pmatrix} \frac{\Delta m^2}{4E} \cos 2\theta & \sqrt{2} G_F N_e \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix}$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\cos 2\theta \sqrt{2} G_F N_e E / \Delta m^2)^2 + \sin^2 2\theta}$$



# What Do We Know?





# What Do We Want to Know?

- Where we have measurements, we want to improve them.

$$[\sin^2 2\theta_{12}, \sin^2 2\theta_{23}, \Delta m_{12}^2, \Delta m_{23}^2]$$

- Where we do not have measurements, we want to obtain them.

$$[\sin^2 2\theta_{13}, \text{sign}(\Delta m_{23}^2), \delta]$$

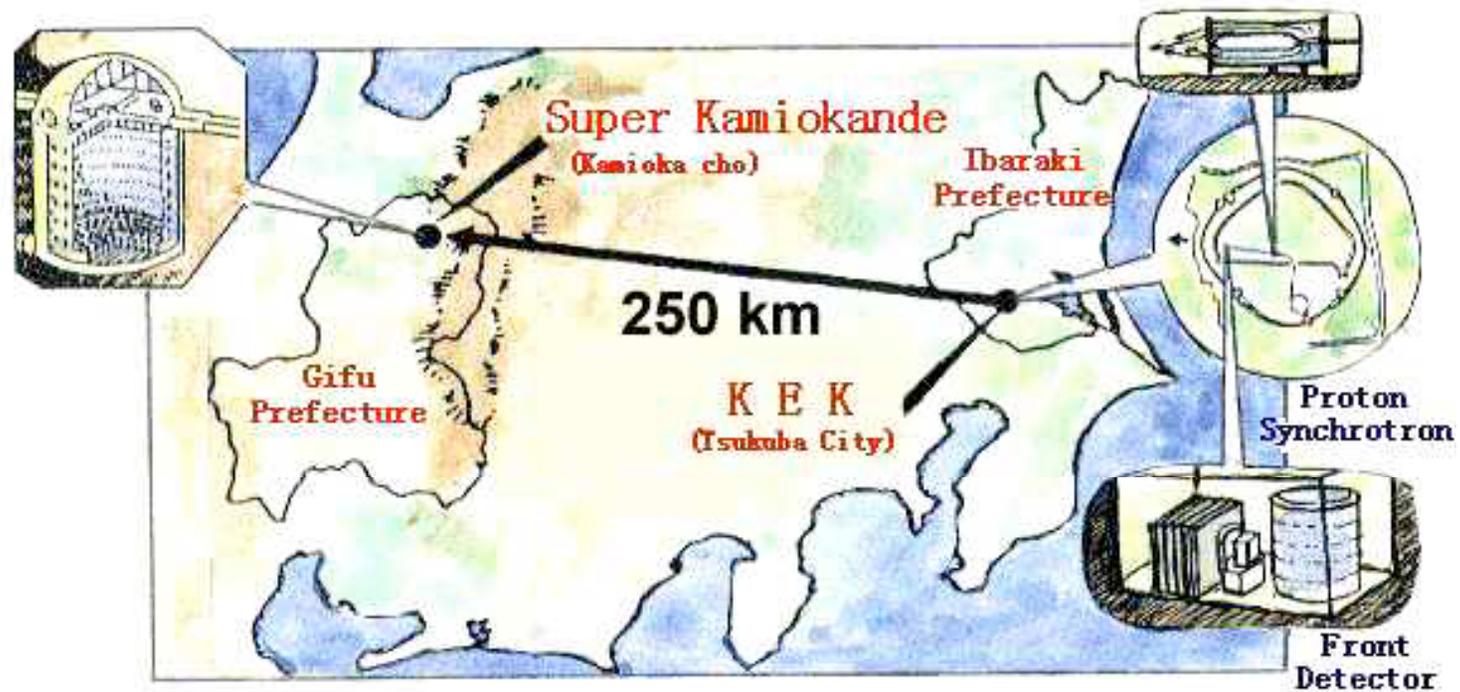
- We want to know if we have the right framework.

$$[\theta_s, \theta \text{ decay, extra dimensions, CPT violation, etc.}]$$



# K2K Layout

- K2K is the first of the long-baseline experiments to study the region of the atmospheric oscillations
  - KEK is a 12 GeV  $p$  synchrotron



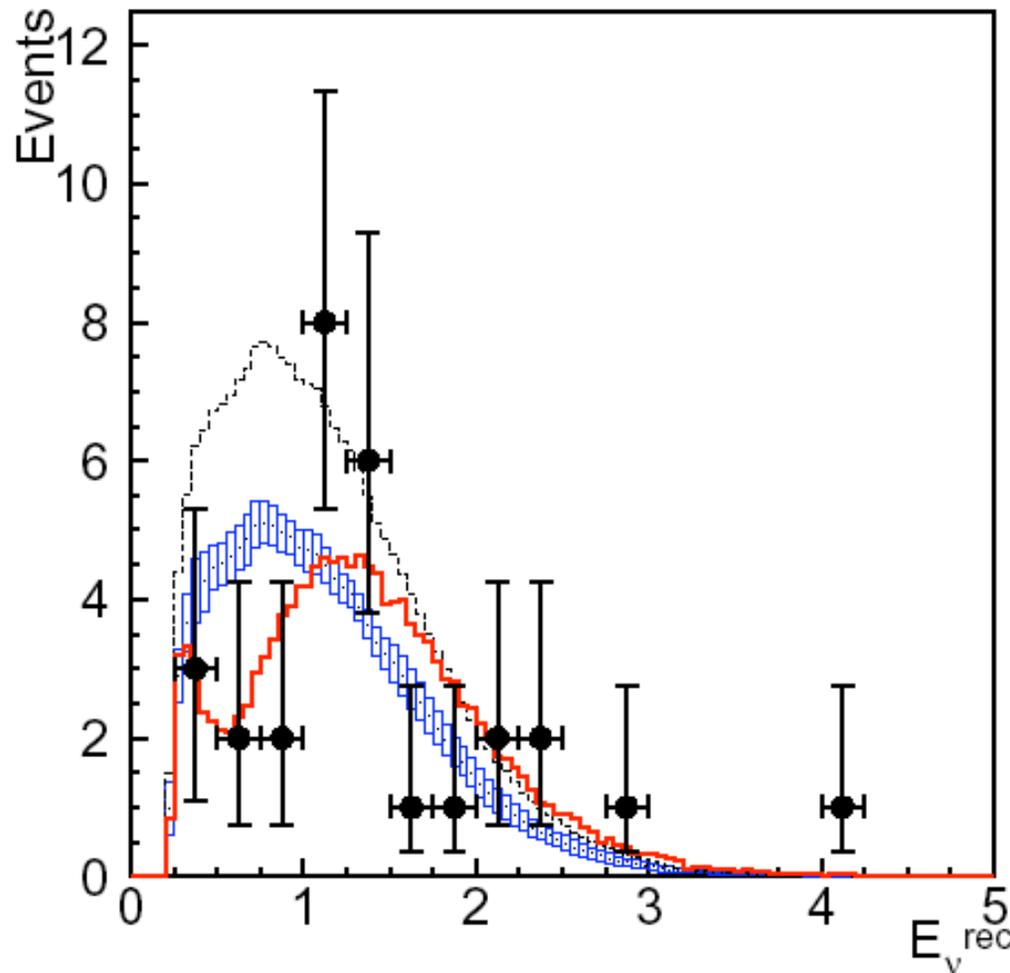


# K2K Results

- **Published in PRL, 30 Jan 2003**
- **Observed 56 events, expected  $80 \pm 6$  for no oscillations**
- **29 1-ring events used for energy spectrum**
- **About 1/2 of total run**



# K2K Spectrum



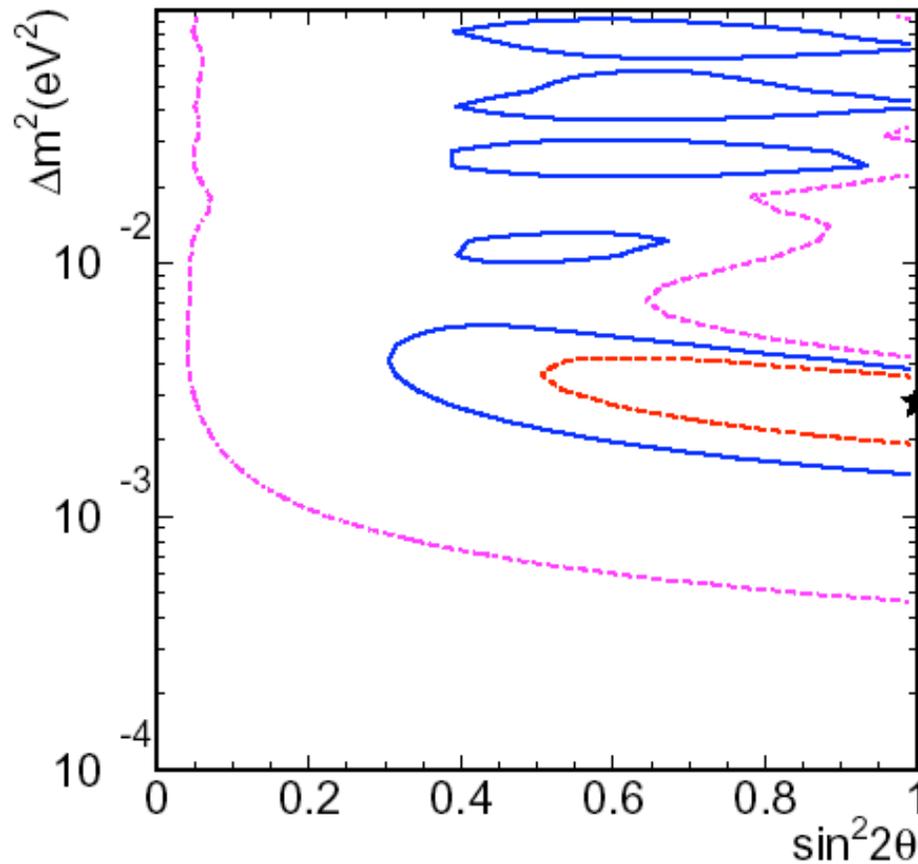
**Black: Expected for no oscillations**

**Blue: Same normalized to number of events**

**Red: Best oscillation fit**



# K2K Latest Results



**Red: 68.4% c.l.**

**Blue: 90% c.l.**

**Magenta: 99% c.l.**

**Star: Best fit:**

$$\Delta m^2 = 2.7 \times 10^{-3} \text{ eV}^2$$

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



# MINOS Layout

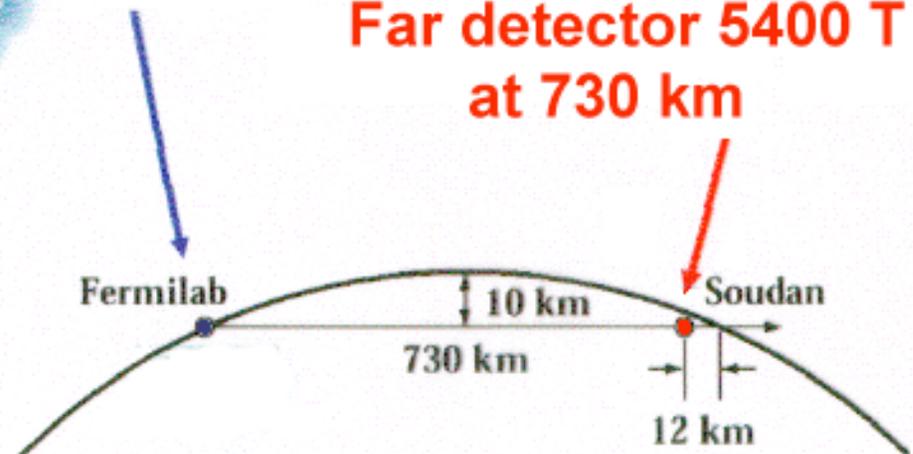
(Main Injector Neutrino Oscillation Search)



Two detector oscillation experiment using Fermilab 120-GeV Main Injector beam

Near detector 980 T at 1 km

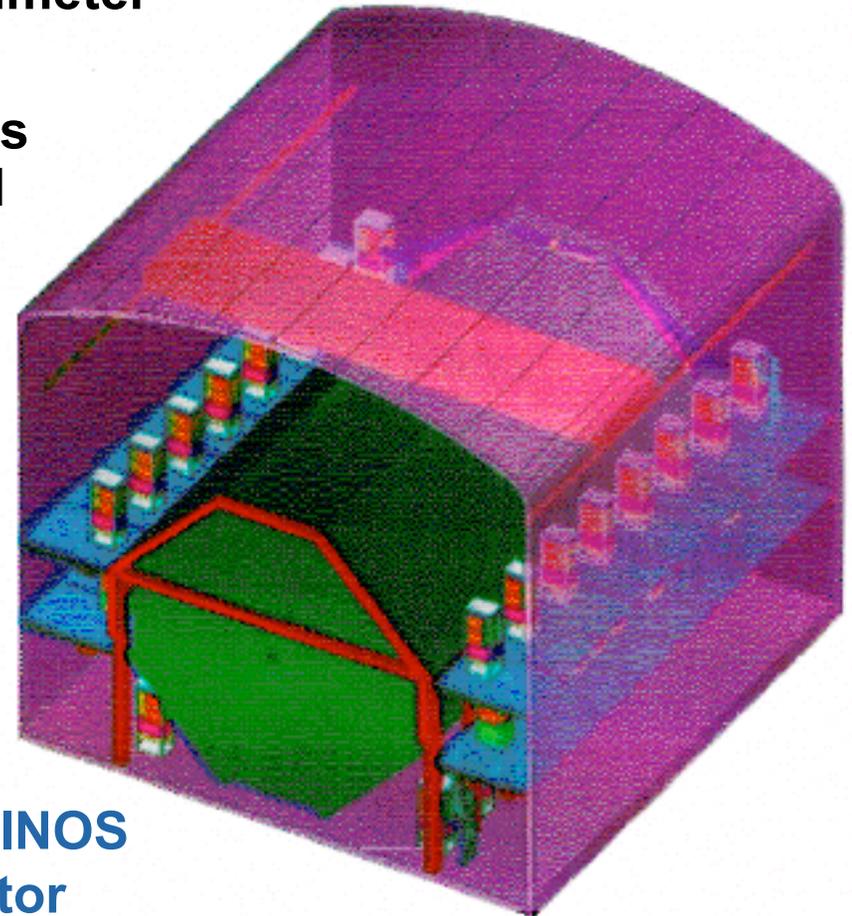
Far detector 5400 T at 730 km





# MINOS Far Detector

- 8m octagonal tracking calorimeter
- 486 layers of 1 in iron plates
- 4.1 cm-wide scintillator strips with WLS fiber readout, read out from both ends
- 8 fibers summed on each PMT pixel
- 25,800 m<sup>2</sup> (6.4 acres) of active detector planes
- Toroidal magnetic field  $\langle B \rangle = 1.3$  T
- Total mass 5.4 kT



Half of MINOS  
far detector



# MINOS Far Detector

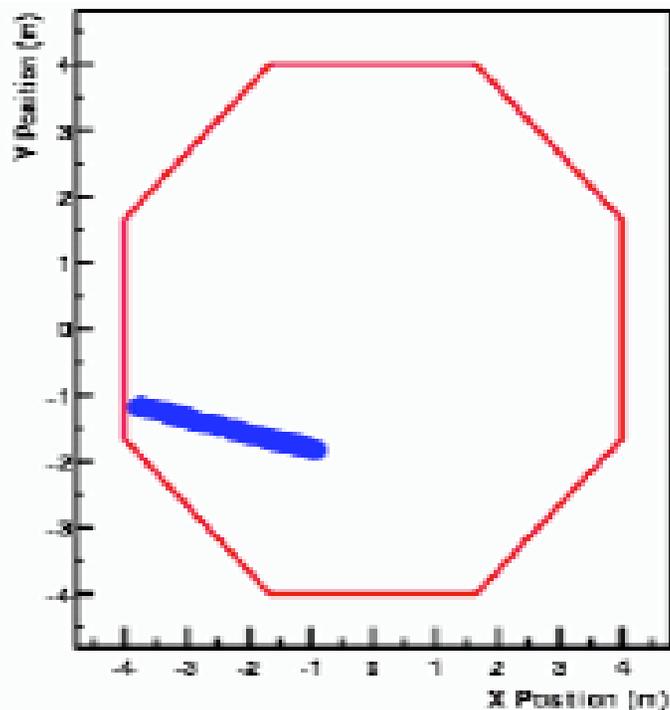


**First module built and running with magnetic field.**

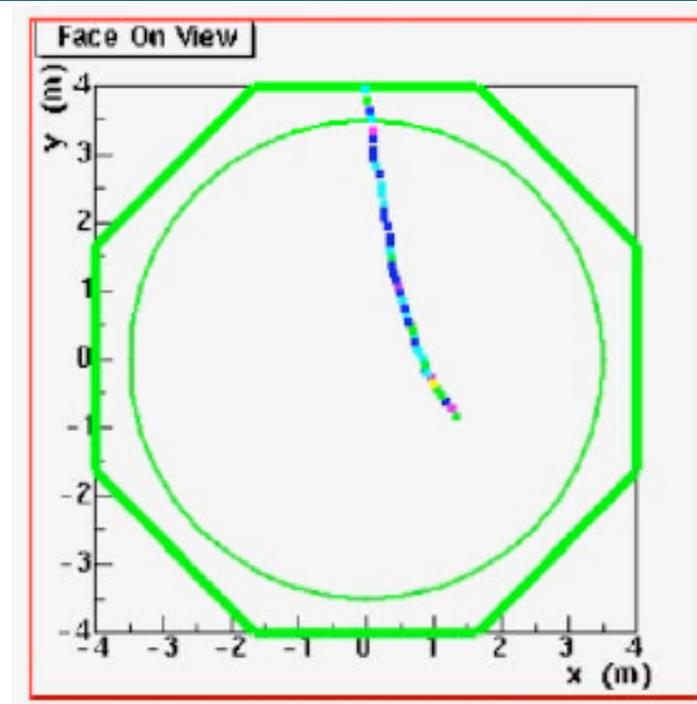
**Now >98% Complete.**



# Far Detector Events



**First upward-going muon (no field)**

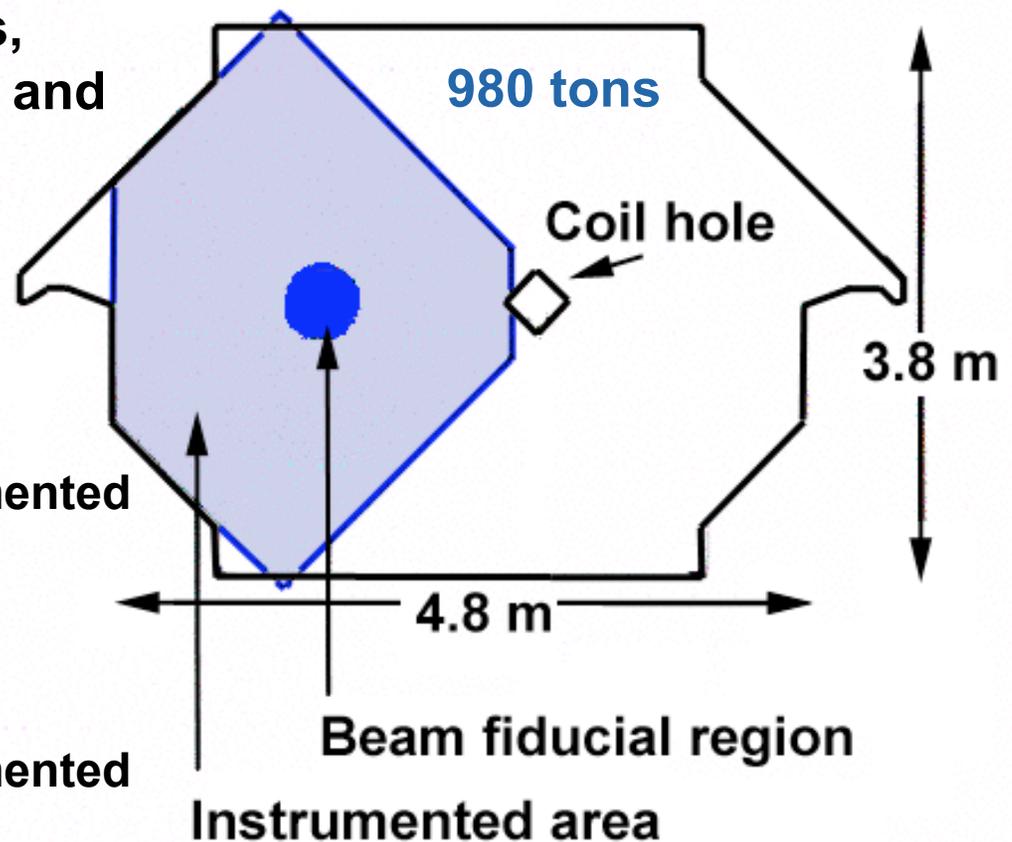


**First stopping muon with magnetic field**



# MINOS Near Detector

- 280 “squashed octagon” plates
- Same plate thickness, scintillator thickness and width as far detector
- Target/calorimeter section: 120 planes
  - 4/5 partial area instrumented
  - 1/5 full area instrumented
- Muon spectrometer section: 160 planes
  - 4/5 uninstrumented
  - 1/5 full area instrumented



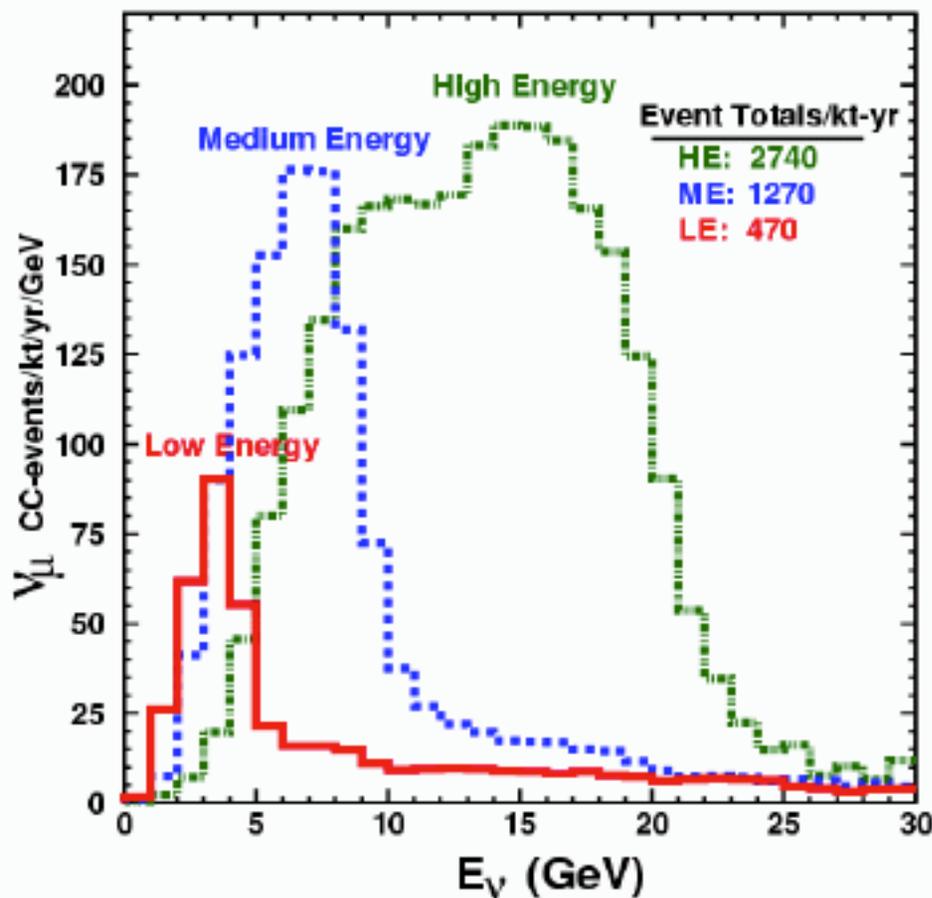


# Near Detector Construction





# MINOS Energy Options



Different beam energies correspond to different horn currents and positions

Will start with low E beam for best sensitivity to match SK results



# MINOS Physics Goals

- **Verify dominant  $\nu_\mu \leftrightarrow \nu_\tau$  oscillations**
  - **$\nu_\tau$  appearance is not necessary.**
  - **$\nu_\mu$  CC disappearance with no NC disappearance and no  $\nu_e$  CC appearance  $\Rightarrow \nu_\mu \leftrightarrow \nu_\tau$  oscillations. There is no other possibility.**
- **Precise measurement of dominant  $\Delta m_{23}^2$  and  $\sin^2 2\theta_{23}$ .**
- **Search for subdominant  $\nu_\mu \leftrightarrow \nu_e$  ( $\sin^2 2\theta_{13}$ ) and  $\nu_\mu \leftrightarrow \nu_s$  oscillations.**
- **Study unconventional explanations: neutrino decay, extra dimensions, etc.**

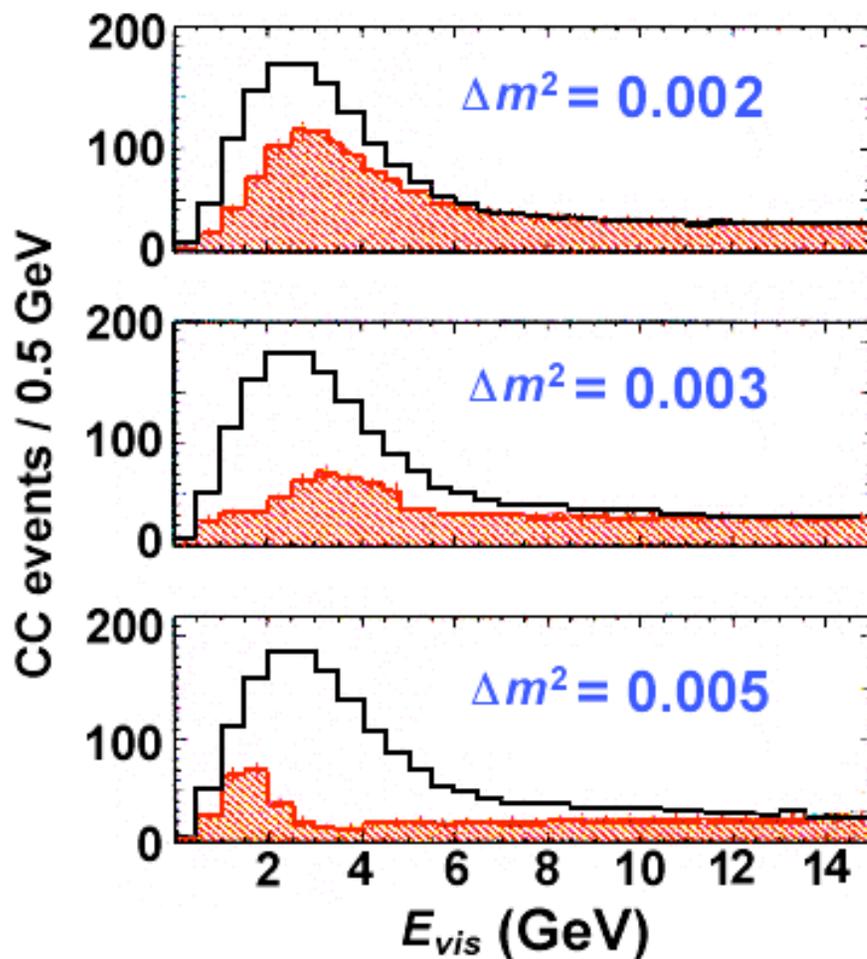


# MINOS Physics Tools

- $\mu$  CC spectrum
  - Information from both rates and shape. The latter is independent of the near / far normalization.
- NC / CC ratio
  - Independent of the near / far normalization .
- $\mu_e$  CC appearance
  - Use topological criteria: fraction of energy in first few radiation lengths, shower asymmetry, etc.



# MINOS CC Spectra



Low-energy beam  
2 year run

Charge current spectra  
for  $\sin^2(2\theta) = 1$

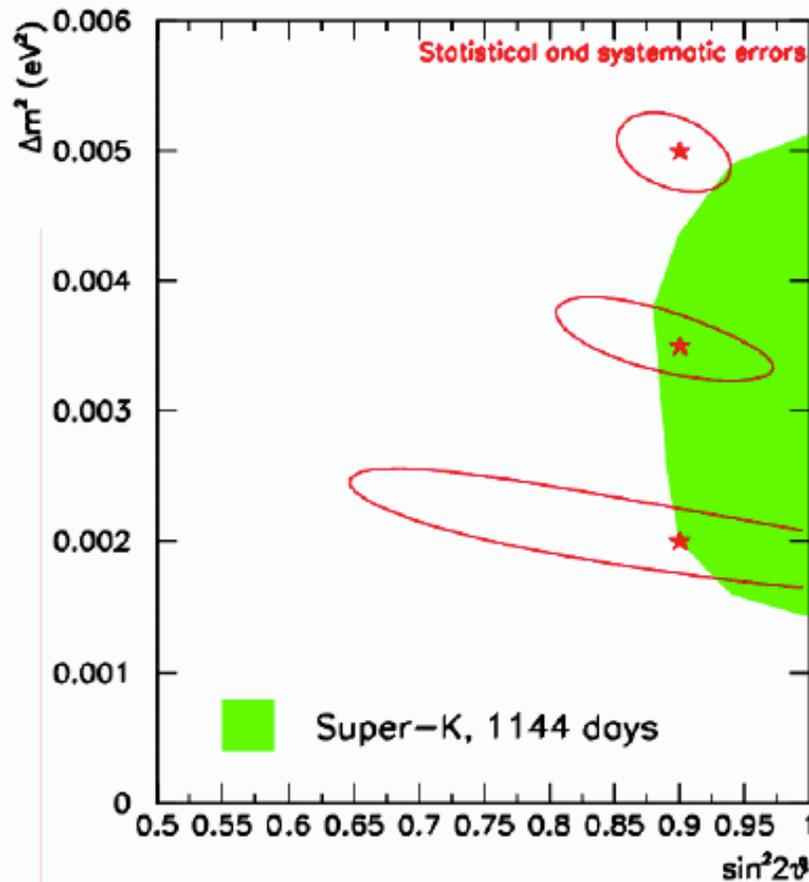
Open = no oscillation  
Shaded = oscillation



# MINOS Sensitivity to



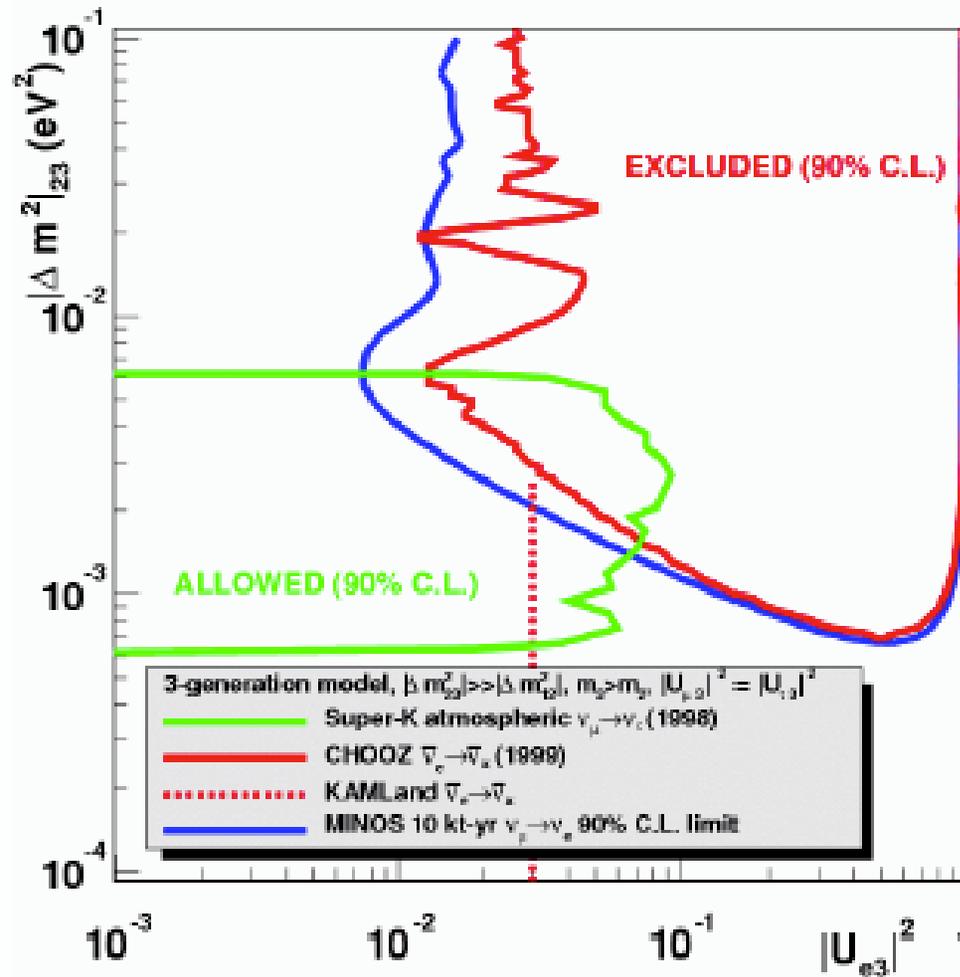
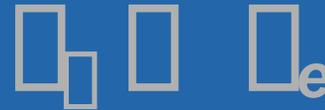
Ph2le, 10 kt. yr., 90% C.L.



Sensitivity to  $\sin^2 2\theta_{23}$  and  $\Delta m^2_{23}$  for a 2-year run



# MINOS Sensitivity to

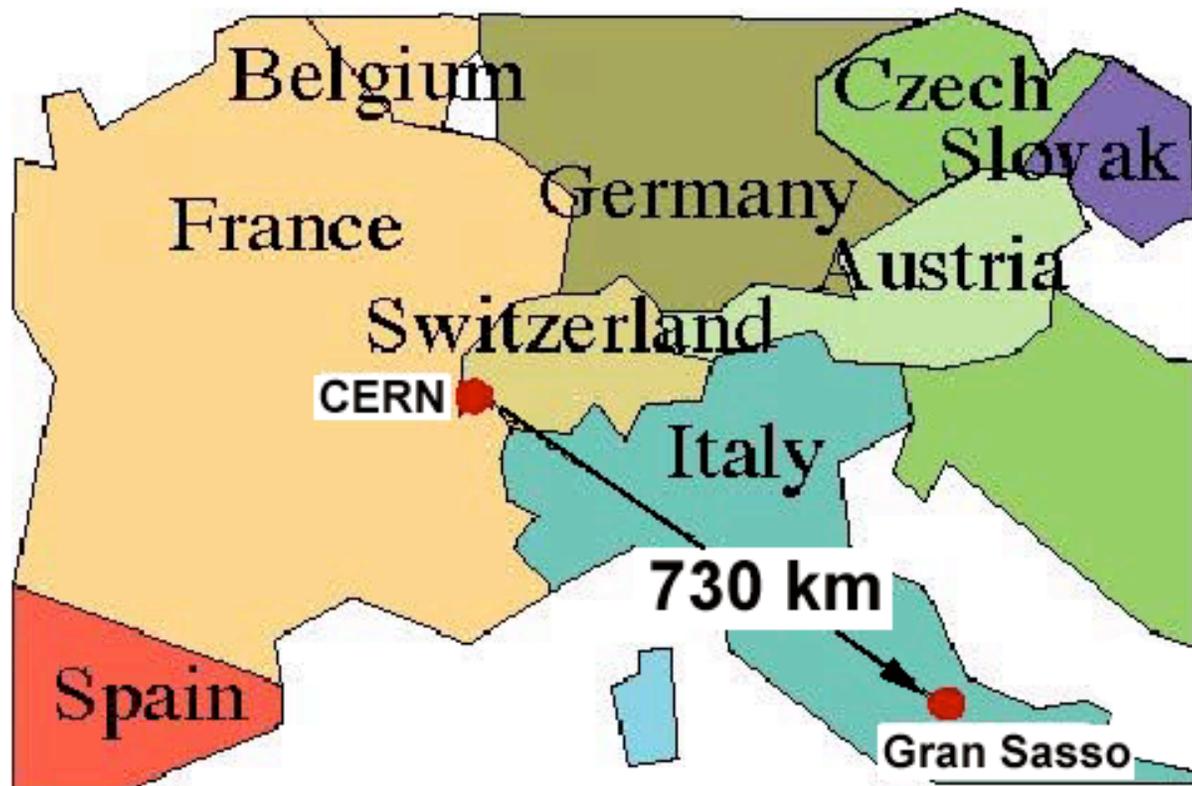


Sensitivity to  $\sin^2 2\theta_{13}$  for a 2-year run

Major background is from higher energy NC events.



# CERN Neutrino Beam to Gran Sasso (CNGS)





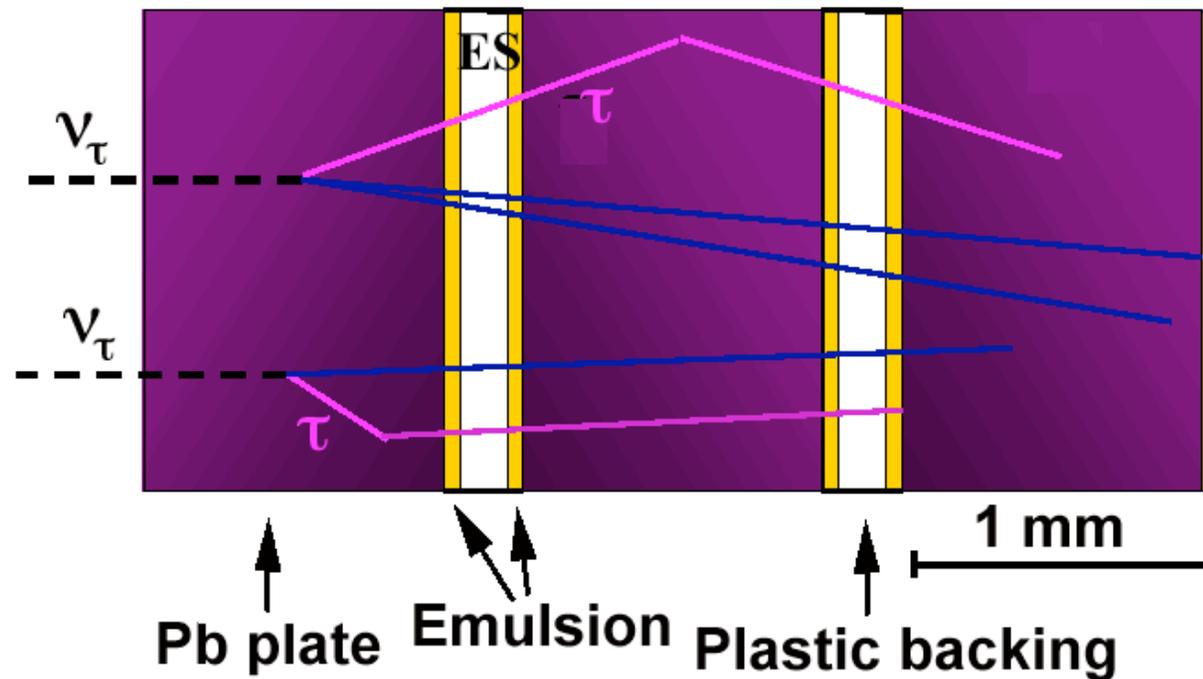
# CNGS / NuMI Comparison

	NuMI	CNGS
$p$ Energy (GeV)	120	400
pot / yr ( $10^{19}$ )	27	4.5
$\nu_{\mu}$ CC events / kT / yr (no oscillations)	2740 HE beam 470 LE beam	2450
Baseline (km)	730	730
Turn on	2005	2006
Near detector(s)	Yes	No



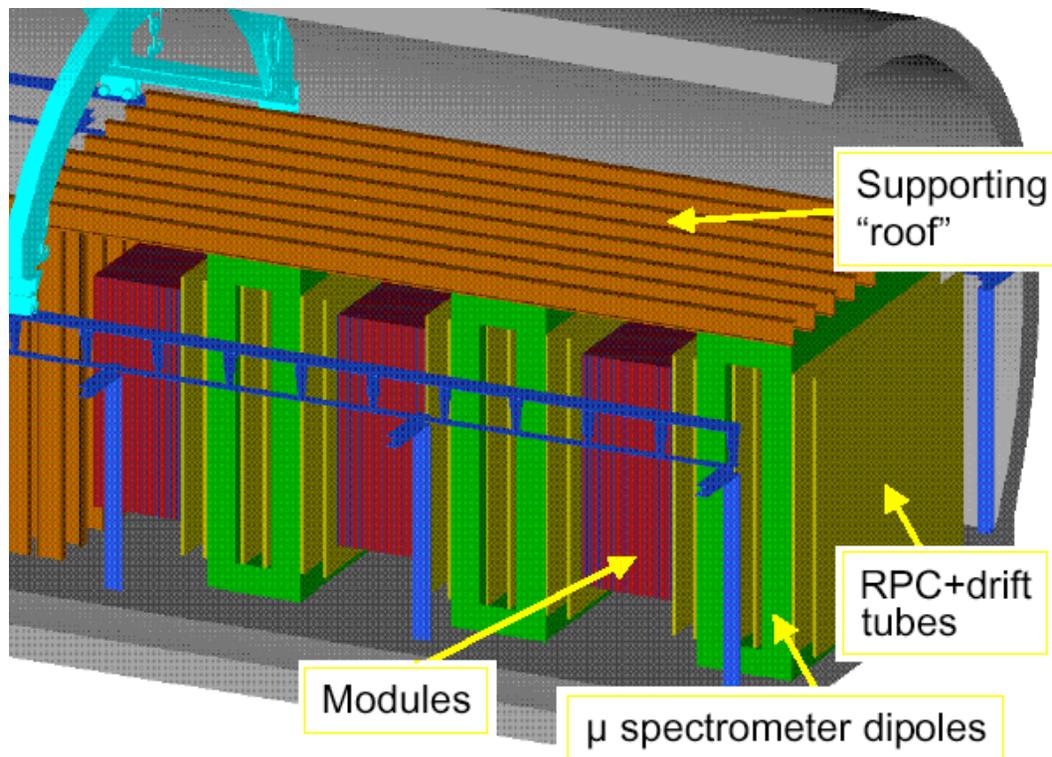
# OPERA Experiment

- OPERA is an approved CNGS proposal for direct detection of  $\bar{\nu}_\tau$  using the ECC (emulsion cloud chamber) technique:





# OPERA Detector



Active mass 2 kT

□ detection efficiency 8.7%

□ 18 events in 5 years for  $\square m^2 = 2.5 \cdot 10^{-3} \text{ eV}^2$



# ICARUS Experiment

**Five 600 T liquid argon TPCs**

**Excellent electron detection**

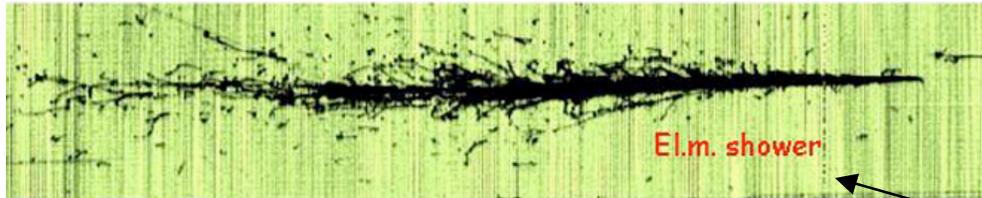
**Has not yet received safety approval.**

**Results from a 300 T prototype**



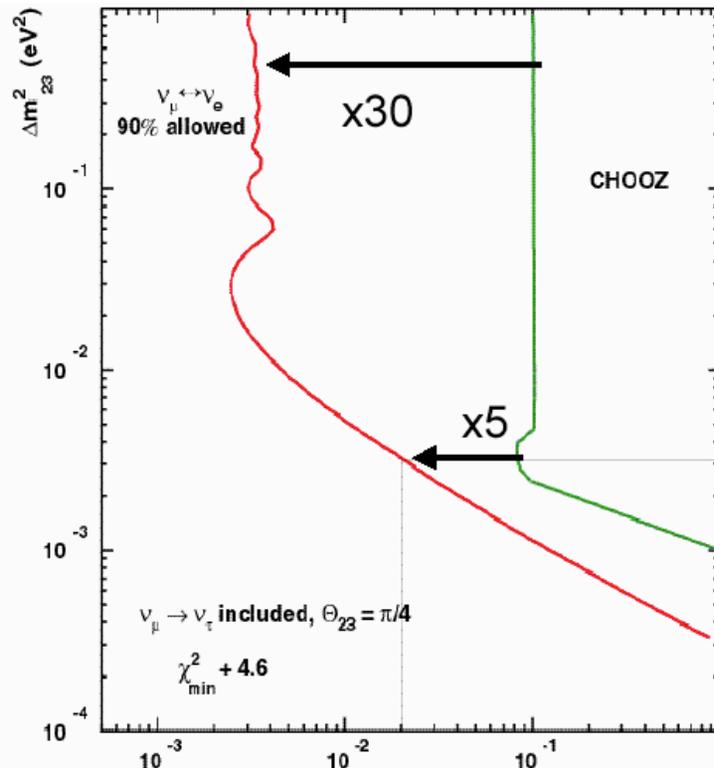


# ICARUS Sensitivity to $\sin^2 2\theta_{13}$



El.m. shower

Electromagnetic shower



5 year run with  
2.45 kT mass

Performance limited by  
lack of a near detector  
and the wrong beam  
energy.



# Off-Axis and Super Beams

- It is clear that the next generation of experiments will concentrate on  $\theta_e$   $\theta_\mu$  oscillations -- needed for
  - $\sin^2 2\theta_{13}$
  - $\text{sign}(\Delta m_{23}^2)$
  - $\theta$

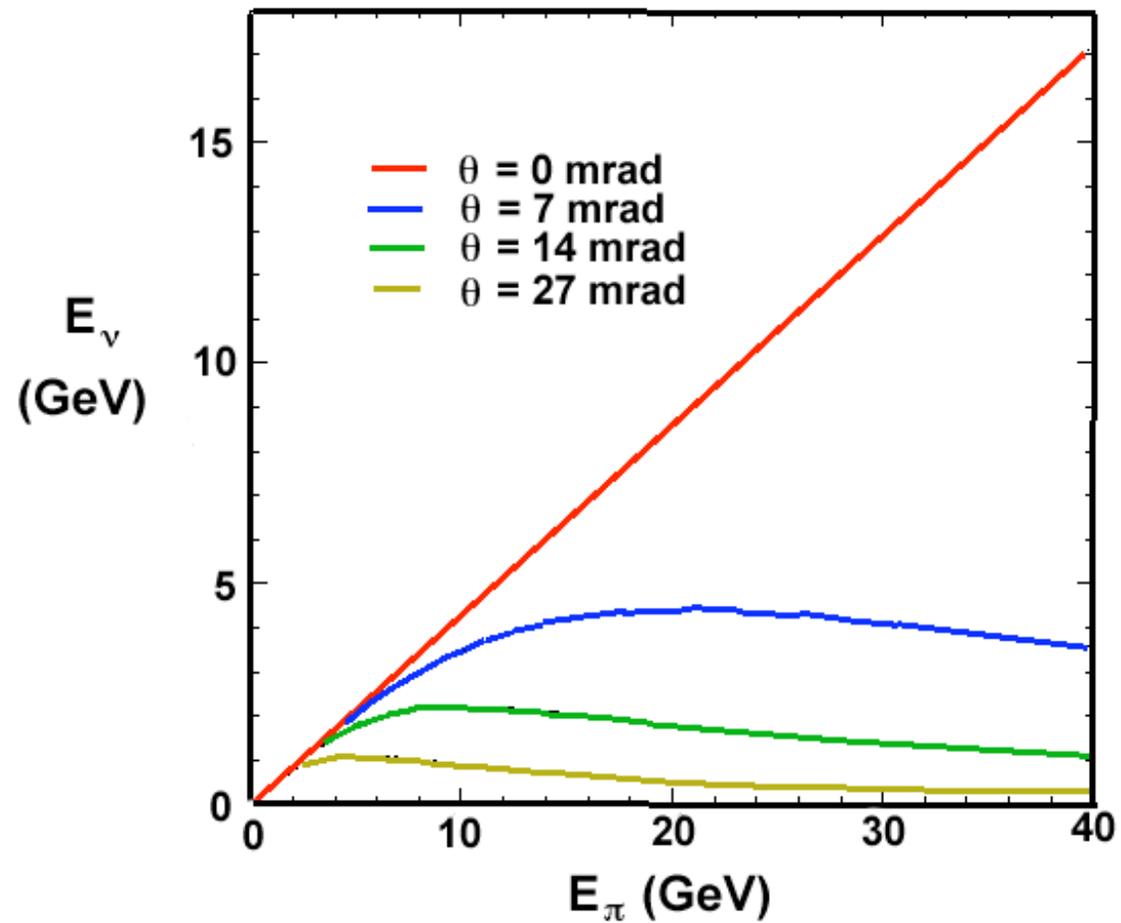


# Off-Axis and Super Beams

- **Want low-energy narrow-band beams at  $\Delta m_{13}^2 \approx \Delta m_{23}^2$  oscillation maximum:**
  - $\nu_e$  appearance maximum
  - $\nu_\mu$  CC disappears
  - Higher-energy NC disappears
- **Want detectors optimized for  $\nu_e$  detection**
- **Want increases in beam flux times detector mass**
- **$\nu$  Off-axis super beams**

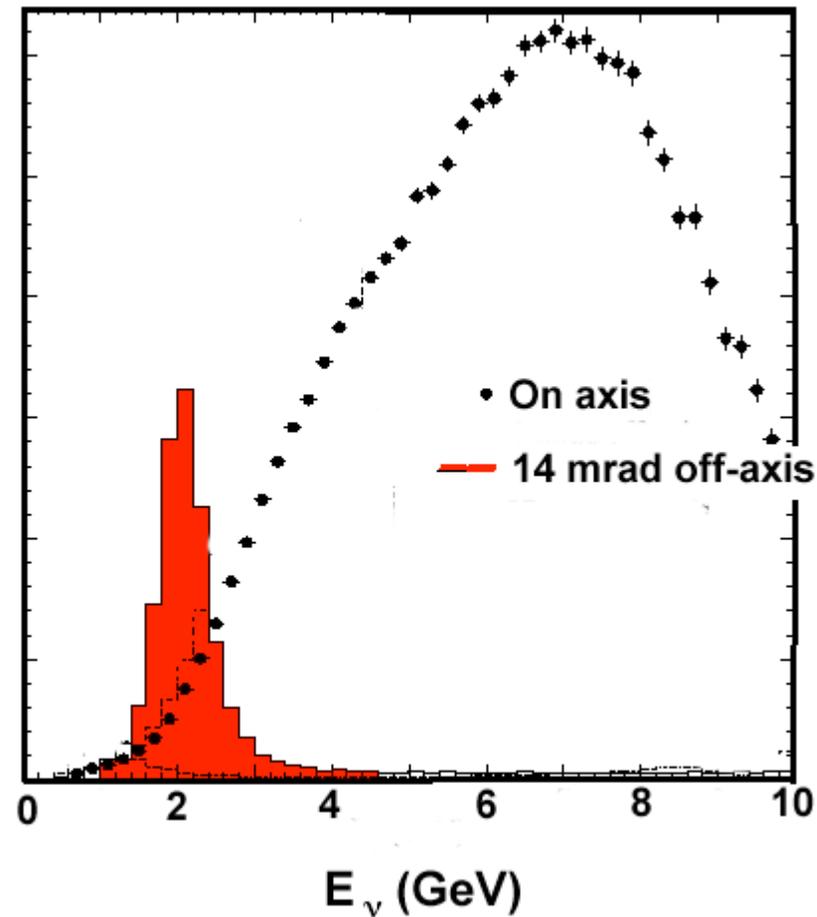


# Off-Axis Kinematics



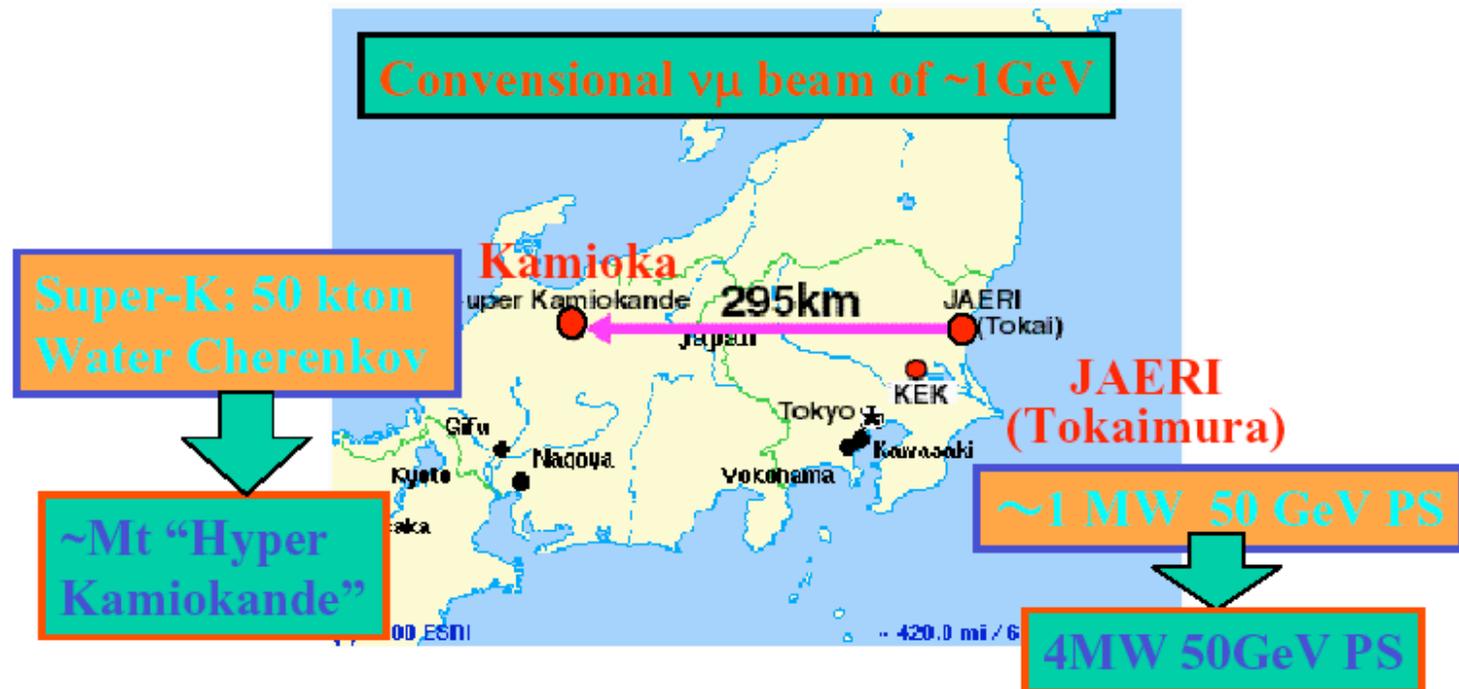


# Off-Axis Spectrum (No oscillations)





# J-PARC Proposal



## 1st Phase

- $\nu_\mu \rightarrow \nu_x$  disappearance
- $\nu_\mu \rightarrow \nu_e$  appearance
- NC measurement

## 2nd Phase

- CPV
- proton decay



# Beams

- **NuMI beam should start in 2005 at 0.25 MW, increasing to 0.4 to 0.8 MW with incremental improvements. With a superconducting proton linac, 2 MW is possible.**
- **J-PARC should have 0.8 MW with a possible second phase to 4 MW**



# Super Beam Detectors

- For  $E \leq 1$  GeV (J-PARC), H<sub>2</sub>O-Cerenkov detectors are favored since quasi-elastic interactions are favored
  - Start with 50kT Super-K
  - Upgrade to 1MT Hyper-K (10 100kT units -- 500 m long!)
- For  $E > 1$  GeV, light sandwich detectors needed because  $\bar{\nu}^0$  decays cannot be separated from electrons in water.
  - 50kT detector being discussed



# Off-Axis/Super Beam Physics (In Vacuum)

- Assume that we will always work at the  $\Delta m_{13}^2 \approx \Delta m_{23}^2$  oscillation maximum, so that  $1.27 \Delta m_{13}^2 L / E = \pi/2 + n\pi$ .
- Assume that  $\sin^2 2\theta_{23} \approx \sin^2 2\theta_{12} \approx 1$ .
- Then the leading term for  $\nu_\mu \rightarrow \nu_e$  oscillations is

$$P_{vac}(\nu_\mu \rightarrow \nu_e) \approx \frac{1}{2} \sin^2 2\theta_{13}$$



# Off-Axis/Super Beam Physics (In Matter)

- In matter,

$$P_{mat}(\nu_\mu \rightarrow \nu_e) \approx 1 \pm \frac{2E}{E_R} P_{vac}(\nu_\mu \rightarrow \nu_e),$$

where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.

$$E_R = \frac{m_{13}^2}{2\sqrt{2}G_F n_e} \approx 11 \text{ GeV for the earth's crust.}$$

□ ~30% effect for NuMI, ~10% effect for J-PARC at the first oscillation maximum.



# Off-Axis/Super Beam Physics (CP Violation)

- The next leading term is CP violating:

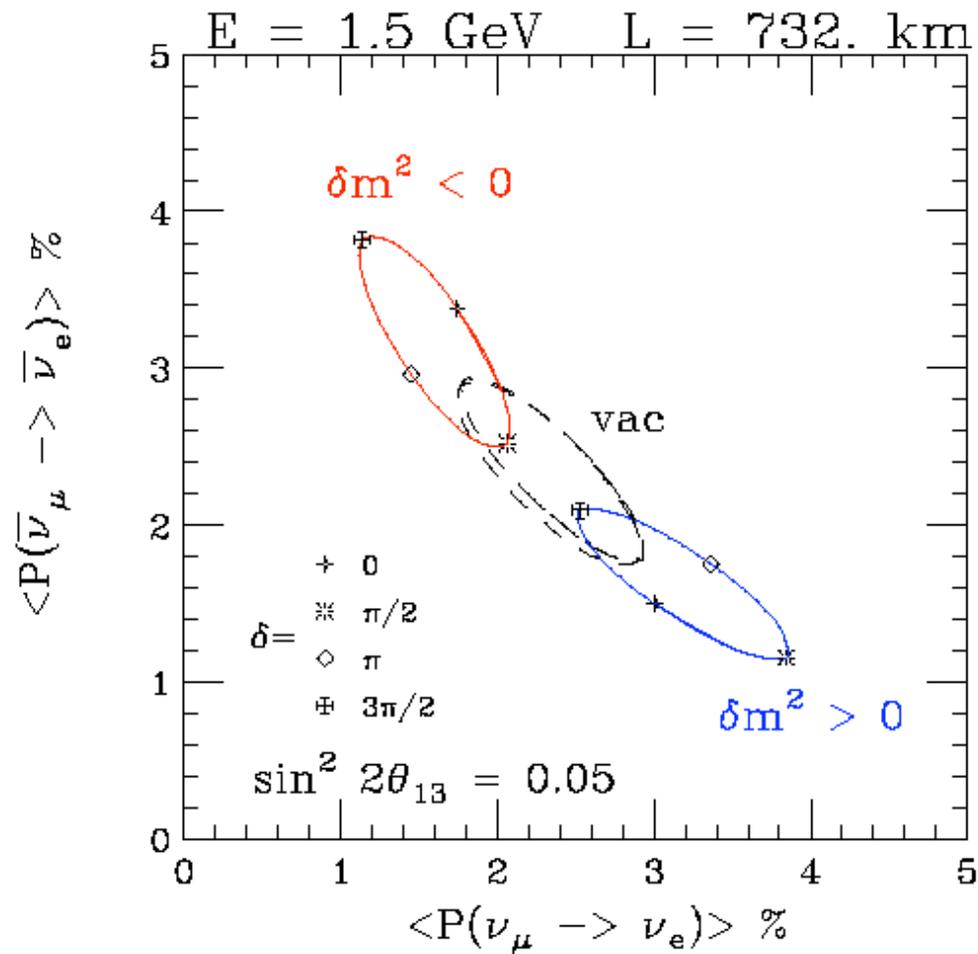
$$P_{CP}(\nu_\mu \rightarrow \nu_e) \approx \pm J \sin\delta \frac{1.27 \text{ eV}^2 L}{E},$$

where  $J = \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \approx \sin 2\theta_{13}$ ,  
and where the top sign is for neutrinos and the bottom sign is for antineutrinos.

- For a single set of measurements, there can be ambiguities between the matter effect and CP violation.



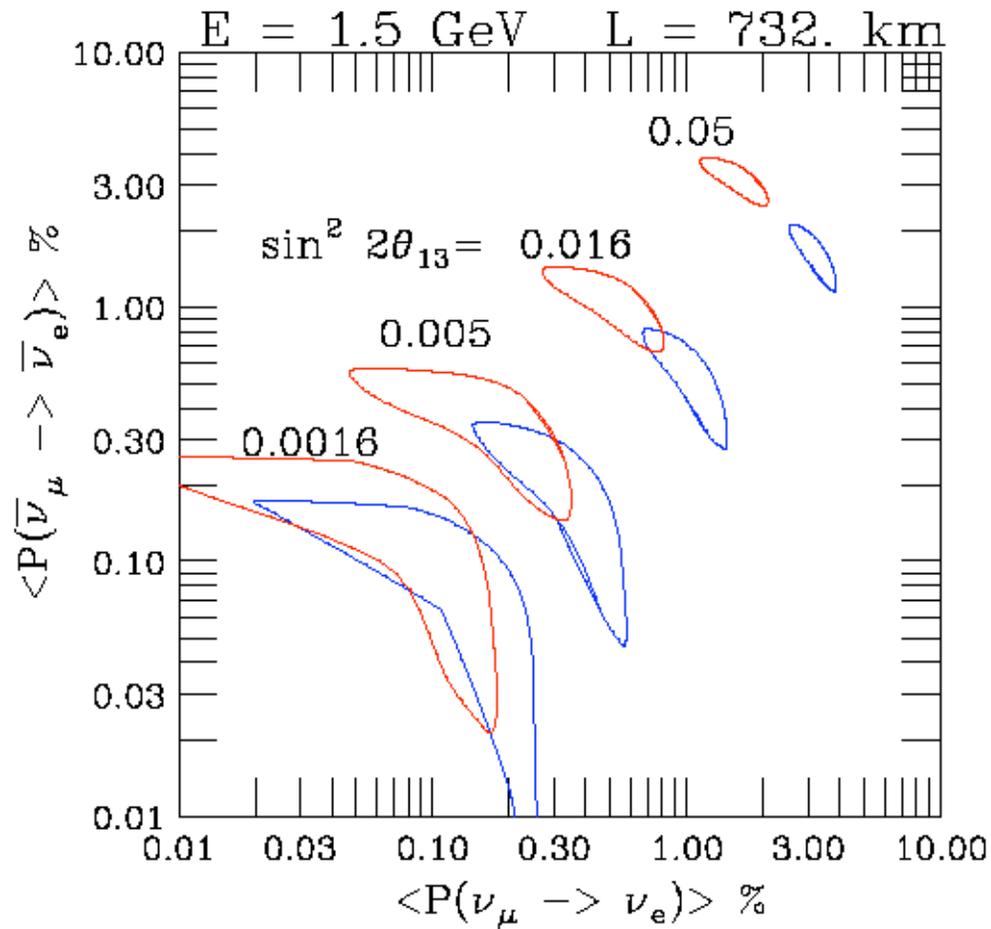
# NuMI Off-Axis Neutrino vs. Antineutrino (1)



$$\Delta m_{12}^2 = 5 \times 10^{15} \text{ (eV)}^2$$



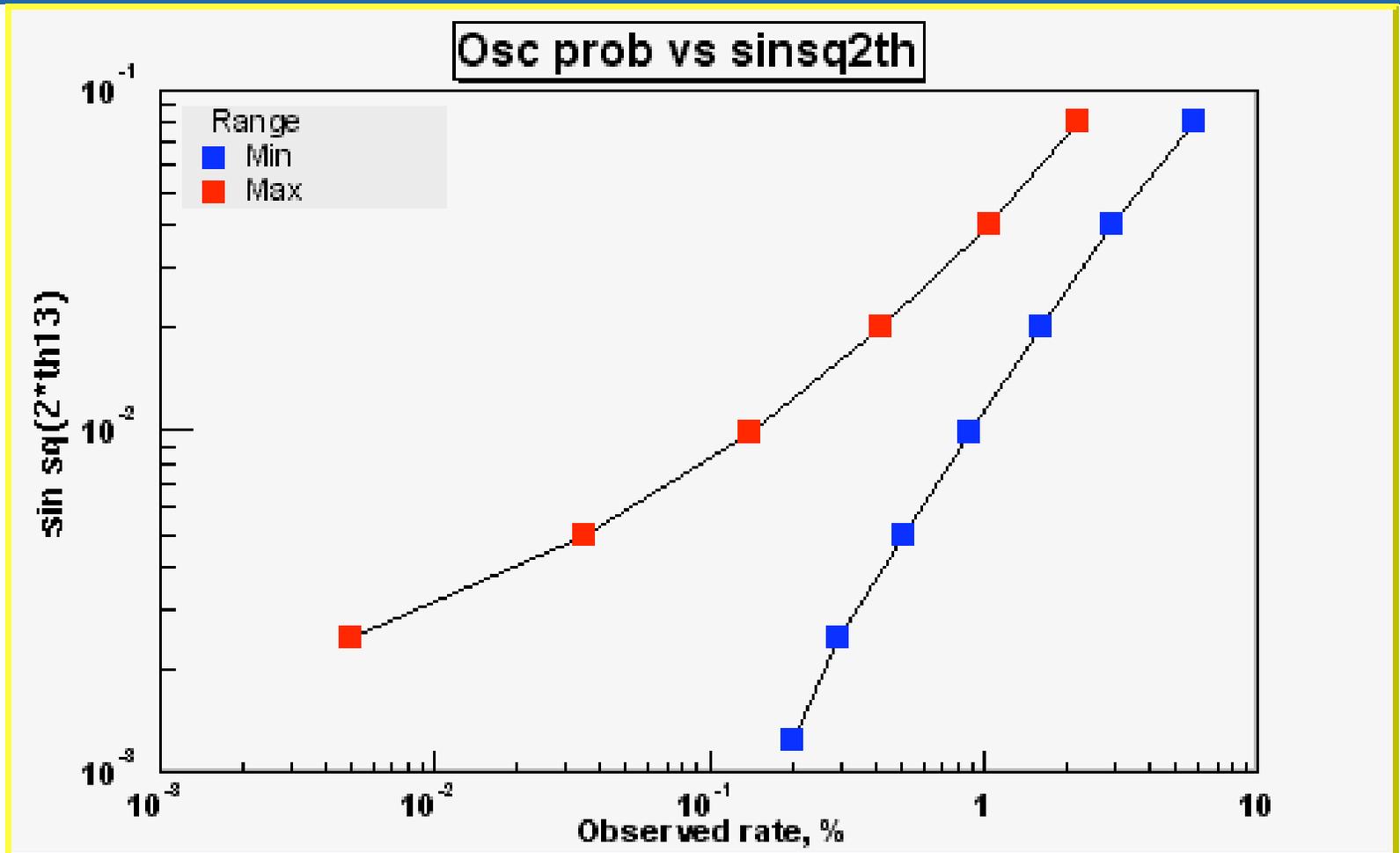
# NuMI Off-Axis Neutrino vs. Antineutrino (2)



$$\Delta m_{12}^2 = 5 \times 10^5 \text{ (eV)}^2$$



# Ambiguities in $\sin^2(2\theta_{13})$ Measurement





# Off-Axis Notes

- The matter effect is binary. Once it is measured, the ambiguity disappears.
- NuMI and J-PARC are complementary. NuMI will have 3 times the matter effect and the same CP violation at the 1st oscillation maximum.
- The 2nd maximum is attractive for a later NuMI stage. The matter effects decrease by 3 and the CP violation increases by 3. However, event rates are much lower.
- Antineutrino running necessary to pin down parameters.
- First phase of both NuMI off-axis and J-PARC should have sensitivity to  $\sin^2 2\theta_{13}$  at 0.01 level. **It is difficult to go below this level with conventional beams.**



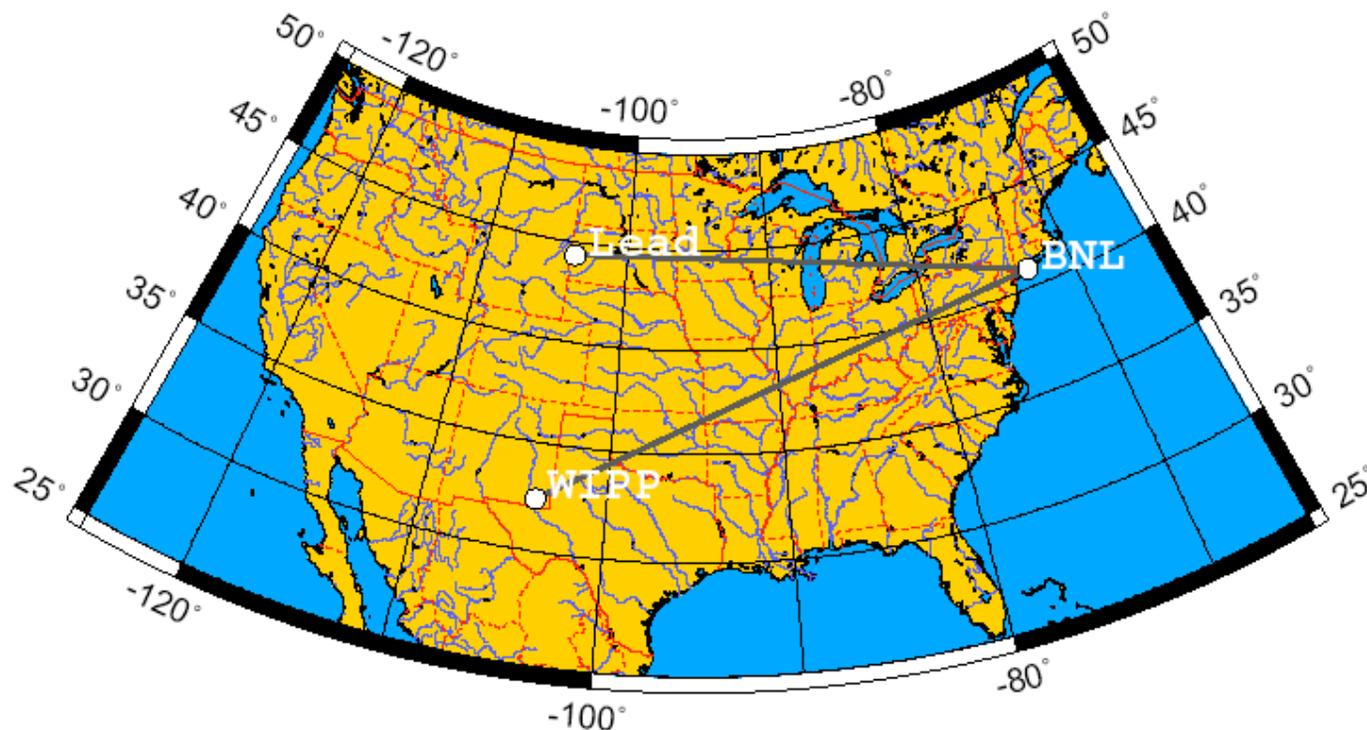
# Reactor Measurement of $\sin^2(2\theta_{13})$

- Two detectors, one close to a reactor, one 1.7 km from the reactor would be sensitive to  $\sin^2(2\theta_{13})$  at the few per cent level.
- No ambiguities – no matter effects because the path is short and energy low, no CP effects because it is a disappearance experiment.
- Needs high level of control of systematics.



# Brookhaven White Paper (1)

- Pushing conventional beams to their limit – very long baseline





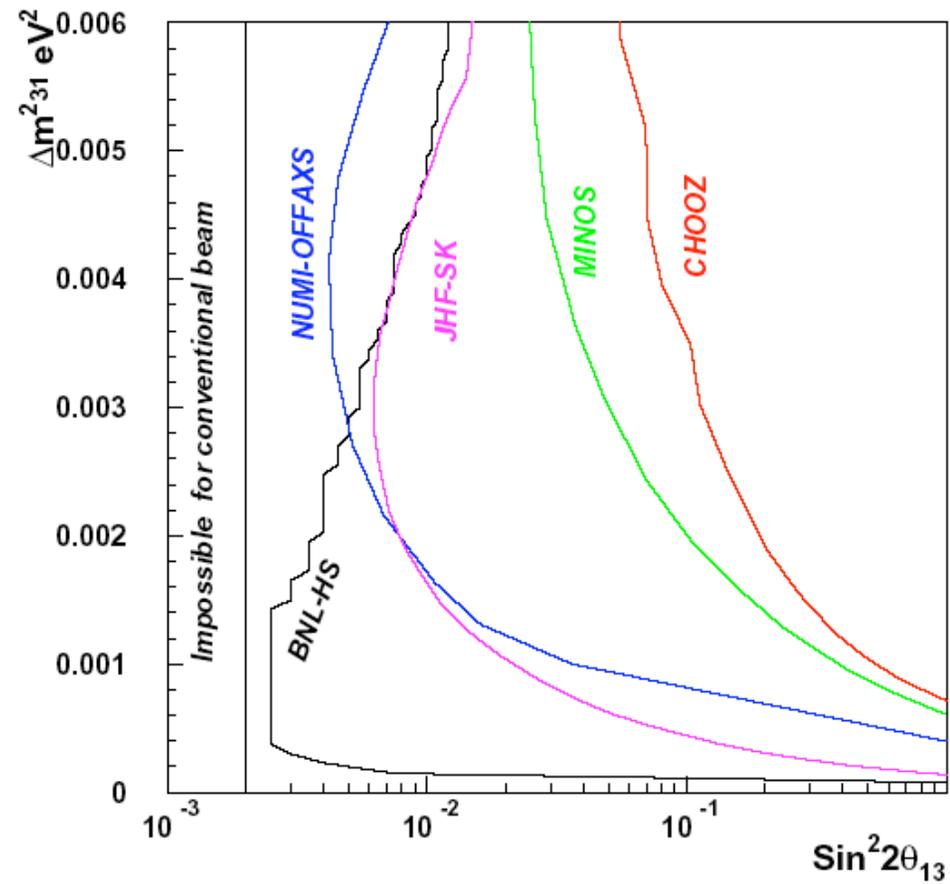
## Brookhaven White Paper (2)

- **Wide band beam (0.5 to 6 GeV)**
- **AGS upgrade from present 0.17 MW to 1 MW 1 GeV superconducting linac**
- **0.5 MT water Cerenkov detector at WIPP or Homestake**



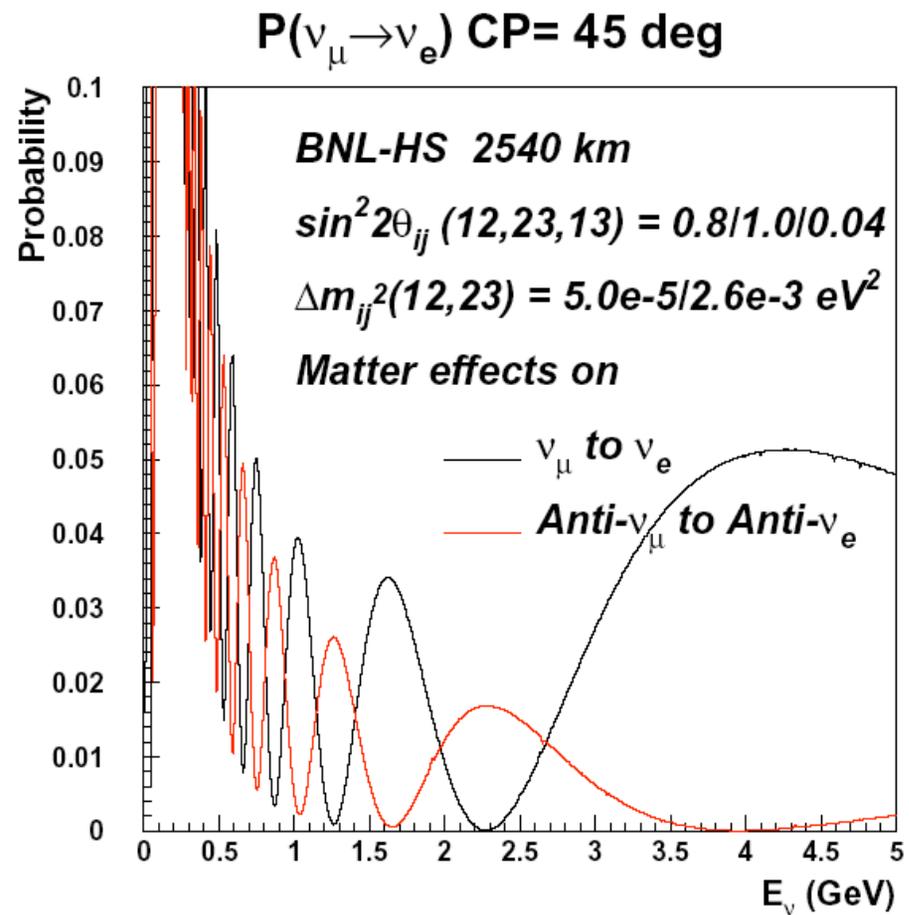
# $\theta_{13}$ Sensitivity

90 % C.L. for  $\text{Sin}^2(2\theta_{13})$





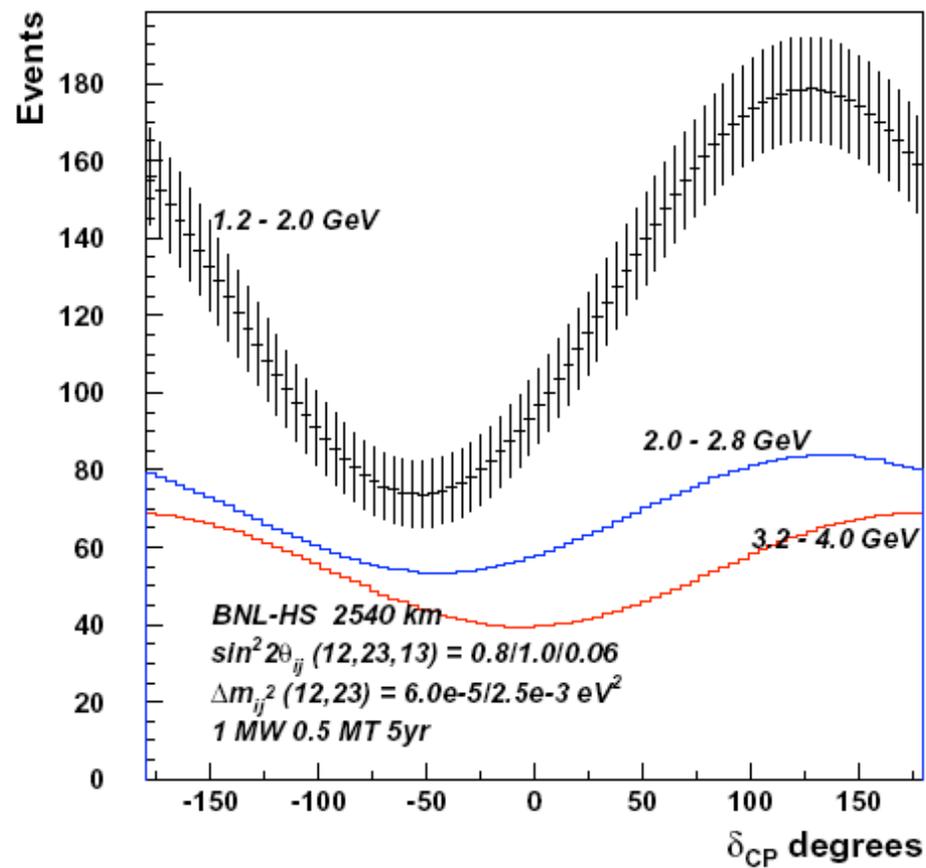
# Very Large Matter Effects





# Large CP Effects with Only Neutrino Running

## Effect of $\delta_{CP}$ in 3 energy bins



$$\sin^2 2\theta_{13} = 0.06$$



# Background-Free Techniques

- To measure very low values of  $\theta_{13}$  ( $< 2^\circ$ ), it will be necessary to employ techniques that are inherently background-free — detection of muons with no  $\nu_\mu$  source.
  - Beta Beams
  - Muon-ring Neutrino Factories



# Beta Beams

- **Proposal by P. Zucchelli hep-ex/0107006**
- **Idea: Accelerate short-lived ions:**
  - Pure sub-GeV  $\bar{\nu}_e$  and  $\nu_e$  beams
  - Known spectrum
  - Only backgrounds are from misidentifications
- **Examples:**
  - ${}^6\text{He} \rightarrow {}^6\text{Li} + e^- \bar{\nu}_e, \langle E \rangle = 1.9 \text{ MeV}, \tau = 0.8 \text{ s}$
  - ${}^{18}\text{Ne} \rightarrow {}^{18}\text{F} + e^+ \nu_e, \langle E \rangle = 1.85 \text{ MeV}, \tau = 1.7 \text{ s}$
- **Need huge water-Cerenkov detector**



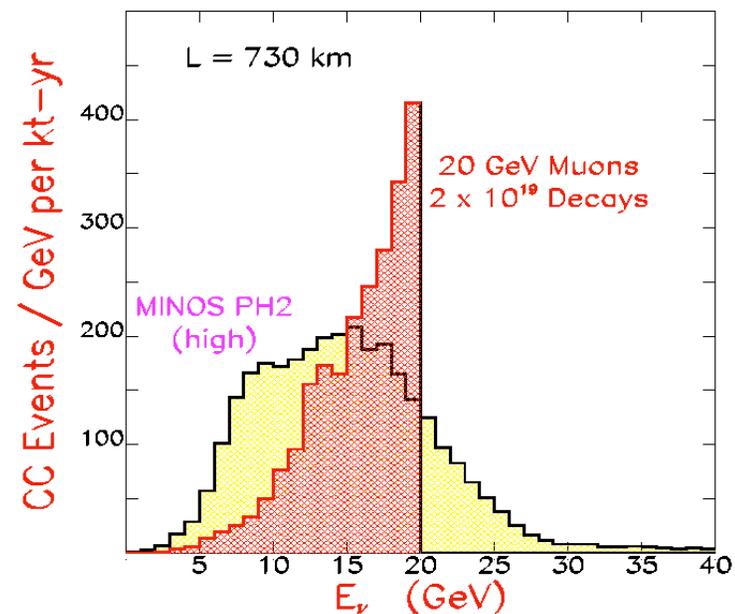
# Muon-Ring Neutrino Factories

- A simple idea: Store muons in a ring with long straight sections and observe neutrinos from the muon decays.
- If  $\mu^+$  stored, then
- Normal CC give only  $\mu^+$  and  $e^-$ .
  - $\nu_\mu \rightarrow \nu_e$  oscillations give  $e^+$ .
  - $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$  oscillations give  $\mu^-$ .
- Need magnetic detection to see wrong-sign leptons and very massive detectors for rate.
- Electron charge difficult  $\square$  emphasis on wrong-sign muon detection.



# Neutrino Factory Advantages

- Beam background free.
- Well-known fluxes from monochromatic parents.
- Narrow band beam.
- Flux increases as  $E_{\nu}^3$ :
  - $E^2$  for divergence.
  - $E$  for the cross section.





# Neutrino Factory Parameters and Physics Goals

- **Parameters under discussion:**
  - $20 \leq E_\nu \leq 50$  GeV
    - Lower bound from  $p_\nu > 4$  GeV for detection
    - Higher  $E_\nu$  is better
  - $10^{19}$  to  $10^{21}$  decays per year
  - Baseline about 3000 km
    - Reason to be discussed
- **Physics goals:**
  - Precise measurement of  $\theta_{13}$
  - Determination of the sign of  $\Delta m_{23}^2$
  - Measurement of CP violation in lepton sector ( $\delta$ )



# Measurement of $\theta_{13}$ , the Sign of $\Delta m_{13}^2$ , and $\delta$

- At long baselines, we want to use the different  $L / E$  dependence to untangle the different terms, including the CP violating term:

$$P(\nu_\mu \rightarrow \nu_e) = 2\theta_{13}^2 \sin^2(1.27 \Delta m_{13}^2 L / E) + 0.81(\Delta m_{12}^2 L / E)^2 \\ + 1.27 \theta_{13} (\Delta m_{12}^2 L / E) \sin(1.27 \Delta m_{13}^2 L / E) \cos(\pm \delta \mp 1.27 \Delta m_{13}^2 L / E)$$

- This requires a fairly large  $L / E$ :  $E \sim 6$  GeV for  $L = 3000$  km.
- The temptation is to increase  $L$  further. This does not work, at least for measuring CP violation, for a somewhat subtle reason.



# Measuring CP Violation

- The problem with long ( $\sim 8000$  km) baselines arises due to the matter effect for  $\Delta m_{12}^2$ .
- The effective  $\Delta m^2$  added by the earth is  $2AE$ , where

$$A = \sqrt{2} G_F \rho_e \approx 1.5 \cdot 10^{14} \text{ eV}^2/\text{GeV}$$

for earth density corresponding to  $L = 8000$  km.

- In the presence of matter

$$\sin \left[ \frac{1.27 \Delta m_{12}^2 L}{E} \right] \rightarrow \frac{\Delta m_{12}^2}{|2AE \pm \Delta m_{12}^2|} \sin \left[ \frac{1.27 |2AE \pm \Delta m_{12}^2| L}{E} \right]$$

- For reasonable energies,  $E \geq 4$  GeV,  $2AE$  is about an order of magnitude larger than  $\Delta m_{12}^2$ . Thus,  $|2AE \pm \Delta m_{12}^2| \approx 2AE$ .



# Measuring CP Violation

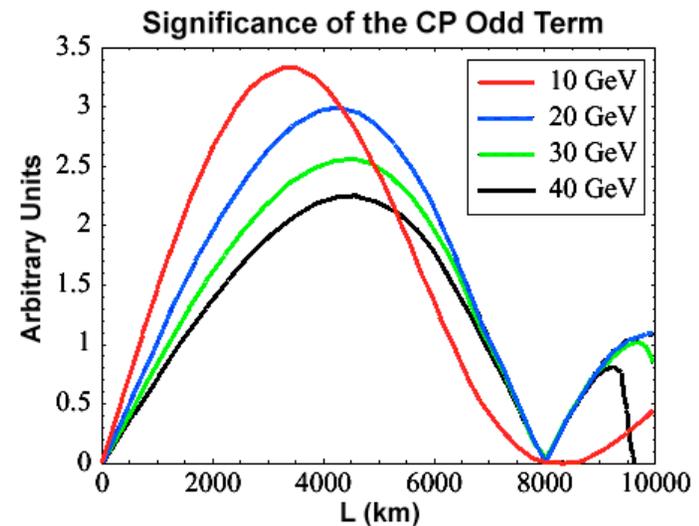
- Therefore, the CP odd term contains a pure matter oscillation,

$$P_{CP}(\nu_\mu \rightarrow \nu_e) \propto \frac{\Delta m_{12}^2}{2AE} \sin(2.54 AL),$$

which goes to zero at 8000 km, independent of all oscillation parameters.

- Calculation by Cervera et al.

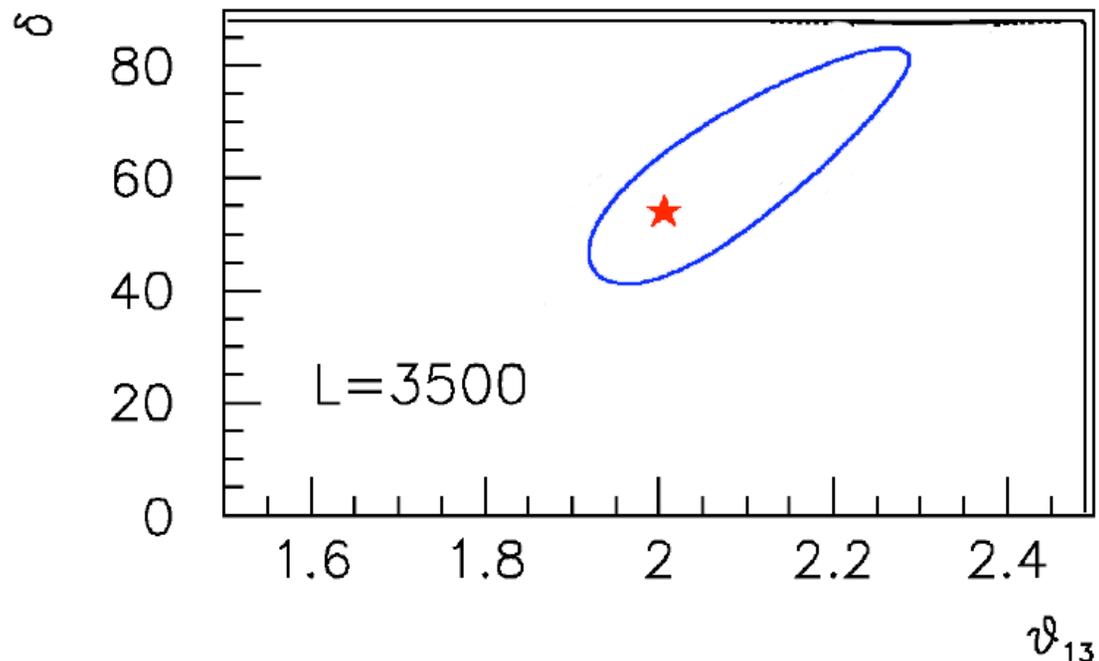
$$\begin{aligned} \Delta m_{23}^2 &= 2.8 \cdot 10^{-3} \text{ eV}^2 \\ \Delta m_{12}^2 &= 1.0 \cdot 10^{-4} \text{ eV}^2 \\ \theta_{23} &= 45^\circ; \quad \theta_{12} = 22.5^\circ \\ \theta_{13} &= 8^\circ; \quad \delta = 90^\circ \end{aligned}$$





# Measuring CP Violation

- Fit at 90% C.L. by Cervera et al. for  $10^{21}$  decays at 50 GeV with a 40 kT detector.
- $\Delta m_{23}^2 = 2.8 \cdot 10^{-3} \text{ eV}^2$ ;  $\Delta m_{12}^2 = 1.0 \cdot 10^{-4} \text{ eV}^2$ 
  - $\theta_{23} = 45^\circ$
  - $\theta_{12} = 22.5^\circ$
  - $\theta_{13} = 2^\circ$
  - $\delta = 54^\circ$







# Conclusion

- **The LMA solar oscillations opens a bright (and probably long) future for the exploration of neutrino parameters.**