The NOvA Experiment: Status and Prospects

Mayly Sanchez
Iowa State University/ANL

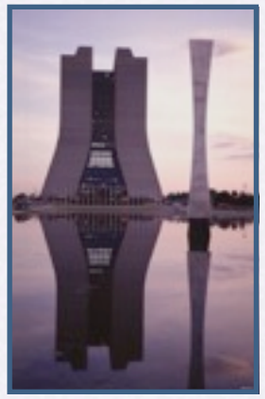
22nd International Workshop on
Weak Interactions and Neutrinos
(WIN'09)
September 14-19, 2009

The NOvA Collaboration

Argonne National Laboratory • University of Athens • California Institute of Technology • University of California, Los Angeles • Fermi National Accelerator Laboratory • College de France • 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 New York, Stony Brook • Northern Illinois University, DeKalb • Northwestern University • Ohio State University, Columbus • Pontifícia Universidade Católica do Rio de Janeiro • University of South Carolina, Columbia • Southern Methodist University • Stanford University • 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

NOvA in a nutshell

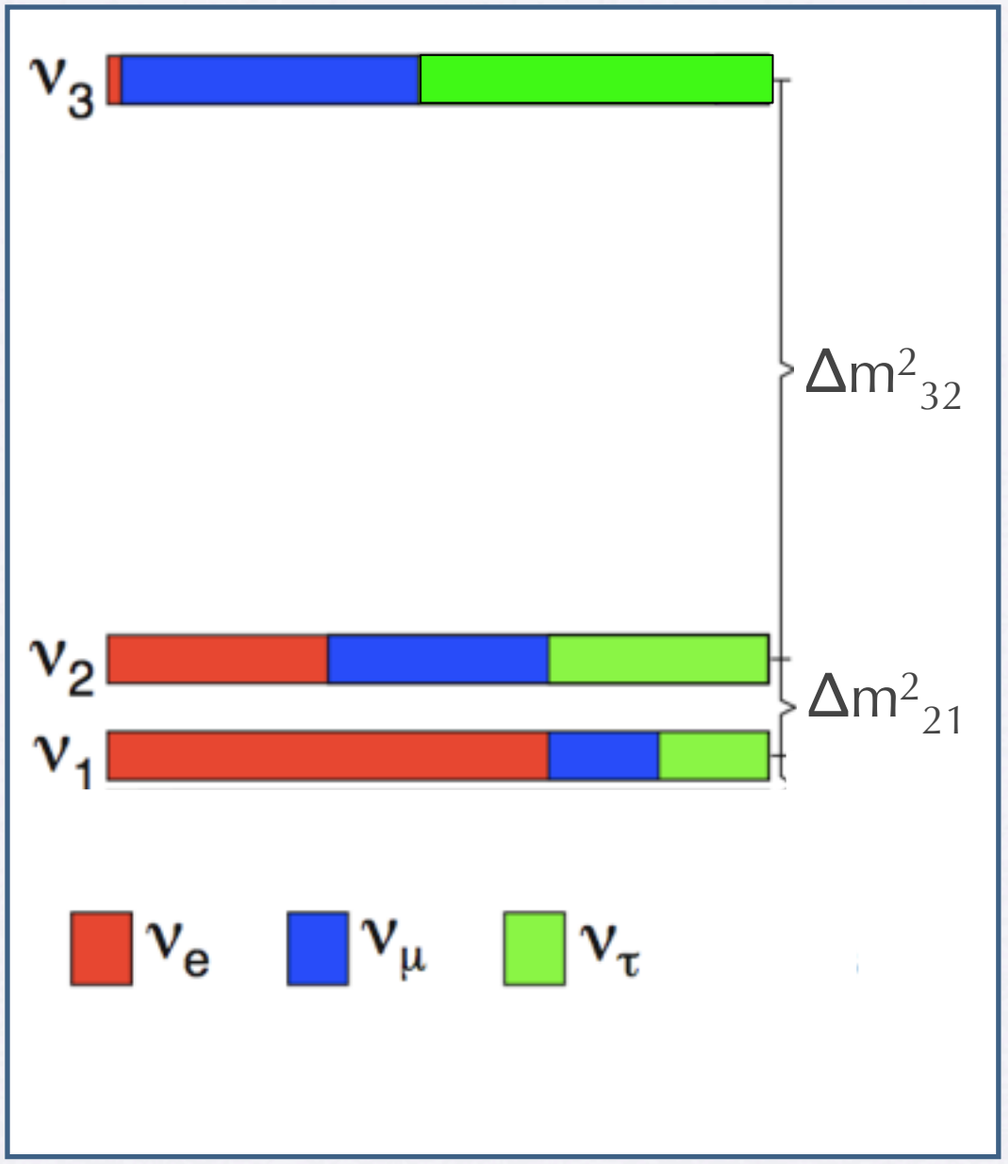
- Use existing high intensity beam of muon neutrinos at Fermilab.
- Construct two detectors, bigger detector off the main axis of the beam.
  - Location reduces background for the search.
- If neutrinos oscillate, electron neutrinos are observed at the Far Detector in Ash River, 810 km away.



2nd generation
← long baseline →

NOvA Physics

What can we measure?



- The atmospheric mass scale: Δm^2_{32}.
- Large mixing angle for atmospheric neutrino oscillations: θ_{23}.
- **The third mixing angle: θ_{13}.**
- **CP violation: δ_{CP}.**
- **Mass ordering for the atmospheric oscillations: the sign of Δm^2_{32}.**

Searching for θ_{13} in ~~MINOS~~ NOvA

- **The probability of ν_e appearance in a ν_μ beam:**

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

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

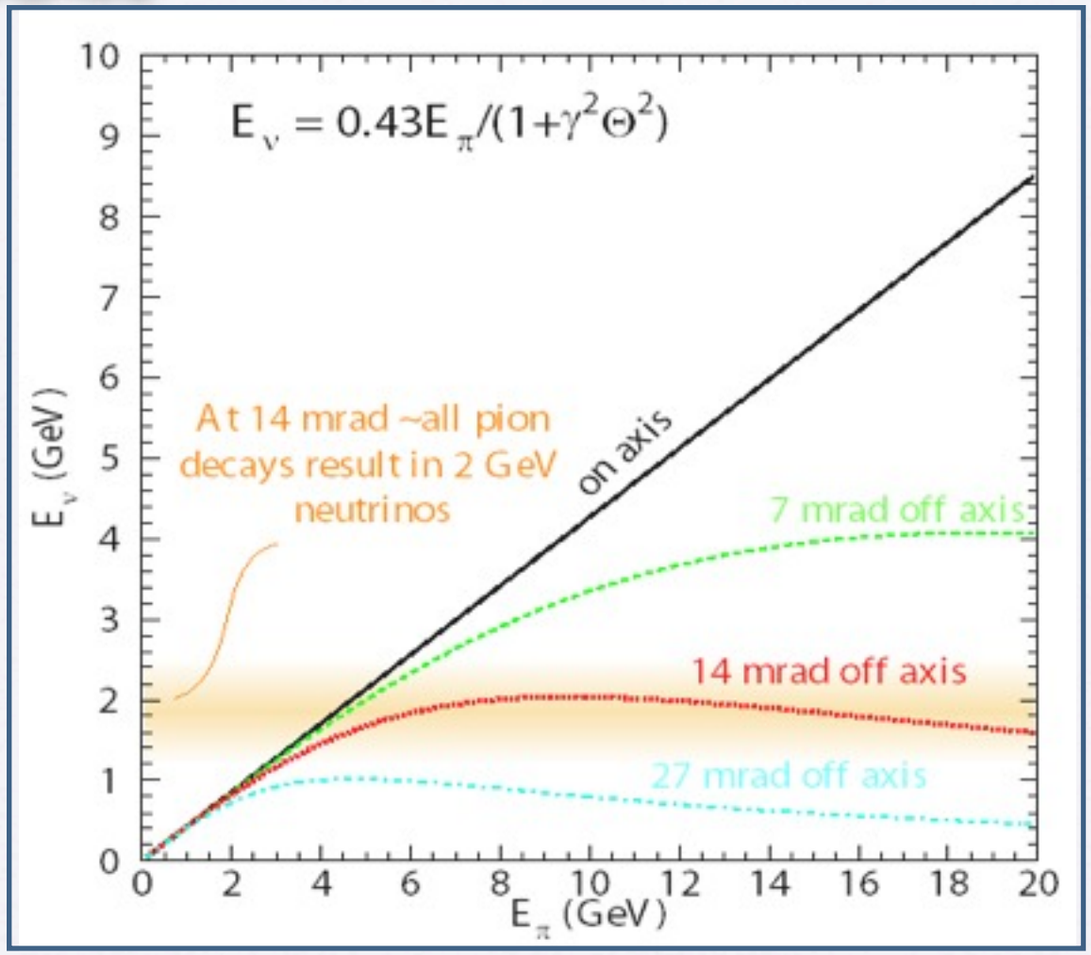
$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$
$$+2\alpha \sin\theta_{13}\cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$
$$-2\alpha \sin\theta_{13}\sin\delta \sin 2\theta_{12} \sin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

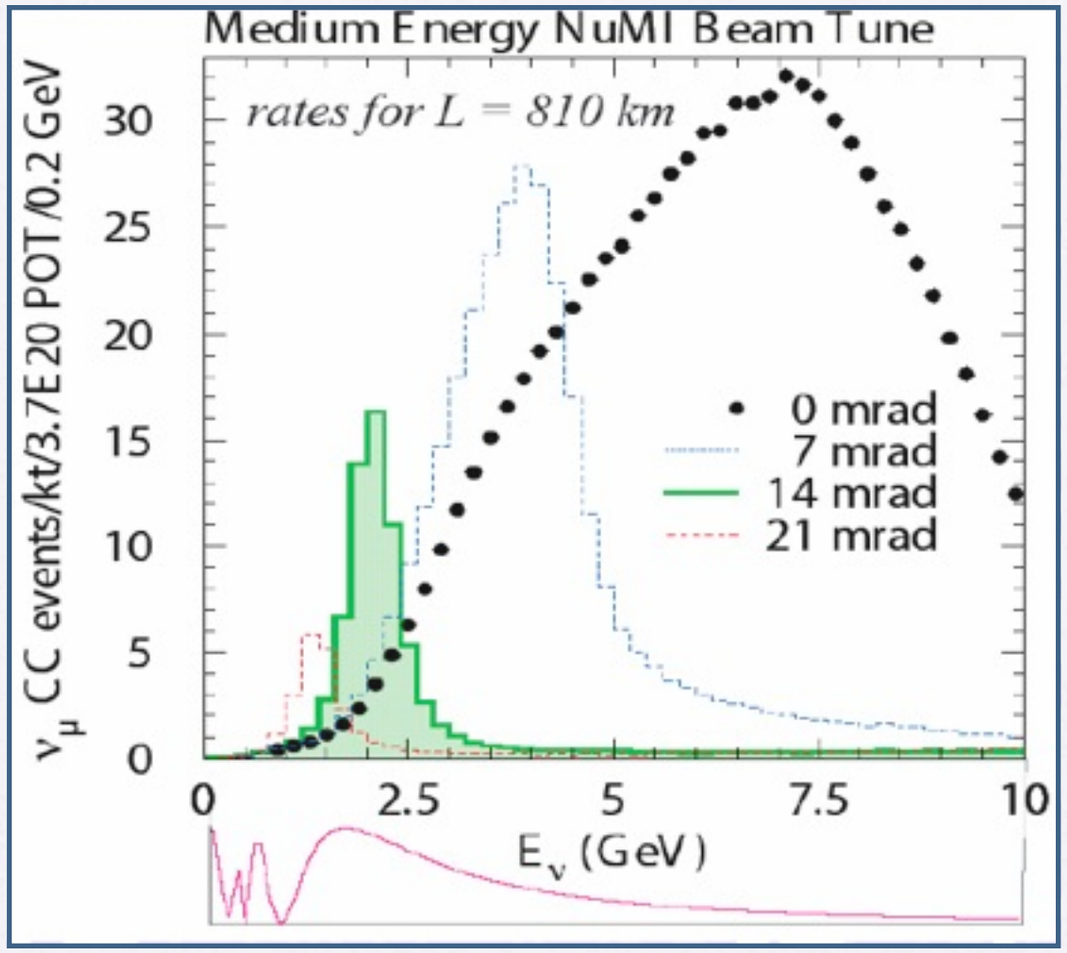
- **Searching for ν_e events in ~~MINOS~~ NOvA, we can access $\sin^2(2\theta_{13})$.**
- Probability depends not only on θ_{13} but also on δ_{CP}. For large θ_{13}, a measurements could be possible.

✳ 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.

✳ A 30% effect in NOvA, compared to 11% in T2K

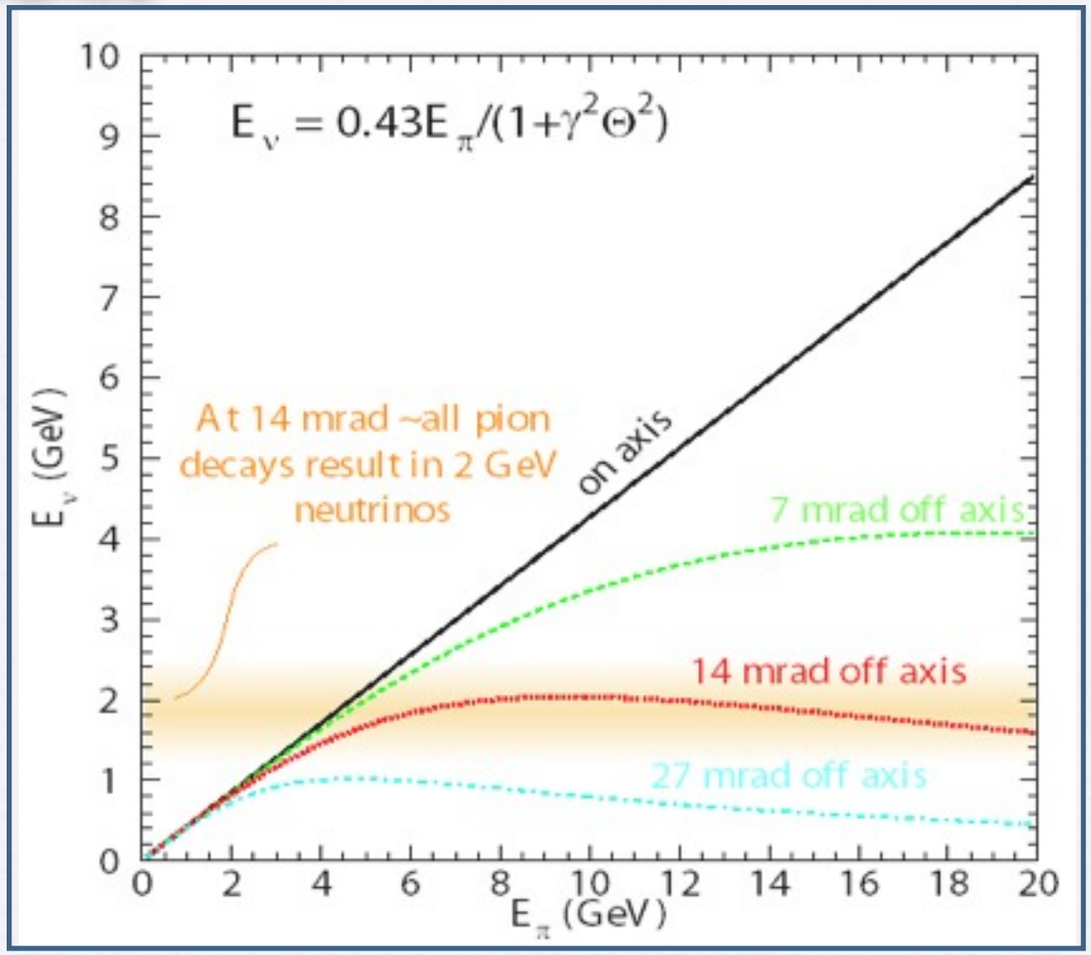
Off-axis NuMI Beam

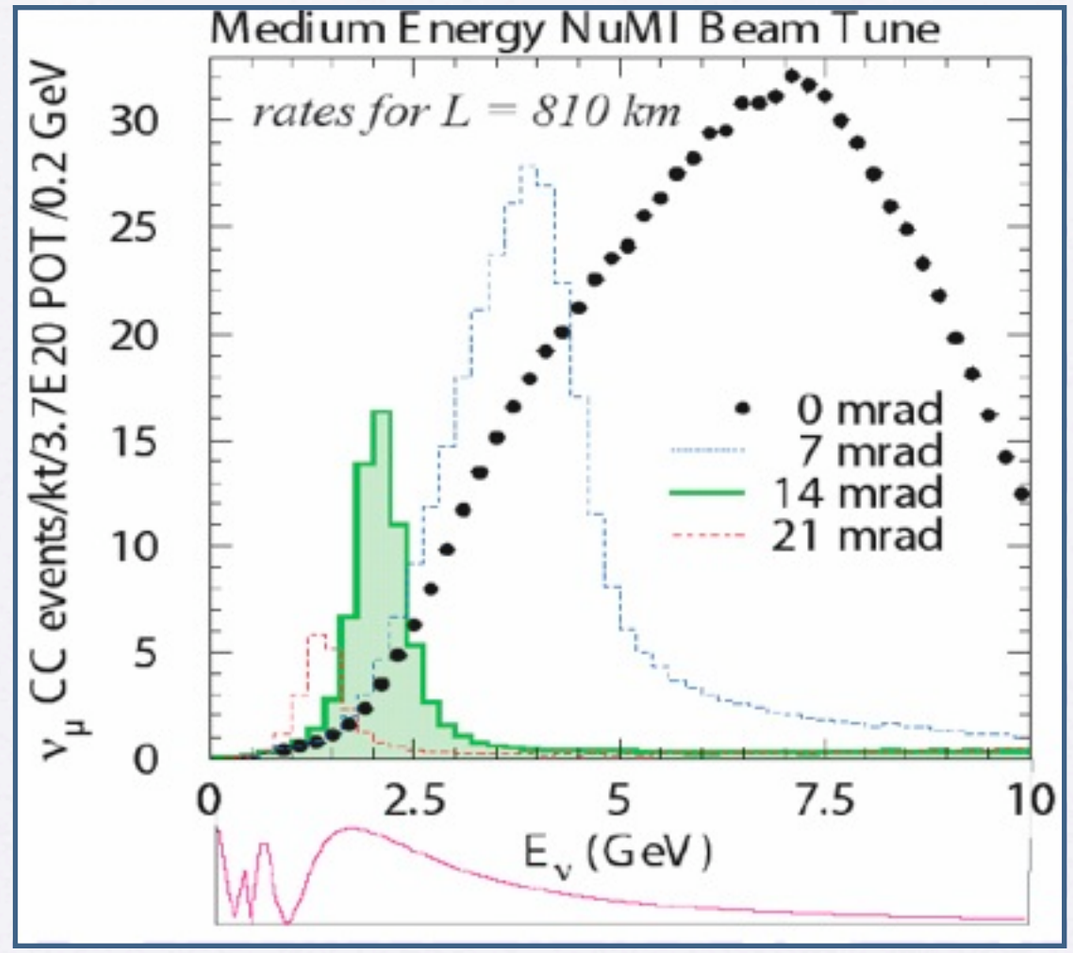




- Off-axis yields a narrow band beam. Peak sits just above oscillation maximum with 5 times the flux than on axis. High energy tail is suppressed.
- Upgrade neutrino beam intensity from 320kW to 700kW:
  - Use the recycler ring to store 12 batches while Main Injector ramps up.
  - Rate of Main Injector increases cycle time from 2.2 sec to 1.33 sec.

Off-axis NuMI Beam

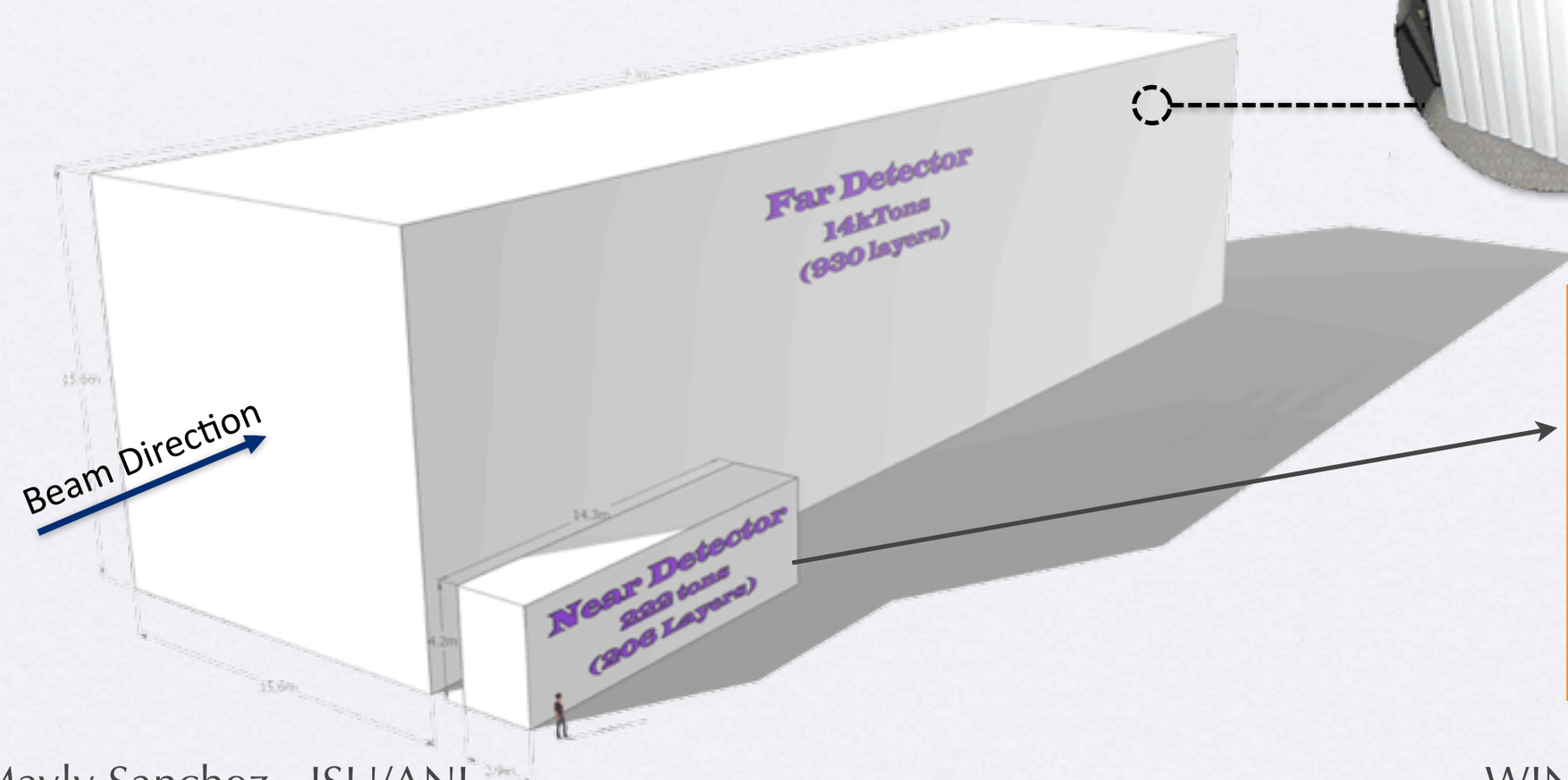




- Beam performance:
  - 10 μsec spill every 1.3 sec.
  - 4.9 x 10^{13} POT/spill.
  - ~3 x 10^{18} POT/day -> 6 x 10^{20} POT/yr.
  - Running plan is 3 yrs ν_μ and 3 yrs $\bar{\nu}_\mu$.

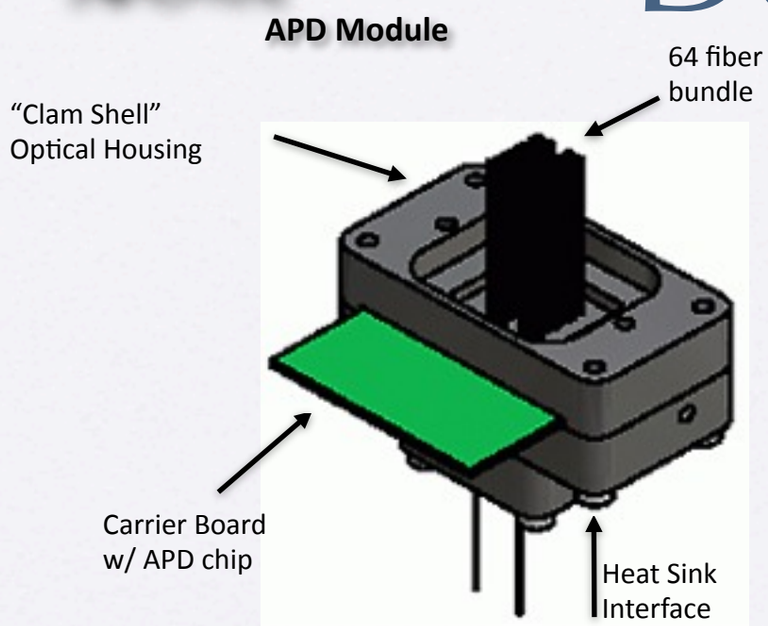
The NOvA Detectors

- 14 kton Detector (~3x MINOS).
- >70% active detector.
- Plastic cells filled with scintillating mineral oil.
- Each plane just 0.15 X_0. Great for electrons (in MINOS 1.44 X_0).
- Cells are 3.9 x 6.0 cm.
- 15.6 x 15.6 x 68 m for Far.
- 4.2 x 2.9 x 15.3 m for Near.

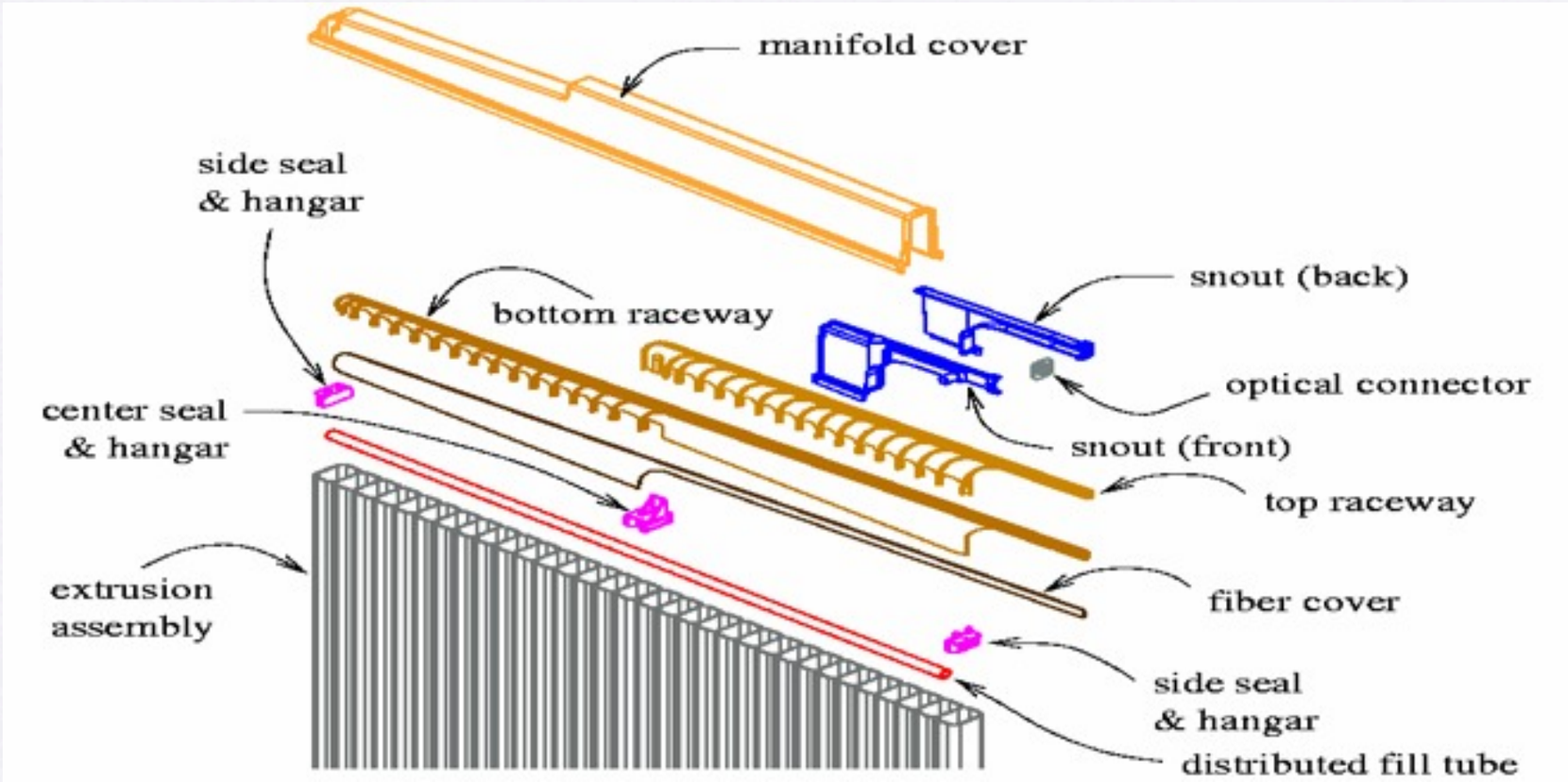


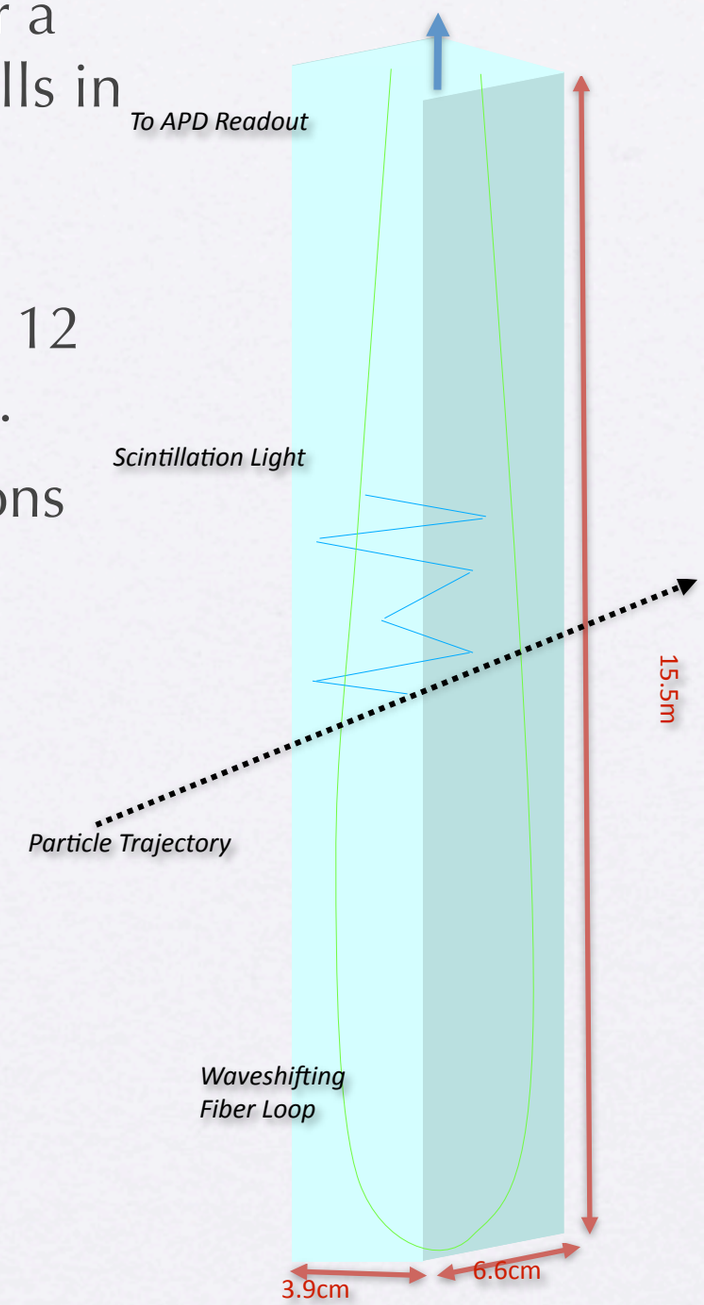
Now also starring as the IPND. To be placed on the surface before going underground at the Fermilab site.

Detector Elements



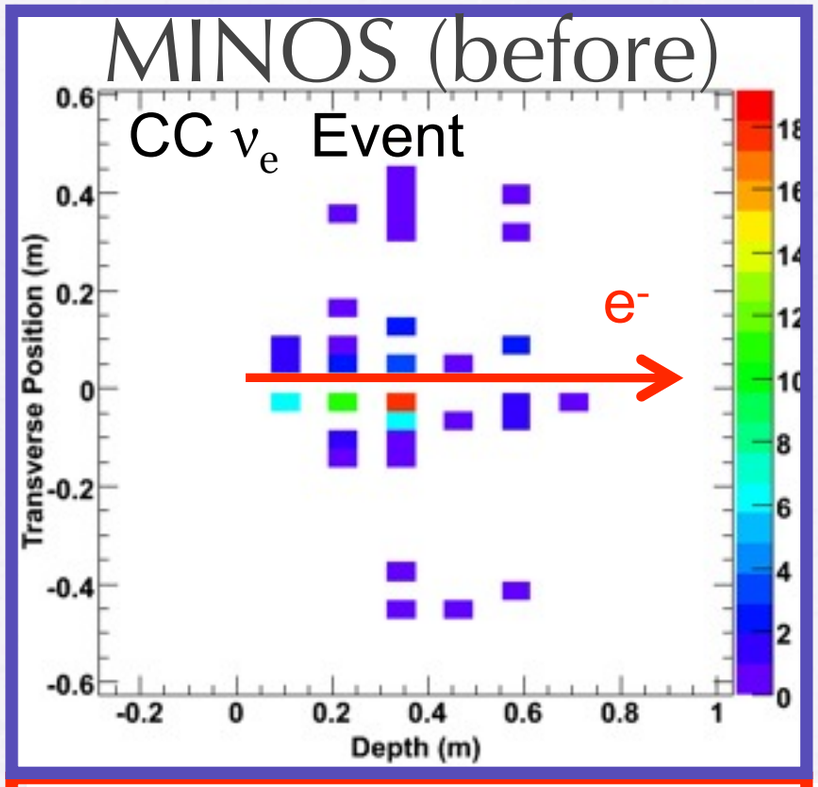
- There are 11,160 detector modules for a total of 357,120 separated detector cells in the NOvA Far Detector.
- Each module is made of two high reflectivity PVC extrusions. Combined 12 module wide X or Y measuring planes.
- 12,500 km of 0.7 mm fiber, 3 M gallons of scintillator.

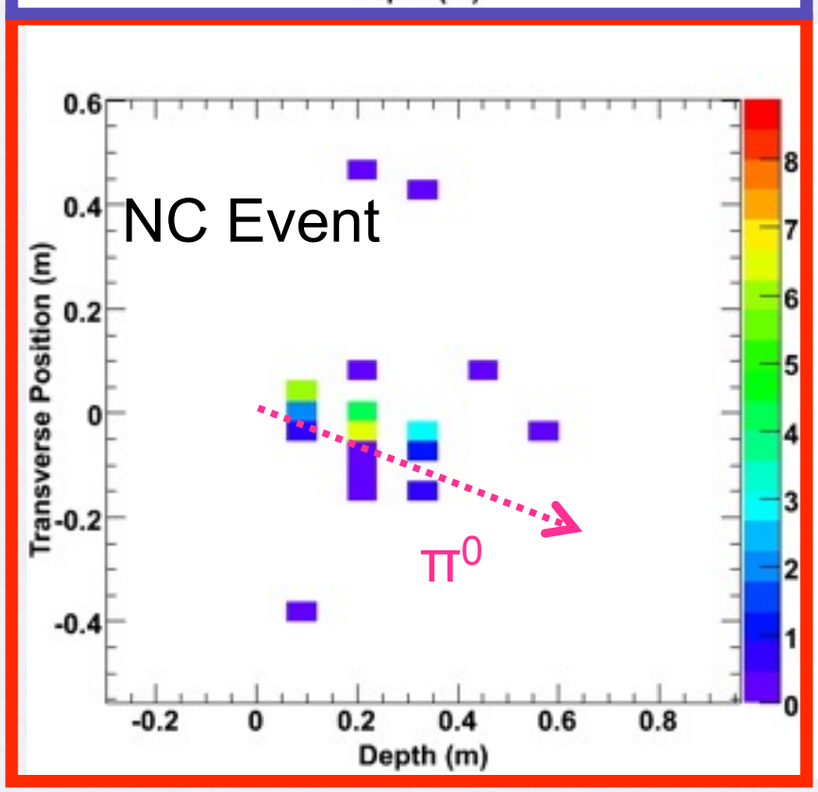




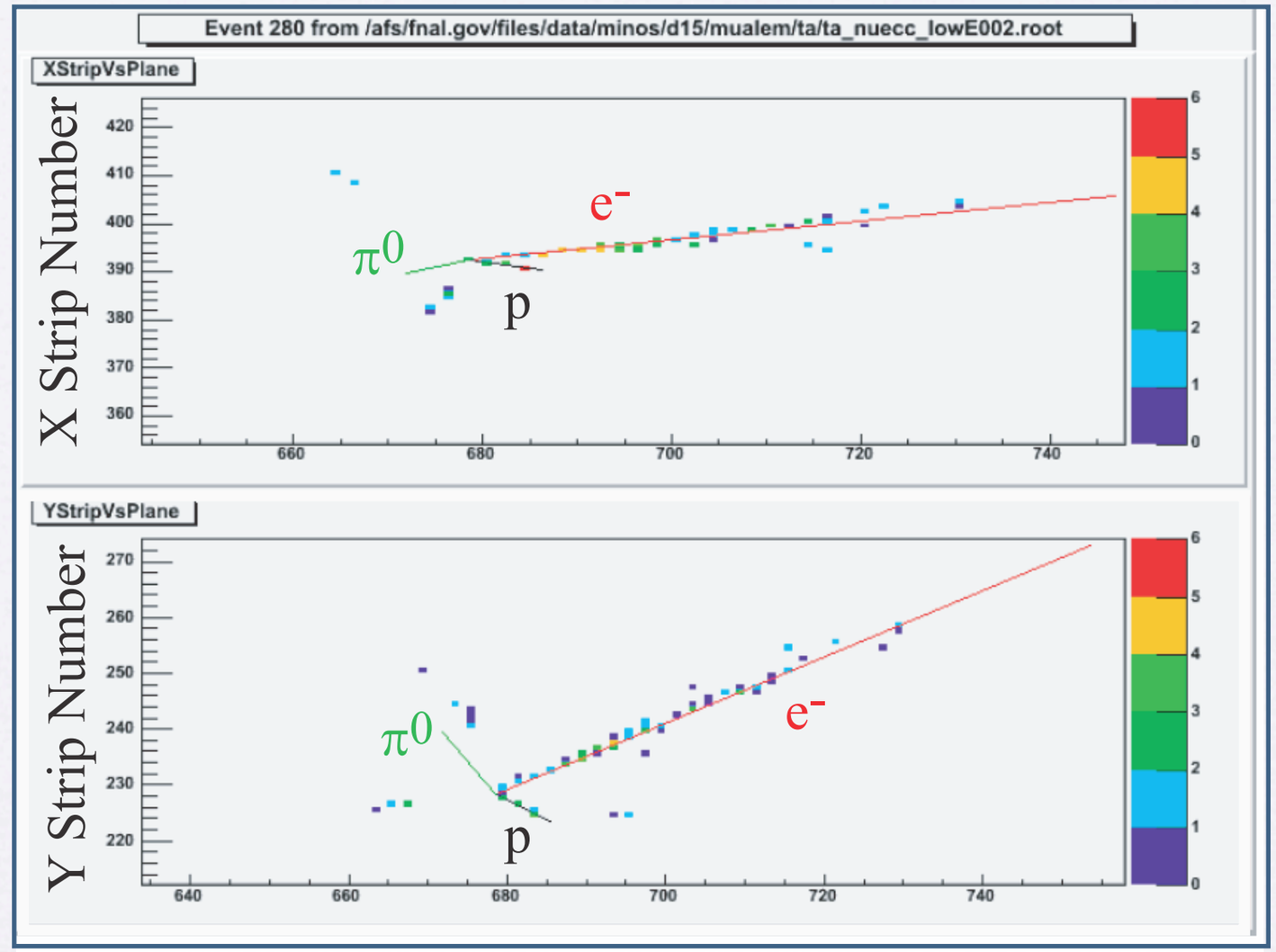
Electrons and Neutral Pions

MINOS (before)





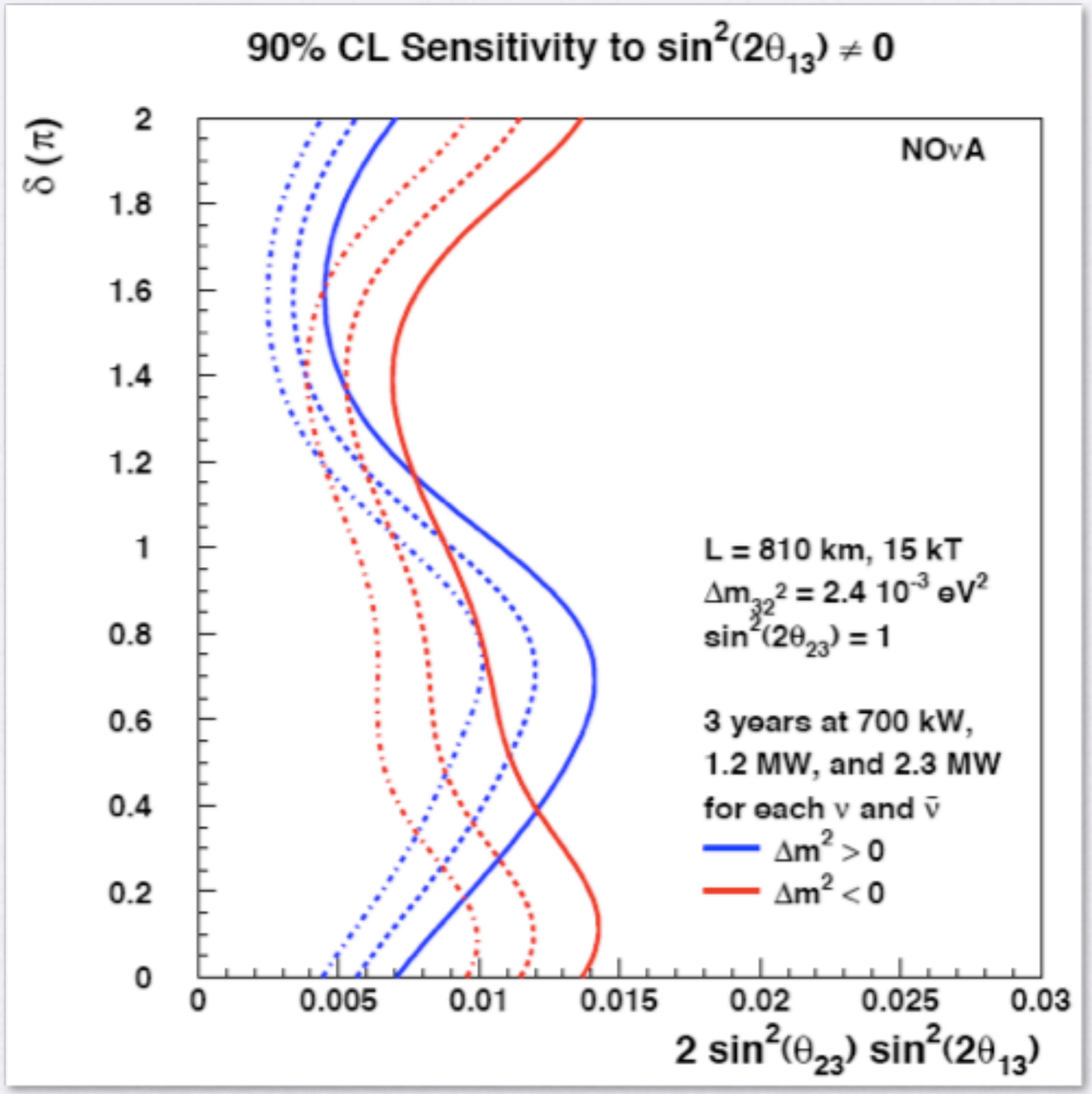
NOvA (after)



NOvA is designed to search for electron neutrino appearance.

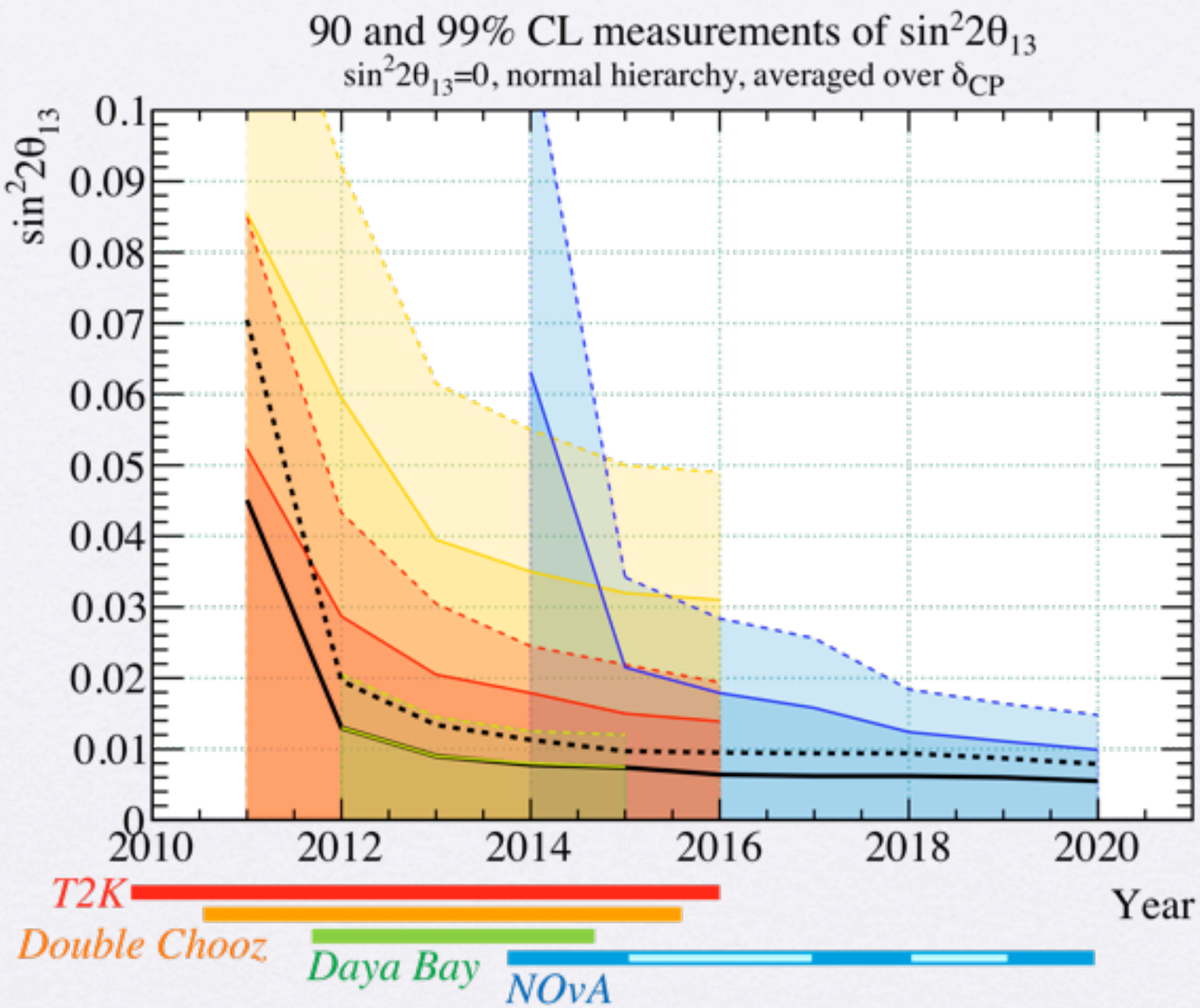
Sensitivity for θ_{13}

- NOvA is sensitive to electron neutrino appearance down by an order of magnitude at 90% CL.
- Reach is for 3 years of running ν_μ and $\bar{\nu}_\mu$.
- Note contours for different beam upgrades.



NOvA's physics reach

Assuming 700 kW beam



- Do interpret the dates with the appropriate amount of salt:
  - Plots for data taken not analyses published.
  - Schedules always change.
- If $\sin^2 2\theta_{13}$ high, NOvA reaches it to make precision measurement.

Current World Data

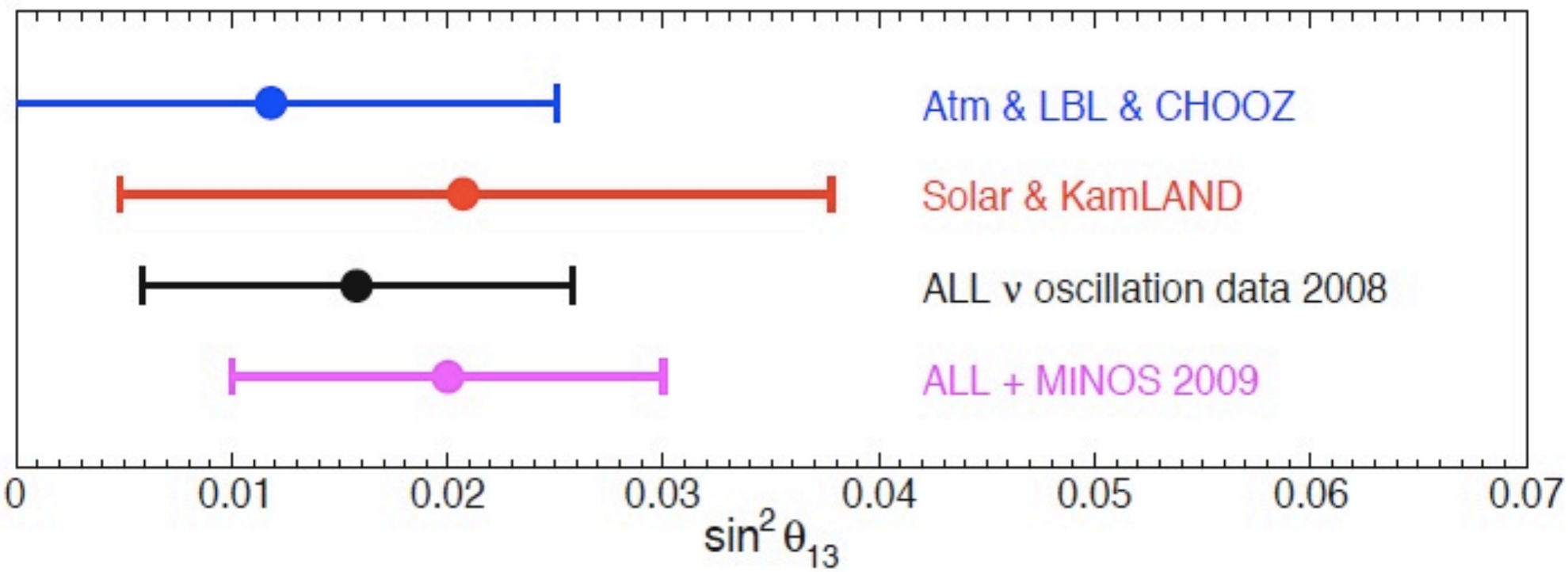
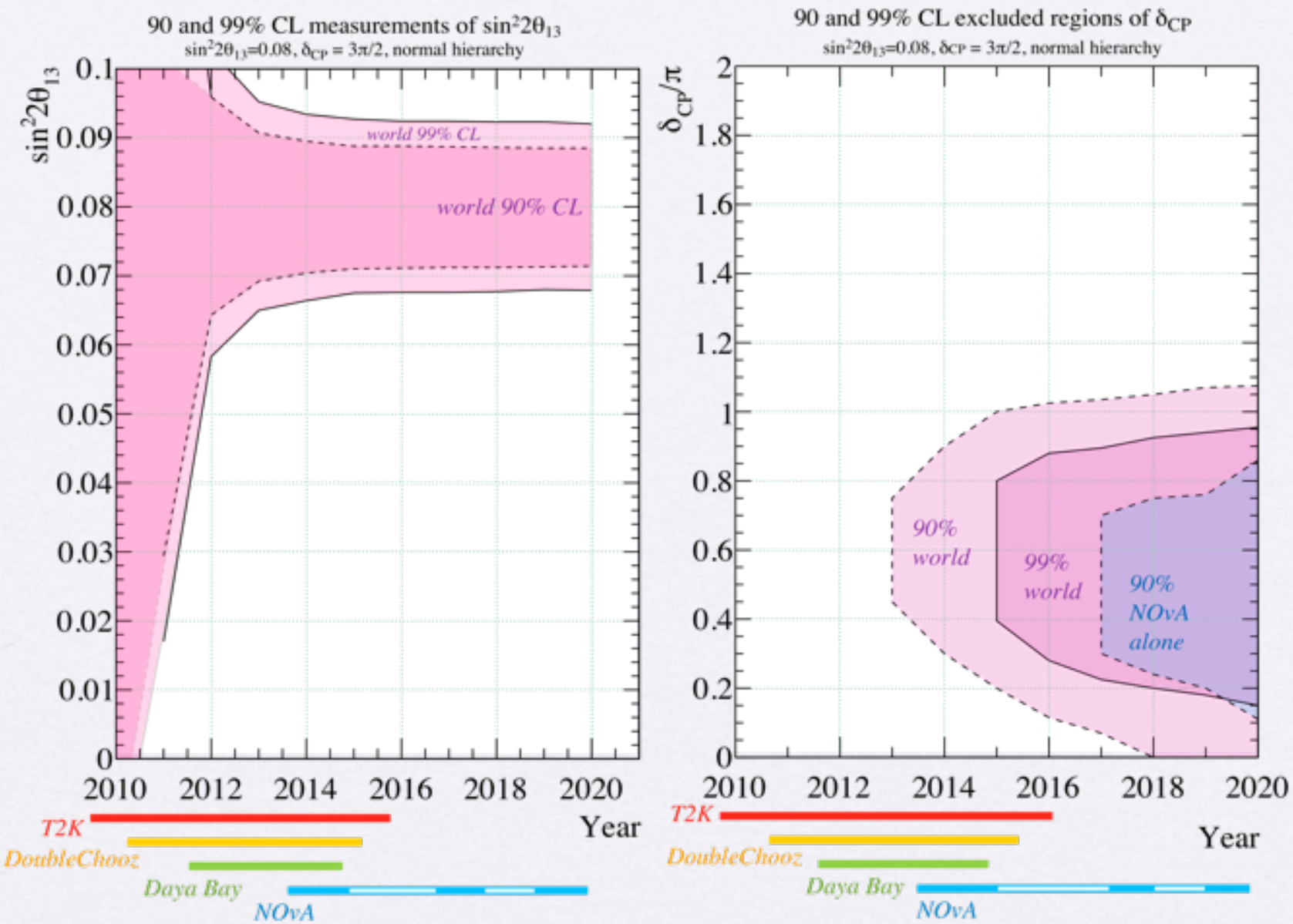


Figure 4: Hints of $\theta_{13} > 0$ from different data sets and combinations: 1σ ranges.

- Recent global fit to the world data by Fogli et al. (arxiv:0905.3549).
- $\sin^2(2\theta_{13})=0$ disfavored at 2 σ.
- Central value for $\sin^2(2\theta_{13}) = 0.08$ (or $\sin^2(\theta_{13})=0.02$).

What if the mixing is large?

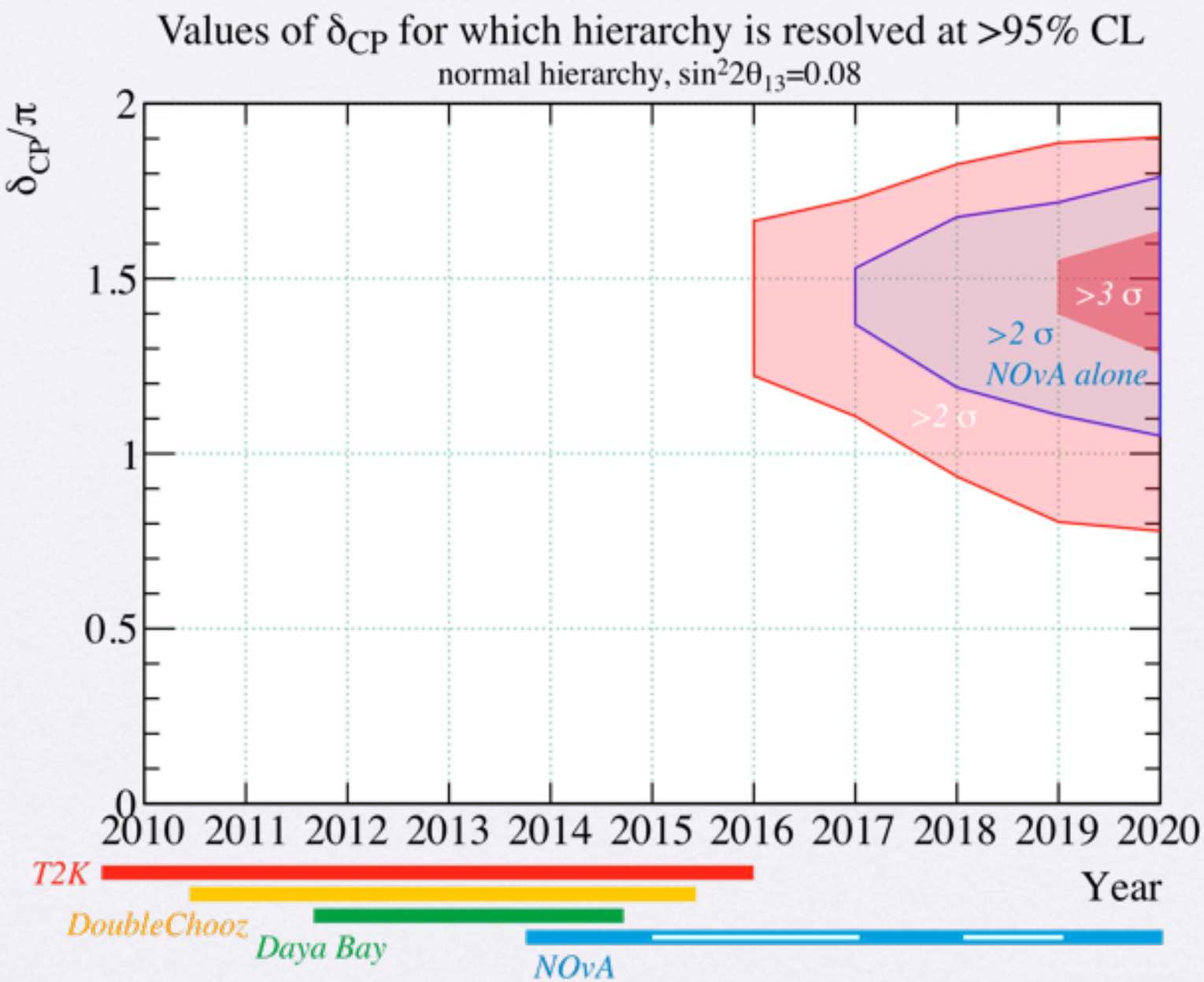
$\sin^2 2\theta_{13}=0.08$



- NOvA can provide information about δ_{CP} on its own.
  - T2K+Daya Bay can contribute.
- All other experiments are combined for the world numbers.
- Just by starting NOvA you cover half the δ_{CP} space.

Resolving the mass hierarchy

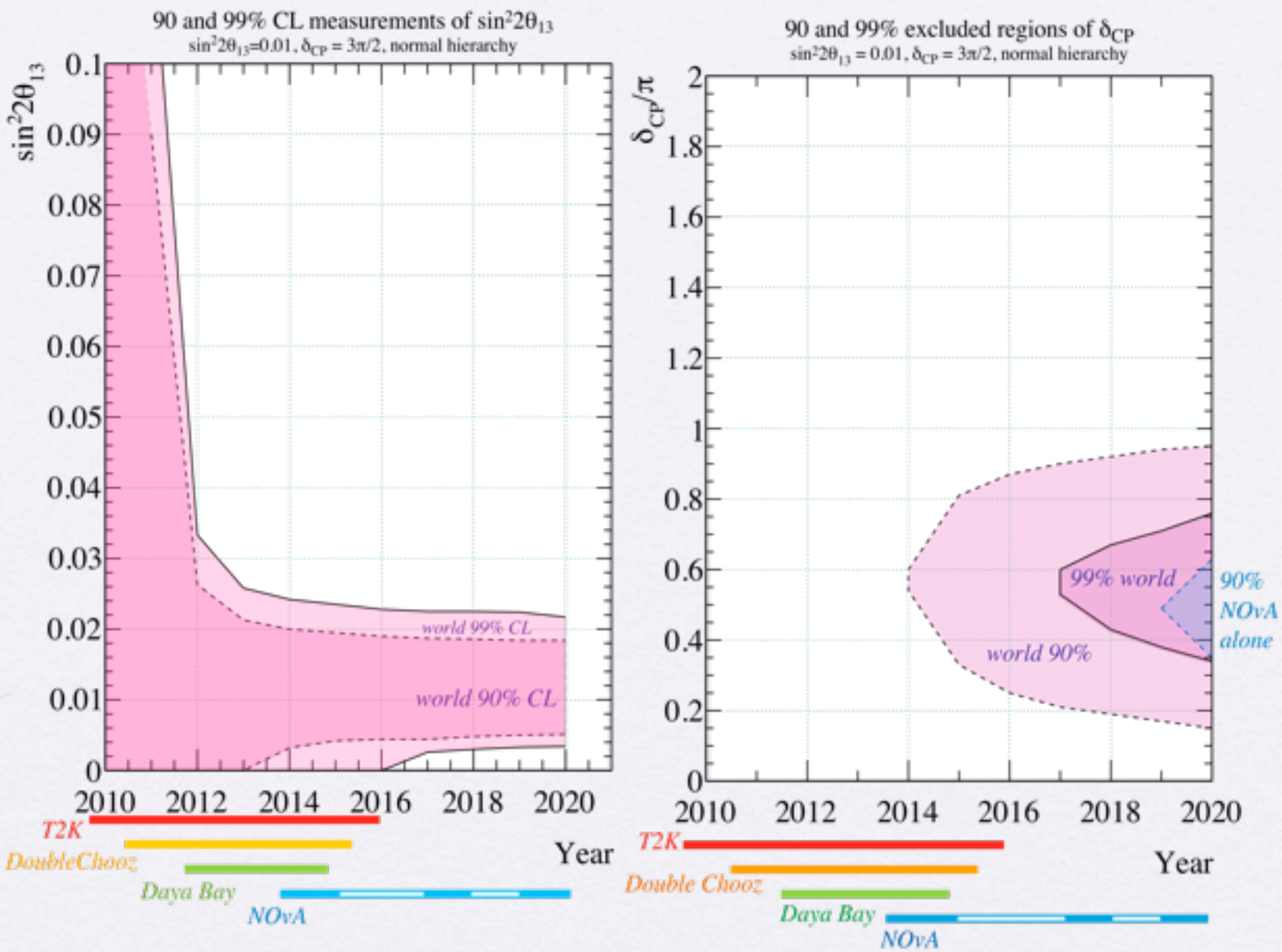
$\sin^2 2\theta_{13}=0.08$



- NOvA can resolve the **mass hierarchy** on its own.
  - T2K+Daya Bay +DChooz+NOvA create the larger exclusion.

What if the mixing is small?

$\sin^2 2\theta_{13}=0.01$

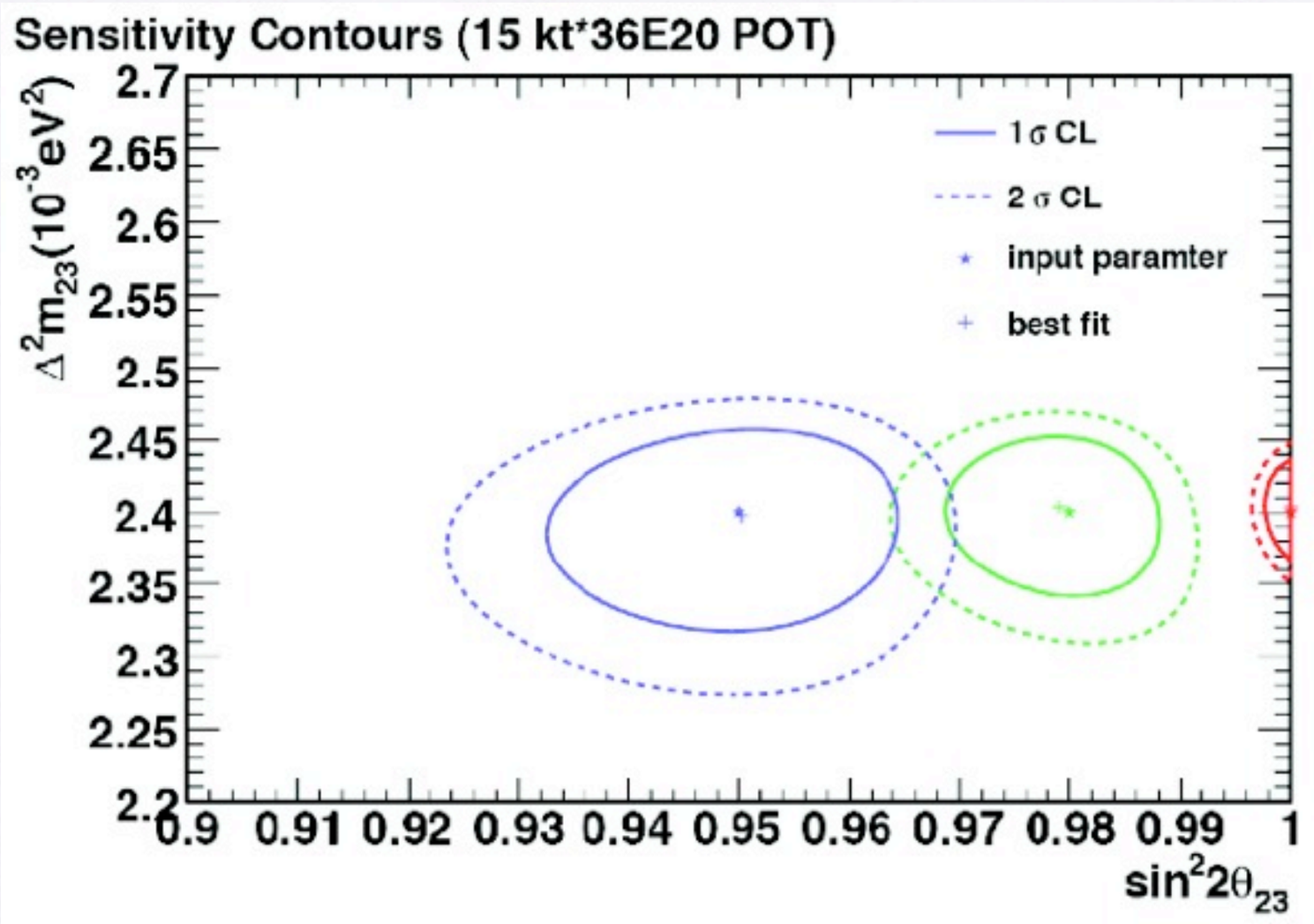


The addition of NOvA data pushes World limit on $\sin^2 2\theta_{13}$ past 99% CL.

- NOvA can provide information about δ_{CP} on its own.
  - T2K+Daya Bay can contribute.
- All other experiments need to be combined for the world numbers.
- Just by starting nova you cover half the δ_{CP} space.

Is the mixing maximal?

Sensitivity on $\sin^2 2\theta_{23}$

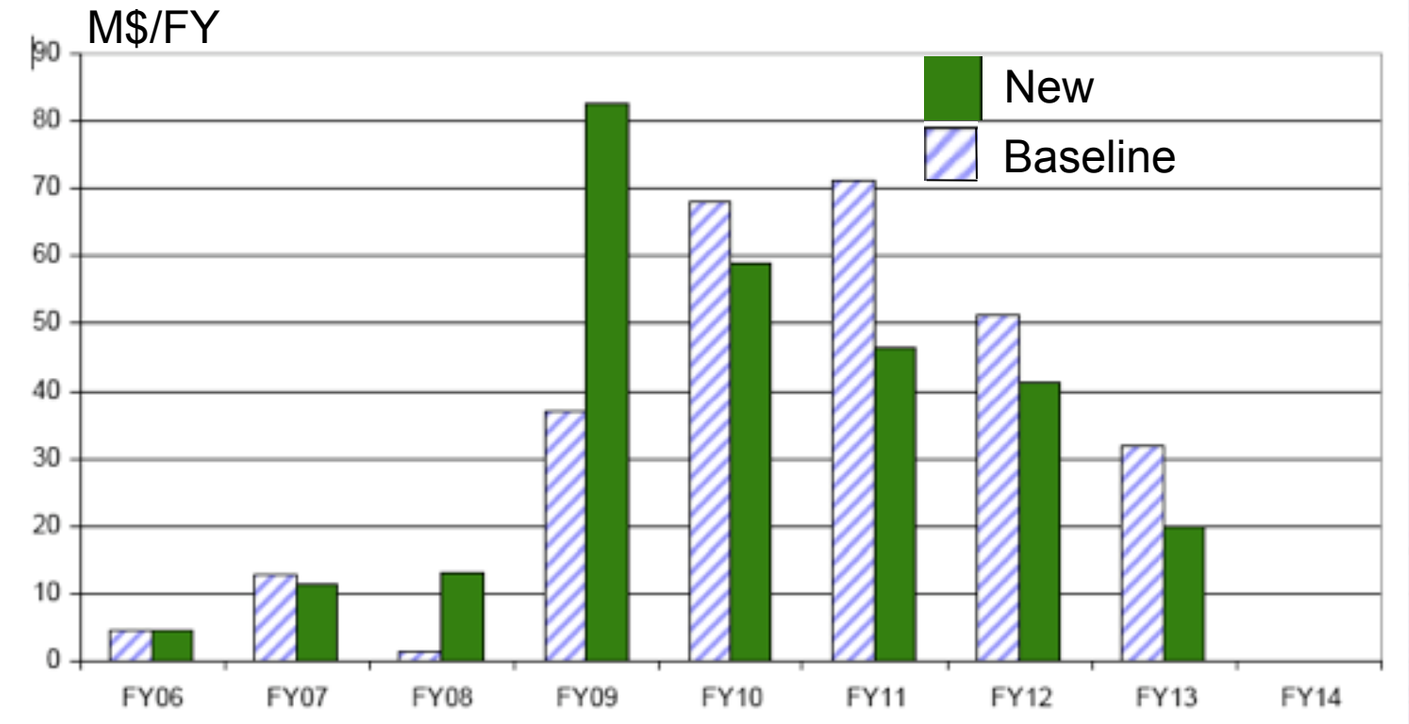


If combined with Double Chooz/Daya Bay it can break the ambiguity in θ_{23}.

- NOvA's narrow band beam centered at the peak of the oscillation, allows for a 1% disappearance measurement.
- Improve one order of magnitude in $\sin^2 2\theta_{23}$.

NOvA Status and Plans

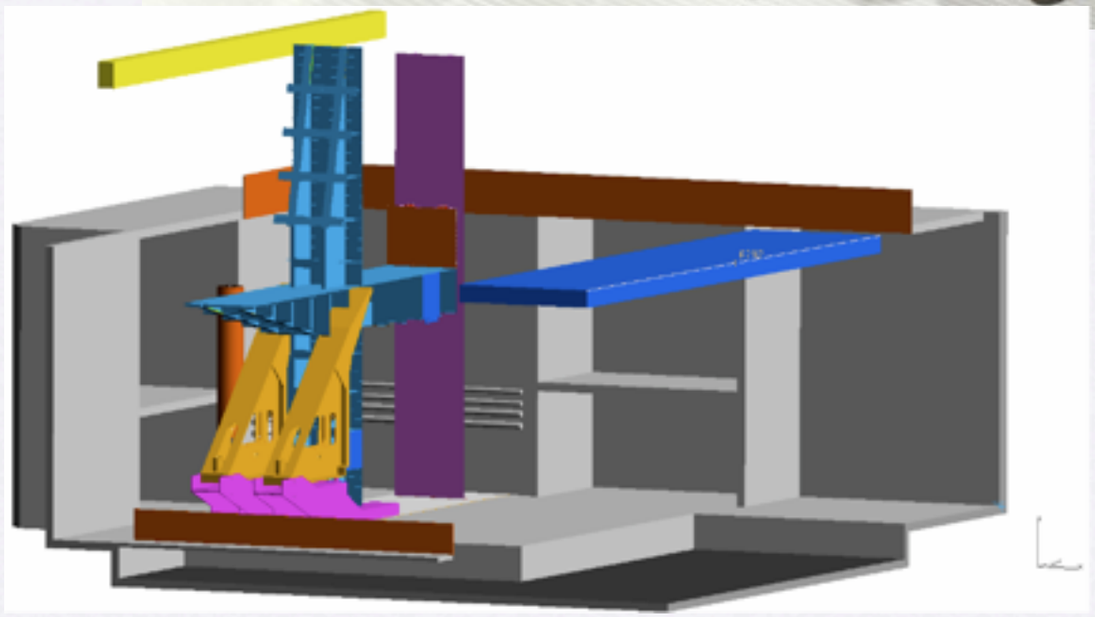
- NOvA has reached CD3a, CD3b is in the works.
- New budget is front loaded, new schedule reflects that:



- Assembly R&D effort is in progress.
- Prototype Near Detector (IPND) will be installed on the surface next year sitting far off axis of the MINOS beam.
- Far Detector site ground broken and building construction has started.

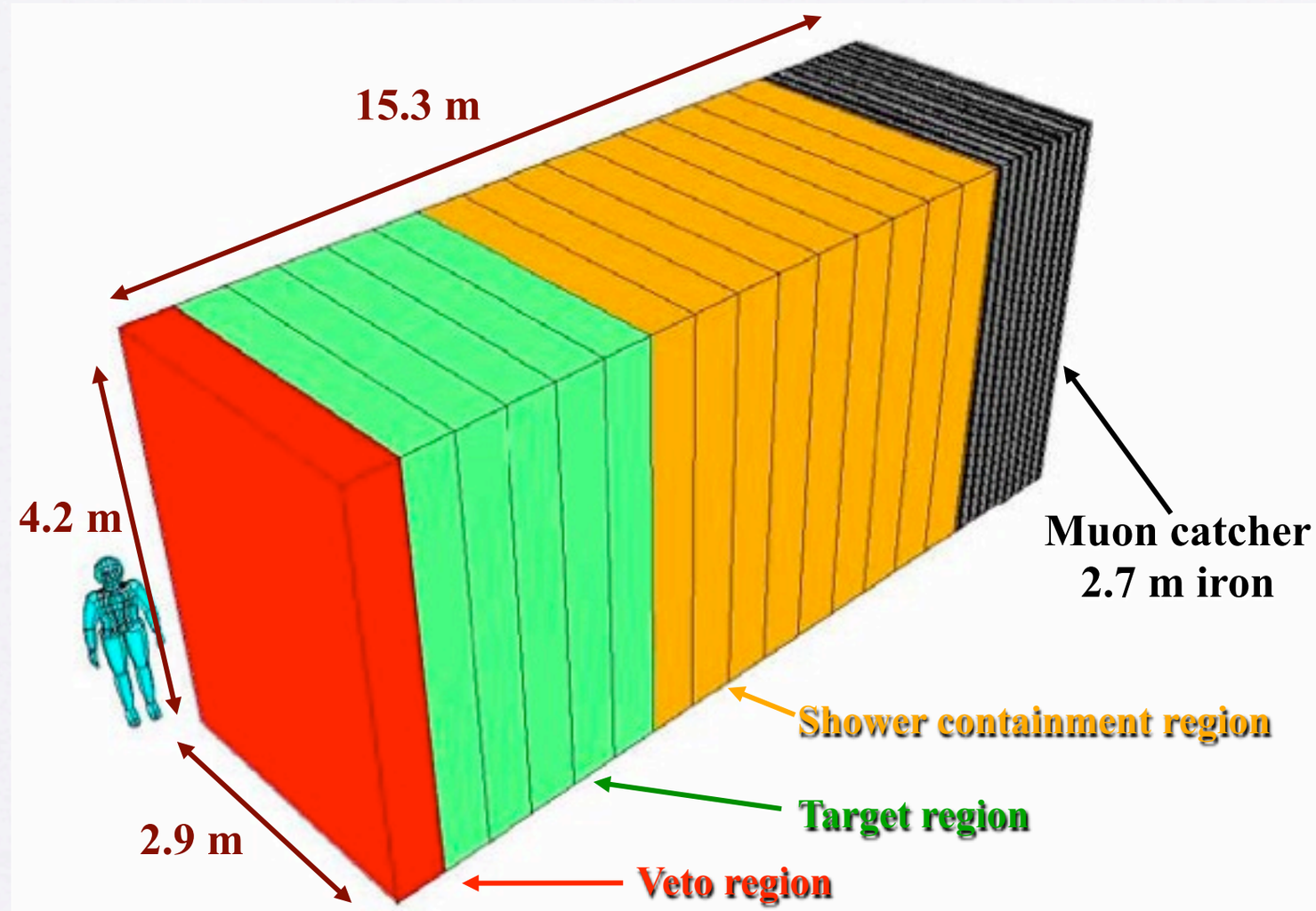
Assembly R&D Effort

- Construction of the Full Scale Assembly Prototype (FSAP) was just completed at Argonne:
  - Construction of 6 full size planes for time and motion studies and placement precision.
- Next will be the Full Height Engineering Prototype (FHEP) which will be mounted in the CDF building.



The Near Detector and the Integration Prototype Near Detector

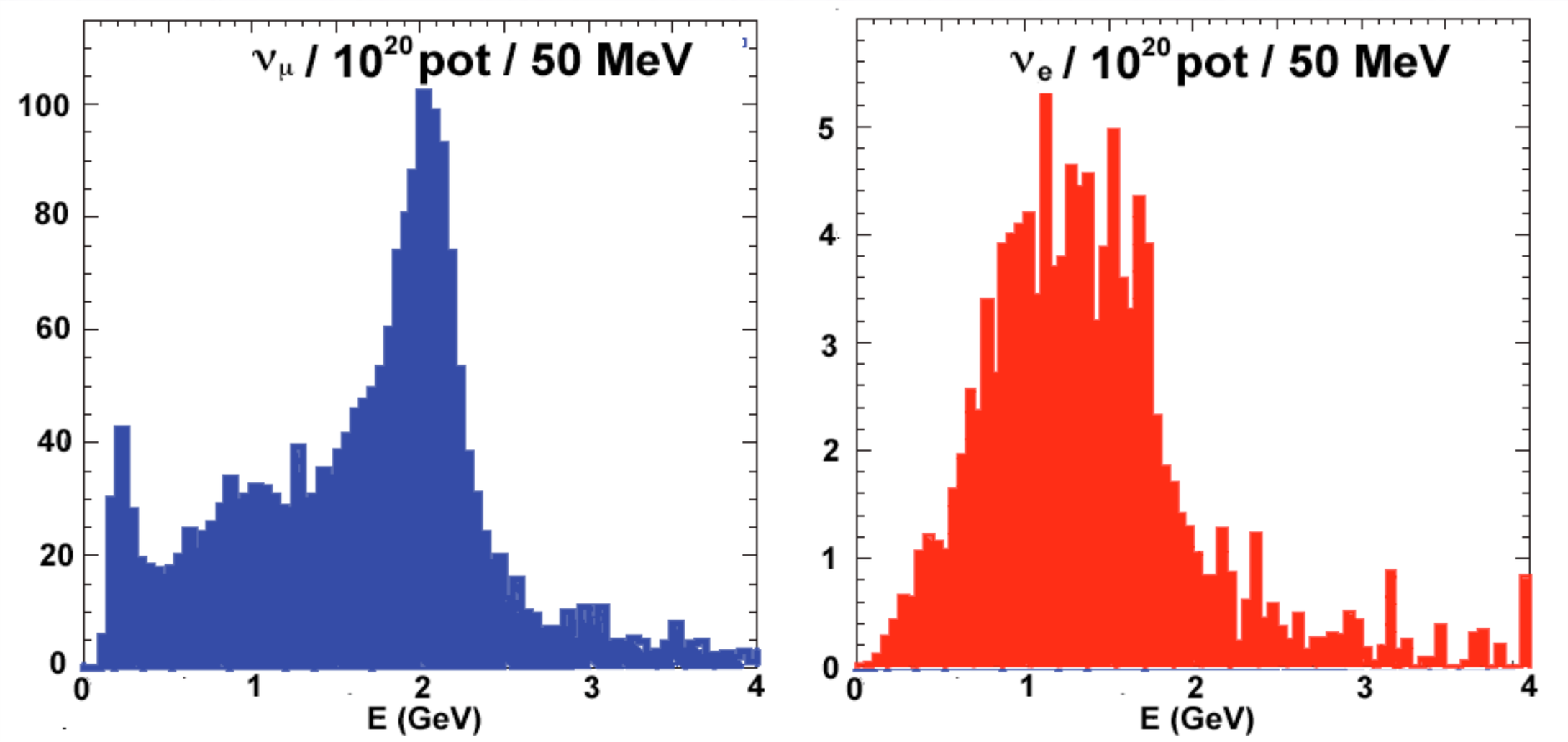
- Test running with the Near Detector placed on the surface outside of the MINOS building.
  - Start taking data Spring 2010.
- By the Fall 2011, it will be moved into the MINOS access tunnel for physics data-taking at 14 mrad just like the Far Detector.



222 tons total mass
125 tons active volume
23 tons fiducial volumen

Integration Prototype Near Detector

- Detector is 107 mrad off-axis from the NuMI beam, dominated by kaon decays.
- Neutrino data will be available to validate reconstruction and simulations in 2010!
- Cross-section measurements could be interesting.



Far Detector site

Aerial view on August 25

Looking South

Ash River, MN

- The whole building will contracted.
- Accelerating procurement of materials:
  - PVC extrusions.
  - Wavelength-shifting. fibers.
  - APDs.
  - Kicker parts.

Far Detector site

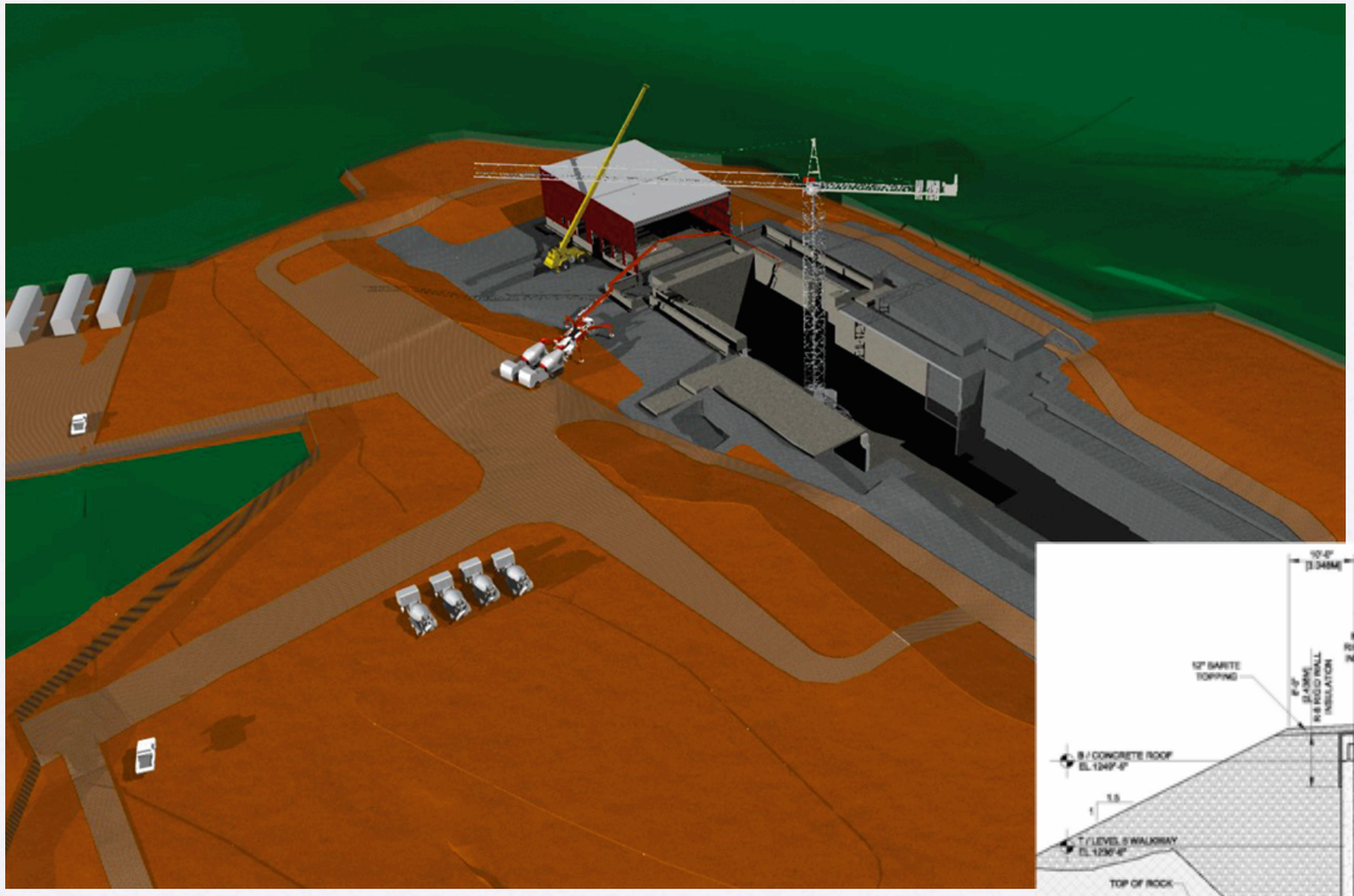
Aerial view on August 25

Looking South

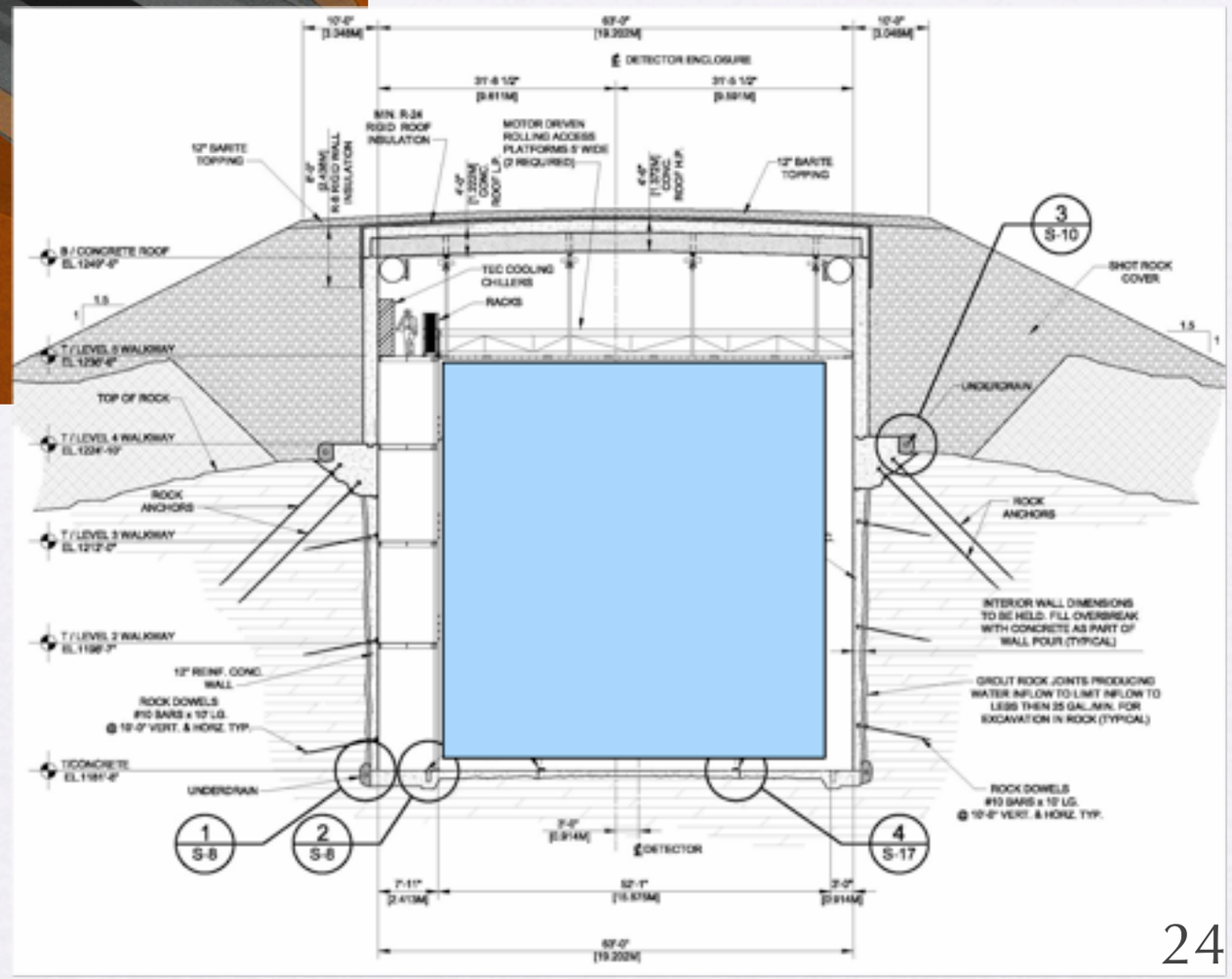
Ash River, MN

- The whole building will contracted.
- Accelerating procurement of materials:
  - PVC extrusions.
  - Wavelength-shifting. fibers.
  - APDs.
  - Kicker parts.

Far Detector site



- Beneficial occupancy:
  - Assembly area July 2010.
  - Full building Nov 2010.



Expected Next Summer

- First 2.5 kT operational by Jan 2012. Full Far Detector operational mid-2013.

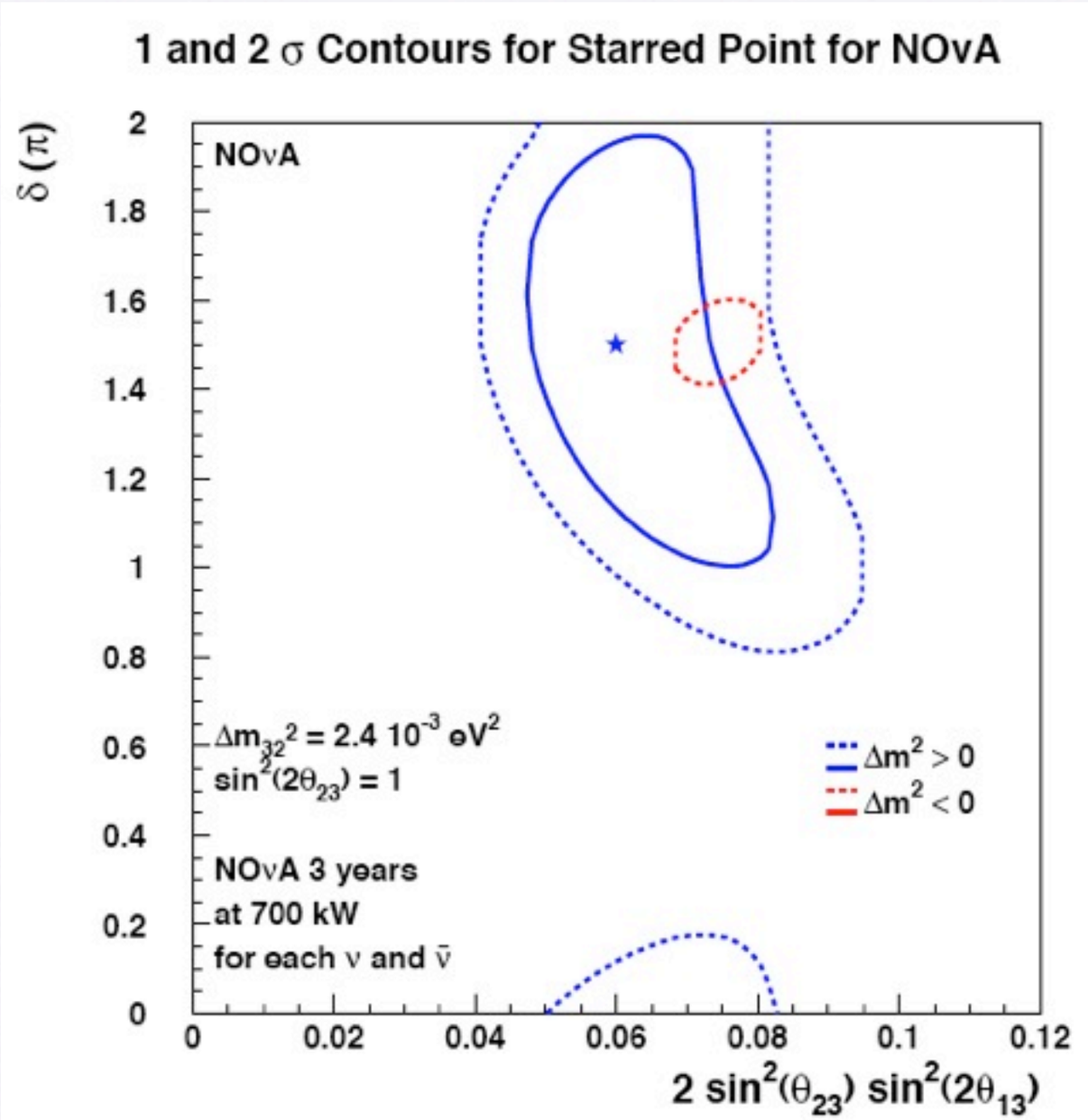
Summary

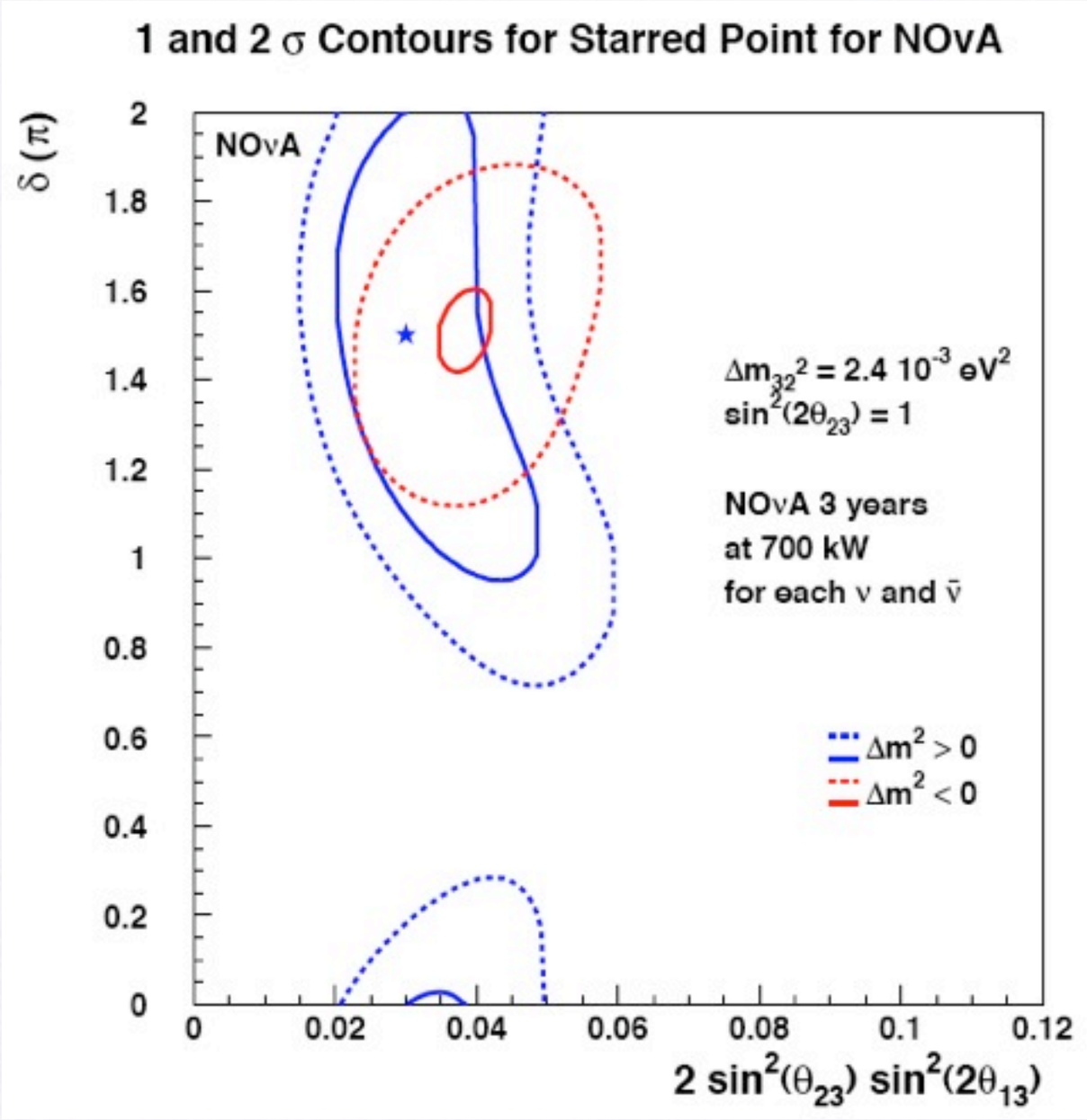
- NOvA has started construction towards having first neutrino data Spring 2010 in the Near Detector placed on the surface. Test integration, simulations, reconstruction. Physics.
- Assembly of Far Detector to start 2011. First 2.5 kT operational by Jan 2012. Full Far Detector operational mid-2013.
- Expected physics reach:
  - One order of magnitude in sensitivity for $\sin^2(2\theta_{13})$.
  - Significant δ_{CP} and mass hierarchy sensitivity.
  - More precise measurements of Δm^2_{32} and $\sin^2 2\theta_{23}$.

If $\sin^2(2\theta_{13})$ is large we will know very soon,
we want to have NOvA ready then!

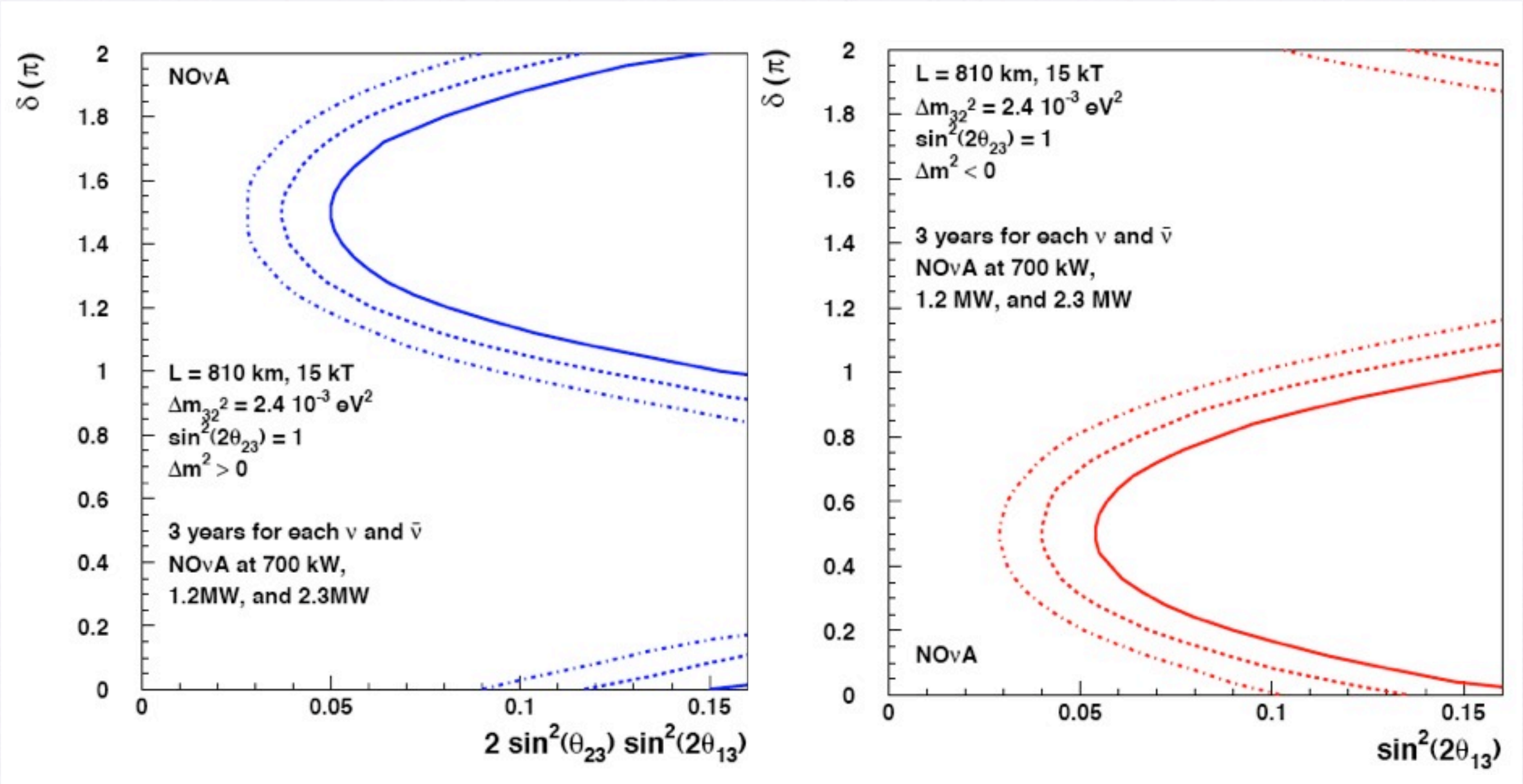
Backup slides

δ vs. θ_{13} Contours: Examples





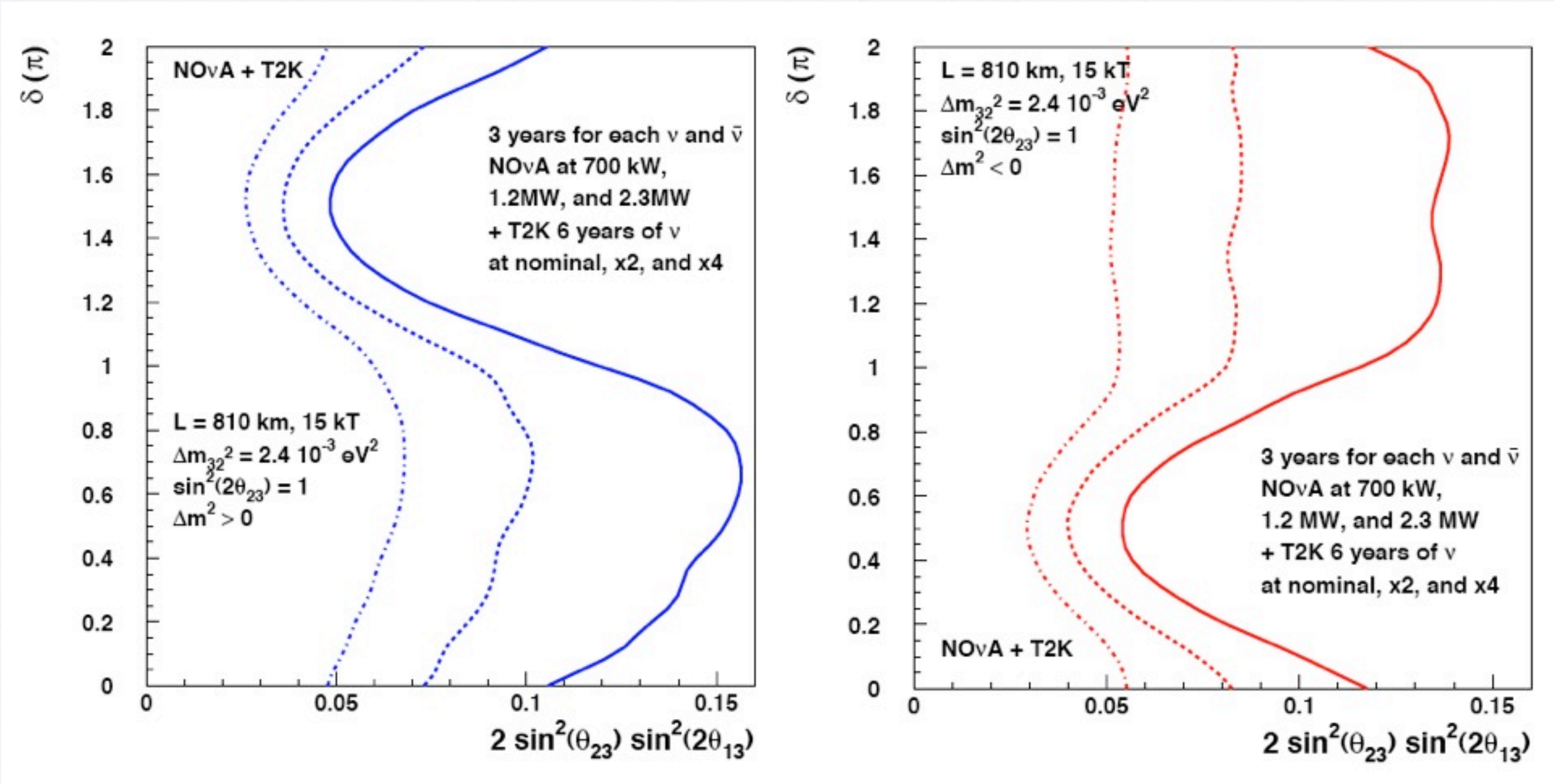
95% CL Resolution of the Mass Ordering NOvA alone



Normal hierarchy

Inverted hierarchy

95% CL Resolution of the Mass Ordering NOνA + T2K

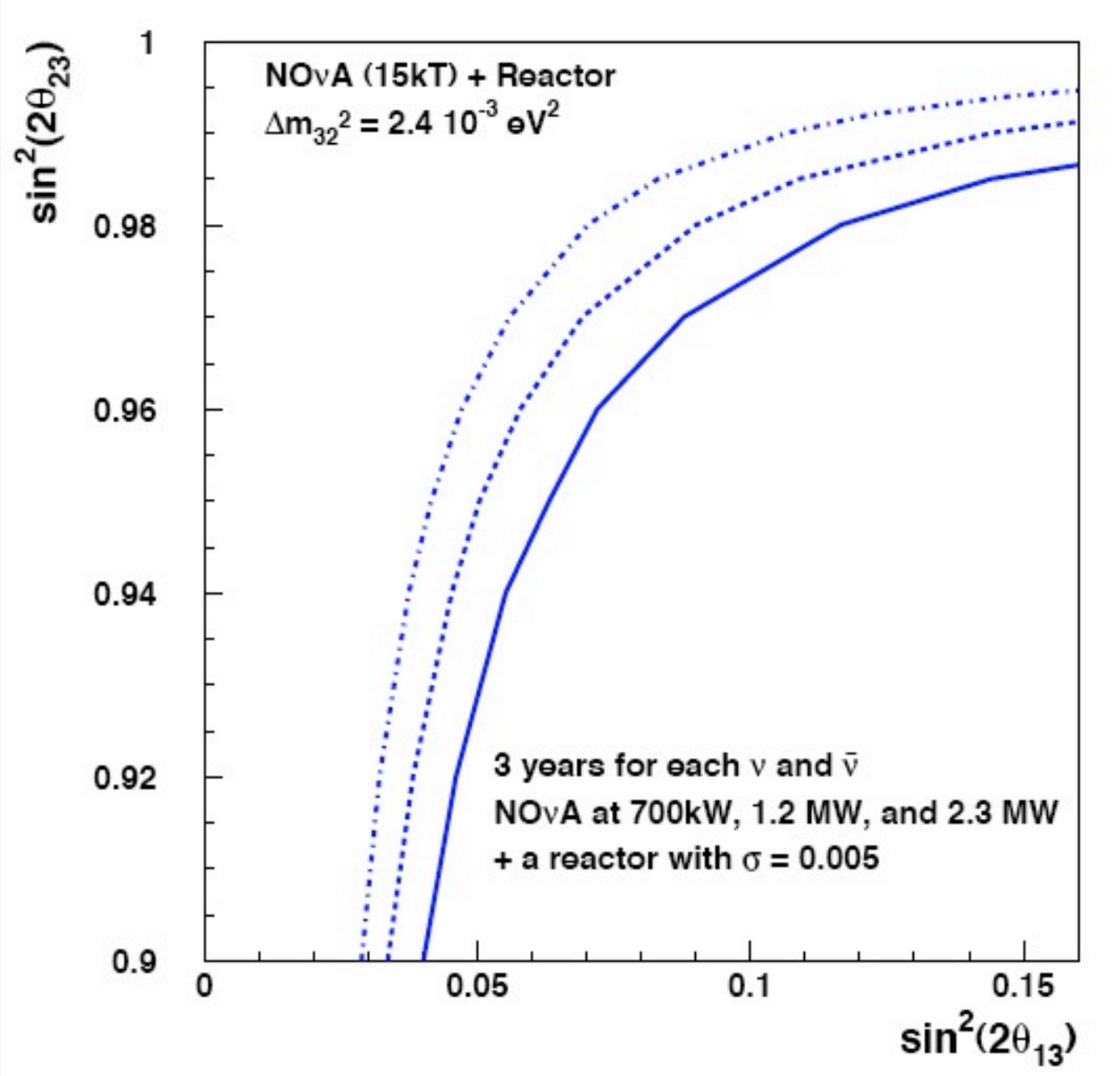


Normal hierarchy

Inverted hierarchy

95% CL Resolution of the θ_{23} ambiguity

- Ambiguity is resolved to the right and below the curves.
- Sensitivity depends on mass ordering, δ_{CP}, and the sign of the ambiguity.
- Curves represent average over parameters.



Proton plans

	Operating Conditions (May 2007)	Proton Plan Multi-batch Slip-stacking in MI	NOνA Multi-batch Slip-stacking in Recycler
8 GeV Intensity (p/Batch)	$4.3 - 4.5 \times 10^{12}$	4.3×10^{12}	4.3×10^{12}
Number of 8 GeV Batches to NuMI	7	11	12
MI Cycle Time (sec)	2.4	2.2	1.3
MI Intensity (protons per pulse or ppp)	3.3×10^{13}	4.5×10^{13}	4.9×10^{13}
MI to NuMI (ppp)	2.45×10^{13}	3.7×10^{13}	4.9×10^{13}
NuMI Beam Power (kW)	192	320	700
Protons/year to NuMI	2×10^{20}	3×10^{20}	6×10^{20}
MI Protons/hour	4.95×10^{16}	7.3×10^{16}	1.3×10^{17}

Expected NuMI operating conditions for NOνA

NuMI operating conditions for MINOS through summer 2007

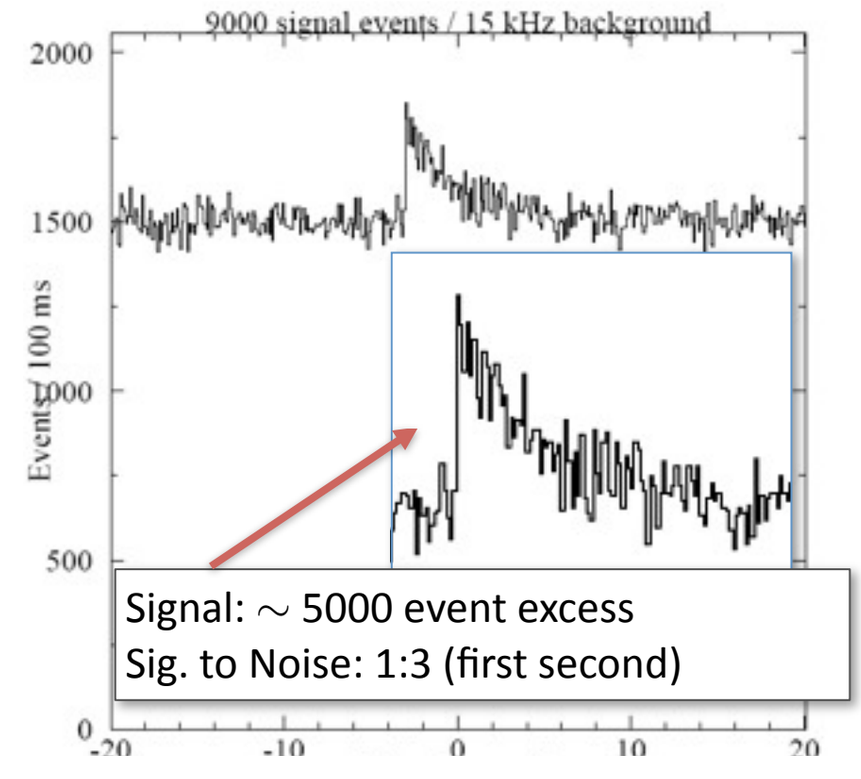
NuMI operating conditions for MINOS fall 2007 to present

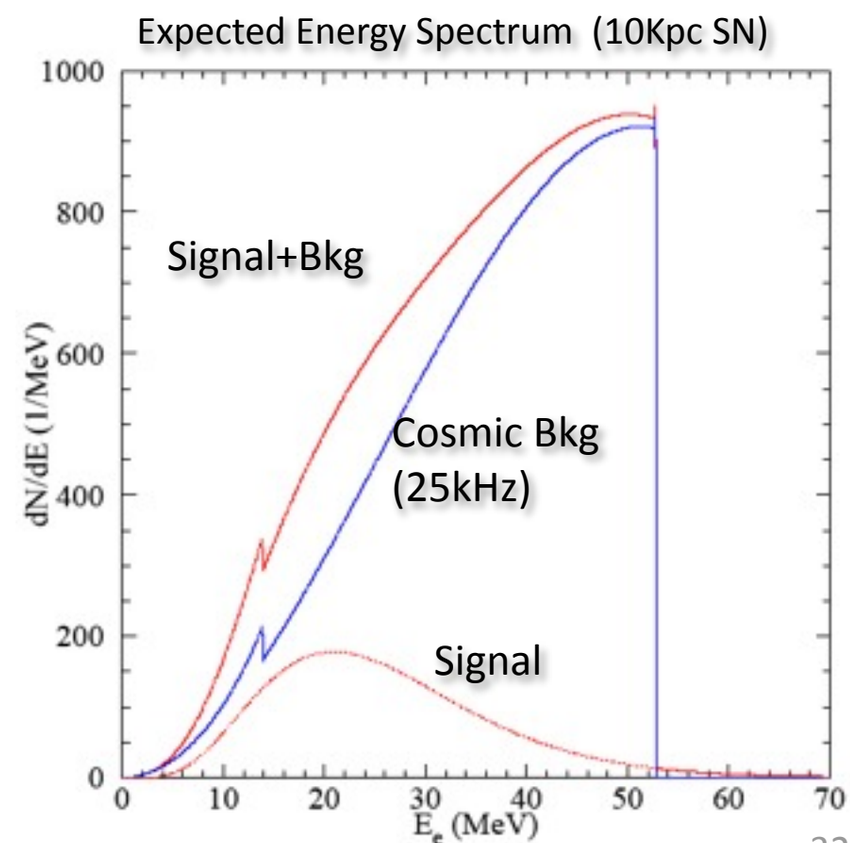
SuperNOνA Detection

- Primary SuperNOνA Signal:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

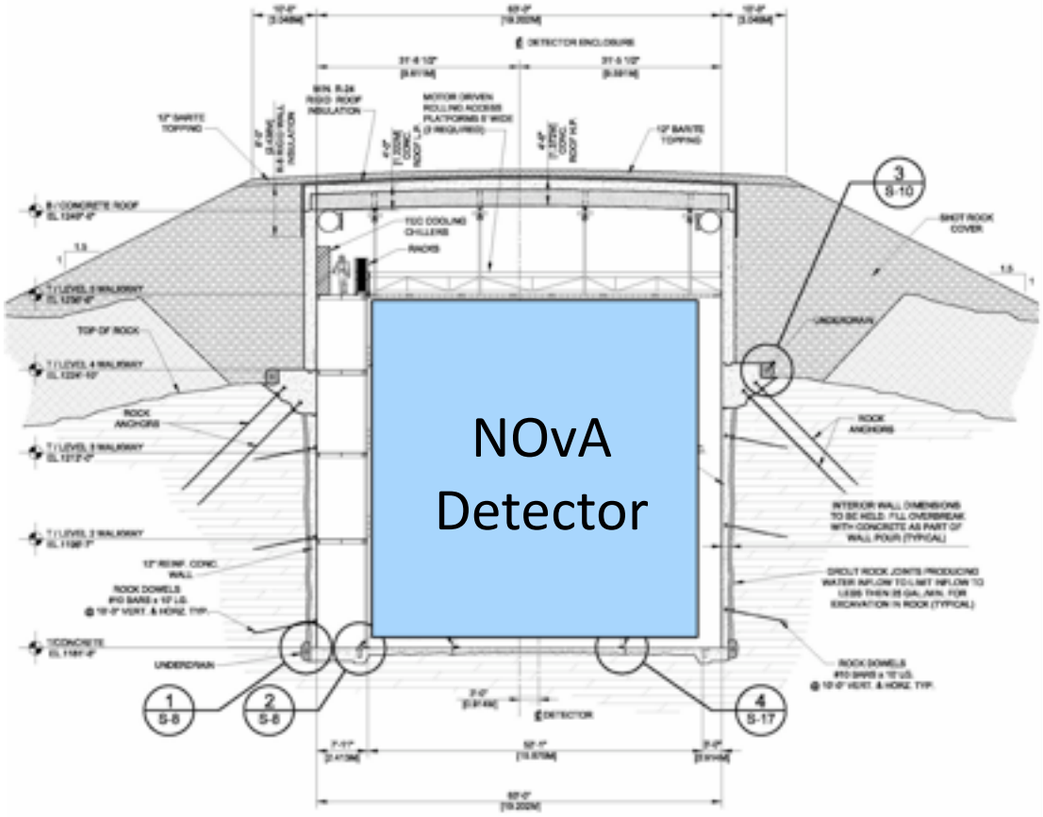
- For a supernova at 10kpc the total signal is expected to contain:
  - 5000 total interactions over a time span of $\approx$ 10s
  - Half the interactions in the first second
  - Energy peaks at 20MeV and falls off to $\sim$ 60MeV
- Challenge is triggering in real time
  - Need data driven open triggering
  - Long event buffering ($\sim$ 30sec)
  - Time window correlation & merging
- NOνA – farm 180 trigger/buffer PCs (min 30s total event buffering)

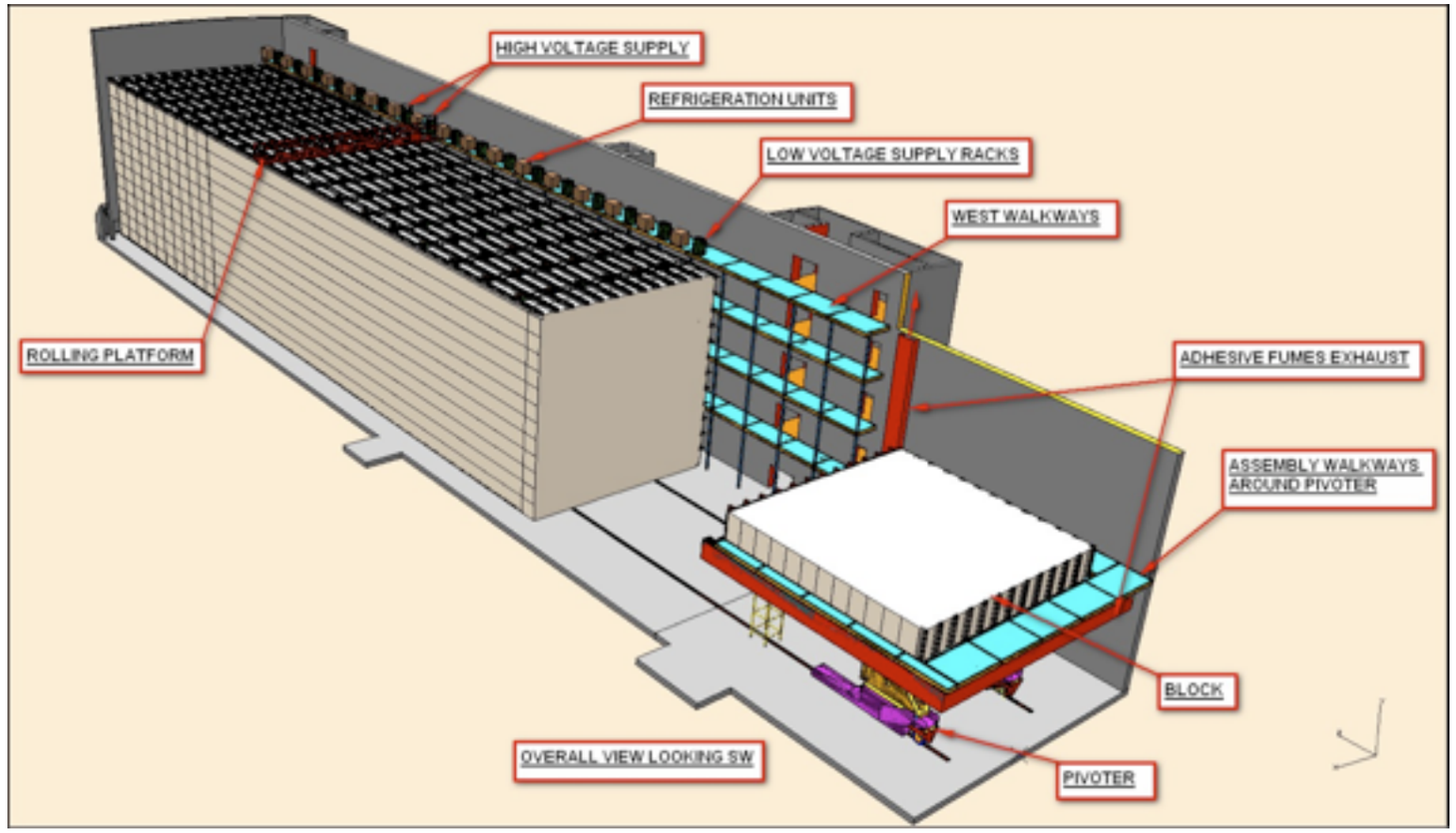




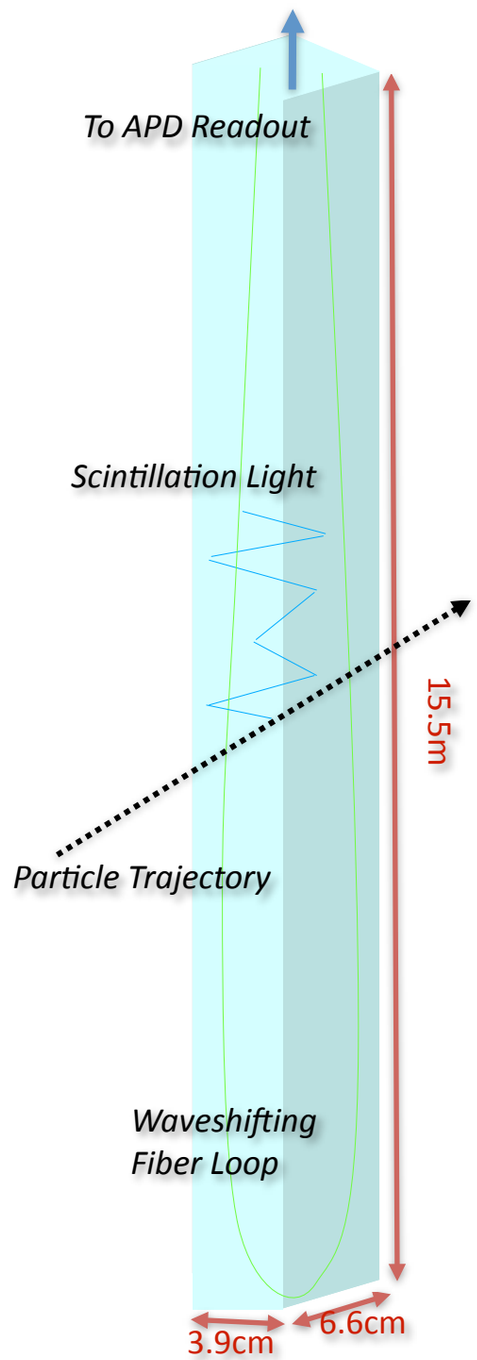
Far Site (Ash River)

- The Ash River site:
  - Provides 810km baseline
  - Sits 11.8 km (14.5 mrad) off the NuMI beam axis
  - Is the most northern site in the United States that was accessible by road (and we had to build an extra 3.6miles of road to get there)
- Detector Hall
  - Designed for up to an 18kt detector
  - Detector is build in place using modules blocks which are assembled and raised.
  - Production physics data collection can start after commissioning of the first few blocks





Detector Cell
Fiber and Scintillator



There are 357,120 cells in NOνA

NOνA Detection Cell

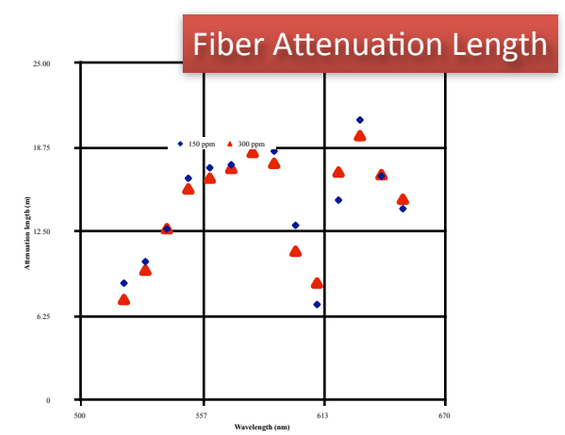
- The base detector unit 3.9x6.6cm cell 15.7m long, filled with a mineral oil based liquid scintillator.
- High reflectivity PVC gives ~8 reflections for emitted light before capture in a wave shifting fiber
- 0.7mm wave shifting fiber loop captures the light and transports it up the cell
- Both fiber ends are read out by a single pixel of the APD.

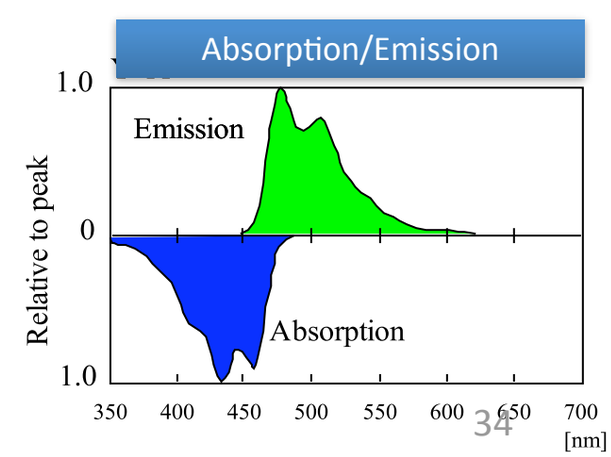
Light Collection

- The scintillator/fiber detection cell is measured to delivers 30-39 p.e. for a muon traversing the far end of the cell
- NOνA uses over 14,000km of fiber

Fiber

The fiber is a double clad 0.7mm fiber doped with 300ppm of a K27 fluorescent dye. The fiber exhibits a long attenuation length for the peak emission spectrum with tests at 300ppm of dye concentration over 15m for the 550nm peak of the spectrum.





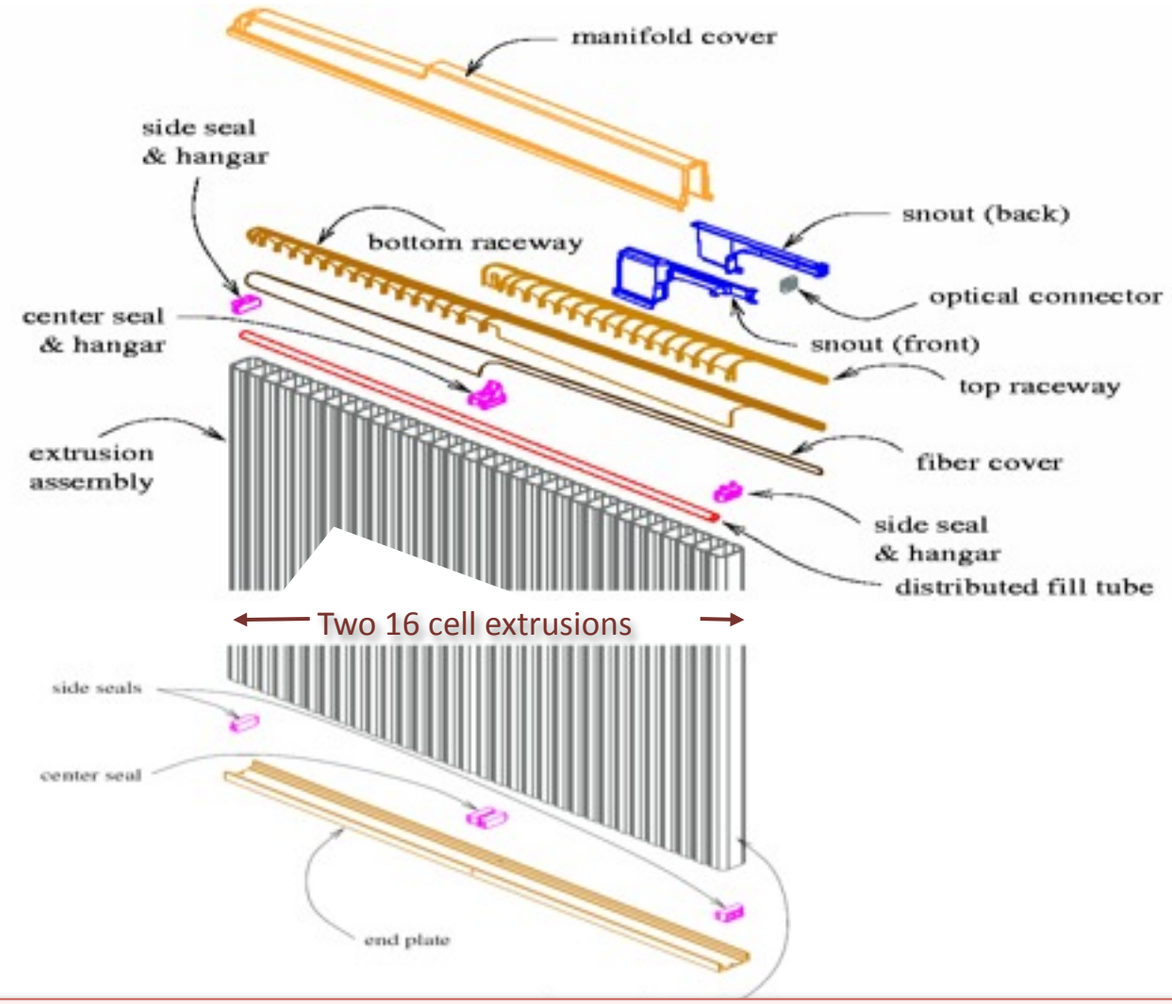
Detector Modules

NOνA Modules

- The NOνA detector module forms the base unit for the detector.
- Each module is made from two 16 cell high reflectivity PVC extrusions bonded into a single 32 cell module
- Includes readout manifold for fiber routing and APD housing

- Combined 12 module wide X or Y measuring planes.
- Each module is capped, and filled with the liquid scintillator.
- These are the primary containment vessel for the 3 million gallons of scintillator material.

- There are 11,160 detector modules with a total of 357,120 separate detection cells in the NOνA Far Detector.



PVC Extrusions

Each extrusion is a single 15.7m (51.5ft) long set of 6x3.9cm cells. Two extrusions are joined to form a single 1.3m wide module

Avalanche Photodiodes – APDs

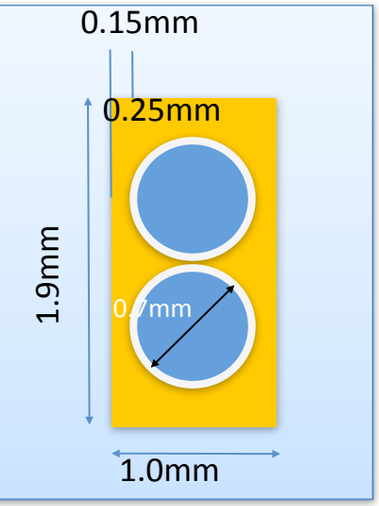
The NOνA Readout

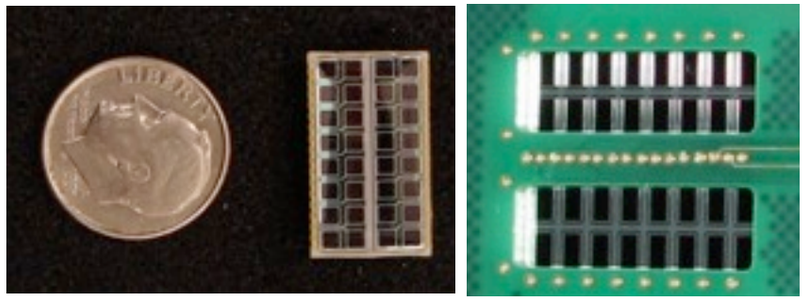
- Require 357,120 optical readout channels
- Custom designed 32 channel APD *(Hamamatsu)*
- High 85% Q.E. above 525nm
- Cooled to -15° to achieve noise rate < 300 electrons

- Operated at gain of 100 for detection of 30-39 photon signal from far end readout
- Signal to noise at far end 10:1

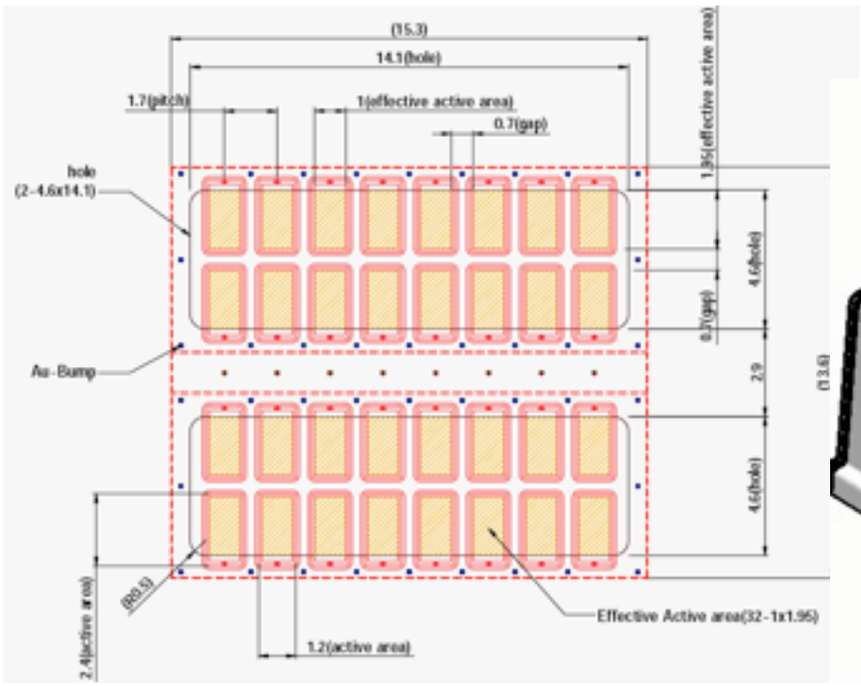
Pixel Geometry

Each pixel is designed to have an active area 1.0mm by 1.9mm to accommodate the aspect ratio of the two 0.7mm fiber ends from a single cell

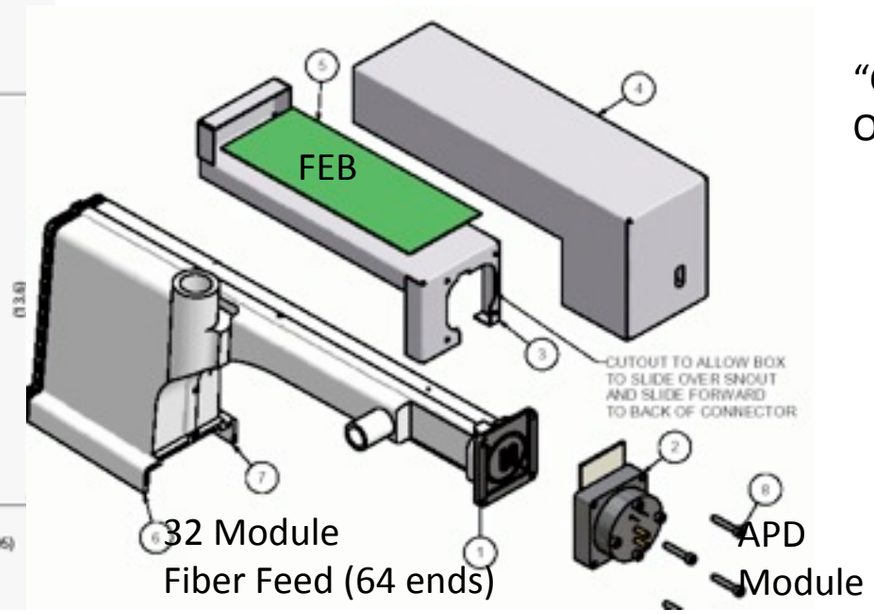




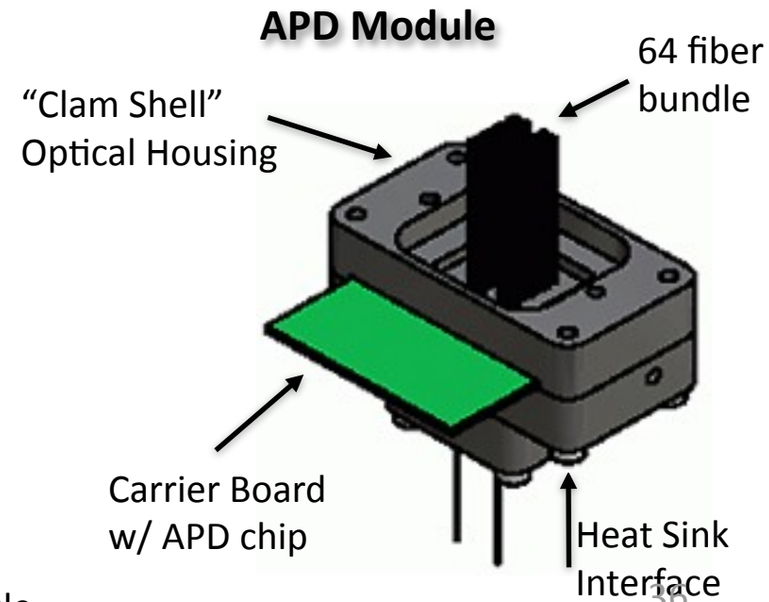
The bare APD is bonded to the carrier board to provide the optical mask and electrical interface



The 32 pixel APD array for the NOνA Readout System



APD Module

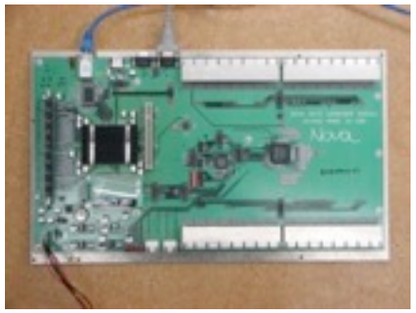


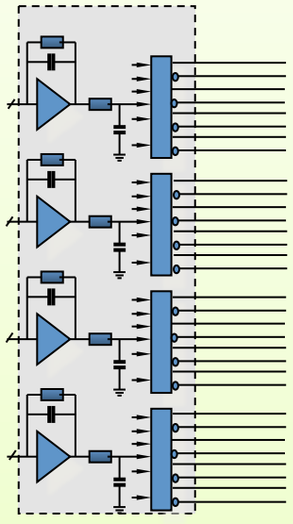
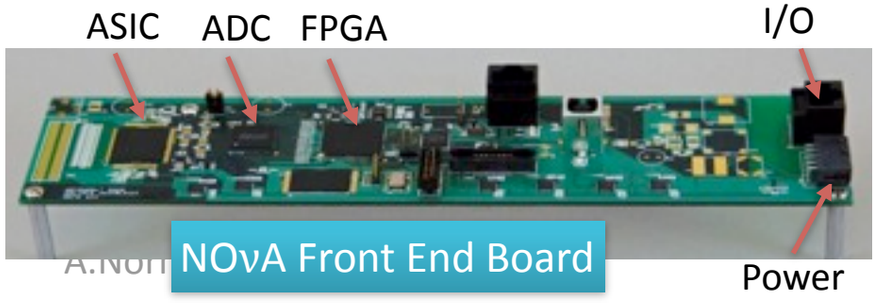
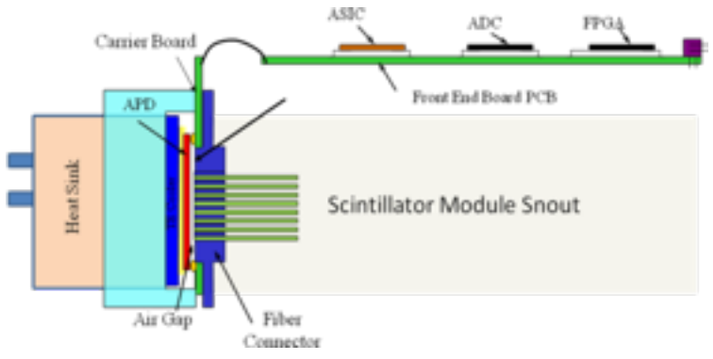
Front End Electronics

- Use a continuous digitization and readout scheme
- APDs are sampled at a 2MHz and a dual correlated sampling procedure is used for signal recognition/zero suppresion
- Done real time on the FPGA, the signals are then dispatched to Collector nodes as “time slices”
- Data Concentrator Modules assemble/order the data and dispatch macro time windows to a “buffer farm” of 180 compute nodes
- Provides minimum 30sec full data buffer for trigger decision
- Dead-timeless system with software based micro/ macro event triggering

Data Concentrators (DCM)

The digitized data streams from 64 front end boards are broadcast over 8B/10B serial links to an associated data concentrator module which orders, filters and buffers the data stream, then repackages the data into an efficient network packet and rebroadcasts it to a specific buffer node for trigger decisions.



FEB ASIC

The custom designed ASIC is an integrator/ shaper with multiplexer running at 16MHz. The channels are Muxed at 8:1 and sent to a 40MHz quad ADC for digitization. For the higher rate near detector the channels are muxed at 2:1 and sent to 4 quad ADCs. ASIC is a low noise device with expected noise < 200 e. rms.