NOνA

NuMI Off-Axis ν_e Appearance Experiment

APS Neutrino Workshop

Brookhaven

5 March 2004

Gary Feldman

Organization

- Concept
- Detector
- Site
- Beam
- Backgrounds
- Simulations
- Physics Potential
- Status and Schedule

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Phases of Long Baseline Experiments

- **Phase 1**
  - **Goals:**
    - **Verify atmospheric results and improve parameter measurement.**
    - **Low sensitivity search for $\nu_\mu \to \nu_e$ oscillations.**
  - **Time scale: Now to next two years.**
  - **Examples:**
    - **K2K**
    - **MINOS**
    - **CNGS**

Phase 2 Experiments

- **Phase 2**
  - **Goals:**
    - Extend the search for $\nu_\mu \rightarrow \nu_e$ oscillations by an order of magnitude.
    - Start to gather information on the mass hierarchy and CP violation.
  - **Time scale: By the end of the decade**
  - **Cost: NuMI scale (~150 M$)**
  - **Examples**
    - JPARC Phase 1
    - NOνA
    - Reactor Experiments

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Phase 3 Experiments

- Phase 3
  - Goals:
    - Resolve the mass hierarchy
    - Measure the CP phase
  - Time scale: Next decade
  - Cost: B$ range (proton driver and massive detector)
  - Examples:
    - JPARC Phase 2
    - CERN SPL and beta beam
    - Brookhaven proposal
    - Extensions to NO□A
    - Neutrino factories (phase 4?)

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How Do We Achieve Our Phase 2 Goals?

- **Go off-axis to get a low-energy narrow-band beam near the atmospheric oscillation maximum (proposed by Brookhaven in 1995)**
  - **ν_e appearance maximum**
  - **ν_μ CC largely disappears**
  - **Higher-energy NC disappears**
- **Build a detector optimized for electron detection**
- **Increase the beam flux times detector mass**
- **Work at a long baseline to maximize matter effects**

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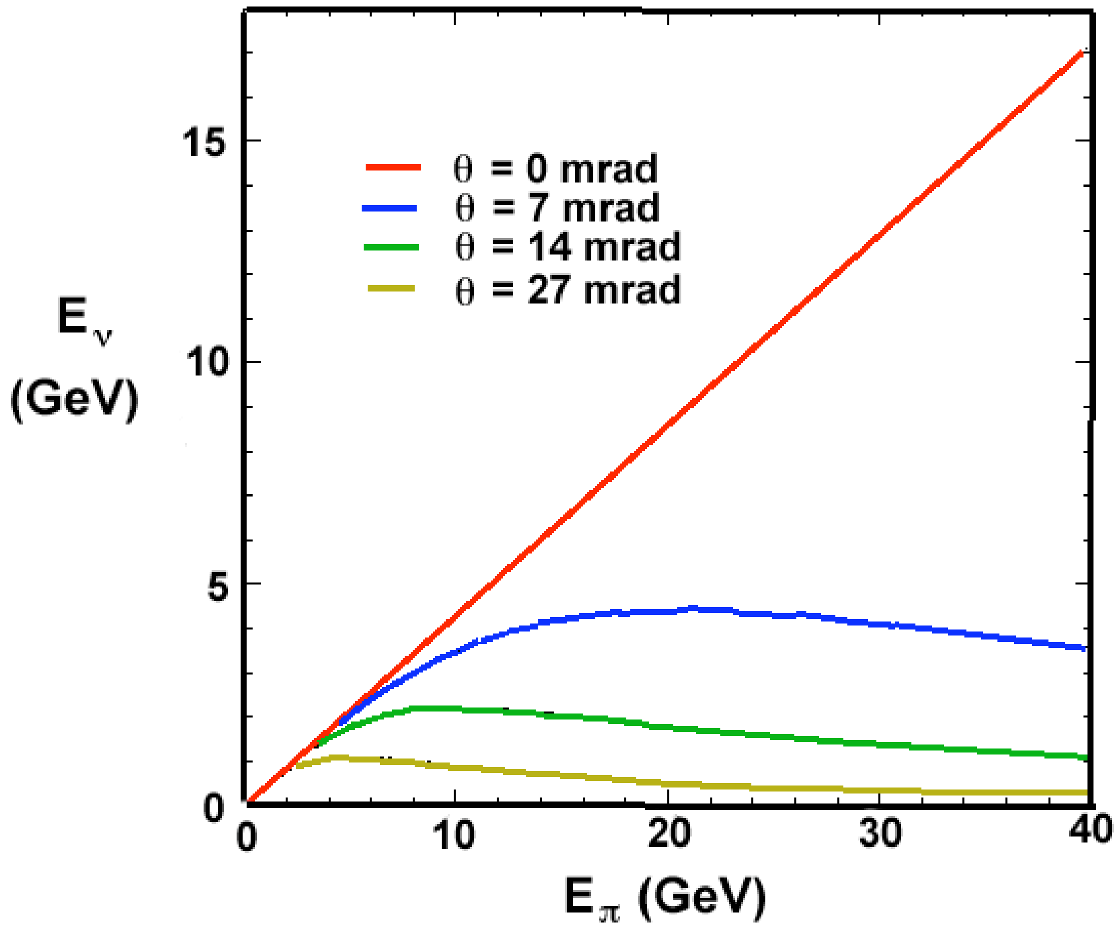
Off-Axis Kinematics



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

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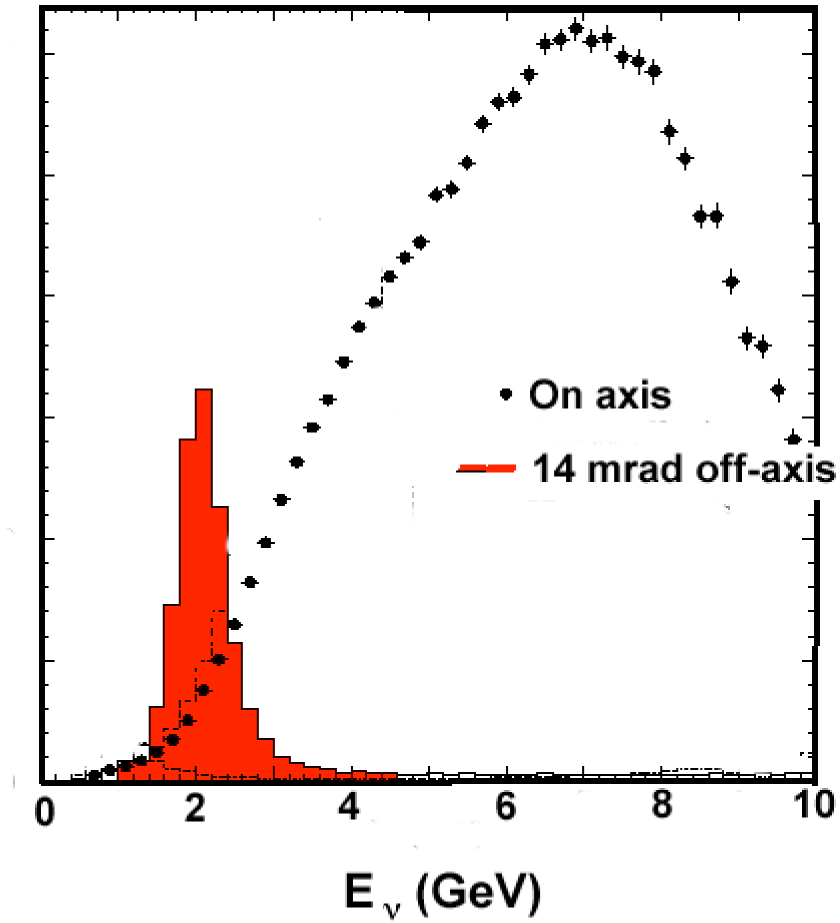
Off-Axis Spectrum (No oscillations)



NOνA Proposal

- NOνA is proposed to be
  - 50 kT
  - Medium-Z sandwich detector
    - Particle board absorber
    - Liquid scintillator strip detectors with APD readout
    - Glass RPC detectors fallback option
  - 810 km baseline, about 12 km off-axis (Ash River, MN)

Why a Medium-Z Sandwich Detector?

- Water Cerenkov does not provide sufficient NC rejection at NuMI energies (~2 GeV).
- Liquid Argon requires R&D beyond the Phase 2 time scale.
- Medium-Z sandwich detectors provide good π^0-electron discrimination.

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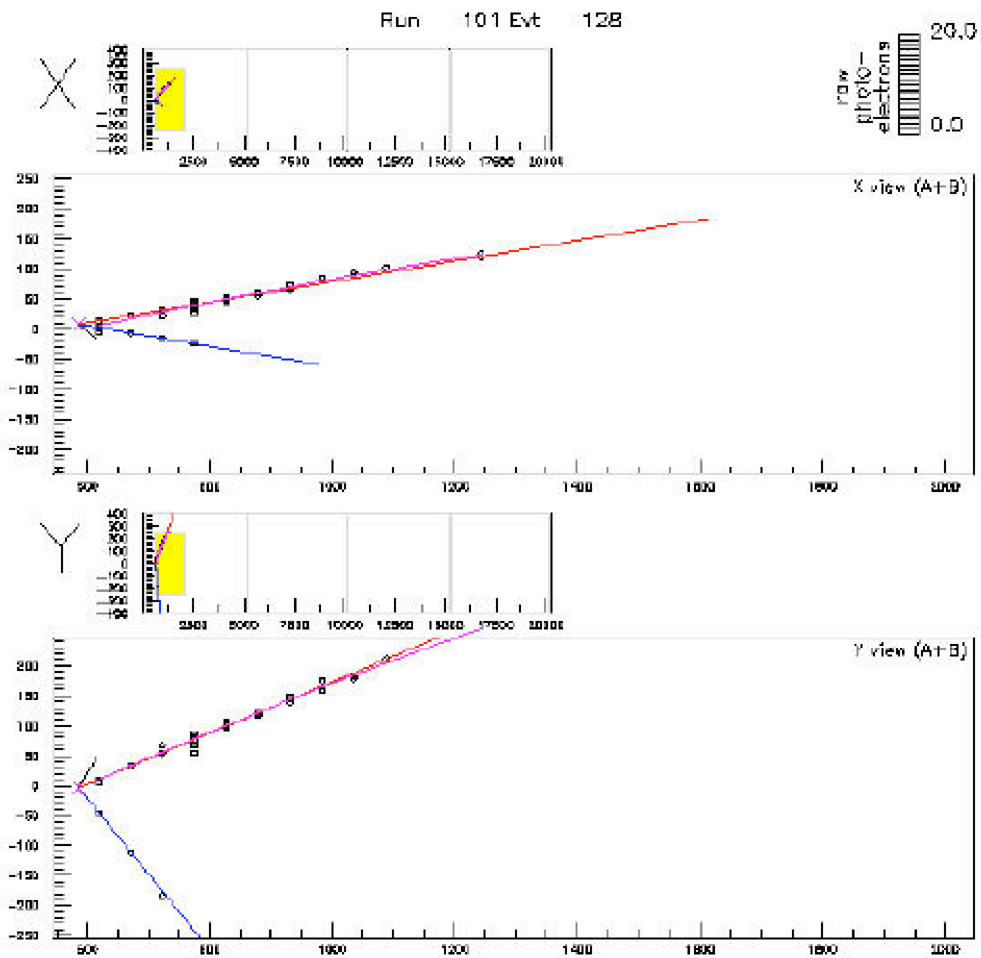
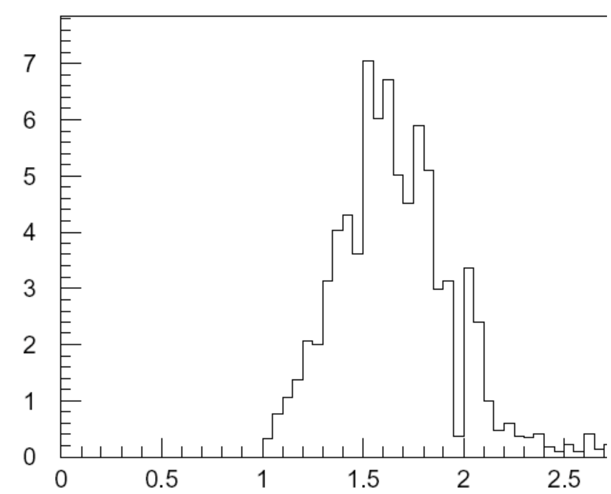
Electron Track



Hits per plane > 1



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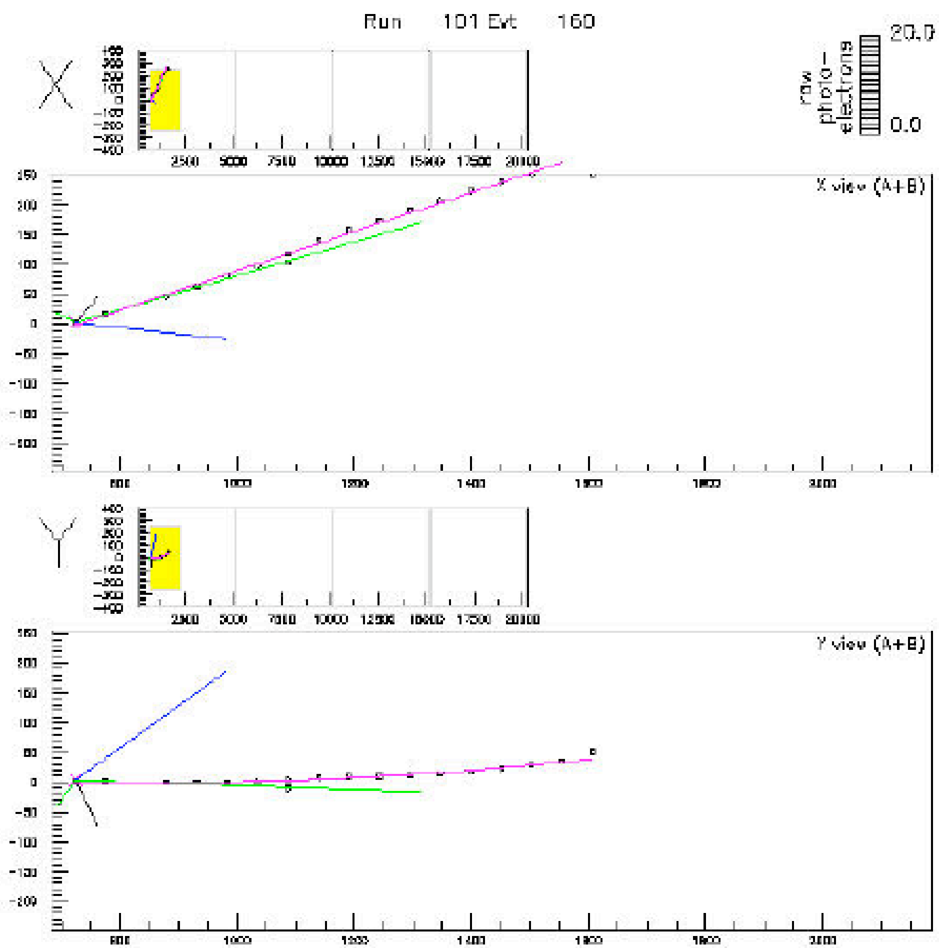
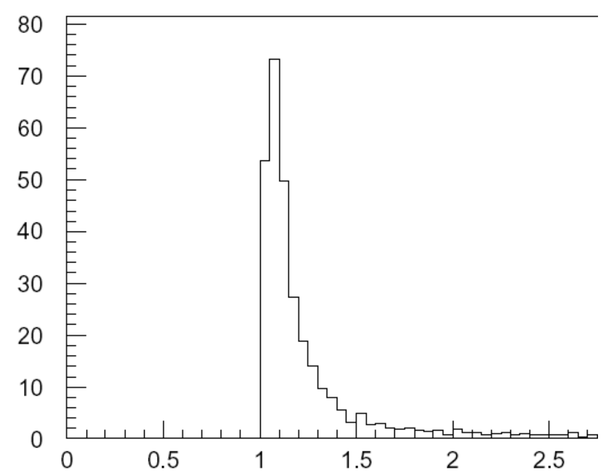
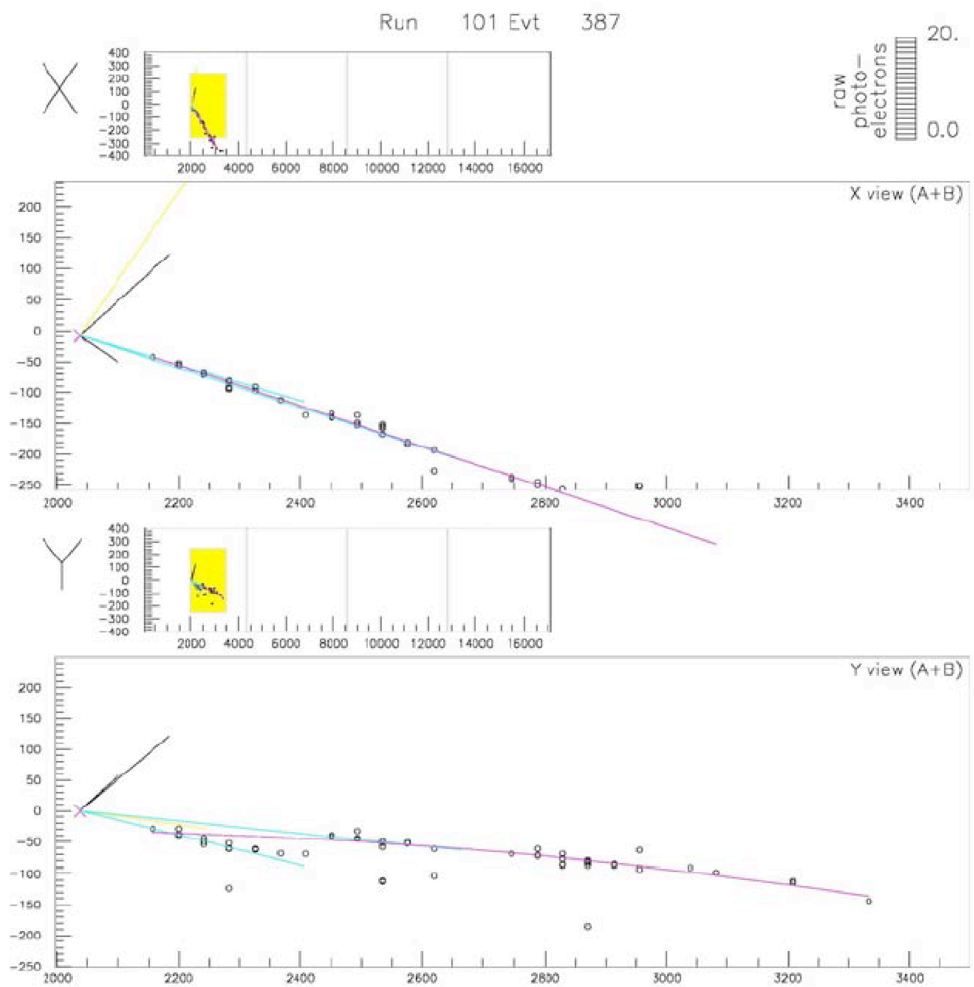
Muon track



Hits per plane ~1



NC with leading π^0



Two tracks with different starting points leading to a “gap”

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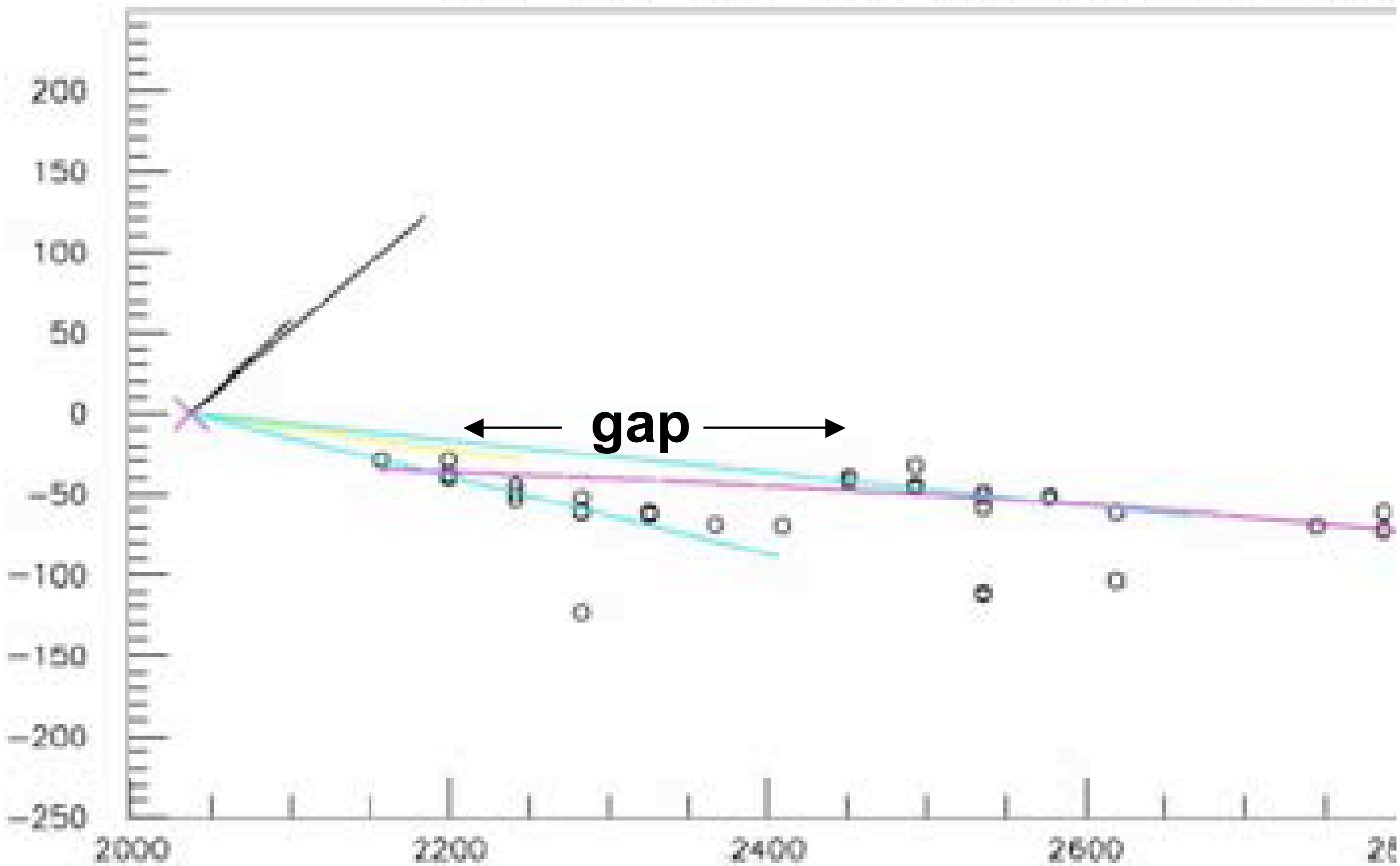
Detail of NC with leading π^0



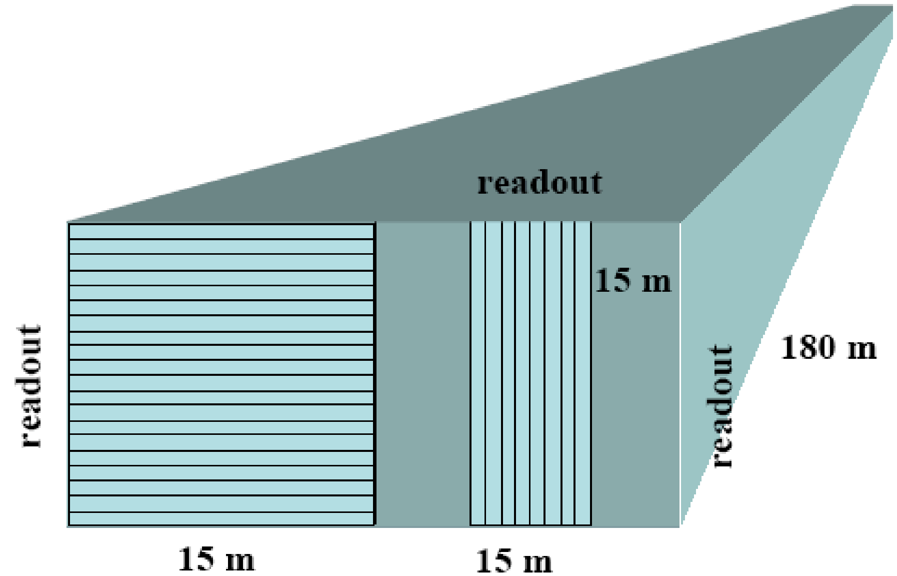
Scintillator Layout

Monolithic structure

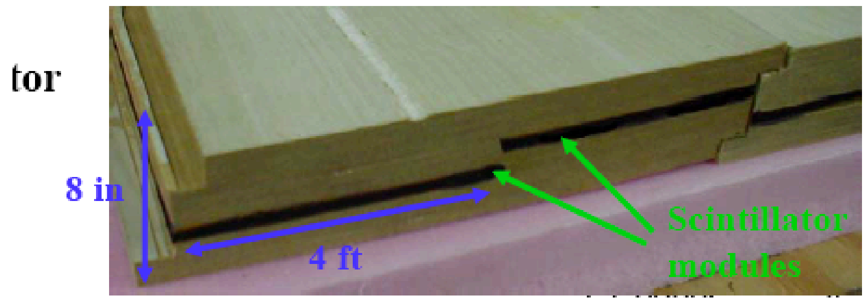
Liquid Scintillator:
1.2 m x 3 cm x 14.4 m
30-cell PCV extrusions,
24 extrusions/plane,
750 planes
= 18 000 extrusions
= 540 000 channels
APD readout

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

TASD being studied



800 planes X, absorber, Y, absorber, … = detector



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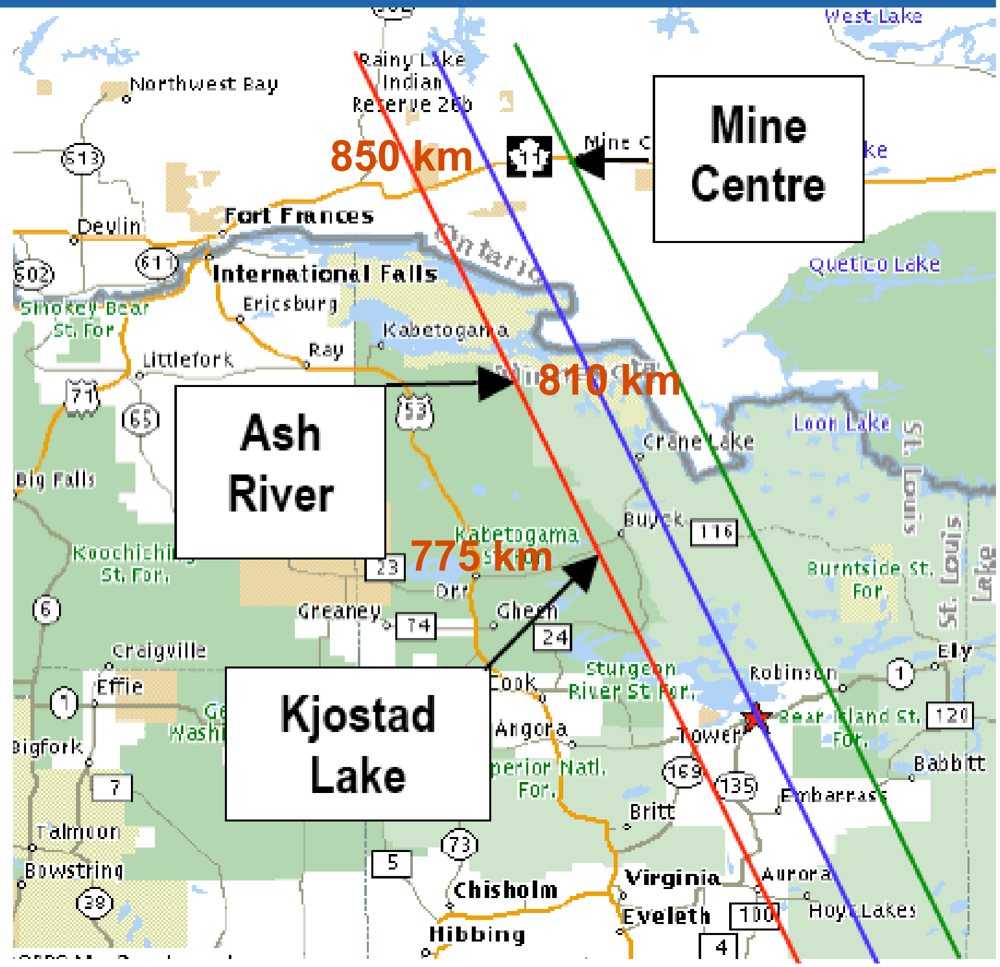
Possible Sites

We are now focusing on the Ash River site.



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Beam Prospects

- MINOS will start next year with $2x10^{20}$ pot/yr
- By 2009, we expect that the MI should deliver $4x10^{20}$ pot/yr. Will most likely require more magnet and RF power to increase the MI cycle rate.
- Further increases in proton intensity requires replacing the 8 GeV Booster. Best option is a superconducting linac (a.k.a. proton driver). A proton driver is being recommended by the Fermilab Long Range Planning Committee and is on the Secretary of Energy's facilities plan (although generic and very long range). A proton driver would allow $20x10^{20}$ pot/yr.

Backgrounds to $\nu_\mu \to \nu_e$

- **Scale of background problem: statistical error on background in 5 yr run is about 15%.**
- **Background composition (typically)**

Beam ν_e CC	54%
NC	34%
ν_μ CC (with unidentified μ)	12%

- **Most direct approach is an off-axis near detector**
  - Beam ν_e CC and NC scale approximately as $1/L^2$.
  - ν_μ CC does not, due to oscillations. Correct by extrapolating identified muons to unidentified muons.
  - Useful cross section measurements from the MINERνA experiment

Simulations

- We have done full simulations, starting with raw hits. The hits are reconstructed and the signal events are separated from the various backgrounds with the use a cut on a likelihood function, based on topological characteristics.
- I have added 5% systematic uncertainty to the background determinations.
- New beam and physics simulations give less sensitive results by a factor of about 1.5. Graphs that have not been redone yet are labeled "Old".

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$P(\nu_\mu \rightarrow \nu_e)$ (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 $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23})\ \times$

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

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$P(\nu_\mu \rightarrow \nu_e)$ (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.

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

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

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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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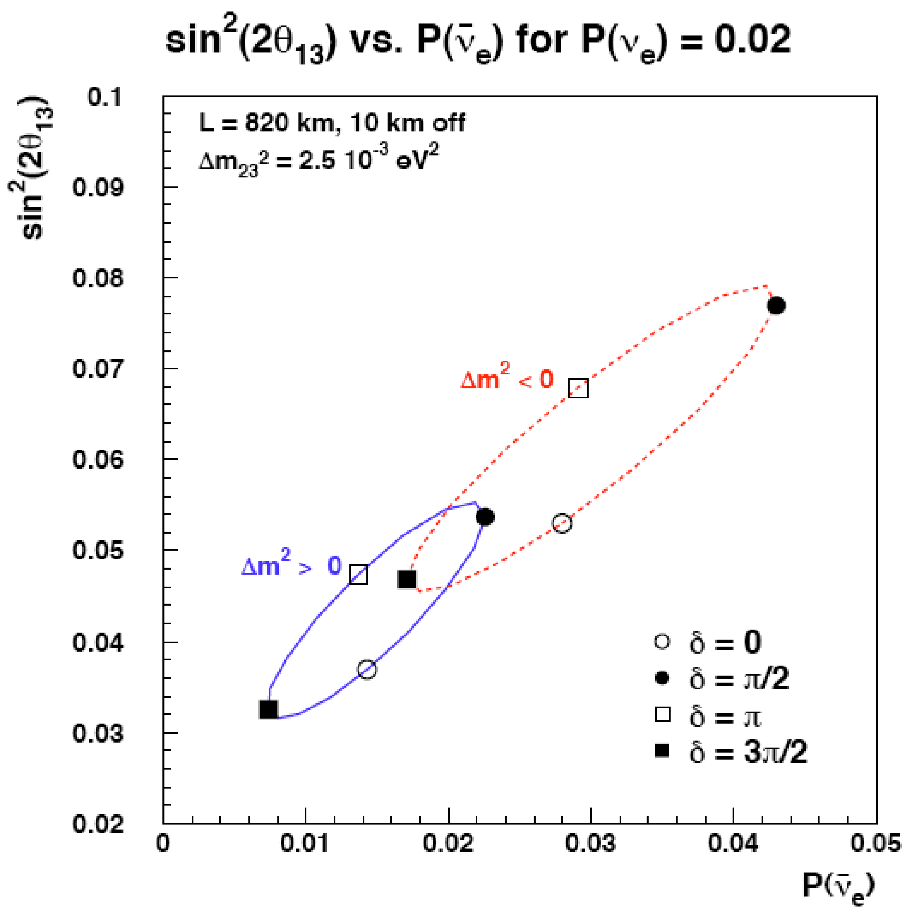
$P(\nu_\mu \rightarrow \nu_e) = 0.02$ at 820 km



Note

(1) Effect of cos(δ) term

(2) Ambiguities

(Hidden ambiguity: P1 µ $\sin^2(\theta_{23})$; if $\sin^2(2\theta_{23}) = 0.95$, $\sin^2(\theta_{23}) = 0.39$ or 0.61)

(1) Rough equivalence of reactor and antineutrino measurements

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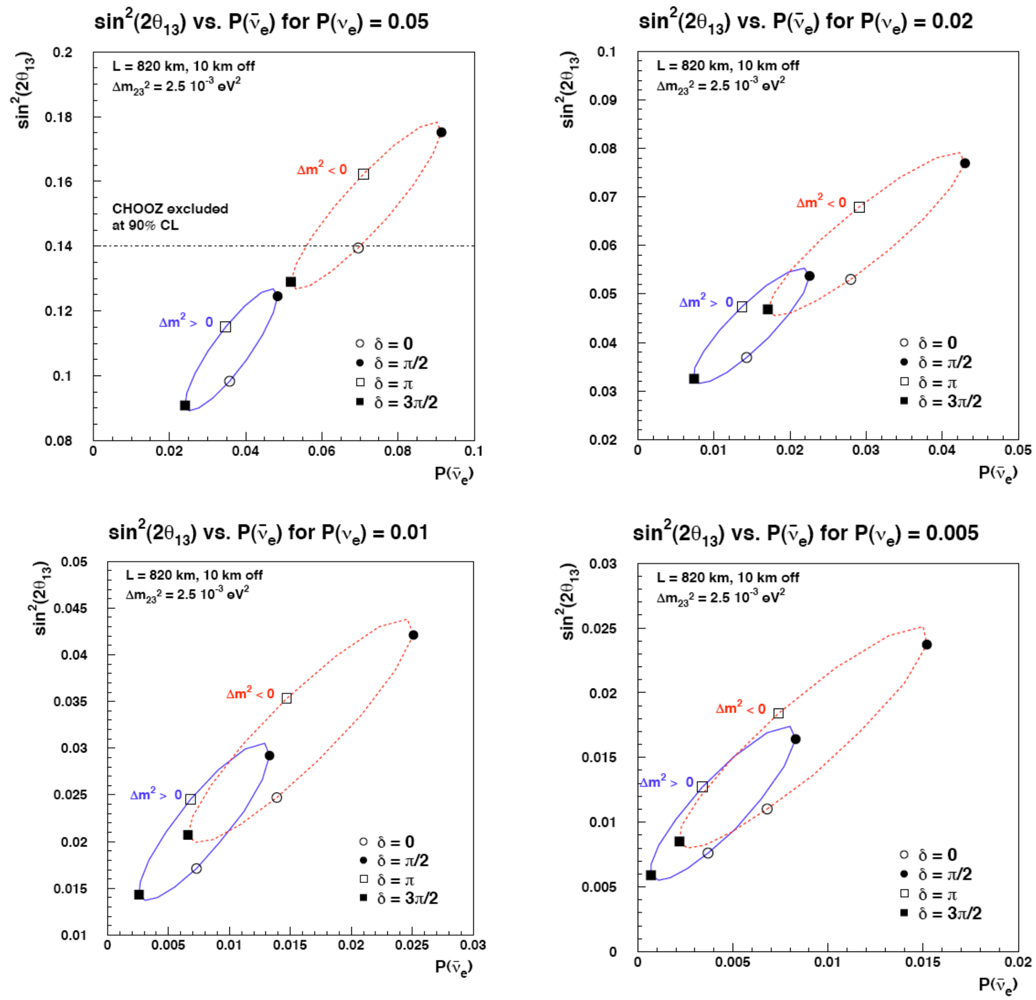
$P(\nu_\mu \rightarrow \nu_e)$ = 0.05, 0.02, 0.01, and 0.005 at 820 km



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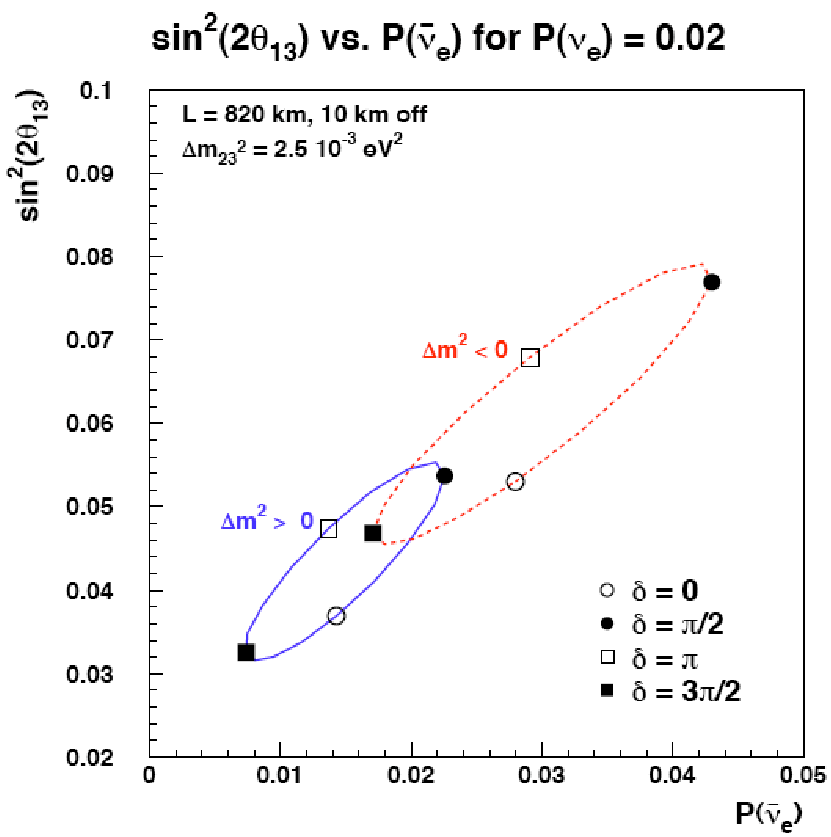
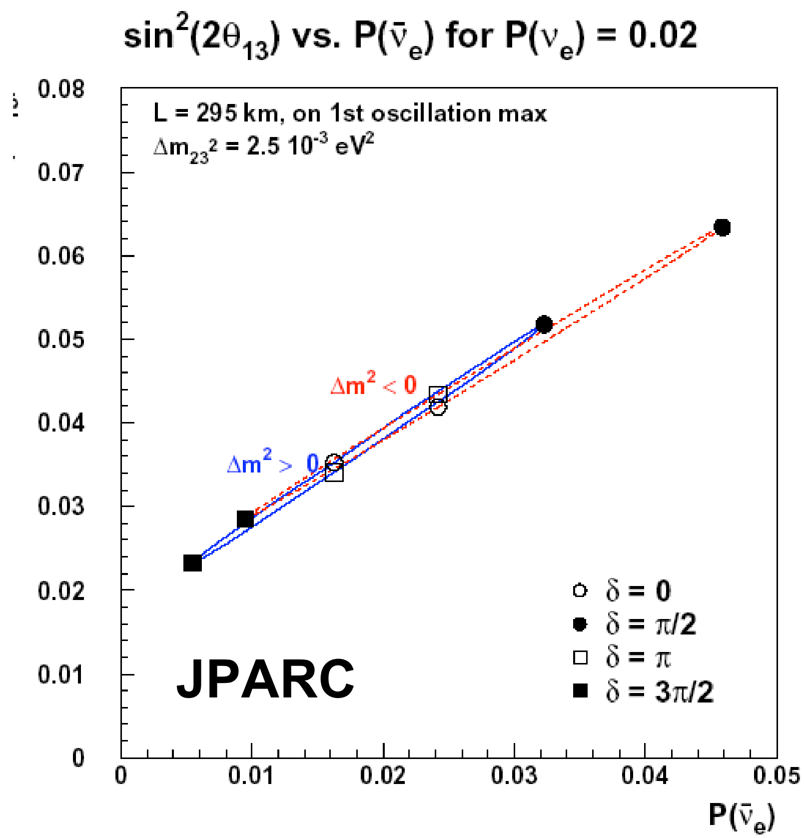
P(□□□ □e) = 0.02 at 820 and 295 km





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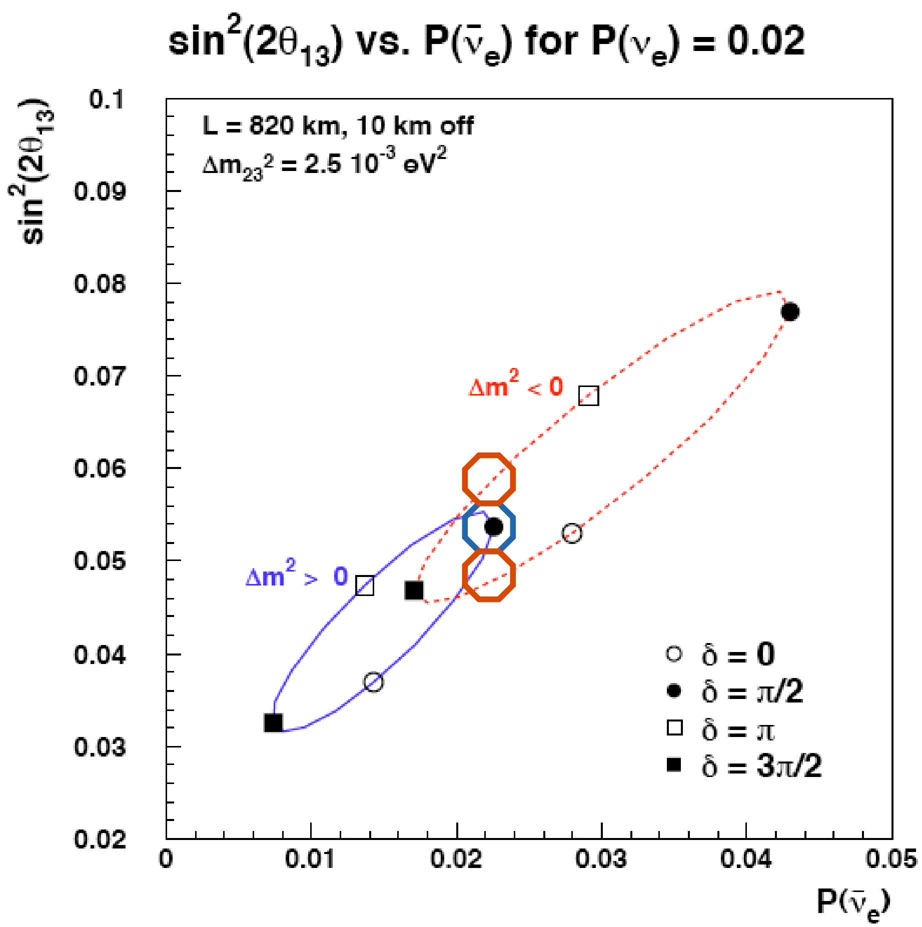
$P(\nu_\mu \to \nu_e) = 0.02$ at 820 km



Note ambiguities between normal hierarchy and inverted hierarchy.

Can combining JPARC and NuMI data help?

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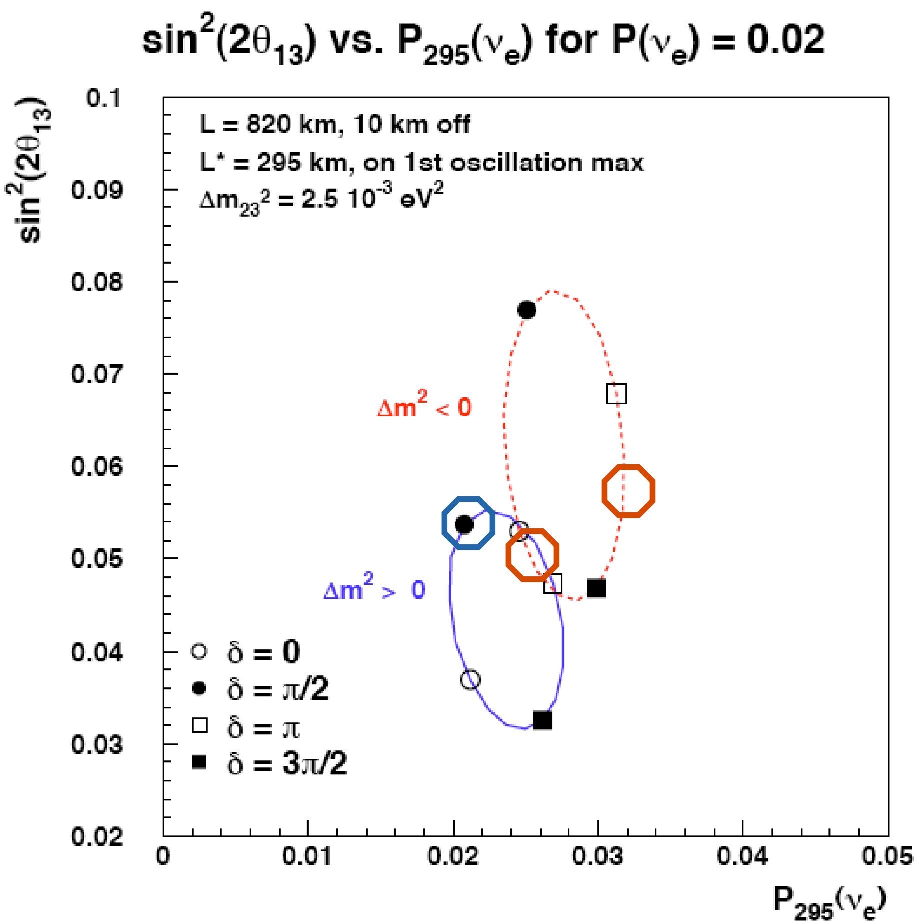
$P(\nu_\mu \rightarrow \nu_e)$ = 0.02 at 820 km vs. $P(\nu_\mu \rightarrow \nu_e)$ at 295 km



Ambiguous points are still fairly close together

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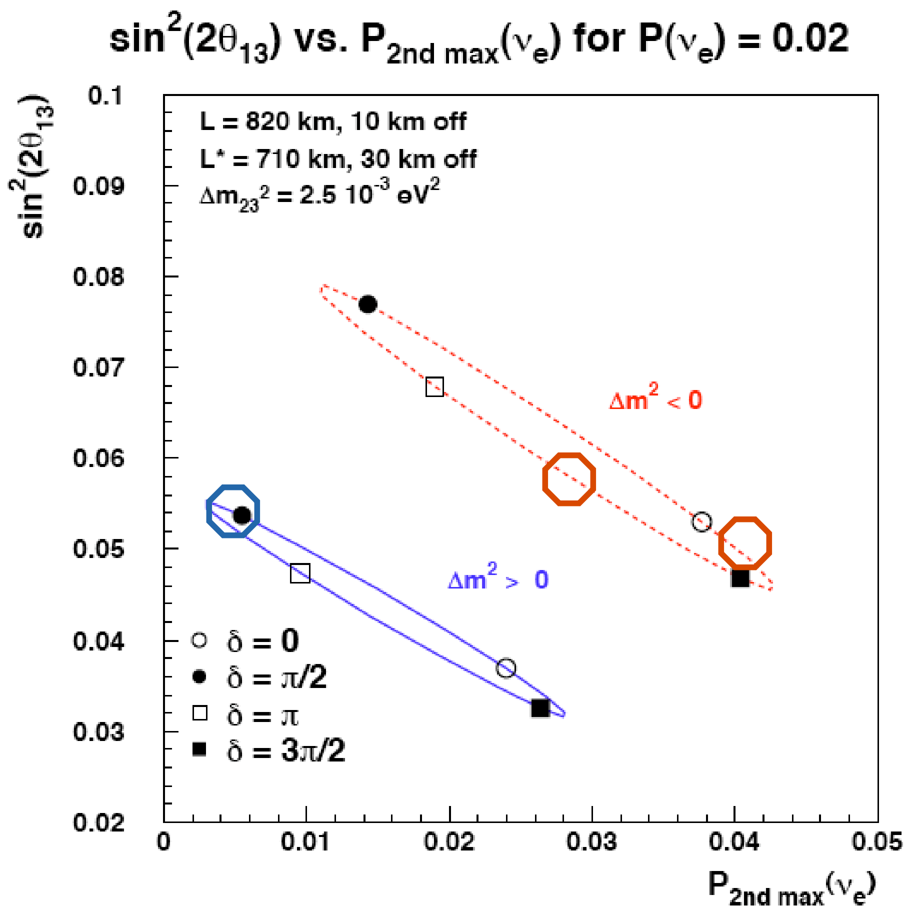
A 2nd Detector at the 2nd Maximum?



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NOνA Goals

- **Primary (Phase 2) 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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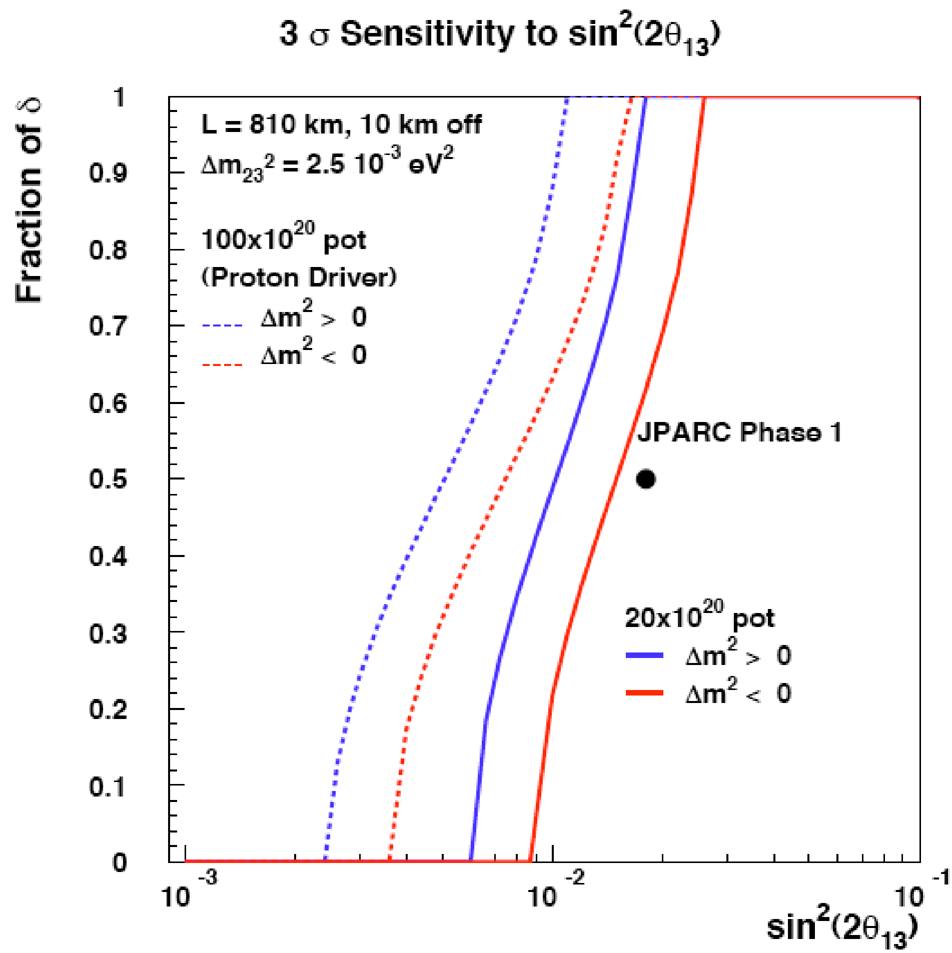
3 Discovery Potential for



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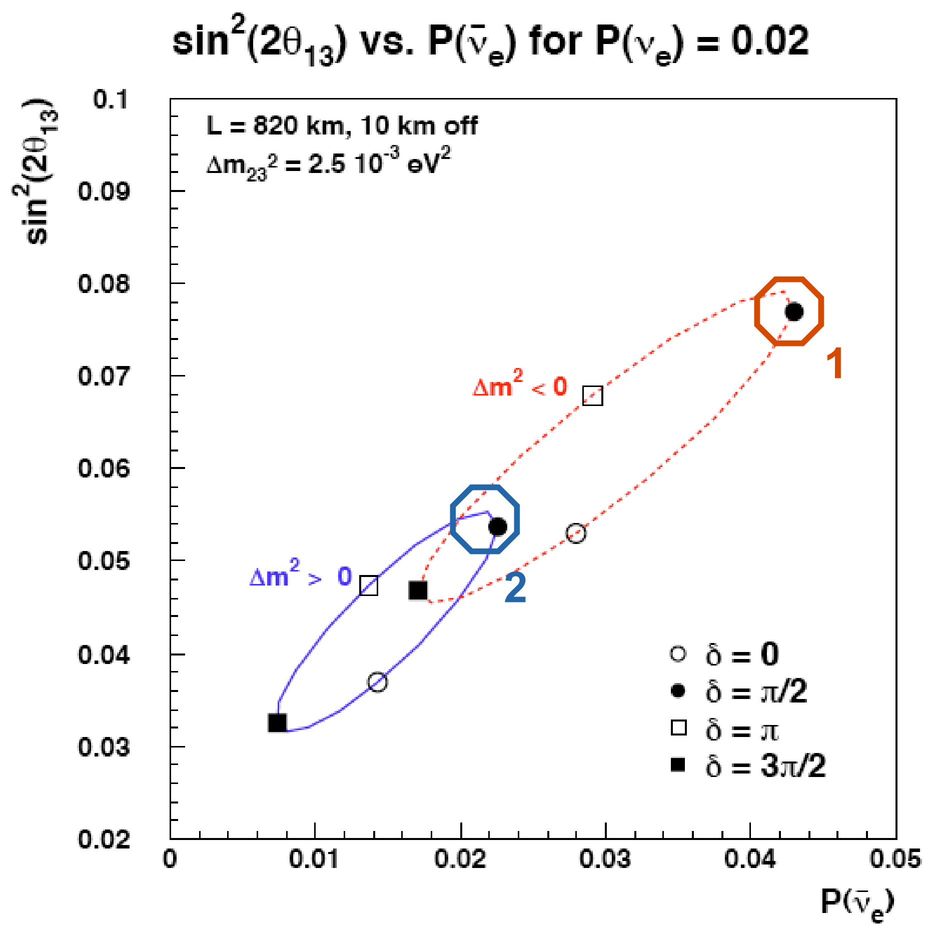
Study Points



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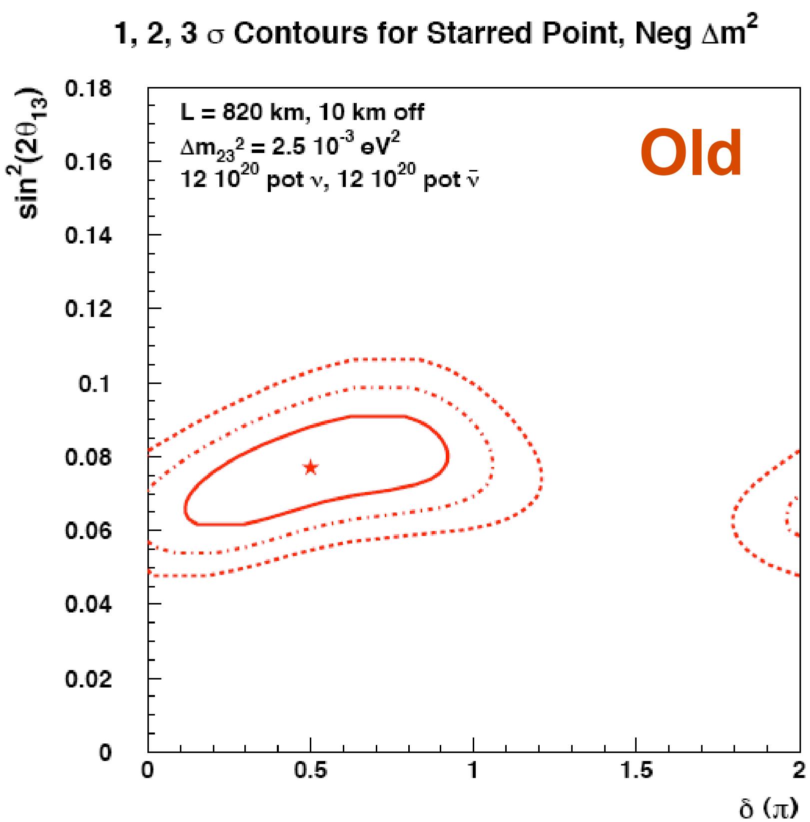
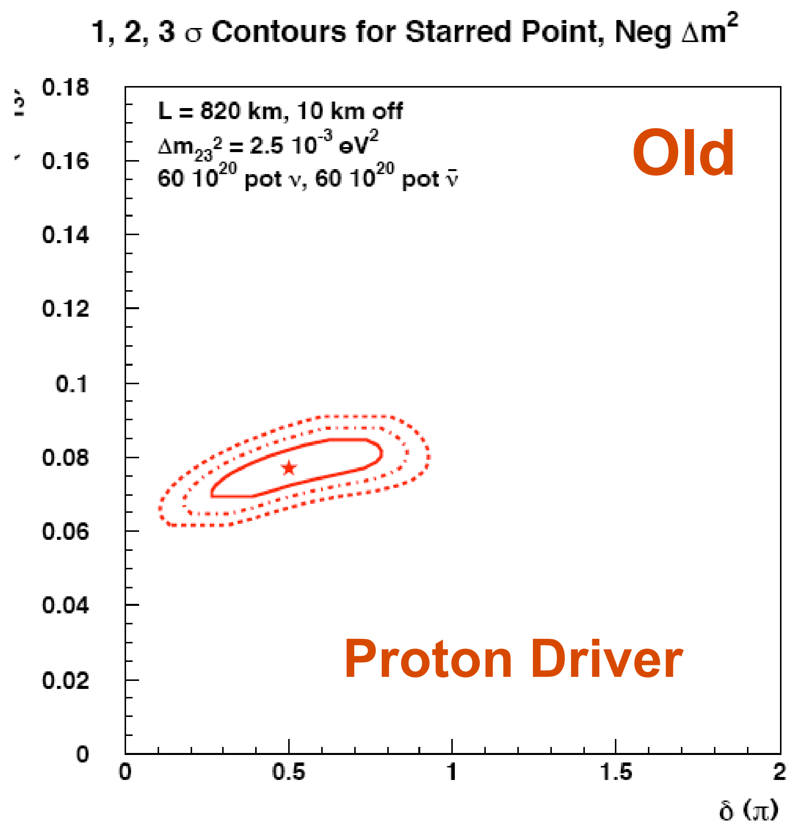
Point 1: NuMI 3 yr □, 3 yr□□ 4 10^{20} and 20 10^{20} pot/yr





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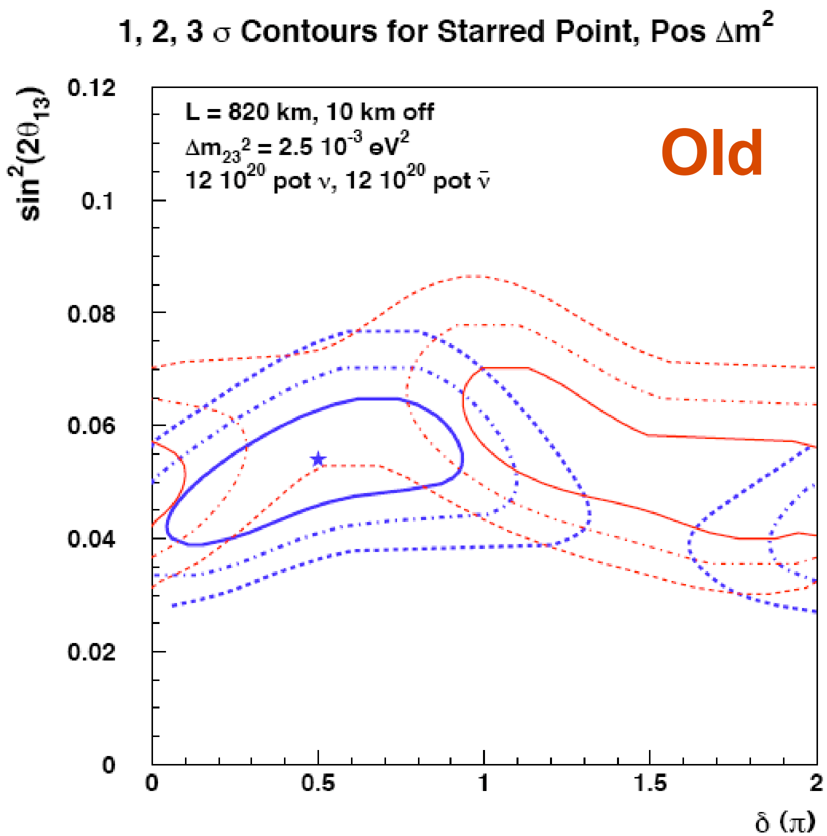
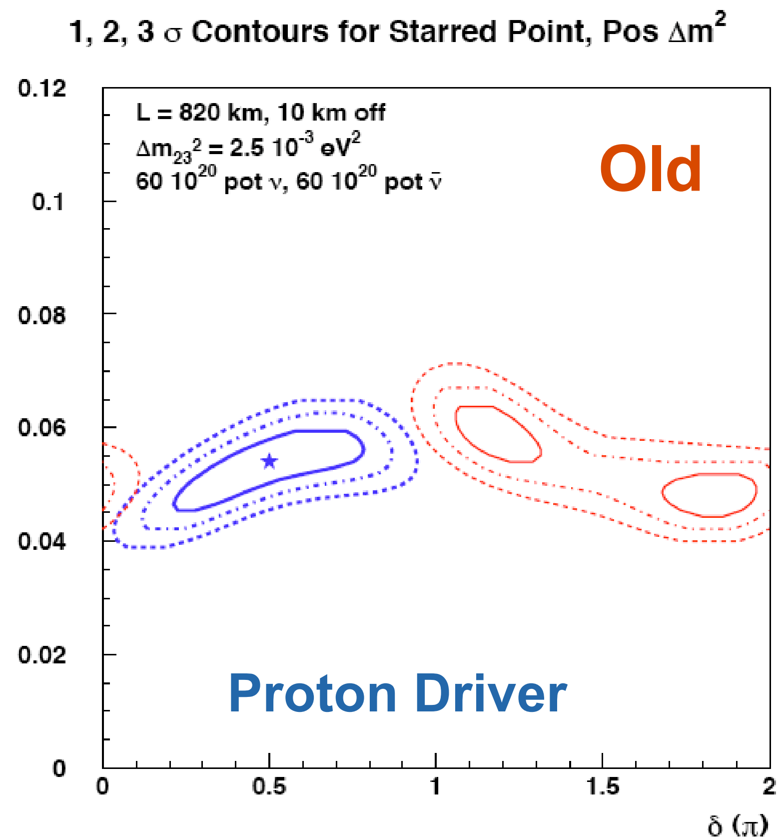
NuMI 3 yr ν, 3 yr ν̄
4 10^{20} and 20 10^{20} pot/yr





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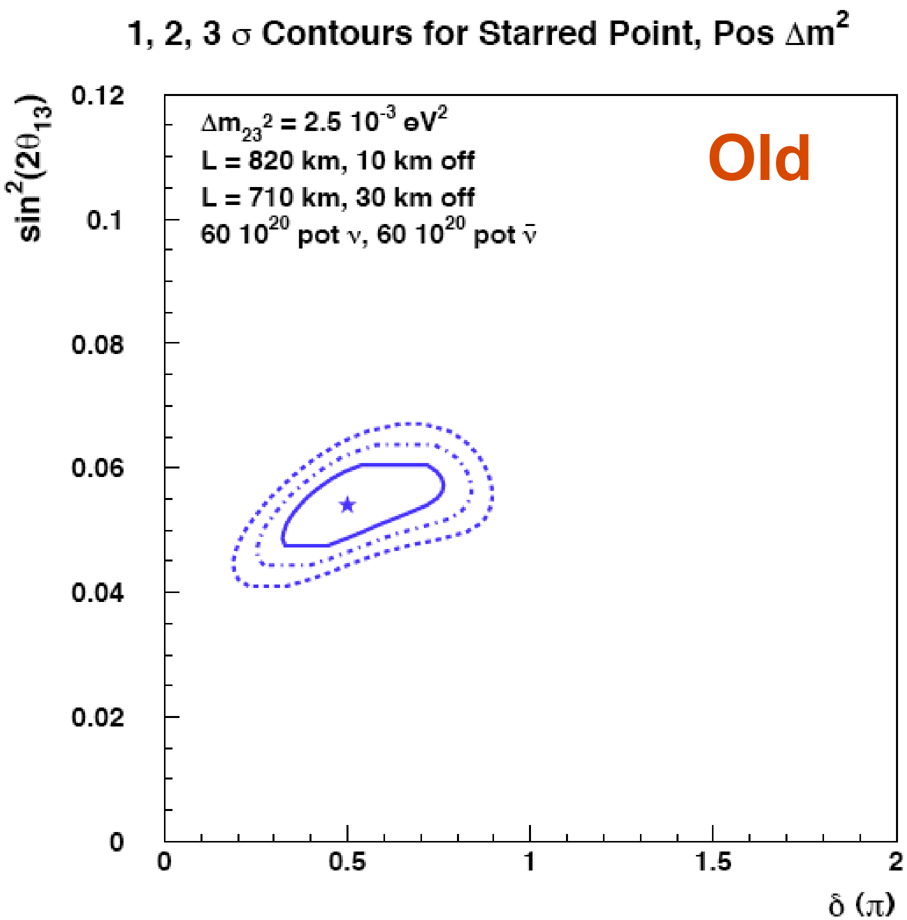
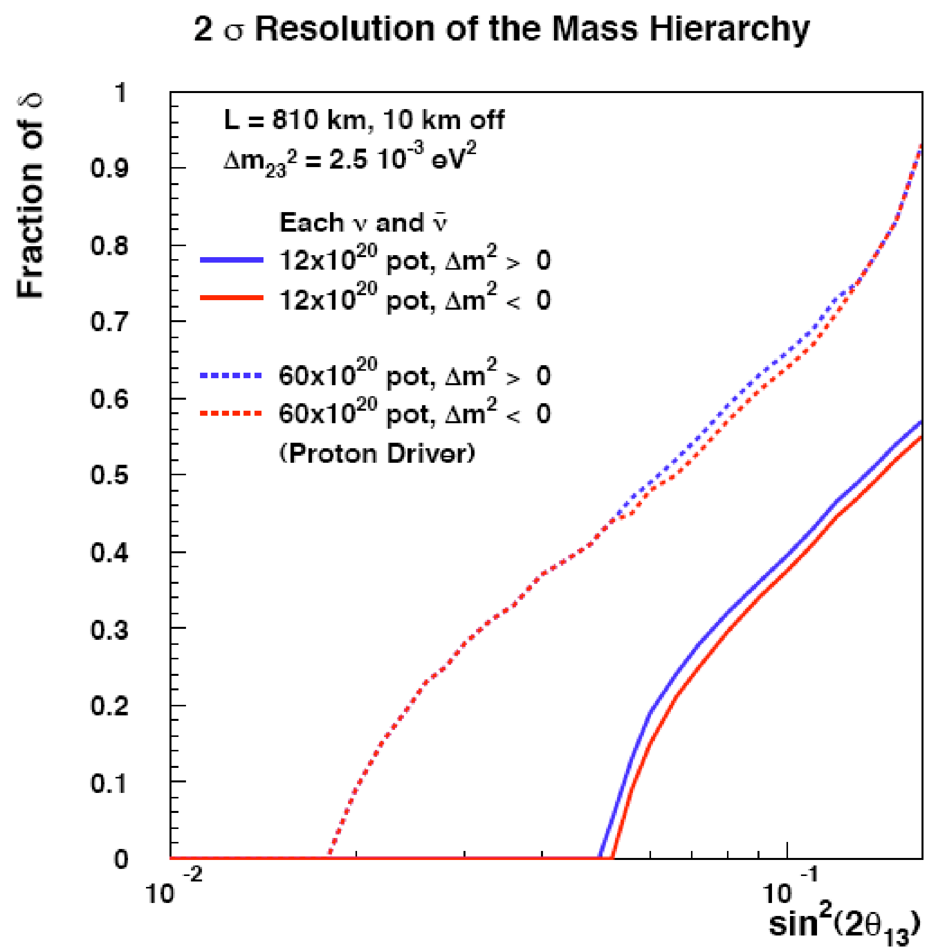
NuMI 3 yr □, 3 yr□□, 2 Detectors and Proton Driver



95% CL Resolution of the Mass Hierarchy



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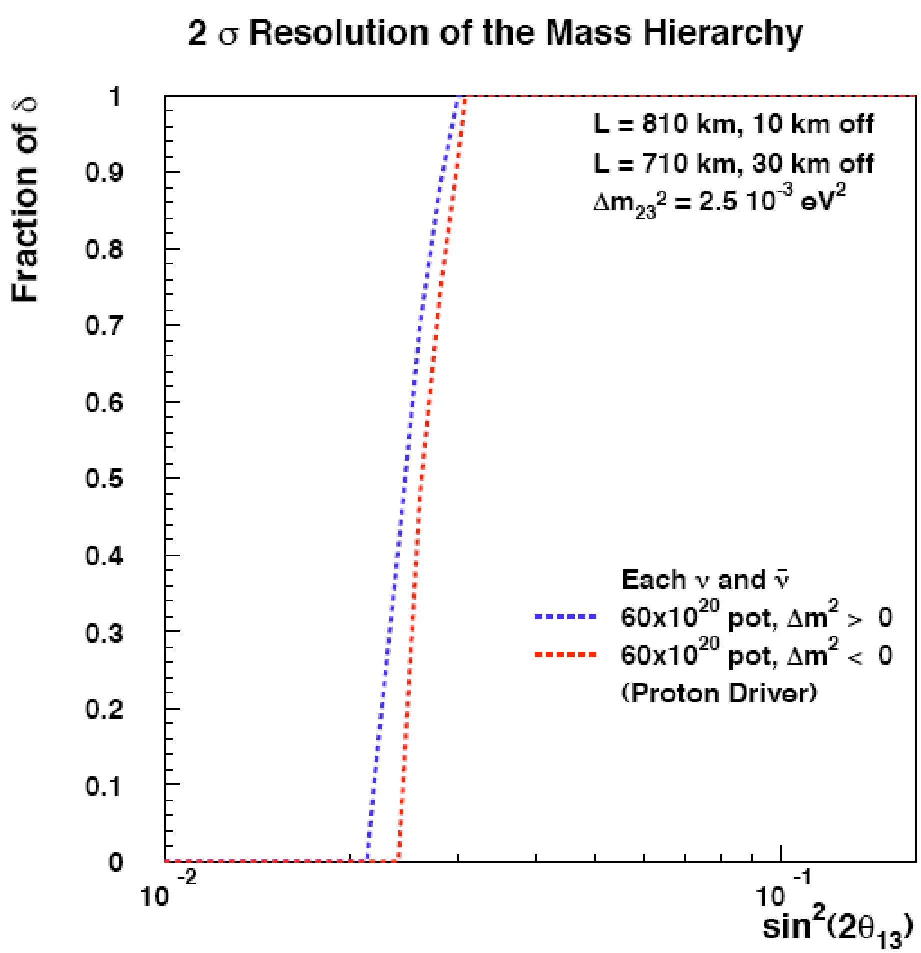
95% CL Resolution of the Mass Hierarchy with 2 Detectors



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Status

- R&D proposal submitted to the NSF in September.
- Progress Report submitted to the Fermilab PAC in December; full proposal will follow in March.
- PAC reaction:
  - "This can potentially become the future flagship experiment in an exciting neutrino physics program at Fermilab."
  - "Given the physics potential of the experiment and the significant detector cost involved, the Committee feels that some assistance from Fermilab for time-critical R&D needs leading to the proposal are justified."
- Temporary governance of the collaboration set up at February collaboration meeting.
- Next collaboration meeting May 15-16.

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Possible Time Scenario

- Spring 2004 - R&D funds from NSF
- June 2004 - Stage 1 Approval from Fermilab
- Summer 2004 - APS study report finished
  - Initial funding proposed for FY06 (Oct. 1, 2005)
- Dec 2004 - Final technology decision
  - Proposal update document submitted to Fermilab
- June 2005 - Final approval by Fermilab
  - Construction funds requested for FY07
- Oct 2006 - Start of construction
- Sept 2008 - Start of data with 25% of detector
- Sept 2010 - Detector construction completed

Comments on Schedule

- The schedule outlined is the technically feasible one with some optimistic assumptions about flow of funds
- The NO□A projected cost is essentially the same as the cost of the whole NuMI project - beam, detectors, conventional construction (~$150M)
- NuMI will take 5 years of funding to complete - mainly because of delay in completion of underground excavation work

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Conclusion

- NO□A is the right next step for the US in the context of a world-wide phased investigation of neutrino physics.
- In conjunction with other efforts, it will provide the information necessary to plan for Phase 3 activities.