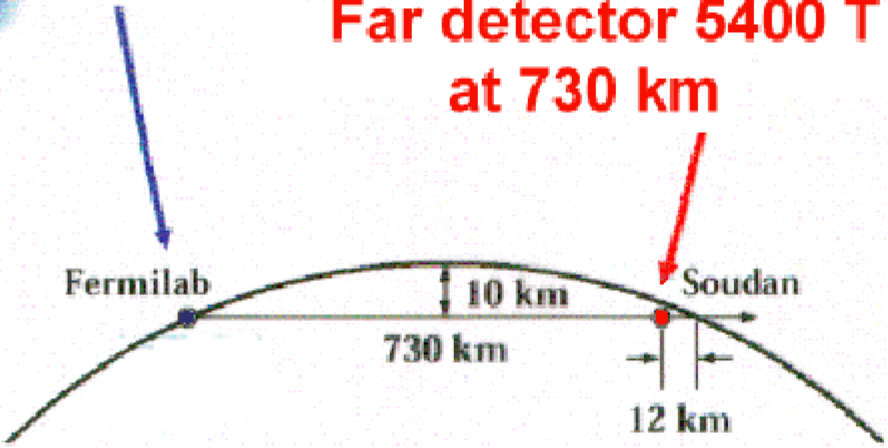
MINOS Layout

Two-detector oscillation experiment to start in 2003

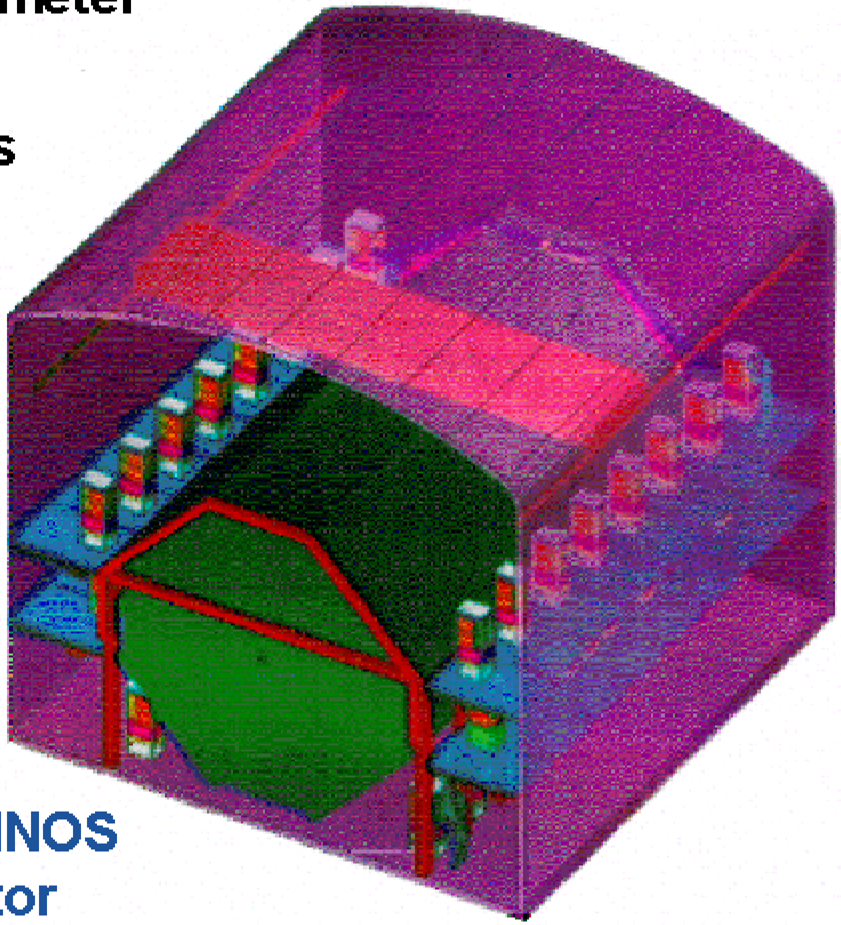
Near detector 980 T at 1 km

Far detector 5400 T at 730 km



MINOS Far Detector

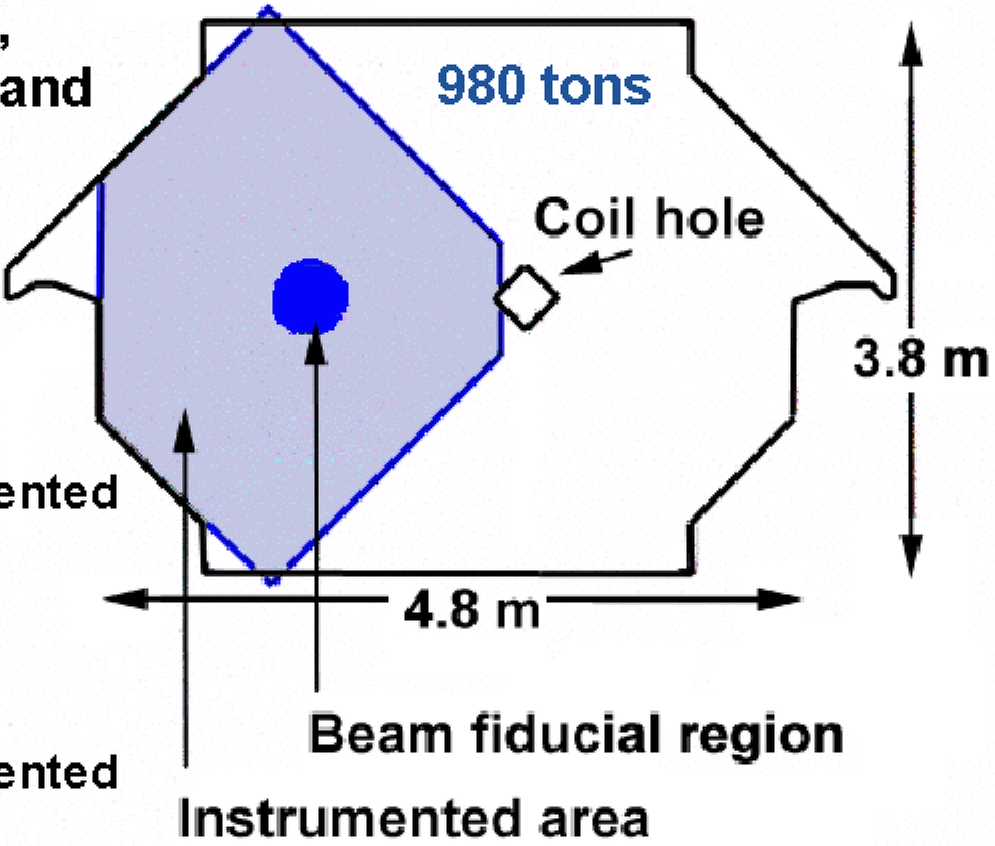
- 8m octagonal tracking calorimeter
- 486 layers of 1 in iron plates
- 4.1 cm-wide scintillator strips with WLS fiber readout, read out from both ends
- 8 fibers summed on each PMT pixel
- 25,800 m^2 (6.4 acres) of active detector planes
- Toroidal magnetic field <B> = 1.3 T
- Total mass 5.4 kT



Half of MINOS far detector

MINOS Near Detector

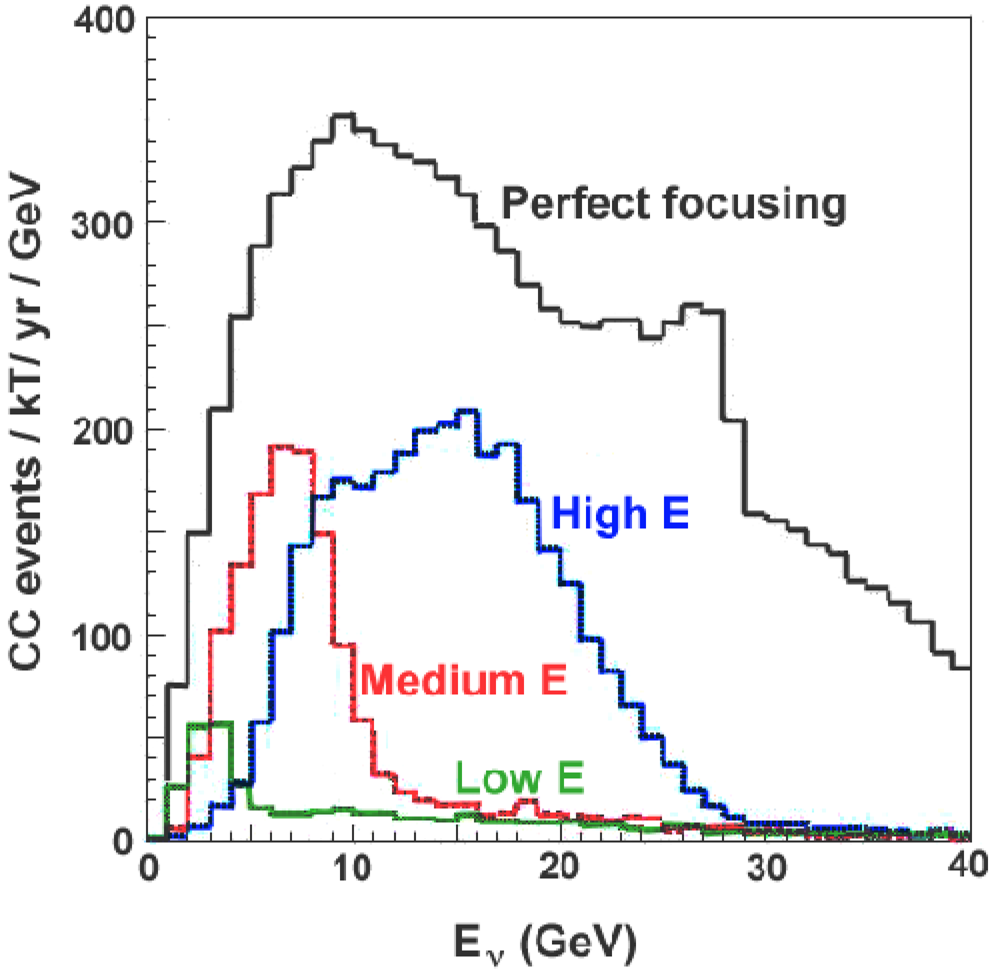
- 280 “squashed octagon” plates
- Same plate thickness, scintillator thickness and width as far detector
- Target/calorimeter section: 120 planes
  - 4/5 partial area instrumented
  - 1/5 full area instrumented
- Muon spectrometer section: 160 planes
  - 4/5 uninstrumented
  - 1/5 full area instrumented



MINOS
Near-Far Detector Differences

	Near	Far	Comments
Rates (8 μs spill)	~ 3 MHz	~ 30 Hz	• Simulations ⇒ not a problem • Low intensity runs
Electronics	Deadtime-less 19 ns digitizations	Sample and hold	• Calibrate in test beam
Readout	Single ended w/ reflector	Double ended	• Similar light levels • Calibrate in test beam
Multiplexing	None	8-fold	• Simulations ⇒ not a problem

MINOS Energy Options

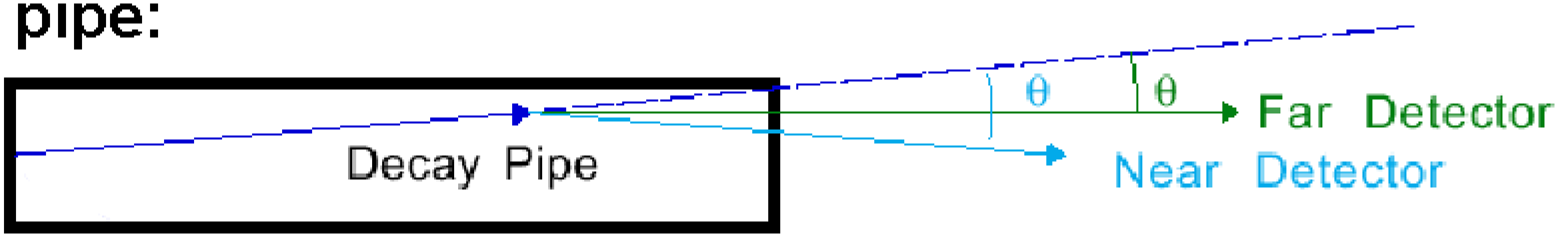


Different beam energies correspond to different horn currents and positions

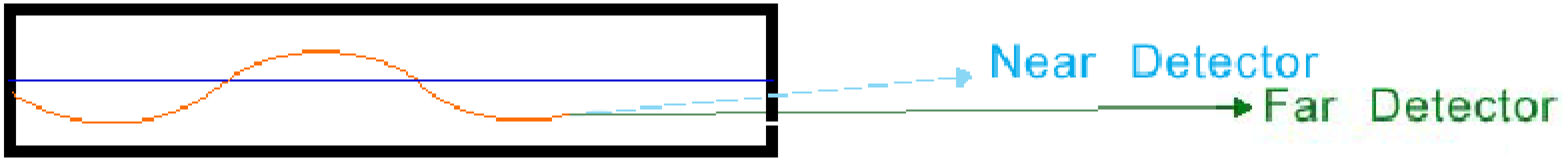
Will start with low E beam for best sensitivity to match SK results

MINOS Near-Far Energy Differences: Hadronic Hose

- Want near and far energy spectra to be identical.
- This is impossible without focusing in the decay pipe:

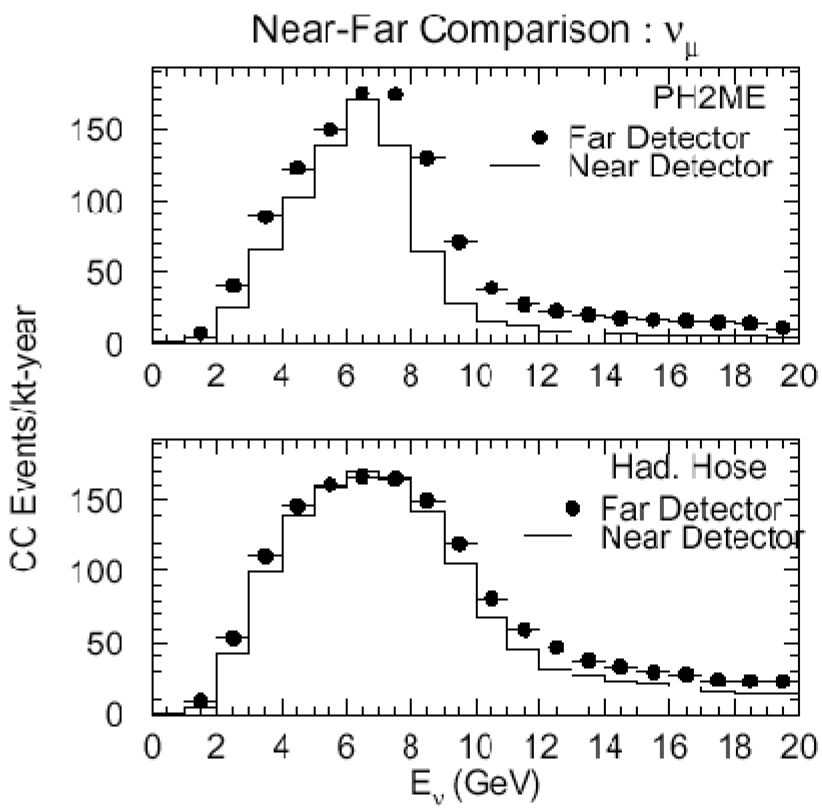


- The solution is the hadronic hose — a wire carrying 1 kA down the center of the beam pipe:

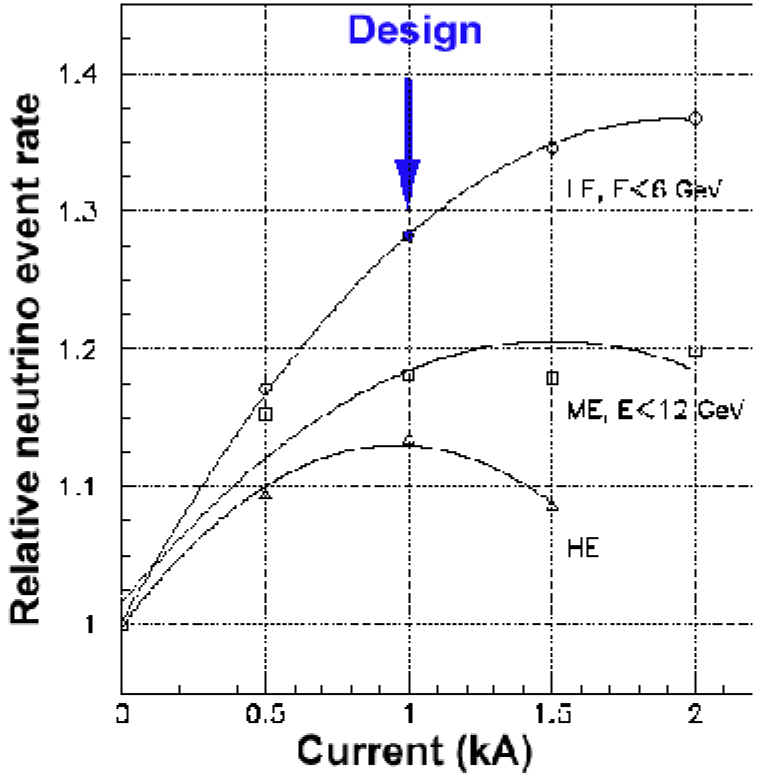


MINOS: Advantages of the Hadronic Hose

- **Better near-far agreement**



- **More events**



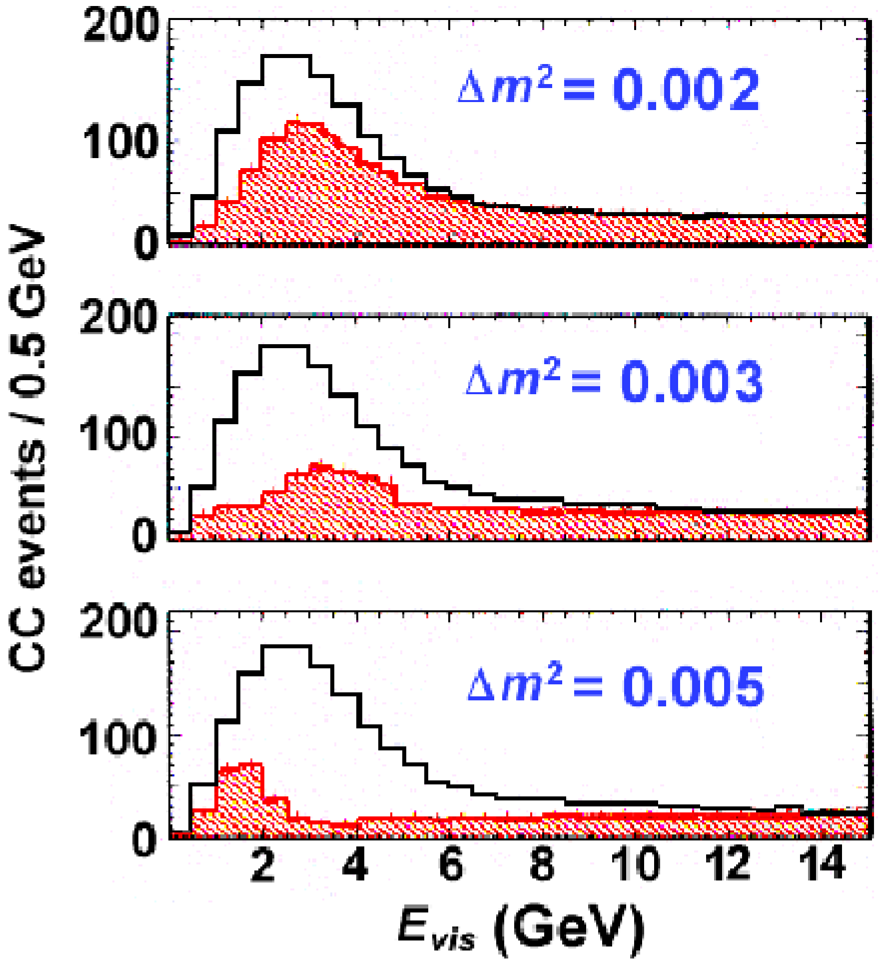
MINOS Physics Goals

- Verify dominant $\nu_\mu \rightarrow \nu_\tau$ oscillations
  - τ appearance is not necessary.
  - ν_μ CC disappearance with no NC disappearance and no ν_e CC appearance $\Rightarrow \nu_\mu \rightarrow \nu_\tau$ oscillations. There is no other possibility.
- Precise measurement of dominant Δm^2 and $\sin^2(2\theta)$.
- Search for subdominant $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_s$ 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

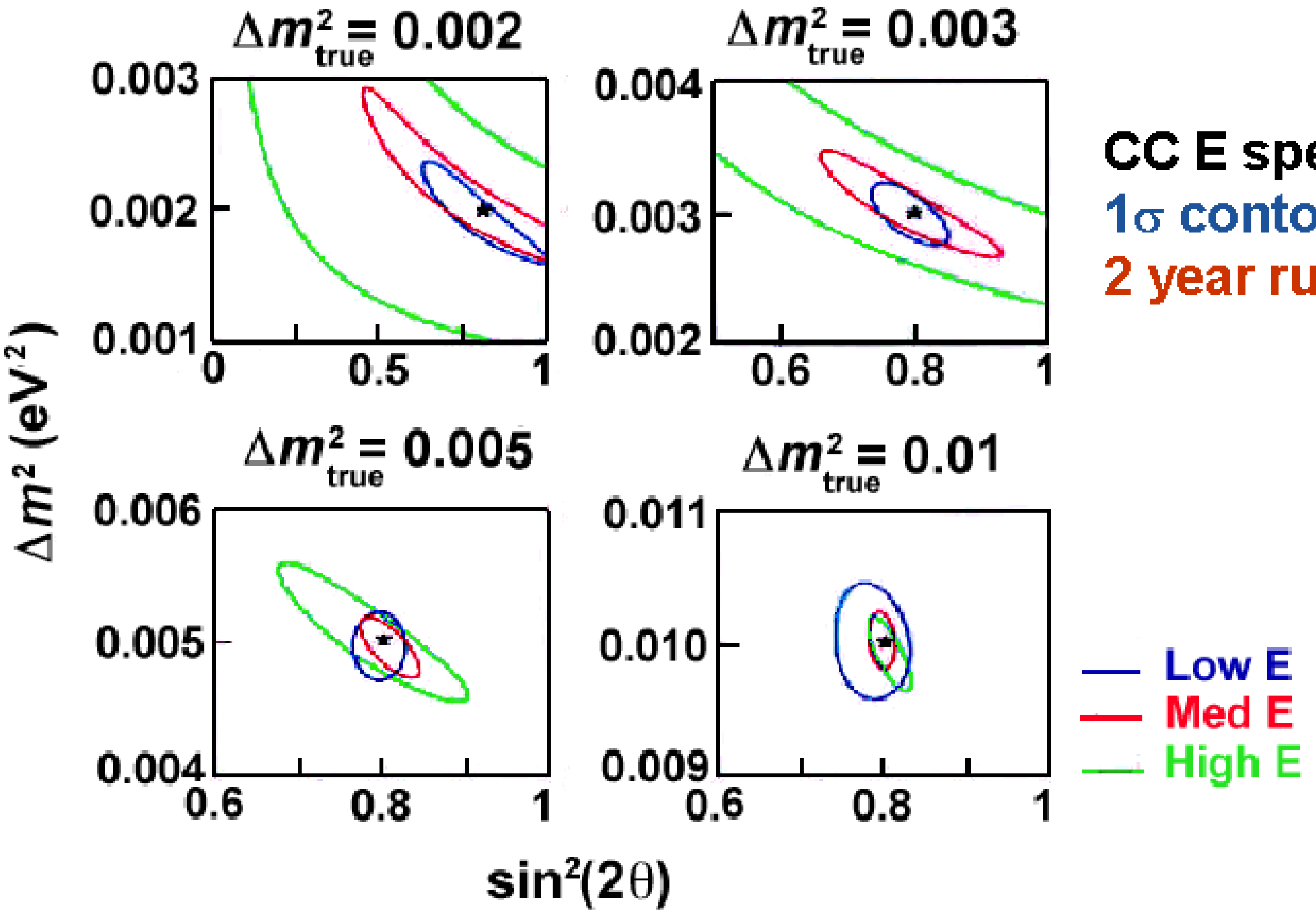


Low-energy beam
2 year run

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

Open = no oscillation
Shaded = oscillation

MINOS Sensitivity

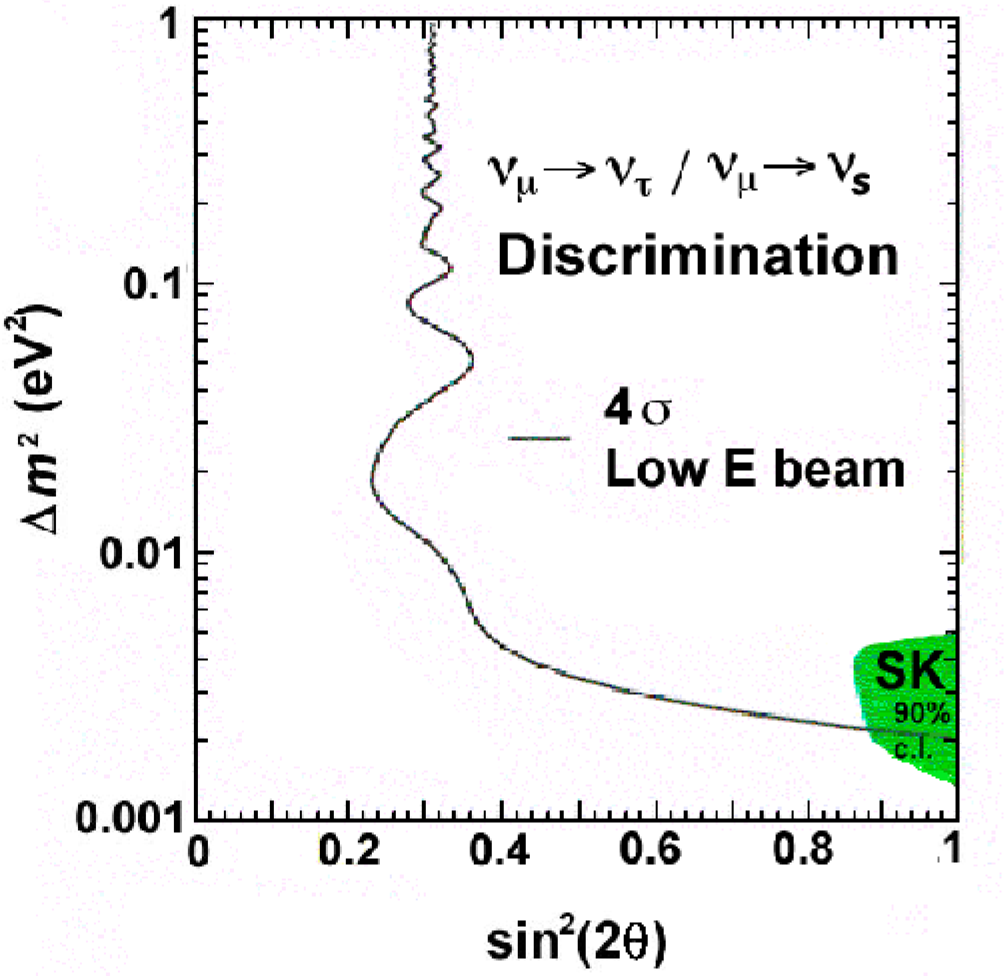


CC E spectrum

1σ contours

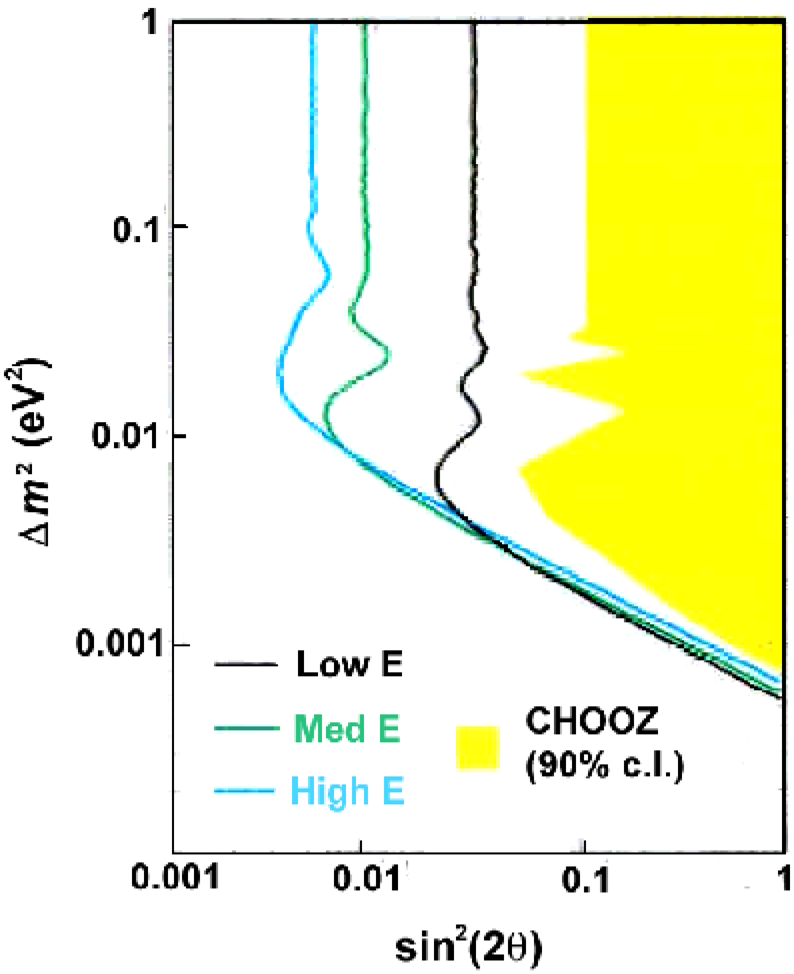
2 year run

MINOS ν_τ vs. ν_s Discrimination



Sterile neutrino discrimination by NC/CC ratio

MINOS $\nu_\mu \rightarrow \nu_e$ Sensitivity



90% c.l. $\nu_\mu \rightarrow \nu_e$ sensitivity

Preliminary graph — improved calculations being done.

Electron identification by topological criteria

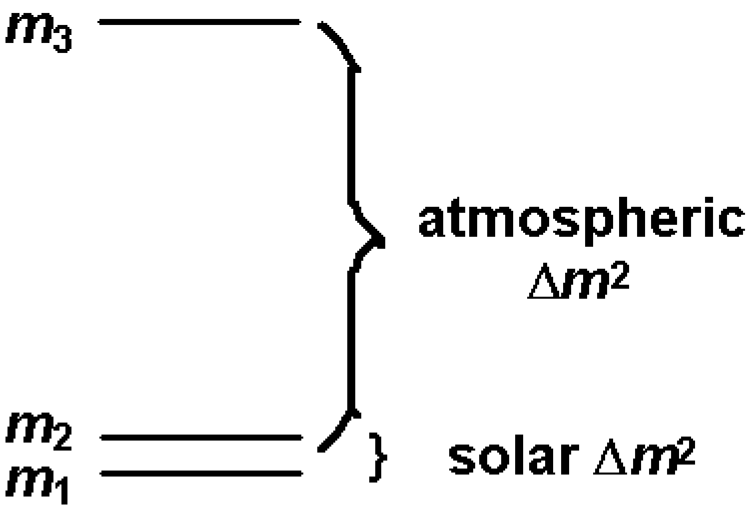
N.B. Graph is incorrect (or at least misleading) for two reasons — see next slide

MINOS: $\nu_\mu \rightarrow \nu_e$ Subtleties

- Need to use 3-neutrino mixing
  - Assume that MINOS is only sensitive to the $\Delta m_{13}^2 \approx \Delta m_{23}^2$ mass scale. Then

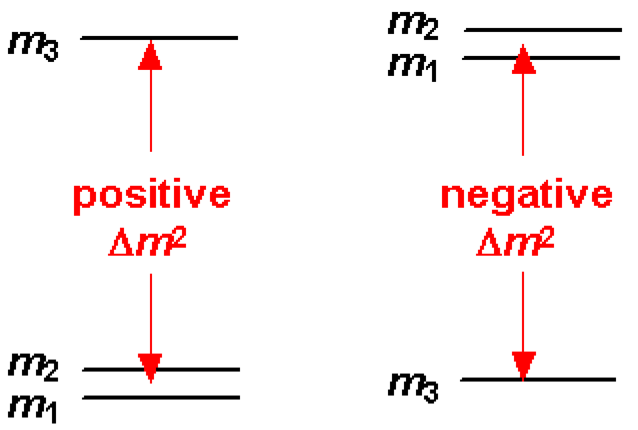
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\, \Delta m^2 L / E).$$

$\theta_{23} \approx \pi/4$ and MINOS loses a factor of 2 in sensitivity to θ_{13} compared to CHOOZ

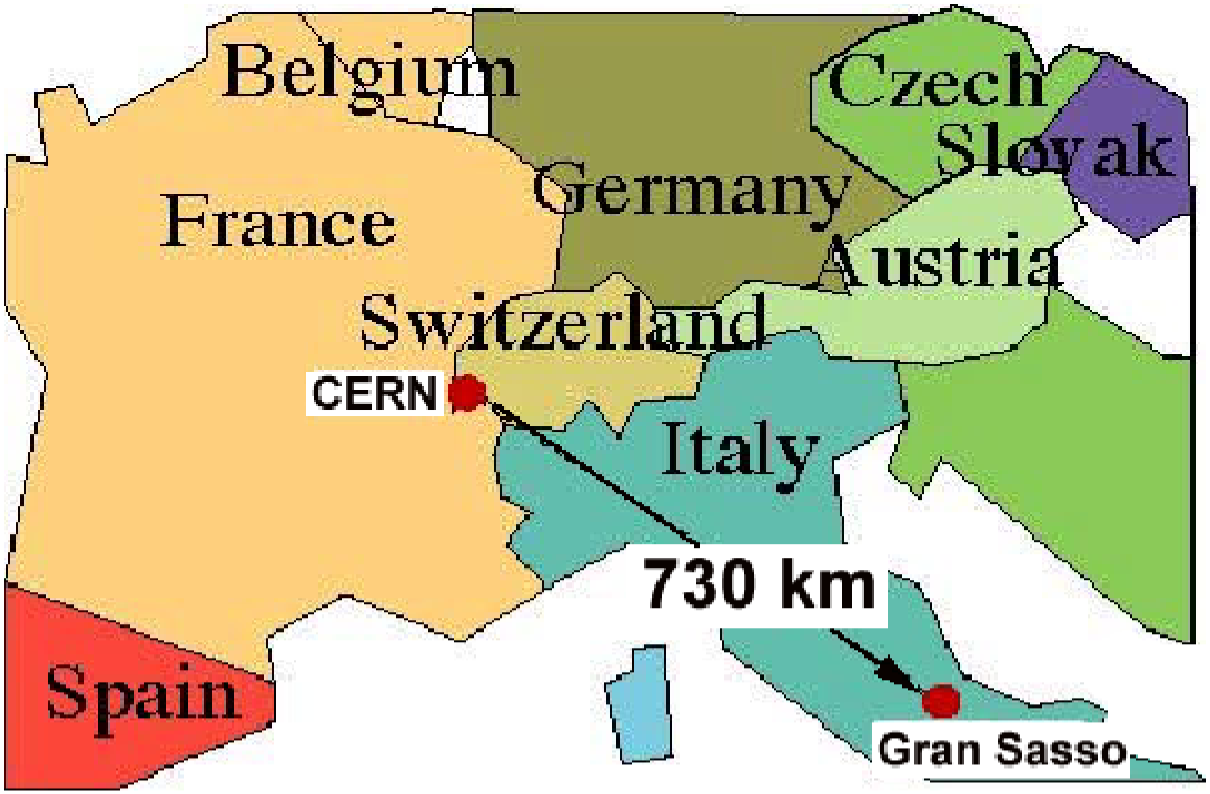


MINOS: $\nu_\mu \rightarrow \nu_e$ Subtleties

- Matter effects are not negligible
  - Matter effects in the earth increase (or decrease) $\nu_\mu \rightarrow \nu_e$ oscillations by about 25% and increase (or decrease) the oscillation length slightly.
  - **If** MINOS can see $\nu_\mu \rightarrow \nu_e$ oscillations, then it can measure the sign of Δm^2 by measuring $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, where the sign of the matter effect reverses.



CERN Neutrino Beam to Gran Sasso (CNGS)



CNGS / NuMI Comparison

	NuMI	CNGS
p Energy (GeV)	120	400
pot / yr (10^{19})	27	4.5
ν_μ CC events / kT / yr (no oscillations)	3200 (High E)	2450
Baseline (km)	730	730
Turn on	2003	2005
Near detector(s)	Yes	No*

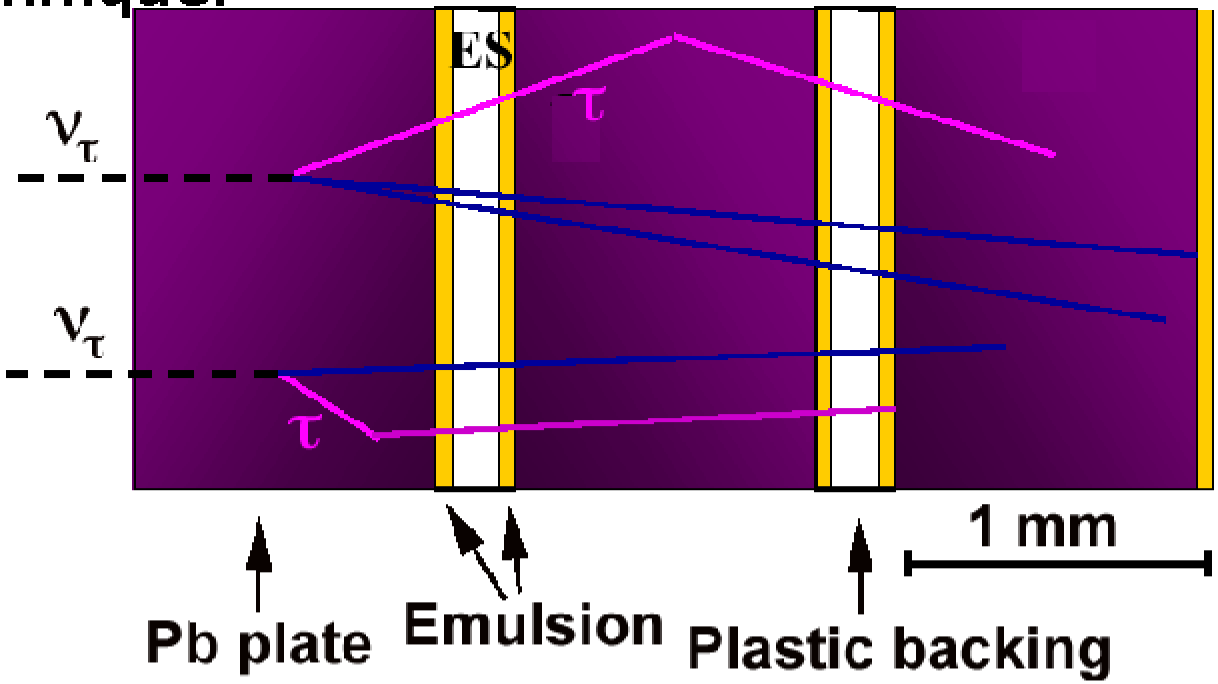
*Bad choice

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 2005 will not be interesting. The rates are low (at $\Delta m^2 = 3\ 10^{-3}$ eV^2, 22 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.

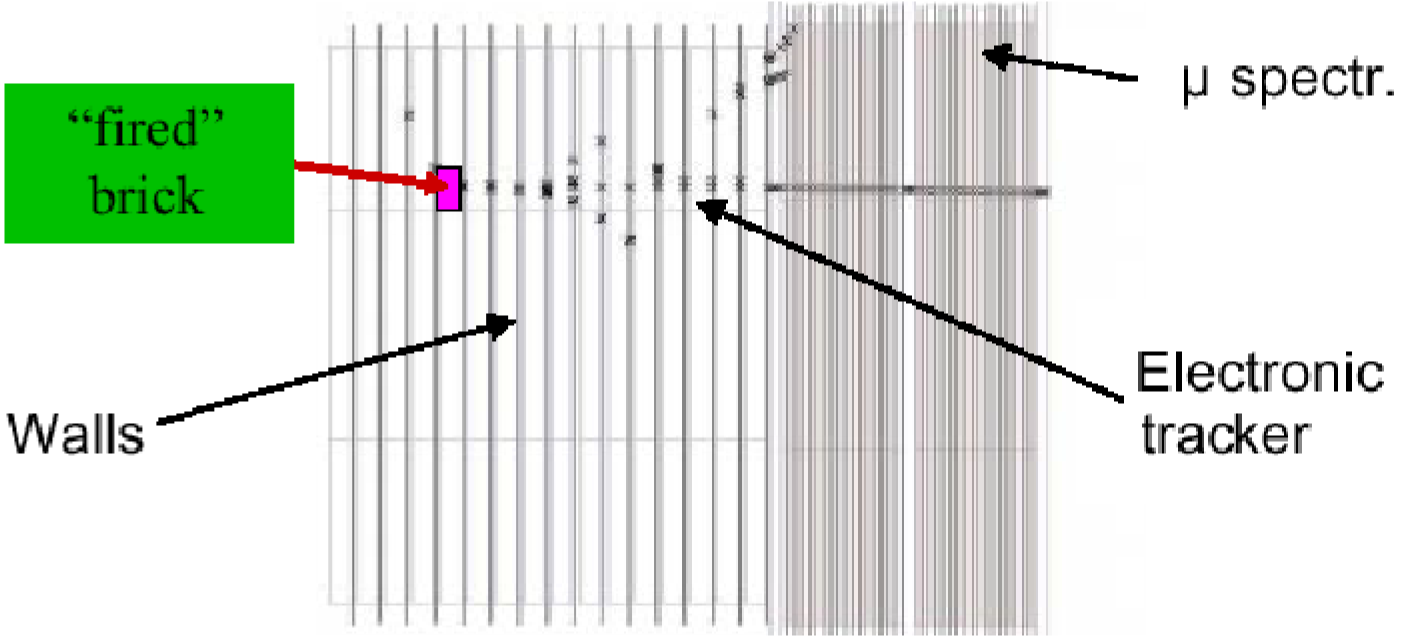
CNGS: OPERA Proposal

- OPERA is a proposal for direct detection of ν_τ using the ECC (emulsion cloud chamber) technique:

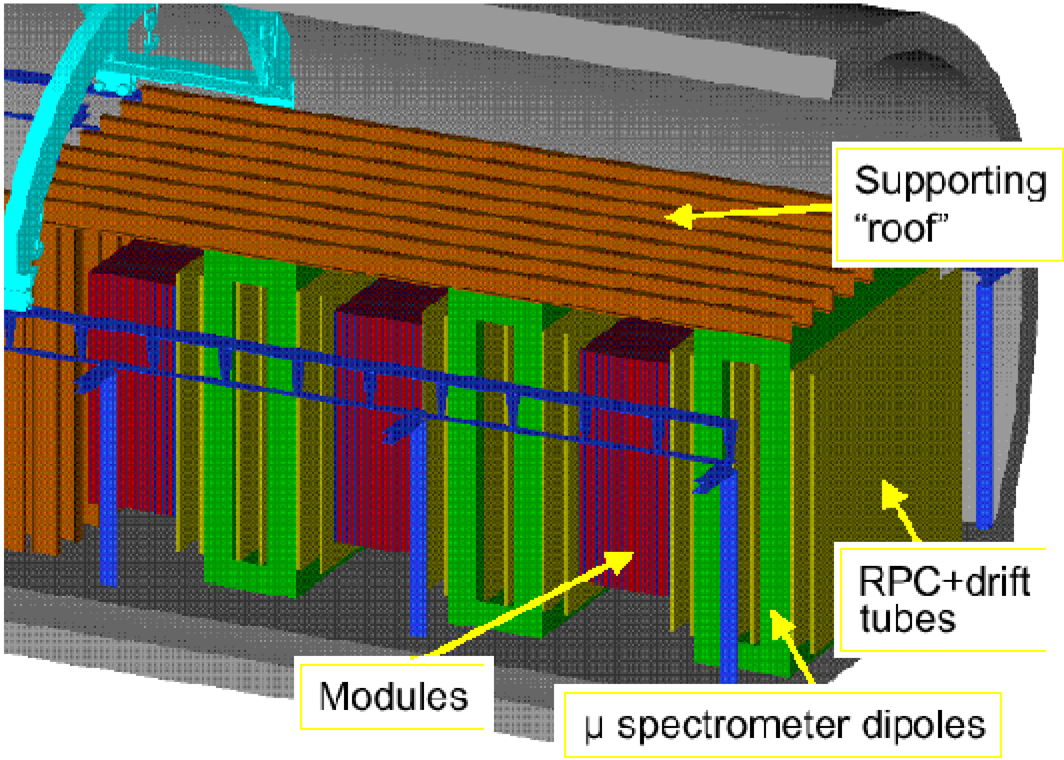


OPERA Detector

- Emulsions are in bricks. A brick with an event is identified by electronic detectors and removed for measurement.



OPERA Detector



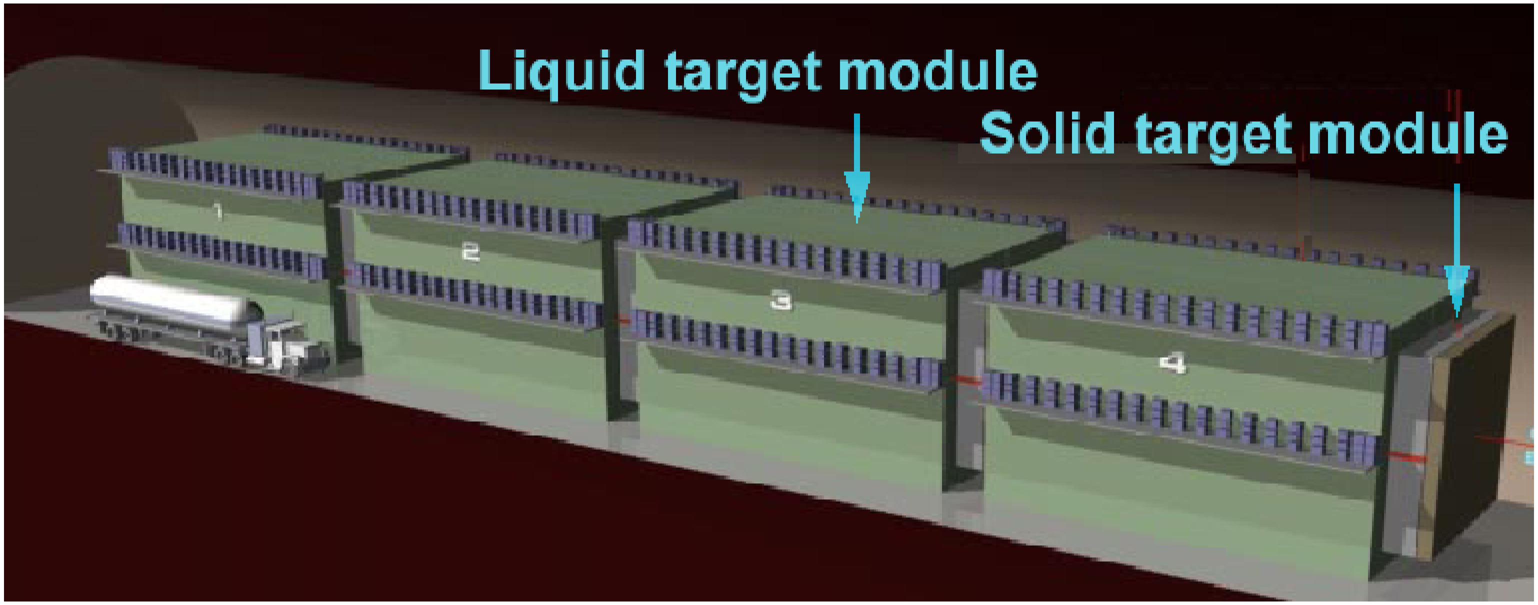
Active mass 2 kT

τ detection efficiency 8.7%

$\Rightarrow$ 18 events in 5 years for $\Delta m^2 = 3.2\ 10^{-3}$ eV^2

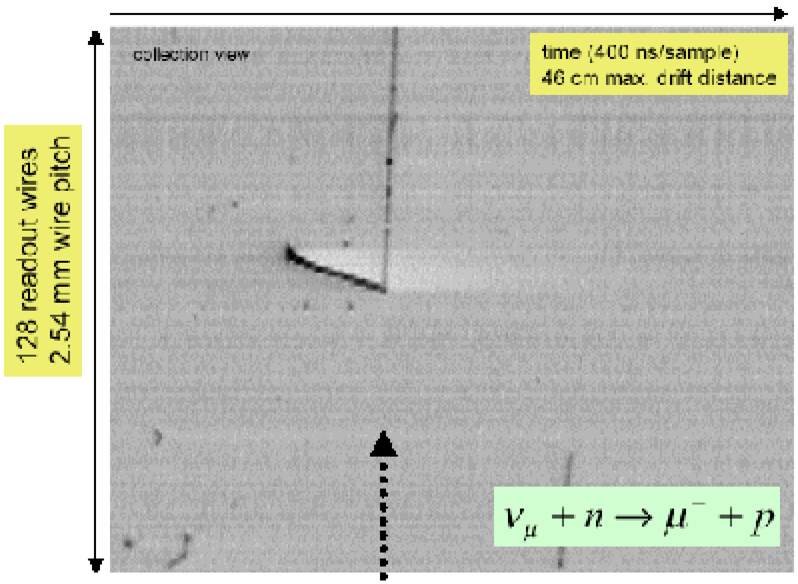
ICANOE Proposal

- ICANOE is a marriage of the ICARUS and NOE proposals
- 4 modules, each with a 1.4 kT LAr TPC and a 0.8 kT solid calorimeter ⇒ 9 kT total



ICANOE: Liquid Argon Detector

- Huge LAr TPCs have bubble-chamber like imaging capabilities, excellent fully-active calorimetry, and excellent particle identification from d*E*/dx and imaging.



$\nu_\mu + n \rightarrow \mu^- + p$

CERN ν-beam

(Chamber located in front of NOMAD detector)

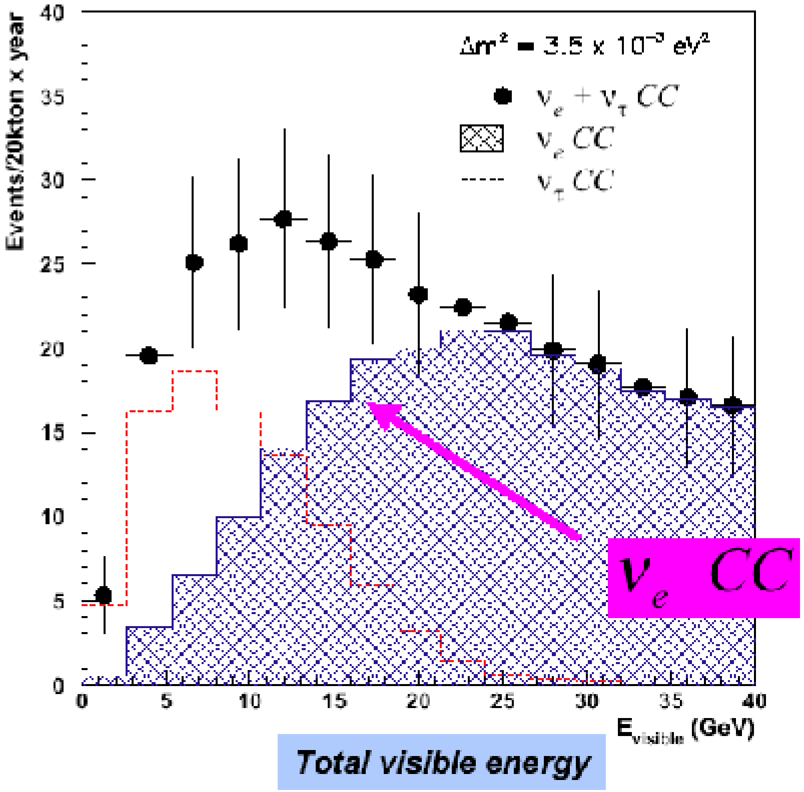
A real quasi-elastic event from a 50 liter test chamber in the CERN ν beam

ICANOE: Solid Detector

- The solid detectors consist of 5 mm magnetized iron plates sandwiched with scintillating fibers and drift tubes.
- They serves as tail-catchers and crosschecks for the LAr and a magnetic spectrometer.

ICANOE: ν_τ Appearance

- ICANOE will detect ν_τ appearance by observing low-energy excess electrons from the $\tau \to e\nu\nu$ decay.
- In 4 years, at $\Delta m^2 = 3\ 10^{-3}$ eV^2, there will be about 90 such events in the ICANOE LAr (100% detection efficiency).
- Analyses can also be done with kinematic cuts for low ν_e background.

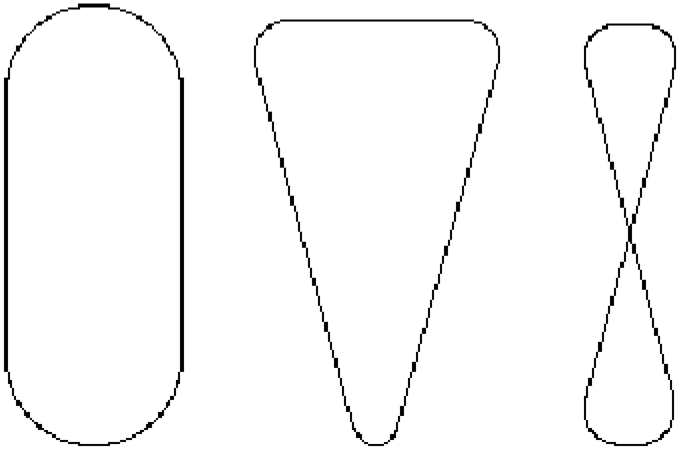


ICANOE: $\nu_\mu \rightarrow \nu_e$ Oscillations

- ICANOE's superb electron identification capabilities allows for a sensitive measurement of θ_{13}.
- However, it will be limited by systematic errors from the lack of a near detector and, probably, the wrong beam tune.

The Future:
A Neutrino Factory?

- A simple idea: Store muons in a ring with long straight sections and observe neutrinos from the muon decays.
- Design can be race-track, triangle, or bow tie. Straight sections need to point down to serve two experiments ⇒ arcs need to point up.

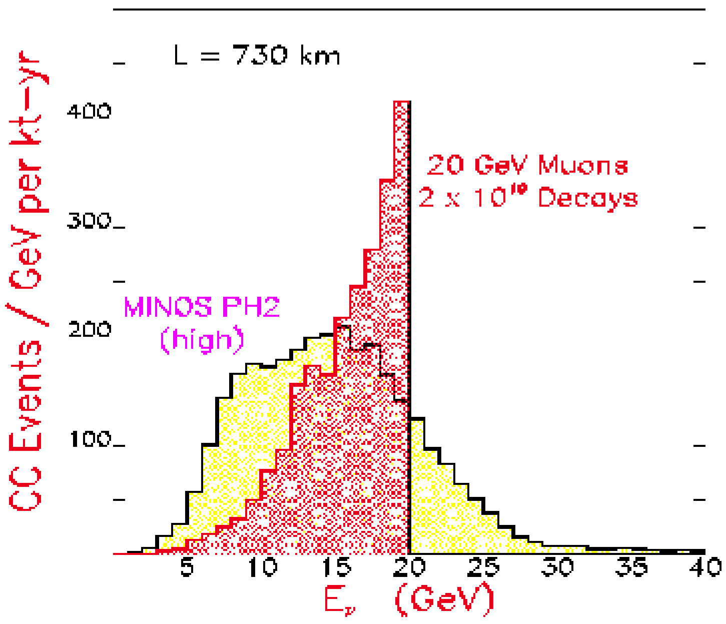


Neutrino Factory Basics

- Like the KARMEN experiment: 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.
  - An advantage?
- Flux increases as E_μ^3:
  - E^2 for divergence.
  - E for the cross section.
  - **Is highest possible E always best?**



Neutrino Factory Parameters and Physics Goals

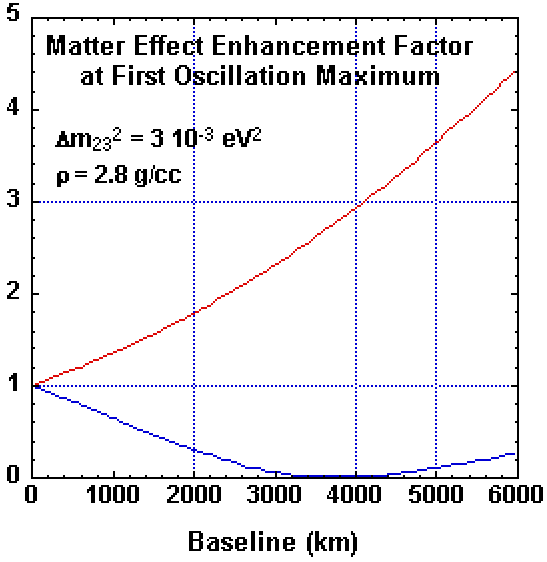
- Parameters under discussion:
  - $20 \leq E_\mu \leq 50$ GeV
    - Lower bound from $p_\mu > 4$ GeV for detection
    - Higher E_μ is better
  - 10^{19} to 10^{21} decays per year
  - Baseline about 3000 km
    - Reason to be discussed
- Physics goals:
  - Precise measurement of θ_{13}
  - Determination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

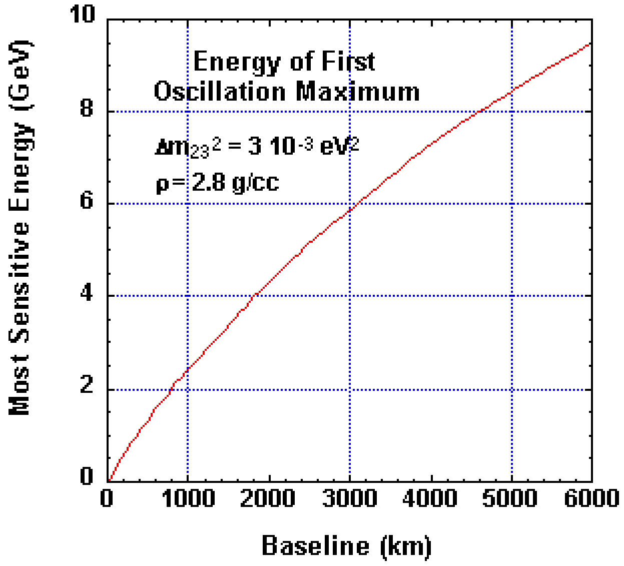
Measurement of θ_{13} and Sign of Δm_{13}^2

- If $\theta_{13} >> \sin(2\theta_{12})\,\Delta m_{12}^2\,L/E$ (true for SMA, low, and vacuum solar solutions), the situation is simple:

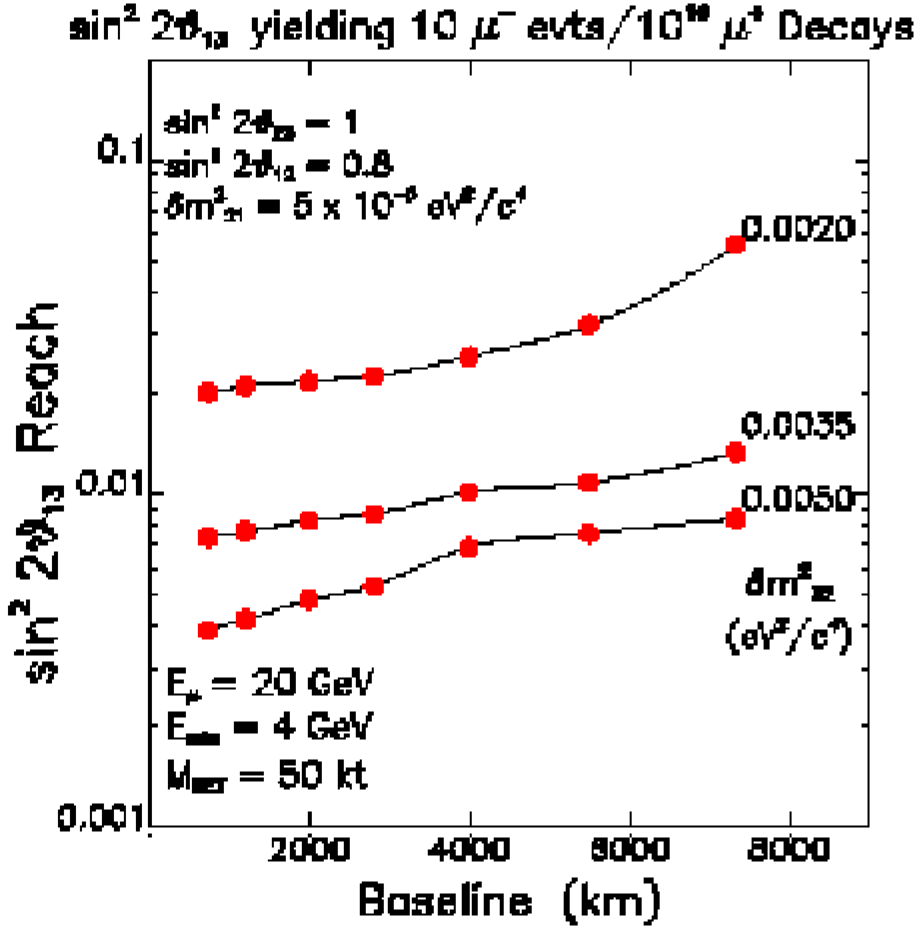
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2(1.27\,\Delta m_{13}^2 L/E),$$

enhanced or reduced by matter effects, as discussed for MINOS.





Measurement of θ_{13} and Sign of Δm_{13}^2

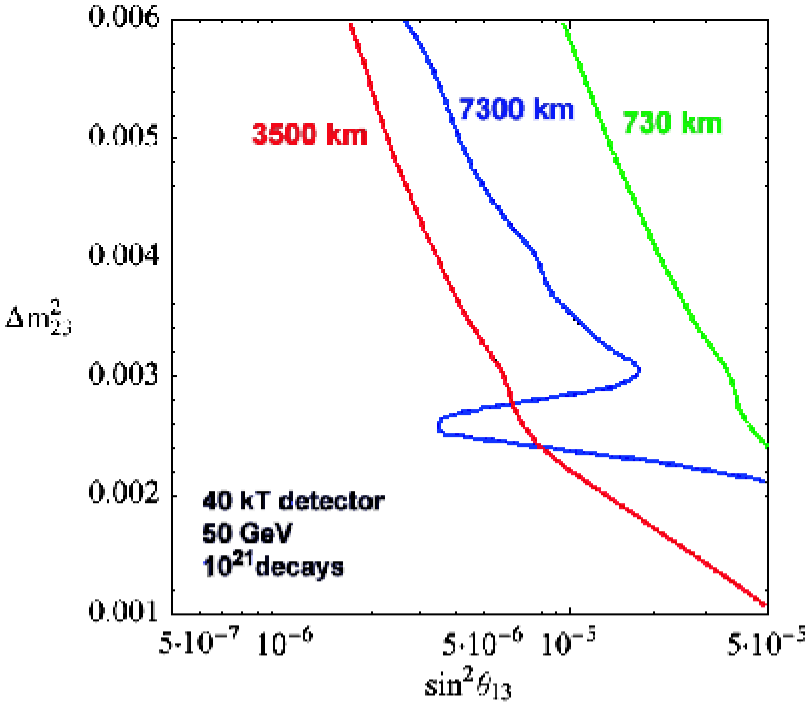


$\sin^2(2\theta_{13})$ reach for 10^{19} decays

(from Barger et al., hep-ph/0003184 v2)

Measurement of θ_{13} and Sign of Δm_{13}^2

- Sensitivity to $\sin^2\theta_{13}$ at 90% c.l. from Cervera, et al., (hep-ph/0002108)



730 km disfavored by backgrounds

7300 km disfavored by statistics

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

- However, if LMA solar oscillation scenario is correct, things are much more complicated (and interesting).
- Sensitivity to the "atmospheric term," the "solar term," and an interference term between them, all modified by matter effects. (The interference term contains the CP violation.)
- To simplify as much as possible, take $\sin^2(2\theta_{23}) = \sin^2(2\theta_{12}) = 1$, and following Cervera, et al., expand to second order in the small parameters θ_{13} and $(\Delta m_{12}^2\ L/E)$, ignoring matter effects:

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

$$+1.27\theta_{13}(\Delta m_{12}^2 L/E)\sin(1.27\Delta m_{13}^2 L/E)\cos(\pm\delta - 1.27\Delta m_{13}^2 L/E)$$

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

- For a short baseline (NuMI or CNGS), each term has the same *L / E* dependence and we measure

$$P(\nu_\mu \to \nu_e) = \left[2\theta_{13}^2 + 0.5(\Delta m_{12}^2 / \Delta m_{13}^2)^2 + \theta_{13}(\Delta m_{12}^2 / \Delta m_{13}^2)\cos(\delta)\right] \times (1.27\,\Delta m_{13}^2 L / E)^2$$

with a small modification due to matter effects.

- If Δm_{12}^2 is known from solar measurements, then θ_{13} can be recovered with a small uncertainty due to the cos(δ) term.
- However, the cos(δ) term cannot be separated from θ_{13}.
- The CP-violating sin(δ) term, which reverses with polarity, is lower order and has been dropped.

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

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

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

- **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

- CP violation only occurs for three or more neutrino flavors. Therefore, it has to be proportional to every MNS matrix element and every oscillatory term. That is why it occurs only in the interference term.
- For this reason, unless the solar solution is LMA, measuring CP violation is hopeless.
- Using the same LMA approximation, the CP odd term in the absence of matter effects is

$$P_{CP-}(\nu_\mu \to \nu_e) = \pm 2\,\theta_{13}\,\sin(\delta)$$
$$\times \sin\left(\frac{1.27\,\Delta m_{12}^2 L}{E}\right)\sin\left(\frac{1.27\,\Delta m_{13}^2 L}{E}\right)\sin\left(\frac{1.27\,\Delta m_{23}^2 L}{E}\right)$$

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

  $$A = \sqrt{2} G_F n_e \cong 1.5 \;\; 10^{-4} \text{ eV}^2/\text{GeV}$$

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

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

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

Measuring CP Violation

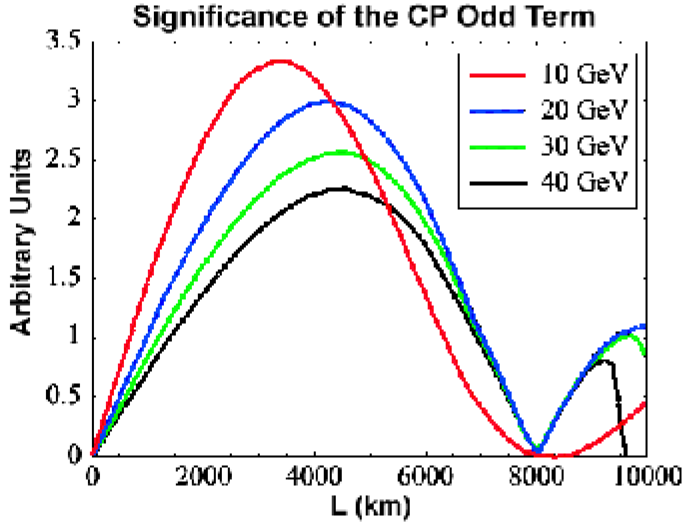
- Therefore, the CP odd term contains a pure matter oscillation,

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

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

- Calculation by Cervera et al.

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



Measuring CP Violation

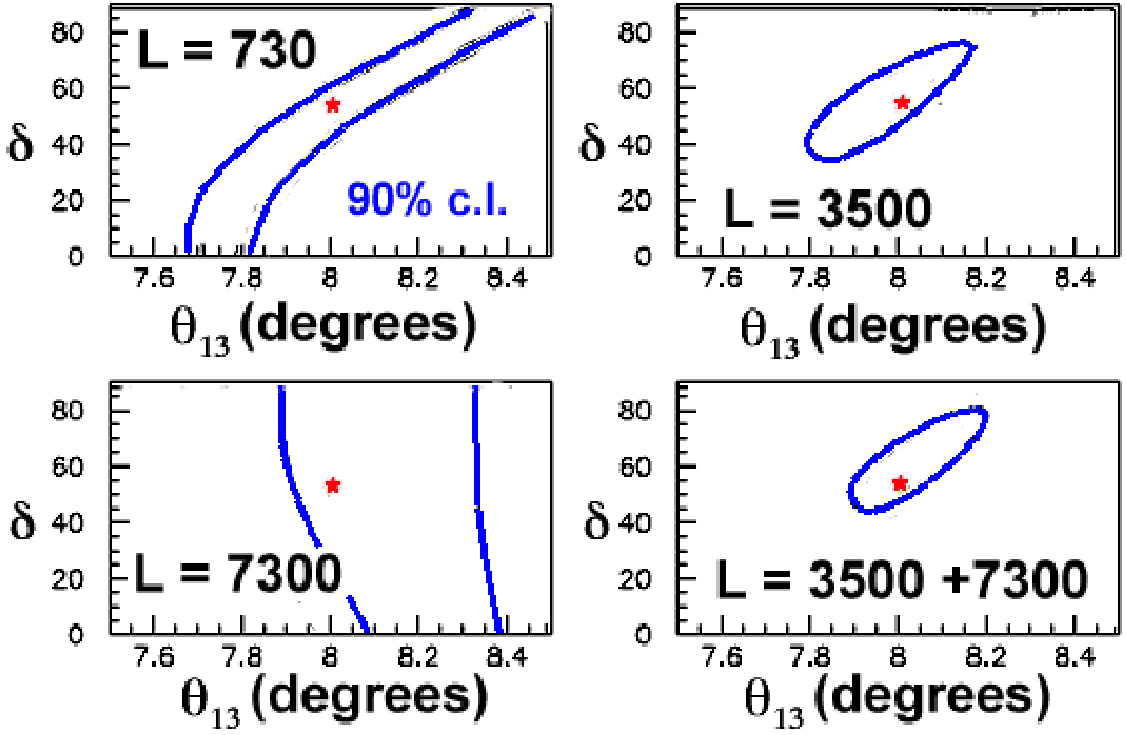
- **Fits by Cervera et al. for 1021 decays at 50 GeV with a 40 kT detector.**
- $\Delta m_{23}^2 = 2.8\ 10^{-3}\ \mathrm{eV}^2$; $\Delta m_{12}^2 = 1.0\ 10^{-4}\ \mathrm{eV}^2$

  $\theta_{23} = 45°$

  $\theta_{12} = 22.5°$

  $\theta_{13} = 8°$

  $\delta = 54°$



Where to Build a Neutrino Factory

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