# The NOvA Experiment

**Mayly Sanchez**

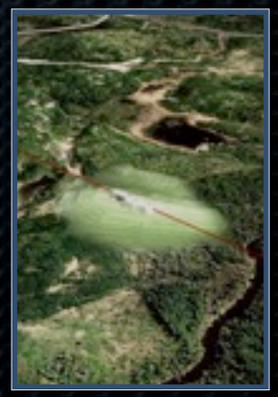
Iowa State University / Argonne National Laboratory

Fermilab User's Meeting
June 12-13, 2012

# NOvA in a nutshell

- Use the upgraded NuMI beam Fermilab.
- Construct a totally active liquid scintillator detector off the main axis of the beam.
  - Detector is 14 mrad off-axis and on the surface.
  - Location reduces background.
- If neutrinos oscillate, electron neutrinos are observed at the Far Detector in Ash River, 810 km away.


2nd generation
← long baseline →



# 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.

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

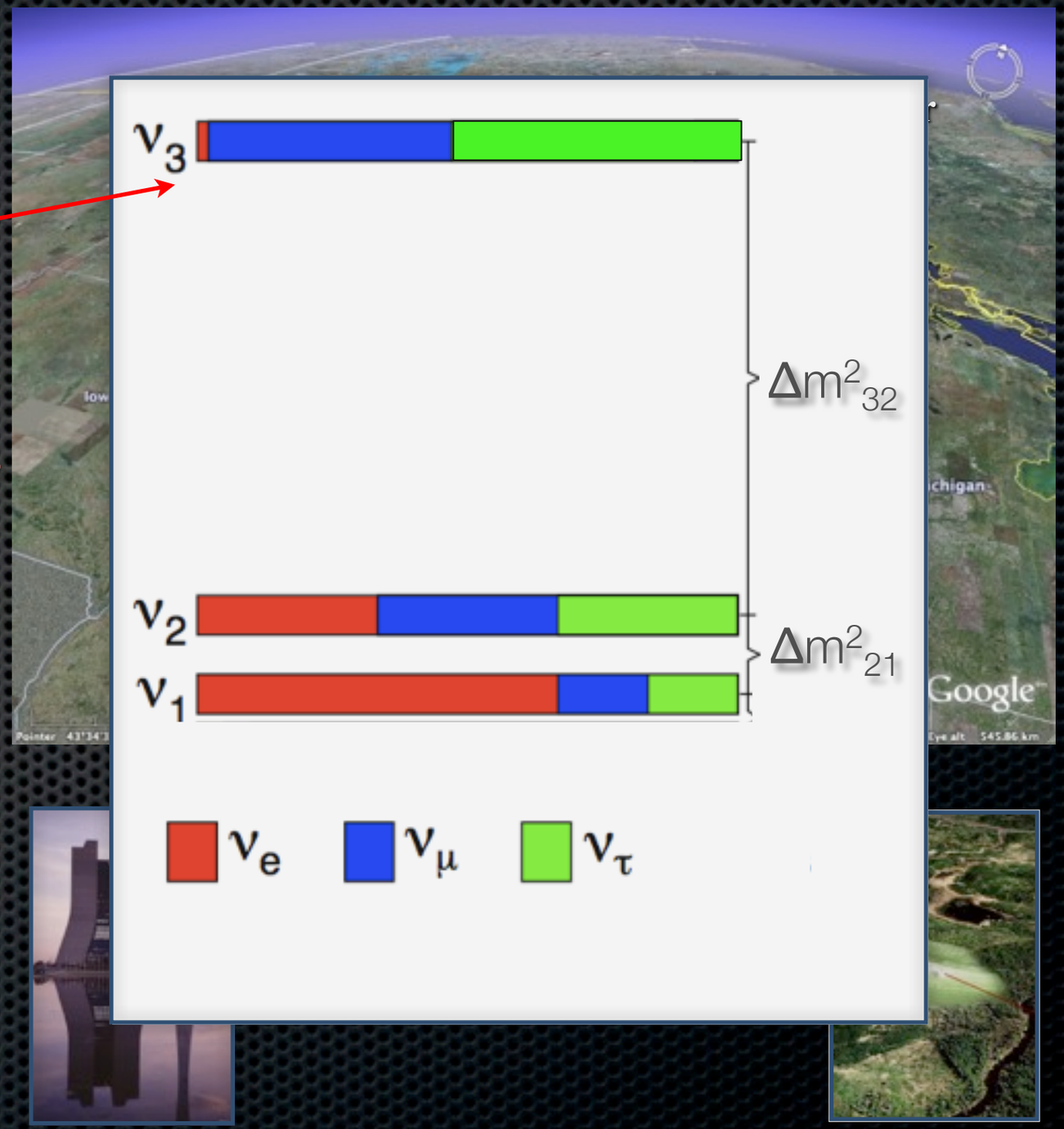
- For the three flavor case we can write a PMNS mixing matrix:

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

- The **(23)** and **(12)** sectors are well known. The **(13)** sector only <u>had</u> a limit!
- If $\sin^2 2\theta_{13}$ is non-zero then we can access $\delta_{CP}$ which might be key to matter anti-matter asymmetry of the universe.

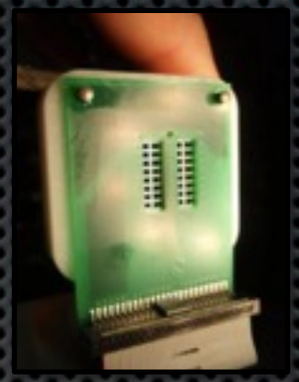
# NOvA physics goals

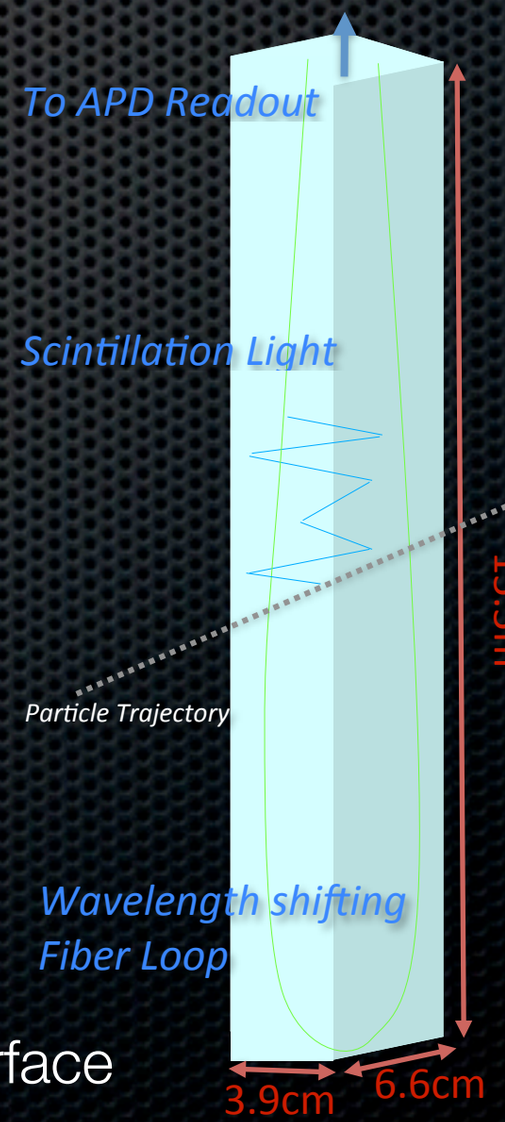
- Measure the oscillation probabilities of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.
  - Measure the mixing angle $\theta_{13}$.
  - Determine neutrino mass hierarchy.
  - Study the phase parameter for CP violation $\delta_{CP}$.
- Precision measurements of $\Delta m^2_{32}$, $\theta_{23}$ by measuring $\nu_\mu \rightarrow \nu_\mu$.
- As well as:
  - $\nu$ cross sections.
  - Sterile neutrinos.
  - Supernova signals.



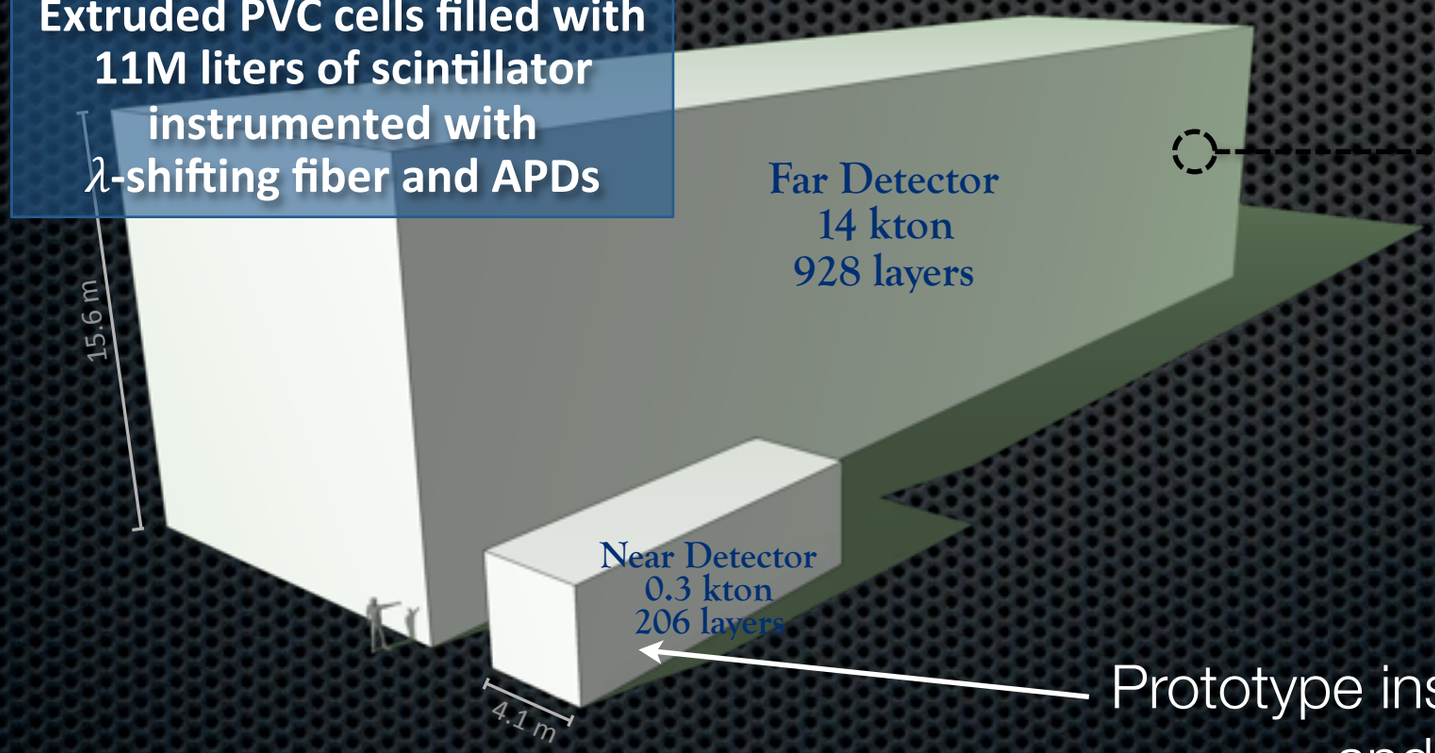
# The NOvA detectors

- 14 kton Far Detector (~3x MINOS).
  - >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 $\pi^0$ .




**Extruded PVC cells filled with 11M liters of scintillator instrumented with $\lambda$-shifting fiber and APDs**

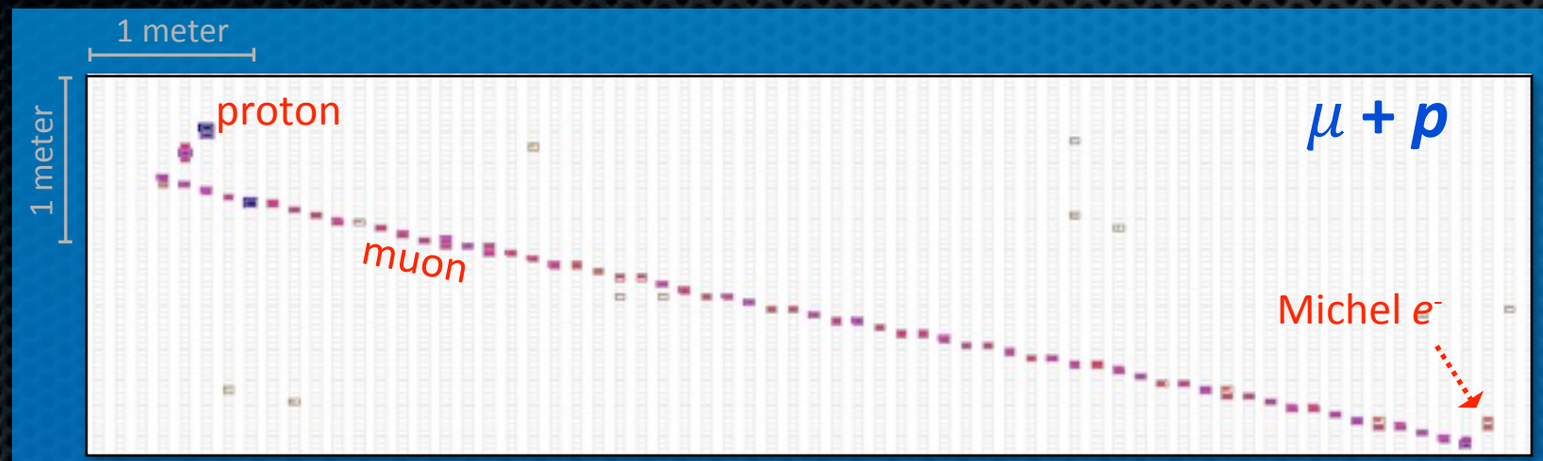


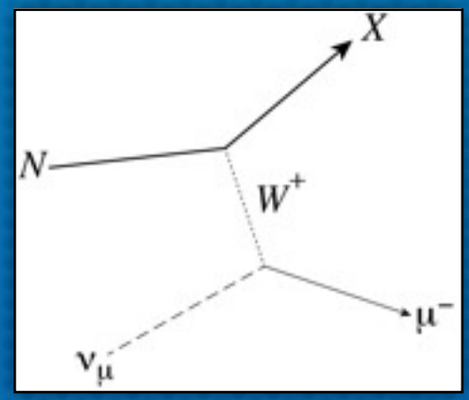

Prototype installed on the surface and taking data!

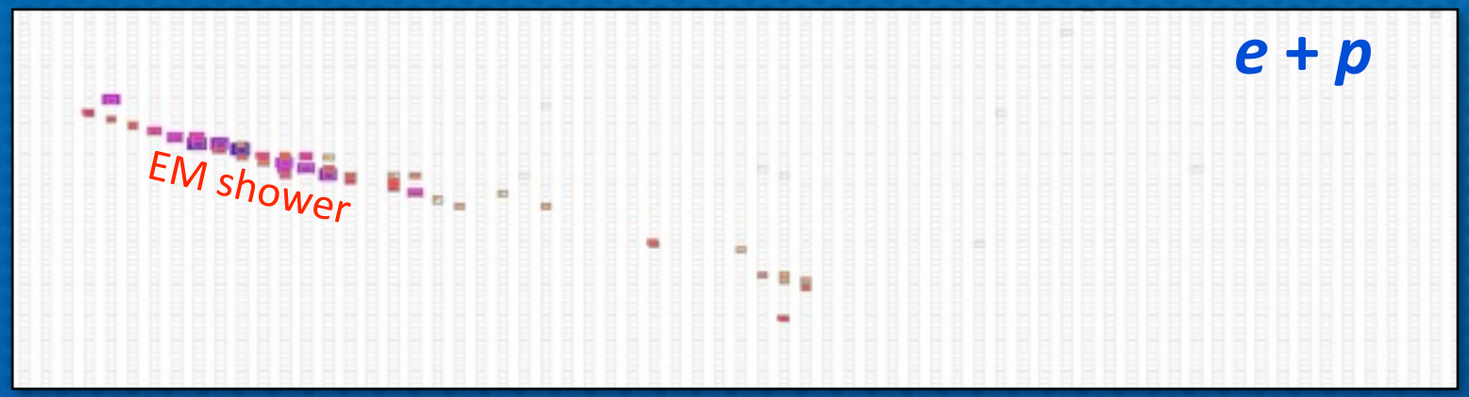
# Neutrino events in NOvA

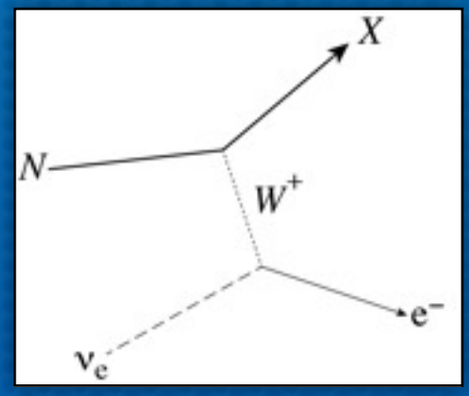
**Excellent spatial granularity for a detector of this scale**

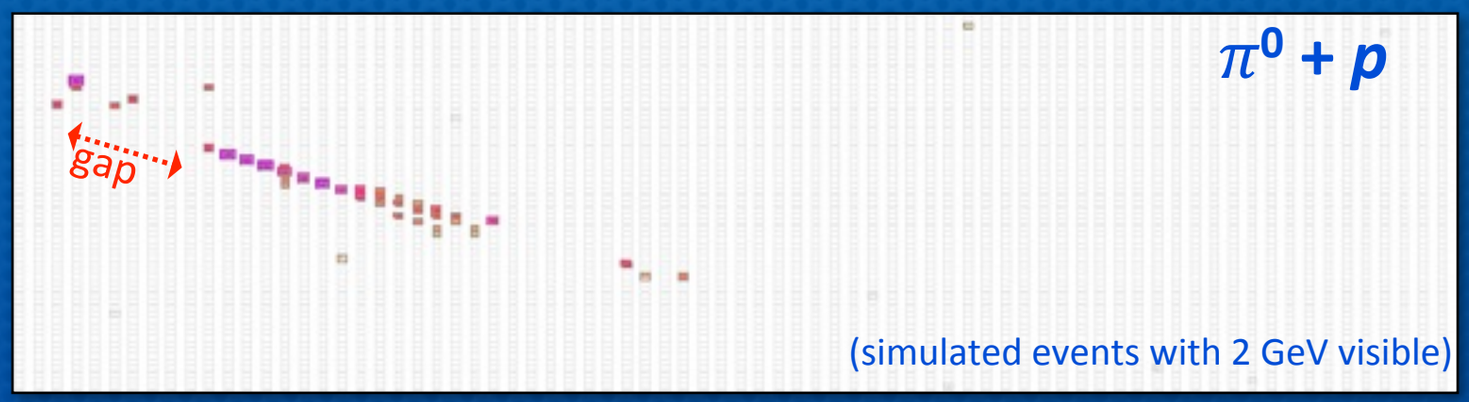
**$X_0$ = 38 cm (6 cell depths, 10 cell widths)**

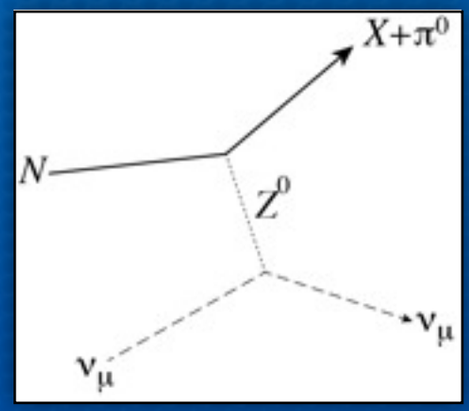


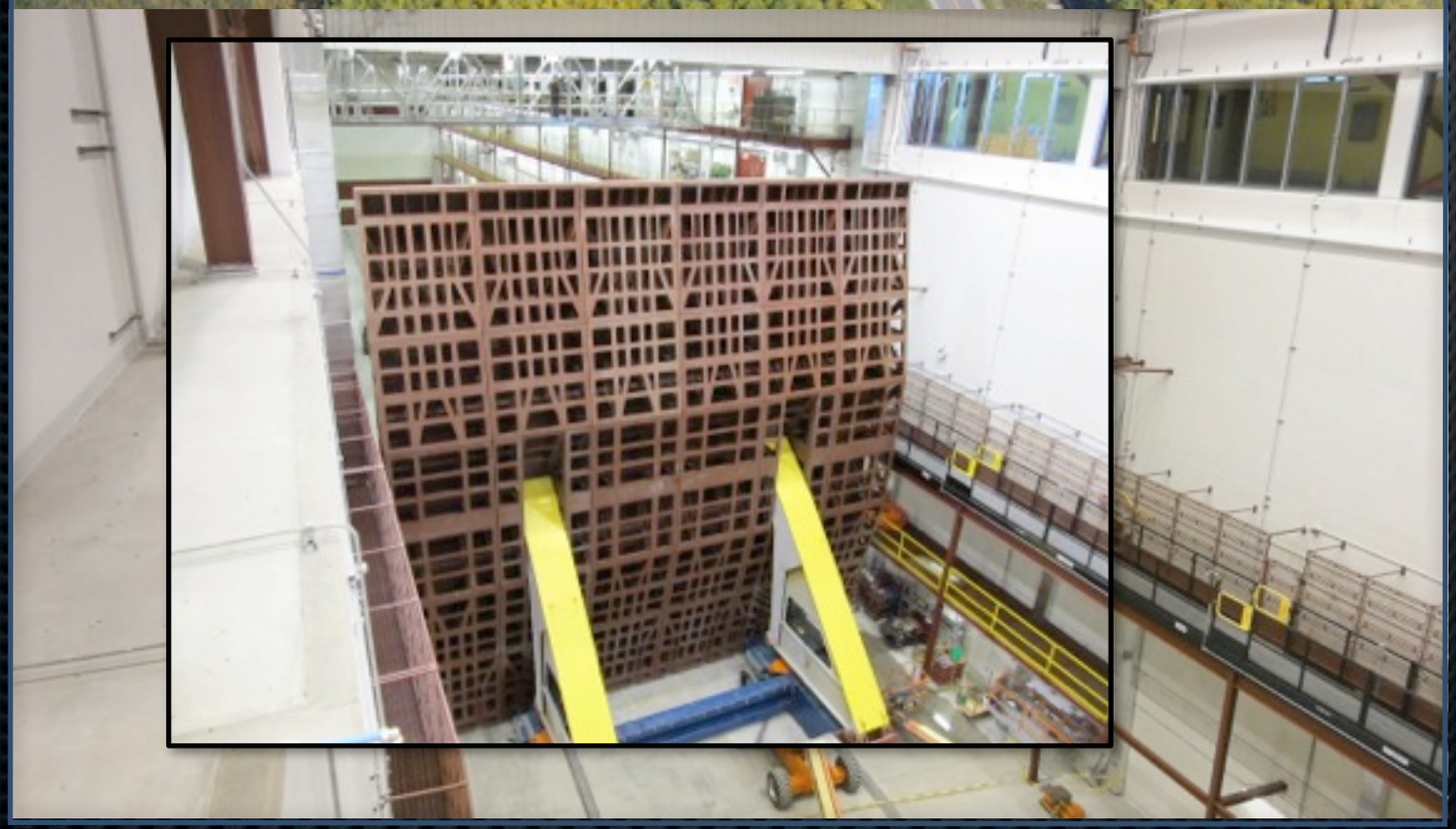



# NOvA construction status

- 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.

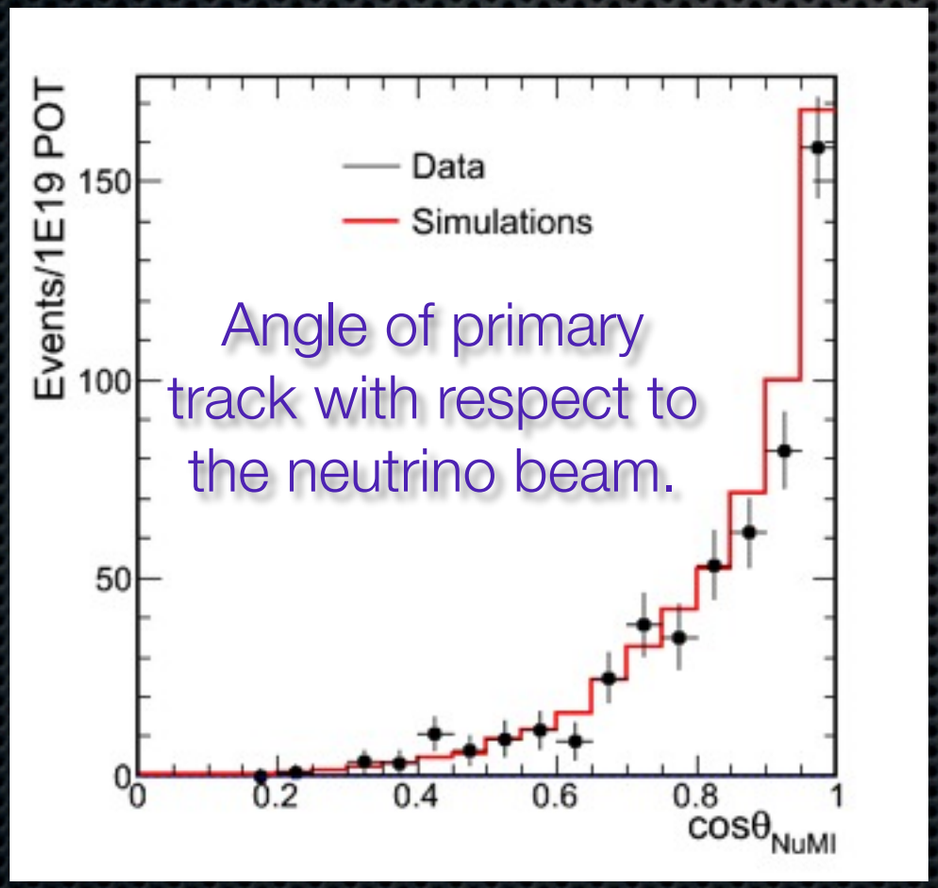
# NOvA construction status

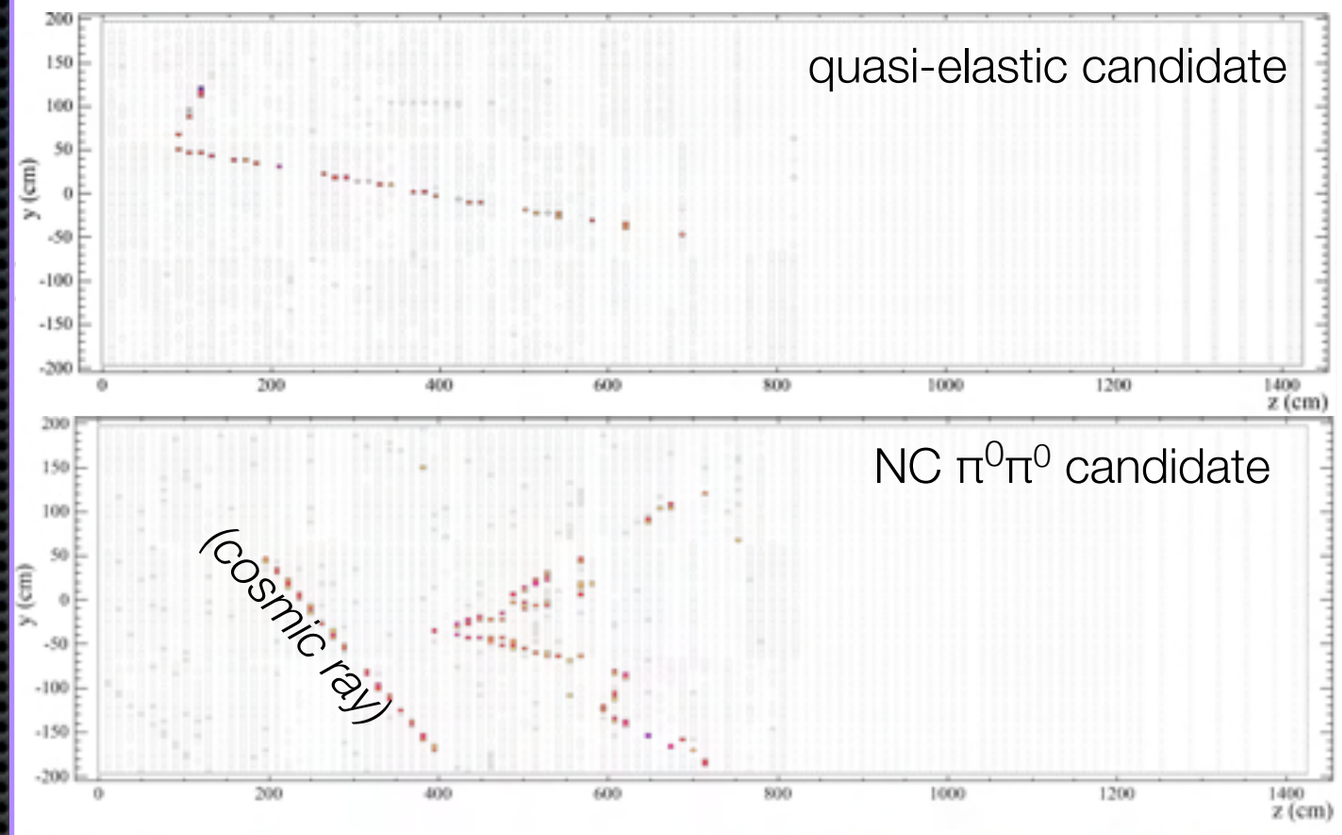


- Far Detector site construction is now complete.
  - The block pivoter is installed at the site.
  - Far Detector first block installation begins this month!
- Upgrade NuMI beam from 350 kW to 700kW initiated May 1, 2012.
- Near Detector cavern excavation and assembly during shutdown.
  - Changed to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

# NOvA 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.



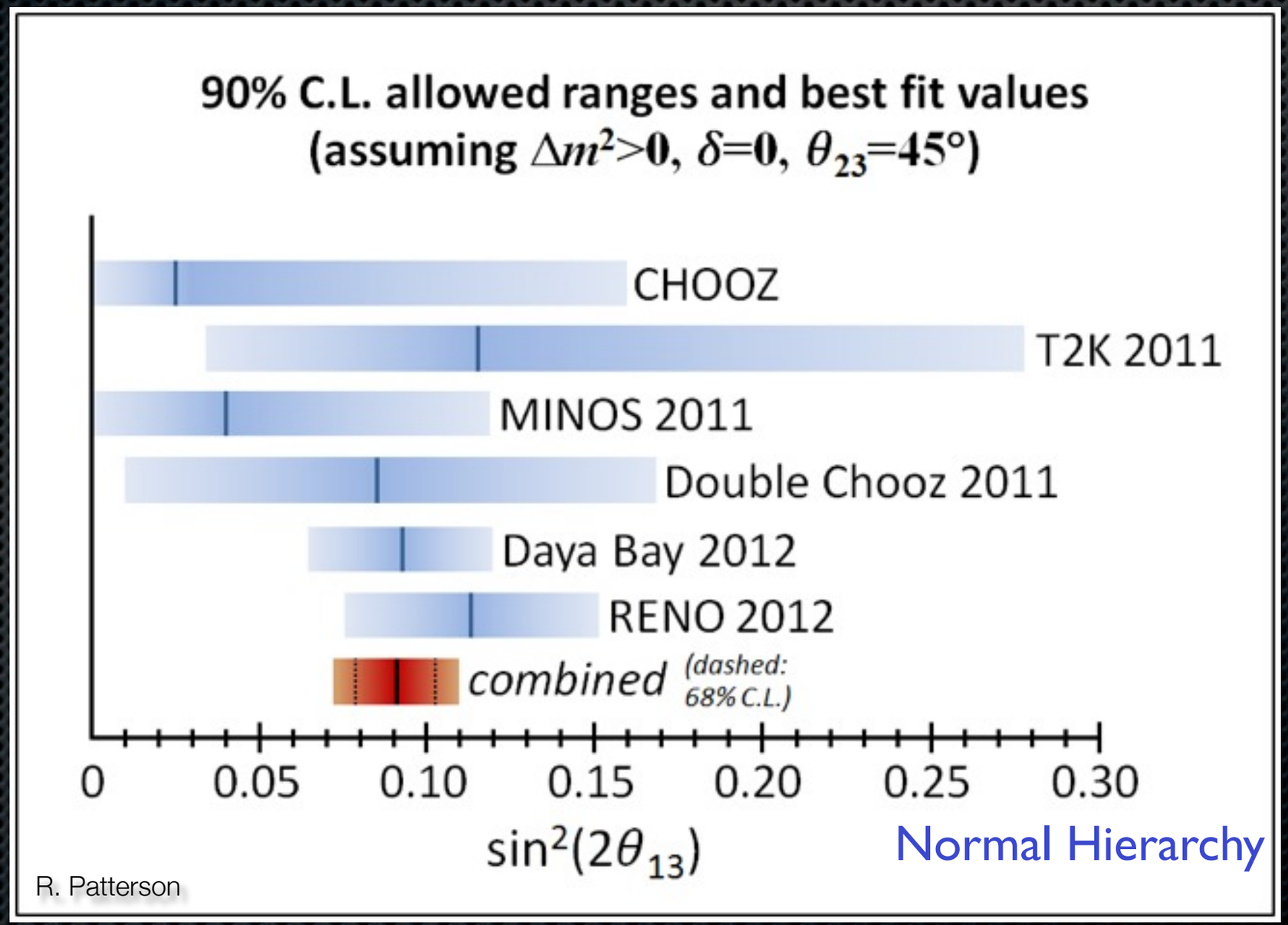

Events from the NuMI beam seen at 110 mrad

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

**2 NOvA Talks at New Perspectives tomorrow**

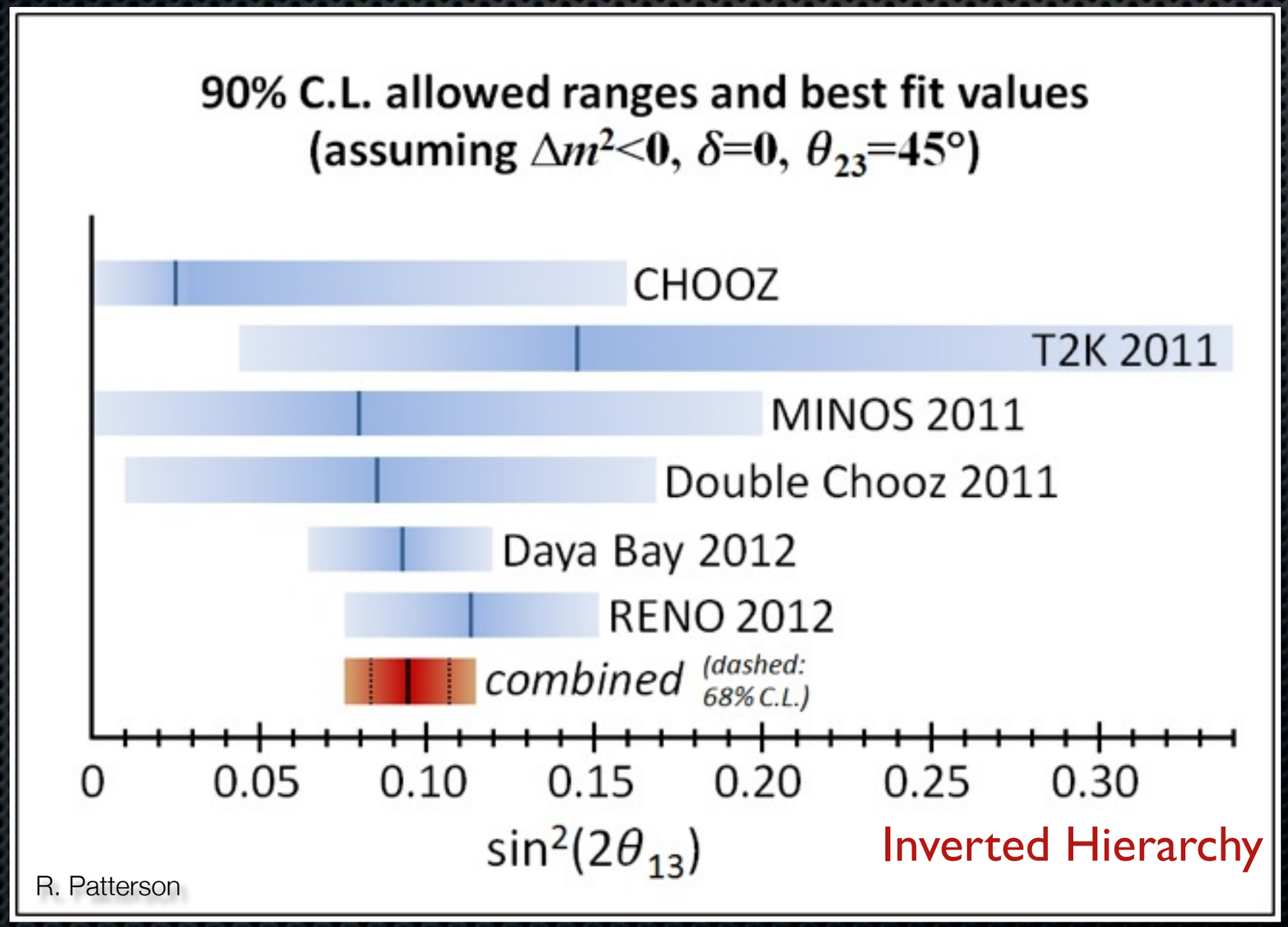
# The status of $\theta_{13}$ before Neutrino 2012

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



# The status of $\theta_{13}$ before Neutrino 2012

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




Mild preference for inverted hierarchy. About ~1 σ.

# Searching for...
# Electron neutrino appearance in NOvA

- The probability of $\nu_e$ appearance in a $\nu_\mu$ beam:

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

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

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

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

- Searching for $\nu_e$ events in NOvA, we can access **$\sin^2(2\theta_{13})$**.
- Probability depends not only on **$\theta_{13}$ but also on $\delta_{CP}$** which might be the key to matter anti-matter asymmetry of the universe. For large $\theta_{13}$ , 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

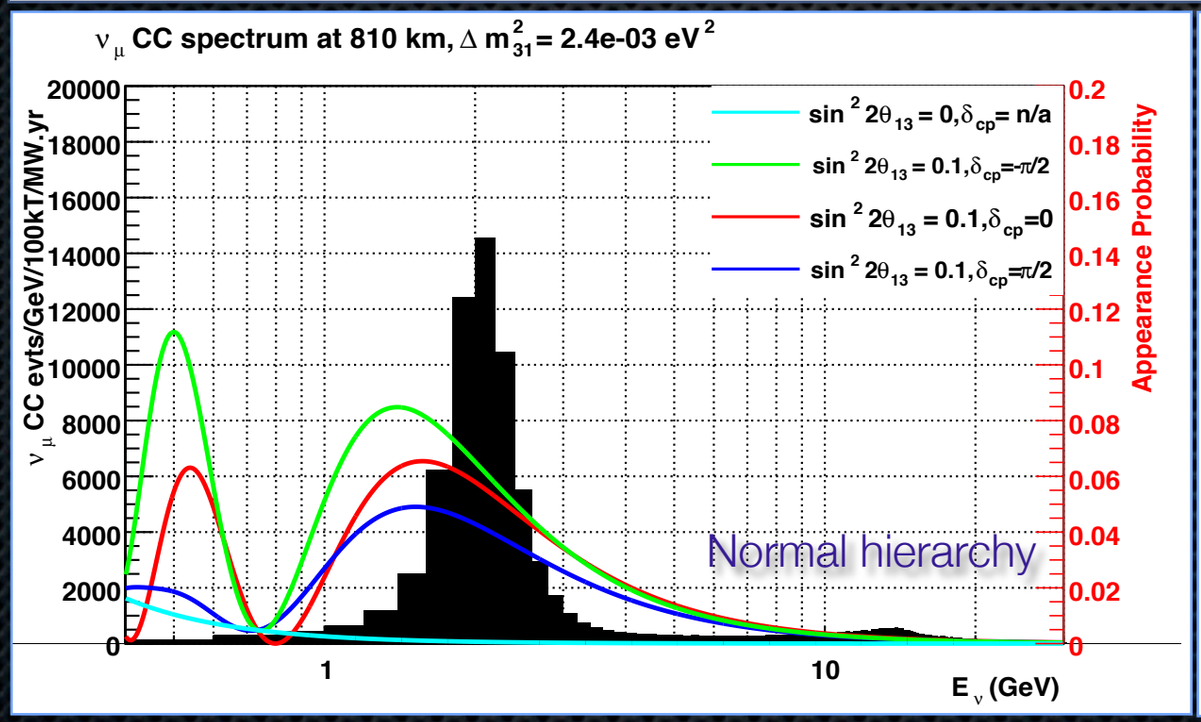
- The probability of $\nu_e$ appearance in a $\nu_\mu$ beam:

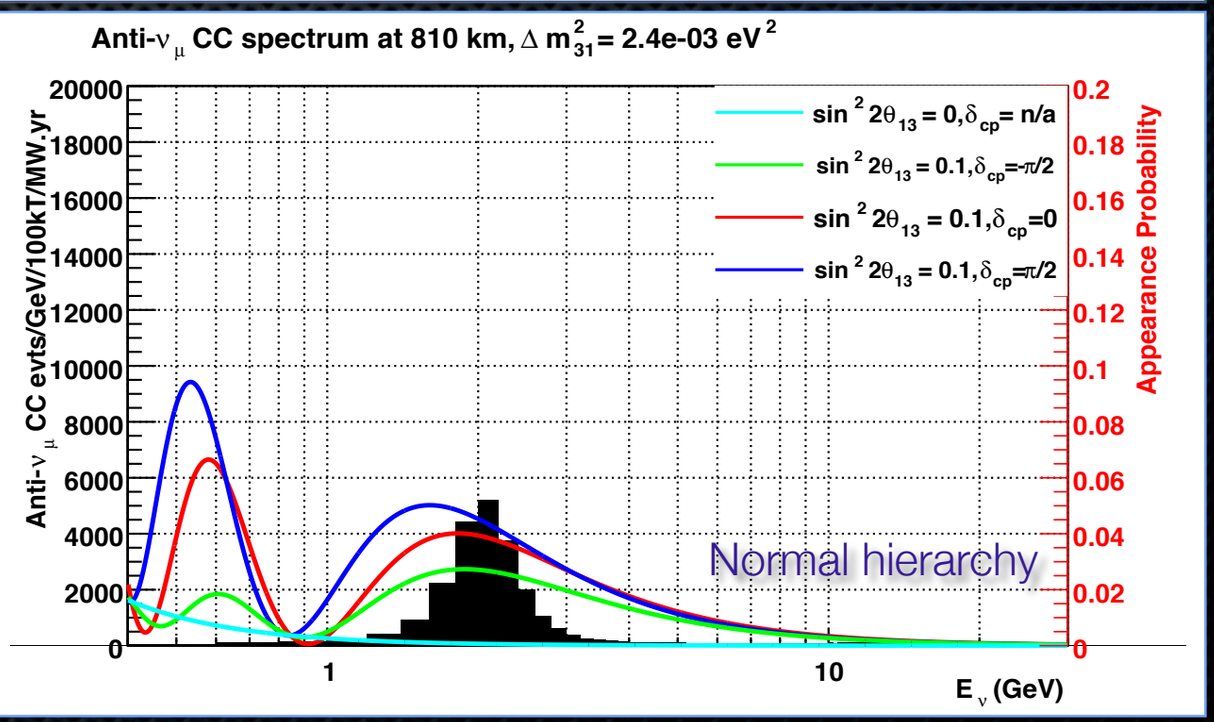
$$A \equiv \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11\ \mathrm{GeV}}$$

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

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

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



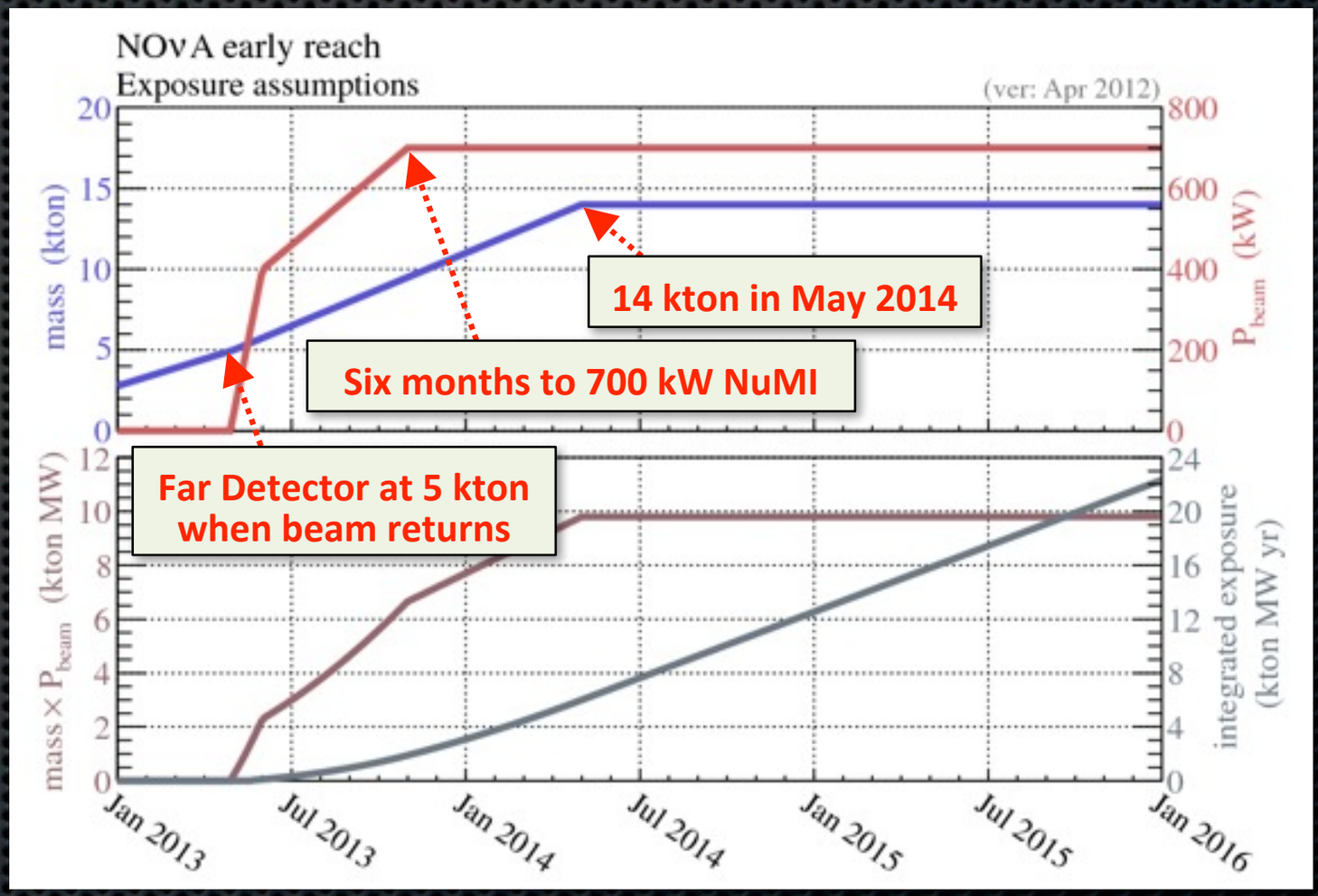



Plots by M. Bishai

# NOvA exposure in early running

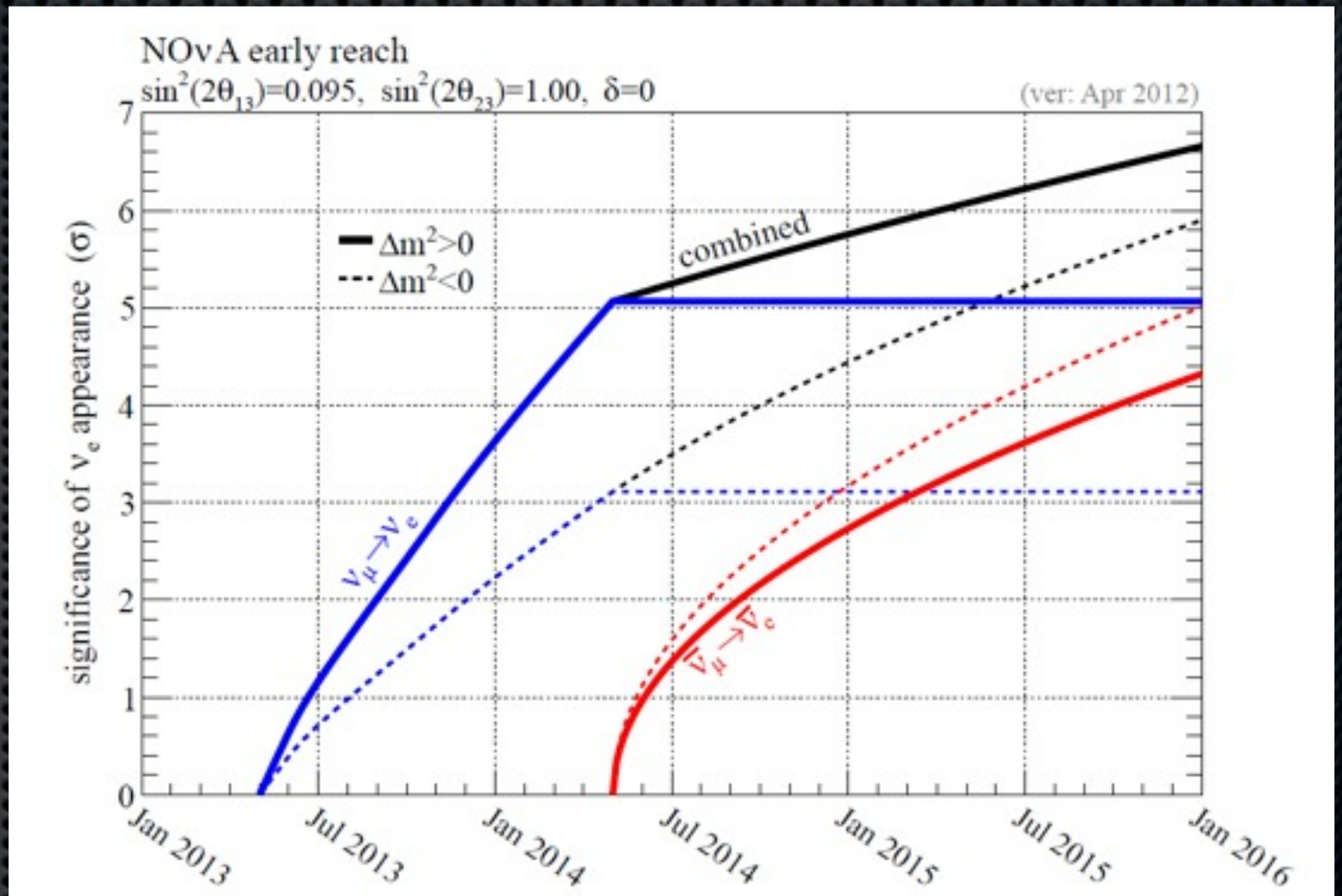
- NOvA will turn on April 2013 with 5 kton of Far detector in place and beam operating at ~ 400 kW
- We will add detector mass at a rate of ~ 1 kton/month
- Beam intensity will ramp up to 700 kW in approximately 6 months from 400 kW.

**Evolution of detector mass and beam power**



# NOvA early reach

- 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 x $10^{20}$ POT.

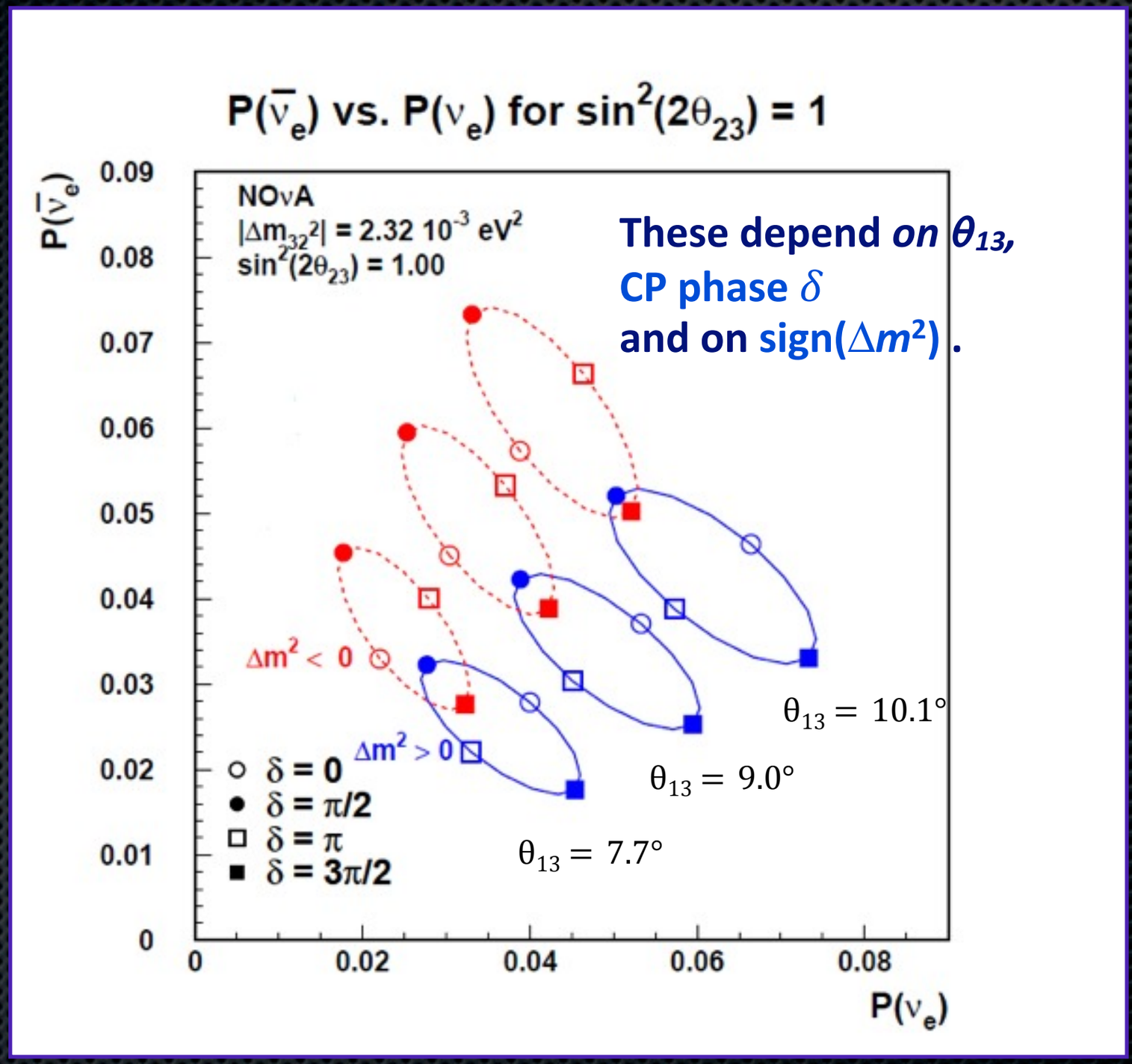



| | signal | total bkgd | NC bkgd | $\nu_\mu$ CC bkgd | $\nu_e$ CC bkgd |
|---|---|---|---|---|---|
| ν (3 yrs) | 72.6 | 34.5 | 20.8 | 5.2 | 8.4 |
| $\bar{\nu}$ (3 yrs) | 33.8 | 16.3 | 10.6 | 0.7 | 5.0 |

Using earlier analysis methods optimized for $\sin^2(2\theta_{13}) = 0.095$.
Signal eff: 45% and NC fake rate 0.1%.

# NOvA physics

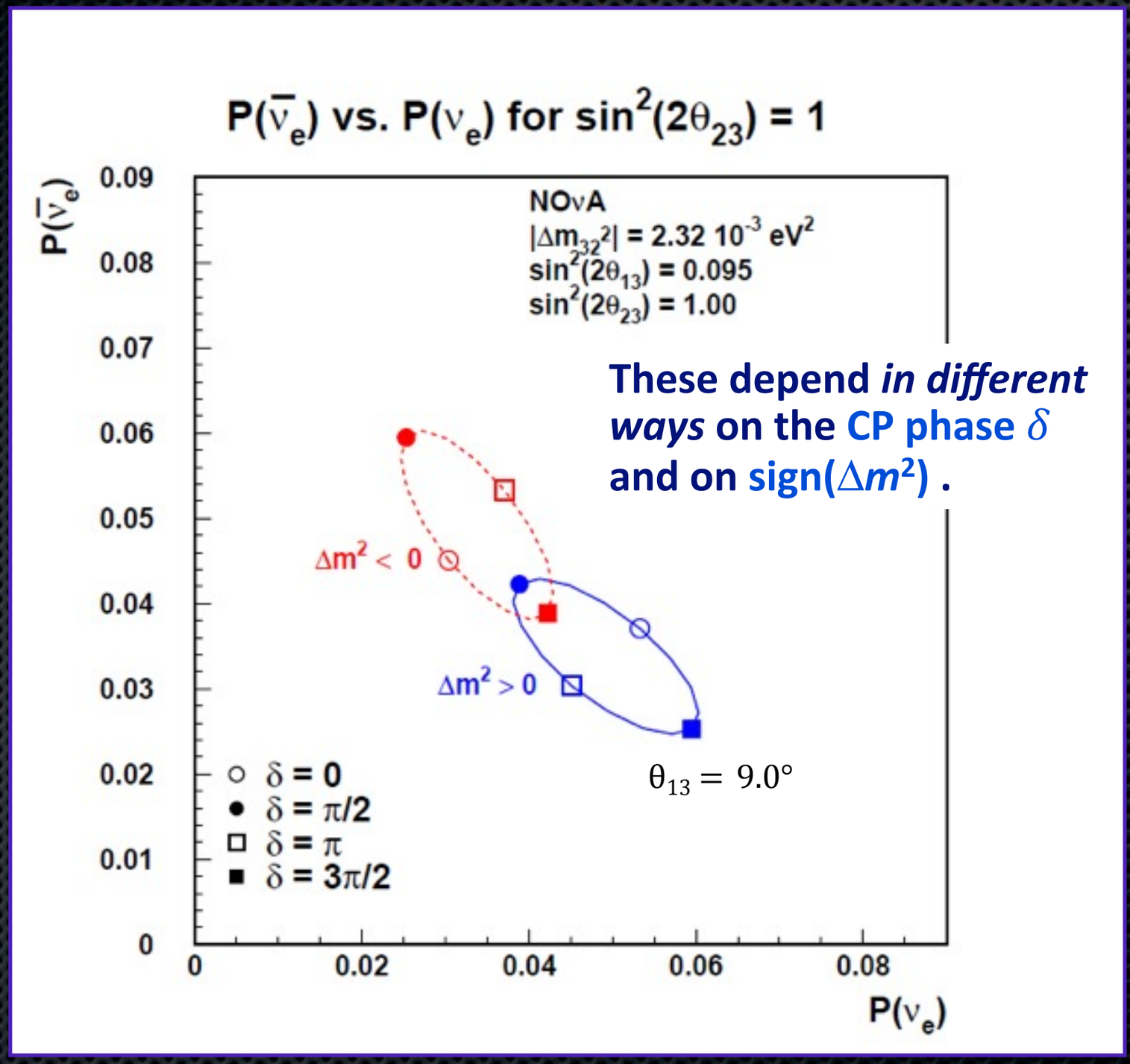
**NO$\nu$A will measure: $P(\nu_\mu \to \nu_e)$ at 2 GeV *and* $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ at 2 GeV**




Now we know $\theta_{13}$ ~ 9 degrees

# NOvA physics

**NO$\nu$A will measure: $P(\nu_\mu \to \nu_e)$ at 2 GeV *and* $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ at 2 GeV**



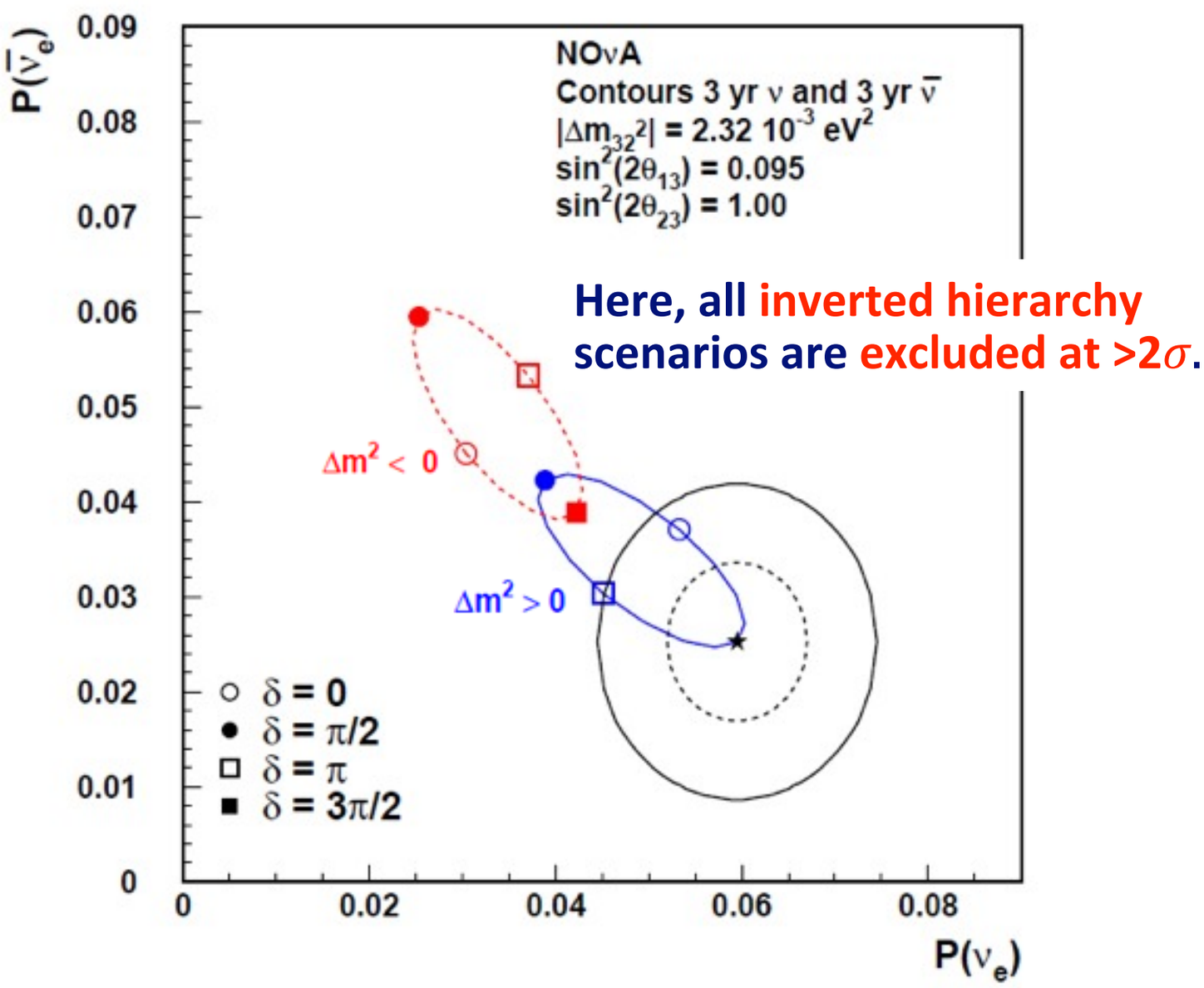

- Large $\theta_{13}$ is good news for NOvA. It reduces the overlap between these bi-probability ellipses, reducing the likelihood of degeneracies.

# NOvA physics

**Example NO$\nu$A result…**

**Our data will yield allowed regions in $P(\bar{\nu}_e)$ vs. $P(\nu_e)$ space**

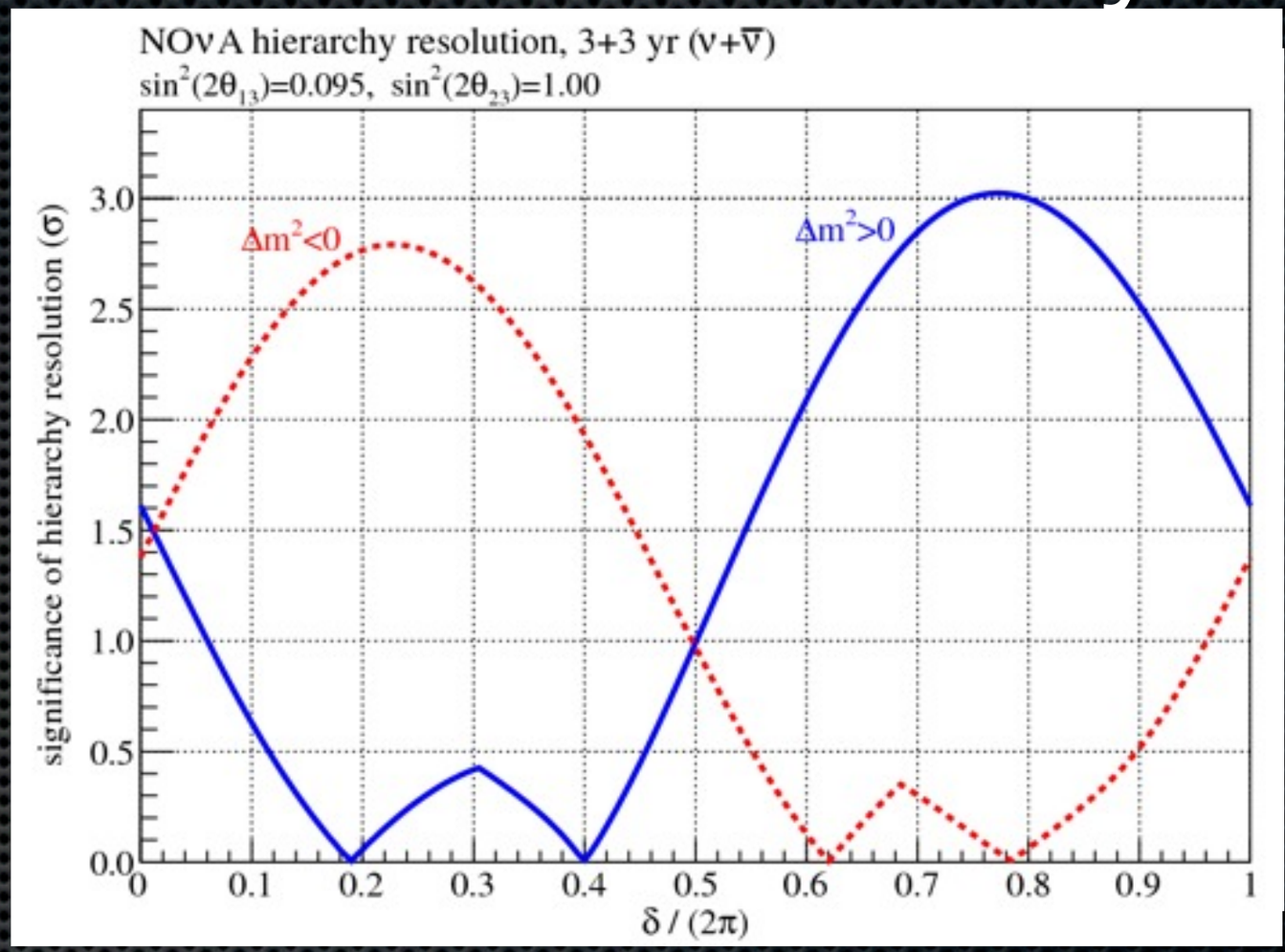
*(3 yr + 3 yr possibility shown)*

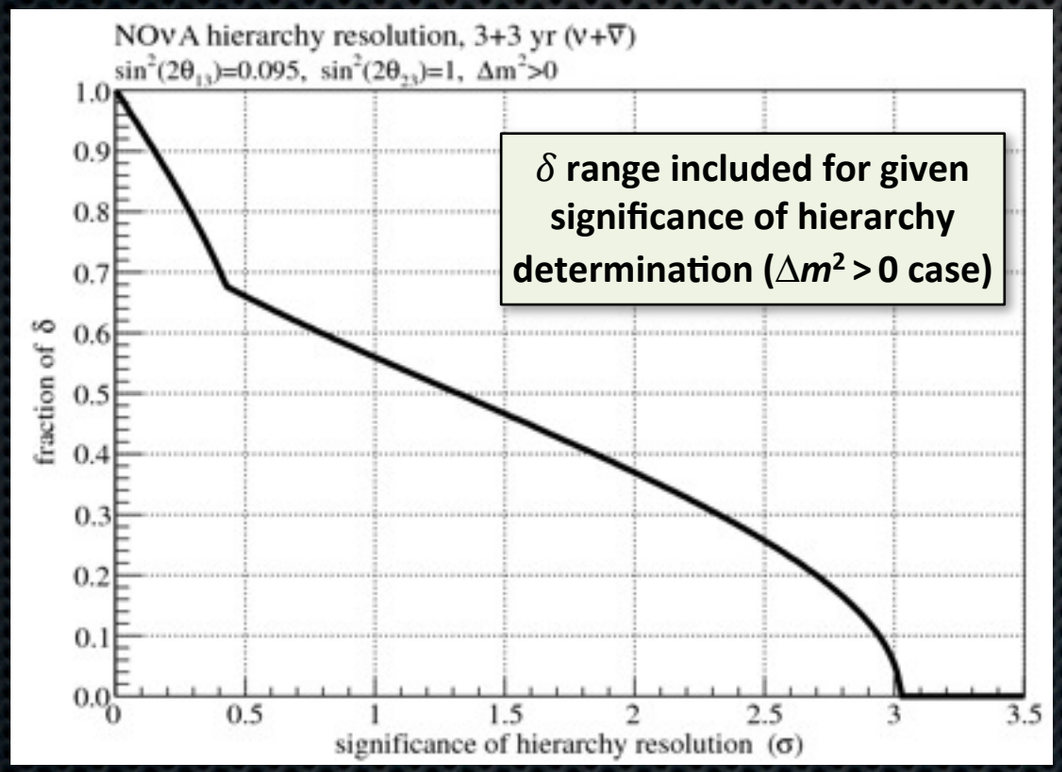



- A measurement of the probabilities might allow resolving the mass hierarchy and provide information on $\delta_{CP}$.

# Resolution of the mass hierarchy

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

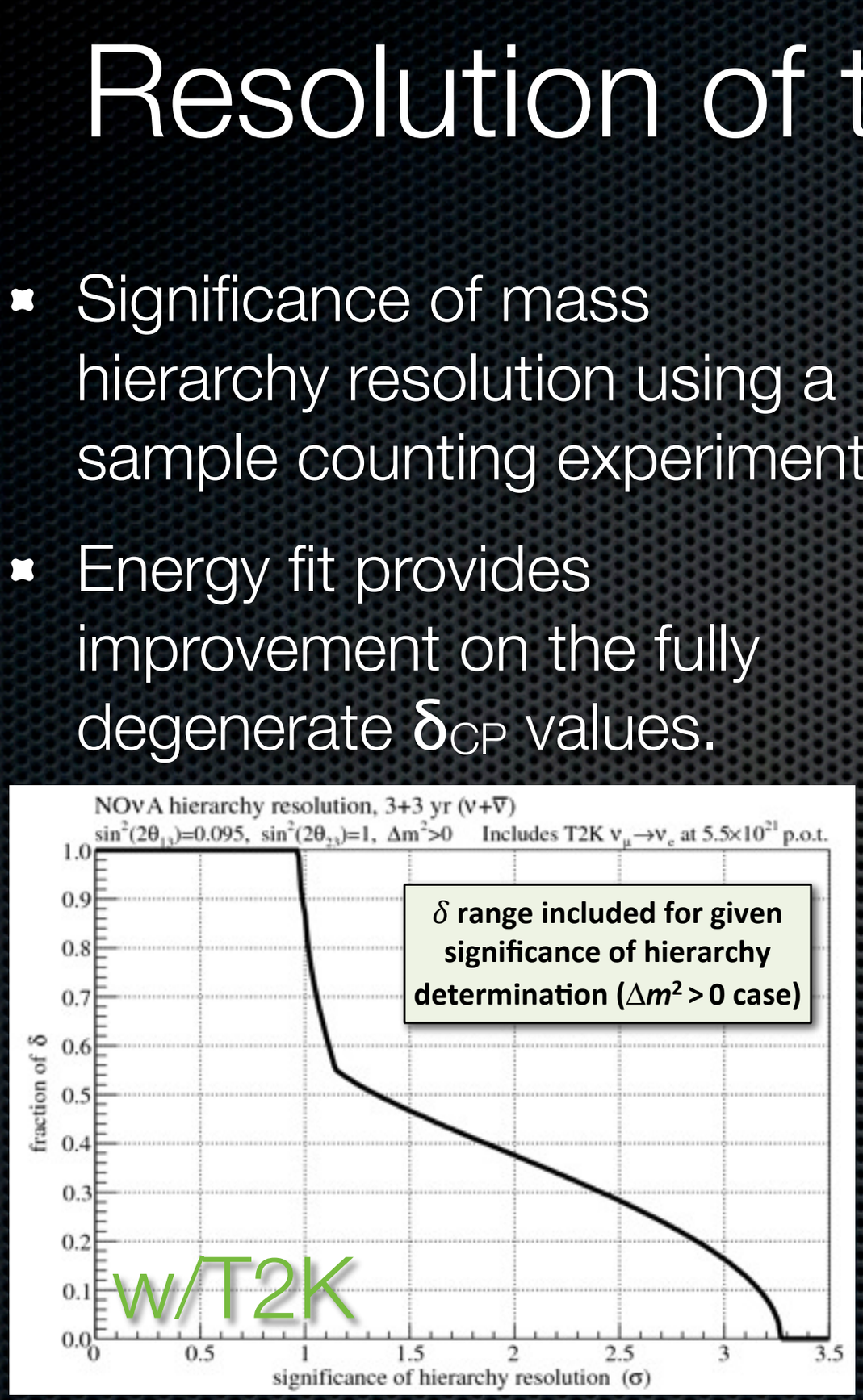


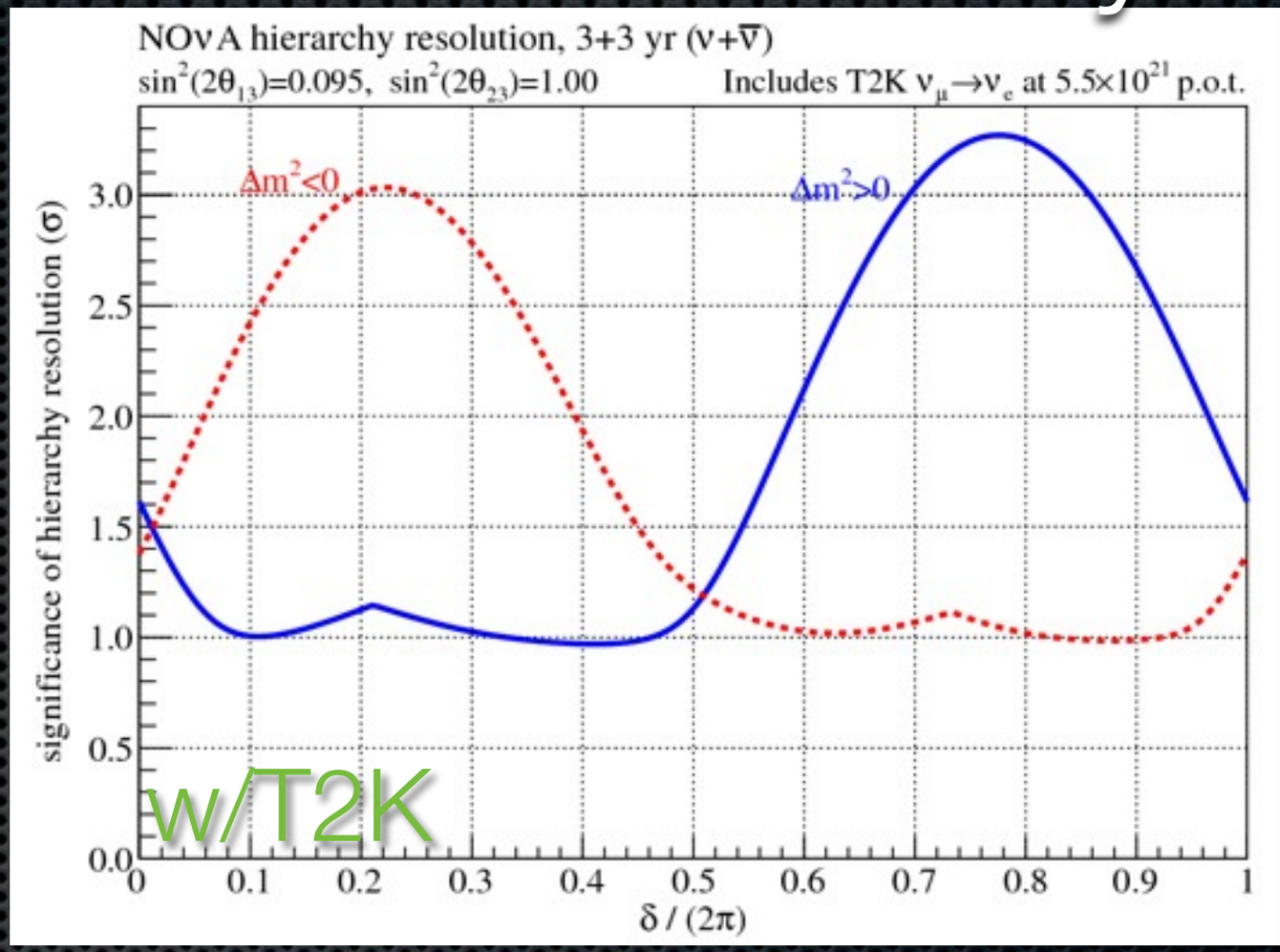




- We can also gain additional sensitivity from T2K's baseline.

# Resolution of the mass hierarchy

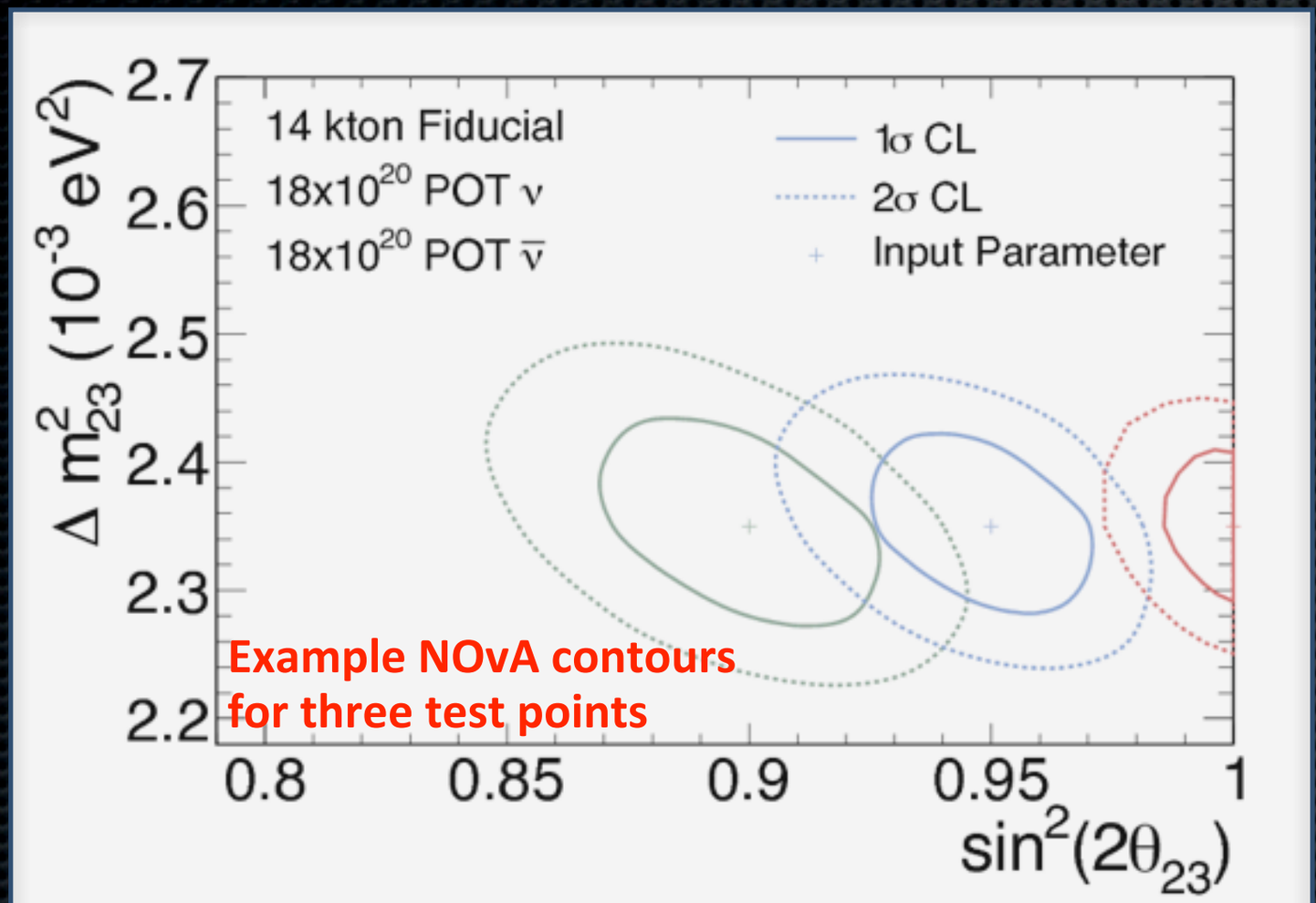
- Significance of mass hierarchy resolution using a sample counting experiment.
- Energy fit provides improvement on the fully degenerate $\delta_{CP}$ values.



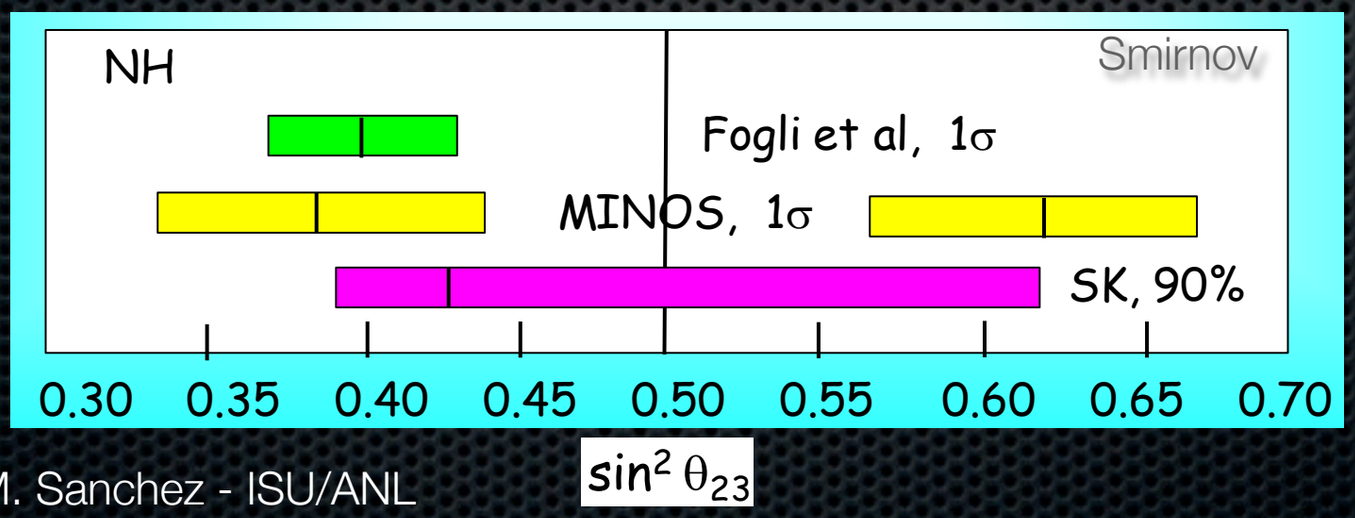



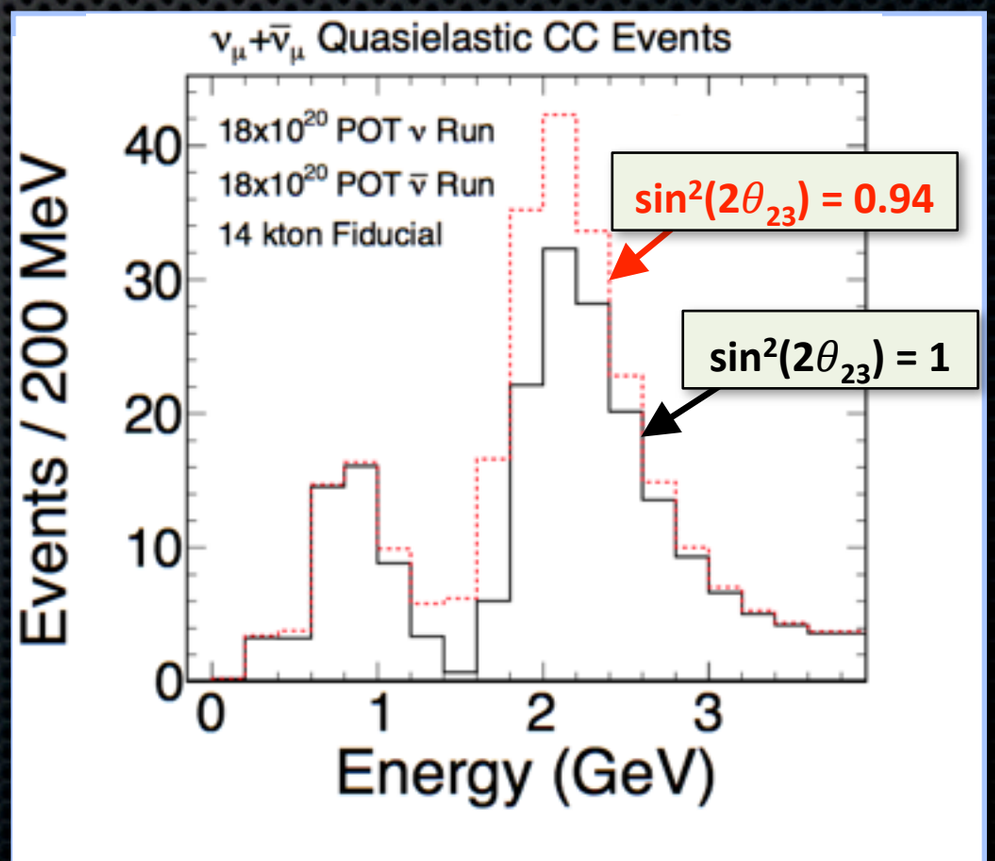

- We can also gain additional sensitivity from T2K's baseline.

# NOvA muon neutrino disappearance




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

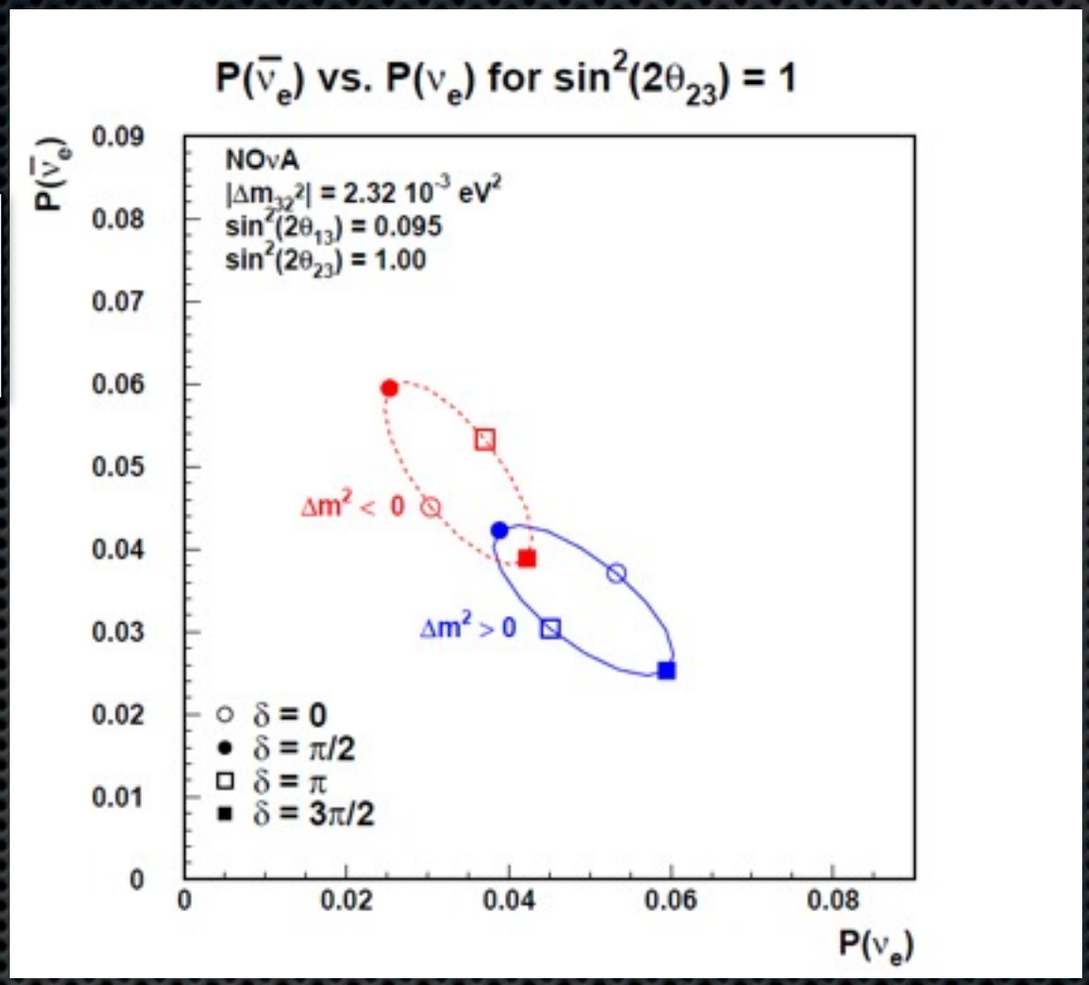


# Non-maximal $\sin^2 2\theta_{23}$

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

⇨ $\theta_{23}$ *octant sensitivity*

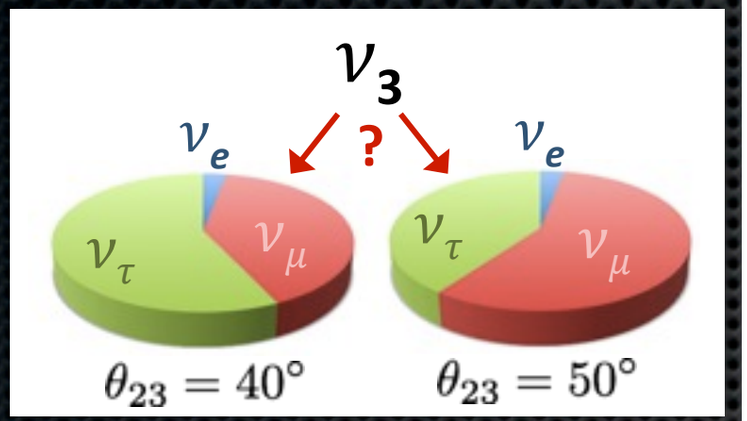


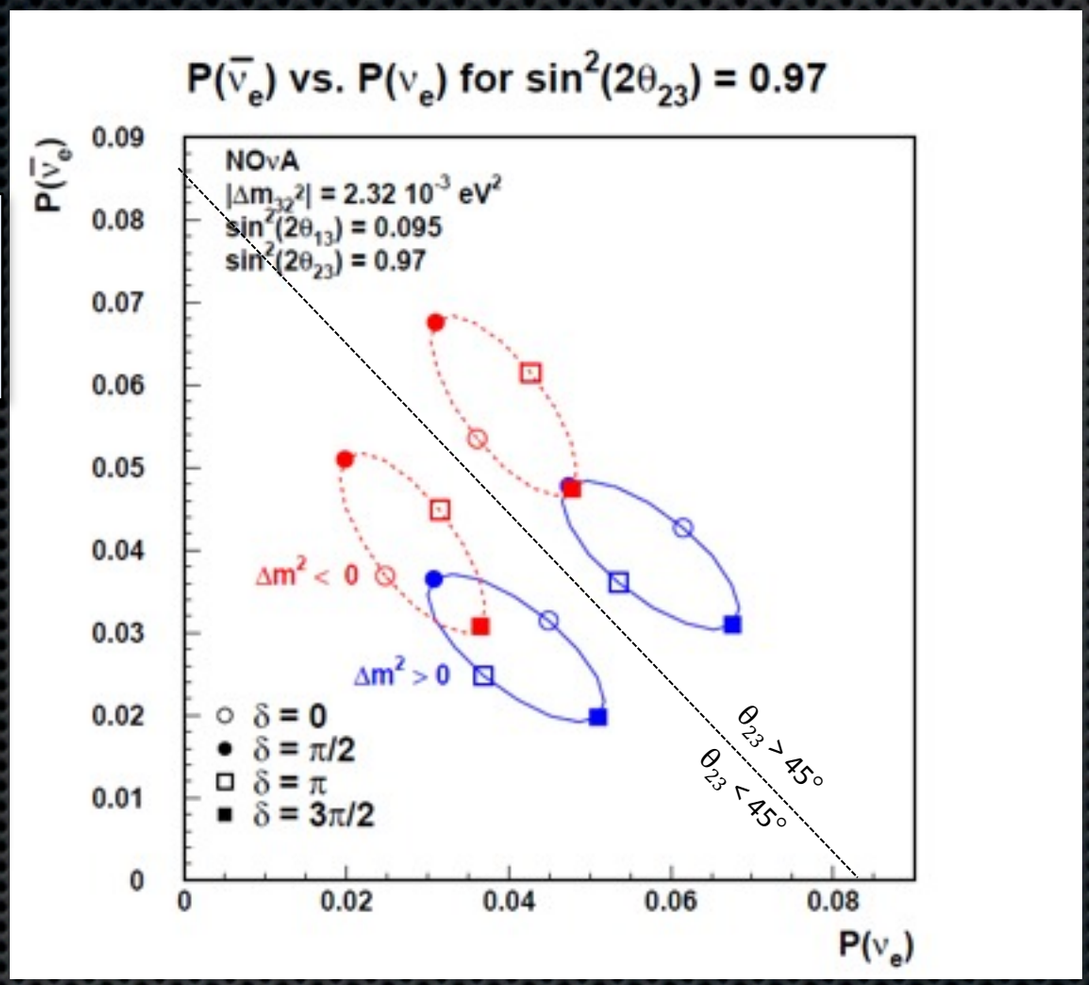

- If $\sin^2(2\theta_{23})$ is not maximal there is an ambiguity as to whether $\theta_{23}$ is larger or smaller than 45°.
- The $\sin^2(\theta_{23})$ term is unimportant when comparing accelerator experiments; however, it is crucial in comparing accelerator to reactor experiments

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

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

⇨ $\theta_{23}$ *octant sensitivity*

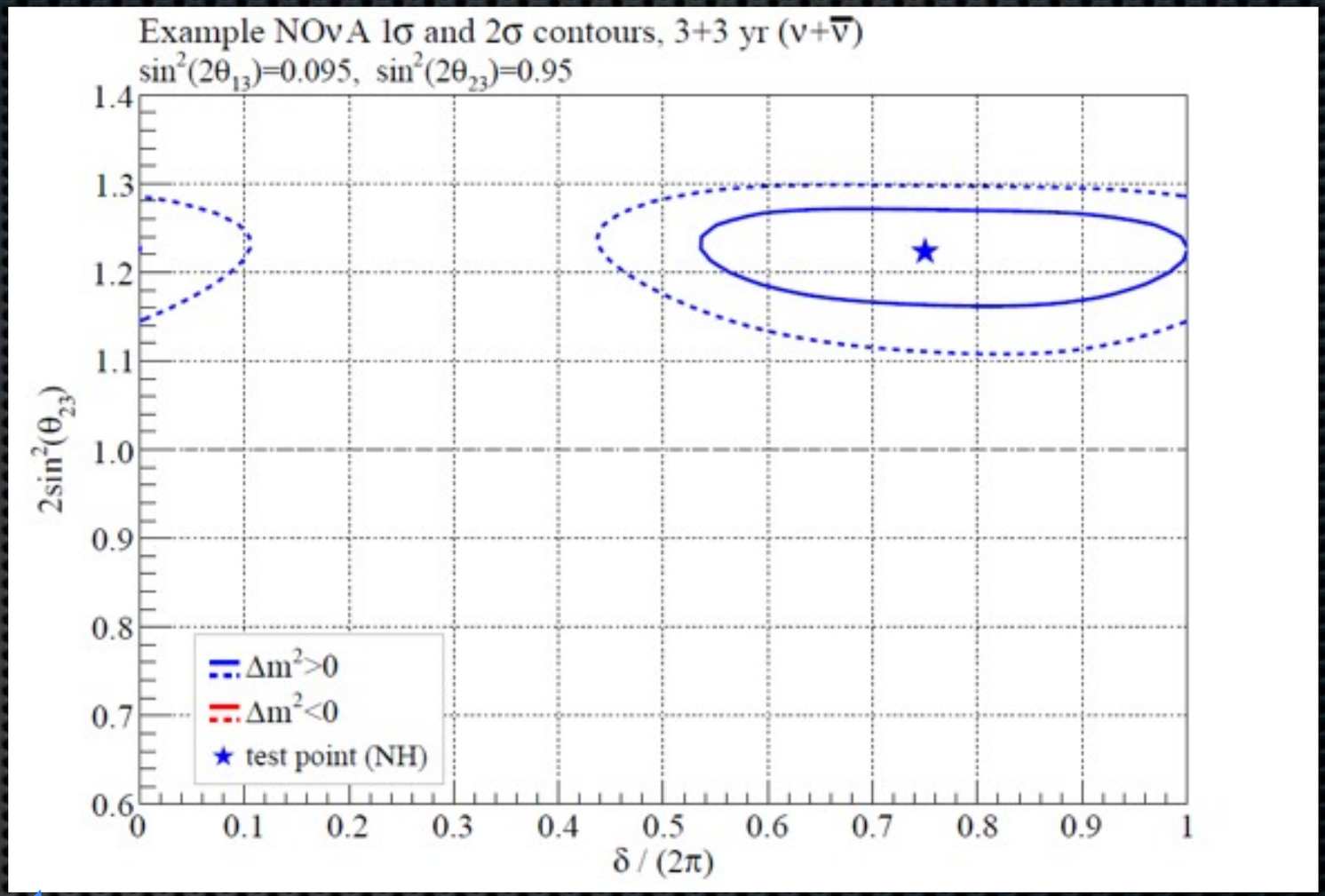


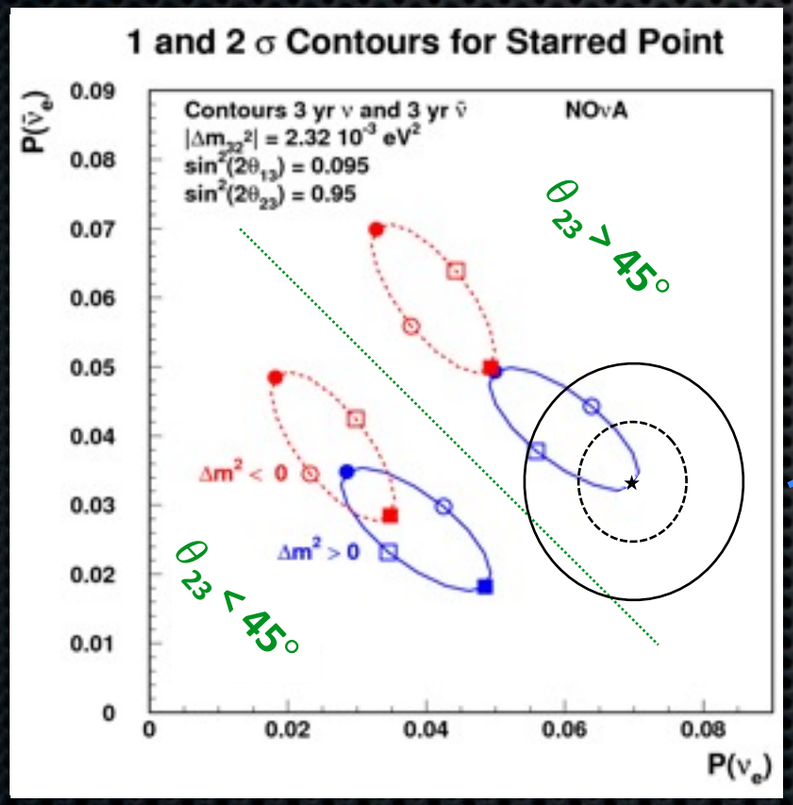




- If $\sin^2(2\theta_{23})$ is not maximal there is an ambiguity as to whether $\theta_{23}$ is larger or smaller than 45°.
- The $\sin^2(\theta_{23})$ term is unimportant when comparing accelerator experiments; however, it is crucial in comparing accelerator to reactor experiments

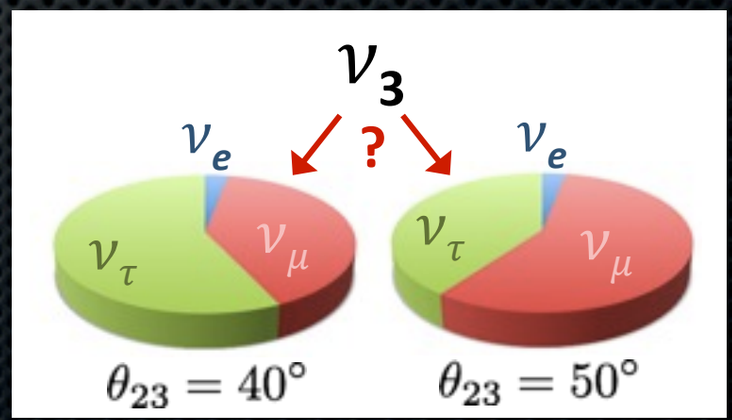
# Non-maximal $\sin^2 2\theta_{23}$ and NOvA

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




***Simultaneous hierarchy, CP phase, and $\theta_{23}$ octant information from NOvA***



- Just a few months ago, **the last unmeasured neutrino mixing angle, $\theta_{13}$,** was around the corner.
  - There is now **definite evidence** that this angle is as large as we could have hoped for.
- **The determination of the mass hierarchy, CP violation and the $\theta_{23}$ quadrant are the next challenges.**
  - NOvA is set to play an important role in solving these.
- **NOvA Far Detector assembly and NuMI upgrade are now underway.**
  - Expect first neutrino events in the partial detector next spring.
- Near Detector on the surface has provided commissioning, cosmic ray and neutrino data.
  - Actively developing analyses for first Far Detector neutrino data.

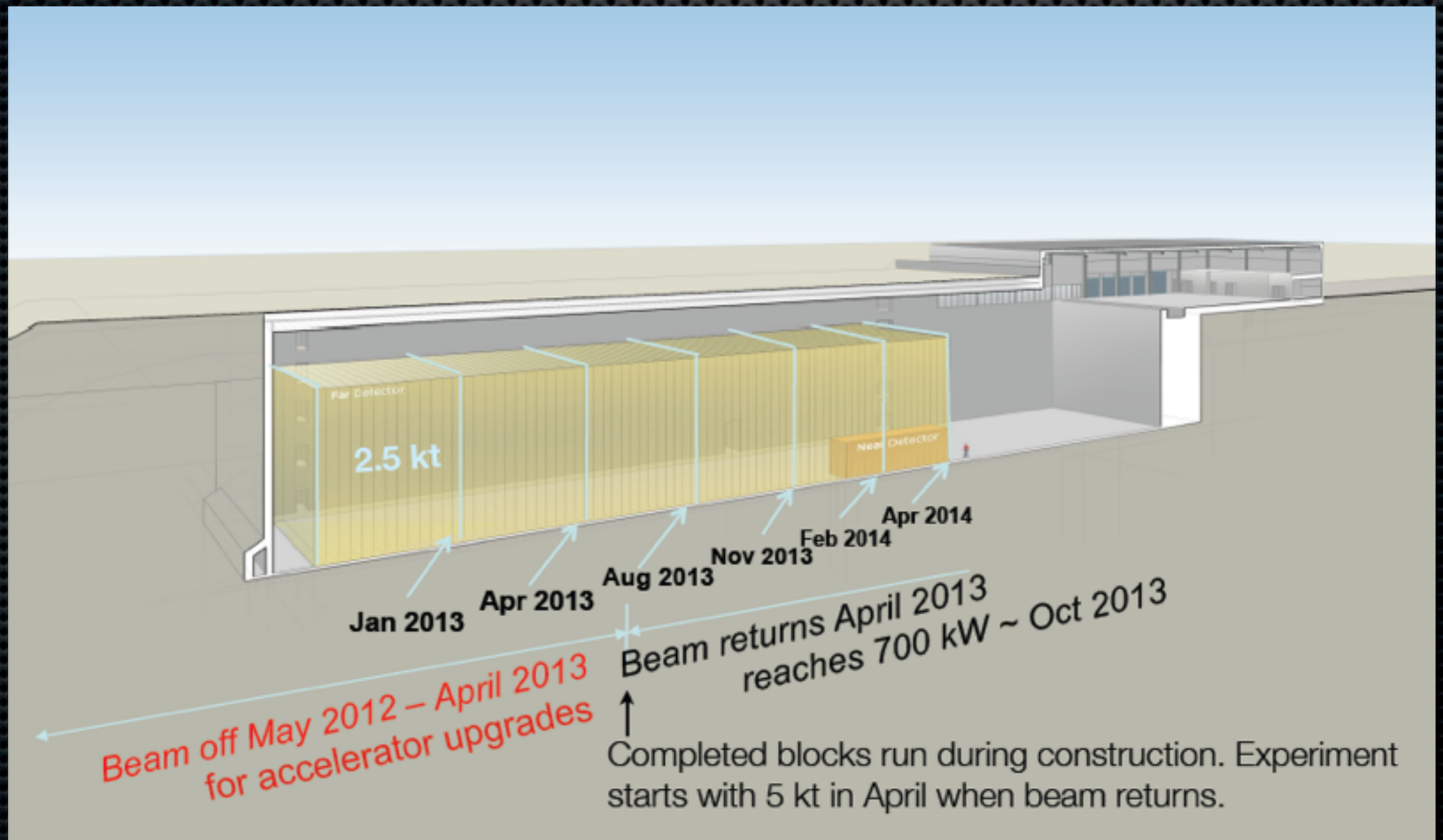
**NOvA Talks at New Perspectives tomorrow**

| | |
|---|---|
| **T. Kutnink** | ***Status of the NOvA Near Detector Prototype*** |
| **M. Betancourt** | ***Status of Quasi-elastic studies in the NOvA Near Detector Prototype*** |

# Backup

# NOvA construction schedule

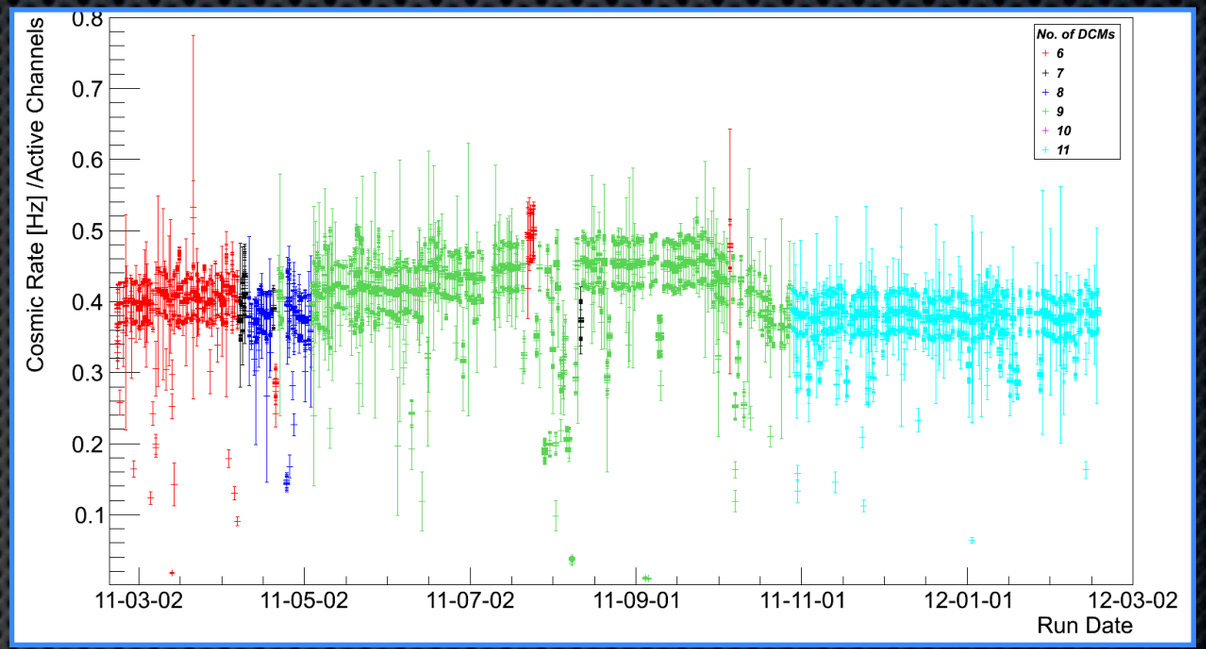
- NOvA will turn on April 2013 with 5 kton of Far detector in place and beam operating at ~ 400 kW
- We will add detector mass at a rate of ~ 1 kton/month
- Beam intensity will ramp up to 700 kW in approximately 6 months

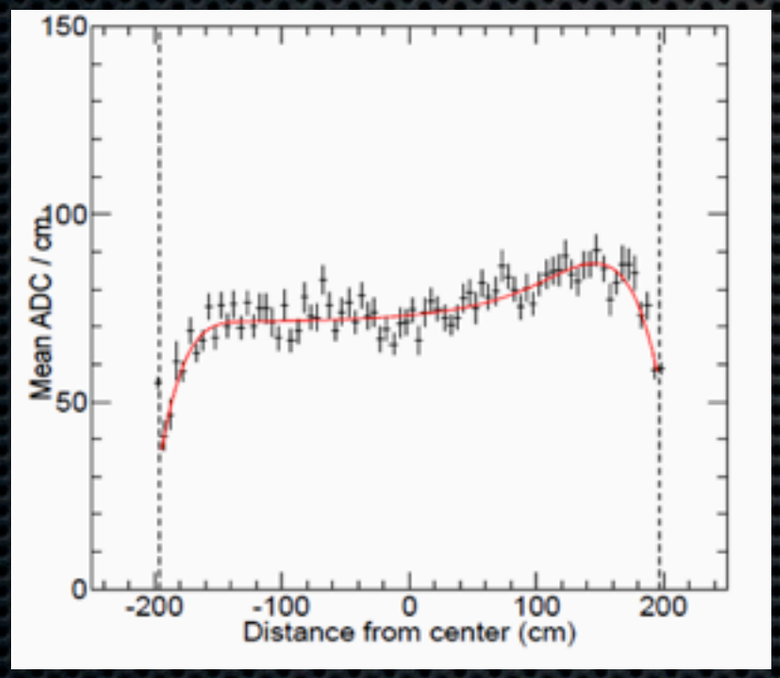


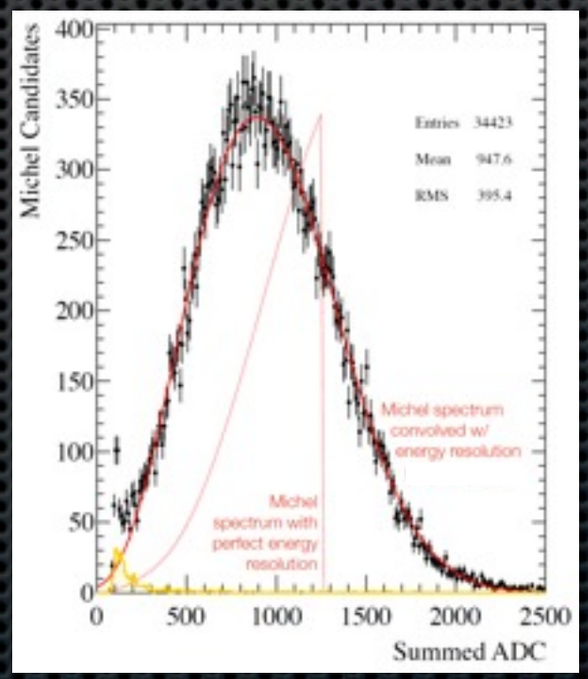
# NOvA Near Detector Prototype

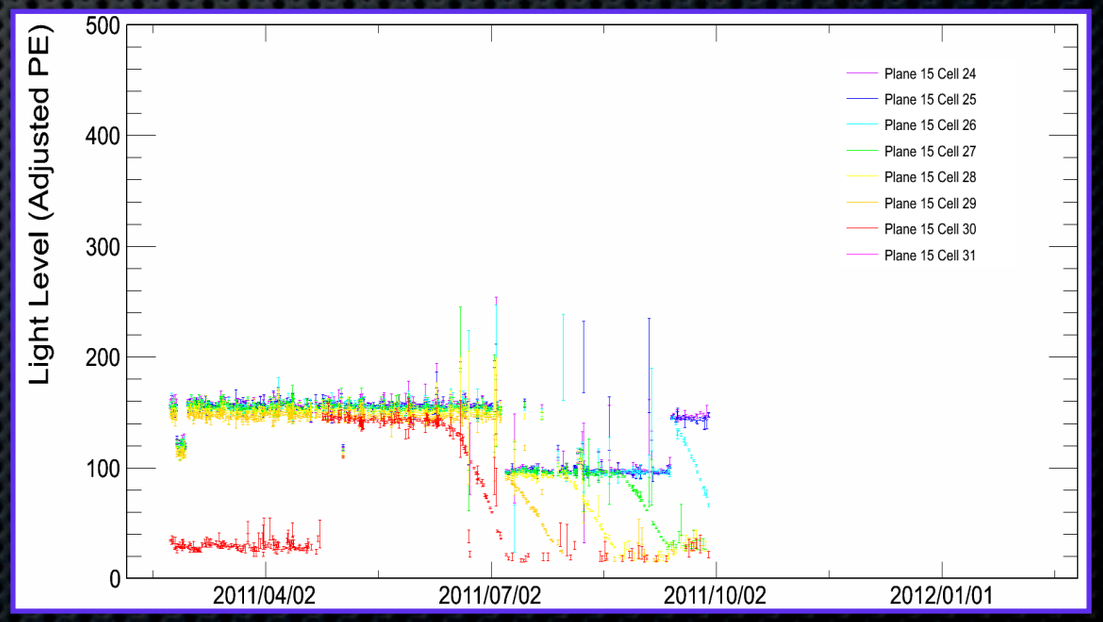
Plenty of cosmic ray data as detector is on surface

- Developing commissioning and calibration techniques:
  - Cosmic rate per number of active channels and light level as a function of of time.
  - Position dependence of cell response (light attenuation) and Michel electrons.



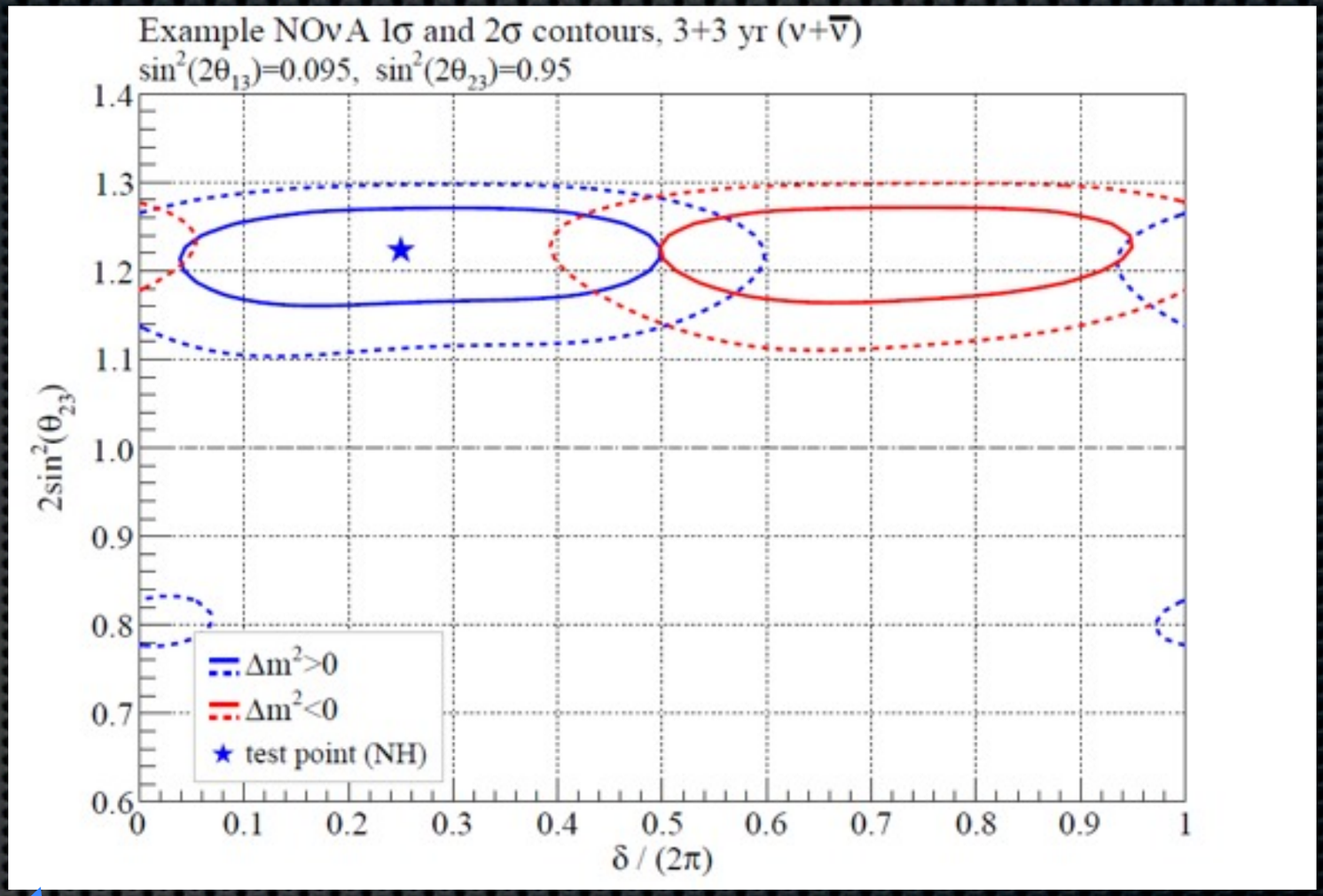



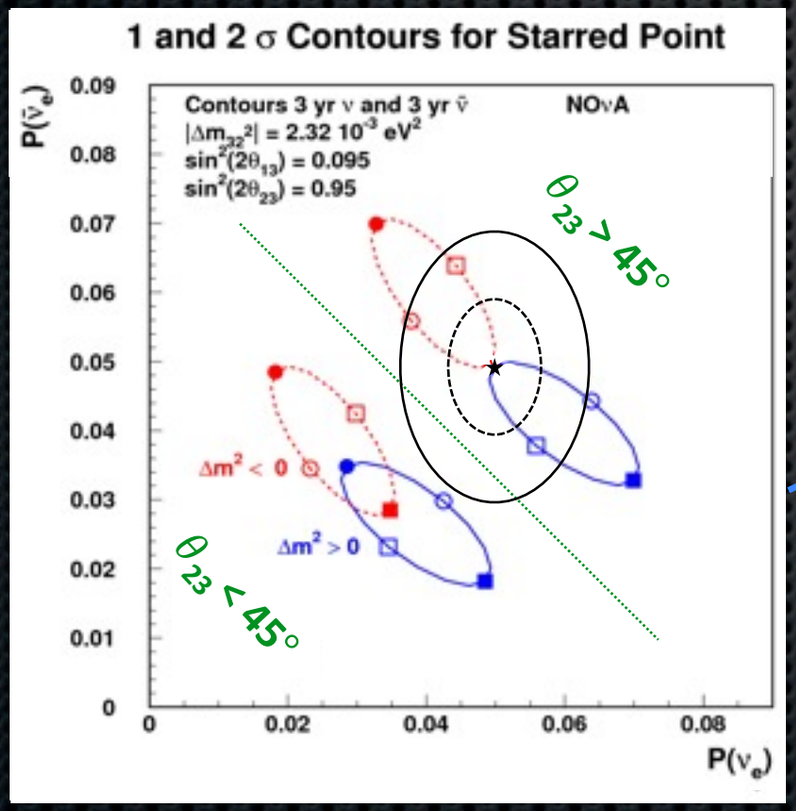



# Non-maximal $\sin^2 2\theta_{23}$ and NOvA

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




*In "degenerate" cases, hierarchy and $\delta$ information is coupled. However $\theta_{23}$ octant information might not.*