Measuring θ_{13} [, sign(Δm_{13}^2), and δ] at Accelerators

HEPAP

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Outline

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

Present Status

- **In the "Standard Model" of neutrino oscillations, there are 8 parameters, 5 of which we know, or will know, reasonably well:**
  - Δm_{23}^2 (2.5 10^{-3} eV^2)
    (New SK value = 2.0 10^{-3} eV^2)
  - Δm_{12}^2 (6.9 10^{-5} eV^2)
  - sign(Δm_{12}^2) (+)
  - $\sin^2(2\theta_{23})$ (1.0)
  - $\sin^2(2\theta_{12})$ (0.83)

Goal

- **Our medium to long-term goal is to measure the other three parameters:**
  - $\sin^2(2\theta_{13})$
  - $\mathrm{sign}(\Delta m_{13}^2)$
  - δ

$P(\nu_\mu \rightarrow \nu_e)$ (in Vacuum)

- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$
  - $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$
  - $P_3 = \mp J \sin(\delta) \sin(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{13}^2\ L/E)$

  where $J = \cos(\theta_{23}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23})$ x

  $\sin(1.27\ \Delta m_{13}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$

$P(\nu_\mu \rightarrow \nu_e)$ (in Matter)

- In matter, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.

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

About a ±30% effect on P_1 for NuMI, but only a ±12% effect for JPARC.

Magnitudes

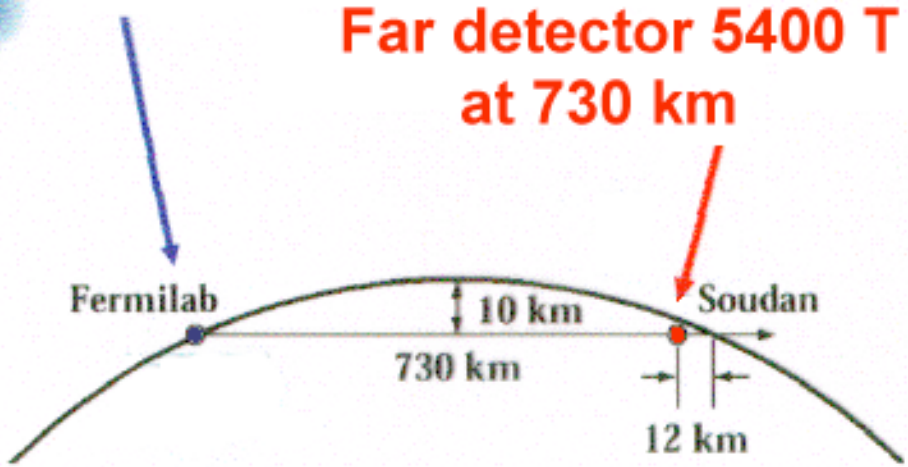
- For long-baseline $\nu_\mu \rightarrow \nu_e$ oscillations, P_1, P_3, P_4, and the matter effects are all the same order of magnitude.
- A measurement of $P(\nu_\mu \rightarrow \nu_e)$ measures "$\sin^2(2\theta_{13})_{eff}$" which is only a crude estimate of $\sin^2(2\theta_{13})$.
- Reactor experiments measure $\sin^2(2\theta_{13})$ directly, but have no sensitivity to $\mathrm{sign}(\Delta m_{13}^2)$ or δ.

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

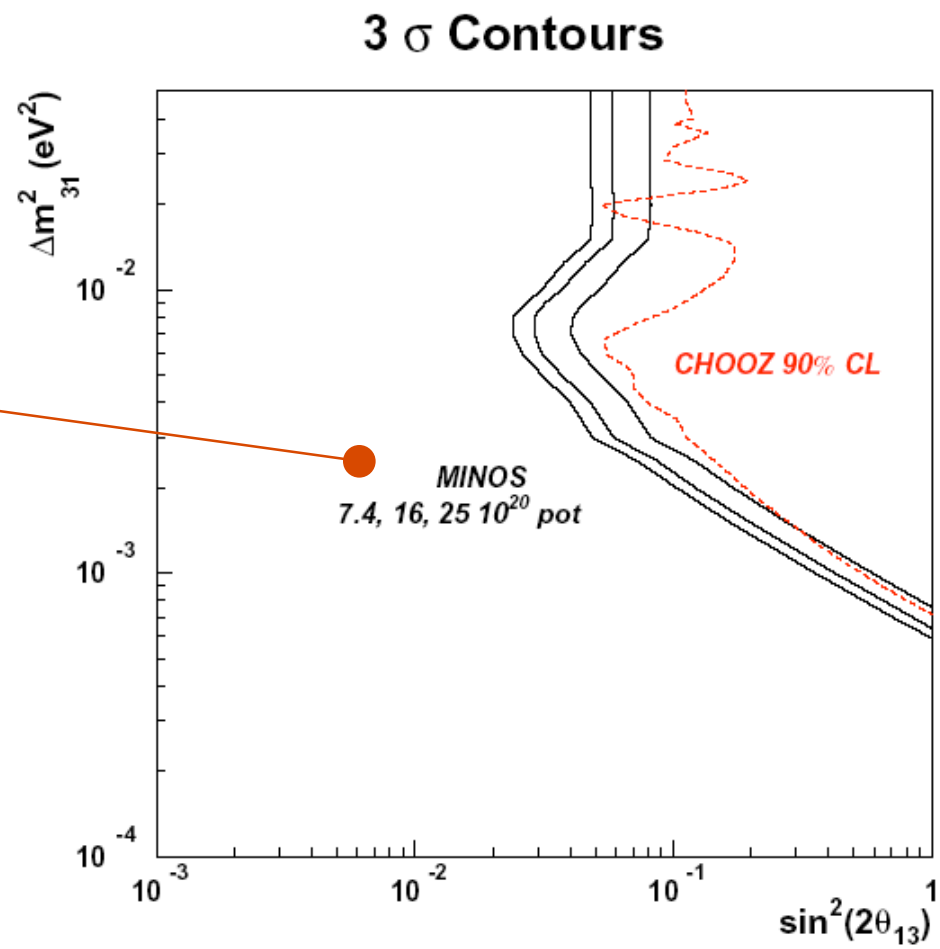


MINOS Far Detector

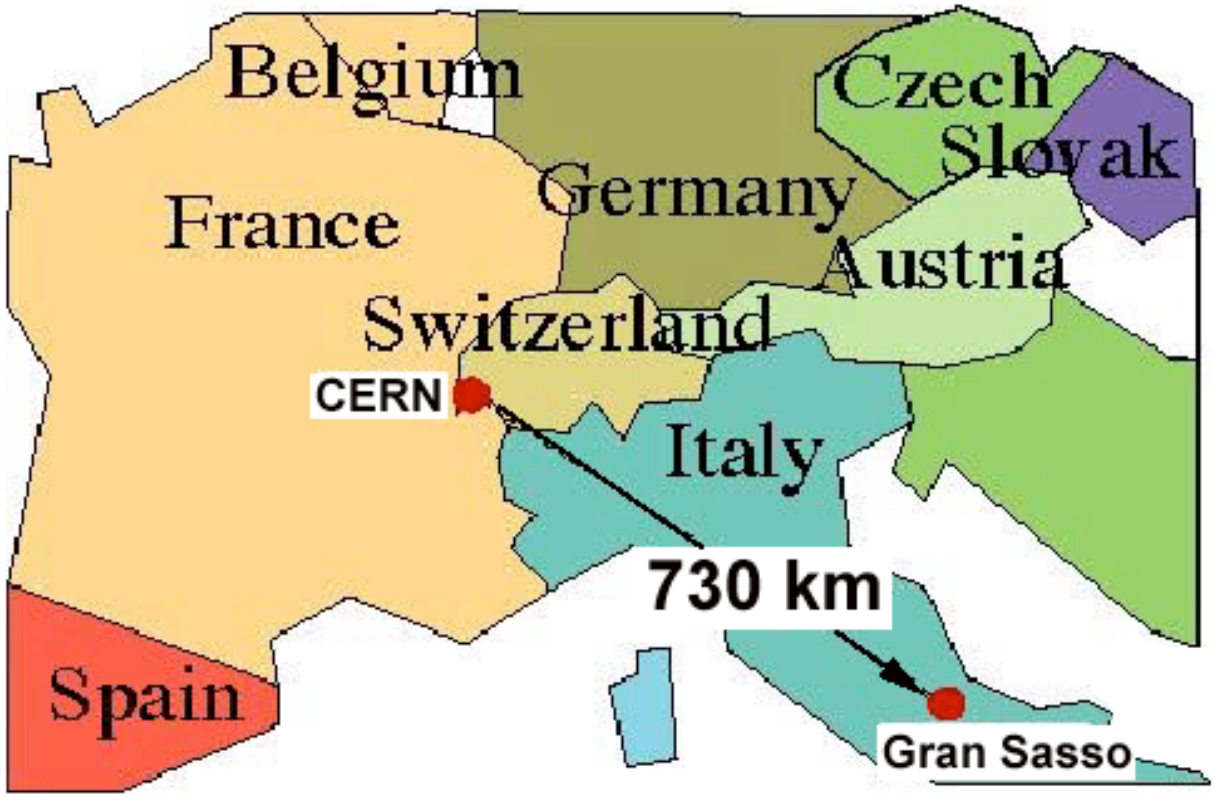
Now Complete, with magnetic field, taking cosmics and waiting for beam.

MINOS Sensitivity to $\nu_\mu \rightarrow \nu_e$ at 3σ Discovery

Off-axis sensitivity



CERN Neutrino Beam to Gran Sasso (CNGS)

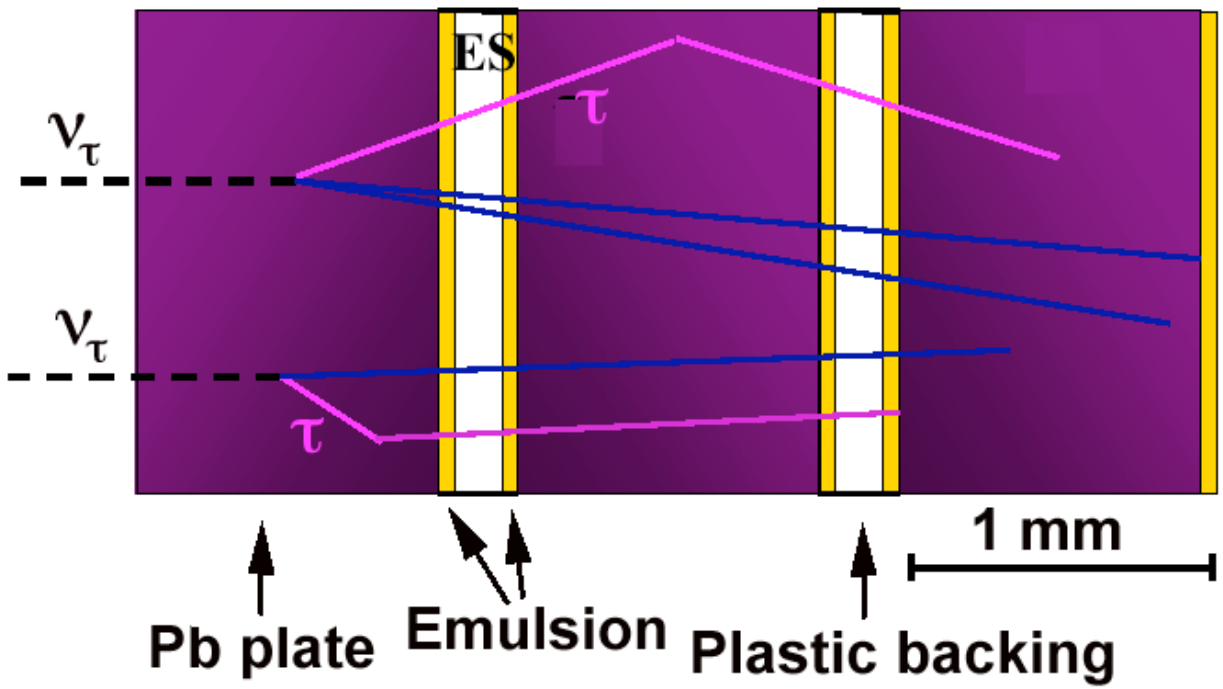


CNGS / NuMI Comparison

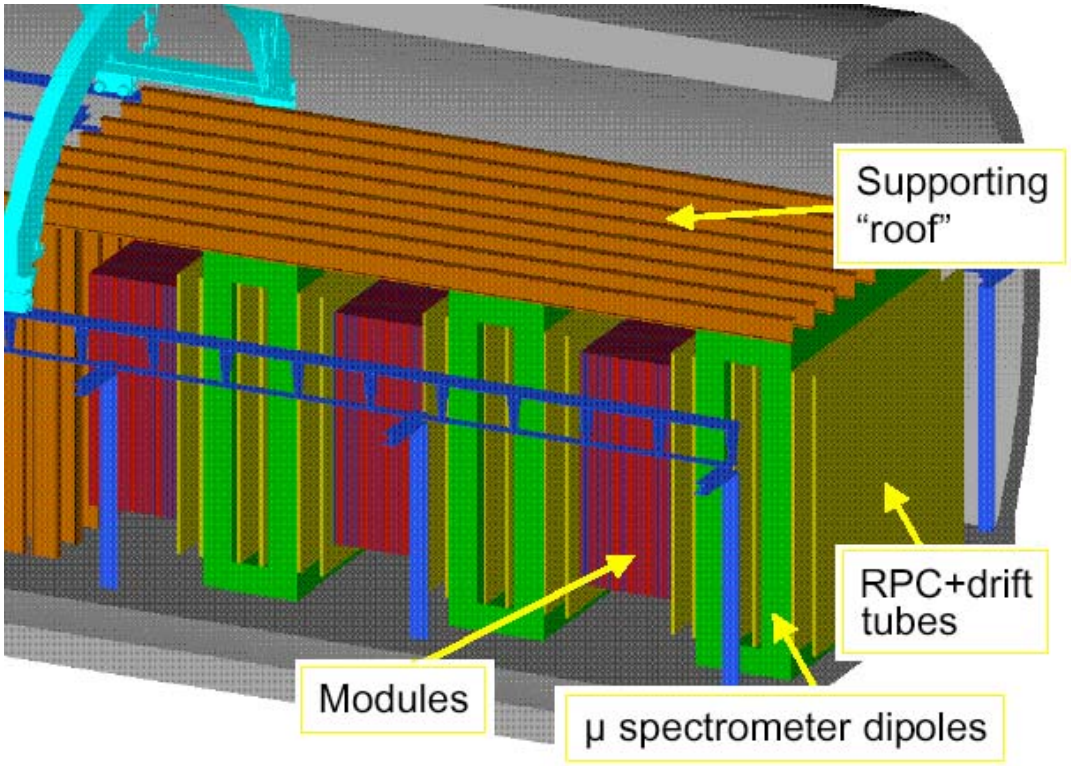
	NuMI	CNGS
p Energy (GeV)	120	400
pot / yr (10^{19})	27	4.5
ν_μ CC events / kT / yr (no oscillations)	2740 HE beam 470 LE beam	2450
Baseline (km)	730	730
Turn on	2005	2006
Near detector(s)	Yes	No

OPERA Experiment

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



OPERA Detector



Active mass 2 kT

τ detection efficiency 8.7%

$\Rightarrow$ 17 events in 5 years for $\Delta m^2 = 2.5\ 10^{-3}\ eV^2$

90% CL sensitivity to $\sin^2(2\theta_{13}) = 0.06$

ICARUS Experiment

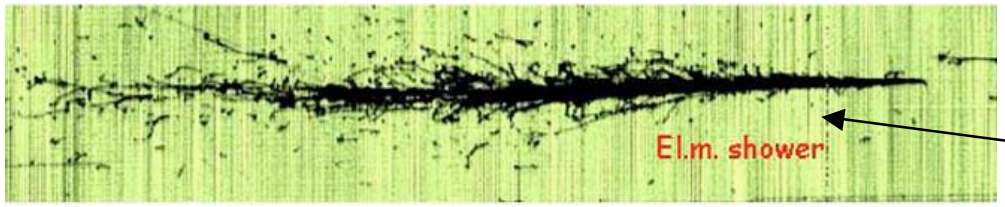
Five 600 T liquid argon TPCs

Excellent electron detection

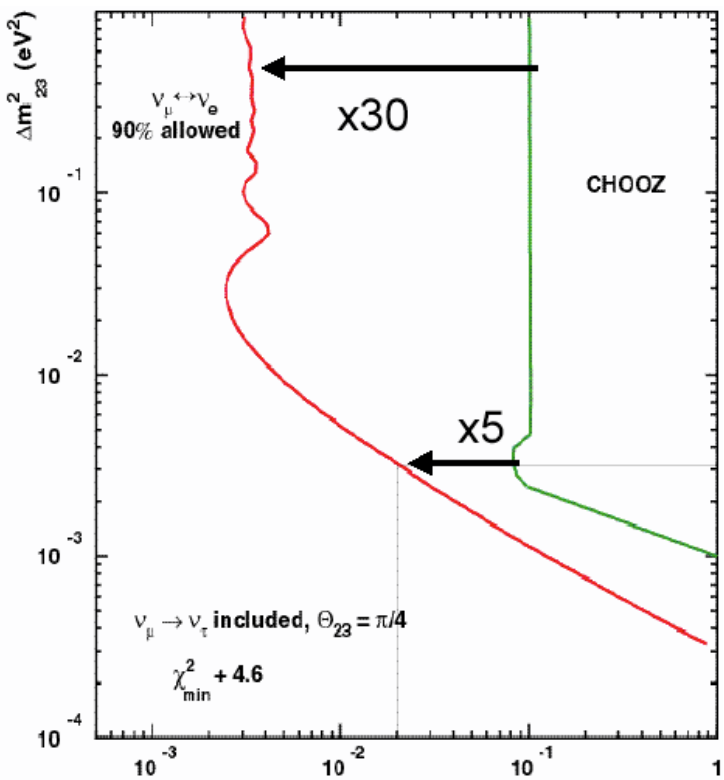
Has not yet received safety approval.

Results from a 300 T prototype

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



Electromagnetic shower

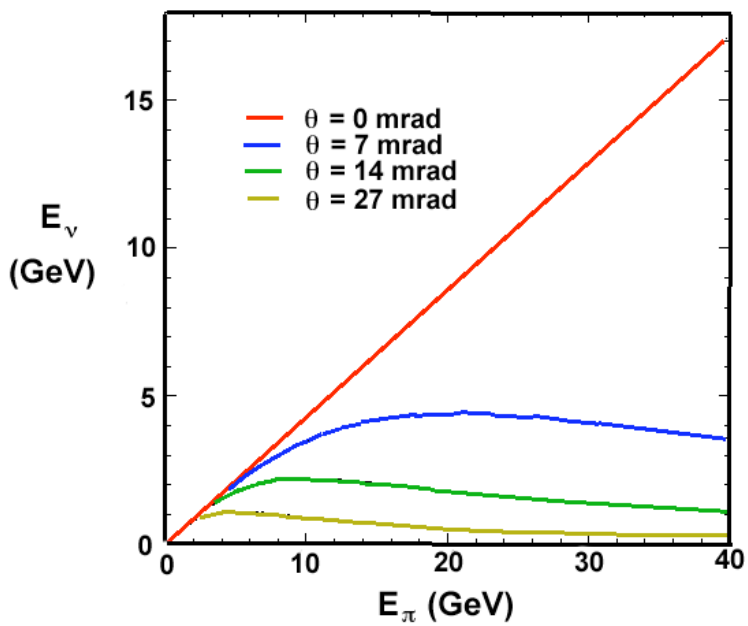


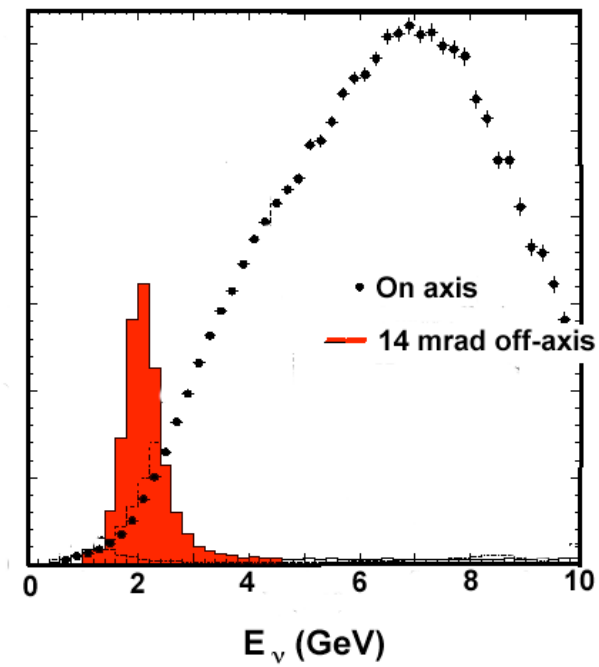
5 year run with 2.45 kT mass

CNGS performance limited By lack of a near detector and the wrong beam energy.

Off-Axis Rationale

- In order to go further and measure $\sin^2(2\theta_{13})$, sign(Δm_{13}^2) and δ, there are proposals for off-axis facilities at NuMI and JPARC.
- An off-axis detector sees a narrow-band beam:





Off-Axis Rationale

- Narrow-band beams at or slightly above the $\Delta m^2_{13} \approx \Delta m^2_{23}$ oscillation maximum are advantages since:
  - ν_e appearance maximum
  - ν_μ CC disappears
  - Higher-energy NC disappears
- Need detectors optimized for ν_e detection
- Need as much beam flux times detector mass as possible.

NuMI Proposal (in preparation)

- 50 kT, medium-Z, fine-grained sandwich detector, using either glass RPCs or scintillator. (Water Cerenkov detectors are not optimum for separating π^0's from electrons above 1 GeV.)
- Cost about 150 M$.
- Sites available in northern Minnesota 9 to 10 km off-axis, 710 to 825 km from Fermilab. (Sites also available in Canada.)

JPARC Proposal

1st Phase

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

2nd Phase

- CPV
- proton decay

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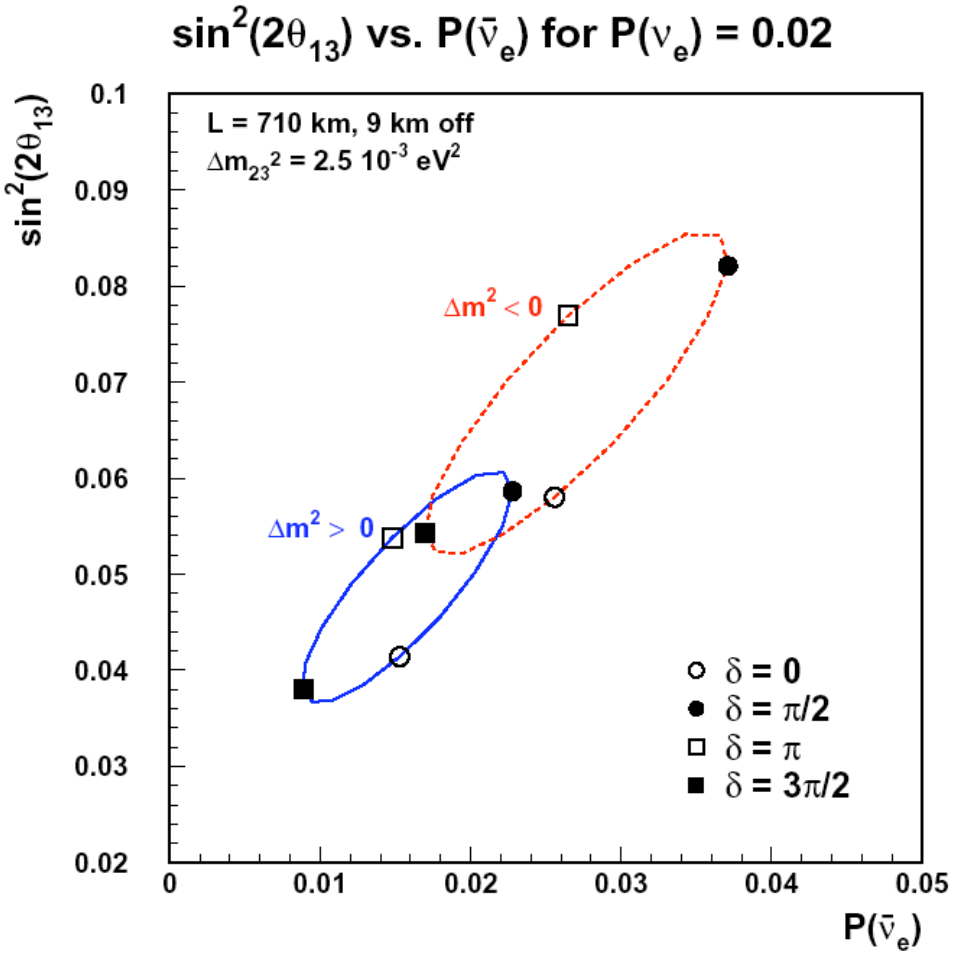
Beams

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

Probability Plots

- To understand what can be measured, I have constructed some plots similar to the bi-probability plots of Minakata and Nunokawa, but more useful.
- Each plot assumes a particular result for a measurement of $P(\nu_\mu \rightarrow \nu_e)$ and shows the possible values of $\sin^2(2\theta_{13})$, $\mathrm{sign}(\Delta m_{13}^2)$, and δ versus the result of another measurement.

$P(\nu_\mu \rightarrow \nu_e) = 0.02$ at 710 km



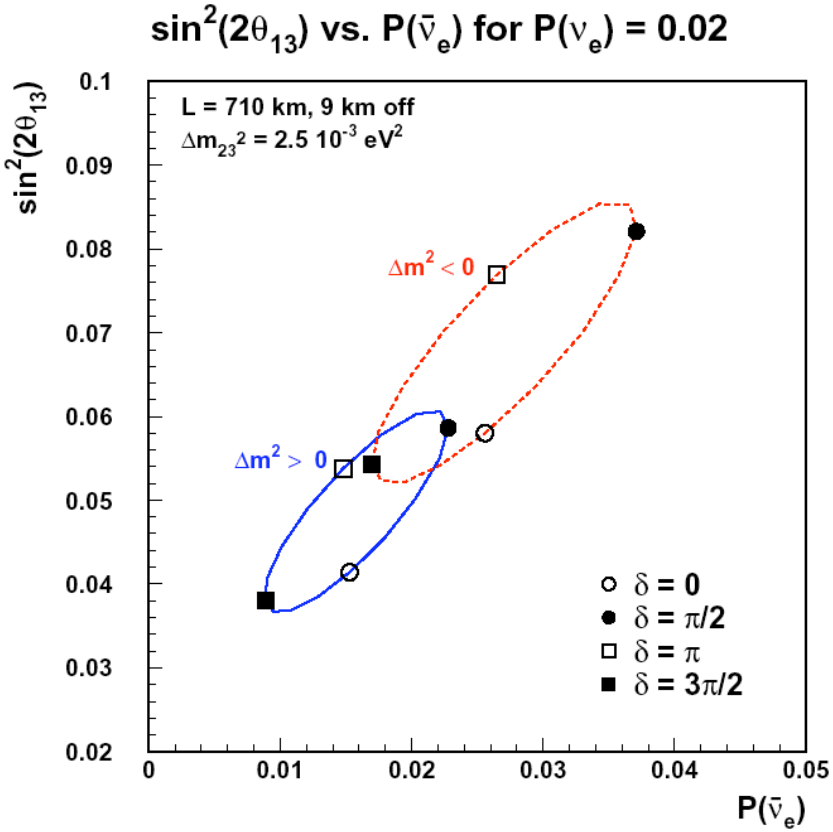
Note

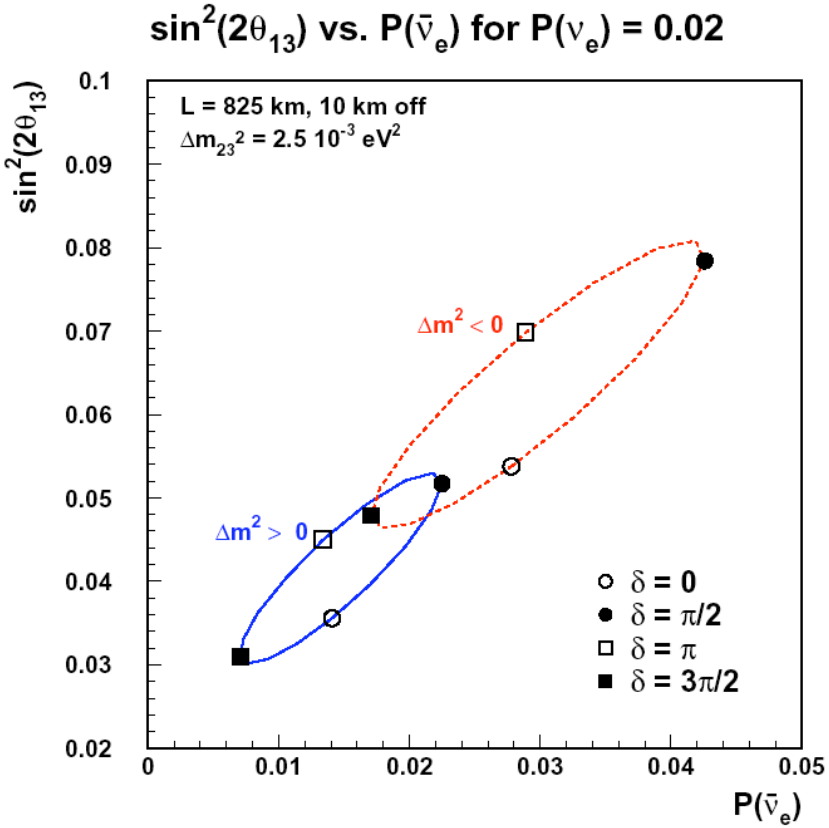
(1) Effect of $\cos(\delta)$ term

(2) Ambiguities

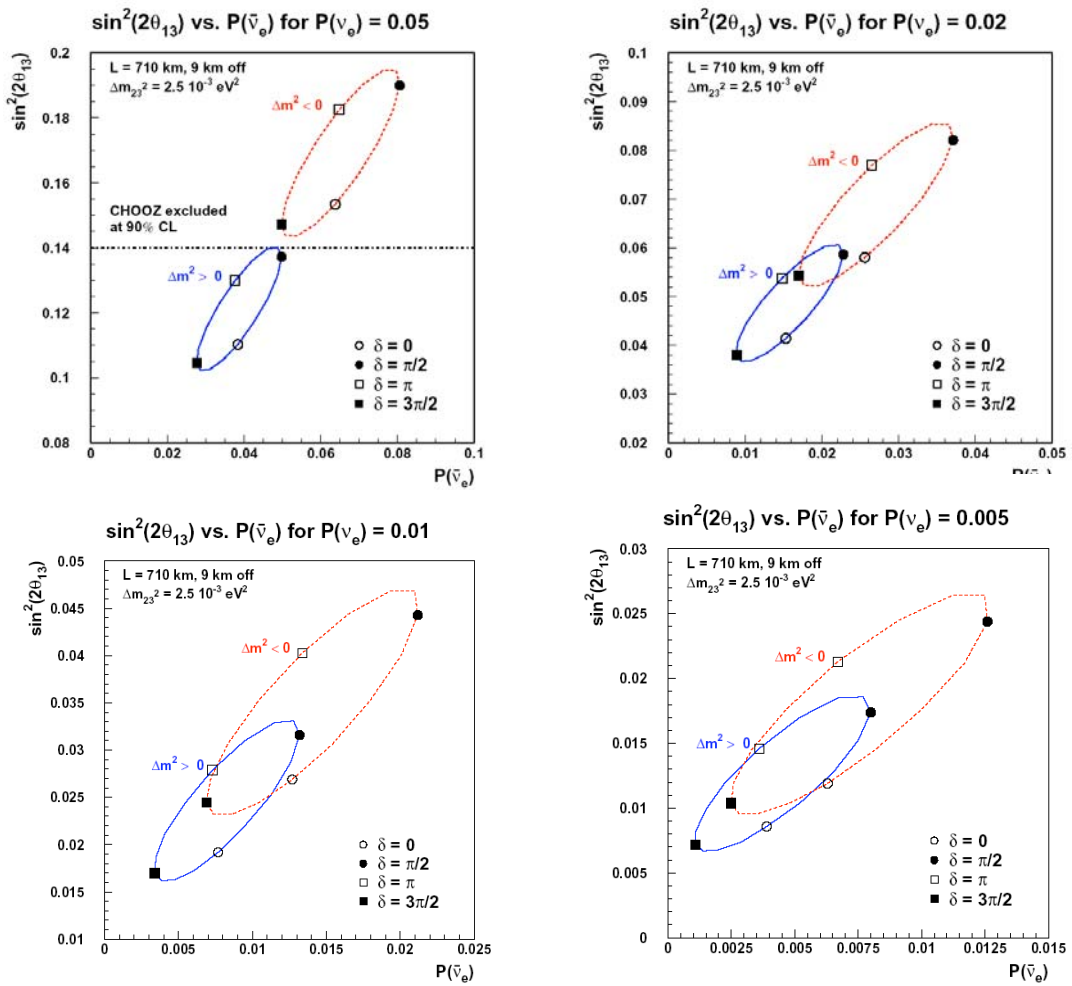
(3) Rough equivalence of reactor and antineutrino measurements

$P(\nu_\mu \rightarrow \nu_e) = 0.02$ at 710 and 825 km

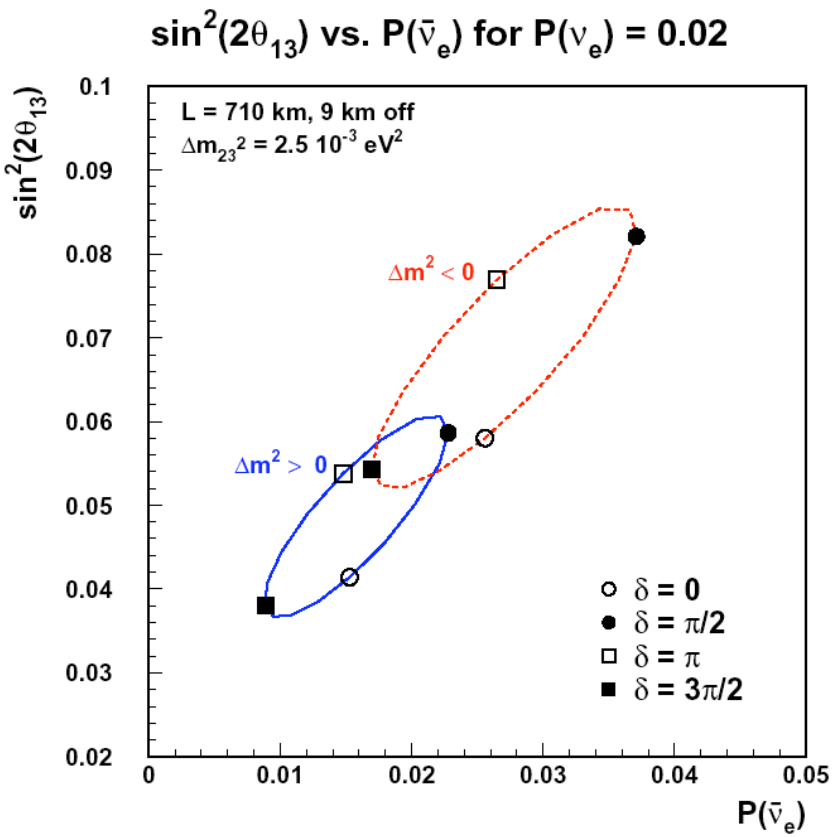


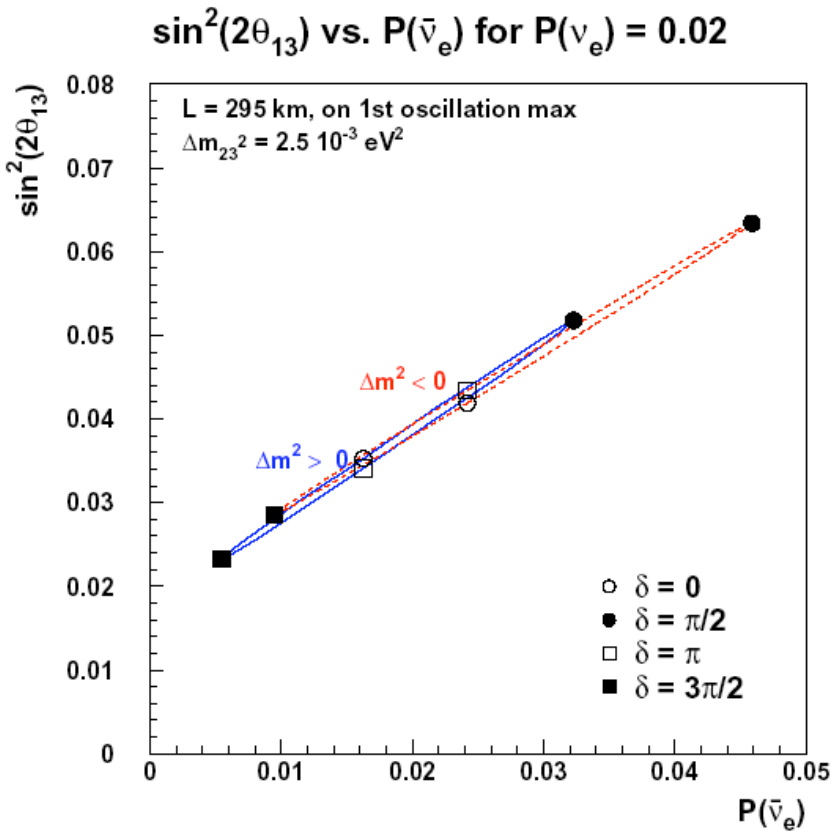


$P(\nu_\mu \rightarrow \nu_e)$ = 0.05, 0.02, 0.01, and 0.005 at 710 km

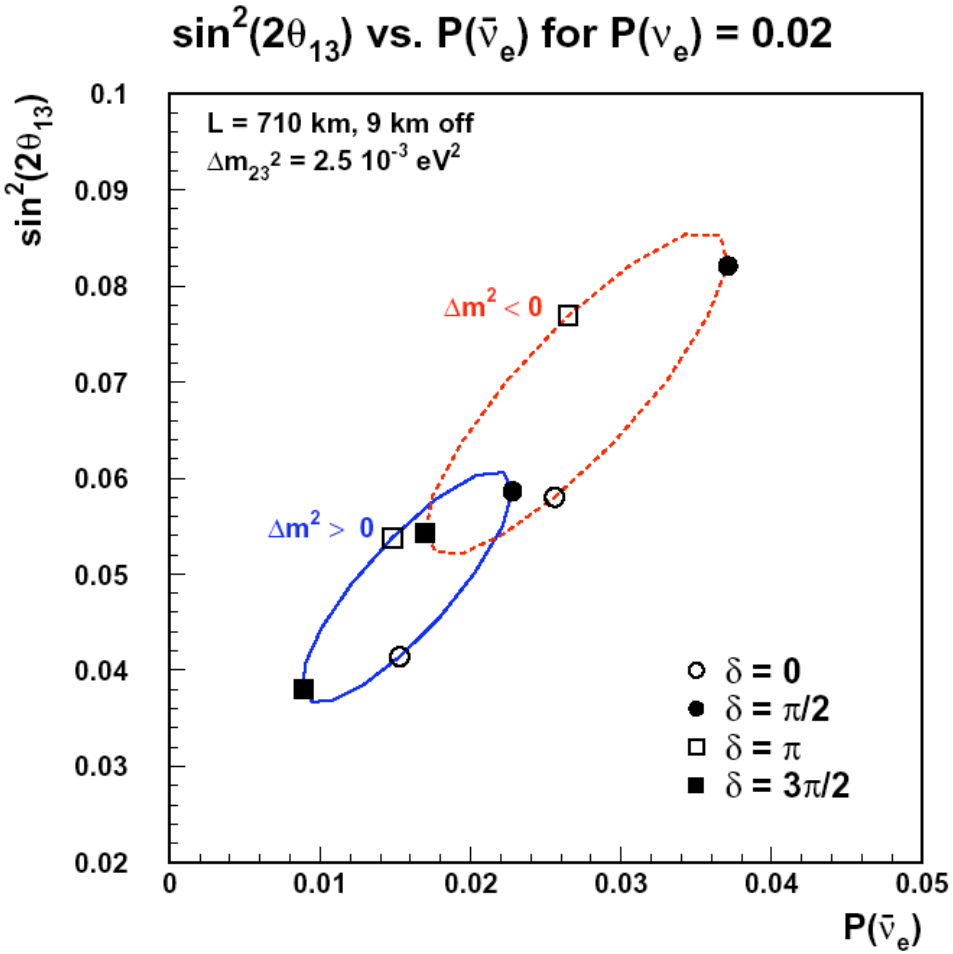


$P(\nu_\mu \rightarrow \nu_e) = 0.02$ at 710 and 295 km





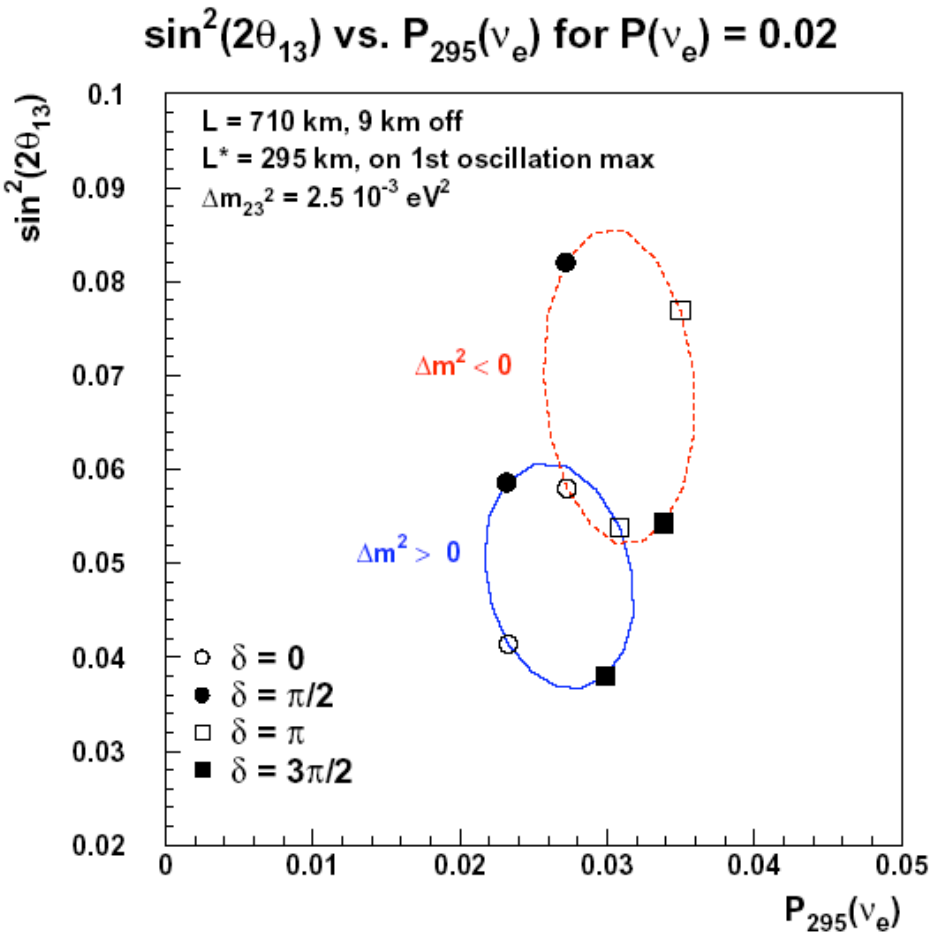
$P(\nu_\mu \rightarrow \nu_e) = 0.02$ at 710 km



Note ambiguities between no CP violation for normal hierarchy and maximal CP violation for inverted hierarchy and vice-versa.

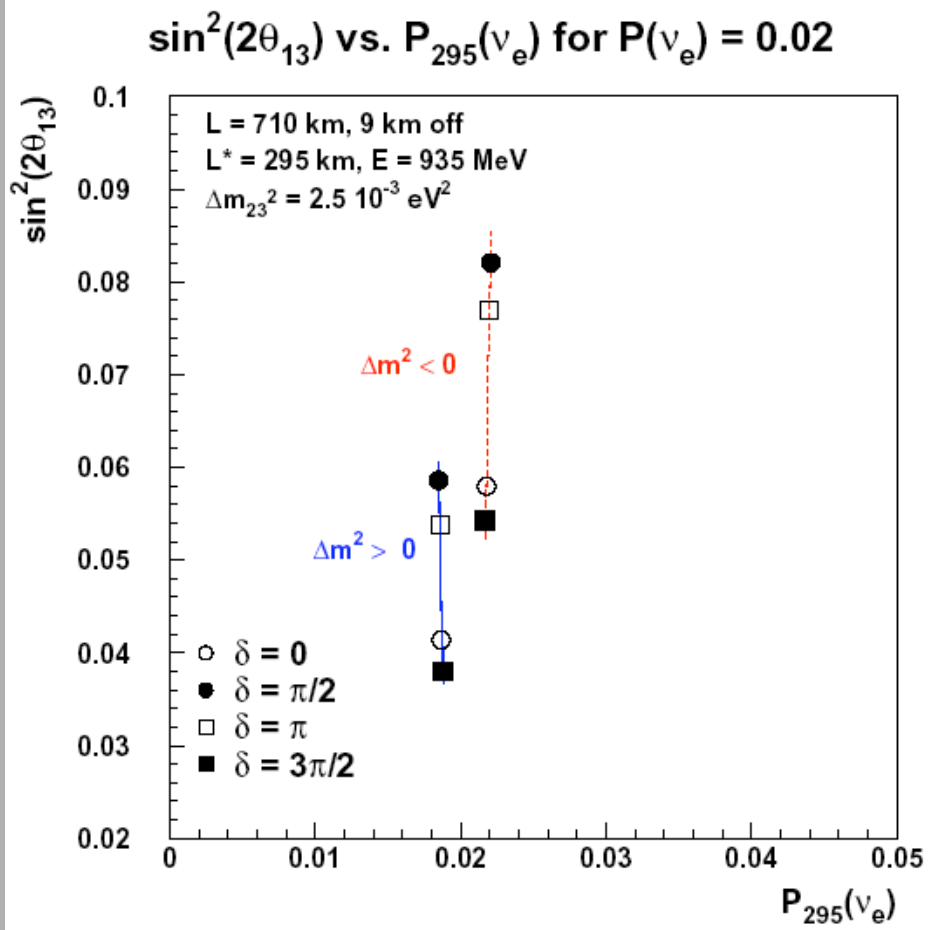
Can combining JPARC and NuMI data help?

$P(\nu_\mu \rightarrow \nu_e) = 0.02$ at 710 km vs. $P(\nu_\mu \rightarrow \nu_e)$ at 295 km



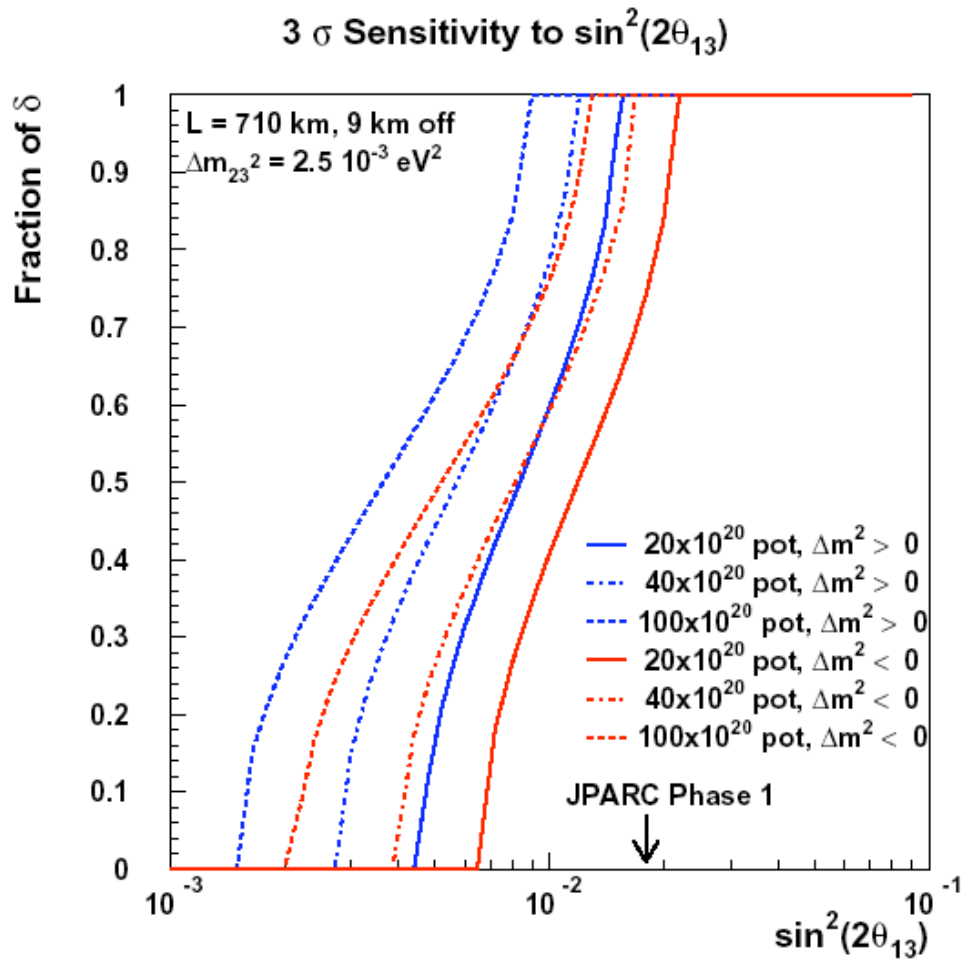
As warned by Parke et al., hierarchy is not resolved by just neutrino running.

Same, but Smaller Off-Axis Angle at 295 km



Hierarchy now resolved in principle, but difference is very small.

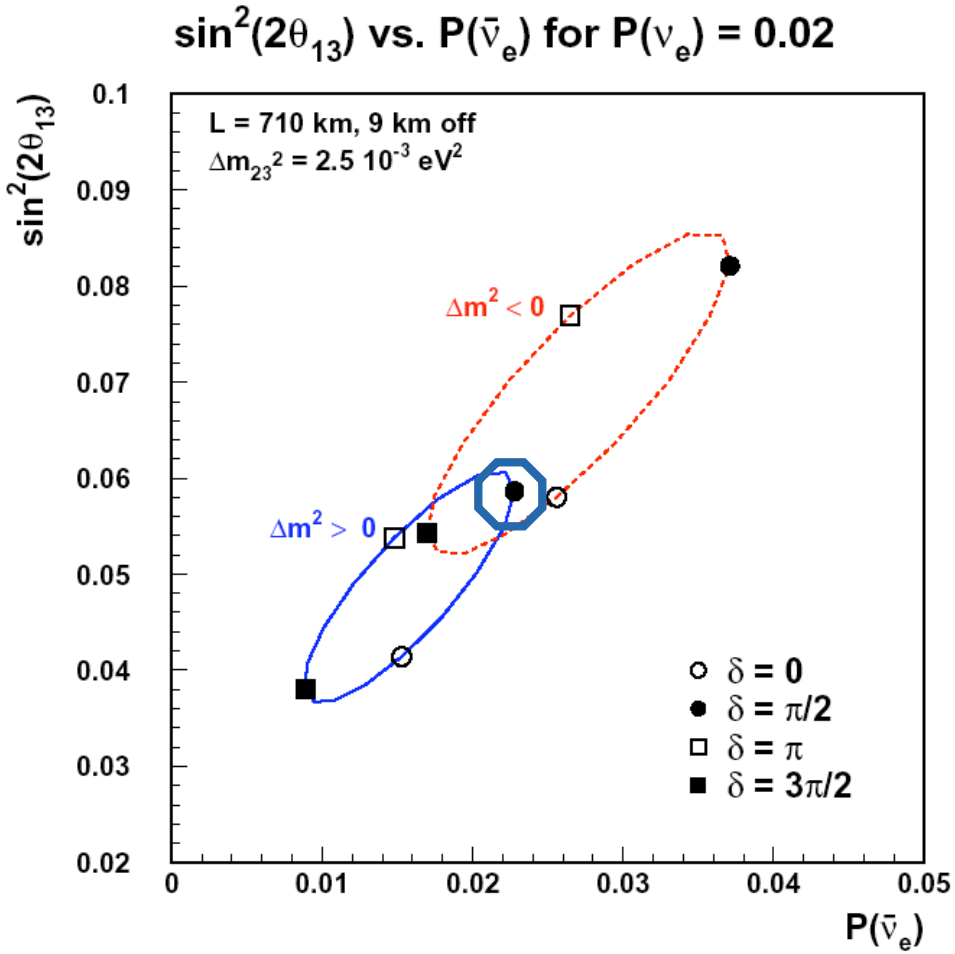
3 σ Discovery Potential for $\nu_\mu \rightarrow \nu_e$



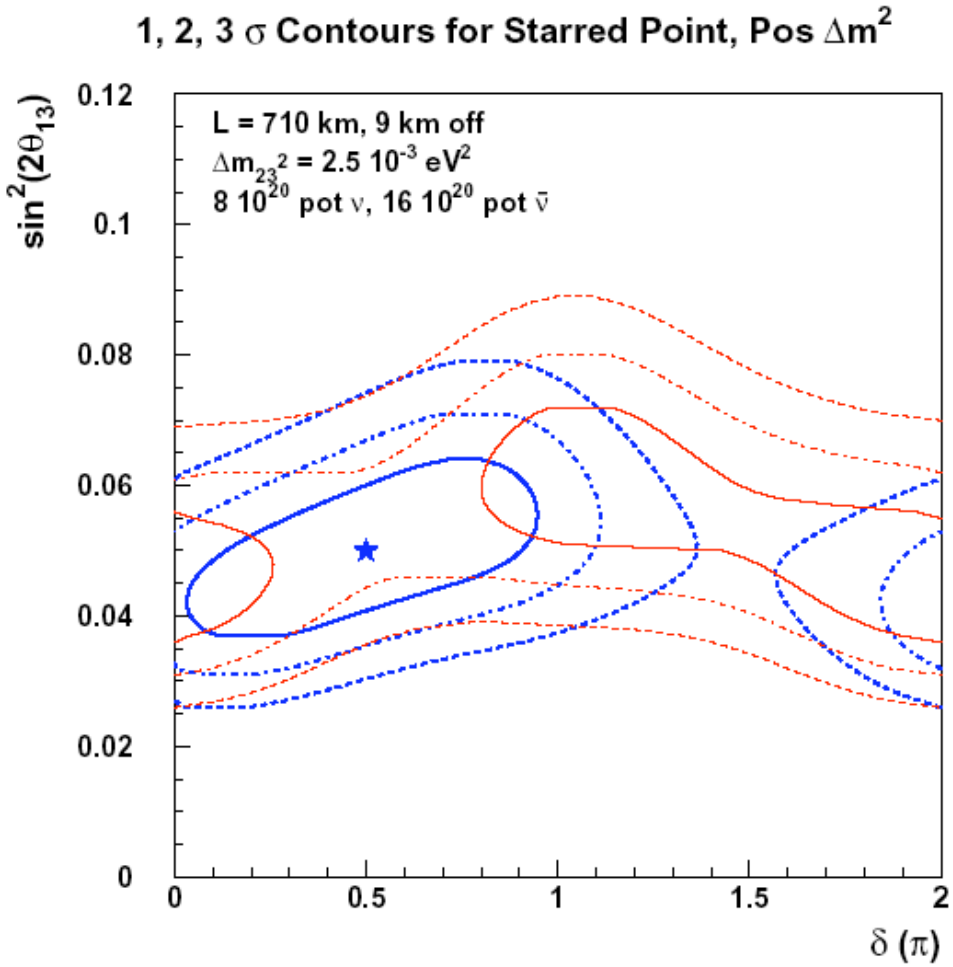
Sensitivities

- To consider sensitivities, I consider one experiment (or one set of experiments) with the expected results and calculate 1, 2, and 3 σ contours based on $\Delta\chi^2$'s, assuming 5% systematic error on the background.

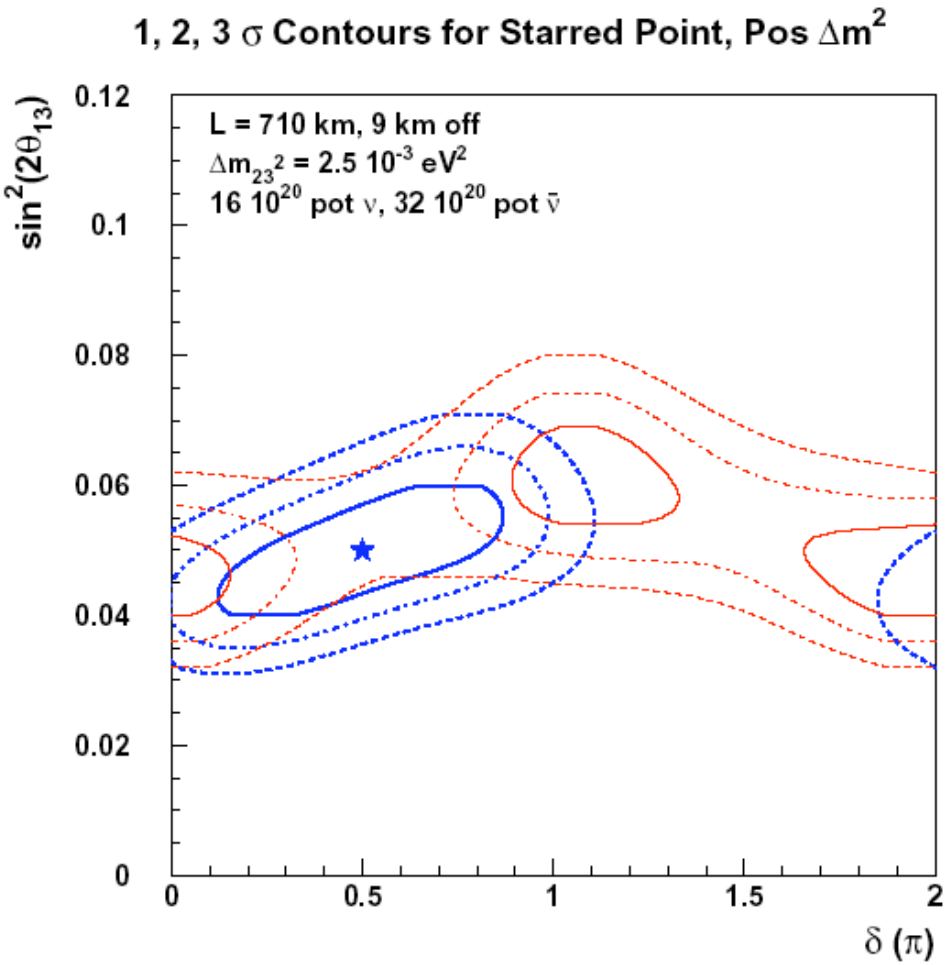
A Study Point



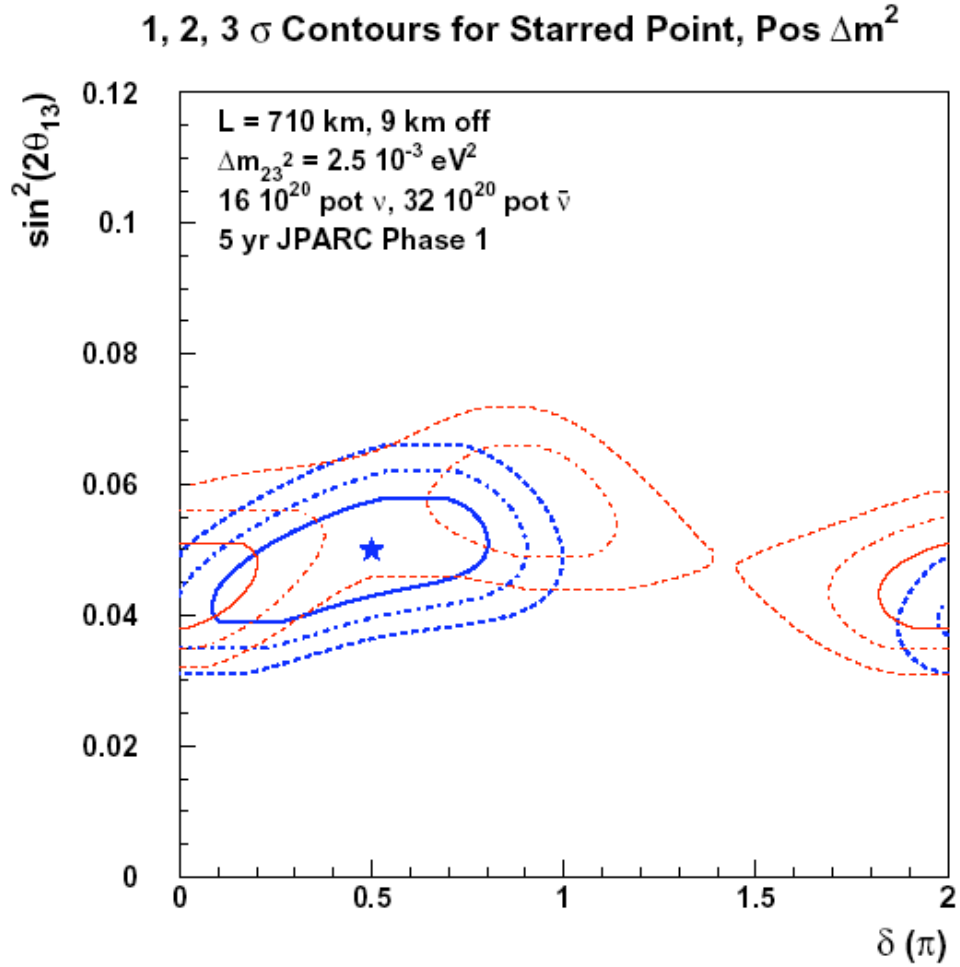
NuMI 2 yr ν, 4 yr $\bar{\nu}$
4 10^{20} pot/yr



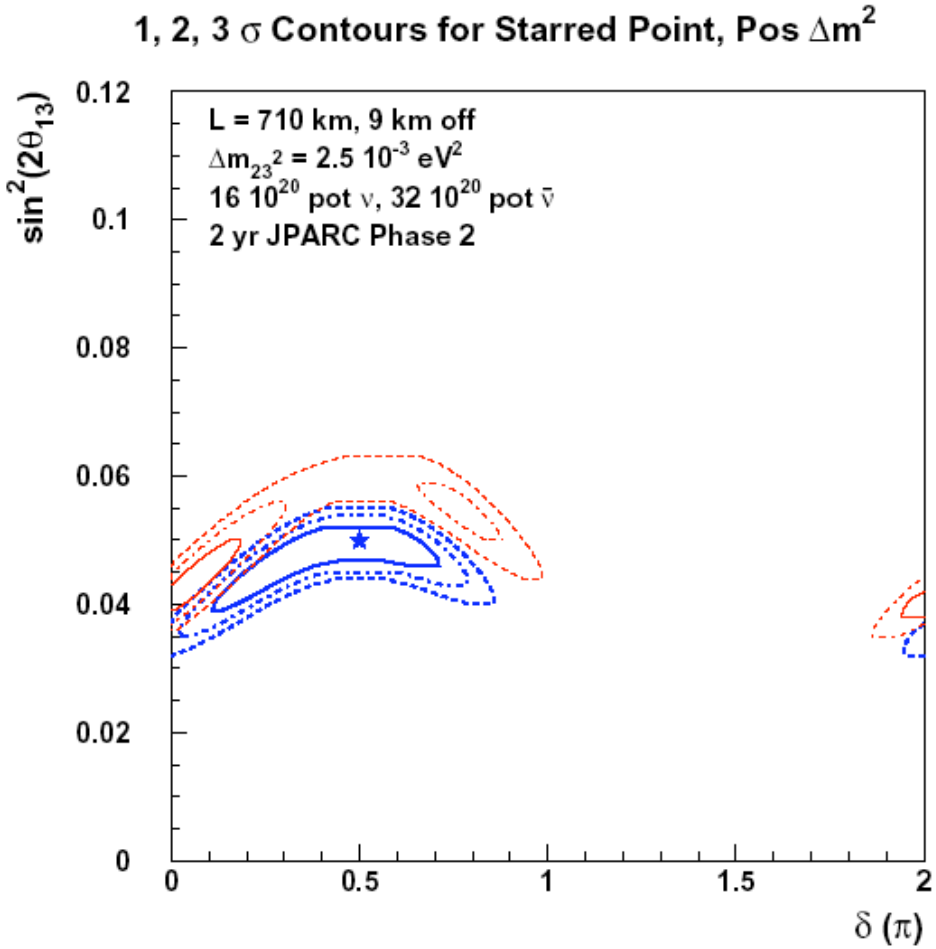
NuMI 2 yr ν, 4 yr $\bar{\nu}$
8 10^{20} pot/yr



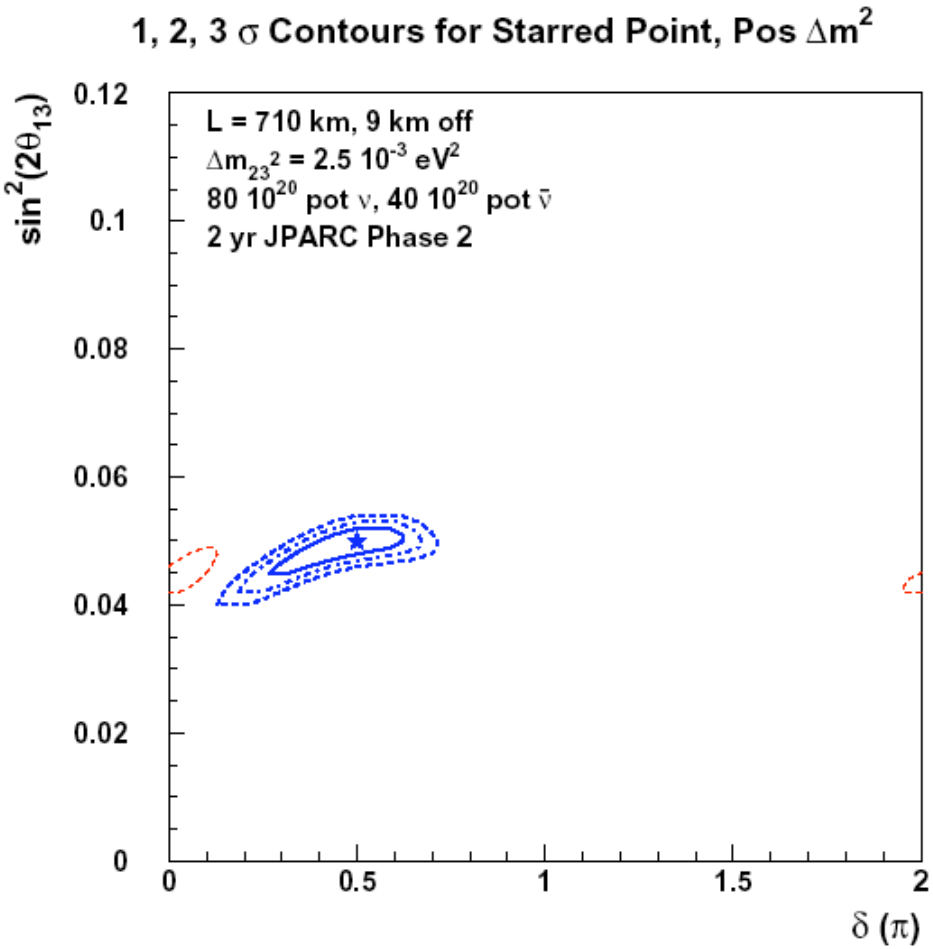
NuMI 2 yr ν, 4 yr $\bar{\nu}$, 8 10^{20} pot/yr and JPARC, Phase 1



NuMI 2 yr ν, 4 yr $\bar{\nu}$, 8 10^{20} pot/yr and JPARC, Phase 2

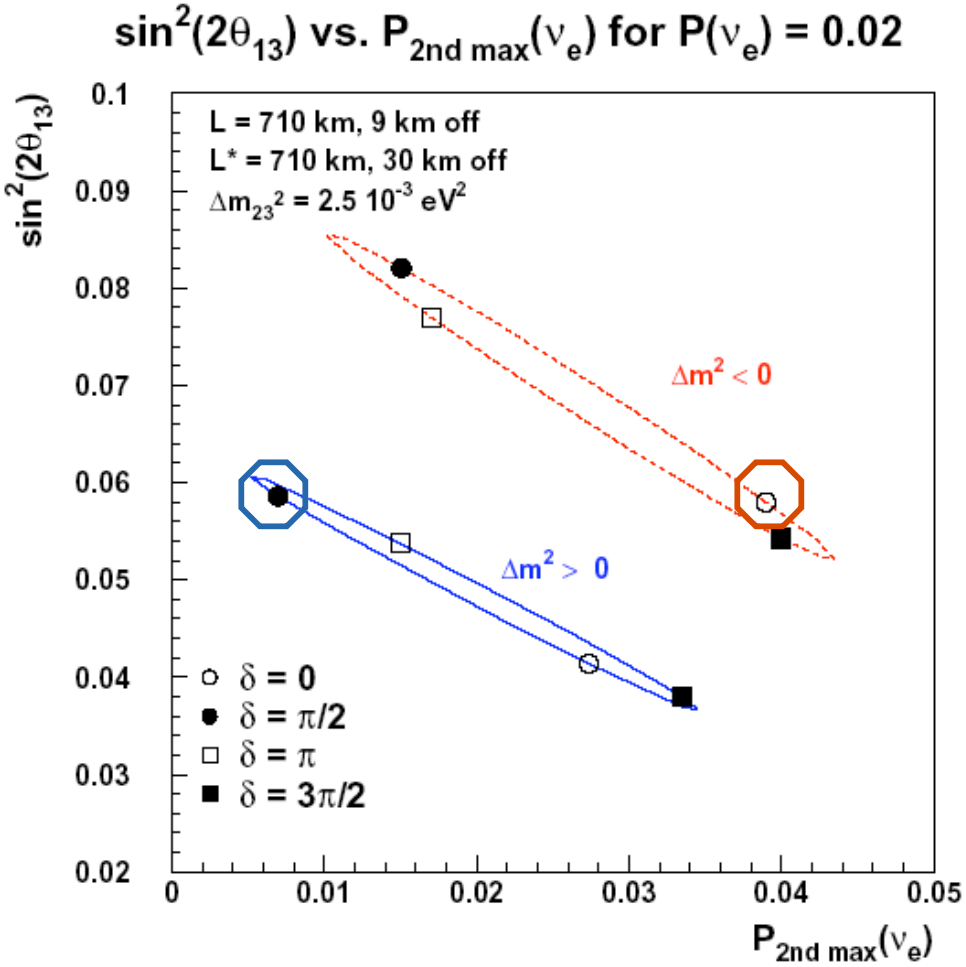


NuMI 4 yr ν, 2 yr $\bar{\nu}$, Proton Driver and JPARC, Phase 2

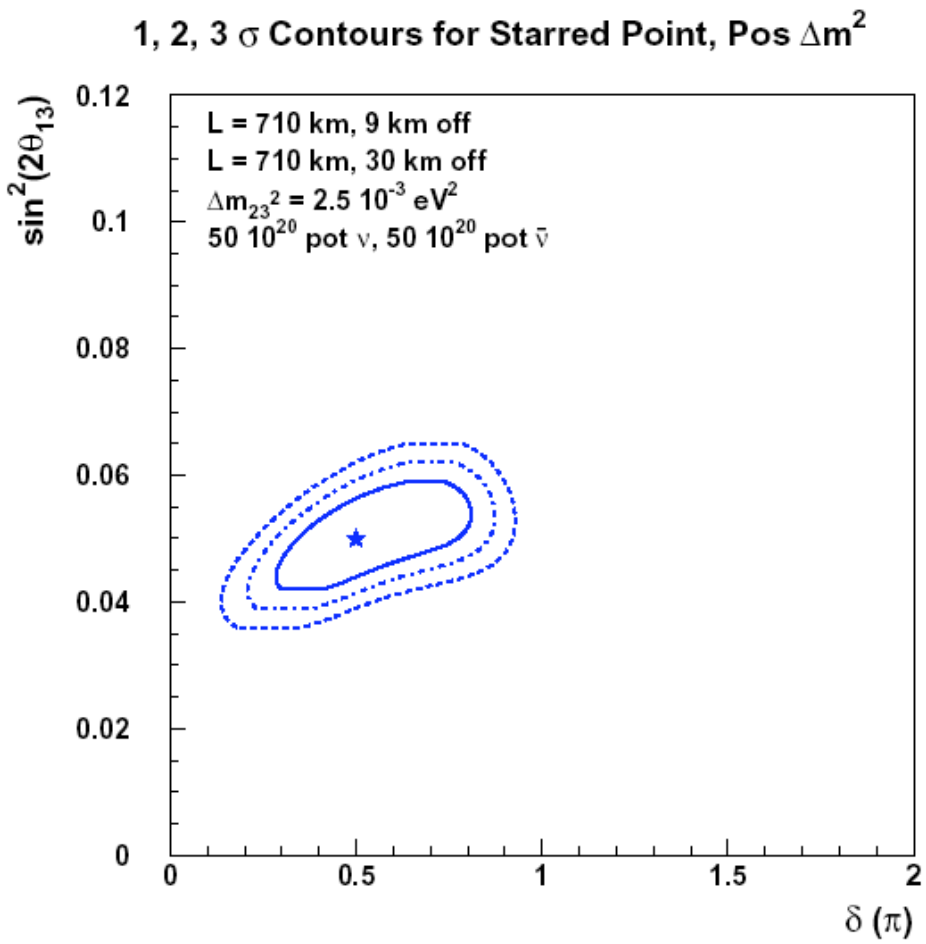


Hierarchy finally resolvable at > 95% CL with 6 yrs of proton driver.

A 2nd Detector at the 2nd Maximum?

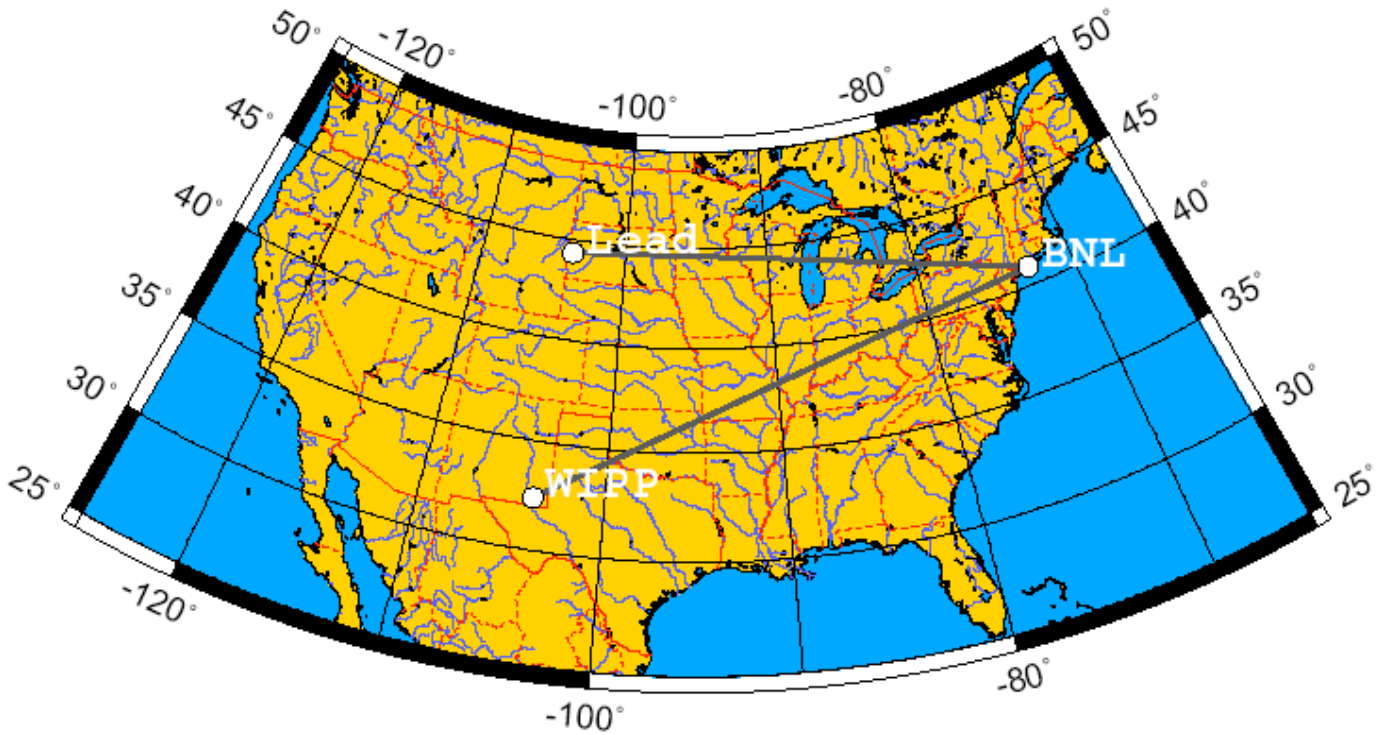


NuMI 2.5 yr ν, 2.5 yr $\bar{\nu}$, 2 Detectors and Proton Driver



Brookhaven White Paper

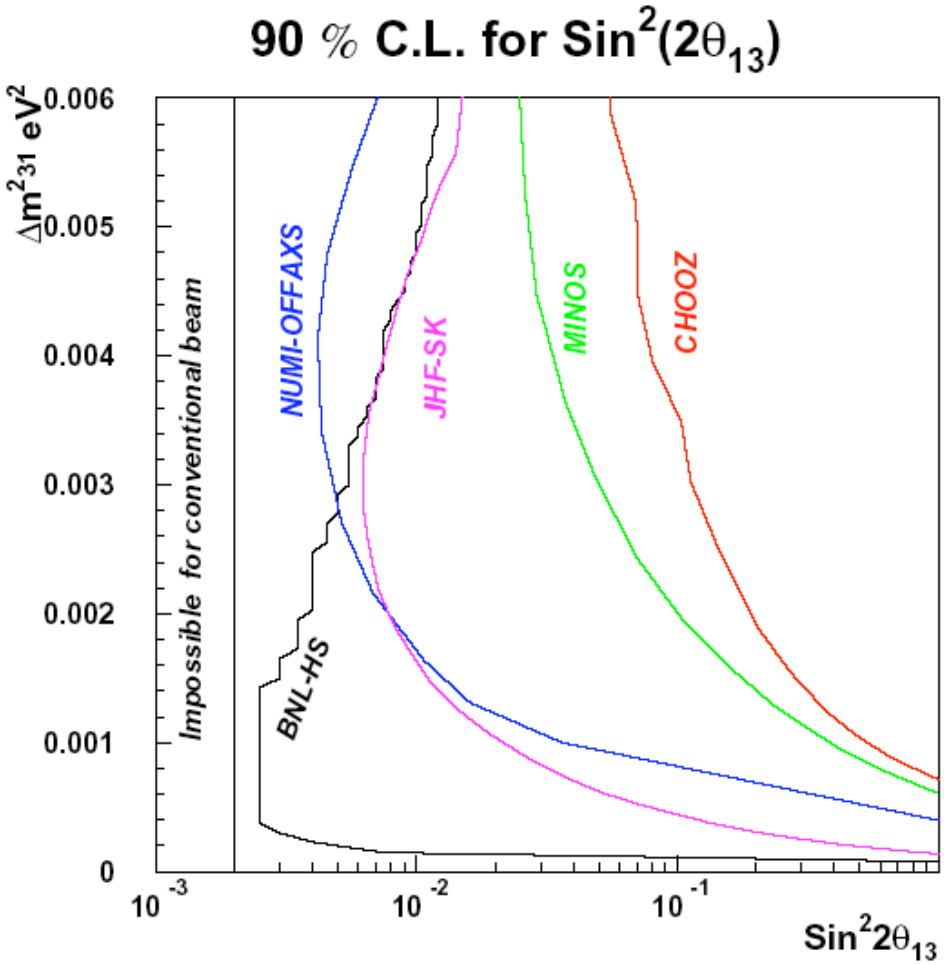
- **Pushing conventional beams to their limit – very long baseline**



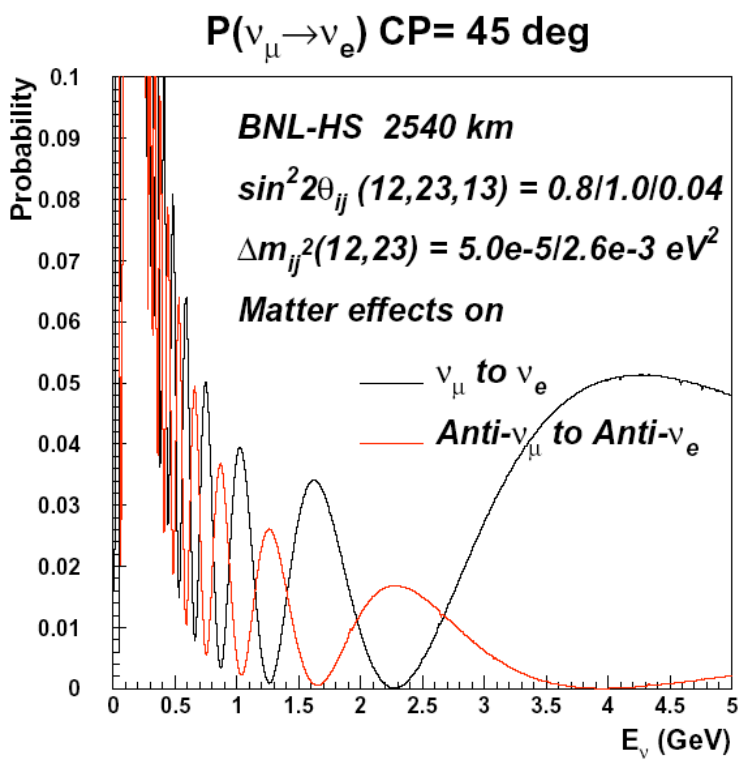
Brookhaven White Paper (2)

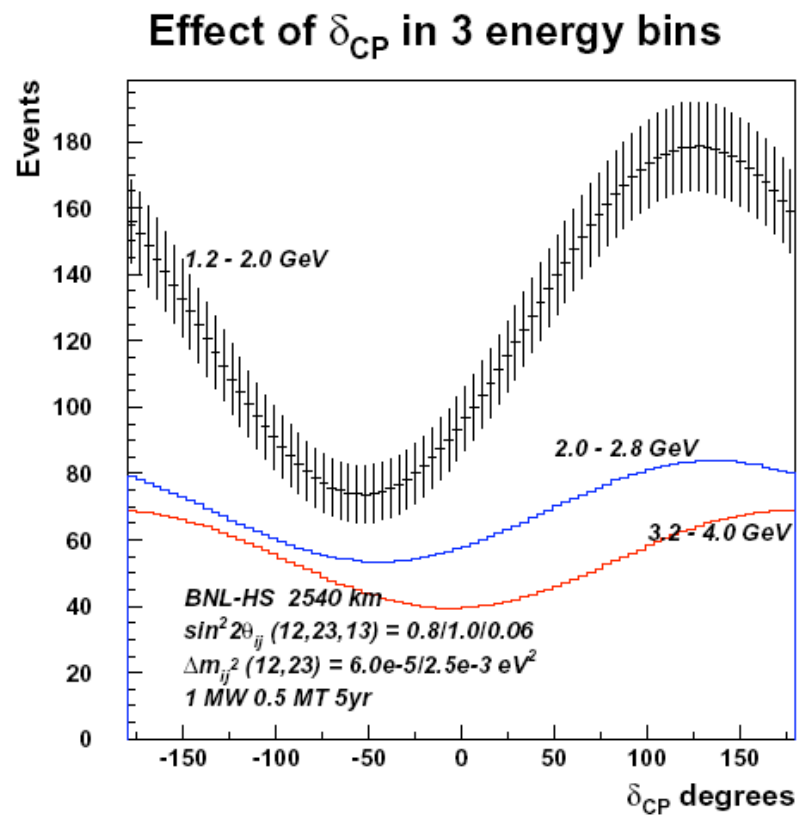
- Wide band beam (0.5 to 6 GeV)
- AGS upgrade from present 0.17 MW to 1 MW 1 GeV superconducting linac
- 0.5 MT water Cerenkov detector at WIPP or Homestake

θ_{13} Sensitivity



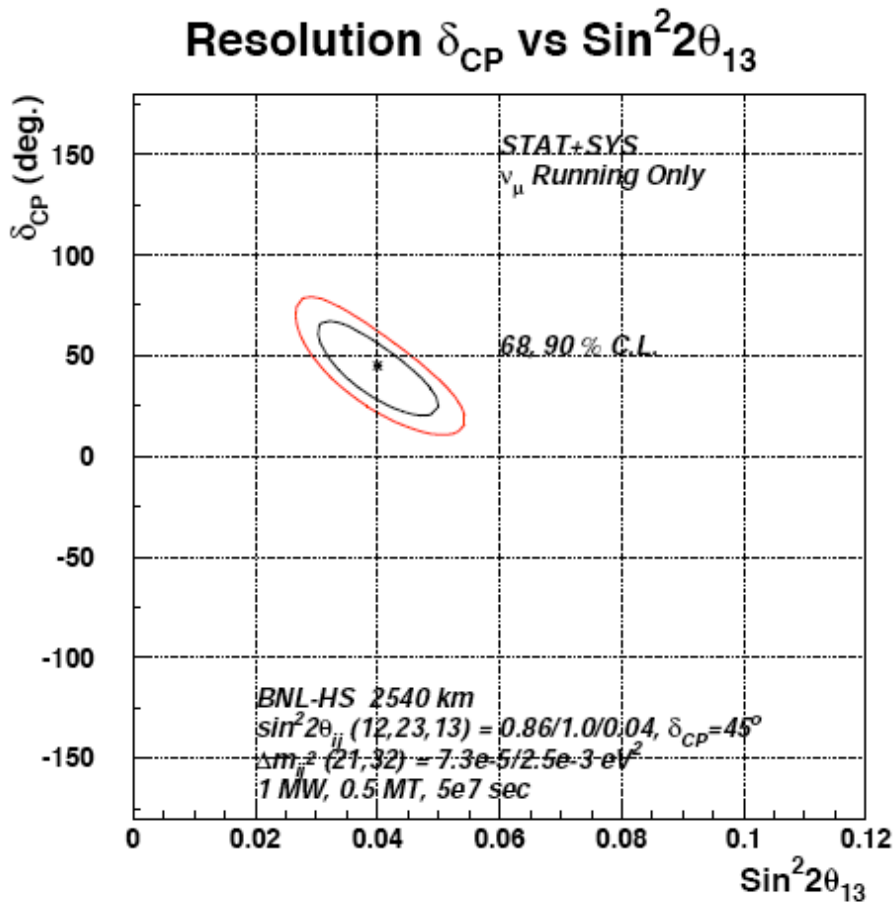
Large Matter and CP Effects With Only ν Running





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

90% CL Sensitivity to $\sin^2(2\theta_{13})$ and δ



Background-Free Techniques

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

Beta Beams

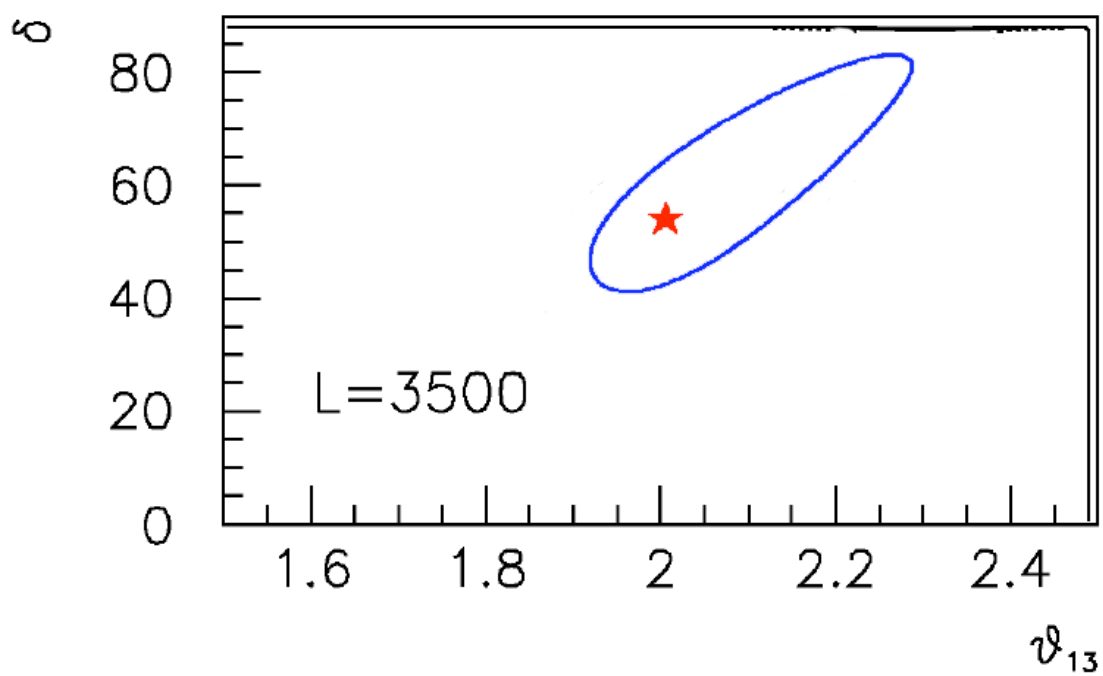
- Proposal by P. Zucchelli hep-ex/0107006
- Idea: Accelerate short-lived ions:
  - Pure sub-GeV ν_e and $\bar{\nu}_e$ beams
  - Known spectrum
  - Only backgrounds are from misidentifications
- Examples:
  - $^{6}\mathrm{He} \rightarrow {}^{6}\mathrm{Li} + e^{-}\bar{\nu}_e, \langle E \rangle = 1.9\ \mathrm{MeV},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

Measuring CP Violation

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



Conclusion

- Measuring the remaining lepton mass and mixing parameters is doable, but is likely to be a long and difficult process.
- It is not a process which can simply be left to the Japanese – a long baseline is essential.
- Options:
  - We can proceed step by step, gaining information on the optimum next stage (NuMI off-axis), or
  - We can proceed more vigorously to a ~B$ facility, depending on available resources and the priorities of the field (BNL white paper).