NOvA Detector Technology with Initial Performance from the Surface Prototype

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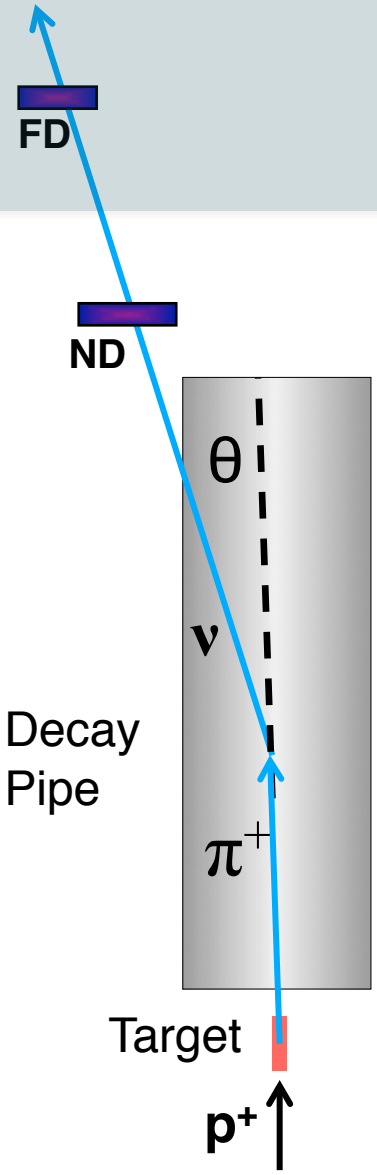
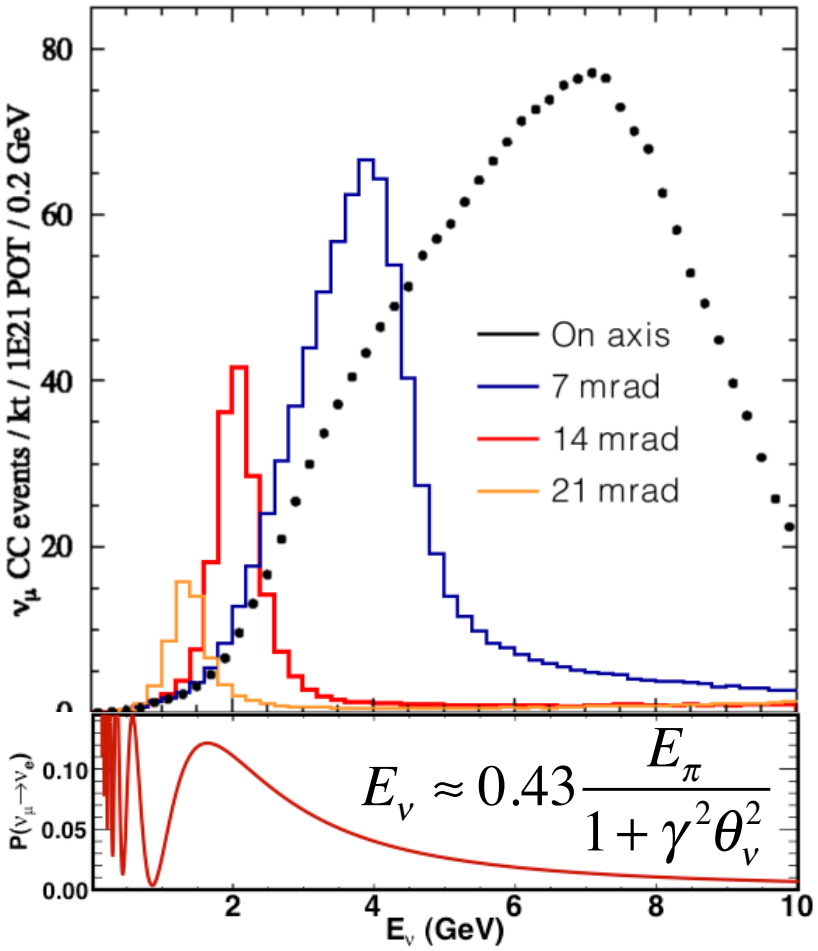
The NOvA Experiment

- Long baseline neutrino oscillation experiment:
  - Near and far detector pair.
  - Off-axis ν @ L/E ~ 400 km/GeV
- Goals:
  - **Search for $\nu_\mu \rightarrow \nu_e$ transitions**
  - measure/limit θ_{13}
  - precision measurements of $|\Delta m^2|$, θ_{23}
  - compare ν/ν̄ oscillations
  - determine mass hierarchy
  - constrain CP violating phase

NOvA Off-Axis Beam

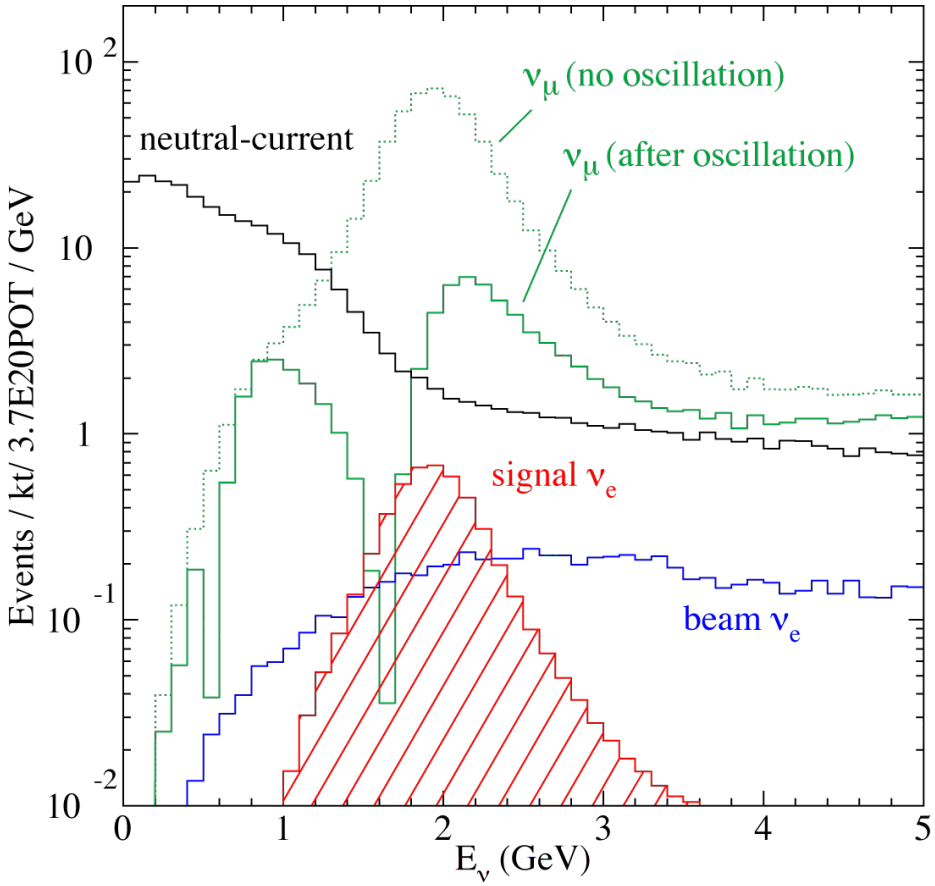




- Upgraded 700 kW beam
- 14 mrad off-axis
- Increased flux near oscillation maximum
- Reduces high energy NC background events
- See Phil Adamson's talk from Tuesday's WG3 for more details.

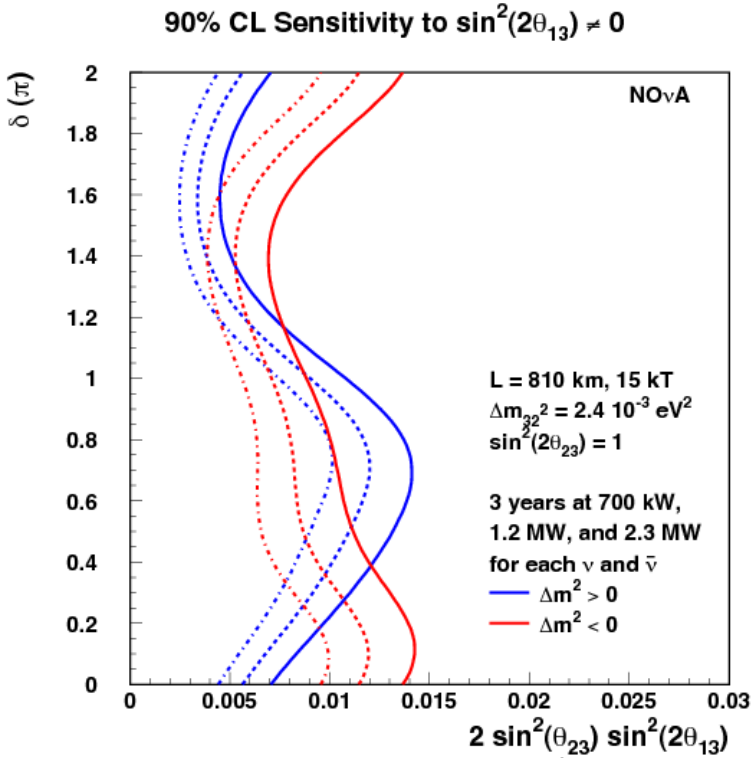
Design Criteria

- Mass of 14 kTon
- Suppression of ν_μ CC and NC backgrounds at the 99% level
- Good ν_e detection efficiency.
- Energy resolution small compared to signal width:
  - Less than 8% for ν_e Charged Current events
  - Less than 4% for Quasi-Elastic ν_μ Charged Current



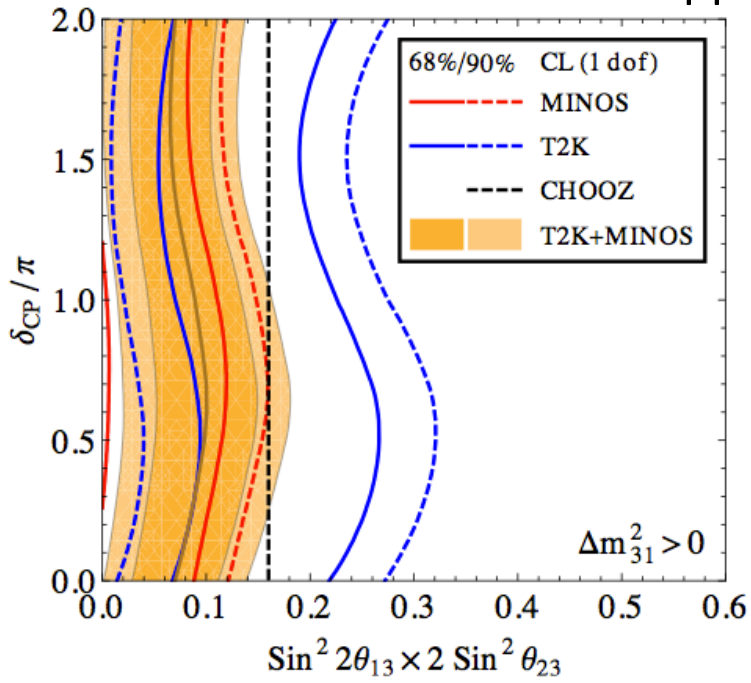
Interaction spectra at 810km, 14 mrad off-axis.
Oscillations: $\Delta m^2=2.5\times10^{-3}eV^2$, $\sin^2(2\theta_{13})=0.01$

Θ_{13} Sensitivities



NOvA Projected

Joachim Kopp

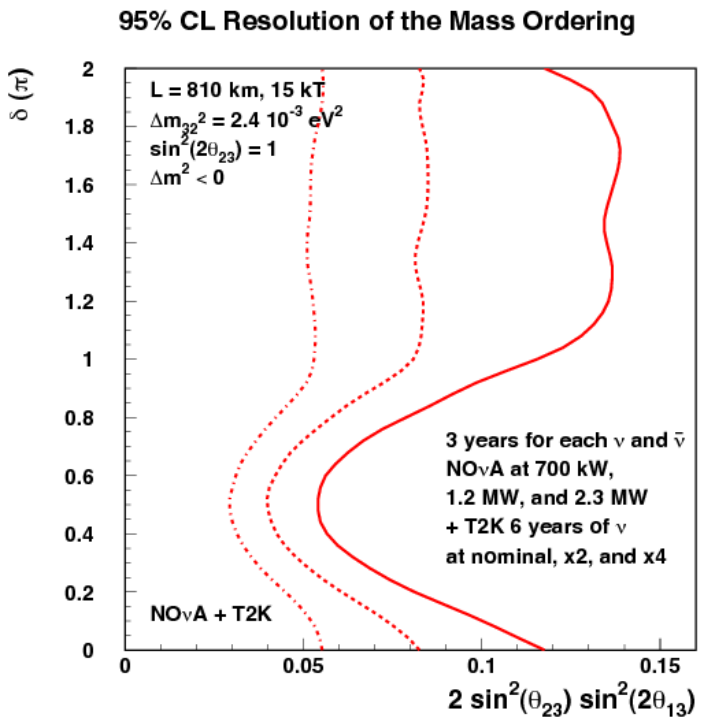


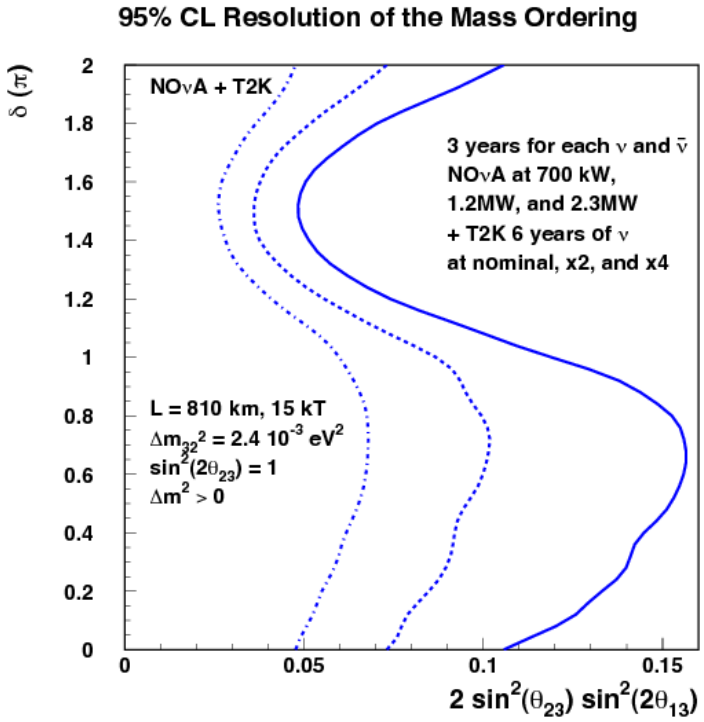
Current Experimental Limits

The NOvA projected 90% CL is similar to the 90% lower bound from T2K.

Mass Ordering Sensitivities

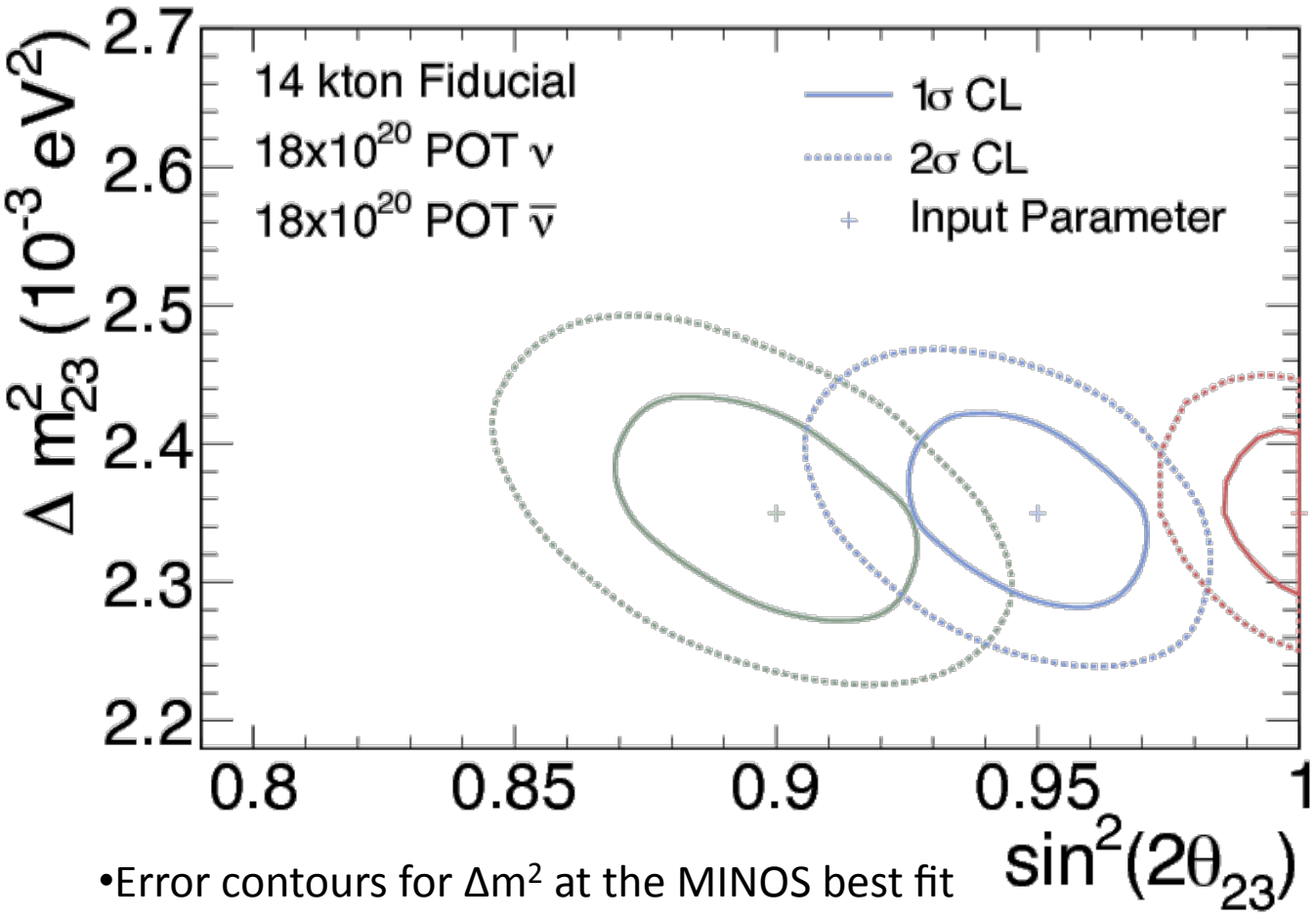
For the 2 GeV neutrino beam used for NOvA, matter effects gives a 30% enhancement/ suppression in the transition probability of neutrinos/anti-neutrinos.





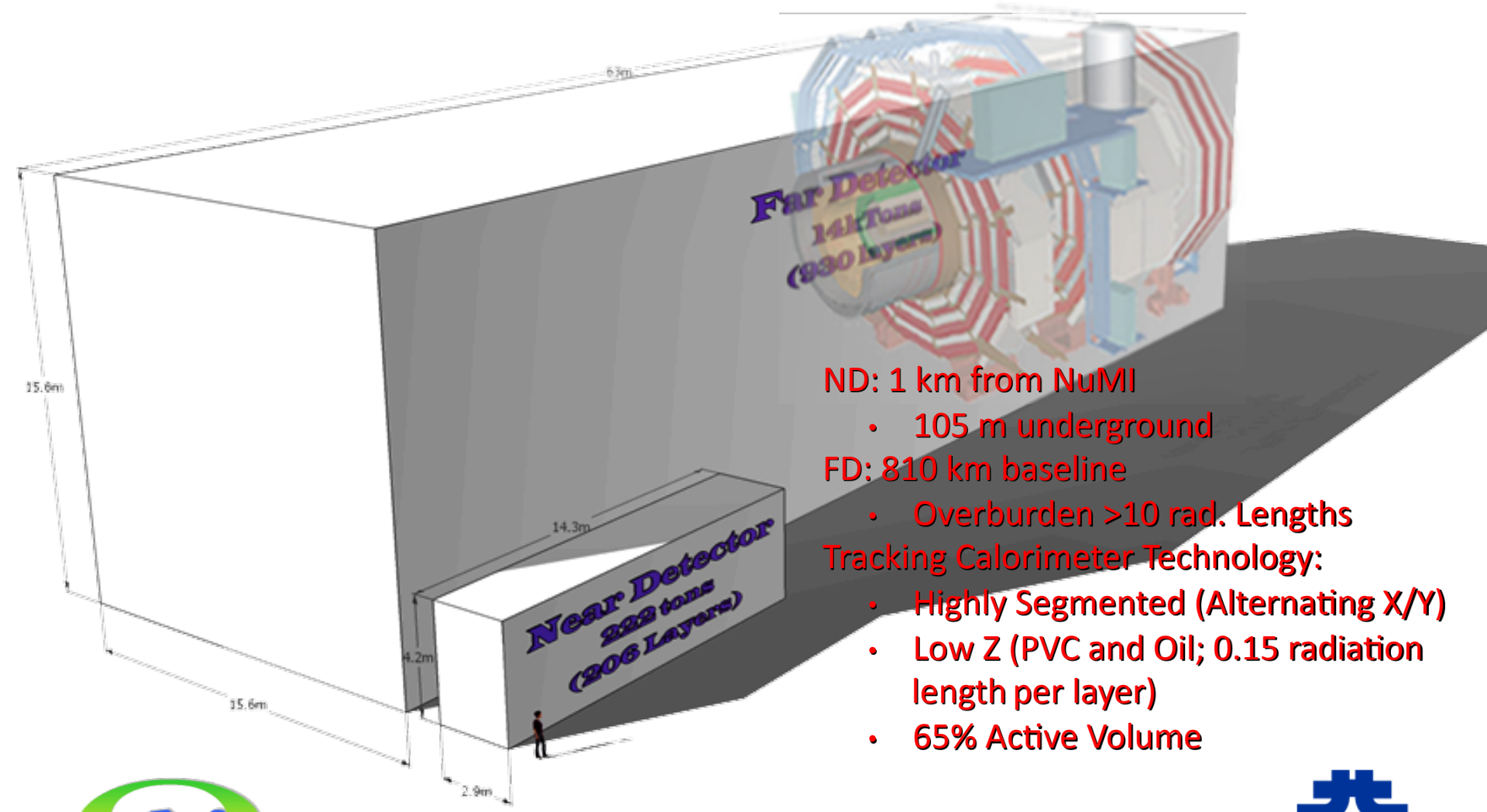
For oscillation parameters to the right of these curves, NOvA will be able resolves the mass hierarchy at better than the 95% C.L.

Precision Θ_{23} Measurement



•Error contours for Δm^2 at the MINOS best fit value and various $\sin2(2\theta_{23})$ choices

The NOvA Detectors



ND: 1 km from NuMI
- 105 m underground

FD: 810 km baseline
- Overburden >10 rad. Lengths

Tracking Calorimeter Technology:
- Highly Segmented (Alternating X/Y)
- Low Z (PVC and Oil; 0.15 radiation length per layer)
- 65% Active Volume

Far Detector Site

Status and Timeline

Beam Upgrade to 700 kW:

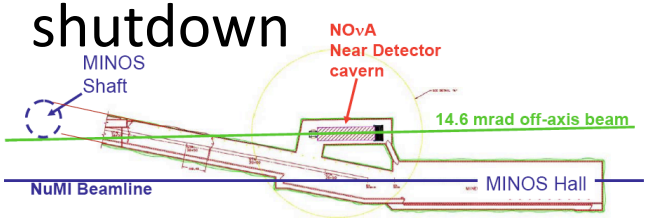
- Accelerator shutdown: March-December 2012

Far Detector (FD):

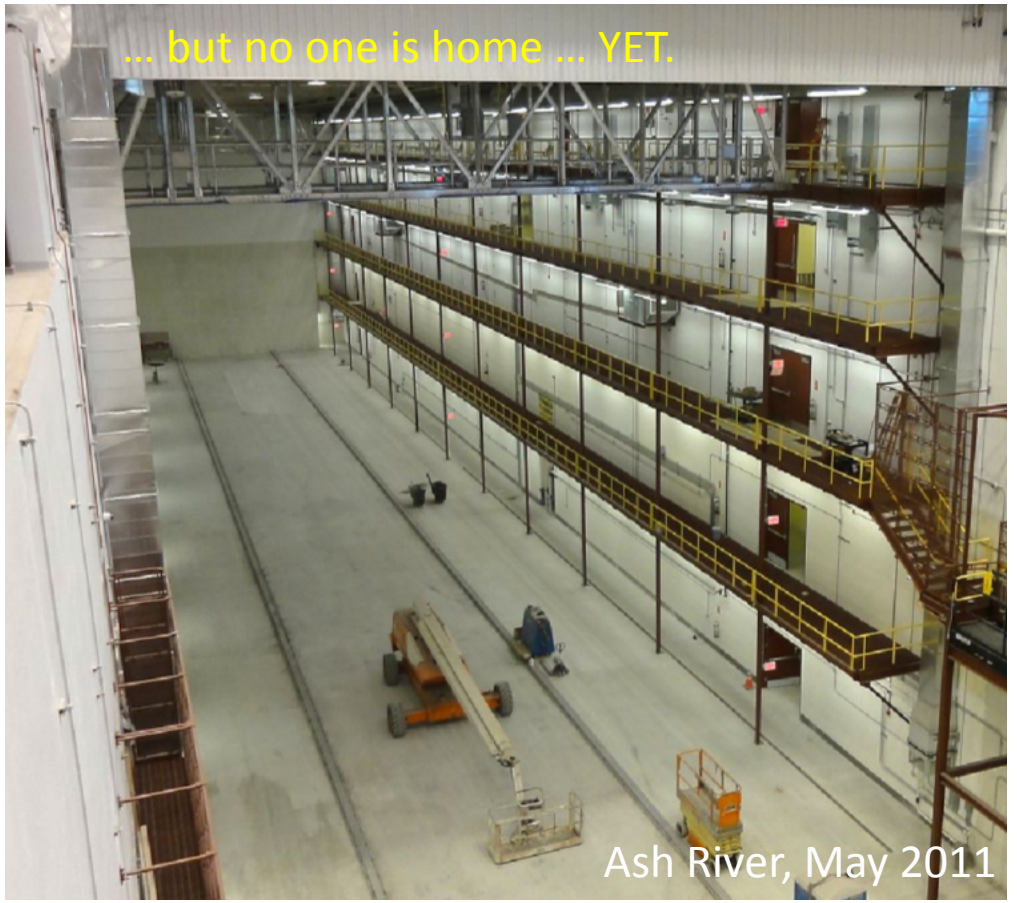
- Construction: Jan 2012
- 1 block before shutdown
- Complete by early 2014

Near Detector:

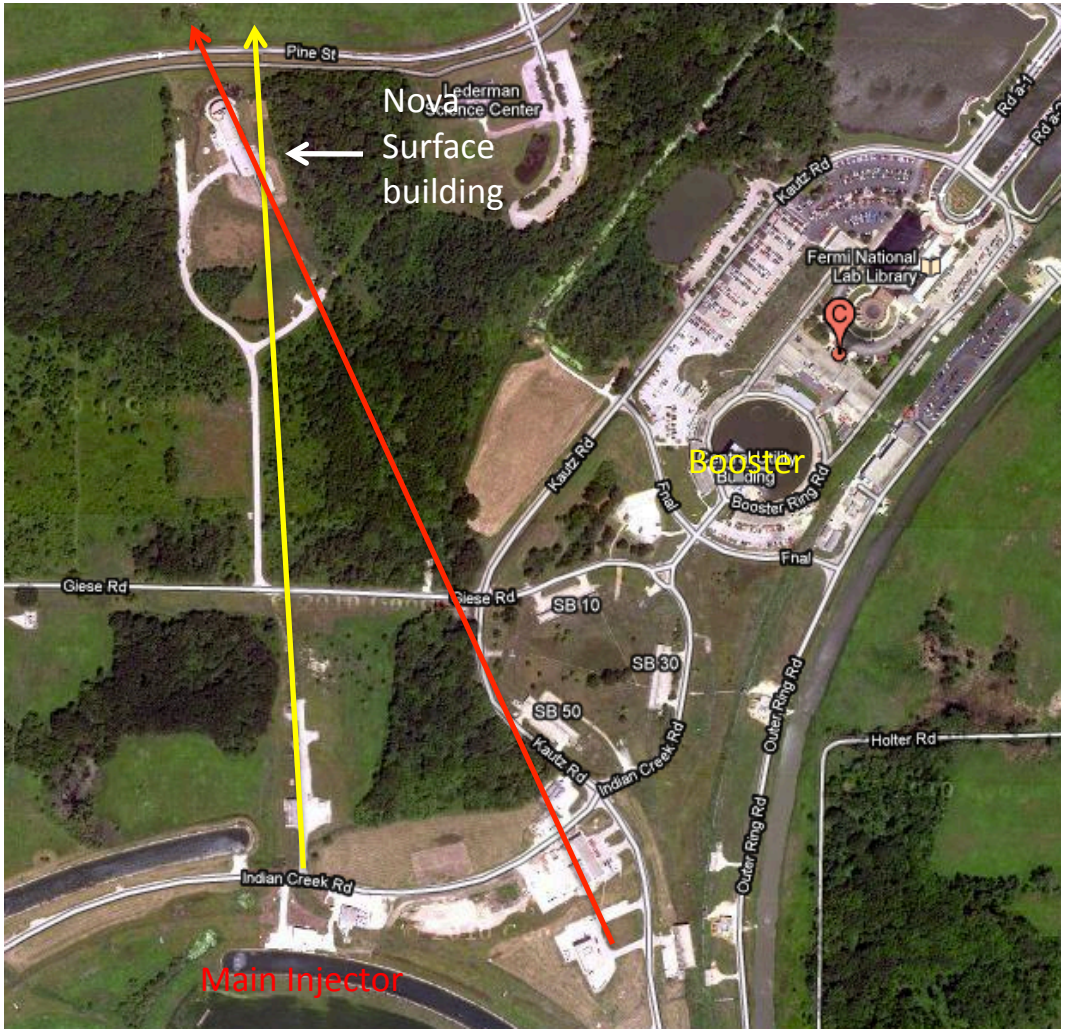
- Cavern excavation during shutdown



- NDOS: Running now!!



Near Detector On the Surface



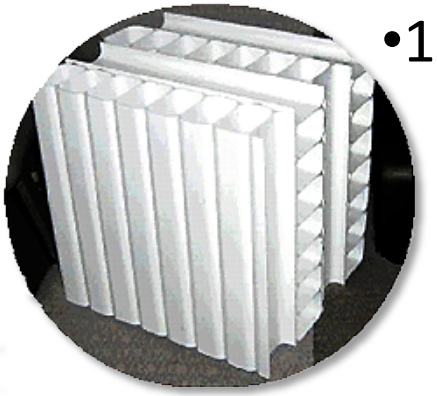
Near Detector on the Surface

•Full size prototype Near Detector (ND) constructed in a mock far detector environment.

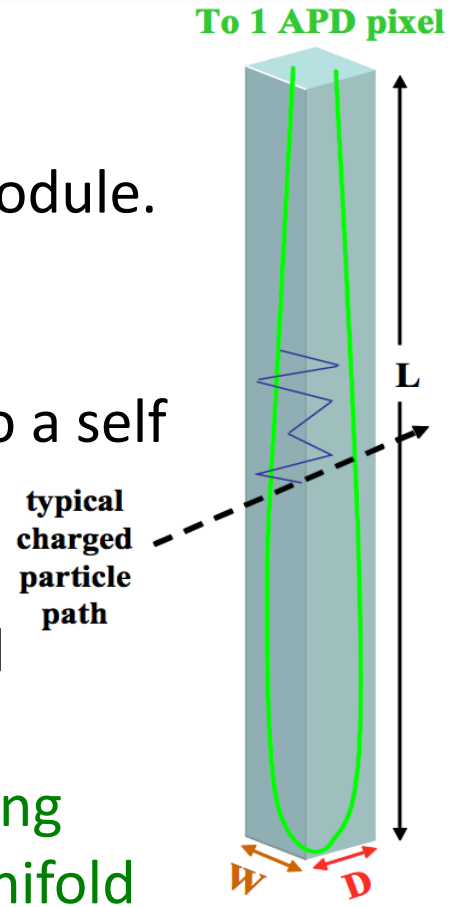
•Collecting data since October 2010

•Virtually all detector subsystems have benefited as we move closer to Far Detector. (Highlighting the major ones here.)

NOvA Cell



- TiO_2 loaded PVC; 90% reflectivity at 430 nm
- 16 extruded together, 32 in a sealed module.
  - 3.8 cm X 5.9 cm cross section
  - ~360,000 cells for 14 kTon.
  - 32 alternating X/Y planes glued into a self supporting block.
- One di-block is our smallest operational unit.



- NDOS: 6 blocks and 1.7 m muon tracker (steel and modules interleaved)
- NDOS/Status: Experience gained in QA/QC. Learning how to ship, handle, repair. (~20% of delivered manifold covers cracked and were repaired. New design for FD.)

~1200 accepted FD extrusions to date.

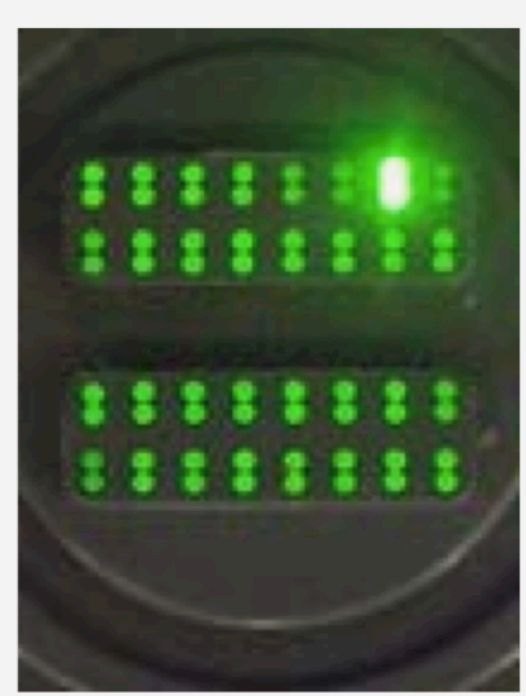
Liquid Scintillator

- 65% of detector mass
- Mineral oil with 5% pseudocumene and wave length shifters producing light at 400 – 450 nm. (Home brew)
- Require equivalent to 80% of the light observed at 1 meter in commercial scintillator. (Bicron BC517P)
- 3.0 million gallons of liquid scintillator at far site.

  (~30k ND)

•NDOS/Status: Experience qualifying and filling scintillator. We have taken possession of ~100,000 gallons of far detector mineral oil.

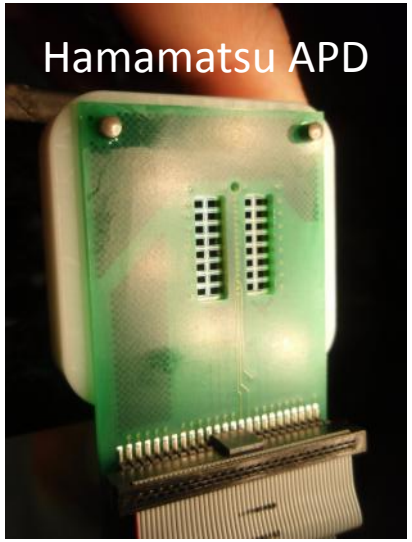
Fibers



- Single sided readout from 0.7 mm diameter looped fiber
- Shifts light to green 490 - 550 nm.
- Light is attenuated by about a factor of ten with redder light (520 – 550 nm) preferentially surviving.
- 13,000 kilometers of wavelength shifting fiber for far detector. (~113 km ND)
- NDOS/Status: Experience in stringing modules. Reworked spooling techniques to minimize tangles. Experience with in-module QA. We received ~50% for FD.

APD (Avalanche Photo Diode)

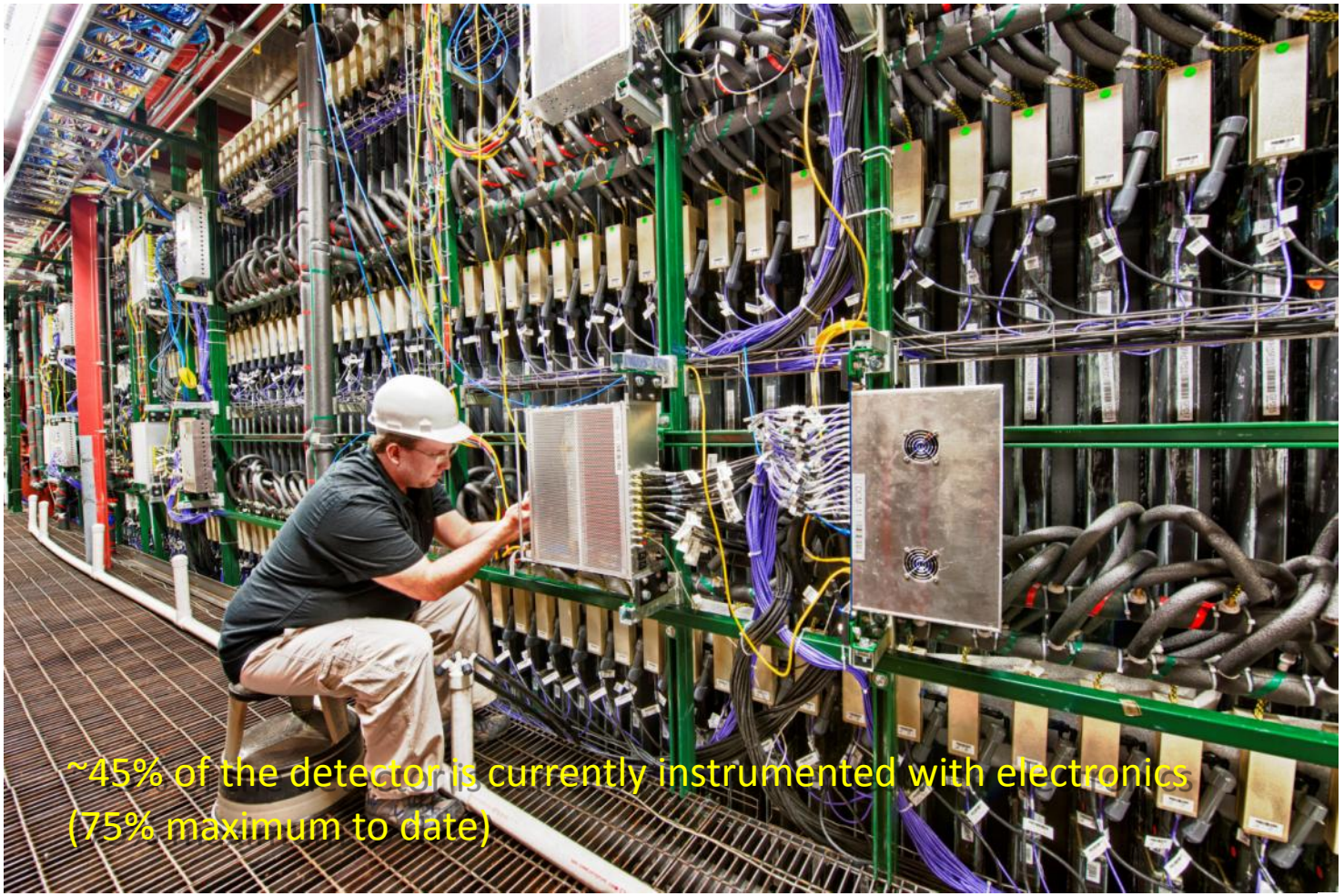
- Array of 32 pixels
- 85% QE for 520 – 550 nm light.
- Gain of 100 @ 375 volts.
- Actively cooled to -15 C.
- Require 20 pe signal from MIP at far end of cell with 10-15 pe threshold. (We expect 38 pe.)
- ~12,000 APDs on FEBs (Front-end boards) (496 ND)
- NDOS: Cleanliness and sealing issues led to noisy channels. 274 installed units removed for cleaning and study. New surface coating and installation techniques under investigation.



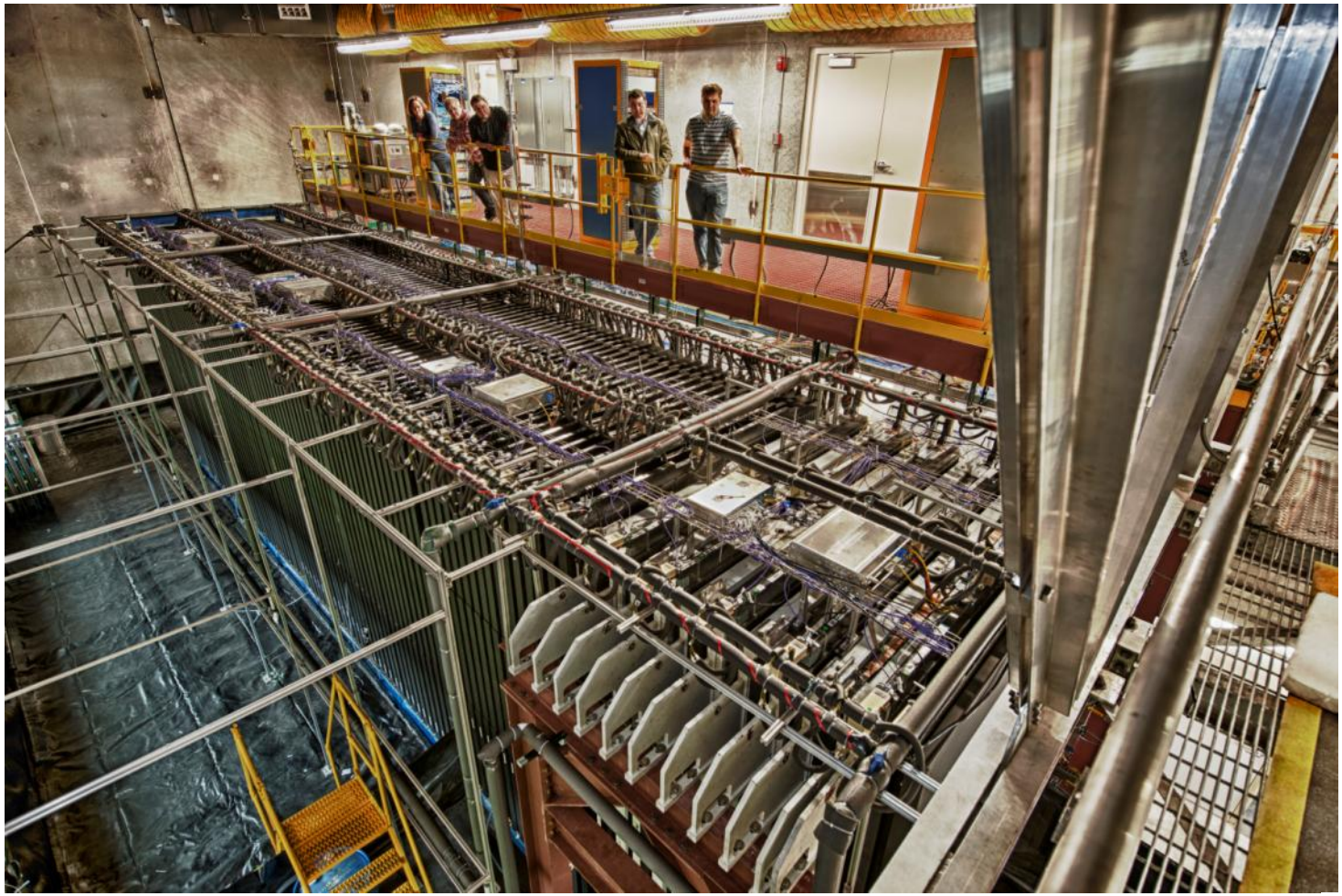
DAQ

- Front-end electronics (FEBs) operate in continuous digitization mode and perform simple baseline subtraction.
- 64 FEBs feed a Data Concentrator Module which packages and passes the data to a processing farm.
- Data is buffered until the arrival of a software spill trigger.
- Achieved stable running with 96% duty factor. (Δt=80ms @ 12Hz trigger)
- NDOS: Since deployment updates to the software have doubled real throughput.

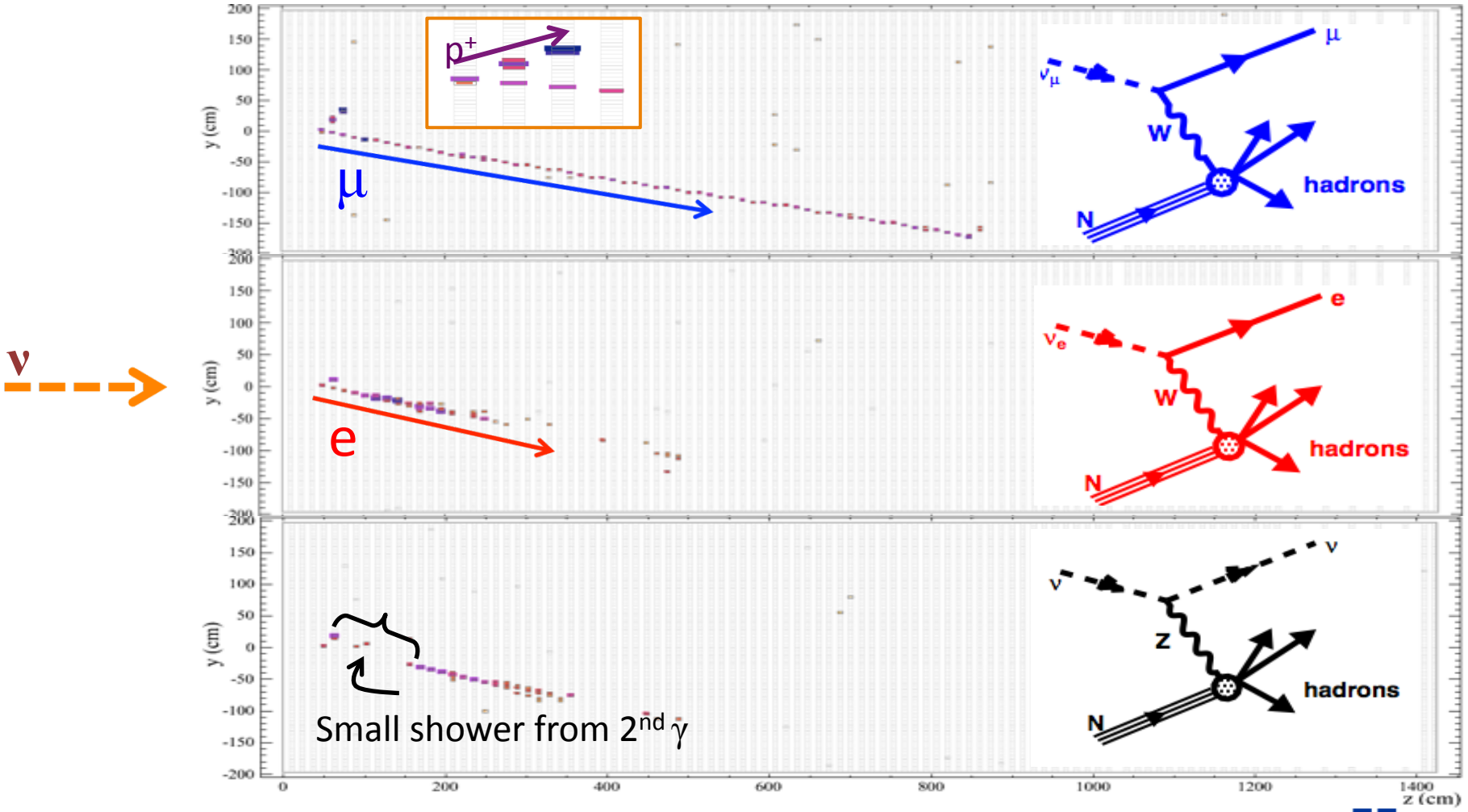
NDOS


~45% of the detector is currently instrumented with electronics
(75% maximum to date)

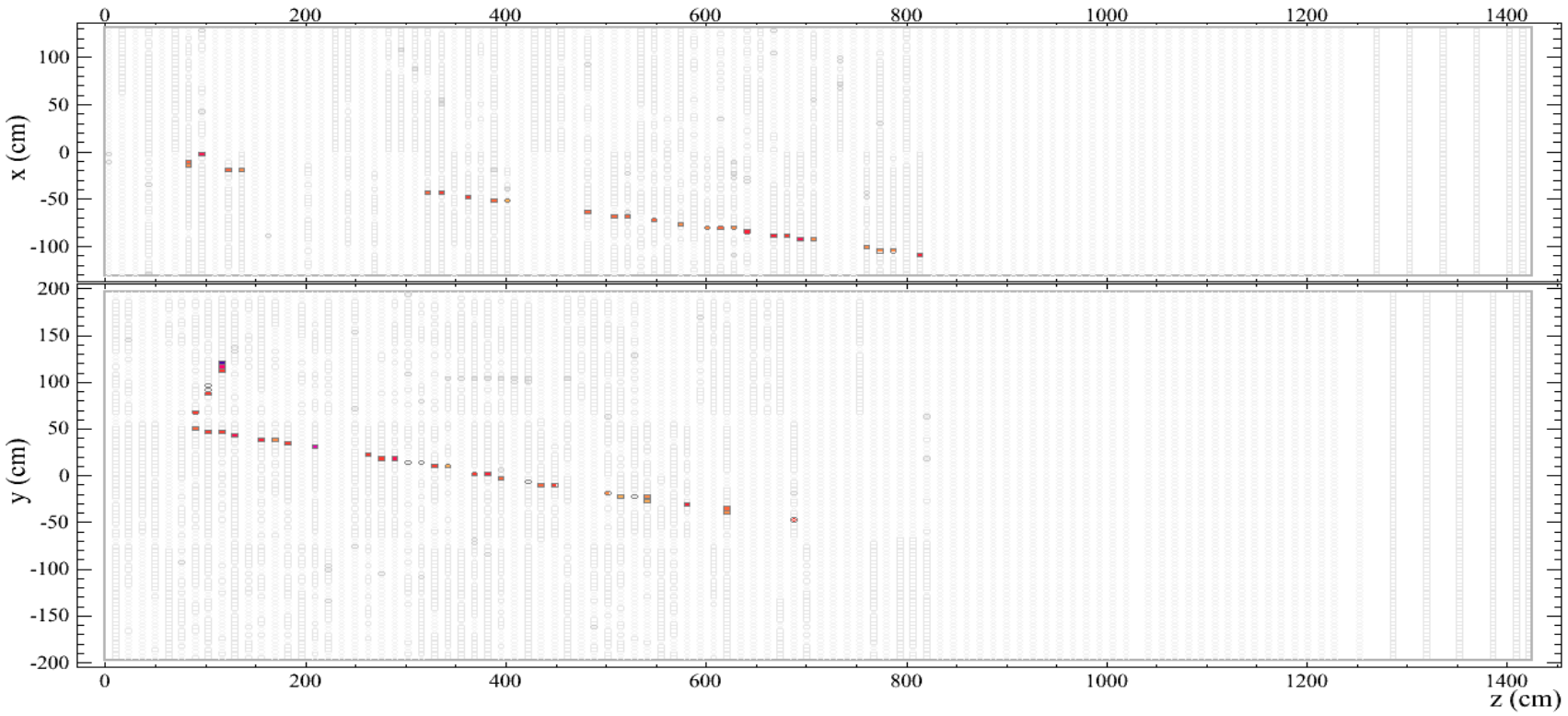
NDOS

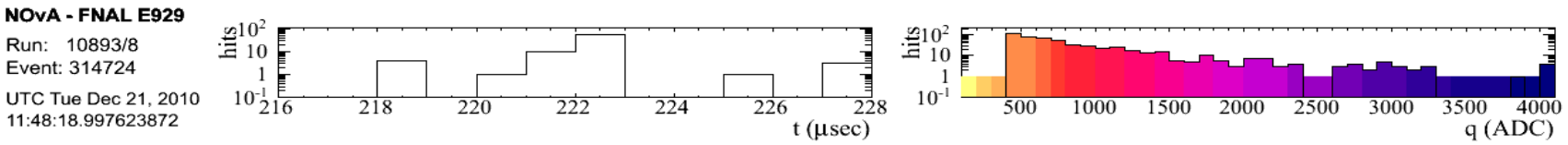


Simulation of Fully Instrumented NDOS

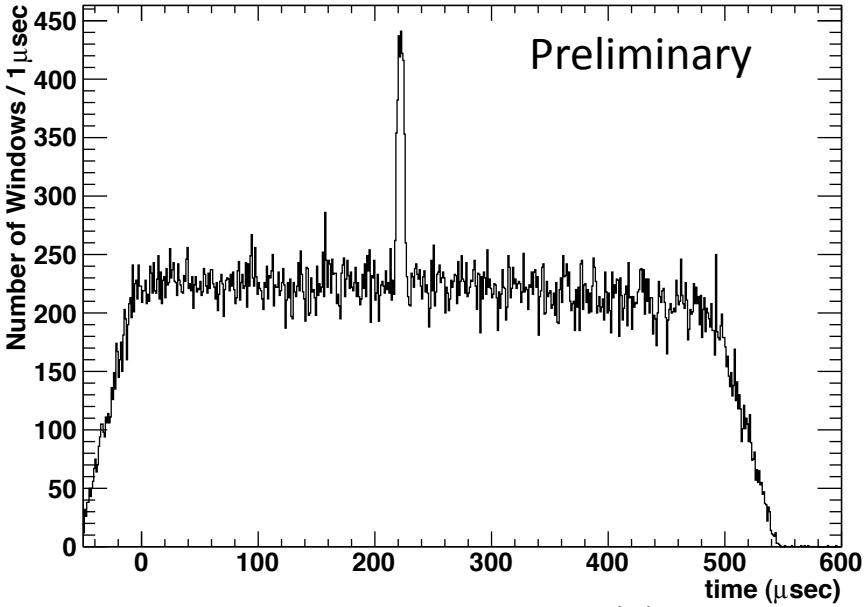


Sample Neutrino Event

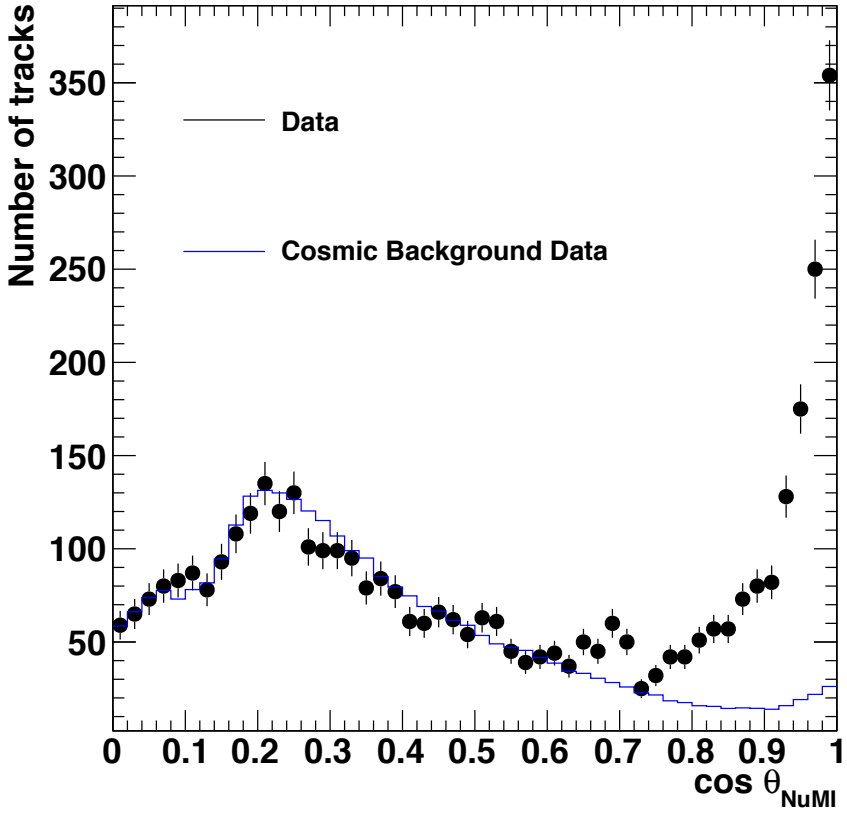




NuMI Neutrinos

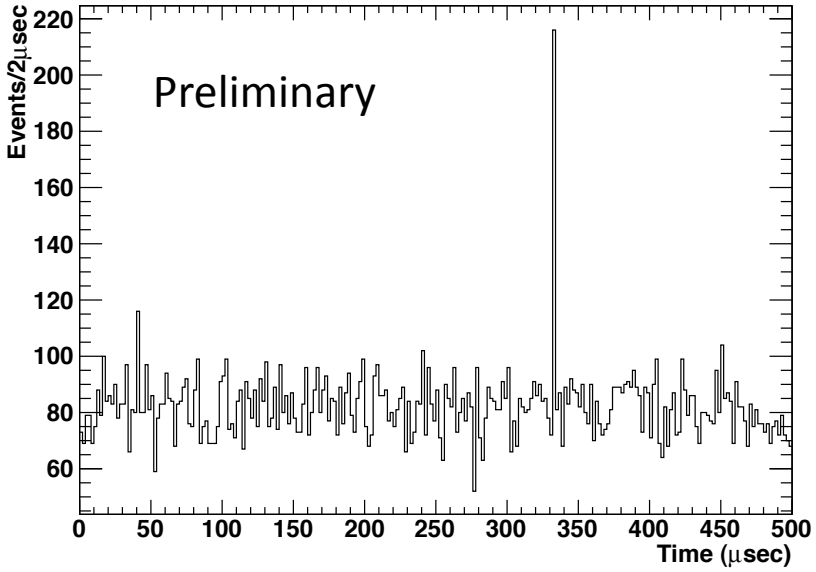


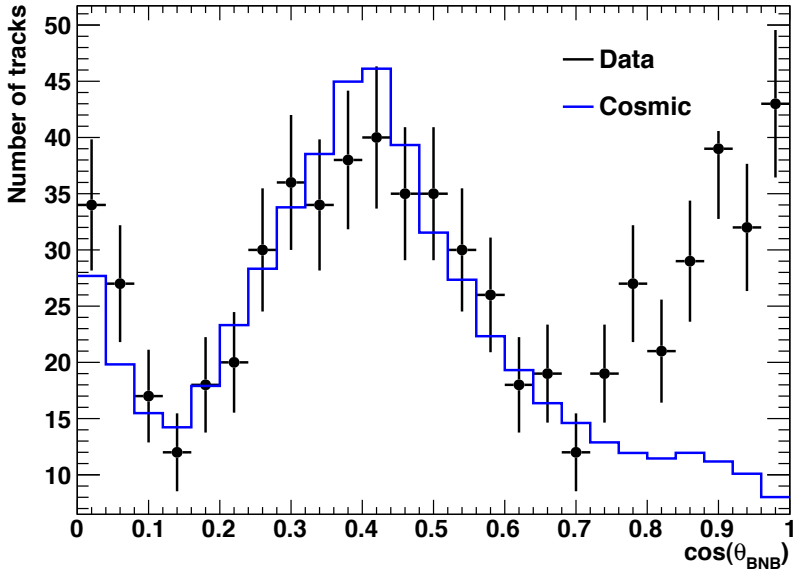
Selection: >=4 hits in each view. Fiducial|x|<110cm, y<140cm and z>50cm and z<770 cm



- 110 mrad off NuMI axis
- 500 μs wide trigger widow @ 0.4 Hz
- 5.6×10^{19} POT reverse horn current beam, 1001 NuMI events (69 cosmic BG)
- 8.4×10^{18} POT forward horn current beam, 253 NuMI events (39 cosmic BG)

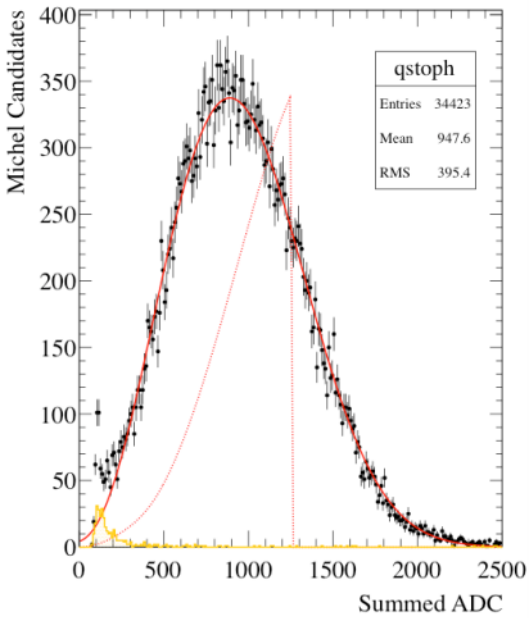
Booster Neutrinos

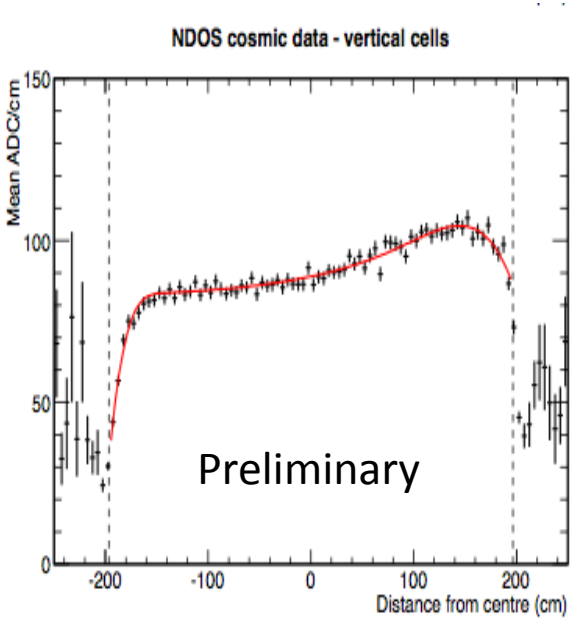


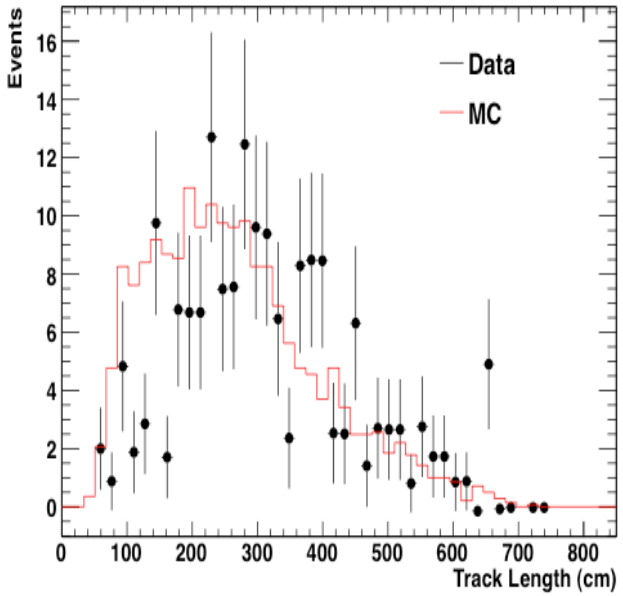


- 500 μs wide trigger widow @ 1.2 Hz
- NDOS nearly on Booster axis
- Detector rotated wrt axis
- 3x10^{19} POT, 222 booster events (92 cosmic BG)

Commissioning/Calibration Experience

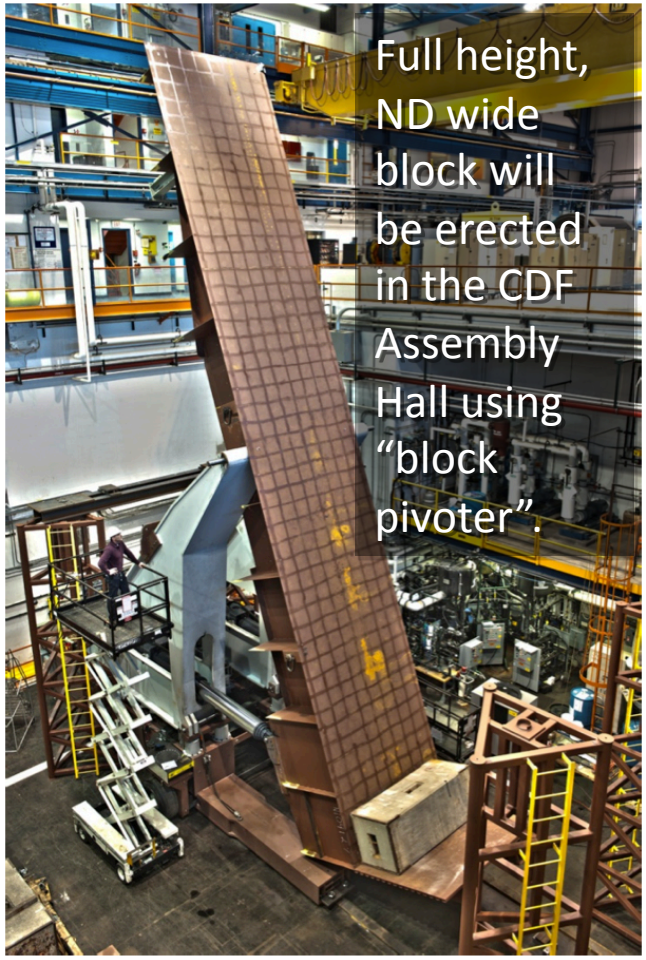


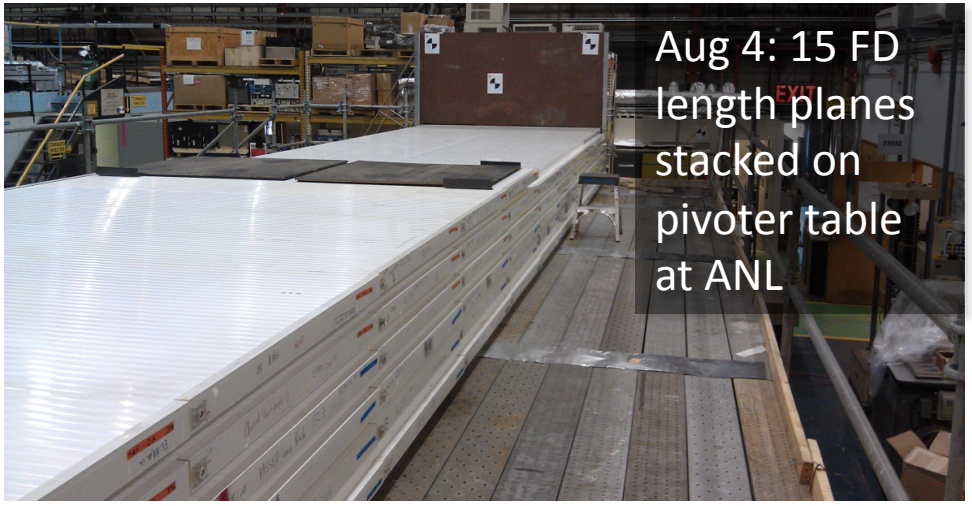




- Use Michel electrons for electro-magnetic energy calibration
- Cosmic muons provide calibration source
- 500 µs wide trigger window @ 10 Hz
- Early look at contained events indicates NuMI MC event rate agrees with data

Full Height Engineering Prototype





Conclusions

- Recent results from T2K are very encouraging for the NOvA program.
- NOvA NDOS is taking data now and has provided critical feedback to all aspects of the experiment.
- Far Detector construction is fast approaching so please … *Stay Tuned!*

110 Physicists, 24 Institutions, 4 Countries

Physics

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U^\dagger \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- $\nu_e, \nu_\mu, \nu_\tau \leftrightarrow \nu_1, \nu_2, \nu_3$
  - Flavor States: creation and detection
  - Mass States: propagation

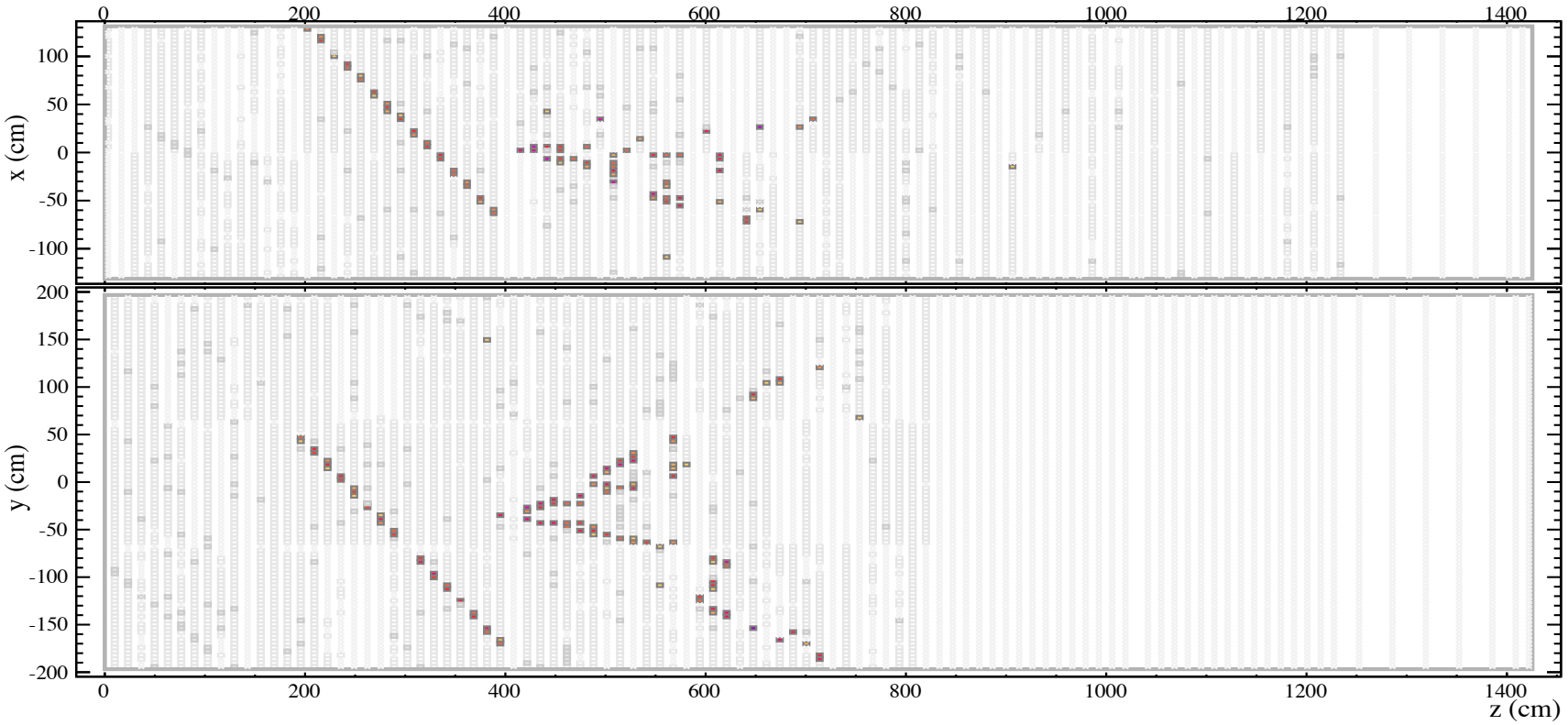
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12}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

(12) Sector: Reactor + Solar and (23) Sector: atmospheric and accelerator are observed.
(13) Sector mixing not yet observed

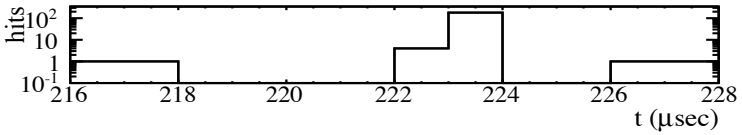
$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

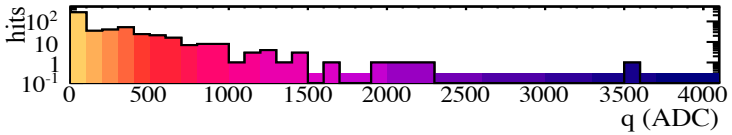
Oscillation probability depends on: dist. traveled (L), ν energy (E), and difference in the squared masses ($\Delta m^2_{ij} = m^2_i - m^2_j$)

Actual Neutrino Events

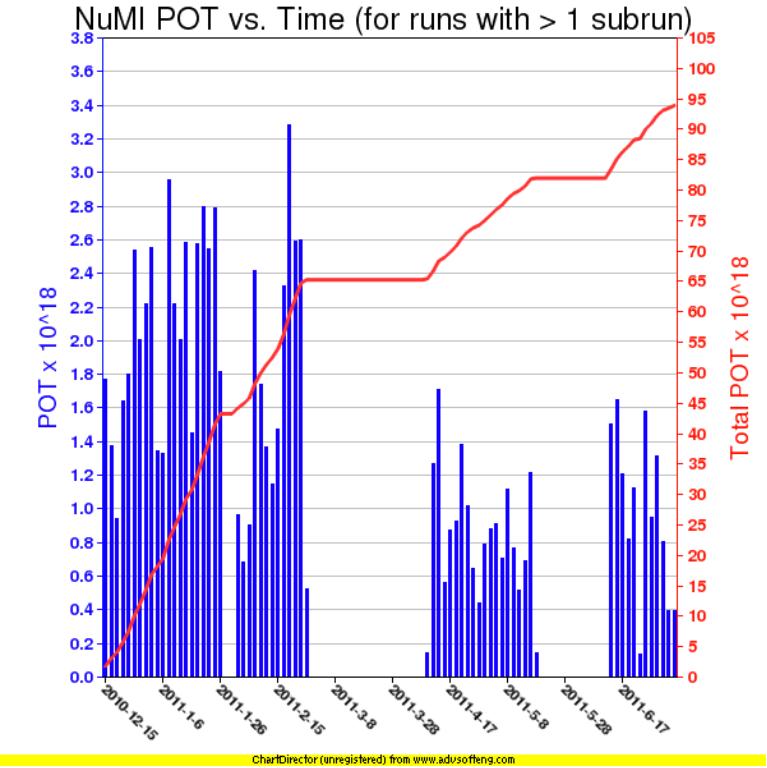


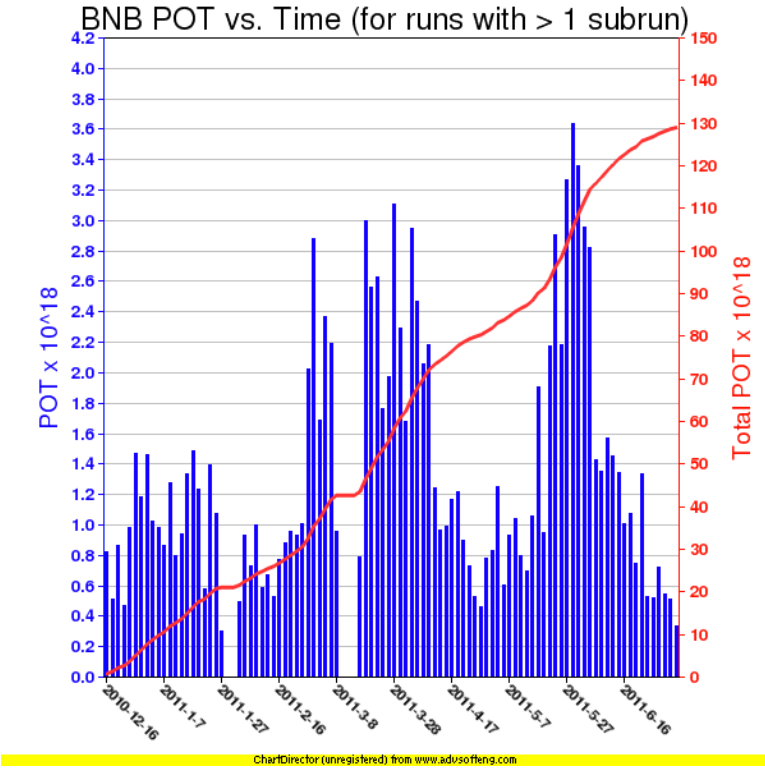
NOvA - FNAL E929
Run: 11956/6
Event: 273516
UTC Mon Apr 11, 2011
00:35:22.853571392





POT Collected



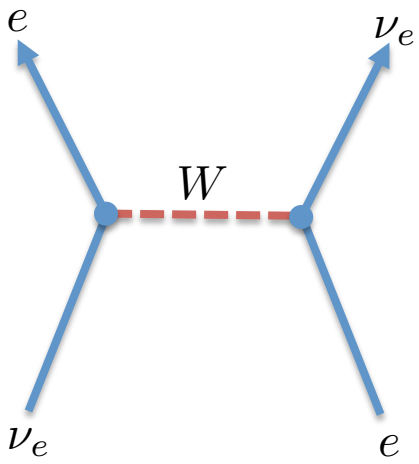


Matter Effect

- The forward scattering amplitudes for neutrinos and anti-neutrinos through normal matter differ due to the inclusion of the extra diagram for interactions off electrons
- This difference breaks the degeneracy in the neutrino mass spectrum and modify the oscillation probability

$$P_{mat}\left(\nu_\mu \to \nu_e\right) \neq P_{mat}\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)$$

- If the experiment is performed at the first peak in the oscillation then the matter effects are primarily a function of the beam energy and approximated by:



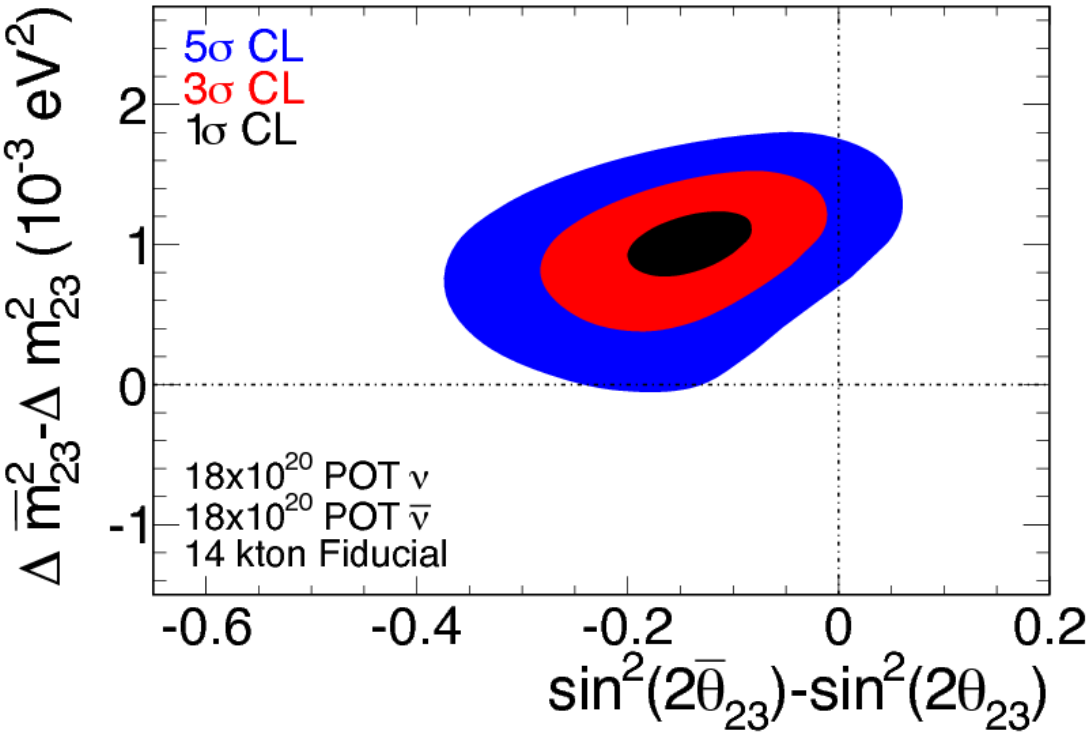
$$P_{mat}\left(\nu_\mu \to \nu_e\right) \approx \left(1 + E/E_R\right) P_{vac}\left(\nu_\mu \to \nu_e\right)$$

$$E_R = \frac{\Delta m^2_{23}}{2\sqrt{2} G_F N_e} \approx 11 GeV$$

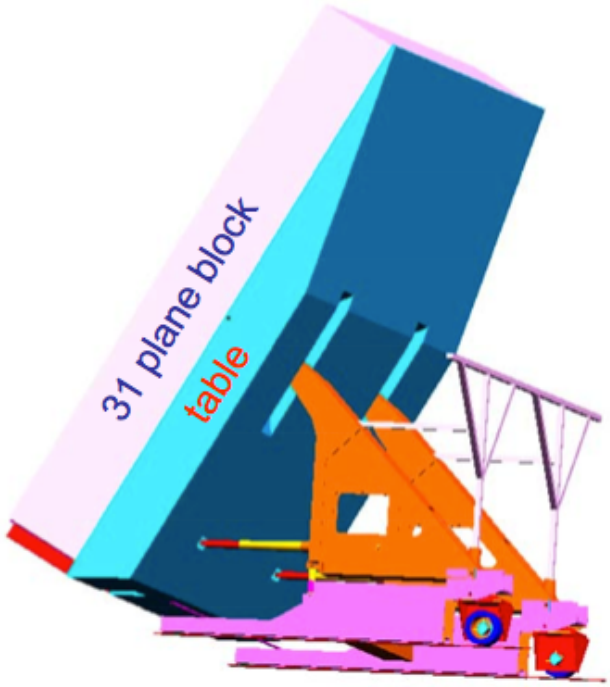
- In the normal hierarchy this matter effect enhances the transition probability for neutrinos and suppresses the probability for antineutrinos transitions
- With an inverted hierarchy the effect is reversed

Neutrino/Anti-neutrino Differences

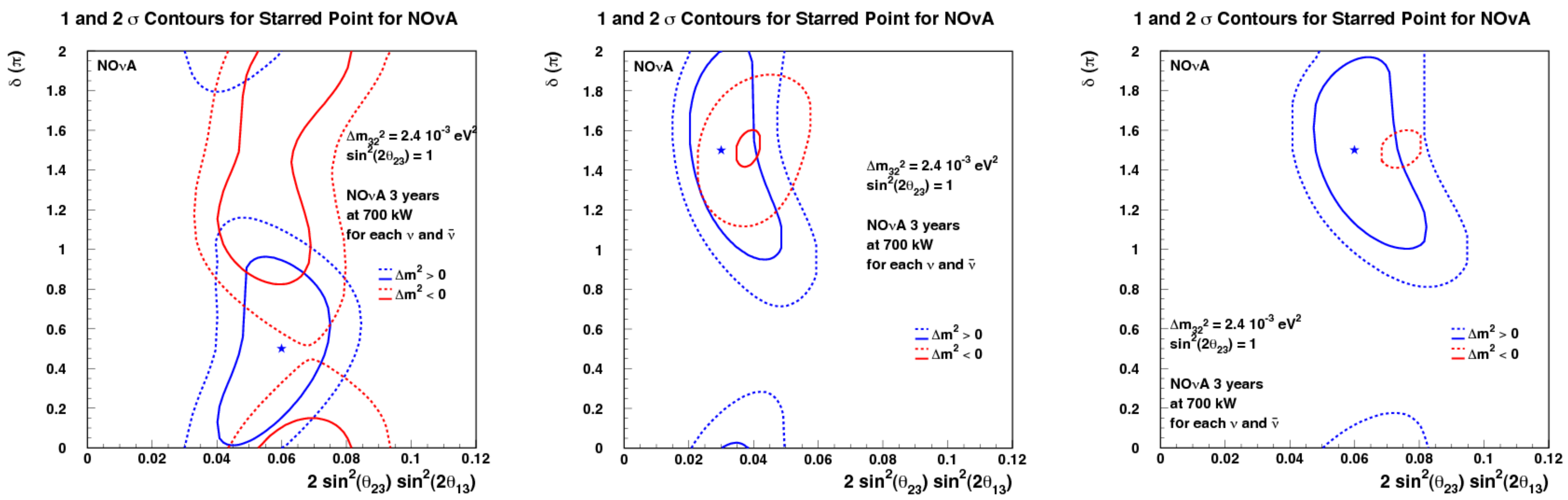
Difference in neutrino and anti-neutrino muon neutrino disappearance parameters. The difference is set to coincide with reported MINOS result. Contours are based on three years of neutrino running and three years of anti-neutrino running and use quasi-elastic events.



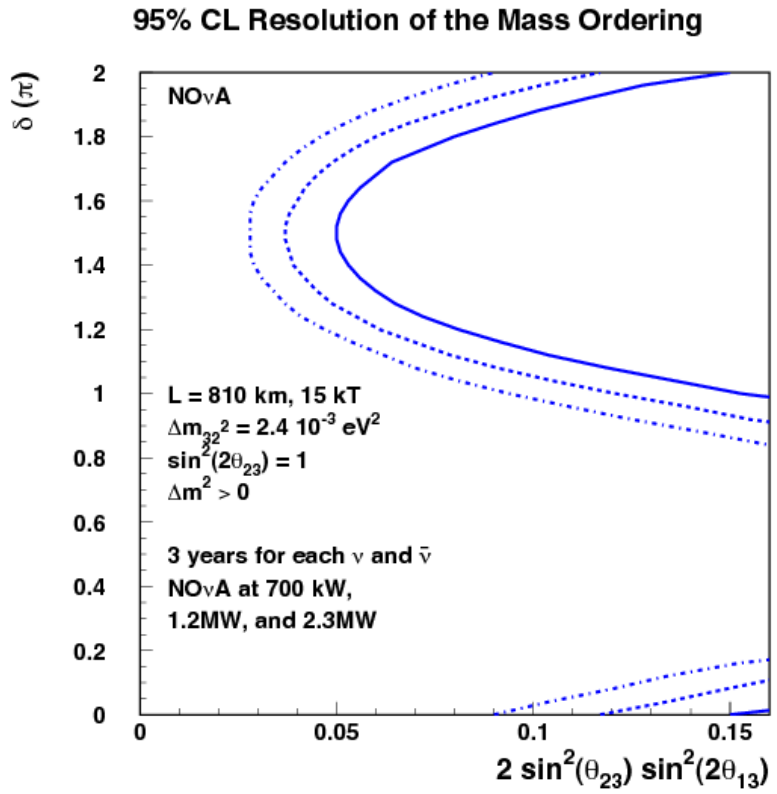
Block Pivoter

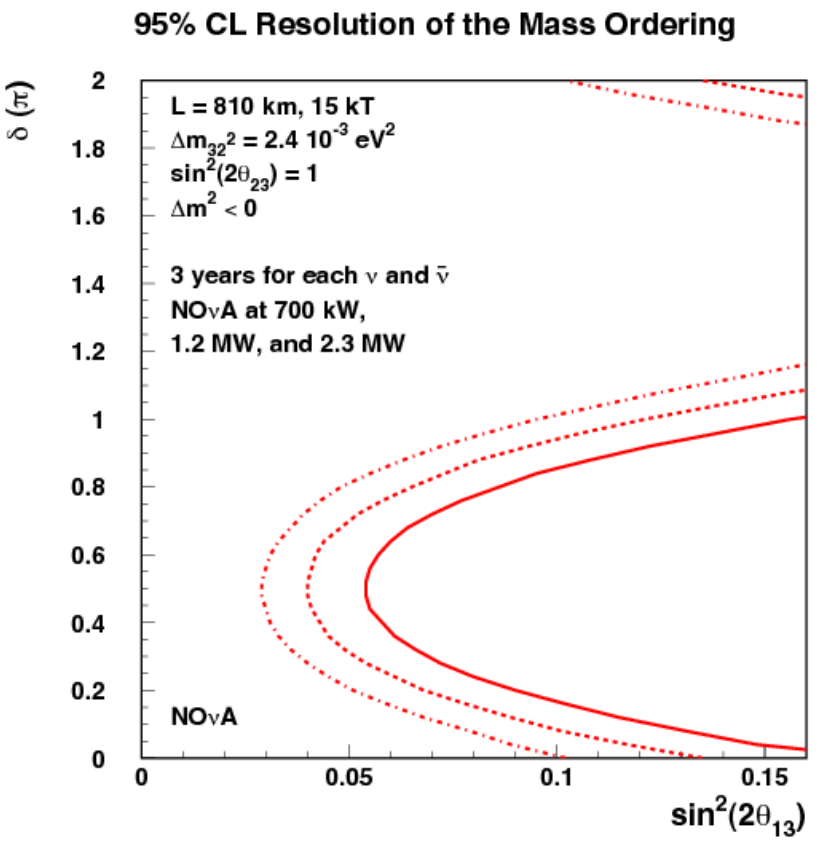


Errors with Measure Central Values



Mass Ordering (NOvA Only)





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