The NOνA Experiment

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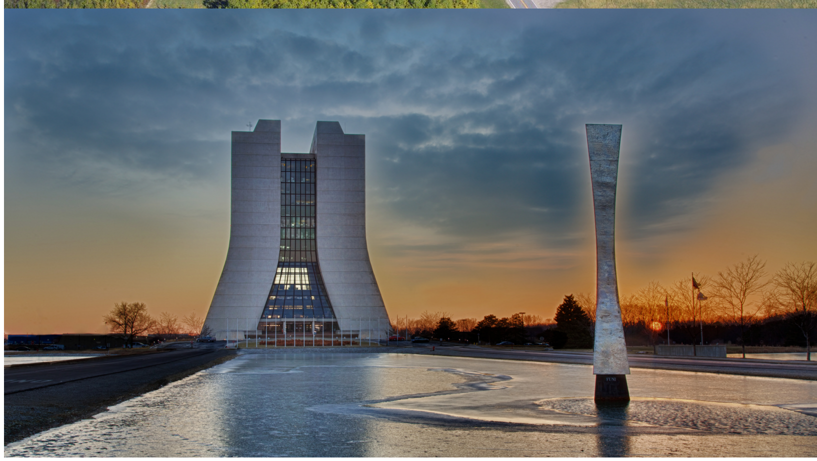
NOνA Collaboration

36 Institutions from 7 countries
181 collaborators

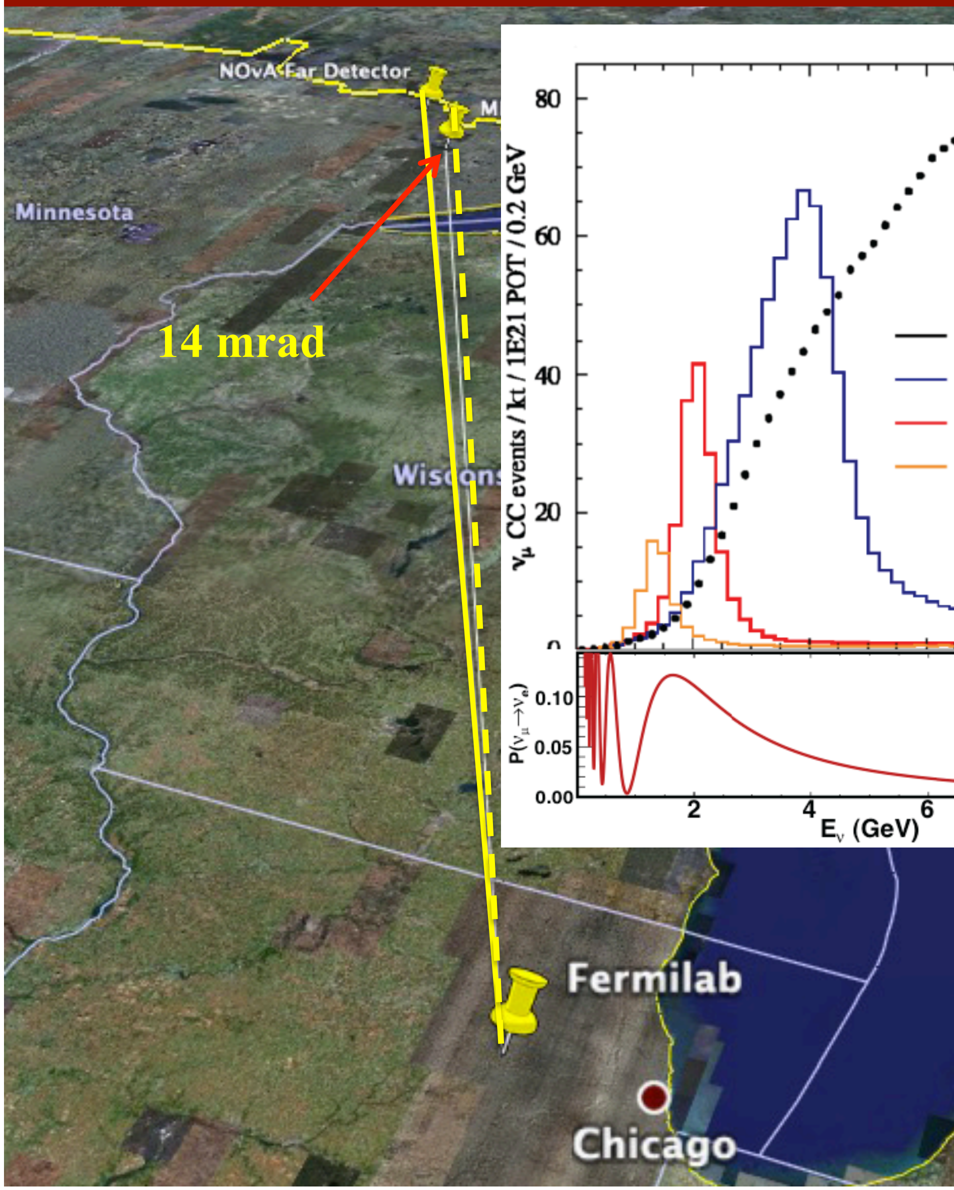
- Argonne National Laboratory·University of Athens·Banaras Hindu University·California Institute of Technology·Institute of Physics of the Academy of Sciences of the Czech Republic·Charles University, Prague·University of Cincinnati·Czech Technical University·University of Delhi·Fermilab·Federal Univ. of Goias · IndianInstitute 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·Winona State University·College of William and Mary

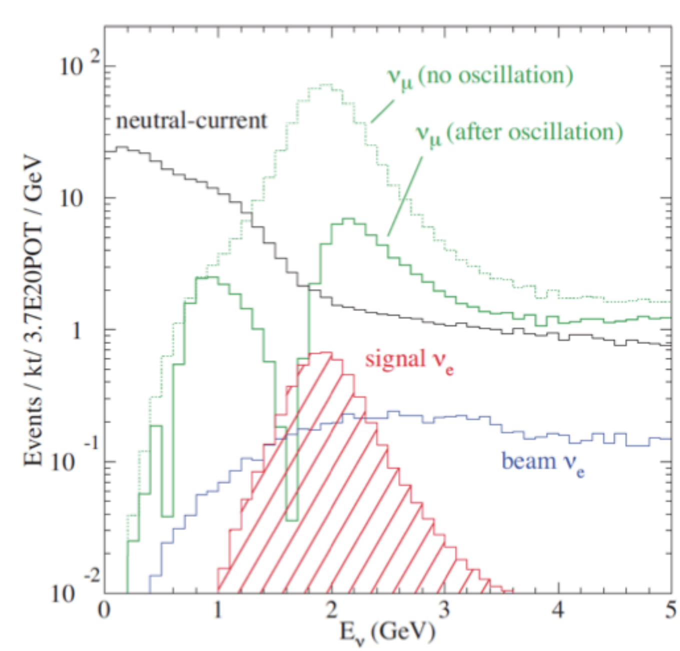
NuMI Off-Axis ν_e Appearance Experiment



- NOvA is a 2-detector ν oscillation experiment, optimized for ν_e identification.
- Upgrading NuMI muon neutrino beam at Fermilab (700 kW).
- Construct a 14 kt liquid scintillator far detector at a distance of 810 km (Ash river, Minnesota) to detect the oscillated beam.
- Functionally identical ~300 ton near detector located at Fermilab to measure unoscillated beam ν to estimate backgrounds in the far detector.

NuMI Off-Axis ν_e Appearance Experiment





Far detector is sited 14 mrad off-axis to produce a narrow-band beam around the oscillation maximum region. Combining with final state interaction cross sections, provides an optimized signal/background separation.

NOvA Physics Goals

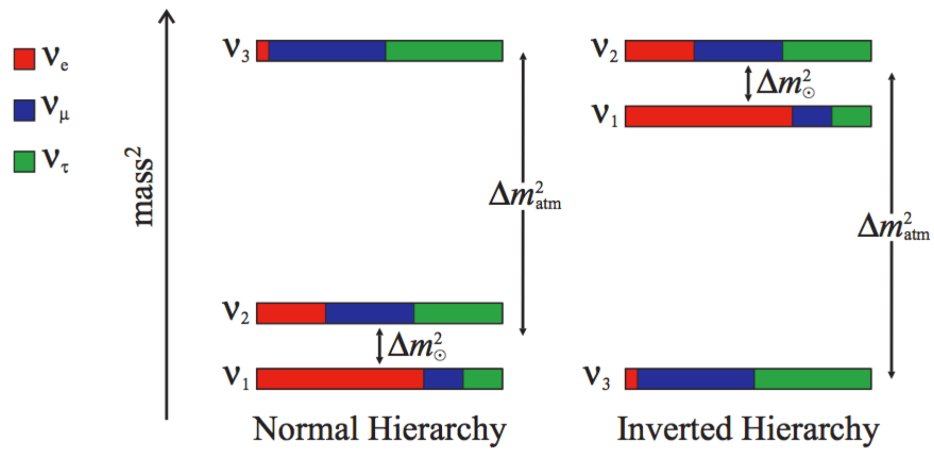
Measuring ν_e appearance probability and ν_μ disappearance probability with ν_u and anti-ν_u beam.

ν_e appearance:

- Measure θ_{13}
- Determine neutrino mass hierarchy
- Resolution of the θ_{23} octant.
- Constrain CP violation phase (δ_{CP})

ν_μ disappearance:

- Precise measurements of $|\Delta m_{32}{}^2|$, θ_{23}

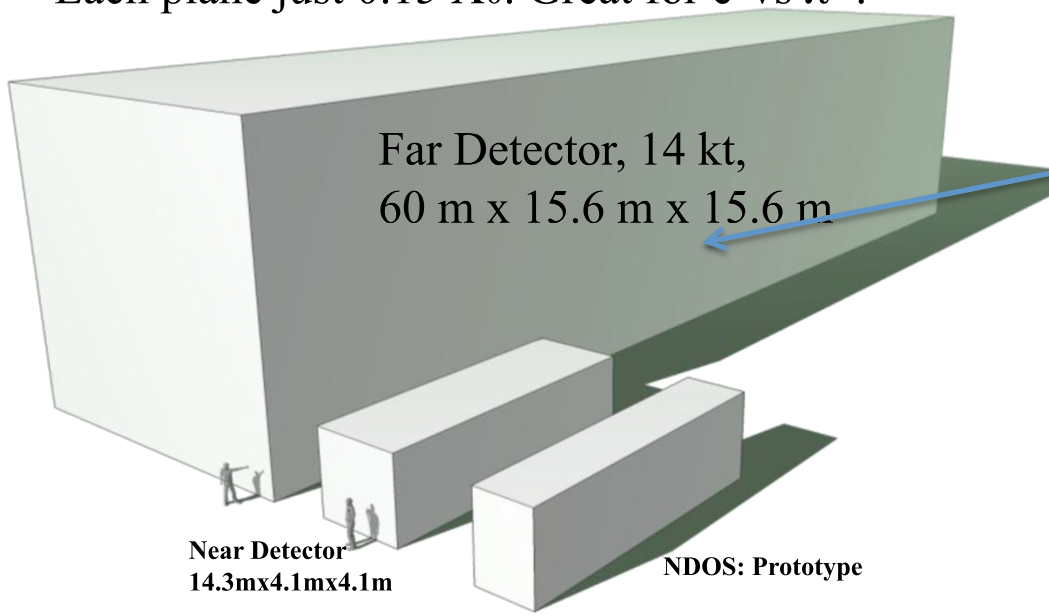


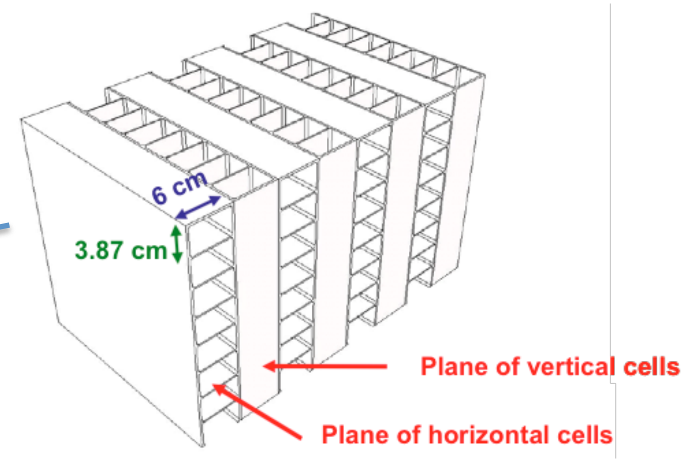
As well as:

- ν_μ cross sections.
- Neutrino magnetic moment.
- Supernova and monopoles.
- Sterile neutrinos.
- Non-standard neutrino interactions.

The NOνA Detectors

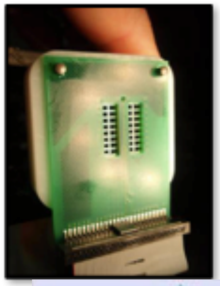
- 14-kton Far Detector ("Largest plastic structure built by man").
- 9-kton active detector.
- 344,064 detector cells read by APDs.
- 0.3 kton Near Detector 18,000 cells/channels.
- Each plane just 0.15 X_0. Great for e^- vs π^0 .

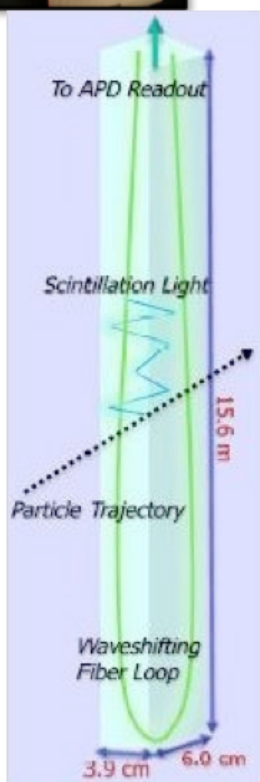




Consist of plastic (PVC) extrusions filled with liquid-scintillator, with wavelength shifting fibers (WLS) connected to avalanche photodiodes (APDs). Assembled in alternating layers of vertical and horizontal extrusions.

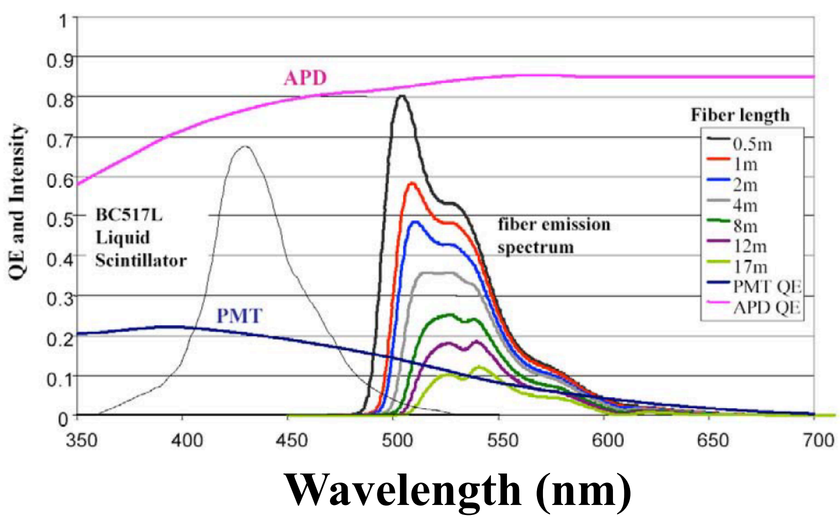
Detectors readout





NOvA basic cell

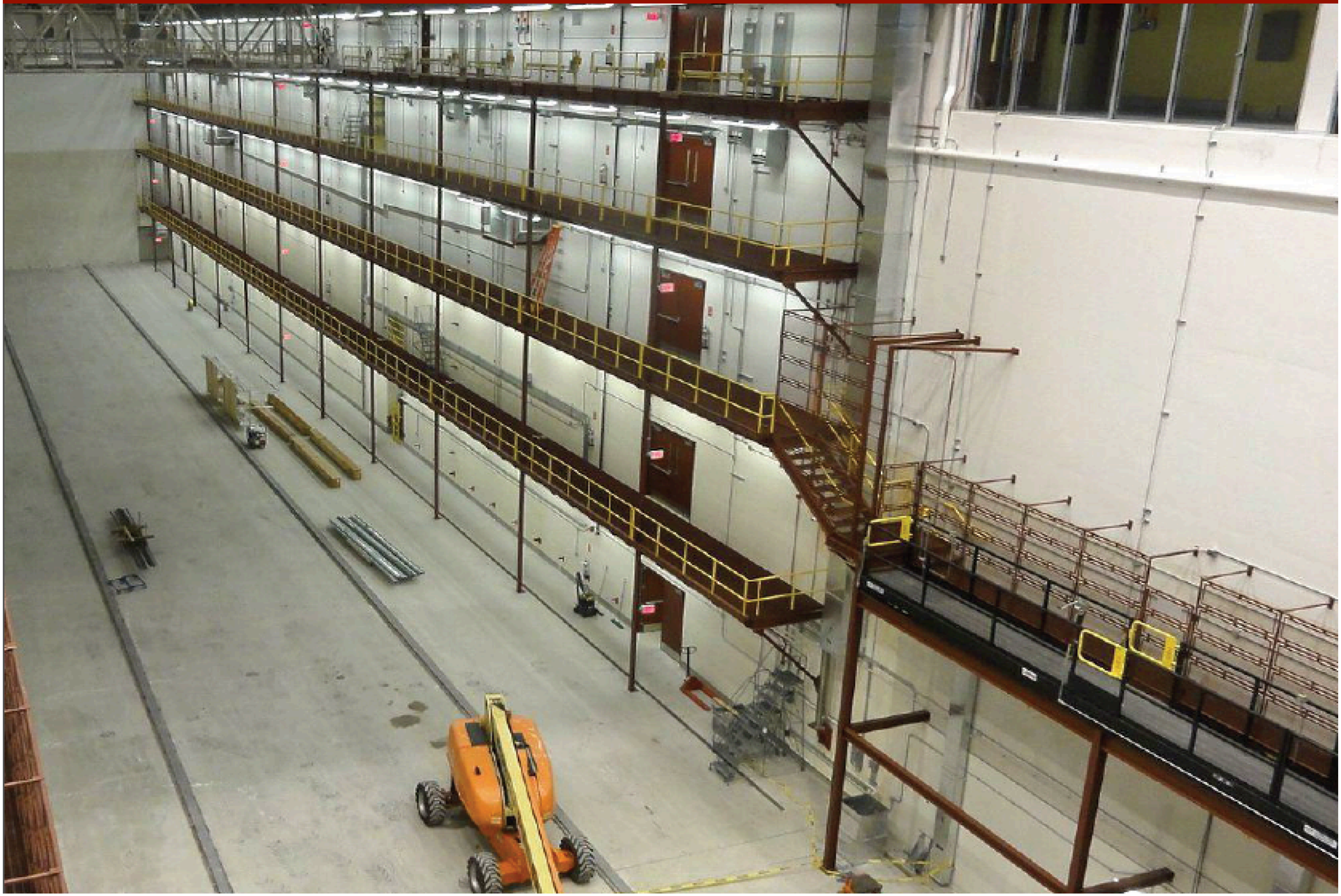
Each cell has a wavelength-shifting fiber routed an Avalanche Photodiode (APD). Scintillation light emitted isotropically and captured in wavelength - shifting fibers that convert wavelength to APD's sensitive region.



APDs have high quantum efficiency and uniform spectral quantum efficiency. This enables the use of very long scintillator modules, thus significantly reducing the electronics channel count.

Far detector construction

Far detector construction

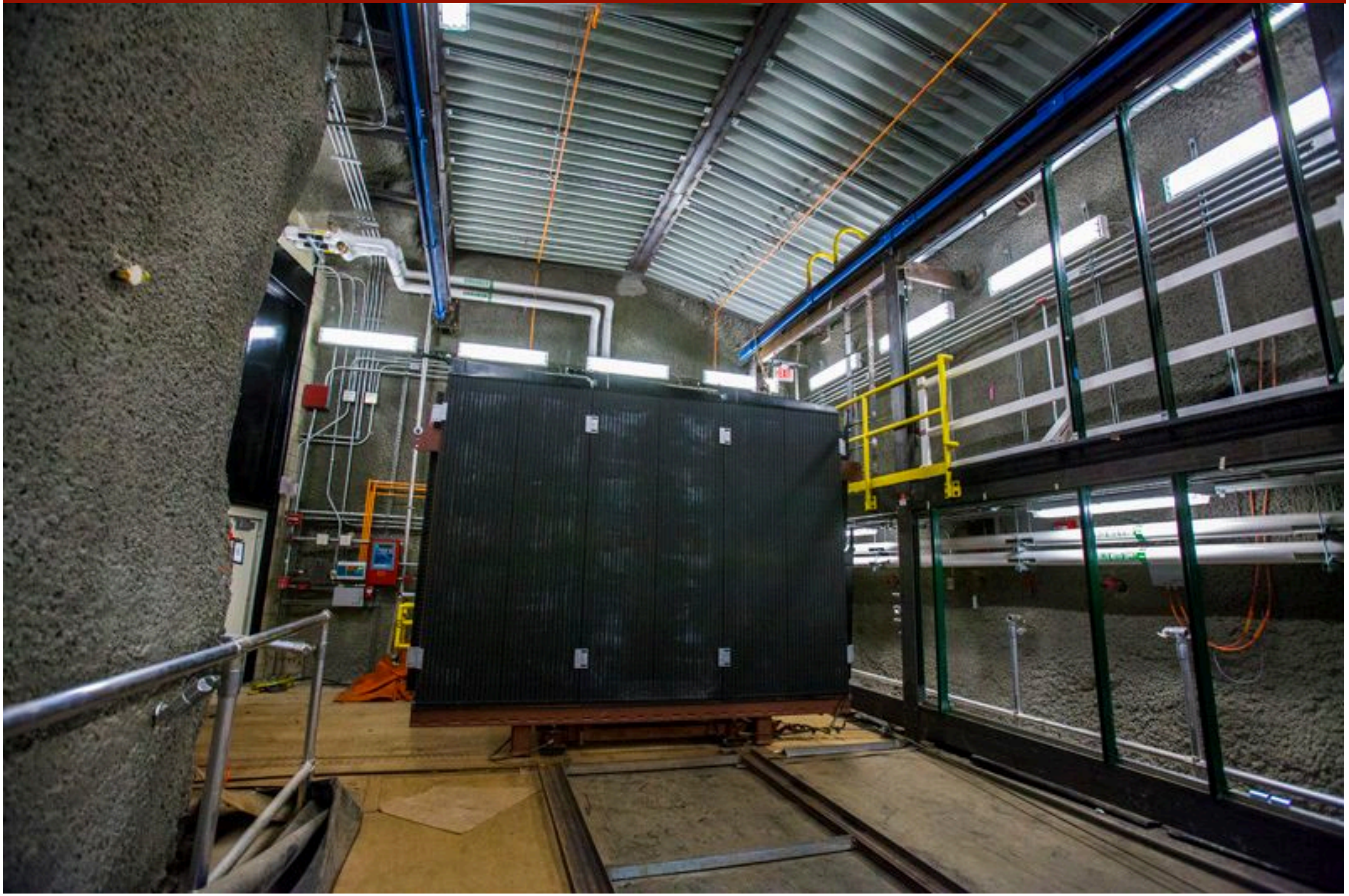


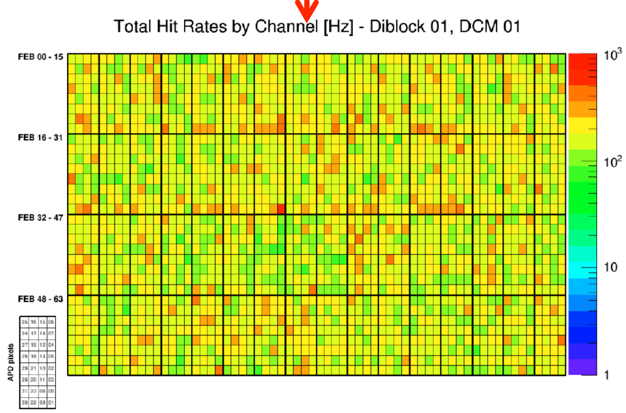
Far detector construction

Far detector construction

Far detector construction

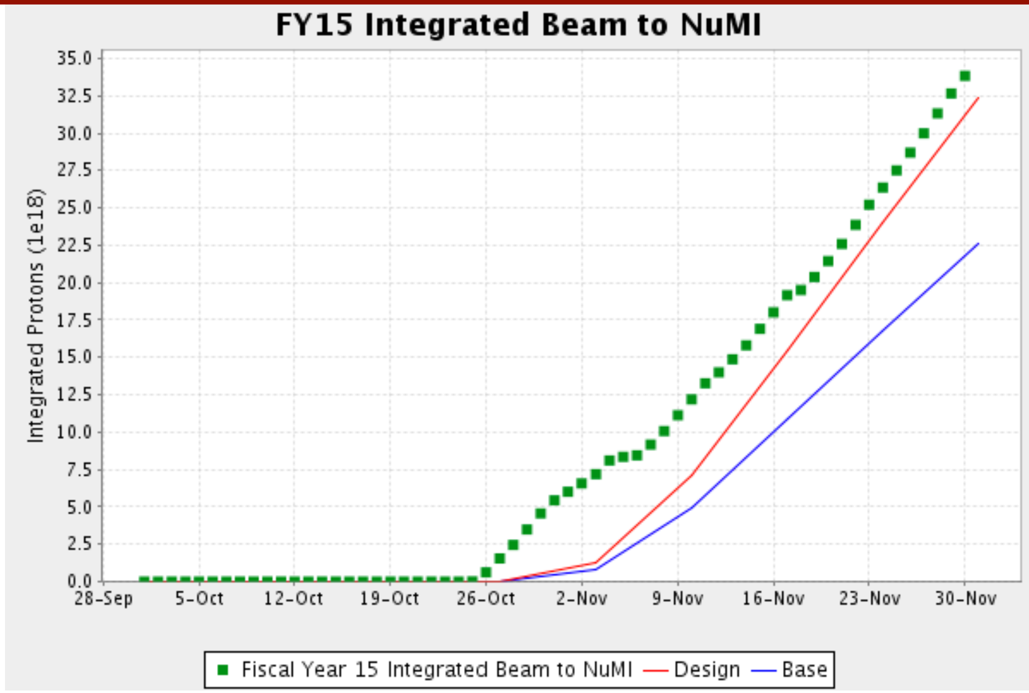
Near detector construction

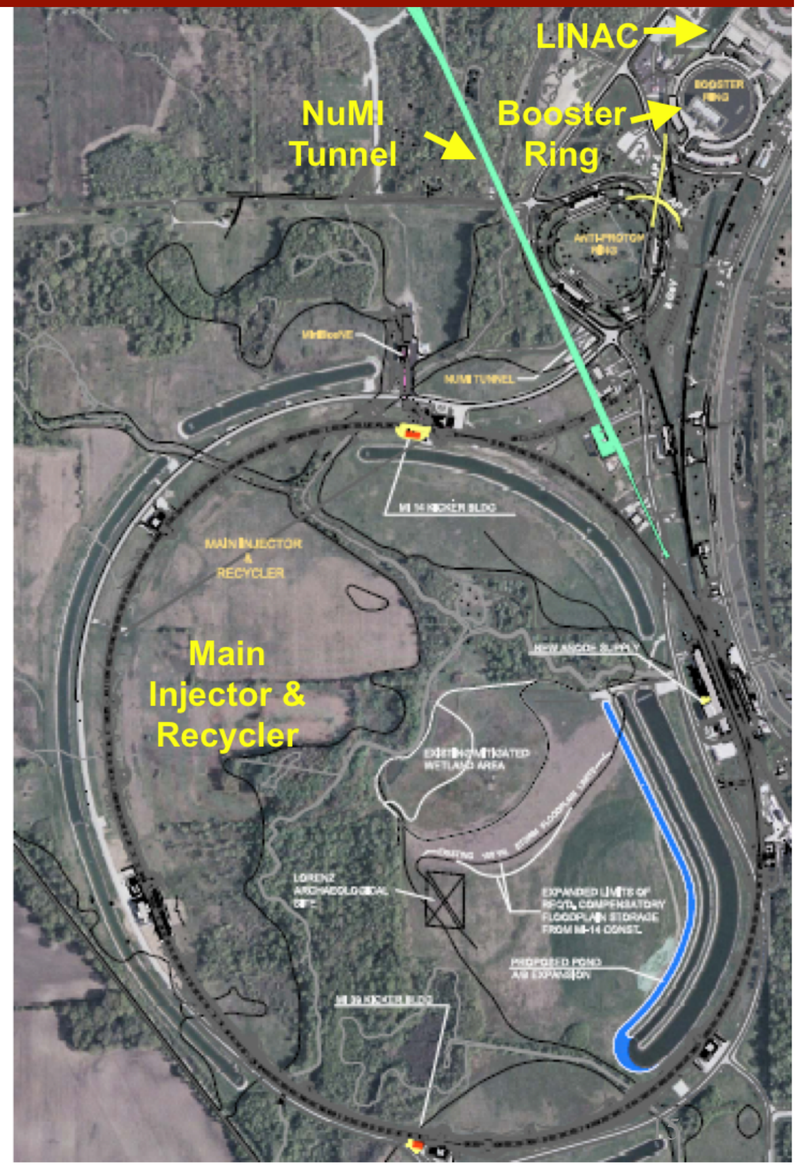




As of September 4th 2014, both far and near detectors are fully commissioned.

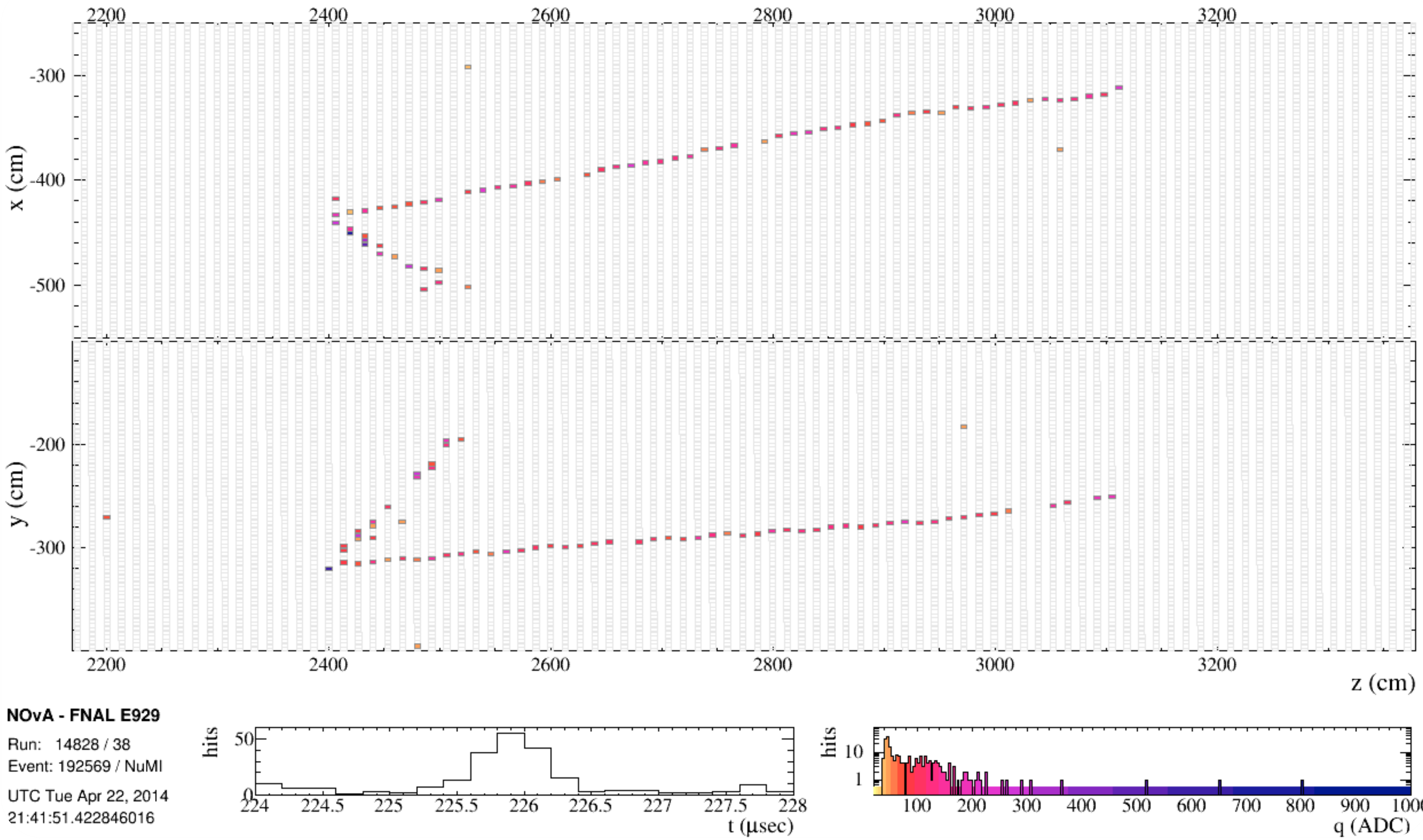
Accelerator and NuMI Upgrades



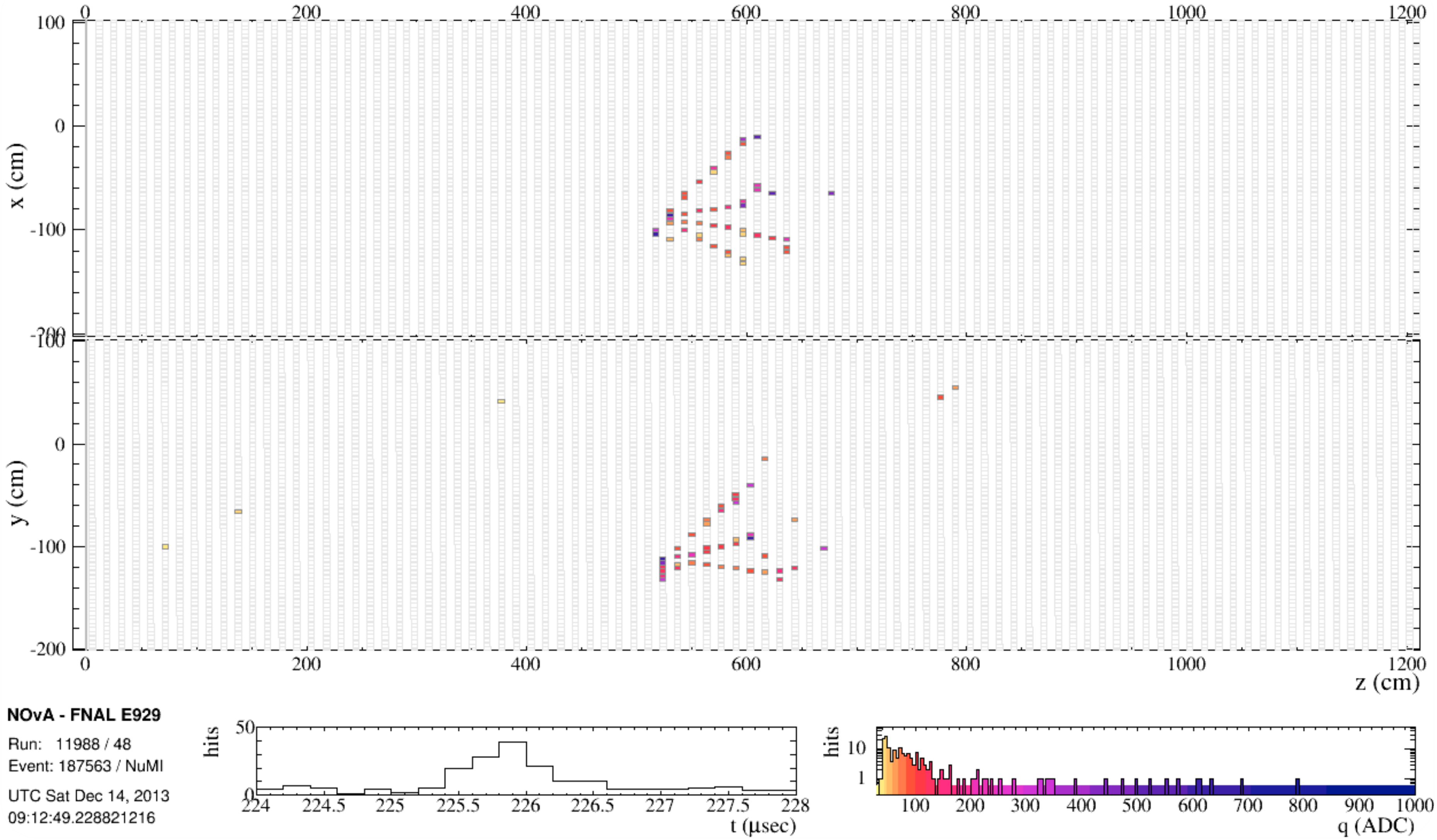


- Upgraded "Neutrinos at the Main Injector" (NuMI) accelerator complex:
  - 320 kW → 700 kW beam power.
  - Nominal NOvA year is $6x10^{20}$ protons on target (POT).
  - $3.3x10^{20}$ POT delivered since August 2013.
  - 500 kW by the end of 2014.

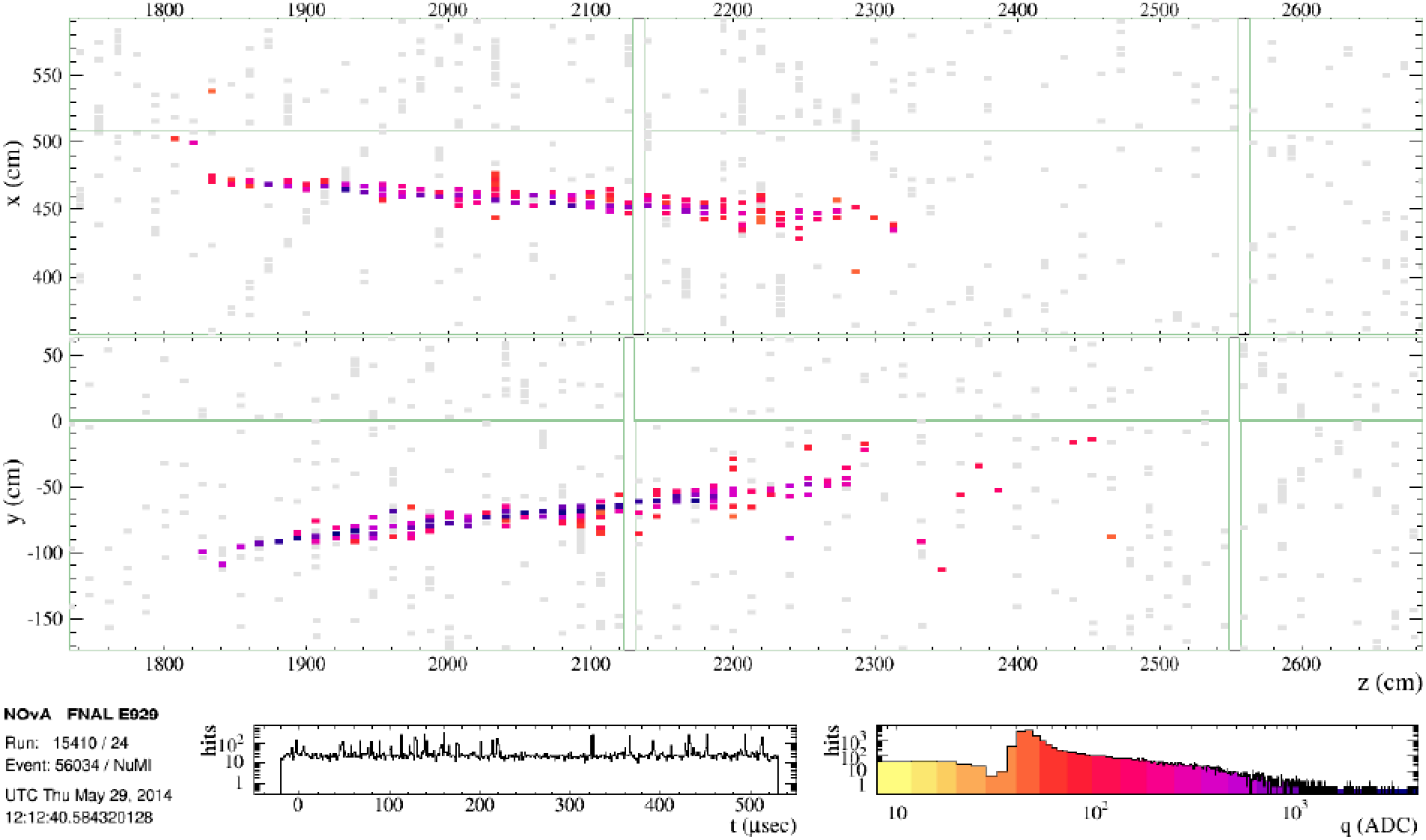
ν_μ-CC candidate in FD



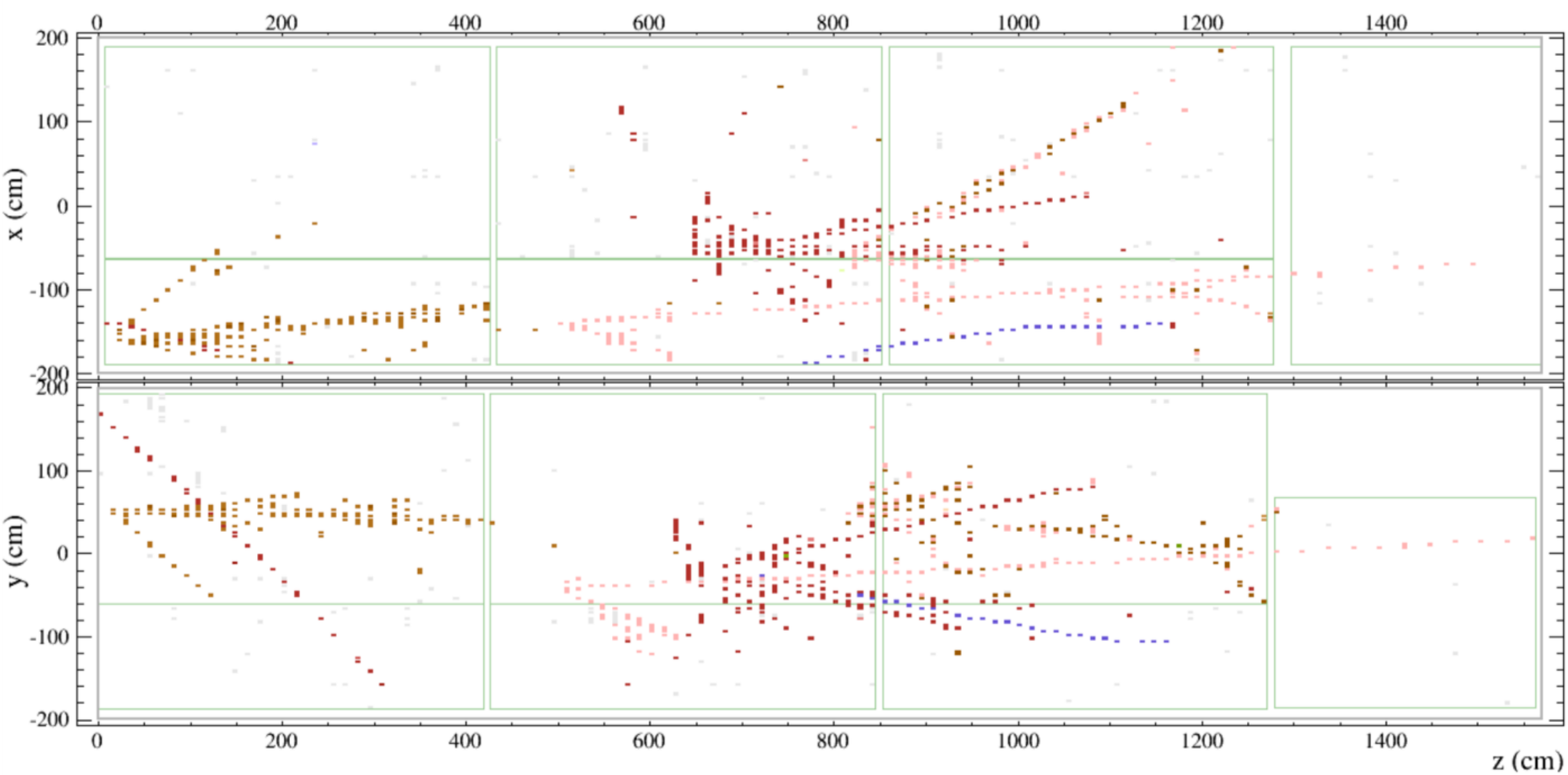
NC candidate in FD



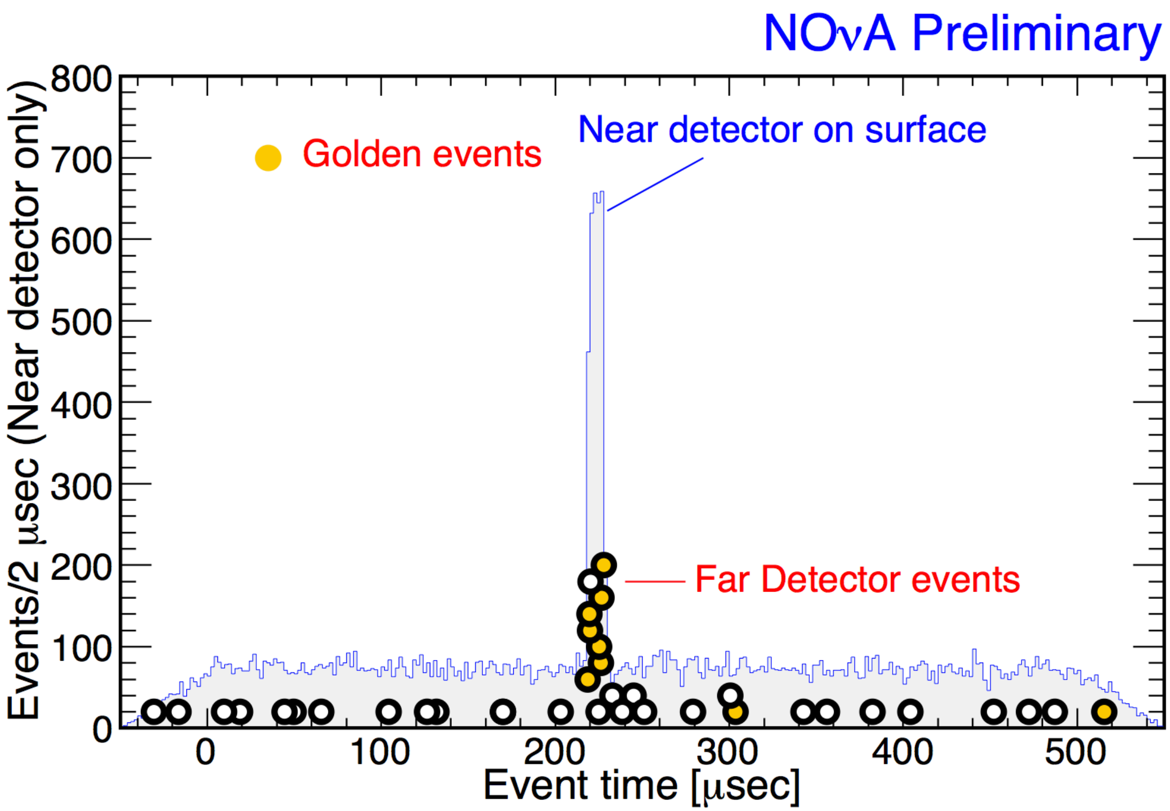
ν_e-CC candidate in FD

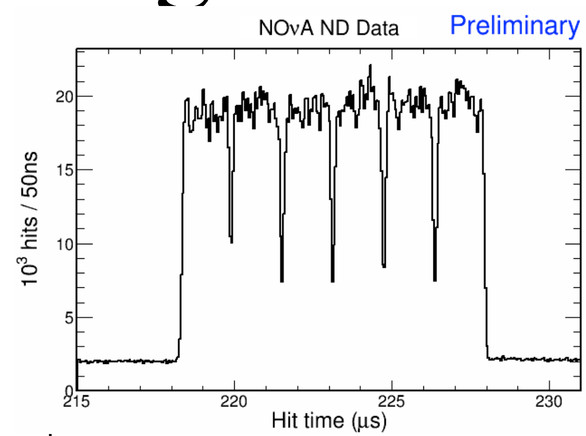


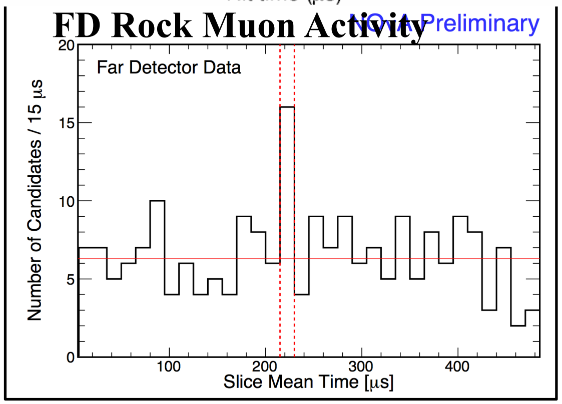
Neutrino candidates in ND



Far Detector ν timing







- Neutrino candidates are observed in both near and far detectors.
- FD neutrino candidates low up of timing peak, showing agreement with expected spill times as measured at our surface detector at FNAL.
- Both FD & ND are nearly completed. NOvA is now taking data for physics.

ν_e appearance at NOvA

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

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

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

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

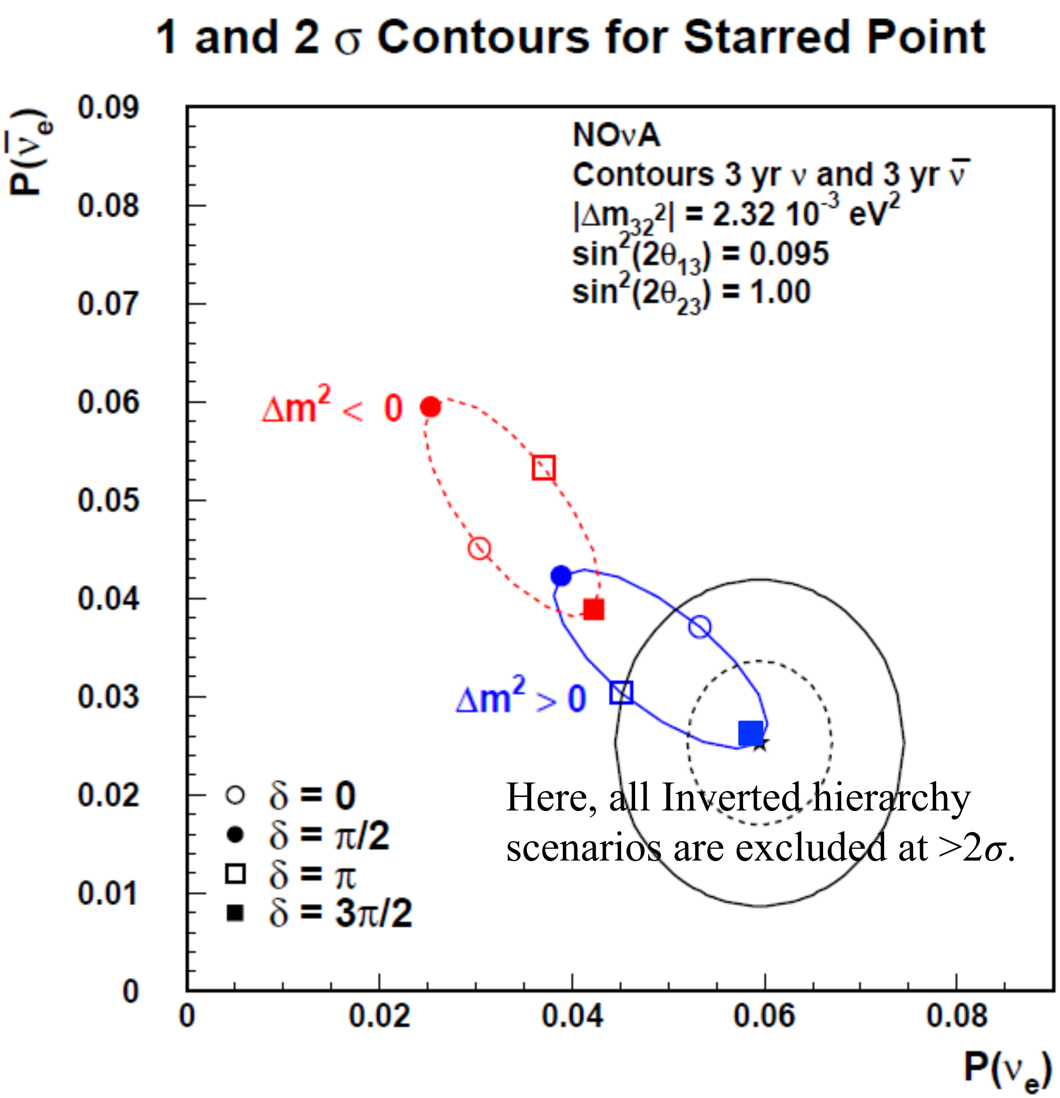
$$-2\alpha \sin\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

- We can investigate mass hierarchy due to θ_{13} is not zero.

- We have some sensitivity for δ_{CP} since θ_{13} is not zero.

- Probability is enhanced or suppressed due to matter effects which depend on the mass hierarchy as well as the sign of A which is determined by neutrino vs. anti-neutrino running.

ν_e appearance at NOνA



- Because the $P(\nu_e)$ and $P(\bar{\nu}_e)$ depend on mass hierarchy and δ_{CP} in different ways, a measurement of the probabilities might allow resolving the mass hierarchy and provide information on δ_{CP}.
- The precision of probabilities measurement depends on θ_{13}. Large θ_{13} also reduces the overlap area of NMH and IMH ellipses. So it is good news for NOνA that θ_{13} is large.

ν_e appearance analysis

- Event reconstruction: Reconstruction chain for cell, track, shower and vertex.

- ν_e identification: identify ν_e in $\nu_\mu \rightarrow \nu_e$ oscillation
  - ANN: Artificial neural network using shower shape based likelihood for particle hypotheses.
  - LEM: Matching events to a Monte Carlo library.

- Detector decomposition.

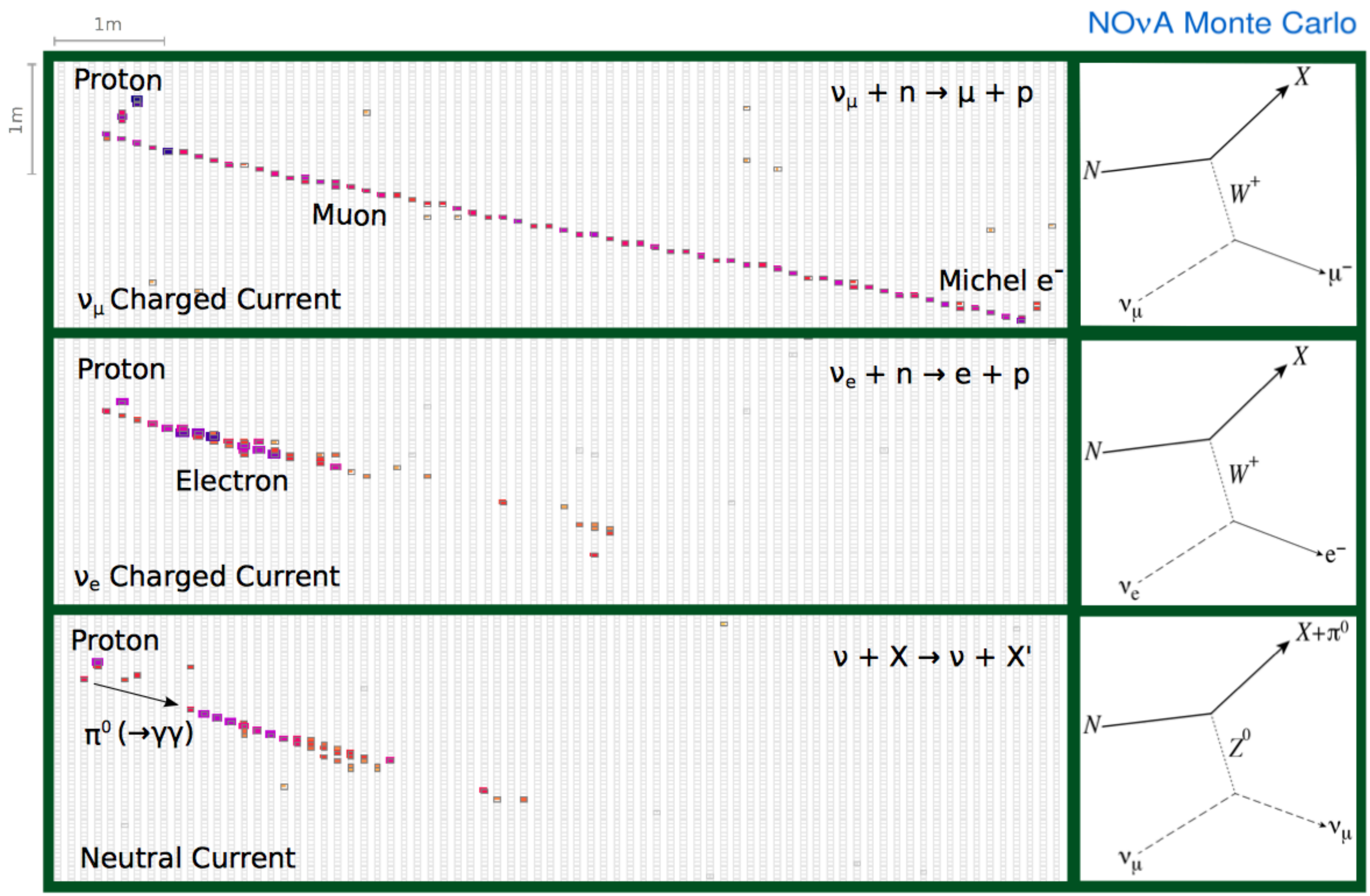
- Extrapolation.

- Sensitivity studies.

ν_e identification (ANN)

- The first task of the ν_e-CC analysis is to identify the electron in ν_e-CC final states from various backgrounds.
- The basic idea is to use shower energy profile to separate electron from $\mu/\gamma/\pi^0$ and other hadrons.
- Different particles have very different energy deposit behaviors in the detector, which makes it possible to identify particles by comparison of shower shapes with different particle hypotheses.

Neutrino Event Topology in NOνA



ν_e identification (ANN)

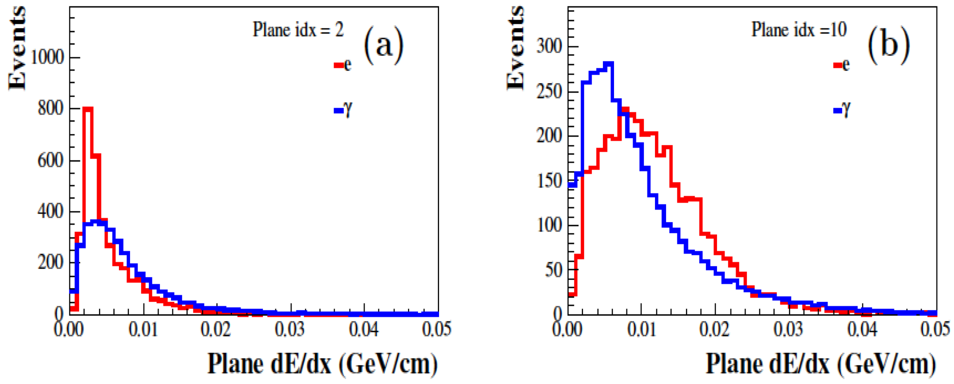


FIG. 8: Longitudinal dE/dx for electrons (red) and photons (blue): (a) Plane index = 2; (b) Plane index = 10.

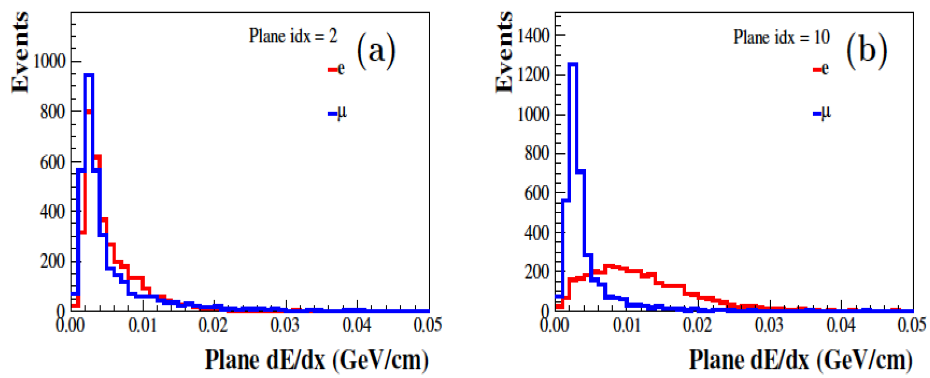
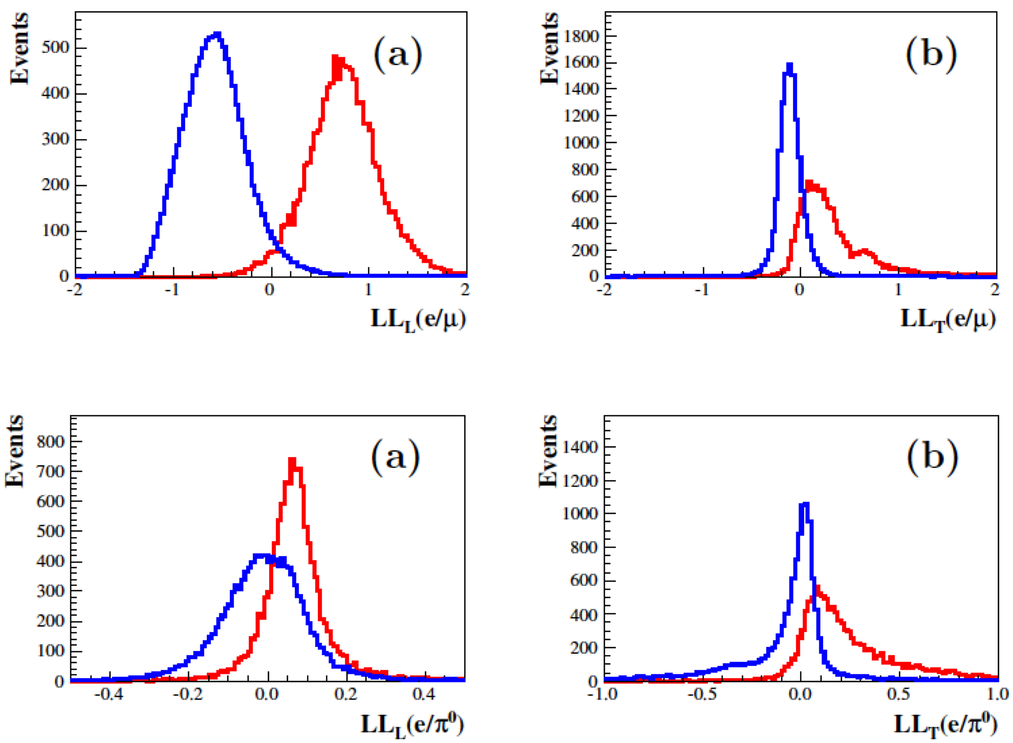


FIG. 9: Longitudinal dE/dx for electrons (red) and muons (blue): (a) Plane index = 2; (b) Plane index = 10.

Calculate the longitudinal dE/dx by plane and calculate the transverse dE/dx by transverse cell index.

These dE/dx can describe profile of each particle: The electron ionizes in the first few planes then starts a shower, the photon is a shower with a gap in the first few planes, and the muon deposits a long minimum ionizing particle (MIP) track.

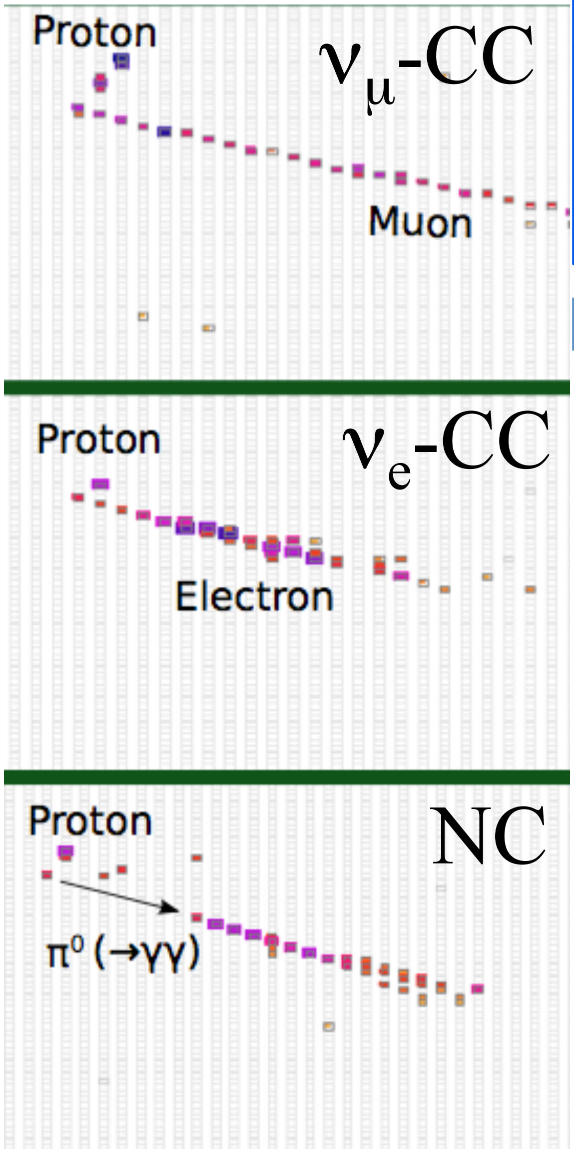
ν_e identification (ANN)



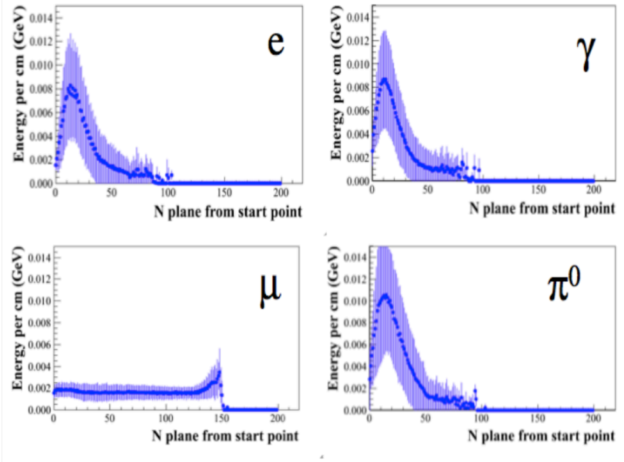
When performing PID on the test sample, we calculate the dE/dx in each plane and transverse cell index. We then calculate the probability and likelihood for each type of particle according to the expected dE/dx histogram for that plane or transverse cell index.

Summing over these plane-by-plane and cell-by-cell likelihoods we have overall longitudinal and transverse likelihoods for each type of particle.

ν_e identification (ANN)

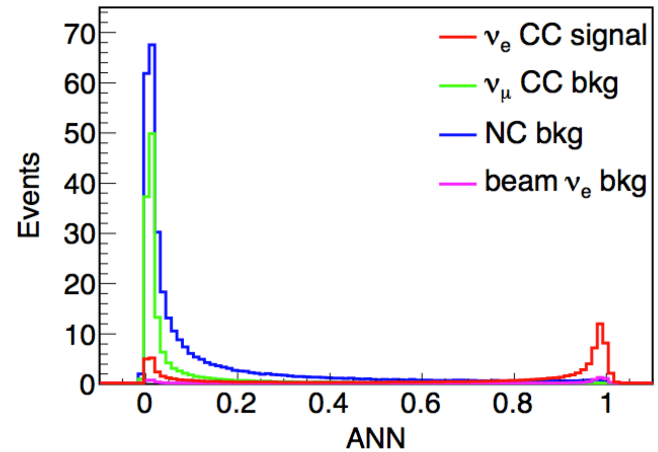


Parameterize energy profile by transverse/longitudinal dE/dx, then likelihood for particle hypotheses.



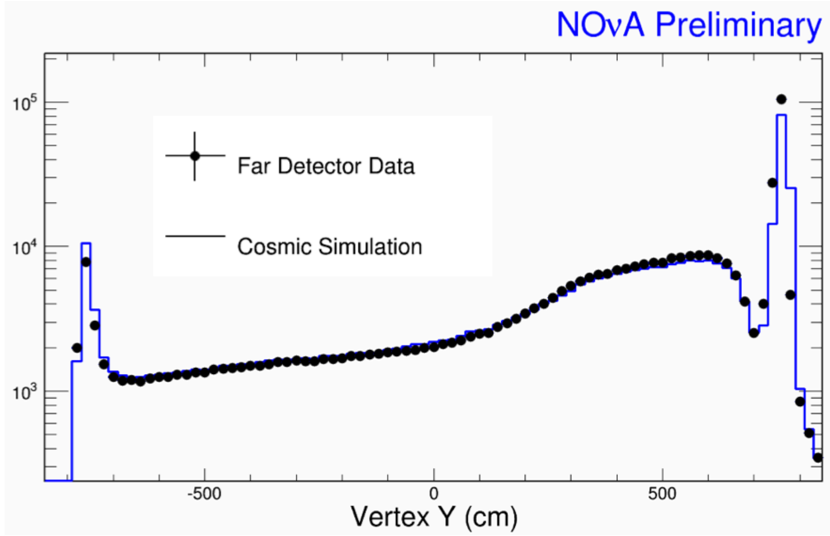
Combine shower shape information with an artificial neural network.

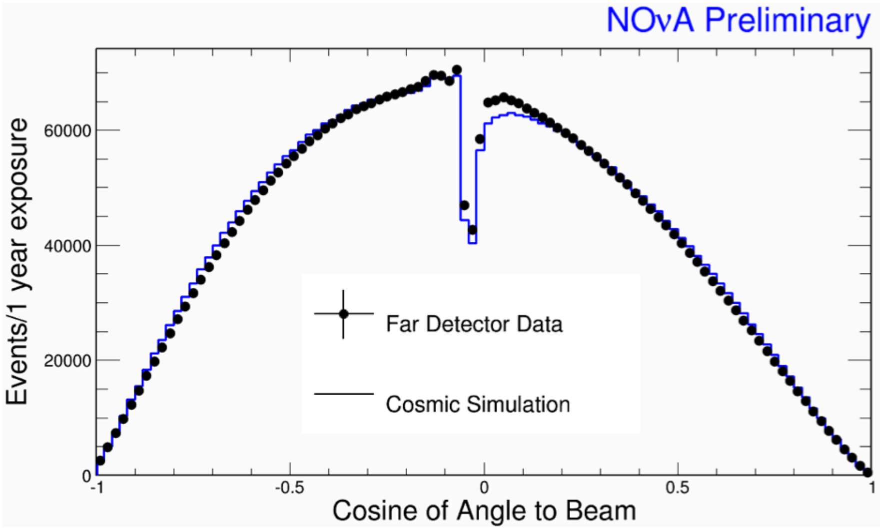
Because NOvA has fine-grained detectors, we are able to see details of energy profiles for different particles.

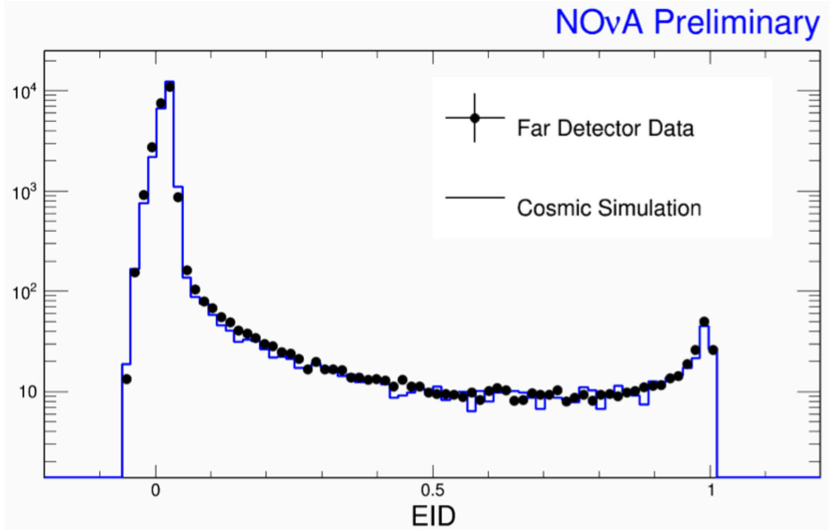


Data/MC comparison

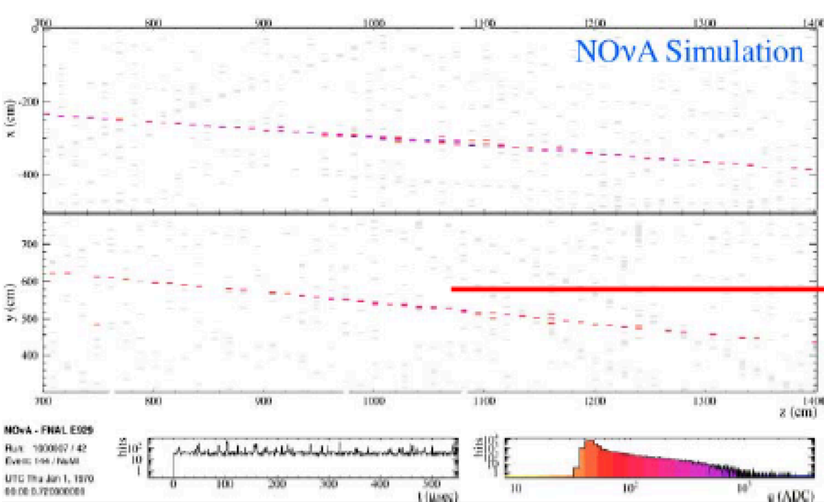
- Using real cosmic ray data for comparison, we verify our simulation and detector modeling.
- Reconstruction variables and PID output has for muon in cosmic rays.

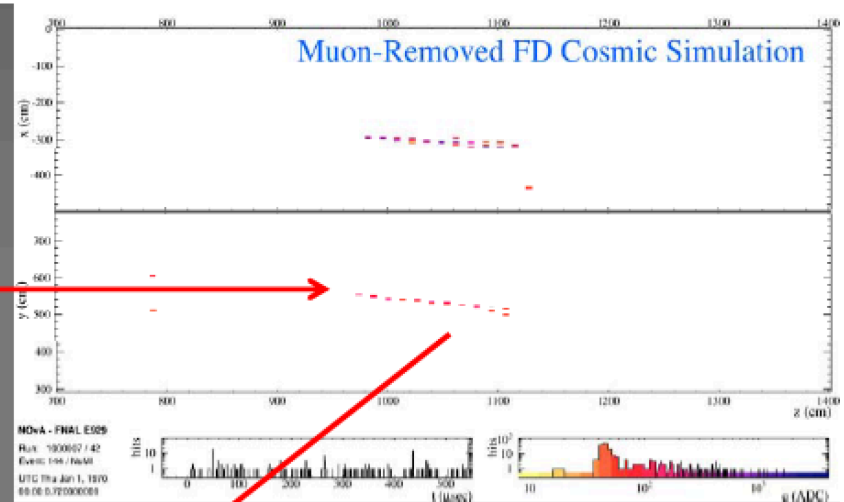


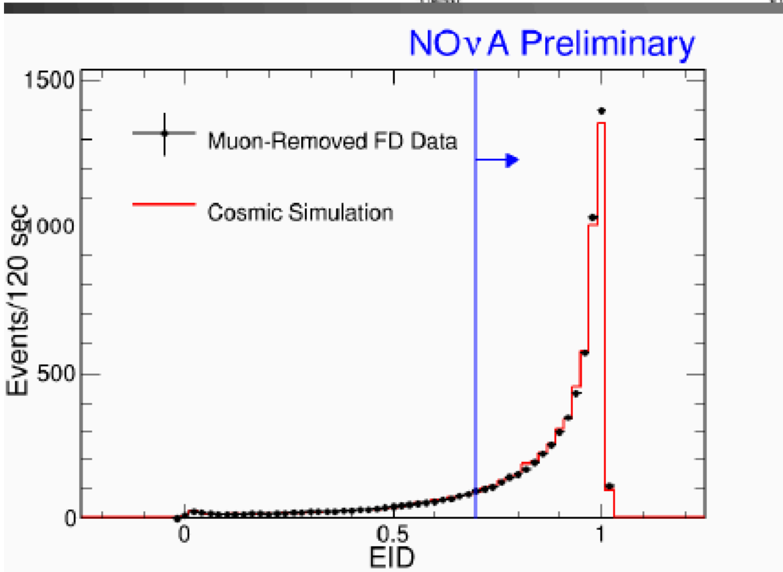




Data/MC comparison



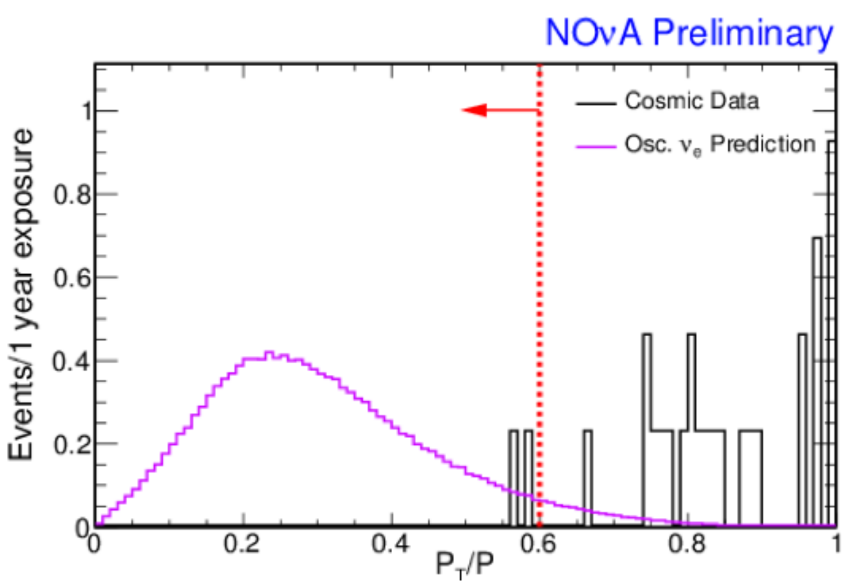


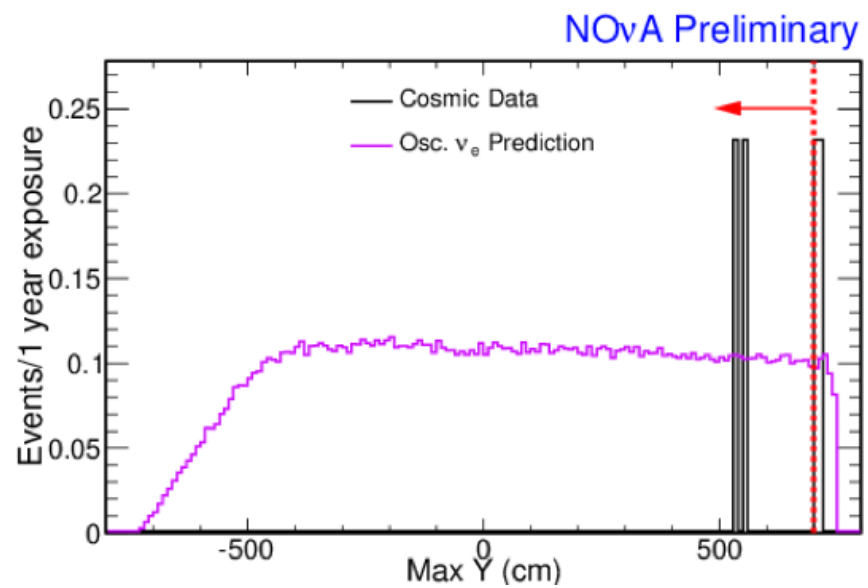


Extract EM shower from CR muon events, and compare EID, etc, with expectations from simulation.

Allows us to validate our signal event modeling without opening the box on FD neutrino events.

Cosmic Rejection for ν_e

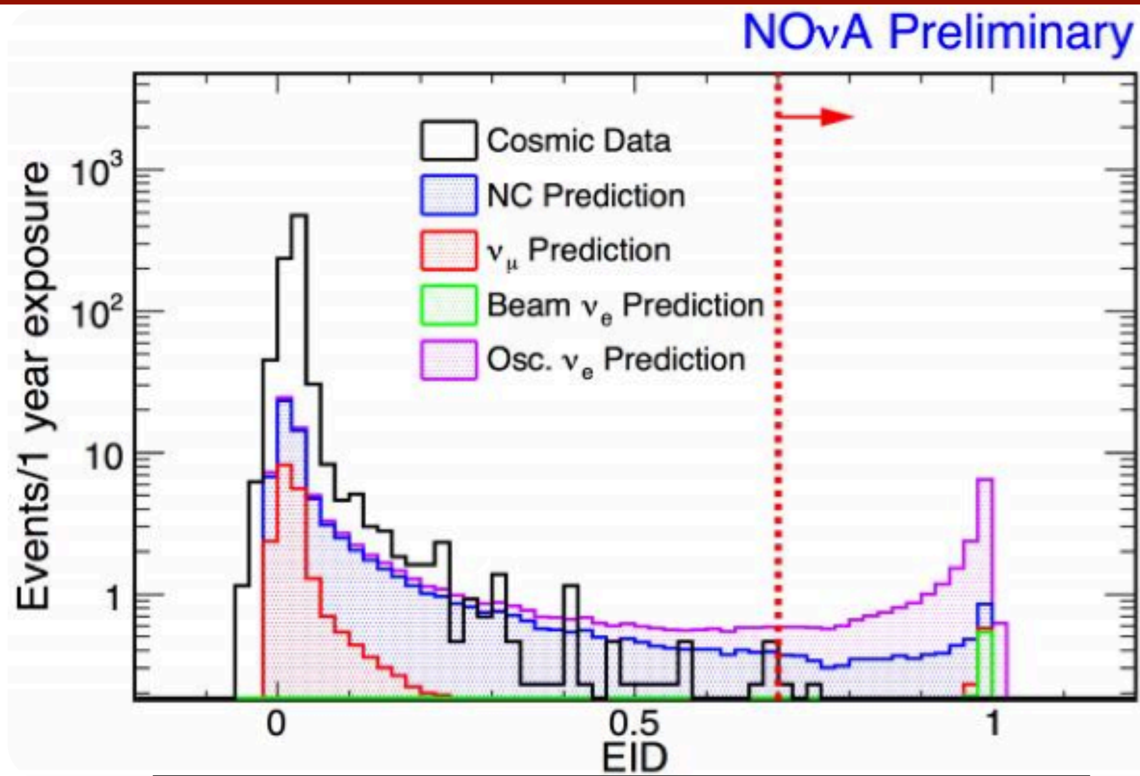




Three simple cuts are used to reject the cosmic induced backgrounds prior to PID

- ***P_t/P*** **- force directionality of showers along the beam**
- ***Max Y hit position*** **– remove particles entering from the top of the detector**
- **Vertex Gap (reconstruction quality)**

Event selection (cosmic rejection)



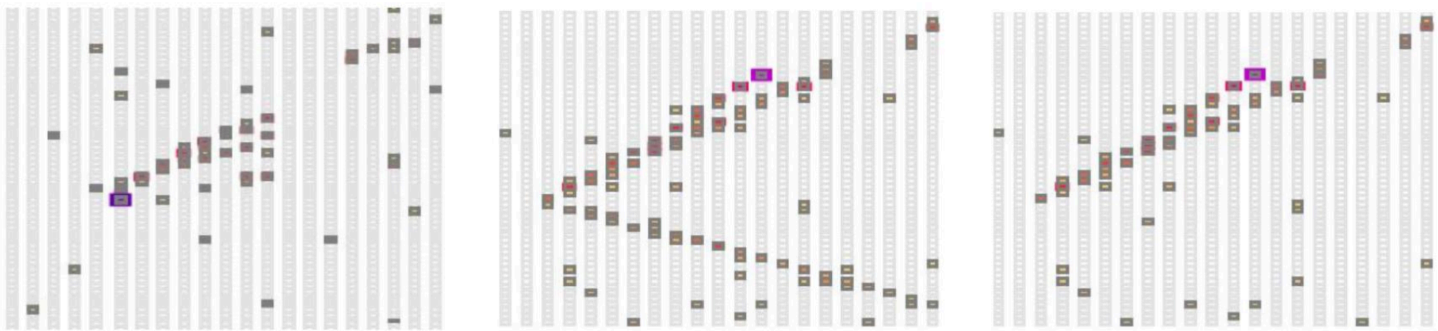
	Osc ν_eCC	Beam Bkg	Cosmic Bkg
1 yr Nominal Exposure			
	36.7	965	19M
Containment & quailty	24.7	106	55k
Cosmic Rejection	21.2	82.9	834
ν_e selection	13.9	6.0	0.46

Achieves 40 million to 1 cosmic rejection

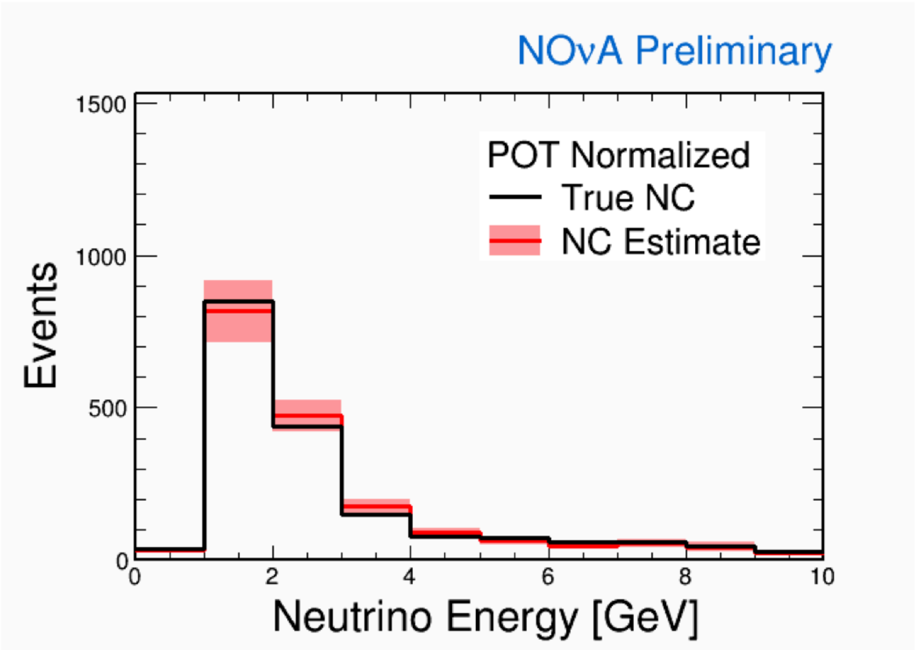
Background Estimate

- Because of neutrino oscillations, the Far Detector Background will not have the same shape as the background in the Near Detector.
- To isolate the NC, CC, and Beam-ve components in the Near Detector we need a data-driven decomposition.
- Once we have a decomposition, we can extrapolate each of these components to the Far Detector.

Muon-Removed Charged Current (MRCC)

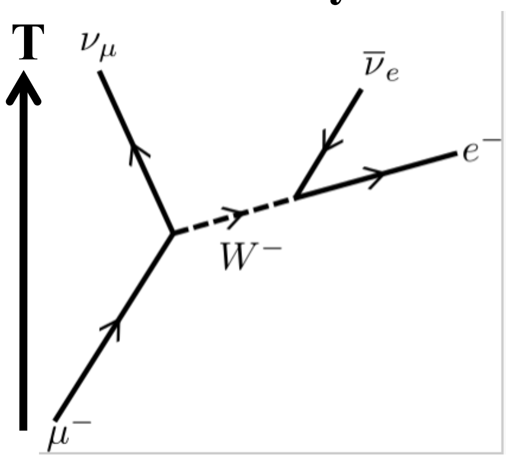


- A $\nu\mu$ CC event produces a long μ track and a hadronic showers in our detector
- Removing the μ track leaves other showers to mimics a NC event.
- The MRCC spectrum in data is scaled by a MC factor giving a NC estimate.

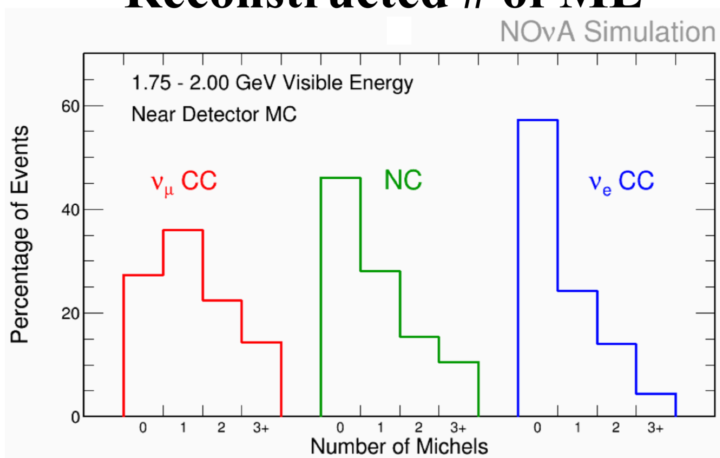


Michel Electron Decomposition

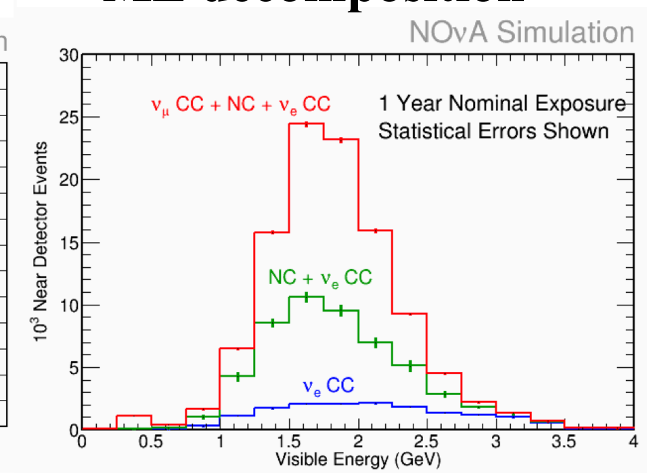
Michel decay of muon



Reconstructed # of ME



ME decomposition



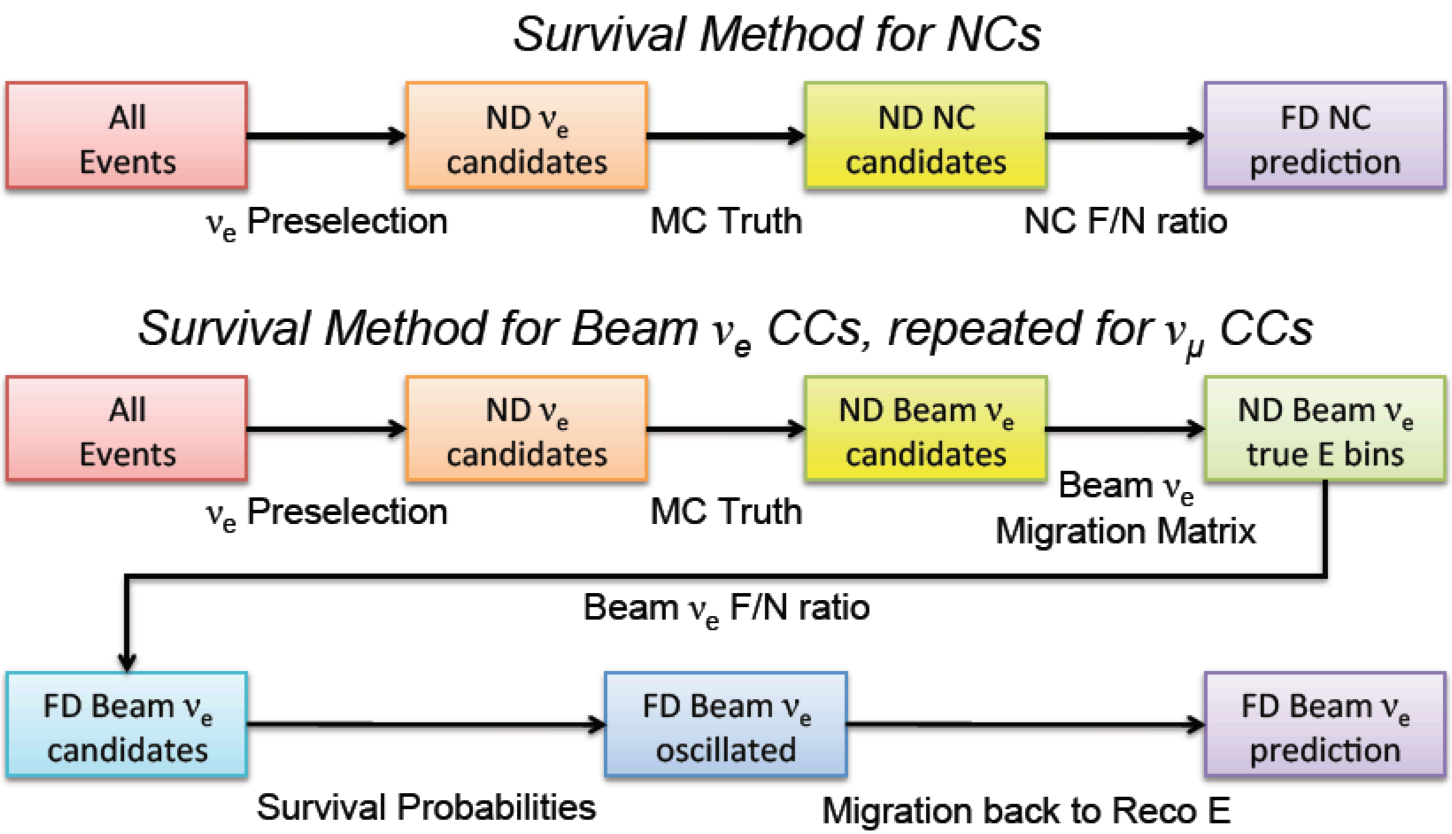
- A ν_μ CC event will have a Michel electron from the primary μ.
- In each energy bin, a $\chi 2$ fit scaling MC Michel electron distributions to data to determine yields of ν_μ-CC, NC and ν_e CC.

Extrapolation

- NOvA Detectors similarly designed to share event efficiencies and purities, and cancel systematic errors.
- Differences in detector flux attributed to kinematic effects encoded in ratio of event rates at FD over ND.
- F/N ratios are applied to near detector data to predict far detector spectrum.

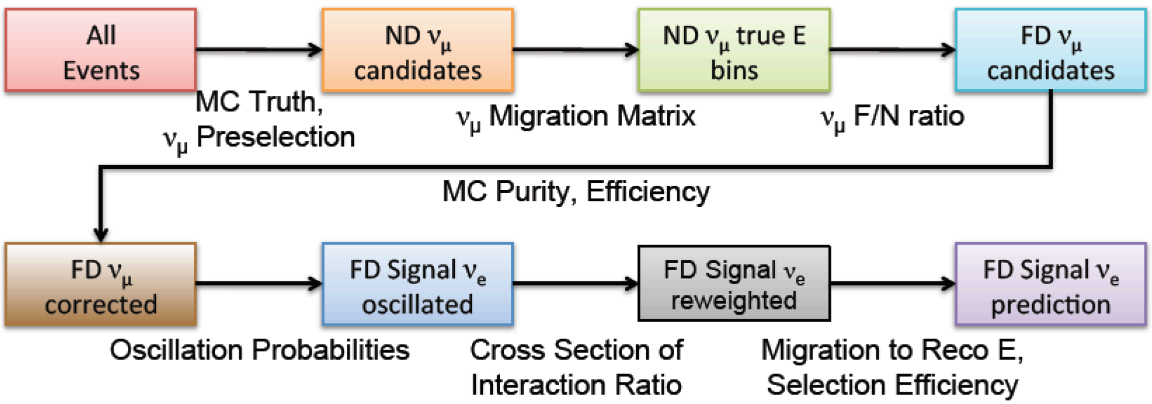
Extrapolation

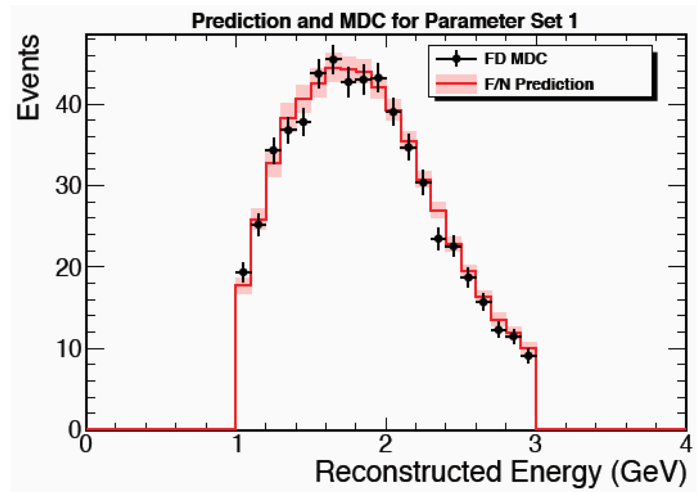
Survival Method used for events that occur in both detectors (from preselected ν_e candidates)



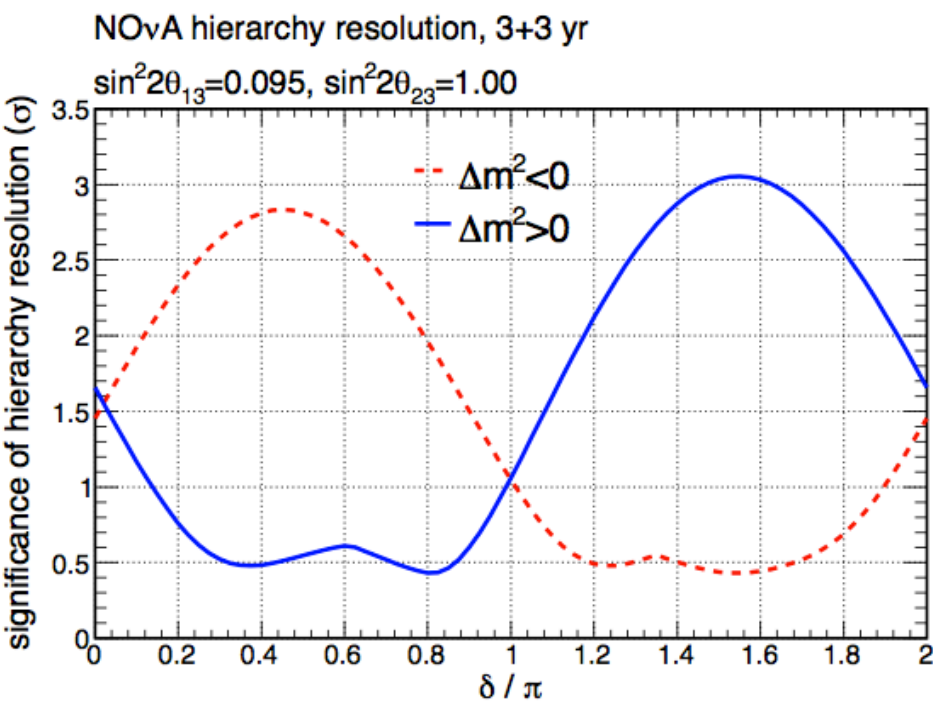
Extrapolation

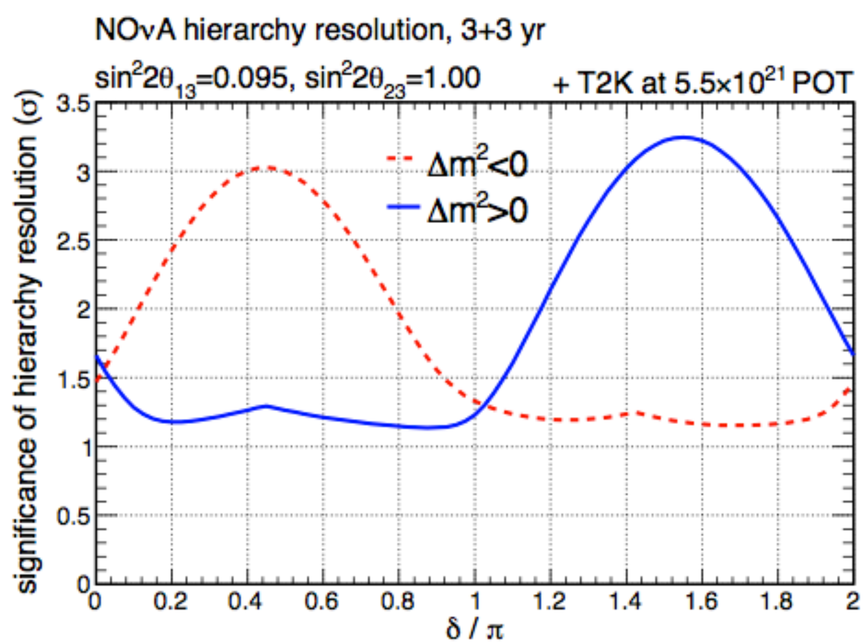
Appearance Method used for signal ν_e CCs and background ν_μ to ν_τ CCs, events which only occur at far detector (from preselected ν_μ candidates)





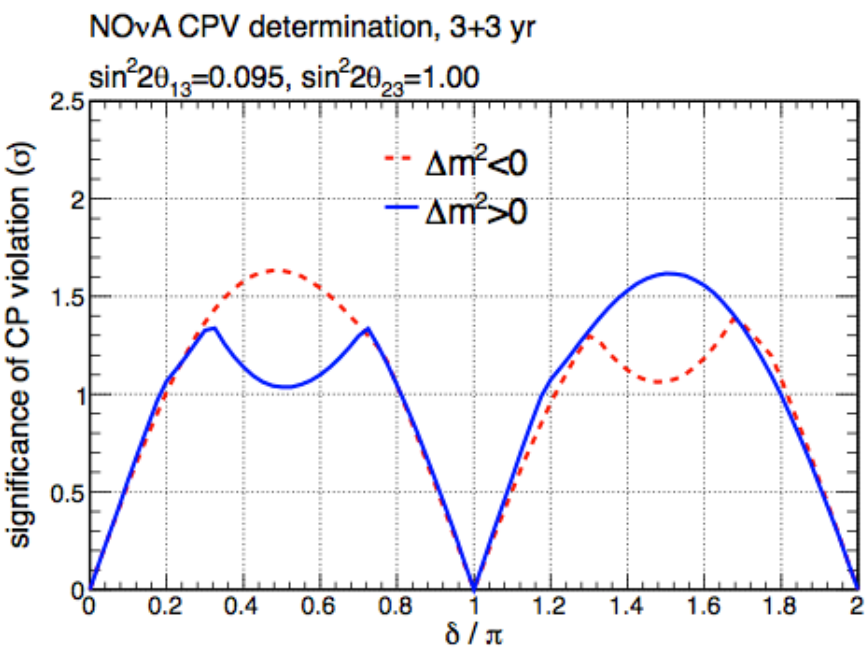
Significance to resolve mass hierarchy

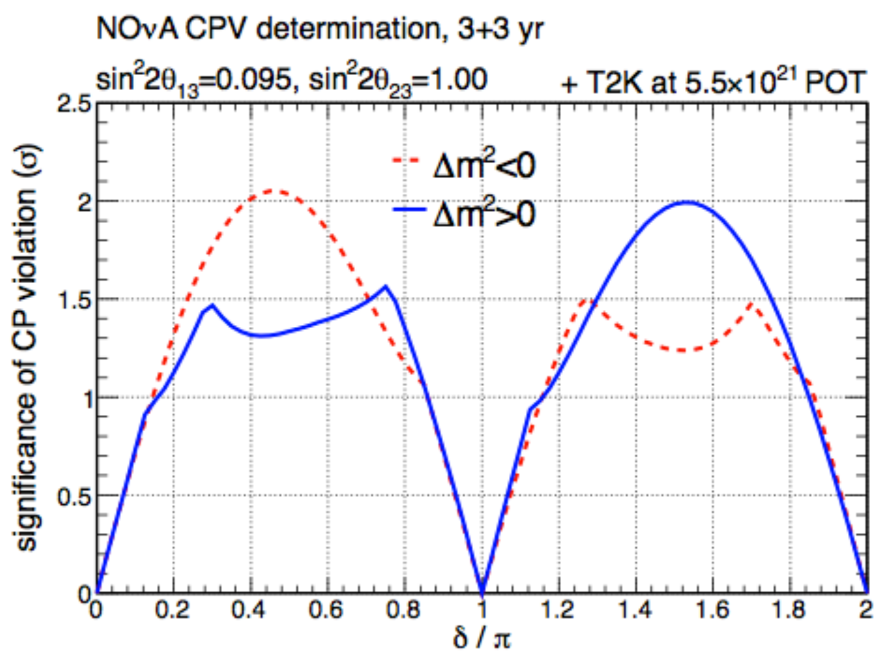




- Results from full simulation, reconstruction, selection, and analysis framework.

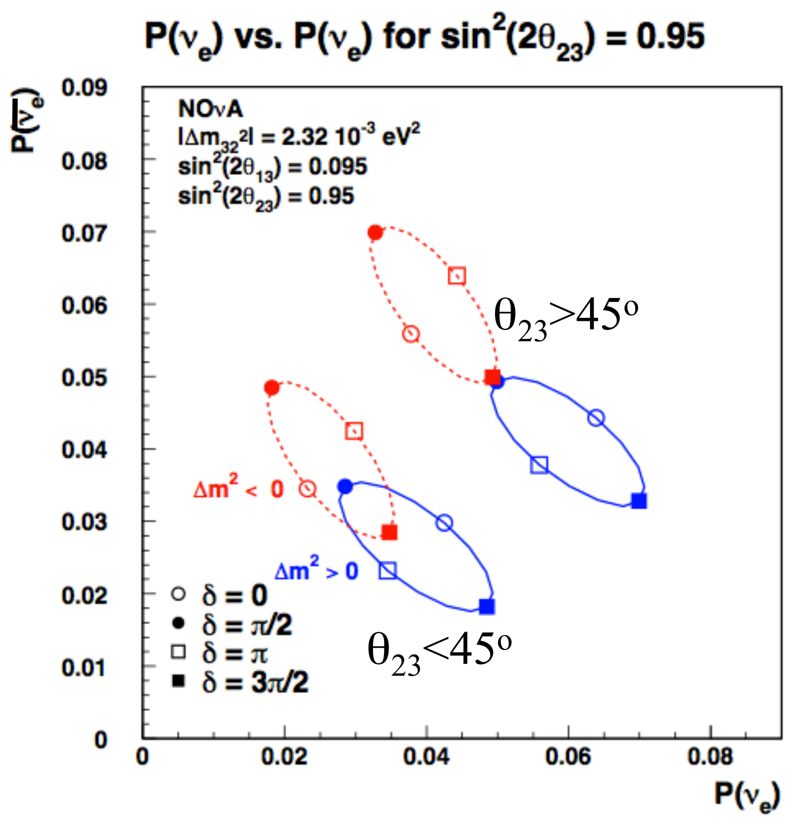
CP violation phase

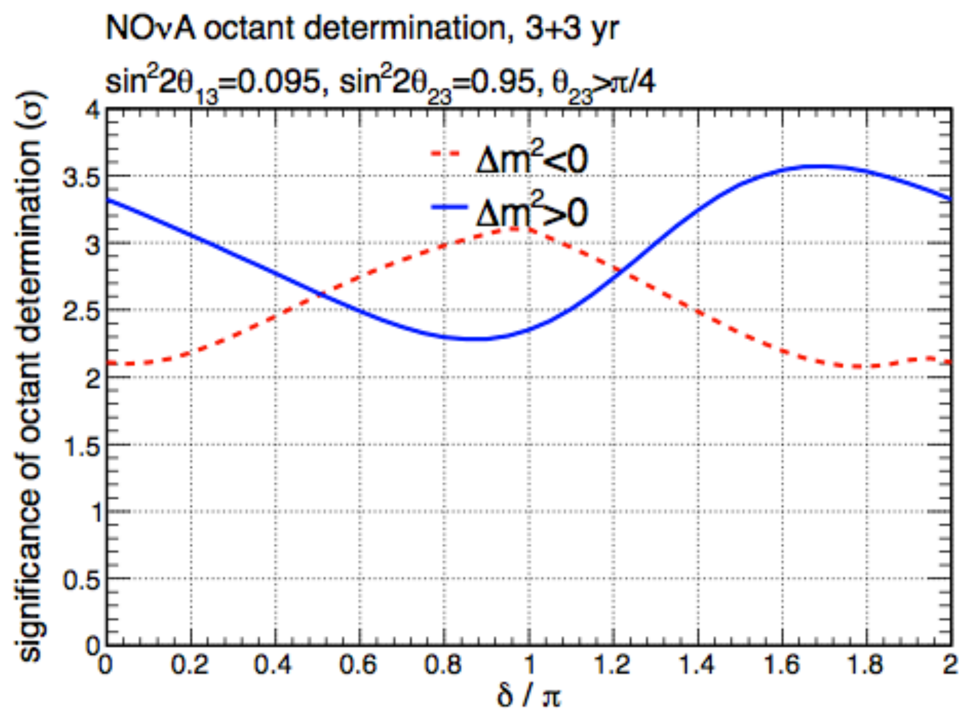




- Results from full simulation, reconstruction, selection, and analysis framework.

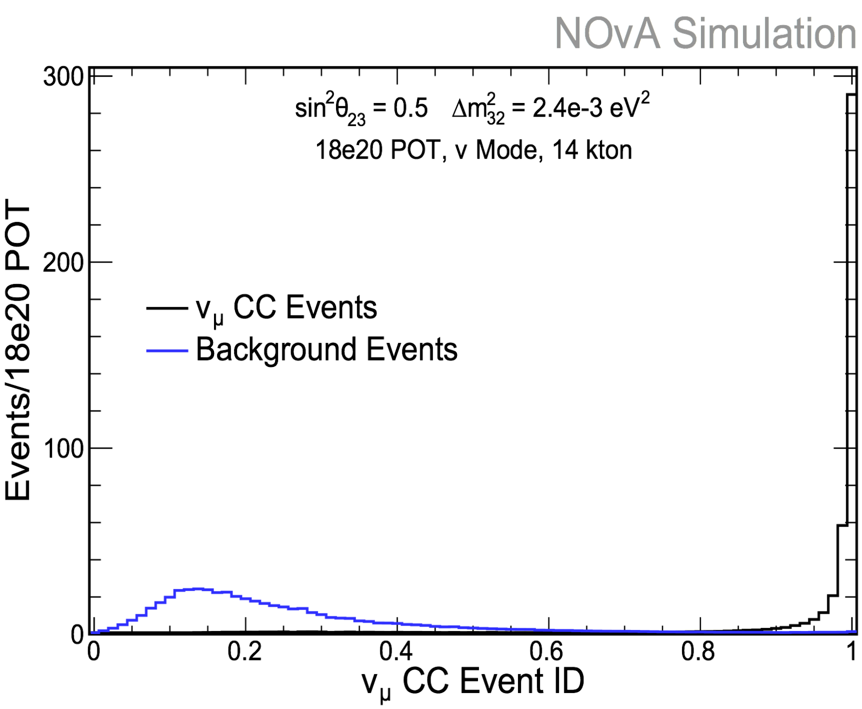
Octant of θ_{23}

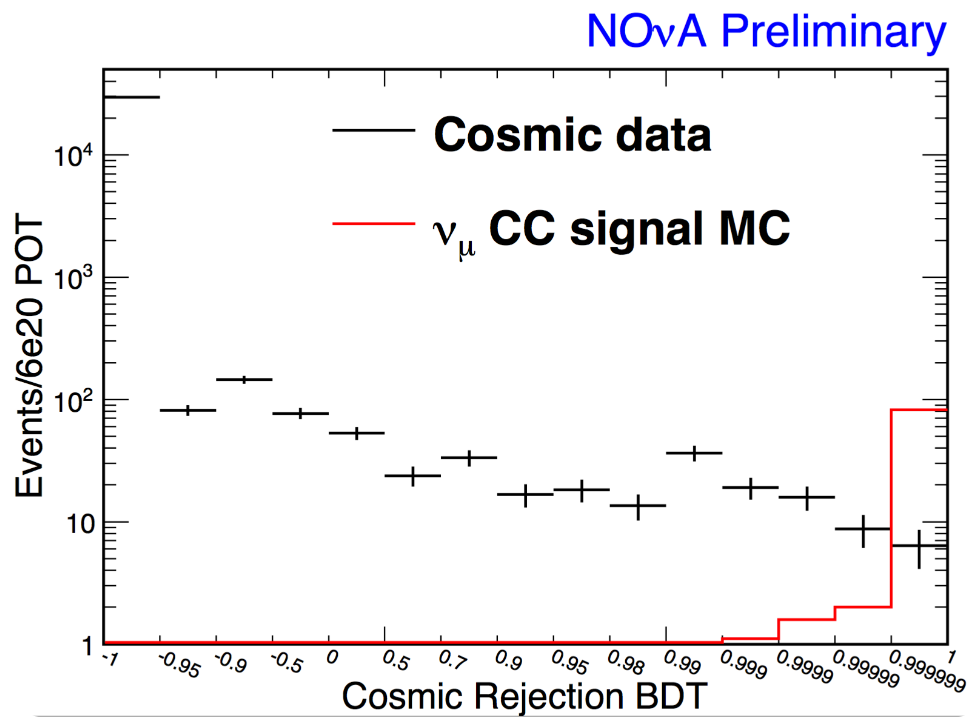




- If $\sin^2(2\theta_{23})$ is not maximal there is an ambiguity as to whether θ_{23} is larger or smaller than 45°.
- The $\sin^2(\theta_{23})$ term is crucial in comparing accelerator to reactor experiments.
- $\sin^2(2\theta_{23})$ is measured in ν_μ disappearance.
- Because $P(\nu_\mu \rightarrow \nu_e)$ is in proportion to $\sin^2(\theta_{23})\sin^2(2\theta_{13})$, it can be used to determine θ_{23} octant.

ν_μ disappearance analysis at NOνA





Multiple selection criteria:

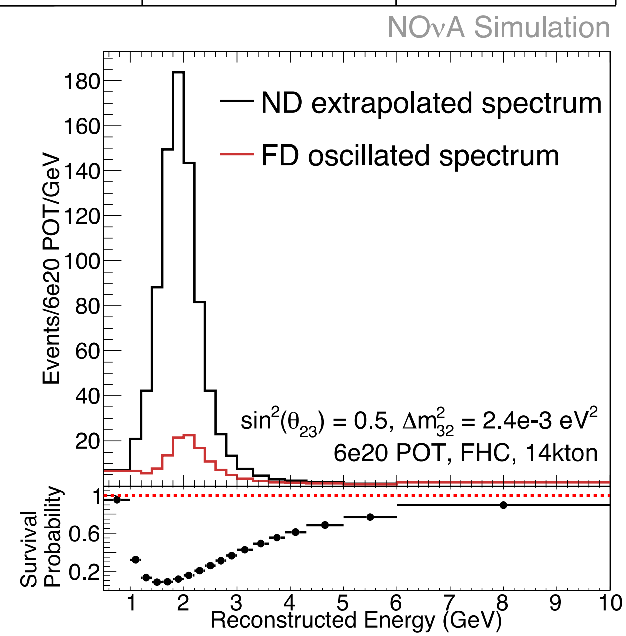
- **Event ID criteria separate ν_μ-CC from NC events**
- **Boosted Decision Tree method for separating out cosmic background**
- **Achieves cosmic rejection 20M:1**

ν_μ disappearance analysis at NOνA

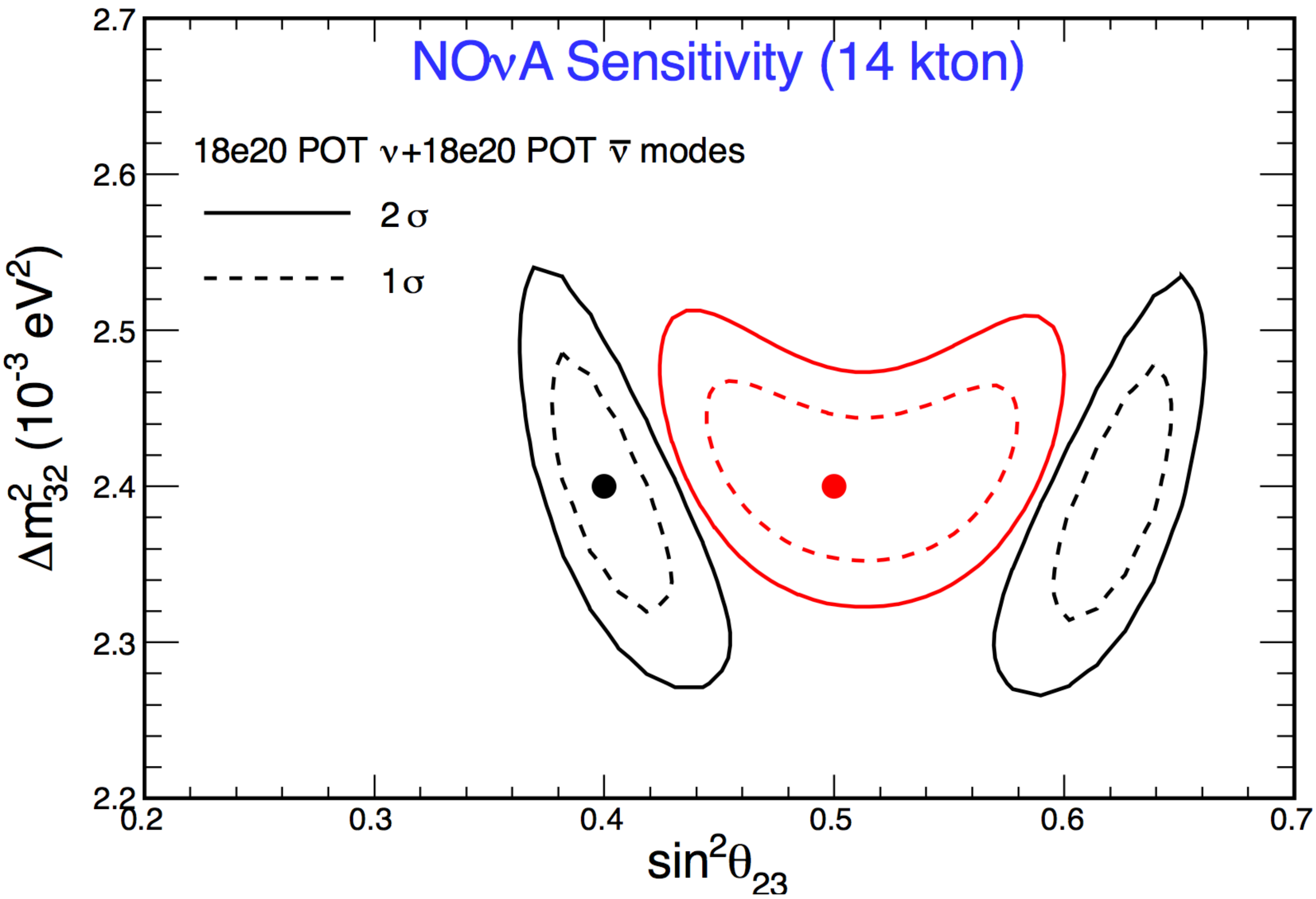
ν_μ Signal and Background Estimates

	Simulation					Data	
Cut	Un-Osc. ν_μ	Osc. ν_μ	NC Bkg	Osc. ν_e	Beam ν_e	Cosmic Bkg	Total Bkg
All Events	669	127	380	37	10	19M	19M
Cosmic Veto	660	125	273	36	10.0	6M	6M
Containment	582	109	195	28	7.5	120k	120k
ν_μ CC ID	460	86	5	0.4	0.2	44k	44k
Cosmic Reject	398	**75**	4	0.3	0.1	1	**5.4**

- Exposure 6×10^{20} POT
- 14 kt total detector mass



ν_μ disappearance analysis at NOνA



Summary

- Physics reach:
  - NOνA has the best chance to investigate mass hierarchy.
  - Can determine θ_{23} octant.
  - Provide first information on CP violation.
  - Look at other physics such as supernova, neutrino magnetic moment, monopoles and non-standard neutrino interactions.

- NOνA is now taking physics data!
  - The NOνA detectors are complete.
  - The NuMI accelerator complex continues ramp to full power.
  - ν's observed in far and near detector.
  - Analysis tools are in place.
  - Demonstrated cosmic rejection 40 million to 1.
  - We are working towards first physics results in 2015.

Thank you!

Backup

Liquid Scintillator

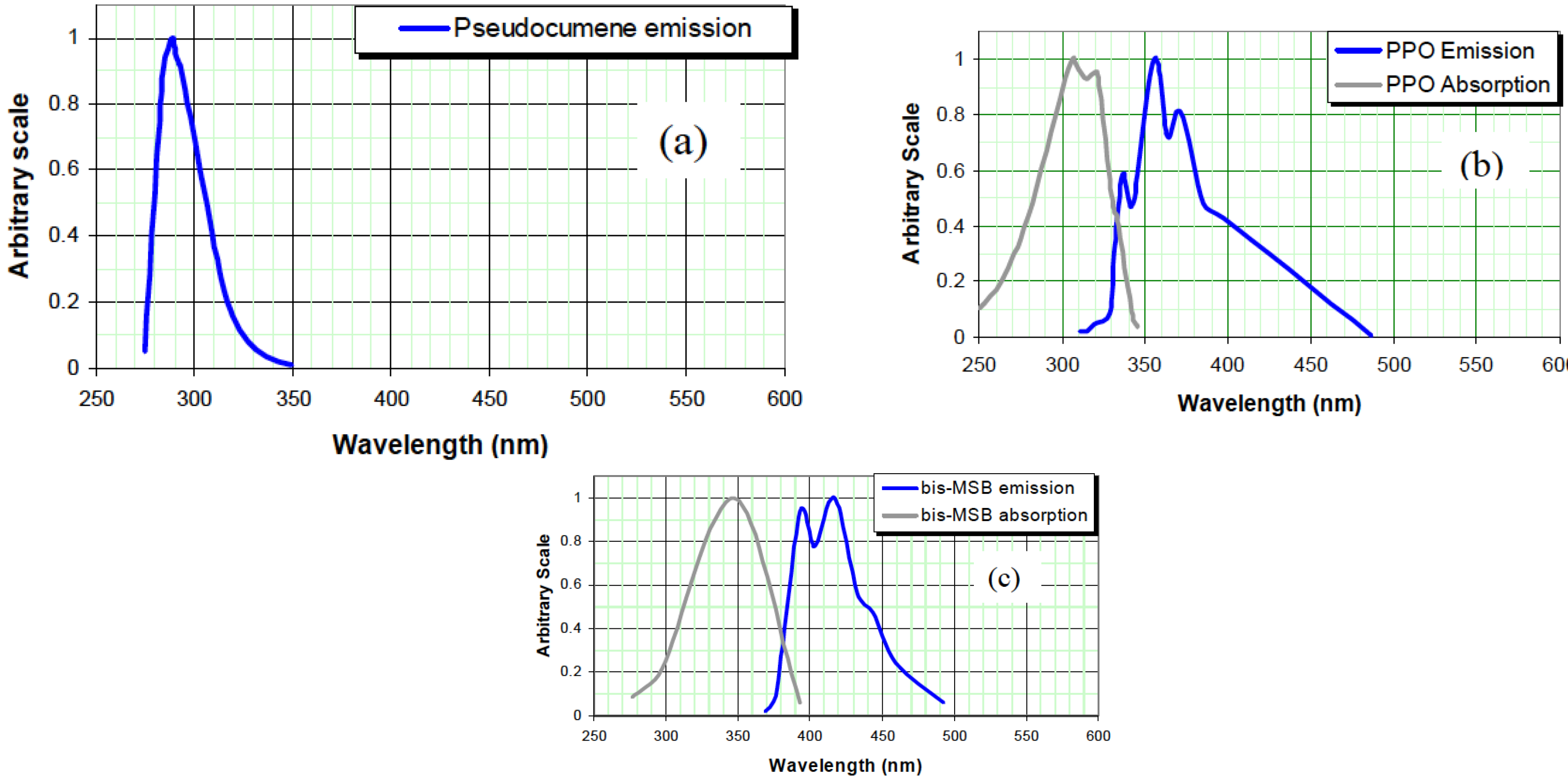
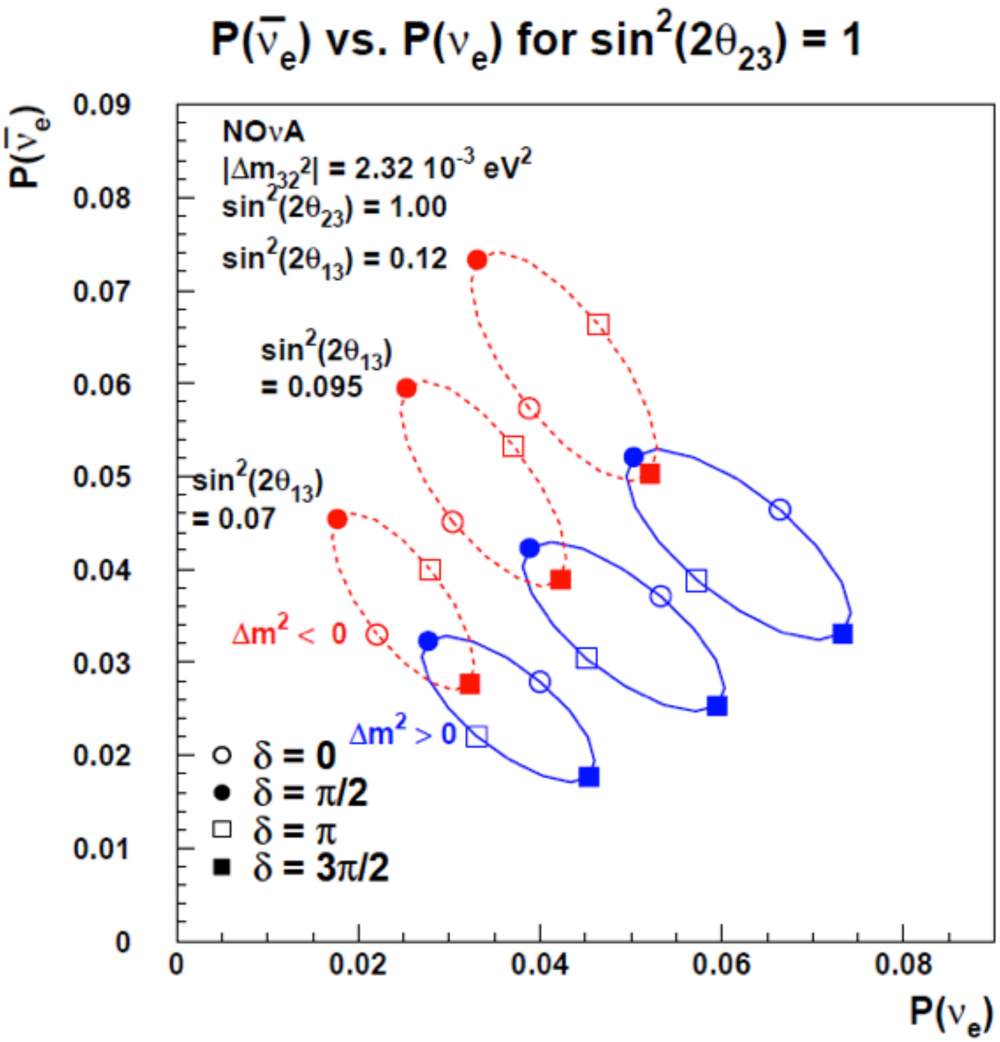


Fig. 10.1: Light production by liquid scintillator. The emission spectrum of the primary scintillant psueudocmene when traversed by an ionizing particle is shown in (a); the absorption and emission spectrum of the first waveshifter PPO is shown in (b); the absorption and emission spectrum of the second waveshifter bis-MSB is shown in (c).

$P(\nu_e)$ vs. $P(\overline{\nu}_e)$ with different θ_{13} assumptions



Mock data challenge– ν_e analysis

Mock data challenge for the first 3 years' data taking. Hidden physics parameters were chosen and all truth information was stripped from the Monte Carlo files. The two analysis techniques got identical results, which agreed with the truth within about 1σ.