The NOνA Experiment
NuMI Off-Axis ν_e Appearance Experiment

R. Ray
DOE Annual Program Review
May 17, 2006

NOνA

- NOνA enhances the U.S. investment in NuMI by using the existing beamline with a second generation detector.
  - 12 km off the NuMI beam line to get a narrow-band beam with more ν at the oscillation maximum
  - 810 km from Fermilab to get a large matter effect
  - Liquid scintillator tracking calorimetry for cost effective, high efficiency ν detection
- Its main physics goal will be the study of $\nu_\mu \rightarrow \nu_e$ oscillations at the atmospheric oscillation length.
- 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

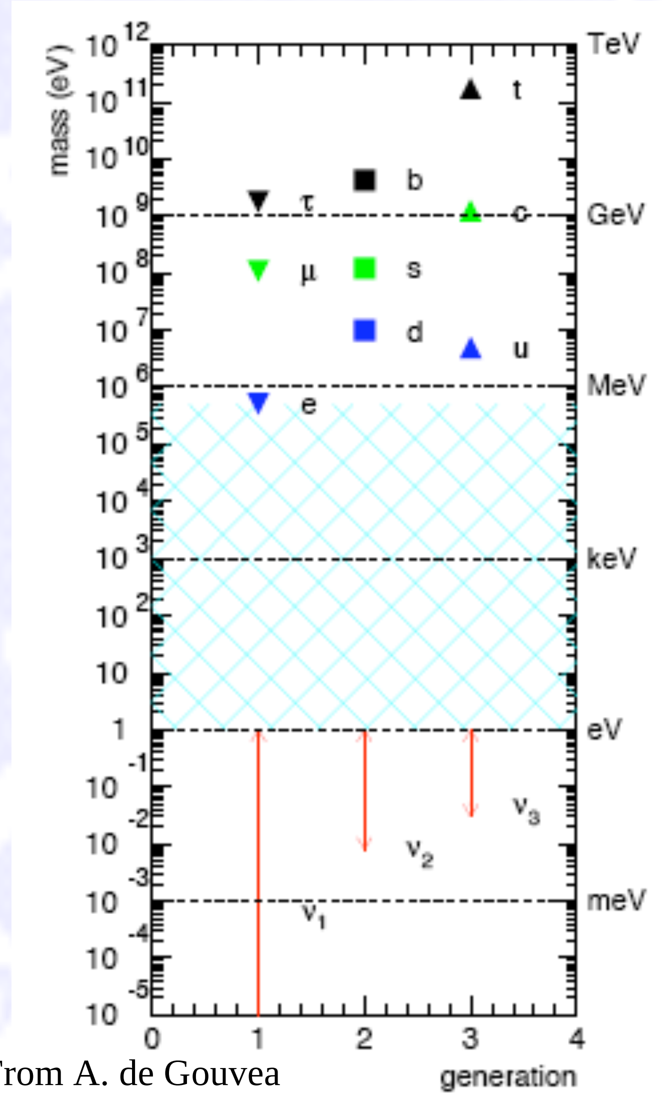
- The NOvA collaboration is 142 scientists and engineers, 28 institutions. Includes ~90 physicists, ~15 post-docs, ~20 engineers, and 15 graduate students.
- Collaborating institutions: *Argonne, Athens, Caltech, College de France, Fermilab, Harvard, Indiana, ITEP, Michigan State, Minnesota-Twin Cities, Minnesota-Duluth, Northern Illinois, Ohio, Ohio State, Oxford, Rutherford, Rio de Janeiro, South Carolina, SMU, Stanford, Texas, Texas A&M, Tufts, UCLA, Virginia, Washington, William and Mary*
- Currently in discussions with Italian institutions

From Fermilab - 42 total including

- 21 scientists
- 10 engineers
- 3 CP
- 2 post docs

~ 20 Fermilab FTEs currently effort reporting to NOνA

First Evidence of Physics Beyond the Standard Model



From A. de Gouvea

NEUTRINOS HAVE MASS!!!!!!

…very tiny masses

We don't know why that is, but we are pretty sure it means something important

Are neutrinos fundamentally different?

Are neutrino masses generated by a distinct dynamical mechanism?

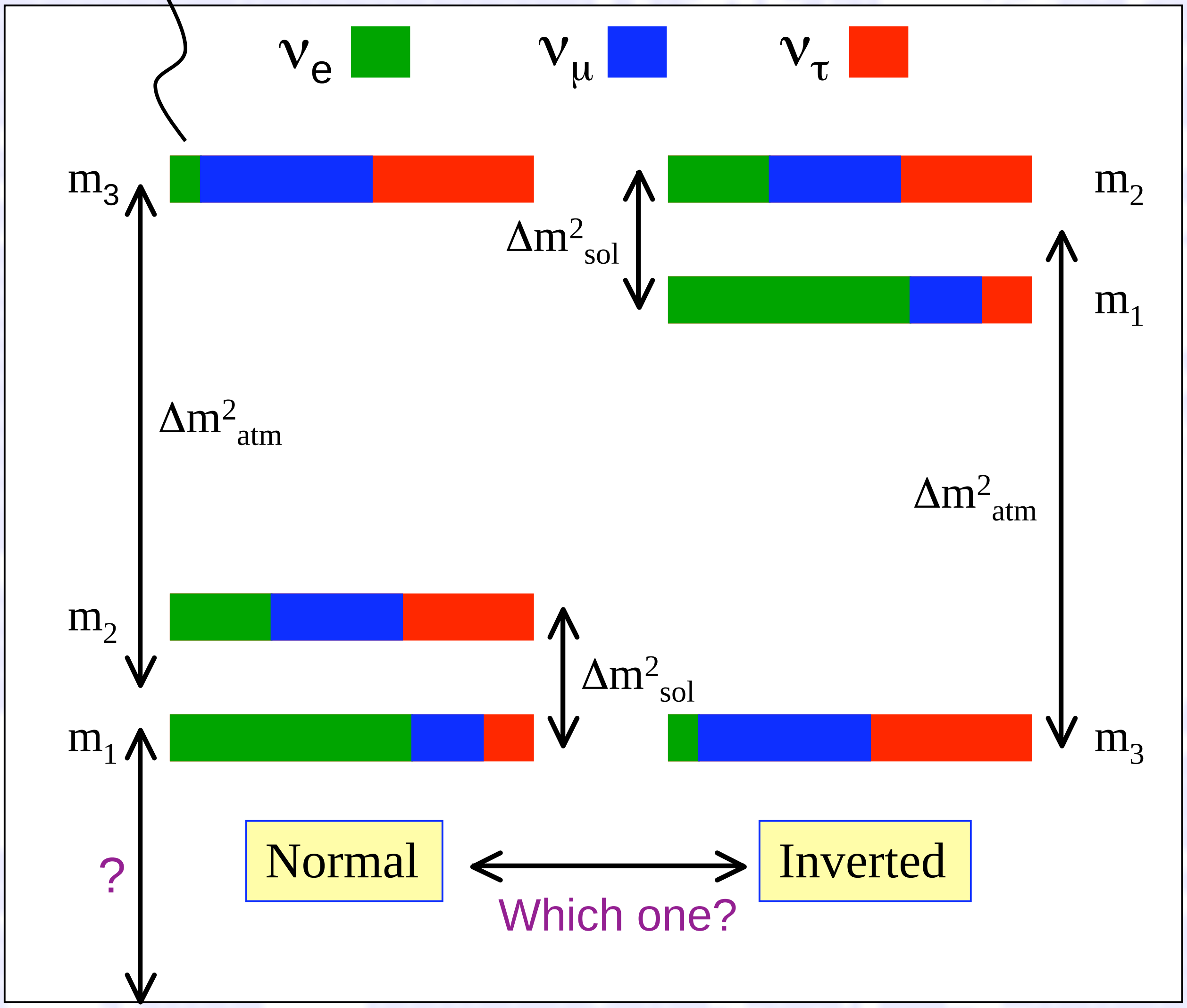
Neutrino Oscillations

- Neutrino oscillations occur because the weak eigenstates are not identical to the mass eigenstates
- The relationship between the weak eigenstates and the mass eigenstates is given by a unitary rotation matrix:

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

What we know, what we would like to know…

How large is this?



Would like to have more precise knowledge of mixing.

How large or small is $Sin^2(2\theta_{13})$?

$Sin^2(2\theta_{13})=0$ would be an interesting symmetry.

Does $Sin^2 2\theta_{23} = 1$? Another interesting symmetry.

Is $m_3 > m_2$?

Is CP violated?

Theory Covers Most Available Phase Space

From A. de Gouvea

$\Delta m^2_{13} > 0$ "typical" prediction of all Type-I see-saw GUT models

inverted hierarchy requires "more flavor structure"

	$\sin\theta_{13}$	$\sin^2 2\theta_{13}$
SO(10)		
Goh, Mohapatra, Ng [40]	0.18	0.13
Orbifold SO(10)		
Asaka, Buchmüller, Covi [41]	0.1	0.04
SO(10) + flavor symmetry		
Babu, Pati, Wilczek [42]	$5.5 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$
Blazek, Raby, Tobe [43]	0.05	0.01
Kitano, Mimura [44]	0.22	0.18
Albright, Barr [45]	0.014	$7.8 \cdot 10^{-4}$
Maekawa [46]	0.22	0.18
Ross, Velasco-Sevilla [47]	0.07	0.02
Chen, Mahanthappa [48]	0.15	0.09
Raby [49]	0.1	0.04
SO(10) + texture		
Buchmüller, Wyler [50]	0.1	0.04
Bando, Obara [51]	0.01 .. 0.06	$4 \cdot 10^{-4}$ .. 0.01
Flavor symmetries		
Grimus, Lavoura [52, 53]	0	0
Grimus, Lavoura [52]	0.3	0.3
Babu, Ma, Valle [54]	0.14	0.08
Kuchimanchi, Mohapatra [55]	0.08 .. 0.4	0.03 .. 0.5
Ohlsson, Seidl [56]	0.07 .. 0.14	0.02 .. 0.08
King, Ross [57]	0.2	0.15
Textures		
Honda, Kaneko, Tanimoto [58]	0.08 .. 0.20	0.03 .. 0.15
Lebed, Martin [59]	0.1	0.04
Bando, Kaneko, Obara, Tanimoto [60]	0.01 .. 0.05	$4 \cdot 10^{-4}$ .. 0.01
Ibarra, Ross [61]	0.2	0.15
3 × 2 see-saw		
Appelquist, Piai, Shrock [62, 63]	0.05	0.01
Frampton, Glashow, Yanagida [64]	0.1	0.04
Mei, Xing [65] (normal hierarchy)	0.07	0.02
(inverted hierarchy)	> 0.006	$> 1.6 \cdot 10^{-4}$
Anarchy		
de Gouvêa, Murayama [66]	> 0.1	> 0.04
Renormalization group enhancement		
Mohapatra, Parida, Rajasekaran [67]	0.08 .. 0.1	0.03 .. 0.04

[from reactor white paper]

Theoretical Expectations:

theoretical models can teach us what θ_{13} values are more likely . . .

Unfortunately, theorists have done too good a job, and people have successfully predicted everything. . .

More data needed to sort things out:

Data Driven Field!

"Ask not what your theorist can do for you, but what you can do for your theorist."

Importance of the Mass Ordering

- Window on very high mass scales:
  - Grand Unified theories favor normal mass ordering
  - Other approaches favor inverted ordering
- If we establish the inverse ordering, the next generation of $0\nu\beta\beta$ experiments can determine if the neutrino is its own antiparticle.
  - If we establish the normal ordering, a negative result from $0\nu\beta\beta$ experiments will be inconclusive.
- To measure CP violation we must resolve the mass ordering since it contributes to an apparent CP violation that we must account for.

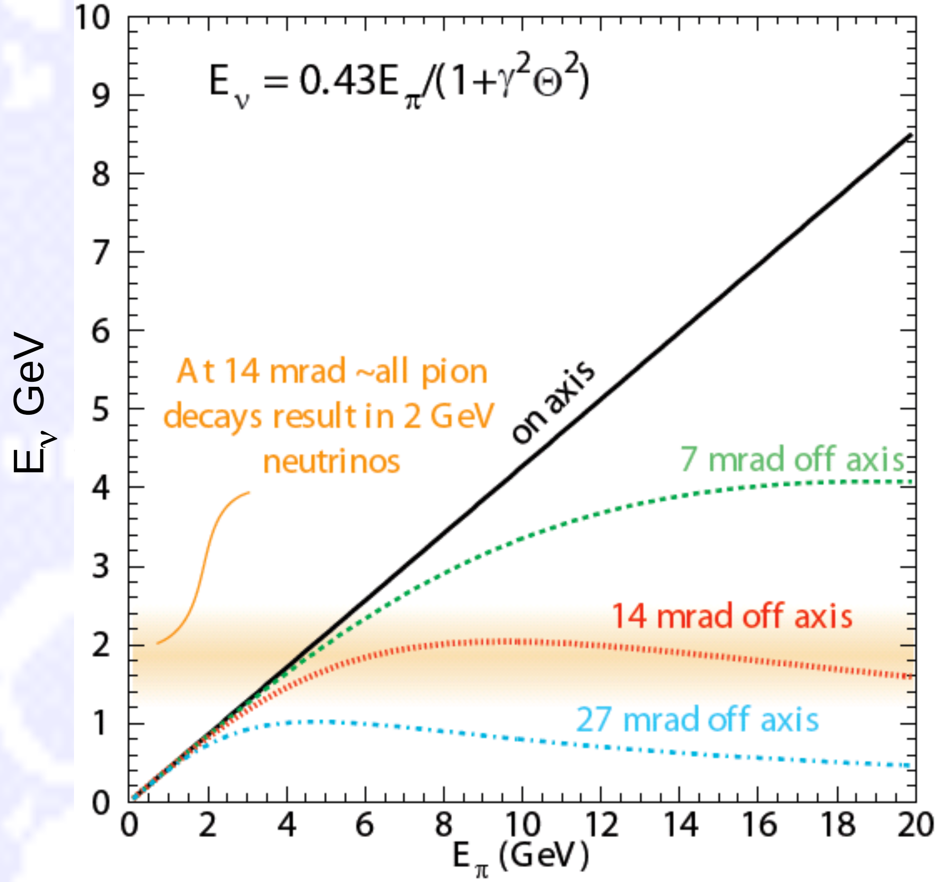
NOνA Physics Goals

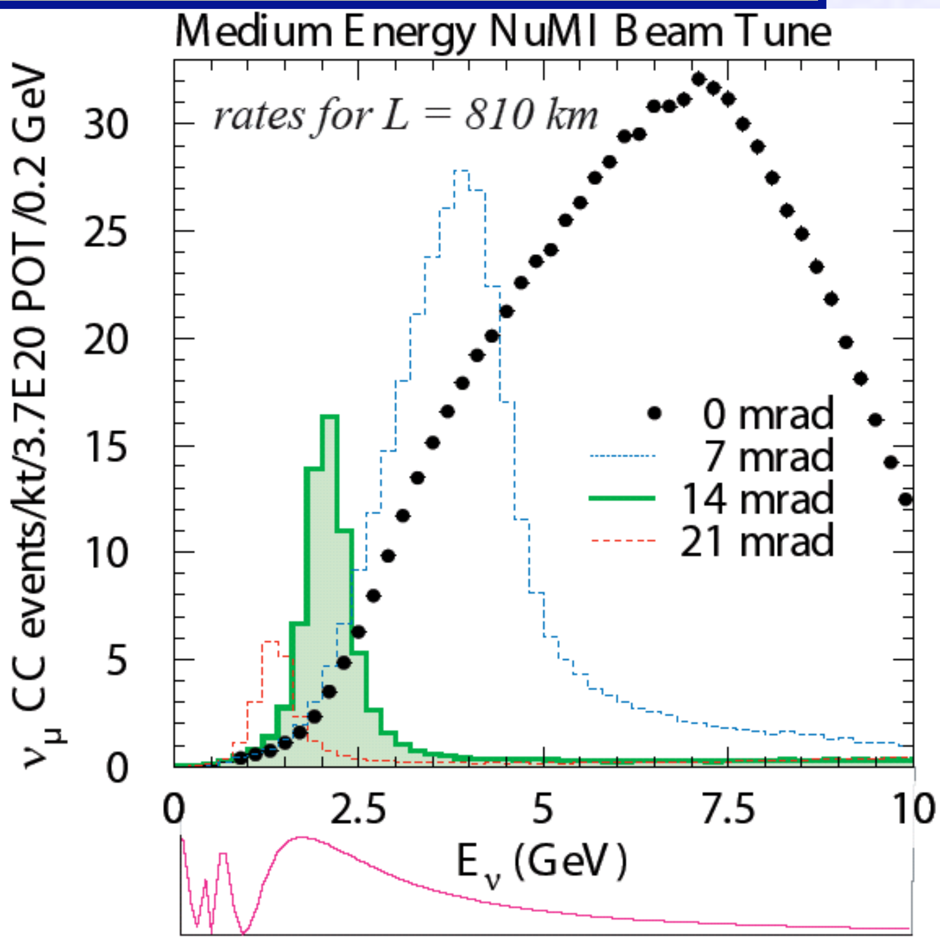
- Establish ν_μ- ν_e oscillations at the atmospheric neutrino length scale for $\sin^2(2\theta_{13})$ >~ 0.01.
- Precision (~1%) measurement of $\sin^2(2\theta_{23})$.
- Study of hierarchy question
- Begin study of CP violation in neutrino sector

Off-Axis Neutrino Beams

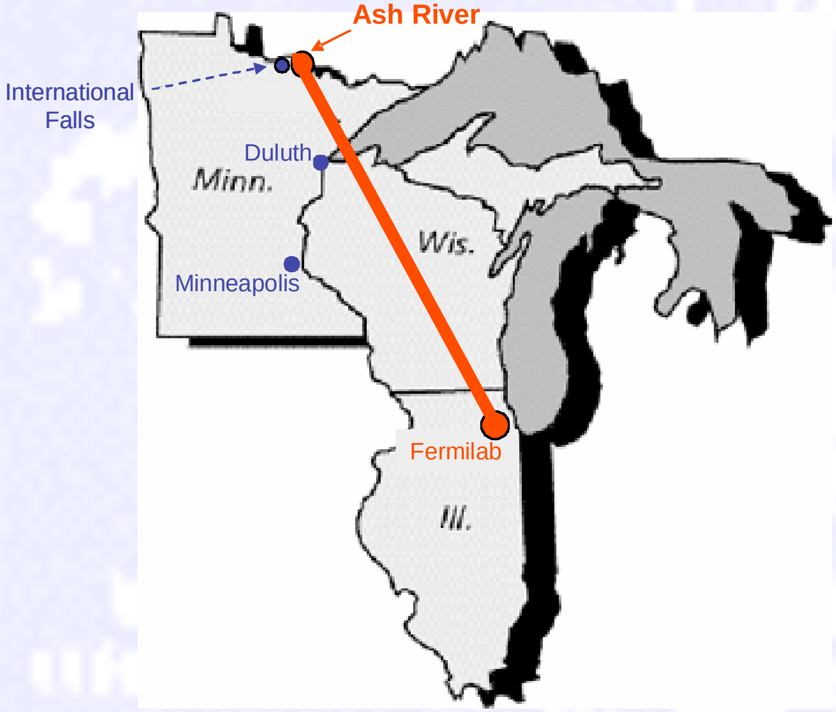
First proposed by BNL E-889

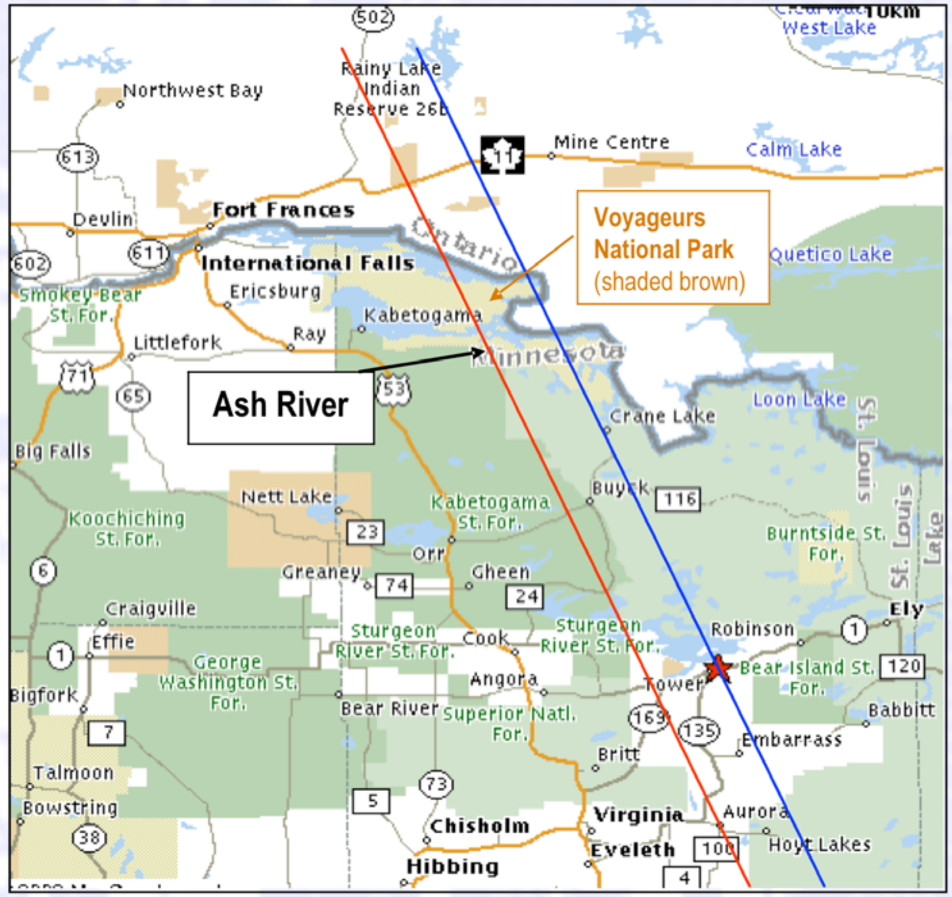
Moving off-axis yields a narrow band beam with more flux where we want it and less background (ν_e's from K decay and higher Energy NC events)





Location of the Far Detector

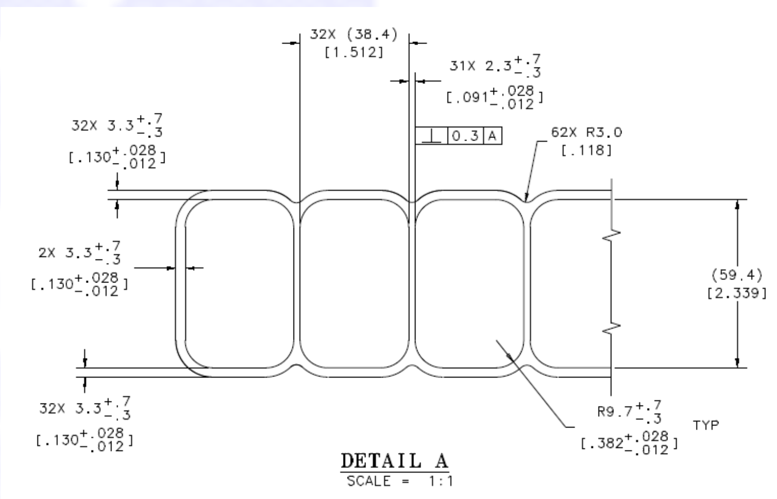


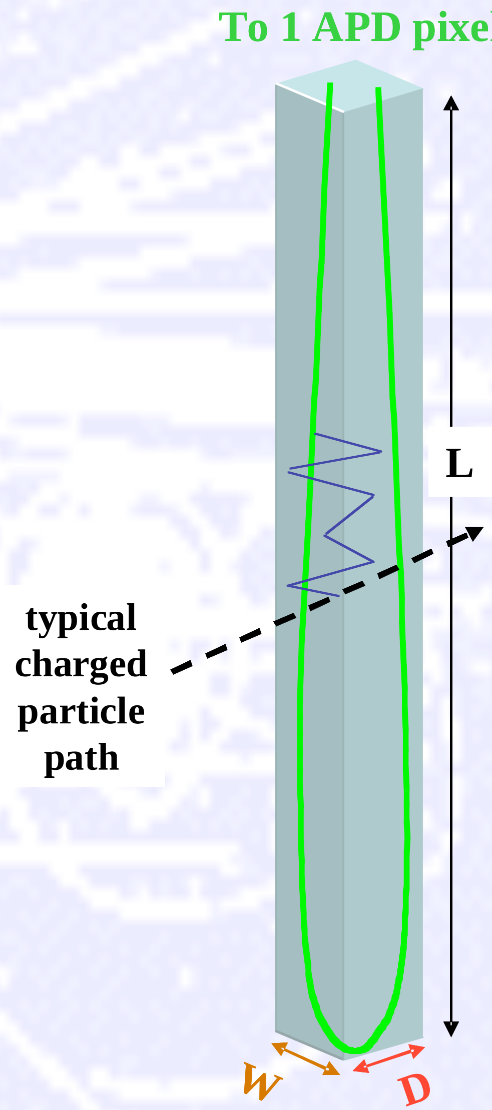


The Ash River site is the furthest available location from Fermilab along the NuMI beamline inside the US. This maximizes NOvA's sensitivity to the mass ordering.

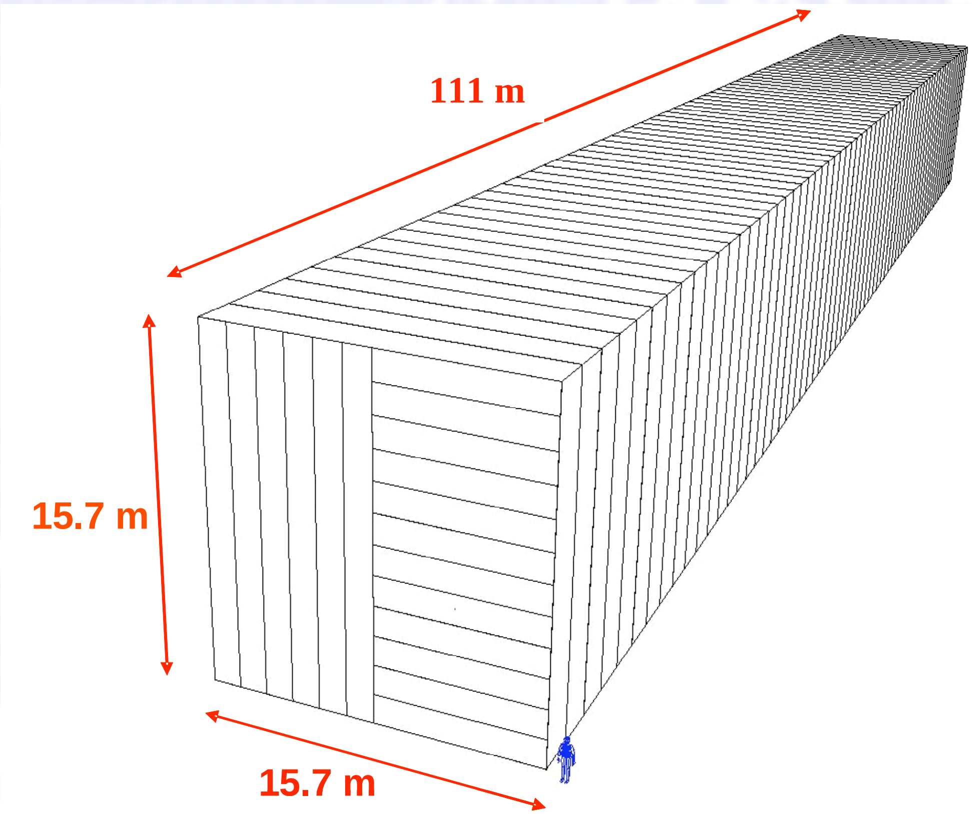
Basic Detector Element

- Liquid scintillator in a 3.8 cm wide, 6 cm deep, 15.7 m long, highly reflective PVC cell.
- Light is collected in a looped 0.8 mm diameter wavelength-shifting fiber, both ends of which terminate on a single pixel of a 32-pixel APD.
- The APD has a Q.E. of 85% and will run at a gain of 100. It must be cooled to -15°C and requires a very low noise amplifier.



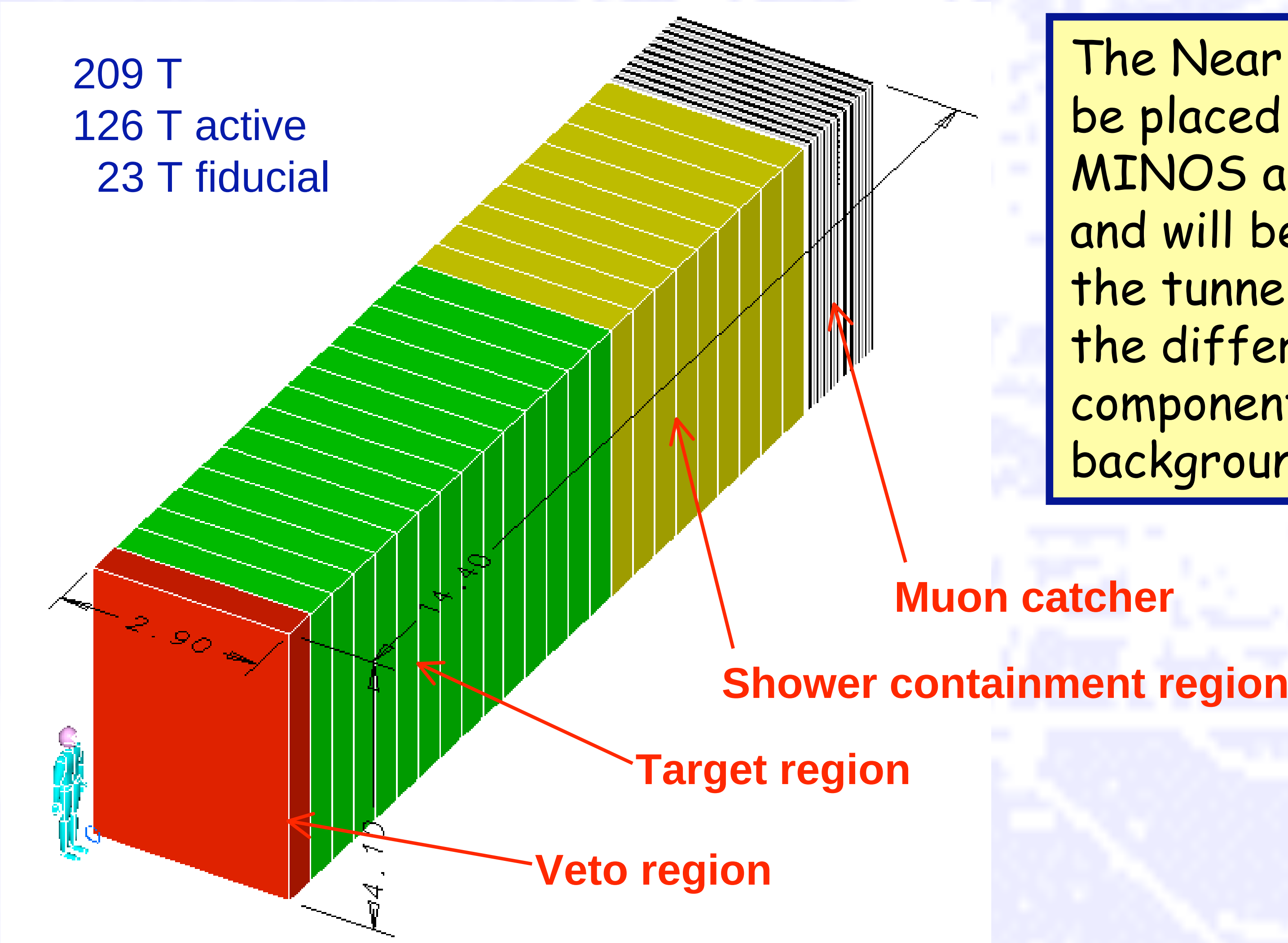


The Far Detector



- The cells are made from 32-cell extrusions.
- 12 extrusions make up a plane.
- The planes alternate horizontal to vertical.
- For structural reasons, the planes are arranged in 31-plane blocks that begin and end with a plane of vertical extrusions.
- There are 54 planes = 1654 planes = 19,848 extrusions = 635,136 cells.
- Data taking can begin as blocks are completed.

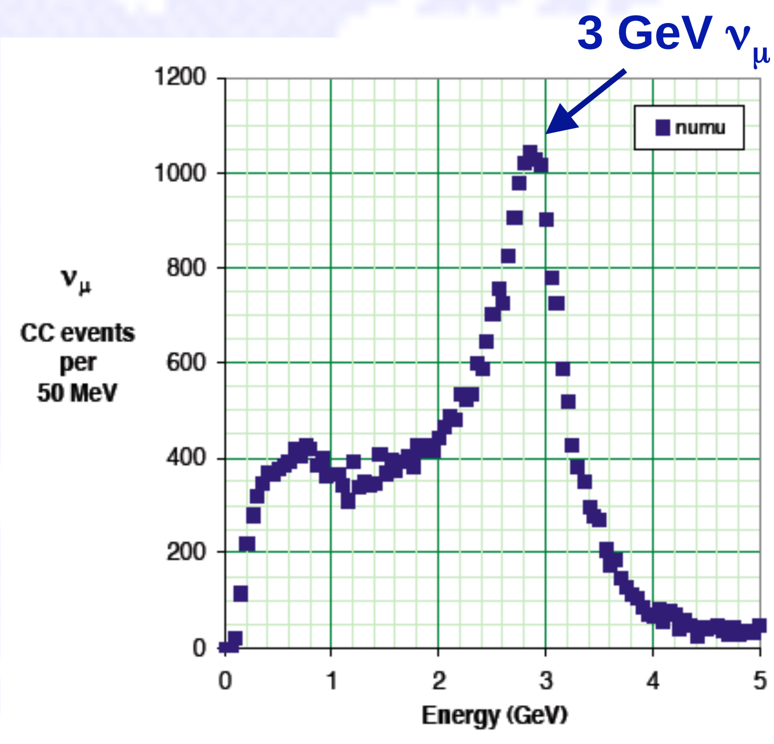
The Near Detector

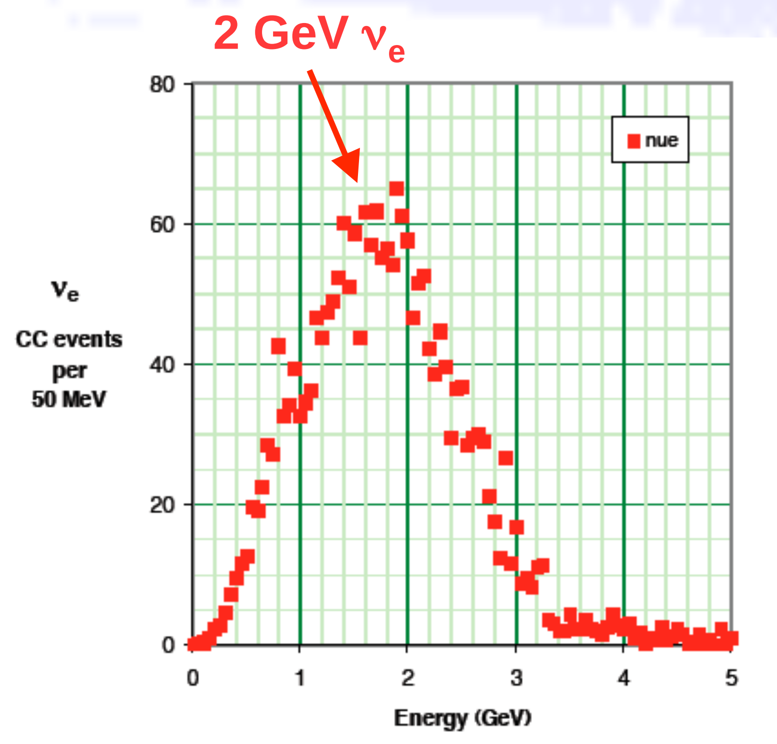


The Near detector will be placed off axis in the MINOS access tunnel and will be movable along the tunnel to measure the different components of the background.

Integration Near Detector Prototype

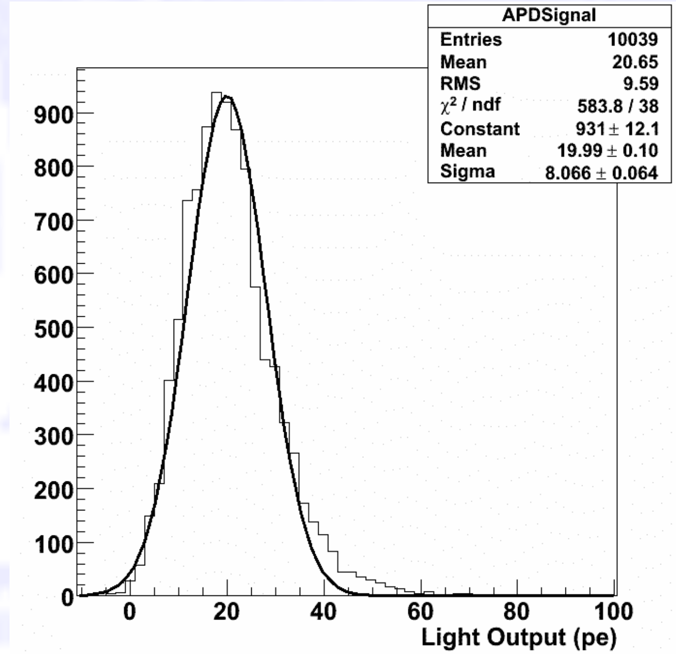
We plan to have a prototype version of the Near Detector running in the MINOS surface building by the end of 2007. It will detect a 75 mr off-axis NuMI beam, dominated by *K* decays.



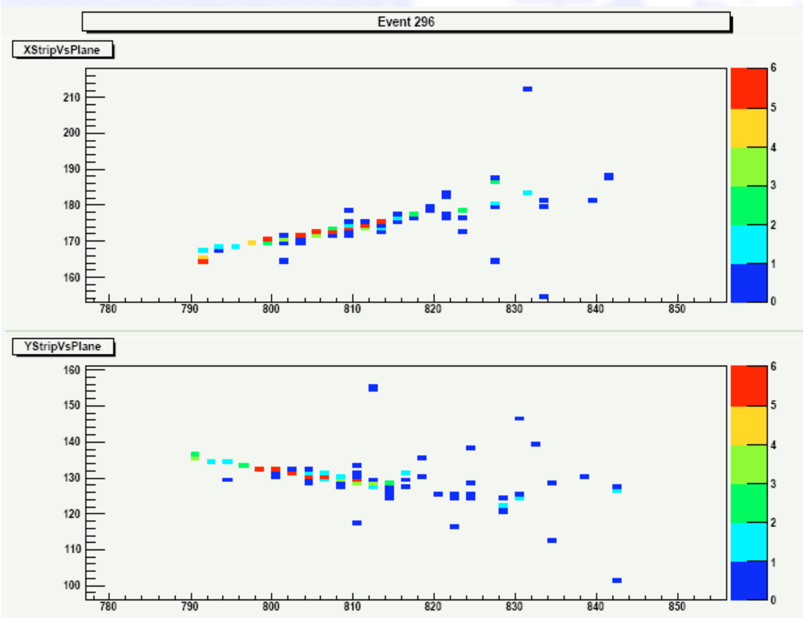


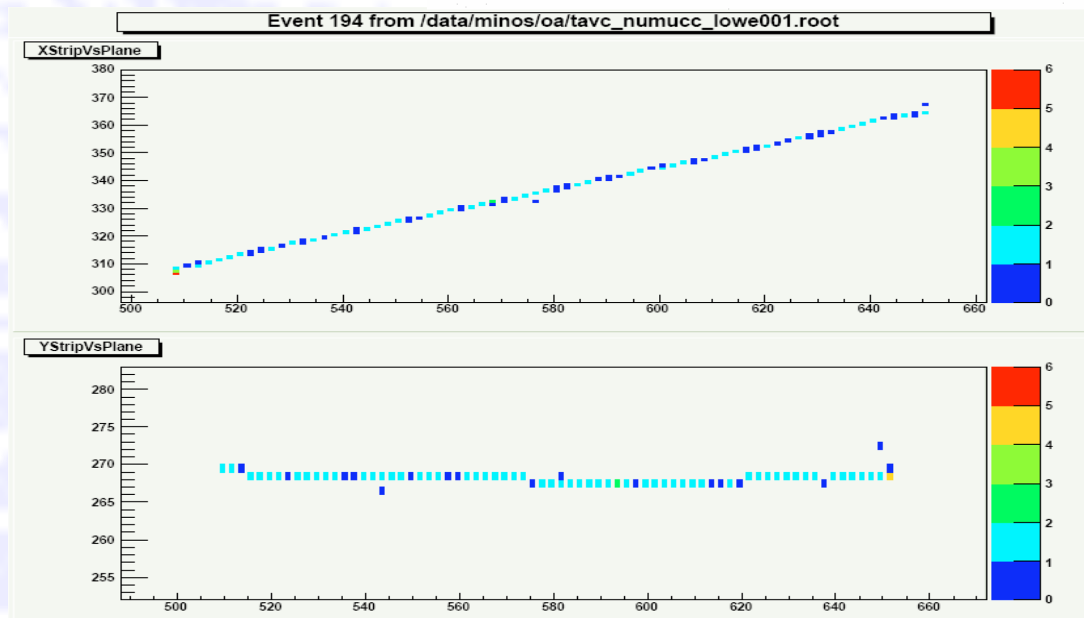
Event Quality

~ 20 p.e. per MIP from the far end of the cell.



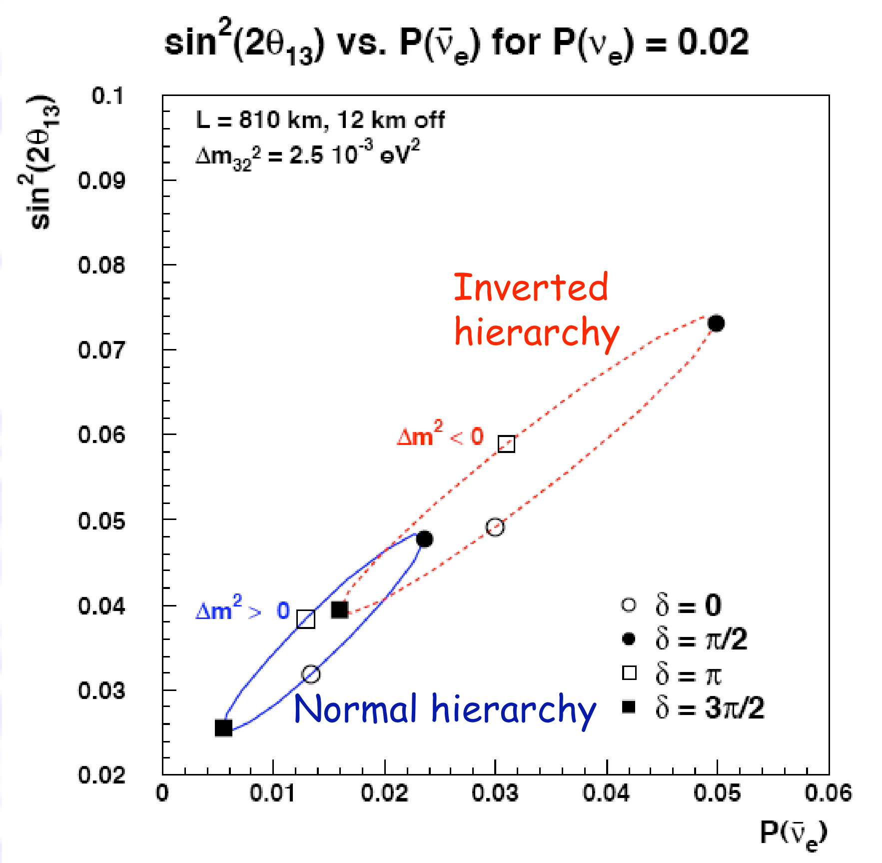
Longitudinal sampling is 0.15 X_0 resulting in excellent e/μ separation.





Interpreting What We Measure

- Experiments measure oscillation probabilities
- Ambiguities in $\sin^2(2\theta_{13})$ due to CP phase δ and mass hierarchy
- Comparison of NOνA and T2K at different baselines can break ambiguities
- Possibly use a 2d NUMI off-axis detector at the 2d oscillation maximum



Simulations

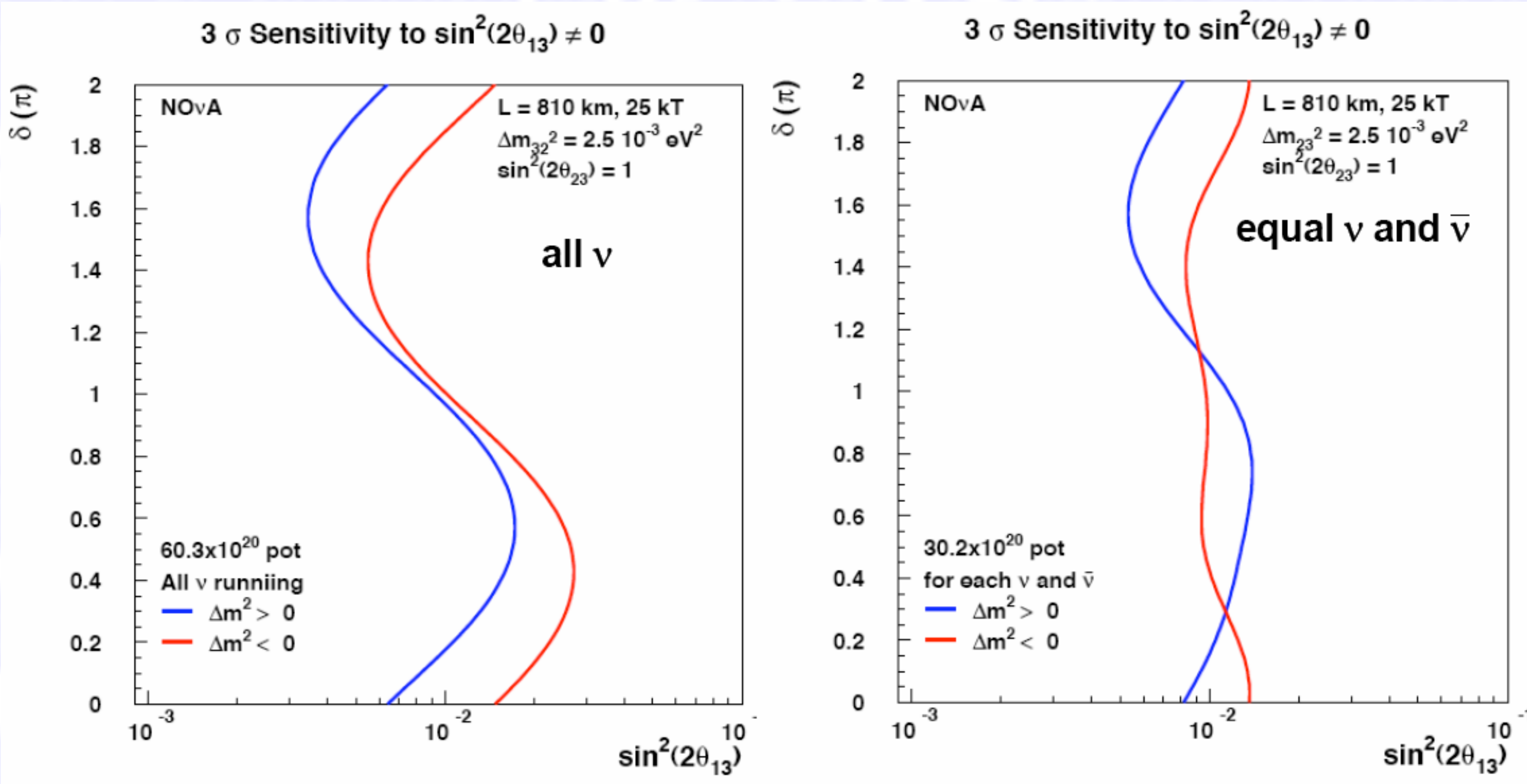
- The physics projections are based on a full reconstruction
  - Full Monte Carlo beam simulation
  - Raw hits are produced by Monte Carlo
  - Hits are reconstructed into physics objects
  - A likelihood function is constructed to separate signal from backgrounds
  - A cut on the likelihood function is made to maximize a figure of merit (FoM) = signal / $\sqrt{\text{background}}$

Proton Plan

The physics projections are also based on a proton plan Developed by the Lab for the post-collider era.

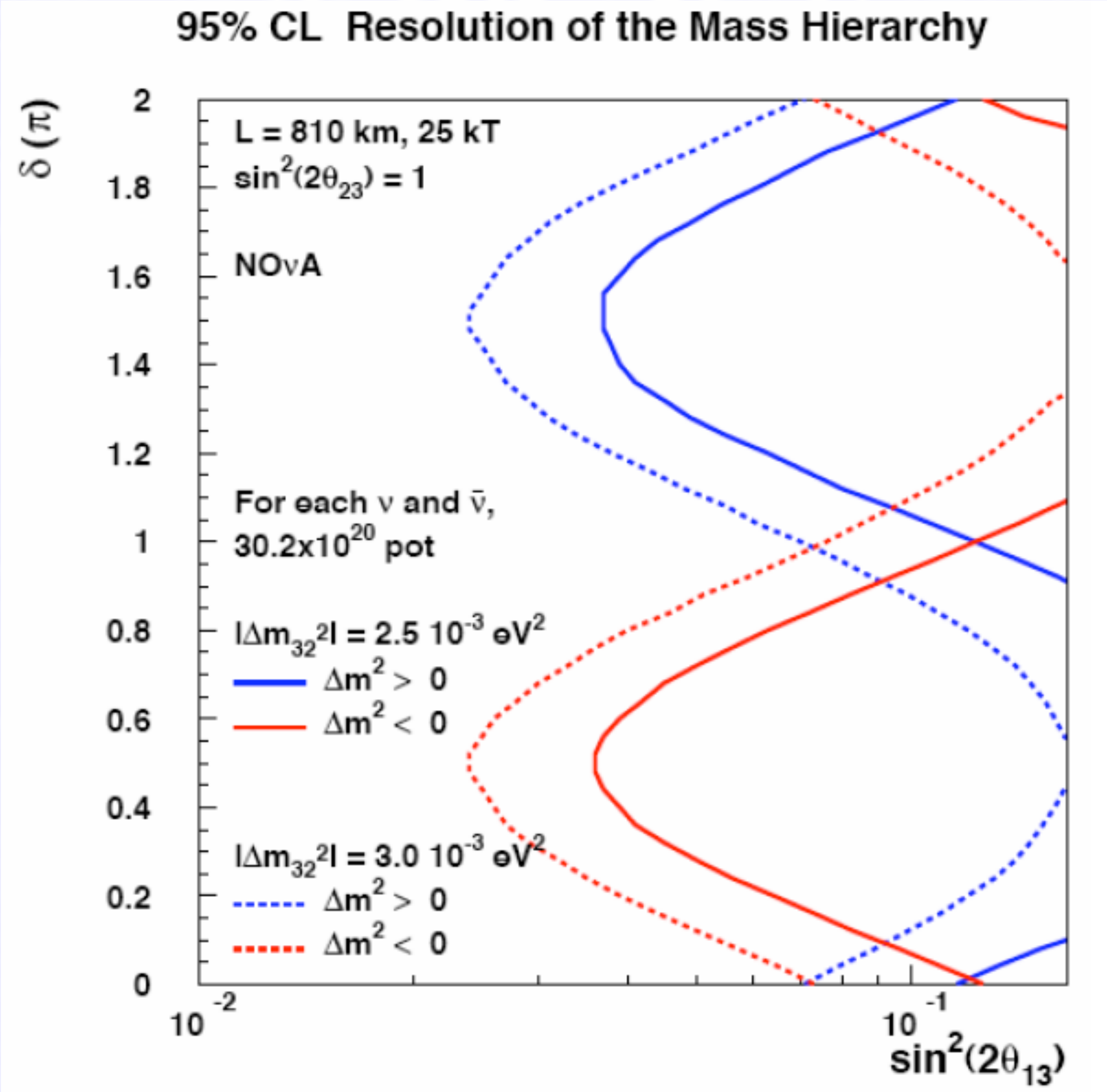
- FY2010: Full year down period to convert Main Injector to a 1 MW proton source.
    - Conversion of the Recycler and Accumulator into proton stackers
    - Construction of Booster-Accumulator and Accumulator - Recycler transfer lines.
    - Main Injector RF upgrade
    - NuMI target upgrade.
- FY2011: 44 weeks of running; 400 kW to 700 kW
- FY2012: 38 weeks of running; 700 kW to 1 MW
- FY2013 and beyond: 44 weeks of running at 1 MW

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



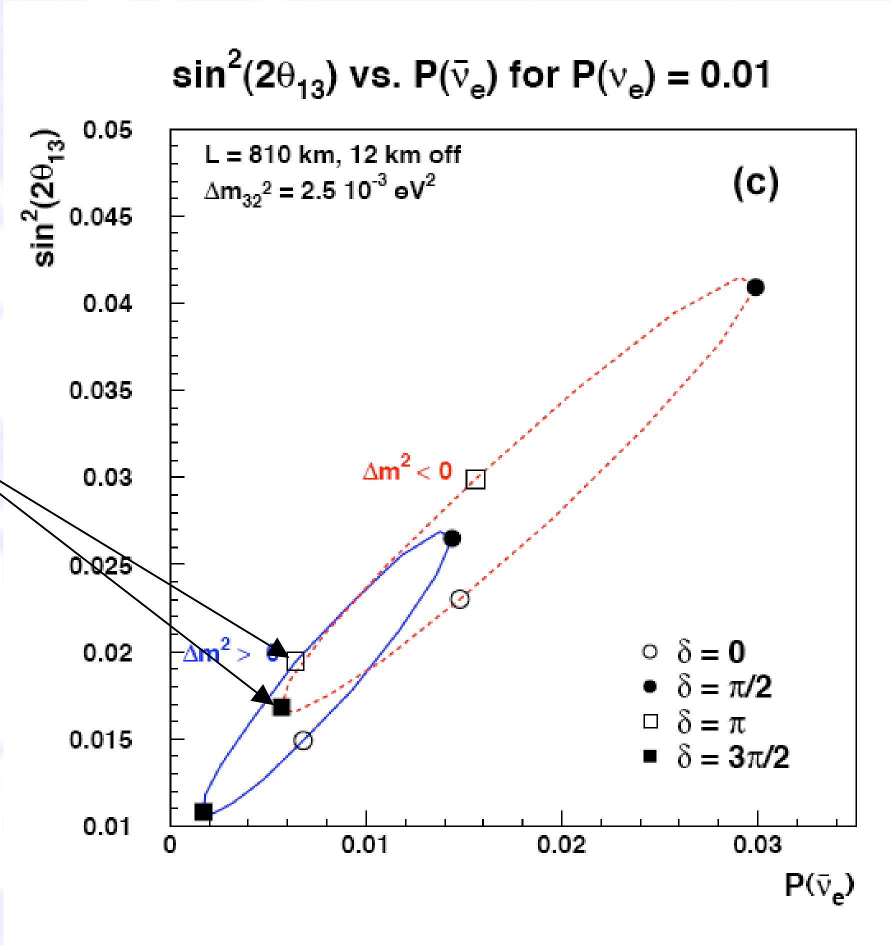
Values of $\sin^2(2\theta_{13})$ for which NOνA can make a 3σ observation of ν_e appearance. Left plot shows sensitivity for a 6 year neutrino run. Plot on right is for 3 years of neutrinos and 3 years of anti-neutrinos.

Resolving the Mass Hierarchy

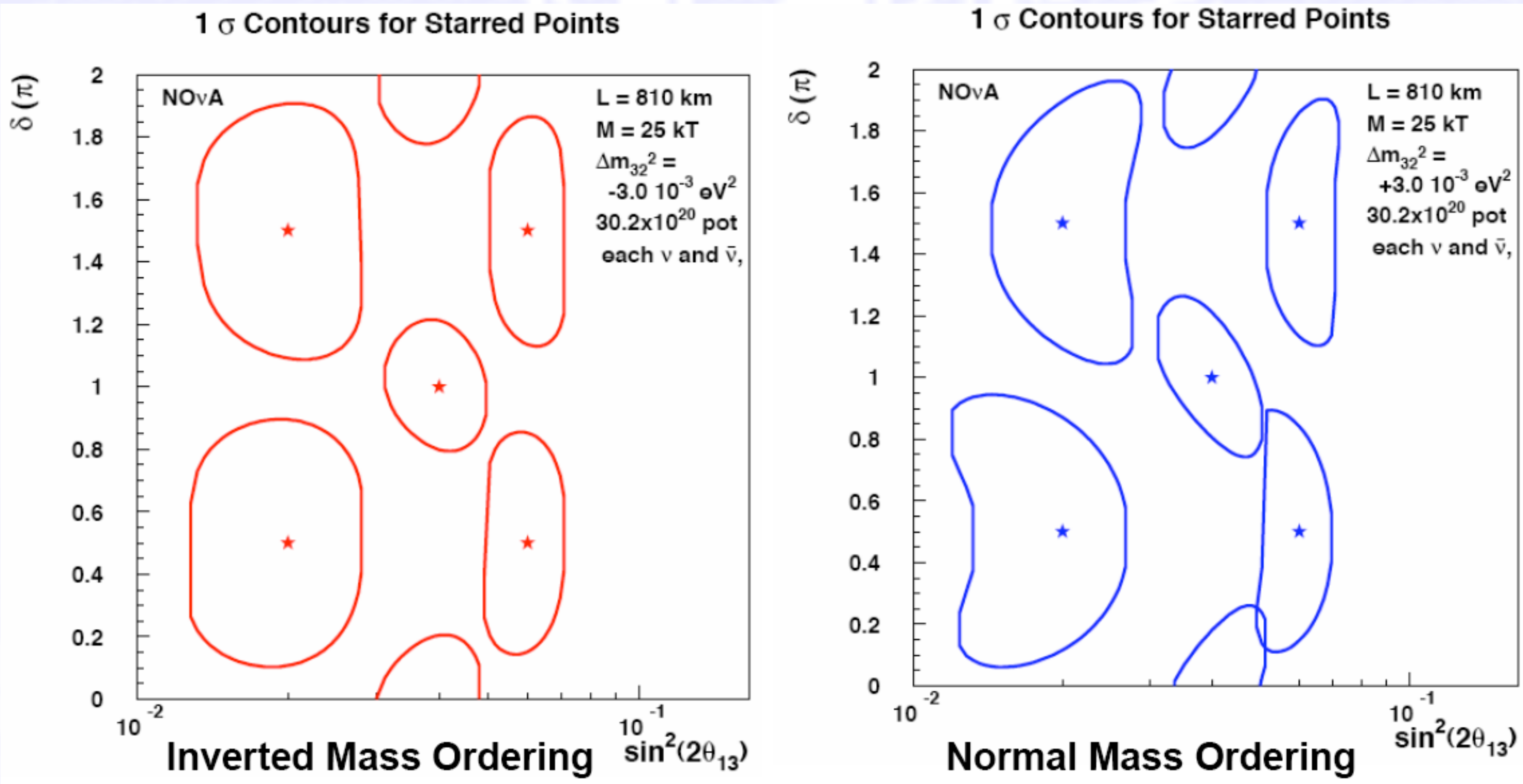


Sensitivity to CP Violation

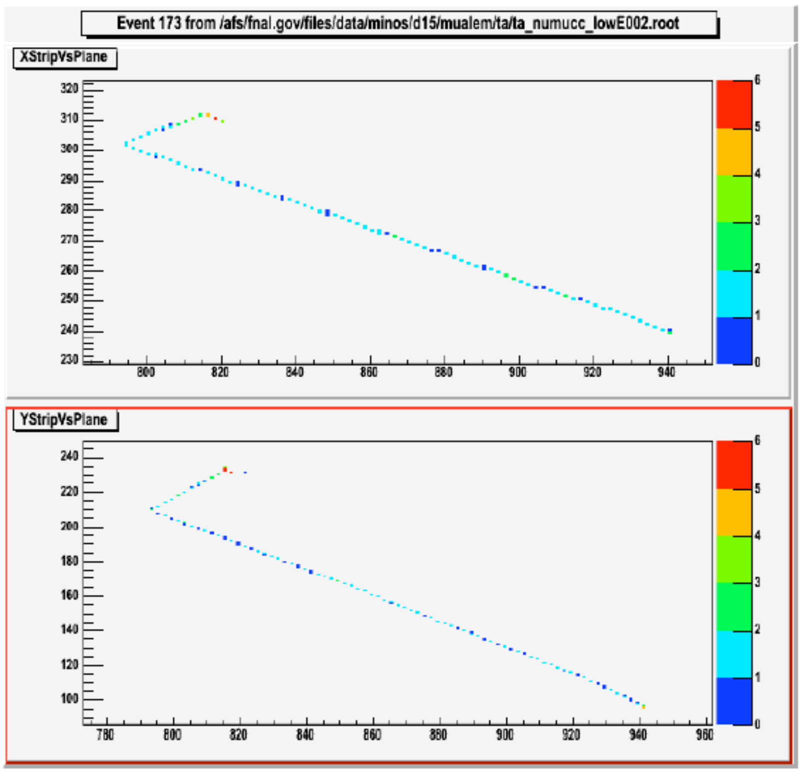
- Long baseline experiments generally need to know the hierarchy to measure the CP phase
- Maximal CPV for one mass ordering can have ν and $\bar{\nu}$ probabilities corresponding to no CPV for the other mass ordering



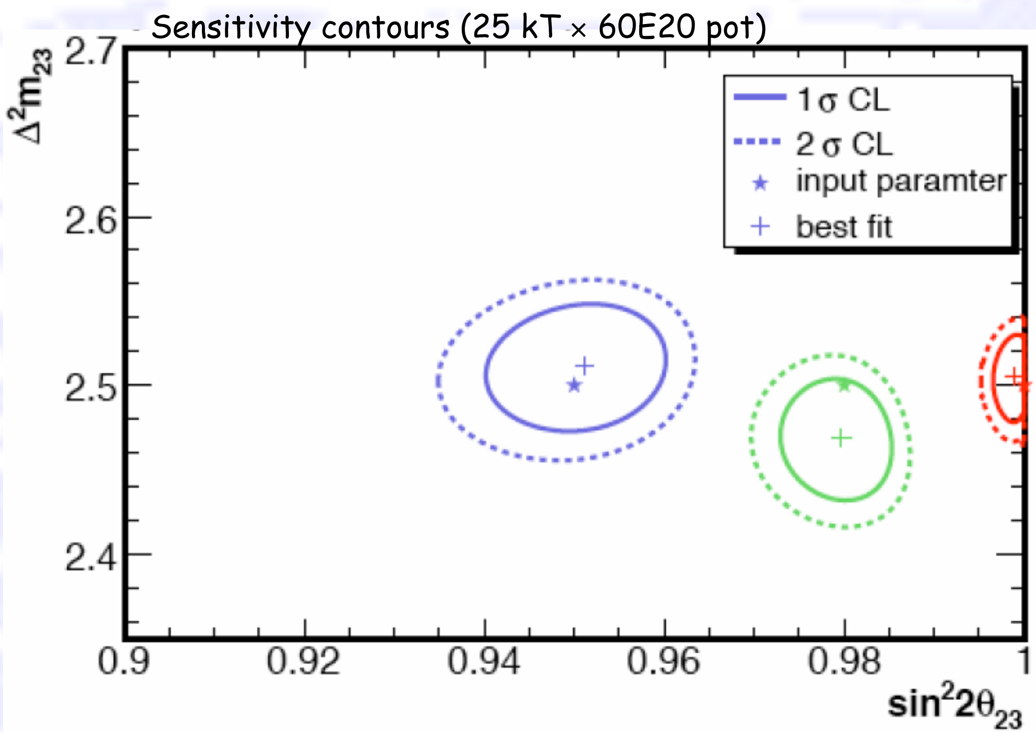
δ vs. $\sin^2(2\theta_{13})$ Contours



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



Narrow-band beam and excellent energy resolution allow a high-precision test of a possible new symmetry ($\sin^2 2\theta_{23} = 1$) by measuring QE ν_μ CC events



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

Otherwise, it can be measured to ~ 0.01.

Schedule

- April 2006: CD-1 review. Unanimous recommendation to approve CD-1.
- Sept. 2006: CD-2 review?
- Oct. 2007: Begin Far Detector enclosure.
- Dec. 2007: Begin operating Integration Near Detector Prototype
- Oct. 2008: First module factory begins operation.
- June 2009: Beneficial occupancy of Far Detector enclosure.
- Nov. 2010: 5 kT completed. Data taking begins.
- Nov 2011: Far Detector completed.

Sensitivity Schedule

Estimated times to establish 3σ sensitivity to $\theta_{13} \neq 0$ (normal mass ordering, $\Delta m^2_{32} = 0.0025\ eV^2$, $\sin^2(2\theta_{23}) = 1$, $\delta = 0$)

- Jan. 2012, if $\sin^2(2\theta_{13}) = 0.05$
- Nov. 2012, if $\sin^2(2\theta_{13}) = 0.02$
- Aug. 2014, if $\sin^2(2\theta_{13}) = 0.01$

Last Year's Accomplishments

- CD-0 signed on Feb 17, 2006
- Positive response from NuSAG.
- Environmental Assessment Work completed for two sites in Northern Minnesota.
- Project team assembled and Project Office staffed.
- Obtained real quotes with scaling indices for most of the cost drivers.
- April 2006: CD-1 review. Unanimous recommendation for CD1 approval.
  - CDR, Project Management Plan, Project Execution Plan, Risk Management Plan, Configuration Management Plan, Hazard Analysis Report, baseline cost range and resource loaded schedule…

Next Year's Goals

Prepare for CD-2 baseline review in the fall:

- Finalize cost and schedule
- Complete major R&D items
  - Extrusions, electronics…
  - Integration Prototype well underway
- Complete engineering and design of cost drivers and critical components.

Prepare for beginning of construction in FY08

- Building
- 32-cell extrusions
- WLS fiber

Fermilab Contributions

- Proton source upgrades
- Project management, cost & schedule, ES&H, procurement…
- Building design
- Front-end ASIC design
- DAQ hardware and software
- Block raiser design and construction
- Near detector mechanical design
- Integration prototype
- Liquid scintillator blending
- Simulations and offline code
- WLS fiber R&D, specification and procurement
- PVC extrusion R&D, engineering and procurement
- PVC resin R&D
- Mechanical engineering simulations

Summary

- NOνA provides an effective utilization of the investment in the NuMI beamline
- It is the right scale project for the present time. (More ambitious programs will have to wait for clarification of the ILC status.)
- It provides the information needed to plan the next step.
- It provides the greatest reach in $\sin^2(2\theta_{13})$.
- It provides the only information on the mass ordering.
- It provides a first look at CP violation in the lepton sector.
- Fermilab is playing a central role in NOνA.