The NOvA Experiment: Status and Physics Reach

Mayly Sanchez

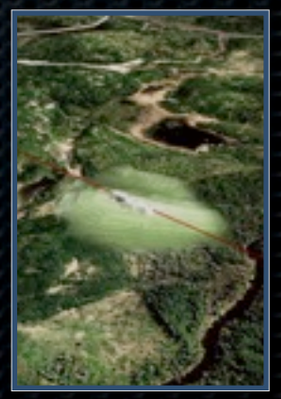
Iowa State University / Argonne National Laboratory

ISOUPS 2013: International Symposium: Opportunities for Underground Physics for Snowmass
Asilomar May 24-27, 2013

NOvA in a nutshell

- Upgrading NuMI **muon neutrino beam** at Fermilab from 350 to 700kW.
- Constructing a totally active **14-kton liquid scintillator detector** on the surface.
  - Detector is **14 mrad off-axis**, this location reduces background from neutral currents.
- Since the neutrino mixing angle θ_{13} is non-zero, **electron neutrinos will be observed** at the Far Detector in Ash River, 810 km away.

2nd generation
← long baseline →



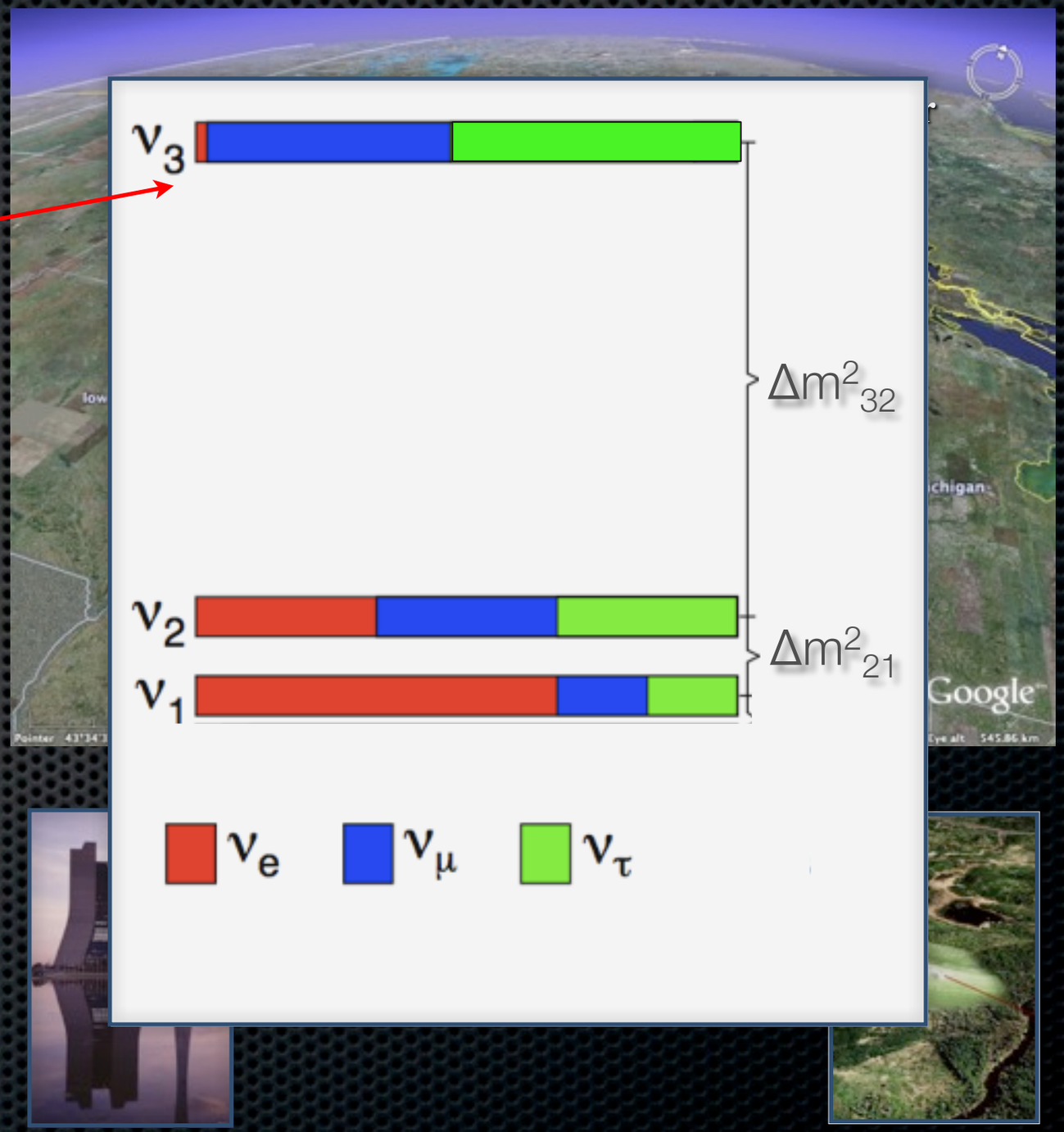
NOvA Collaboration

35 Institutions from 7 countries
181 collaborators
122 PhD physicists/ 23 Graduate students

Argonne National Laboratory · University of Athens · Banaras Hindu University · California Institute of Technology · Institute of Physics of the Academy of Sciences of the Czech Republic · Charles University, Prague · University of Cincinnati · Czech Technical University · University of Delhi · Fermilab · Indian Institute of Technology, Guwahati · Harvard University · Indian Institute of Technology · University of Hyderabad · Indiana University · Iowa State University · University of Jammu · Lebedev Physical Institute · Michigan State University · University of Minnesota, Crookston · University of Minnesota, Duluth · University of Minnesota, Twin Cities · Institute for Nuclear Research, Moscow · Panjab University · University of South Carolina · Southern Methodist University · Stanford University · University of Sussex · University of Tennessee · University of Texas at Austin · Tufts University · University of Virginia · Wichita State University · College of William and Mary

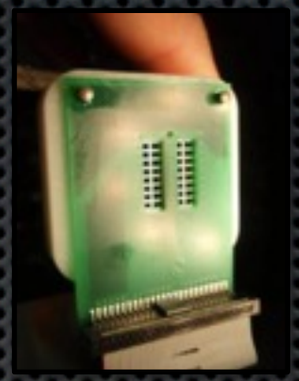
NOvA physics goals

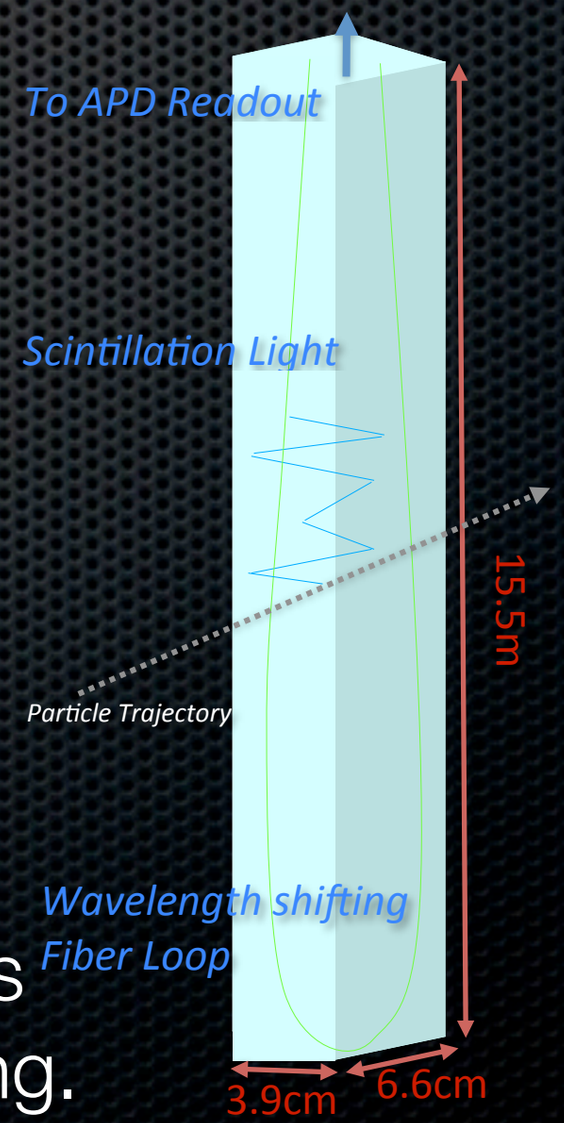
- Measure the oscillation probabilities of $\nu_\mu \rightarrow \nu_e$,$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ as well as $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$.
  - Measure the mixing angle θ_{13}.
  - Determine neutrino mass hierarchy.
  - Study the phase parameter for CP violation δ_{CP}.
  - Resolution of the θ_{23} octant.
  - Precision measurements of Δm^2_{32}, θ_{23}.
- As well as:
  - ν cross sections.
  - Sterile neutrinos.
  - Supernovae and monopoles!

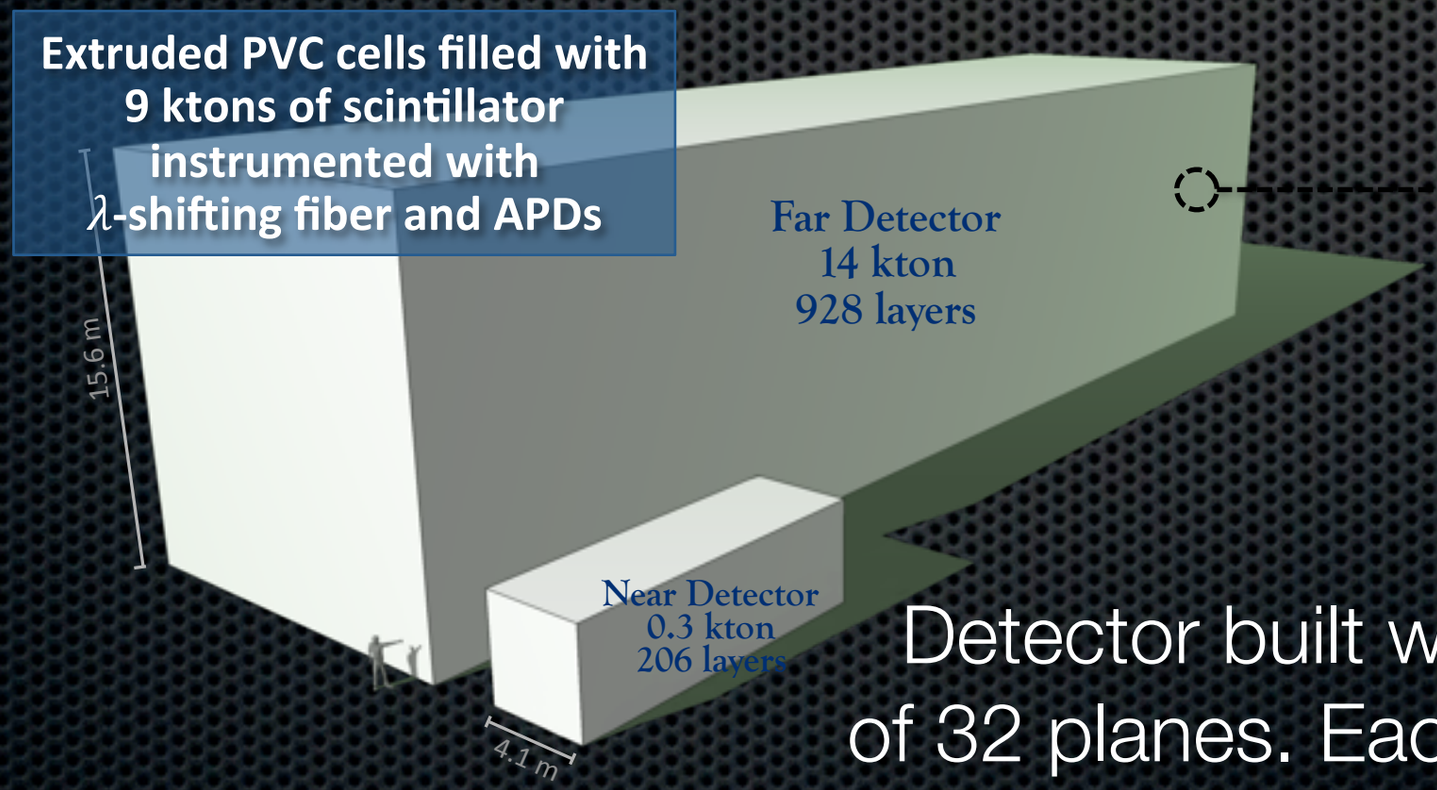


The NOvA detectors

- 14-kton Far Detector (~3x MINOS).
  - 65% active detector.
  - 344,064 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 .





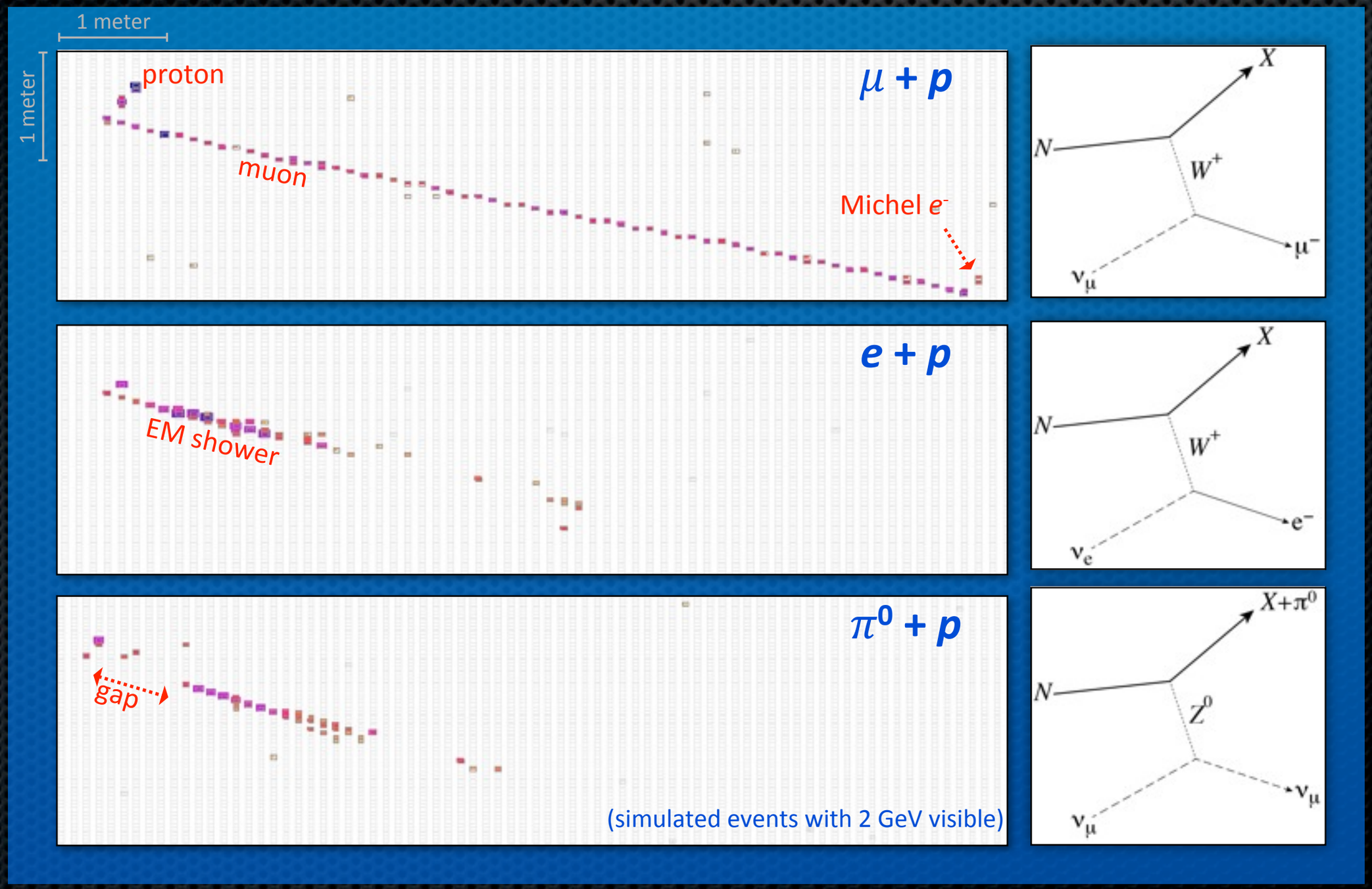


Detector built with 28 blocks of 32 planes. Each is ~2m long. Each di-block is 1 kton

Neutrino events in NOvA

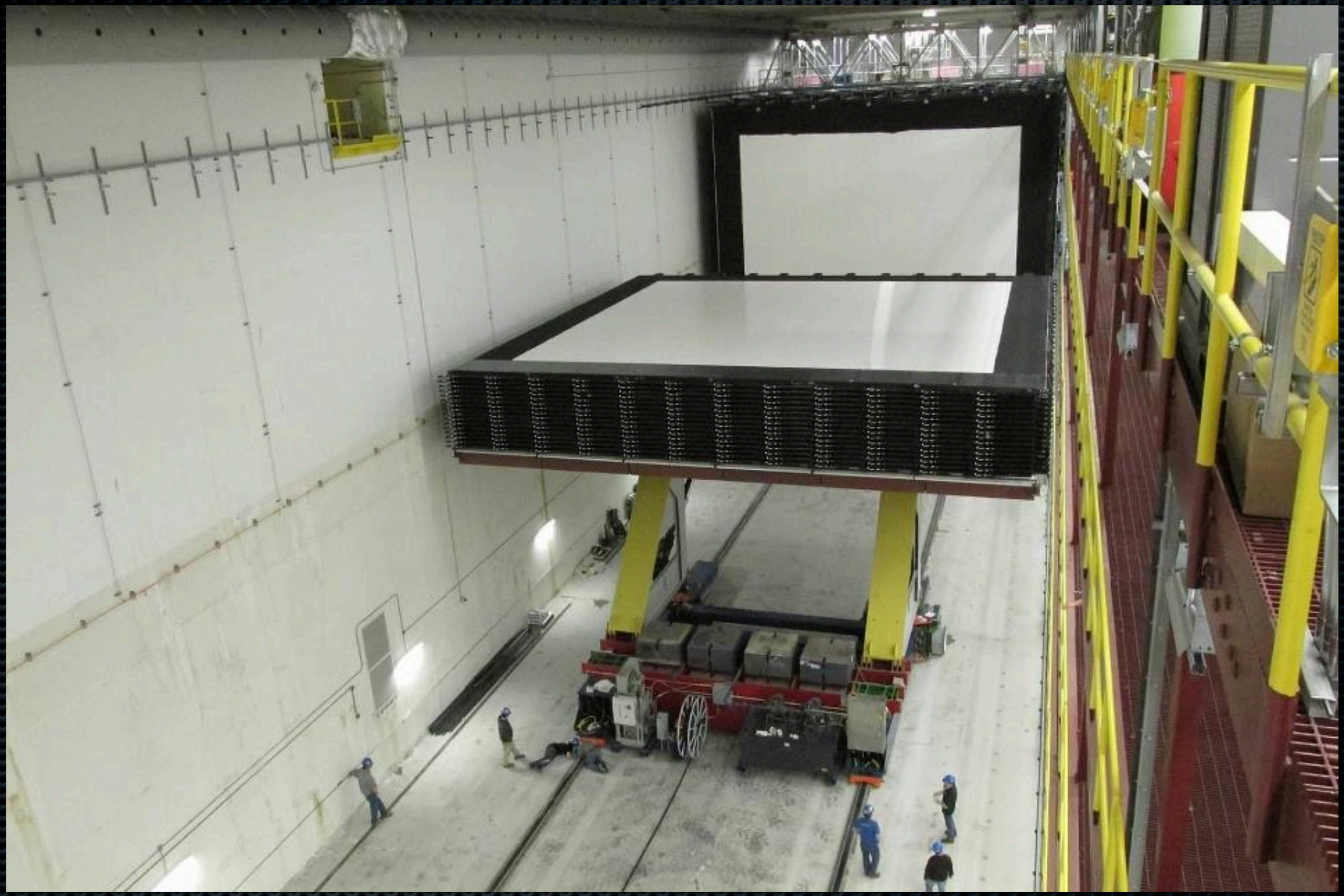
Excellent spatial granularity for a detector of this scale

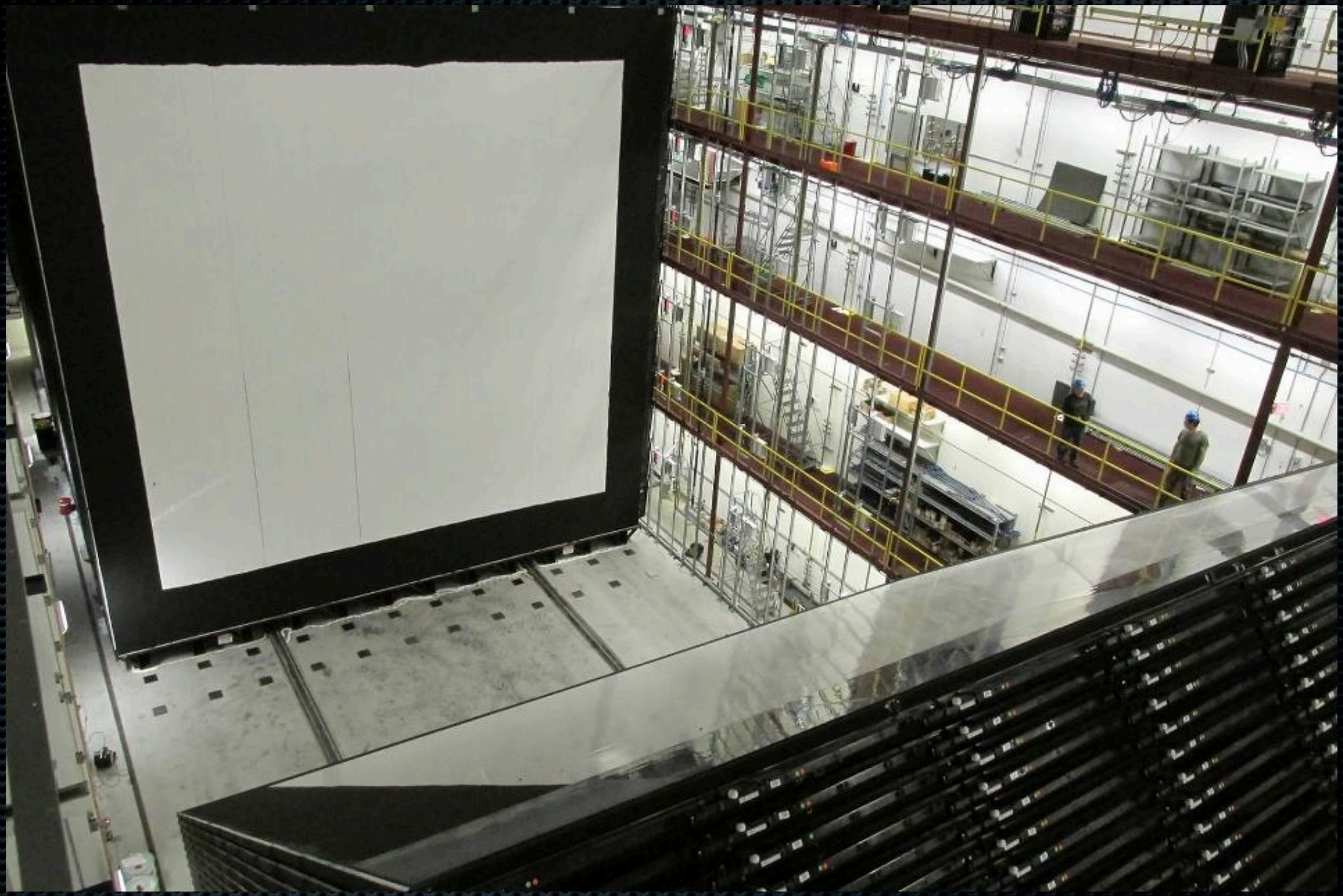
X_0 = 38 cm (6 cell depths, 10 cell widths)



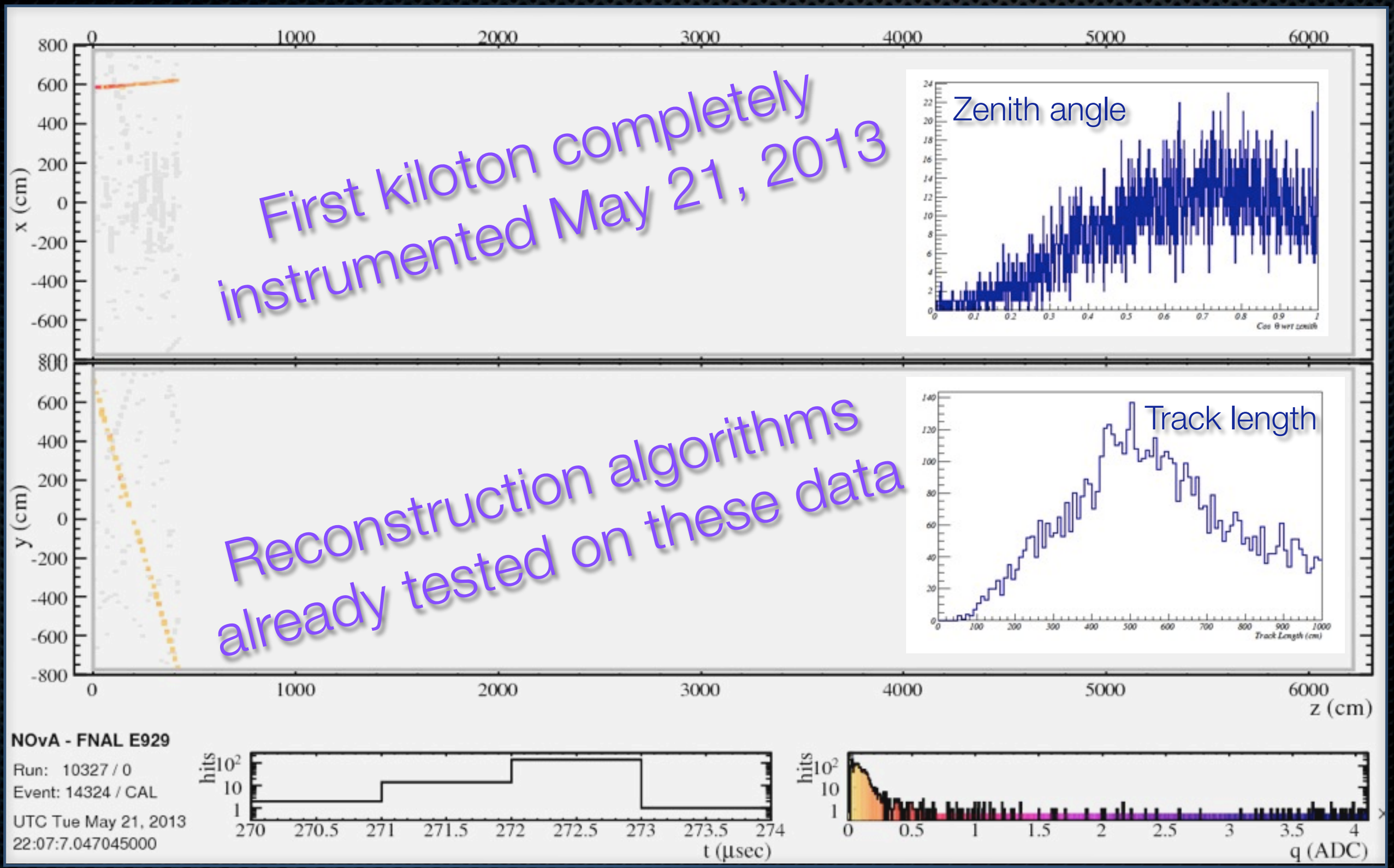
NOvA construction status

- The NOvA Far Detector construction is in progress.
  - The site at Ash River was completed last year.
- NOvA assembly and commissioning is in full swing:
  - 50% of the blocks have been installed.
  - 25% of the detector has been filled.

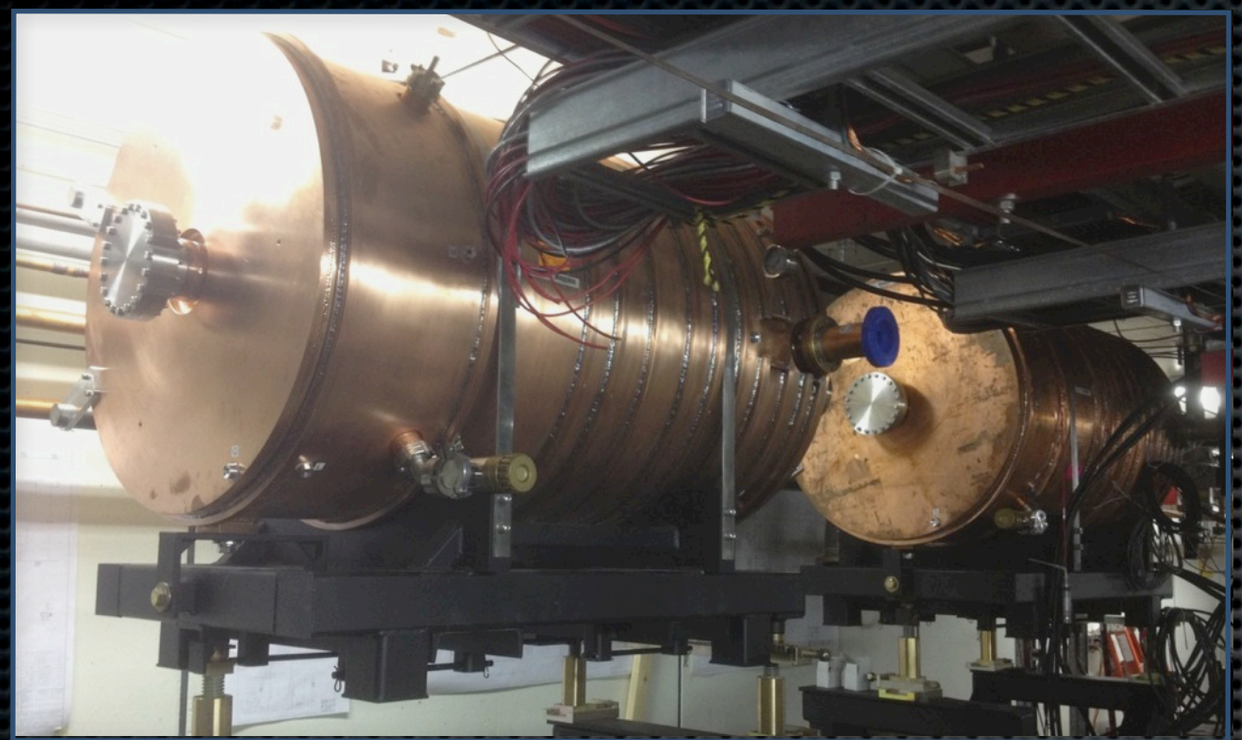




NOvA first FD cosmic ray data



NOvA construction status

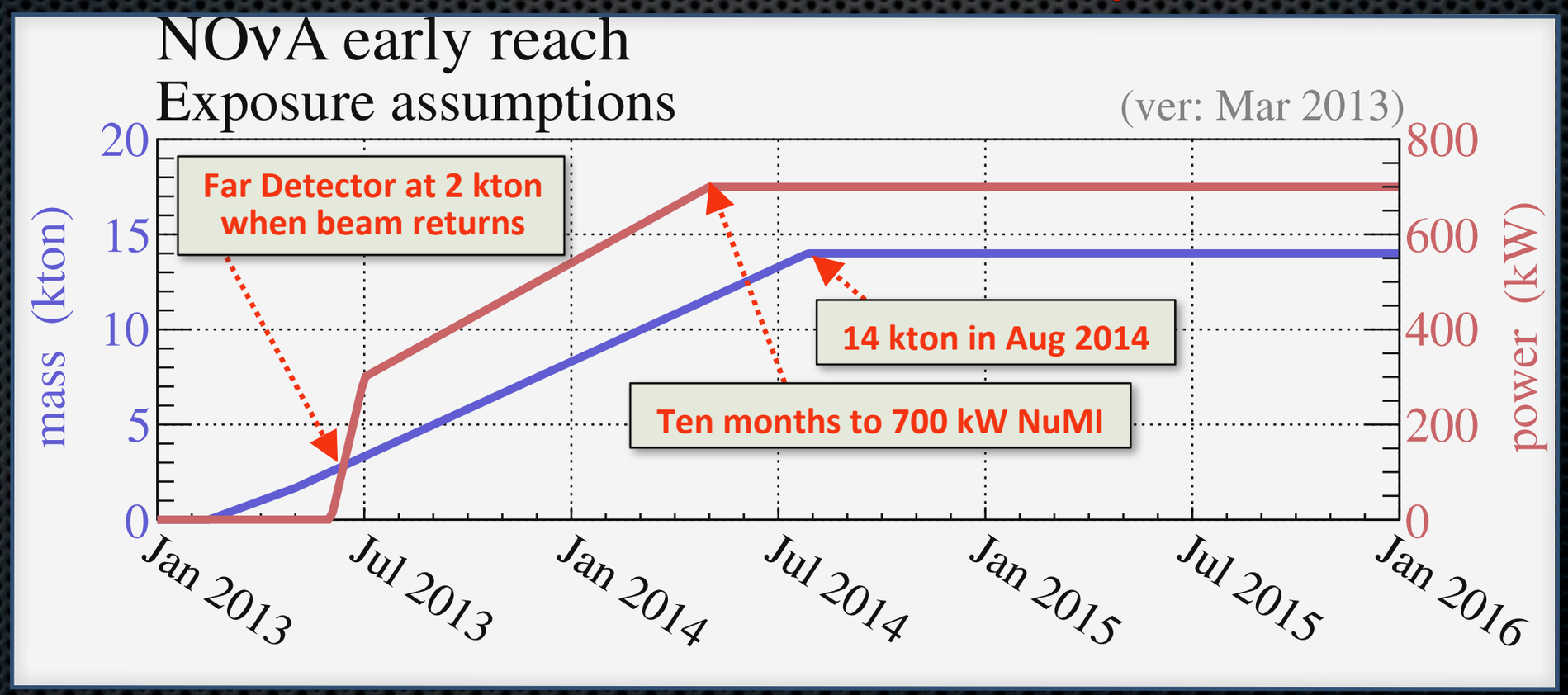


- Upgrade NuMI beam from 350 kW to 700kW initiated last year.
  - Beam starts mid-June at 400kW.
  - Ramping up to 700kW with booster upgrades.
- Near Detector cavern excavation is complete.
  - Installation starting soon.

NOvA exposure in early running

- NOvA will turn on mid-June with ~2 kton of Far Detector in place and beam operating at ~ 400 kW
- Far Detector complete in August 2014.
- Beam intensity will ramp up to 700 kW in approximately 10 months.

Evolution of detector mass and beam power



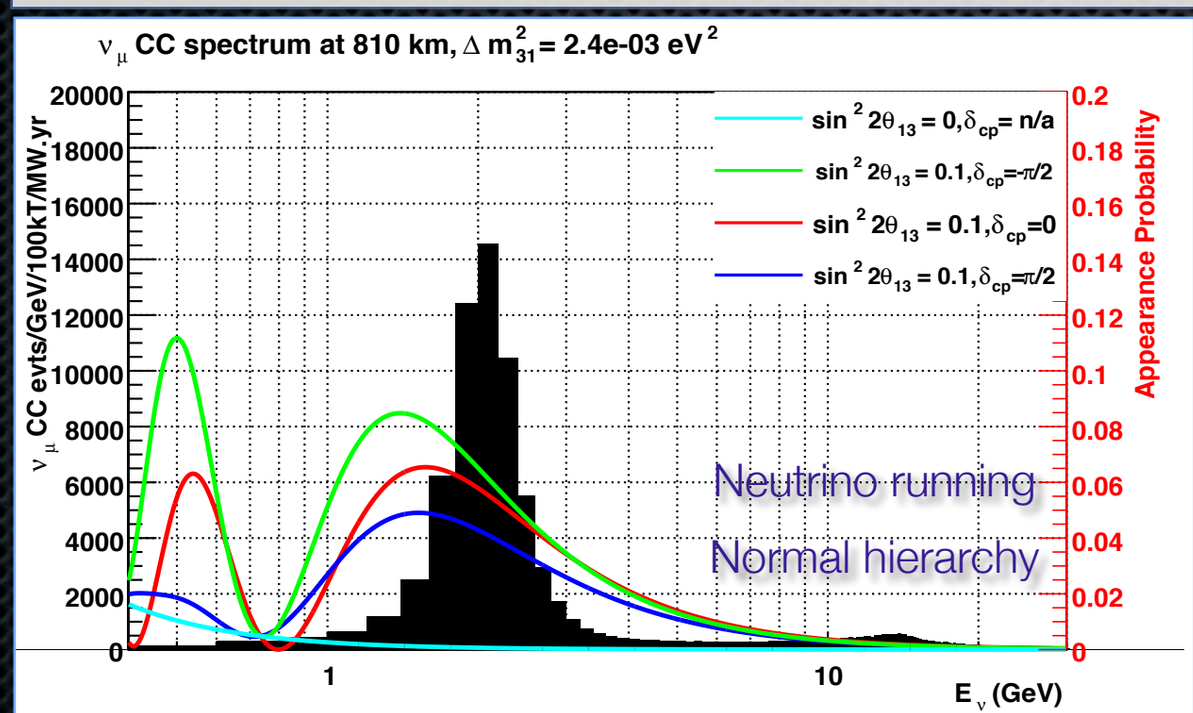
Electron neutrino appearance in NOvA

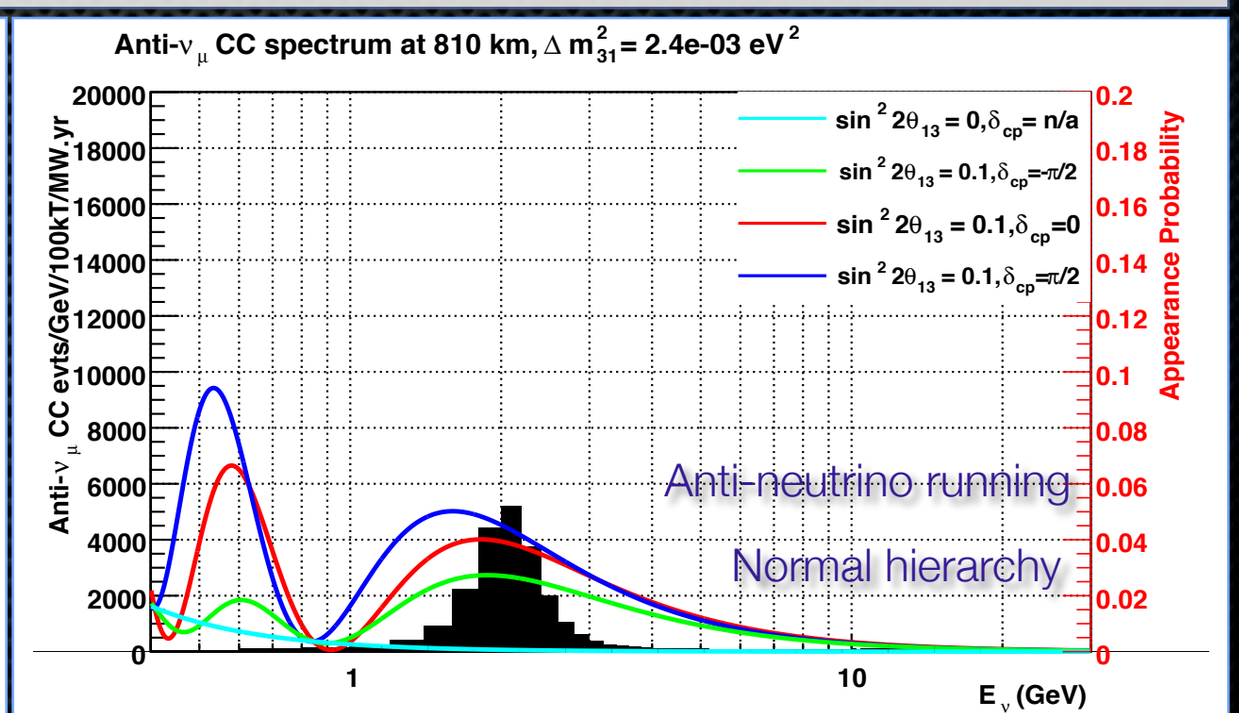
- The probability of ν_e appearance in a ν_μ beam:

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

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2 (A-1)\Delta}{(A-1)^2}$$
$$+ 2\alpha \sin\theta_{13} \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$
$$- 2\alpha \sin\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$

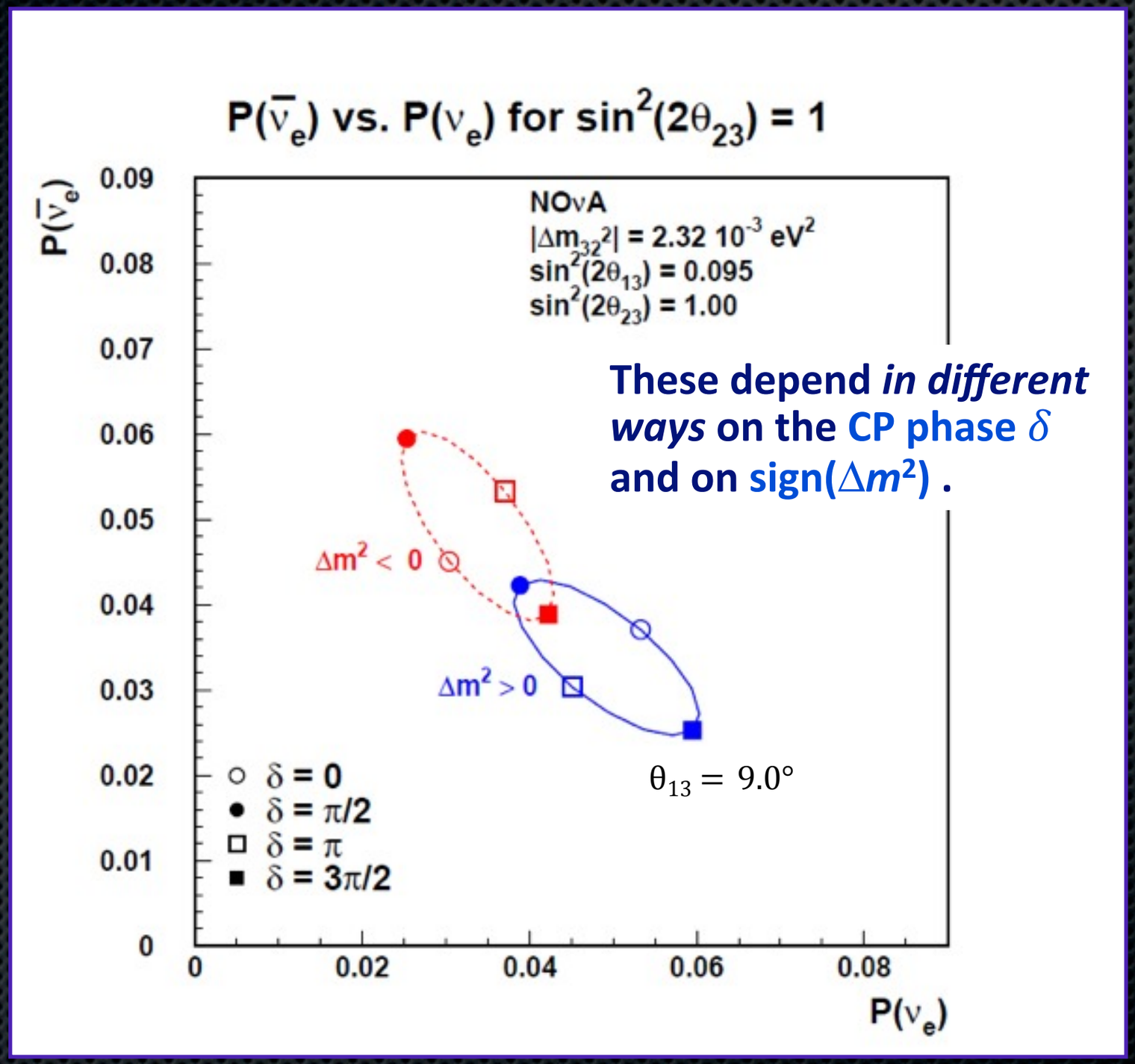




Plots by M. Bishai

NOvA physics

NOνA will measure: $P(\nu_\mu \to \nu_e)$ at 2 GeV *and* **$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ at 2 GeV**



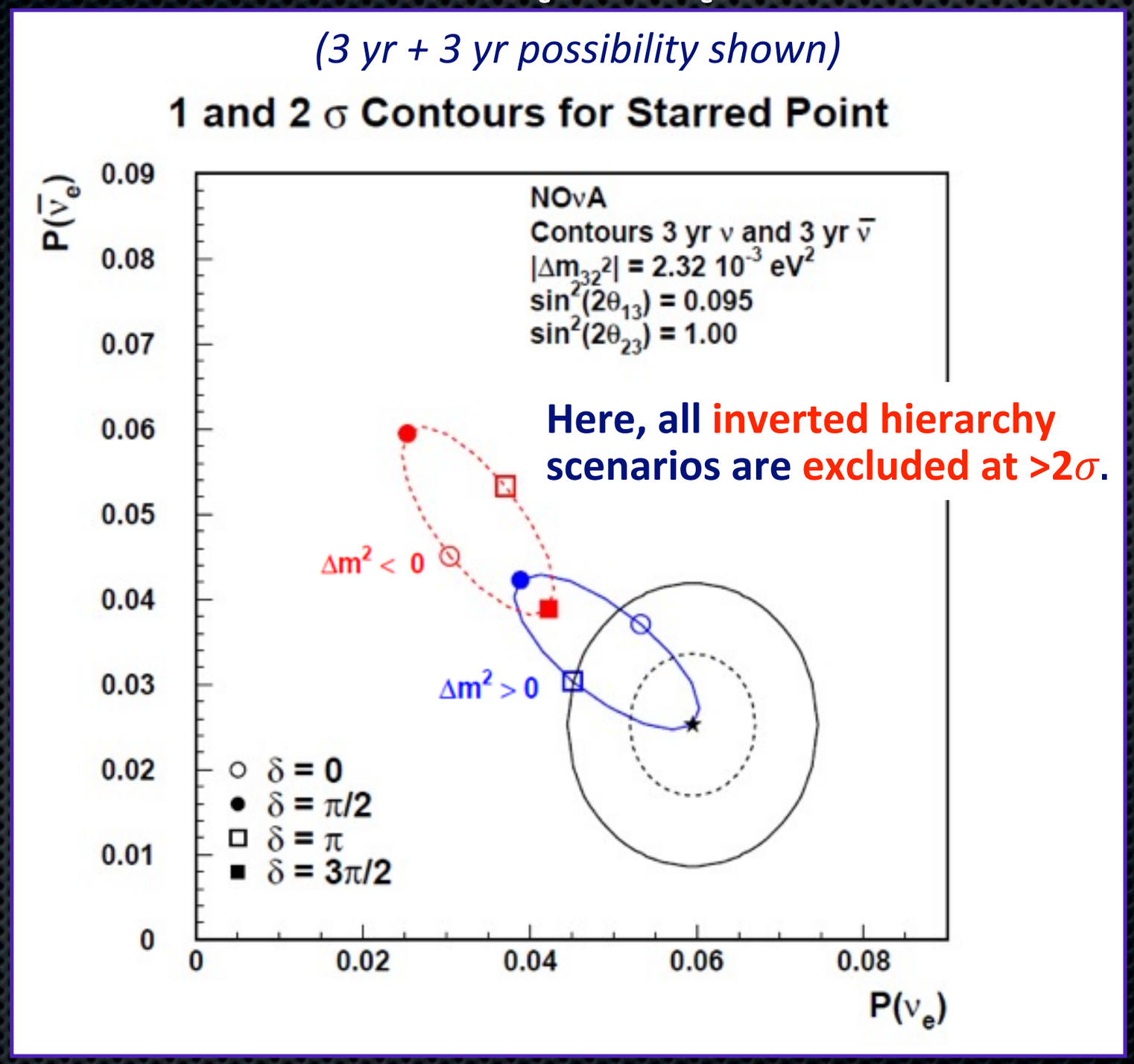
- Large θ_{13} is good news for NOvA. It reduces the overlap between these bi-probability ellipses, reducing the likelihood of degeneracies.

NOvA physics

Example NOνA result…

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

(3 yr + 3 yr possibility shown)



Here, all inverted hierarchy scenarios are excluded at >2σ.

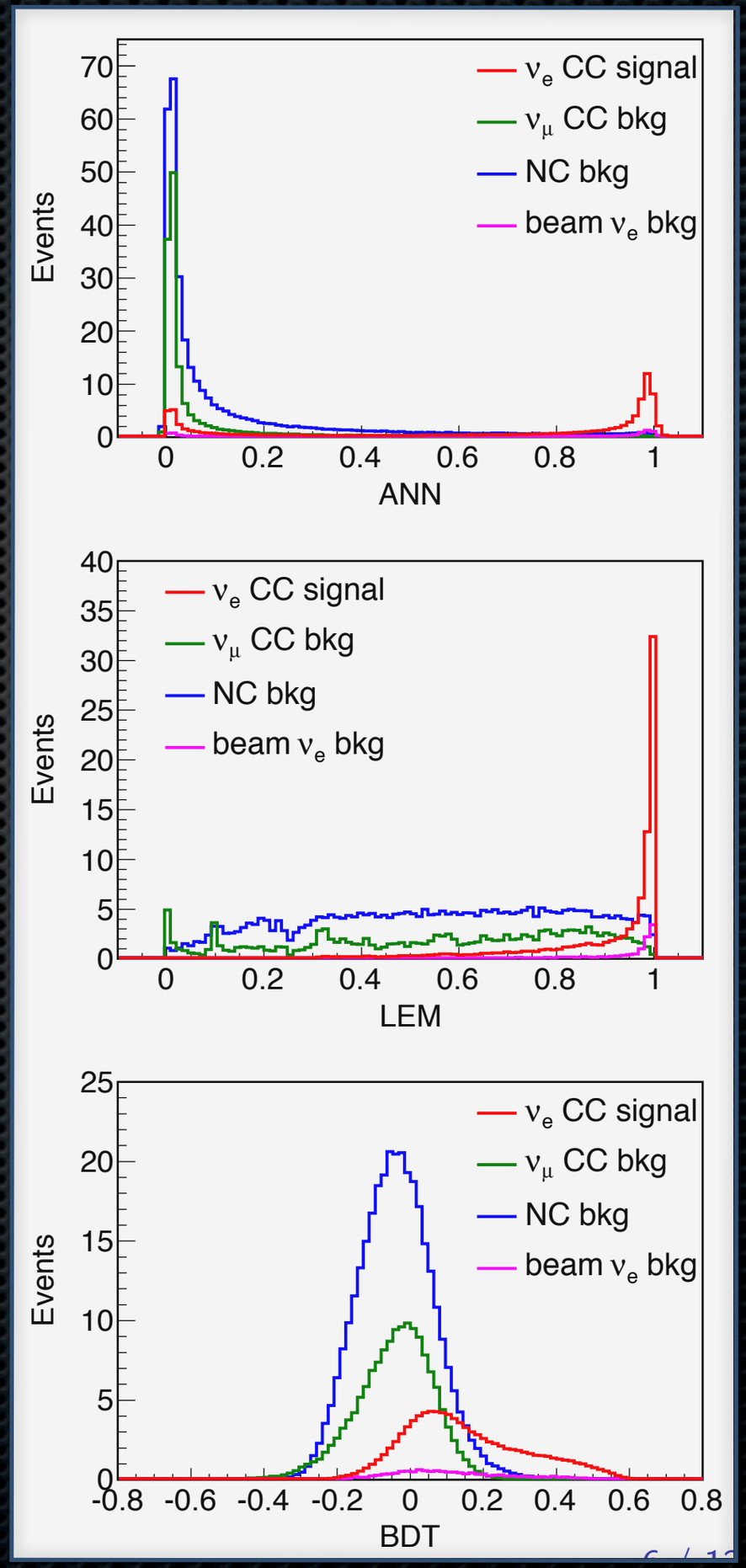
- A measurement of the probabilities might allow resolving the mass hierarchy and provide information on δ_{CP}.

Electron neutrino selection

- Several particle ID algorithms have been developed:
  - ANN: Likelihood ratios for particle hypotheses.
  - LEM: Matching to Monte Carlo library events.
  - BDT: boosted decision tree on simple reconstructed quantities.
- Good separation of electron neutrino signal from background.

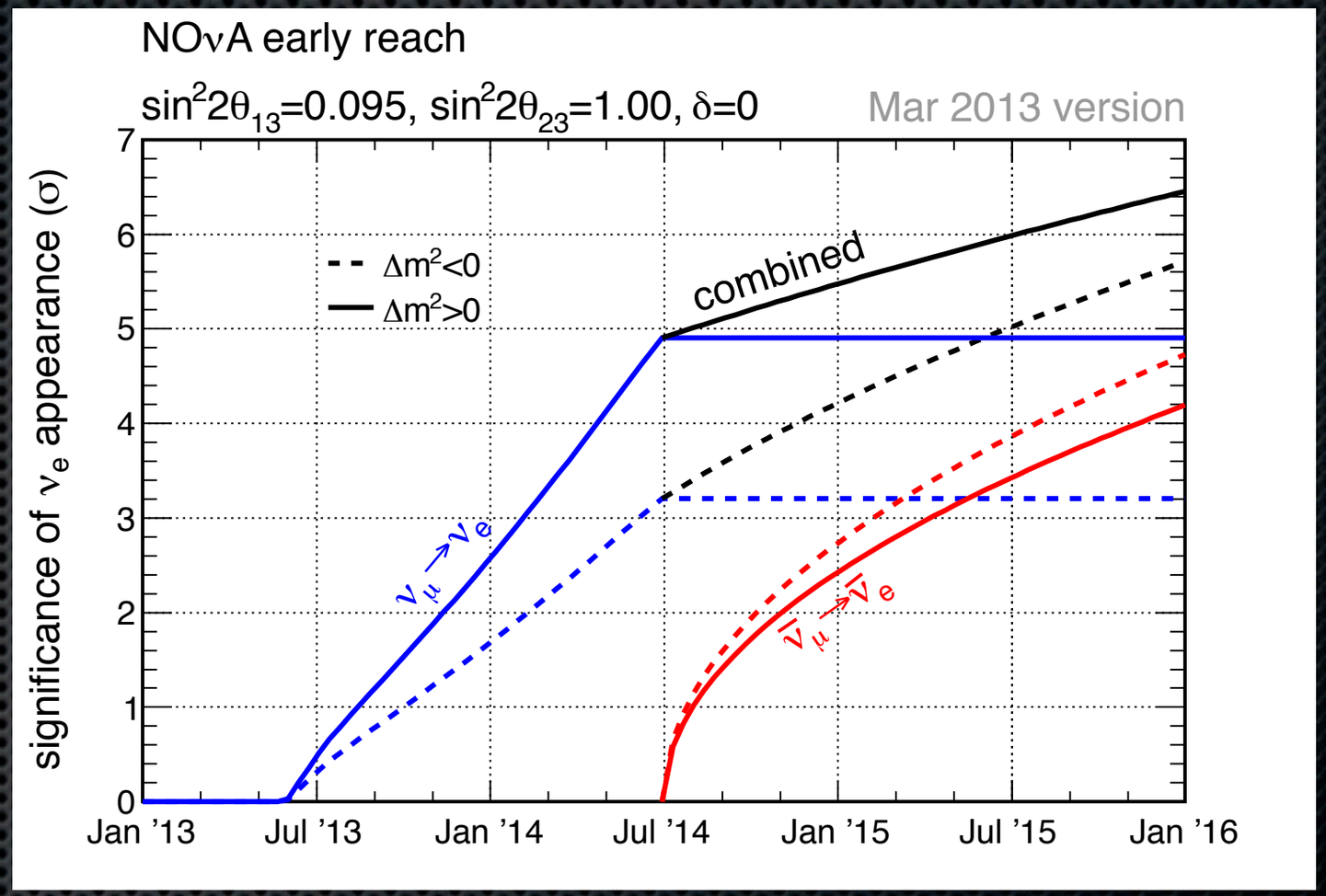
ANN	signal	total bkgd	NC bkgd	ν_μ CC bkgd	ν_e CC bkgd
ν (3 yrs)	56	28	17	4	7
$\bar{\nu}$ (3 yrs)	26	14	9	1	4

Signal eff: ~30-40% and NC fake rate ~0.3%.



NOvA first objective

- 5σ observation of $\nu_\mu \rightarrow \nu_e$ in first year if normal hierarchy (even with partial detector and beam commissioning!)
- Nominal run plan 3 years in each mode at 6 x 10^{20} POT/year for a total of 18 x 10^{20} POT in each mode.
  - Start running with neutrinos.
  - Switch to anti-neutrino running as needed.

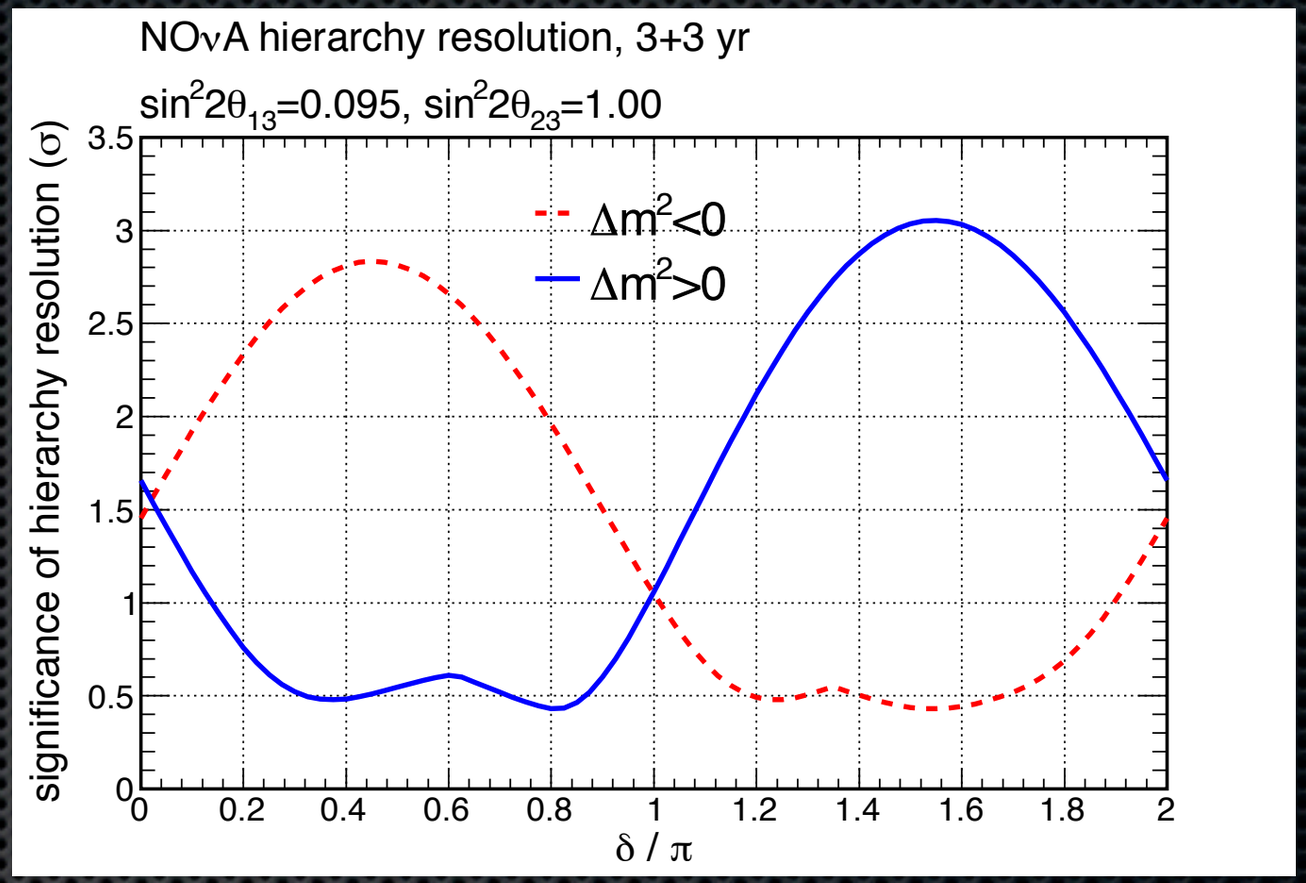


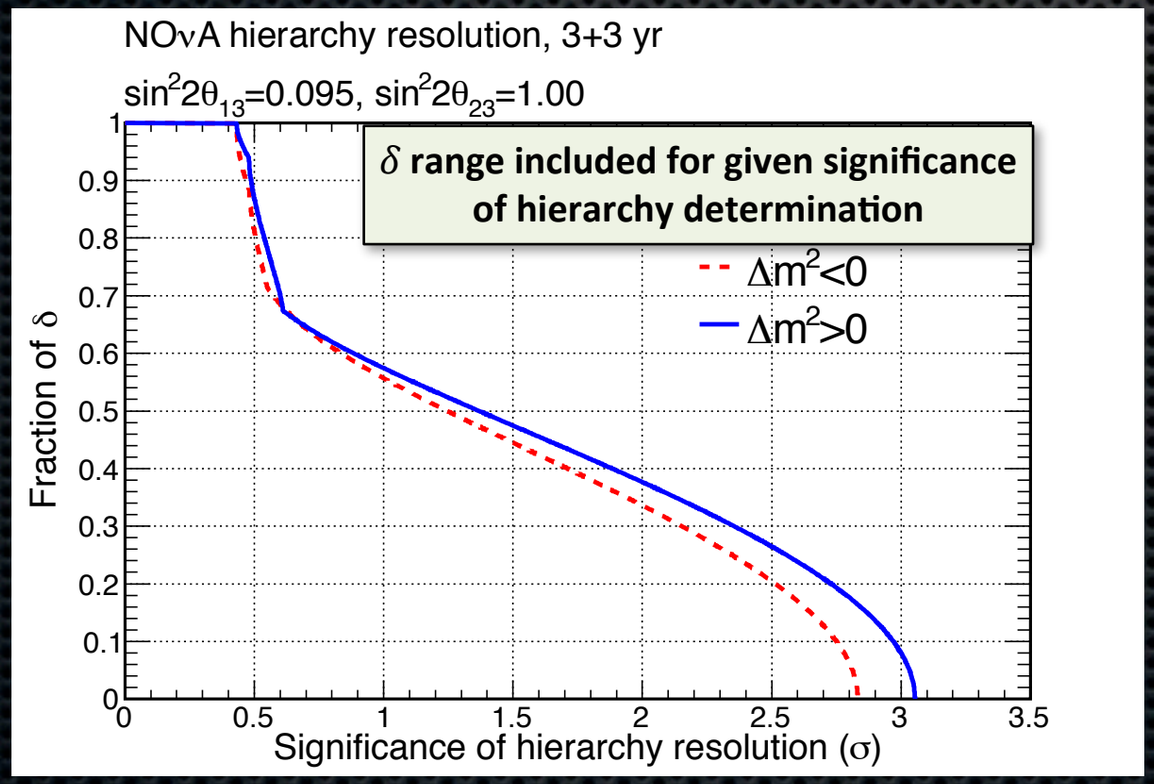
	signal	total bkgd	NC bkgd	ν_μ CC bkgd	ν_e CC bkgd
ν (3 yrs)	56	28	17	4	7
$\bar{\nu}$ (3 yrs)	26	14	9	1	4

Using newly developed PIDs (ANN) optimized for $\sin^2(2\theta_{13}) = 0.095$.
Signal eff: ~30-40% and NC fake rate ~0.3%.

Resolution of the mass hierarchy

- Significance of mass hierarchy resolution using energy spectrum.
- Energy fit provides improvement on the fully degenerate δ_{CP} values.

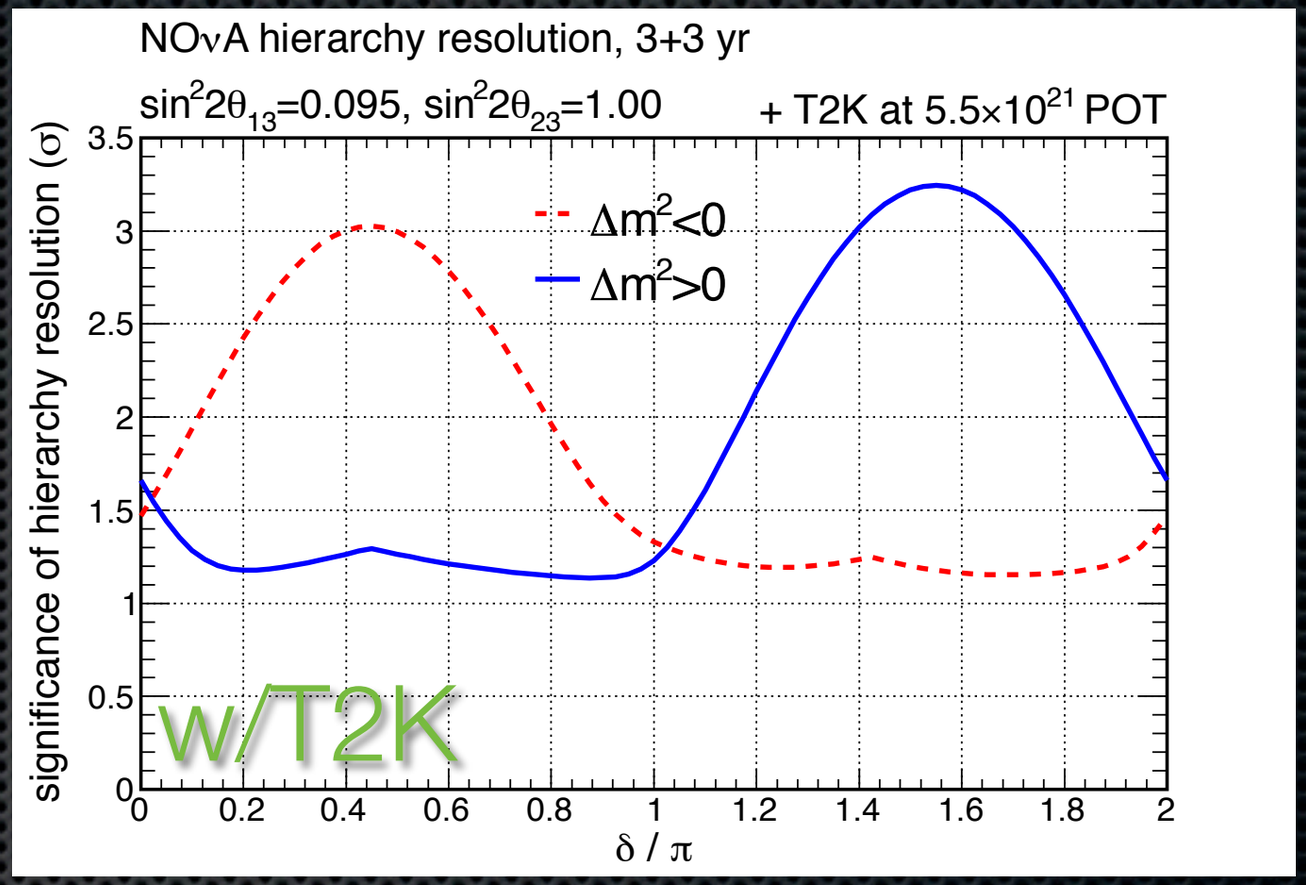


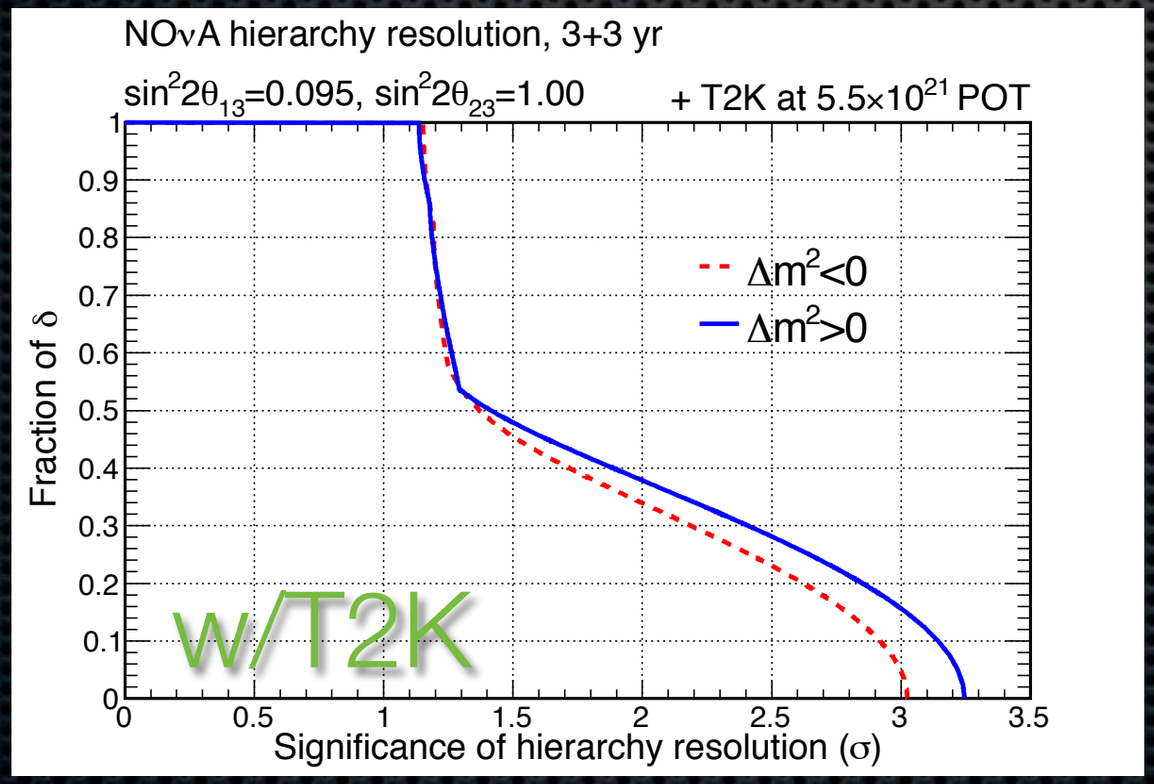


- Results from full simulation, reconstruction, selection, and analysis framework.
  - FD only. Extrapolation methods from ND in progress.

Resolution of the mass hierarchy

- Significance of mass hierarchy resolution using energy spectrum.
- Energy fit provides improvement on the fully degenerate δ_{CP} values.

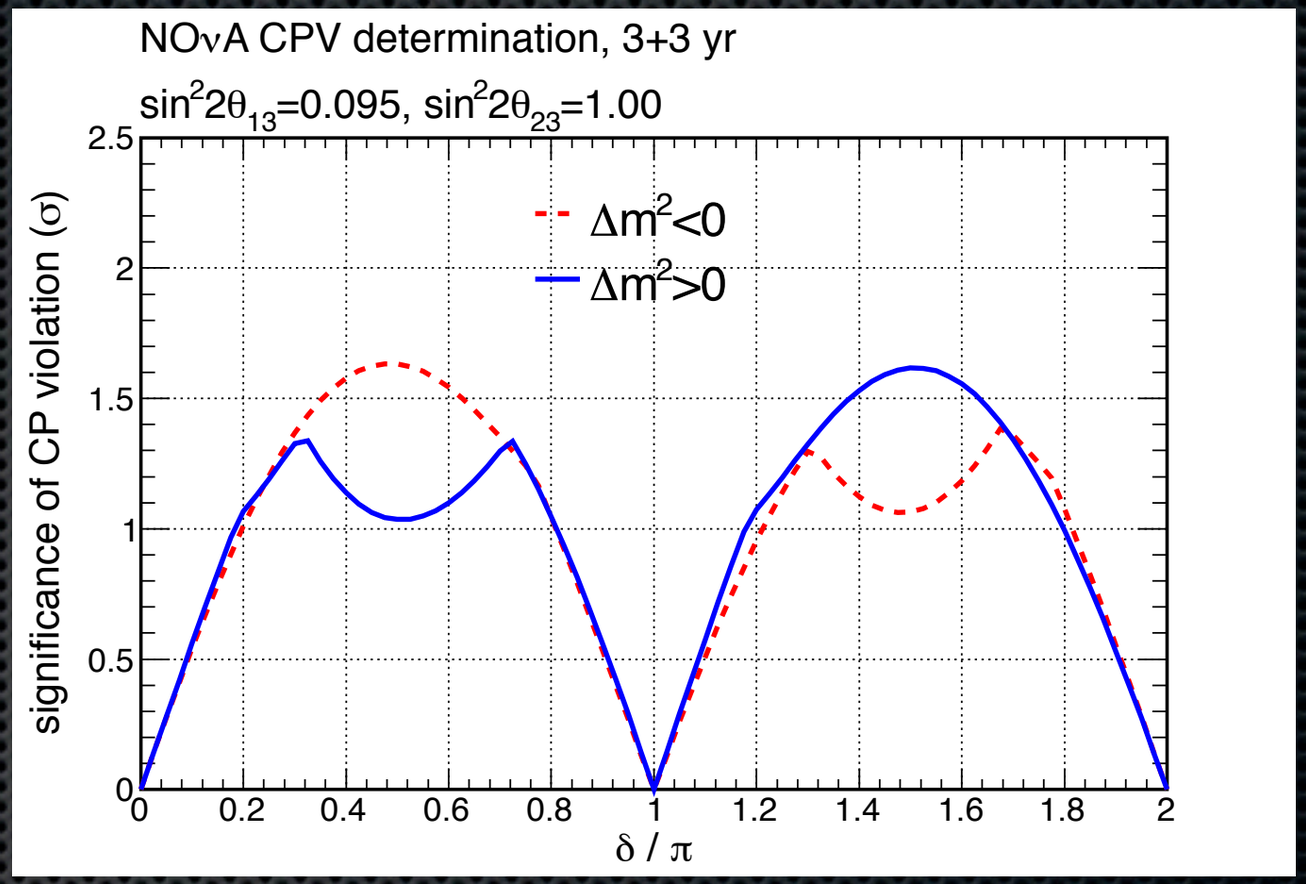


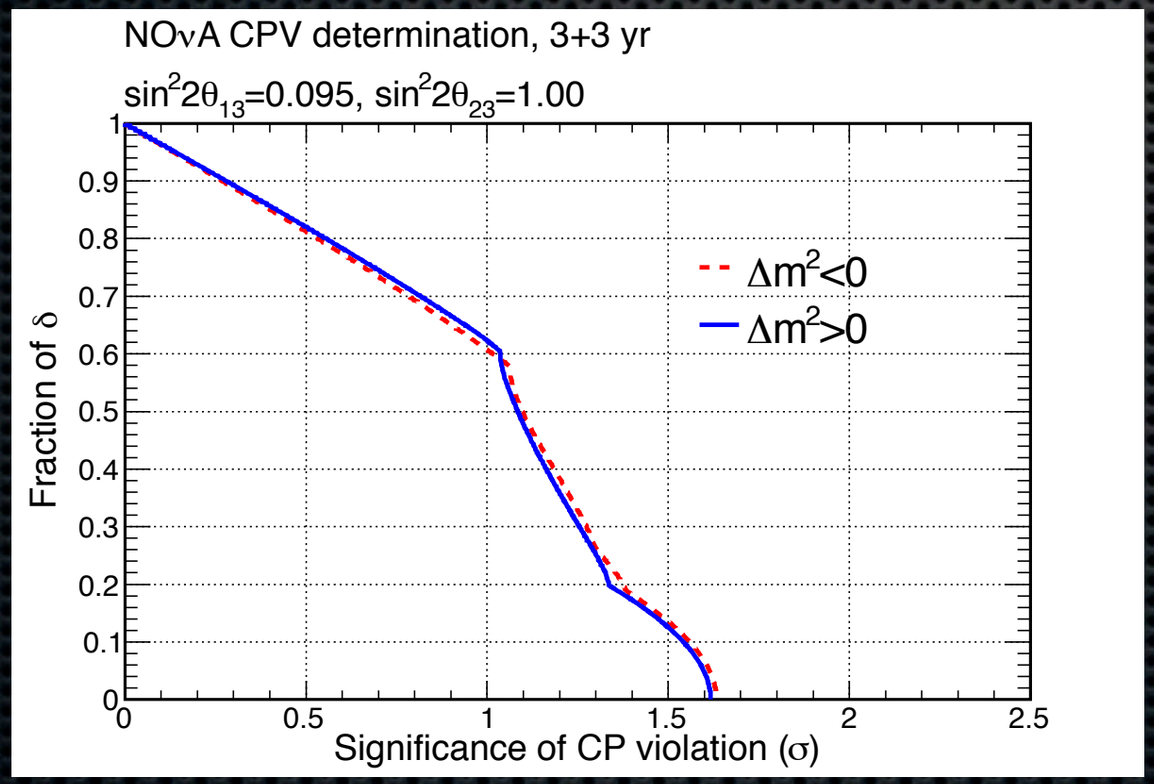


- Differences in baseline/ matter effects between NOvA and T2K can provide additional information.

Study of CP violation phase

- Significance of CP violation using energy spectrum.
- Assumes that mass hierarchy is unknown.



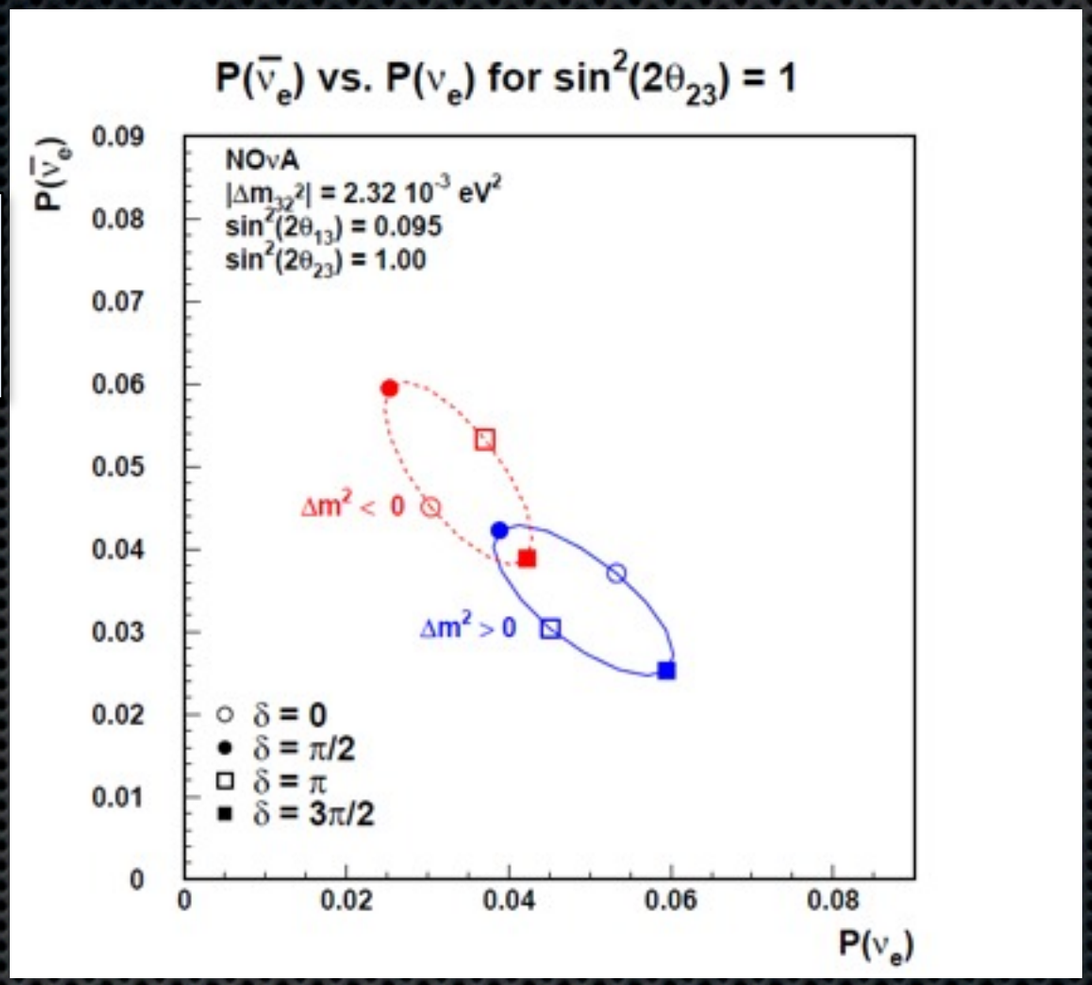


- Results from full simulation, reconstruction, selection, and analysis framework.
  - FD only. Extrapolation methods from ND in progress.

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

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

⇨ θ_{23} ***octant sensitivity***

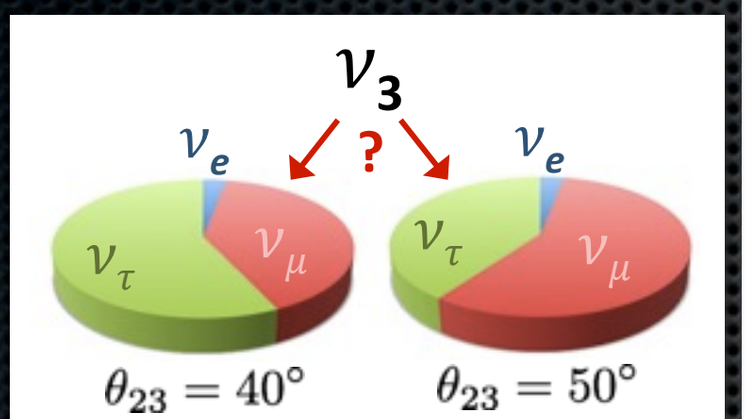


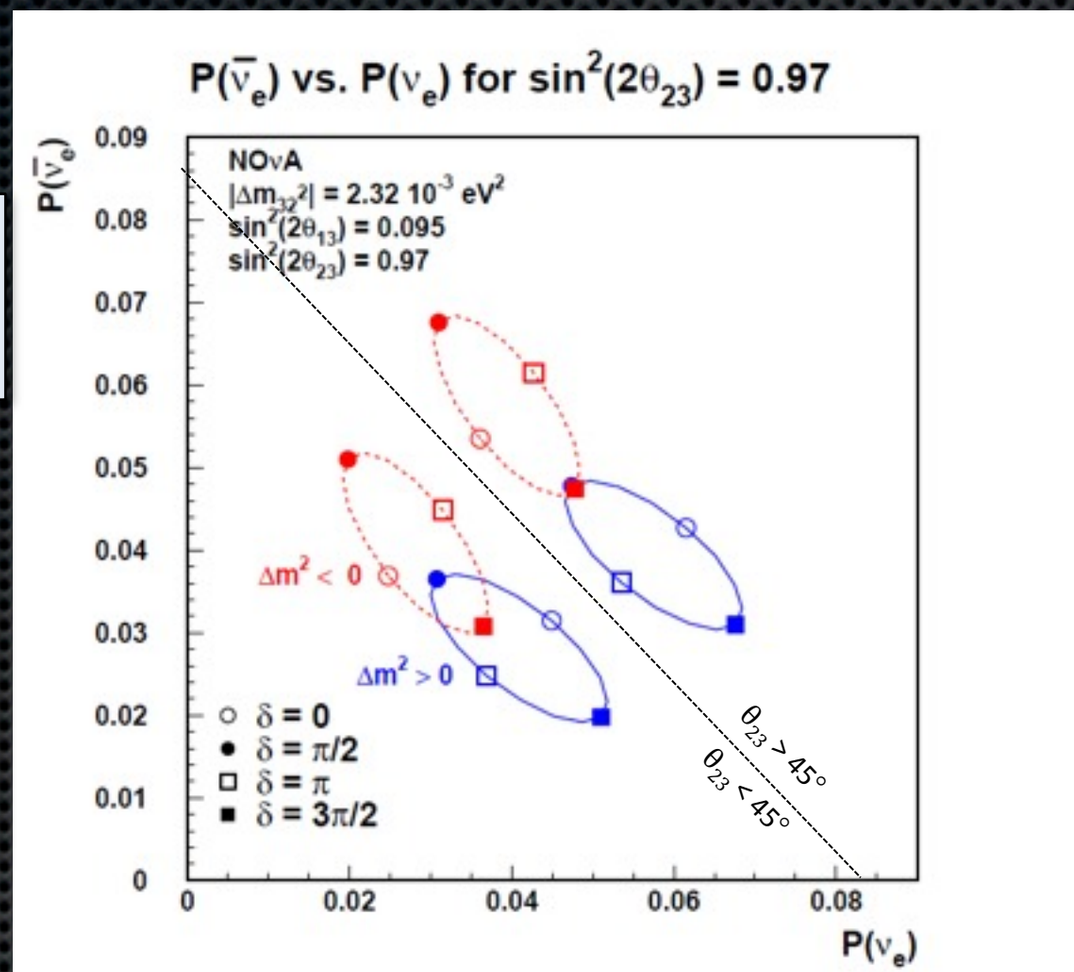
- If $\sin^2(2\theta_{23})$ is not maximal there is an ambiguity as to whether θ_{23} is larger or smaller than 45°.
- The $\sin^2(\theta_{23})$ term is unimportant when comparing accelerator experiments; however, it is crucial in comparing accelerator to reactor experiments

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

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

⇨ θ_{23} *octant sensitivity*

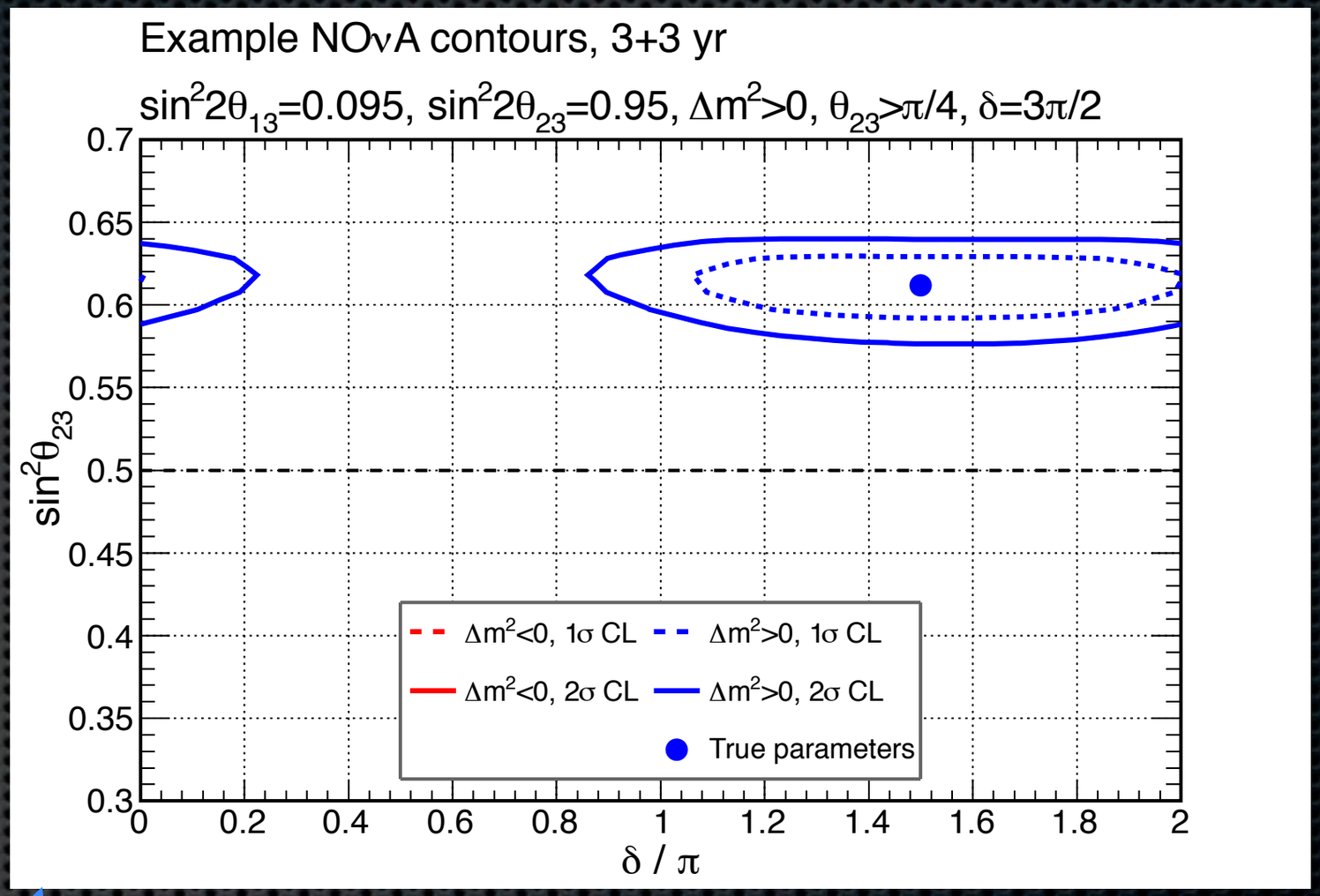


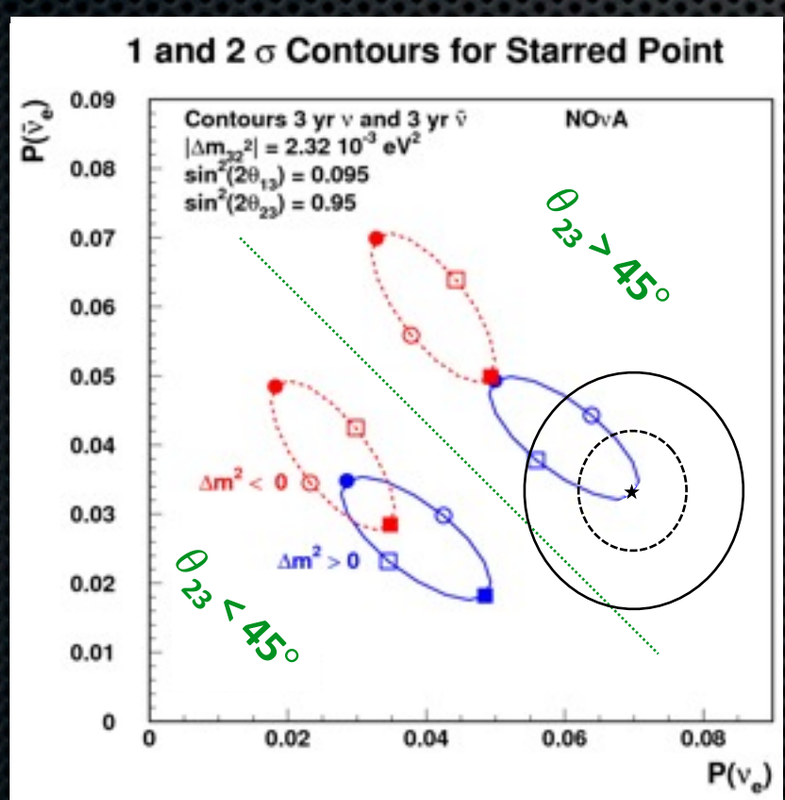


- If $\sin^2(2\theta_{23})$ is not maximal there is an ambiguity as to whether θ_{23} is larger or smaller than 45°.
- The $\sin^2(\theta_{23})$ term is unimportant when comparing accelerator experiments; however, it is crucial in comparing accelerator to reactor experiments

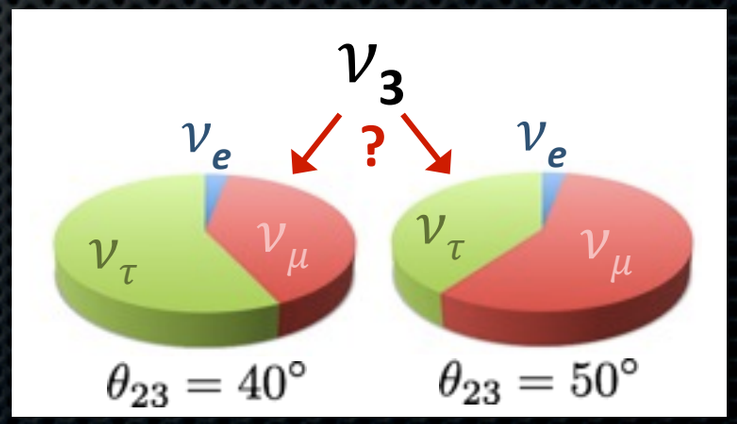
Non-maximal $\sin^2 2\theta_{23}$ and NOvA

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



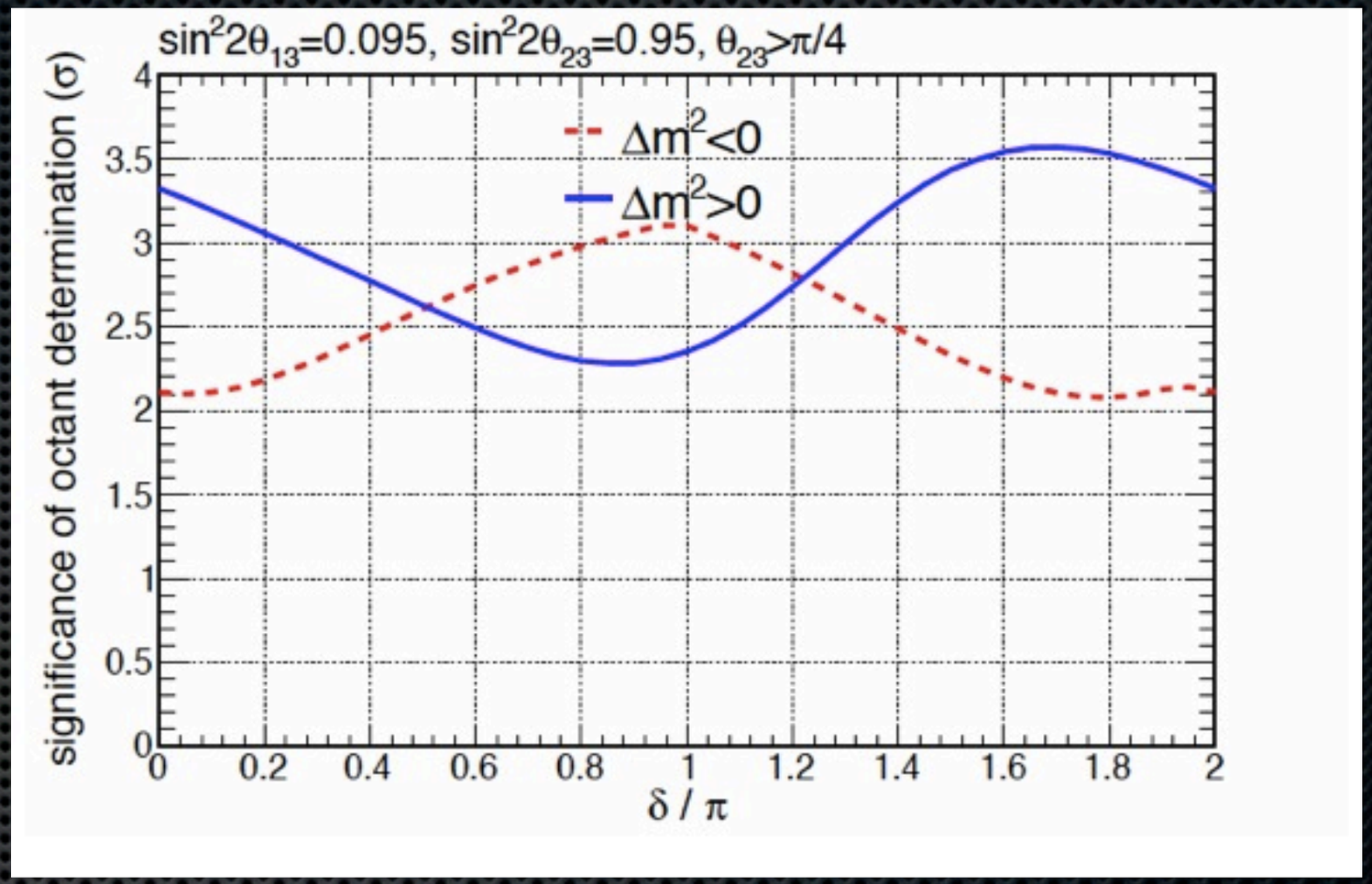


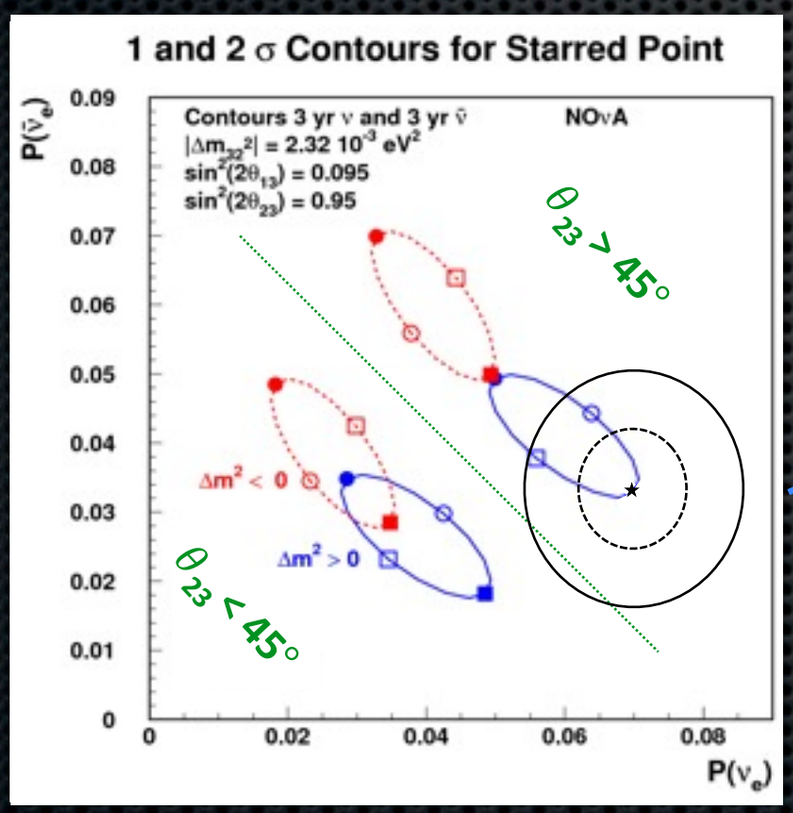
Simultaneous hierarchy, CP phase, and θ_{23} octant information from NOvA



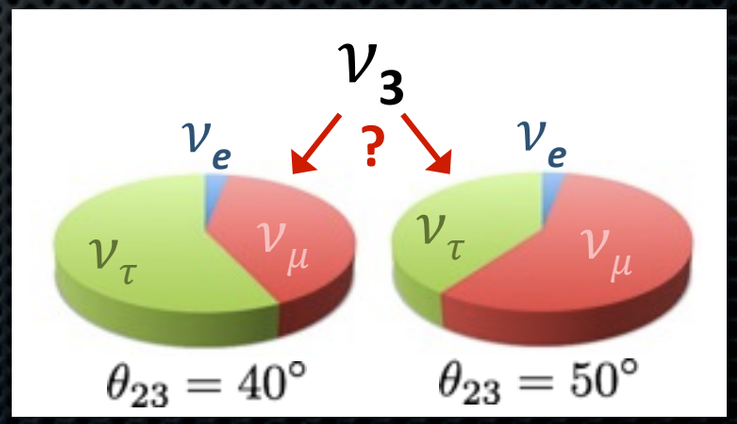
Non-maximal $\sin^2 2\theta_{23}$ and NOvA

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

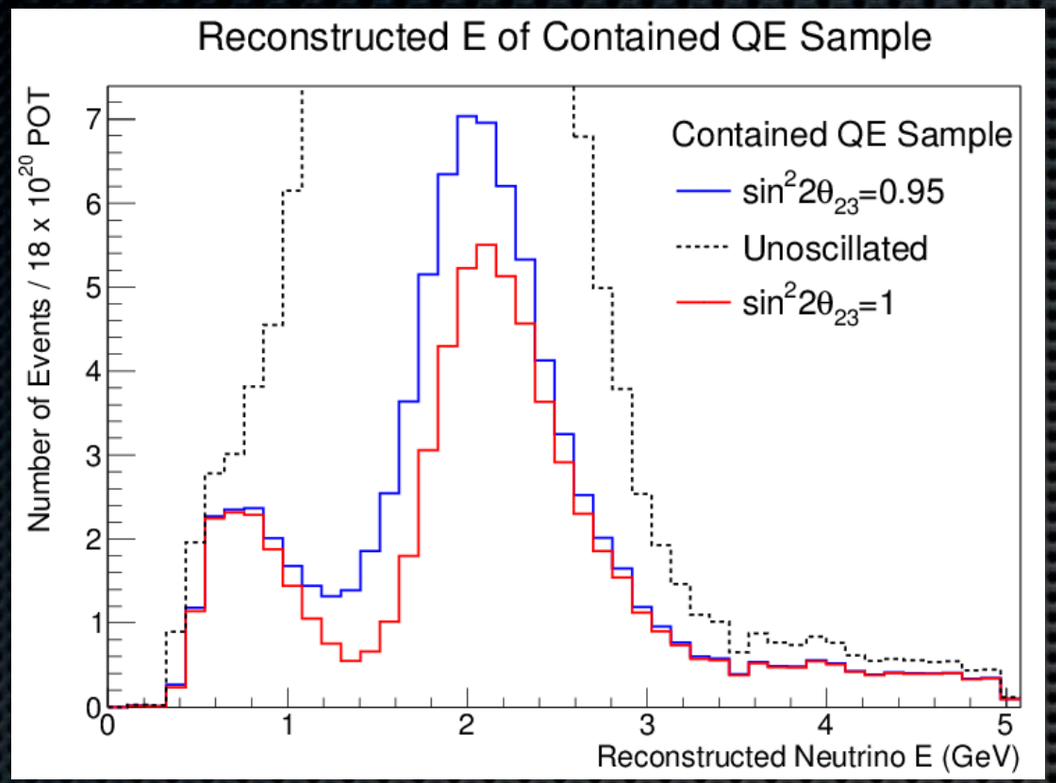


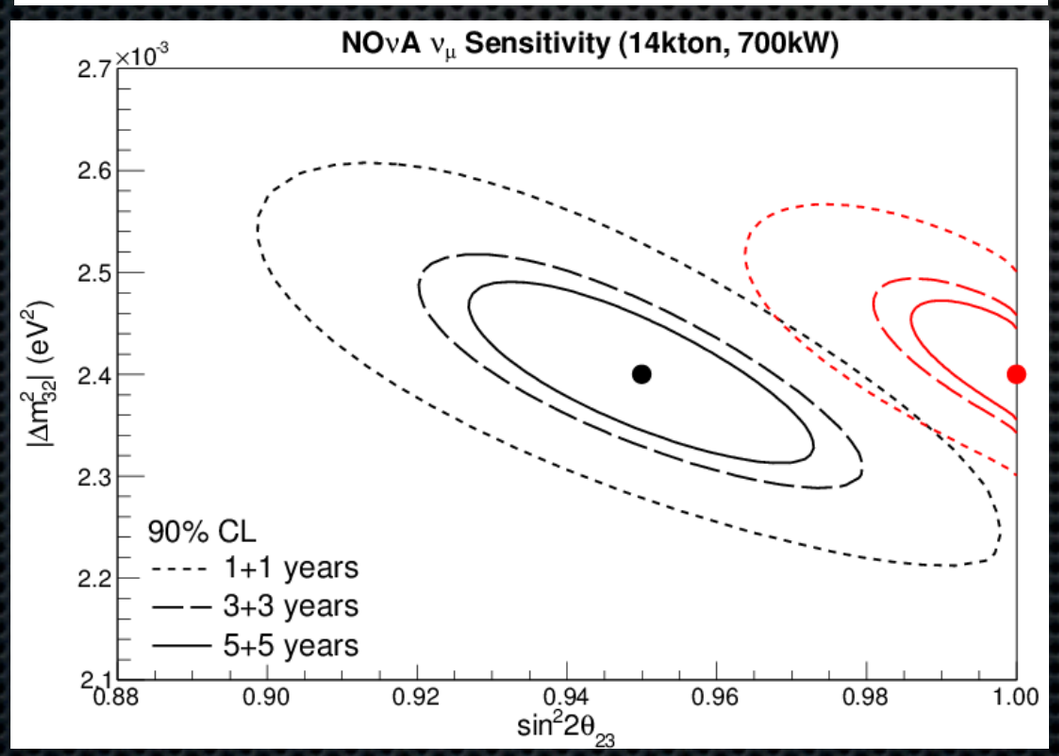


Simultaneous hierarchy, CP phase, and θ_{23} octant information from NOvA

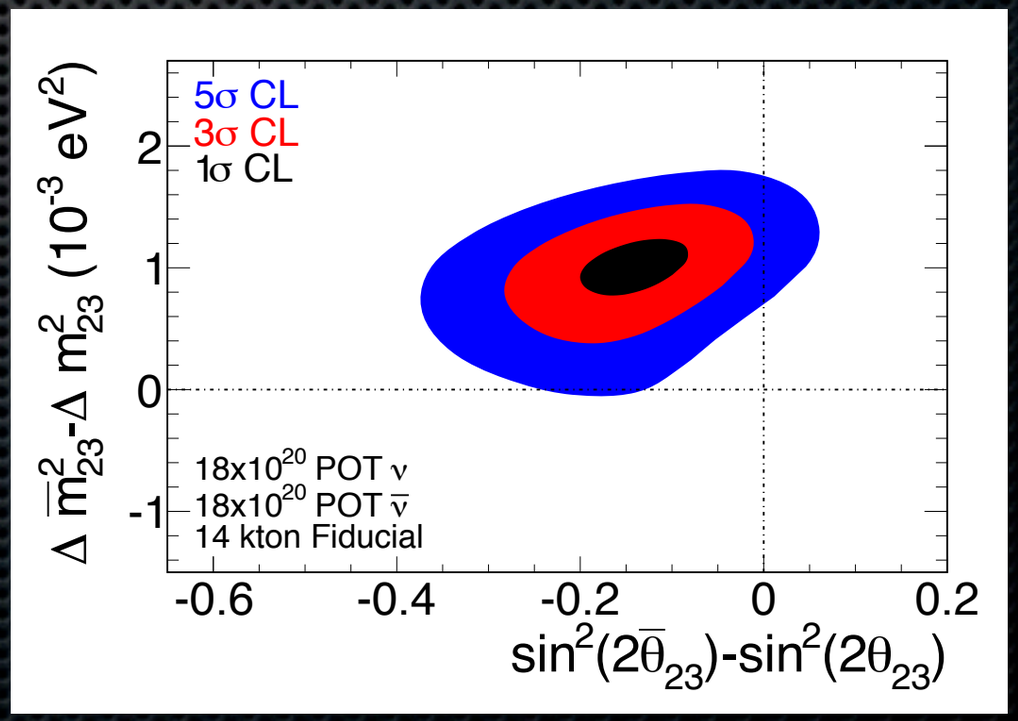


NOvA muon neutrino disappearance





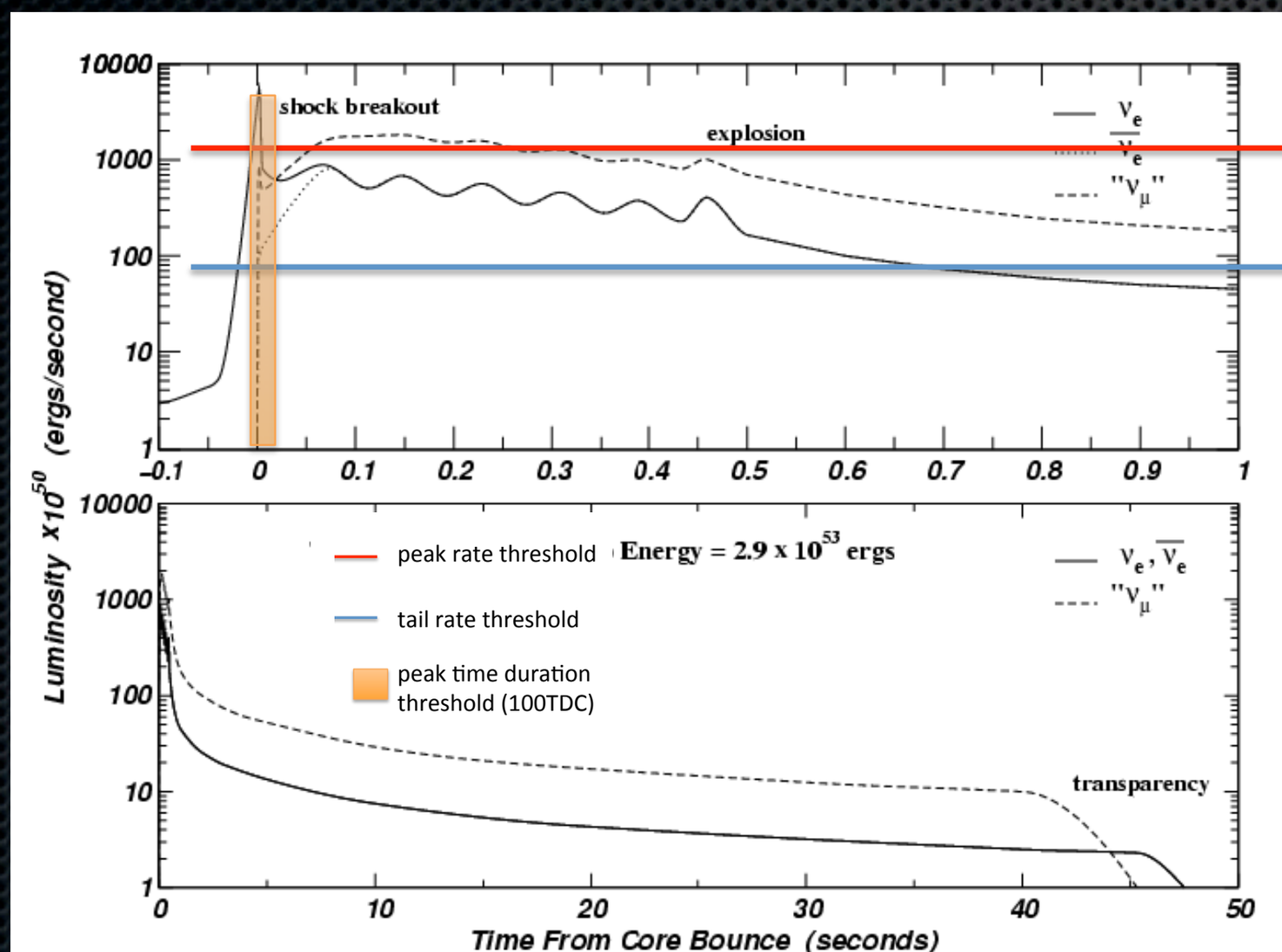
- NOvA's will do a few % measurement in Δm^2_{32} and $\sin^2 2\theta_{23}$.
- Improvement of one order of magnitude in $\sin^2 2\theta_{23}$. It might not be maximal.
- Measurement for neutrinos and anti-neutrinos separately.



One more thing...

One more thing... supernovae

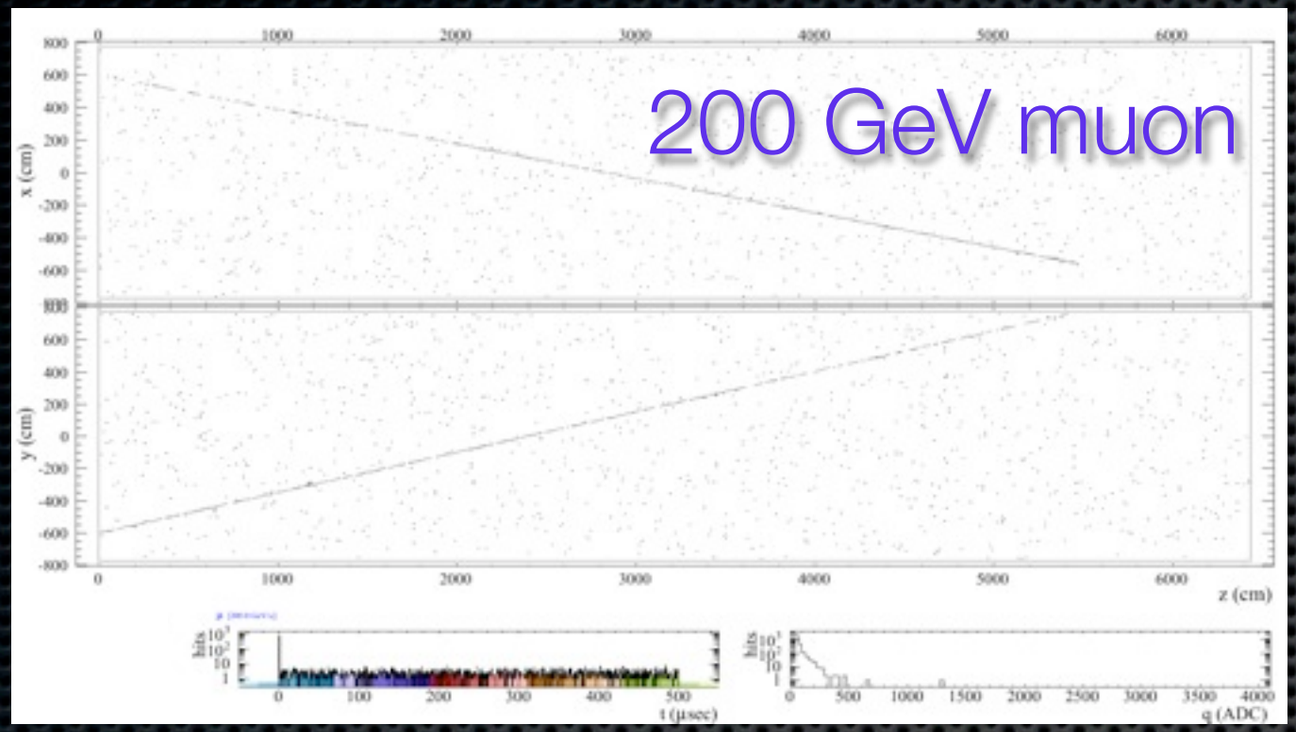
- NOvA is not underground, however it is a segmented detector with a very flexible trigger.

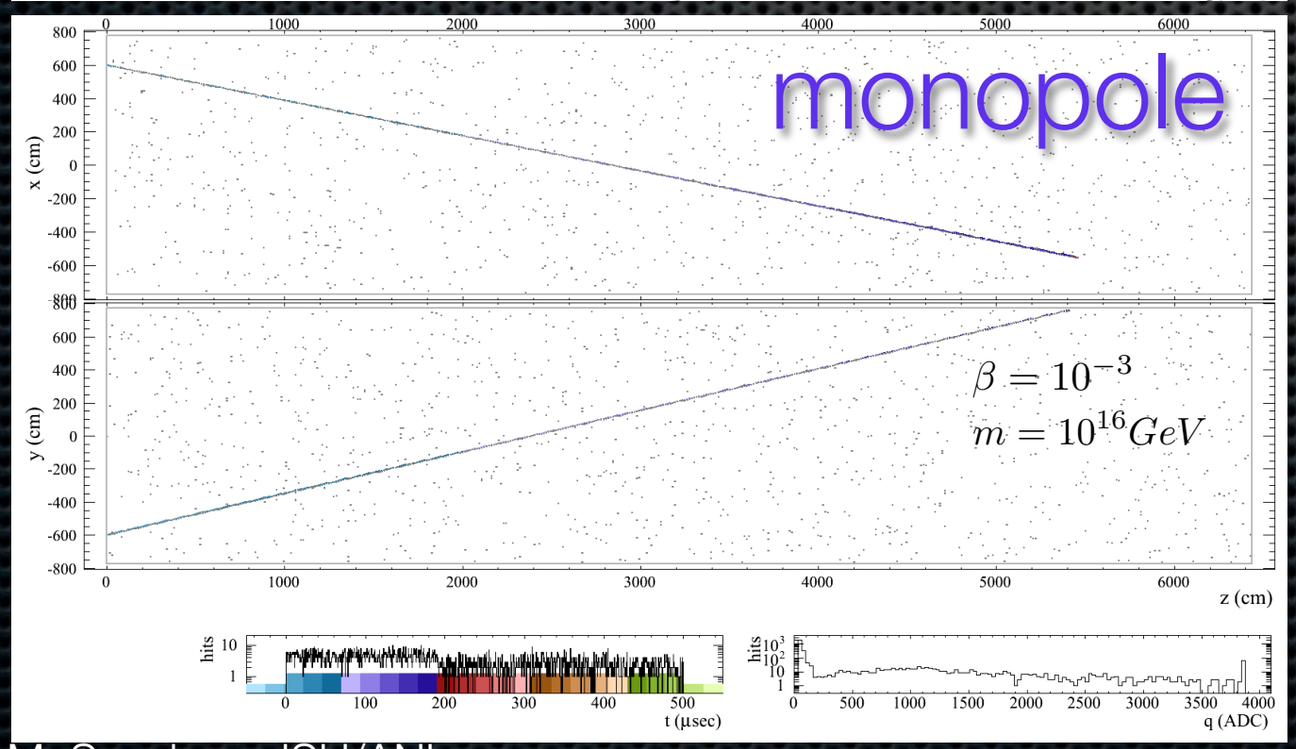


- We will see ~4K neutrinos for a supernova burst in our galaxy.
- NOvA has continuous digitization which allows us to look for unusual 2-3 plane coincidence rates.
- Within the first 10 ms it will raise above a peak threshold, signaling to record these and future data.

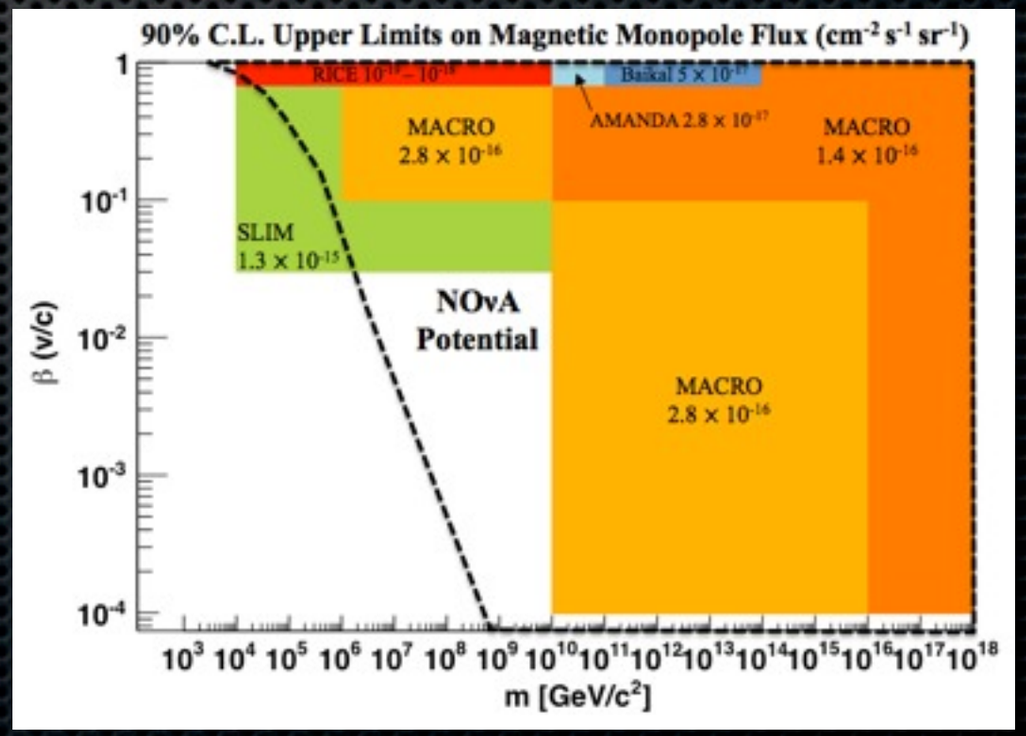
NOvA can provide information on time profile and energy of SN neutrinos

One other thing... monopoles





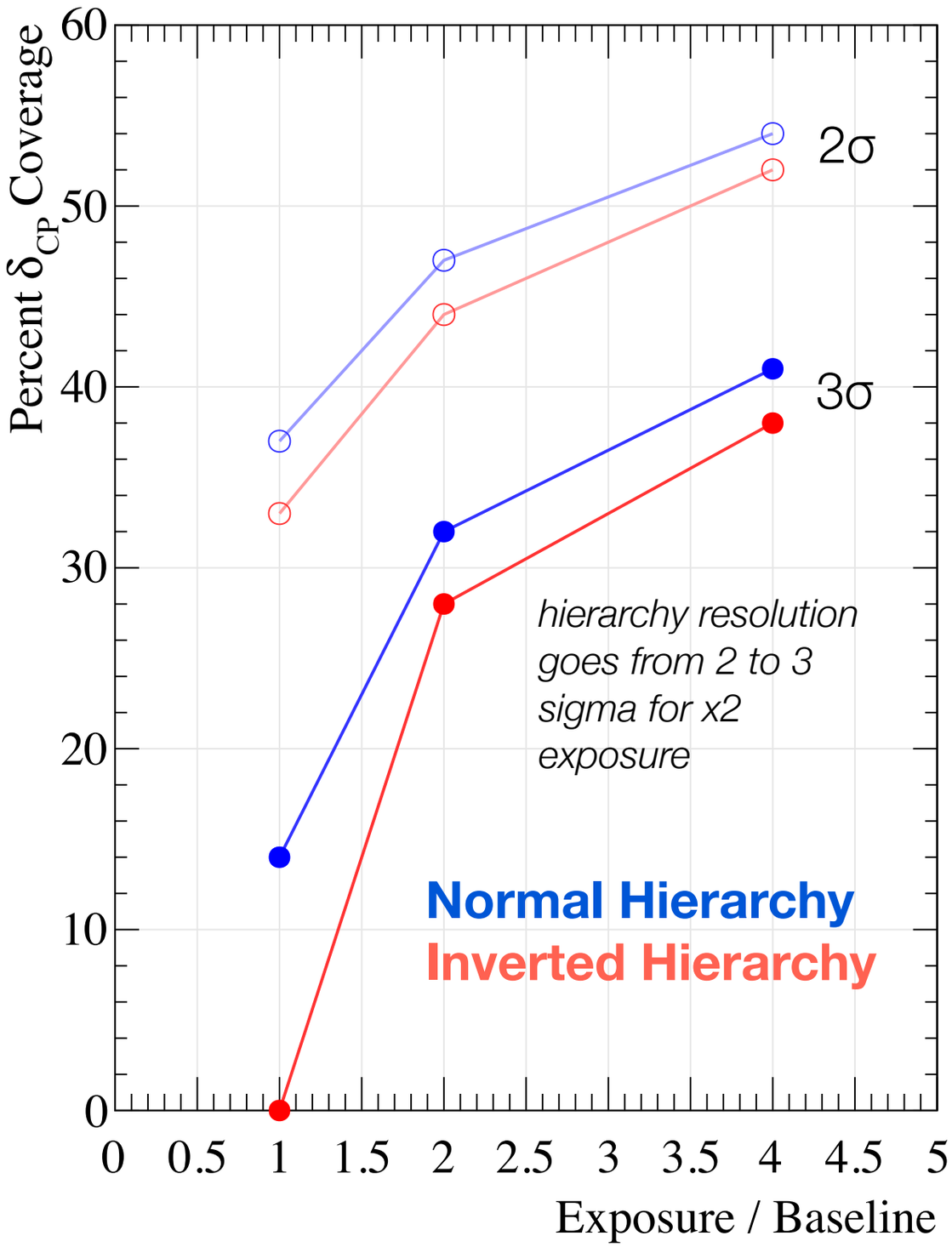
- A magnetic monopole track is slower and higher ionizing than an energetic muon.
- Small overburden gives us sensitivity to a low-mass low-beta region not probed by other experiments.



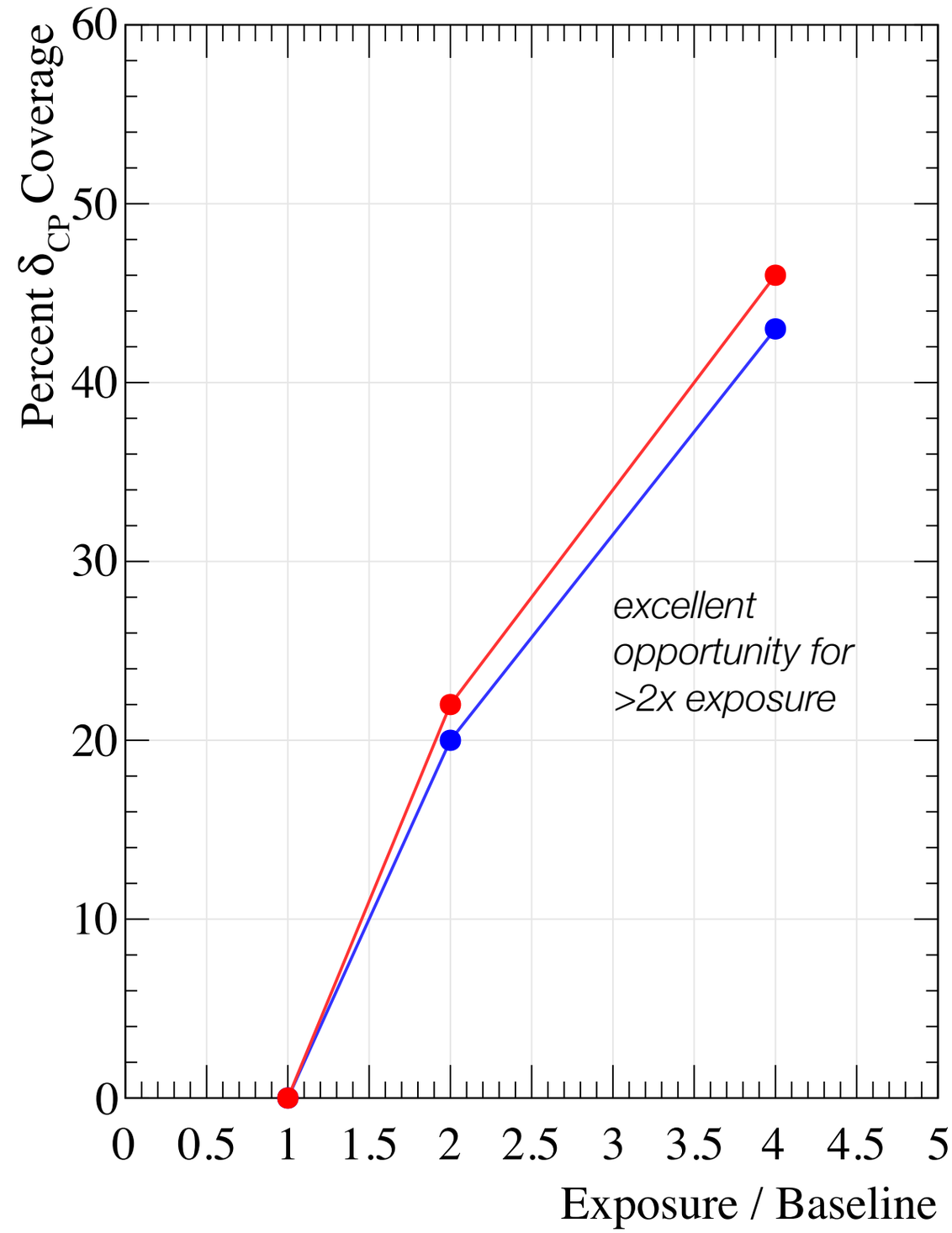
- There is now **definite evidence** that the **neutrino mixing angle, θ_{13},** is as large as we could have hoped for.
- **The determination of the mass hierarchy, CP violation and the θ_{23} quadrant are the next challenges.**
  - NOvA has unique capabilities to address these questions during the next 6 years.
- **NOvA Far Detector commissioning and NuMI upgrade are now underway.**
  - Full simulation, reconstruction, selection, and analysis framework has been developed for Far Detector data. Currently developing data driven methods and extrapolation from Near Detector.
  - First cosmic rays have been observed in the first complete FD kiloton. Reconstruction and selection algorithms are being exercised as we speak.
- **NOvA has the potential to look at other physics:** supernovae and monopoles.

Backup

Extending NOvA's reach



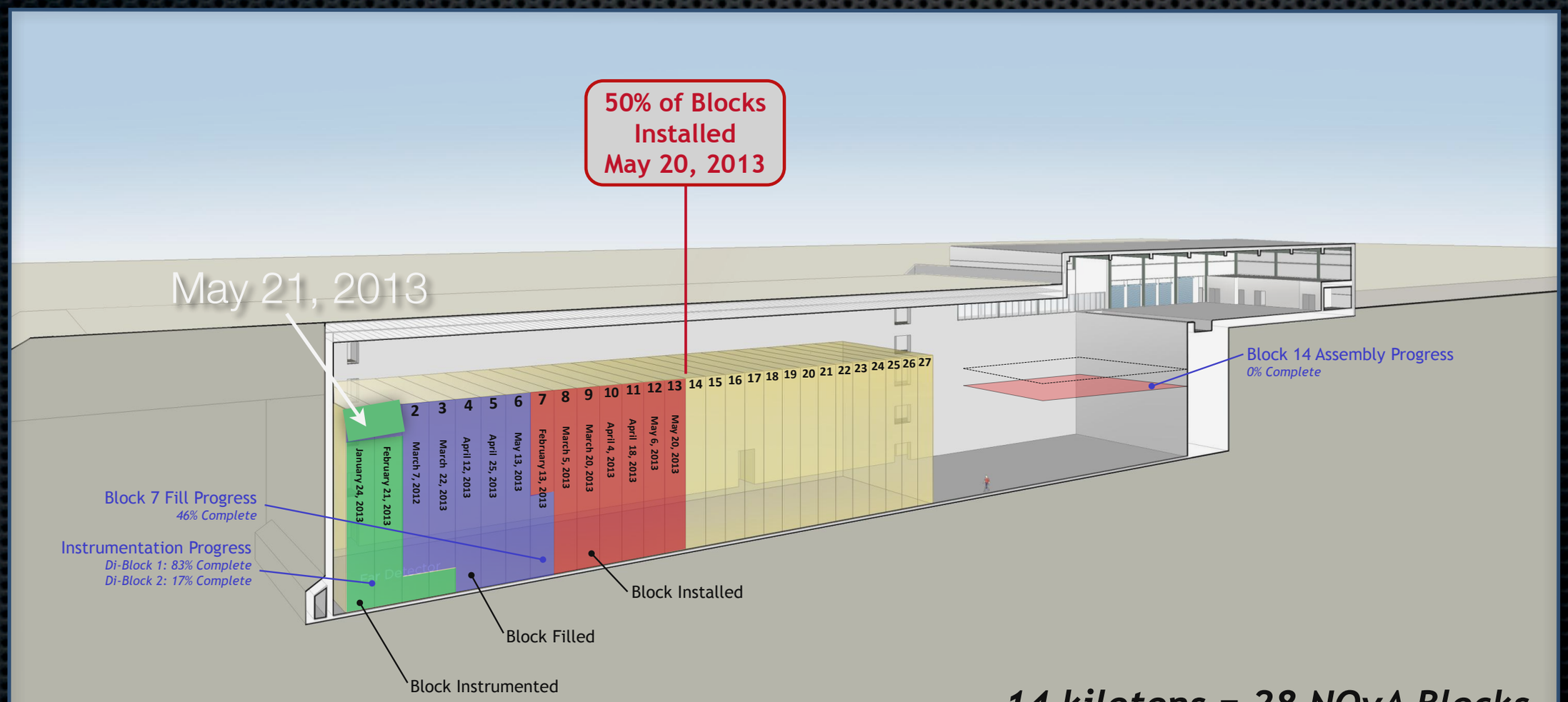
Hierarchy Determination



95% CPV Sensitivity

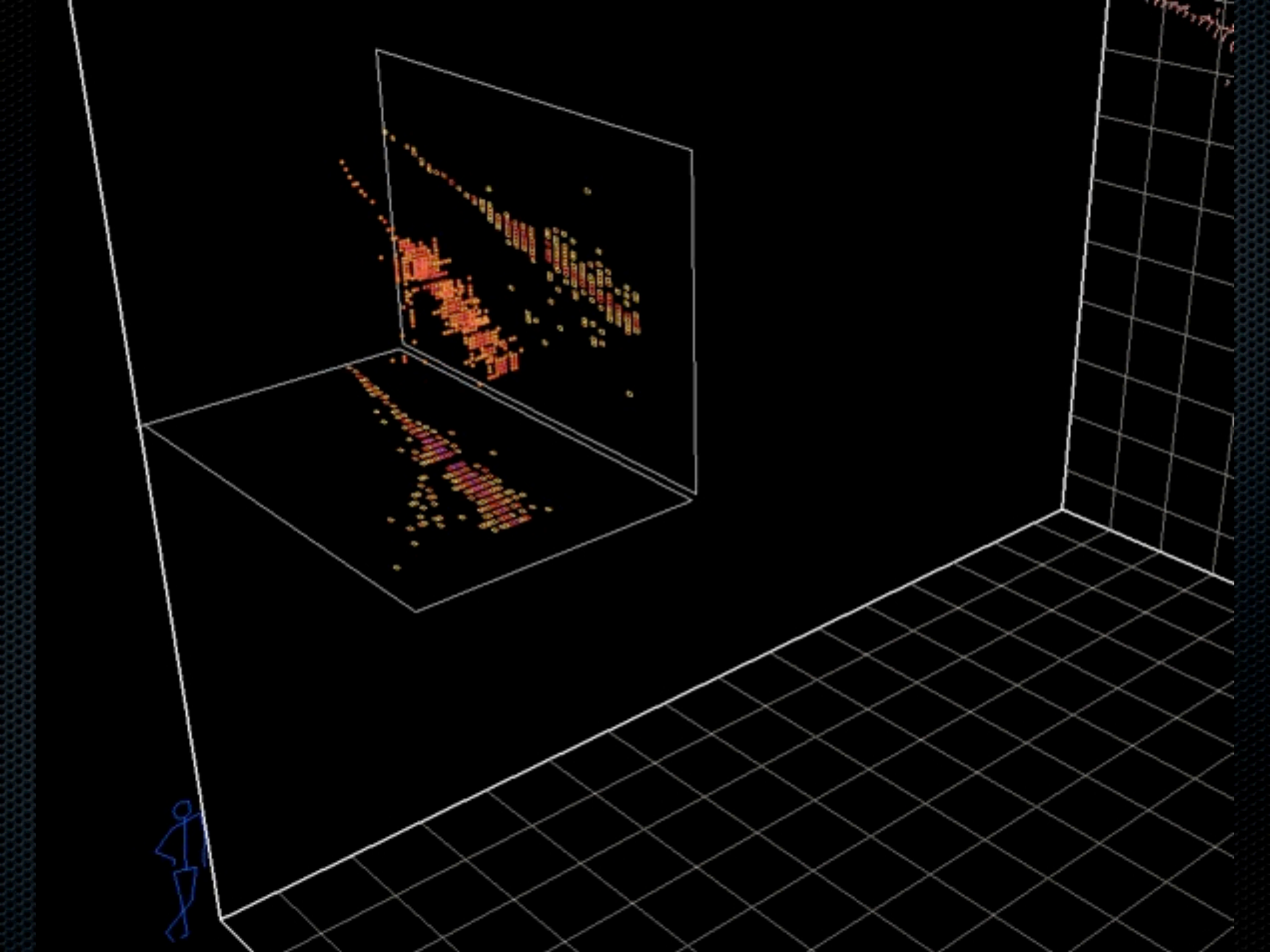
NOvA construction status

- NOvA assembly and commissioning is in full swing:
  - 50% of the blocks have been installed!
  - First diblock (1 kton) has been instrumented!



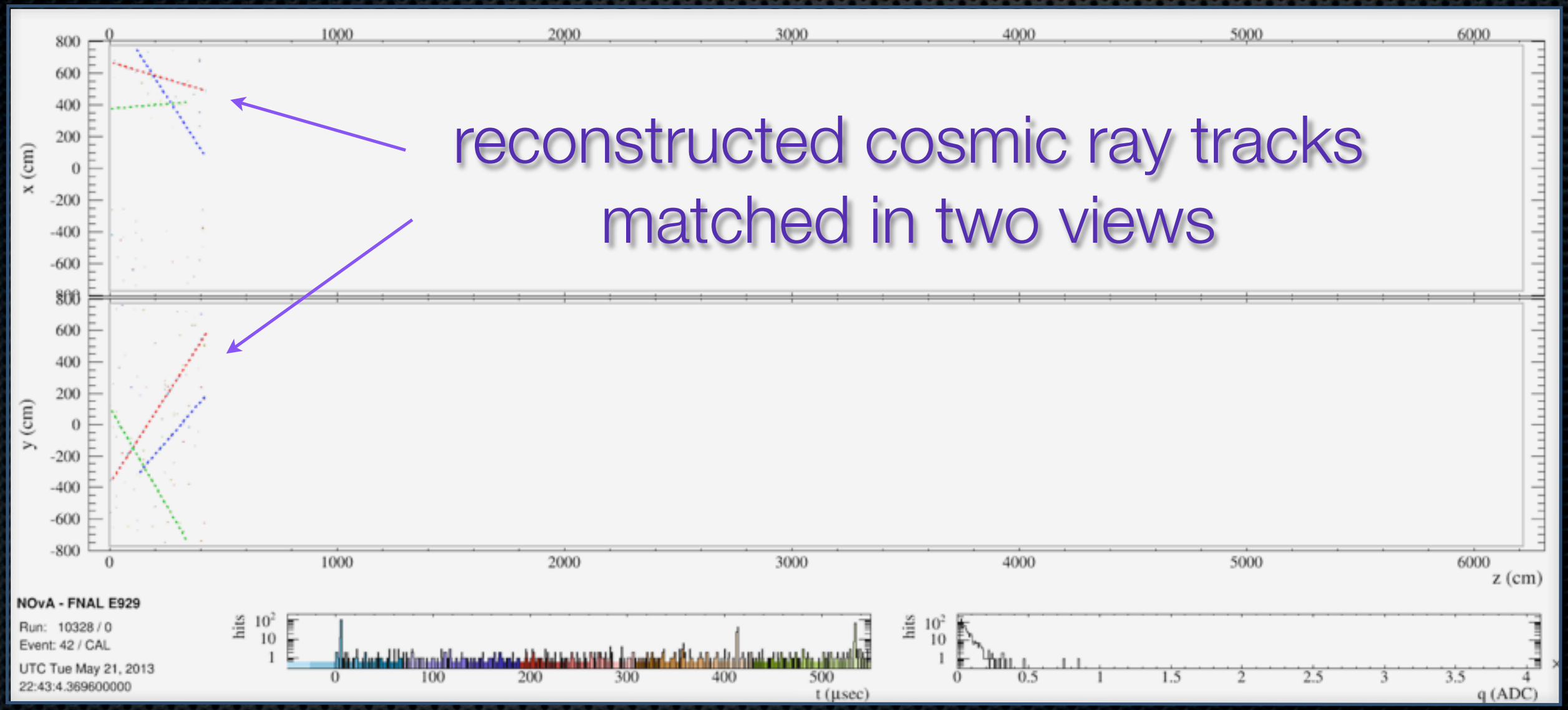
14 kilotons = 28 NOvA Blocks

14 blocks of PVC modules are assembled and installed in place
7.46 blocks are filled with liquid scintillator
2.0 blocks are outfitted with electronics



NOvA first cosmic ray data

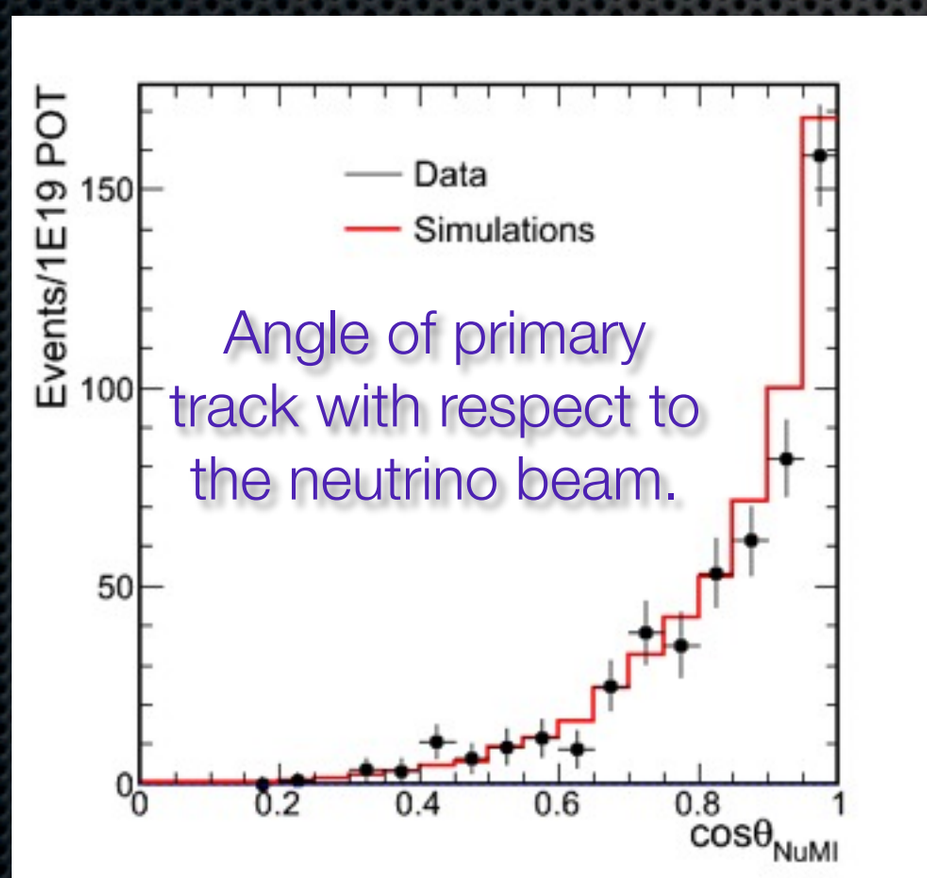
- Reconstruction algorithms being tested on first FD data.

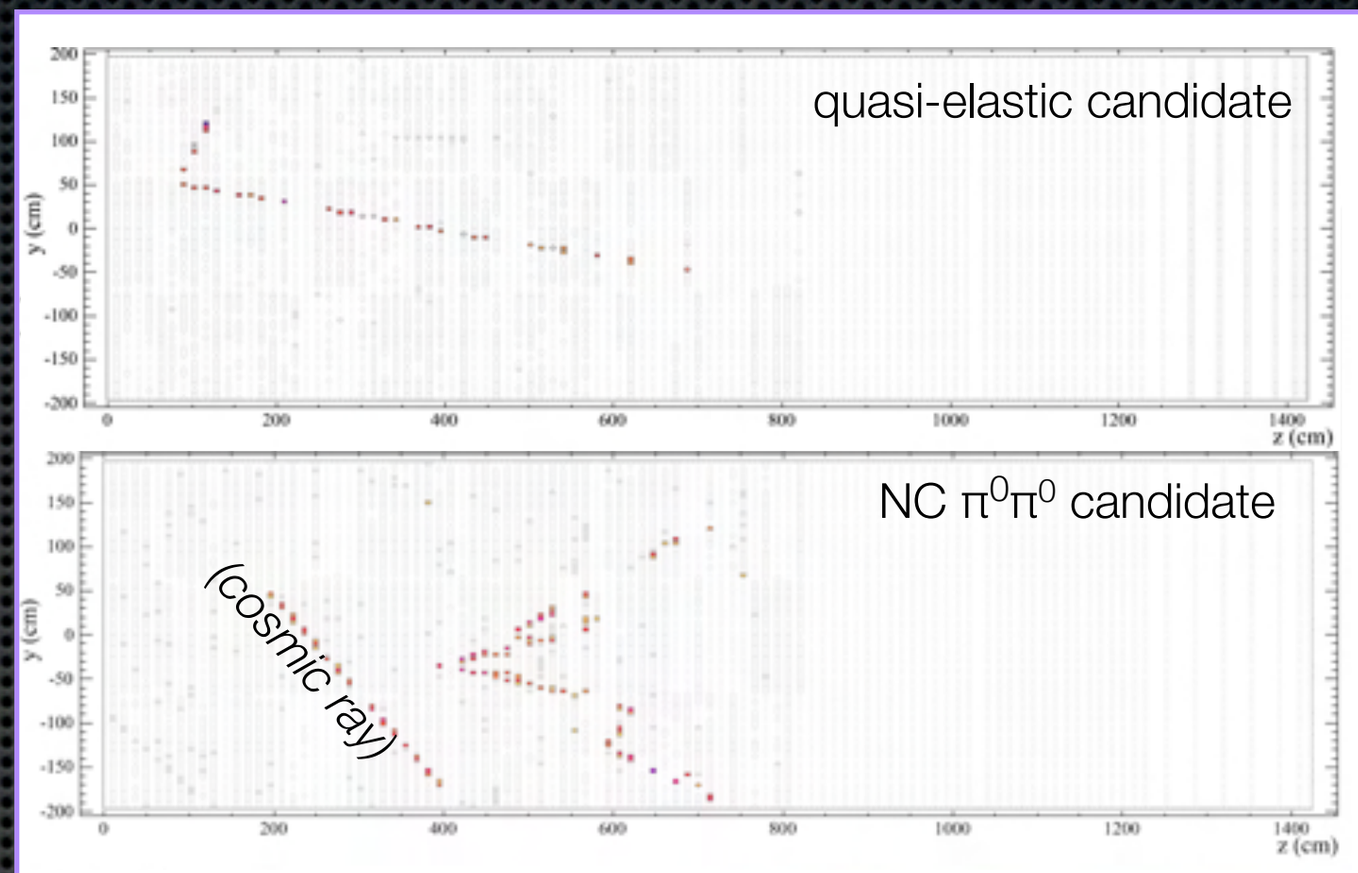


- Algorithms had already been heavily tested in ND prototype.

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.





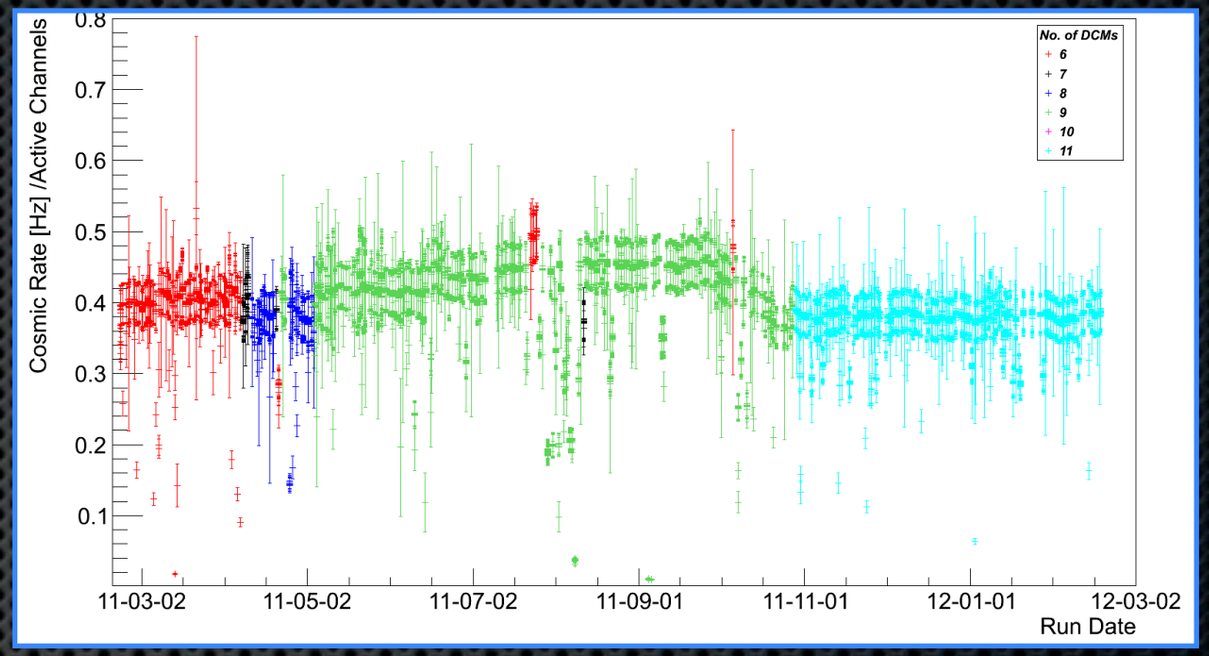
Events from the NuMI beam seen at 110 mrad

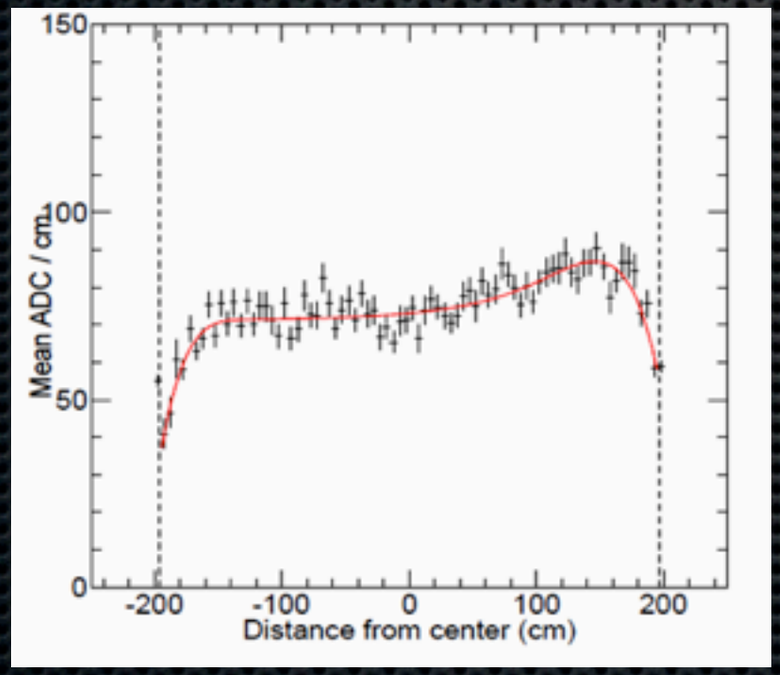
- Data is useful for detector operations.
- Benchmarking calibration, reconstruction and simulations.

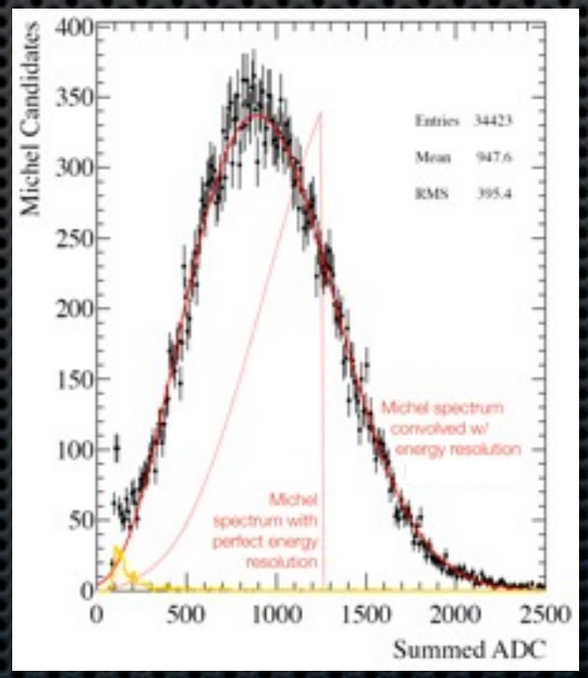
NOvA Near Detector Prototype

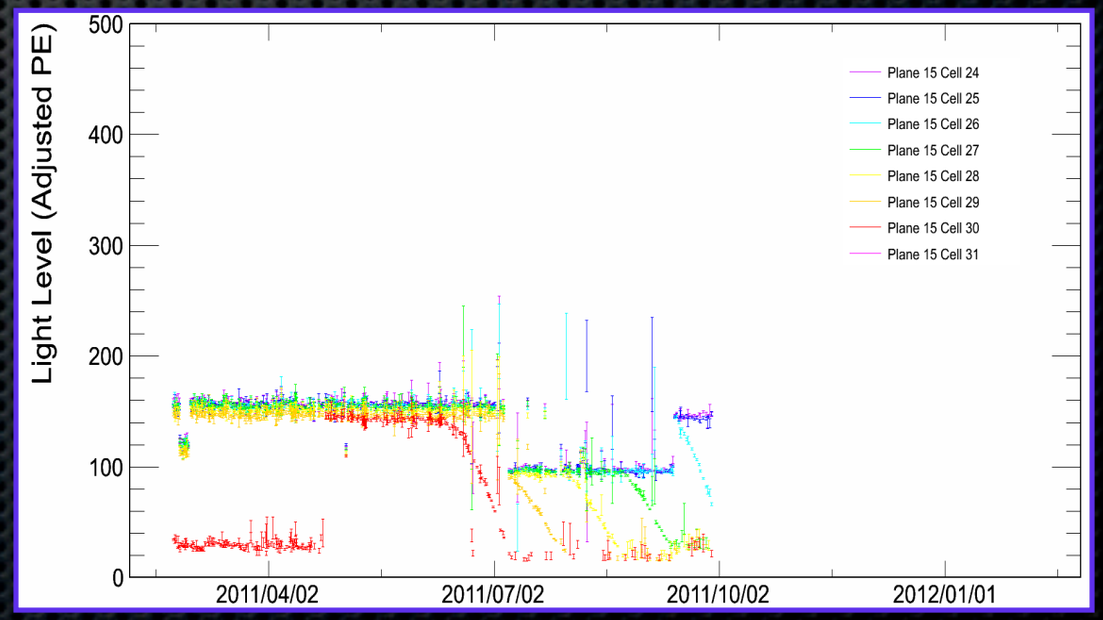
Plenty of cosmic ray data as detector is on surface

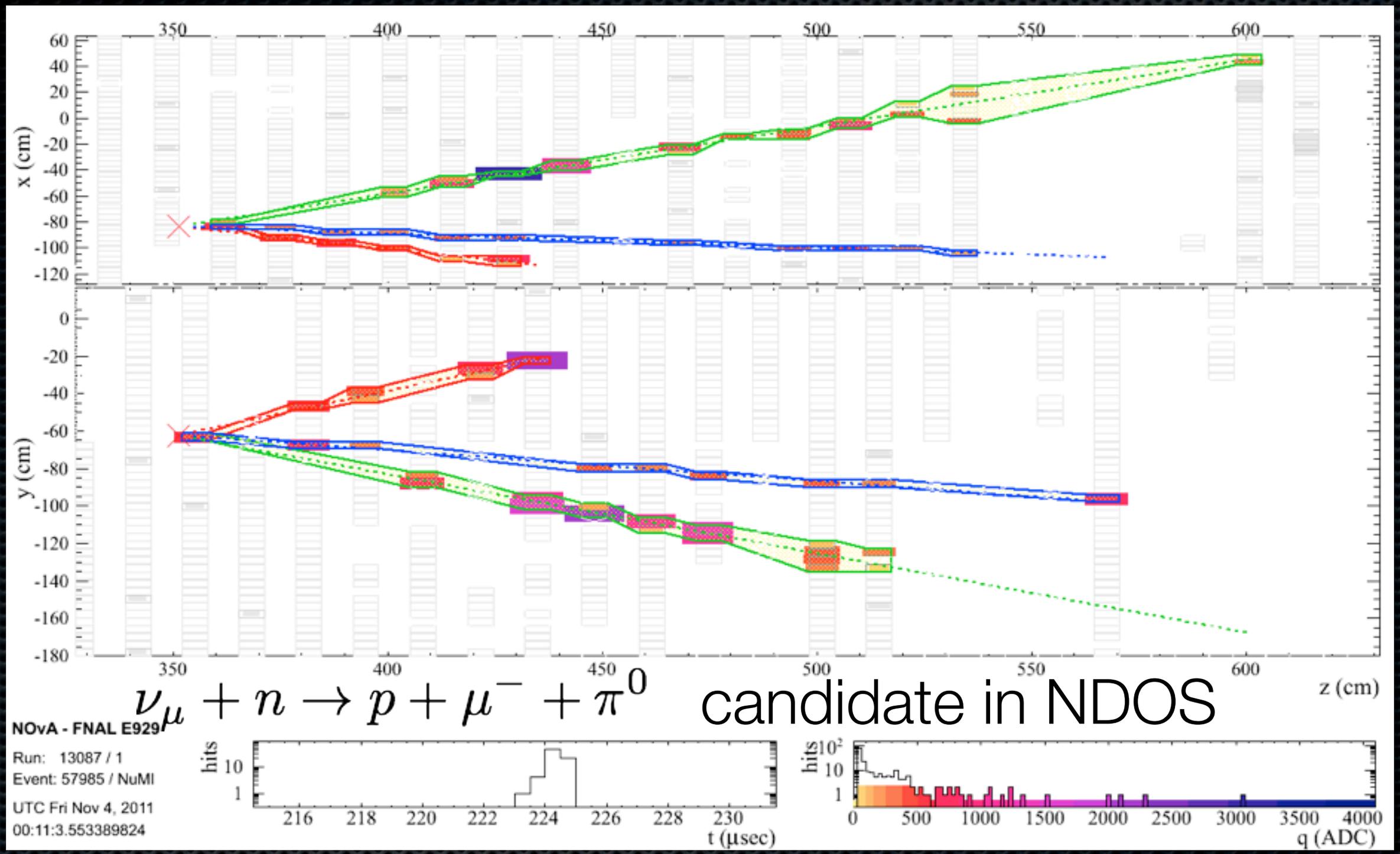
- Developing commissioning and calibration techniques:
  - Cosmic rate per number of active channels and light level as a function of of time.
  - Position dependence of cell response (light attenuation) and Michel electrons.





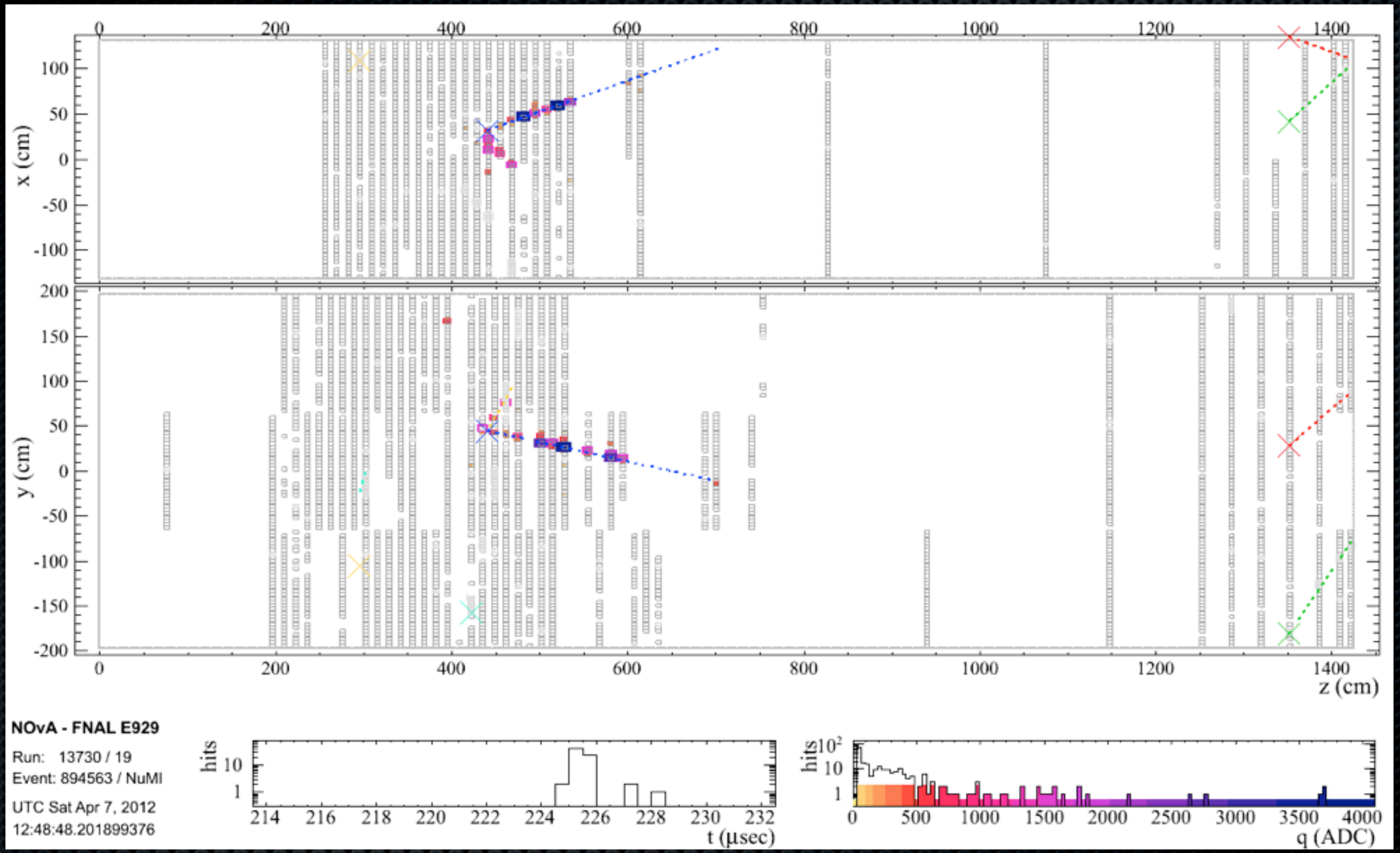






$\nu_\mu + n \rightarrow p + \mu^- + \pi^0$ candidate in NDOS

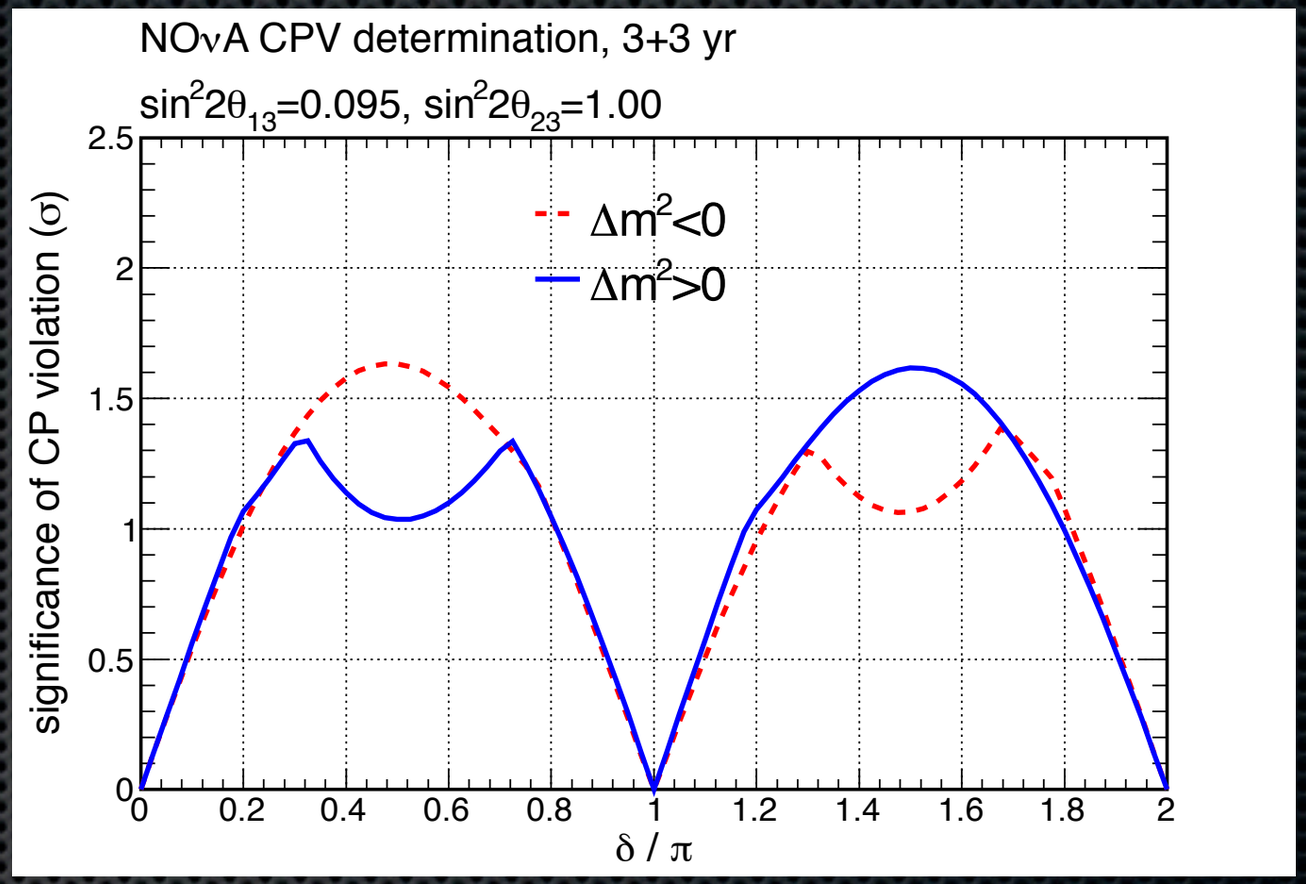
Reconstruction works even in the sparsely instrumented NDOS detector (shown here).
Performance on fully instrumented far detector is much better.

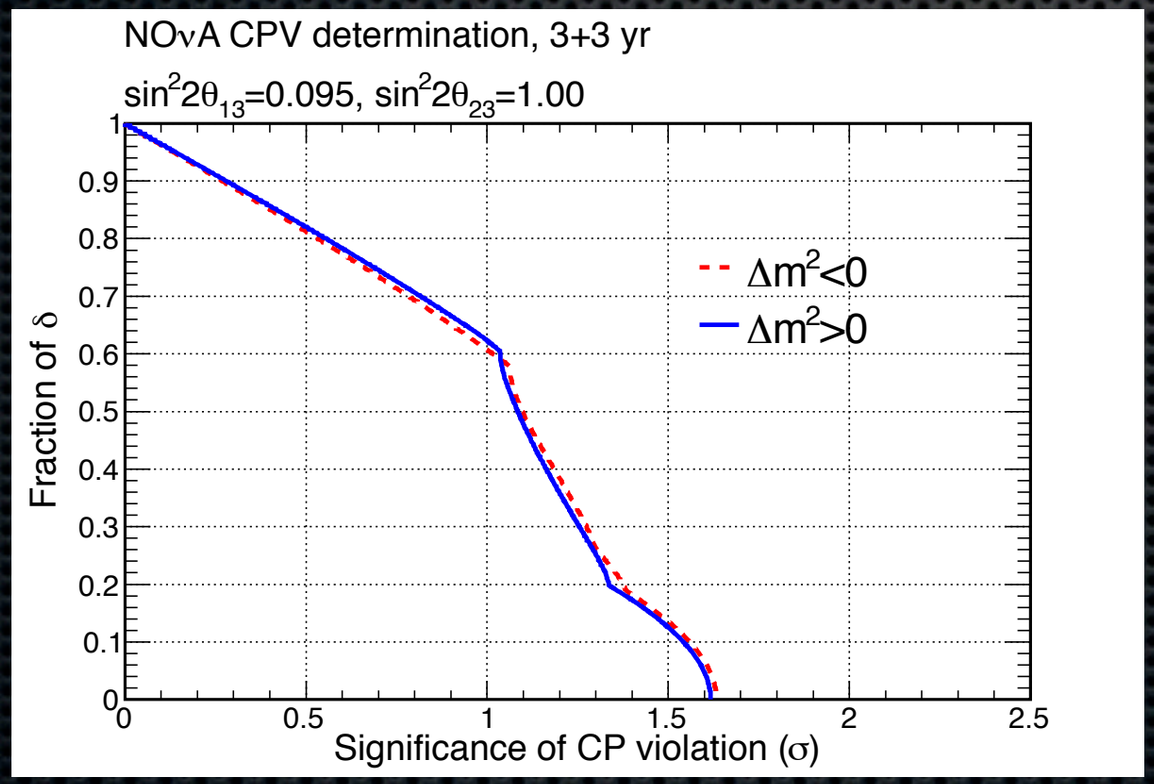


ν_e charged-current quasi-elastic event at NDOS

Study of CP violation

- Significance of CP violation using energy spectrum.
- Assumes that mass hierarchy is unknown.

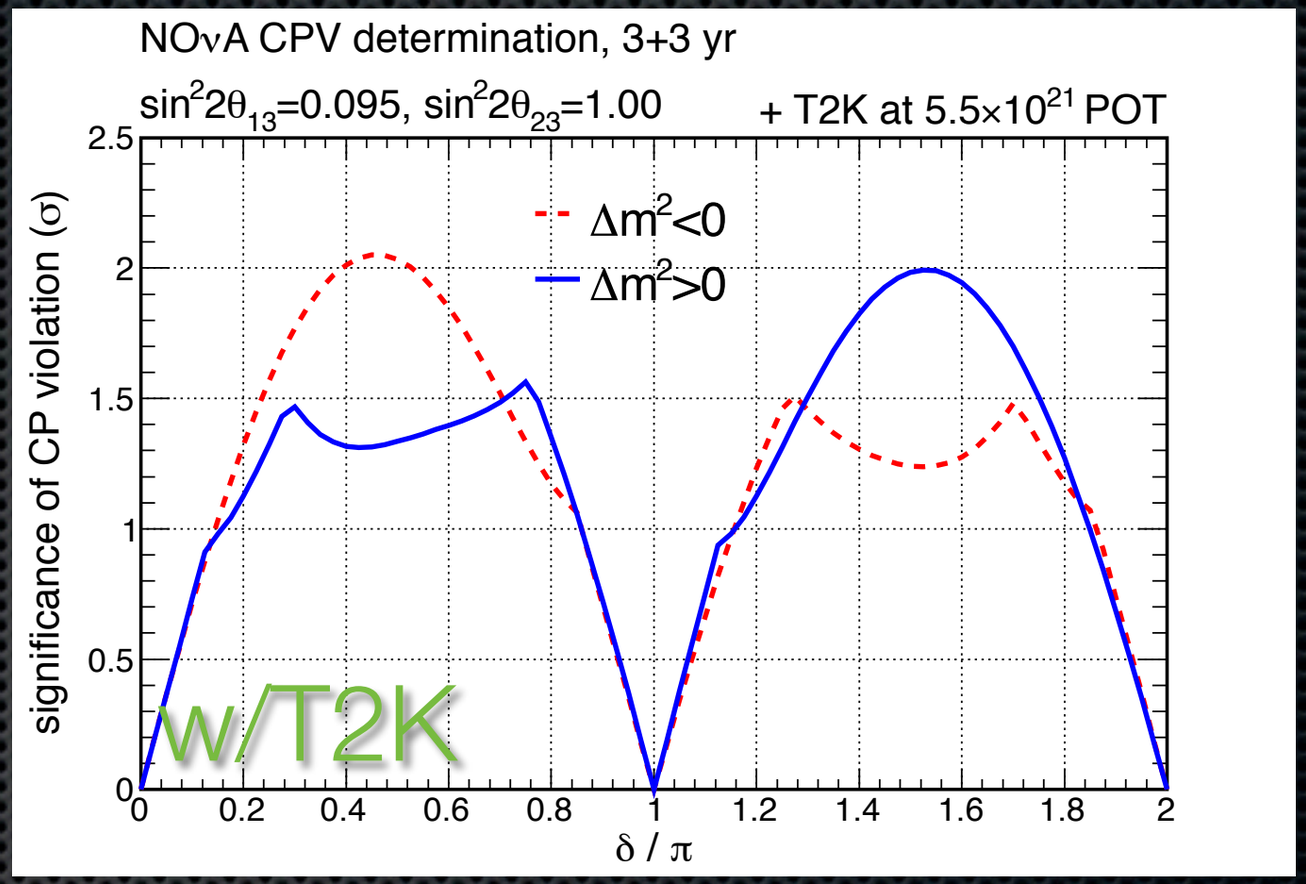


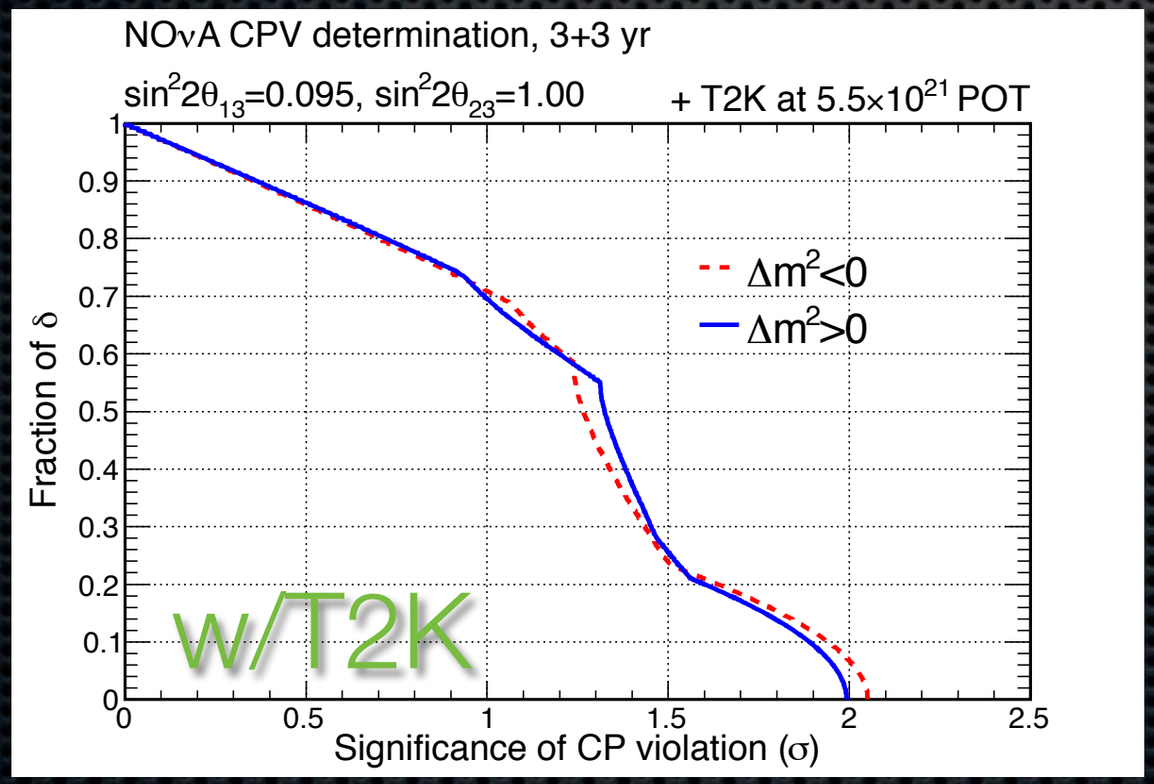


- Results from full simulation, reconstruction, selection, and analysis framework.
  - FD only. Extrapolation methods from ND in progress.

Study of CP violation

- Significance of CP violation using energy spectrum.
- Assumes that mass hierarchy is unknown.

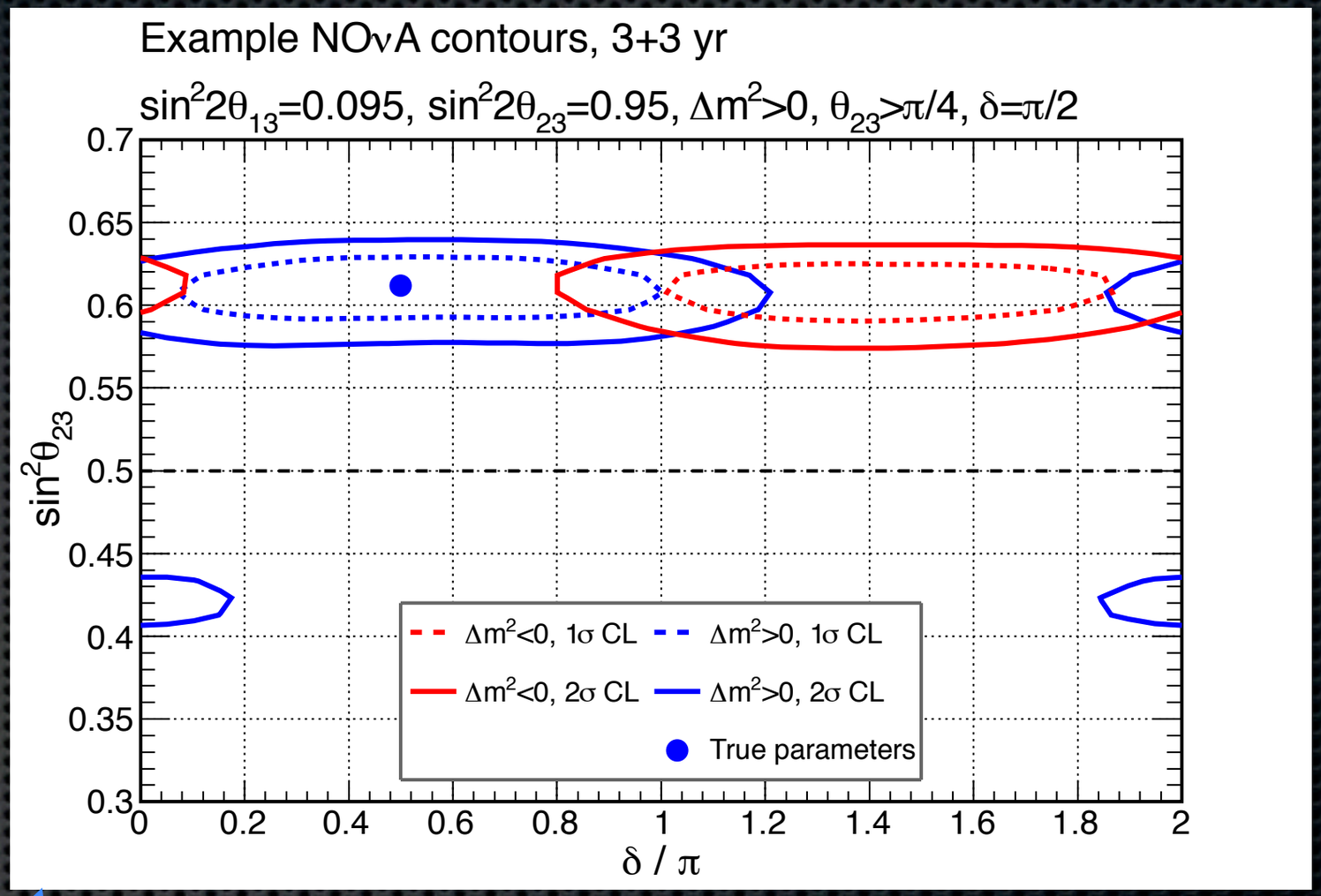


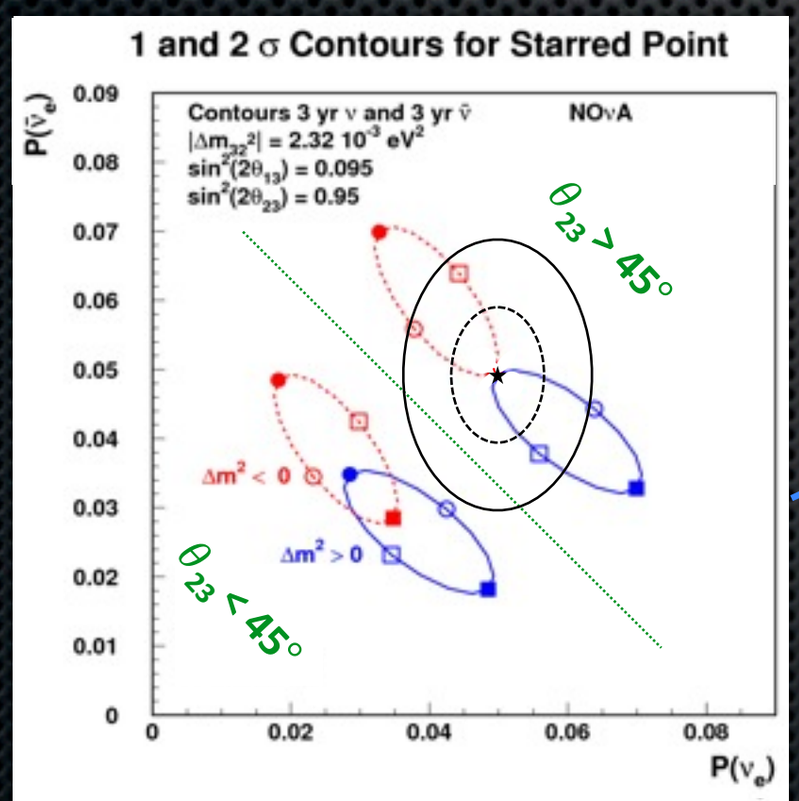


- Differences in baseline/ matter effects between NOvA and T2K can provide additional information.

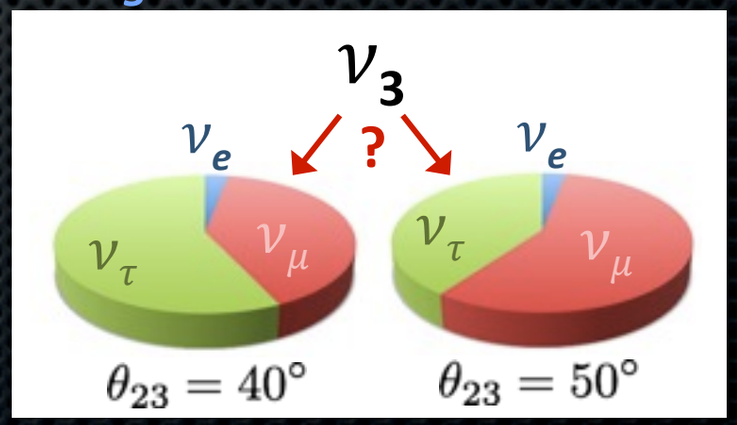
Non-maximal $\sin^2 2\theta_{23}$ and NOvA

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





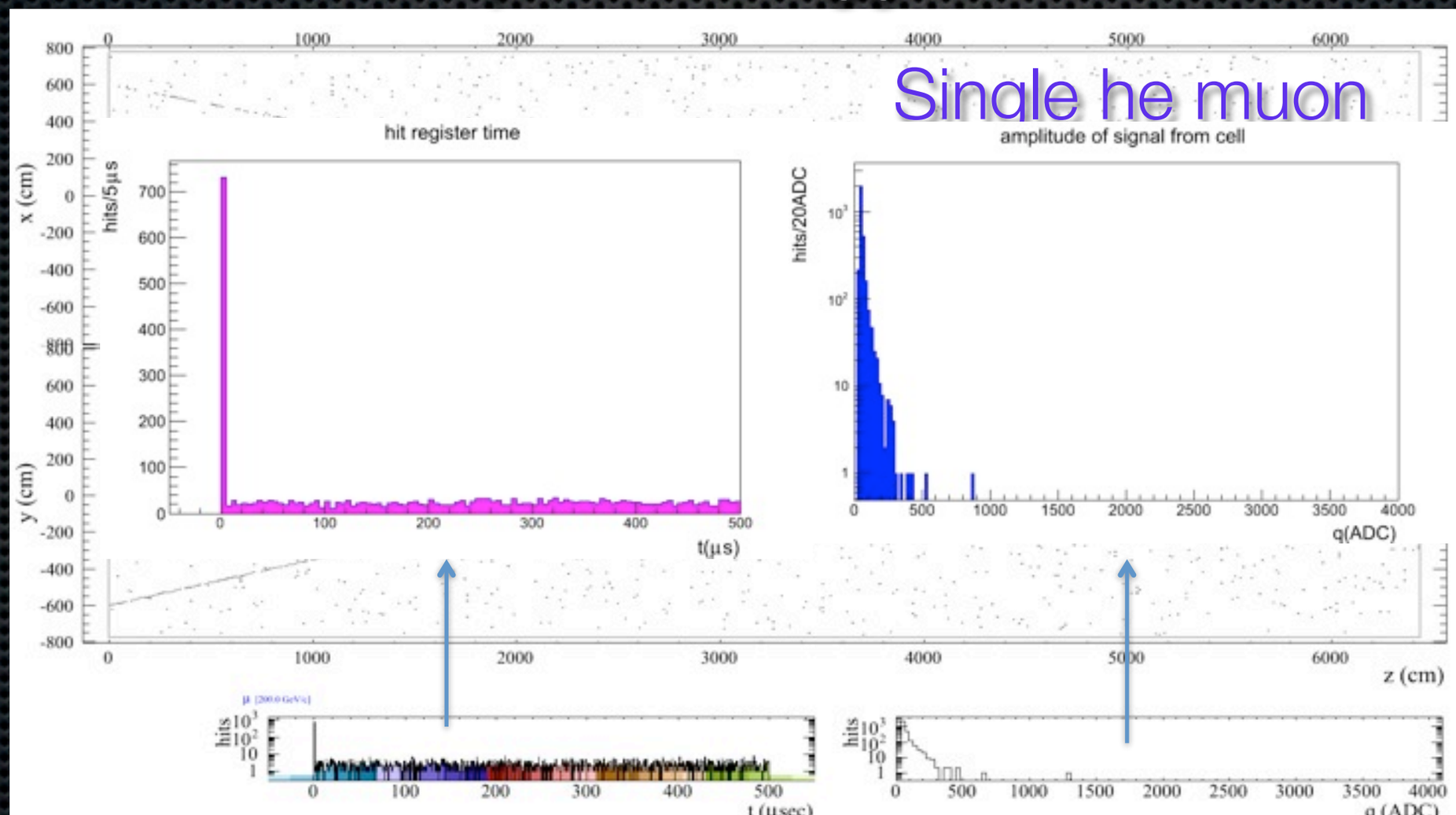
In "degenerate" cases, hierarchy and δ information is coupled. However θ_{23} octant information might not.



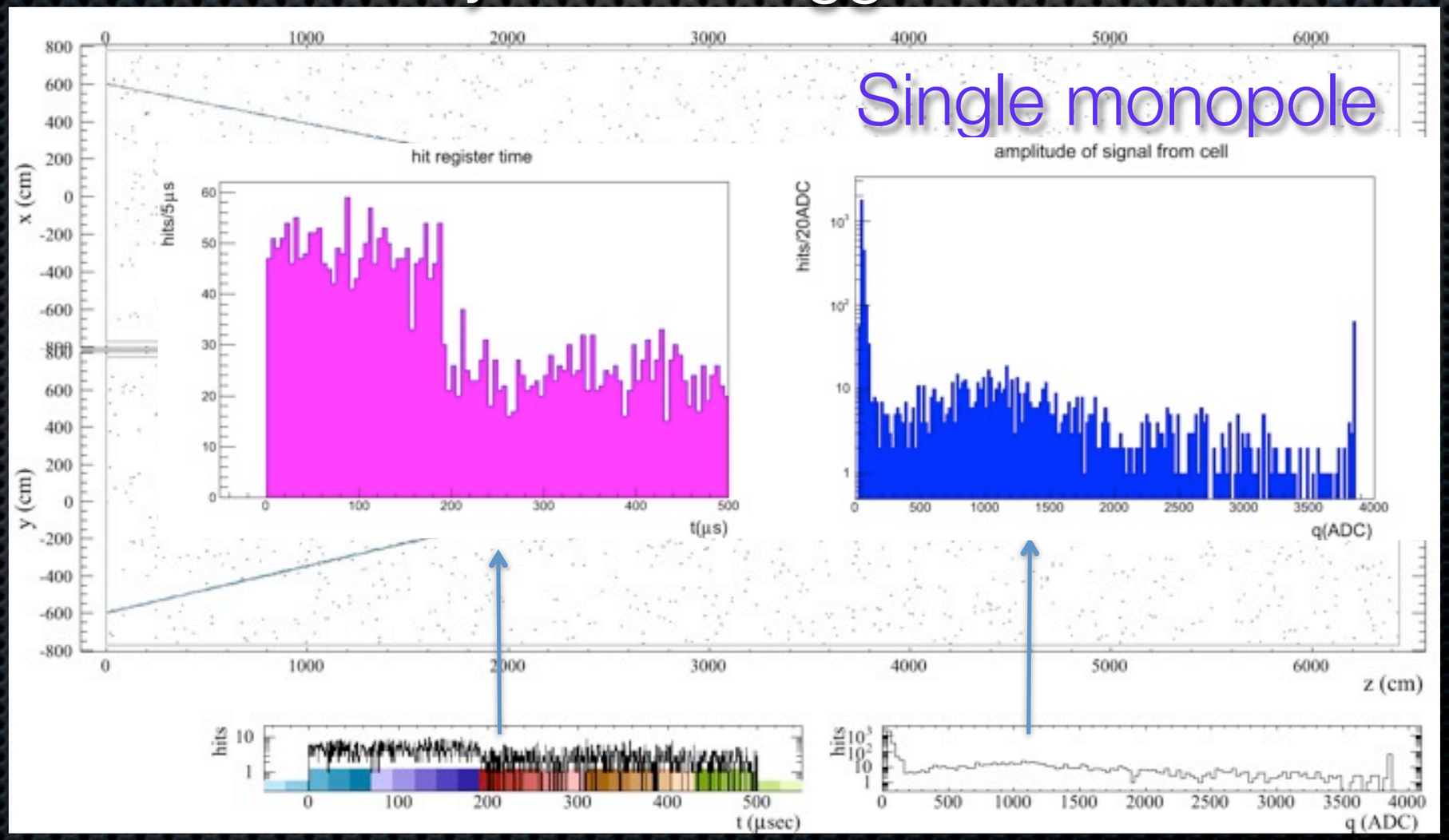
One more thing...

Supernovas and monopoles

- NOvA is not underground, however it is a segmented detector with a very flexible trigger.



One more thing...

Supernovas and monopoles

- NOvA is not underground, however it is a segmented detector with a very flexible trigger.