Prospects for Neutrino Physics

- **Limit to neutrino oscillations**
- **Assume MiniBooNE will not confirm 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
- **Prospects**
  - **Planned experiments**
  - **Superbeams**
  - **Neutrino factories**

Vacuum Oscillations

- Matter effects: In vacuum,

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

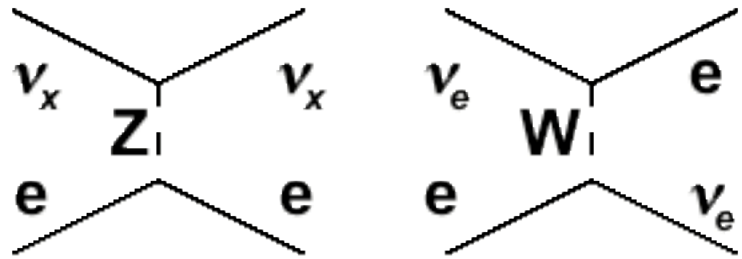
$$P(\nu_e \to \nu_x) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

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

L is in km, and E is in GeV

Matter Oscillations

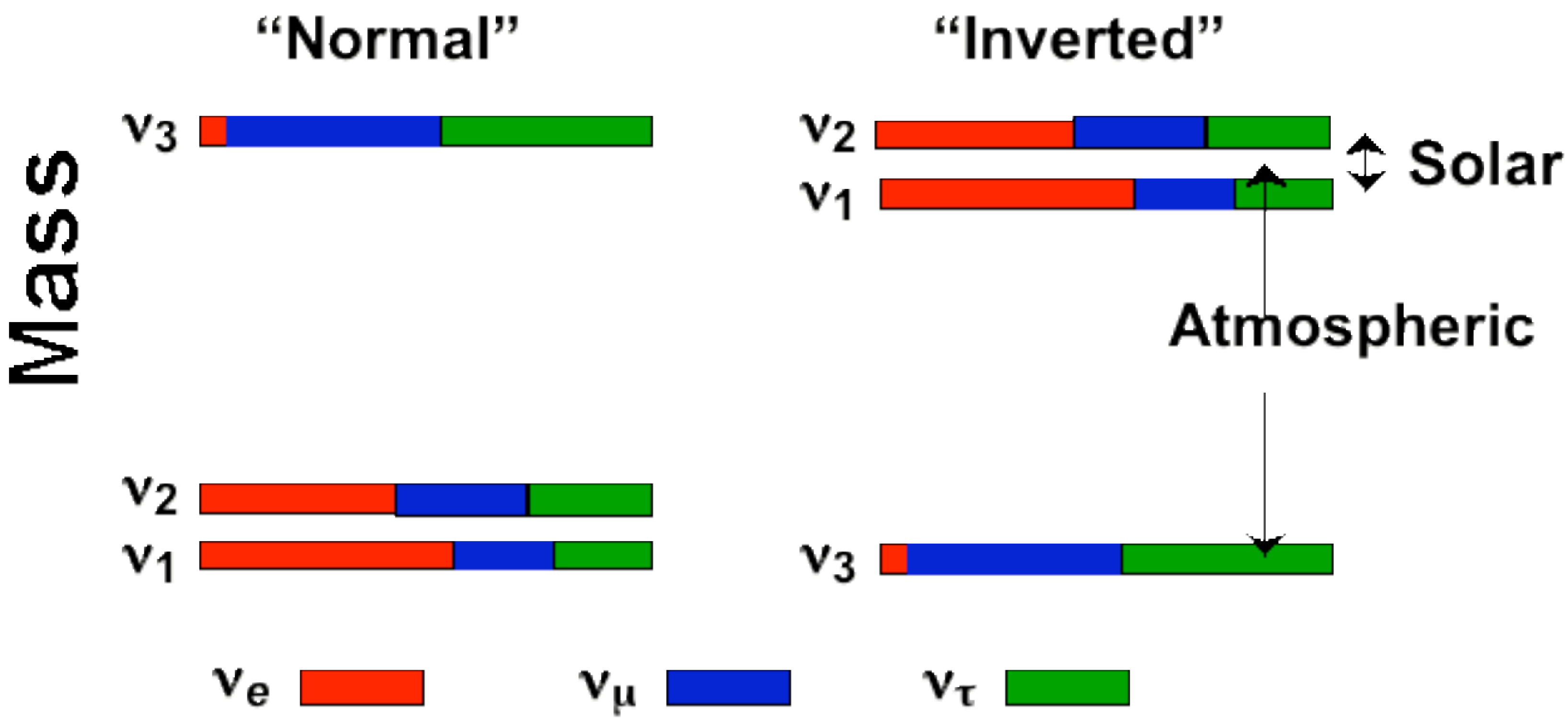
- **Matter effects: In matter ν_e's interact differently than ν_x's.**



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

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

What Do We Know?



What Do We Want to Know?

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

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

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

  $[\sin^2 2\theta_{13}, \mathrm{sign}(\Delta m^2_{23}), \delta]$

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

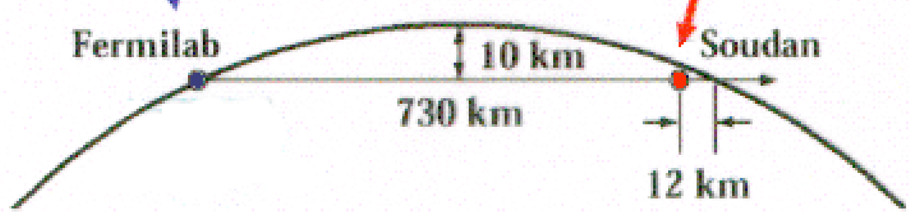
  [ν_s, $\beta\beta$ decay, extra dimensions, CPT violation, etc.]

MINOS Layout
(Main Injector Neutrino Oscillation Search)

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

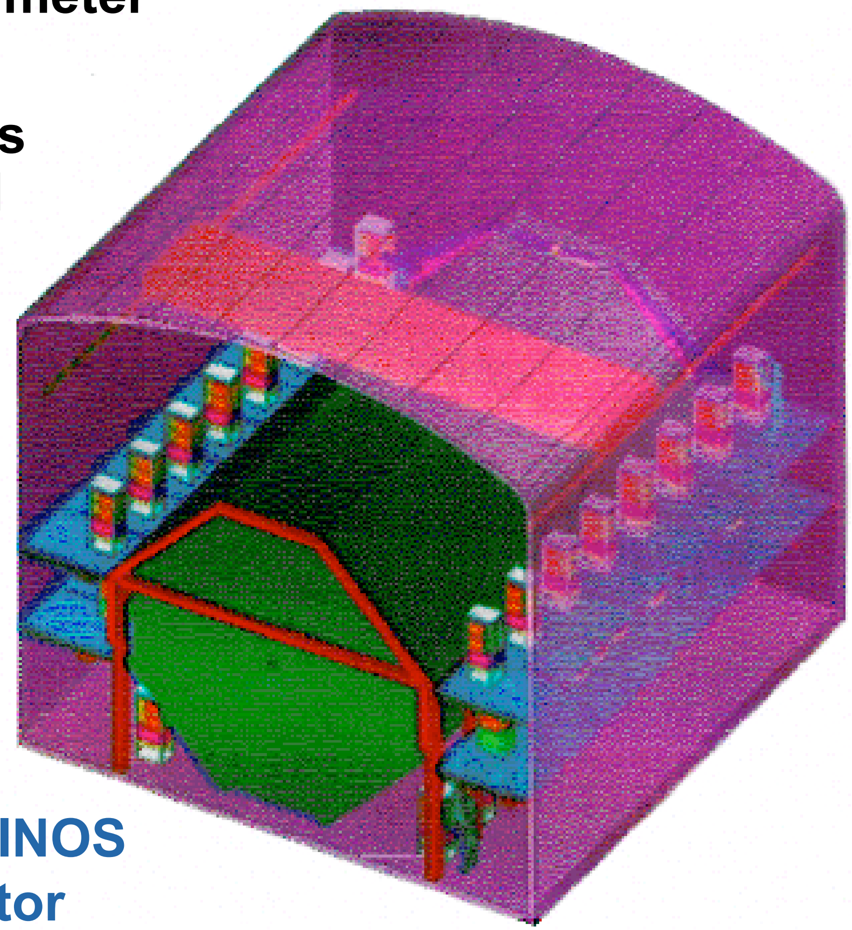
Near detector 980 T at 1 km

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^2 (6.4 acres) of active detector planes
- Toroidal magnetic field <B> = 1.3 T
- Total mass 5.4 kT

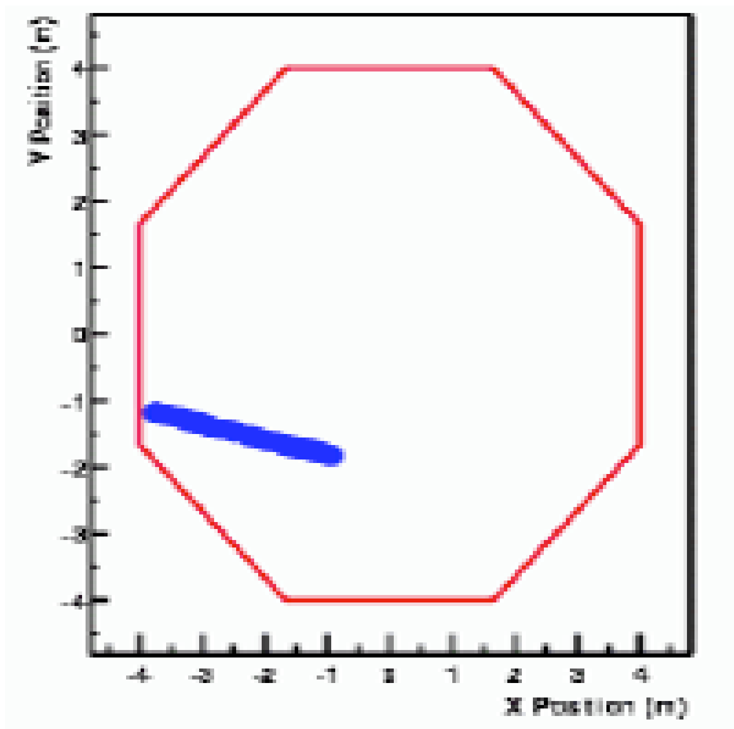


Half of MINOS far detector

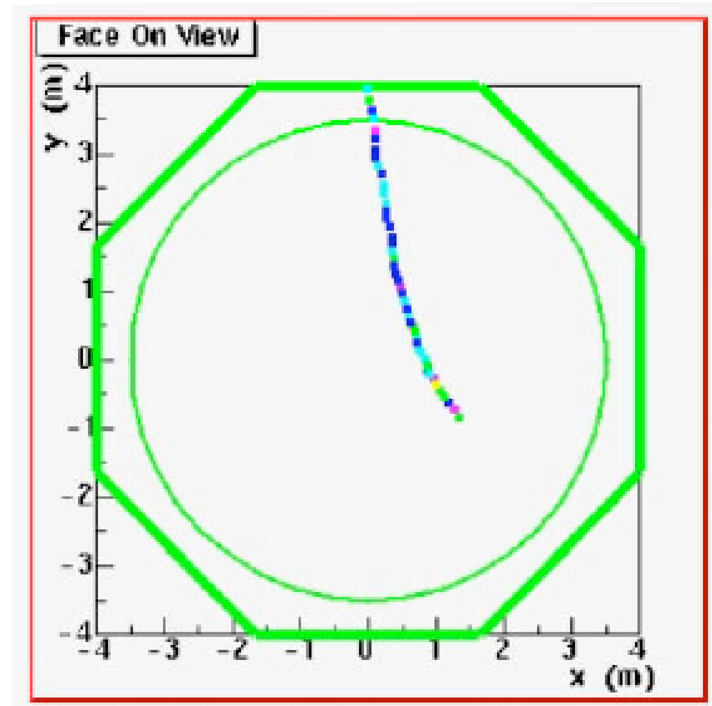
MINOS Far Detector

First module built and running with magnetic field. Now 3/4 Done.

Far Detector Events



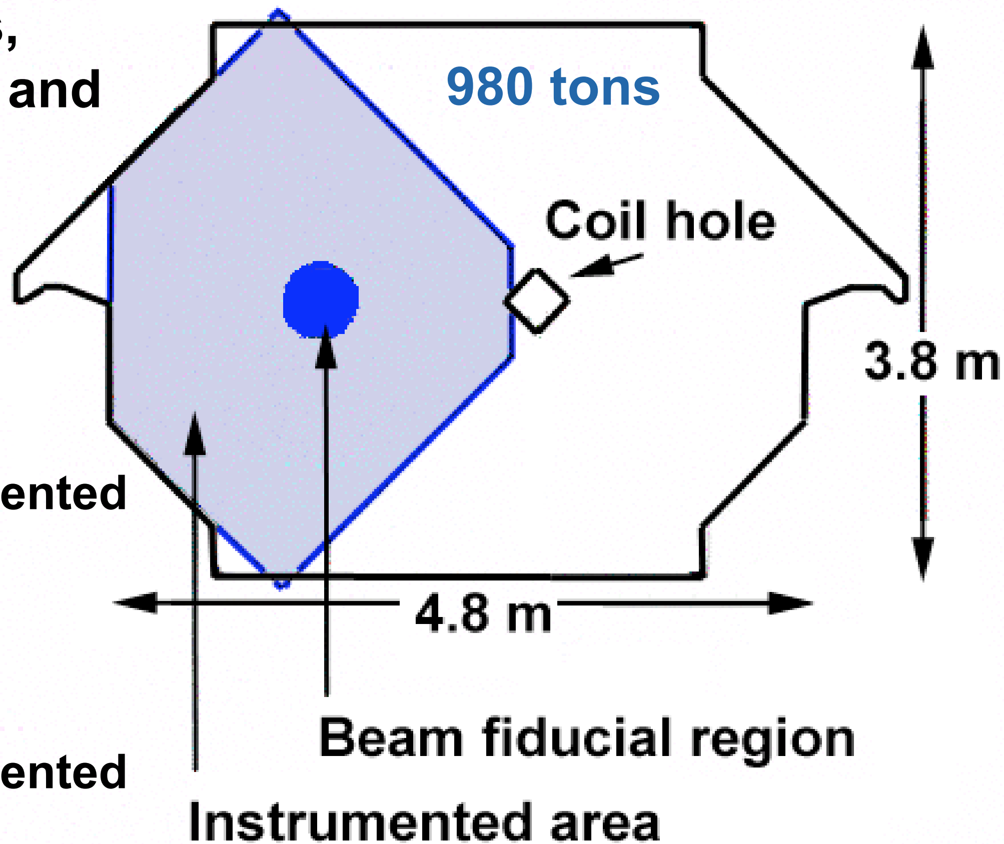
First upward-going muon (no field)



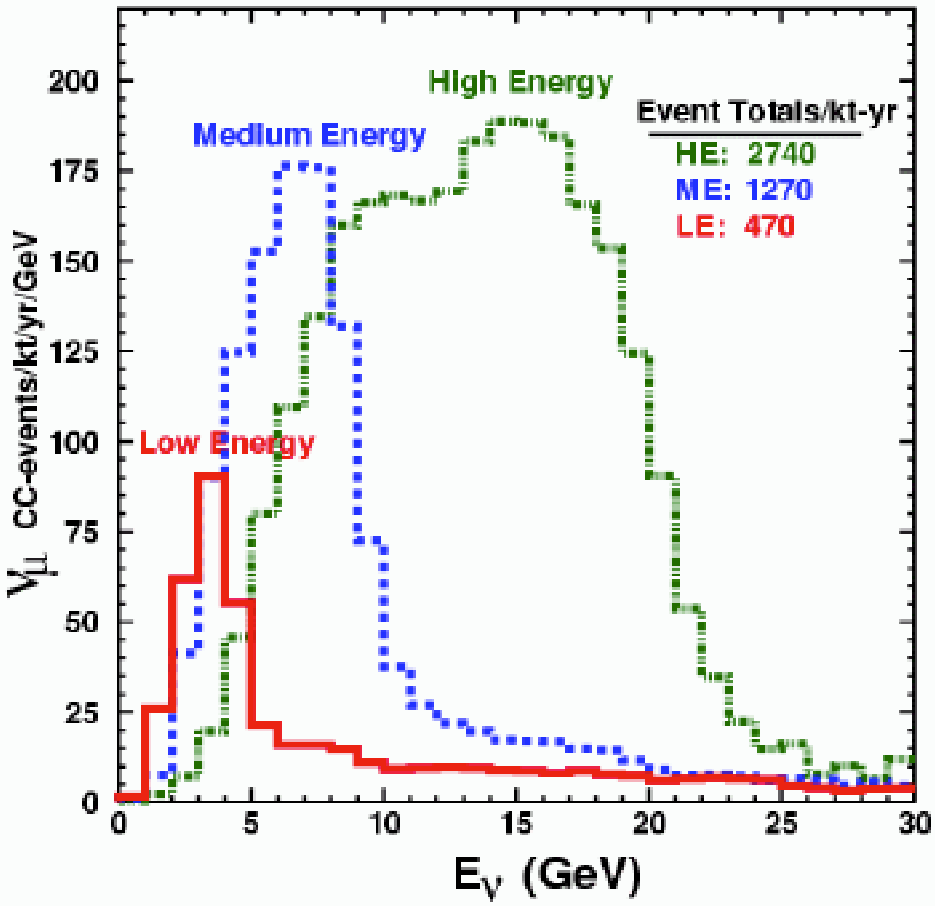
First stopping muon with magnetic field

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



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

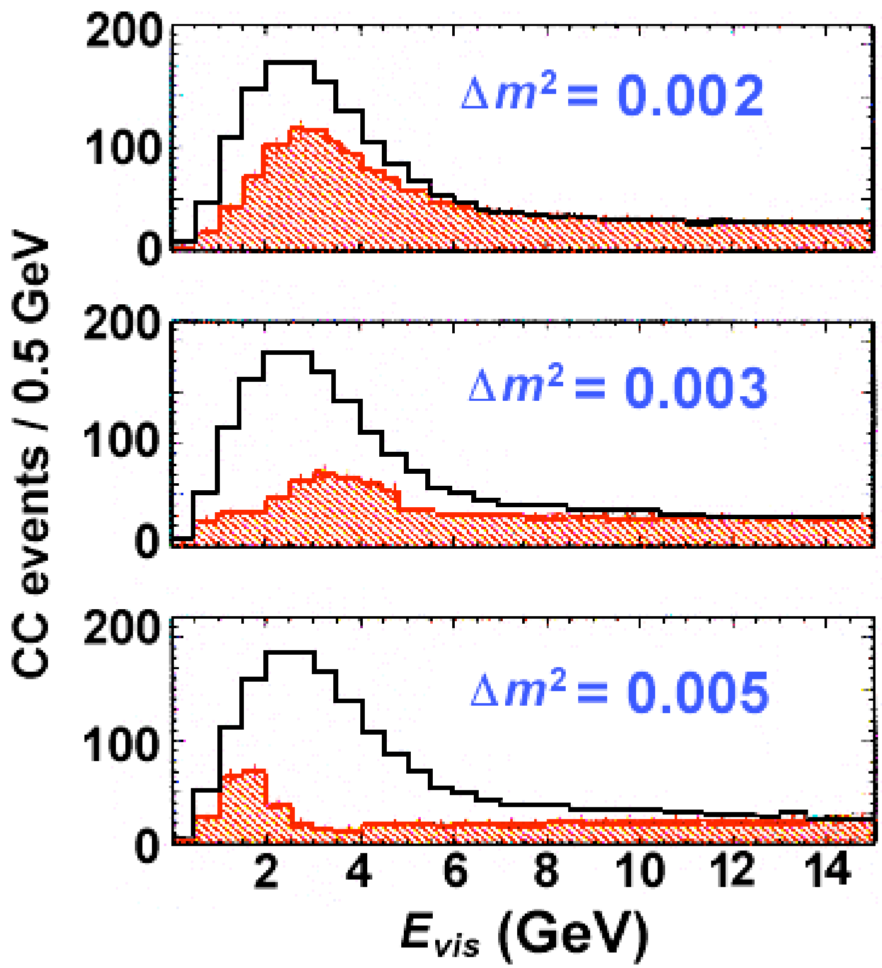
MINOS Physics Goals

- **Verify dominant $□_□ □ \ □_□$ oscillations**
  - **□appearance is not necessary.**
  - **$□_□$ CC disappearance with no NC disappearance and no $□_e$ CC appearance □ $□_□ □ \ □_□$ oscillations. There is no other possibility.**
- **Precise measurement of dominant $□m_{23}^2$ and $\sin^2 2□_{23}$.**
- **Search for subdominant $□_□ □ \ □_e$ ($\sin^2 2□_{13}$) and $□_□ □ \ □_s$ oscillations.**
- **Study unconventional explanations: neutrino decay, extra dimensions, etc.**

MINOS Physics Tools

- ν_μ 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 .
- ν_e CC appearance
  - Use topological criteria: fraction of energy in first few radiation lengths, shower asymmetry, etc.

MINOS CC Spectra

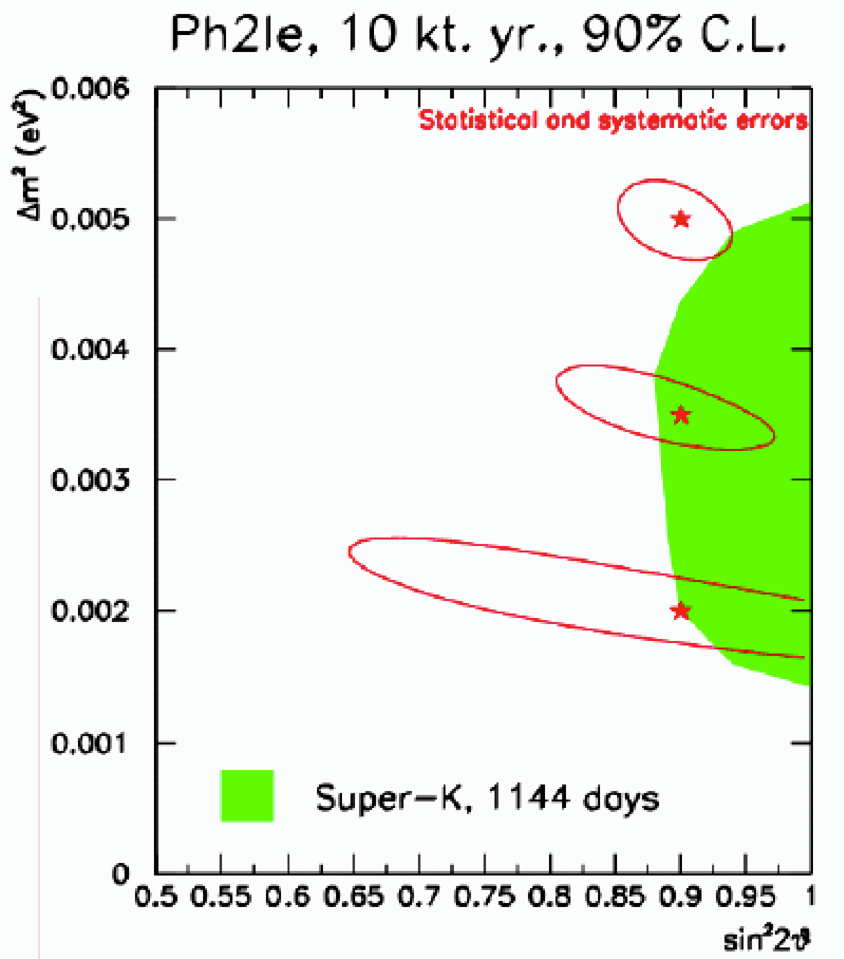


Low-energy beam
2 year run

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

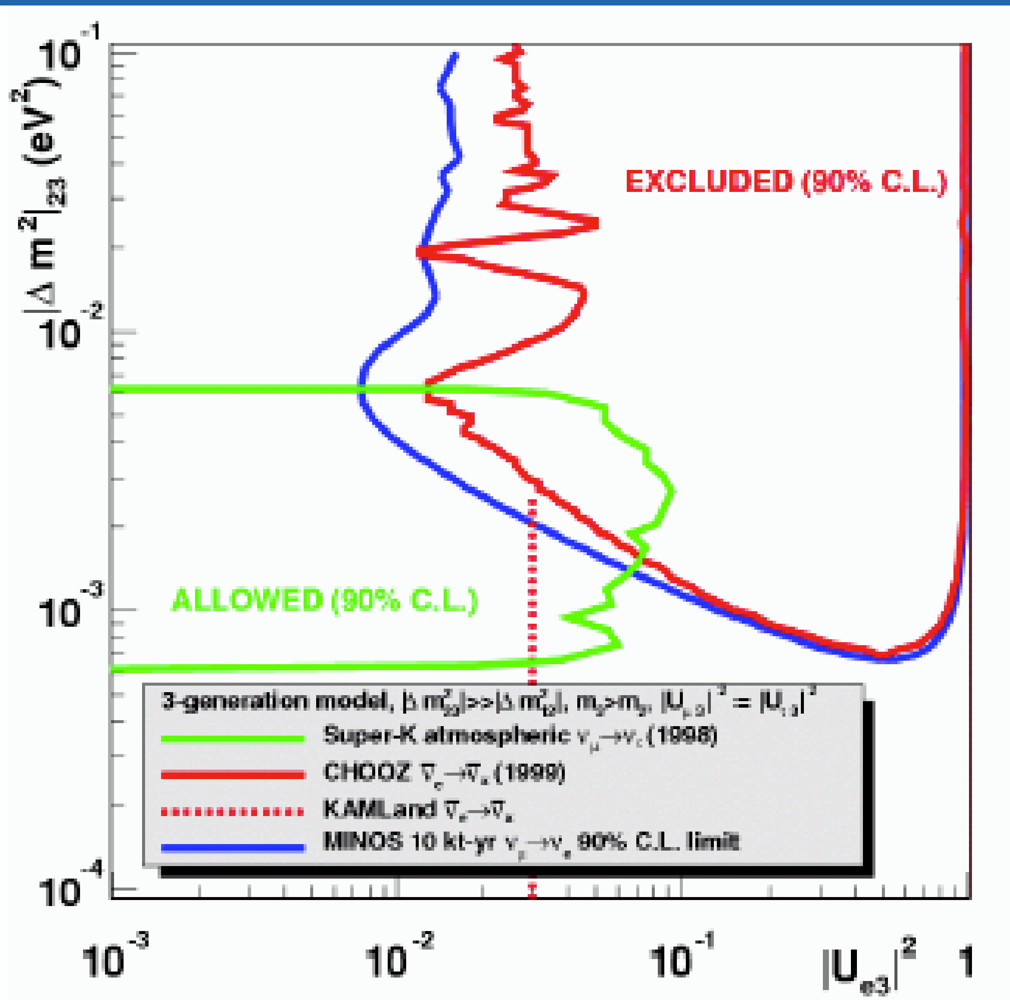
Open = no oscillation
Shaded = oscillation

MINOS Sensitivity to $\nu_\mu \rightarrow \nu_\tau$



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

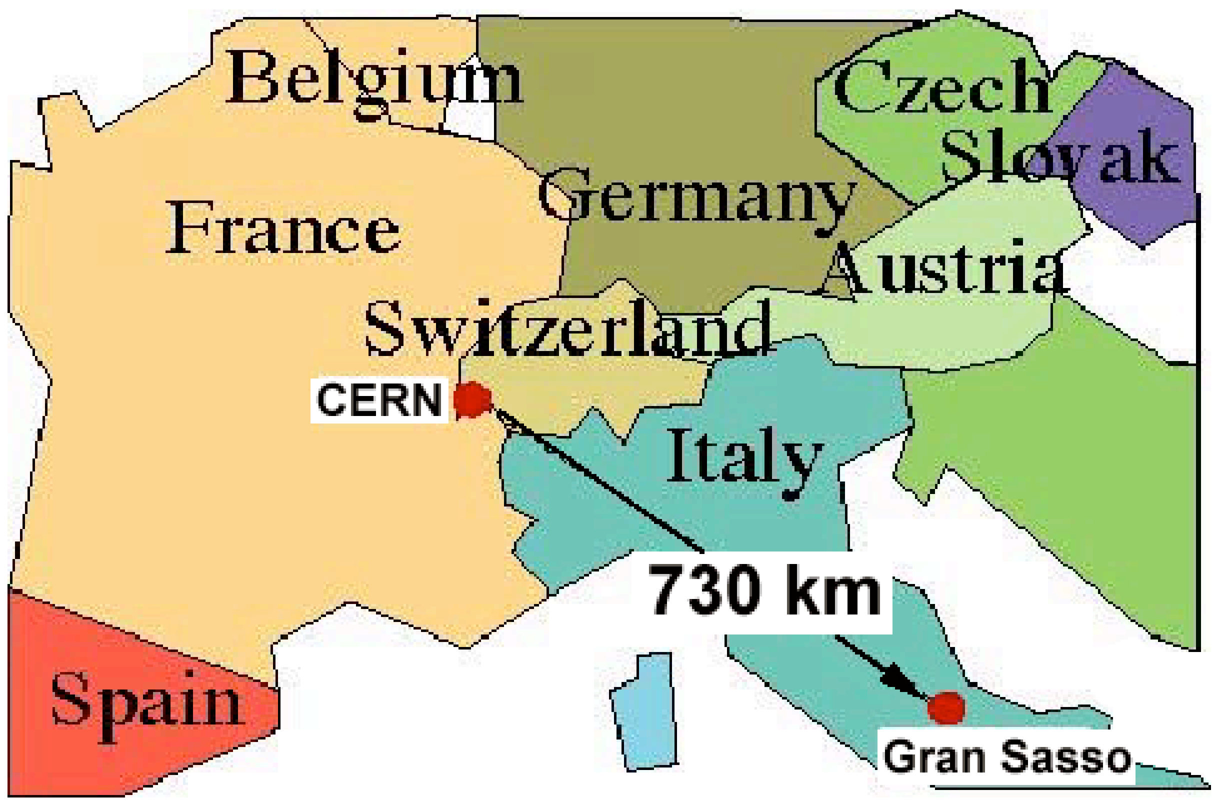
MINOS Sensitivity to $\nu_\mu \to \nu_e$



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
□□ 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*

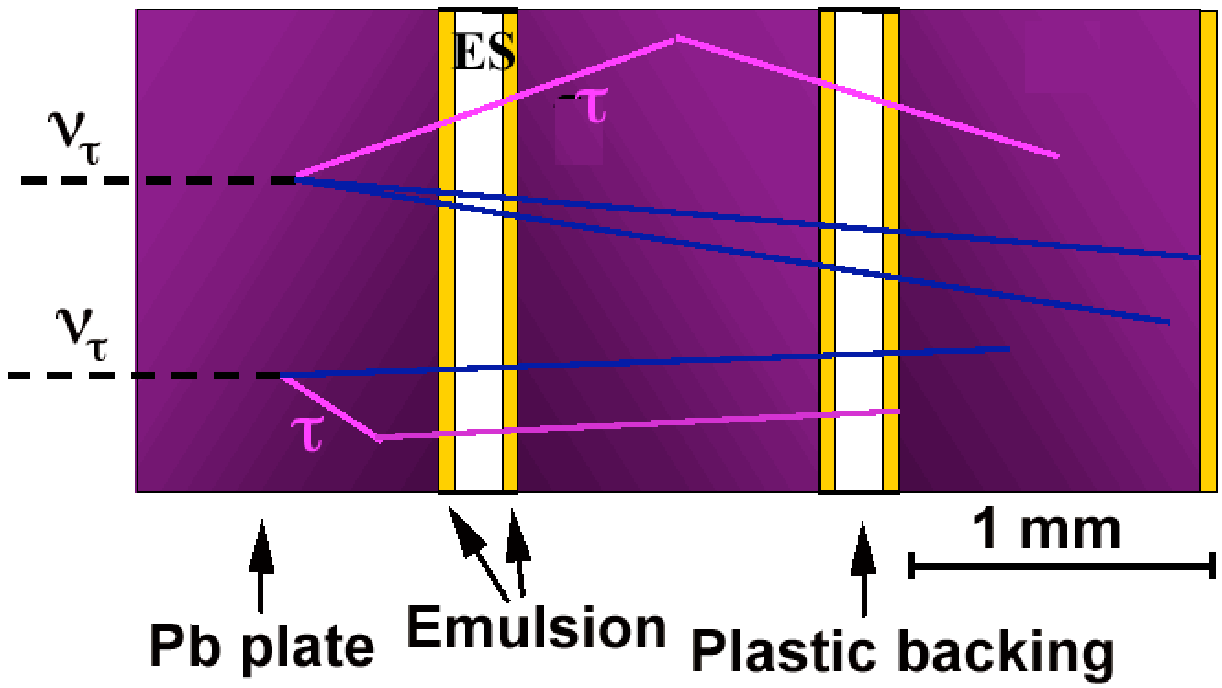
*Bad choice

CNGS: Why No Near Detectors?

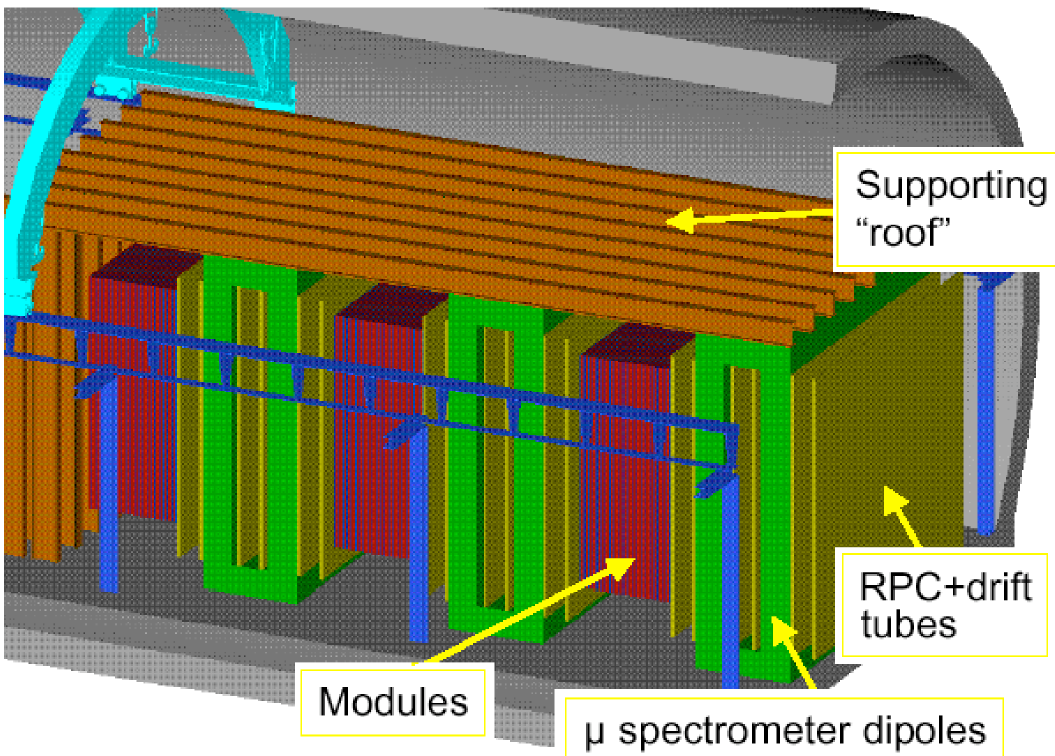
- **CERN says that the purpose of CNGS is to do appearance experiments, particularly ν_τ appearance, and for these experiments near detectors are not necessary.**
- **The argument is weak:**
  - **Granting the argument for ν_τ appearance, observing direct ν_τ appearance in 2006 will not be interesting. The rates are low (at $\Delta m^2 = 2.5\ 10^{-3}\ \mathrm{eV}^2$, 15 events / kT-yr, before efficiency corrections), so precise measurements cannot be done.**
  - **Two detectors are always better than one, since they allow for a good control of systematic errors and provide discovery potential.**

OPERA Experiment

- **OPERA is an approved CNGS proposal for direct detection of ν_τ using the ECC (emulsion cloud chamber) technique:**



OPERA Detector



Active mass 2 kT

τ detection efficiency 8.7%

□ 11 events in 5 years for $\Delta m^2 = 2.5\ 10^{-3}\ eV^2$

ICARUS Experiment

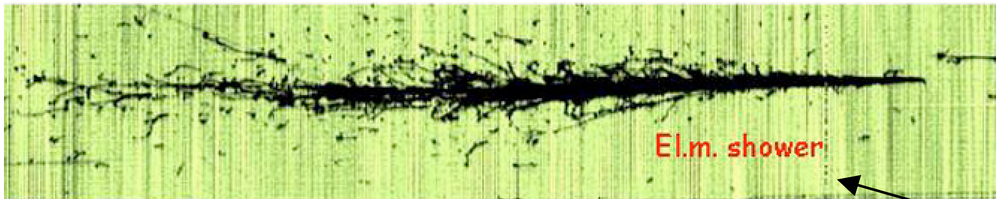
Five 600 T liquid argon TPCs

Excellent electron detection

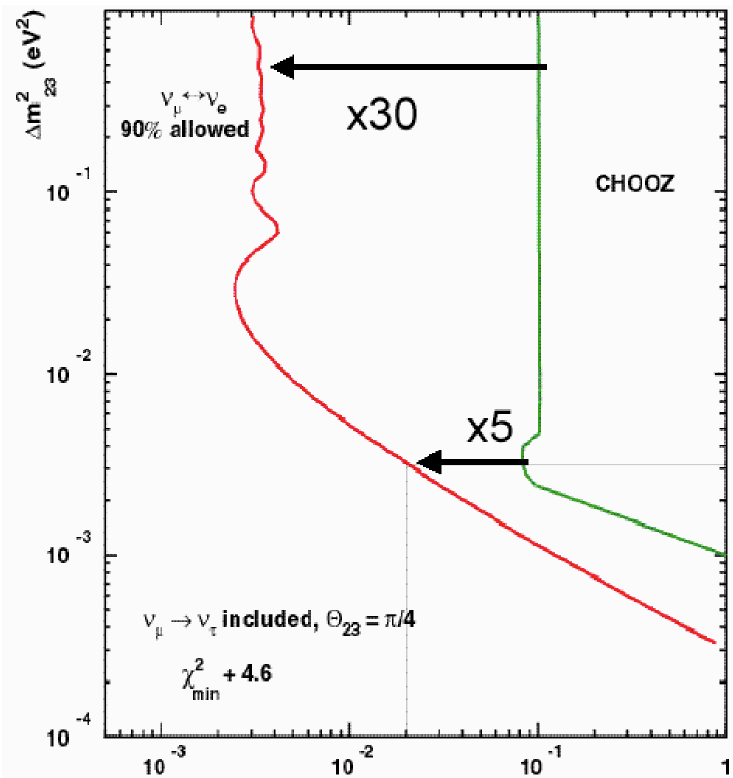
Has not yet received safety approval.

Results from a 300 T prototype

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



Electromagnetic shower



5 year run with 2.45 kT mass

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

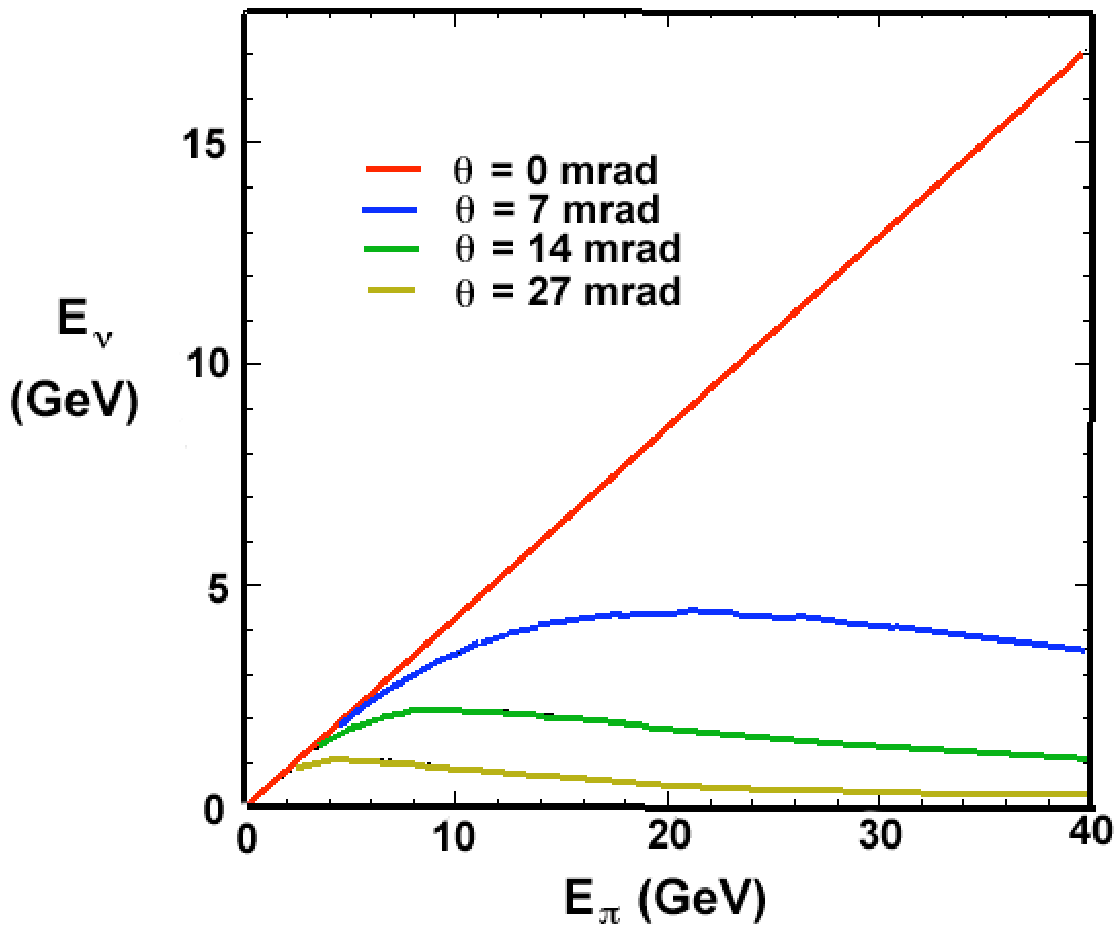
Off-Axis and Super Beams

- **It is clear that the next generation of experiments will concentrate on $\nu_e \leftrightarrow \nu_\mu$ oscillations -- needed for**
  - **$\sin^2 2\theta_{13}$**
  - **sign(Δm^2_{23})**
  - **δ**

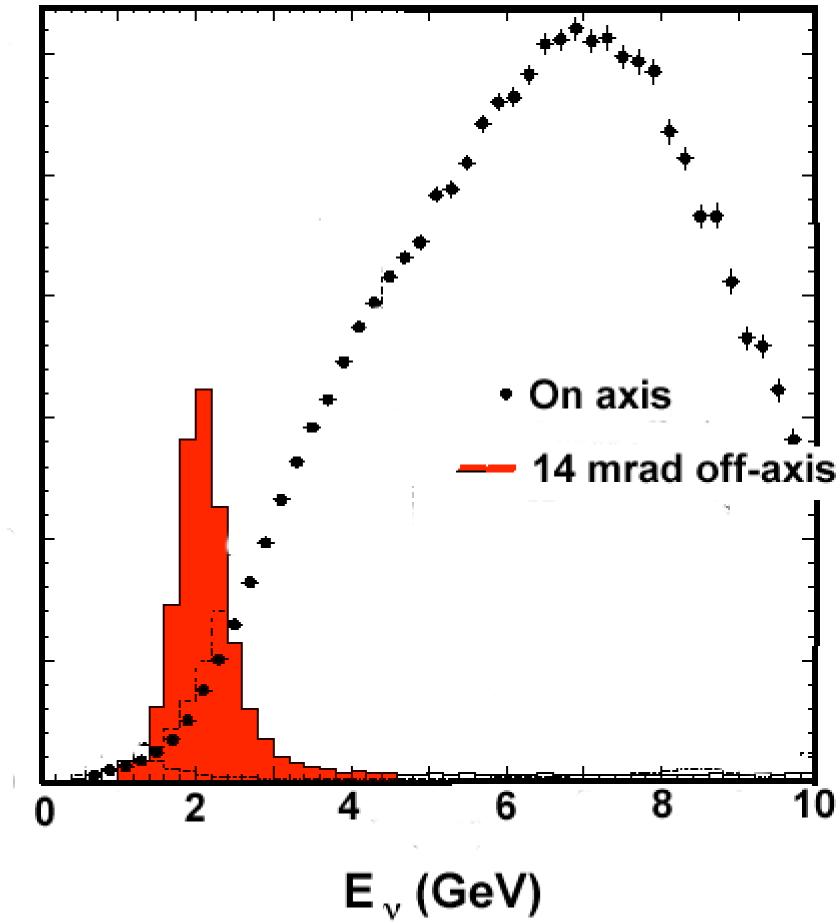
Off-Axis and Super Beams

- Want low-energy narrow-band beams at $\Delta m^2_{13} \approx \Delta m^2_{23}$ oscillation maximum:
  - ν_e appearance maximum
  - ν_μ CC disappears
  - Higher-energy NC disappears
- Want detectors optimized for ν_e detection
- Want increases in beam flux times detector mass
- $\Rightarrow$ Off-axis super beams

Off-Axis Kinematics



Off-Axis Spectrum (No oscillations)



JHF Proposal

Convensional νμ beam of ~1GeV

Super-K: 50 kton Water Cherenkov

~Mt "Hyper Kamiokande"

JAERI (Tokaimura)

~1 MW 50 GeV PS

4MW 50GeV PS

1st Phase

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

2nd Phase

- CPV
- proton decay

5

(High Intensity) Proton Accelerators (Nakaya, 2002)

	Power (MW)	Energy (GeV)	Intensity (10^{12} ppp)	Rep. rate (Hz)
KEK-PS	0.005	12	6	0.45
AGS	0.14	24	60	0.6
FNAL-MI	0.41	120	40	0.53
SPS	0.3	400	35	0.16
JHF-I	0.77	50	330	0.29
Super-AGS	1.3	28	120	2.5
FNAL-proton driver-I	1.2	16	30	15
SPL	4	2.2	230	50
JHF-II	4	50		

(Super) Neutrino Beams (Nakaya, 2002)

	$\langle E_\nu \rangle$ (GeV)	L (km)	#CC ν/kt/yr	$L/L_{osci.}$*	$f(\nu_e)$ @peak
K2K	1.3	250	2	0.47	~1%
NuMi (High E)	15	730	3100	0.12	0.6%
NuMi (Low E)	3.5	730	469	0.51	1.2%
CNGS	17.7	732	2448	0.10	0.8%
JHF-I	0.7	295	133	1.02	0.2%
Numi off-axis	2.0	730	~80	0.89	0.5%
Super AGS	1.5	2540	11	4.1	0.5%
JHF-II	0.7	295	691	1.02	0.2%
SPL	0.26	130	16.3	1.21	0.4%
β beam**	0.58	130	84	0.54	-------

Super Beam Detectors

- For E ≤ 1 GeV (JHF), H_2O-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 π^0 decays cannot be separated from electrons in water.

Off-Axis/Super Beam Physics (In Vacuum)

- Assume that we will always work at the $\Delta m^2_{13} \approx \Delta m^2_{23}$ oscillation maximum, so that $1.27 \Delta m^2_{13} L / E = \pi / 2 + n\pi$.

- Assume that $\sin^2 2\theta_{23} \approx \sin^2 2\theta_{12} \approx 1$.

- Then the leading term for $\nu_\mu \to \nu_e$ oscillations is

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

Off-Axis/Super Beam Physics (In Matter)

- **In matter,**

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

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

$$E_R = \frac{\Delta m^2_{13}}{2\sqrt{2} G_F \rho_e} \approx 11 \text{ GeV for the earth's crust.}$$

$\Rightarrow$ **~30% effect for NuMI, ~10% effect for JHF at the first oscillation maximum.**

Off-Axis/Super Beam Physics (CP Violation)

- The next leading term is CP violating:

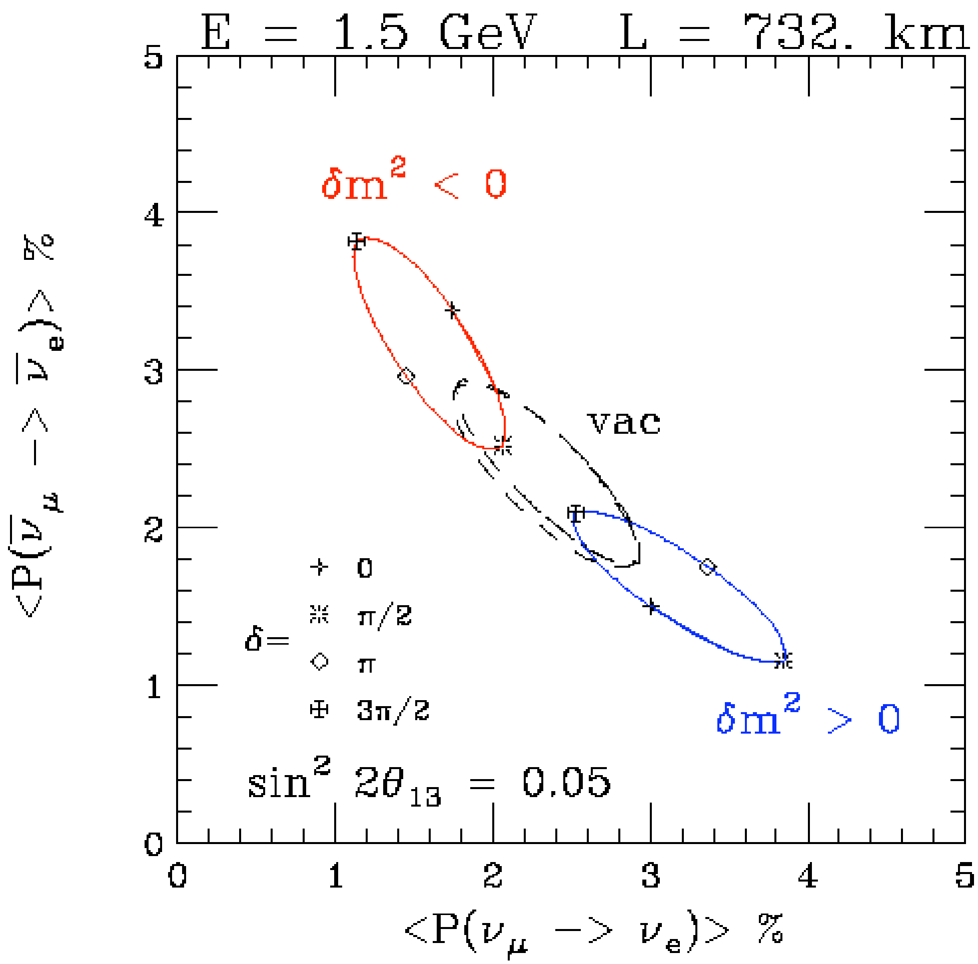
$$P_{CP}(\nu_\mu \to \nu_e) \approx \pm J \sin\delta \, \frac{1.27\, \Delta m^2_{12} L}{E},$$

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.

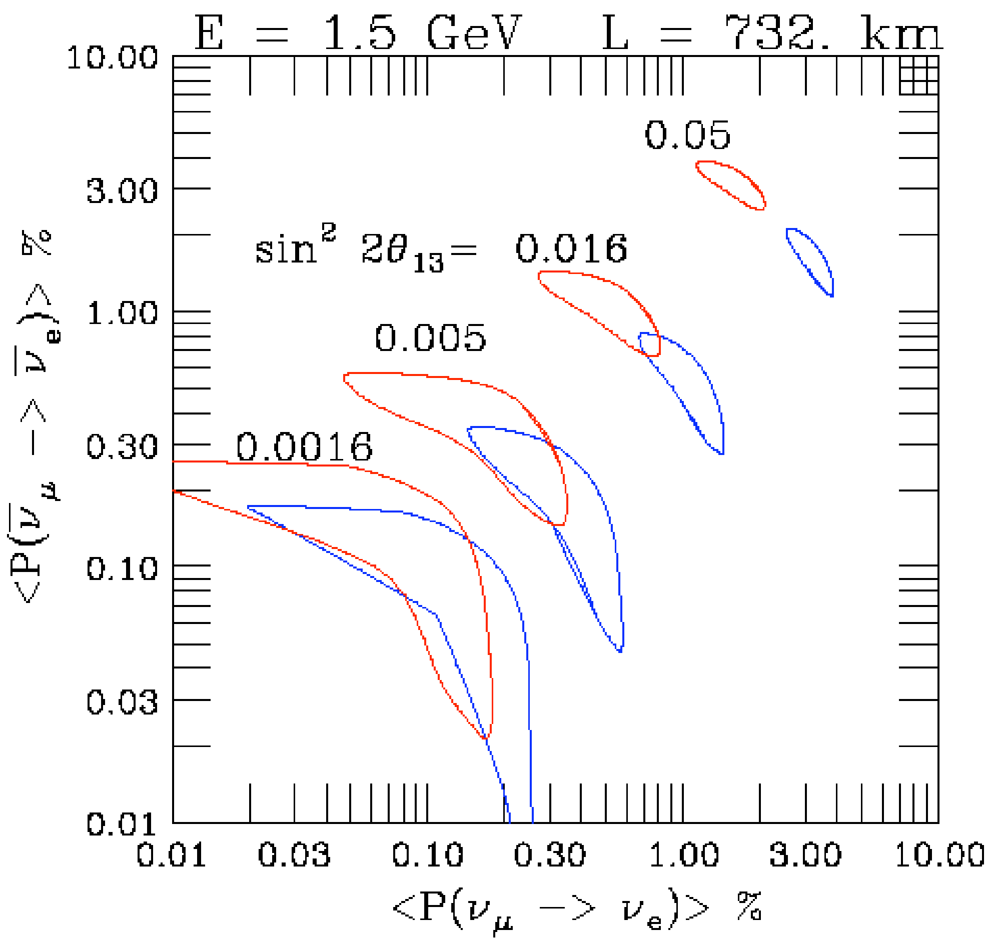
- For a single set of measurements, there can be ambiguities between the matter effect and CP violation.

NuMI Off-Axis
Neutrino vs. Antineutrino (1)



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

NuMI Off-Axis
Neutrino vs. Antineutrino (2)



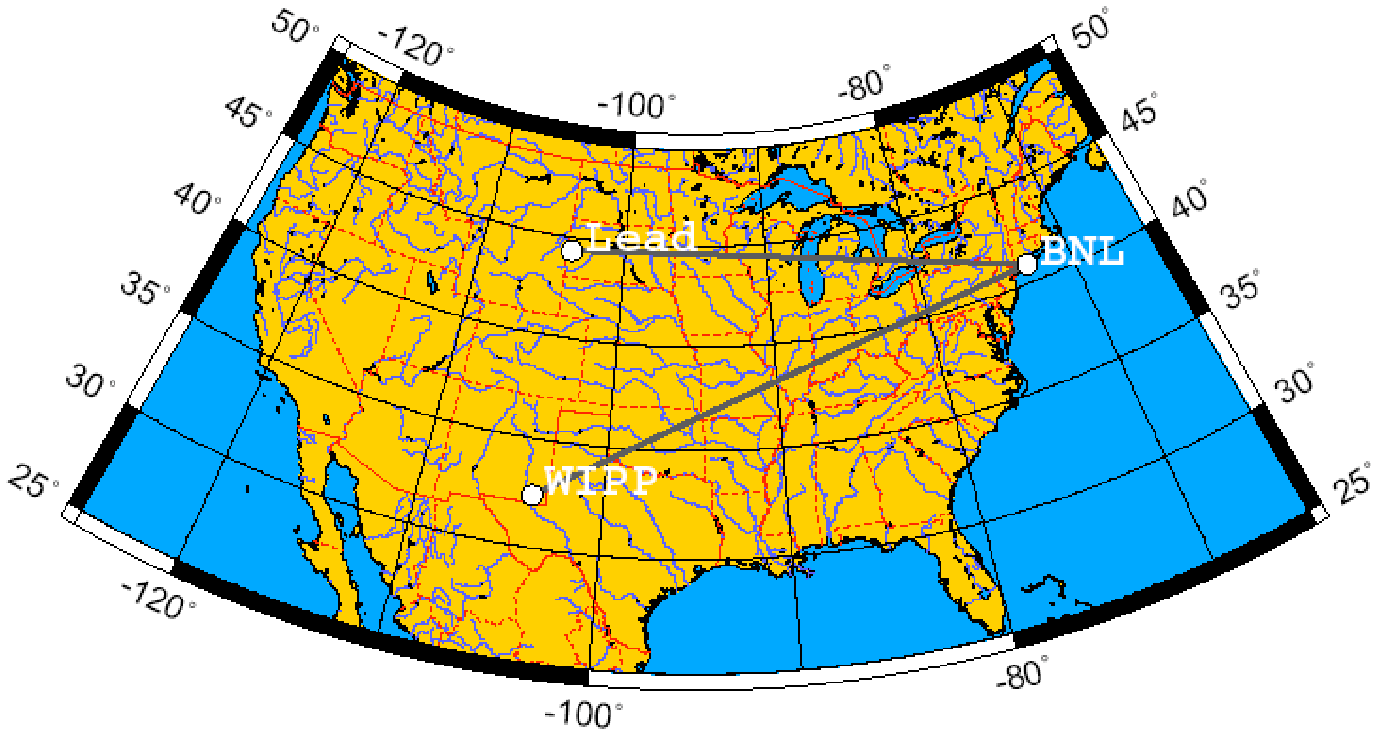
$\Delta m^2_{12} = 5 \times 10^{-5}\ (\mathrm{eV})^2$

Off-Axis Notes

- The matter effect is binary. Once it is measured, the ambiguity disappears.
- NuMI and JHF 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.
- Greater sensitivity with new Fermilab proton driver
- First phase of both NuMI off-axis and JHF should have sensitivity to $\sin^2 2\theta_{13}$ at 0.01 level. It is difficult to go below this level with conventional beams.

Brookhaven White Paper (1)

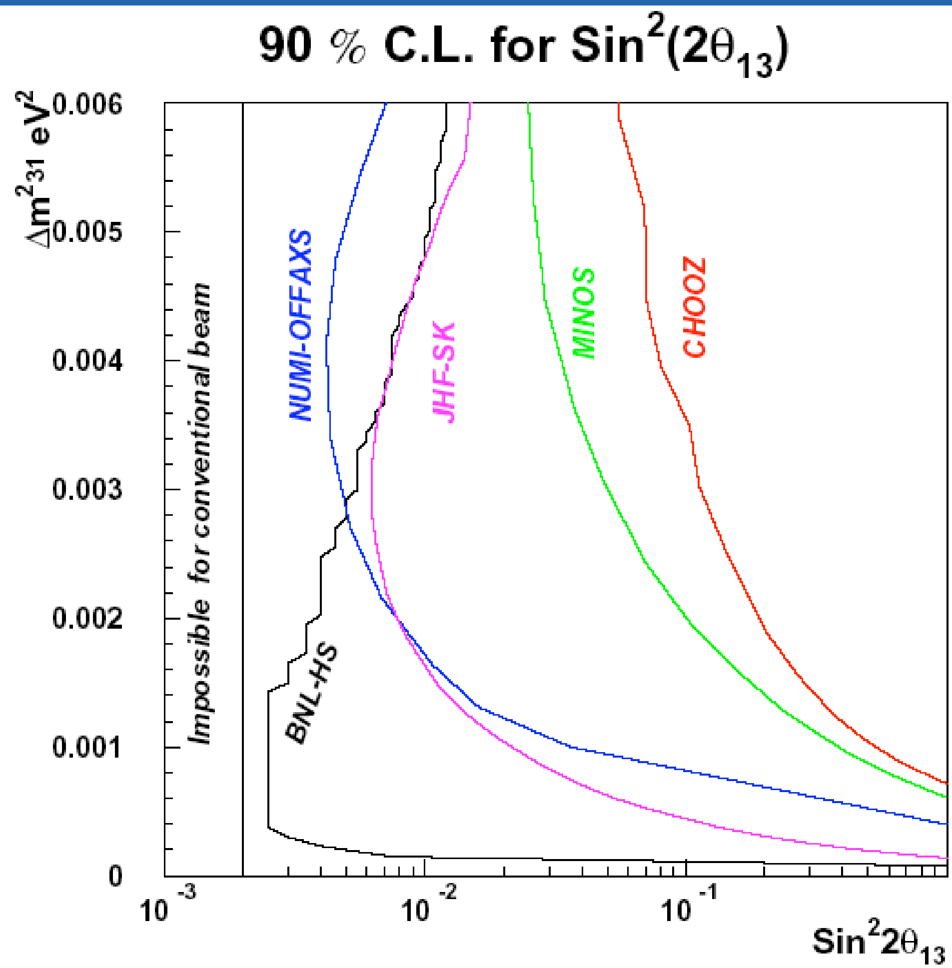
- **Pushing conventional beams to their limit – very long baseline**



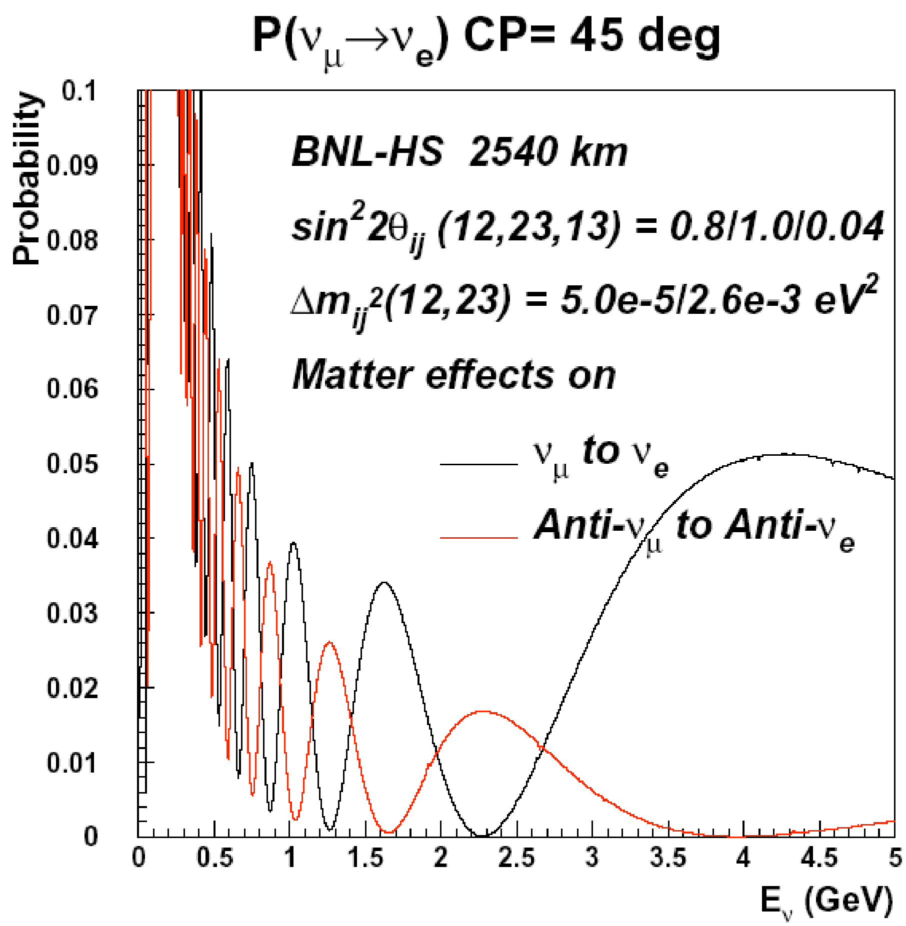
Brookhaven White Paper (2)

- 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

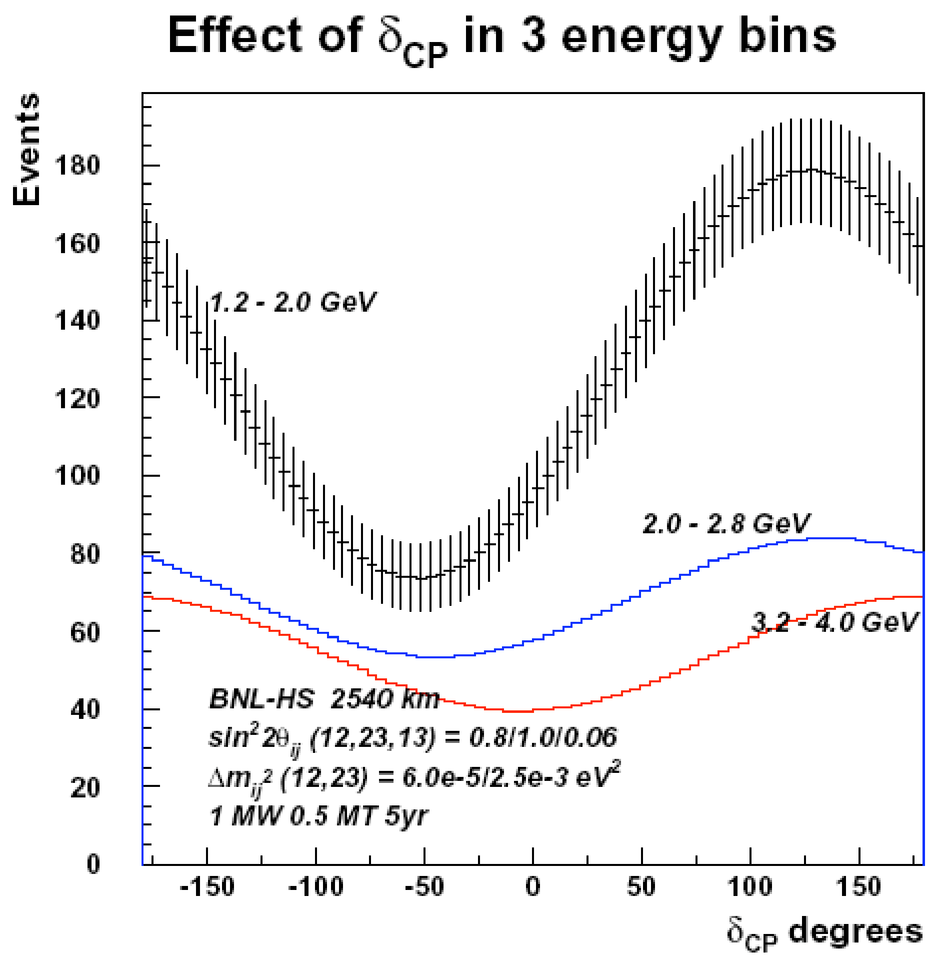
θ_{13} Sensitivity



Very Large Matter Effects



Large CP Effects with Only Neutrino Running



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

The Future: A Neutrino Factory?

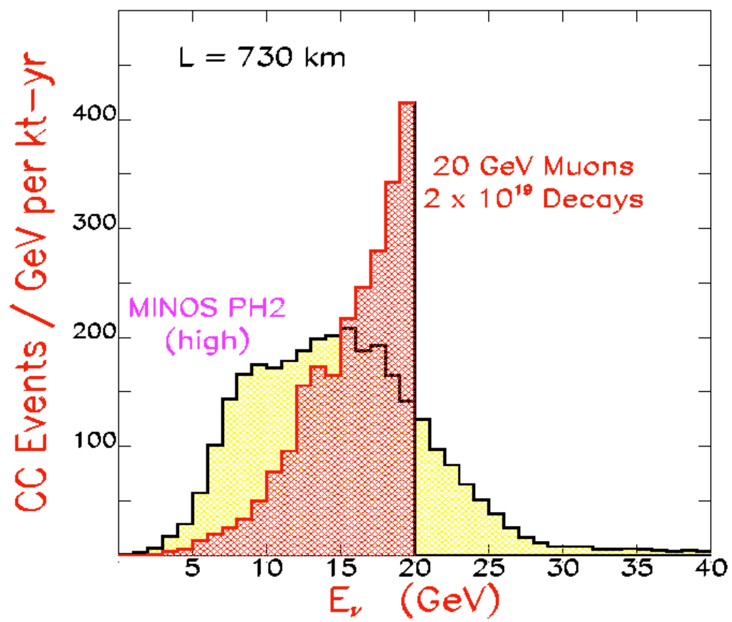
- If $\sin^2 2\theta_{13} < 0.01$, a neutrino factory will probably be necessary to explore the physics
- A simple idea: Store muons in a ring with long straight sections and observe neutrinos from the muon decays.

Neutrino Factory Basics

- If μ^+ stored, then $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$.
- Normal CC give only μ^+ and e^-.
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations give e^+.
  - $\nu_e \rightarrow \nu_\mu$ oscillations give μ^-.
- Need magnetic detection to see wrong-sign leptons and very massive detectors for rate.
- Electron charge difficult $\rightarrow$ 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_ν^3:
  - E^2 for divergence.
  - E for the cross section.



Neutrino Factory Parameters and Physics Goals

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

Measurement of θ_{13}, the Sign of Δm_{13}^2, and δ

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

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

- This requires a fairly large *L / E*: *E* ~ 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 (~8000 km) baselines arises due to the matter effect for Δm_{12}^2.
- The effective Δm^2 added by the earth is $2AE$, where

$$A = \sqrt{2} G_F \rho_e \approx 1.5 \times 10^{-4}\ \mathrm{eV}^2/\mathrm{GeV}$$

  for earth density corresponding to L = 8000 km.
- In the presence of matter

$$\sin\left(\frac{1.27 \Delta m_{12}^2 L}{E}\right) \to \frac{\Delta m_{12}^2}{|-2AE \pm \Delta m_{12}^2|} \sin\left(\frac{1.27\,|-2AE \pm \Delta m_{12}^2|\,L}{E}\right)$$

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

Measuring CP Violation

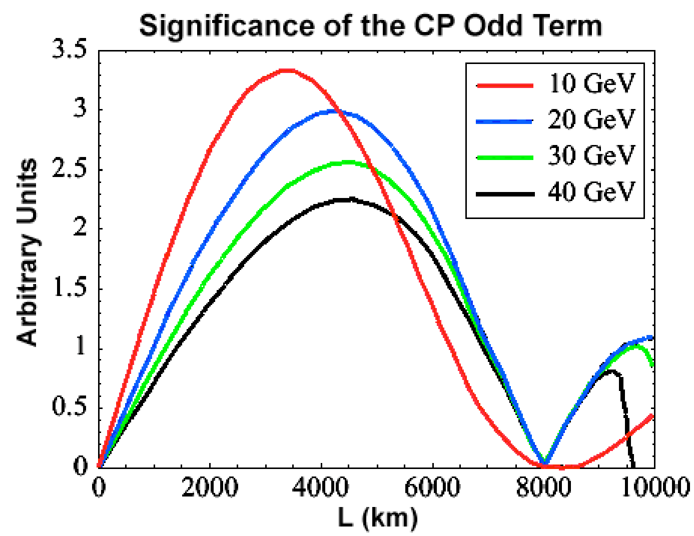
- Therefore, the CP odd term contains a pure matter oscillation,

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

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

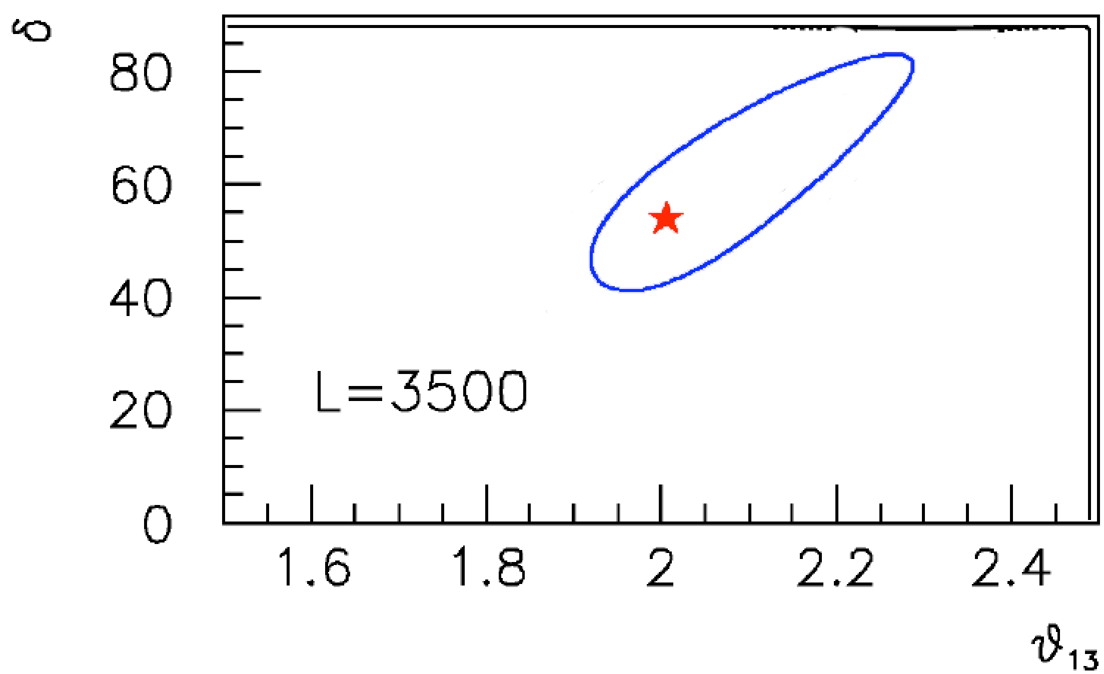
- Calculation by Cervera et al.

$\Delta m_{23}^2 = 2.8\ 10^{-3}\ \mathrm{eV}^2$
$\Delta m_{12}^2 = 1.0\ 10^{-4}\ \mathrm{eV}^2$
$\theta_{23} = 45^o$; $\theta_{12} = 22.5^o$
$\theta_{13} = 8^o$; $\delta = 90^o$



Measuring CP Violation

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



Where to Build a Neutrino Factory

- **For a ~3000 km baseline, the choices are quite limited.**

Conclusion

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