NOvA Goals and Sensitivities

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for the NOvA Collaboration

Project X Physics Workshop

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NOvA Physics Goals

- Is our model for neutrino oscillations correct?
  - Underlying question – best tested by rigorous comparison of data to the model
  - Feeds into larger questions of
    - Leptogenesis
    - Beyond Standard Model Physics
    - Particle / anti-particle nature of neutrinos

Within our model of neutrino oscillations

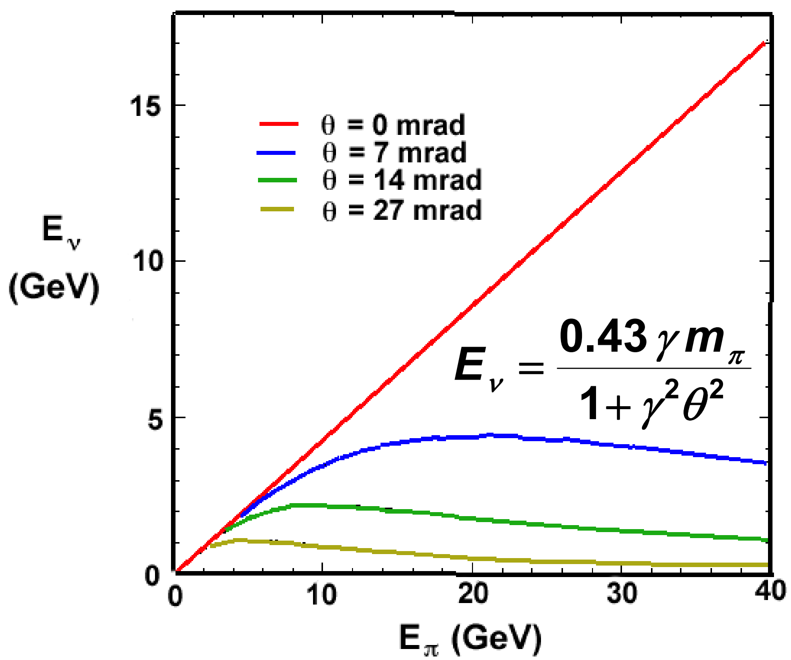
- Value of θ_{13}
- Is θ_{23} maximal?
- Mass structure of the neutrinos
  - Unique ability of NOvA in this next generation of experiments
- Do neutrinos violate CP?

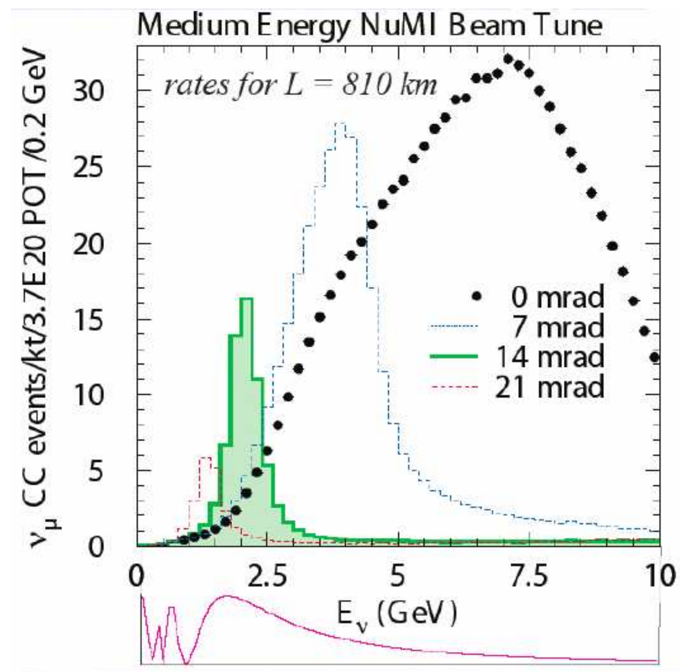
The NOνA Experiment

- Second-generation 2-detector experiment on the NuMI beamline
  - Optimized for the detection of $\nu_\mu \rightarrow \nu_e$ oscillations
- The NOνA detectors are "totally active" tracking liquid scintillator calorimeters
  - Sited off-axis to take advantage of a narrow-band beam
  - Low-Z composition
  - High segmentation
- The NOνA project also includes accelerator upgrades to bring the beam power from 400 kW to 700 kW
- NOνA's unique feature is its long baseline (810 km), which gives it sensitivity to the neutrino mass ordering
- NOνA is complementary to both T2K and Daya Bay

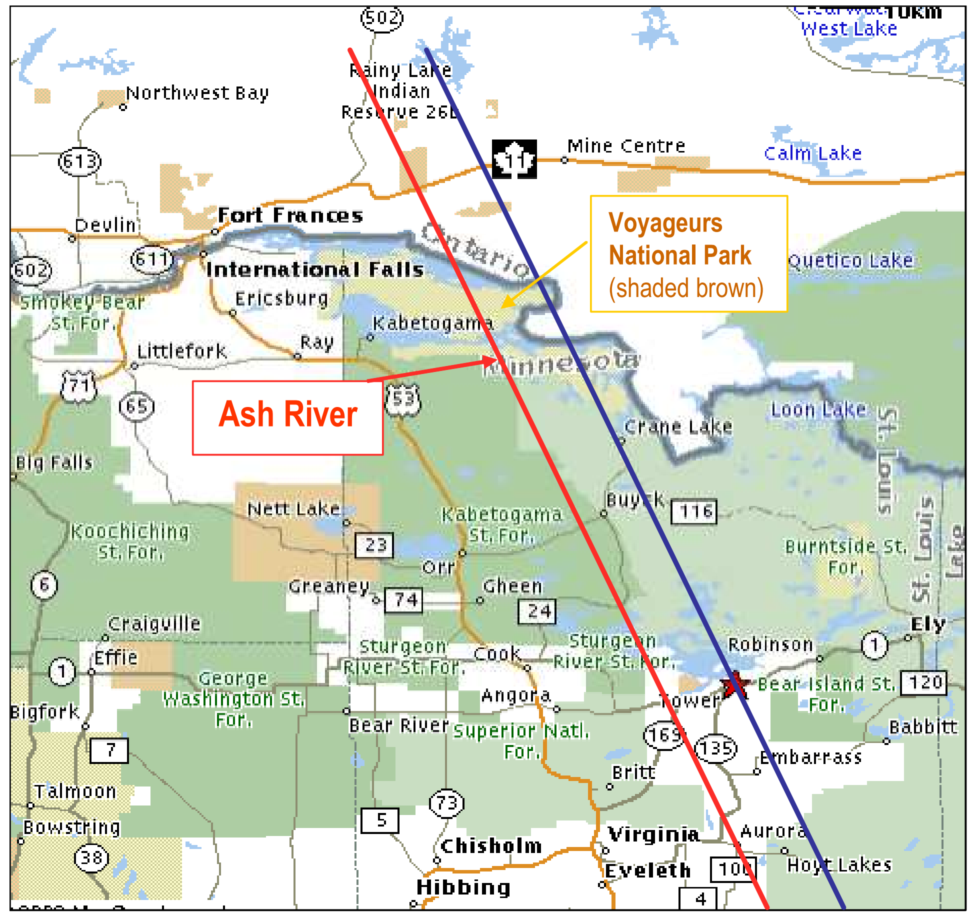
Off-Axis Beam

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



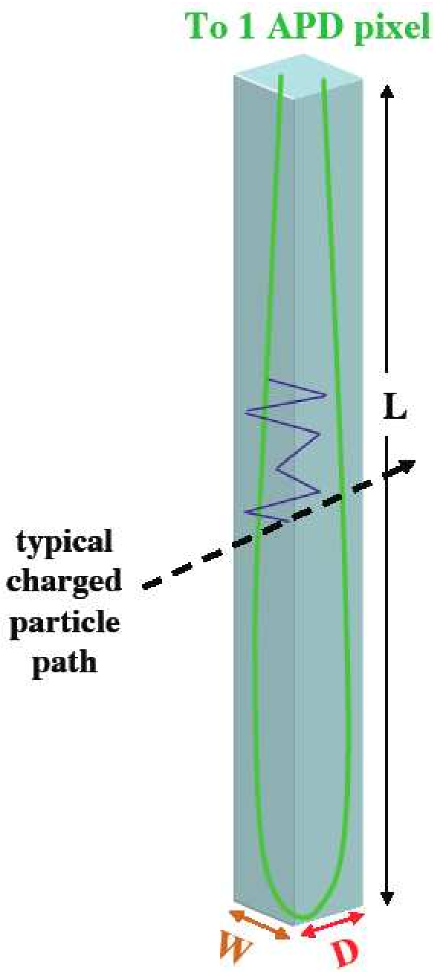


Far Detector Location



- Ash River is the furthest available site from Fermilab along the NuMI beamline
- Maximizes NOνA's sensitivity to the mass ordering

NOνA Basic Detector Element

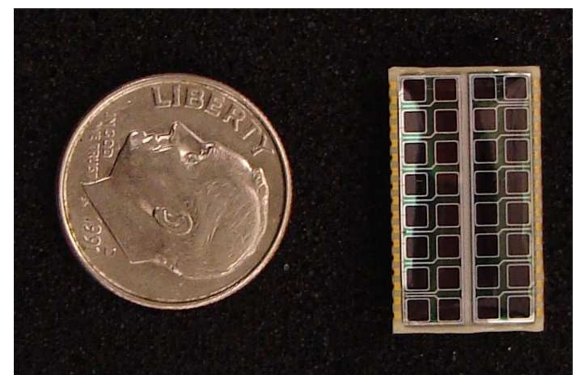


Liquid scintillator in a 4 cm wide, 6 cm deep, 15.7 m long, highly reflective PVC cell.

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).

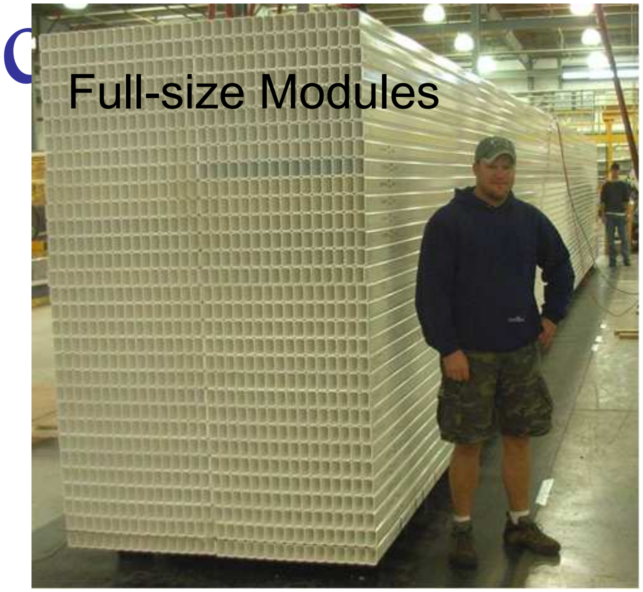
The APD has peak quantum efficiency of 85%. It will be run at a gain of 100. It must be cooled to -15^{o}C and requires a very low noise amplifier.

Fiber Stringing Machine



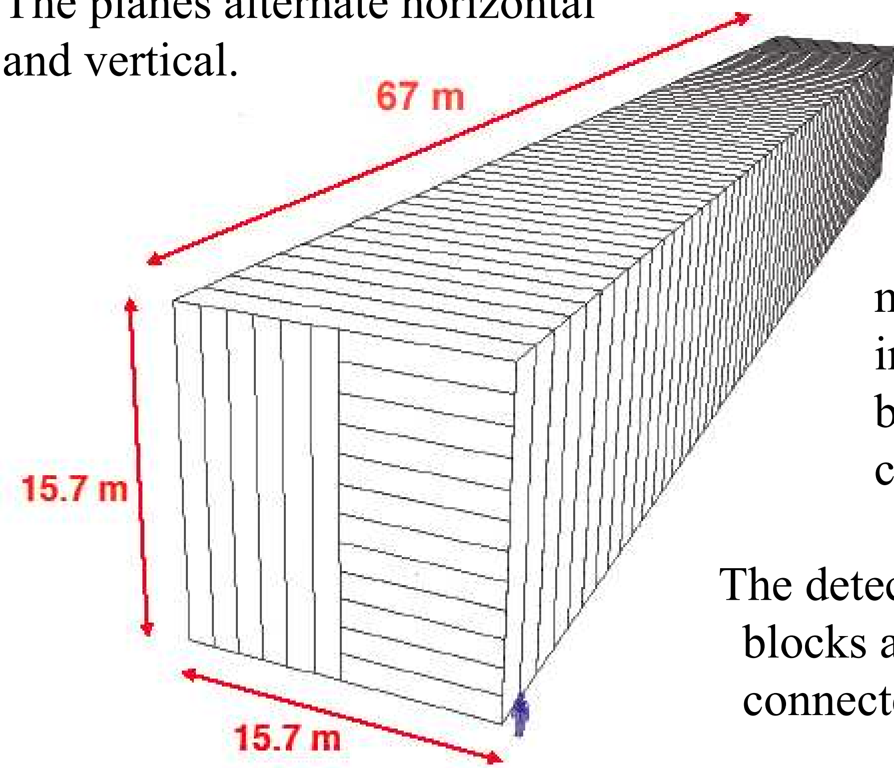
32-cell APD

Far Detec



The cells are made from 32-cell extrusions.

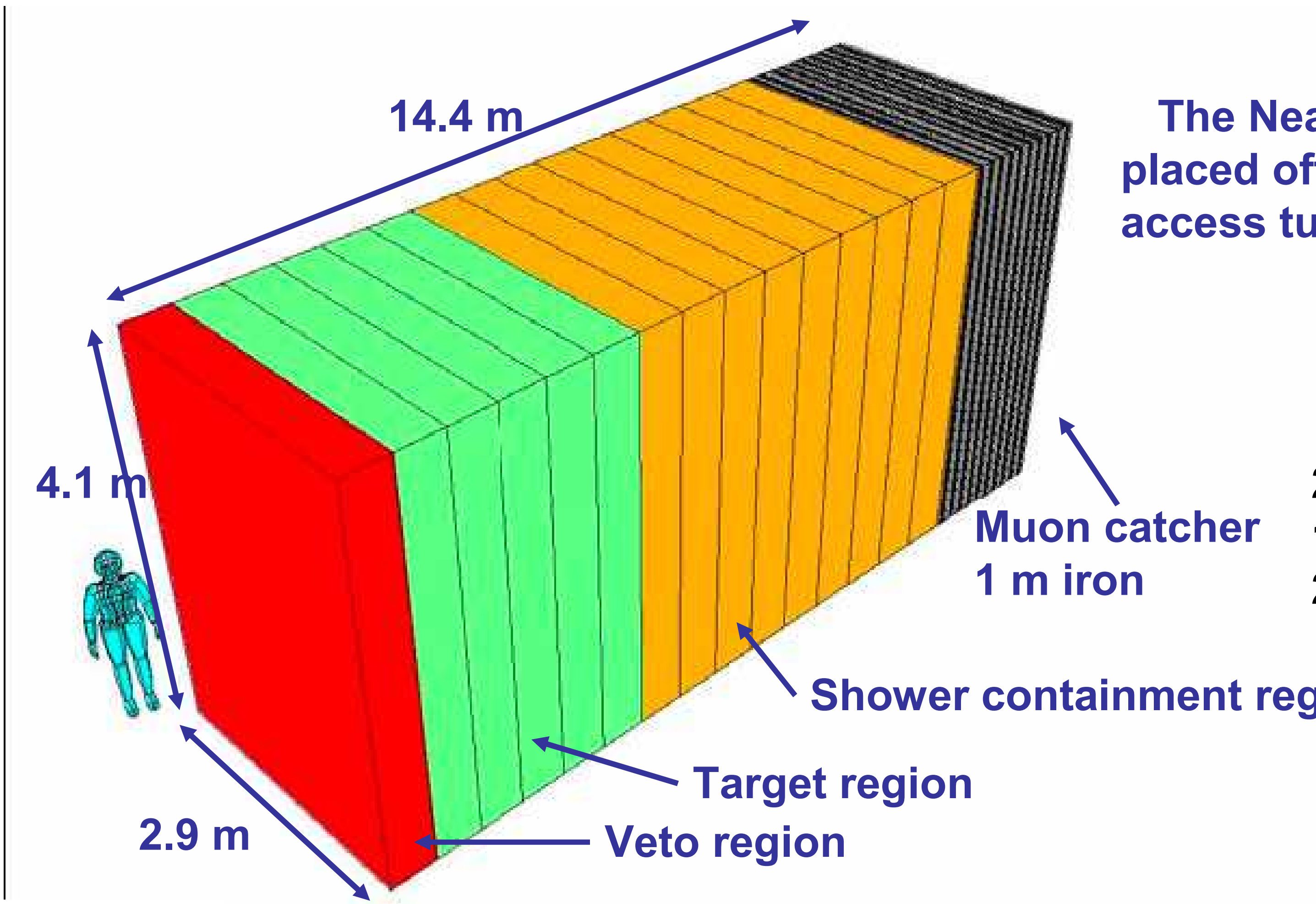
12 extrusion modules make up a plane. The planes alternate horizontal and vertical.



There are 1003 planes, for a total mass of 15 kT. There is enough room in the building for 18 kT, which can be built if we can preserve half of our contingency.

The detector can start taking data as soon as blocks are filled and the electronics connected.

The Near Detector

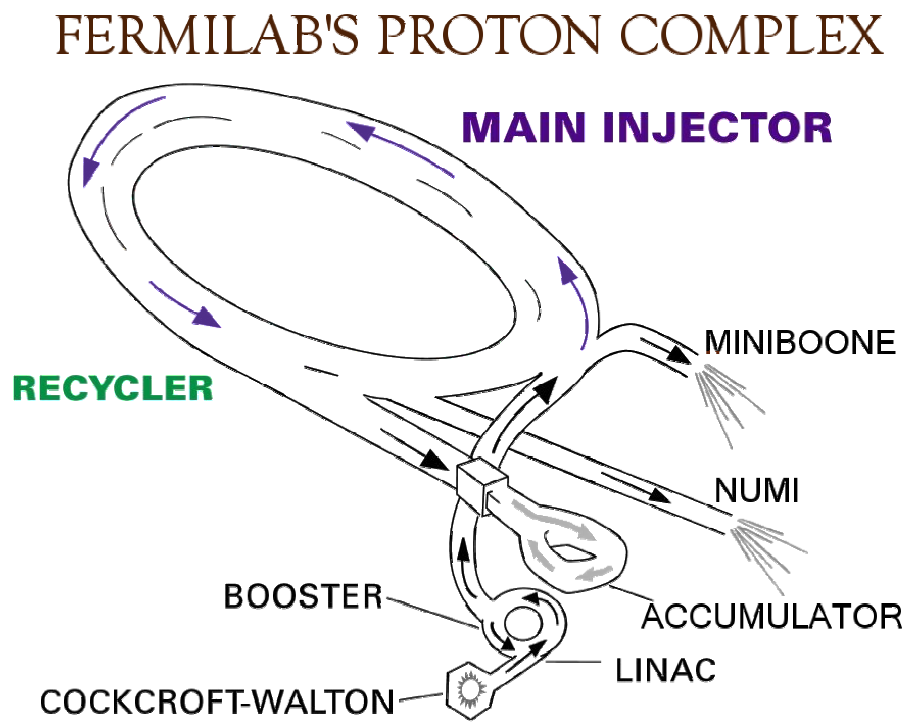


The Near Detector will be placed off-axis in the MINOS access tunnel.

209 T
126 T totally active
23 T fiducial

ANU: Accelerator and NuMI Upgrades

- Reconfigure the proton complex to produce a 700 kW proton beam
  - ➢ Booster injection into Recycler
  - ➢ Slip-stacking in the Recycler
    - With beam cleaning to reduce losses
  - ➢ Transfer to Main Injector
  - ➢ Acceleration in the Main Injector to 120 GeV
  - ➢ Deliver ~ 6 x 10^{20} protons / yr
- NuMI beamline upgrades to accommodate higher beam power
  - ➢ New target and horns
  - ➢ Second horn moved downstream to optimize focusing for off-axis beam
  - ➢ Upgraded cooling of beam devices and shielding



Recent NOνA History

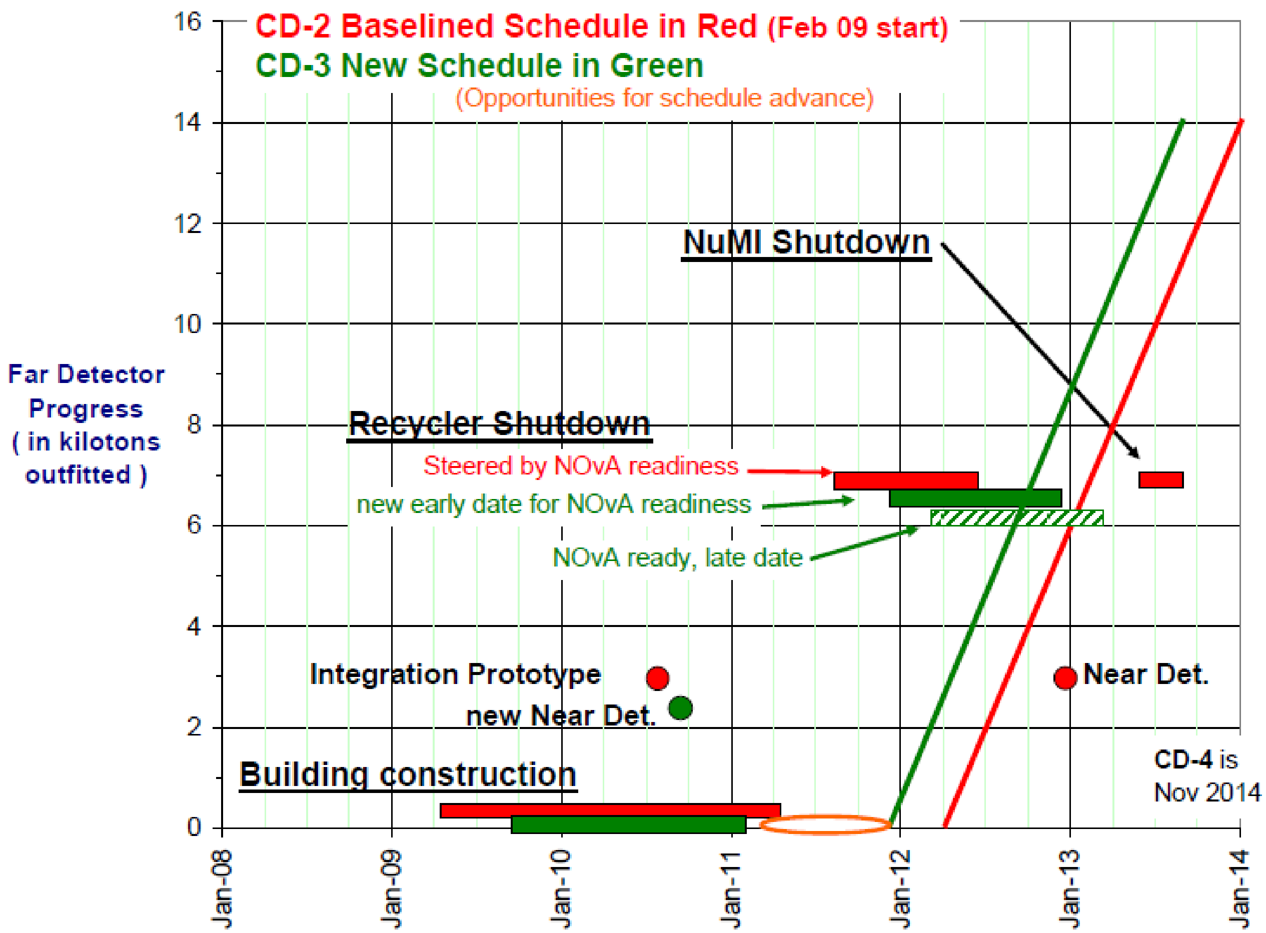
- Oct 2007 Passed CD2/3a Review, baselined at $270M
- Dec 2007 Zeroed out of the Omnibus Funding Bill
- Feb 2008 OHEP asks NOνA to plan for an FY09 start; TPC increased to $278M for escalation.
- Jul 2008 NOνA receives $9M in Supplemental Funding Bill. Restart is difficult since personnel have have been assigned to other projects.
- Oct 2008 Start of Continuing Resolution; NOνA funded for partial FY09.
- Mar 2009 NOνA receives $55M in stimulus funding plus $28M in regular funding.
- May 2009 Ground broken at Ash River
- Oct 2009 NOνA receives CD-3b from DOE – full construction start

NOνA Ground Breaking
1 May 2009

Ash River Excavation

New and Improved Schedule

- Replanning with new funding and workforce availability
  - All possible items advanced
  - Accelerator shutdowns combined



2018 Scenario

- Detector being assembled 2012-2013
- 700 kW beam available in 2013
  - Some commissioning needed, but initially there will be little competition for protons
- End of 2018 corresponds to almost 6 year of 700 kW collection on full detector
  - One of the primary planning periods for NOvA

Note: NoVA was initially envisioned to run on one of 700 kW, 1.2 MW, or 2.3 MW. Our “2018 scenario” corresponds to the weakest of these sensitivities, but shows that the reach of NOvA could be improved substantially with higher beam powers and/or extended running.

Vacuum Oscillation Cheat-sheet

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

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

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

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

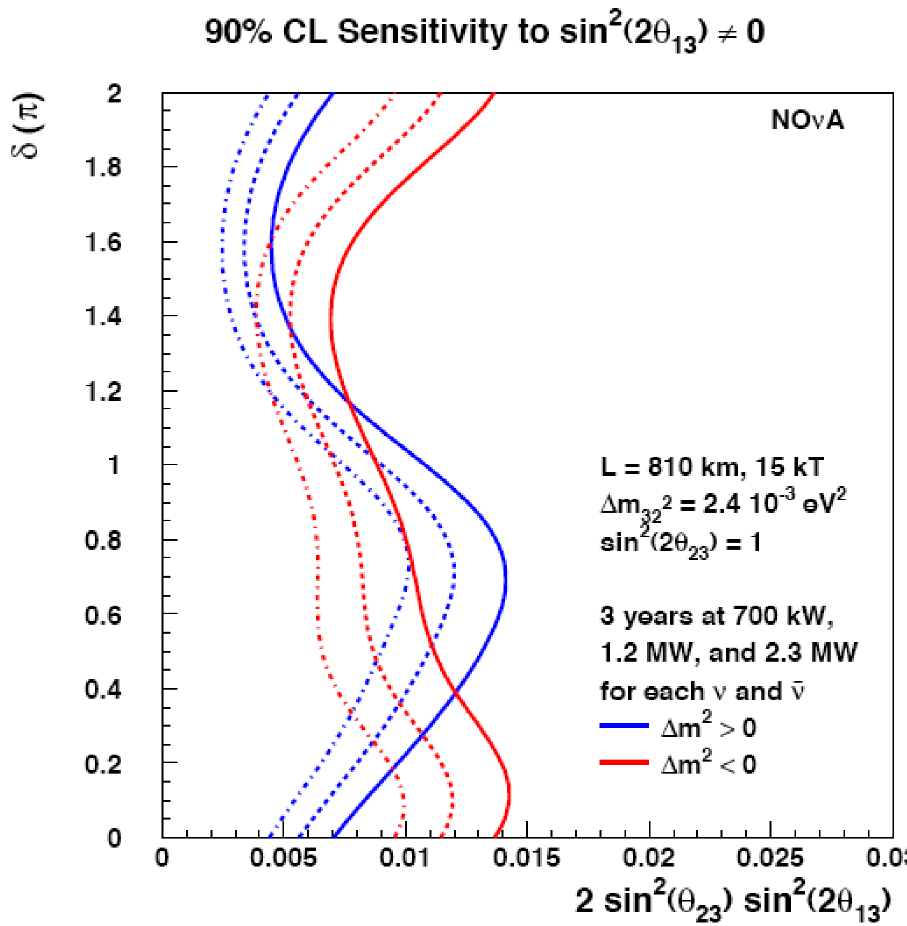
$$E_R = \frac{\Delta m^2_{13}}{2\sqrt{2} G_F \rho_e} \approx 11 \text{ GeV for the earth's crust.}$$

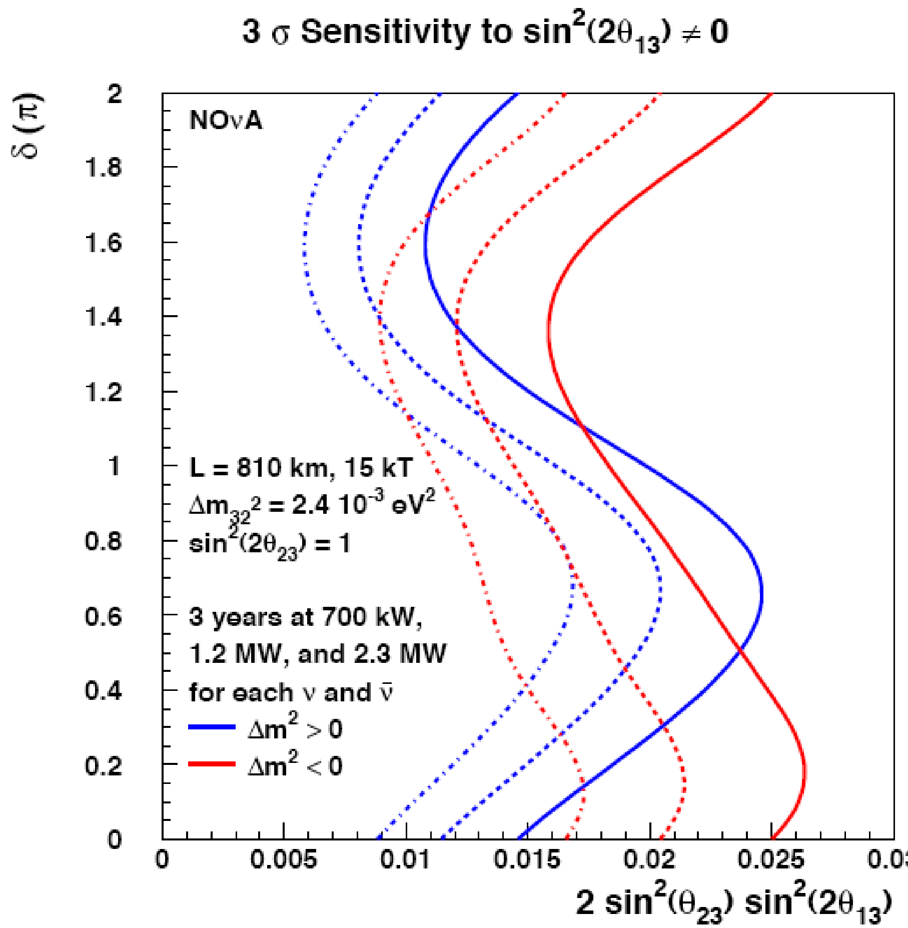
About a ±30% effect for NuMI, but only a ±11% effect for T2K.

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

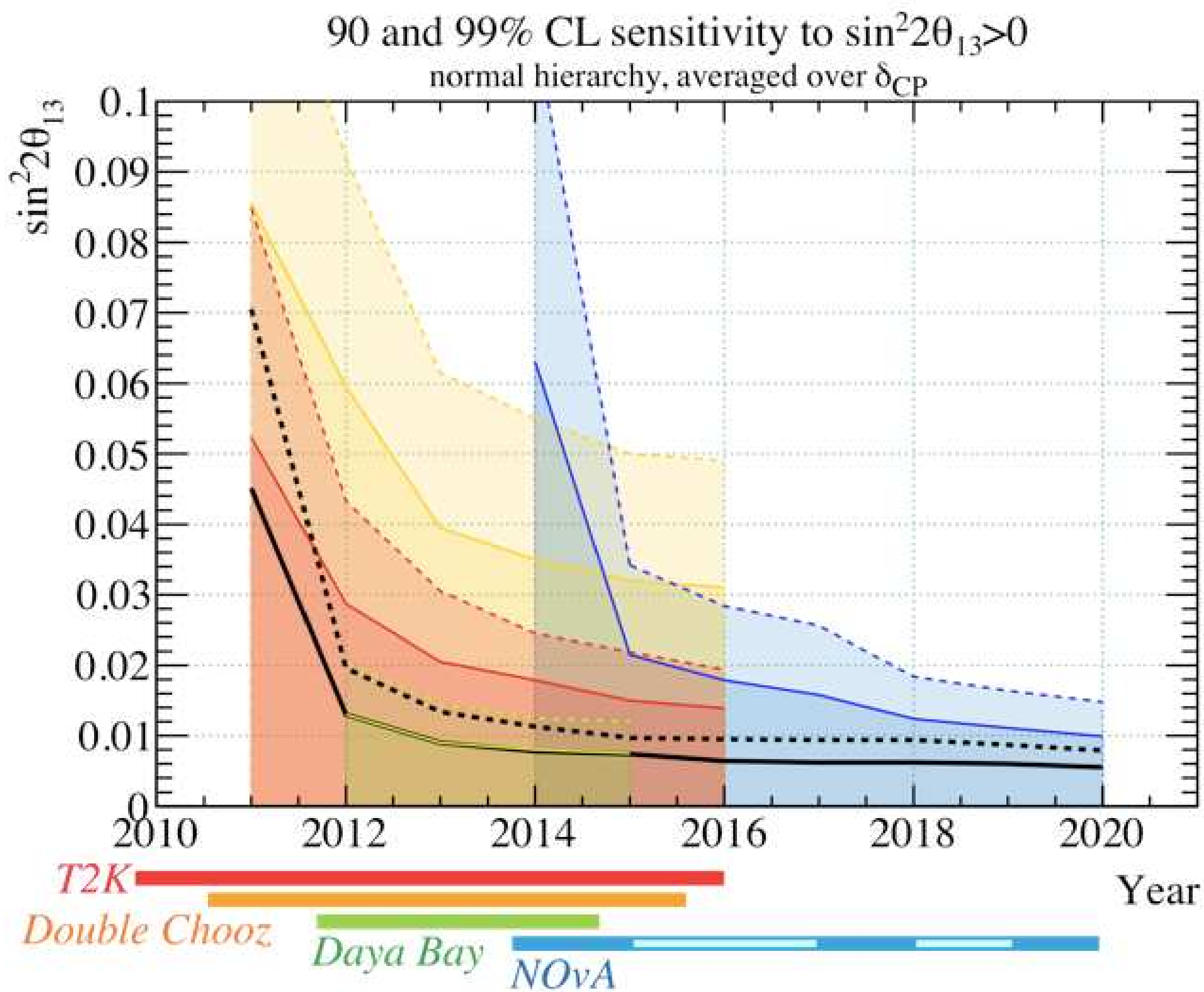
Sensitivity to $\sin^2(2\theta_{13}) \neq 0$

- to below 0.015





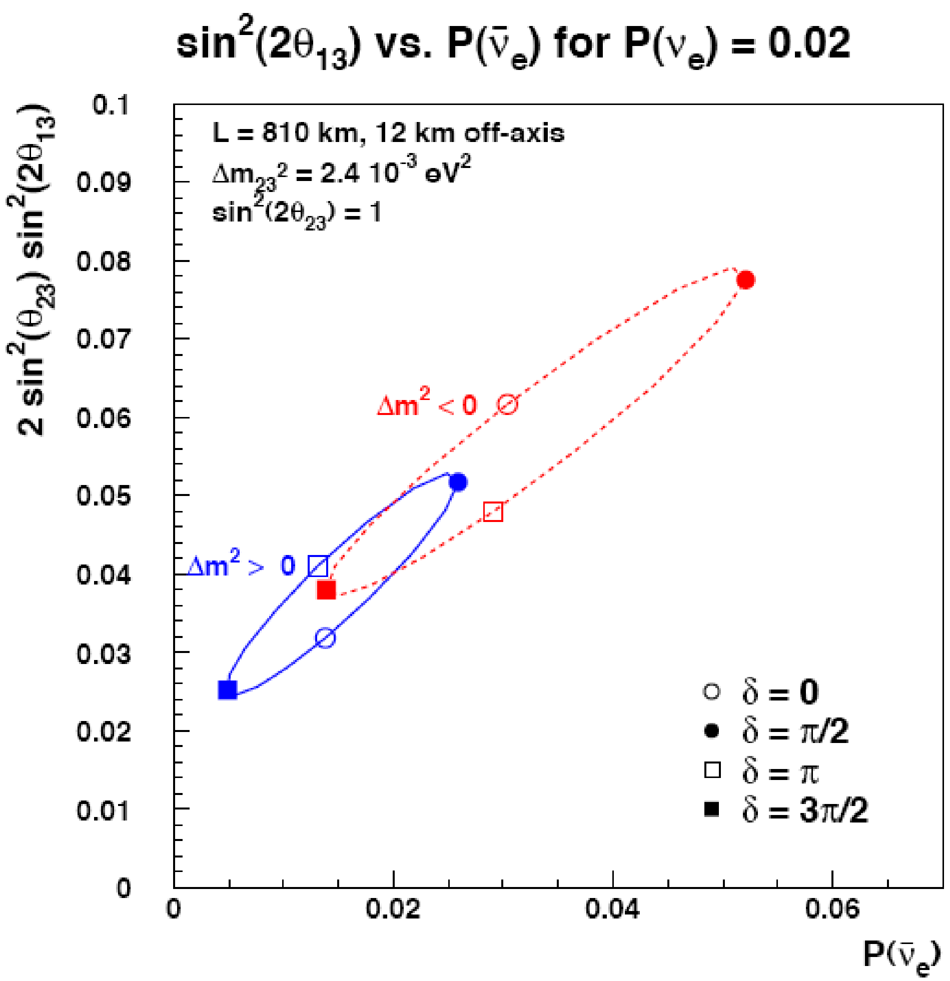
Progress toward $\theta_{13} > 0$



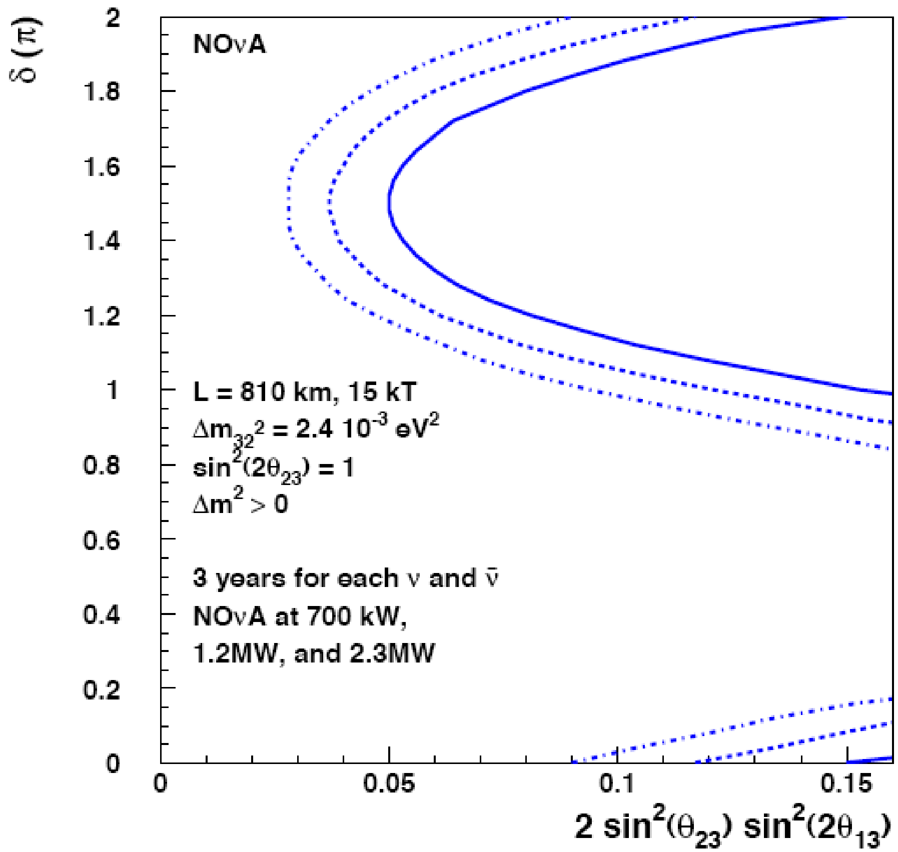
Mass Ordering

- To measure CP violation, we need to resolve the mass ordering, since it contributes an apparent CP violation that we must correct for.
- If the CP-violating term goes in the same direction as the matter effect, then there is no ambiguity and NOνA can determine the mass ordering by itself, given sufficient integrated beam.
- If the CP-violating term goes in the opposite direction as the matter effect, then there is an inherent ambiguity and NOνA cannot determine the mass ordering by itself. But it can be determined, in principle, by comparing NOνA and T2K.
  - If the neutrino oscillation probability is larger in NOνA than in T2K, it is the normal mass ordering; if the opposite, it is the inverted mass ordering.

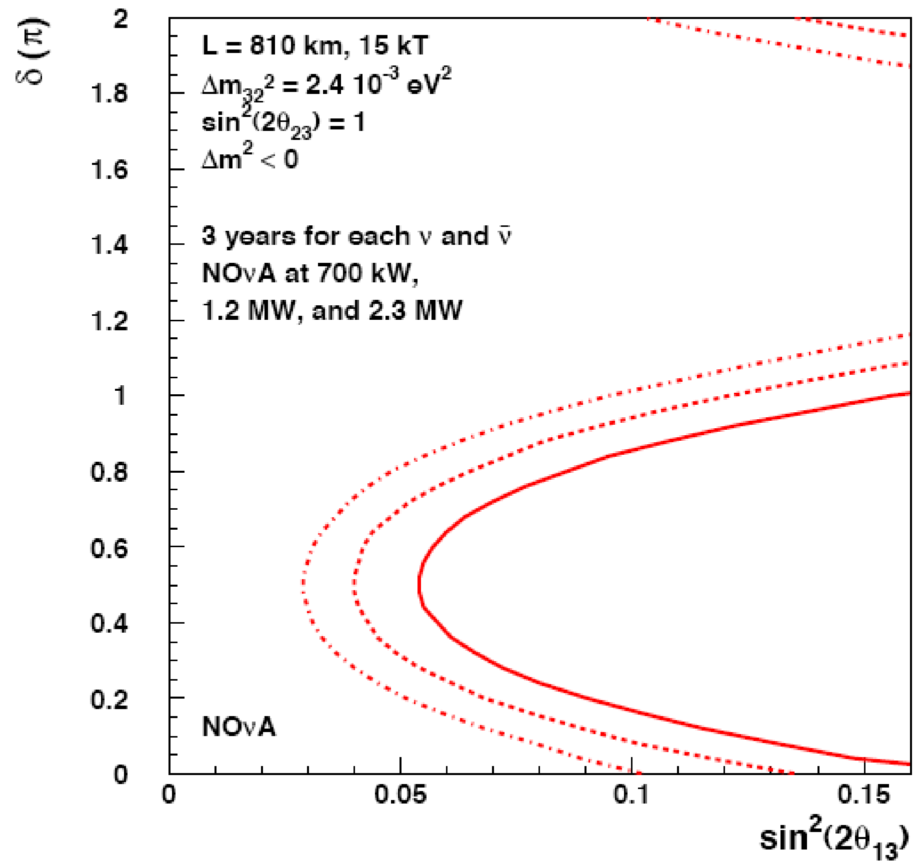
Parameters Consistent with a 2% $\nu_\mu \to \nu_e$ Oscillation Probability



95% CL Resolution of the Mass Ordering NOνA Alone



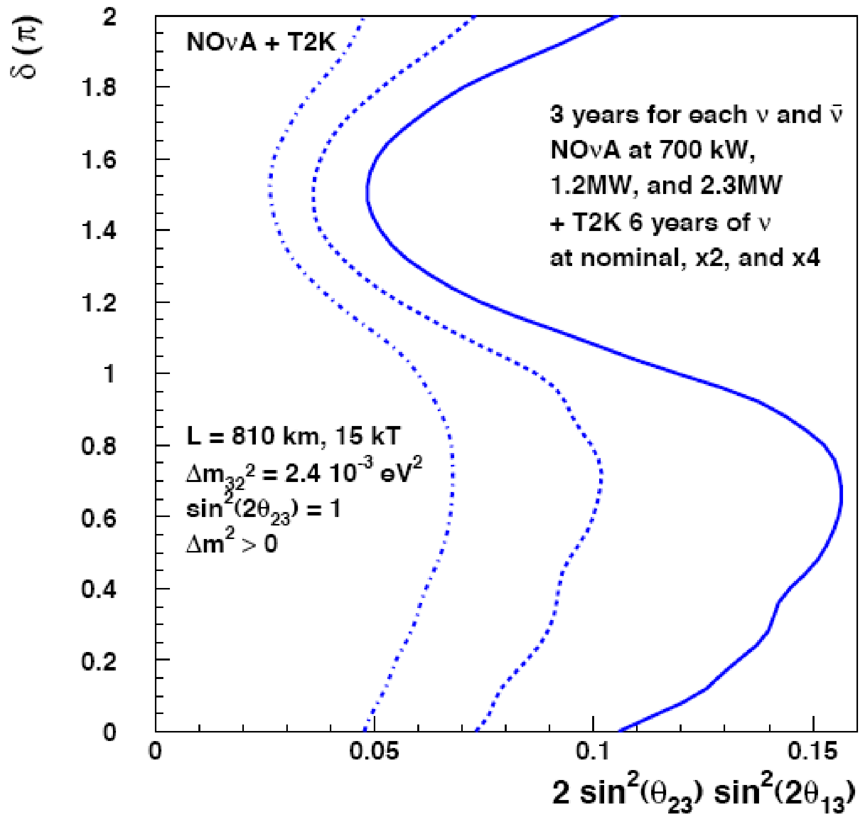
Normal Ordering



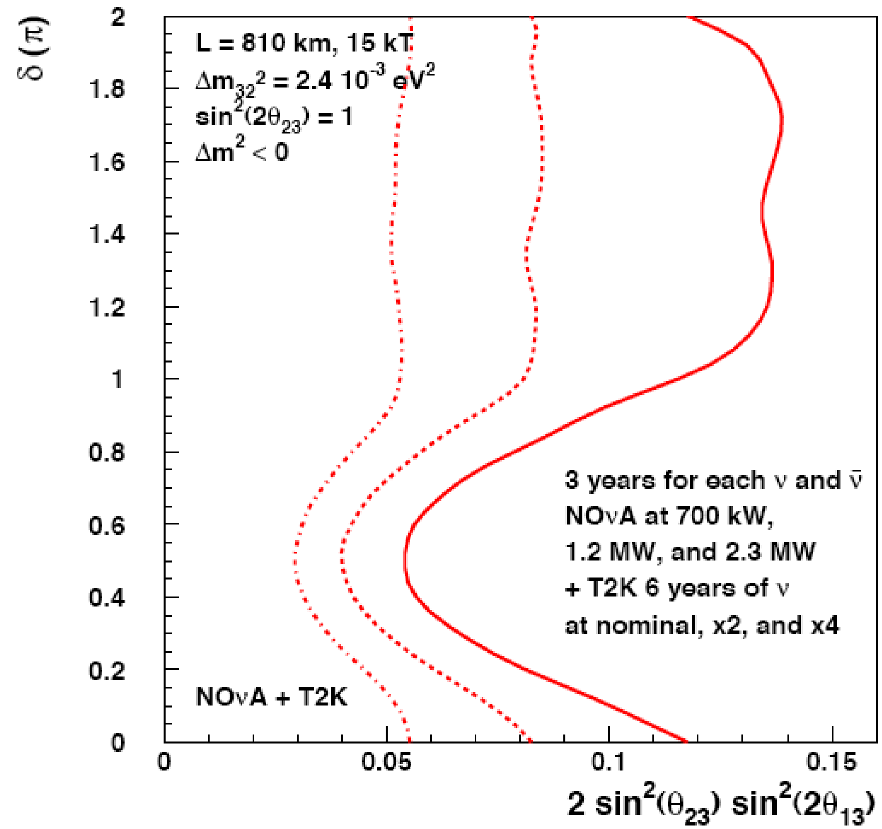
Inverted Ordering

95% CL Resolution of the Mass Ordering NOνA Plus T2K

- Hierarchy accessible for larger mixing angles

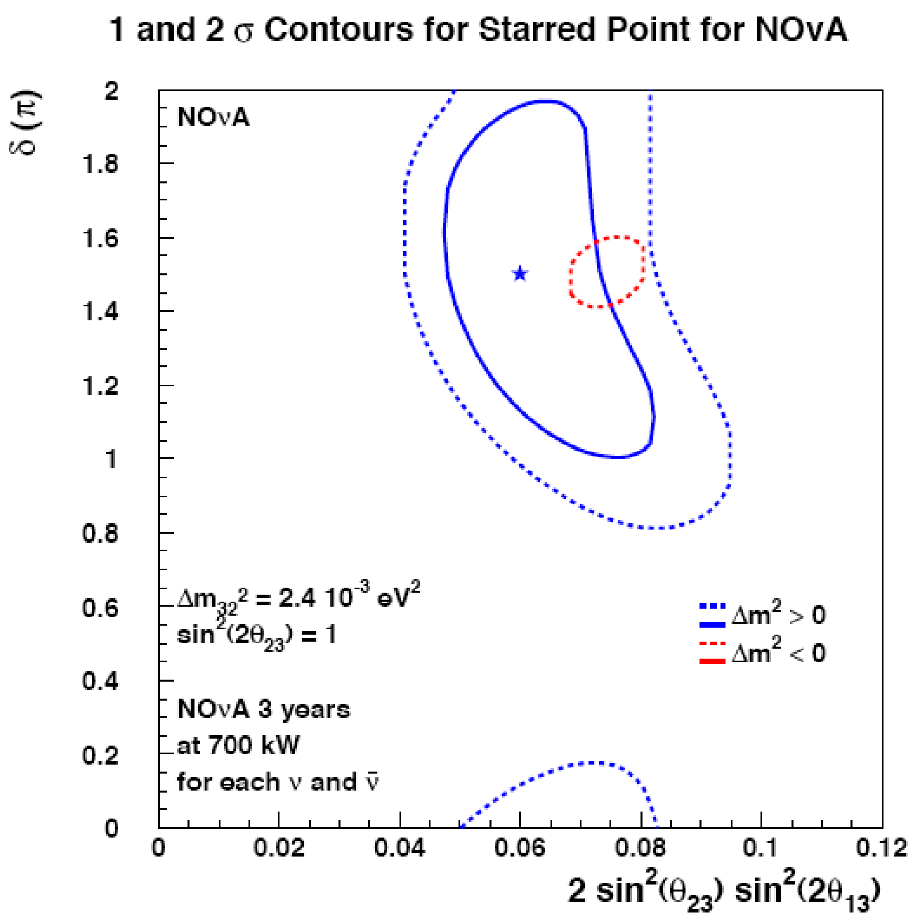


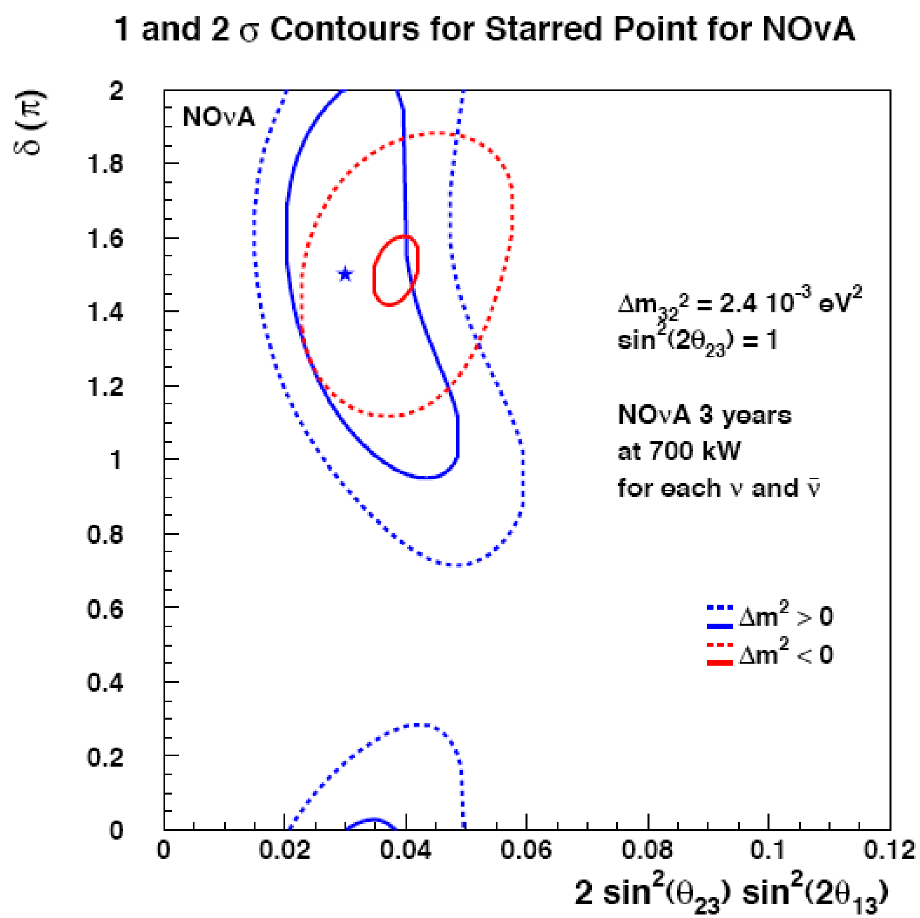
Normal Ordering



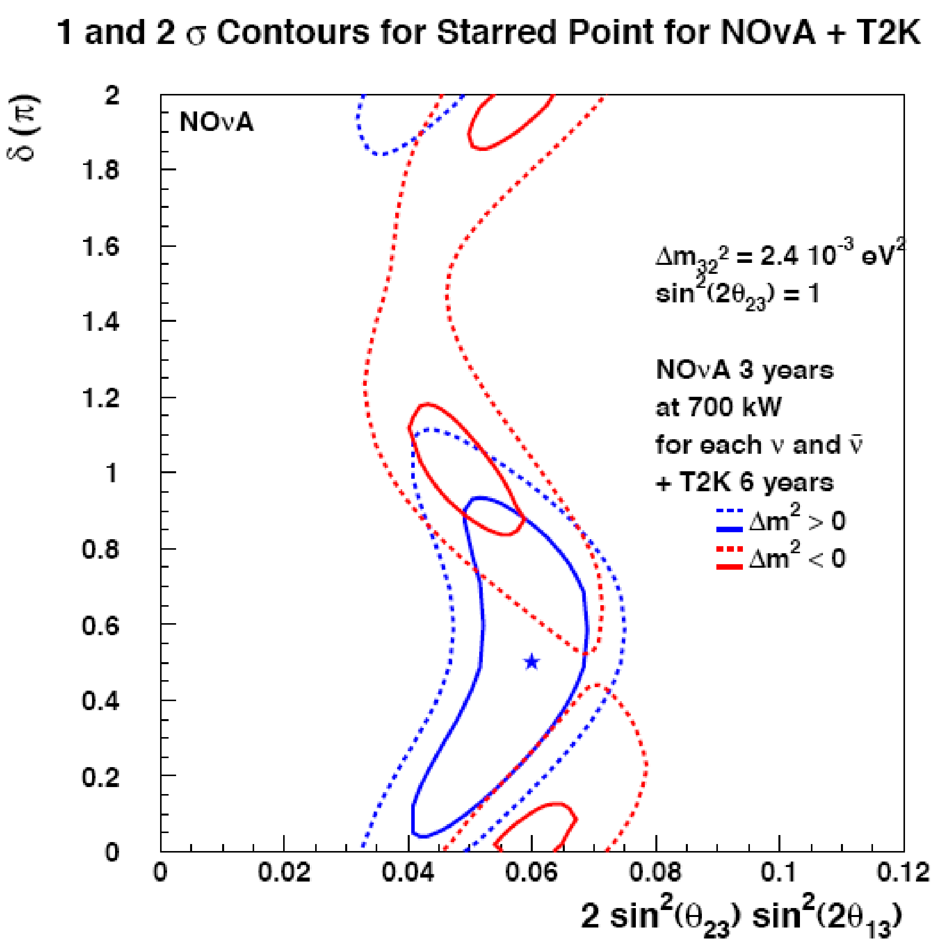
Inverted Ordering

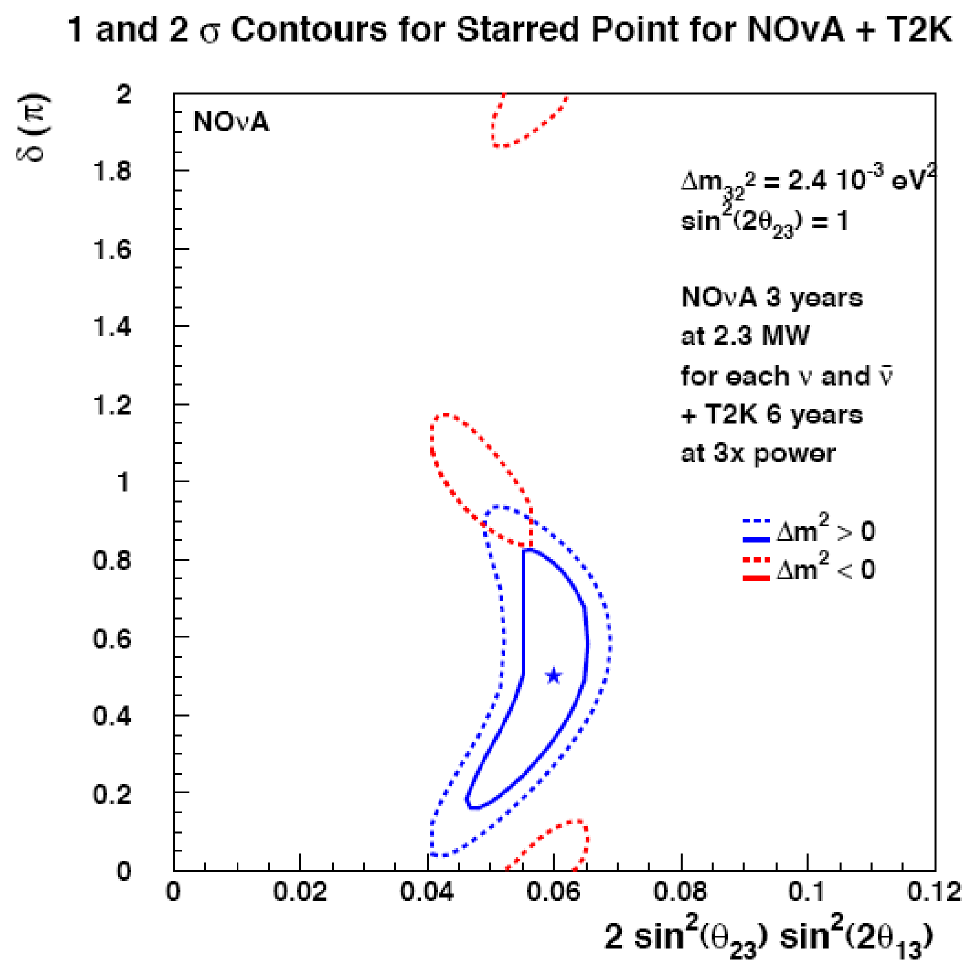
CP Violation δ vs. θ_{13} Contours: Best Possible δ





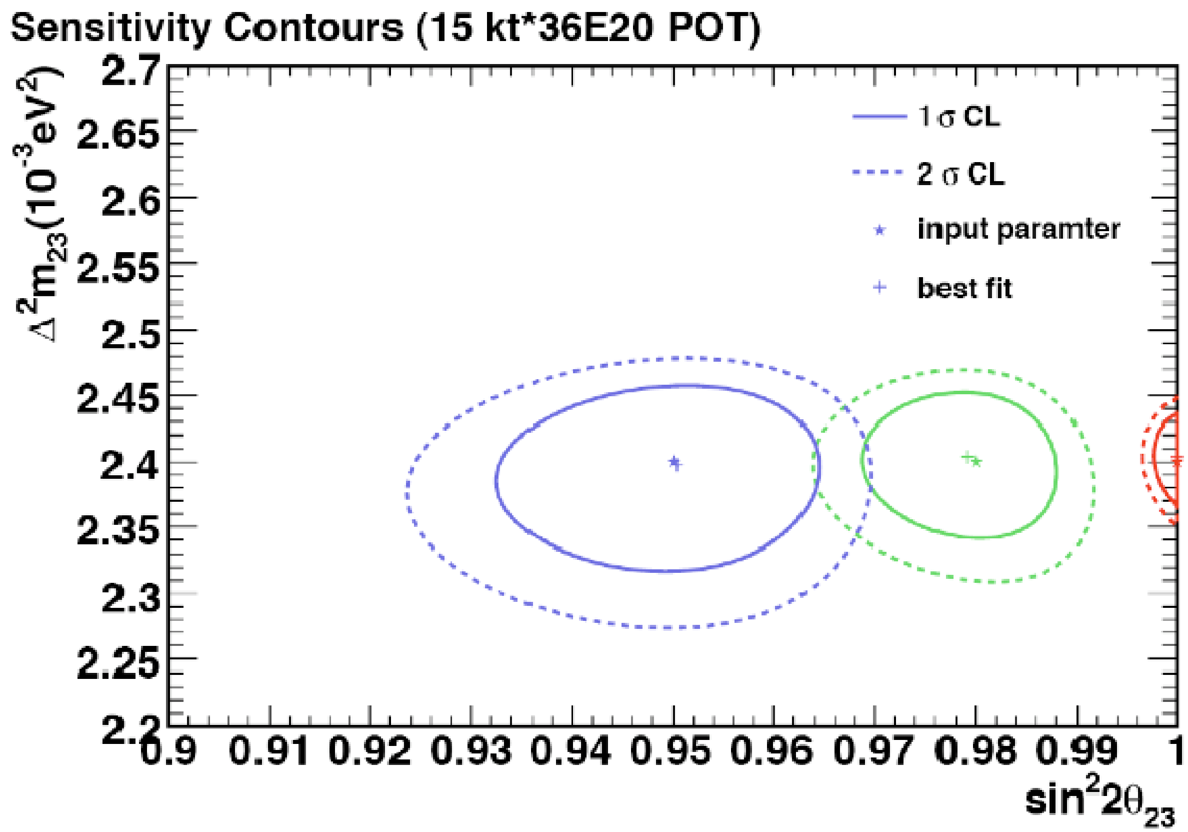
δ vs. θ_{13} Contours: Worst Possible δ T2K and NOvA Combined





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

This calculation uses NOνA's excellent energy resolution on ν_μ CC events.

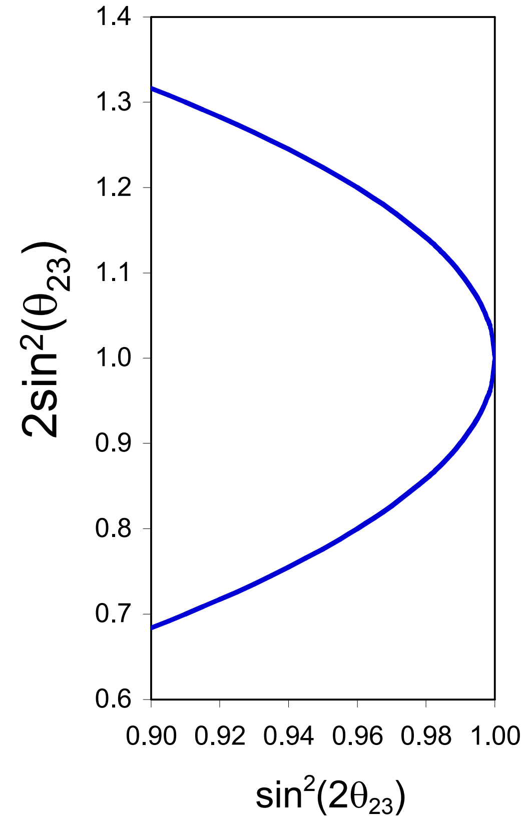


Reactor vs. Accelerator

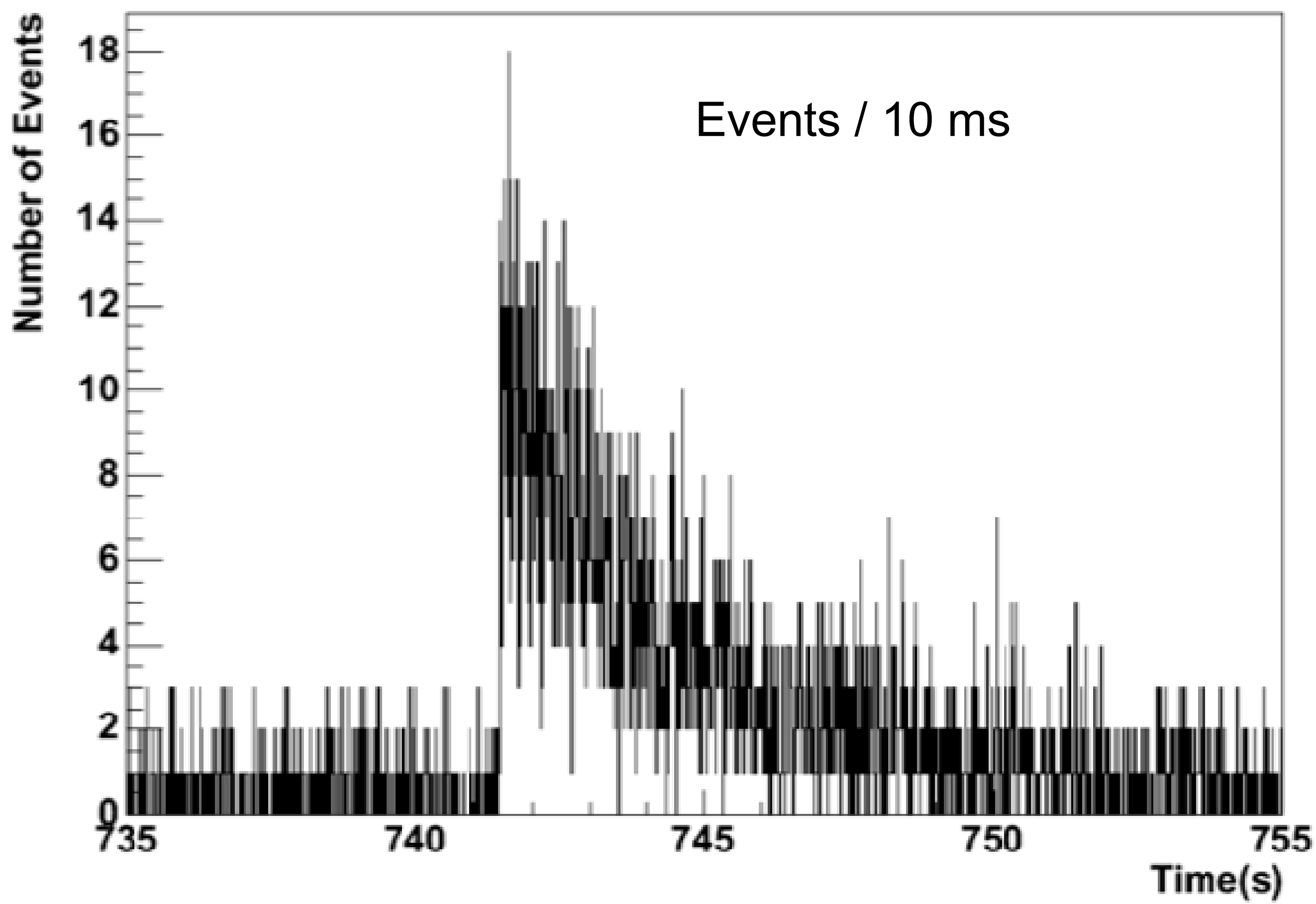
Reactor and accelerator experiments do not measure the same thing. Reactors are sensitive to $\sin^2(2\theta_{13})$, while accelerators are mostly sensitive to $\sin^2(\theta_{23})\ \sin^2(2\theta_{13})$.
If $\theta_{23} \neq \pi/4$, these quantities can be quite different.

The good news is that a comparison of NOνA and Daya Bay can break this ambiguity and determine whether ν_3 couples more to ν_μ or ν_τ, Determining the octant of θ_{23}.

$2\ \sin^2(\theta_{23})$ vs. $\sin^2(2\theta_{23})$



Galactic Supernova Signal



NOνA would see burst of 5000 events for a supernova at the center of the galaxy

Summary

- NOvA is fully approved and construction is proceeding apace
  - Detector and beam to be available 2013
- $\mathrm{Sin}^2(2\theta_{13})$ accessible to below .01
- Hierarchy accessible above $\sin^2(2\theta_{13}) = .05$ for ideal CP violation
  - Otherwise only above .1 in combination with T2K
- CP violation possibly accessible for the highest θ_{13} in combination with other experiments
- Improved bounds on θ_{23}
  - Possibly determine octant
- Supernova and other physics (for another talk…)

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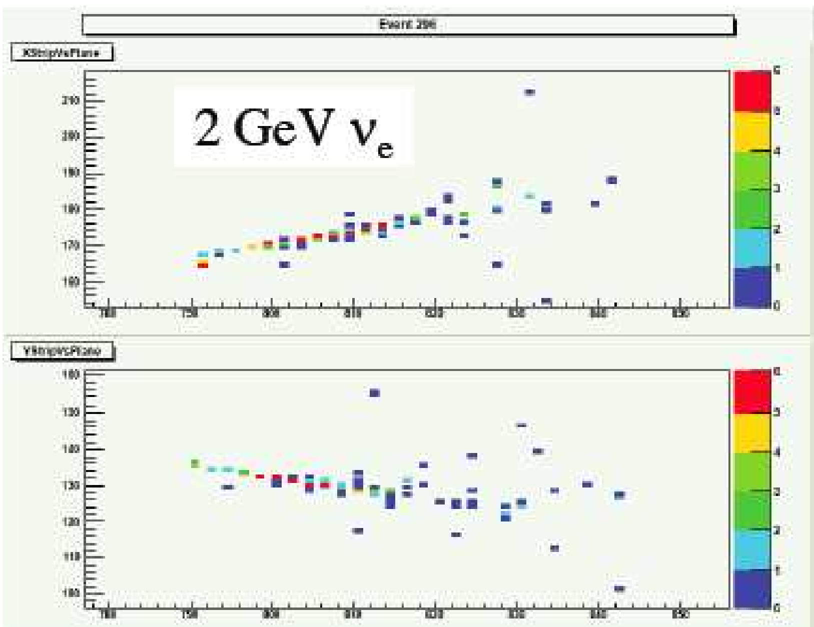
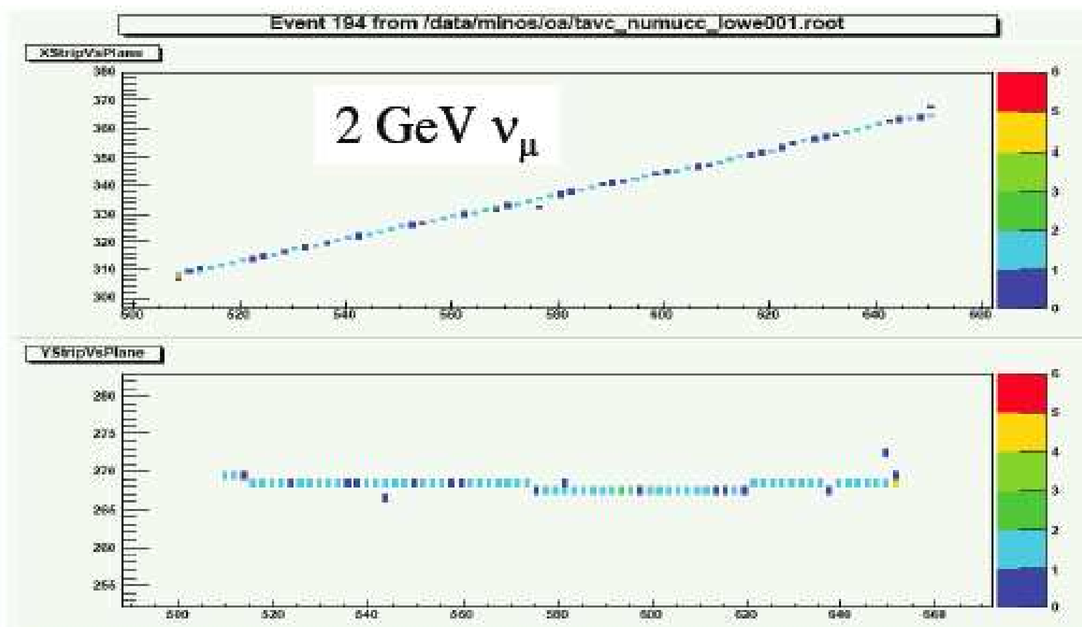
Event Quality

Longitudinal sampling is ~0.2 X_0, which gives excellent μ-e separation.

A 2-GeV muon is 60 planes long.





ν_e CC event

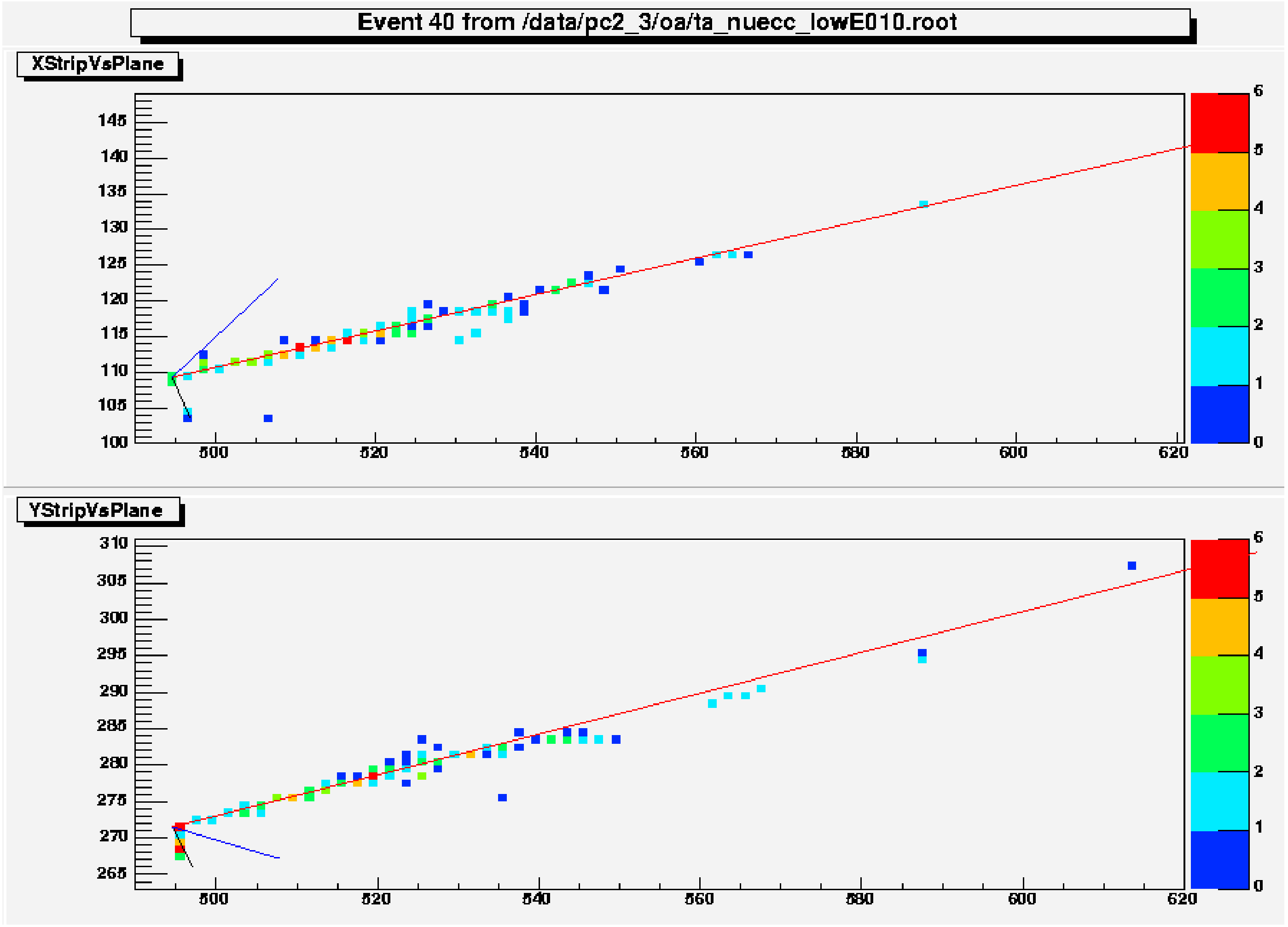
$\nu_e p \rightarrow e^- p \pi^+$

E_ν=2.5GeV

E_e=1.9GeV

E_p=1.1GeV

E_π=0.2GeV



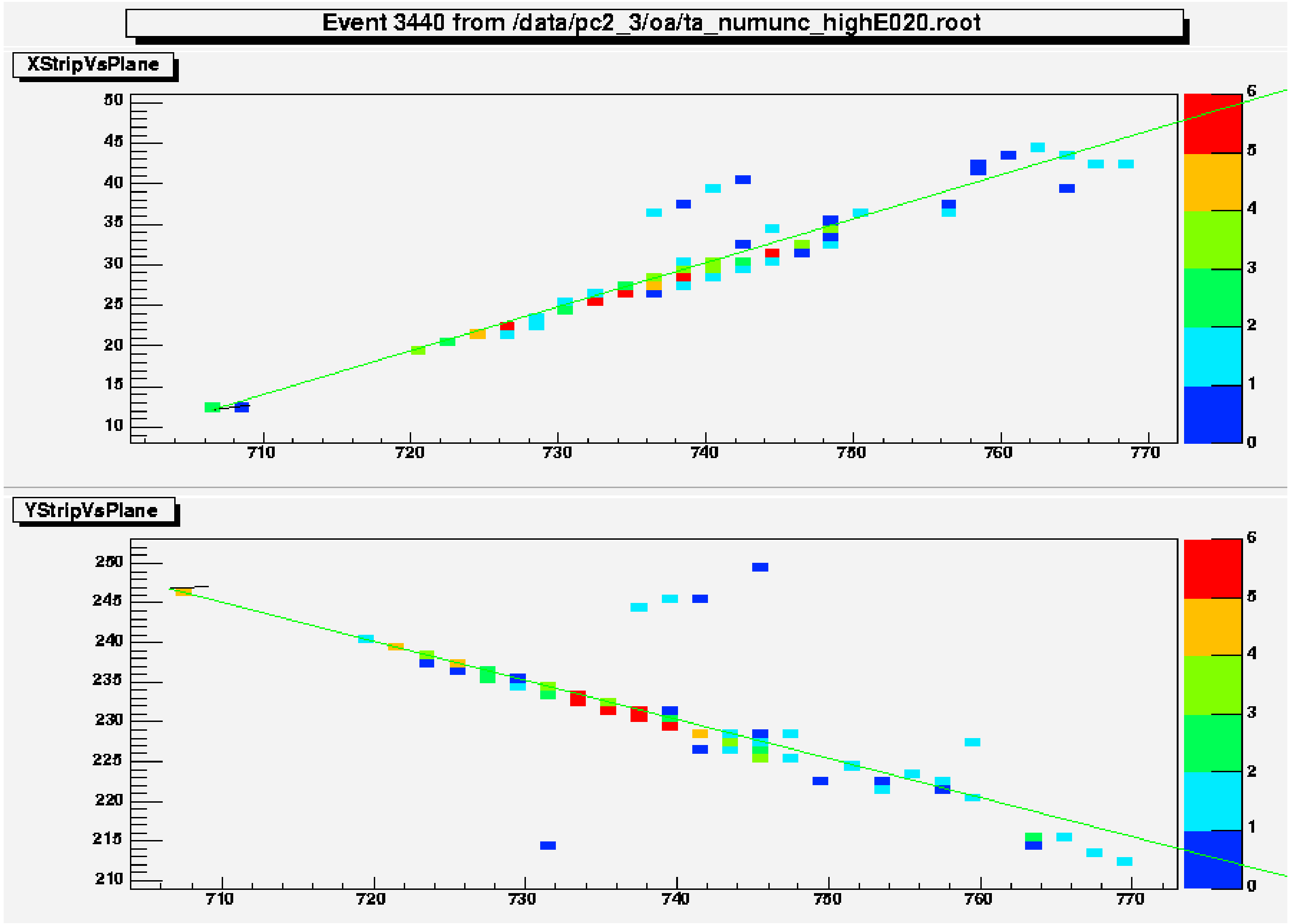
Background NC event

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

E_ν=10.6 GeV

E_p=1.04GeV

$E_{\pi o}$ =1.97GeV



Mass Hierarchy