The NOvA Experiment

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NOvA Collaboration

ANL / Athens / Banaras Hindu University/ Caltech / Institute of Physics ASCR / Charles University / Cochin University / University of Delhi / FNAL / IIT Guwahati/ Harvard / University of Hyderabad/ IIT Hyderabad / Indiana / Iowa State / University of Jammu/ Lebedev / Michigan State/ Minnesota, Crookston / Minnesota, Duluth / Minnesota, Twin Cities / INR Moscow / Panjab University/ South Carolina SMU / Stanford / Tennessee / Texas, Austin / Tufts / Virginia / WSU / William & Mary

NOvA Experiment

- Use the upgraded NuMI beam at Fermilab.
- Construct a totally active liquid scintillator detector off the main axis of the beam.
  - Far detector is 14 mrad off- axis and on the surface.
  - Near detector is also 14 mrad off-axis but underground.
  - Location reduces background.

2nd generation
Long baseline

- If neutrinos oscillate, electron neutrinos are observed at the Far Detector in Ash River, 810 km away.

Neutrino oscillations basics

- The flavor eigenstates are linear combinations of the mass eigenstates.

$$|\nu_\alpha\rangle = \sum_{k=1}^{n} U_{\alpha k} |\nu_k\rangle \quad (\alpha = e, \mu, \tau)$$

- There is a non-zero probability of detecting a different neutrino flavor than that produced at the source.

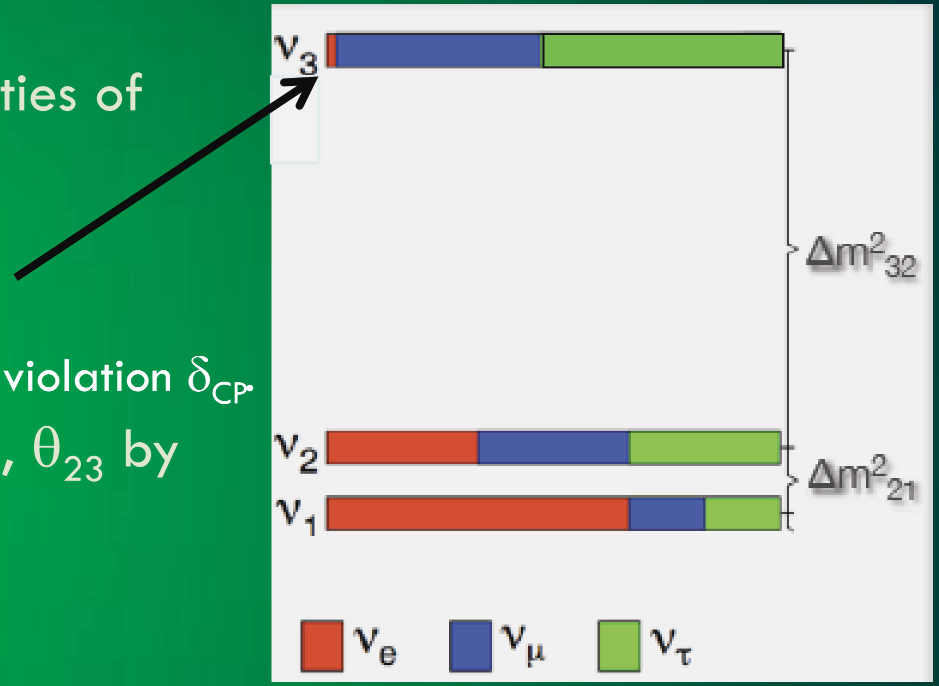
$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta) \sin^2\left(\frac{1.27 \Delta m_{23}{}^2 L}{E_\nu}\right)$$

- For the three flavor case we can write a PMNS mixing matrix:

$$\mathbf{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

NOvA physics goals

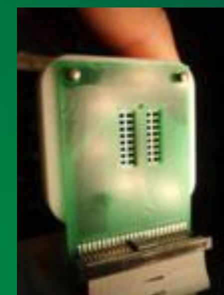
- Measure the oscillation probabilities of $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$.
  - Measure the mixing angle θ_{13}.
  - Determine neutrino mass hierarchy.
  - Study the phase parameter for CP violation δ_{CP}.
- Precision measurements of Δm^2_{32}, θ_{23} by measuring $\nu_\mu \rightarrow \nu_\mu$
- As well as:
  - ν cross sections.
  - Sterile neutrinos.
  - Supernova signals.
  - Non-oscillation measurements(e.g. Magnetic Monopoles, neutrino magnetic moment).



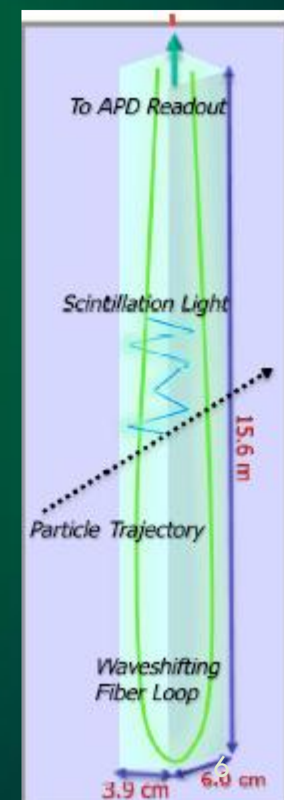
The NOvA detectors

- 14 kton Far Detector
  - >70% active detector.
  - 360,000 detector cells read by APDs.
- 0.3 kton Near Detector
  - 18,000 cells (channels).
- Each plane just 0.15 X_0. Great for e^- vs π^0 .

32-pixel APD



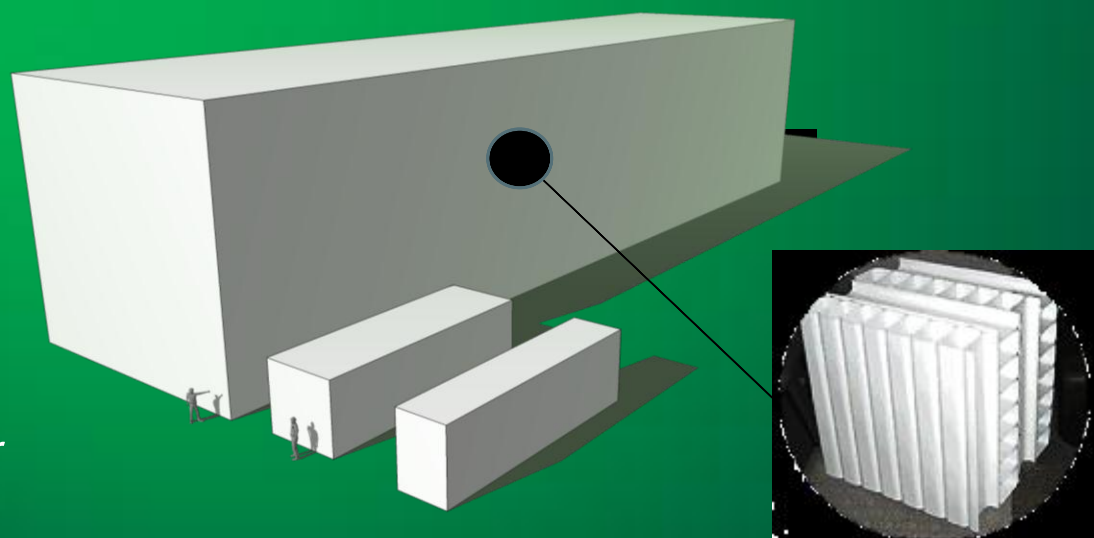
Both ends of a fiber to one pixel



Far detector
14 kton
928 planes

Near detector
0.3 kton

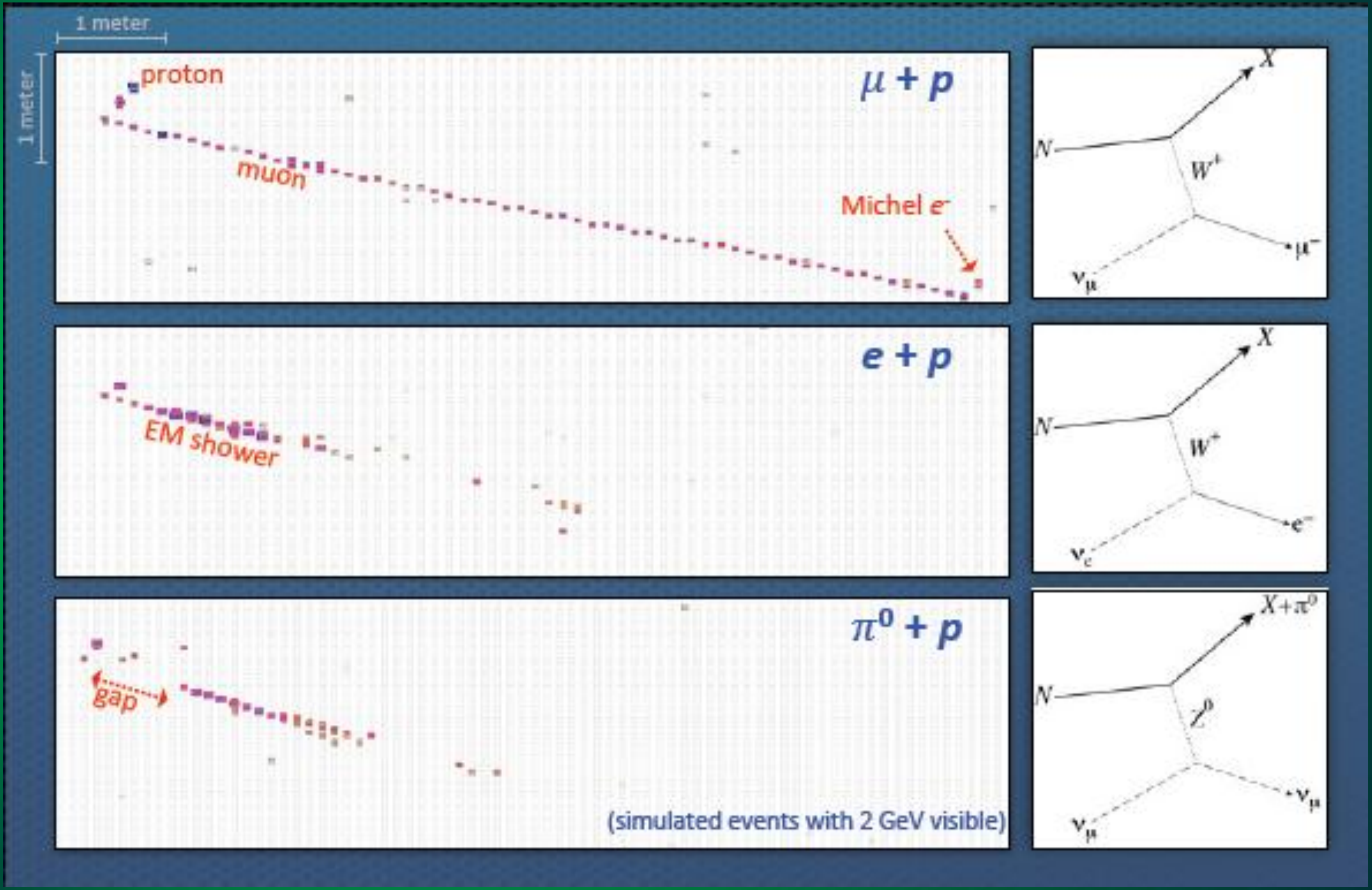
Prototype detecor
0.2 kton



MC Events in NOvA

Excellent granularity for a detector of this scale

X_0 = 38 cm (6 cell depths, 10 cell widths)



Far detector laboratory complete

Beneficial occupancy of Ash River laboratory on April 13, 2011

NOvA construction status

- Far Detector site construction is now complete.
  - The block pivoter is installed at the site.
  - Far Detector first block installation begins this month!
- Upgrade NuMI beam from
  - 350 kW to 700kW initiated May 1, 2012.
- Near Detector cavern excavation and assembly during shutdown.
  - Changed to 96 x 96 cell design to improve event containment.

NOvA construction status

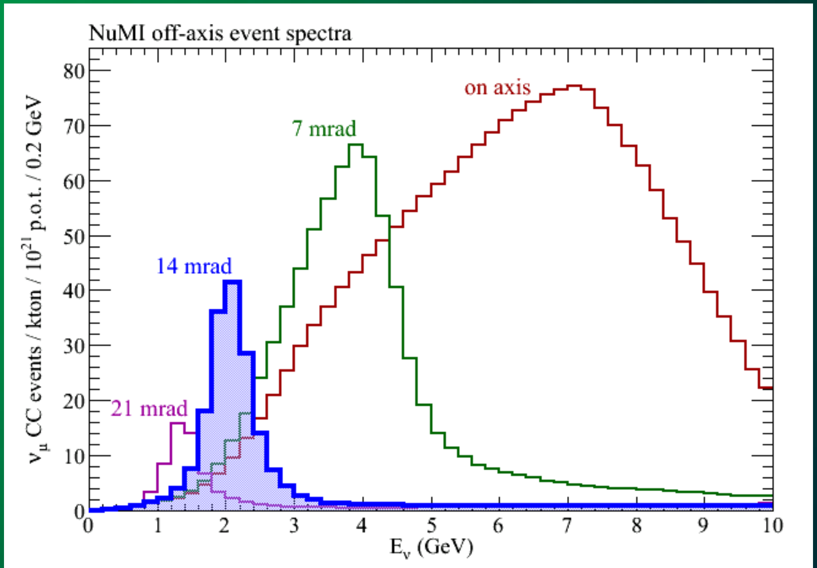
- First layer of modules is permanently placed on the pivoter table at Ash River, MN - July 26, 2012

Accelerator and NuMI Upgrades

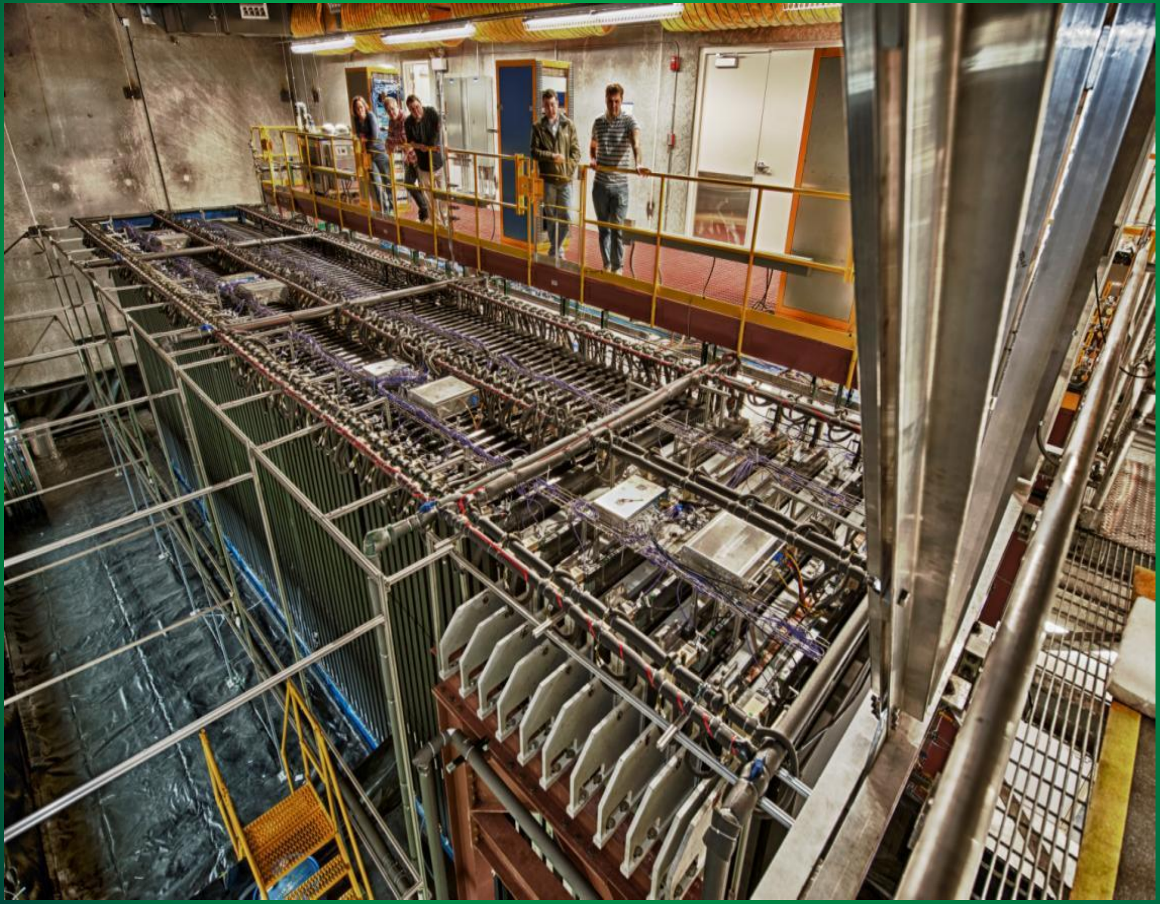
- **Taking the NuMI source from ~350 kW to 700 kW**
  - **Year-long accelerator shutdown underway (since May 1)**
  - **Turn Recycler from antiproton to proton ring** *injection & extraction lines, associated kickers & instrumentation, 53 MHz RF*
  - **Shorten Main Injector cycle from 2.2 seconds to 1.33 seconds** *RF upgrades, power supply upgrades*
  - **Overhaul of NuMI target station for 700 kW running**

- **Beam to return May 2013.**
  - **Six month ramp-up to 700 kW.**

Event rate vs. E_ν at various angles relative to the NuMI beam axis **NOνA :**
14 mrad → *spectrum peaks sharply at 2 GeV*



Prototype Near Detector

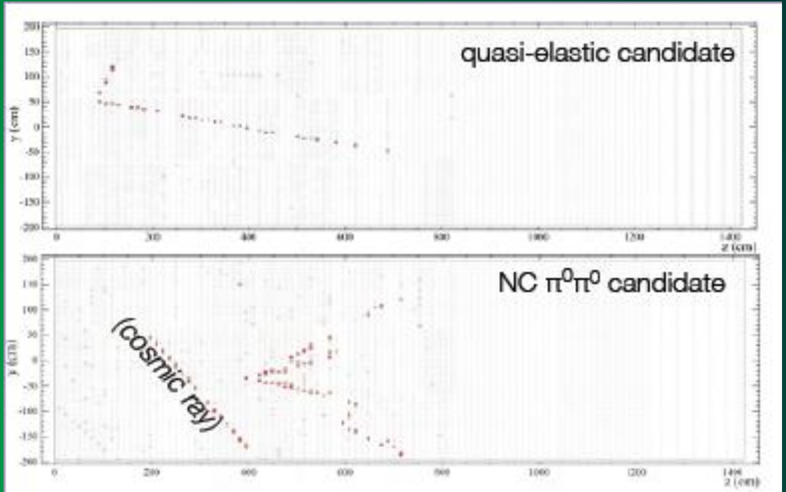


"NDOS" (Near Detector on Surface)

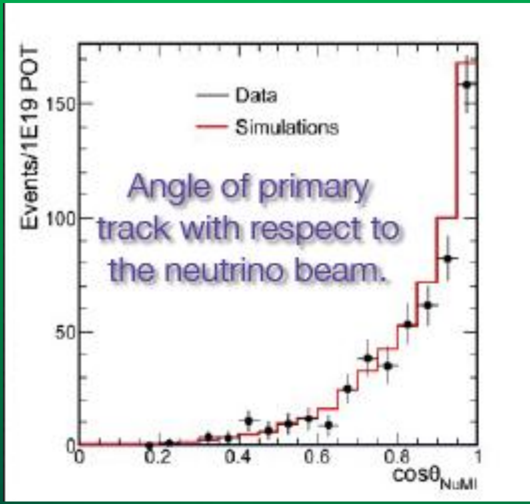
- Component production, installation, and integration tests and adjustments
  - DAQ development
  - Calibration, simulation, reconstruction development using real data
  - Flux and cross sections

NOvA Near Detector Prototype

- Near Detector Prototype installed on surface at Fermilab.
- 5000 neutrino events from the NuMI beam observed.
- Neutrino candidate data matches well to Monte Carlo.



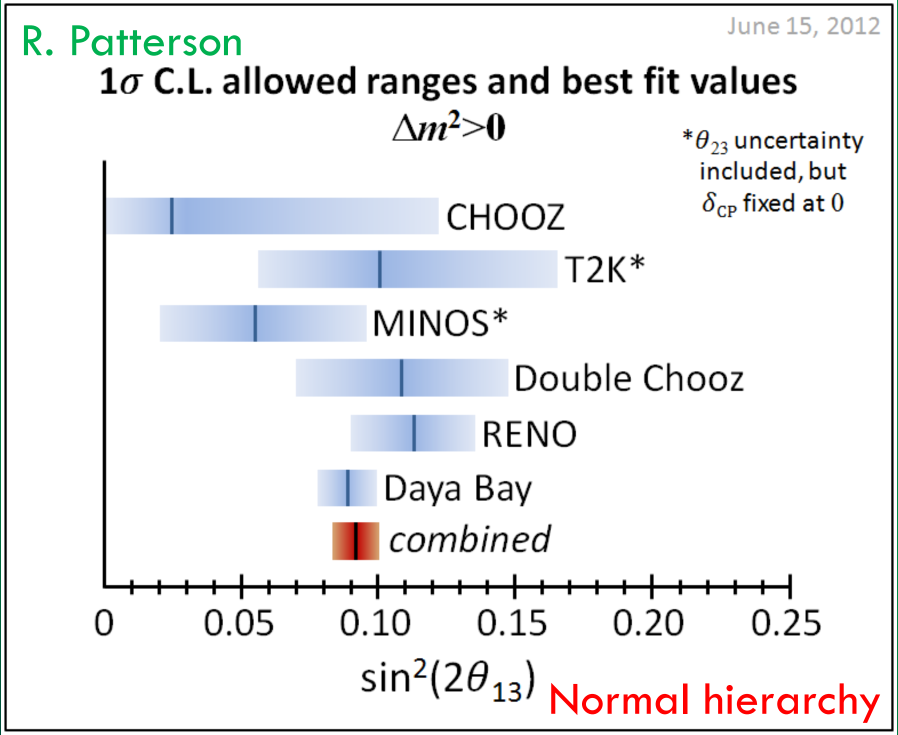
Events from the NuMI beam seen at 110 mrad

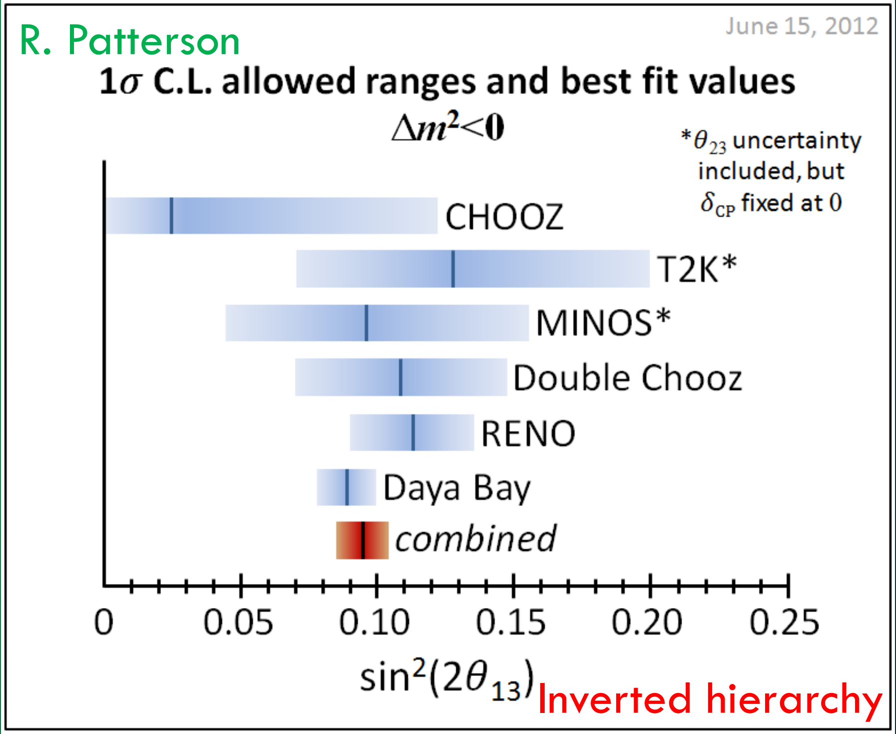


- Data is useful for detector operations.
- Benchmarking calibration, reconstruction and simulations.

The status of θ_{13}

- This year we will go from not knowing this parameter at all to having measured it down to 8%.





Mild preference for inverted hierarchy.

Electron neutrino appearance in NOvA

- The probability of ν_e appearance in a ν_μ beam:

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$
$$+2\alpha \sin\theta_{13} \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$
$$-2\alpha \sin\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$A \equiv \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11\ \mathrm{GeV}}$$

- Searching for ν_e events in NOvA, we can access $\sin^2(2\theta_{13})$.
- Probability depends not only on θ_{13} but also on $\delta_{CP,}$ which might be the key to matter anti-matter asymmetry of the universe. For large θ_{13} , a measurement could be possible.
- Probability is enhanced or suppressed due to matter effects which depend on the mass hierarchy i.e. the sign of $\Delta m^2_{31} \sim \Delta m^2_{32}$ as well as neutrino vs. anti-neutrino running.

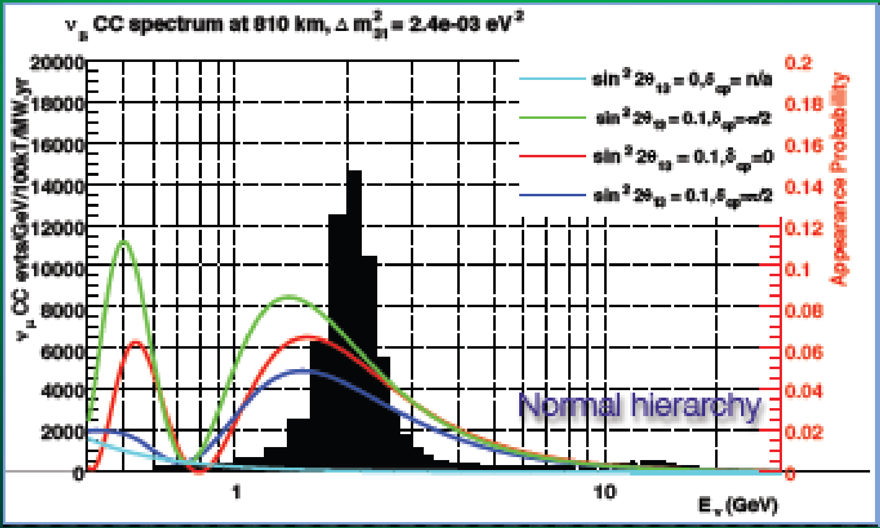
Electron neutrino appearance in NOvA

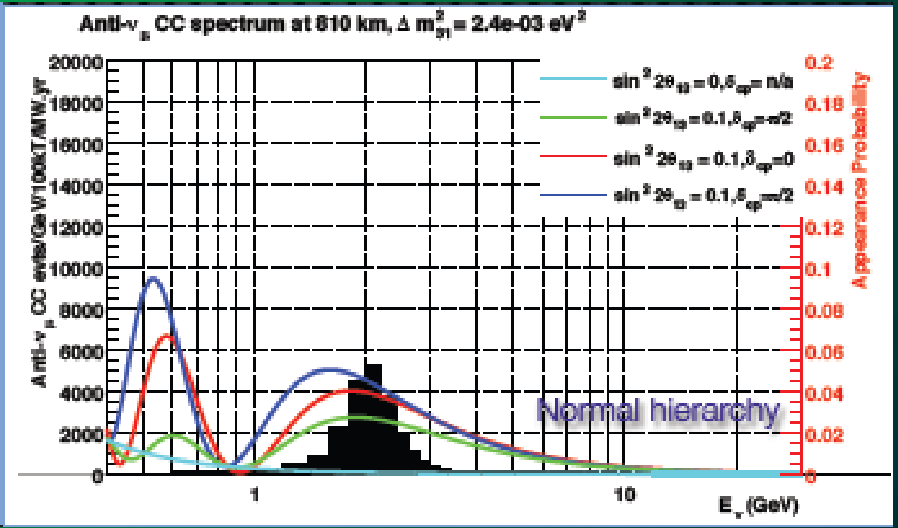
- The probability of ν_e appearance in a ν_μ beam:

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad A \equiv \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11\ \mathrm{GeV}}$$

$$+2\alpha \sin\theta_{13}\cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$-2\alpha \sin\theta_{13}\sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

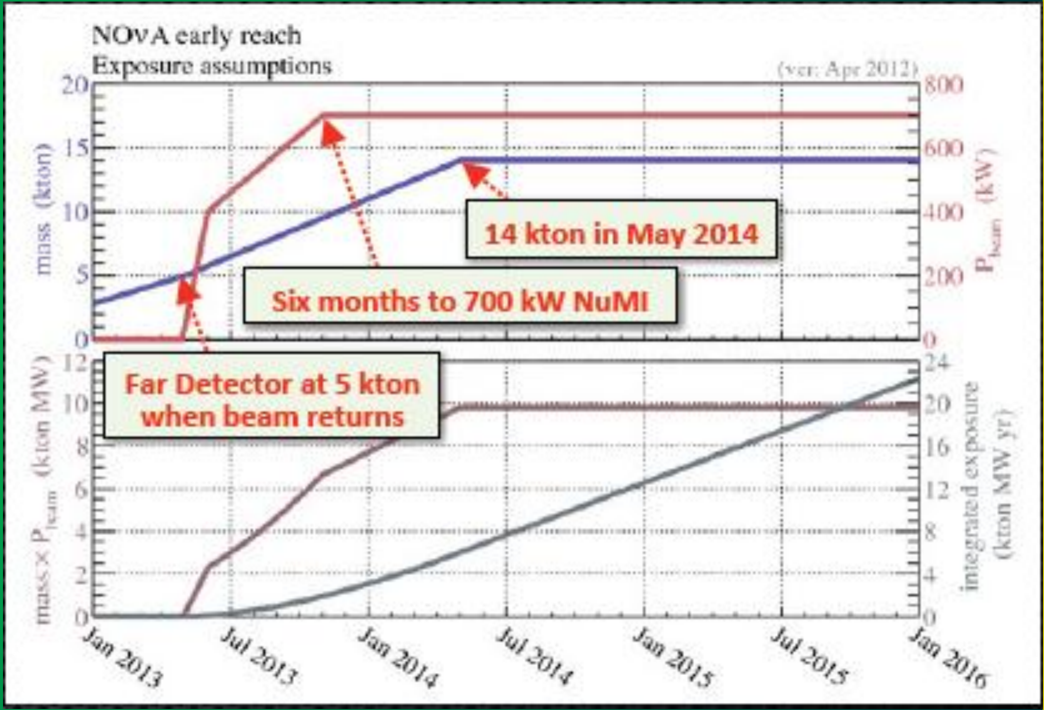




Beam Plots by M. Bishai

NOvA exposure in early running

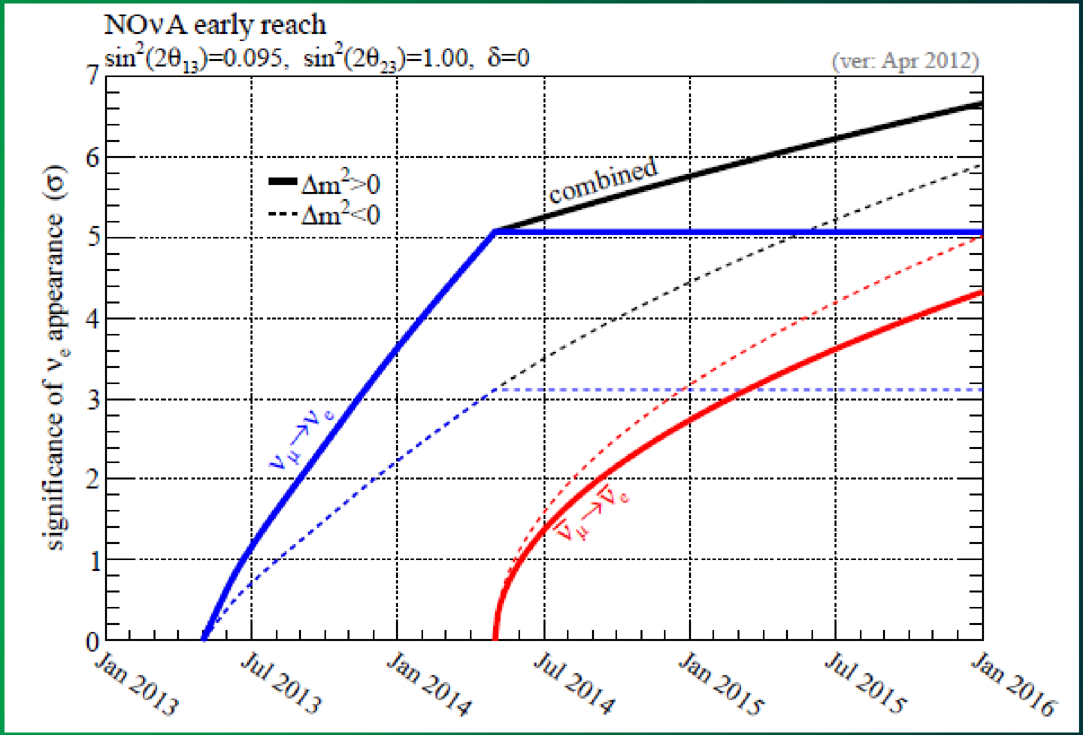
- NOvA will turn on April 2013 with 5 kton of Far detector in place and beam operating at ~ 400 kW
- We will add detector mass at a rate of ~ 1 kton/month
- Beam intensity will ramp up to 700 kW in approximately 6 months from 400 kW.



NOvA early reach

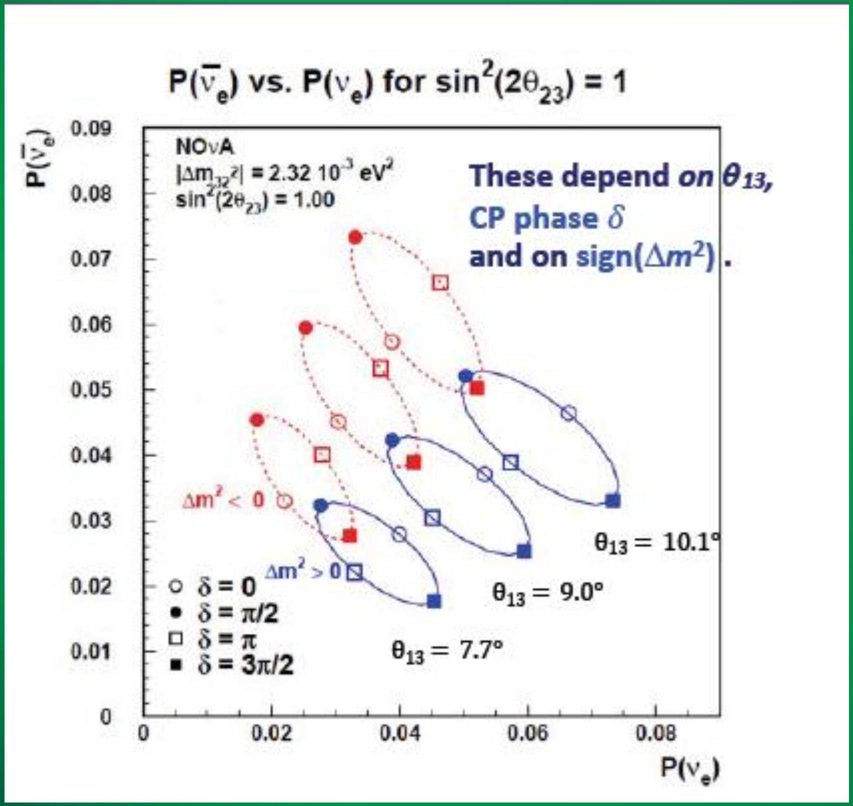
Using earlier analysis methods optimized for $\sin^2(2\theta_{13}) = 0.095$.
Signal eff: 45% and NC fake rate ~1%.

- We will start with neutrino running:
  - 5σ observation of $\nu_\mu \rightarrow \nu_e$ in first year if normal hierarchy (even with partial detector and beam commissioning!)
- Switch to anti-neutrino running as needed.
- Nominal run plan 3 years in each mode at 6×10^{20} POT



Beam	signal	Total Bkgd	NC bkgd	ν_μ CC bkgd	ν_e CC bkgd
neutrino	68	32	19	5	8
antineutrino	32	15	10	<1	5

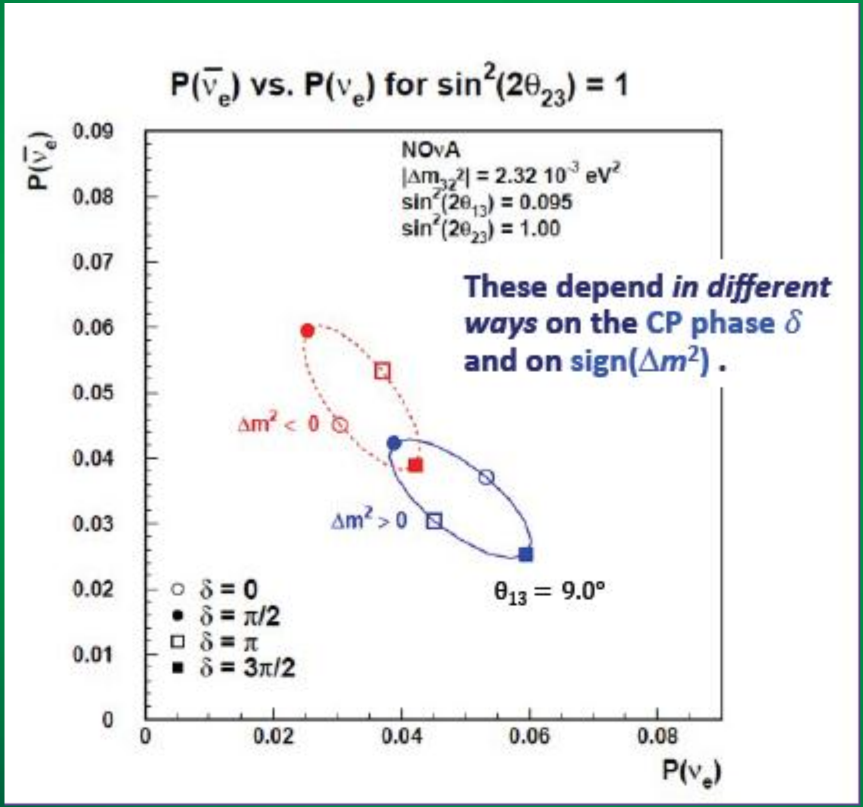
NOvA physics



NOvA will measure: P($\nu_\mu \rightarrow \nu_e$) at 2 GeV and P(anti-$\nu_\mu \rightarrow$ anti-ν_e) at 2 GeV

Now we know θ_{13} ~ 9 degrees

NOvA physics



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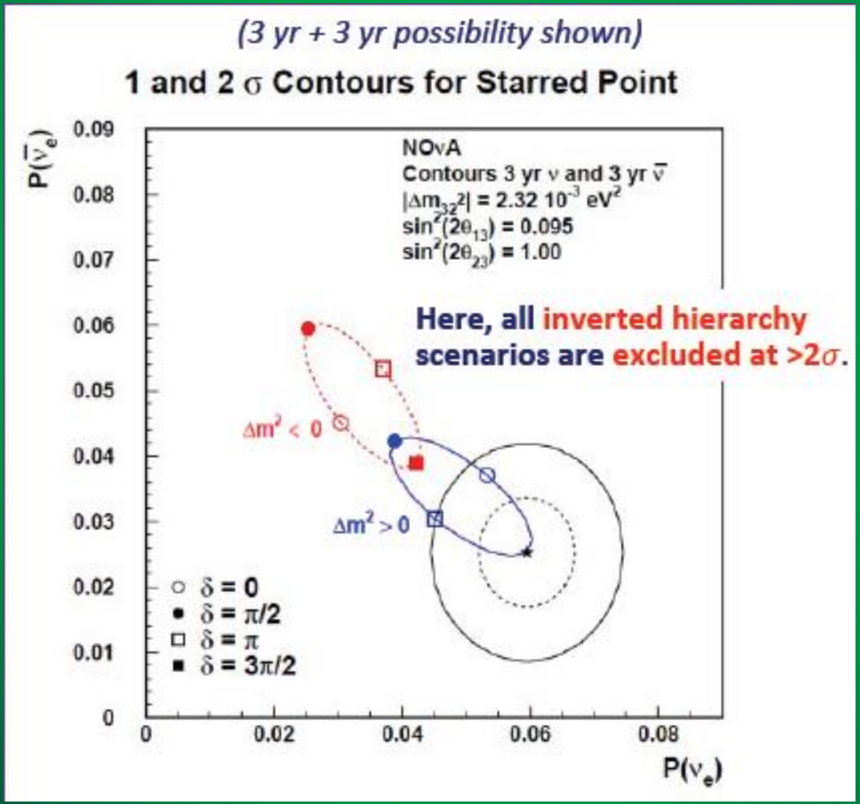
Large θ_{13} is good news for NOvA.
It reduces the overlap between these bi-probability ellipses, reducing the likelihood of degeneracies

NOvA physics



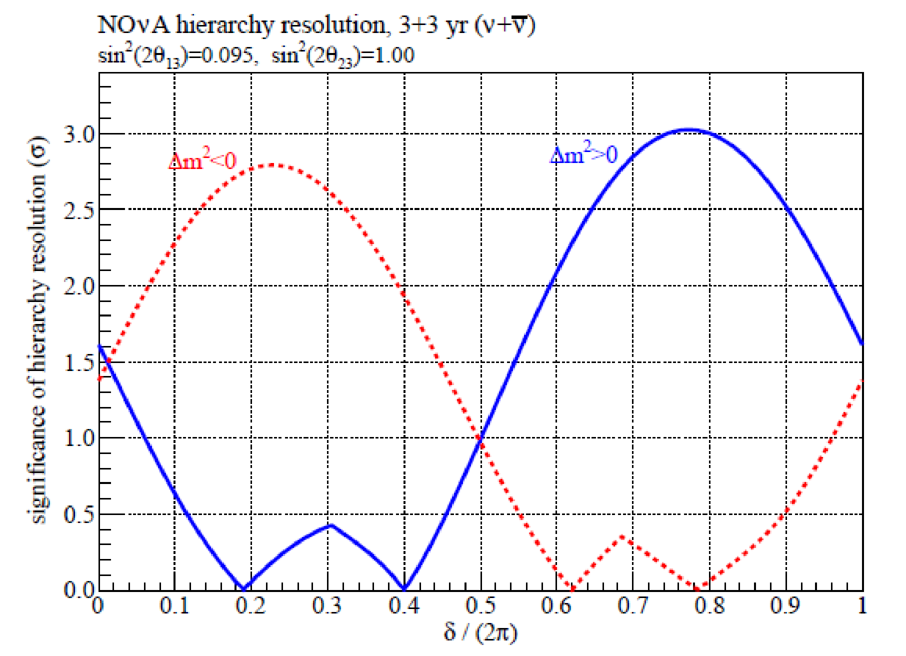
Example NOνA result

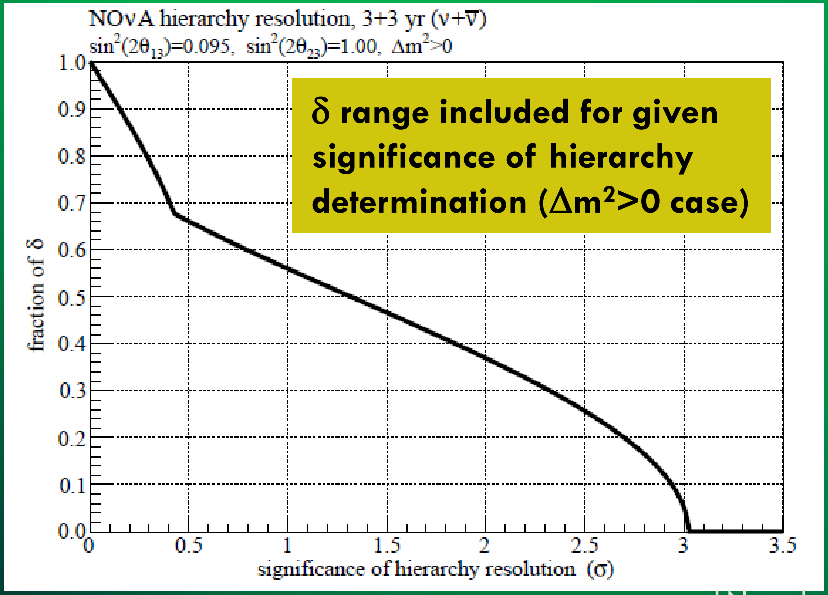
Our data will yield allowed regions in P(anti-ν_e) vs. P(ν_e) space

A measurement of the probabilities might allow resolving the mass hierarchy and provide information on δ_{CP}.

Resolution of the mass hierarchy

- Significance of mass hierarchy resolution using a sample counting experiment.
- Energy fit provides improvement on the fully degenerate δ_{CP} values.





We can also gain additional sensitivity from T2K's baseline.

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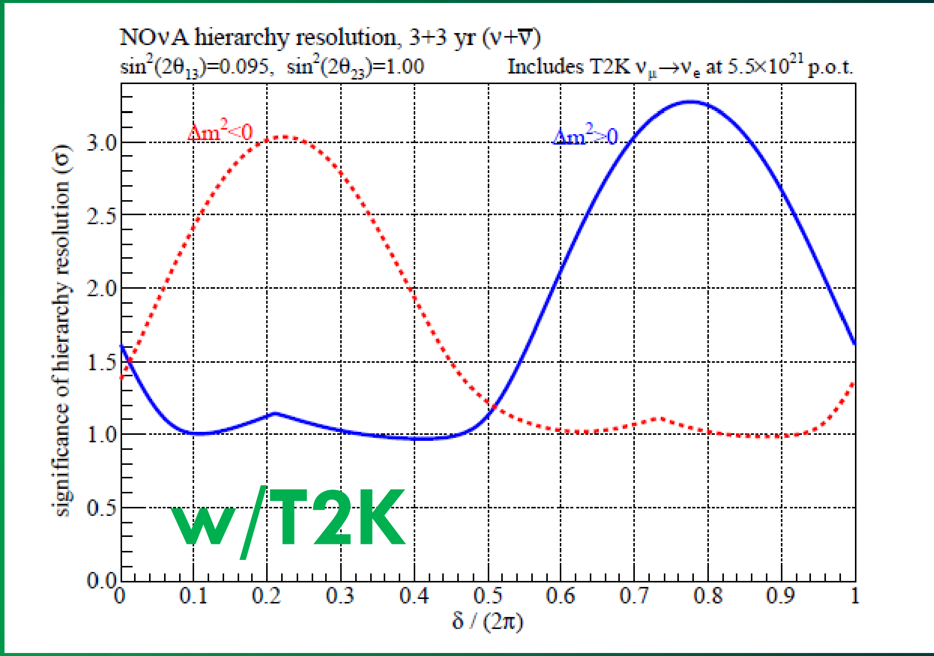
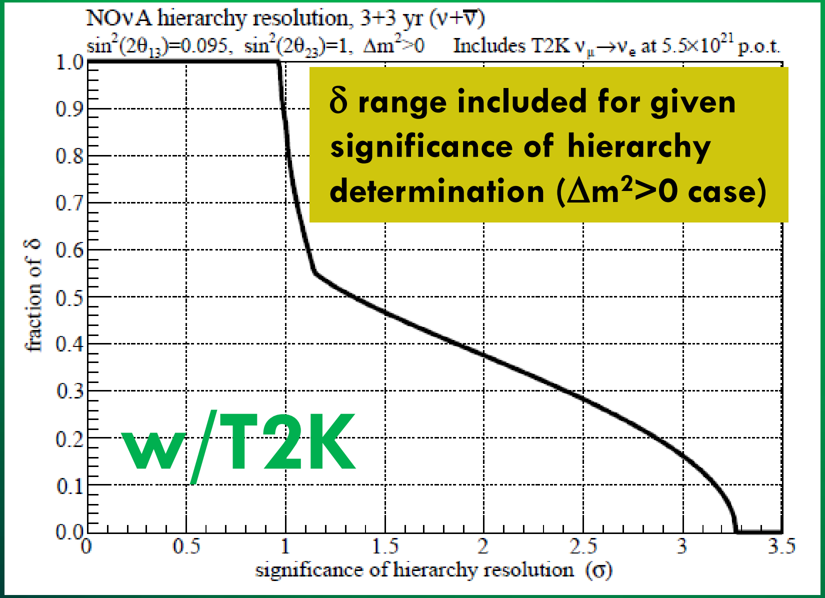
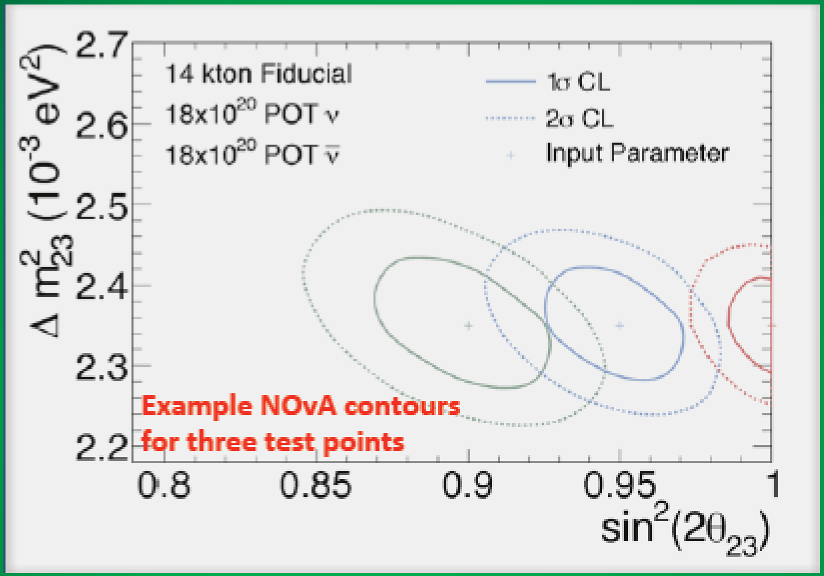


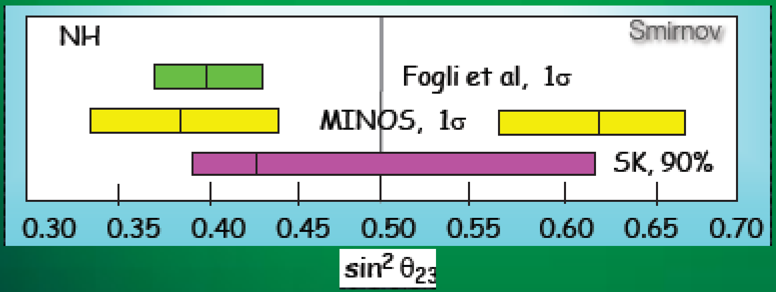


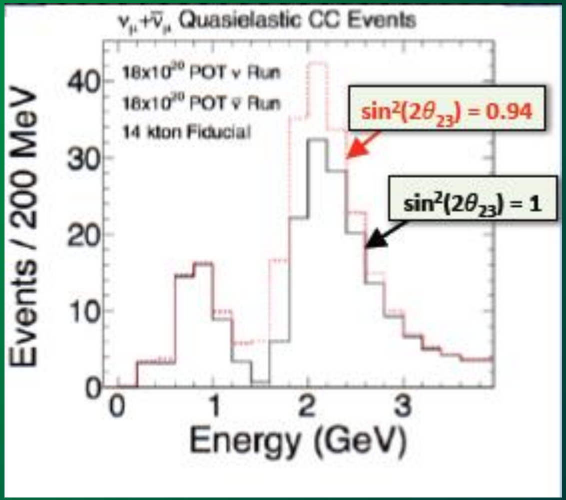
We can also gain additional sensitivity from T2K's baseline.

NOvA muon neutrino disappearance



- NOvA's will do a few % measurement in Δm^2_{32} and $\sin^2 2\theta_{23}$.
- Improvement of one order of magnitude in $\sin^2 2\theta_{23}$.
- It might not be maximal.

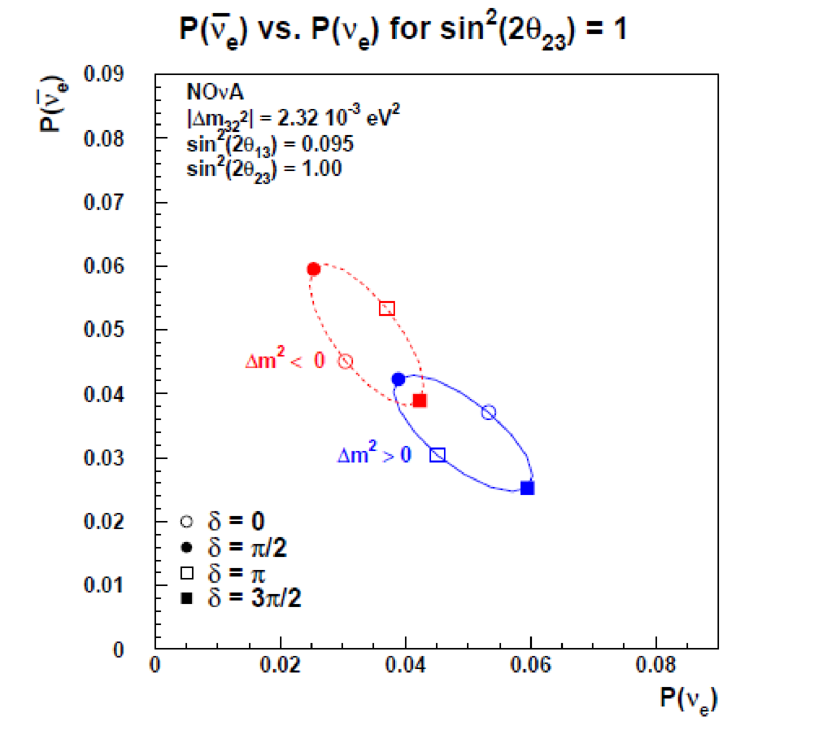




Non-maximal $\sin^2 2\theta_{23}$

$P(\nu_e) \propto \sin^2(\theta_{23})\sin^2(2\theta_{13})$

$\Rightarrow$ ***θ_{23} octant sensitivity***



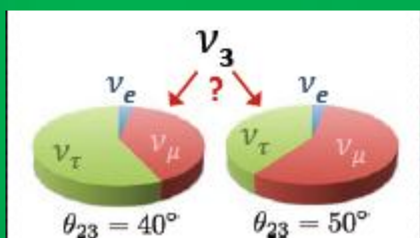
If $\sin^2 2\theta_{23}$ is not maximal there is an ambiguity as to whether θ_{23} is larger or smaller than 45°.

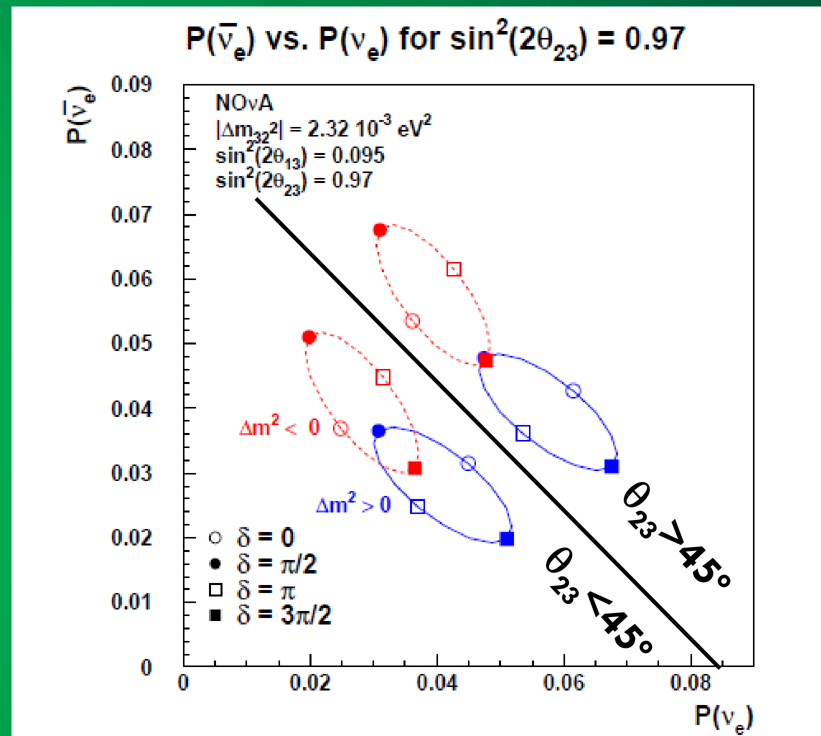
The $\sin^2 2\theta_{23}$ term is unimportant when comparing accelerator experiments; however, it is crucial in comparing accelerator to reactor experiments

Non-maximal $\sin^2 2\theta_{23}$

$P(\nu_e) \propto \sin^2(\theta_{23})\sin^2(2\theta_{13})$

⇨ θ_{23} *octant sensitivity*





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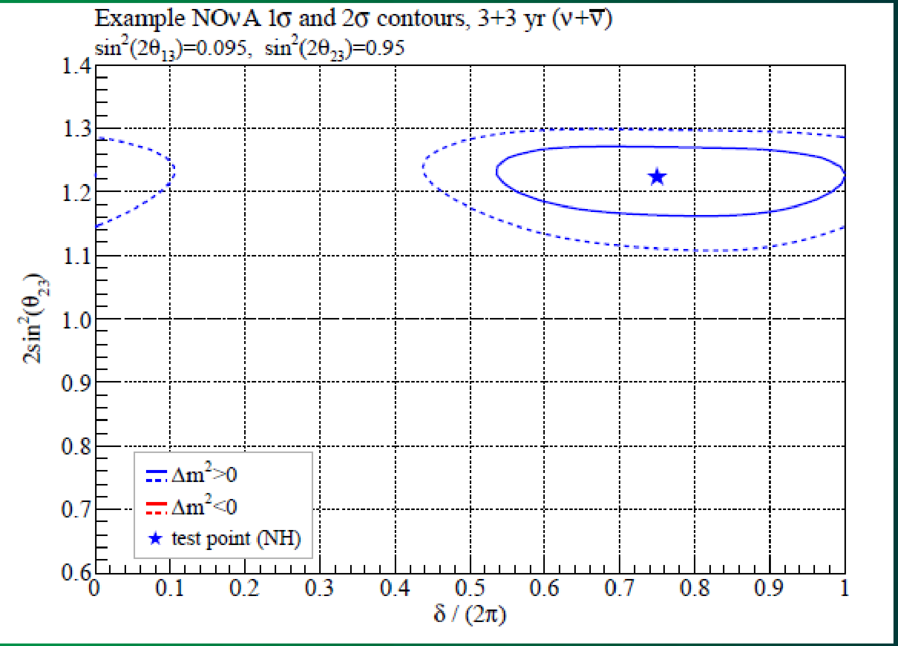
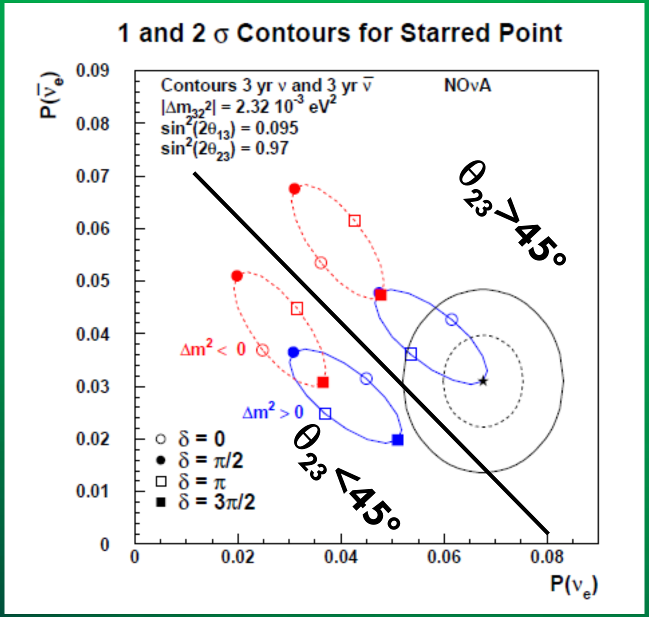
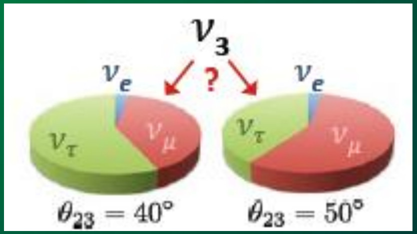
Non-maximal $\sin^2 2\theta_{23}$ and NOvA

Expected contours for one example scenario using 3 years of data for each neutrino mode.





Simultaneous hierarchy, CP phase, and θ_{23} octant information from NOvA



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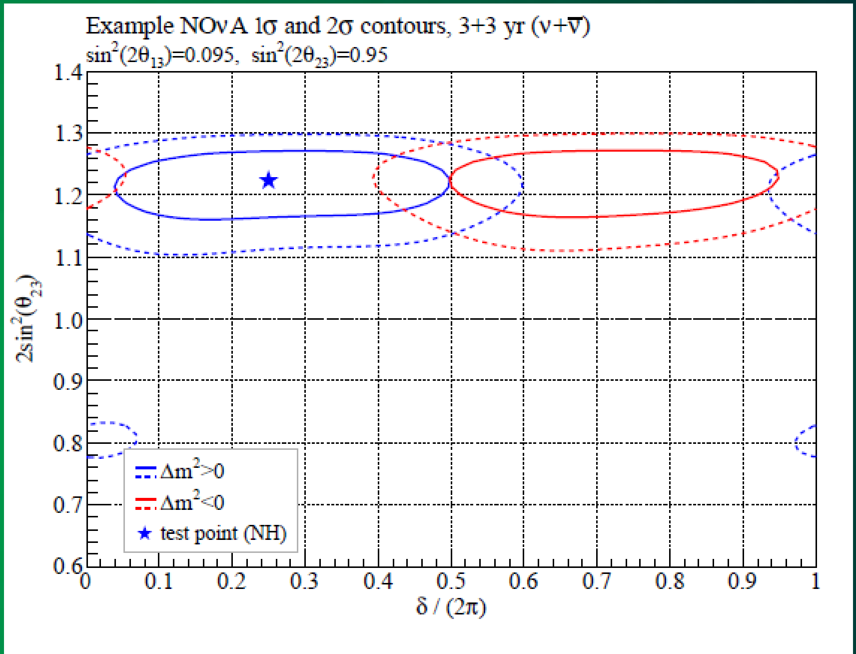
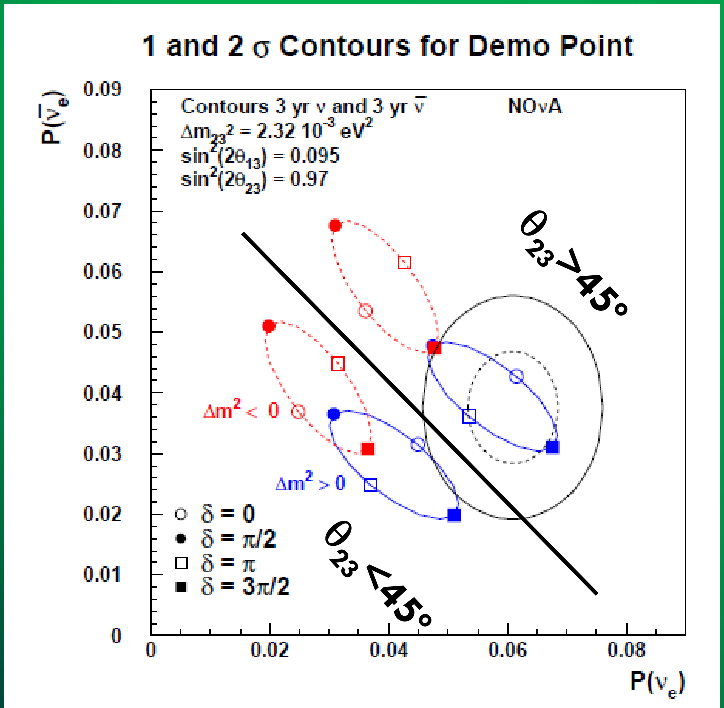
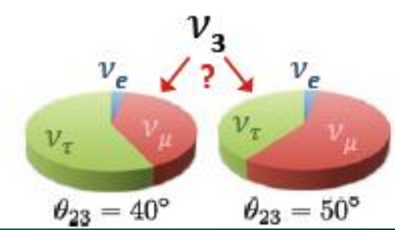




In "degenerate" cases, hierarchy and δ information is coupled. θ_{23} octant information is not.



Summary

- There is now **definite evidence** that θ_{13} angle is as large as we could have hoped for.
- **NOνA program** $\rightarrow$ *mass hierarchy, δ_{CP}, θ_{23} $\rightarrow$ broad range of ν-sector measurement*
- **NOνA FD assembly underway at Ash River!**
  - **NuMI upgrades underway $\rightarrow$ 700 kW**
  - **First neutrino events in the partial FD next Spring**
  - **NDOS run:** $\rightarrow$ *commissioning, cosmic ray, and neutrino data $\rightarrow$ invaluable for assembly practice and analysis development*
- **Actively developing analyses for 1st FD data** $\rightarrow$ *aiming to surpass the sensitivities shown in this talk*