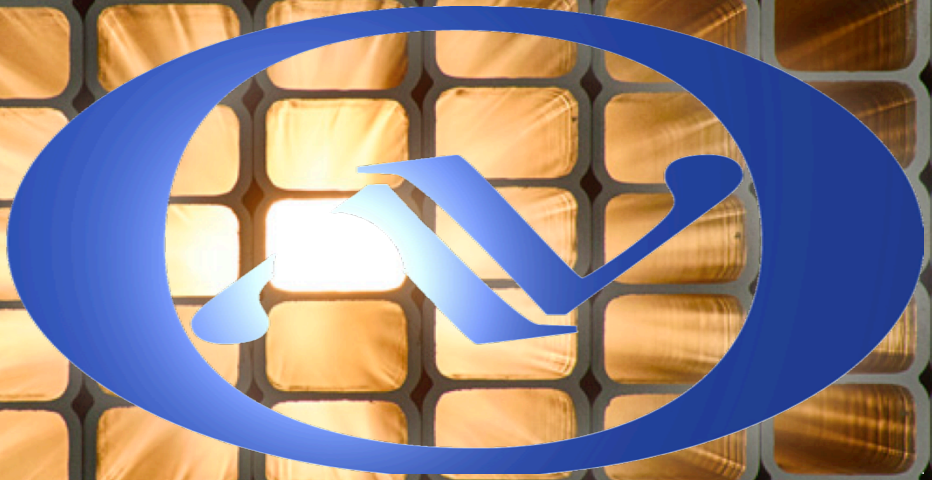
The NOvA Experiment: Current Status



Mathew Muether, Fermilab

Presented at NNN 2013 for the NOvA Collaboration

November 11th, 2013

Outline

- NOvA – NuMI Off-Axis ν_e Appearance Experiment
- Fermilab's Flagship Intensity Frontier Experiment
- Far detector located in Ash River, MN

This talk will cover:
- Detector Design
- Current status of the project
- Initial look at data from the Far Detector
- Expected physics sensitivities

(NOvA is extremely active right now)

NOvA Collaboration

- ARGONNE NATIONAL LABORATORY
- CALIFORNIA INSTITUTE OF TECHNOLOGY
- UNIVERISTY OF CINCINNATI
- FERMILAB
- HARVARD UNIVERSITY
- INDIANA UNIVERSITY
- IOWA STATE UNIVERSITY
- MICHIGAN STATE UNIVERSITY
- UNIVERSITY OF MINNESOTA – CROOKSTON
- UNIVERSITY OF MINNESOTA – DULUTH
- UNIVERSITY OF MINNESOTA
- UNIVERSITY OF SOUTH CAROLINA
- SOUTHERN METHODIST UNIVERSITY
- STANFORD UNIVERSITY
- UNIVERSITY OF TENNESSEE
- UNIVERSITY OF TEXAS AT AUSTIN
- TUFTS UNIVERSITY
- UNIVERSITY OF VIRGINIA
- WICHITA STATE UNIVERSITY
- COLLEGE OF WILLIAM AND MARY
- SOUTH DAKOTA SCHOOL OF MINES AND TECH
- WINONA STATE UNIVERSITY

- INSTITUTE OF PHYSICS OF THE ACADEMY OF SCIENCES OF THE CZECH REPUBLIC
- CHARLES UNIVERSITY IN PRAGUE, INSTITUTE FOR PARTICLE AND NUCLEAR PHYSICS
- CZECH TECHNICAL UNIVERSITY

- LEBEDEV PHYSICAL INSTITUTE
- INSTITUTE FOR NUC. RESEARCH, MOSCOW
- JOINT INST. FOR NUC RESEARCH, DUBNA

- UNIVERSITY OF ATHENS

- UNIVERSITY OF SUSSEX

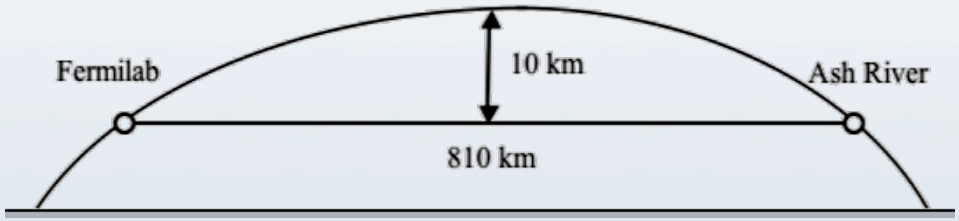
- BANARAS HINDU UNIVERSITY
- UNIVERSITY OF DELHI
- COCHIN UNIVERSITY OF SCI. AND TECH.
- INDIAN INSTITUTE OF TECHNOLOGY, GUWAHATI
- INDIAN INSTITUTE OF TECHNOLOGY, HYDERABAD
- UNIVERSITY OF HYDERABAD
- UNIVERSITY OF JAMMU
- PANJAB UNIVERISTY

- UNIVERSIDADE FEDERAL de GOIAS

170+ scientists and engineers from 39 institutions, 7 countries

NOvA Program

- Long-baseline neutrino oscillation experiment; 14 mrad Off-axis @ L/E ~ 400 km/GeV
- Near detector to charecterize the beam
- Far detector for oscillation study



- Physics scope:

$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ apperance

- Measure θ_{13}
- ν mass ordering
- CP violating phase

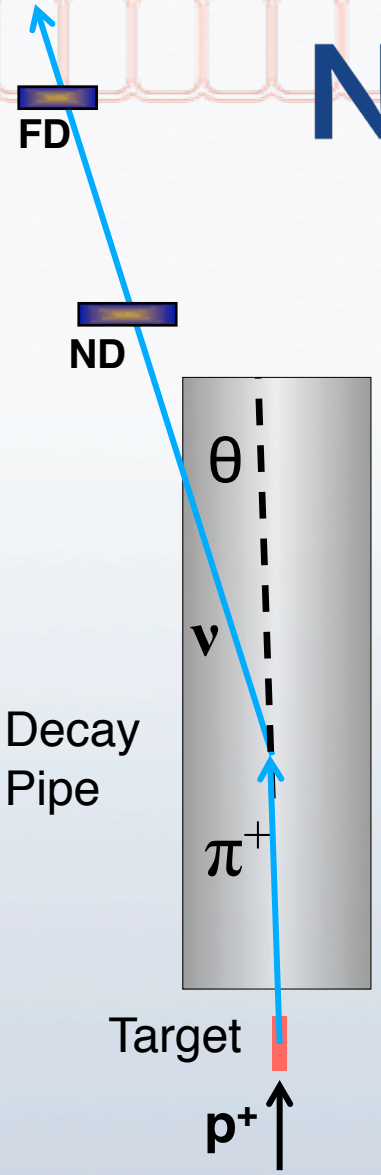
$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$ disapperance

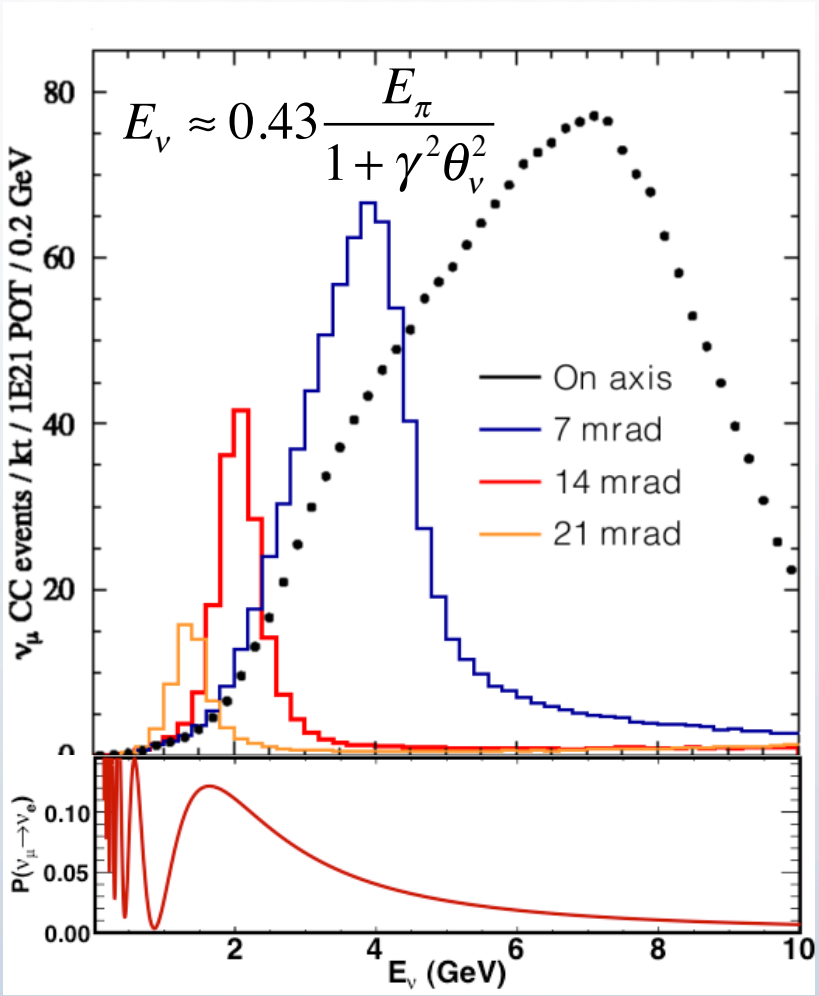
- Precision measurement of θ_{23}, $|\Delta m_{21}{}^2|$

Cross-sections from near detector

Other exotics

NuMI Off-axis Beam

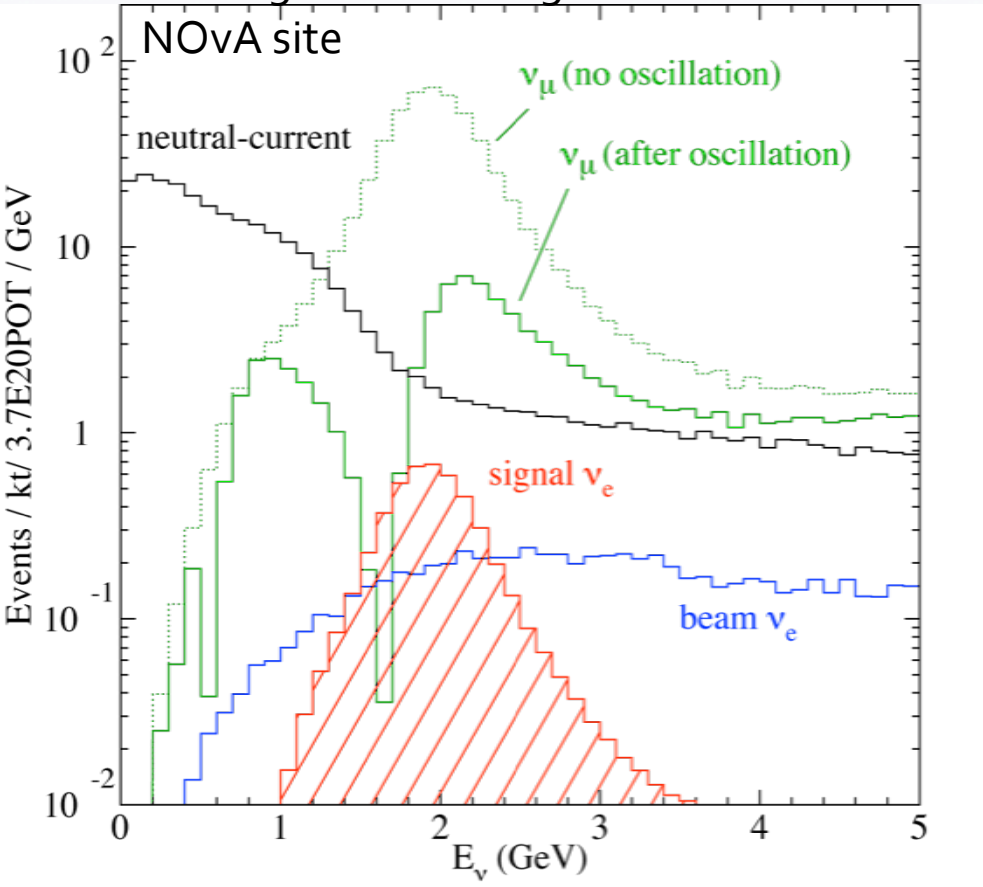




- NOvA detectors are 14 mrad off-axis in a narrow band beam
- Increases flux near oscillation maximum
- Reduces high energy NC background events
- Upgrades towards doubling power from 350kW to 700 kW in-progress

Expected Event Specta

Raw signal and background rates for the NOvA site

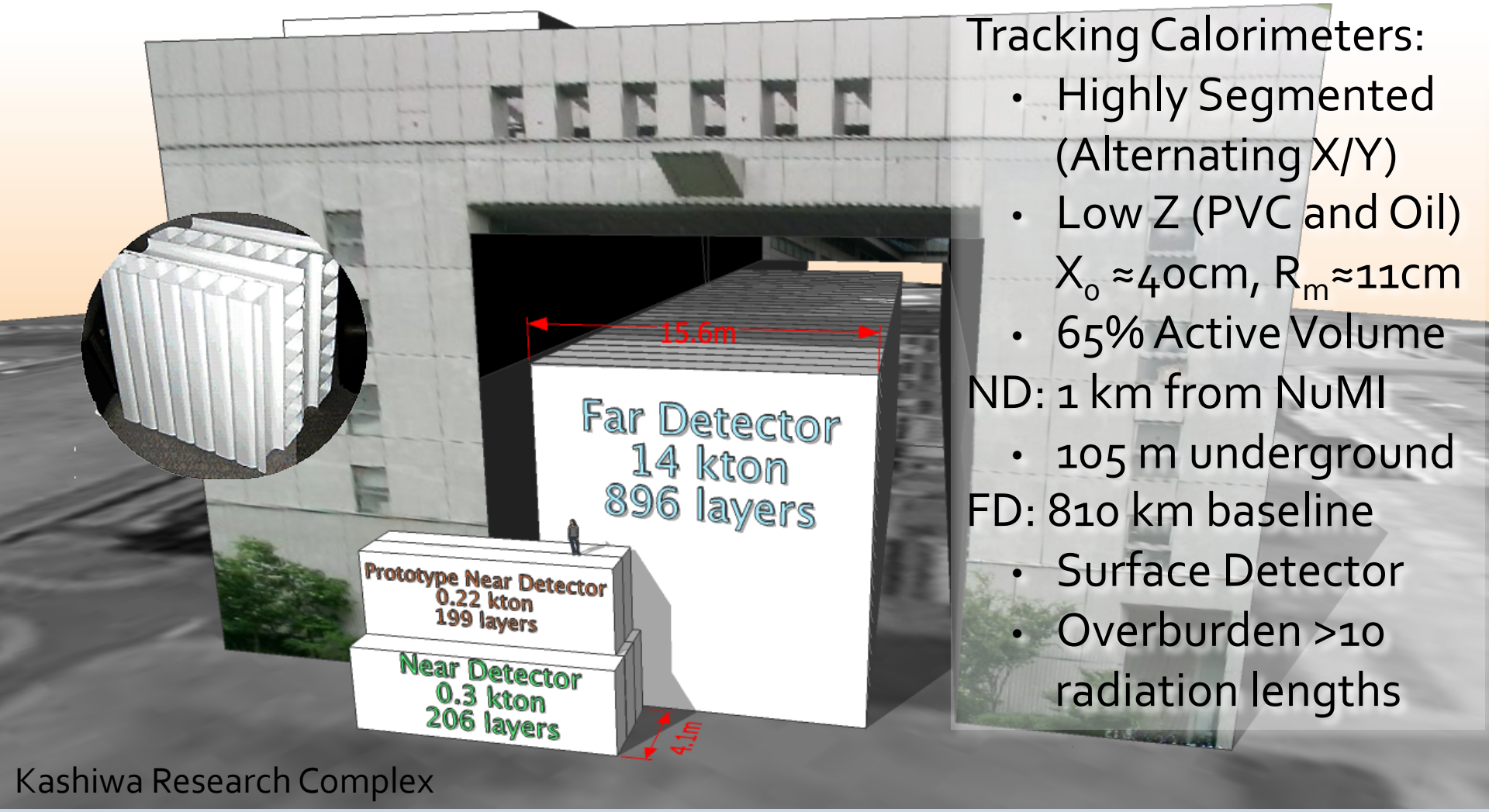


Interaction spectra at 810km, 14 mrad off-axis.
Oscillations: $\Delta m^2=2.5x10^{-3}eV^2$, $\sin^2(2\theta_{13})=0.01$

Detector design criteria:

- Optimized for ν_e detection
- Suppression of ν_μ CC and NC backgrounds at the 99% level
- Energy resolutions small compared to signal width:
  - Less than 8% for ν_e CC

NOvA Detector Suite



Kashiwa Research Complex

Tracking Calorimeters:

- Highly Segmented (Alternating X/Y)
- Low Z (PVC and Oil) $X_0 \approx 40cm$, $R_m \approx 11cm$
- 65% Active Volume

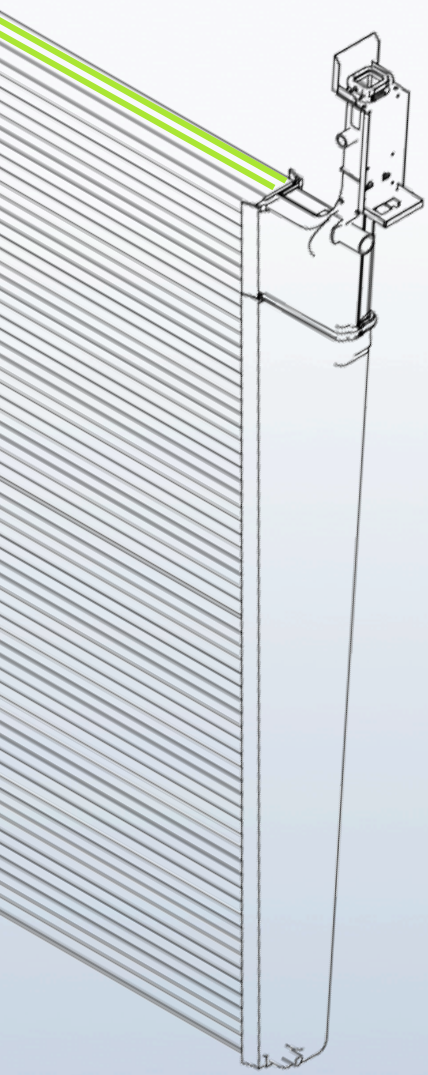
ND: 1 km from NuMI

- 105 m underground

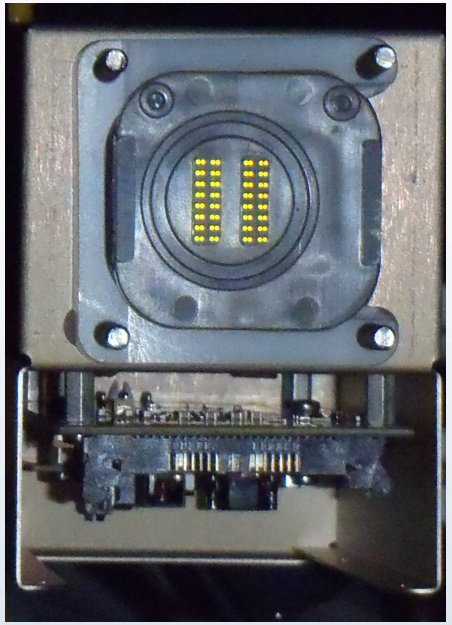
FD: 810 km baseline

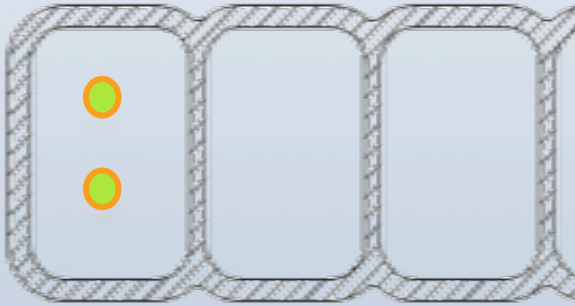
- Surface Detector
- Overburden >10 radiation lengths

Detector Module



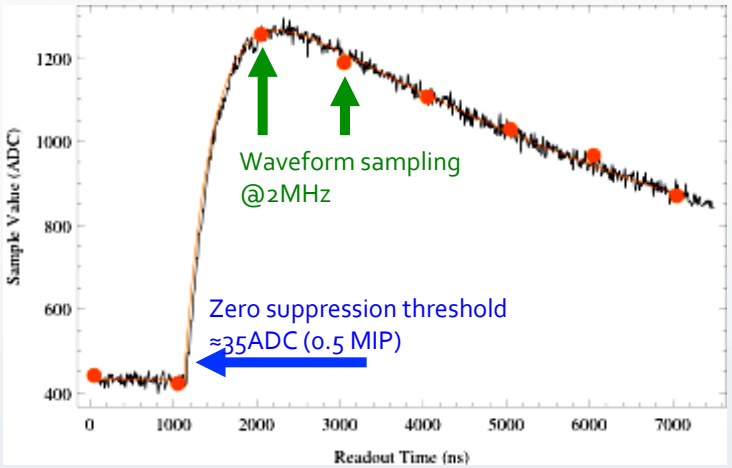
- Cross-section of cell 4cm X 6cm
- Runs entire width of detector (15.6m for far detector)
- Filled with scintillator and instrumented with looped wavelength-shifting fiber
- 32 sealed extruded PVC cells
- Both ends of looped fiber routed to an optical connector
- 11,500 km of wavelength shifting fiber in total
- 10.5 million liters of scintillator

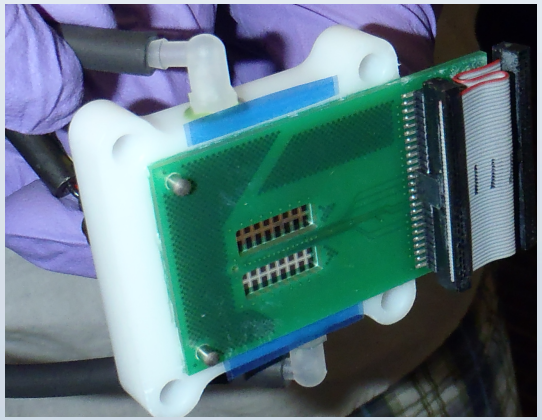




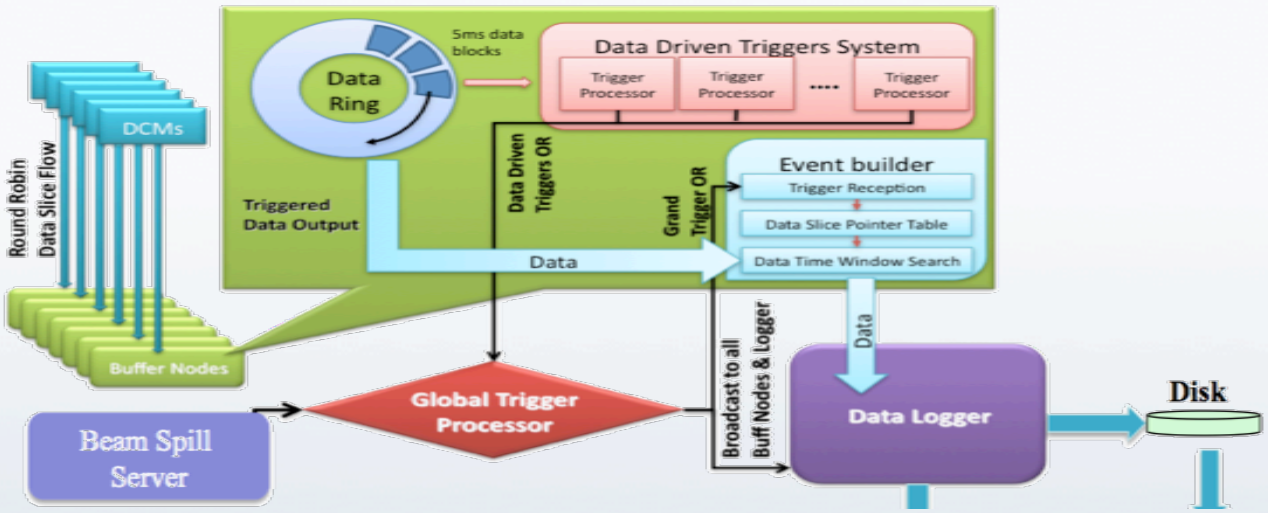
Detector Readout

- Array of 32 avalanche photo-diodes mated to optical connector
- 85% QE for 520 – 550 nm light.
- Gain of 100 @ 375 volts.
- Controlled environmental conditions
- Actively cooled to -15 C.
- 38 pe signal from MIP at far end of cell (10-12 MeV dep. en)
- Signal digitized by on module front end electronics (FEBs)
- 10-15 pe threshold for data written out
- ~12,000 APDs on FEBs at far detector



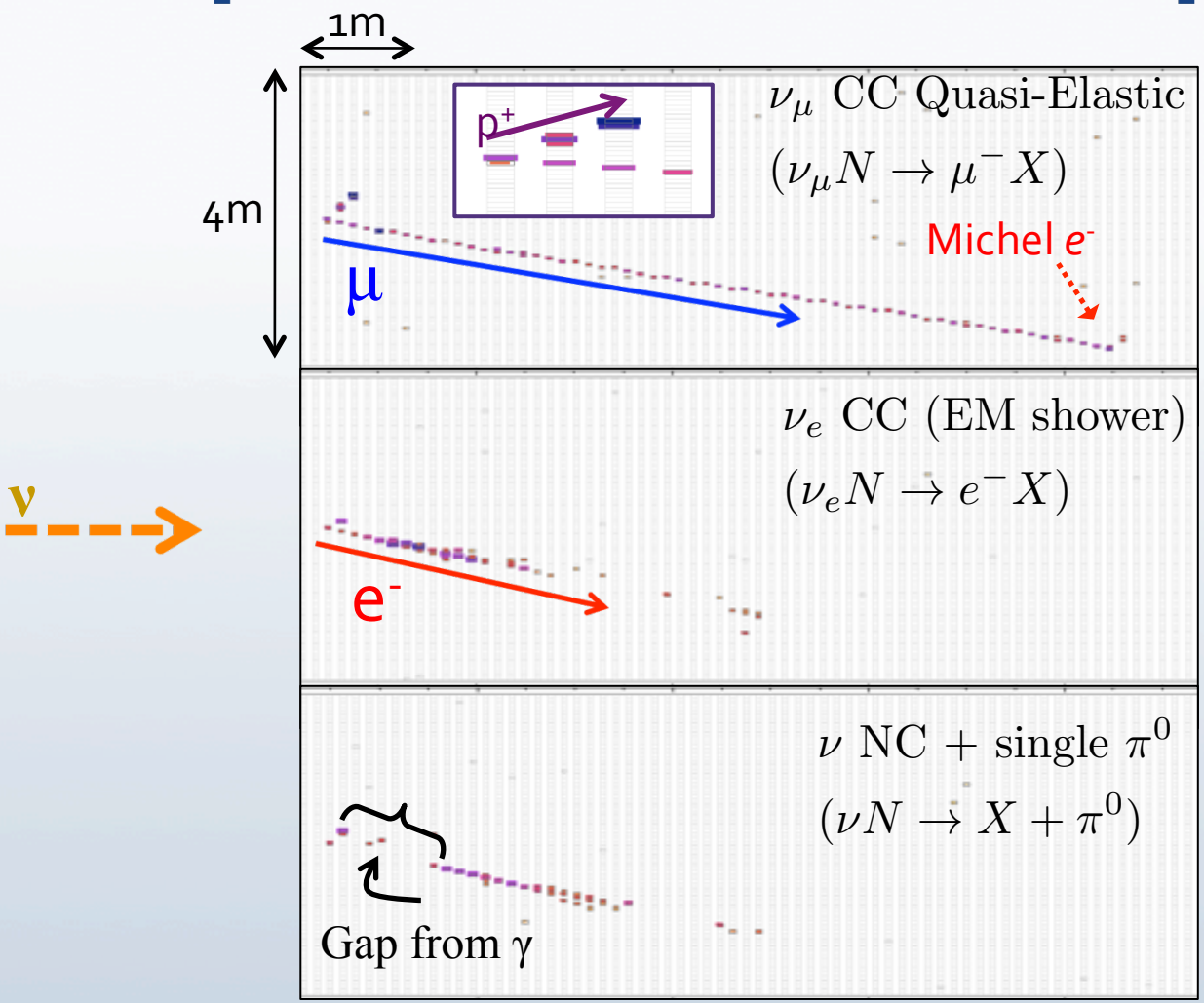


Data Aquistion

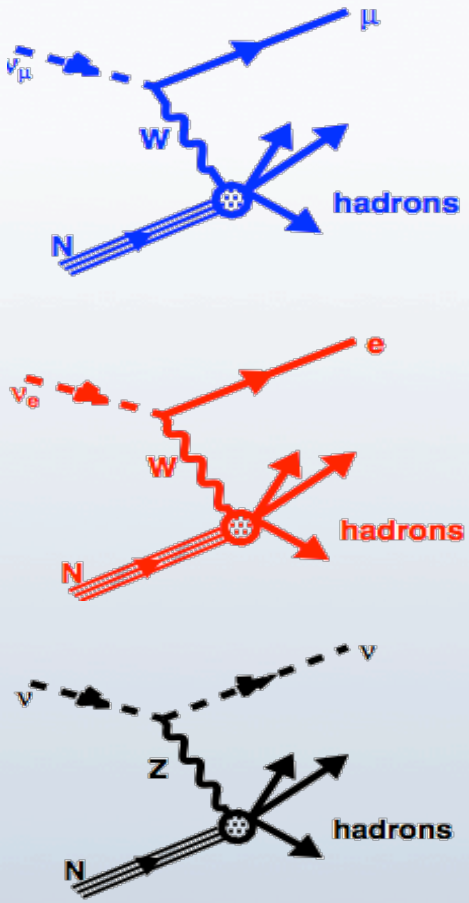


- 64 FEBs feed a Data Concentrator Module which packages and passes the data to a processing farm.
- Data is continuously buffered for several seconds until the arrival of a software spill trigger at which point it is written to disk.
- Beam spill and data driven triggers are available
- System is synchronized by an external timing system to GPS

Expected Event Topologies



(simulated 2 GeV events)



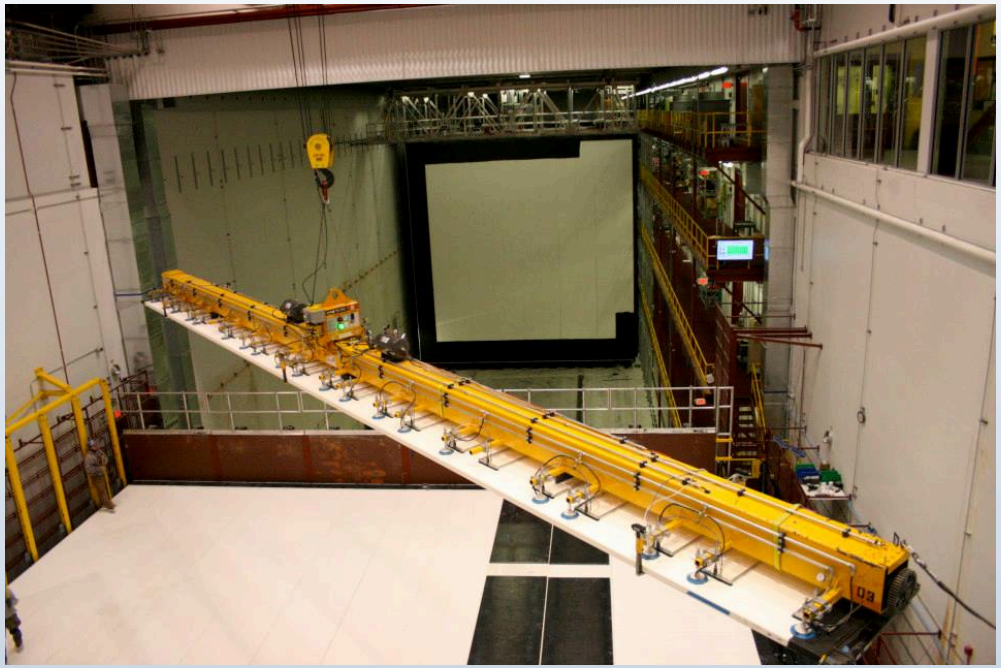
Quick Survey of Project Status

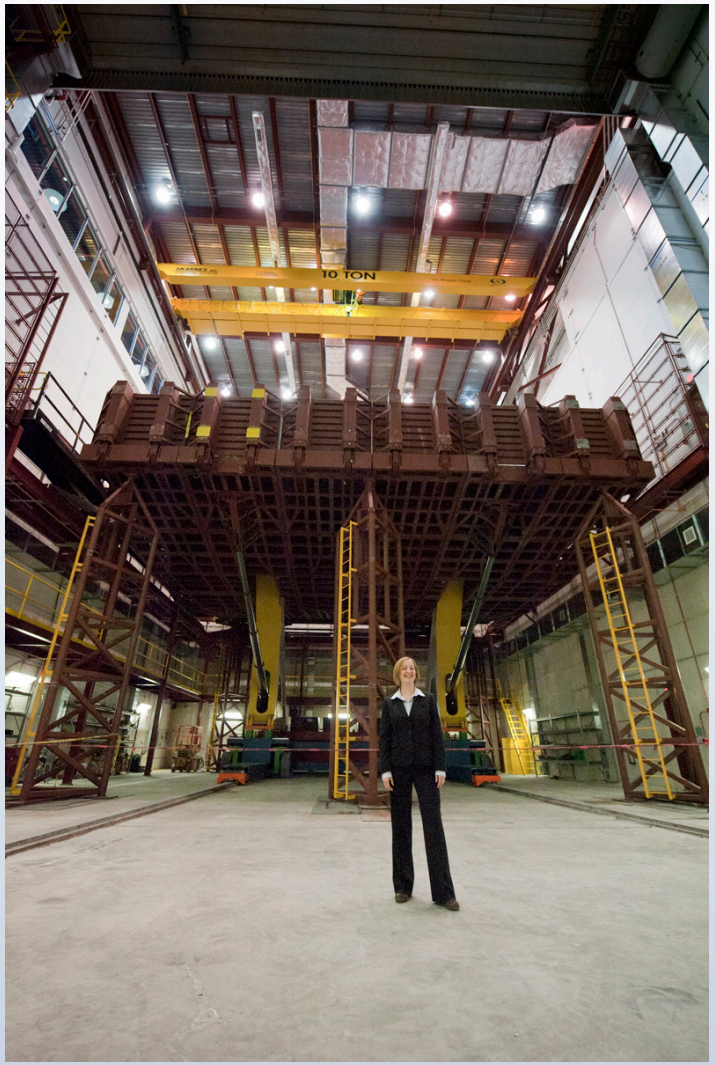
The module factory at the University of Minnesota is in full production and ships modules weekly.

Far Detector Status

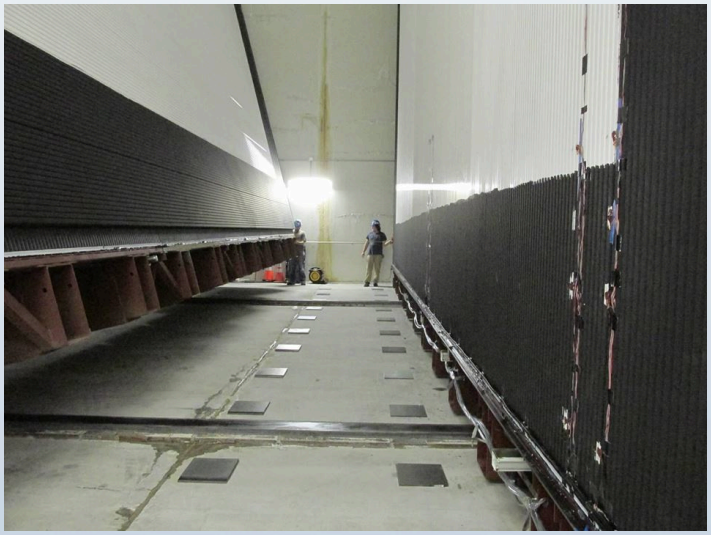
Far Detector Assembly

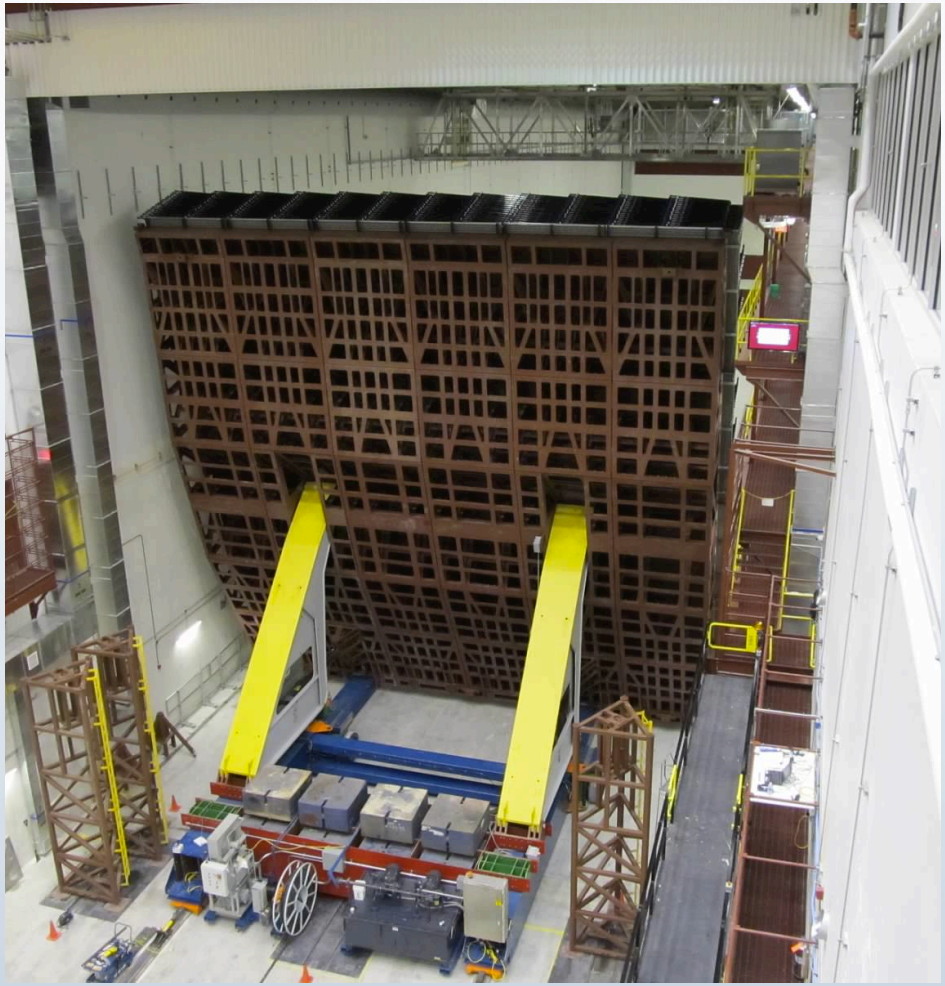
- The block assembly, placement, and outfitting operations are underway!
- Watch the progress at http://www.fnal.gov/pub/webcams/nova_webcam/





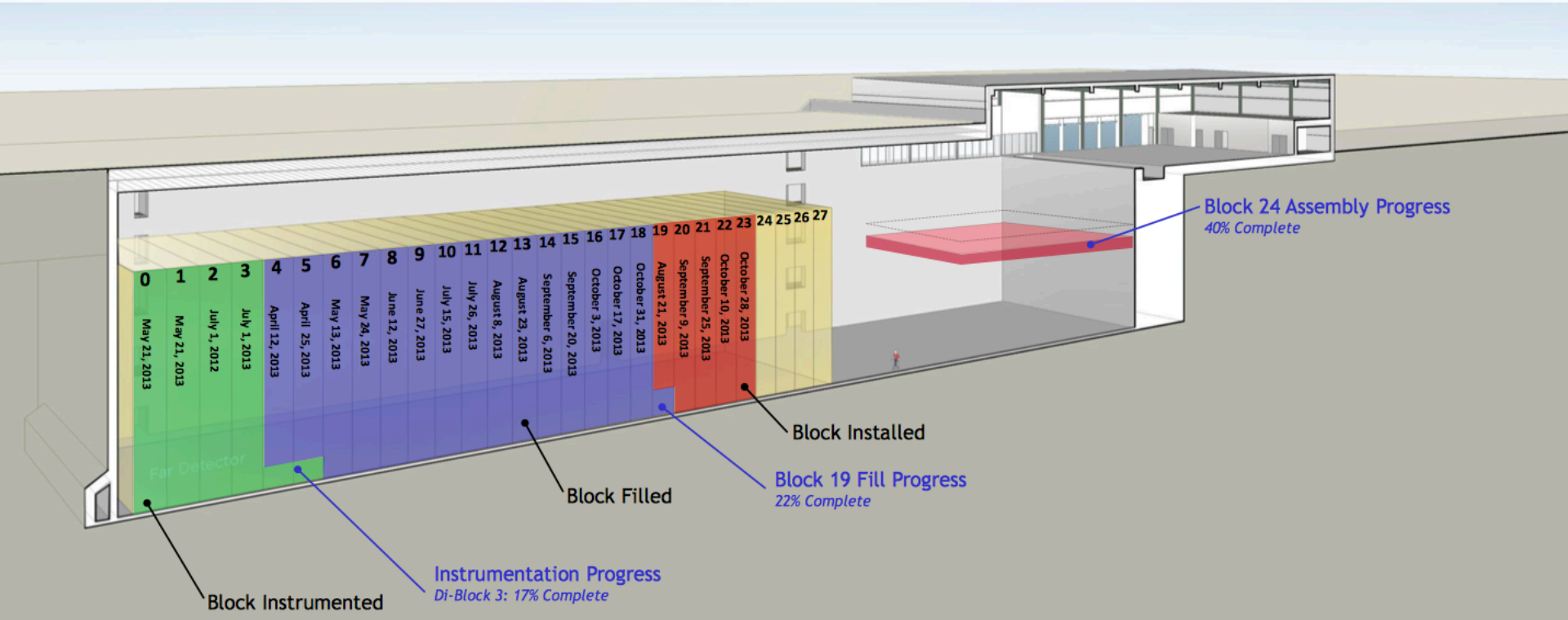
Far Detector Assembly





Far Detector Assembly

Far Detector Status



14 kilotons = 28 NOvA Blocks

24 blocks of PVC modules are assembled and installed in place

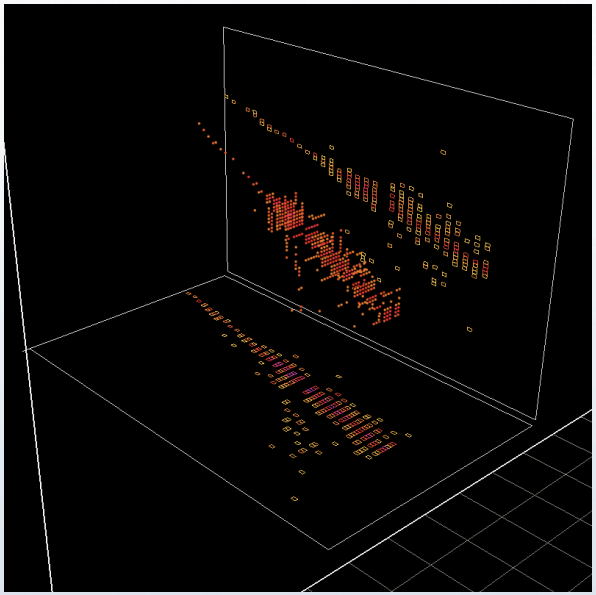
19.22 blocks are filled with liquid scintillator

4.34 blocks are outfitted with electronics

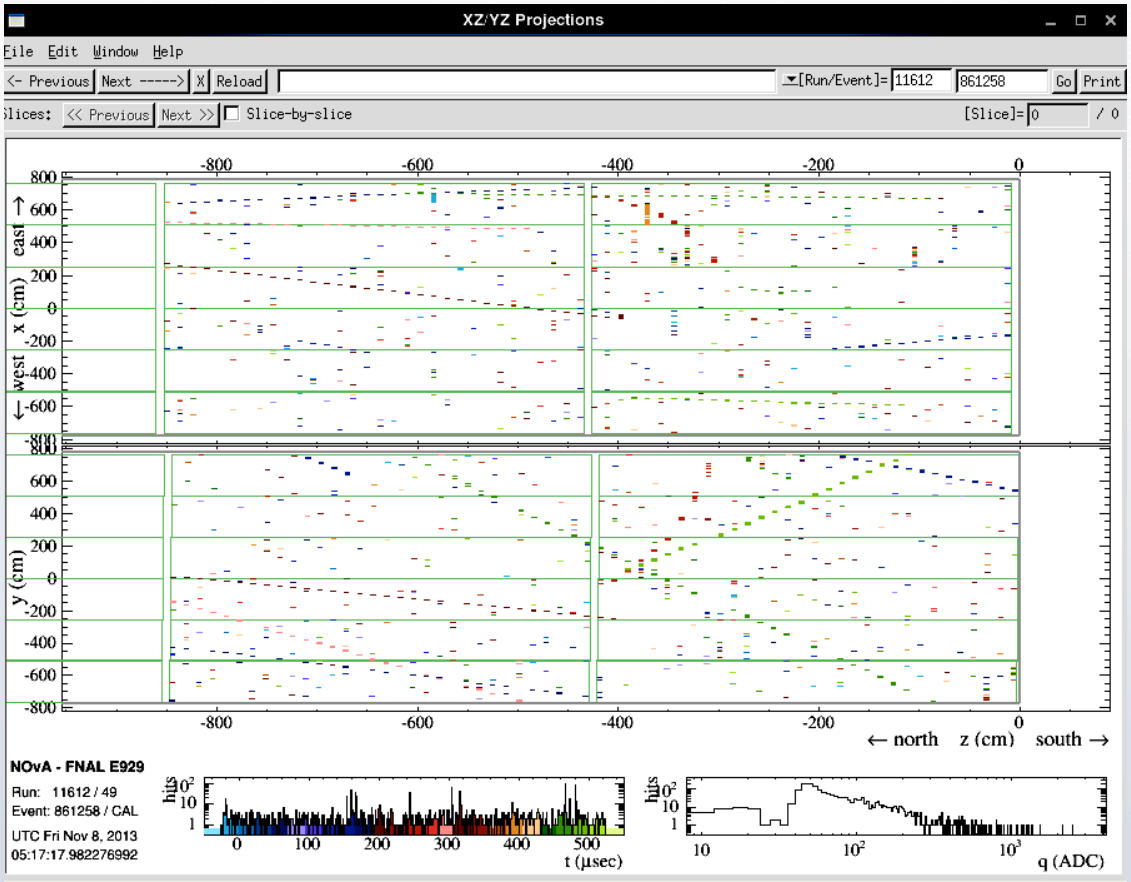
Far Detector Status

Far Detector Status

Some first cosmic events



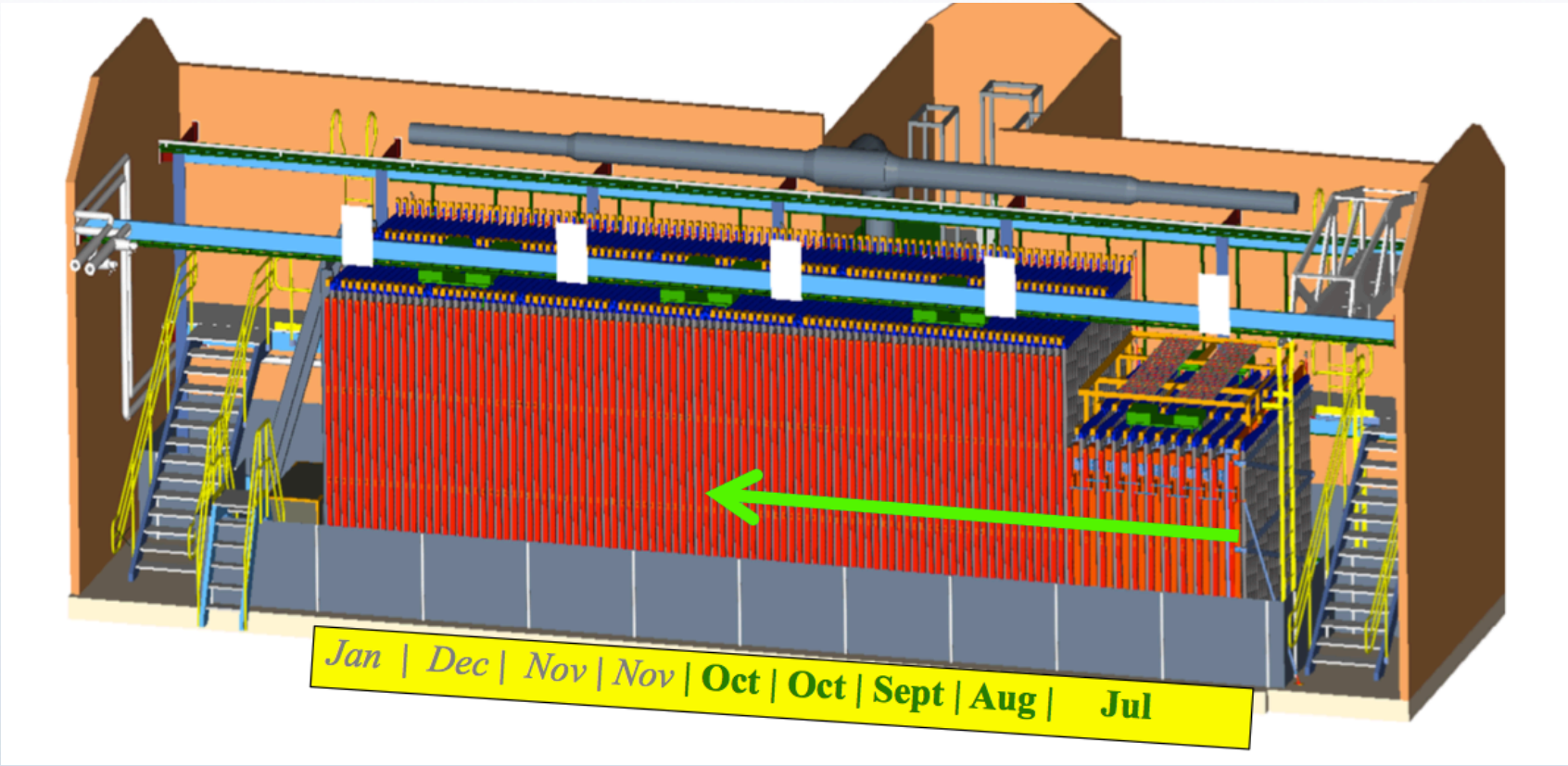
First 3D track recorded in the detector. Event was recorded on 21 May 2013.



Current event display of 2 diblocks running cold with APDs at full gain.

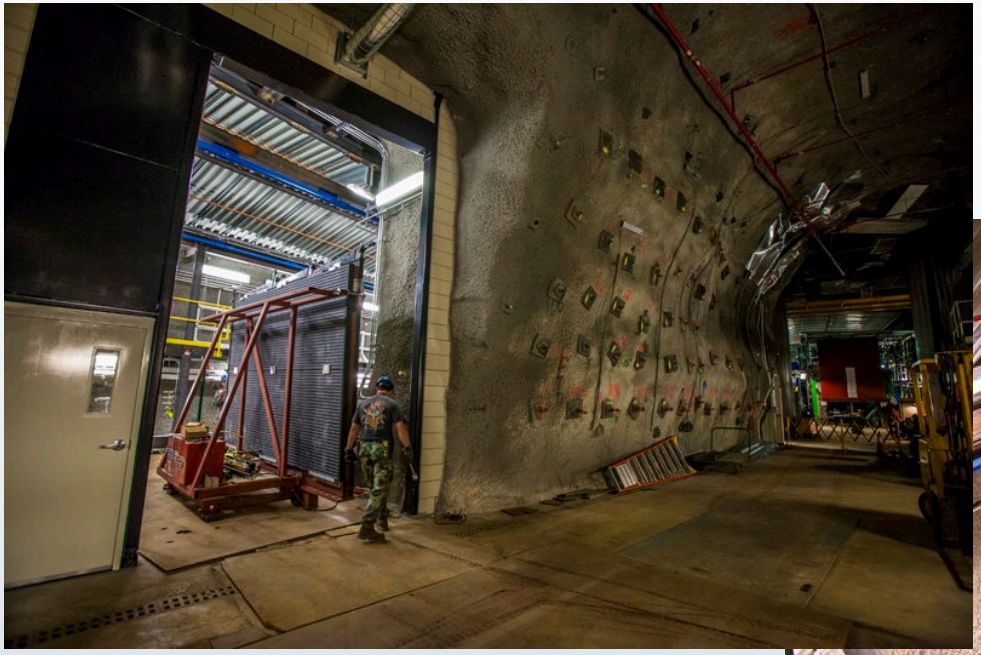
Near Detector Status

Near Detector Status



The near detector is scheduled for completion in early 2014.

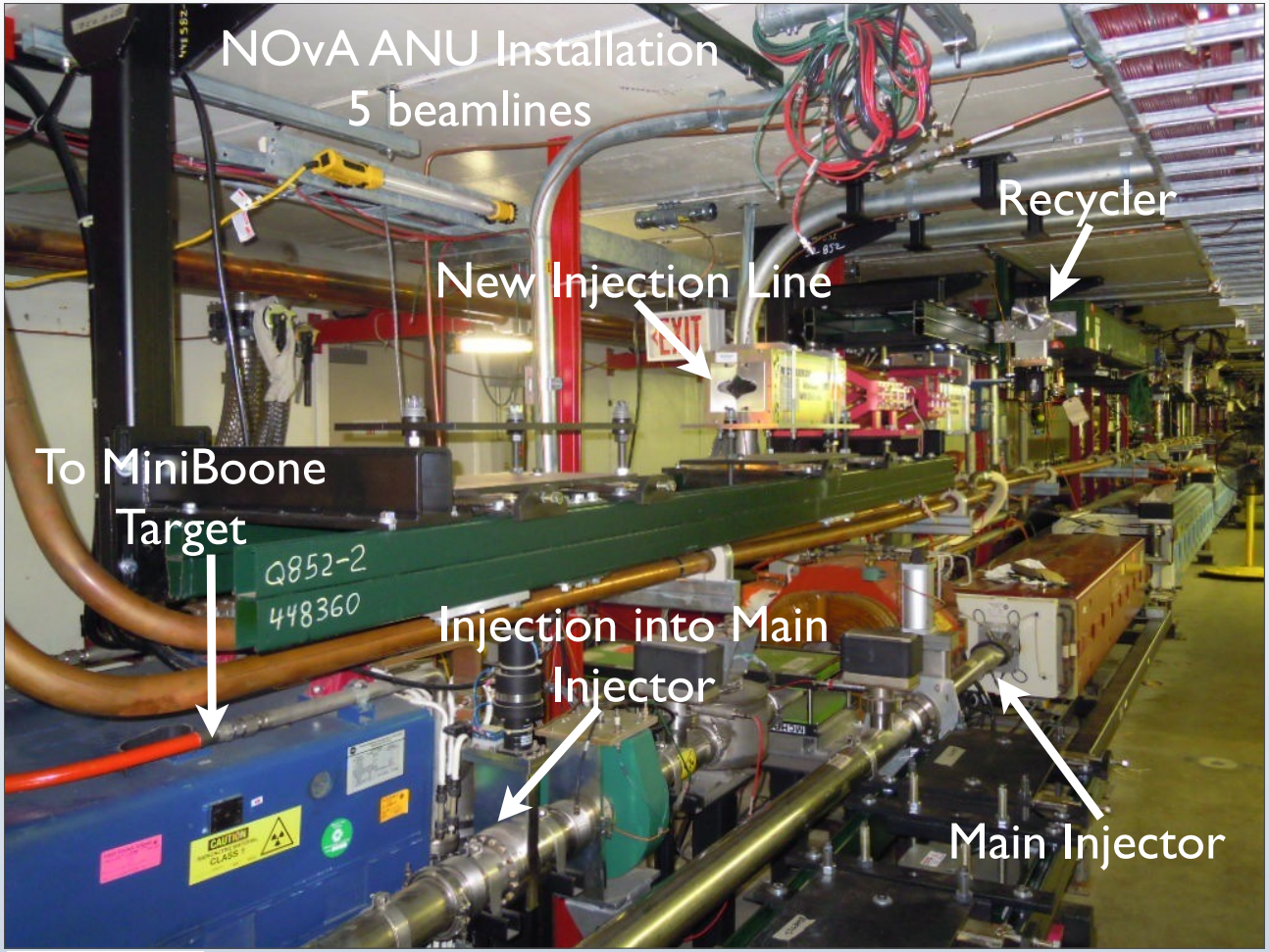
Near Detector Status



First muon catcher planes

First near detector block

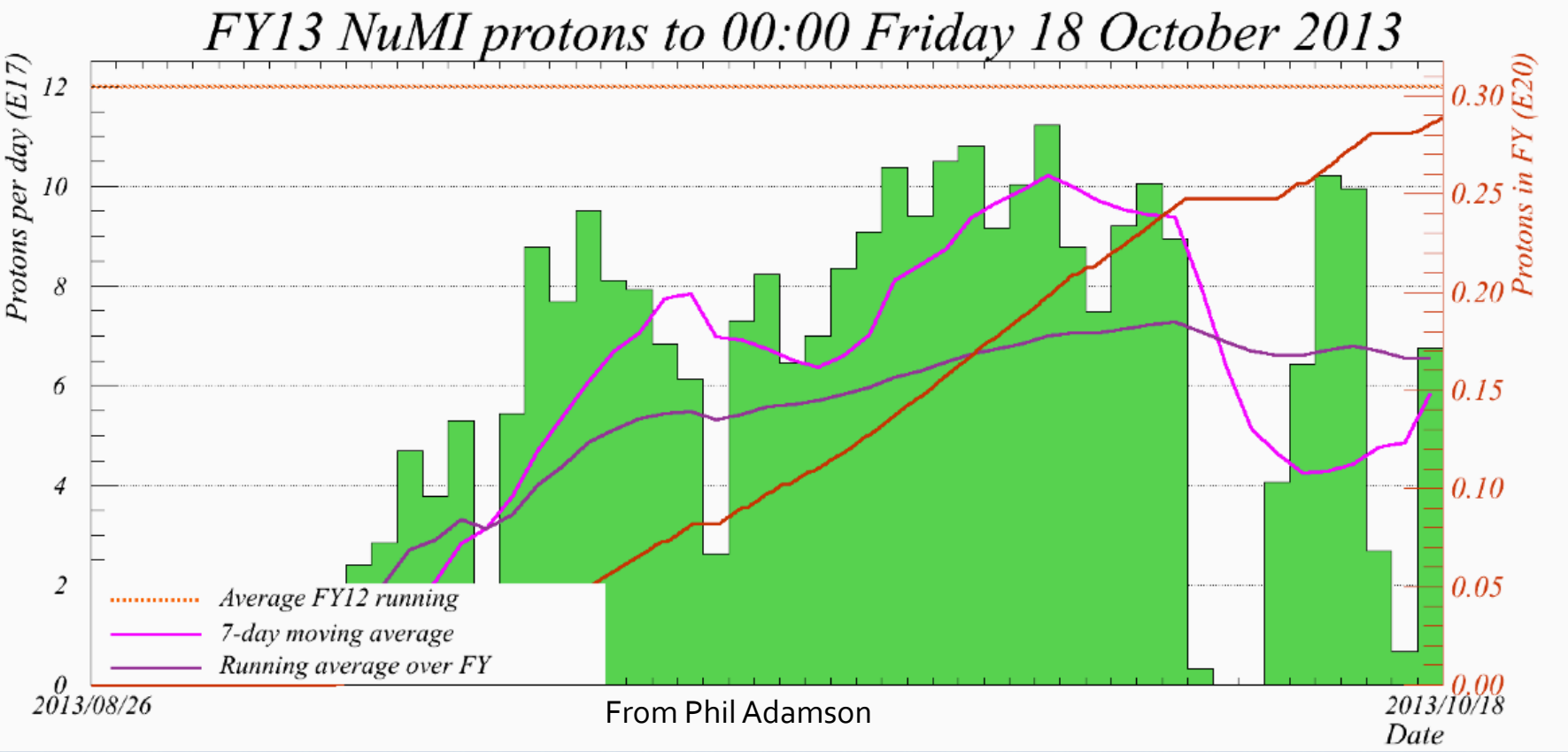
Beam Upgrade



Initial upgrade to the NuMI beamline is complete, on the way to 700kW.

- **Turned Recycler from antiproton to proton ring**
- **Shortened Main Injector cycle from 2.2 seconds to 1.33 seconds**
- **Overhauled NuMI target station for 700 kW running**

Beam Upgrade

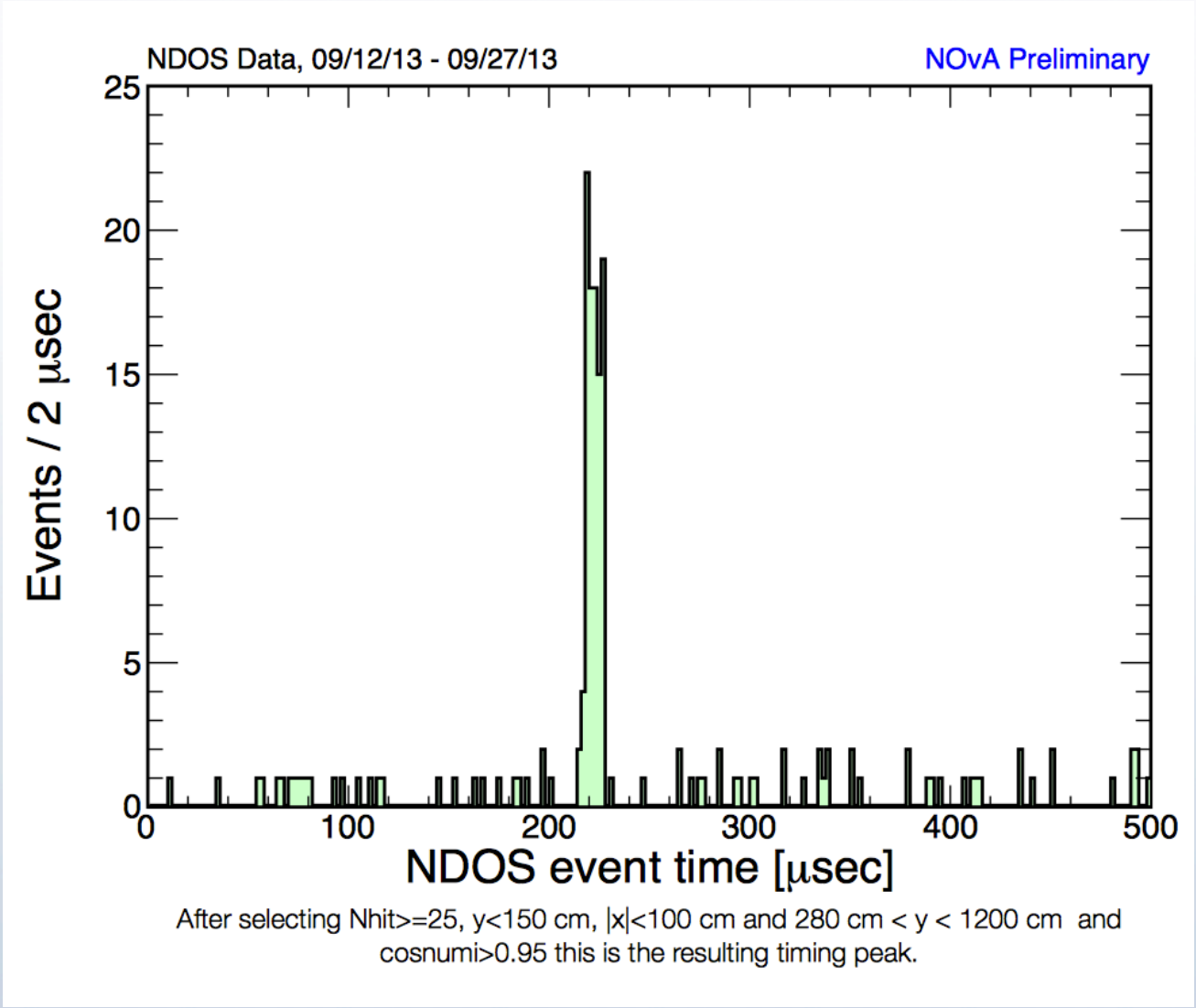


From Phil Adamson

Currently: 250-280 kW

- Once recycler is operational: Up to 500 kW
- Following Booster RF upgrades: 600-700 kW (as early as 2014)

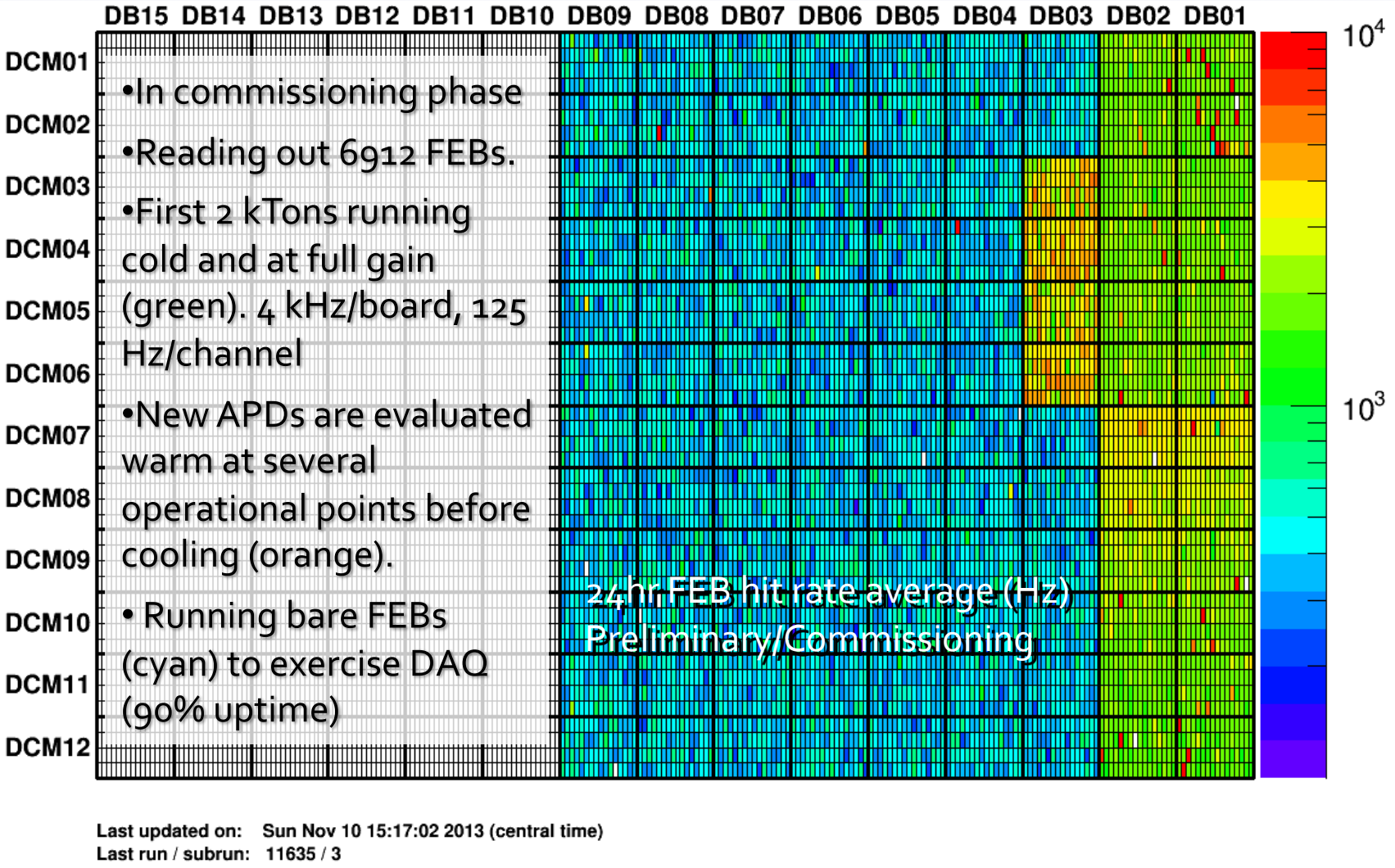
NDOS Beam activity



Timing peak of events in NOvA surface prototype detector (NDOS) exactly where NuMI activity is expected.

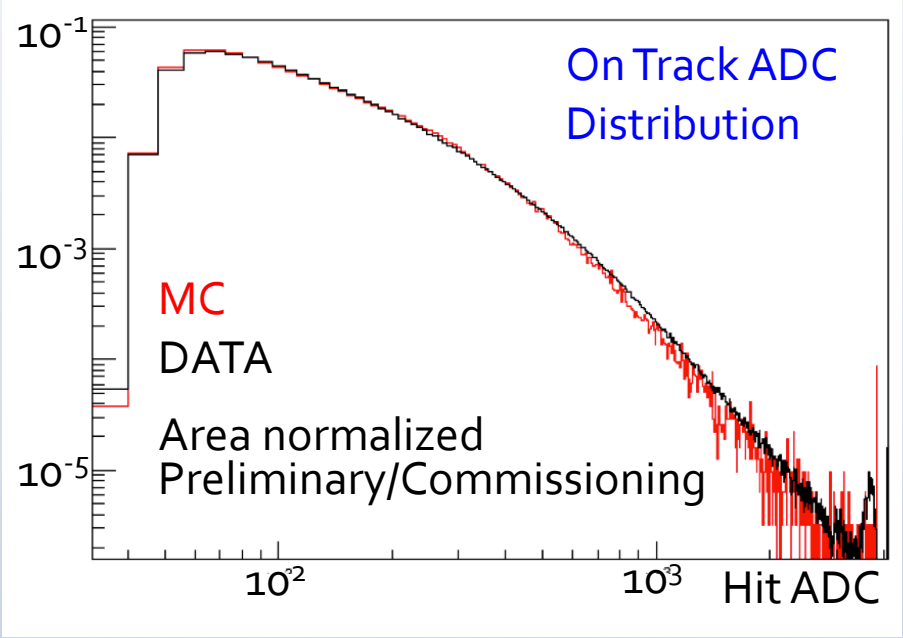
Studies with the FD are ongoing.

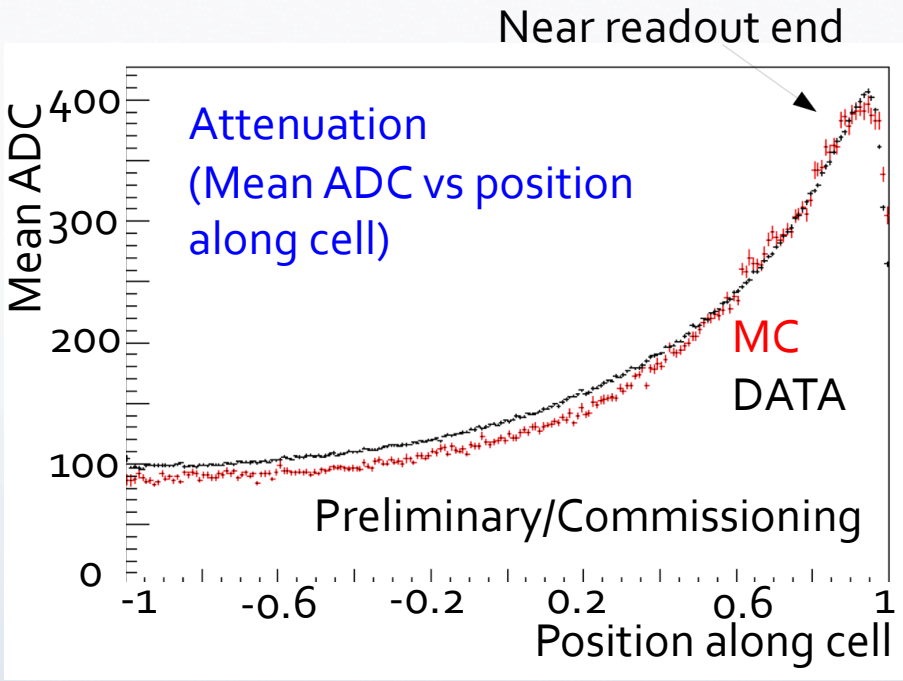
Detector Commisioning



Calibration

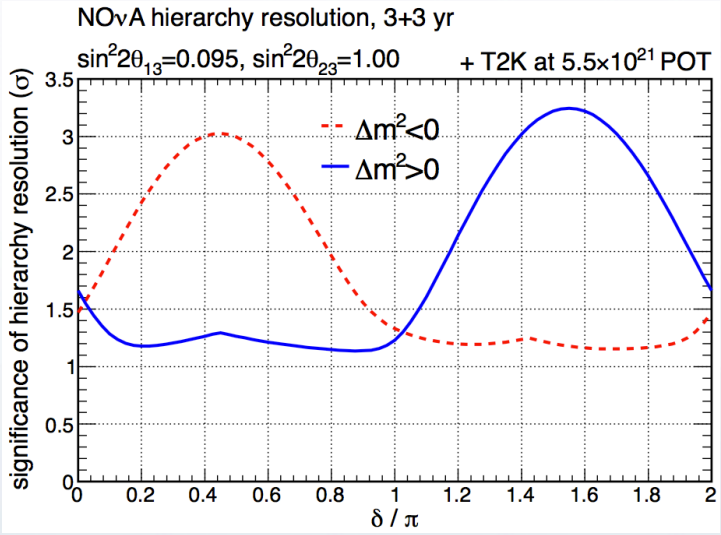
- We are making initial comparisons with our simulation and beginning to tune Monte Carlo.
- These two plots show a very early but promising comparison of attenuation effects and ADC distribution.

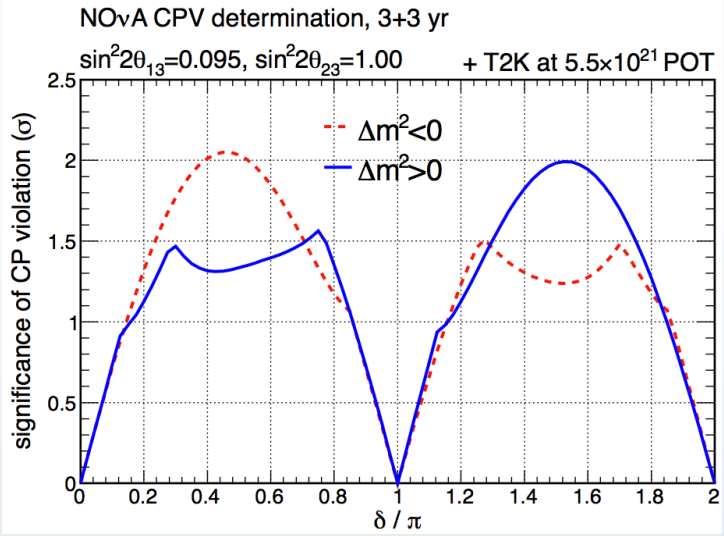


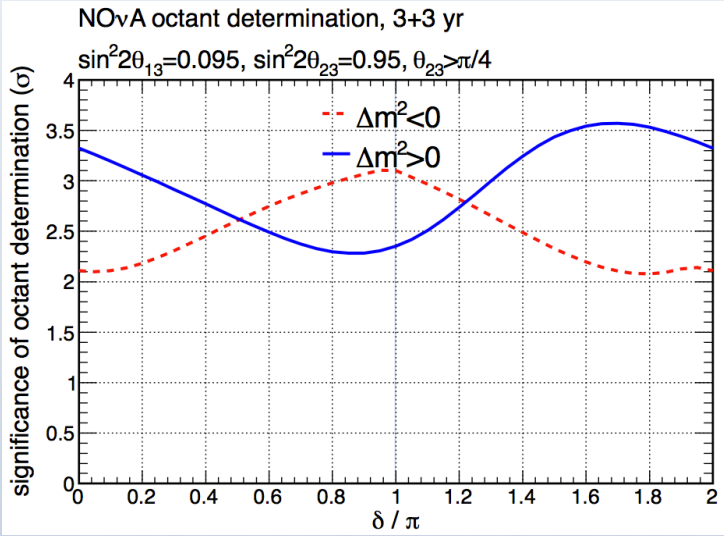


- Position along cell: 1 is near readout end.
- Data from the first 2 kTons, for 24 hr run
- First attempt to tune noise, ADC to PE, and deal with bad channels.
- Focus of analysis effort currently, improvements are coming daily.

Physics Reach







Sensitivities assume

- $\sin^2 2\theta_{13}$=0.095
- 3 years neutrino + 3 years anti-neutrinos running
- Optimization for ~4% oscillation probability
- 10% uncertainty on backgrounds

Conclusion

- NOvA Far Detector construction is rapidly approaching completion.
- Commissioning of outfitted portions of the detector is underway.
- NuMI is running well and further upgrades are progressing
- Near Detector installation is in progress.
- We are excited to soon add to the world knowledge on mass hierarchy, δ_{CP}, and θ_{23}, along with our extended physics programs.

@NOvANuz

Become a fan at
facebook.com/novaexperiment

BACKUPS

Example measurement

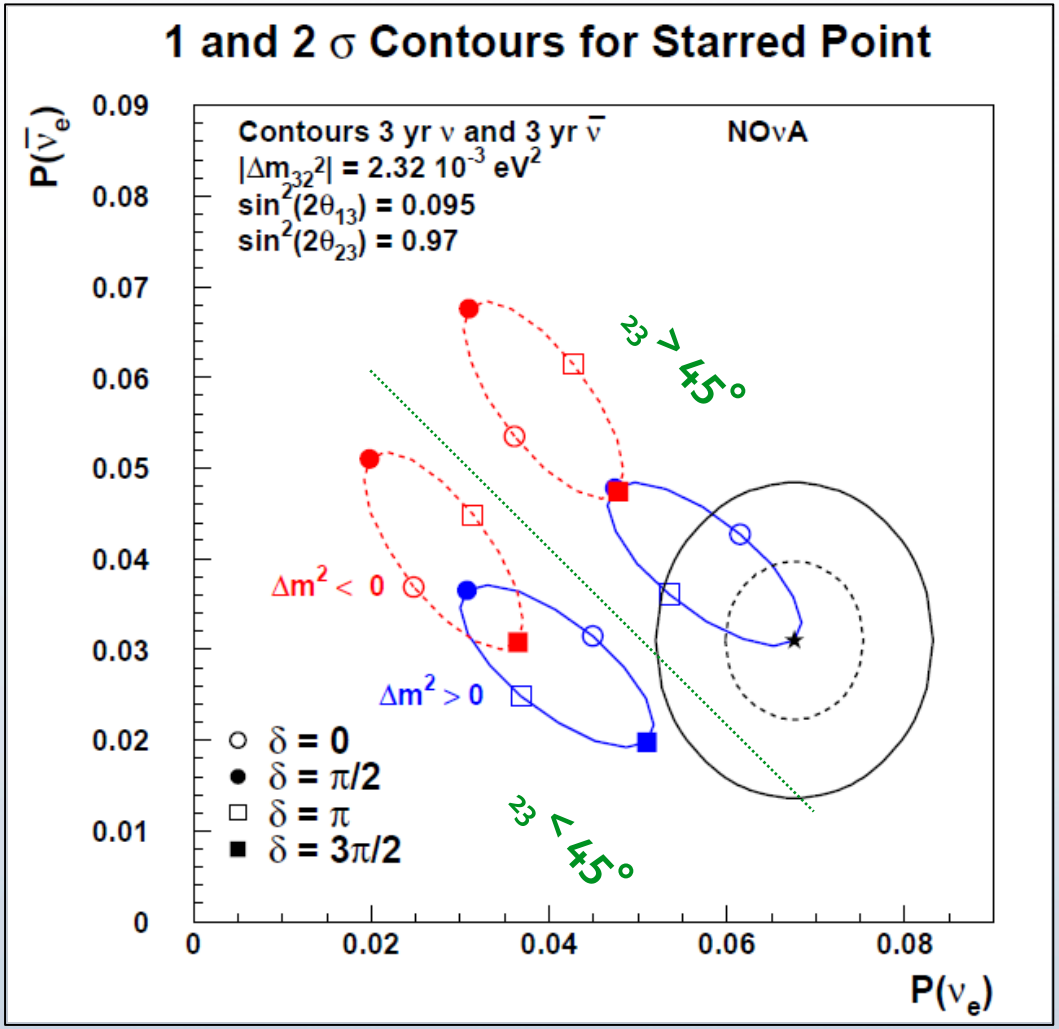
NOvA will measure:

$P(\nu_\mu \rightarrow \nu_e)$ **at 2 GeV**

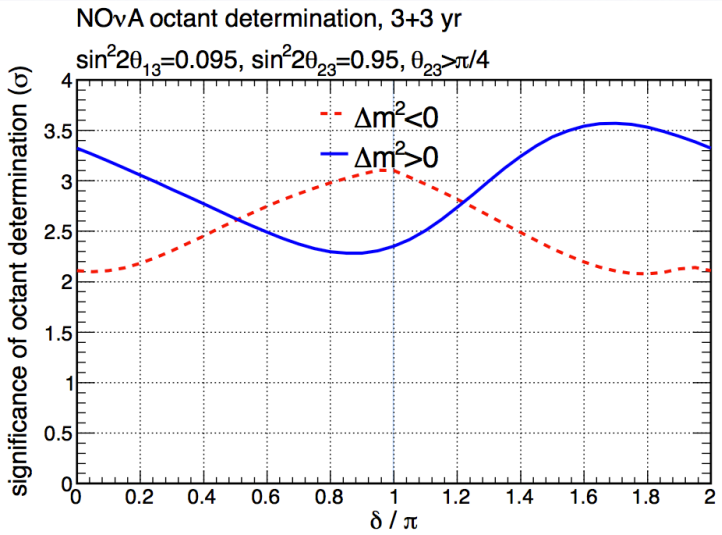
and

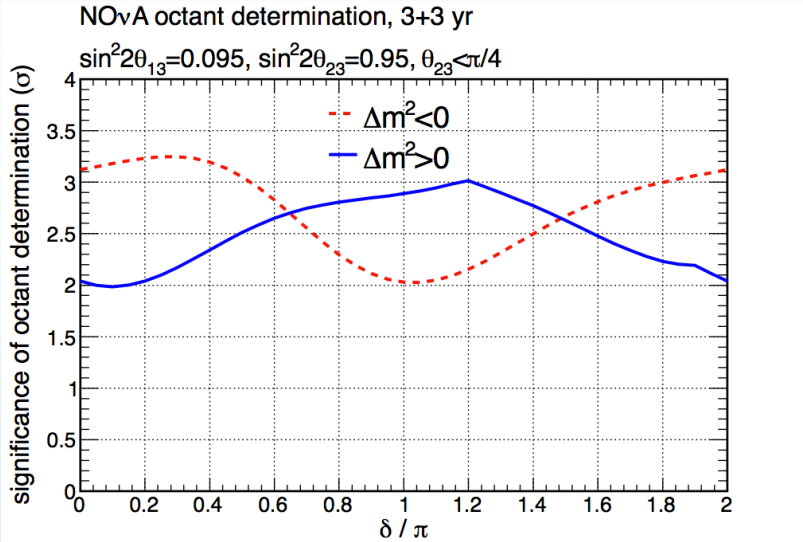
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ **at 2 GeV**

- Starred point is a example NOvA measurement with 1- and 2-sigma contours.
- Depends on CP phase δ, sign(Δm^2) , and $\sin^2(\theta_{23})$.
- Red and blue ellipses show expected oscillation probabilities for choices of these parameters
- Simultaneous information on all three parameters

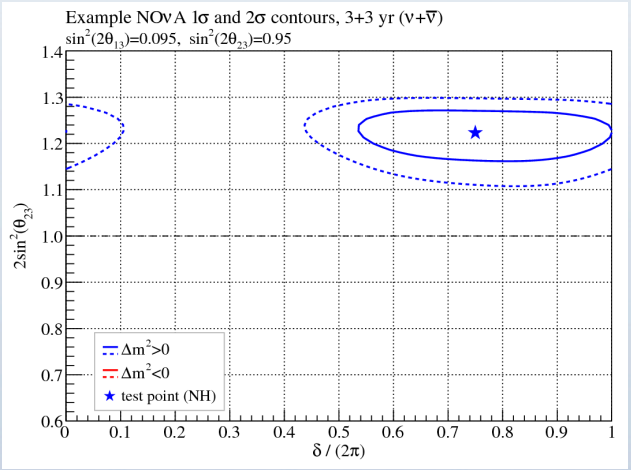


θ_{23} octant sensitivity



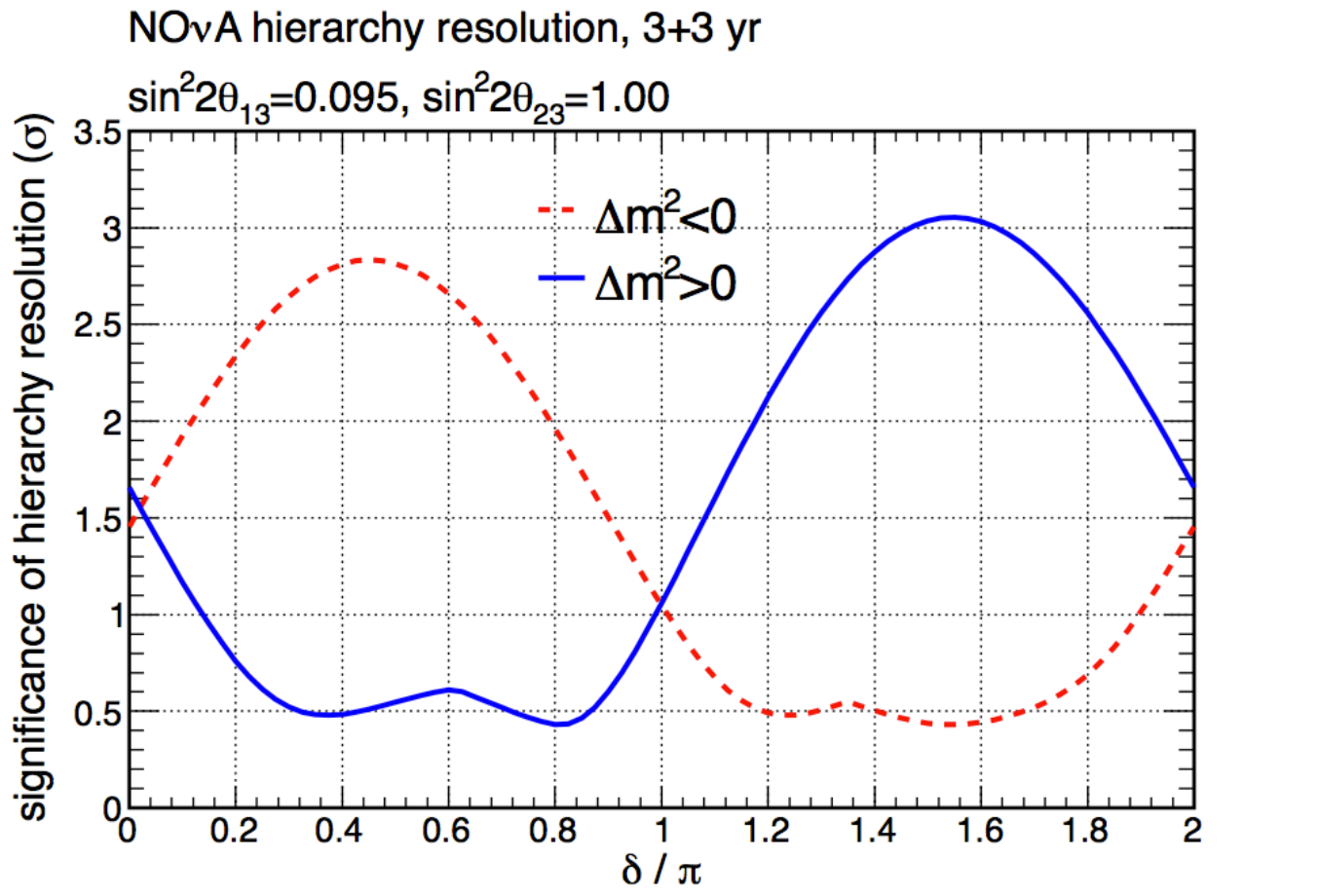


The contours are 2D confidence intervals, representing our sensitivity to a joint measurement of $2\sin^2(\theta_{23})$ and delta



Mass ordering sensitivity

Significance with which NOvA can establish the mass ordering



Example measurement

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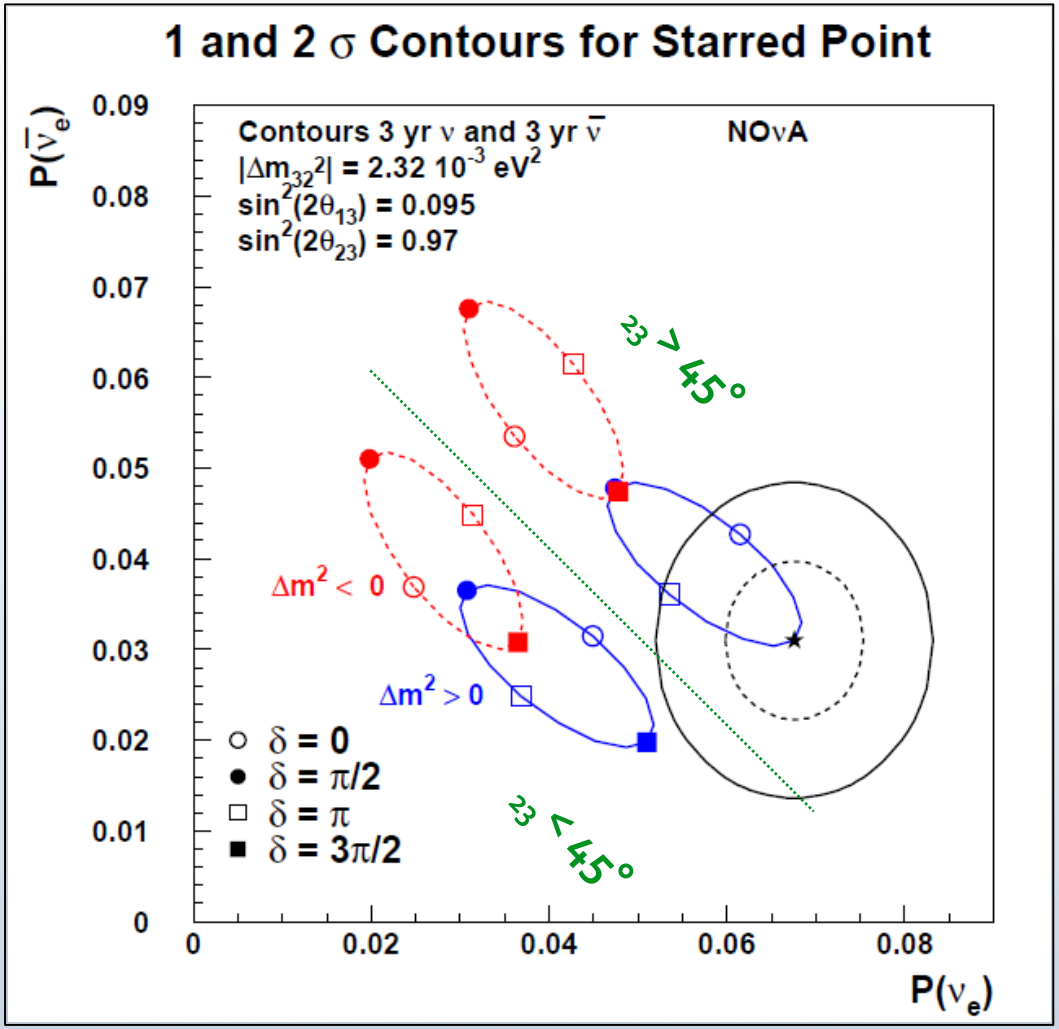
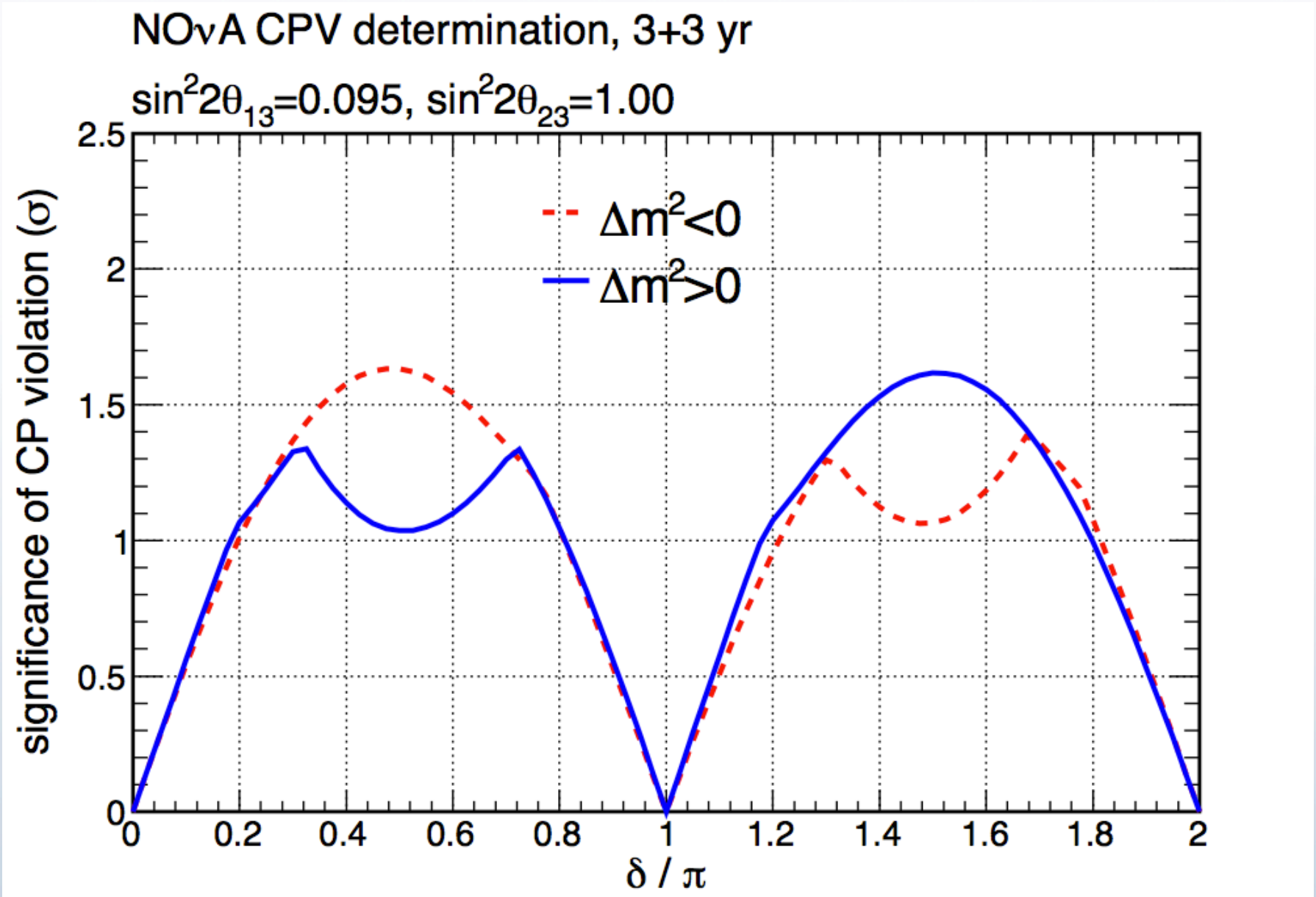
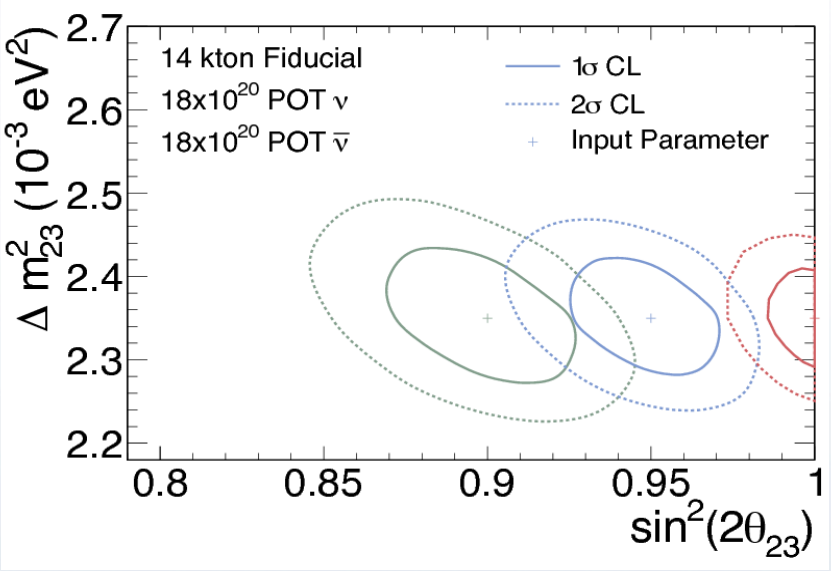
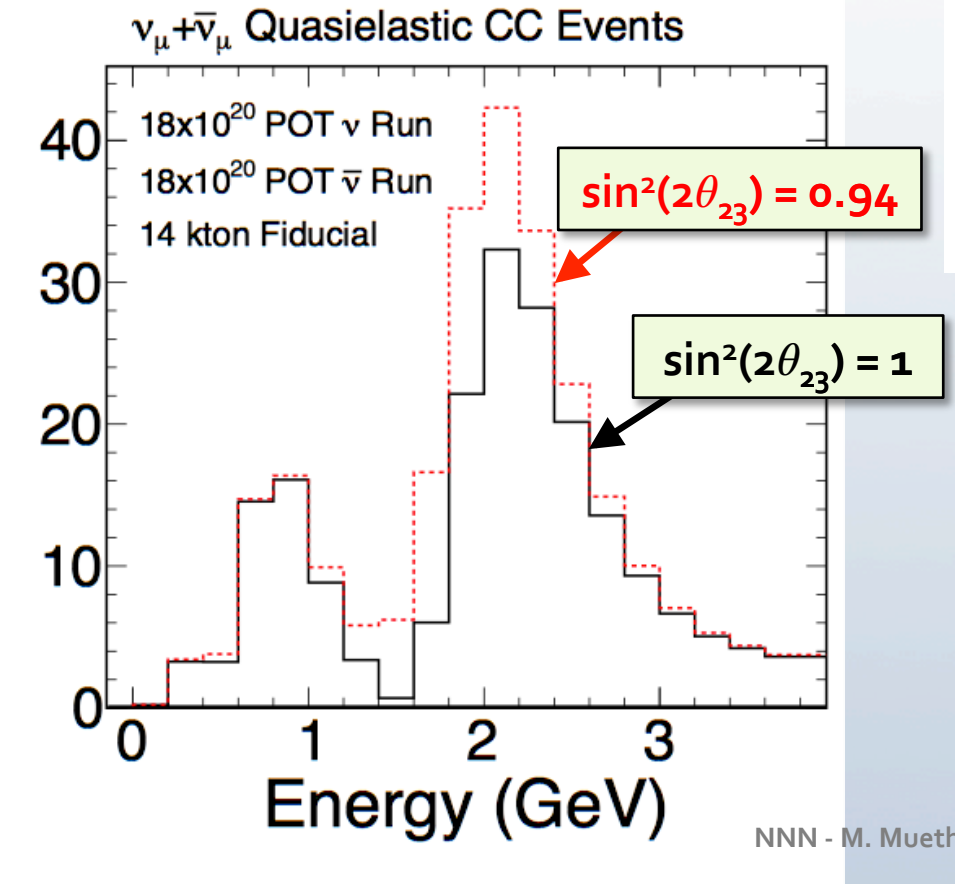



NOνA CPV determination, 3+3 yr
sin²2θ13=0.095, sin²2θ23=1.00
Δm²<0
Δm²>0
significance of CP violation (σ)
δ / π
0
0.5
1
1.5
2
2.5
0.2
0.4
0.6
0.8
1.2
1.4
1.6
1.8

Backup

Example NOνA contours for three test points →

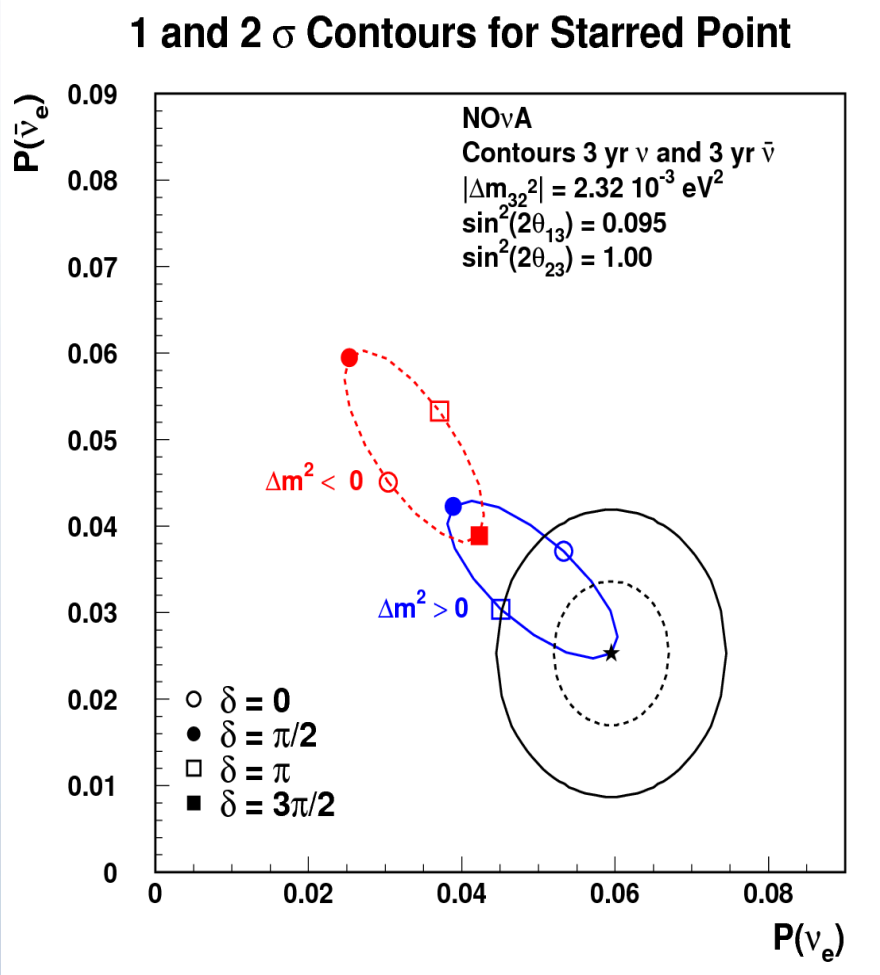




4% energy resolution for the QE sample.

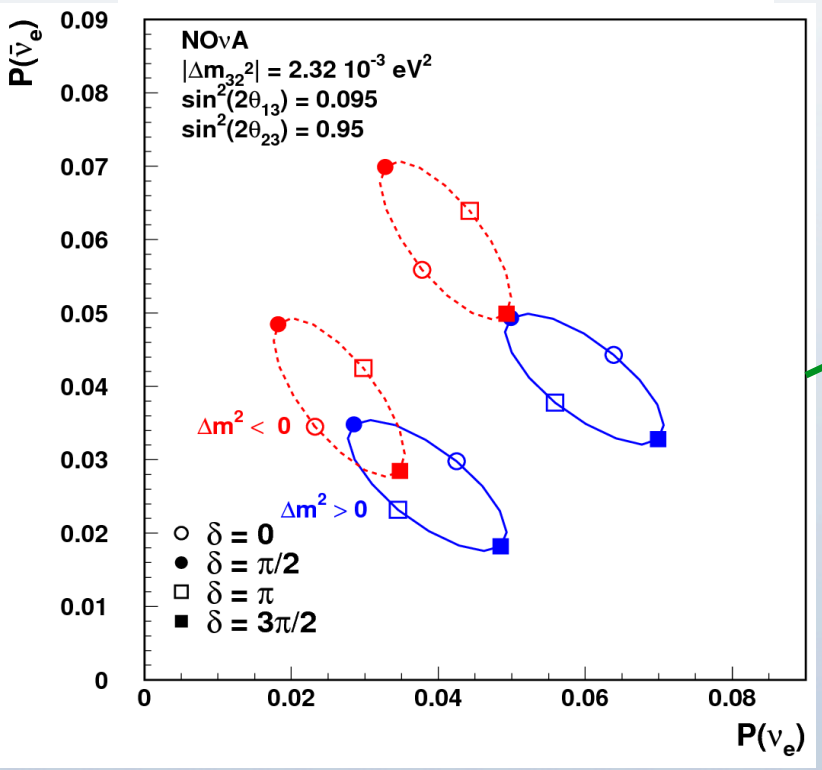
Inclusive ν_μ CC sample should be background-free

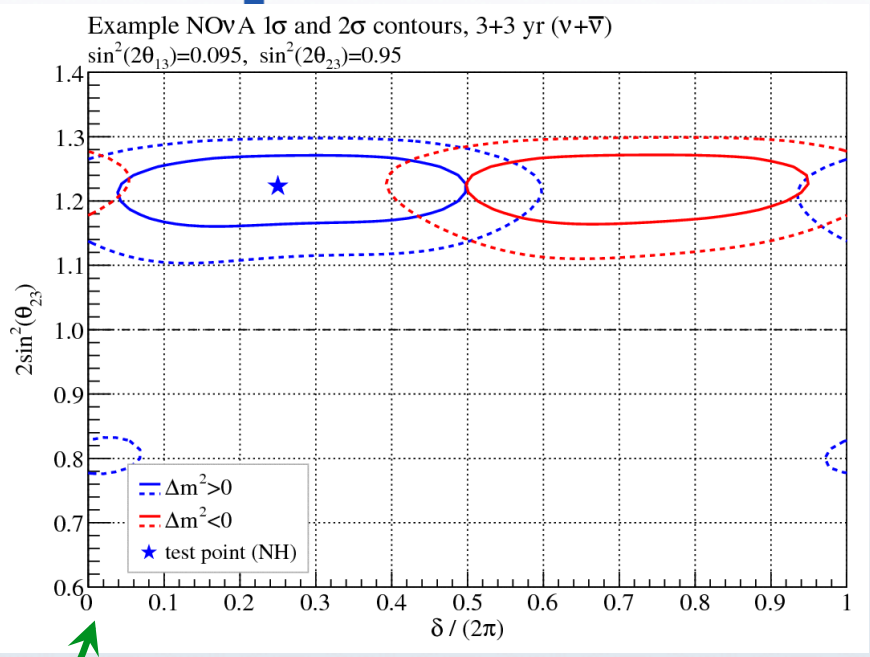
Backup


1 and 2 σ Contours for Starred Point
NOνA
Contours 3 yr ν and 3 yr ν̄
|Δm32²| = 2.32 10⁻³ eV²
sin²(2θ13) = 0.095
sin²(2θ23) = 1.00
Δm² < 0
Δm² > 0
δ = 0
δ = π/2
δ = π
δ = 3π/2
P(ν̄e)
P(νe)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0
0.02
0.04
0.06
0.08

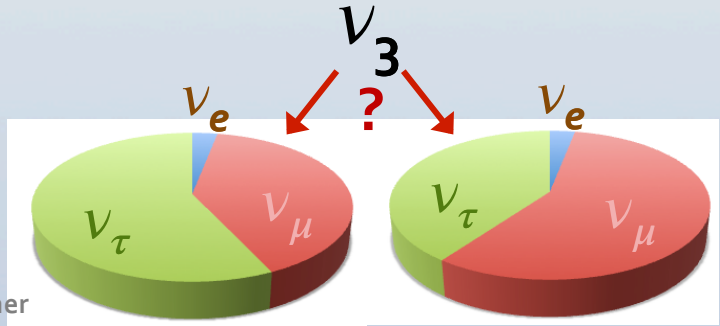
Backup

Expected NOνA contours for one example scenario at 3 yr + 3 yr





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



Backup

- NOvA measures $P(\nu_\mu \to \nu_e)$ and $P(\bar{\mu}_\nu \to \bar{\nu}_e)$ over an 810 km baseline at a central energy of 2GeV.

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1^2)}$$

$$\overset{(+)}{-} 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin\Delta$$

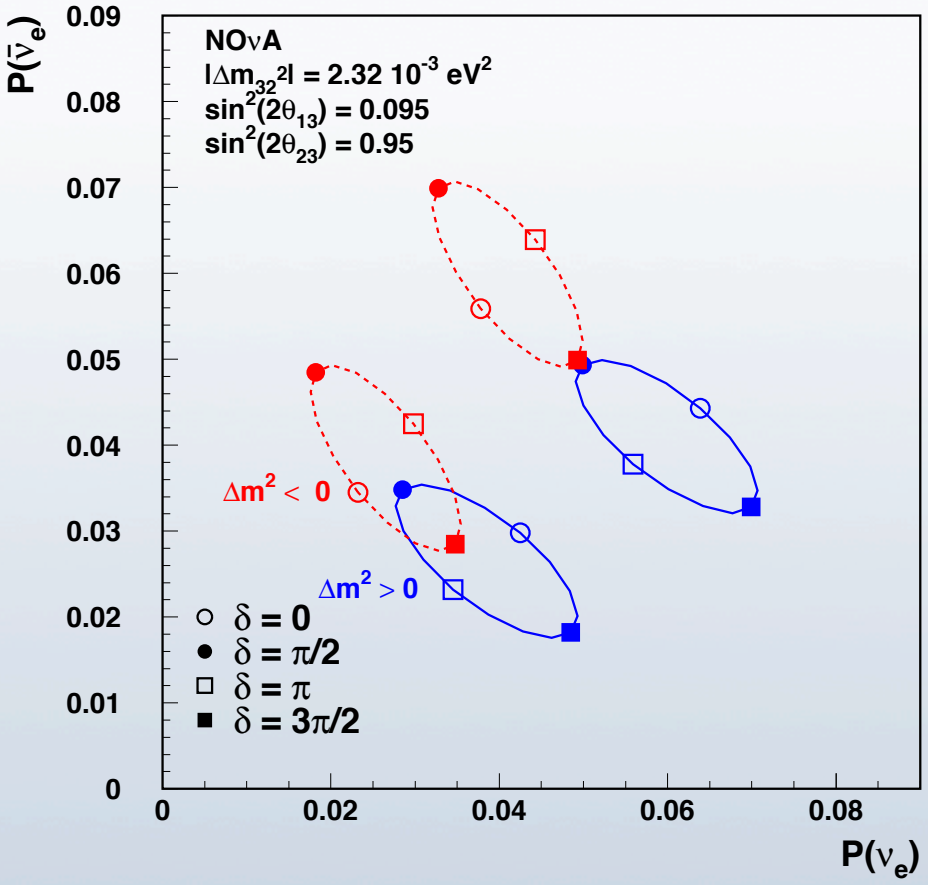
$$+ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \cos\Delta$$

$$\text{Where: } \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \quad \Delta = \Delta m^2_{31} \frac{L}{4E} \quad A = \overset{(-)}{+} G_f N_e \frac{L}{\sqrt{2}\Delta}$$

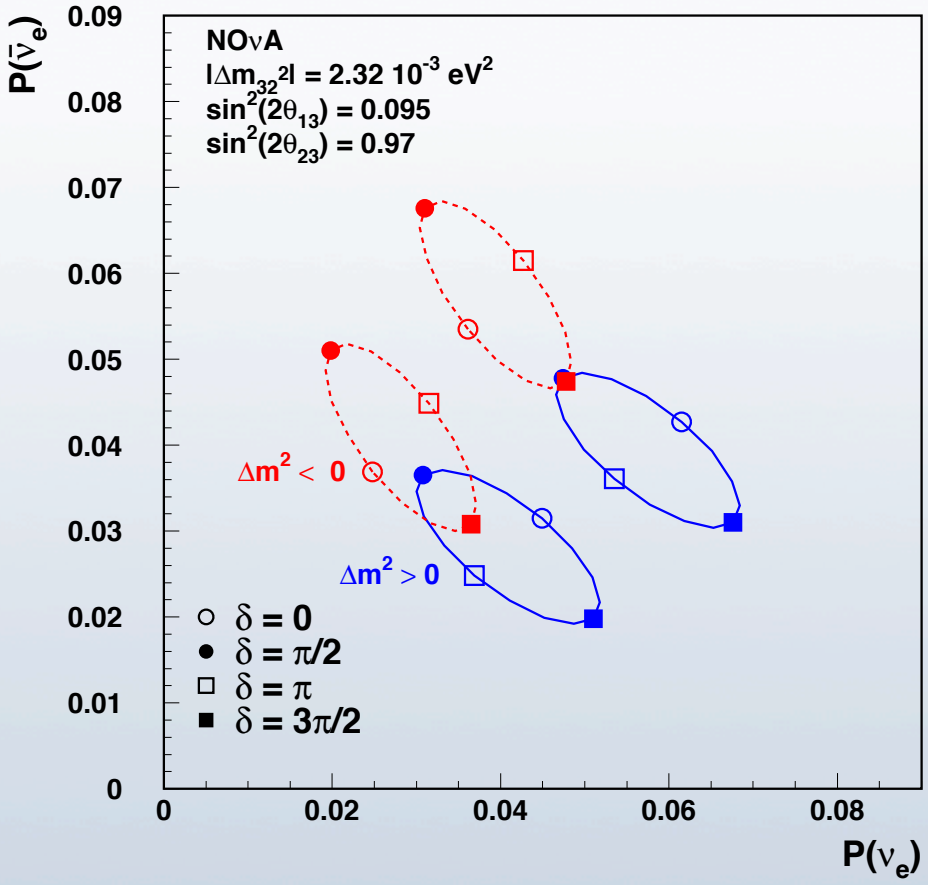
- The transition probability is dependent on θ_{13}, θ_{23}, δ_{CP} and Δm_{31}
- The reactor measurements do not have the these dependencies

Backup

$P(\bar{\nu}_e)$ vs. $P(\nu_e)$ for $\sin^2(2\theta_{23}) = 0.95$

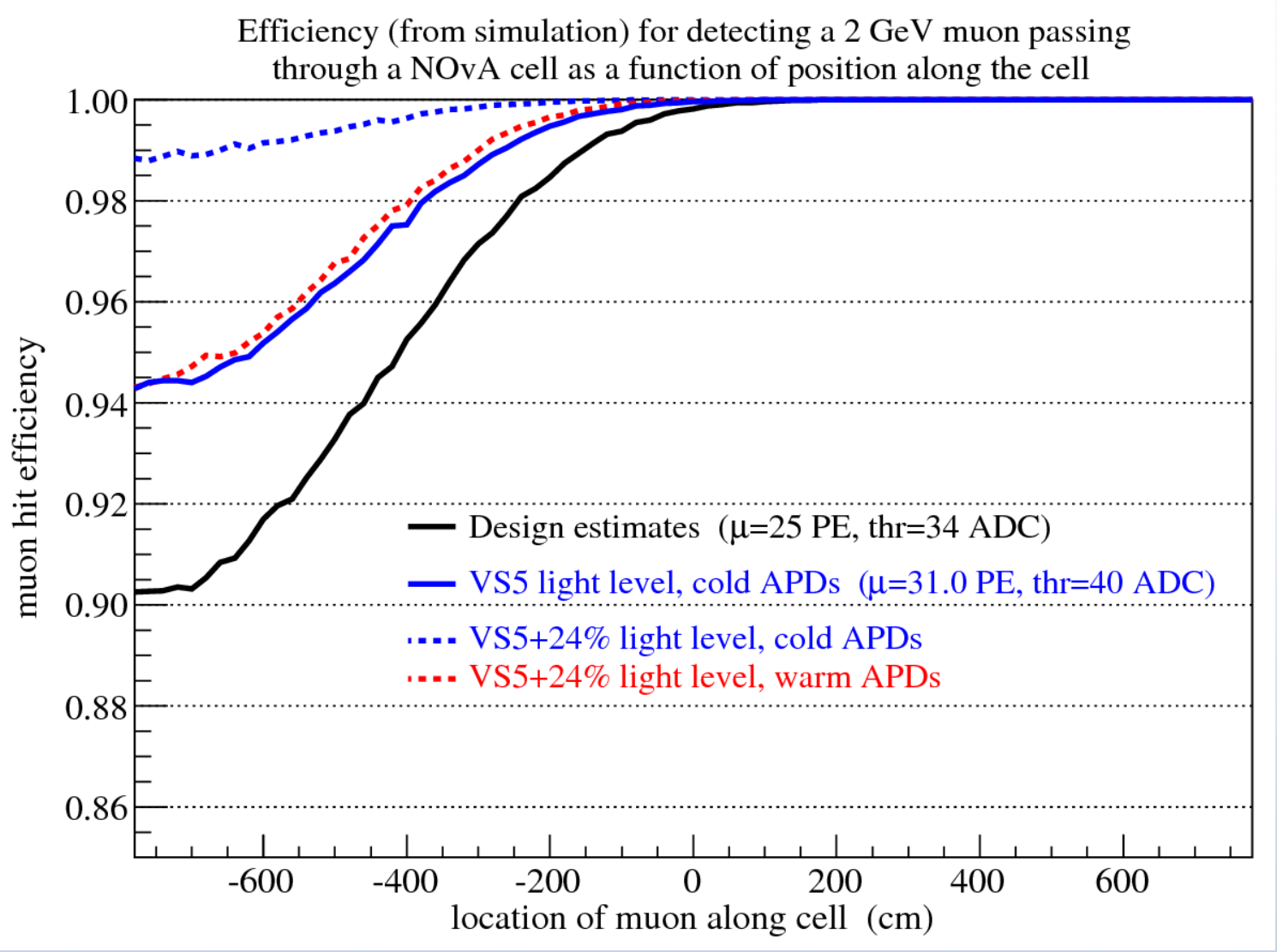


$P(\bar{\nu}_e)$ vs. $P(\nu_e)$ for $\sin^2(2\theta_{23}) = 0.97$

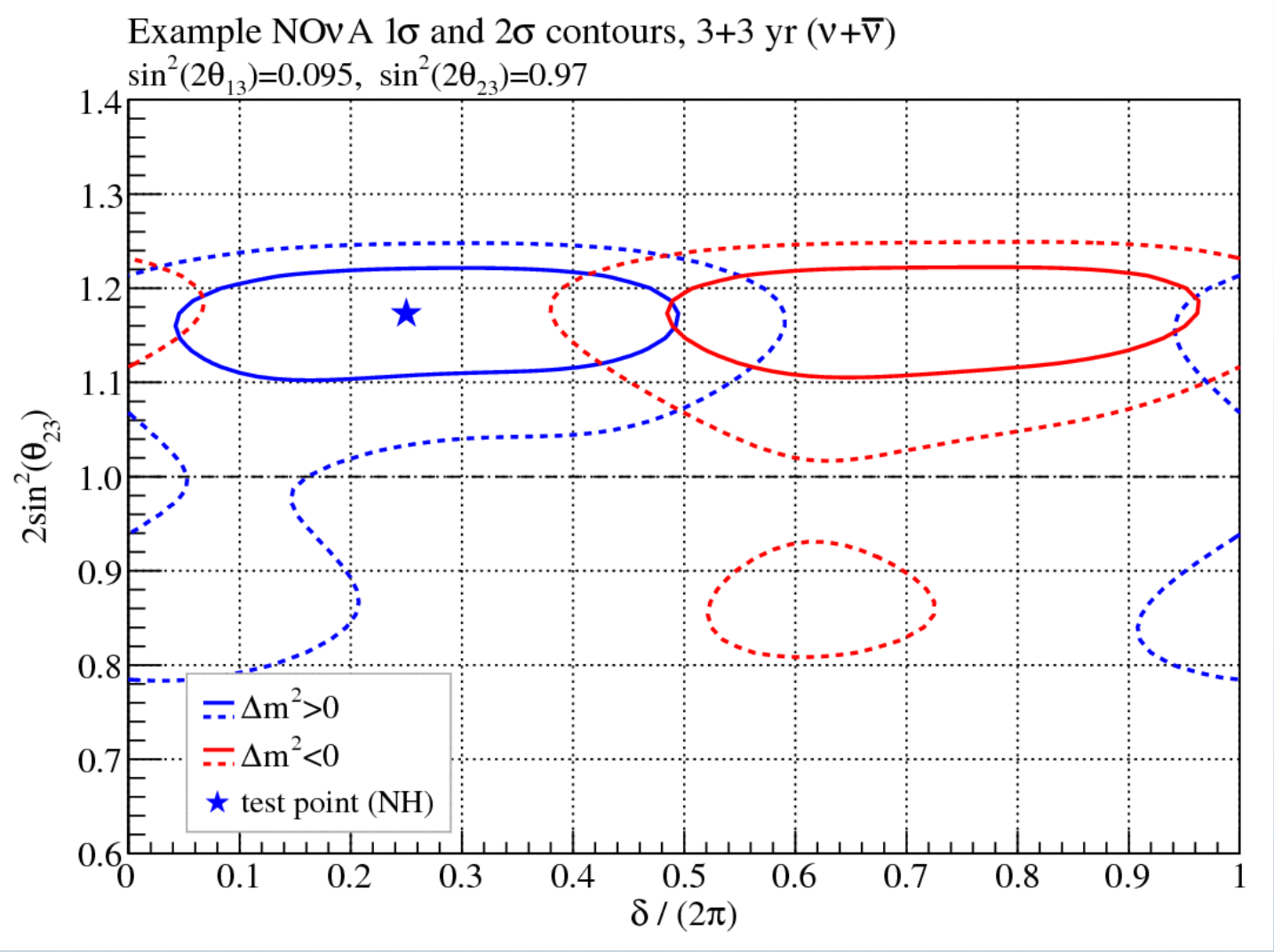


Backup

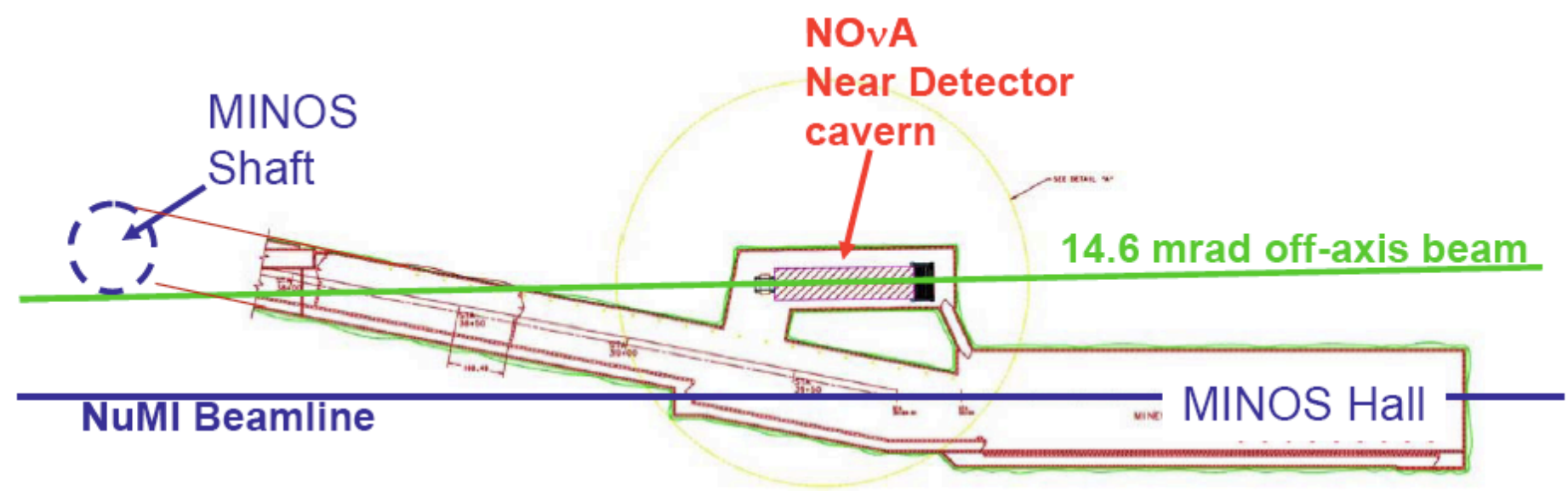
Backup


Efficiency (from simulation) for detecting a 2 GeV muon passing through a NOvA cell as a function of position along the cell
muon hit efficiency
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
-600
-400
-200
0
200
400
600
location of muon along cell (cm)
Design estimates (μ=25 PE, thr=34 ADC)
VS5 light level, cold APDs (μ=31.0 PE, thr=40 ADC)
VS5+24% light level, cold APDs
VS5+24% light level, warm APDs

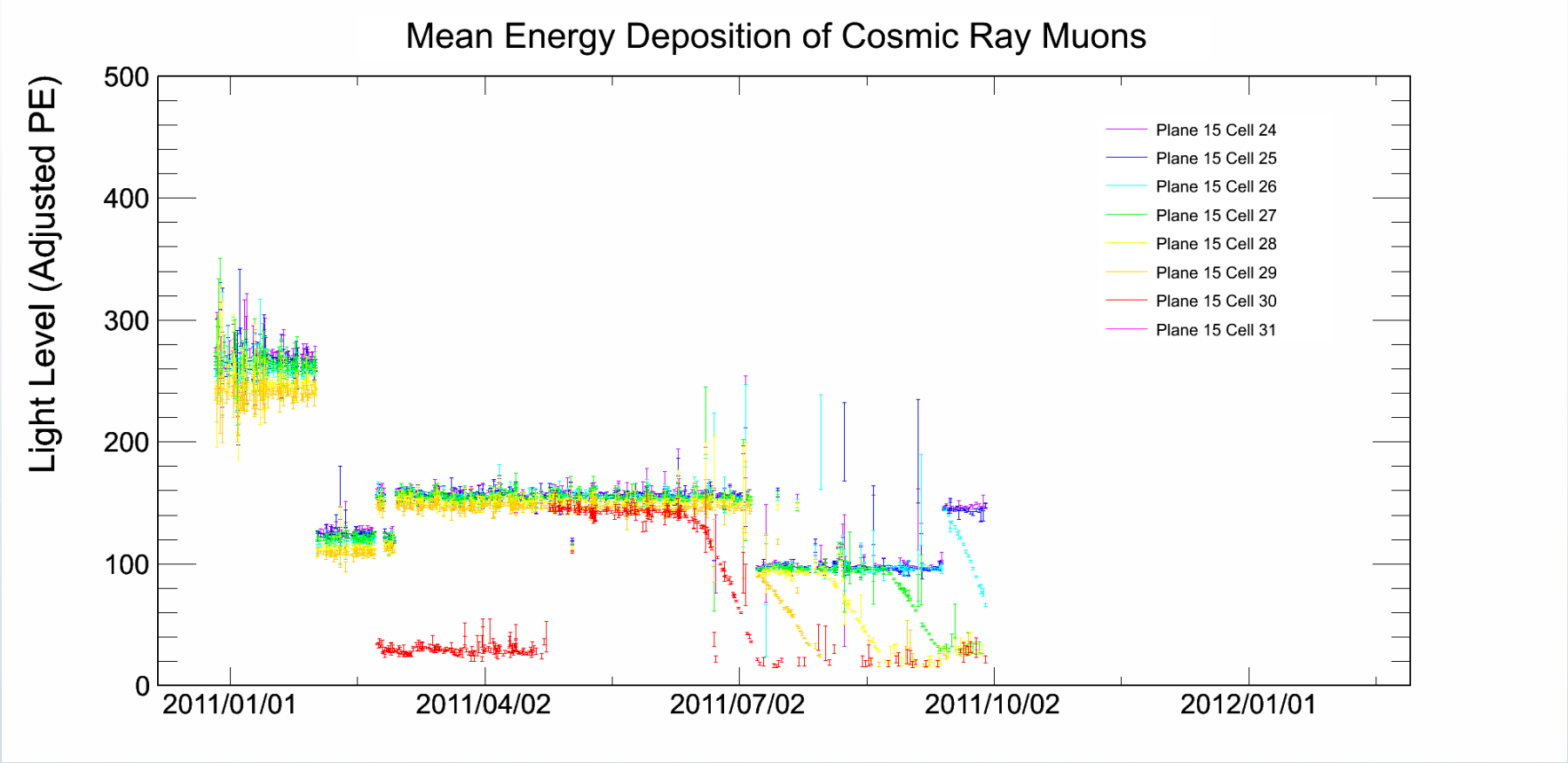
Backup


Example NOνA 1σ and 2σ contours, 3+3 yr (ν+ν̄)
sin²(2θ13)=0.095, sin²(2θ23)=0.97
2sin²(θ23)
δ / (2π)
Δm²>0
Δm²<0
test point (NH)

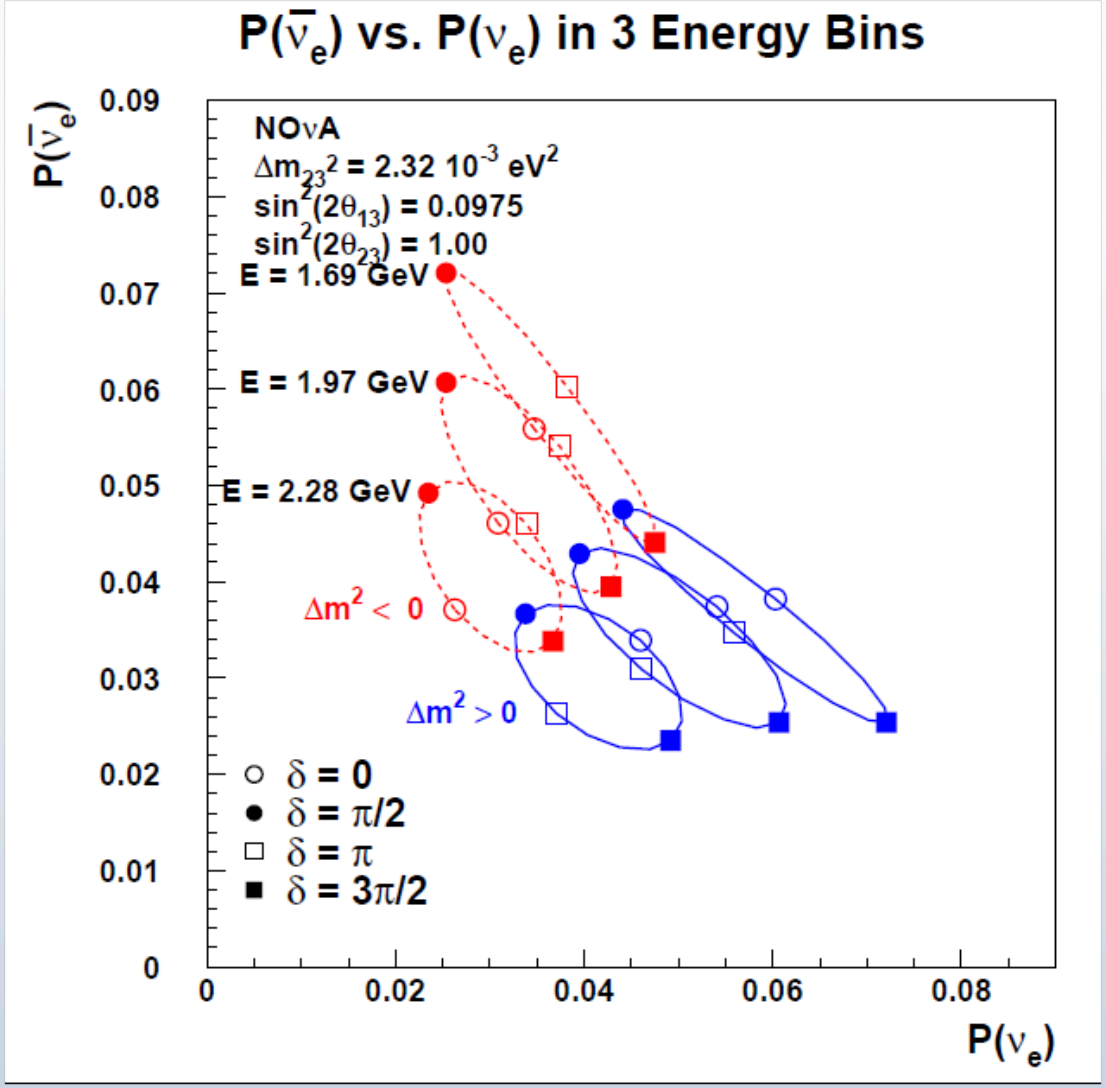
Backup


NOνA
Near Detector
cavern
MINOS
Shaft
14.6 mrad off-axis beam
NuMI Beamline
MINOS Hall

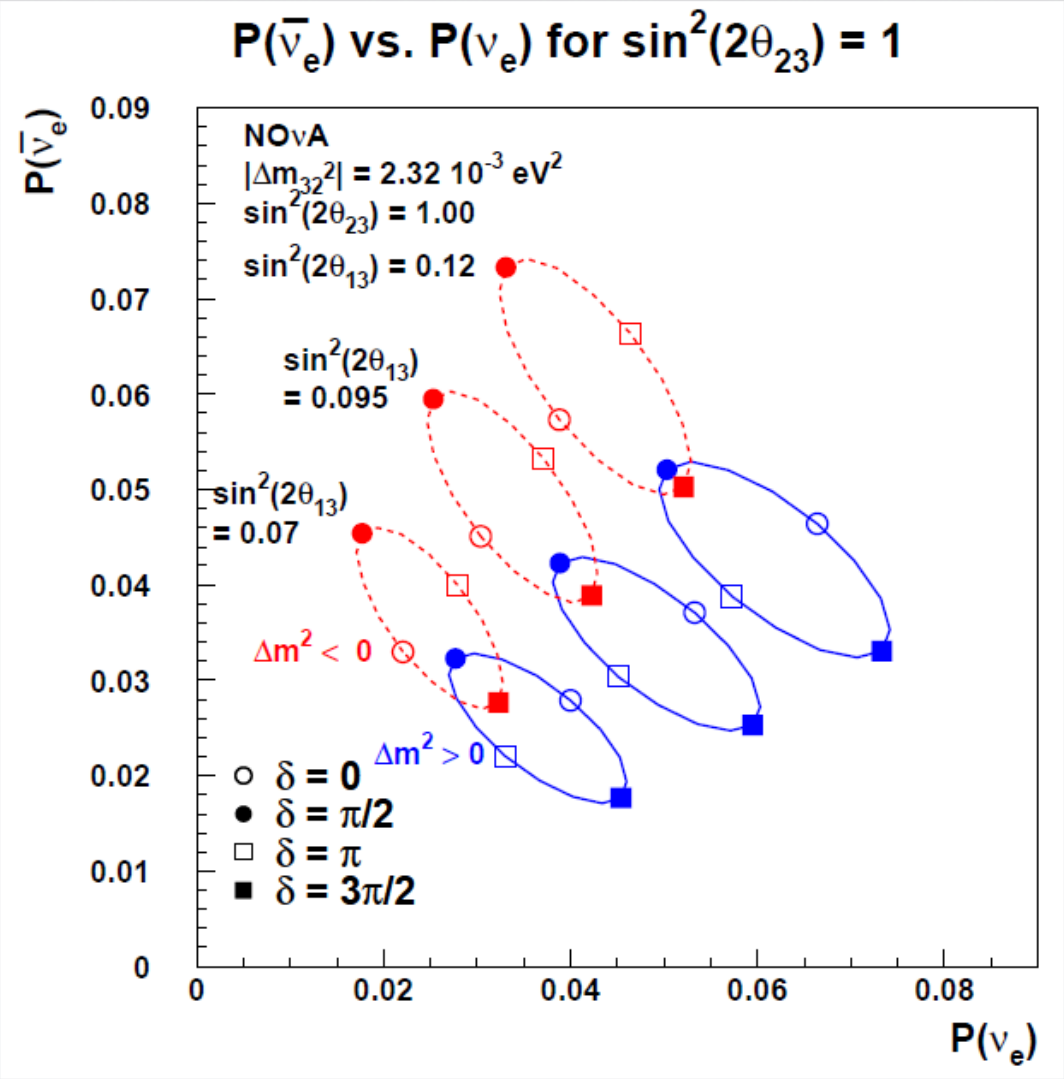
Backup


Mean Energy Deposition of Cosmic Ray Muons
Light Level (Adjusted PE)
500
400
300
200
100
0
2011/01/01
2011/04/02
2011/07/02
2011/10/02
2012/01/01
Plane 15 Cell 24
Plane 15 Cell 25
Plane 15 Cell 26
Plane 15 Cell 27
Plane 15 Cell 28
Plane 15 Cell 29
Plane 15 Cell 30
Plane 15 Cell 31

Backup


P($\bar{\nu}_e$) vs. P(ν_e) in 3 Energy Bins
NOνA
$\Delta m_{23}^2 = 2.32\ 10^{-3}\ eV^2$
$\sin^2(2\theta_{13}) = 0.0975$
$\sin^2(2\theta_{23}) = 1.00$
E = 1.69 GeV
E = 1.97 GeV
E = 2.28 GeV
$\Delta m^2 < 0$
$\Delta m^2 > 0$
δ = 0
δ = π/2
δ = π
δ = 3π/2
P($\bar{\nu}_e$)
P(ν_e)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.02
0.04
0.06
0.08

Backup


P(ν̄e) vs. P(νe) for sin²(2θ23) = 1
NOνA
|Δm32²| = 2.32 10⁻³ eV²
sin²(2θ23) = 1.00
sin²(2θ13) = 0.12
sin²(2θ13) = 0.095
sin²(2θ13) = 0.07
Δm² < 0
Δm² > 0
δ = 0
δ = π/2
δ = π
δ = 3π/2
P(ν̄e)
P(νe)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.02
0.04
0.06
0.08

System Prototype

- Prototype Near Detector on the Surface (NDOS) constructed in a mock far detector environment.
- Collecting cosmic and neutrino data since October 2010

- Invaluable in understanding production, installation, integration, and operations.

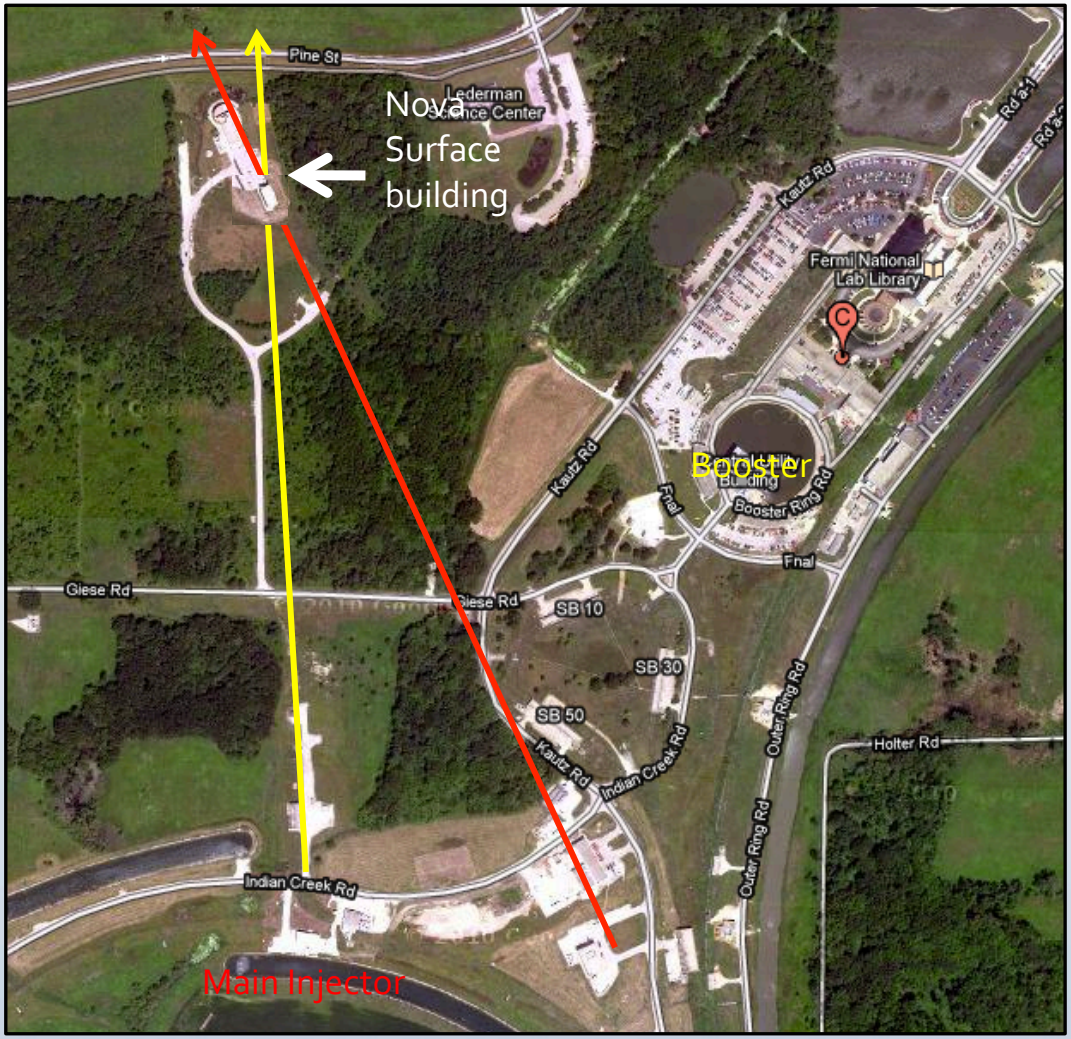
Location of Prototype

110 mrad off NuMI axis due to surface position

500 μs wide trigger window @ 0.4 Hz

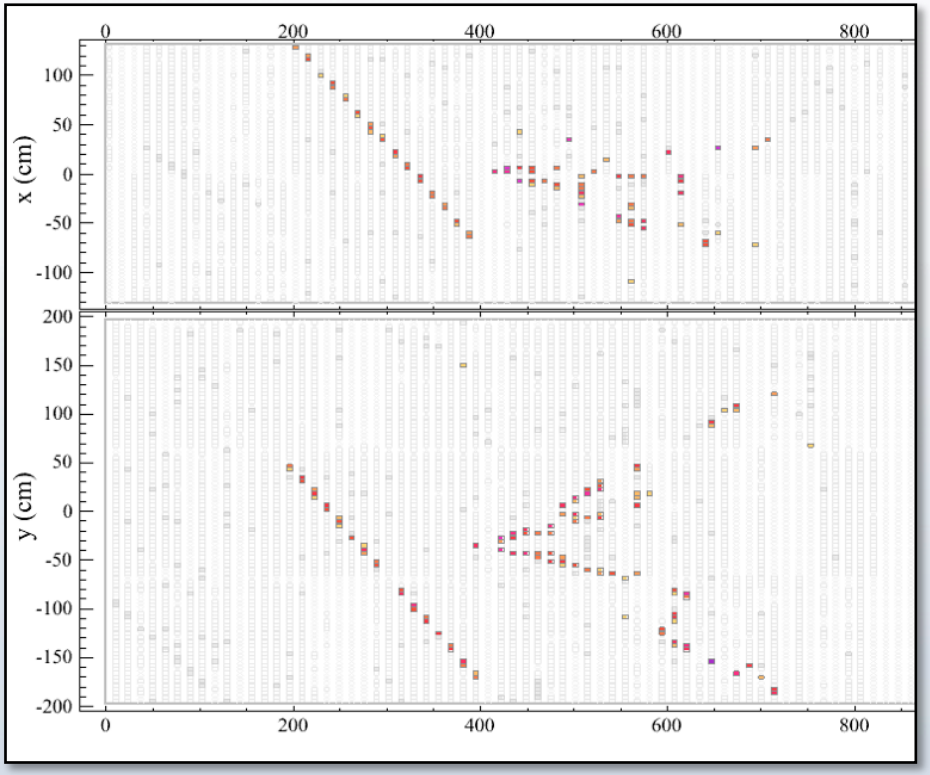
On-axis for booster (but rotated)

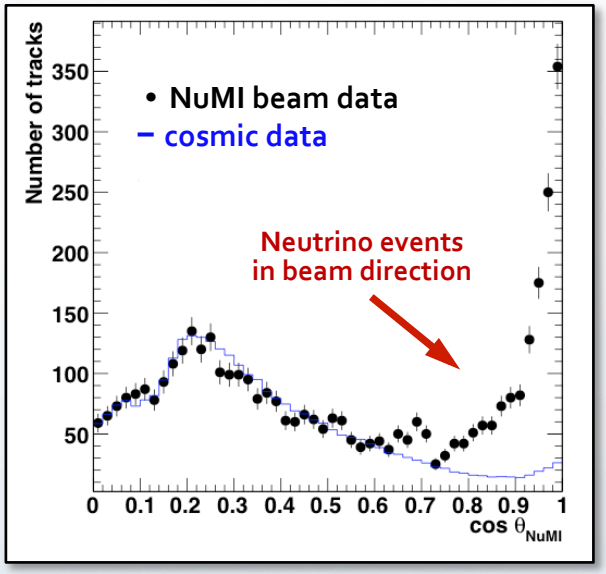
500 μs wide trigger window @ 1.2 Hz

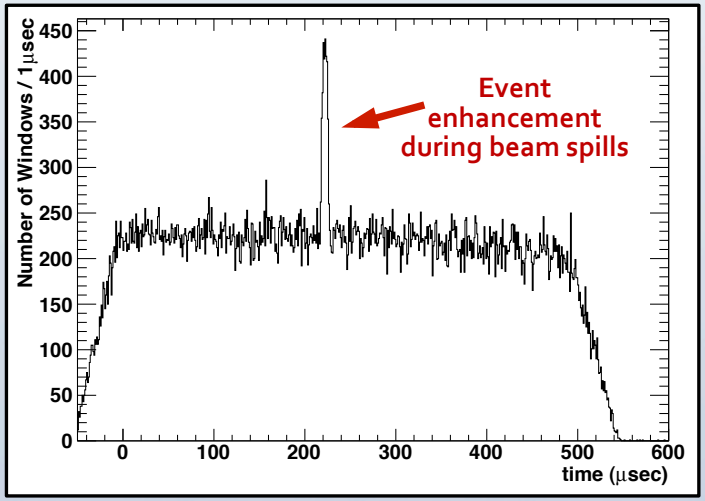


Prototype Events

NuMI neutrino interactions

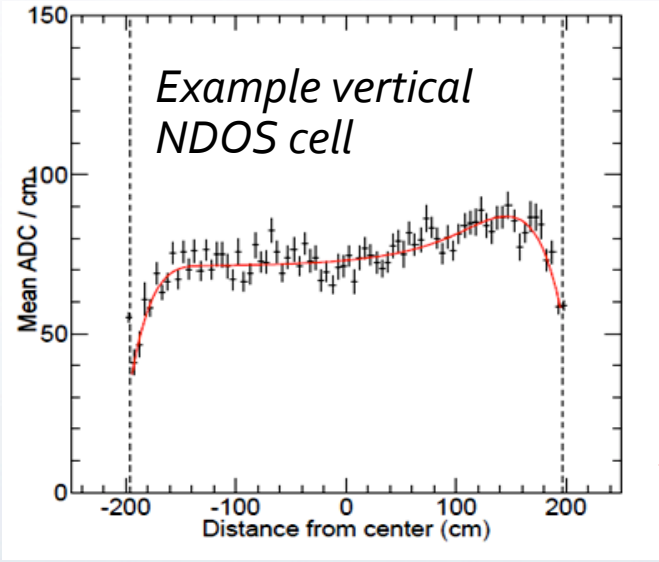






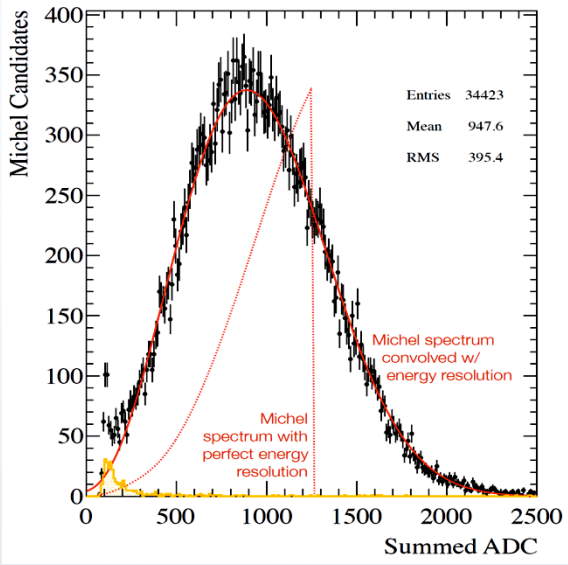
Similar distributions seen for the booster beam with lower efficiency

NDOS Calibration

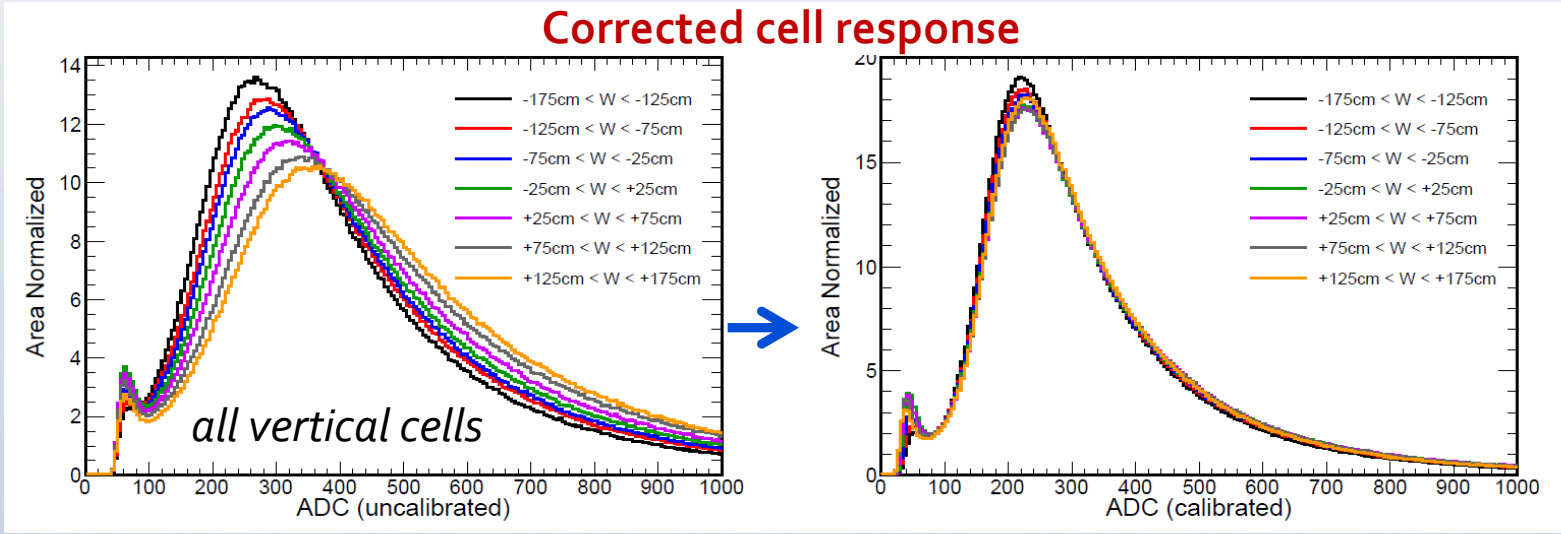


Michel electrons (energy calibration)

Position dependence of cell response (light attenuation, etc.)



Corrected cell response



NDOS Neutrinos

NuMI neutrino events at NDOS

- **Two example distributions:** *angle of primary track w.r.t. the neutrino beam*, **and** *total visible energy [in photoelectrons]*
- **Our Monte Carlo simulation agrees well with observations**