Off Axis

The NuMI Off-Axis Experiment

NO-VE Workshop

Venice

4 December 2003

Gary Feldman

Off Axis

Off-Axis Beams

- It is clear that the next generation of experiments will concentrate on $\nu_e \leftrightarrows \nu_\mu$ oscillations, which are needed for
  - $\sin^2(2\theta_{13})$
  - sign(Δm_{13}^2)
  - δ

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Off-Axis Rationale

- Want low-energy narrow-band beams at the $\Delta m^2_{13} \Delta \Delta m^2_{23}$ 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
- ⇒ NuMI Off-axis Experiment

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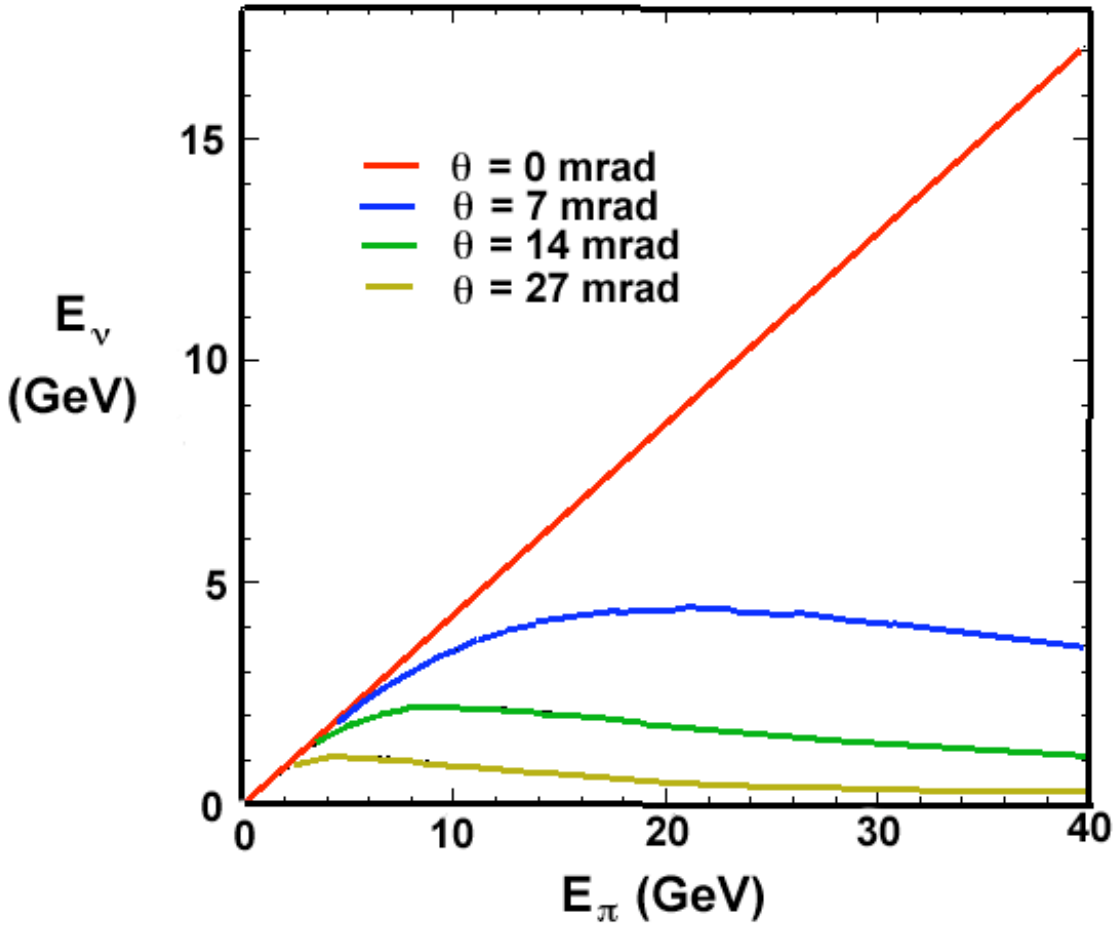
Off-Axis Kinematics



$$E_{\nu} = \frac{0.43 E_{\pi} m_{\pi}}{1 + \theta^2 \theta^2}$$

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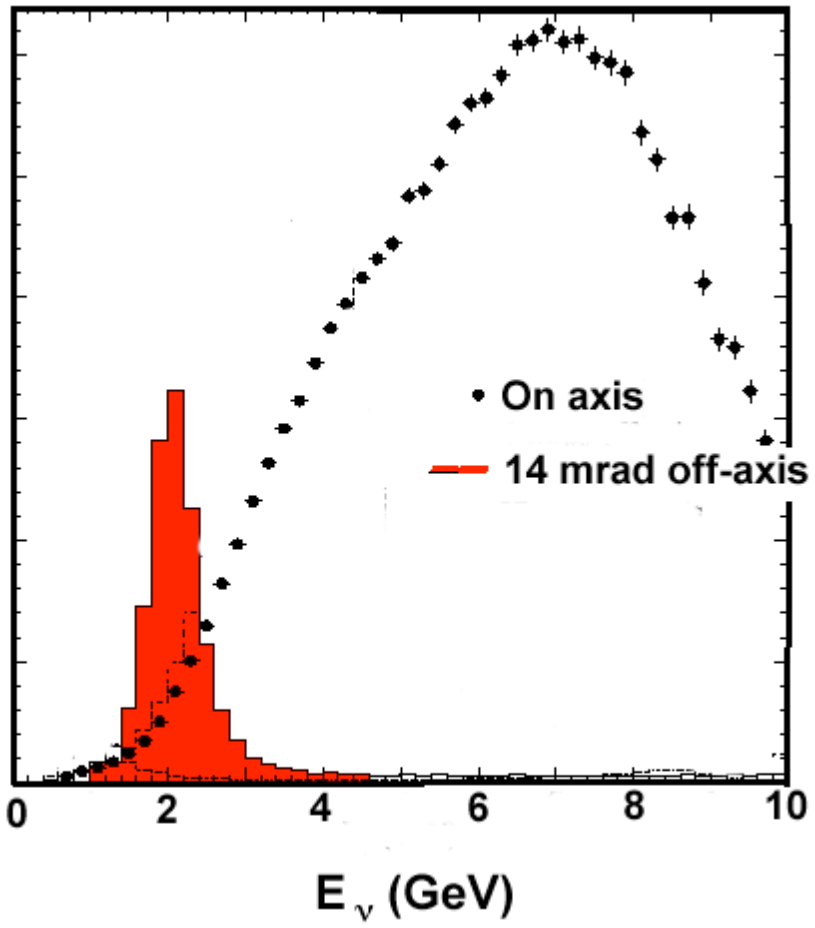
Off-Axis Spectrum (No oscillations)



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NuMI Off-Axis Proposal

- **The Off-Axis experiment is proposed to be**
  - **50 kT**
  - **Medium-Z sandwich detector**
    - **Particle board absorber**
    - **Liquid scintillator strip detectors with APD readout**
    - **Glass RPC detectors backup option**
    - **We will re-evaluate the technology decision in a year.**
  - **810 km baseline, about 12 km off-axis (Ash River, MN)**
  - **Current cost estimate about 170 M$**
  - **Collaboration of 33 institutions from 8 countries; seeking additional collaborators**
    - **One day meeting in Cambridge, England, January 12**

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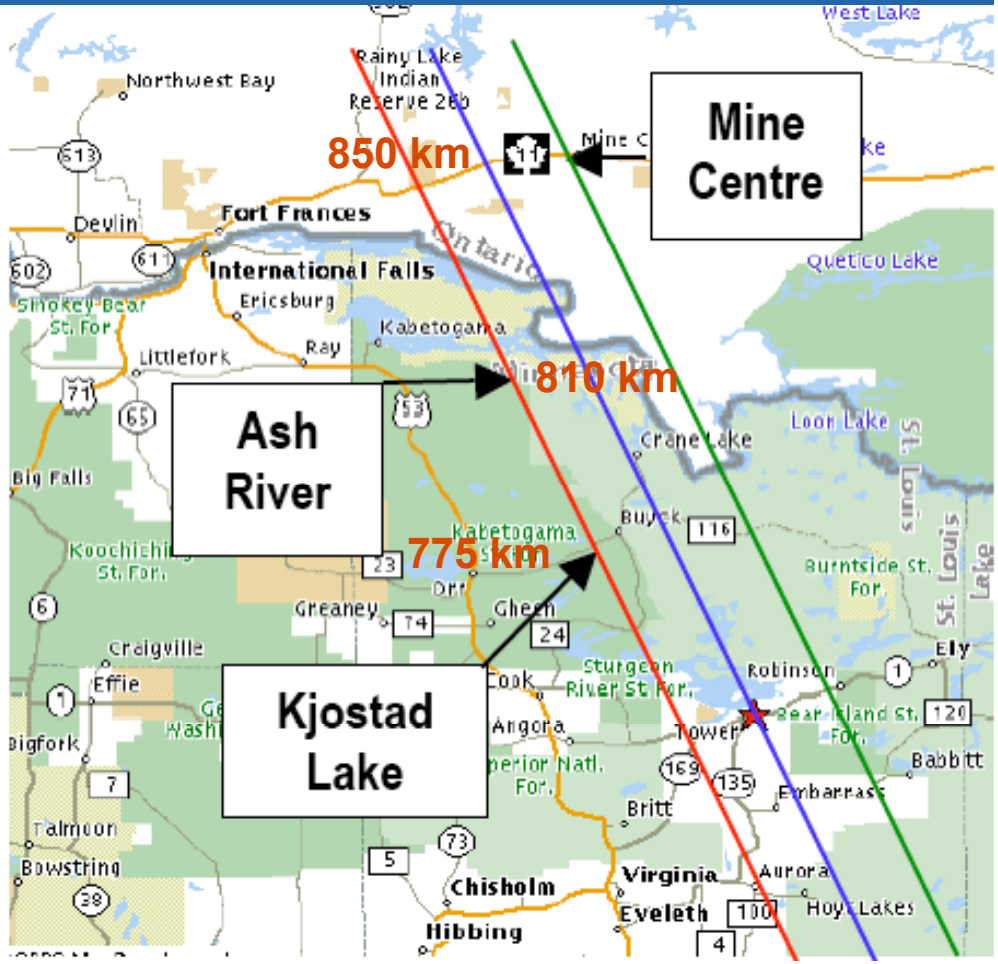
Possible Sites

We are now focusing on the Ash River site.



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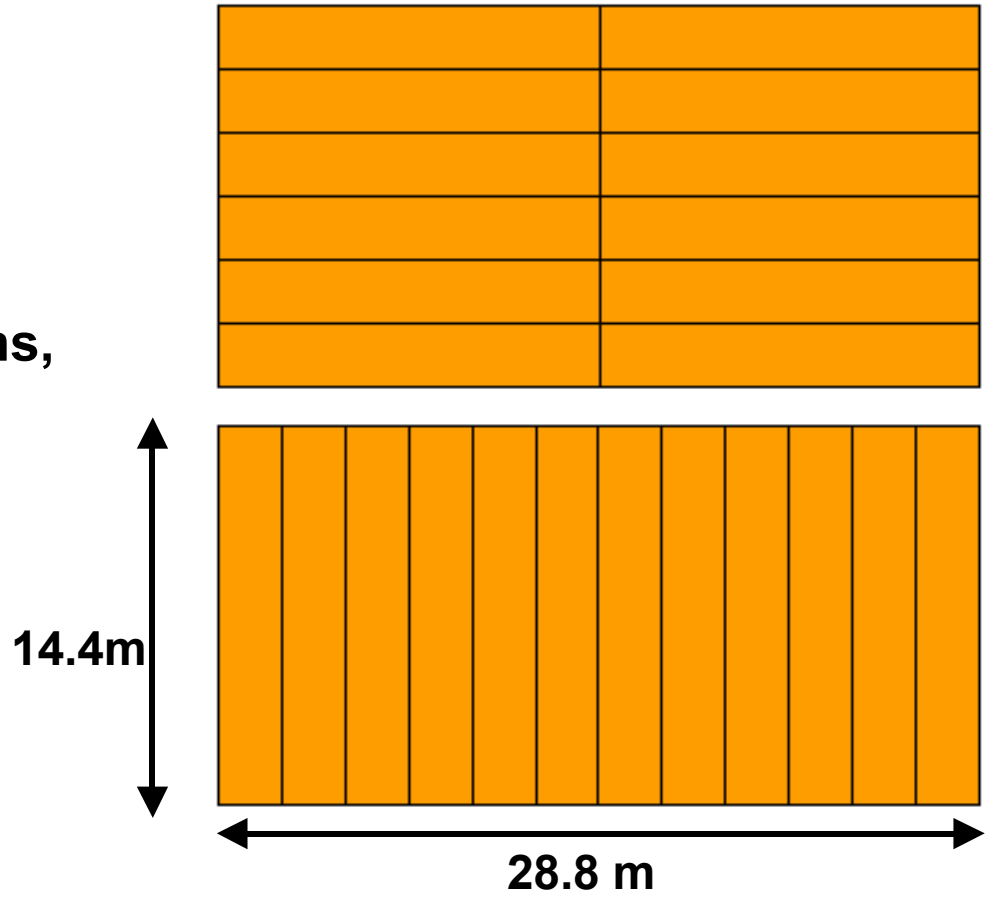
Scintillator Layout

Monolithic structure

Liquid Scintillator:
1.2 m x 3 cm x 14.4 m
30-cell PCV extrusions,
24 extrusions/plane,
750 planes
= 18 000 extrusions
= 540 000 channels

Absorber:
20 cm particleboard/ plane (~1/3 X_o)



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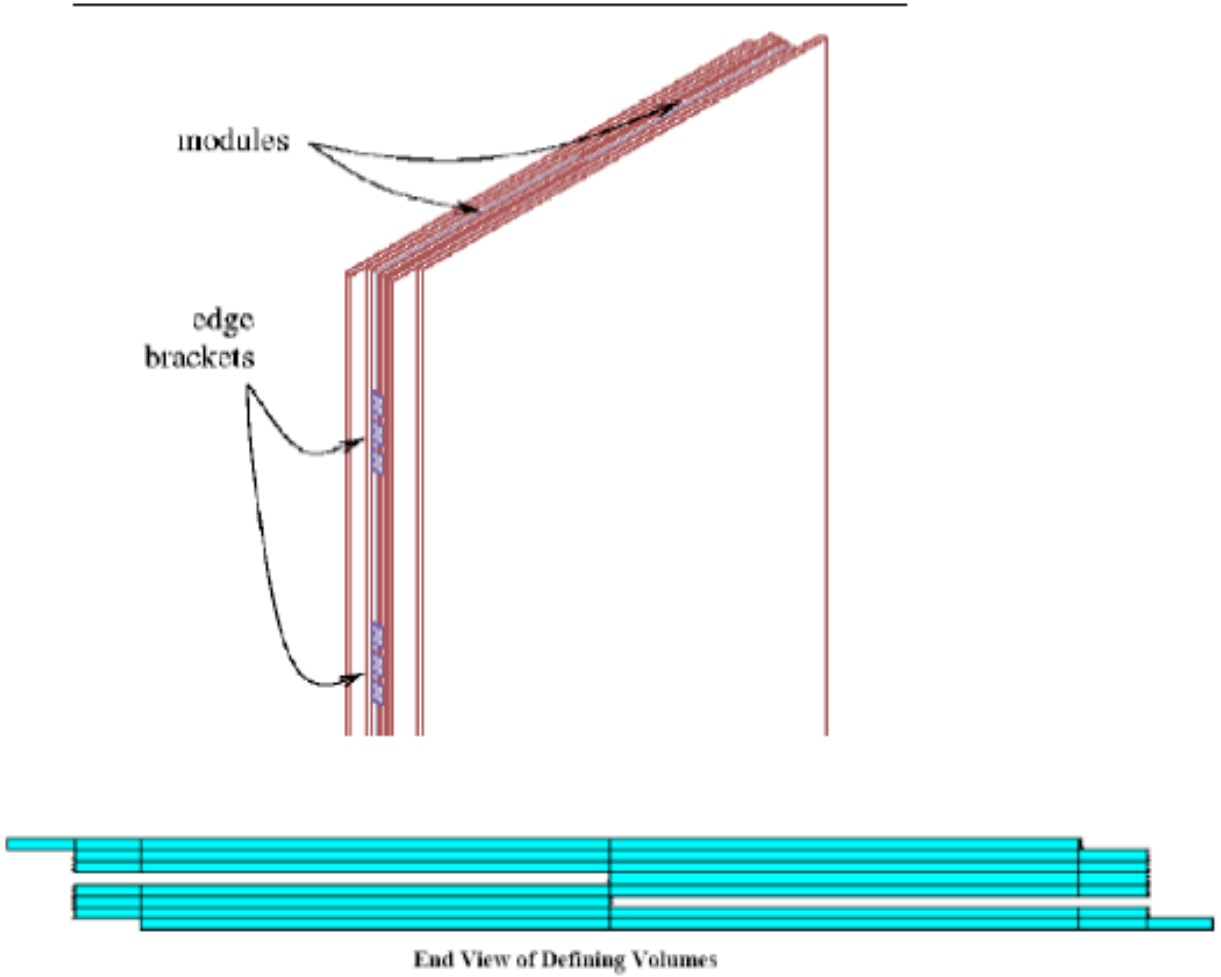
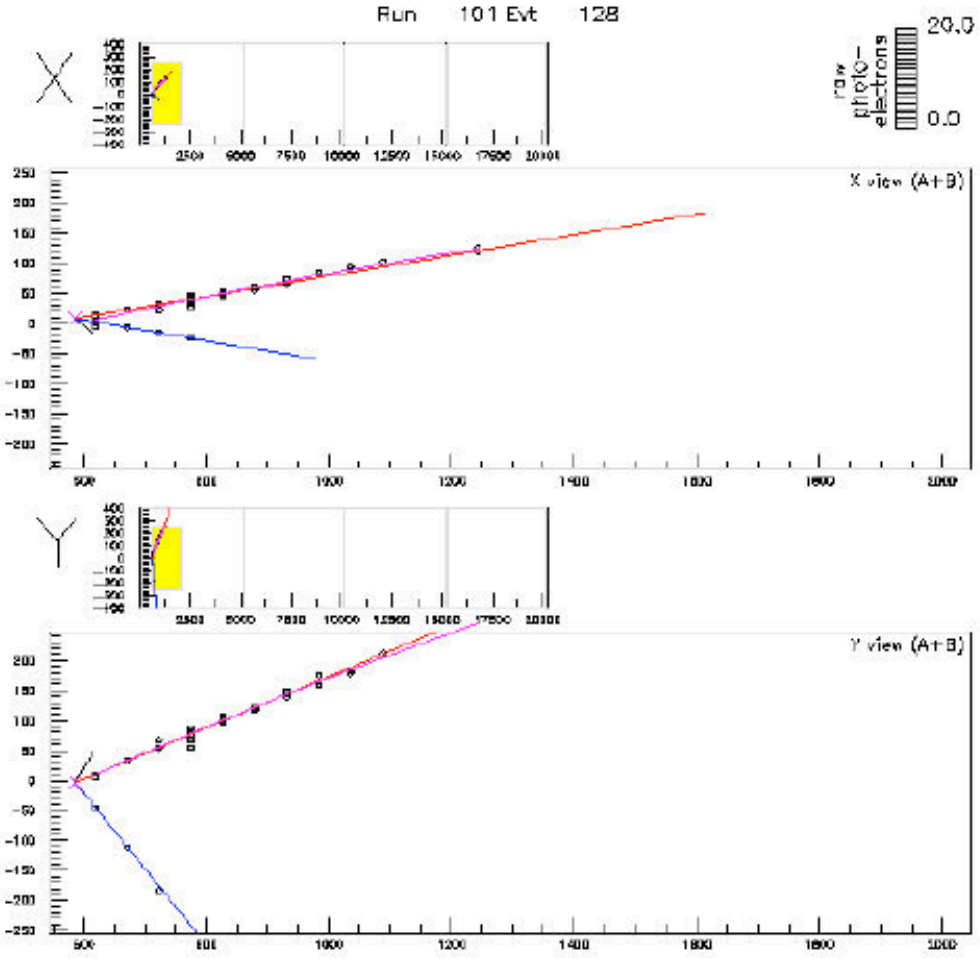
Absorber Structure Details



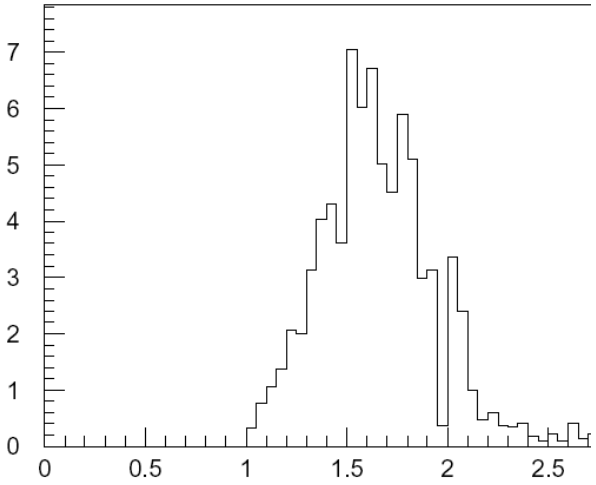
End View of Defining Volumes

Off Axis

Electron Track



Hits per plane > 1



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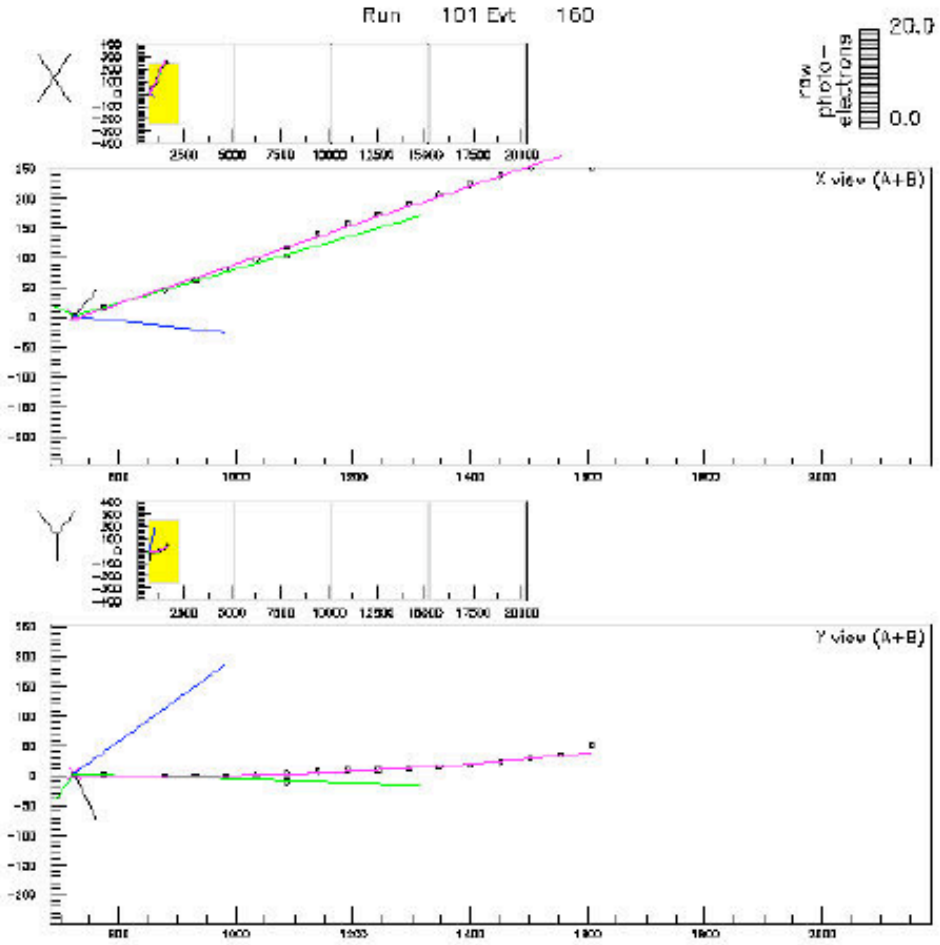
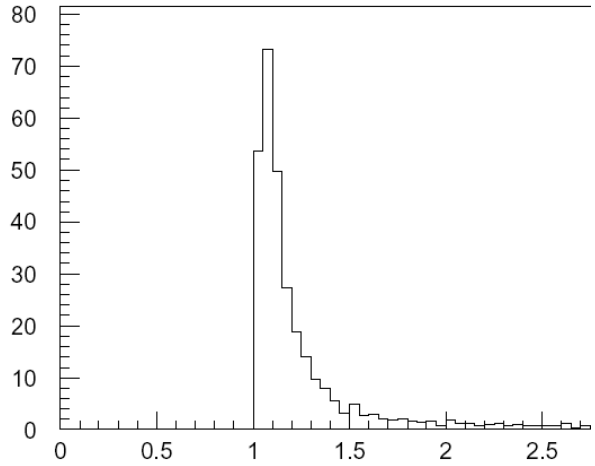
Muon track



Hits per plane ~1



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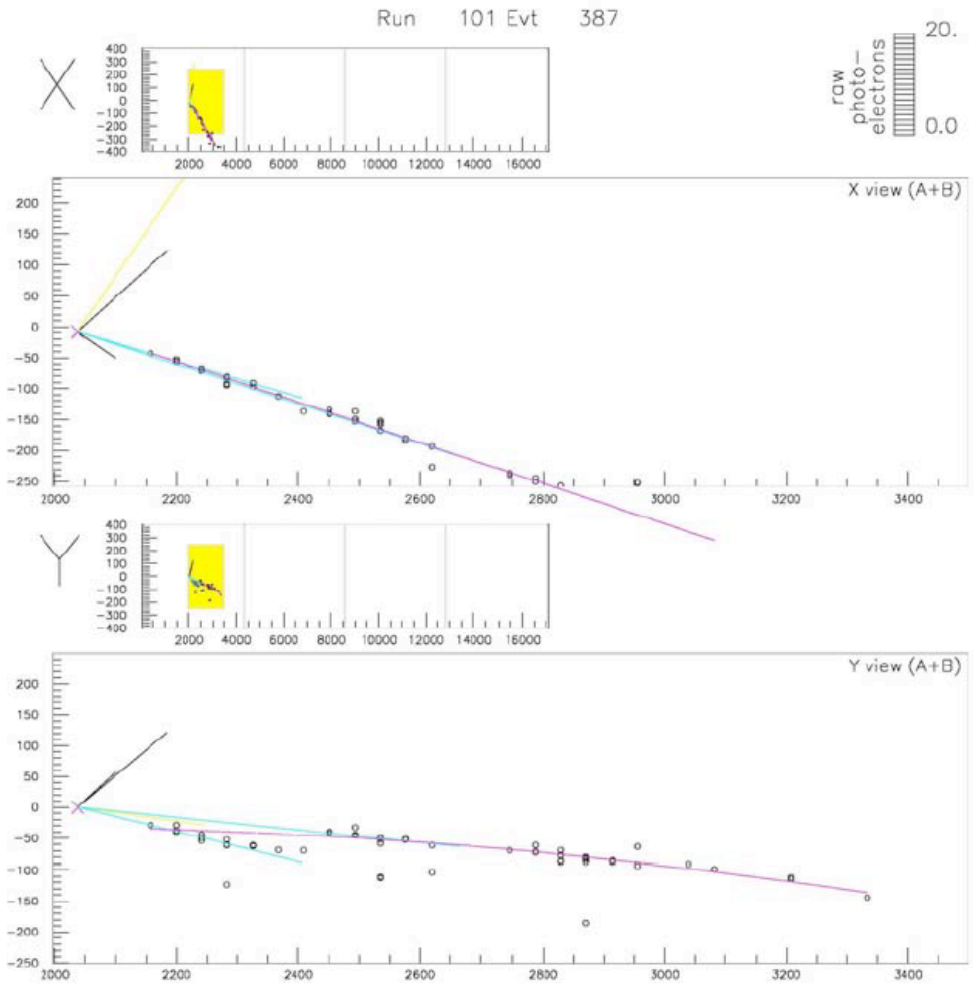
NC with leading π^0



Two tracks with different starting points leading to a "gap"

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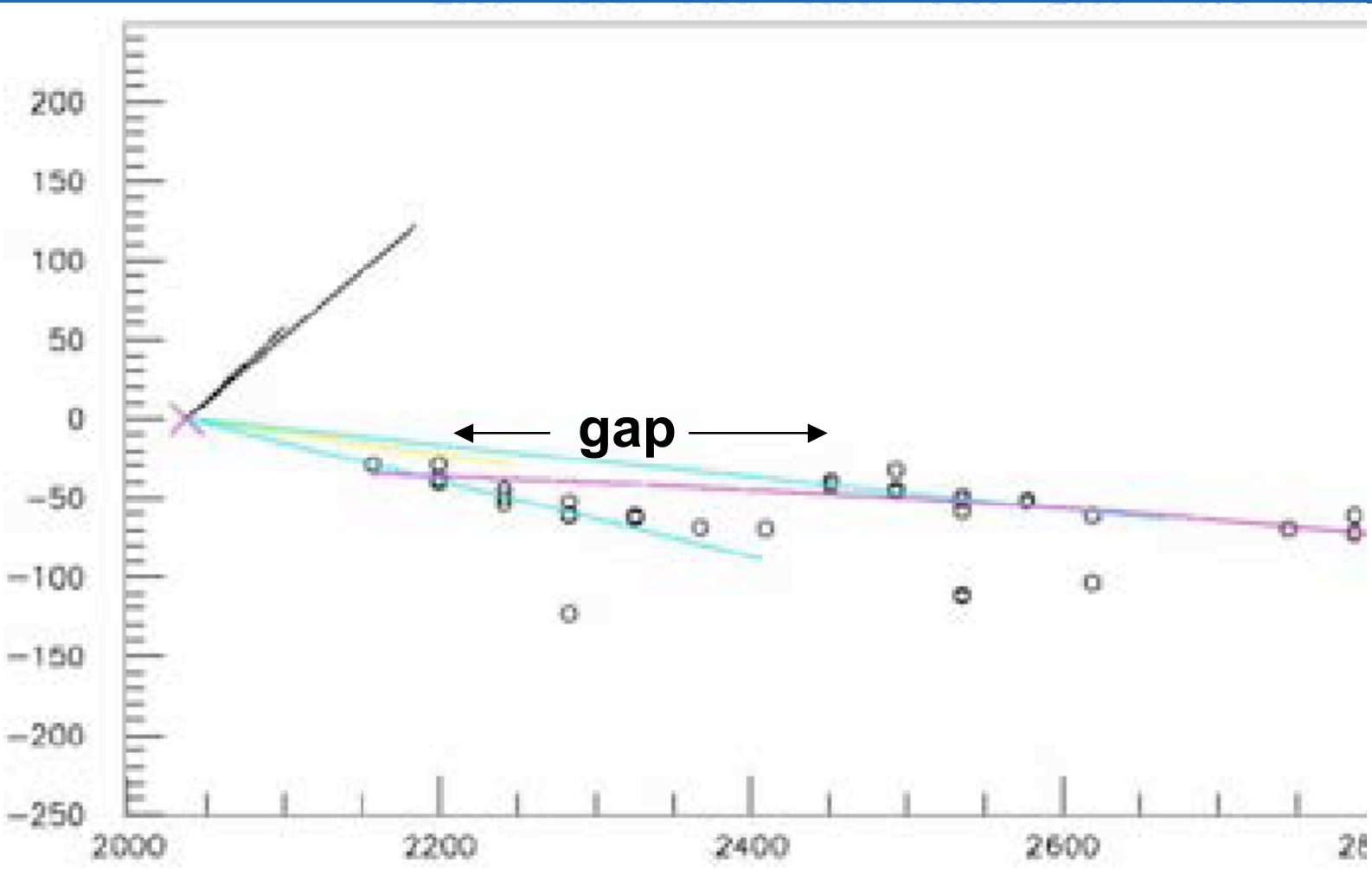
Detail of NC with leading π^0



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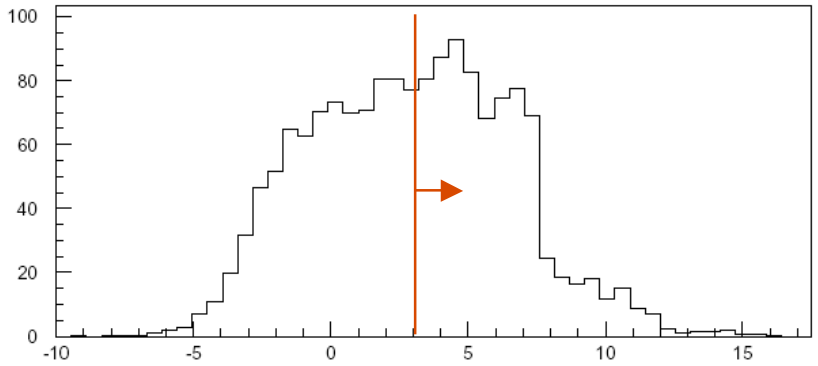
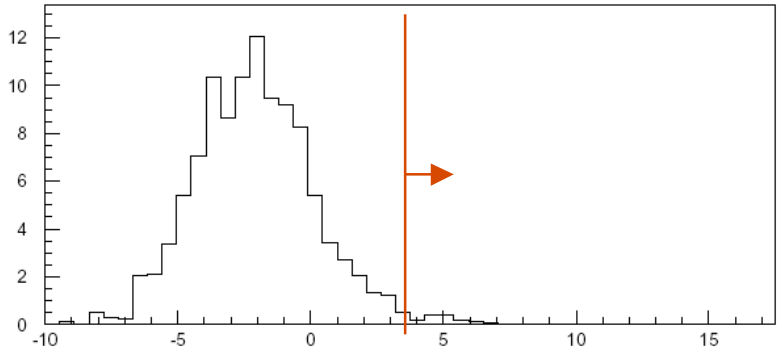
NC Backgrounds

- **NC backgrounds can be rejected by a likelihood analysis based on topological parameters**

Signal Likelihood



NC Likelihood



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

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

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

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

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P(□μ □ □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.

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

About a ±23% effect for NuMI, but only a ±10% effect for JPARC .

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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 sign(Δm_{13}^2) or δ.

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Probability Plots

- **Probability plots assumes a particular result for a measurement of P($\nu_\mu \to \nu_e$) and show**
  - **The possible values of $\sin^2(2\theta_{13})$, sign(Δm_{13}^2), and δ consistent with this measurement, and**
  - **How another another measurement would discriminate among them.**

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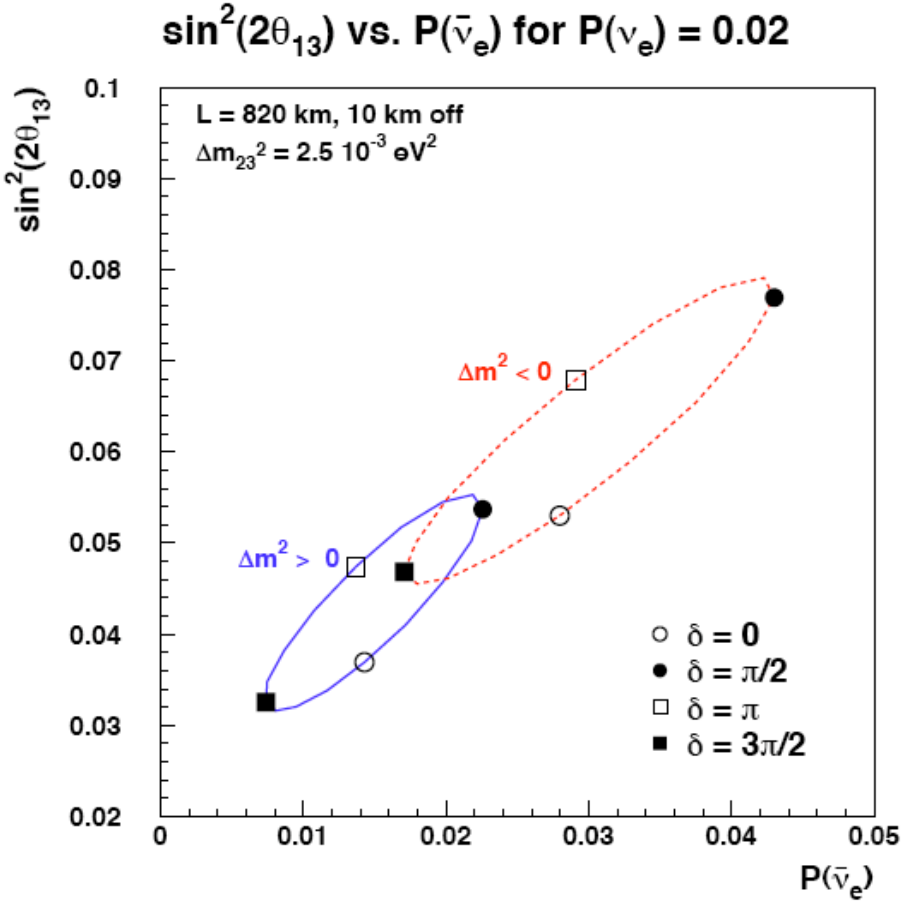
P(□μ □ □e) = 0.02 at 820 km



Note

(1) Effect of cos(□) term

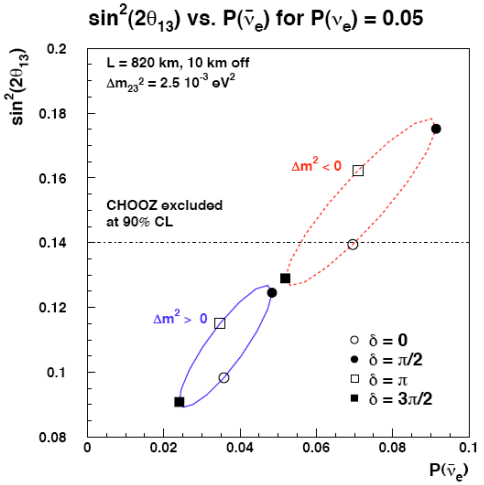
(2) Ambiguities

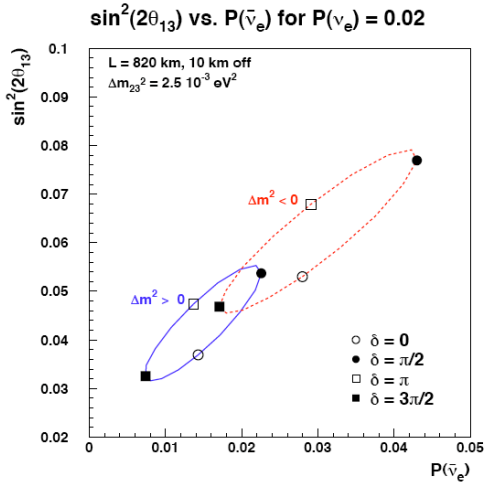
(Hidden ambiguity: P1 μ sin²(□23); if sin²(2□23) = 0.95, sin²(□23) = 0.39 or 0.61)

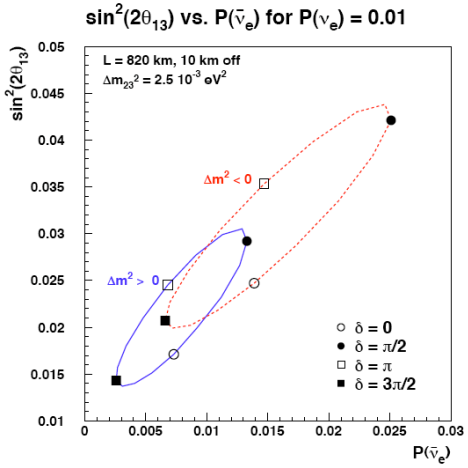
(1) Rough equivalence of reactor and antineutrino measurements

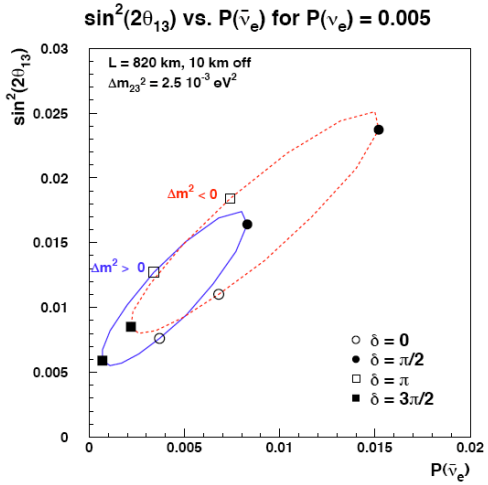
Off Axis

P(□□ □e) = 0.05, 0.02, 0.01, and 0.005 at 820 km



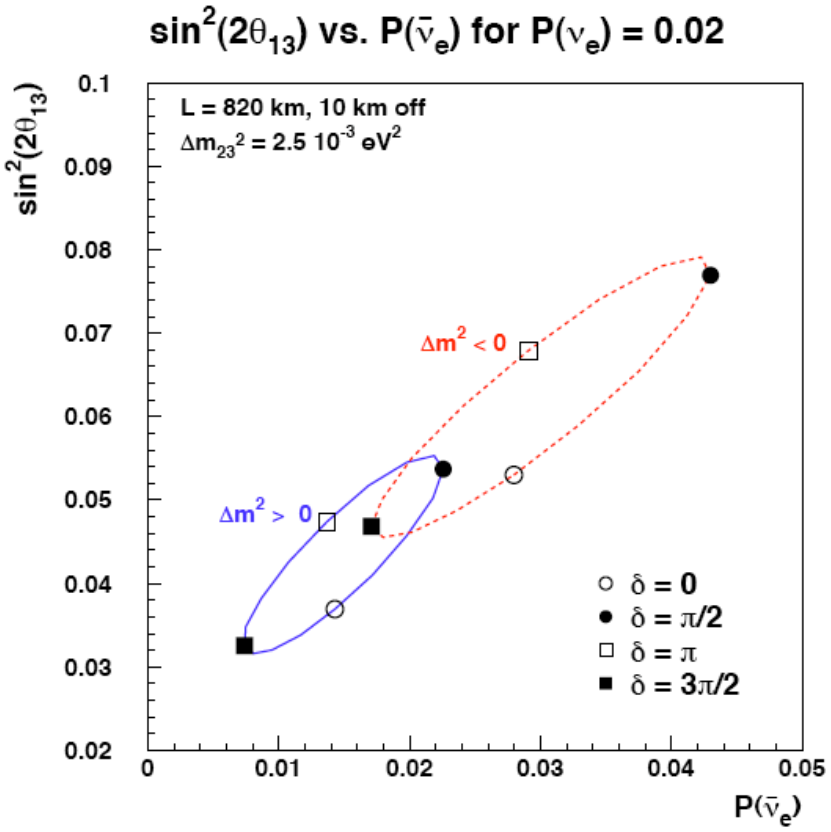


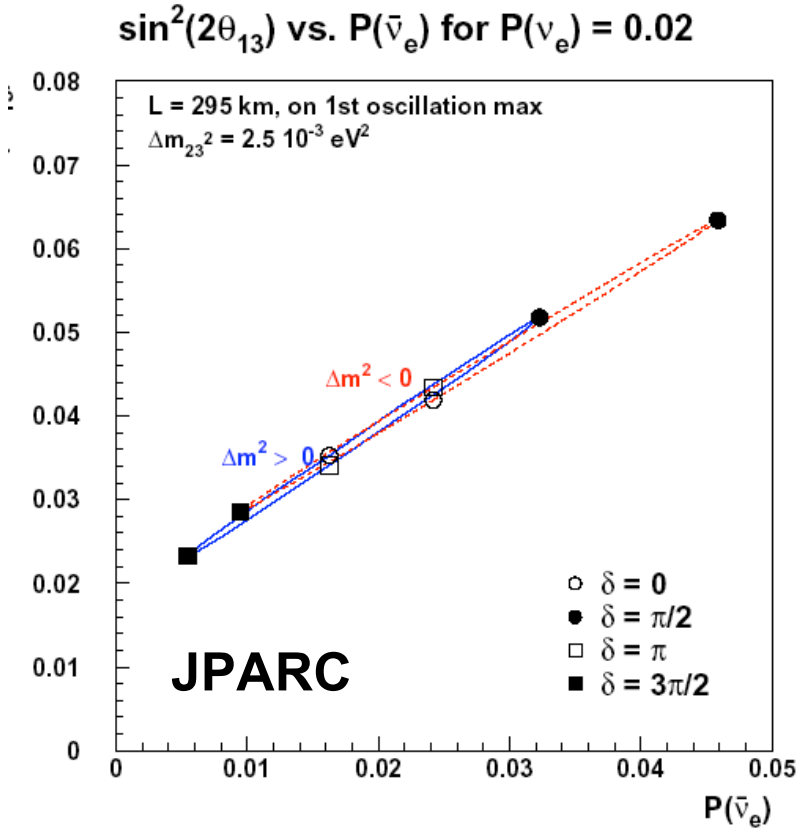




Off Axis

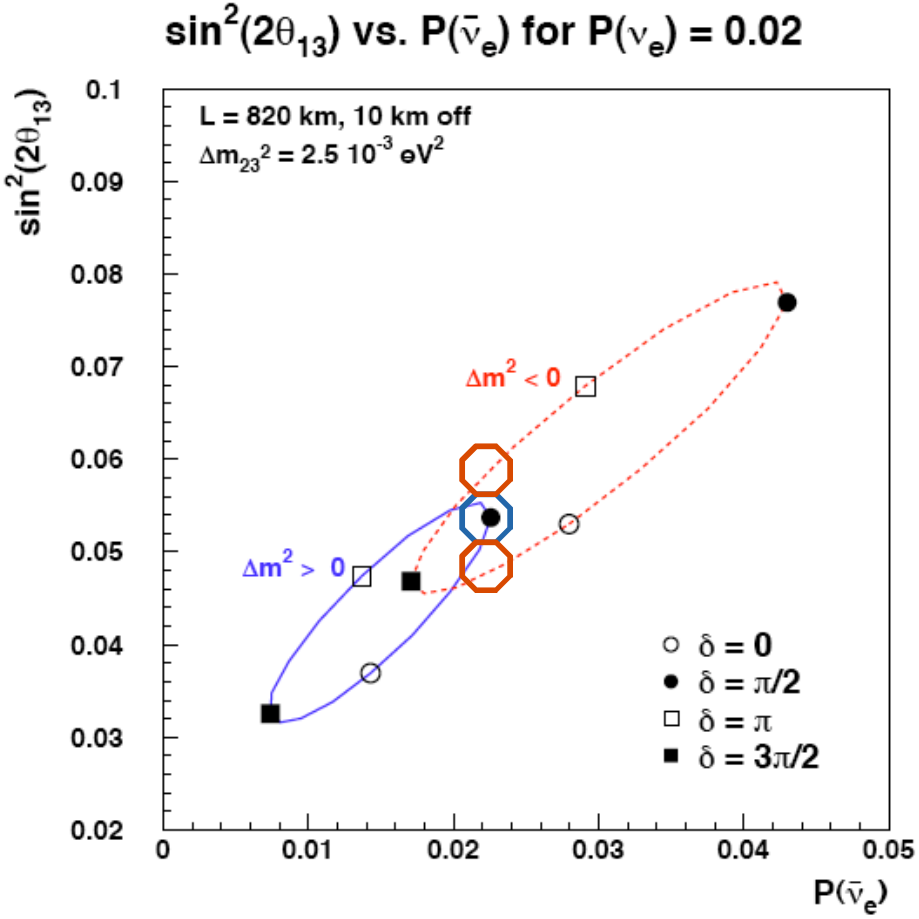
P(□□ □e) = 0.02 at 820 and 295 km





Off Axis

P(□□ □e) = 0.02 at 820 km

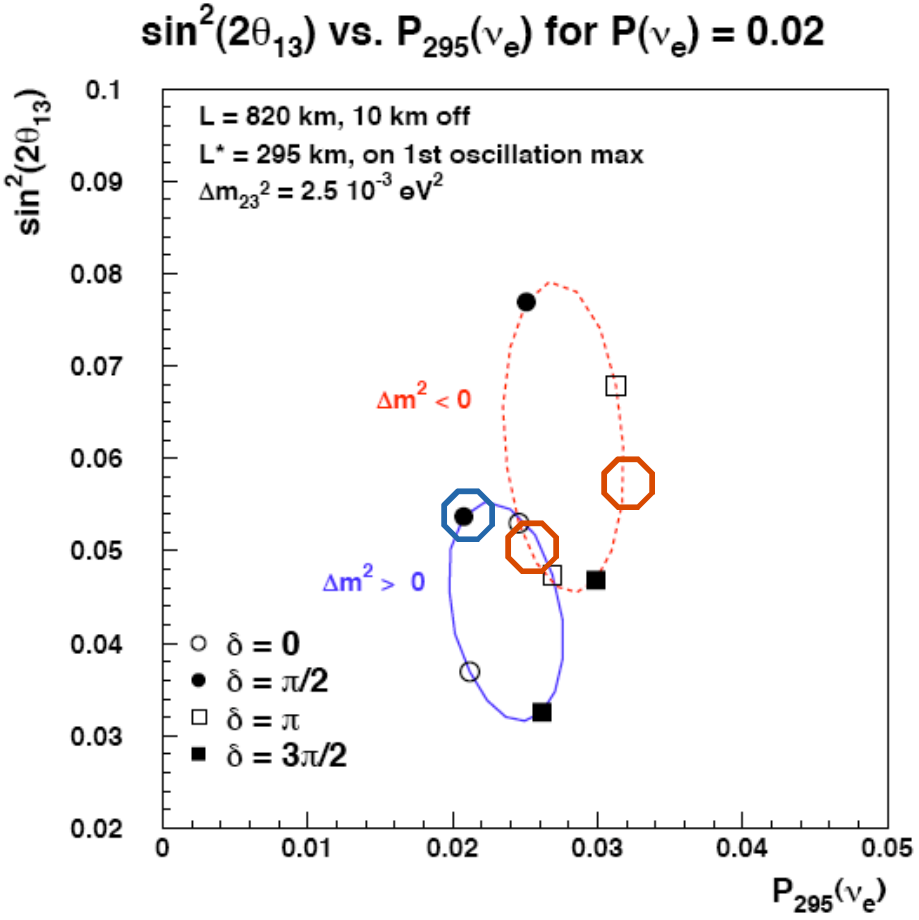


Note ambiguities between normal hierarchy and inverted hierarchy.

Can combining JPARC and NuMI data help?

Off Axis

P(□μ□ □e) = 0.02 at 820 km vs. P(□μ□ □e) at 295 km



Ambiguous points are still fairly close together

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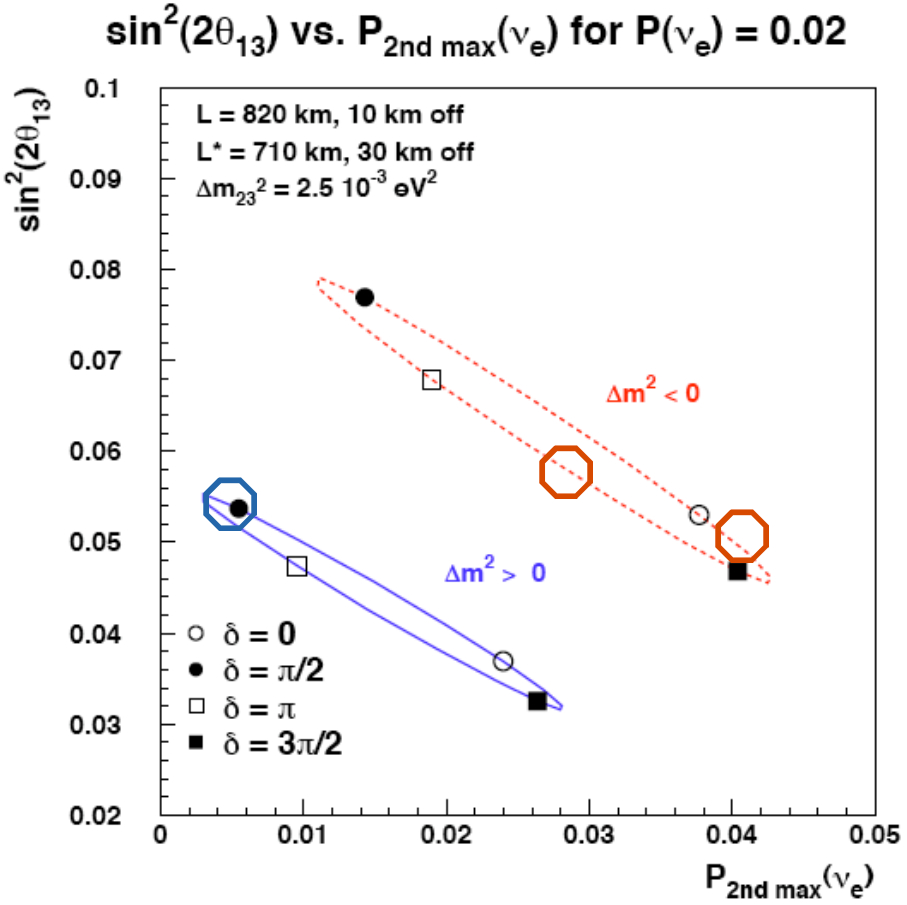
A 2nd Detector at the 2nd Maximum?



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Goals of the Off-Axis Experiment

- **Primary goal: Find evidence for $\nu_\mu \to \nu_e$, determining $\sin^2(2\theta_{13})$ to a factor of 2.**
- **Longer term goal: Determine the mass hierarchy.**
- **Ultimate goal: Precision measurement of the CP-violating phase δ.**

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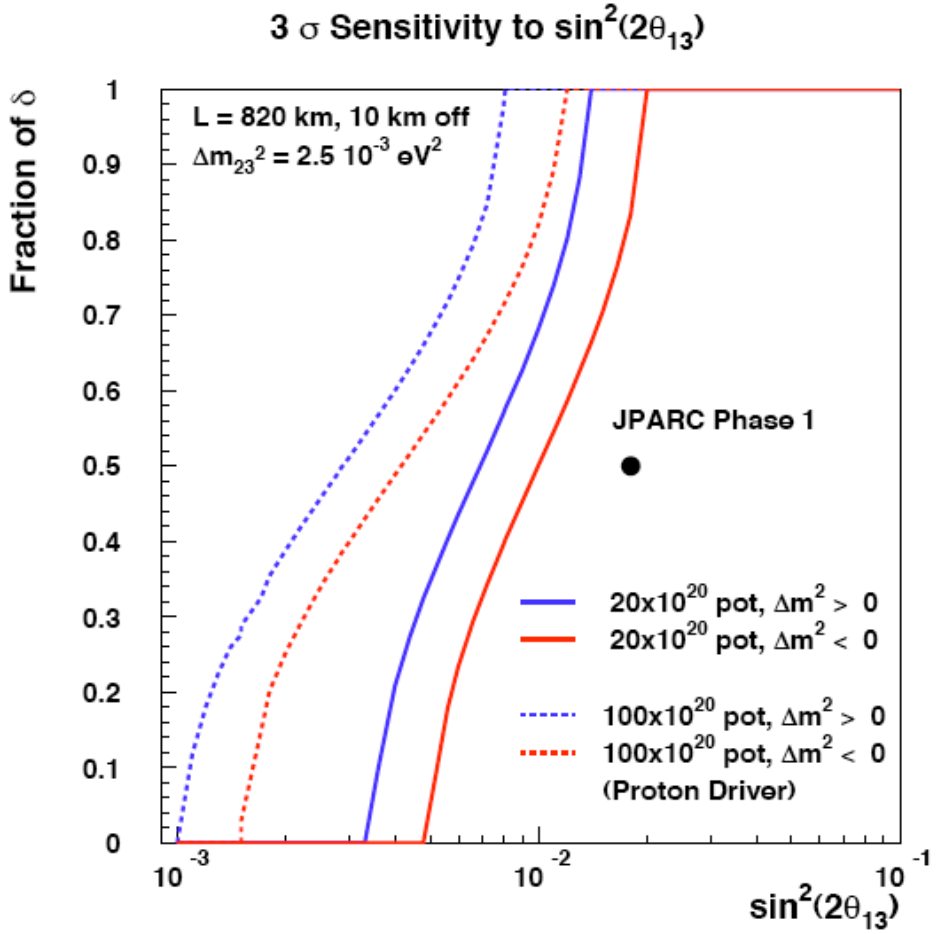
3 □ Discovery Potential for □□ □e



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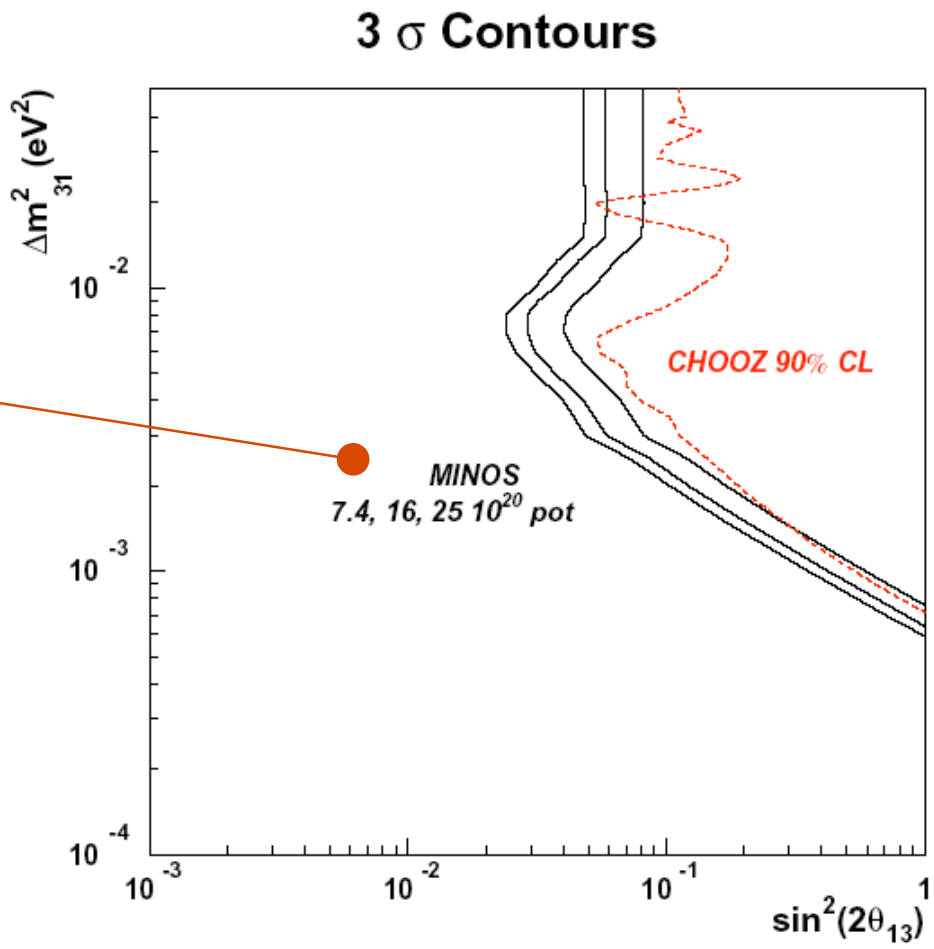
MINOS Sensitivity to $\nu_\mu \to \nu_e$ at 3σ Discovery

Off-Axis Goal



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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.

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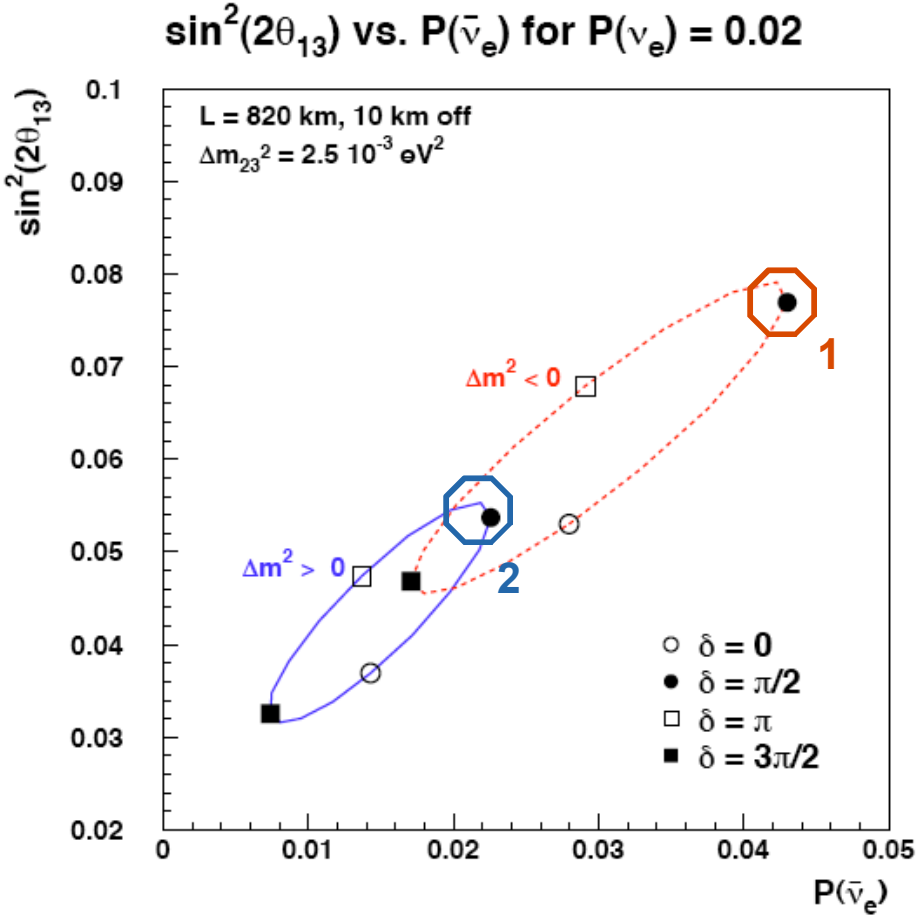
Study Points



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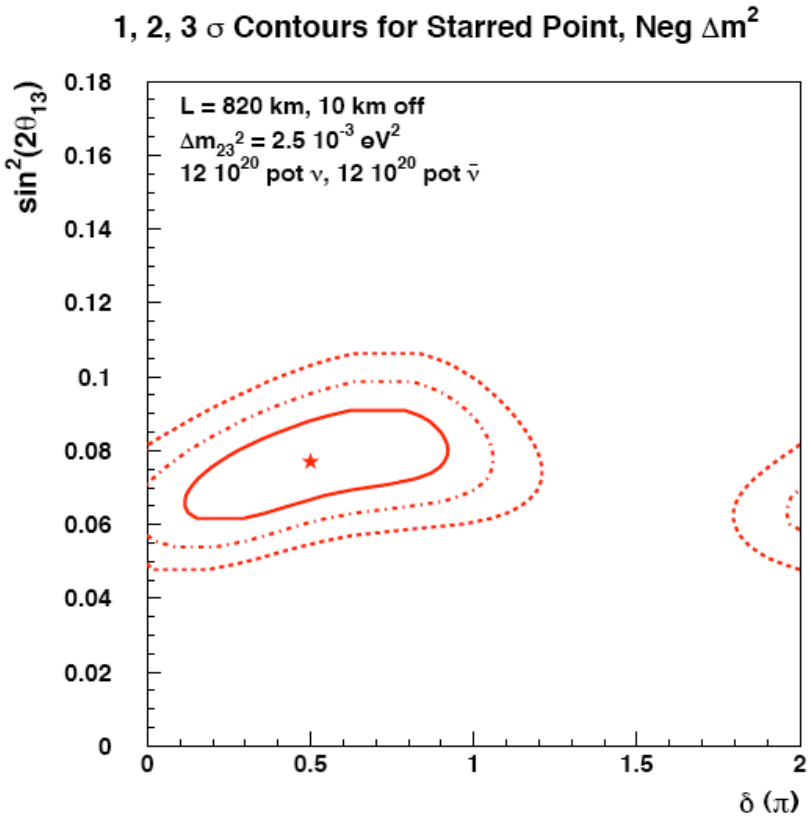
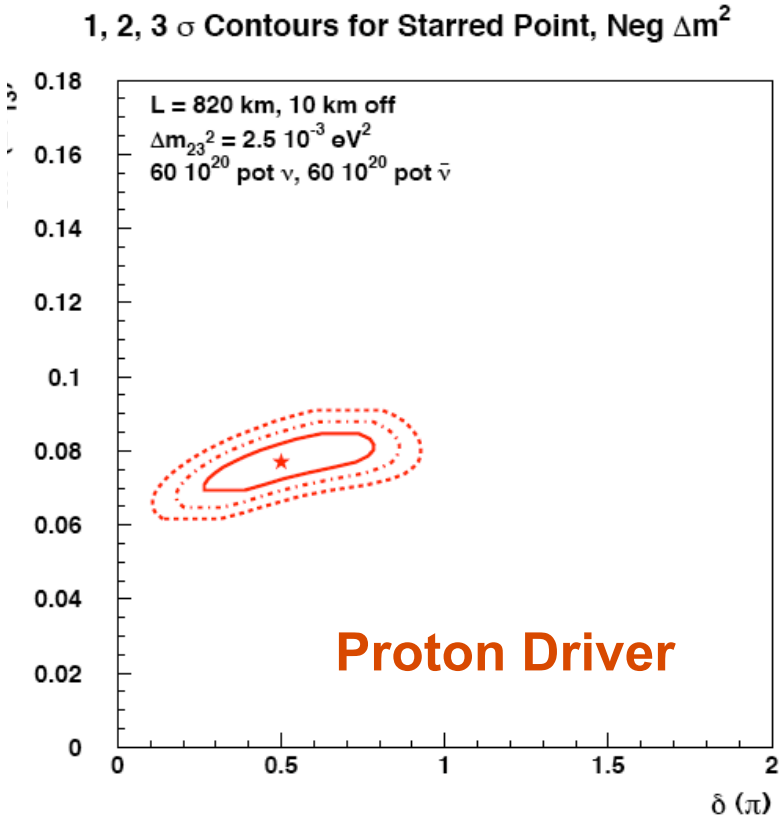
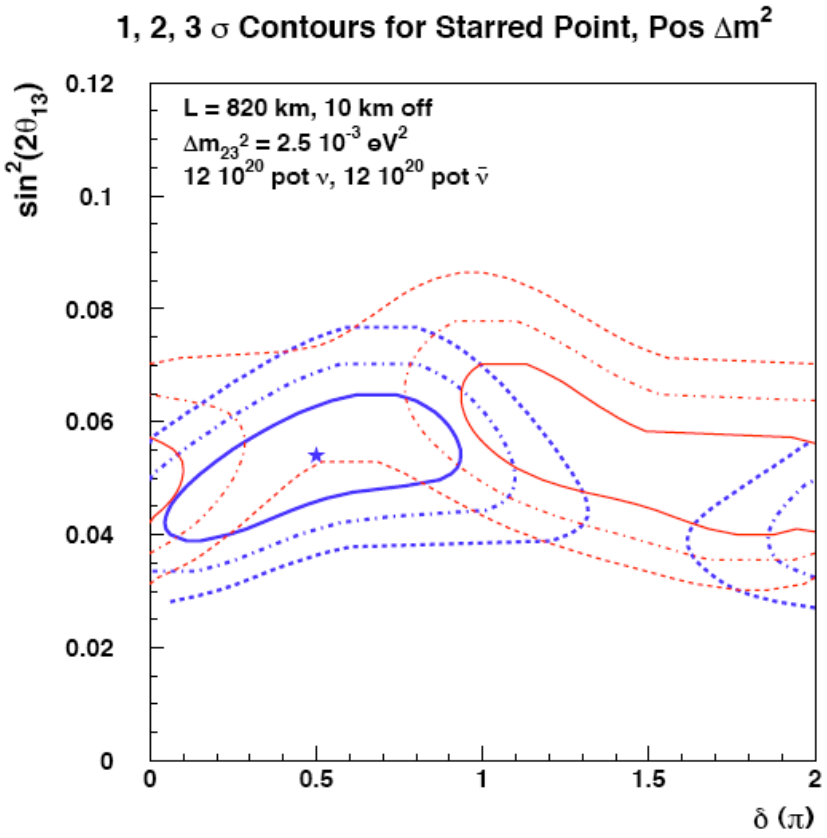
Point 1: NuMI 3 yr □, 3 yr□□
4 10^{20} and 20 10^{20} pot/yr

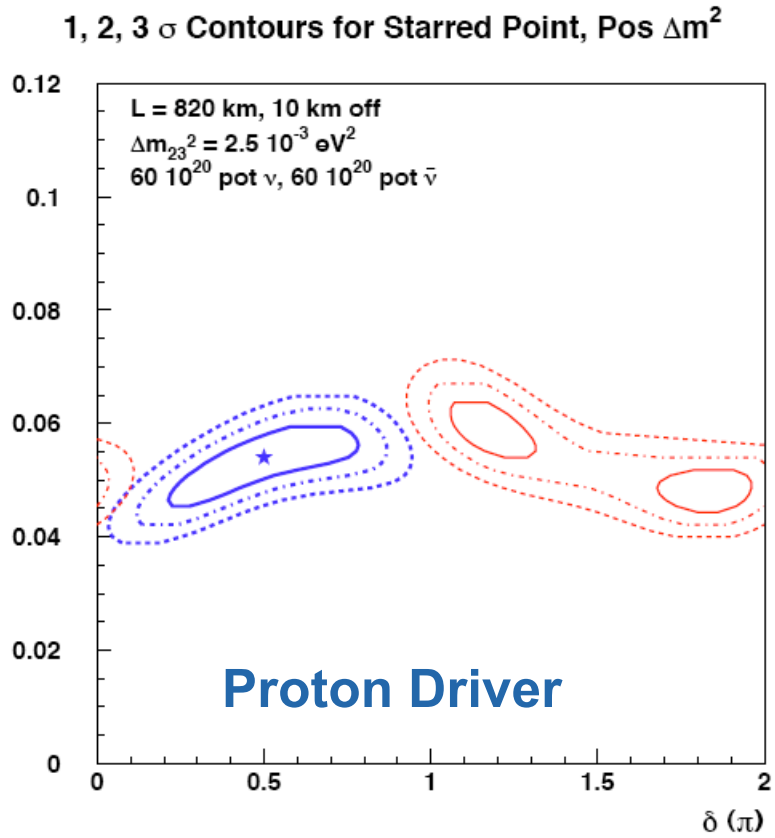




Off Axis

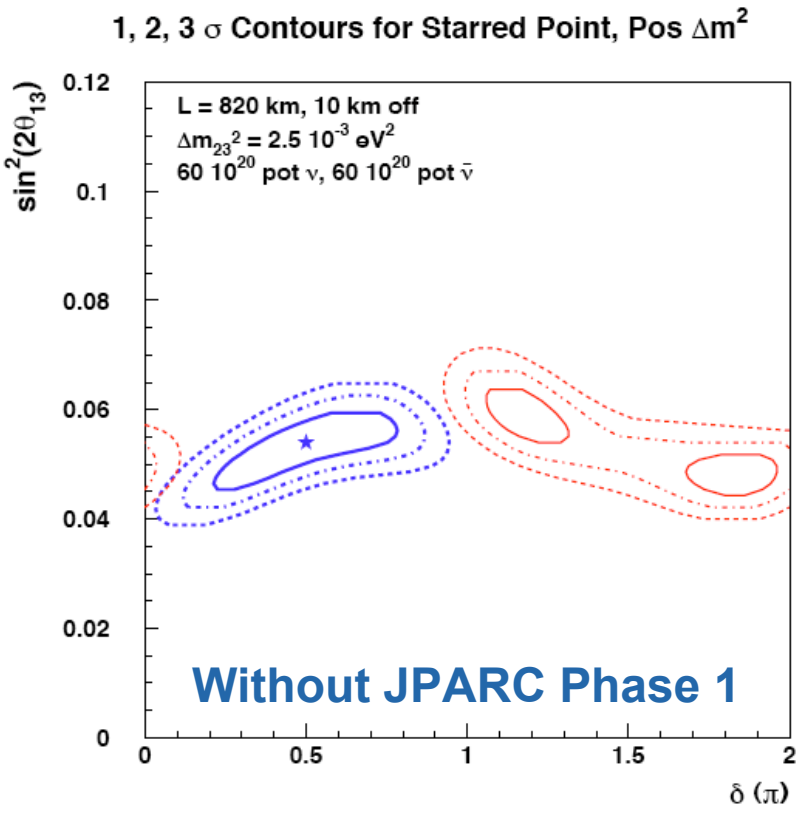
NuMI 3 yr □, 3 yr□□
4 10^{20} and 20 10^{20} pot/yr

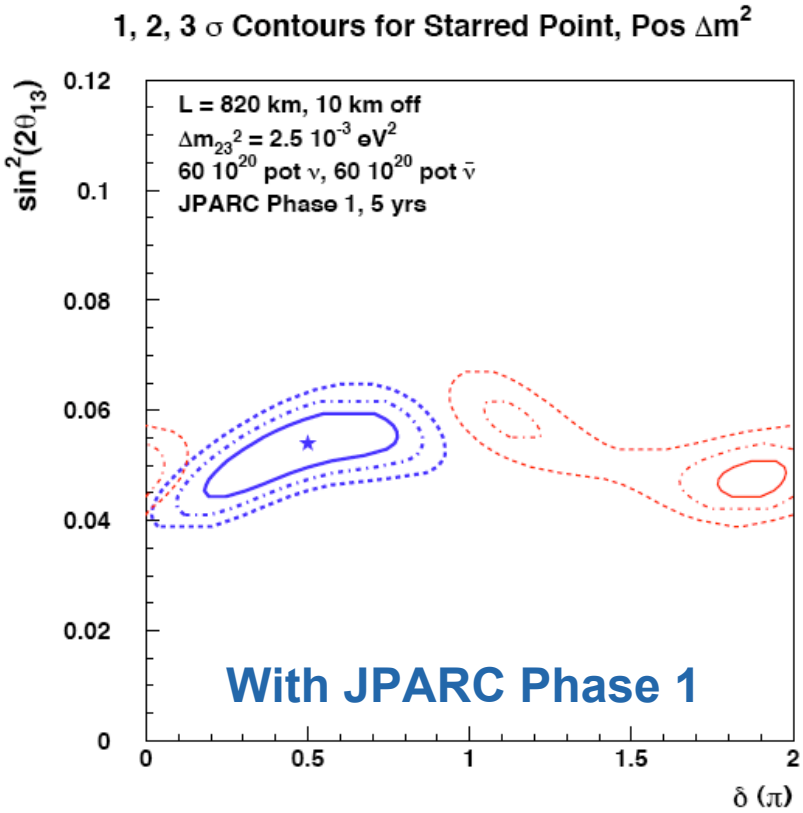




Off Axis

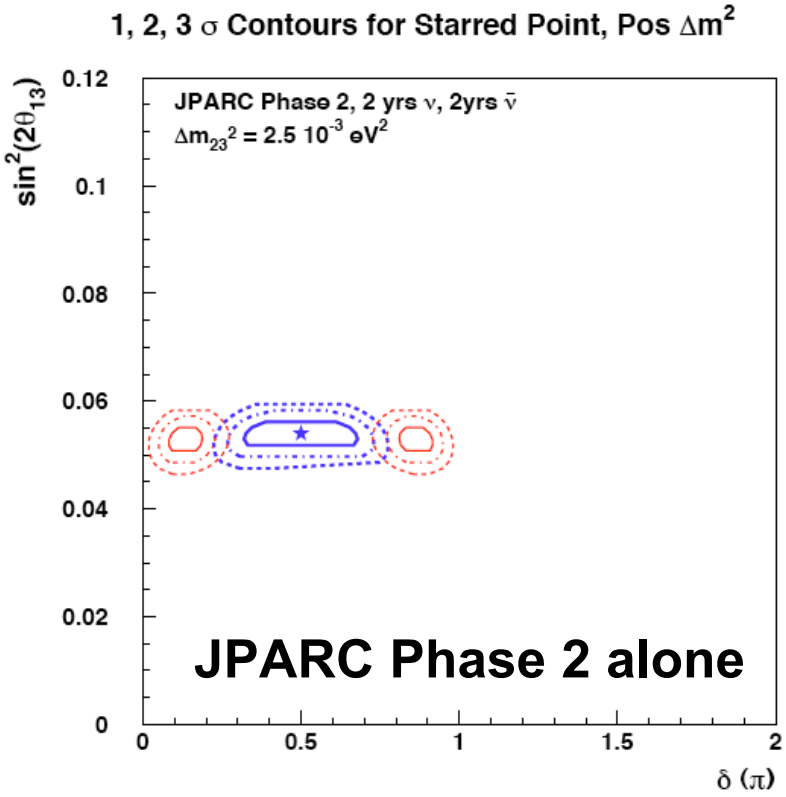
NuMI 3 yr □, 3 yr□□, 20 10^{20} pot/yr and JPARC, Phase 1

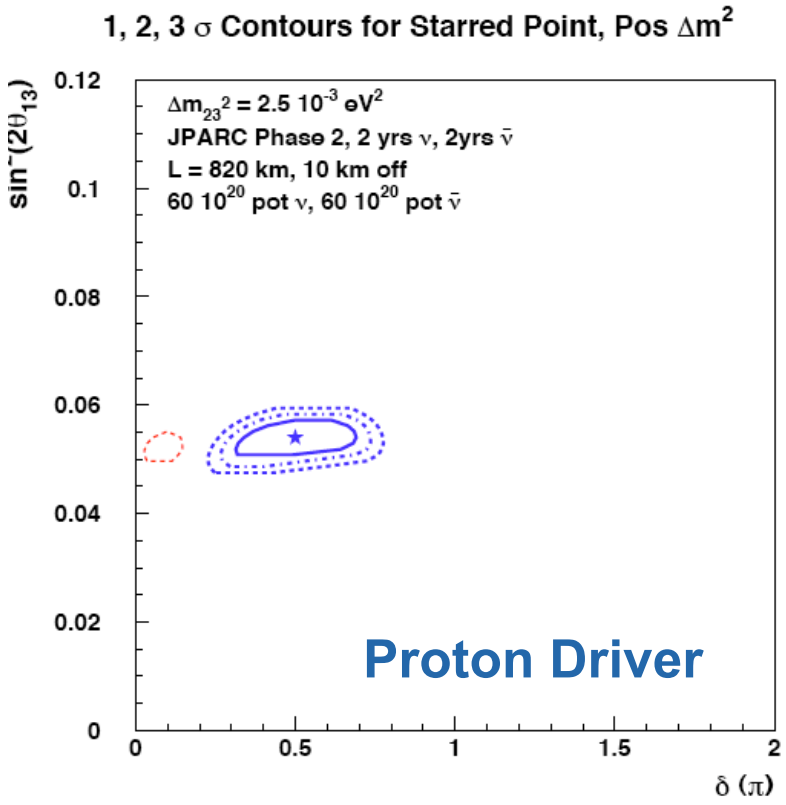




Off Axis

NuMI 3 yr □, 3 yr□□, 20 10^{20} pot/yr and JPARC Phase 2, 2 yr □, 2 yr□□





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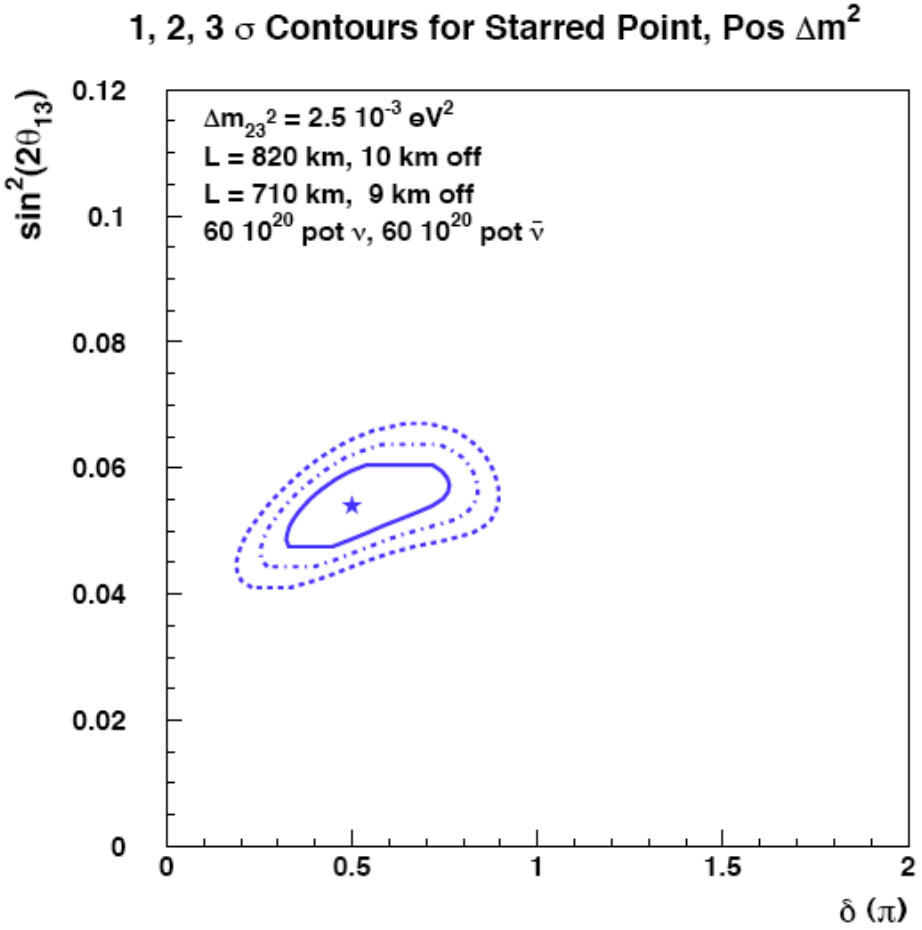
NuMI 3 yr □, 3 yr□□, 2 Detectors and Proton Driver



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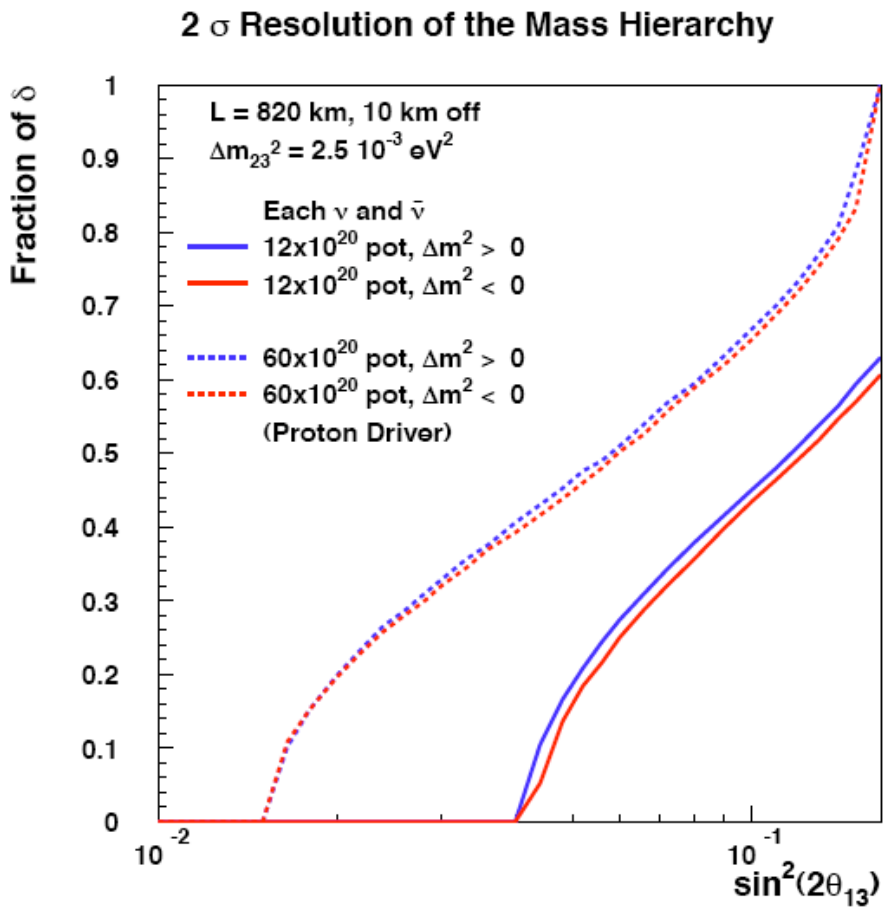
95% CL Resolution of the Mass Hierarchy



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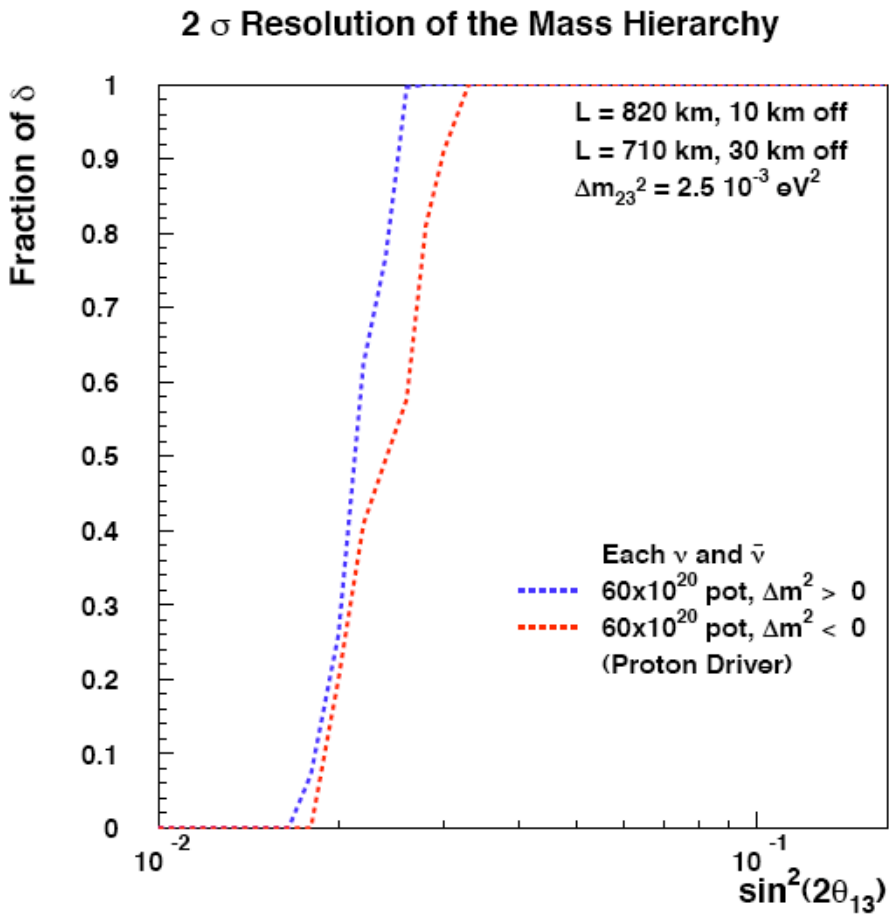
95% CL Resolution of the Mass Hierarchy with 2 Detectors



Off Axis

Status and Prospects

- **Proposal**
  - **Letter of Intent Submitted 2002**
  - **Progress Report just submitted this week**
  - **Full proposal will be submitted in March 2004**
- **Interest in neutrino oscillations has greatly increased during the past year**
  - **HEPAP request APS study beginning next week**
  - **Fermilab Long-Range Planning committee sees neutrino oscillations as a major part of Fermilab's future program**
  - **Secretary of Energy lists a neutrino superbeam as one of four high-energy projects in "Facilities for the Future of Science."**