The NOνA Experiment

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Why are Neutrinos Particularly Interesting?

- **Masses are anomalously low**
  - **From CMB data $m_\nu < 0.2$ eV/$c^2 \cong 0.0000004\ m_e$**
  - **A Window on the the GUT Scale? (seesaw mechanism)**
- **Only fundamental fermion which can be its own antiparticle (Majorana particle)**
- **Could be responsible for the matter/antimatter asymmetry of the universe (leptogenesis)**

Seesaw Mechanism

- **Right-handed neutrinos have no weak interactions and thus are not confined to the weak mass scale. Postulate both a GUT-scale right-handed Marjorana neutrino N_R and both Majorana and Dirac mass terms in the Lagrangian:**

$$\mathcal{L} = \tfrac{1}{2} M_{ij} \overline{N}_{R_i} N_{R_j} + \lambda_{ij} \begin{pmatrix} \nu_L, & e_L \end{pmatrix}_i \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} N_{R_j} + \text{h.c.}$$

Dropping the flavor index, this results in a mass matrix

$$\begin{pmatrix} 0 & m_l \\ m_l & M \end{pmatrix}, \quad \textit{where } m_l = \lambda \langle \phi \rangle,$$

a "normal" fermionic mass.

Seesaw Mechanism

Diagonalizing the mass matrix to obtain the physical masses yields,

$$m_N \approx M \quad \text{and} \quad m_\nu = \frac{m_l^2}{M}.$$

This is the seesaw mechanism.

Leptogenesis

- To explain how our matter-dominated universe arose from a matter-antimatter symmetric big bang, we need (Sakharov conditions)
  - Lepton and baryon number violation
  - CP violation (Standard Model quark CP violation not sufficient)
  - Thermal non-equilibrium
- Majorana neutrinos can provide these conditions.

Leptogenesis

- **CP-violating decays of *N*'s in the big bang era provides a source of lepton-number violation.**
  - **Example:** $N \rightarrow h\nu \neq \overline{N} \rightarrow h\overline{\nu}$

- **GUT-level (B - L)-conserving interactions convert the lepton-number asymmetry to a baryon asymmetry.**

Neutrino Oscillations

- **Neutrino oscillations occur because the weak eigenstates and not identical to the mass eigenstates.**
- **Neutrinos are always produced and detected in weak eigenstates, but they propagate in mass eigenstates.**
- **To the extent that the masses of the mass eigenstates are different, the phase relations generated by the propagation ($e^{-iEt/\hbar}$) change, producing the oscillation.**

Mixing Matrix

- **The relationship between the weak eigenstates and the mass eigenstates is given by a unitary rotation matrix:**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mixing Matrix

- **The mixing matrix can be specified by 3 angles and one complex phase:**

$$|\nu_l\rangle = U|\nu_n\rangle, \quad \text{where} \quad (c_{ij} \equiv \cos\theta_{ij}, \quad s_{ij} \equiv \sin\theta_{ij})$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\nu_\mu \rightarrow \nu_\tau$ atmospheric $\quad$ $\nu_\mu \rightarrow \nu_e$ atmospheric $\quad$ $\nu_e \rightarrow \nu_\mu, \nu_\tau$ solar

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Vacuum Oscillations

- When a 2 x 2 oscillation is sufficient, in vacuum,

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

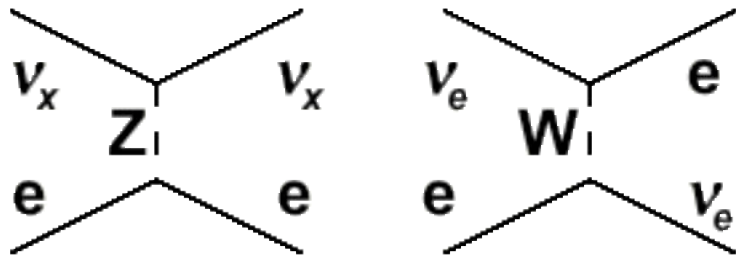
$$P(\nu_e \rightarrow \nu_x) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

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

L is in km, and E is in GeV

Matter Oscillations

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



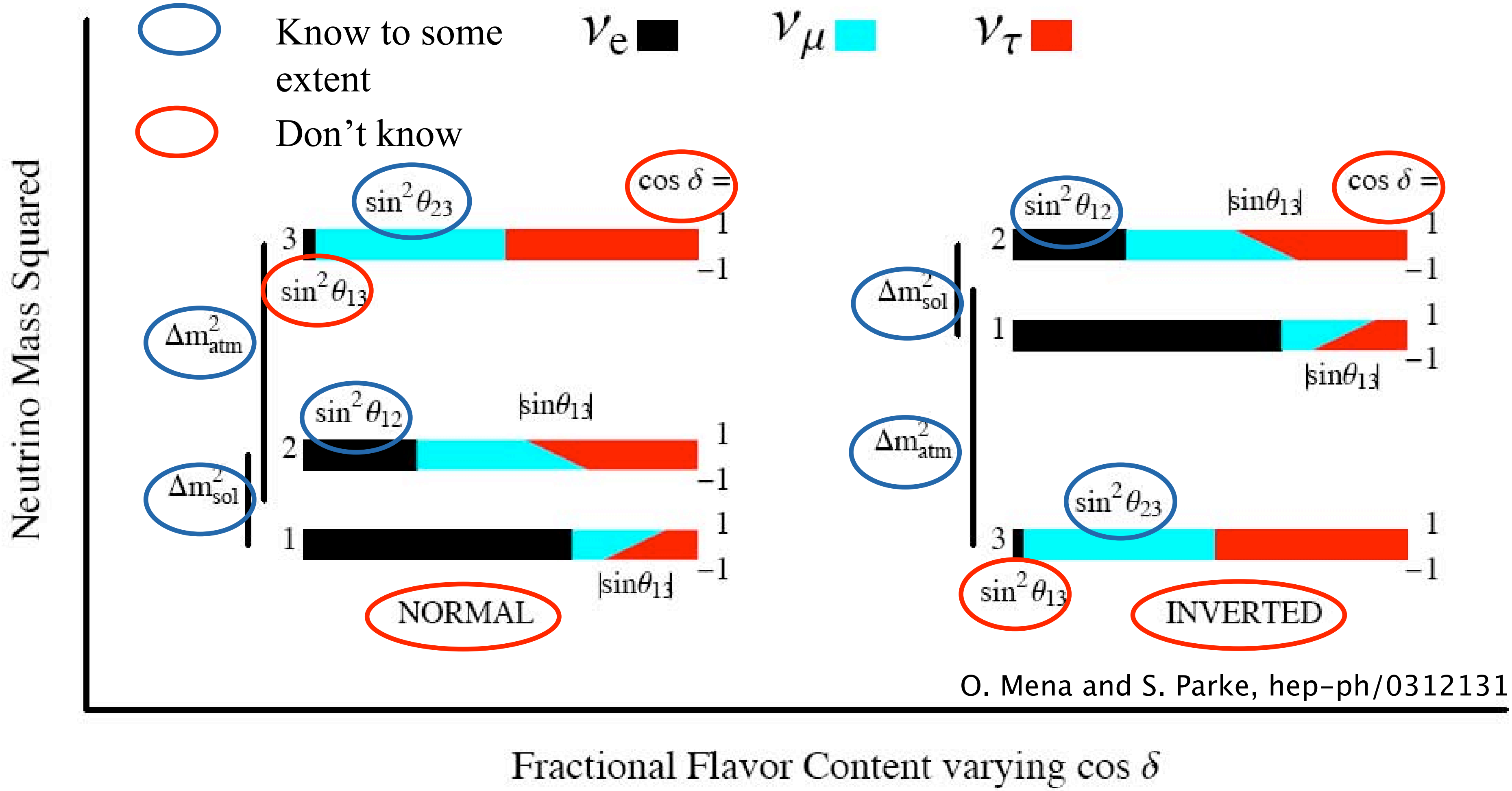
$$H = \begin{pmatrix} \frac{\Delta m^2}{4E}\cos 2\theta - \sqrt{2}G_F\rho_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & -\frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

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

What Have We Learned?

- From observing neutrinos from the sun and reactors, we have learned that $\nu_e \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_\tau$ with $L/E \approx$ 15 000 km/GeV, with a large but not maximal mixing angle, θ_{12}.
- From observing neutrinos produced in the atmosphere by cosmic rays and 1st generation accelerator experiments (K2K and MINOS) we have learned that $\nu_\mu \rightarrow \nu_\tau$ with $L/E \approx$ 500 km/GeV, with a mixing angle, θ_{23}, consistent with being maximal.

What We Know and What We Don't Know



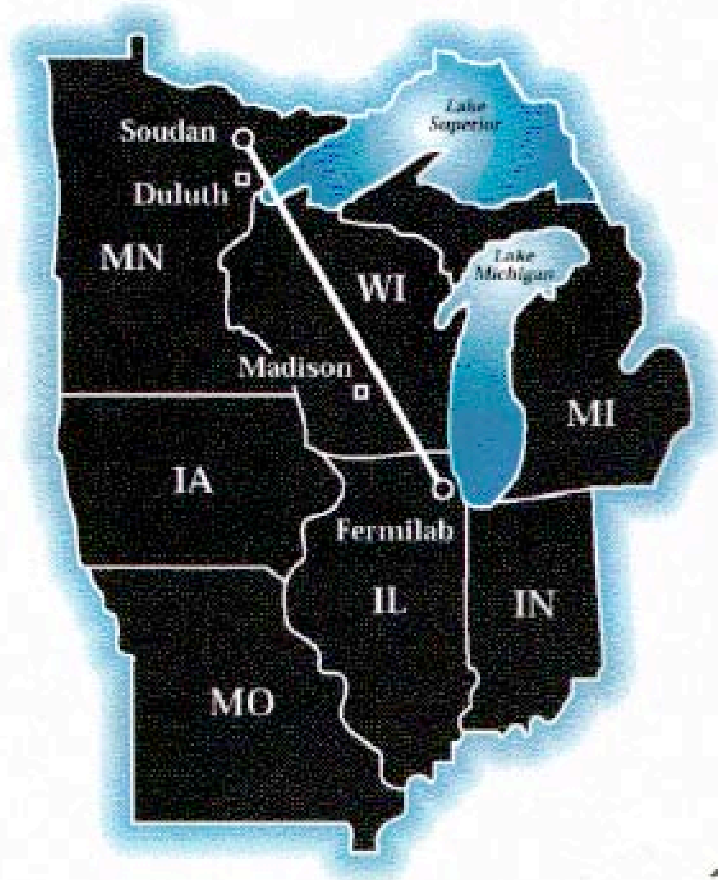
One Anomaly

- A Los Alamos experiment with stopped pions (LSND) has reported evidence for oscillations of $\bar{\nu}_\mu \to \bar{\nu}_e$ with $\Delta m^2 > 0.1\,(\mathrm{eV})^2$.
- Such an oscillation requires a sterile neutrino since three active neutrinos admit only two independent Δm^2s.
- Such a neutrino would be only very marginally consistent with solar and atmospheric data.
- This effect is being checked currently by MiniBooNE, a Fermilab experiment.
- A confirmation would be exciting and require rethinking some of our plans.

1st Generation Long Baseline Experiments

- For the past few years we have been running the first generation of long baseline accelerator experiments
  - K2K: Low statistics experiment in Japan now completed.
  - CNGS: Gran Sasso program started last year.
  - MINOS: Fermilab experiment started in 2005.
- First generation goals:
  - Verify dominant $\nu_\mu \rightarrow \nu_\tau$ oscillations
  - Precise measurement of dominant Δm_{23}^2 and $\sin^2 2\theta_{23}$
  - Search for subdominant $\nu_\mu \rightarrow \nu_e (\sin^2 2\theta_{13})$ and $\nu_\mu \rightarrow \nu_s$ oscillations

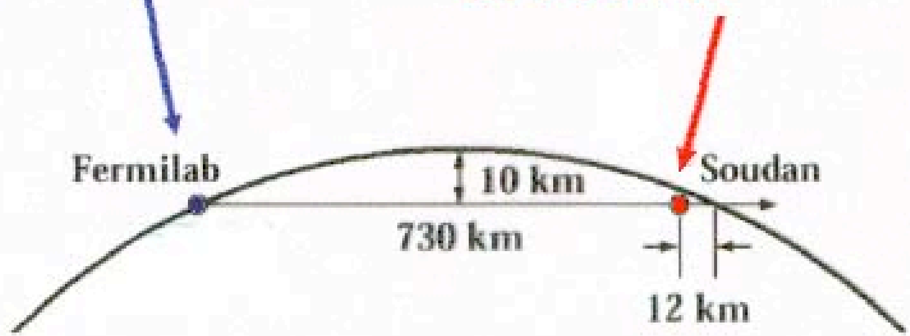
MINOS Layout
(**M**ain **I**njector **N**eutrino **O**scillation **S**earch)



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

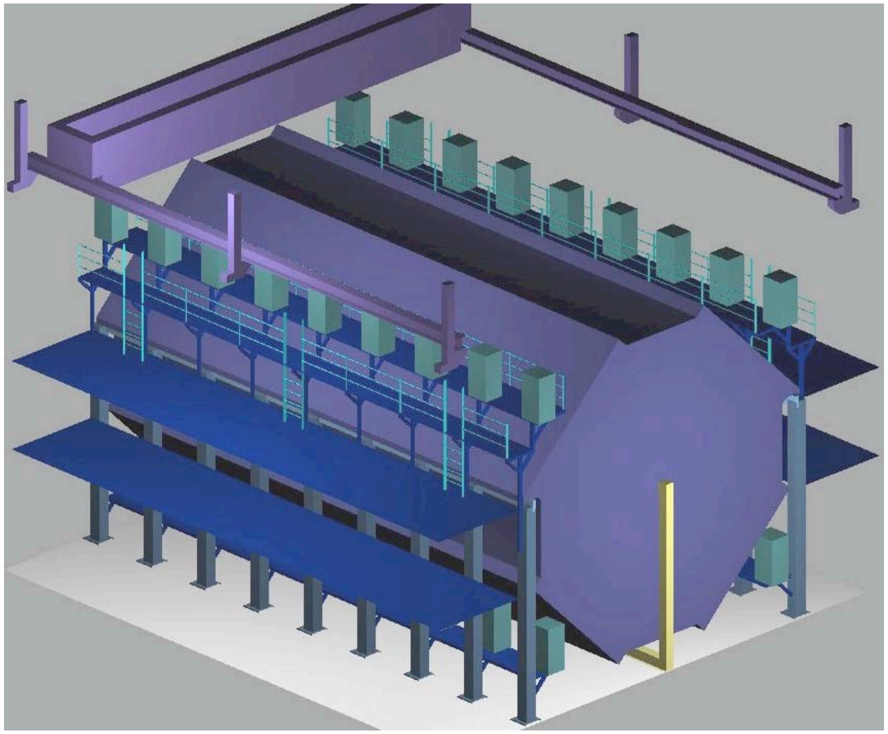
Near detector 980 T at 1 km

Far detector 5400 T at 730 km

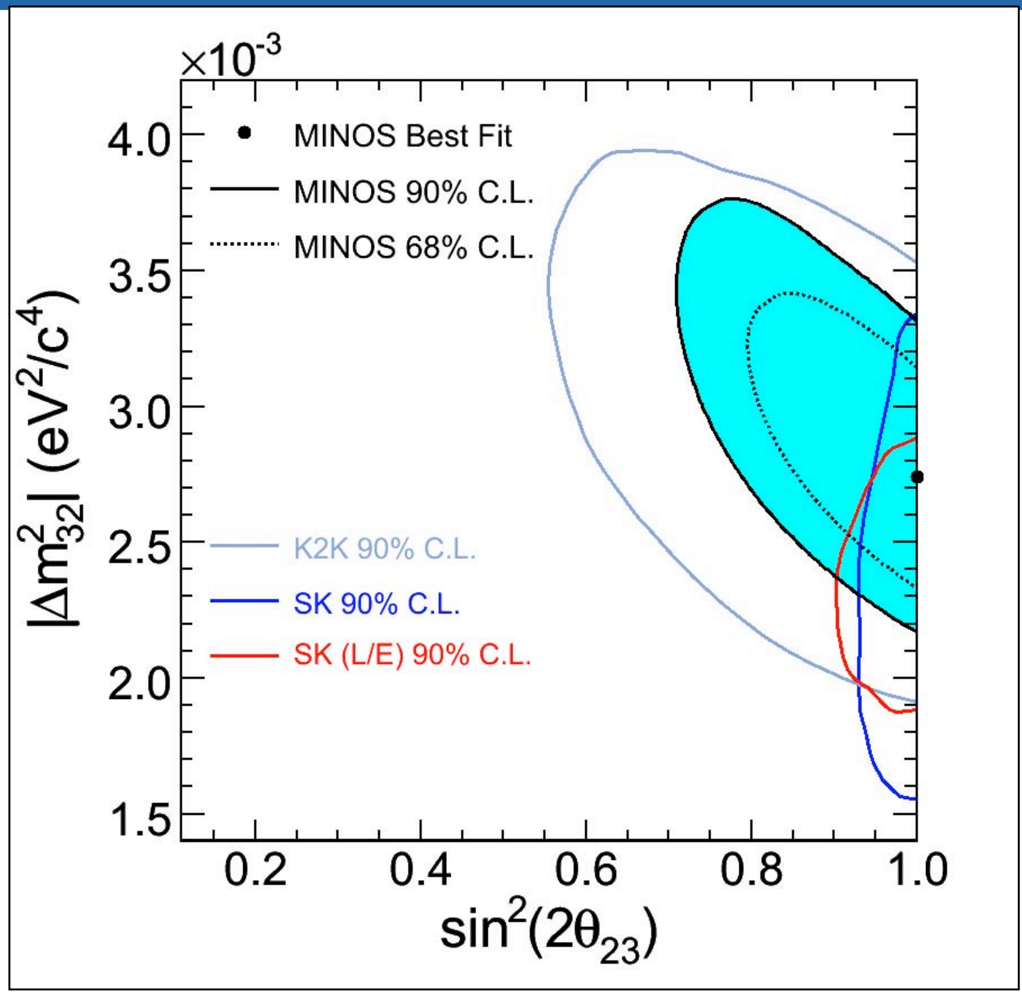


MINOS Far Detector

- 8m octagonal tracking calorimeter
- 484 layers of 2.54 cm Fe plates
- 4.1 cm-wide scintillator strips with WLS fiber readout, read out from both ends
- 8 fibers summed on each PMT pixel; 16 pixels/PMT
- 25,800 m^2 of active detector planes
- Toroidal magnetic field <B> = 1.3 T
- Total mass 5.4 kT



MINOS 1st Year Results



NOνA:
NuMI Off-Axis ν_e Appearance Experiment

- NOνA will be a 2nd generation experiment on the NuMI beamline. Its Far Detector will be a 20 kT totally active, tracking liquid scintillator calorimeter located near Ash River, MN, 810 km from Fermilab and 12 km off the center of the NuMI beamline.
- Its main physics goal will be the study of $\nu_\mu \to \nu_e$ oscillations at the atmospheric oscillation length with an order of magnitude more sensitivity than the MINOS experiment.
- Its unique characteristic is its long baseline, which allows access to matter effects, which can be used to determine the ordering of the neutrino mass states.

The NOνA Collaboration

135 physicists and engineers from 27 institutions

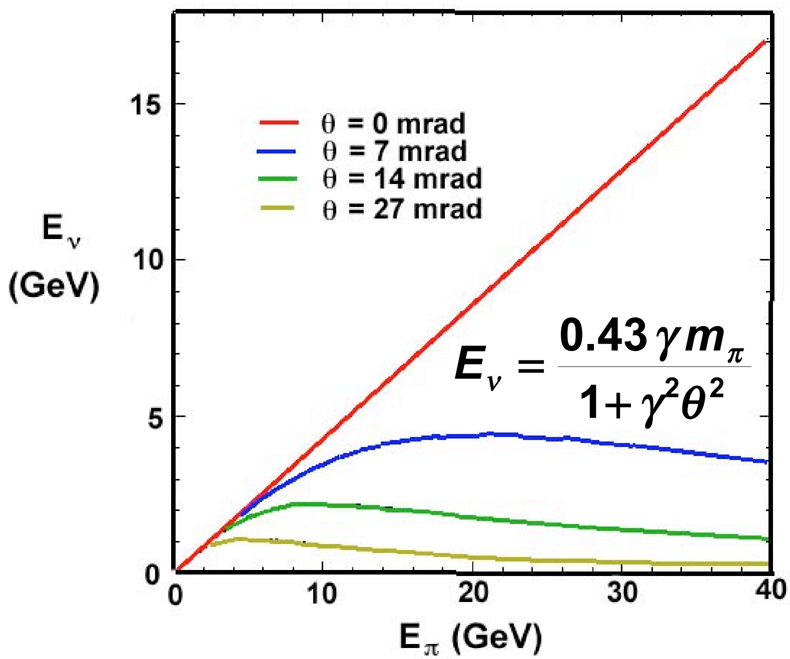
Argonne, Athens, Caltech, College de France, Fermilab, Harvard, Indiana, ITEP, Lebedev, Michigan State, Minnesota-Twin Cities, Minnesota-Duluth, Munich, Northern Illinois, Ohio State, Rio de Janeiro, South Carolina, SMU, Stanford, Texas-Austin, Texas-Dallas, Texas A&M, Tufts, UCLA, Virginia, Washington, William and Mary

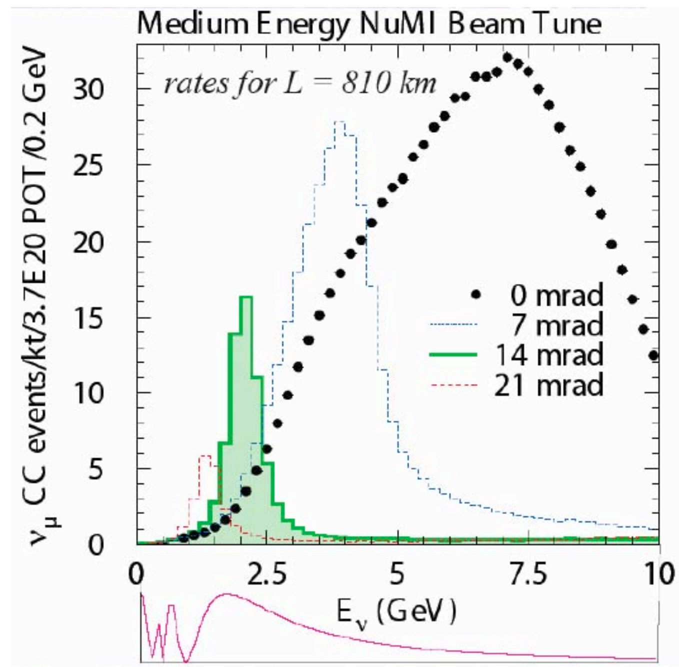
How Do We Gain an Order of Magnitude in Sensitivity?

- Place the far detector off-axis (more flux and less background).
- Optimize the far detector for electron identification (0.15 X_0 vs. 1.5 X_0 longitudinal segmentation)
- Increase the mass of the far detector by a factor of 4.
- Increase the beam power by a factor of 6 (from the present beam).

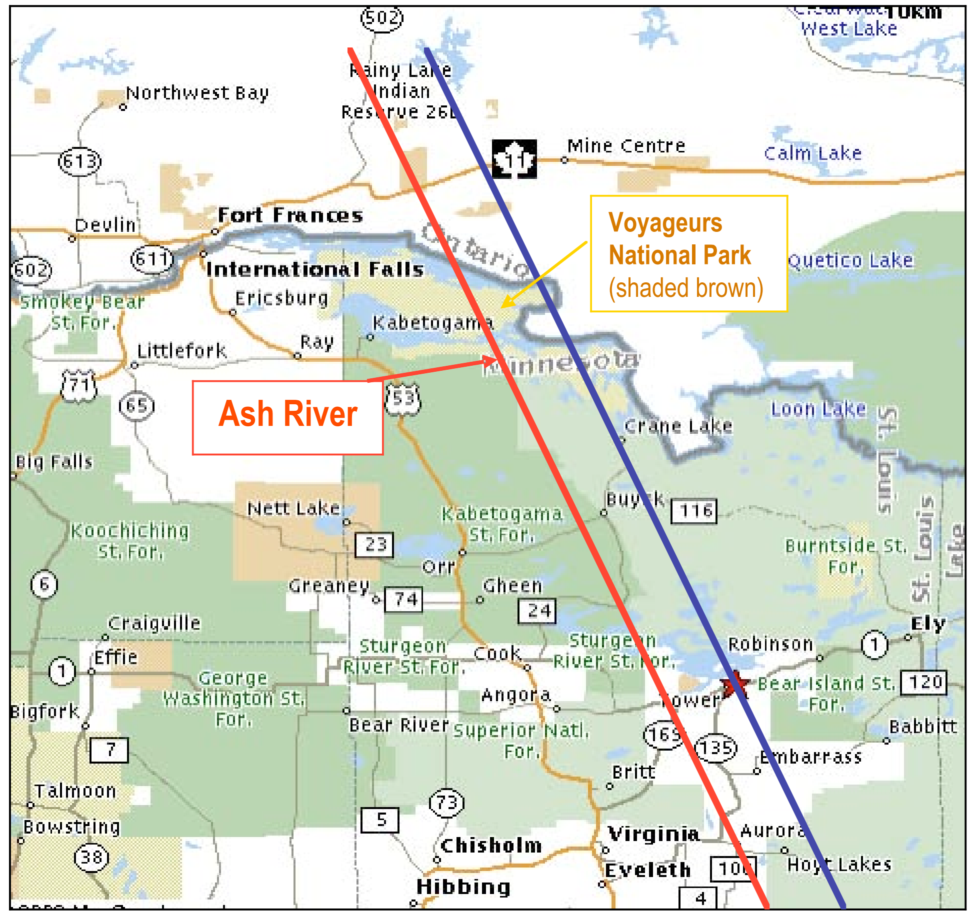
Why Off-Axis?

- Both Phase 2 experiments, NOνA and T2K are sited off the neutrino beam axis. This yields a narrow band beam:
  - More flux and less background (ν_e's from *K* decay and higher-energy NC events)



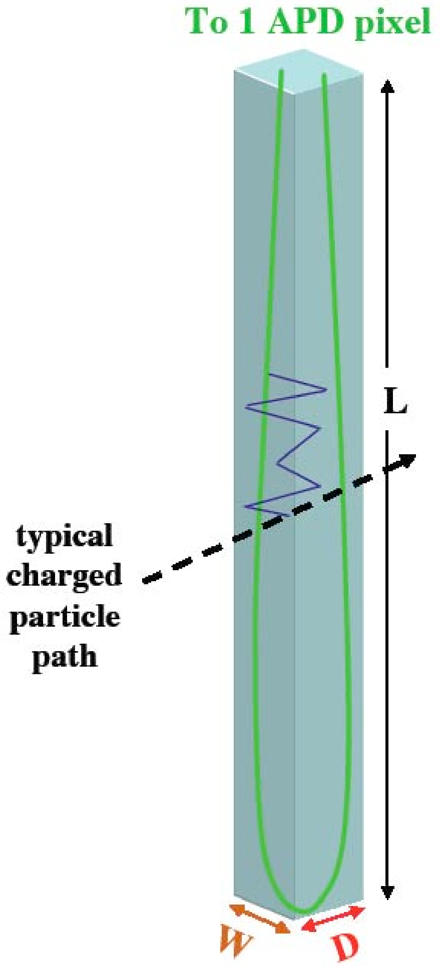


Why Ash River?



The Ash River site is the furthest available site from Fermilab along the NuMI beamline. This maximizes NOνA's sensitivity to the mass ordering.

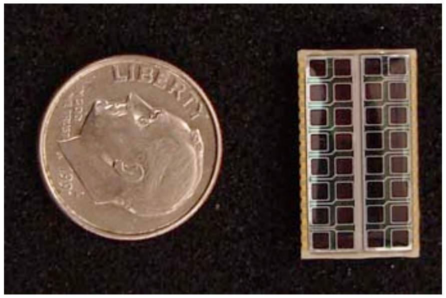
Basic Detector Element



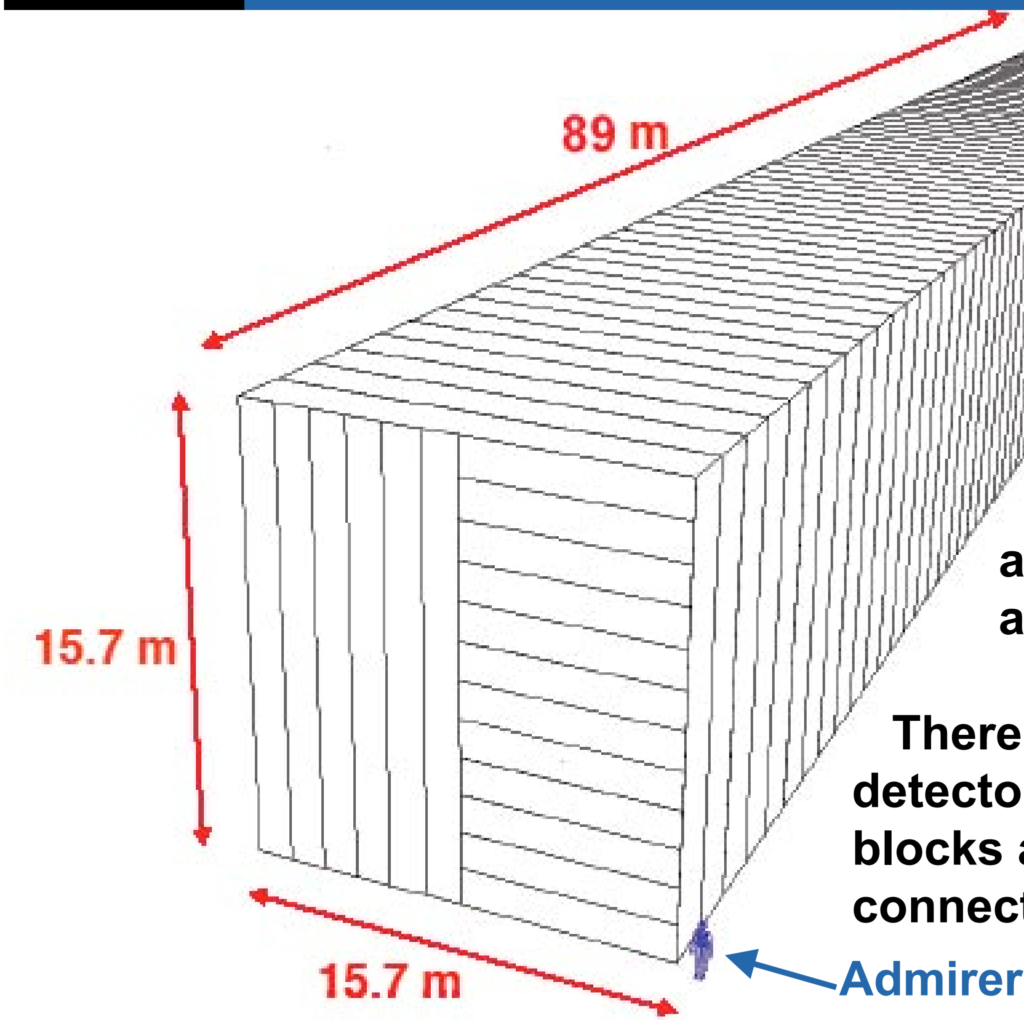
Liquid scintillator in a 4 cm wide, 6 cm deep, 15.7 m long, highly reflective PVC cell.

Light is collected in a U-shaped 0.7 mm wavelength-shifting fiber, both ends of which terminate in a pixel of a 32-pixel avalanche photodiode (APD).

The APD has peak quantum efficiency of 85%. It will be run at a gain of 100. It must be cooled to -15^{o}C and requires a very low noise amplifier.



The Far Detector



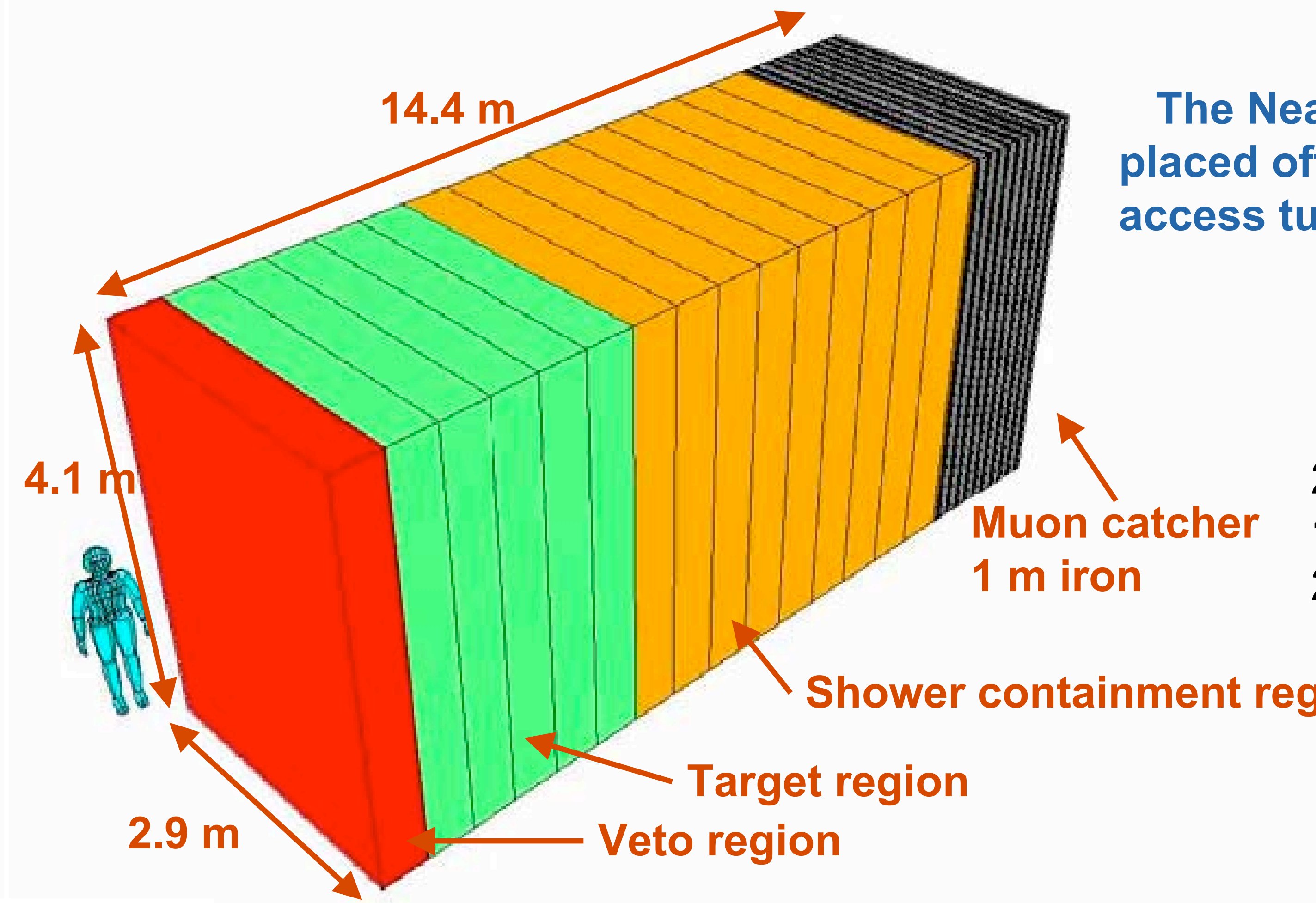
The cells are made from 32-cell extrusions.

12 extrusion modules make up a plane. The planes alternate horizontal and vertical.

For structural reasons, the planes are arranged in 31-plane blocks, beginning and ending in a vertical plane.

There are 43 blocks = 1333 planes. The detector can start taking data as soon as blocks are filled and the electronics connected.

The Near Detector

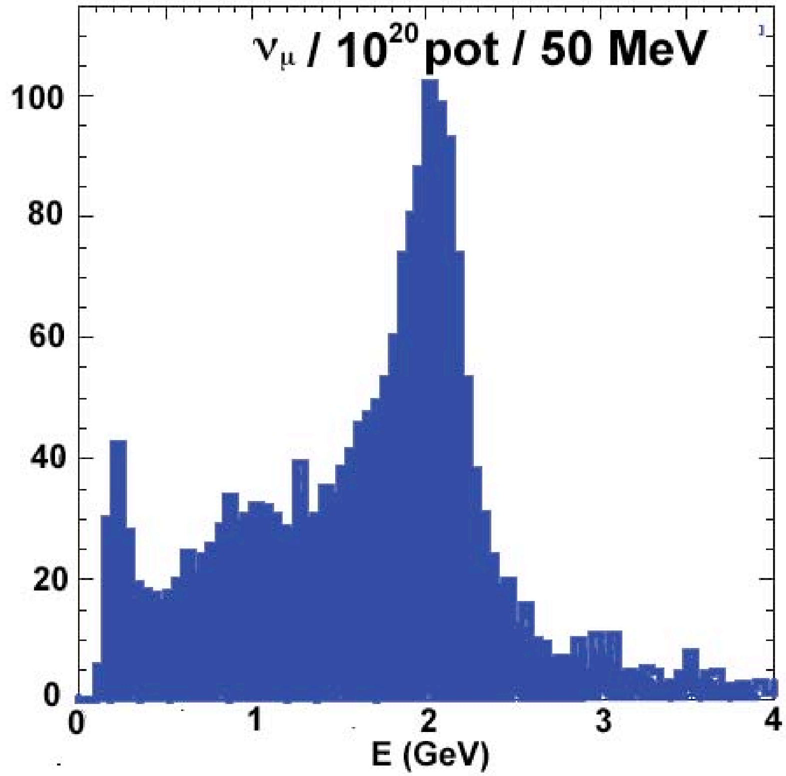


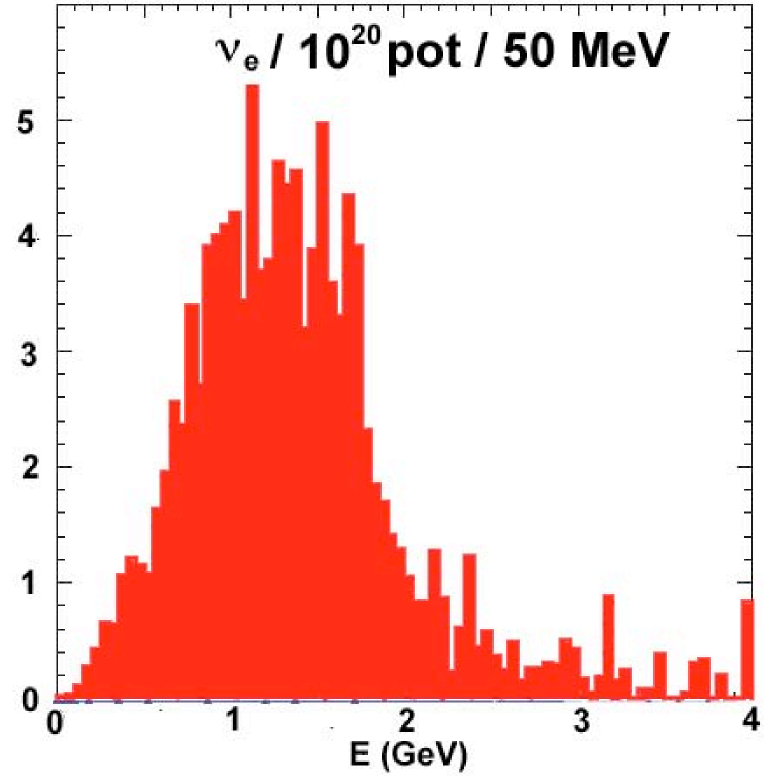
The Near Detector will be placed off-axis in the MINOS access tunnel.

209 T
126 T totally active
23 T fiducial

The Integration Prototype Near Detector

We plan to have a prototype version of the Near Detector running in the MINOS surface building next year.
It will detect a 107 mr off-axis NuMI beam, dominated by *K* decays.

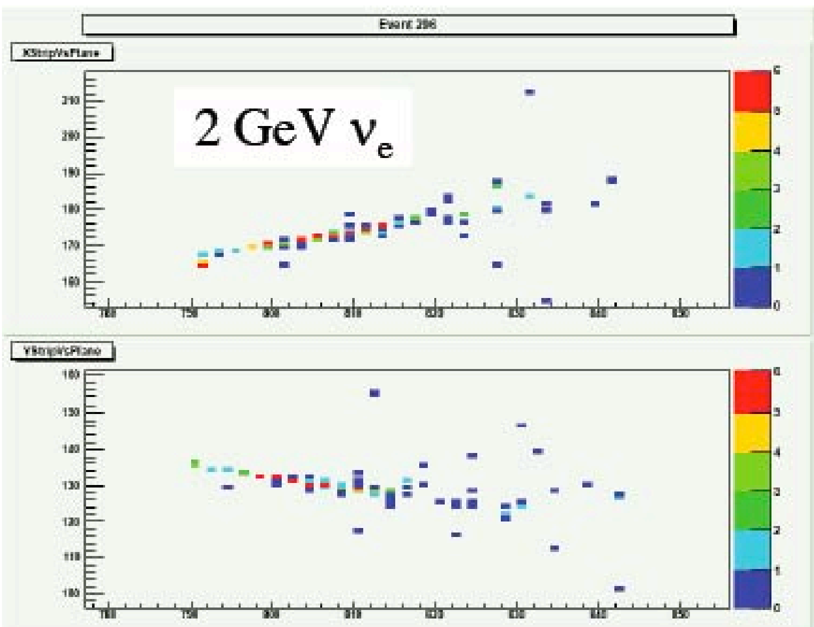


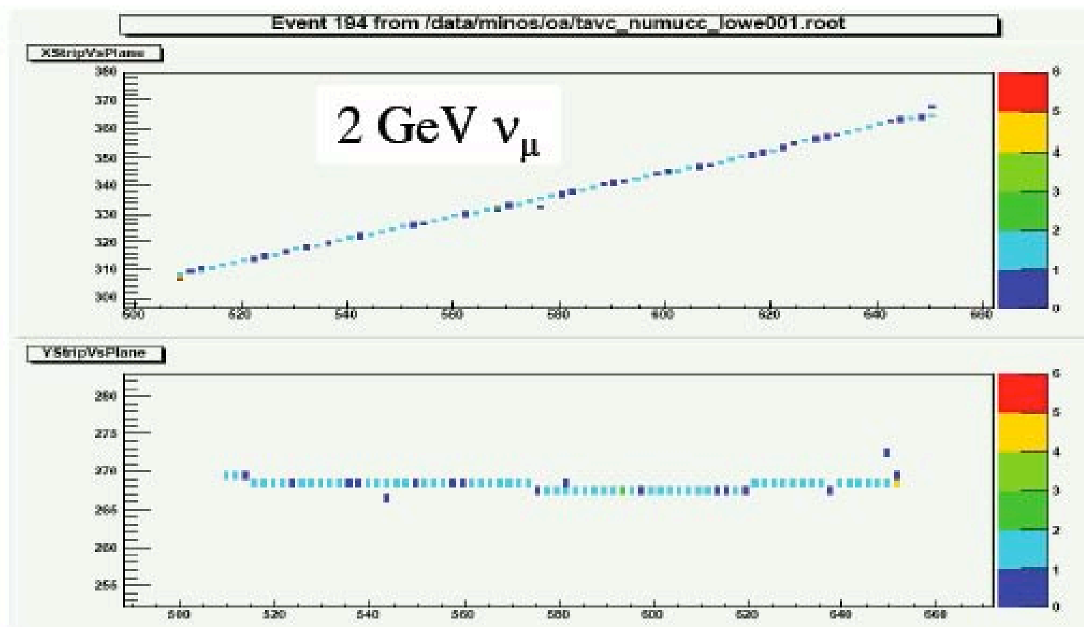


Event Quality

Longitudinal sampling is 0.15 X0, which gives excellent μ-e separation.

A 2-GeV muon is 60 planes long.





ν_e CC event

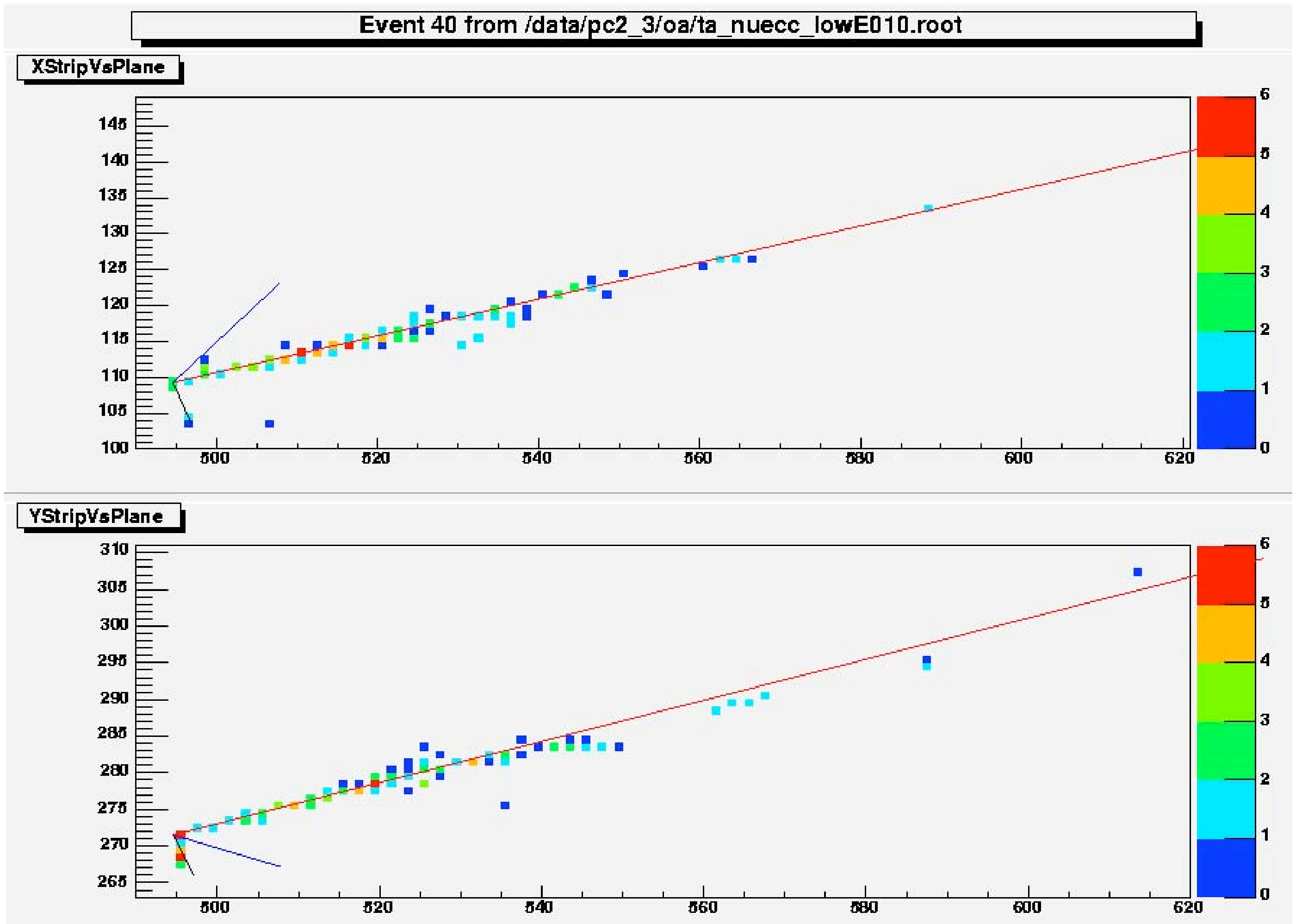
$\nu_e p \rightarrow e^- p \pi^+$

E_ν=2.5GeV

E_e=1.9GeV

E_p=1.1GeV

E_π=0.2GeV



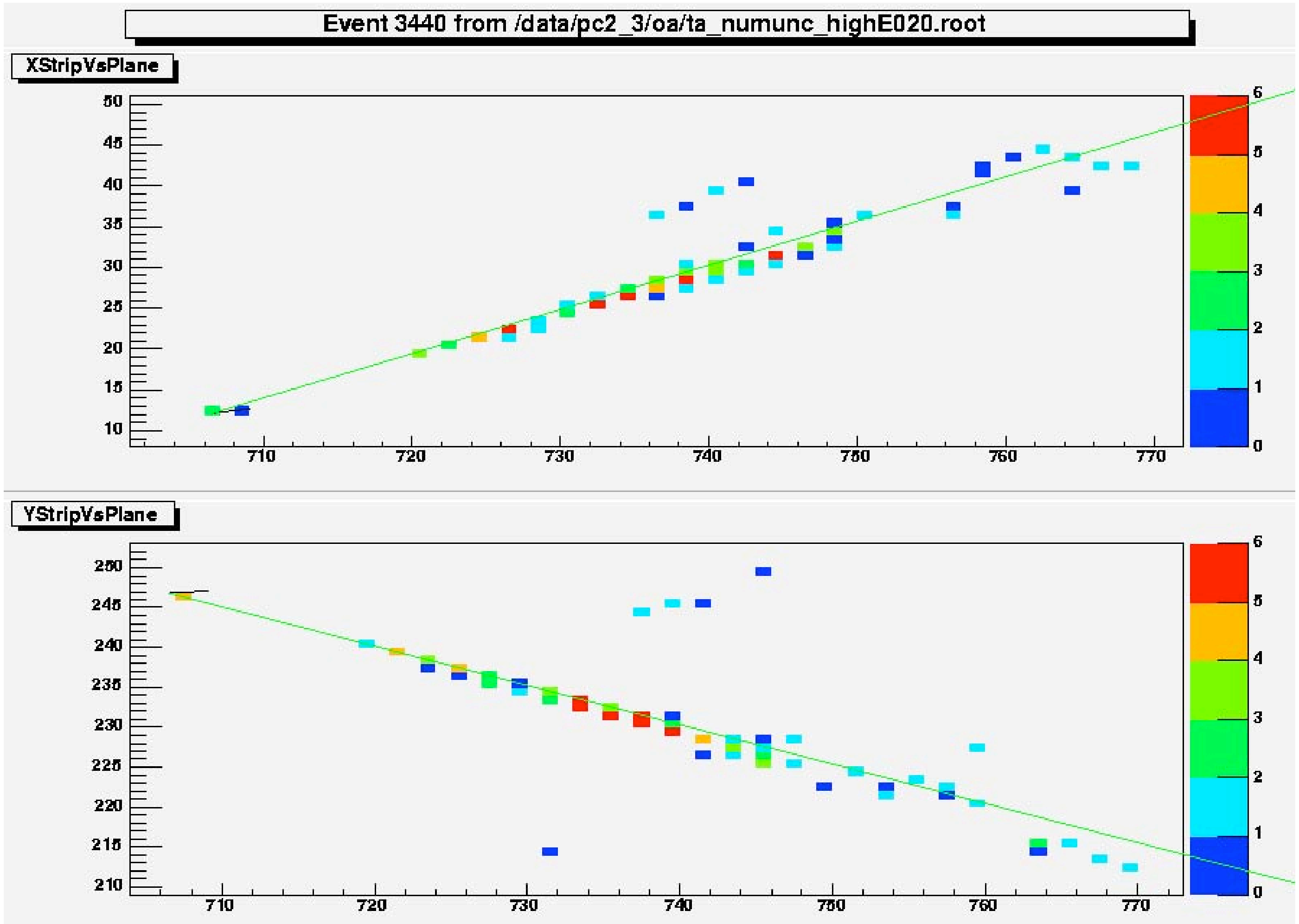
Background NC event

$\nu_\mu N \rightarrow \nu_\mu p \pi^o$

E_ν=10.6 GeV

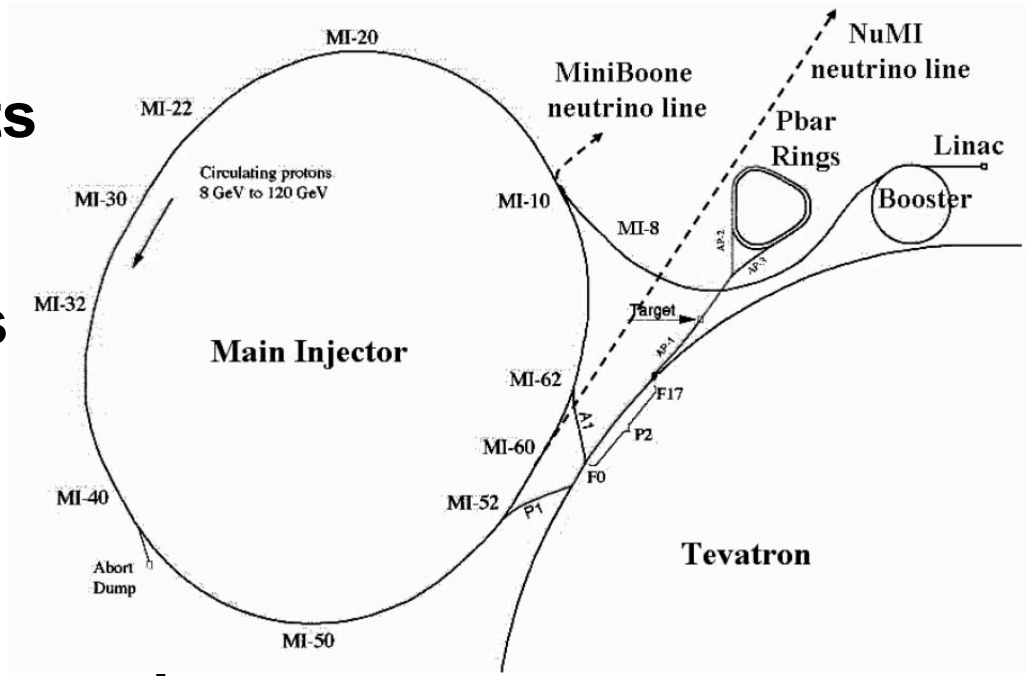
E_p=1.04GeV

$E_{\pi o}$ =1.97GeV



Beam Operation

- **Basic operation: The Booster injects 6 batches into the MI at 15 Hz. The MI then ramps up, extracts the beam and ramps down.**



- **There is a 8-GeV Recycler ring above the MI, and an Accumulator in the Pbar Rings.**

Beam Upgrades

- Present: 2 slip-stacked batches to p-bar production and 5 single batches to NuMI (200 kW)
- Proton Plan 1 (2008-9): 2 slip-stacked batches to p-bar production and 8 slip-stacked batches and 1 single batch to NuMI (320 kW). 2.2 s cycle.
- Proton Plan 2 (2010-12): 12 slip-stacked batches to the Recycler, then single shot to the MI running at a 1.33 s cycle. (700 kW)
- SNuMI (Super NuMI): Momentum stack 3 Booster batches into the Accumulator, which injects them into the Recycler (for 18 batches total), then single shot to the MI running at a 1.33 s cycle. (1200 kW)

A Recent Hiccup

- Proton Plan 2 was to be run as a "campaign." However, the OMB recently directed the DOE to combine Proton Plan 2 and NOνA into a single project.
- This, along with the continuing resolution, will delay us by a few months because now PP2 and NOνA must go through CD-2 together and PP2 is not as far advanced as NOνA, and it must reorganize as a project.

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

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

  } Atmospheric-solar interference (for P_3 and P_4)

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

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

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

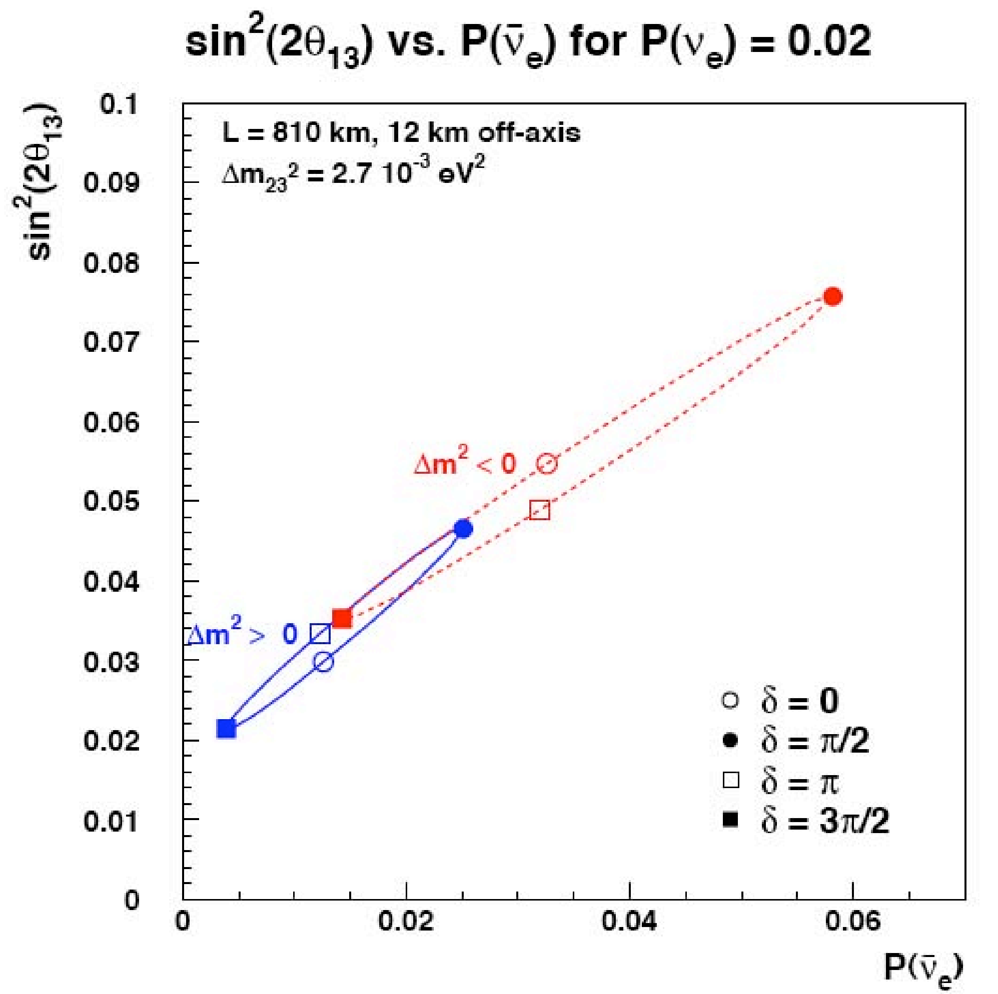
- In matter at oscillation maximum, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.

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

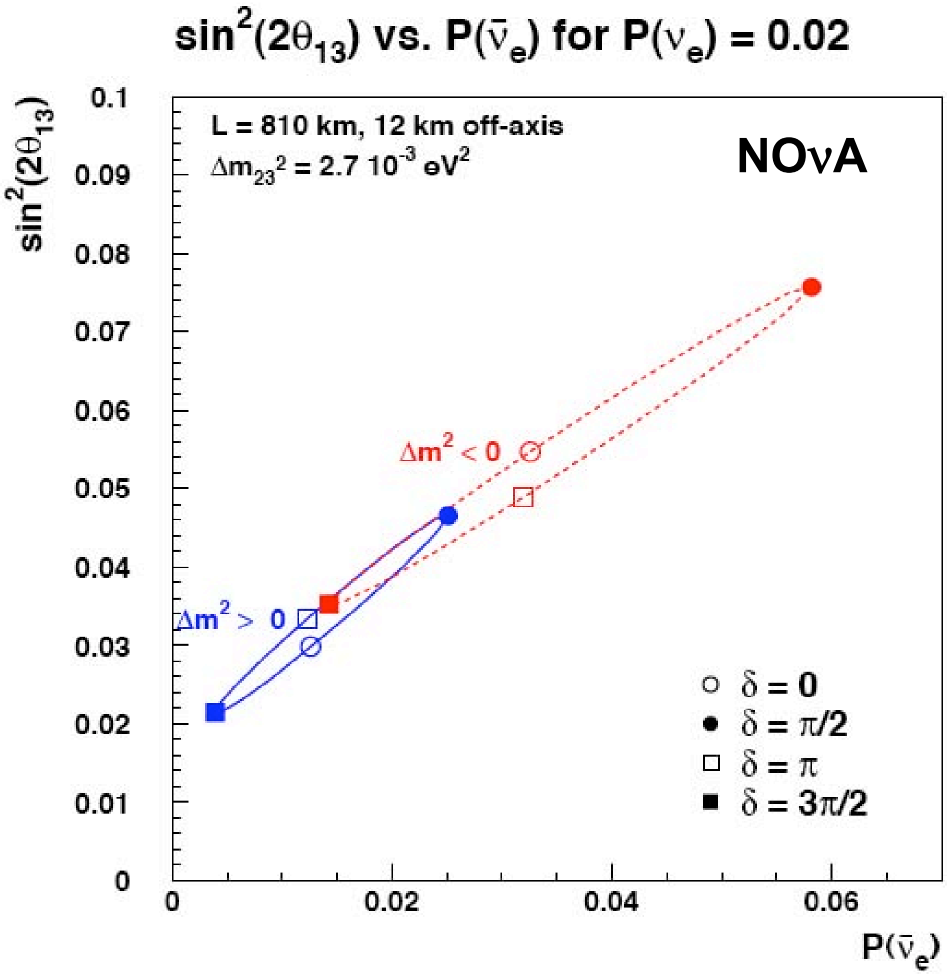
About a ±30% effect for NuMI, but only a ±11% effect for T2K.

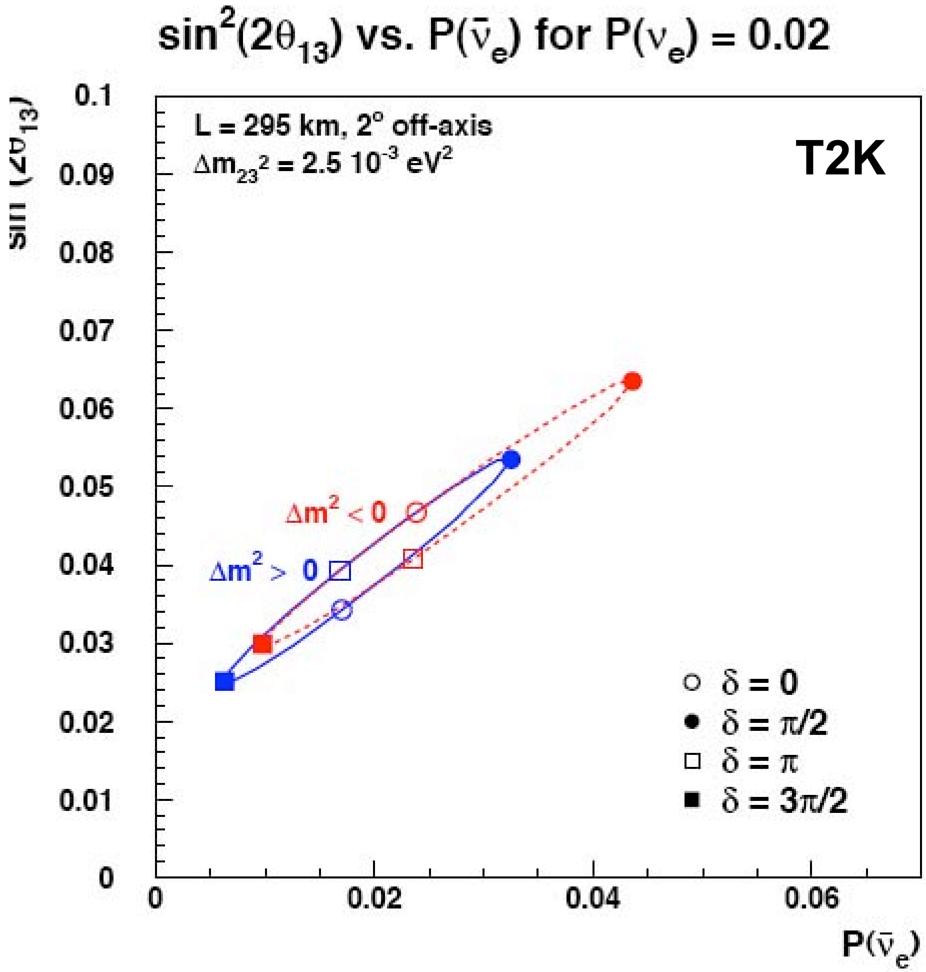
However, the effect is reduced for energies above the oscillation maximum and increased for energies below.

Parameters Consistent with a 2% $\nu_\mu \rightarrow \nu_e$ Oscillation



Parameters Consistent with a 2% $\nu_\mu \rightarrow \nu_e$ Oscillation

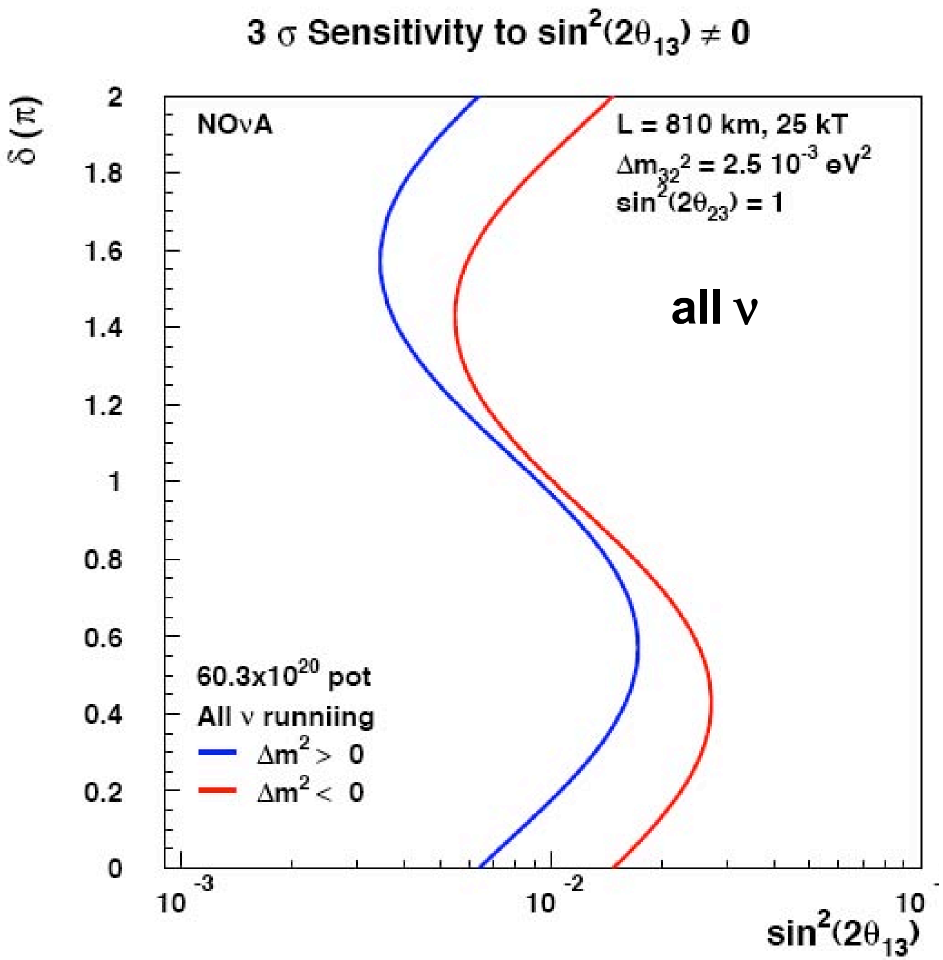


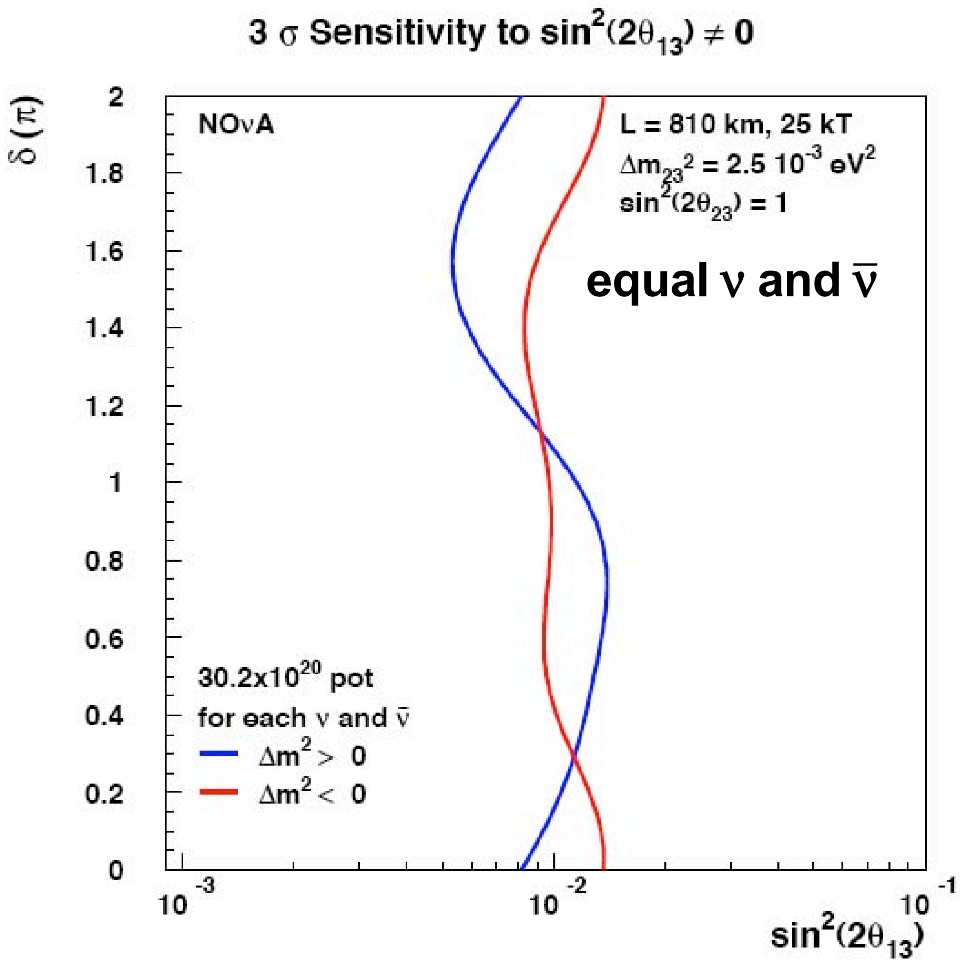


Simulations

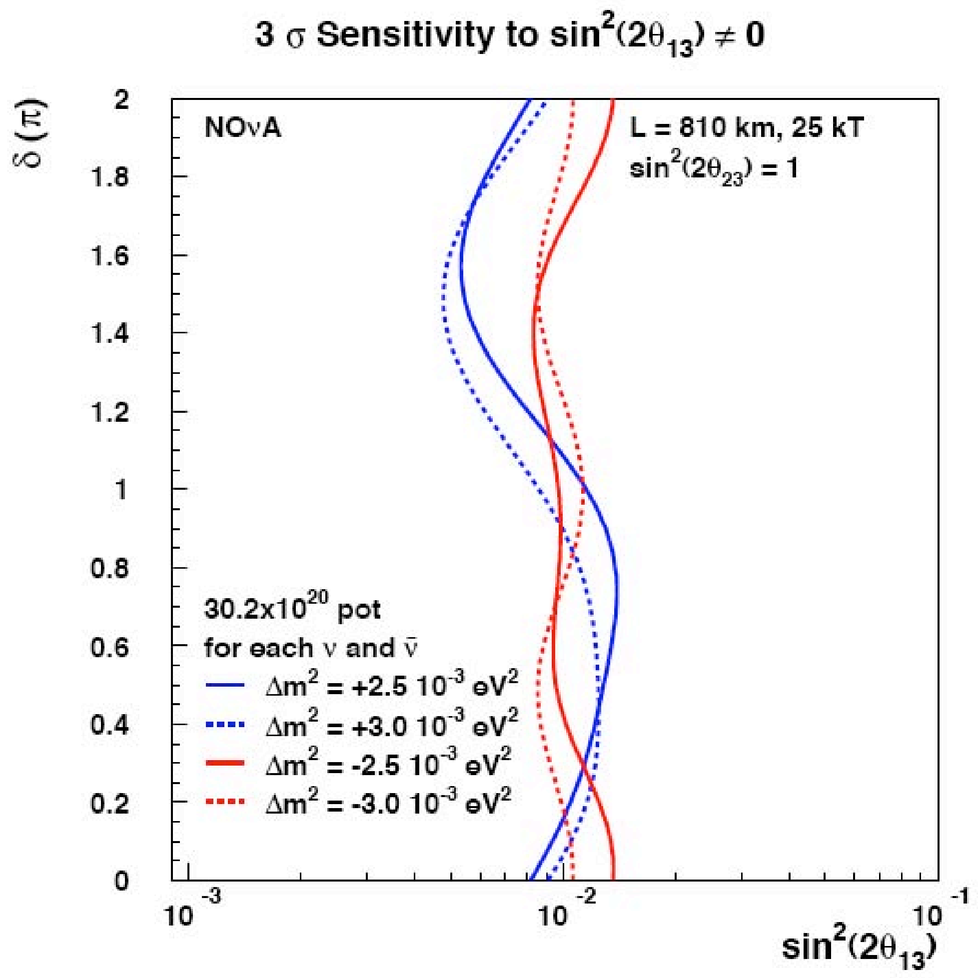
- The physics projections are based on a full reconstruction:
  - Raw hits are produce by a Monte Carlo simulation.
  - The hits are reconstructed into physics objects.
  - A likelihood function is constructed to separate ν_e events from backgrounds.
  - A cut on the likelihood function is made to maximize a figure of merit (FoM) = $\text{signal}/\sqrt{\text{background}}$.
- These projections are for 25 kT, 1 MW beam power, a derating factor of 0.69. They need to be updated to 20 kT, 1.2 MW, and 0.61.
- We are also actively working on improving the reconstruction and event recognition.

3 σ Sensitivity to $\theta_{13} \neq 0$





Comparison of Δm^2 = 0.0025 and 0.0030 eV^2

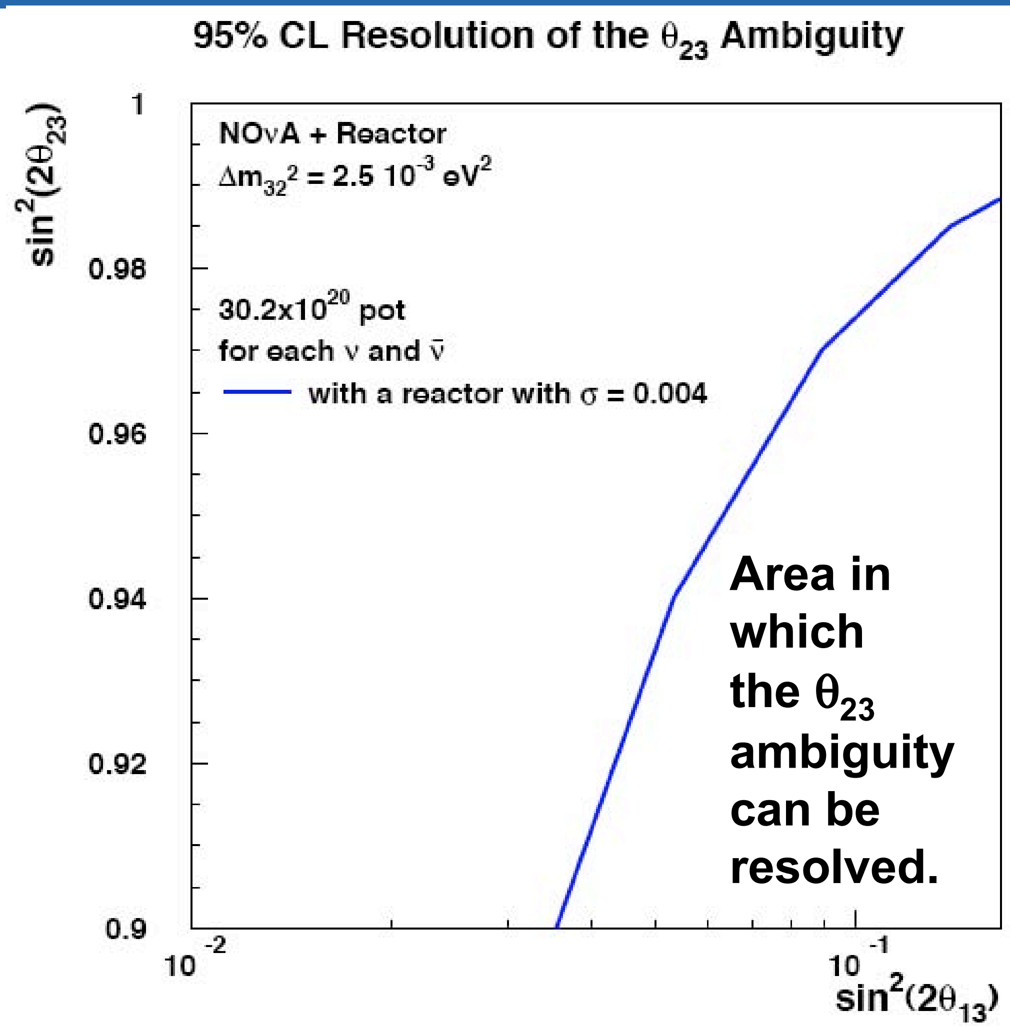


Not a great deal of difference

Comment

- There will be an ambiguity in comparing accelerator and reactor experiments if the θ_{23} mixing is not maximal.
  - Reactor experiments are sensitive to $\sin^2(2\theta_{13})$.
  - Accelerator experiments are largely sensitive to $\sin^2(\theta_{23})\sin^2(2\theta_{13})$.
  - This is the difference between $\nu_e \leftrightarrow \nu_\mu$ mixing (accelerators) and $\nu_e \leftrightarrow (\nu_\mu + \nu_\tau)$ mixing (reactors).
- Resolving this ambiguity is the main complementarity between the two types of experiments. It can be done if the θ_{23} mixing is sufficiently non-maximal and $\sin^2(2\theta_{13})$ is sufficiently large. (See next slide.)

95% CL Resolution of the θ_{23} Ambiguity

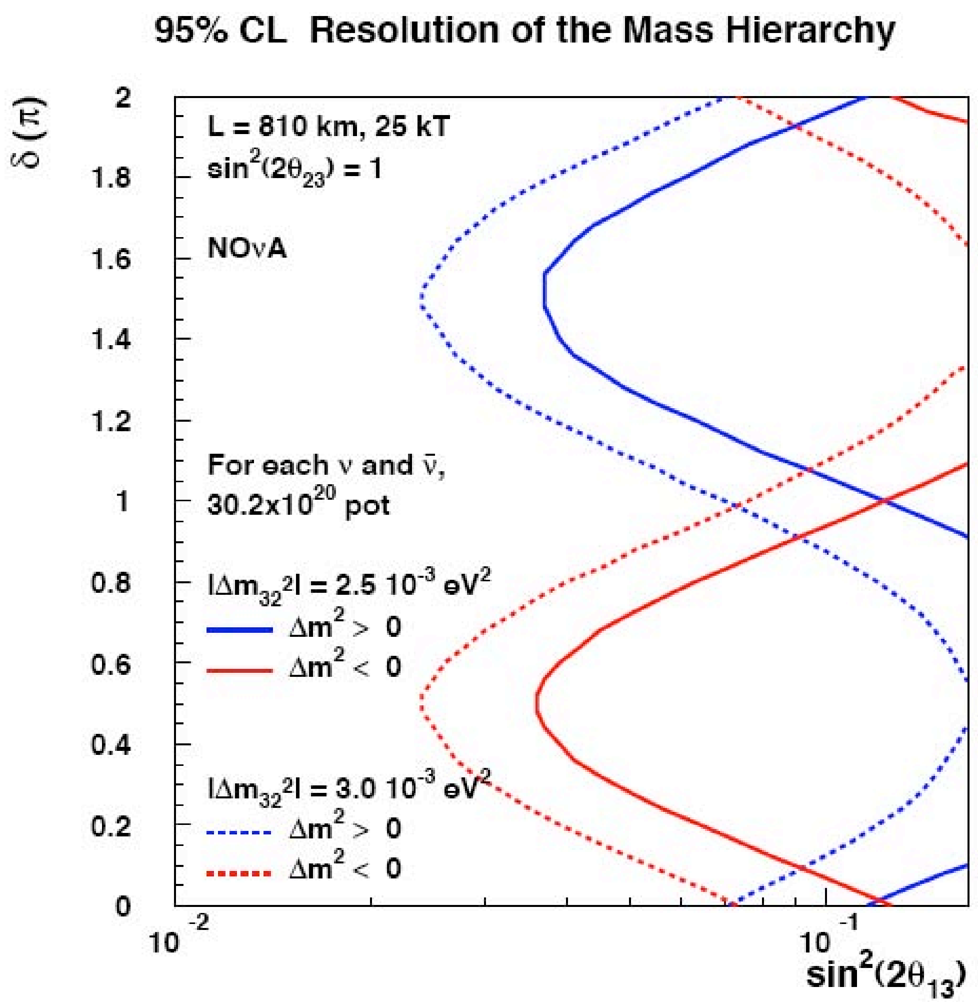


(There is some sensitivity to the mass ordering and δ. The blue line represents an average over these parameters.)

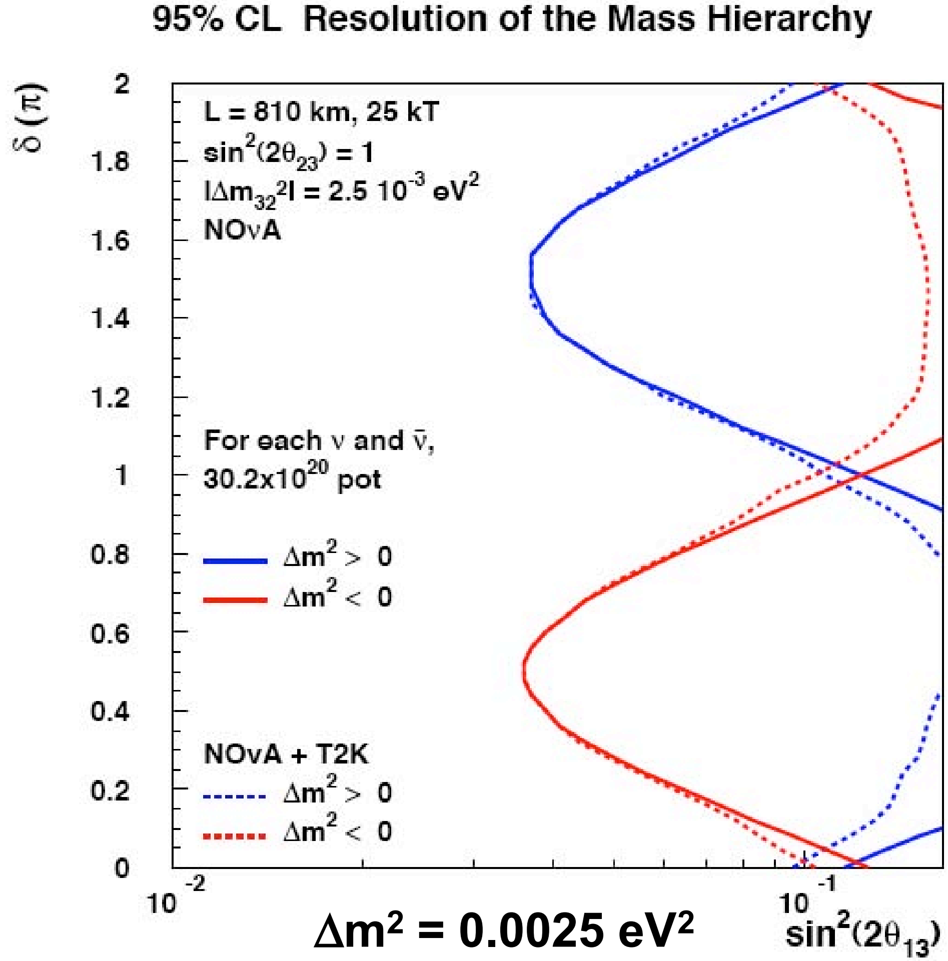
Importance of the Mass Ordering

- Window on very high energy scales: grand unified theories favor the normal mass ordering, but other approaches favor the inverted ordering.
- If we establish the inverted ordering, then the next generation of neutrinoless double beta decay experiment can decide whether the neutrino is its own antiparticle. However, if the normal ordering is established, a negative result from these experiments will be inconclusive.
- To measure CP violation, we need to resolve the mass ordering, since it contributes an apparent CP violation that we must correct for.

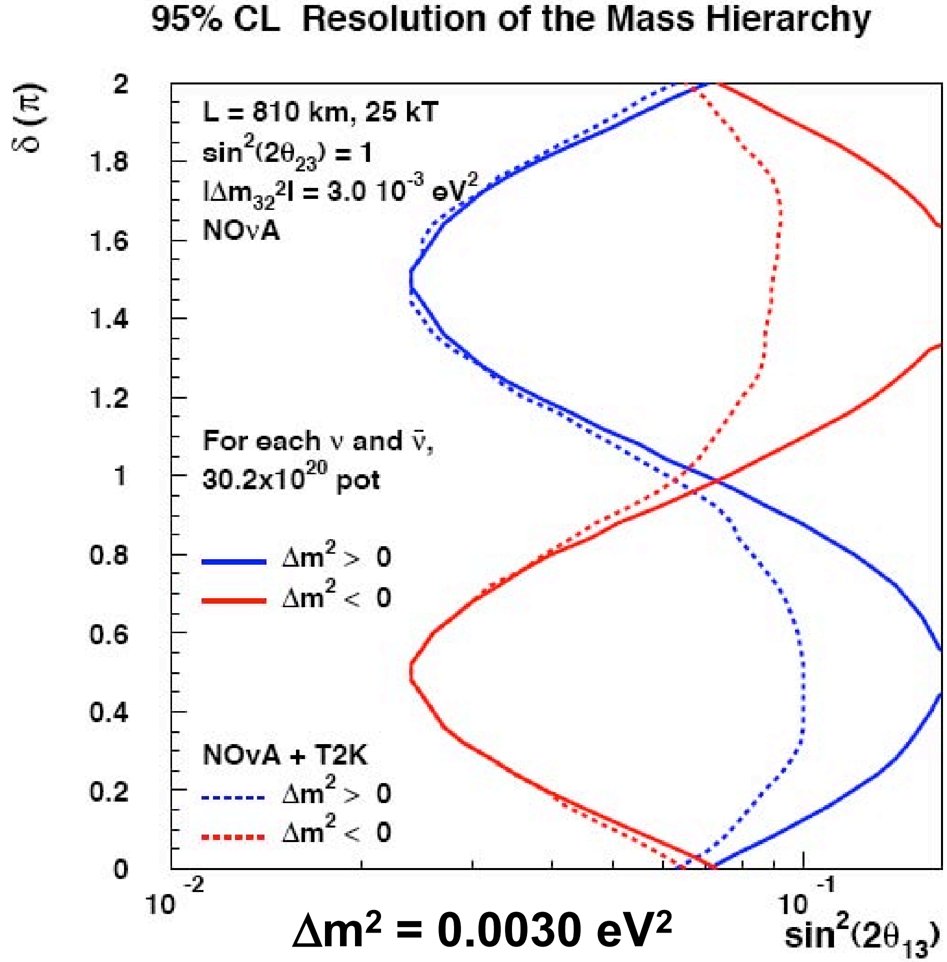
95% CL Resolution of the Mass Ordering



Combining NOνA and T2K



$\Delta m^2 = 0.0025\ eV^2$

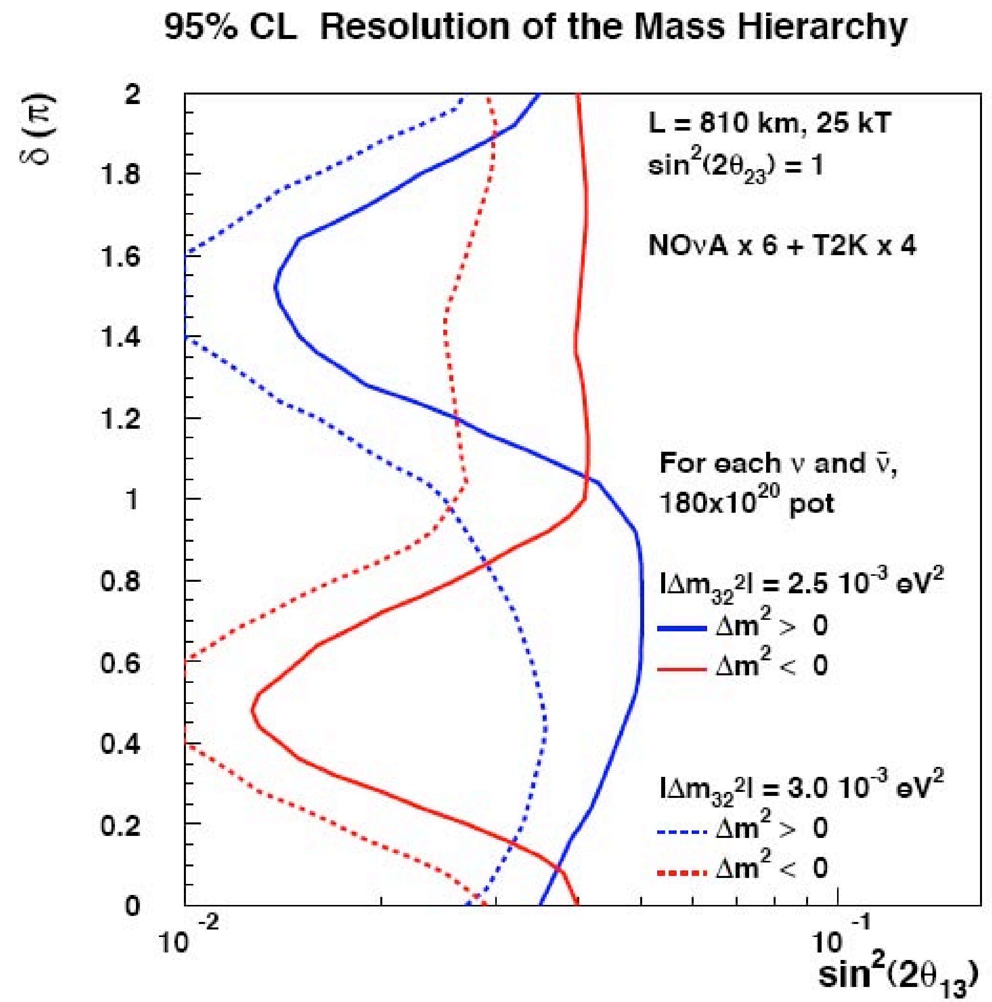


$\Delta m^2 = 0.0030\ eV^2$

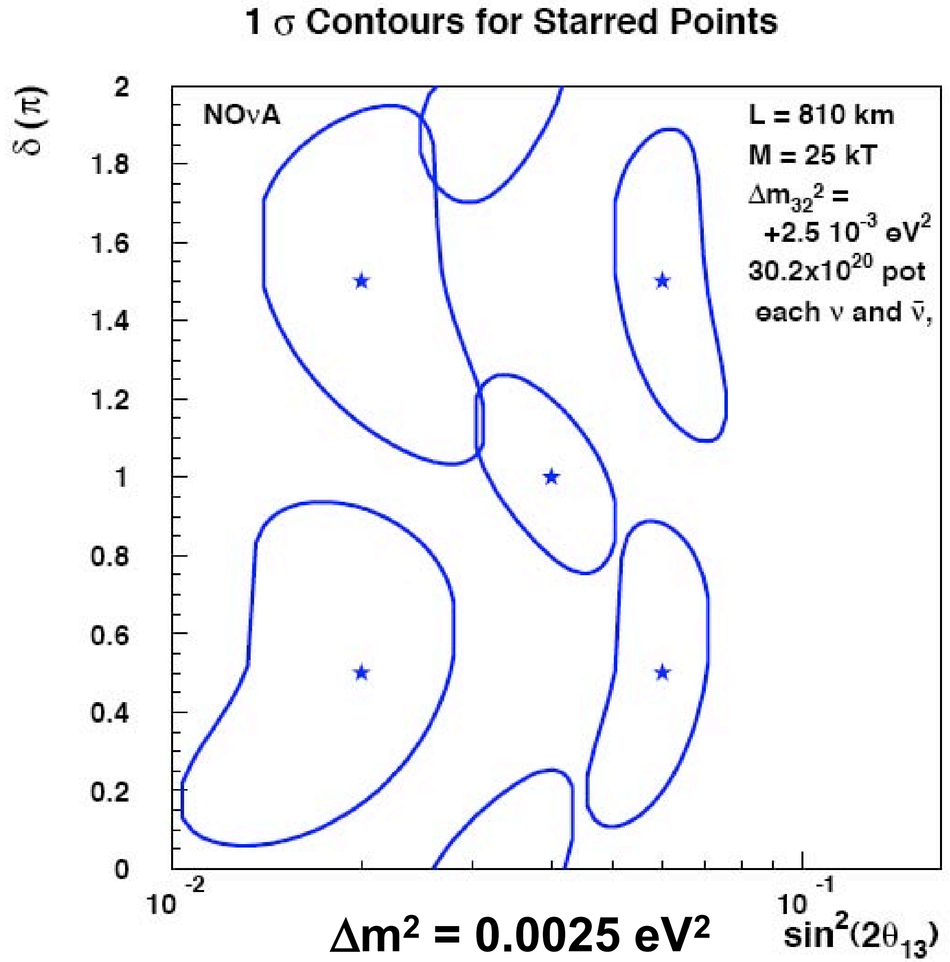
A Possible NOνA II Proposal

- **Assume a NOνA-size LA detector, which would be the equivalent of 4 NOνA detectors. Add past and future NOνA runs to make an equivalent total of 6 NOνA detectors running for 6 years.**
- **Assume that T2K upgrades its proton source by a factor of 4.**

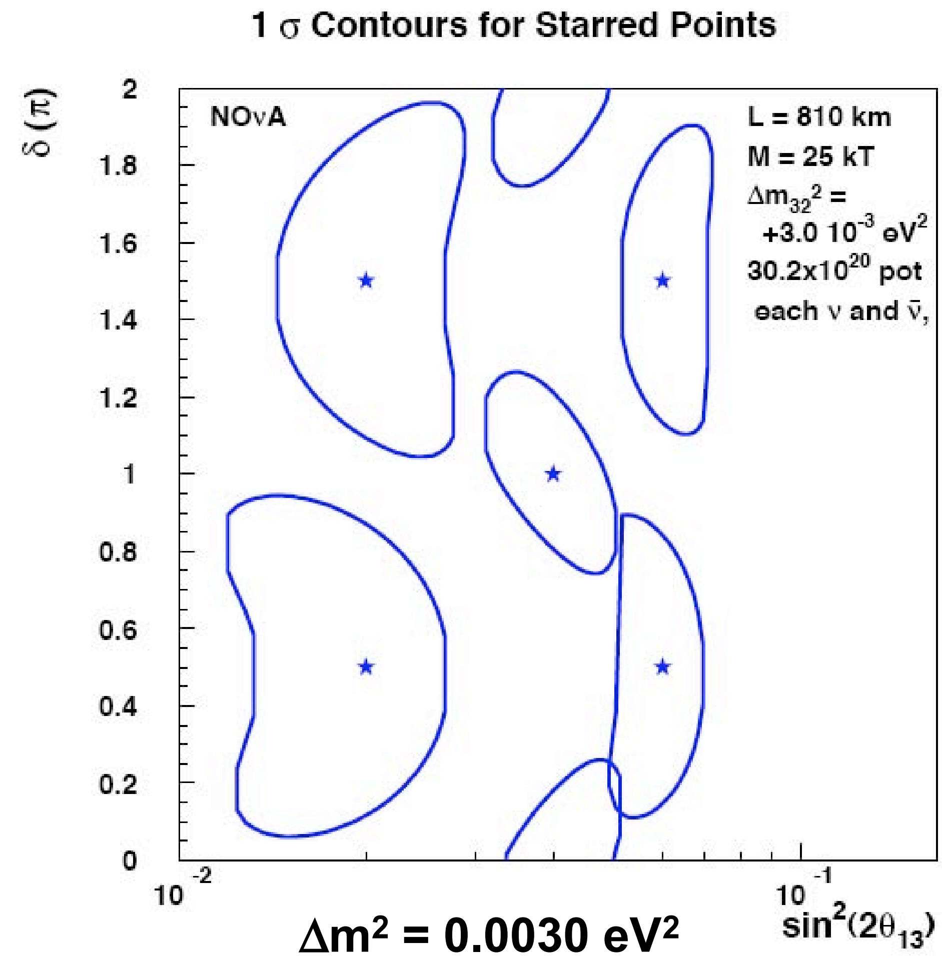
Combining NOνA II with T2K II



Back to NOνA I: δ vs. $\sin^2(2\theta_{13})$ Contours

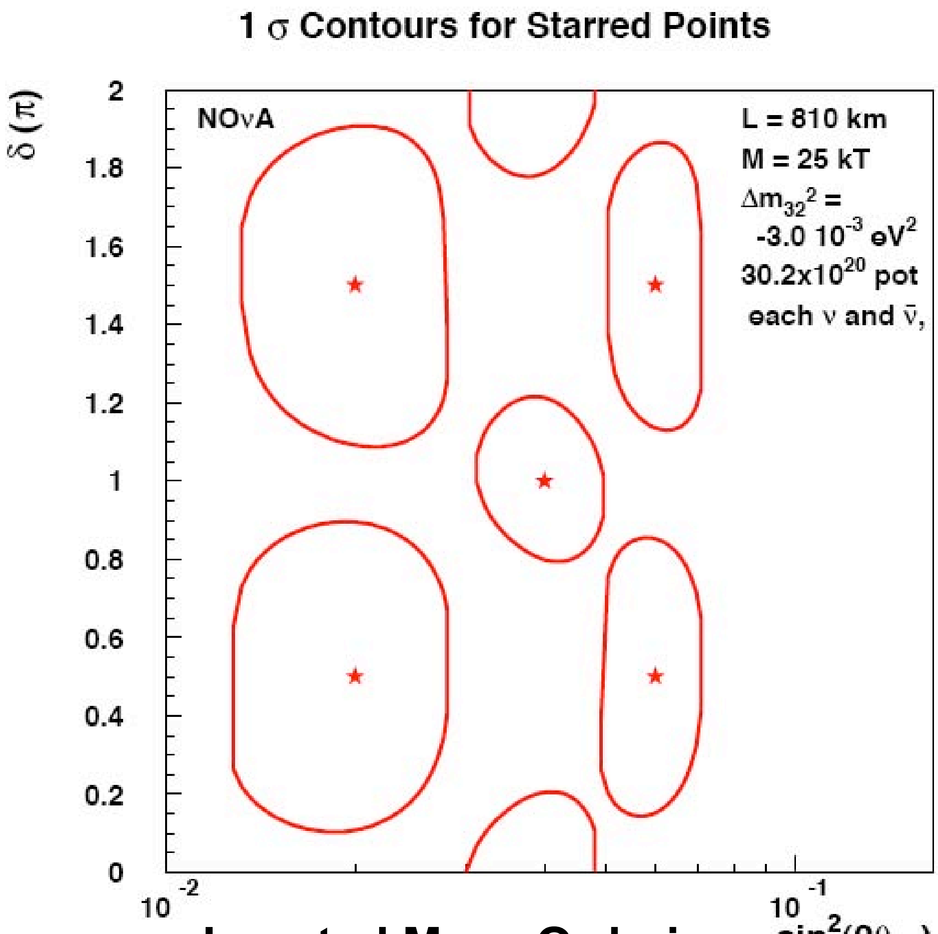


$\Delta m^2 = 0.0025\ eV^2$

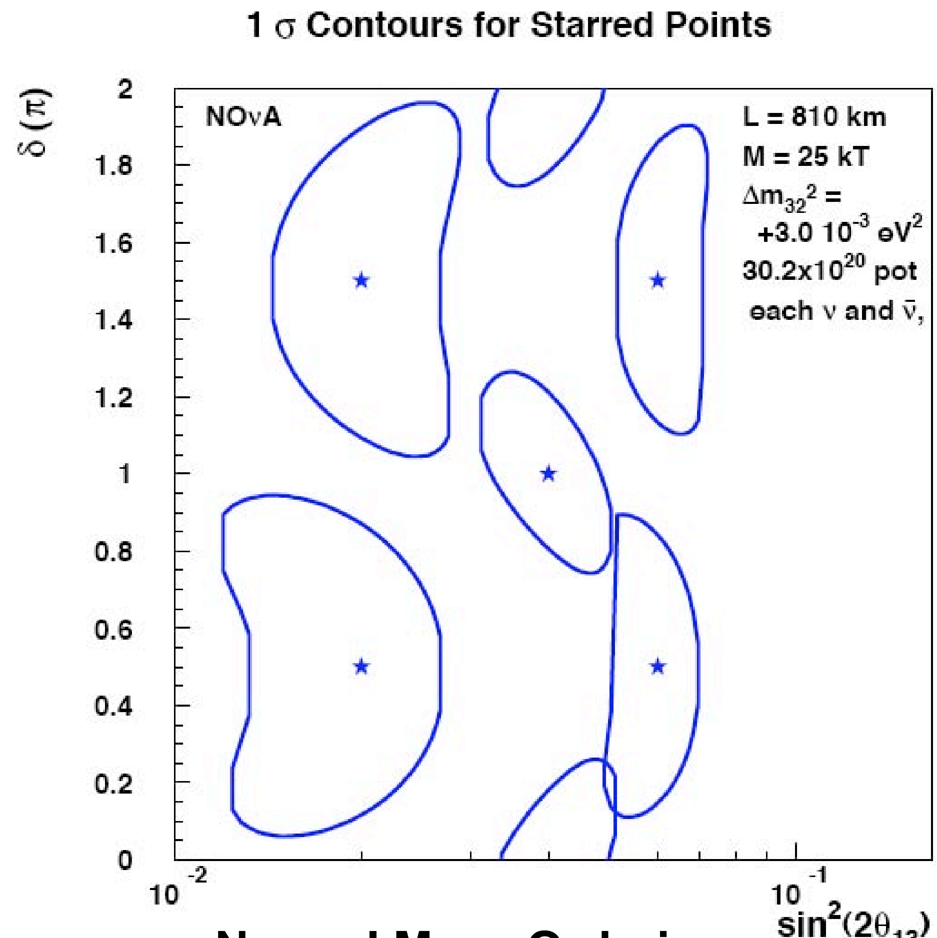


$\Delta m^2 = 0.0030\ eV^2$

δ vs. $\sin^2(2\theta_{13})$ Contours: Normal vs. Inverted Mass

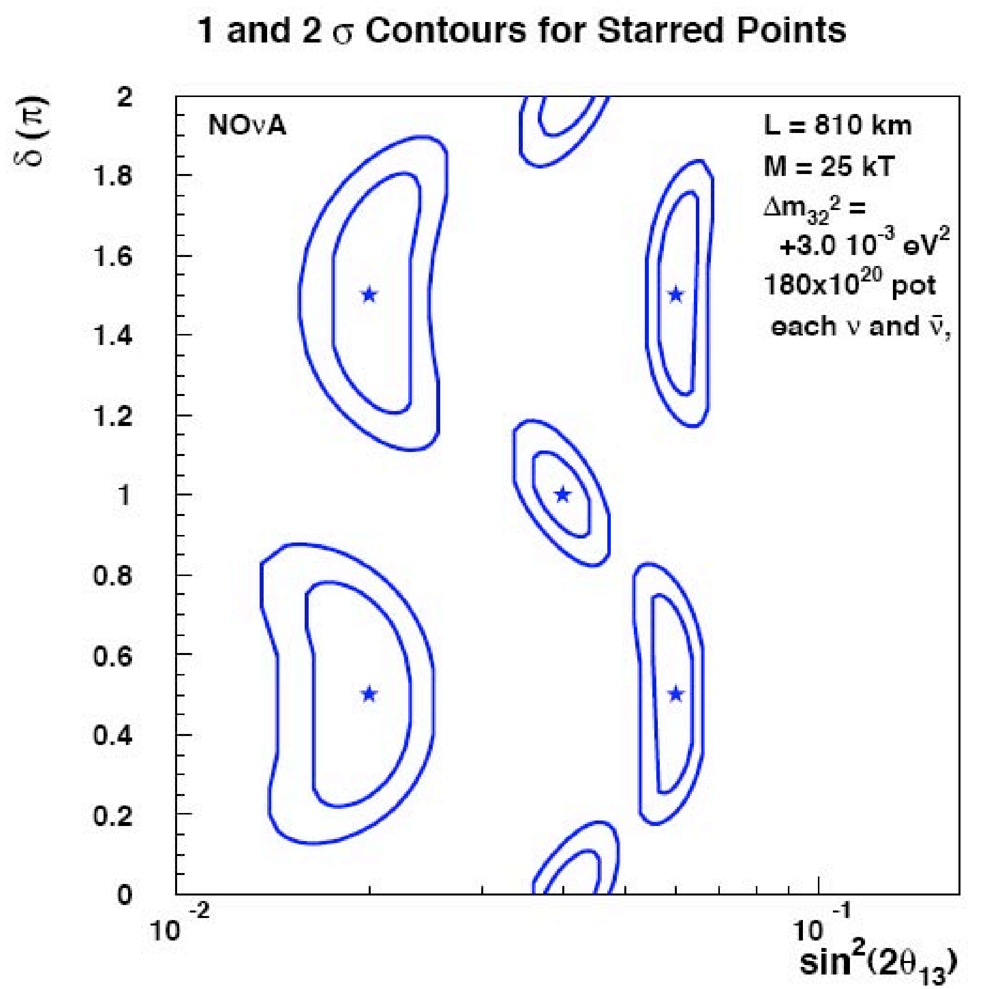


Inverted Mass Ordering



Normal Mass Ordering

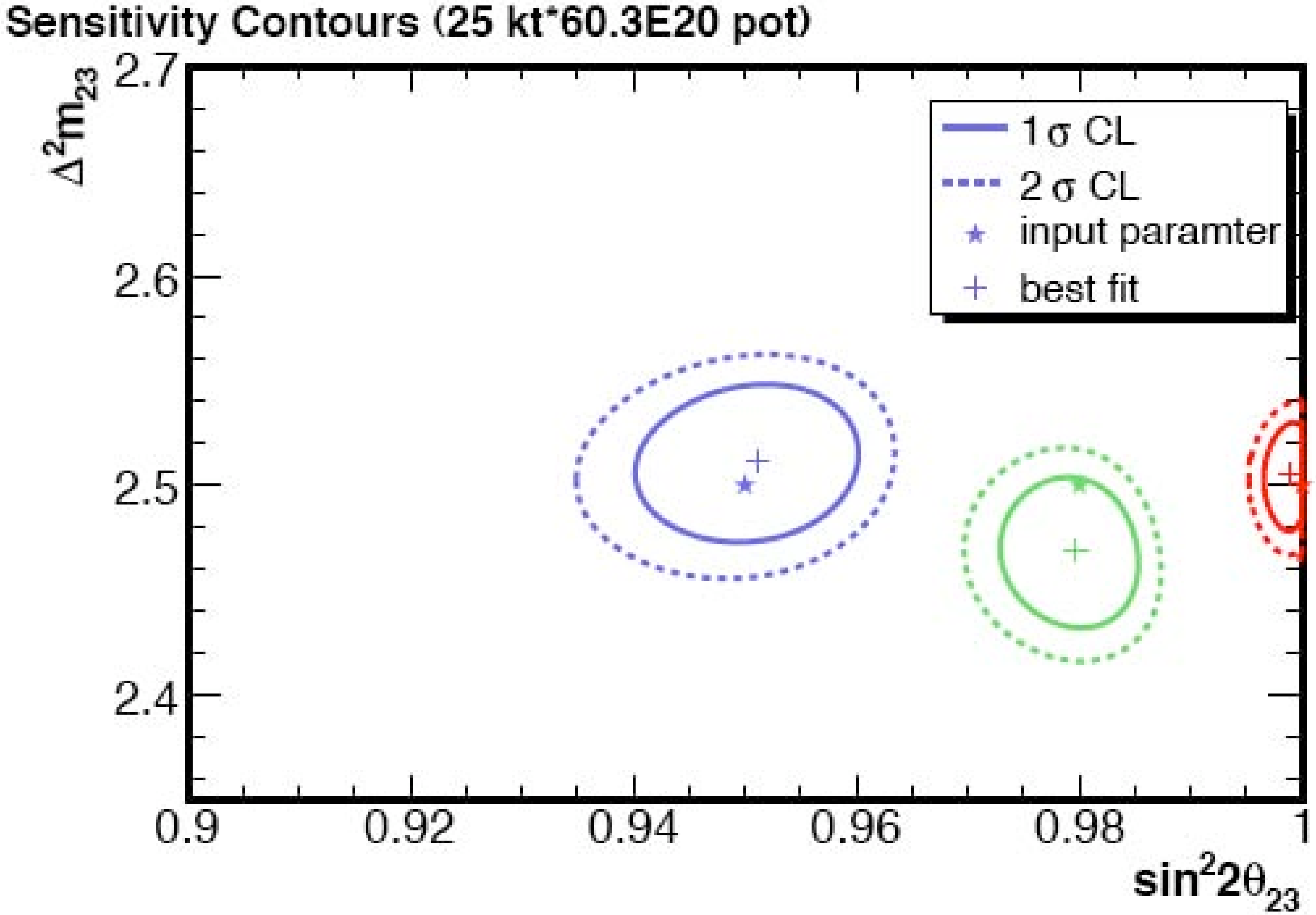
δ vs. $\sin^2(2\theta_{13})$ Contours: 6 x NOνA



Measurement of $\sin^2(2\theta_{23})$

- Whether the atmospheric mixing is maximal is an important question both practically (comparison of reactor and accelerator measurements) and theoretically (Is there a symmetry that induces maximal mixing?).
- The combination of the narrow-band beam and NOνA's excellent energy resolution allows it to do a high-precision measurement of $\sin^2(2\theta_{23})$ by measuring quasielastic ν_μ CC events.

Measurement of $\sin^2(2\theta_{23})$



If $\sin^2(2\theta_{23}) = 1$, then it can be measured to 0.004.

Otherwise, it can be measured to ~0.01.

Schedule

- Our CD-1 schedule calls for the first 5 kT to be completed by Nov 2010, and for us to start taking data then. It calls for the detector to be completed by Nov 2011. For the reasons I gave earlier, these dates will slip by a few months.

Sensitivity Schedule

- Estimated times to establish 3 σ sensitivity to $\theta_{13} \neq 0$ (normal mass ordering, $\Delta m_{32}^2 = 0.0027$ eV^2, $\sin^2(2\theta_{23}) = 1.$, $\delta = 0$):
  - Jan 2012, if $\sin^2(2\theta_{23}) = 0.05$
  - Aug 2013, if $\sin^2(2\theta_{23}) = 0.02$
  - Dec 2015, if $\sin^2(2\theta_{23}) = 0.01$

Conclusions

- NOνA provides an effective utilization of the investment in the NuMI beamline, improving MINOS measurements by about an order of magnitude
- It is the right scale project for the present time. (More ambitious programs will need to wait for clarification of the ILC status.)
- It provides the information needed to plan the next step after NOνA.
- It provides a sensitivity to $\sin^2(2\theta_{13})$ comparable to T2K and Daya Bay.
- It provides the only information on the mass ordering.
- It provides low-precision data on CP violation in the lepton sector.