Status of the NOνA Experiment

Sarah Budd
Argonne National Lab
On behalf of the NOνA Collaboration

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NOνA Collaboration

- Argonne National Laboratory
- University of Athens
- California Institute of Technology
- University of California, Los Angeles
- Fermi National Accelerator Laboratory
- Harvard University
- Indiana University
- Lebedev Physical Institute
- Michigan State University
- University of Minnesota, Duluth
- University of Minnesota, Minneapolis
- The Institute for Nuclear Research, Moscow
- Technische Universität München,Munich
- State University of NewYork, Stony Brook
- Northern Illinois University, DeKalb
- Northwestern University
- Pontifícia Universidade Católica do Rio de Janeiro
- University of South Carolina, Columbia
- Southern Methodist University
- Stanford University
- University of Tennessee, Knoxville
- Texas A&M University
- University of Texas, Austin
- University of Texas, Dallas
- Tufts University
- University of, Virginia, Charlottesville
- The College of William and Mary
- Wichita State University

Outline

- Overview of neutrino oscillations
- Introduction to the NOνA experiment
- Physics opportunities using NOνA
- Project timeline
- Status of prototype detector construction, near detector construction, far detector site preparation and preparations for far detector construction

Neutrino Oscillation

- Neutrino oscillations occur because the flavor eigenstates are not identical to the mass eigenstates
- Neutrinos are nearly always produced/detected in flavor eigenstates, but propagate in mass eigenstates
- Oscillations are described by the PNMS mixing matrix
  - Specified by three angles and phase
  - Generally parameterized as follows

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

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

Super-K , MINOS *MINOS, K2K, Chooz* *SNO, Kamland*

Neutrino Oscillation
Two neutrino model

When a 2 x 2 oscillation is sufficient (in vacuum)

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

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

Replace Θ, Δm with Θ_m, Δm_m

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

Full Oscillation Probability

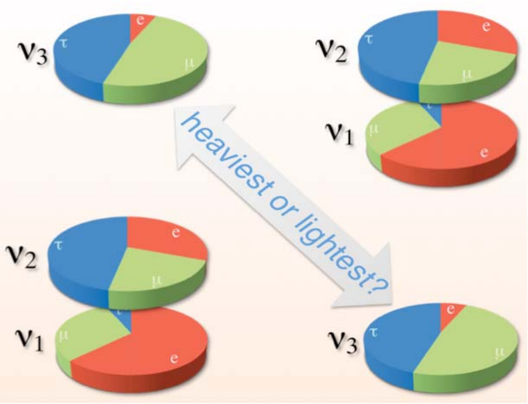
- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$

  $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$

  $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$

  $P_3 = J \sin(\delta) \sin(1.27\ \Delta m_{13}^2\ L/E)$

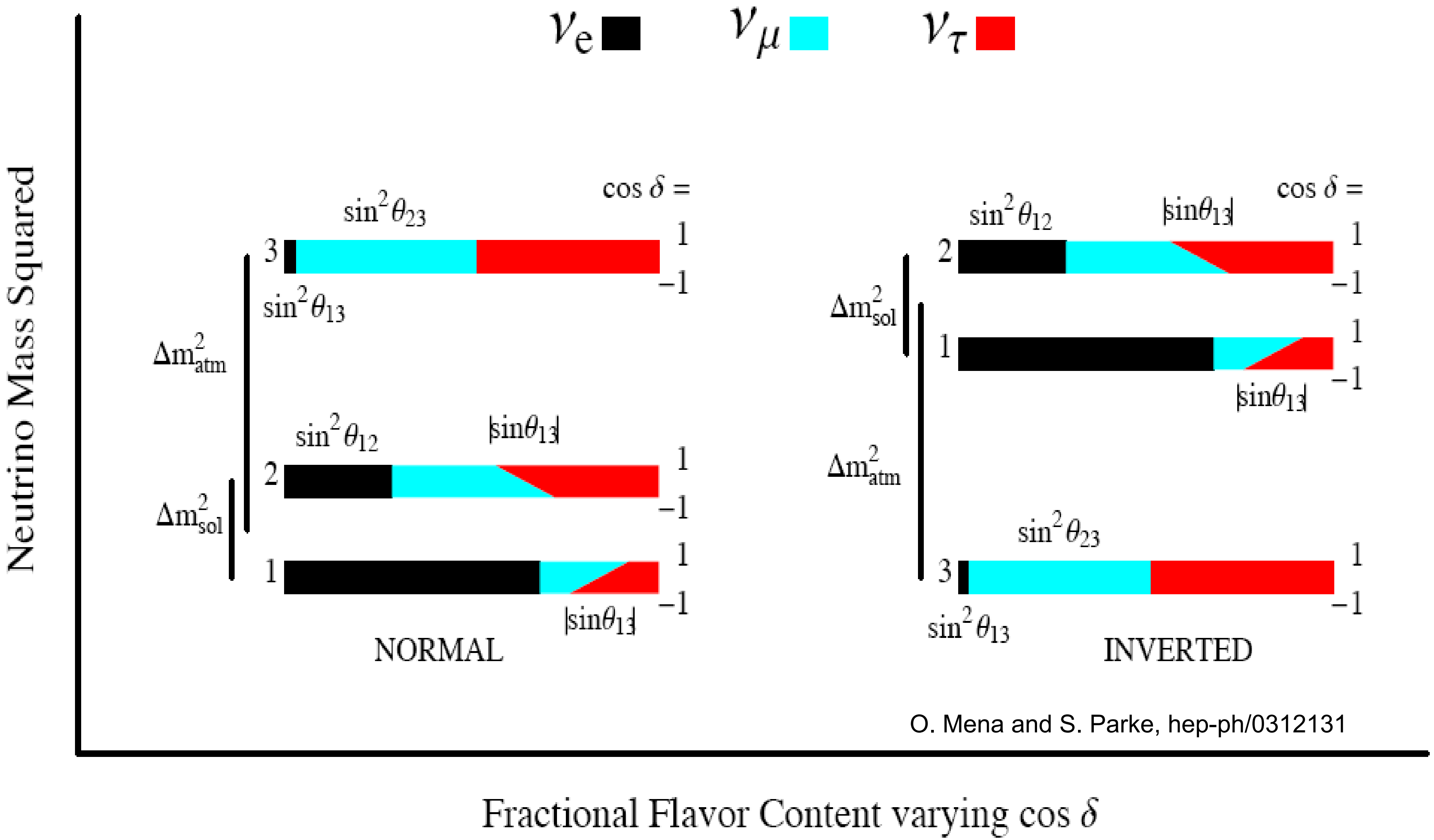
  $P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{13}^2\ L/E)$



$J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \times \sin(1.27\ \Delta m_{13}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$

- In matter at oscillation maximum, P_1 multiplied by $\sim(1 \pm 2E/E_R)$ and P_3 & P_4 will be multiplied by $\sim(1 \pm E/E_R)$
- top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy, bottom sign for antineutrinos with normal mass hierarchy, and neutrinos with inverted mass hierarchy
- $E_R = \Delta m^2_{13}/[2\sqrt{2}G_F\rho_E] \approx 11$ GeV for earth's crust
- ~±30% effect for NuMI (810 km baseline), ±11% effect for T2K (295 km baseline)

What do we know?

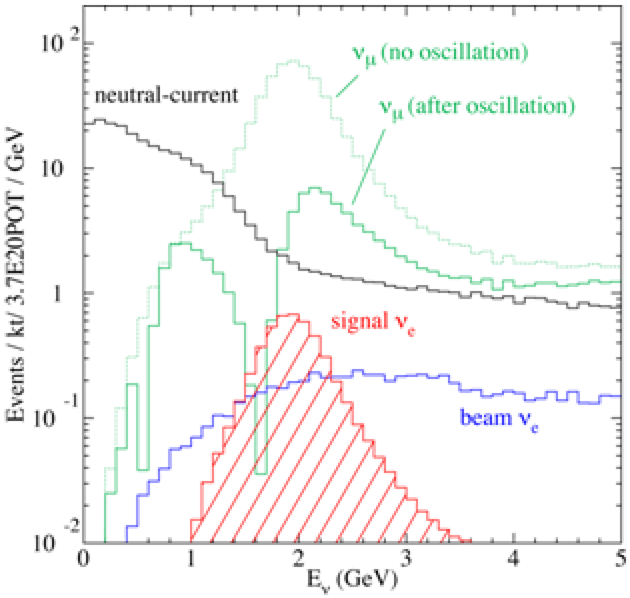


The NOνA Experiment

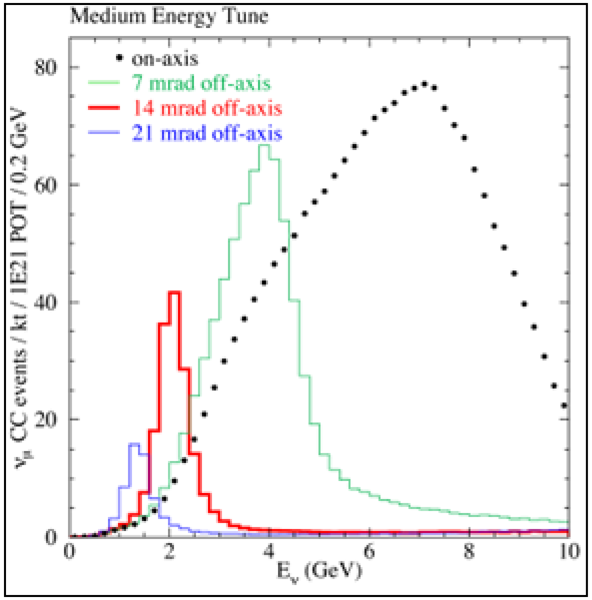
- NuMI Off-Axis ν_e Appearance Experiment
- 14kt Far Detector, 14mr off-axis, in Ash River MN
  - L=810 km E~=2GeV
- 220t Near Detector, at Fermilab
- Upgraded NuMI beamline for medium energy running
- Run for 6 years
  - 3 years each of neutrino and anti-neutrino dominated beam
- Goals
  - Measurement of θ_{13}
  - Determination of mass hierarchy via matter effects
  - Begin to localize δ_{CP}
  - Precise Measurement of $\sin^2(2\theta_{23})$

Why is NOνA off-axis?

- Off-axis yields a narrow band beam
- Better background rejection, higher signal/background
  - Backgrounds: ν_e's from *K* decay and higher-energy NC events



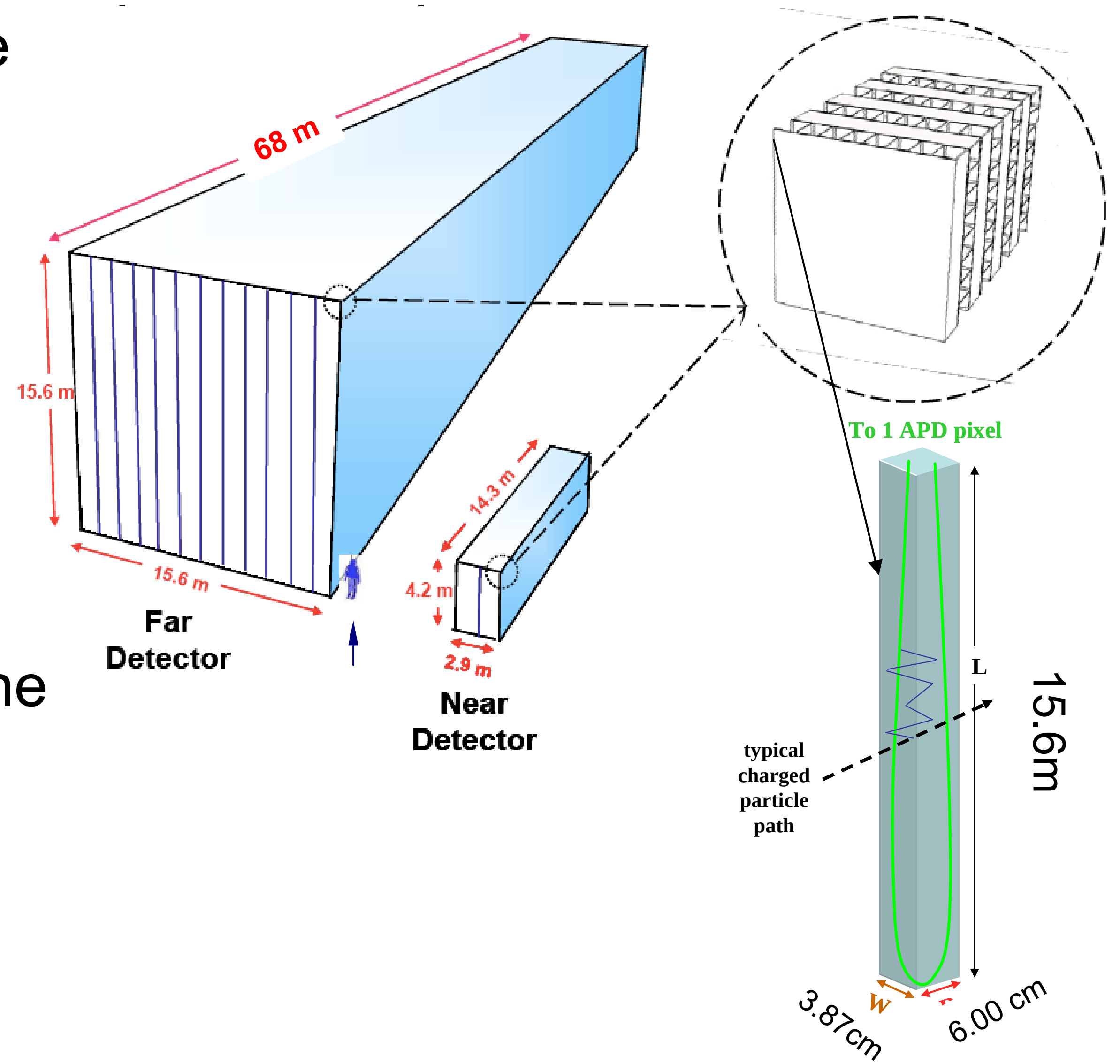
Raw signal and background rates for the NOνA FD site. The red bump is a signal at the CHOOZ limit. Energy resolution helps to reduce the beam nue backgrounds.



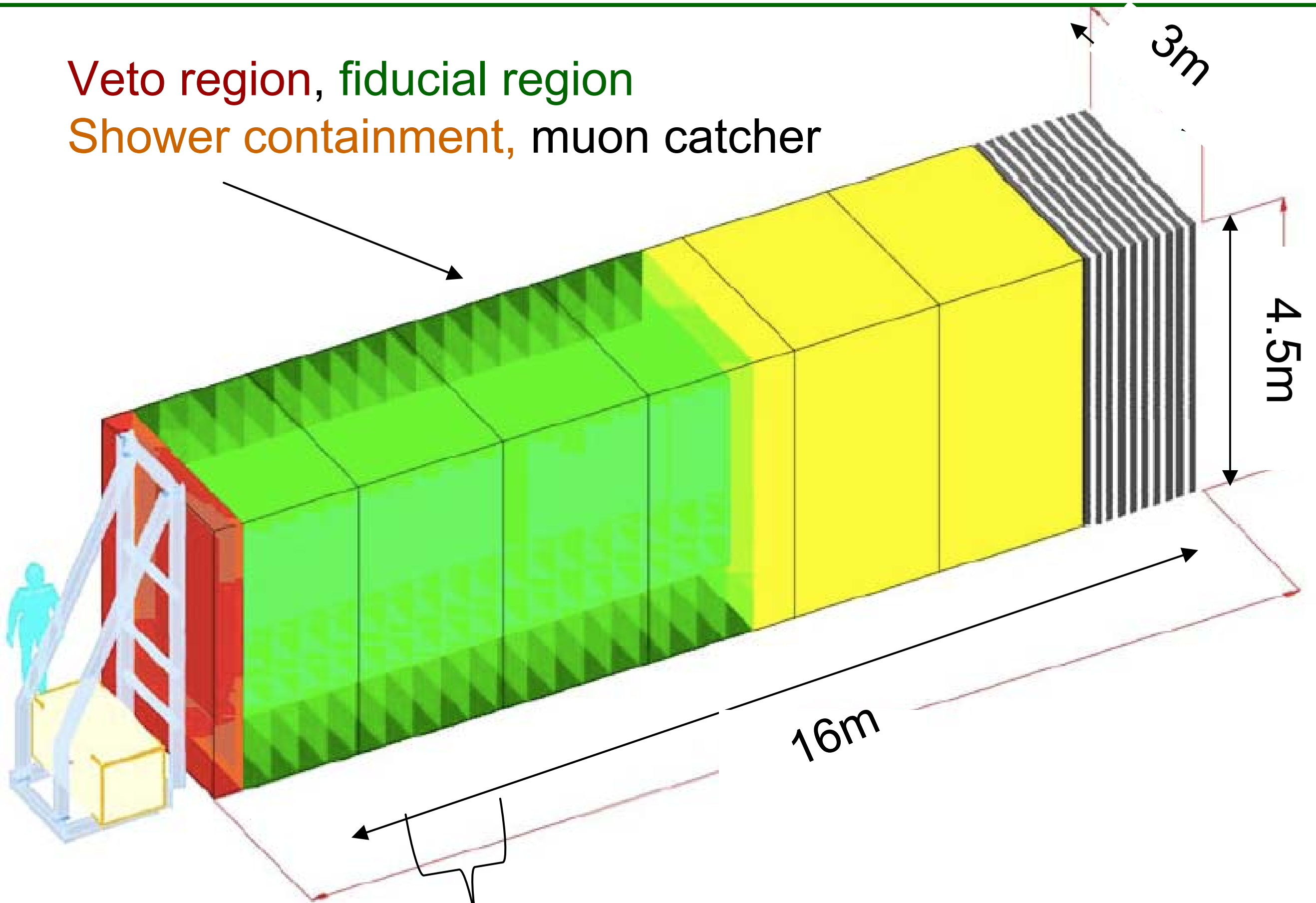
The neutrino spectra (flux times total cross-section) produced at the MINOS far detector site for the different NuMI tunes

The NOνA Far Detector

- FD: 14 kt, 73% Active Volume, 1003 planes
- PVC cell for primary containment
- Filled with liquid scintillator
- Each cell contains a wavelength shifting fiber
- Read out by avalanche Photodiode
- Planes Alternate vertical & horizontal orientation



The Near Detector



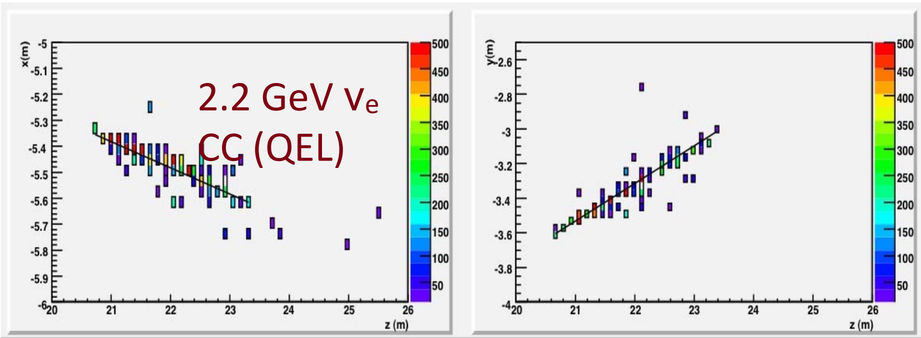
- 6 blocks of 31 planes plus a muon catcher.
- All parts are fully active liquid scintillator cells identical to the far detector.
- Downstream of the active region is a 1.7 meter long muon catcher region of steel interspersed with 10 active planes of liquid scintillator
- First located on the surface, than moved to final underground location

Near Detector on the Surface

- The Near Detector on the Surface (NDOS) is the full near detector, located off axis near the MINOS surface building
- Used to investigate
  - Construction methods for the far detector
  - Study off-axis beam, tune simulation
  - Characterize surface backgrounds
  - Develop event selection algorithms
  - Demonstrate electron neutrino identification

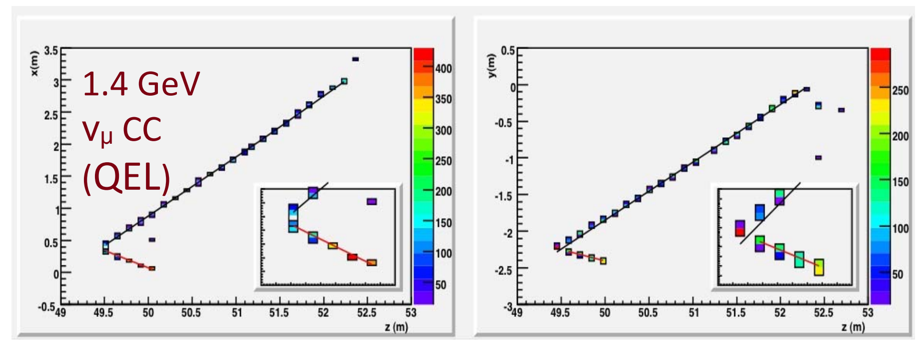
NOνA Detector Simulated Performance

ν_e CC event



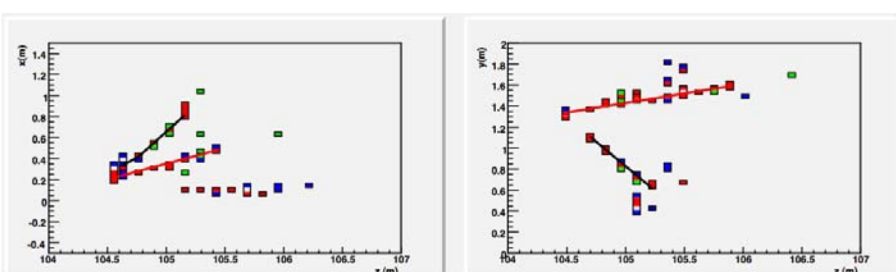
20 26 20 26

ν_μ CC event



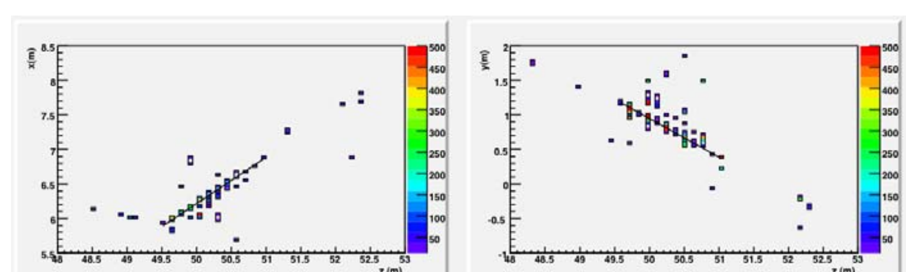
49 53 49 53

Neutral Current
Easy to identify by gap between vertex and showers



104 107 104 107

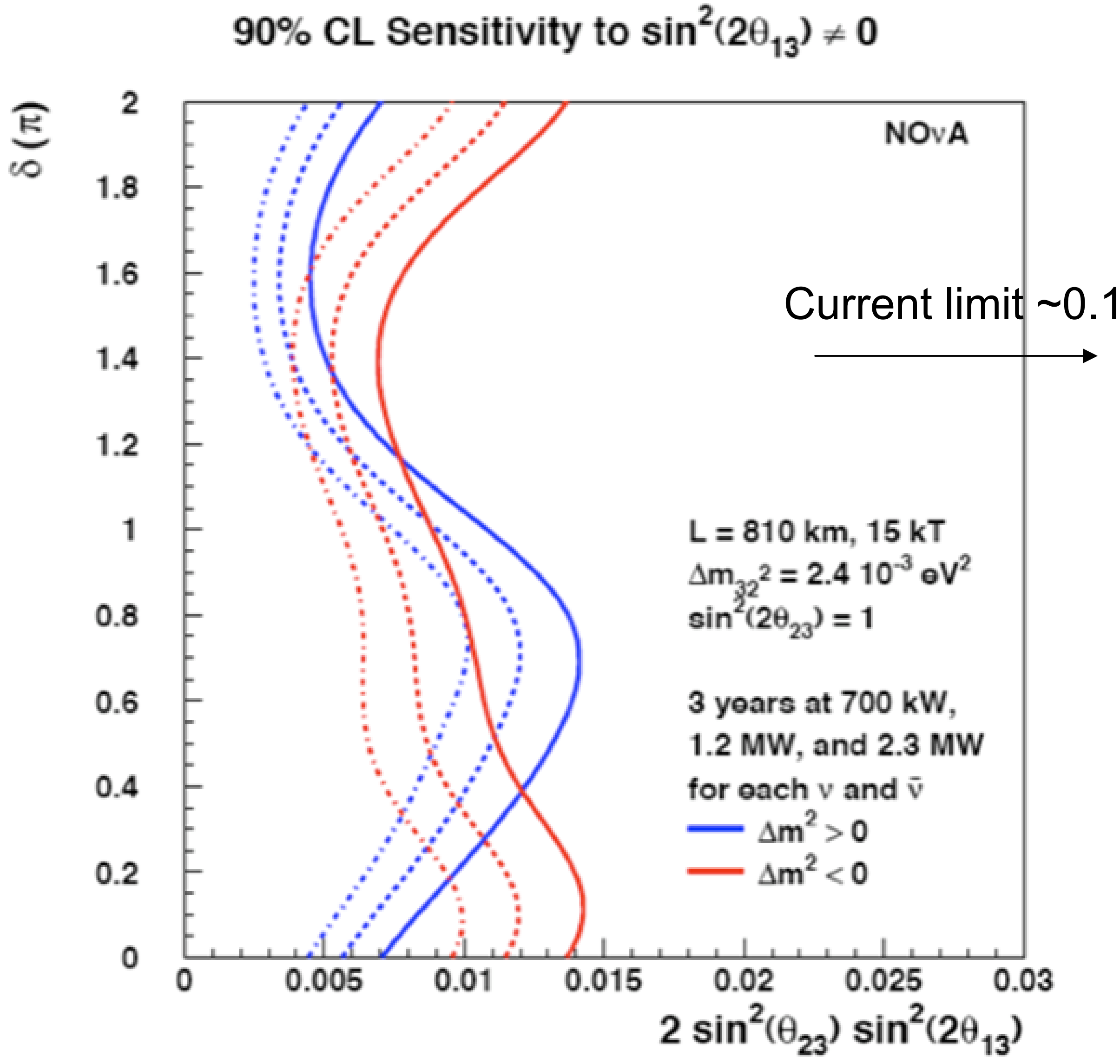
Neutral Current
Highly electromagnetic final state.
Develop ANN to try to reject



48 53 48 53

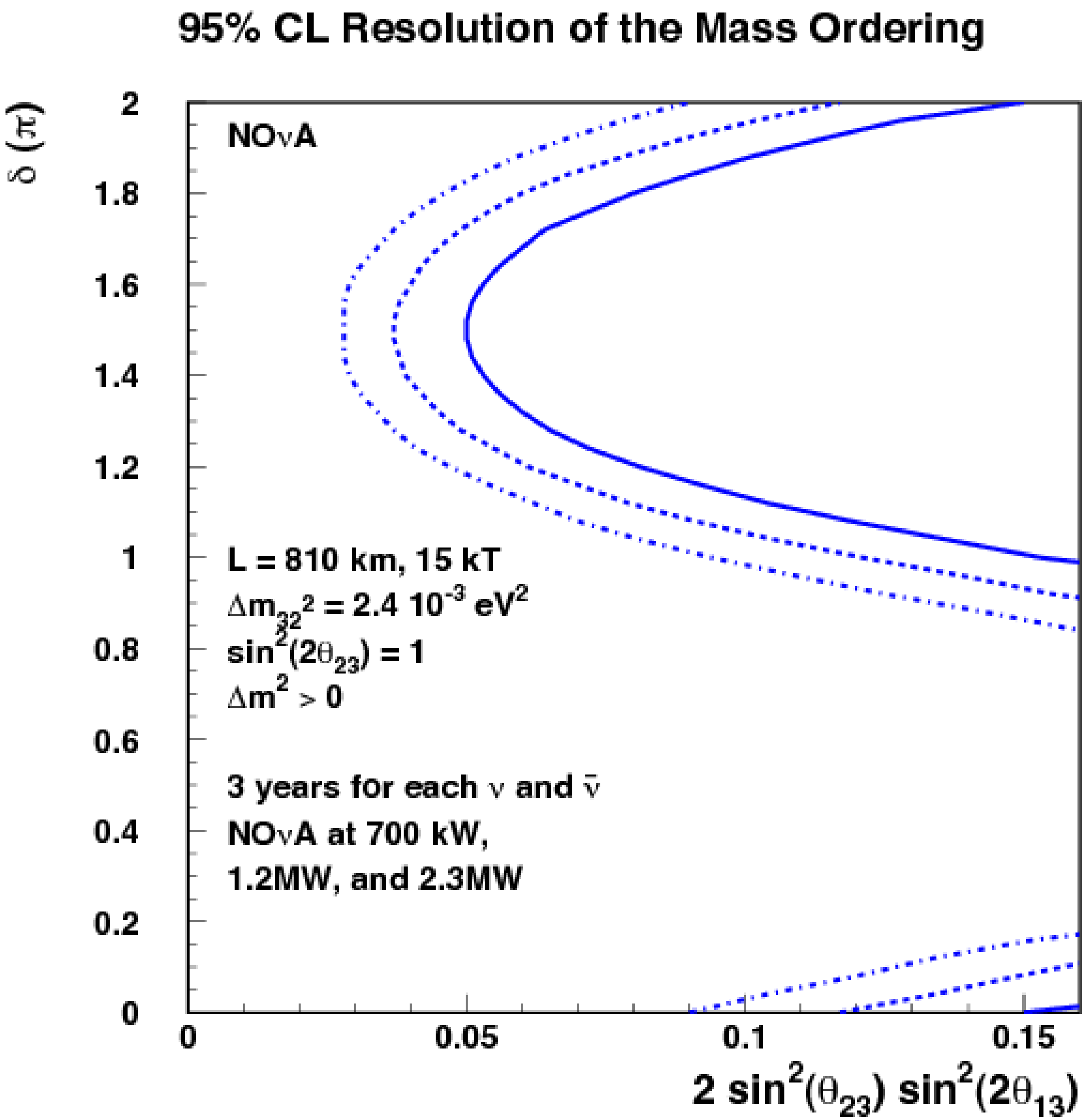
Sensitivity to Θ_{13}

- The blue curves assume normal mass hierarchy while the red curves show the inverted hierarchy case.
- Sensitivity depends on mass hierarchy and δ
- Solid line is planned beam energy (700kW), dashed curves represent beam upgrades



What are the relative masses of neutrinos?

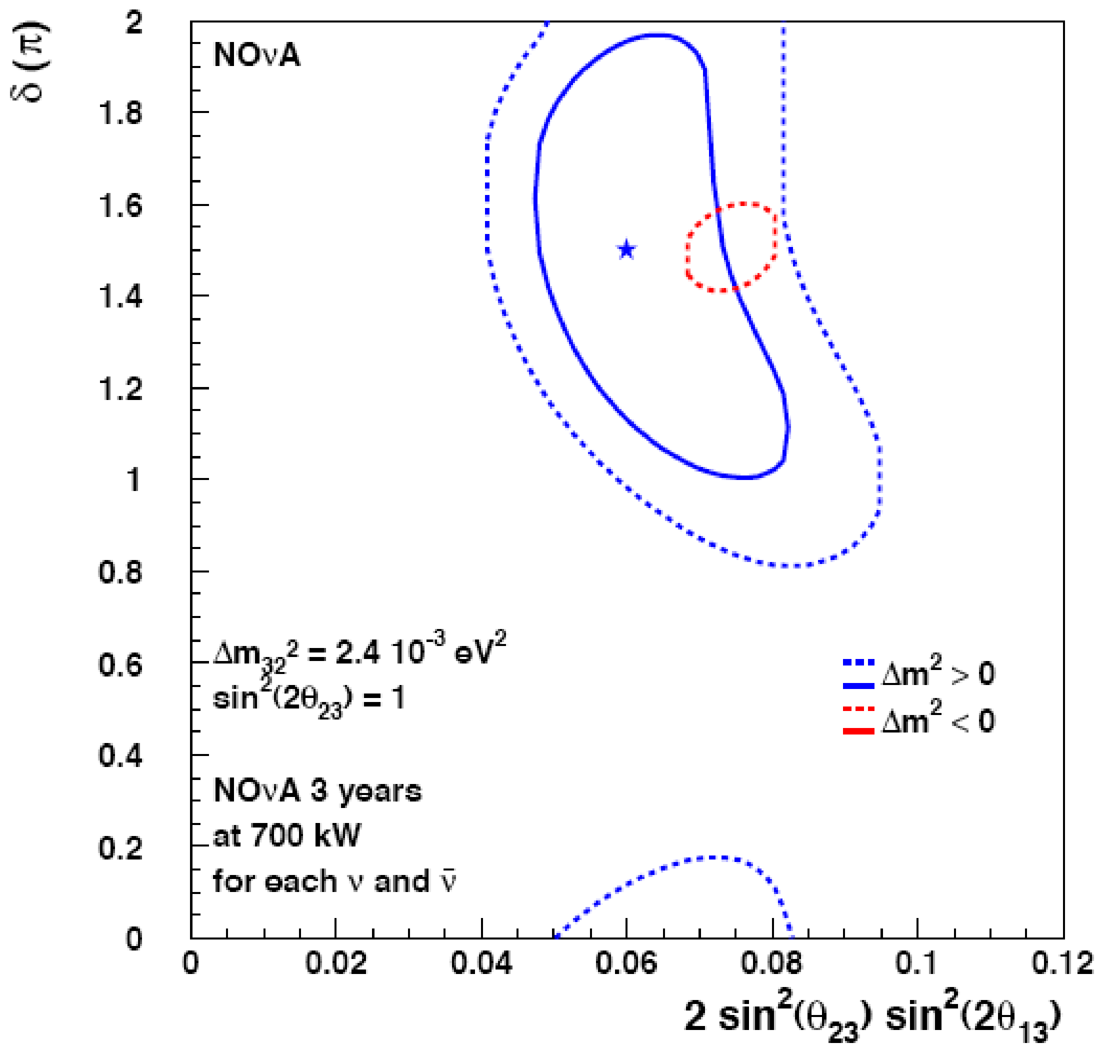
- For oscillation parameters to right of these curves, NOνA resolves the neutrino mass hierarch at 95% C.L.
- The curves are calculated for a 15 kt detector, 6 years of running split evenly between neutrino and anti-neutrino running
- Intensities at the baseline 700 kW as well as upgrades of 1.2 MW and 2.3 MW



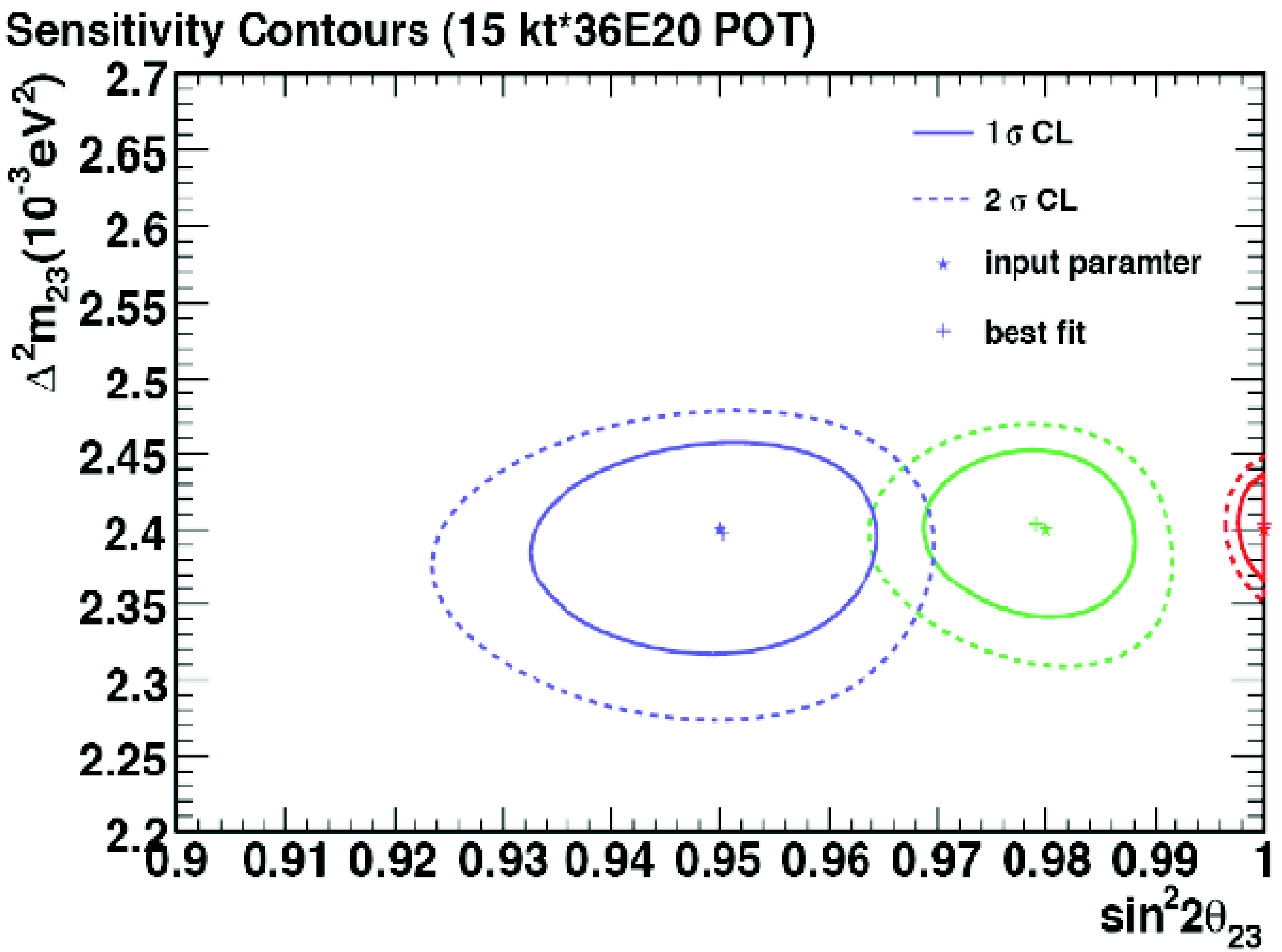
Do Neutrino Oscillations violate CP?

- NOνA provides the first look into the CP violating parameter space
- 1- and 2-σ measurement contours for NoνA Oscillations with parameters chosen at the starred point.
- Sensitivity requires 3 years each of neutrino and anti-neutrino running

1 and 2 σ Contours for Starred Point for NOvA

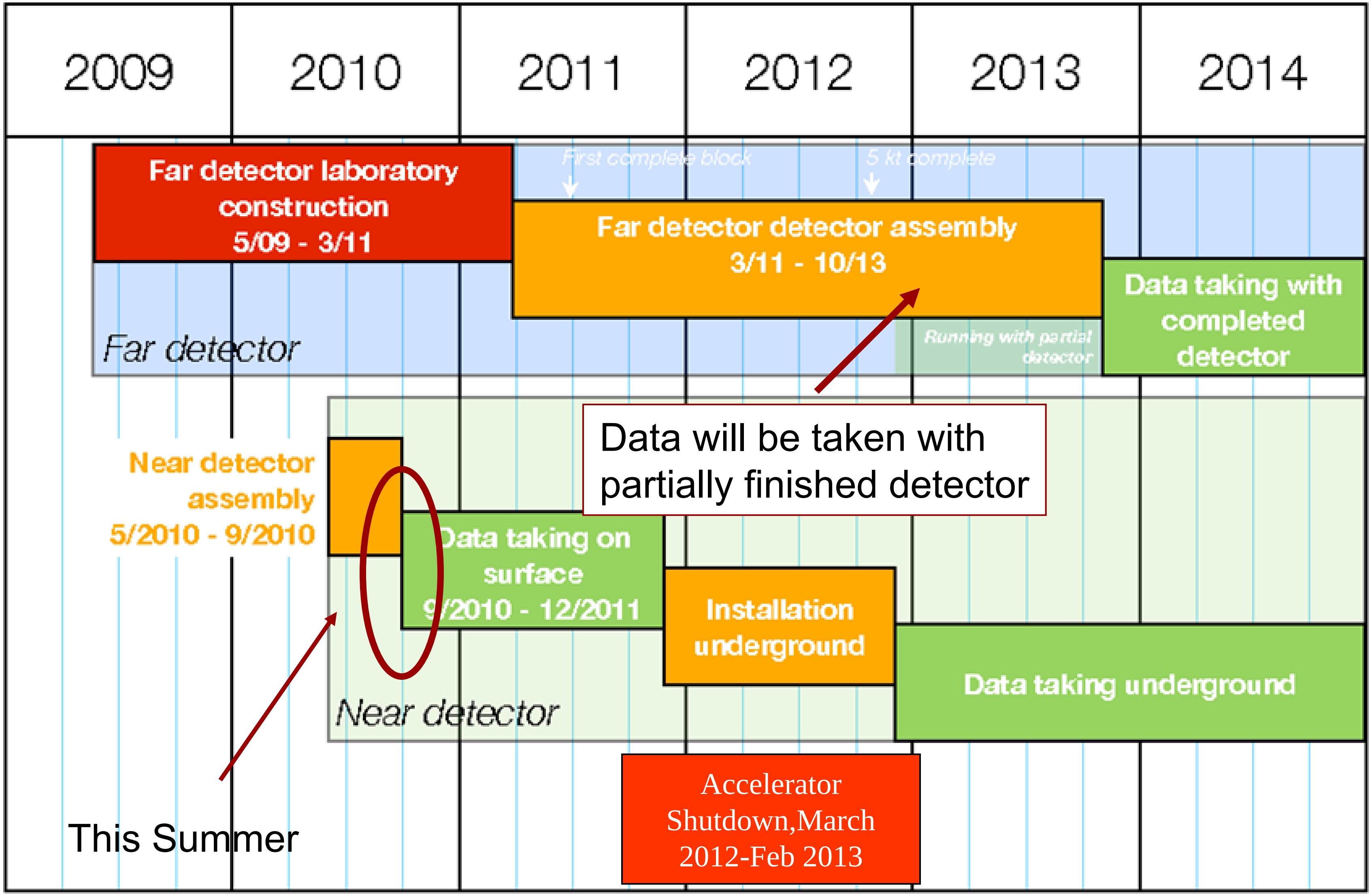


Is Θ_{23} maximal?



- NOνA can improve the sensitivity Of the Θ_{23} mixing angle by over an order-of-magnitude over MINOS.
- Red, green and blue are different input parameters

NOvA Schedule

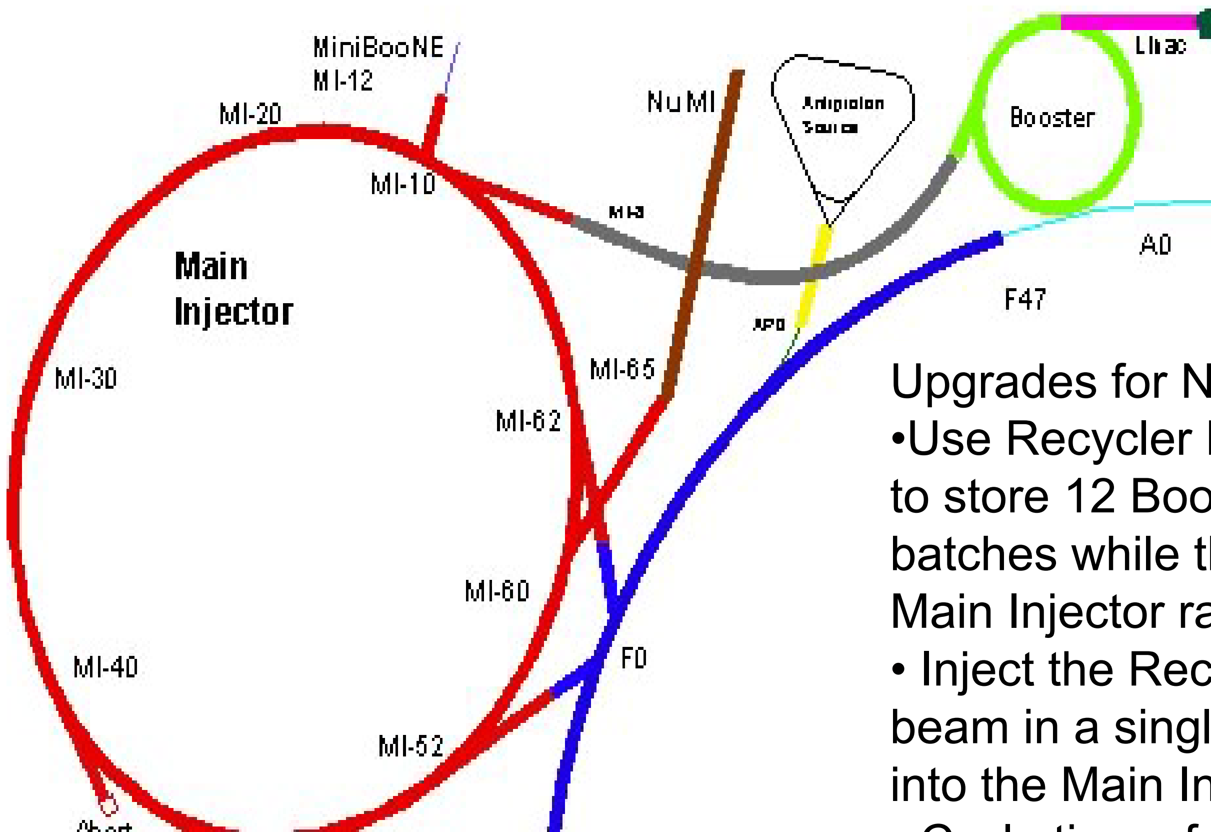


NuMI Operation

Current Situation

The Booster injects 11 batches (9 for NuMI and 2 for antiproton production) into the Main Injector at 15 Hz

The Main Injector then ramps up, extracts the beam and ramps down in a 2.2s cycle time



Upgrades for NOνA:

- Use Recycler Ring to store 12 Booster batches while the Main Injector ramps
- Inject the Recycler beam in a single turn into the Main Injector
- Cycle time of 1.33 s
- New target design for medium intensity running

Proton Plans

	Present Operating Conditions	Noνa Multi-batch Slip-stacking in Recycler	
Number of 8 GeV Batches to NuMI	9	12	
MI Cycle Time (sec)	2.2	1.3	
MI Intensity (protons per pulse or ppp)	3.5×10^{13}	4.9×10^{13}	
NuMI Beam Power (kW)	310 kW	700 kW	

Accelerator Upgrades Are on schedule

Infrastructure

- Near Detector will be first located in a newly constructed building near the MINOS service building
  - Near Detector service building is nearly finished and outfitted
  - Near Detector will be moved to final location, off-axis in an underground cavern near the minos detector, in ~1.5yrs
- Meanwhile, the far-detector infrastructure is also being constructed
  - Groundbreaking was May 1, 2009
  - Expect beneficial occupancy sometime at the end of this year

Far/Near Site Construction

Near detector building is ready

Far Detector Site is under construction
Above: 60 ft deep excavation with concrete floor
Right: Looking up towards receiving dock and gluing area

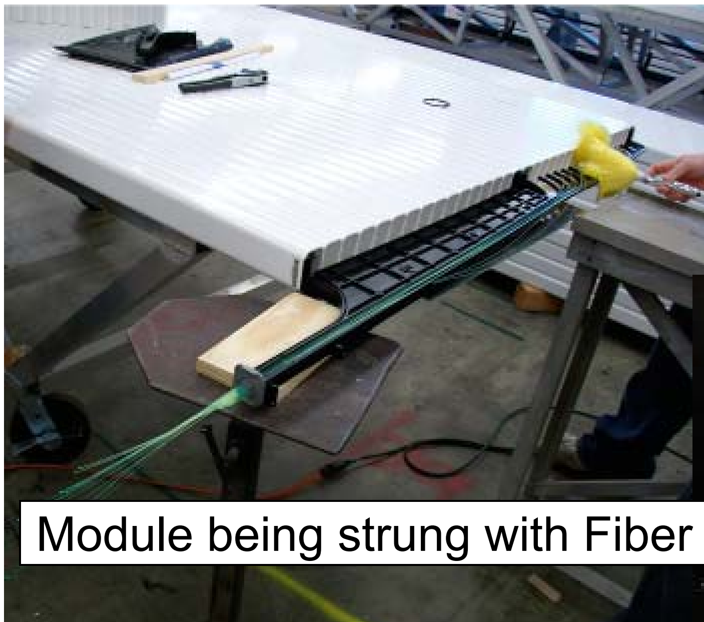
PVC Extrusion

PVC extrusion coming off assembly line

New far detector extrusion dies

- PVC resin vendor and extruder has been selected
- PVC extrusions are made for Near Detector, extrusion factory is gearing up for Far Detector production

Module Factory



The Module factory at University of Minnesota is producing near detector modules and gearing up for the production of far detector modules

Recently took occupancy of a new factory space big enough for construction of for far detector modules

Block Construction at Argonne

Near Detector lifting fixture

Glue machine

Compression fixture

First Far Detector Prototype

- The FSAP (Full Size Assembly prototype) was the first far detector prototype.
- Several full size FD planes
- First test of assembly methods
- Finished Summer '09

Completed NDOS Prototype Block

The first mechanical prototype block (protoblock)

- Constructed at Argonne
- Raised in the MINOS service building

Block Handling

Raising the Problock at Argonne using a large crane

Test lowering the protoblock 300ft down into the MINOS shaft at Fermilab

First Near Detector Block

First block being shipped to Fermilab

- First block, finished in April, second block finished last week
- Block Construction is ongoing at Argonne
- Plan to be finished by mid-summer
- Instrumentation begins in June

First block at Fermilab

Final Far Detector Prototype

Far Detector table and bookend at Fermilab

The FHEP (Full Height Engineering Prototype) Far Detector Prototype will be constructed at Argonne in September-November

Far detector lifting beam in action

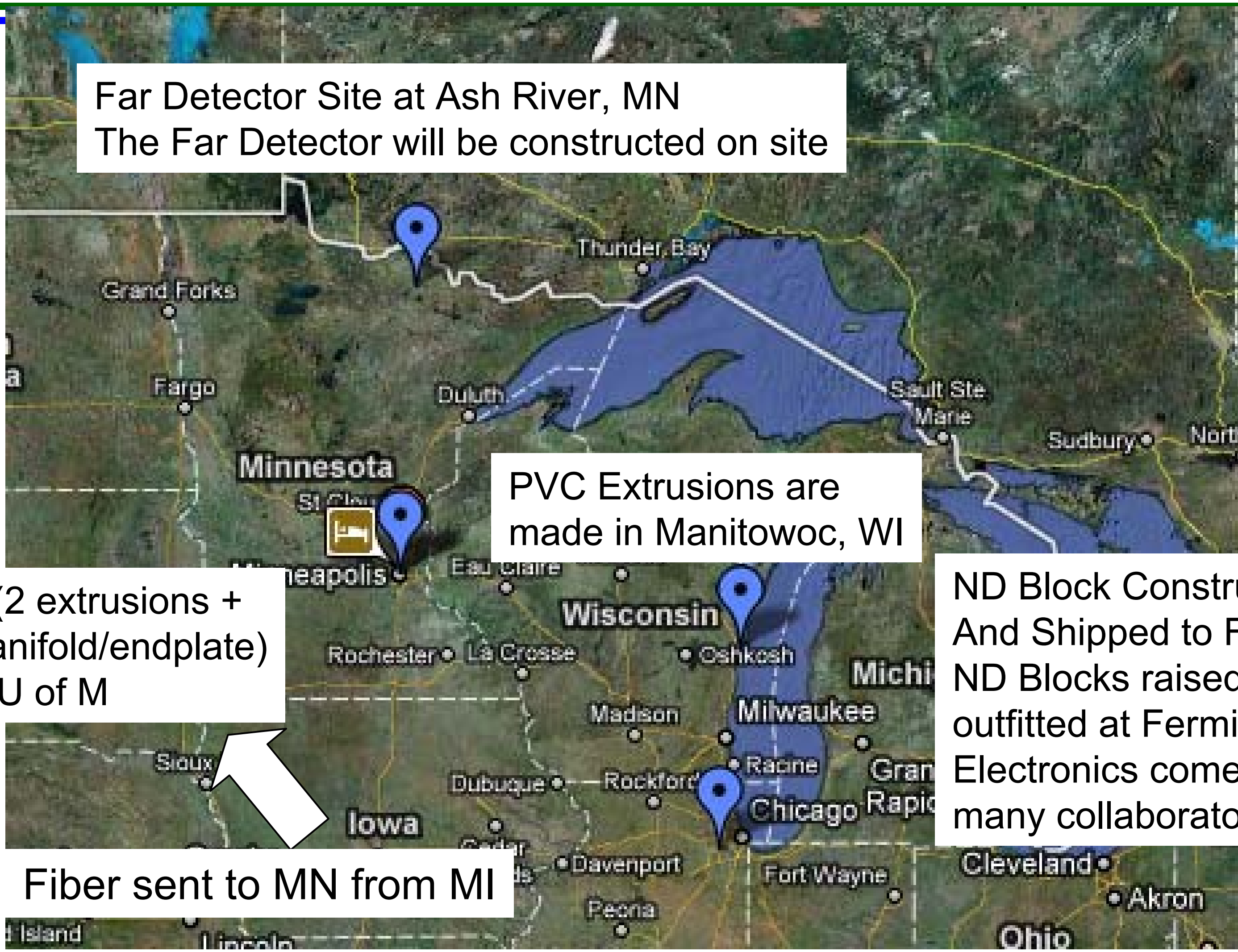
- Will be taken to Fermilab to be filled and stood up
- Used to study filling, construction, long term PVC behavior

Conclusions

- The NOνA Experiment consists of two new detectors in an upgraded the NuMI Beamline
  - Off-axis FD is located at Ash River, MN
  - Near Detector located off-axis near MINOS cavern
- Sensitive to many neutrino mixing parameters
  - Measurement of θ_{13}
  - Determination of mass hierarchy
  - Measure δ_{CP}
  - Precise Measurement of $\sin^2(2\theta_{23})$
- Near Detector Assembly is underway
  - Should be taking data with the Near-Detector on the surface by this fall!
  - Expect to collect data on the surface for about a year
- Far Detector Assembly is also gearing up
  - Complete 2013, useful data before
- Accelerator upgrades are on track

BACKUP

Block Construction is a Group Effort



Far Detector Site at Ash River, MN
The Far Detector will be constructed on site

PVC Extrusions are made in Manitowoc, WI

Modules (2 extrusions + fiber + manifold/endplate) made at U of M

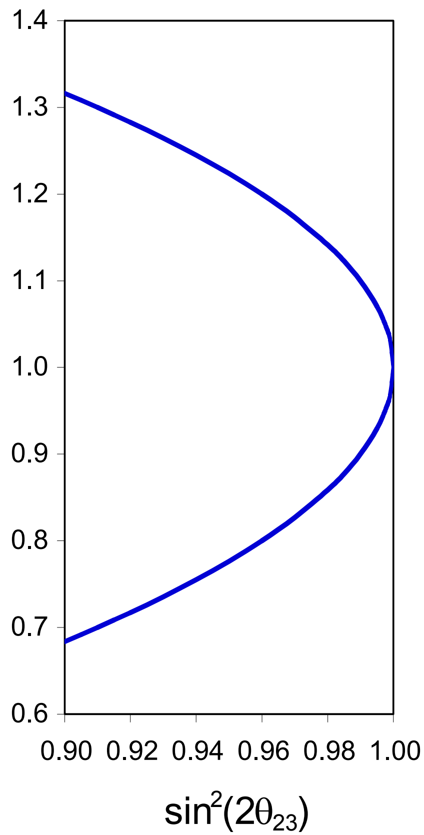
ND Block Constructed at Argonne
And Shipped to Fermilab
ND Blocks raised, filled and outfitted at Fermilab
Electronics come from many collaborators

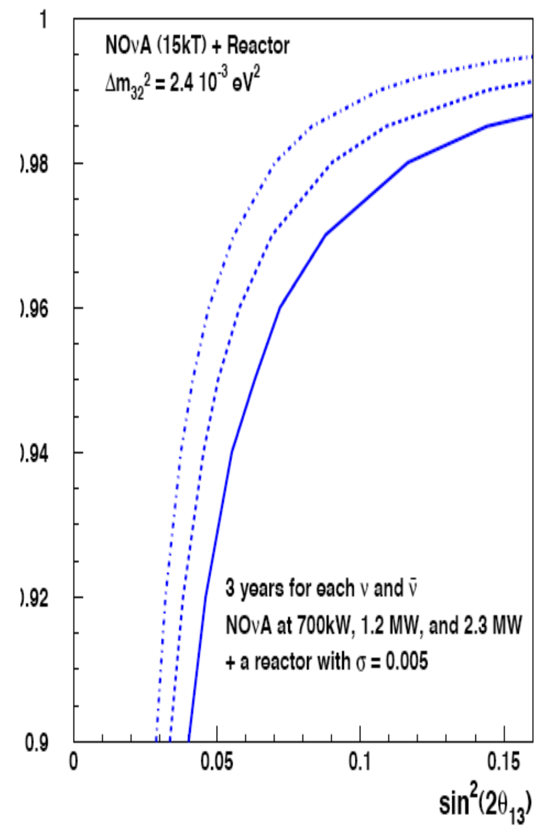
Fiber sent to MN from MI

Reactor and Accelerator Experiments?

- Reactors sensitive to: sin2(2q13)
- Accelerators sensitive to: $2 \sin^2(\Theta_{23}) \sin^2(2 \Theta_{13})$
- Can be very different away from $\Theta_{23} = \pi/4$! →
- Comparison of NOnA and
- Double Chooz/Daya Bay can break the
- ambiguity to determine whether n3 couples
- more to nm or nt
- 95% CL Resolution of the Θ_{23} ambiguity

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





Why Study Neutrinos?

Masses are anomalously low

- Mass hierarchy is unknown:

  Normal ($m_3 > m_1, m_2$) or

  Inverted ($m_3 < m_1, m_2$)

Only fundamental fermion which can be its own antiparticle

- Majorana particle or Dirac particle?

Could be responsible for the matter/antimatter asymmetry of the universe (leptogenesis)

- Seesaw mechanism for right-handed neutrinos
- Size of possible CP-violation in neutrinos?

What Do We Know So Far?

ν_e from the sun:

- $\nu_e \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_\tau$ with $L/E \approx 15{,}000$ km/GeV
- Mixing angle (θ_{12}) is large but not maximal

ν_μ produced in the atmosphere by cosmic rays & 1st generation accelerator experiments (K2K and MINOS):

- $\nu_\mu \rightarrow \nu_\tau$ with $L/E \approx 500$ km/GeV
- Mixing angle (θ_{23}) consistent with being maximal

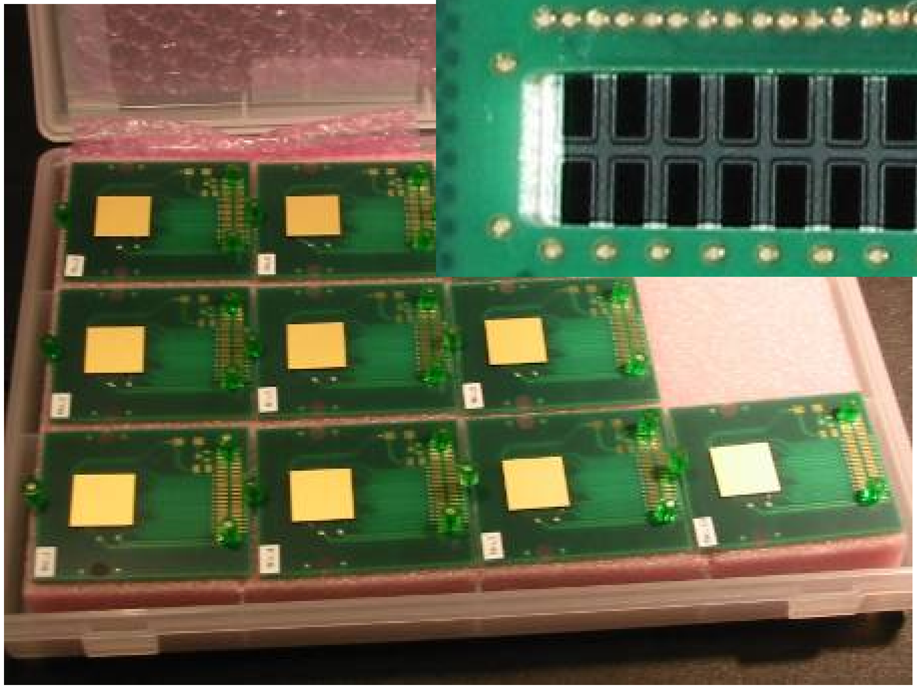
Mixing Matrix

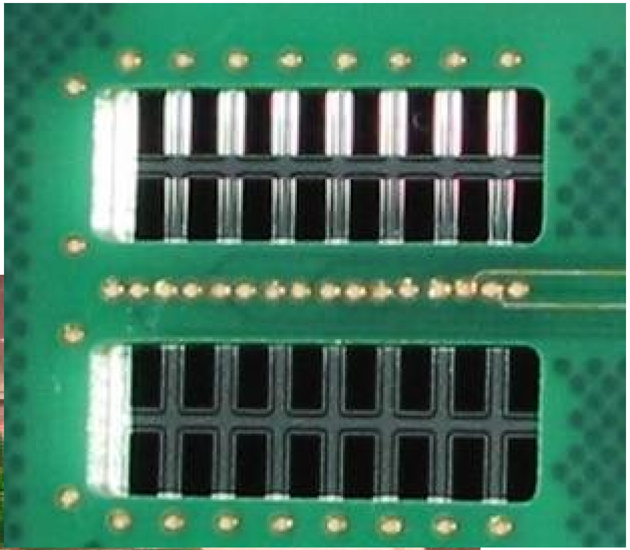
Relationship between weak eigenstates and mass eigenstates is given by a unitary rotation matrix:

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

APD Photodetector

- Hamamatsu Si Avalanche Photodiode (APD)
  - Custom design to match to fiber aspect ratio
  - APD's are being ordered for the near detector





APD Advantage

APD has the best photodetection efficiency matched to our WLS fiber spectrum

APD operation more stable than PMT