NOvA: Electron Neutrino Appearance Analysis and Future

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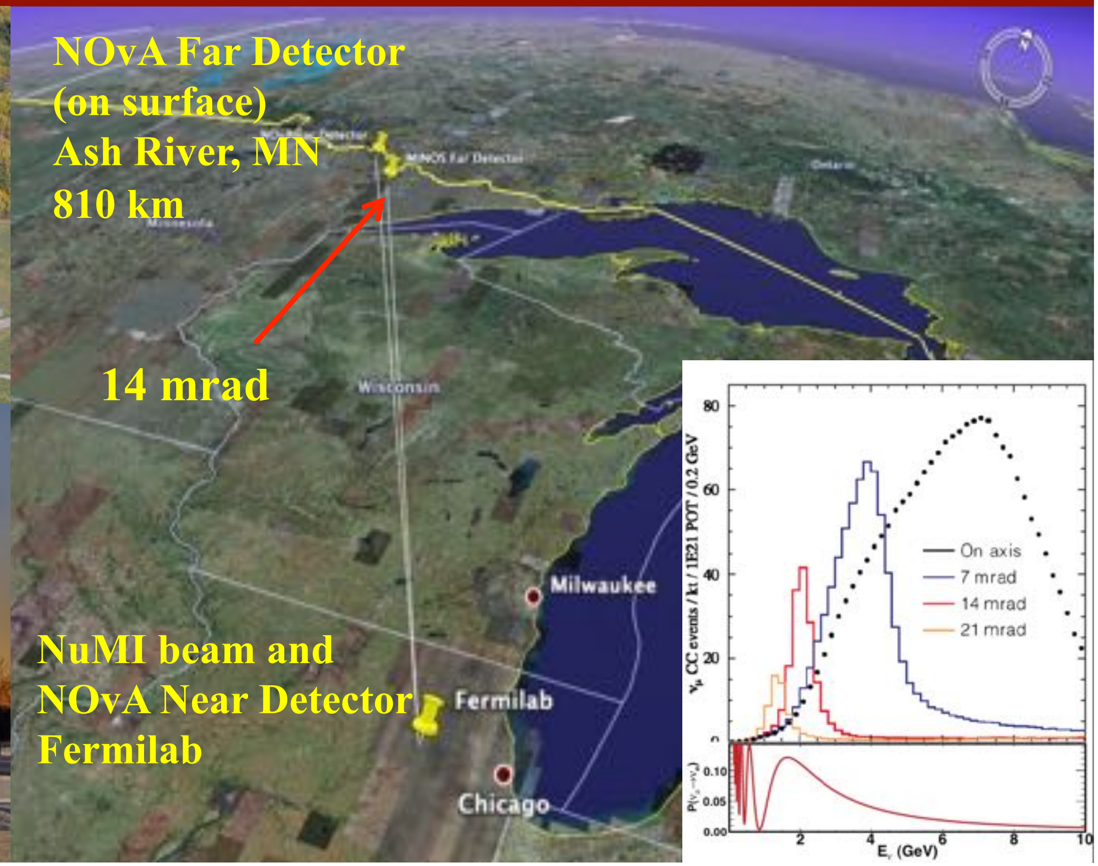
NuMI Off-Axis ν_e Appearance Experiment



- NOνA 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. The baseline is sensitive to mass order.
- Far/Near detector is sited 14 mrad off-axis to produce a narrow-band beam around the oscillation maximum region.

NOνA Physics Goals

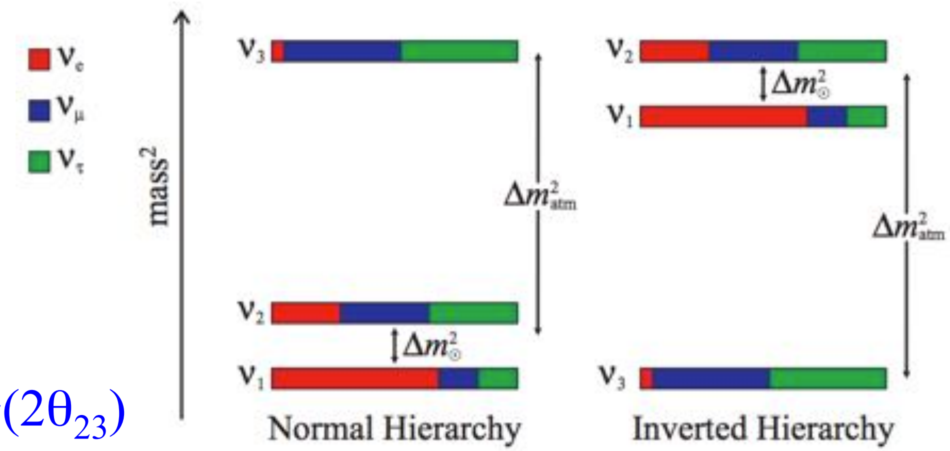
Measuring ν_e appearance probability and ν_μ disappearance probability with ν_u and anti-ν_u beam.

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 $|\Delta m_{32}^2|$, $\sin^2(2\theta_{23})$



As well as:

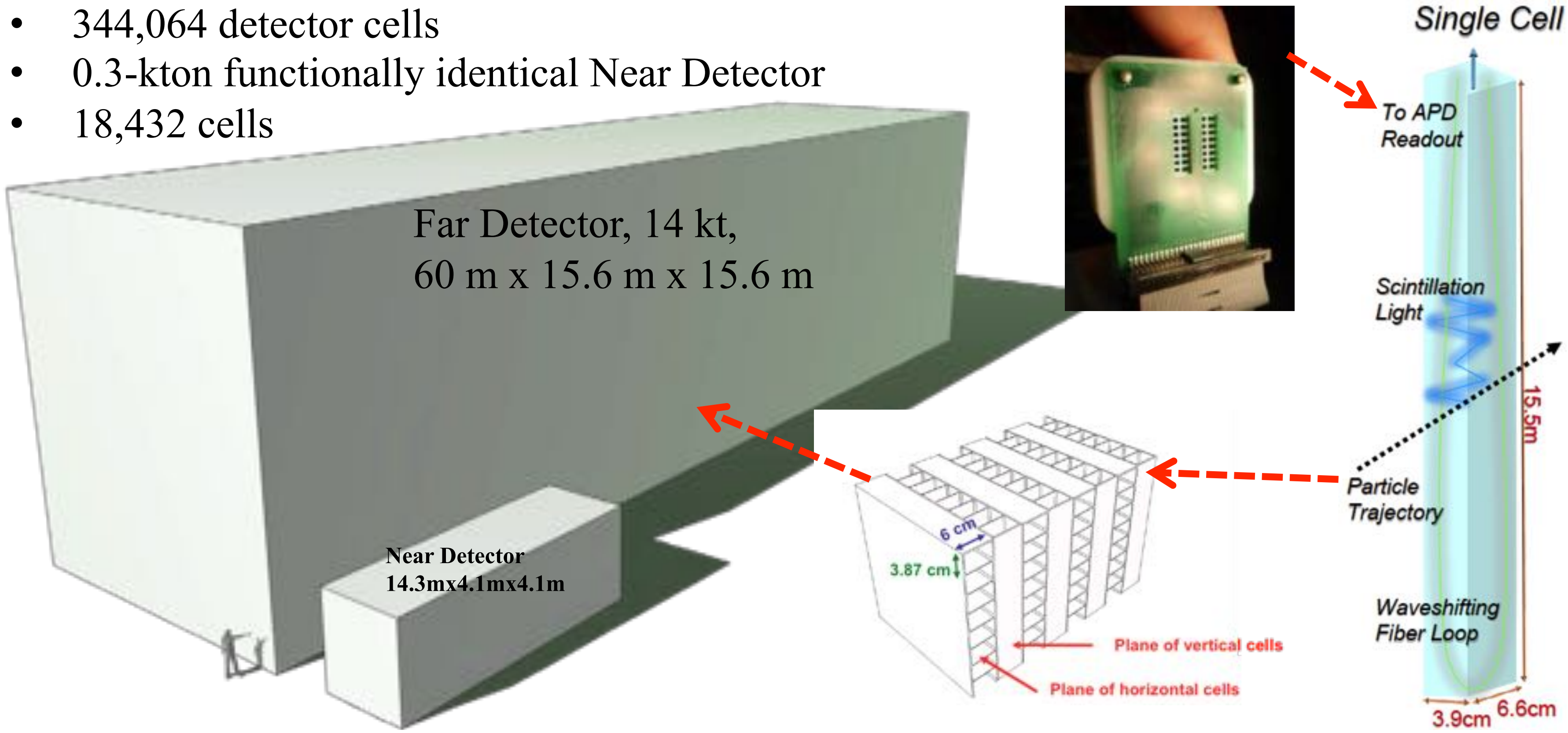
- ν cross sections.
- Neutrino magnetic moment.
- Supernova.
- Monopoles.
- Sterile neutrinos.
- Non-standard neutrino interactions.

First Analysis status

- Preparing the first ν_e and ν_μ analysis.
- Blind analysis: blinding PID for FD neutrino data. Use FD cosmic data and ND data for Data/MC study and background study.
- NuMI Beam has ramped up to 420kW, using 1.9E20 POT FD data for the first analysis.
- All reconstruction/analysis tools are in place.
- Cosmic rejection study has been done.
- Data/MC study with ND and cosmic data has been done.
- About to open the box, will release result late summer/early fall.

The NOνA Detectors

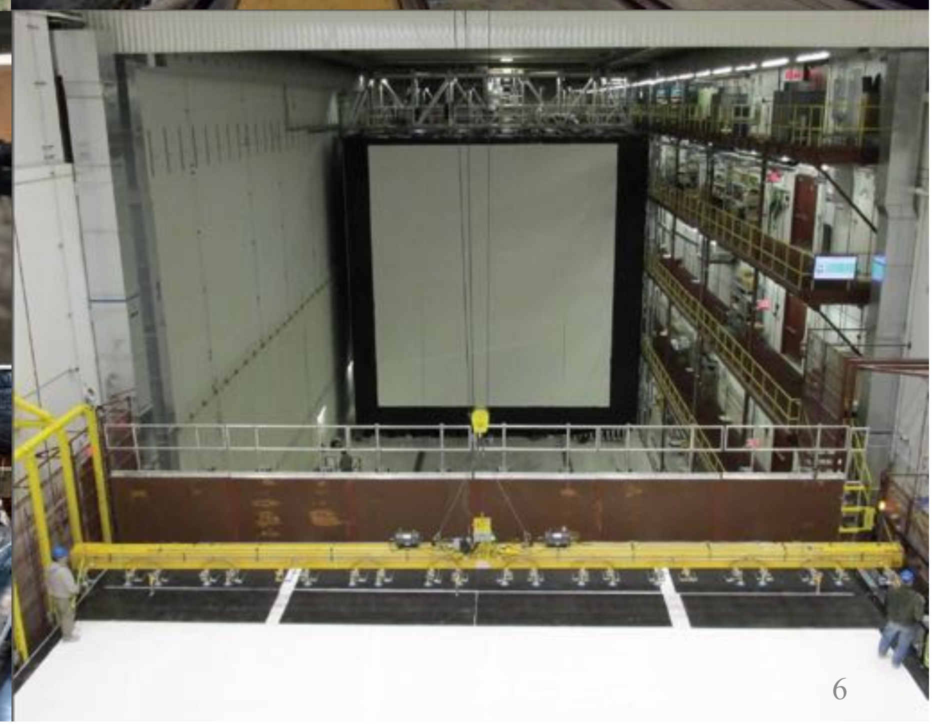
- 14-kton Far Detector
- 344,064 detector cells
- 0.3-kton functionally identical Near Detector
- 18,432 cells

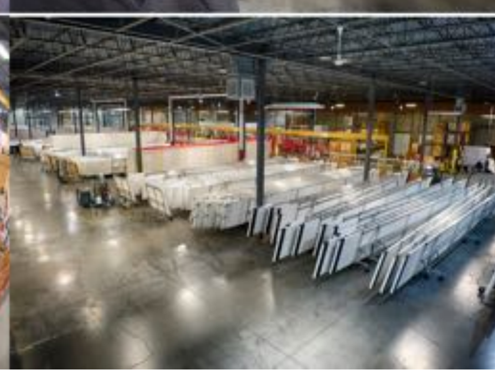


- Composed of PVC modules extruded to form long tube-like cells : 16m long in FD, 4m ND.
- Each cell is filled with liquid scintillator and has a loop of wavelength-shifting fiber routed to an Avalanche Photodiode (APD).
- Cells arranged in planes, assembled in alternating planes of vertical and horizontal extrusions.
- Each plane just 0.15 X_0. Great for e^- vs π^0 .

NOvA construction (2009-2014)

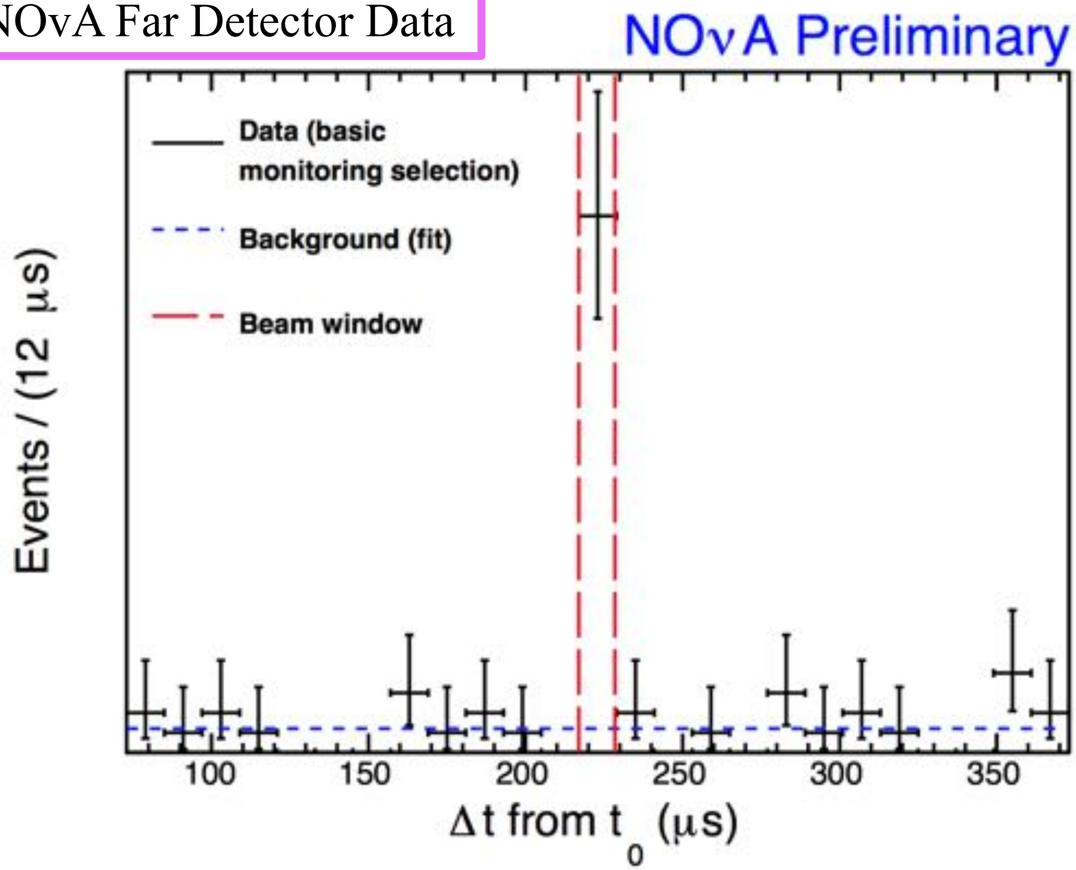
As of September 4th 2014, both far and near detectors are fully commissioned.

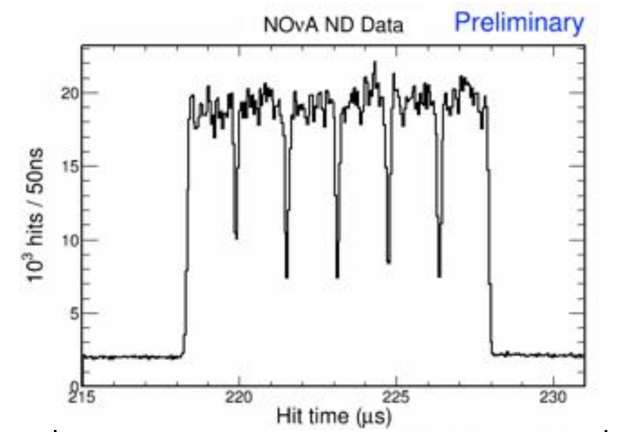


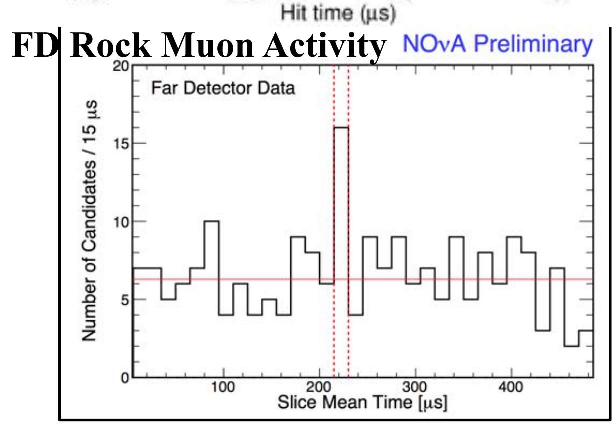


Far/Near Detector ν timing

NOvA Far Detector Data

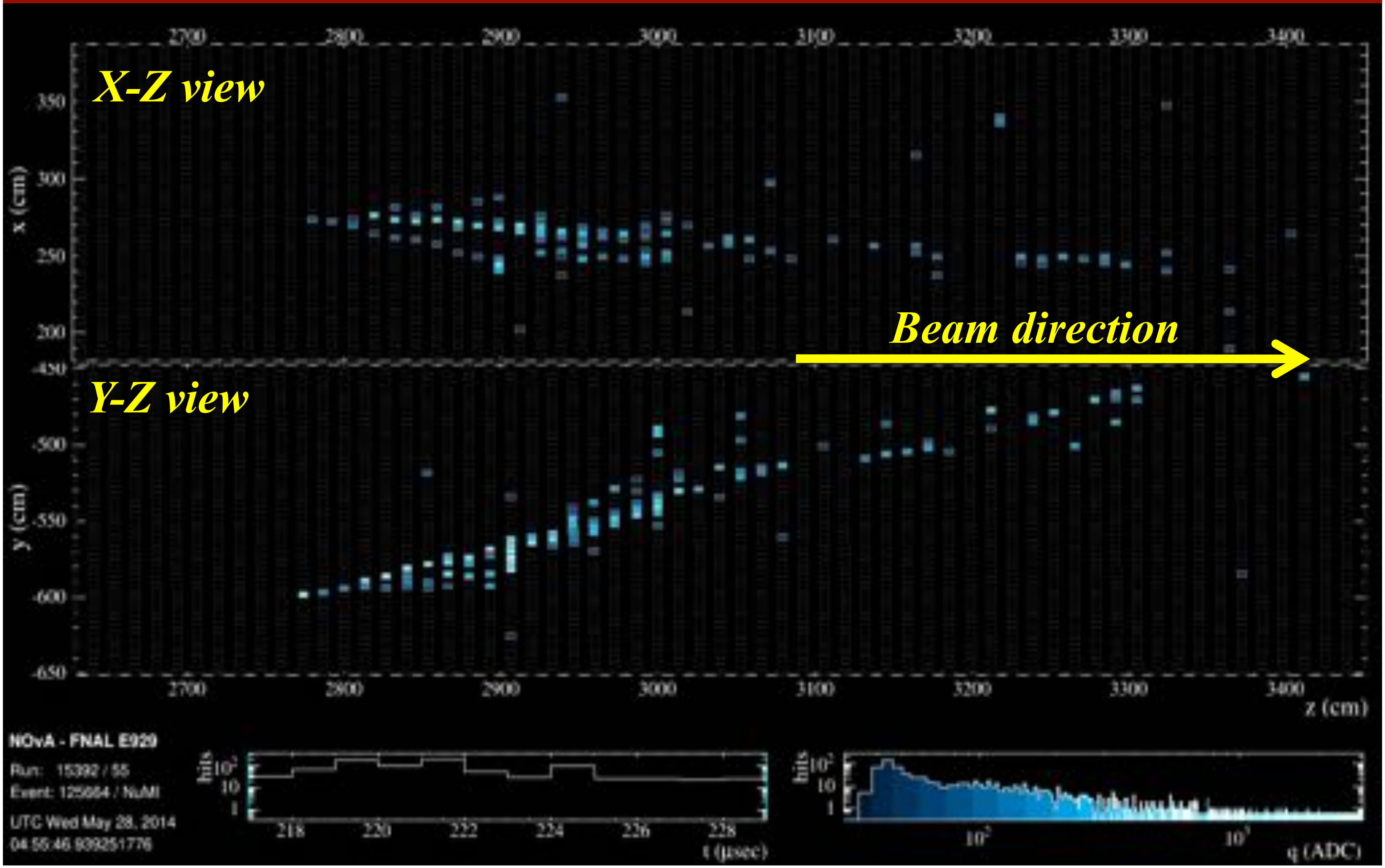




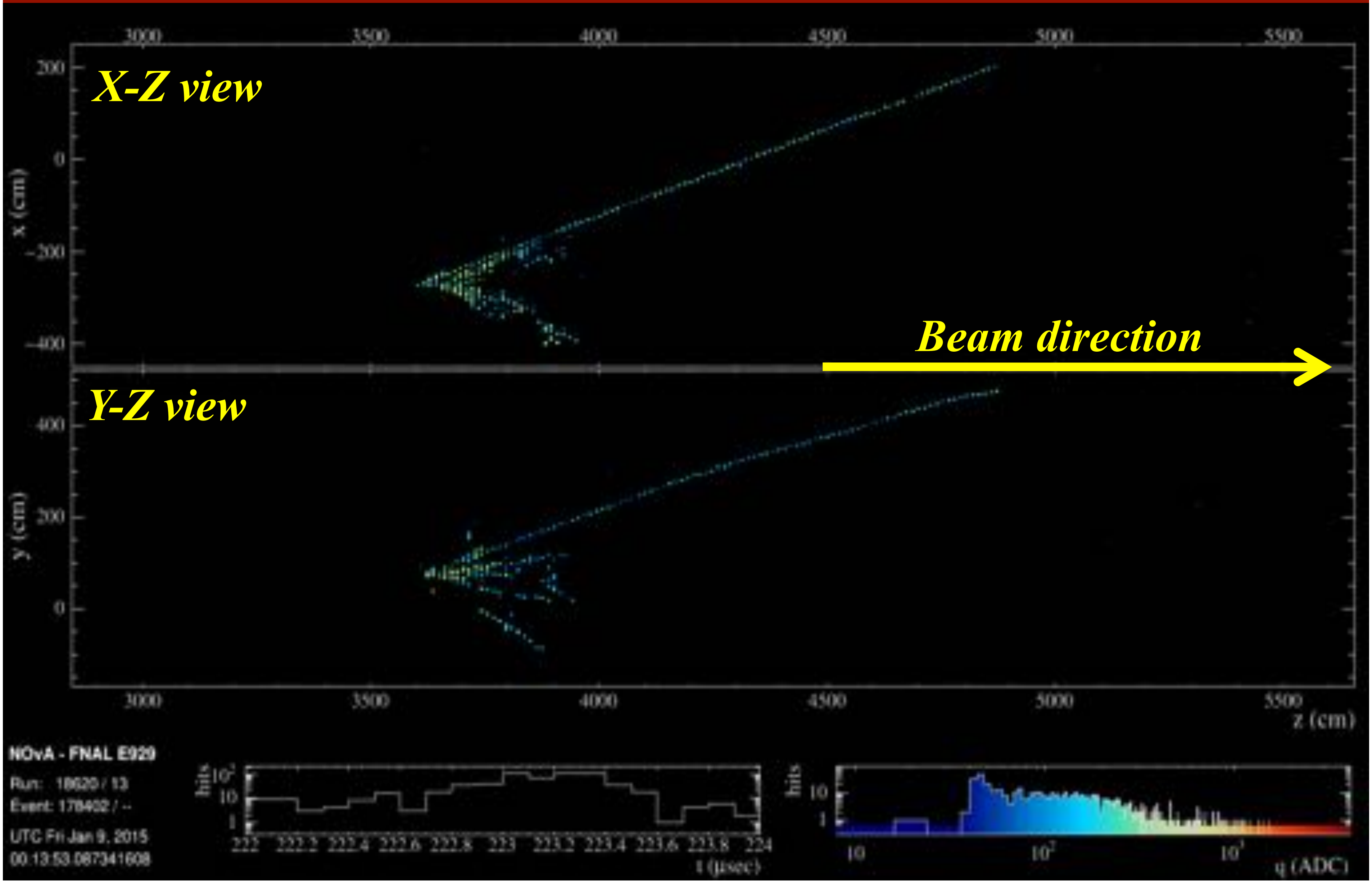


- Neutrino candidates are observed in both near and far detectors.
- Far Detector neutrino candidates blow up of timing peak, showing agreement with expected spill times as measured at our Near Detector at FNAL.
- Both FD & ND are completed. NOvA is now taking data for physics.

Neutrino candidate in FD

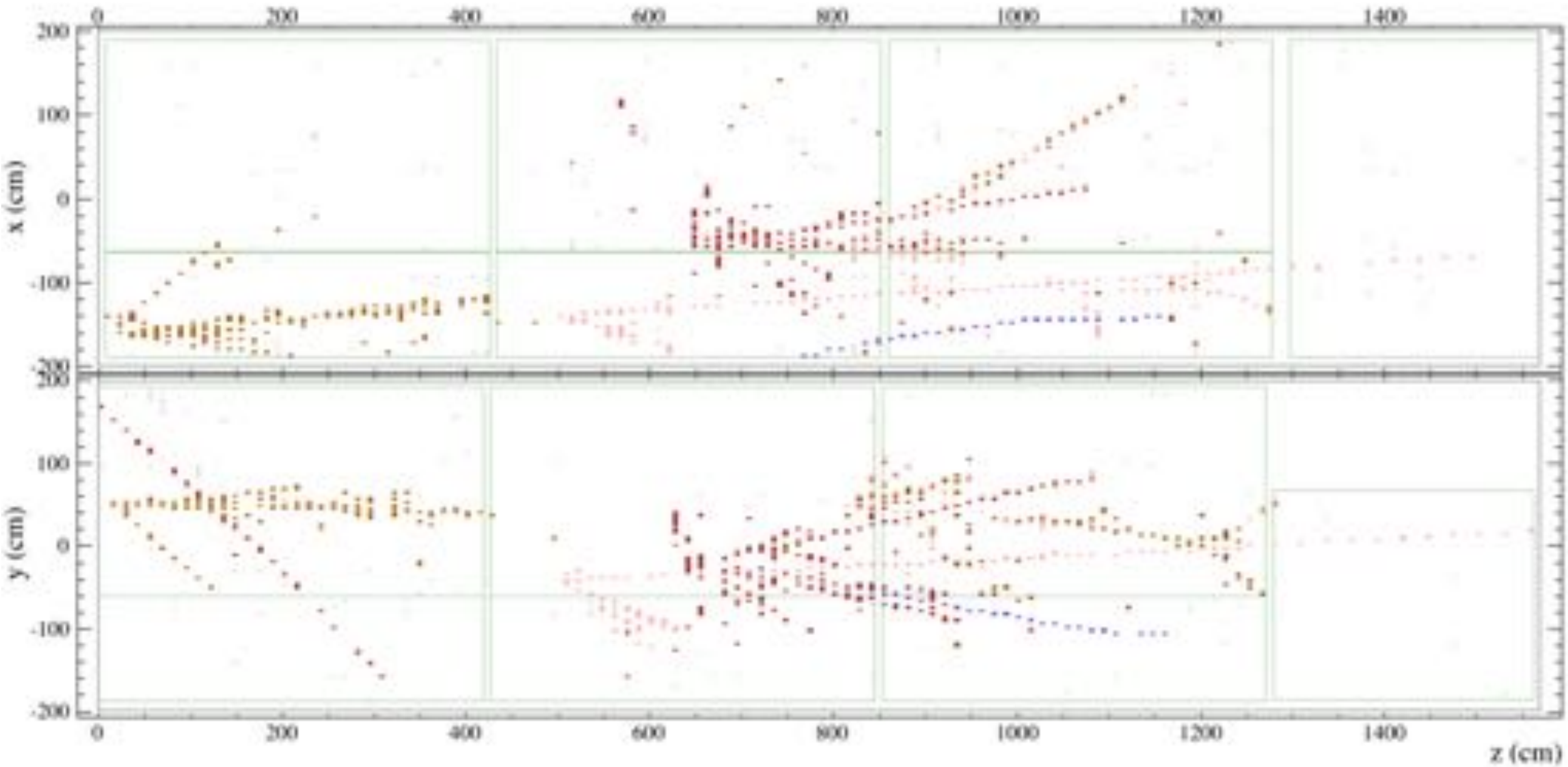


Neutrino candidate in FD



Neutrino candidates in ND

Because beam intensity is much higher in the near detector, there are more than one neutrinos in one trigger window.



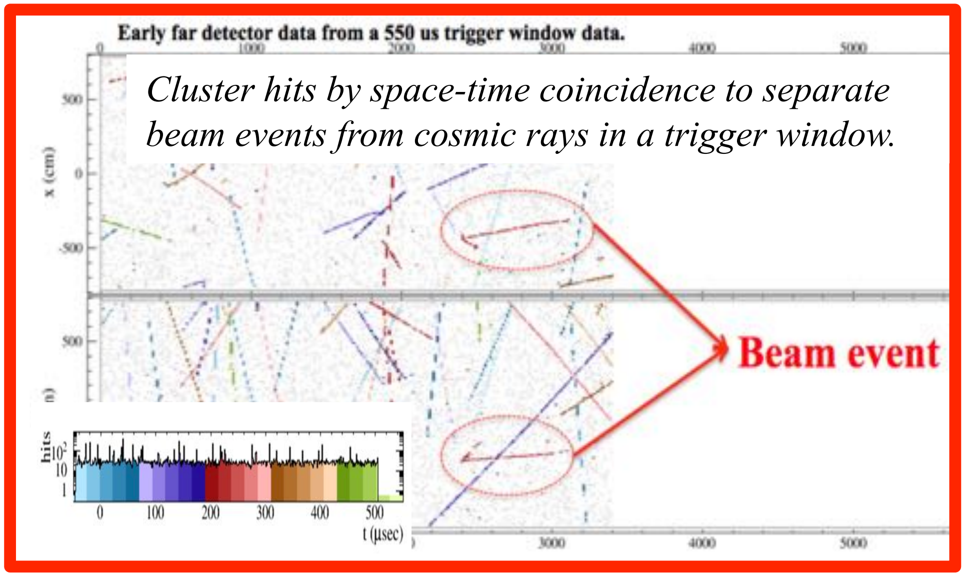
ν_e appearance analysis

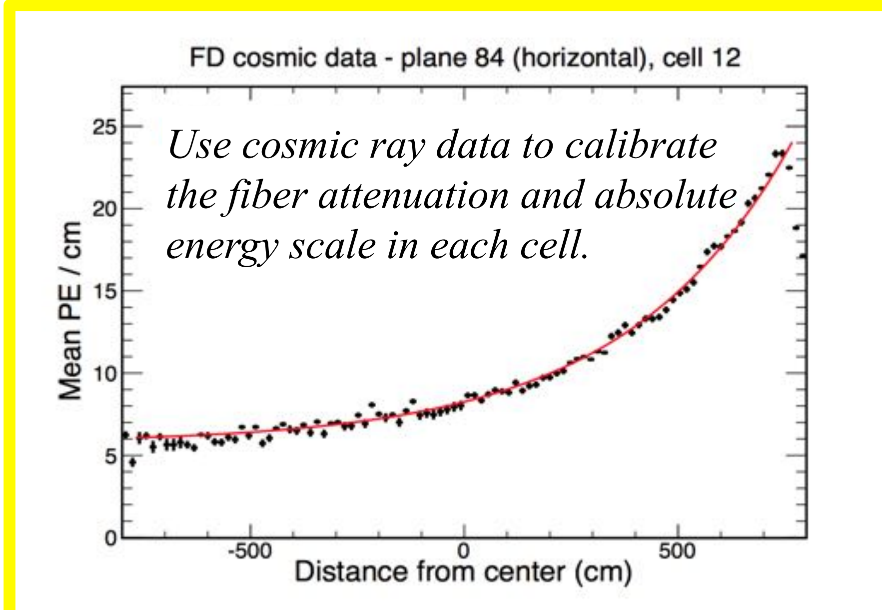
- ν_e event reconstruction: clustering, calibration, reconstruct event vertex and prongs (showers).
- ν_e identification: identify ν_e in $\nu_\mu \rightarrow \nu_e$ oscillation
  - ANN (LID): Artificial neural network using shower shape based likelihood for particle hypotheses.
  - LEM: Matching events to a Monte Carlo library.
- Decomposition: To isolate the NC, CC, and Beam-ν_e components in the Near Detector
- Extrapolation: extrapolate each of these components to the Far Detector.
- Sensitivity studies.

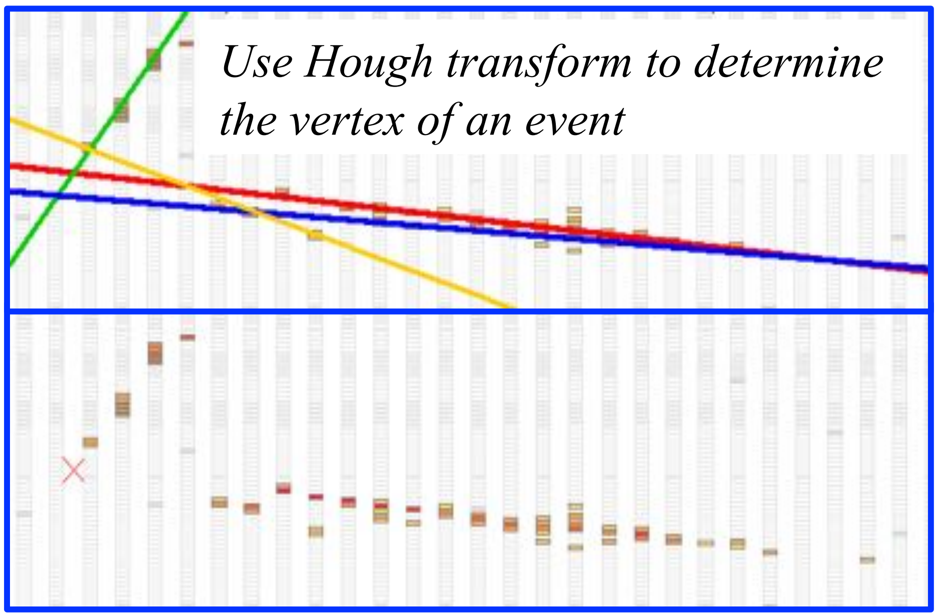
PID distributions are blinded for the FD neutrino data, look at ND data and FD cosmic data before we open the box.

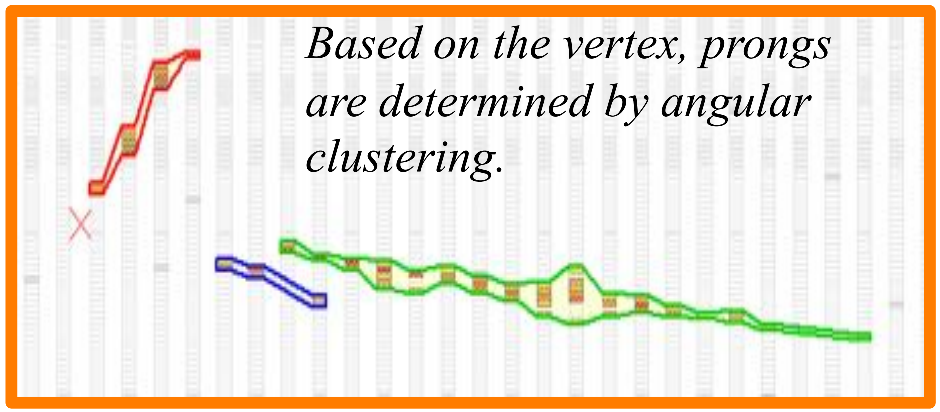
- The first analysis is a cut-and-count analysis, using $1.9\text{x}10^{20}$ POT Far Detector data (1/3 standard running year). Expect to have ~3σ (S/sqrt(B)) sensitivity to observing ν_μ-ν_e oscillations.

Event reconstruction







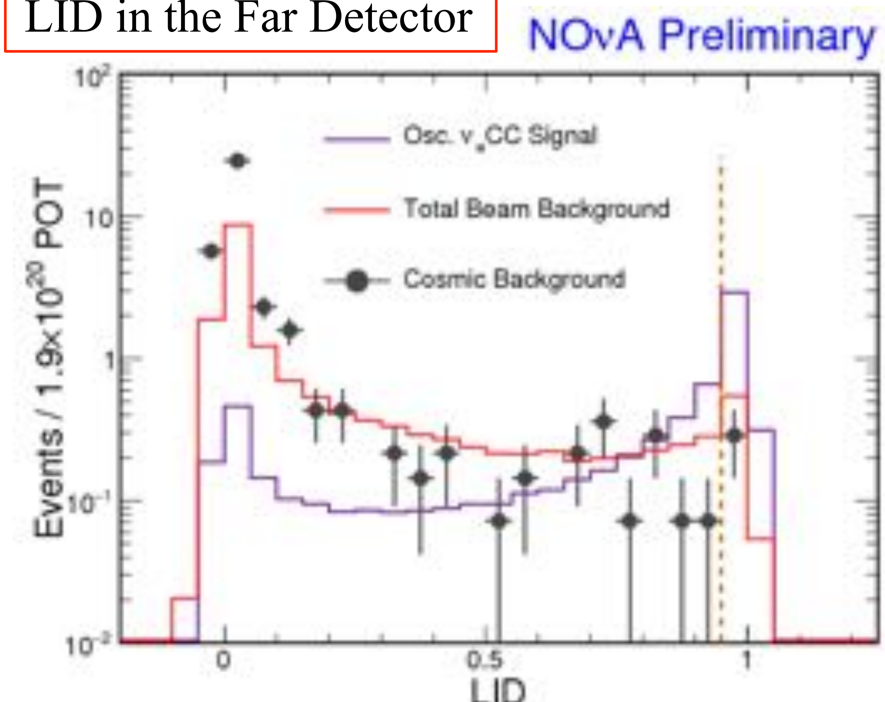


Prong energy profile, vertex and event topology go in to PID.

Far Detector Event Selection

	Cosmic background, LID	Cosmic background, LEM
No cut	1.49E+07	1.49E+07
Reconstruction Quality	5.34E+06	6.72E+06
containment	638325	967101
Cosmic rejection	5409.79	5791.31
preselection	37.19	59.06
PID	0.29	0.29

LID in the Far Detector



Because the NOvA FD is on surface, the rejection of cosmic rays is extremely important.

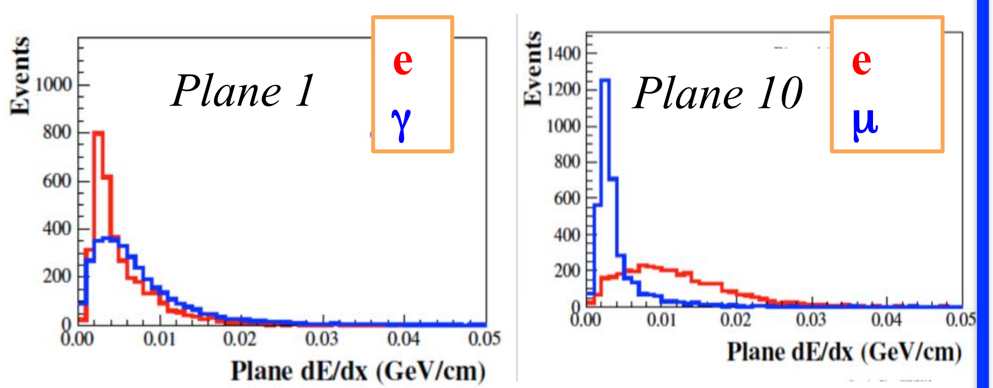
Three simple cuts are used to reject the cosmic induced backgrounds prior to PID

- 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 – assure reconstruction quality

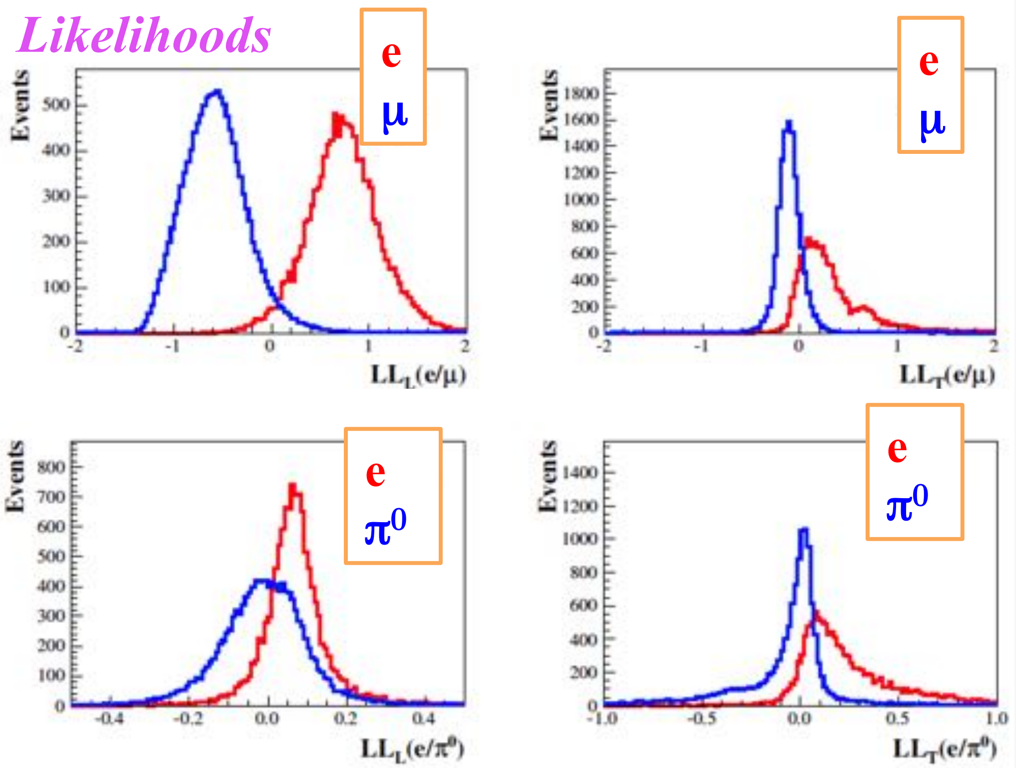
Achieves 40 million to 1 cosmic rejection.

ν_e identification (LID)

dE/dx in a plane



Likelihoods

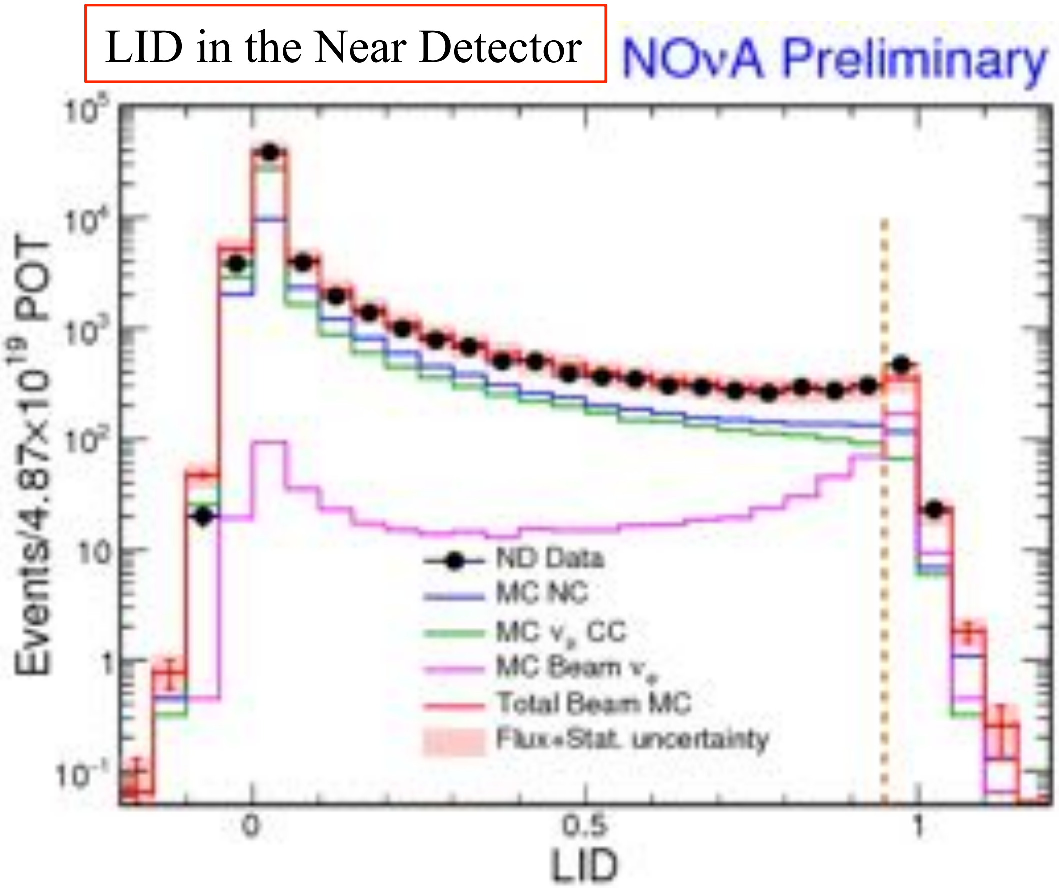


- For an unidentified particle, we compare its dE/dx with the expected dE/dx histograms by each plane and transverse cell index to construct the probability and likelihood for each particle hypotheses. In this way we can describe the 3-D development for a shower in detail.
- Summing over these plane-by-plane and cell-by-cell likelihoods we have overall longitudinal and transverse likelihoods for each type of particle.
- The difference of log-likelihoods indicates the identity of the particle, for example: LL(e/μ)=LL(e)-LL(μ).

ν_e identification (LID)

- Particle likelihoods, amongst other event topology variables, are used as inputs to an Artificial Neural Net (ANN) for the final PID.
- Selection based on containment and topology to select ND background similar to Far Detector.
- Near Detector data is decomposed in energy bins and then extrapolated with oscillation weights into a Far Detector predicted spectrum.

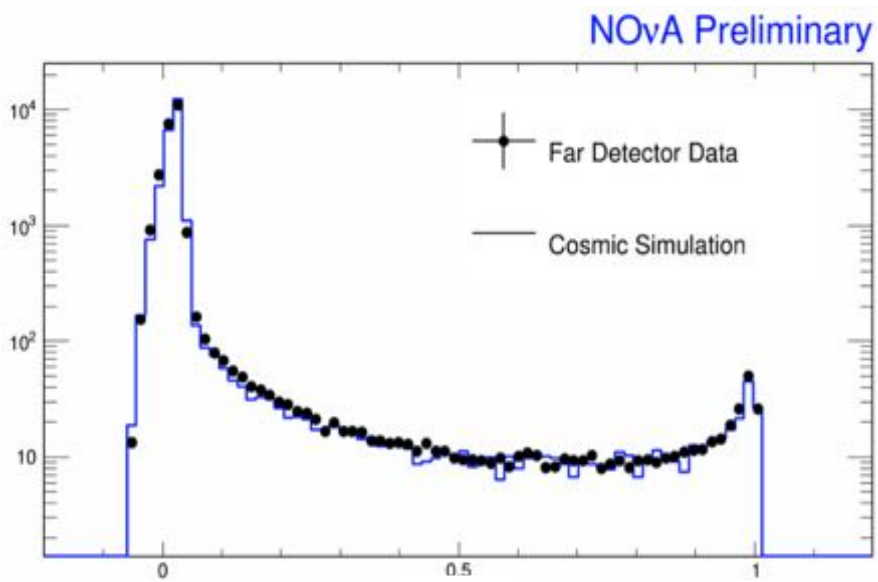
LID in the Near Detector



Data/MC comparison

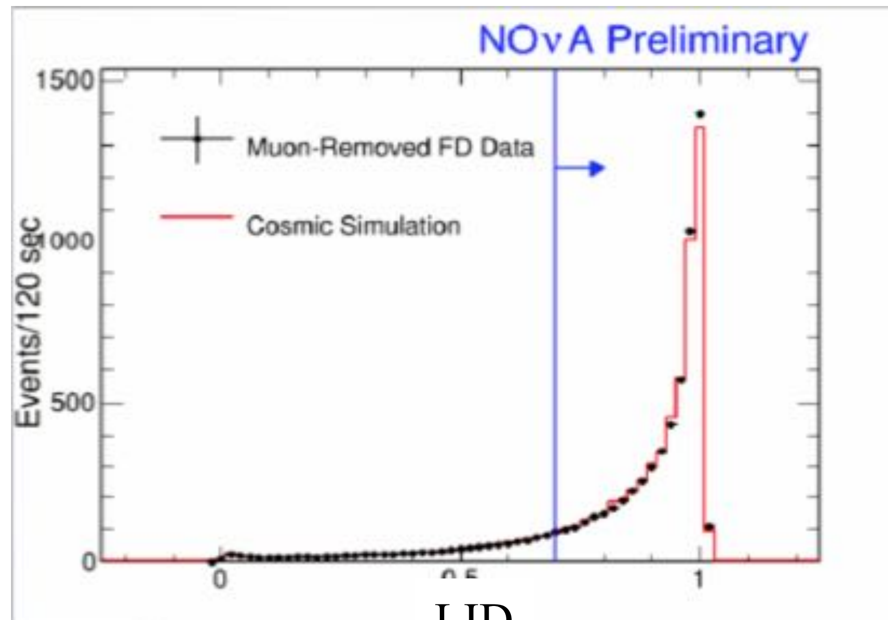
- Using real cosmic ray data for comparison, we verify our simulation and detector modeling.
- Reconstruction variables and PID output has been validated for muon in cosmic rays.

LID Data/MC for cosmic muon in FD



LID

LID Data/MC for cosmic EM showers in FD



LID

Expected First ν_e Appearance Result (1.936×10^{20} POT)

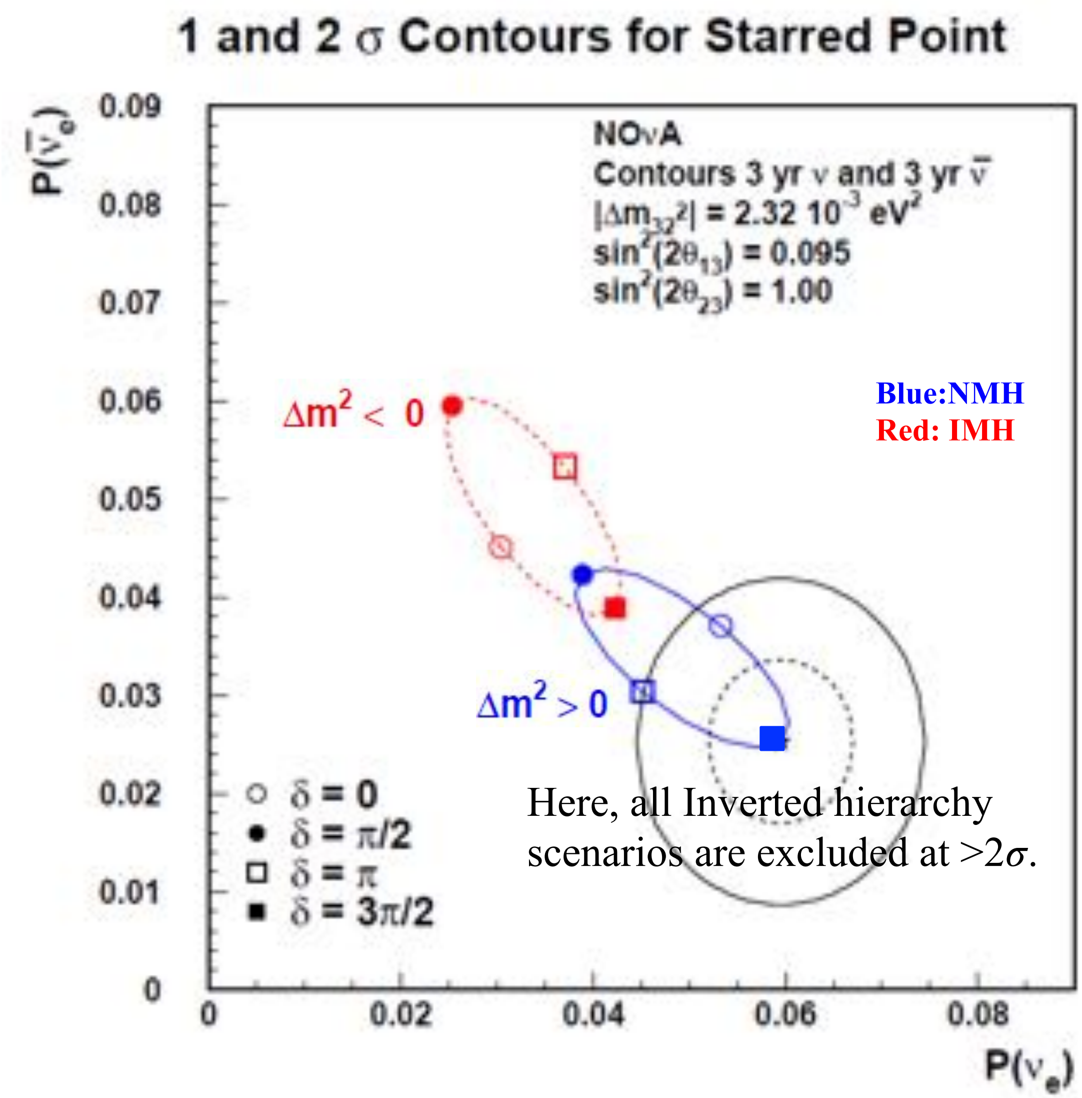
Predictions of neutrino signal and background event counts come from Near Detector data extrapolated the Far Detector scaled to a full detector equivalent of $1.9\text{x}10^{20}$ POT for the analysis period after preselection and PID cuts have been applied. Cosmic background data has been scaled to 96 live-seconds.

Representative oscillation weight chosen (no matter effect, $\delta CP = 0$, $\sin^2 2\theta_{13} = 0.095$)

	Osc. ν_e CC	Total bkg.	ν_μ CC	NC	Beam ν_e CC	Cosmic data
LID	3.25	1.02	0.05	0.32	0.33	0.29
LEM	3.48	1.14	0.05	0.41	0.36	0.29

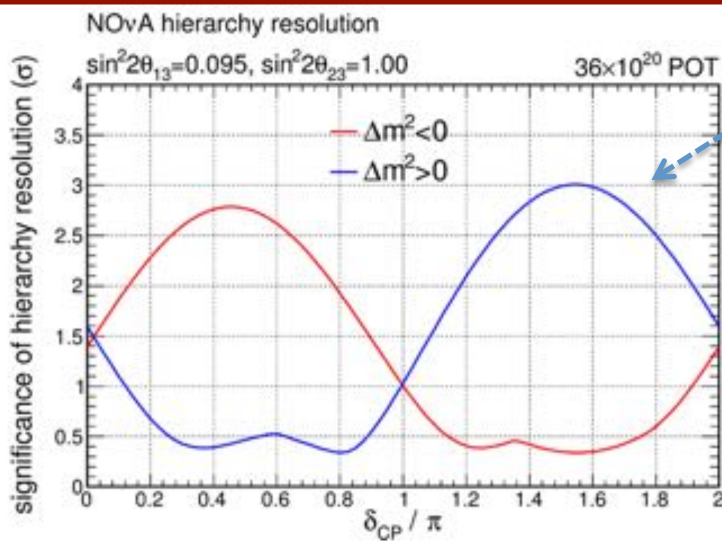
Plan to open box this summer - results late summer/early fall

Resolve mass hierarchy with $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



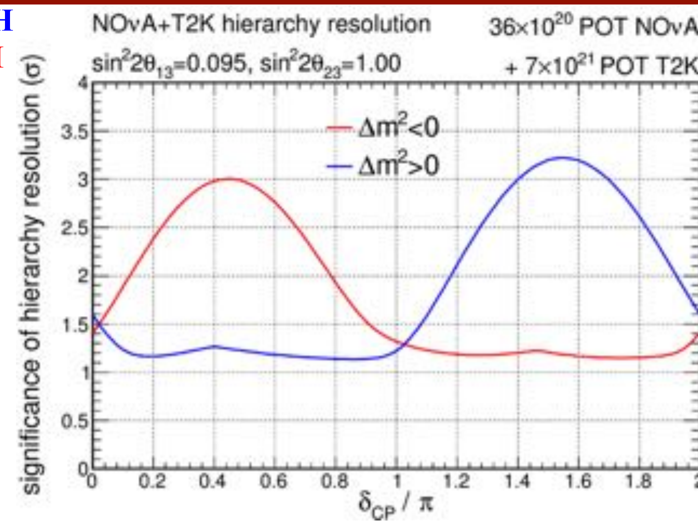
- Because the $P(\nu_e)$ and $P(\bar{\nu}_e)$ depend on mass hierarchy and δ_{CP} in different ways, a measurement of $P(\nu_e)$ vs. $P(\bar{\nu}_e)$ allows resolving the mass hierarchy and provide information on δ_{CP}.
- The precision of probabilities measurement depends on θ_{13}.
- $P(\nu_e)$ vs. $P(\bar{\nu}_e)$ also depends on the octant of θ_{23}.

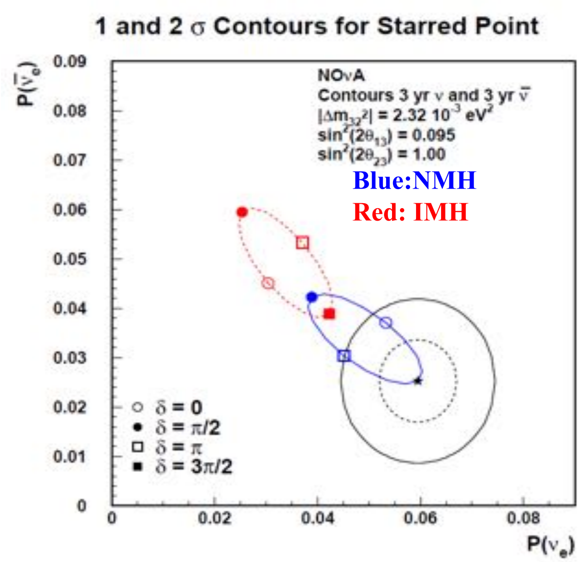
Significance to resolve mass hierarchy

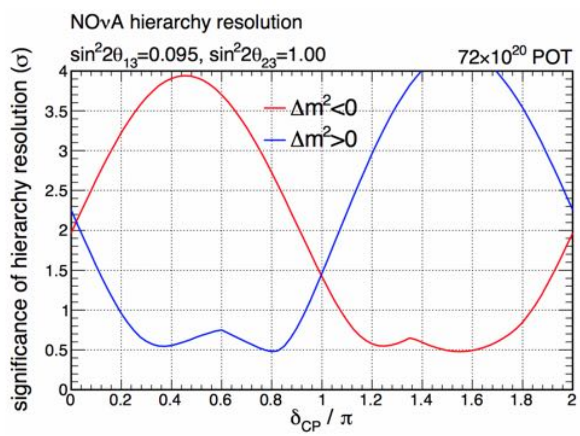


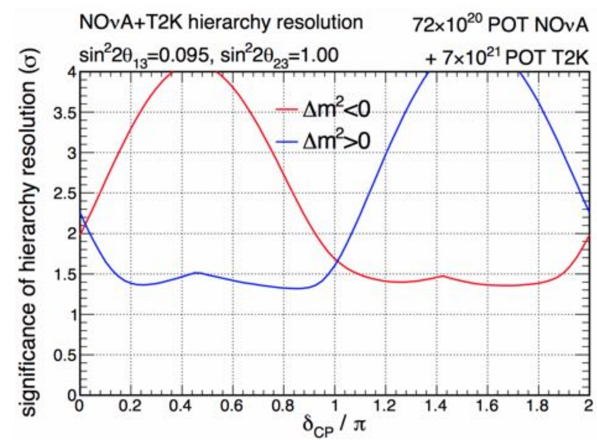
Blue:NMH
Red: IMH

T2K prefer this side

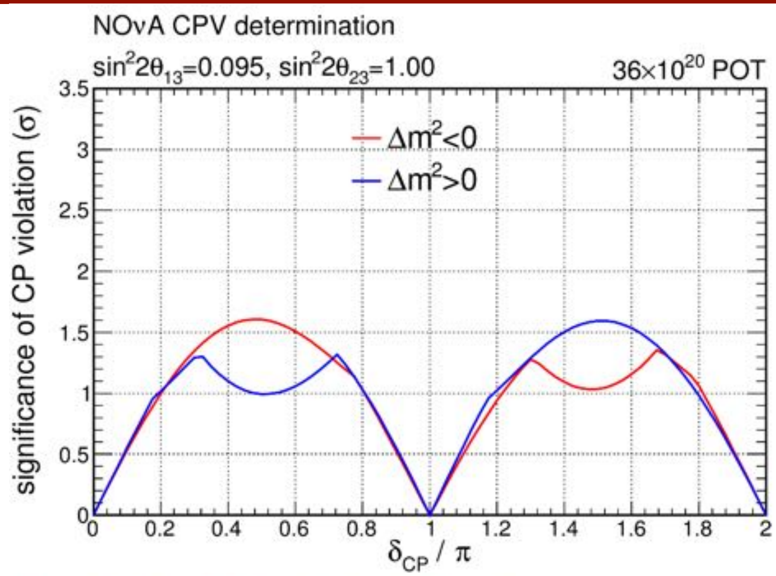








CP violation phase



Blue:NMH
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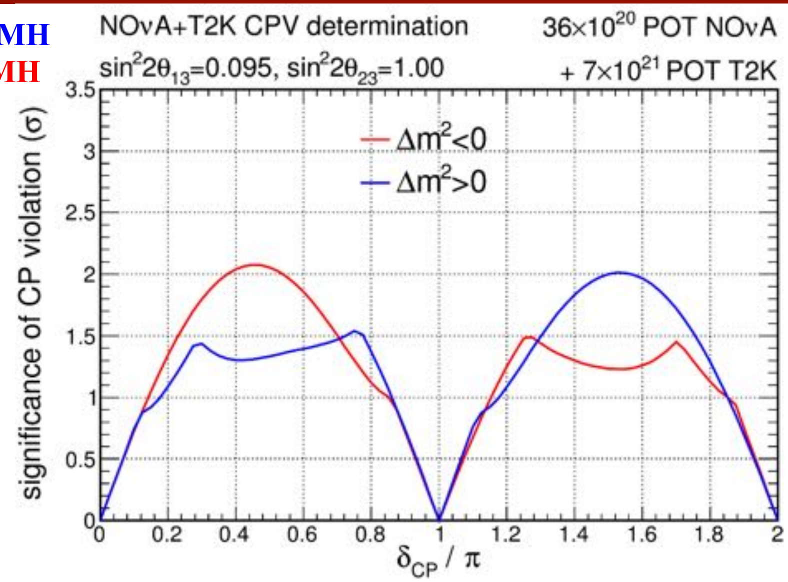
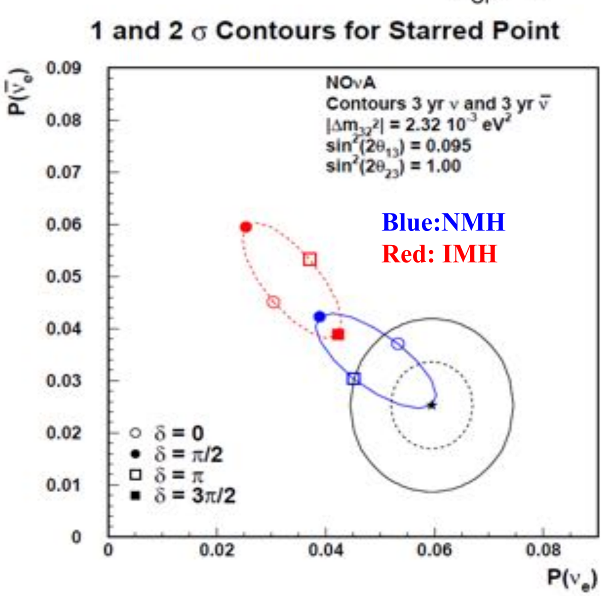
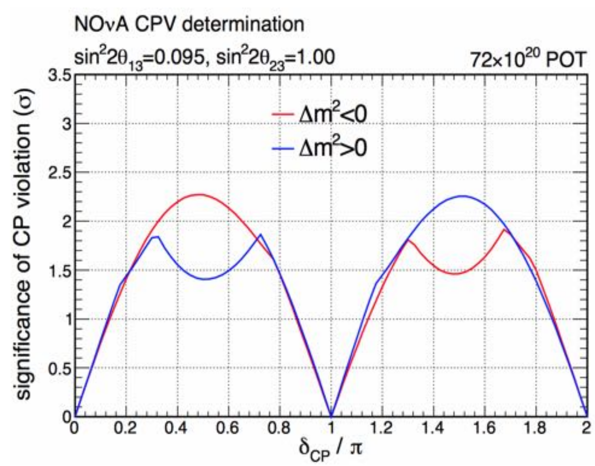
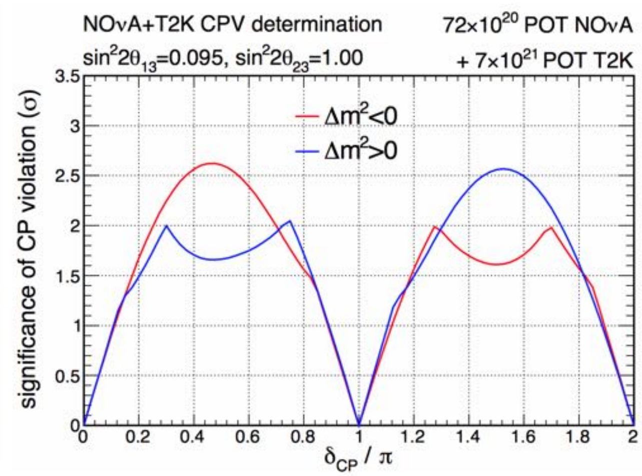






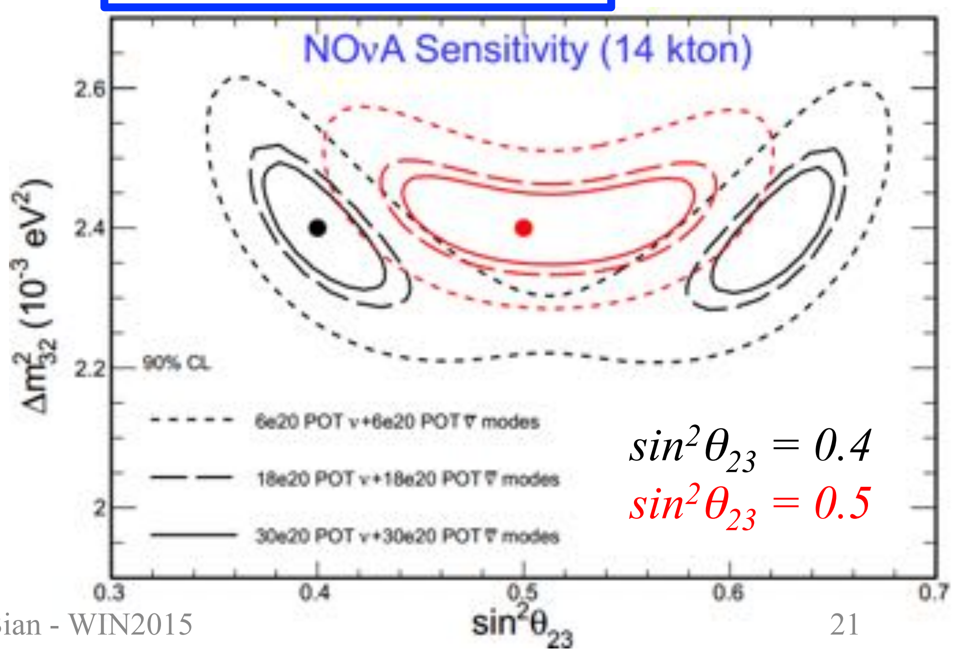


ν_μ disappearance analysis at NOvA

Expected Result for 6×10^{20} POT

	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**

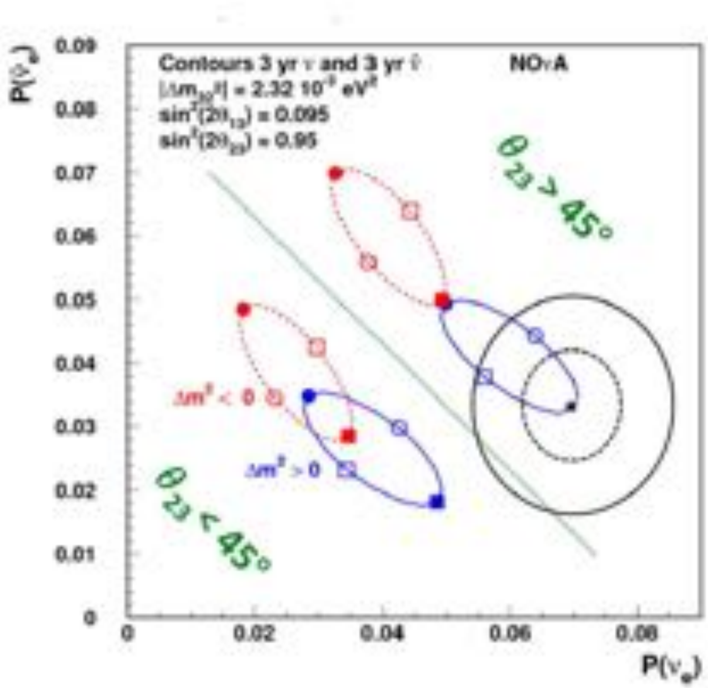
Standard NOvA running

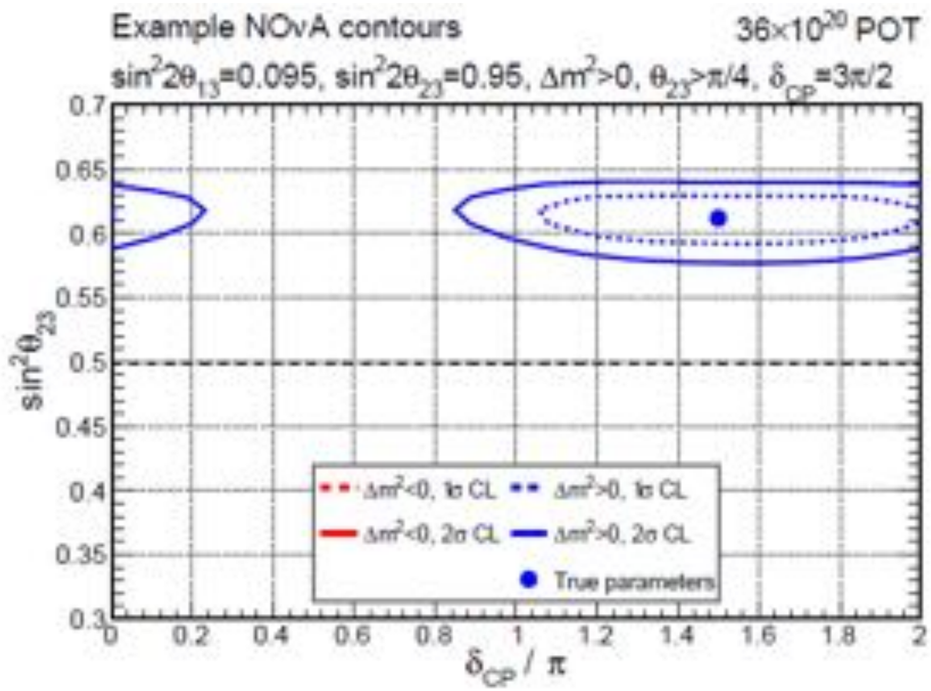


Multiple selection criteria:

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

Combined ν_e+ν_μ analysis for θ_{23} and Octant of θ_{23} (36×10^{20} POT running)





- If $\sin^2(2\theta_{23})$ is not maximal there is an ambiguity as to whether θ_{23} is larger or smaller than 45°.
- ν_μ disappearance can measure $\sin^2(2\theta_{23})$ but can not determine the sign of $\sin(2\theta_{23})$.
- The $\sin^2(\theta_{23})$ term is crucial in comparing accelerator to reactor experiments.
- 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.

Summary

- Physics reach:
  - NOνA has the best chance to investigate mass hierarchy.
  - Can determine θ_{23} octant.
  - Provide 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 NOvA detectors are complete.
  - The NuMI beam 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 late this summer/ early fall.

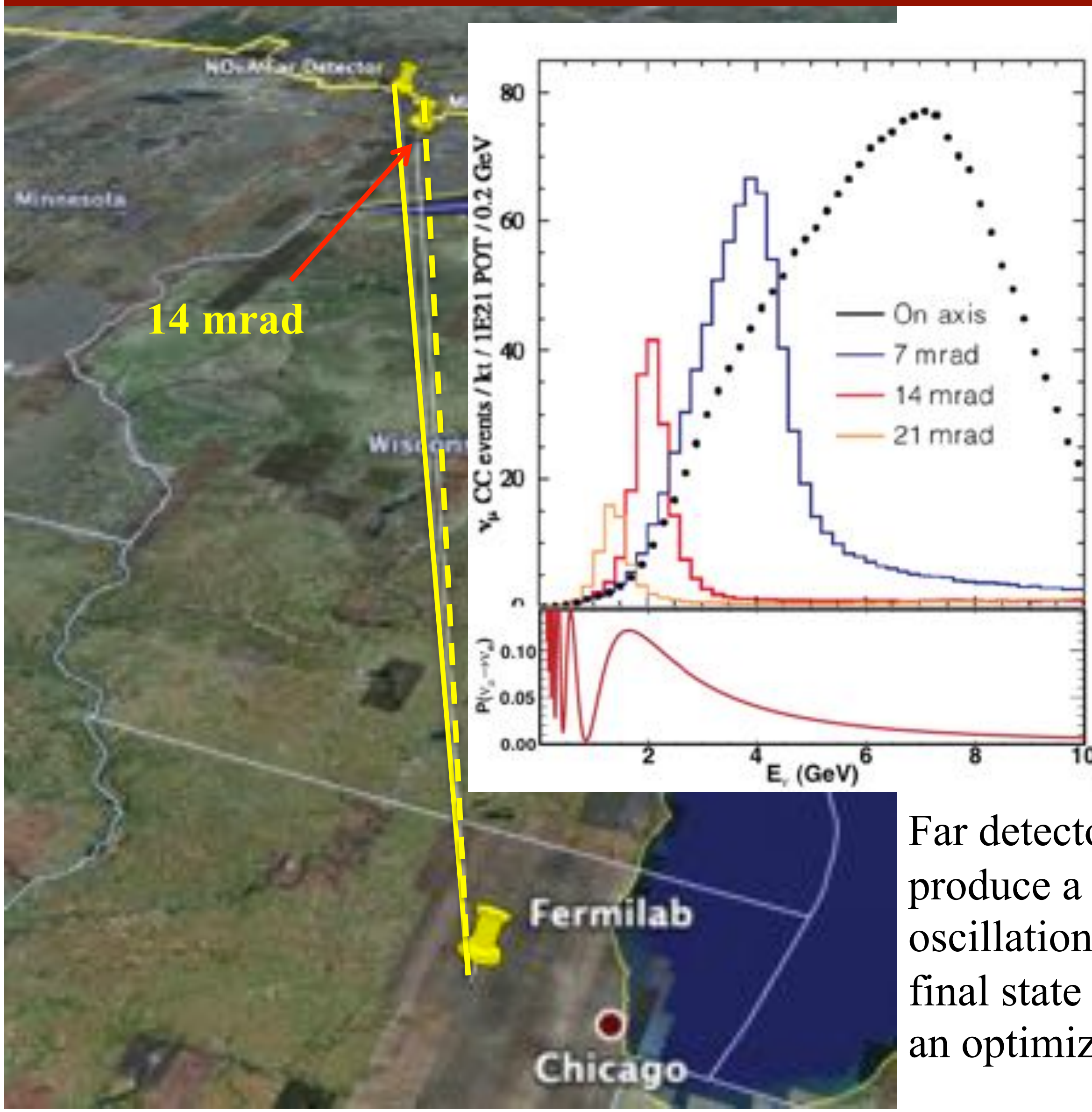
NOνA Collaboration

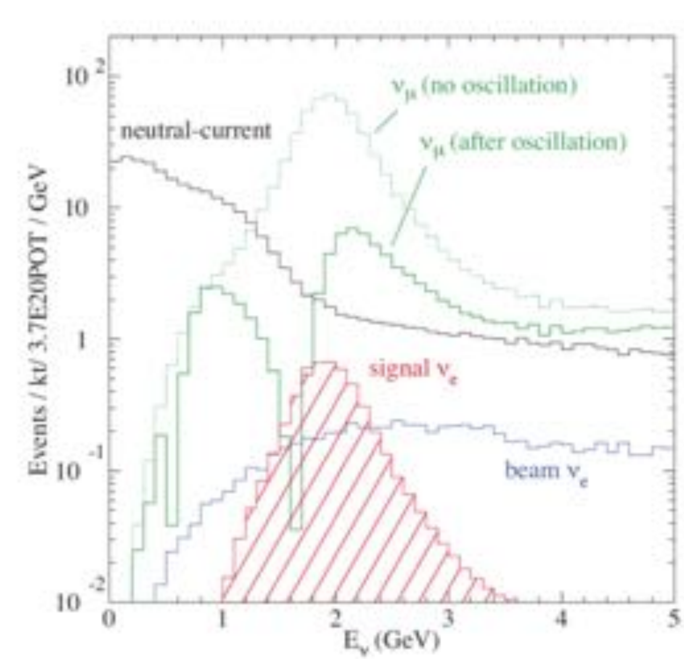
36 Institutions from 7 countries
181 collaborators

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

Backup

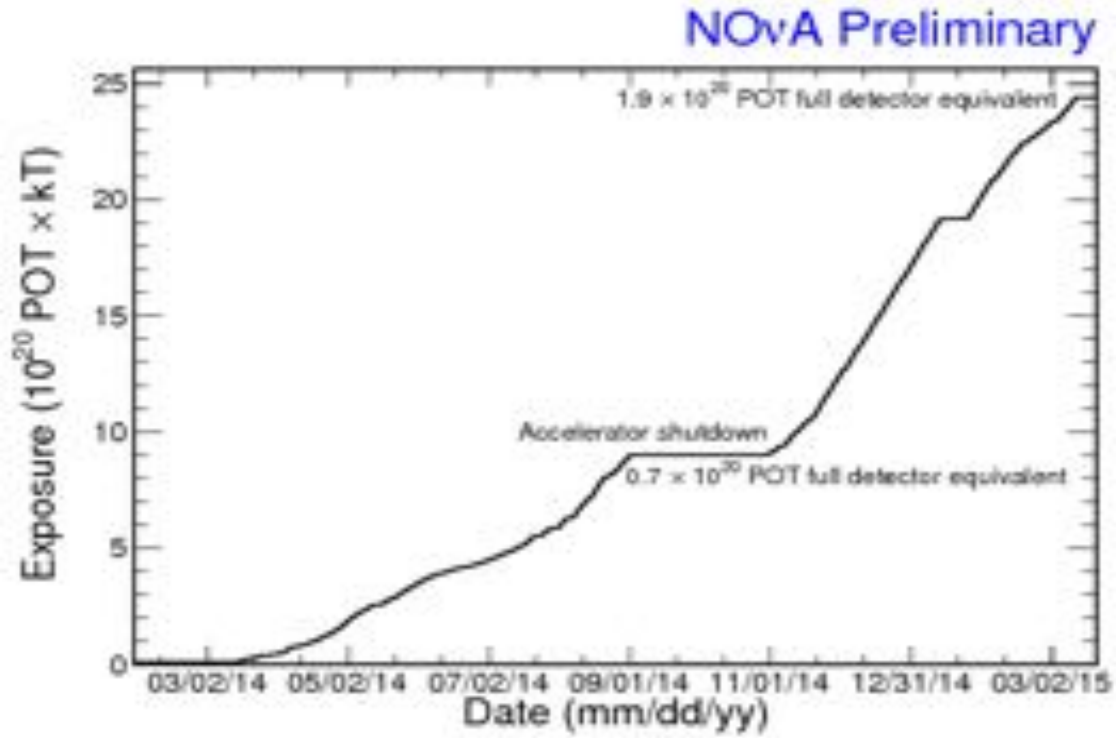
NuMI Off-Axis ν_e Appearance Experiment

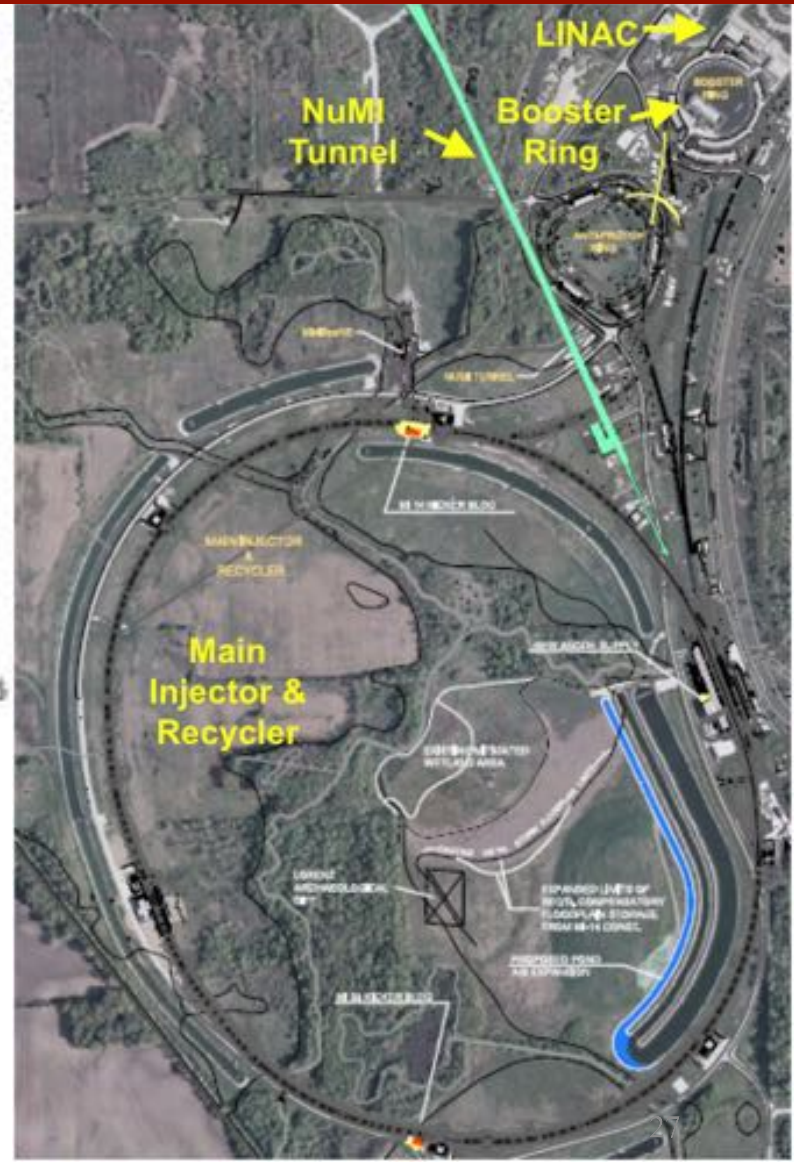




Far detector is sited 14 mrad off-axis to produce a narrow-band beam around the oscillation maximum region. Combining with final state interaction cross sections, provides an optimized signal/background separation.

Accelerator and NuMI Upgrades





- **Upgraded "Neutrinos at the Main Injector" (NuMI) accelerator complex:**
  - **We update the NuMI beam power from 320 kW to 700 kW.**
  - **Nominal NOvA year is 6×10^{20} protons on target (POT).**
  - **Beam power is ~400kW, will ramp up to 700kW**

ν_e appearance formula

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$
$$+2\alpha \sin\theta_{13} \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$
$$\overset{(+)}{-}2\alpha \sin\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

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

- 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_μ disappearance formula

Flavor oscillation in general: $$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U^*_{\alpha j} U_{\beta j} e^{-im_j^2 L/2E} \right|^2$$

ν_μ survival probability: $$P(\nu_\mu \to \nu_\mu) \approx 1 - sin^2(2\theta_{23}) sin^2 \left(\underbrace{\frac{1.27 \Delta m_{23}{}^2 L}{E}}_{\Delta_{23}} \right)$$

ν_e appearance probability:

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx P_{atm} + P_{sol} + 2\sqrt{P_{atm} P_{sol}} [\cos(\Delta_{32})\cos(\delta) \mp \sin(\Delta_{32})\sin(\delta)]$$

$$P_{atm} \equiv \sin^2(\Theta_{23})\sin^2(2\Theta_{13}) \frac{\sin^2(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2} (\Delta_{31})^2$$

$$P_{sol} \equiv \cos^2(\Theta_{23})\sin^2(2\Theta_{12}) \frac{\sin^2(\mp aL)}{(\mp aL)^2} (\Delta_{21})^2$$

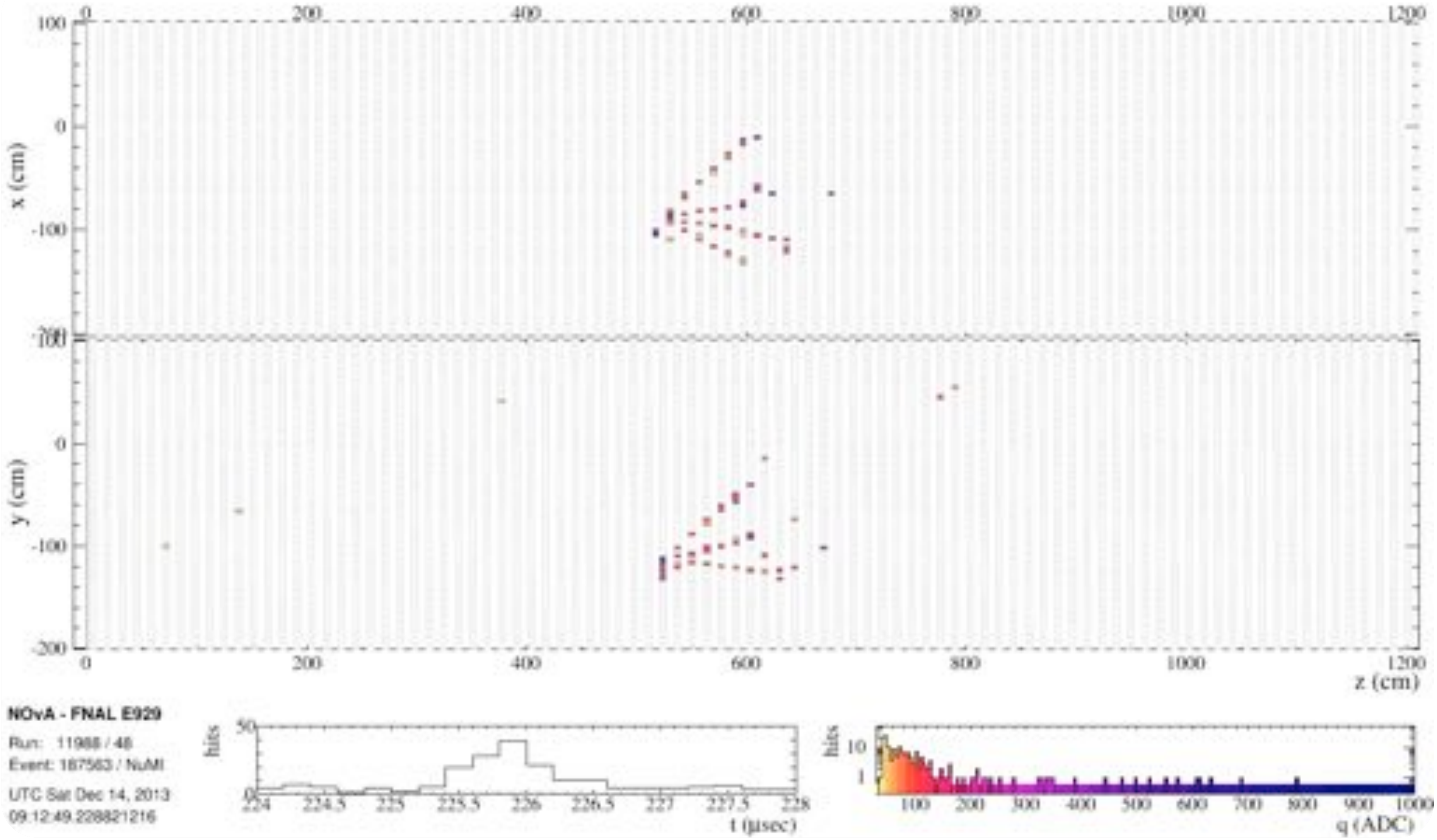
"$-$" = *neutrinos*

"$+$" = *anti − neutrinos*

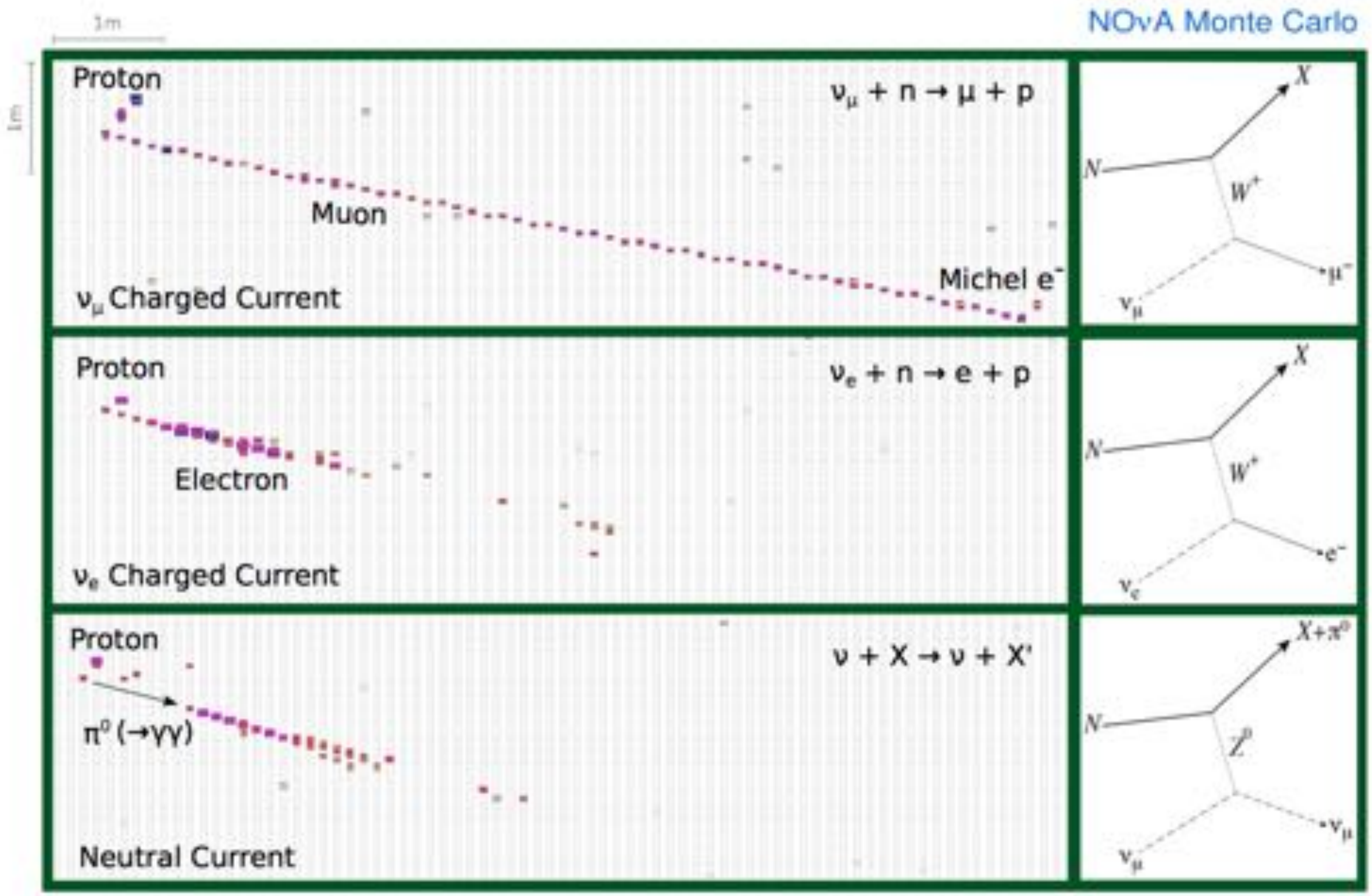
$a \equiv G_F N_e / \sqrt{2}$

N_e = *electron density in Earth*

NC candidate in FD

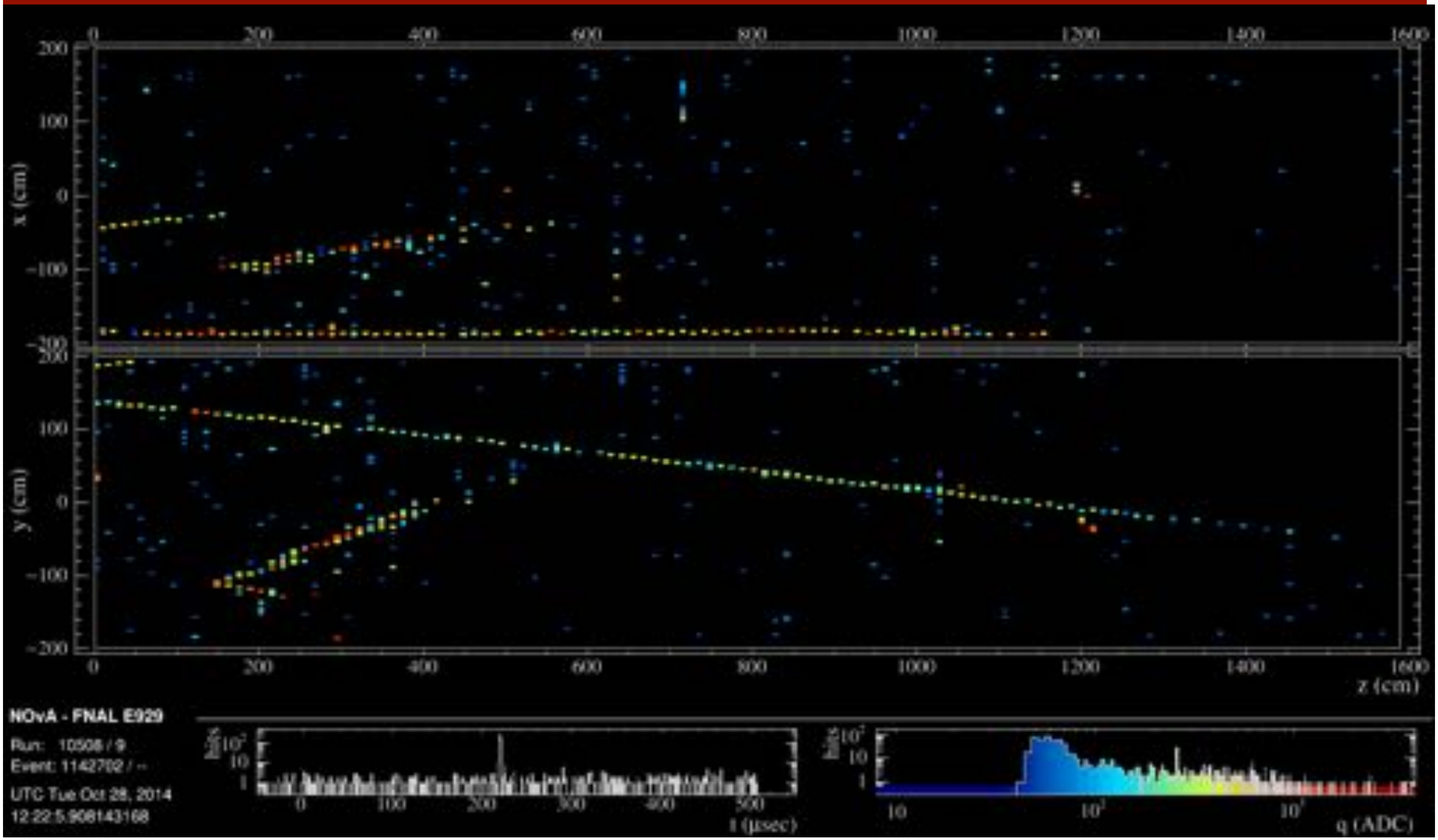


Neutrino Event Topology in NOνA

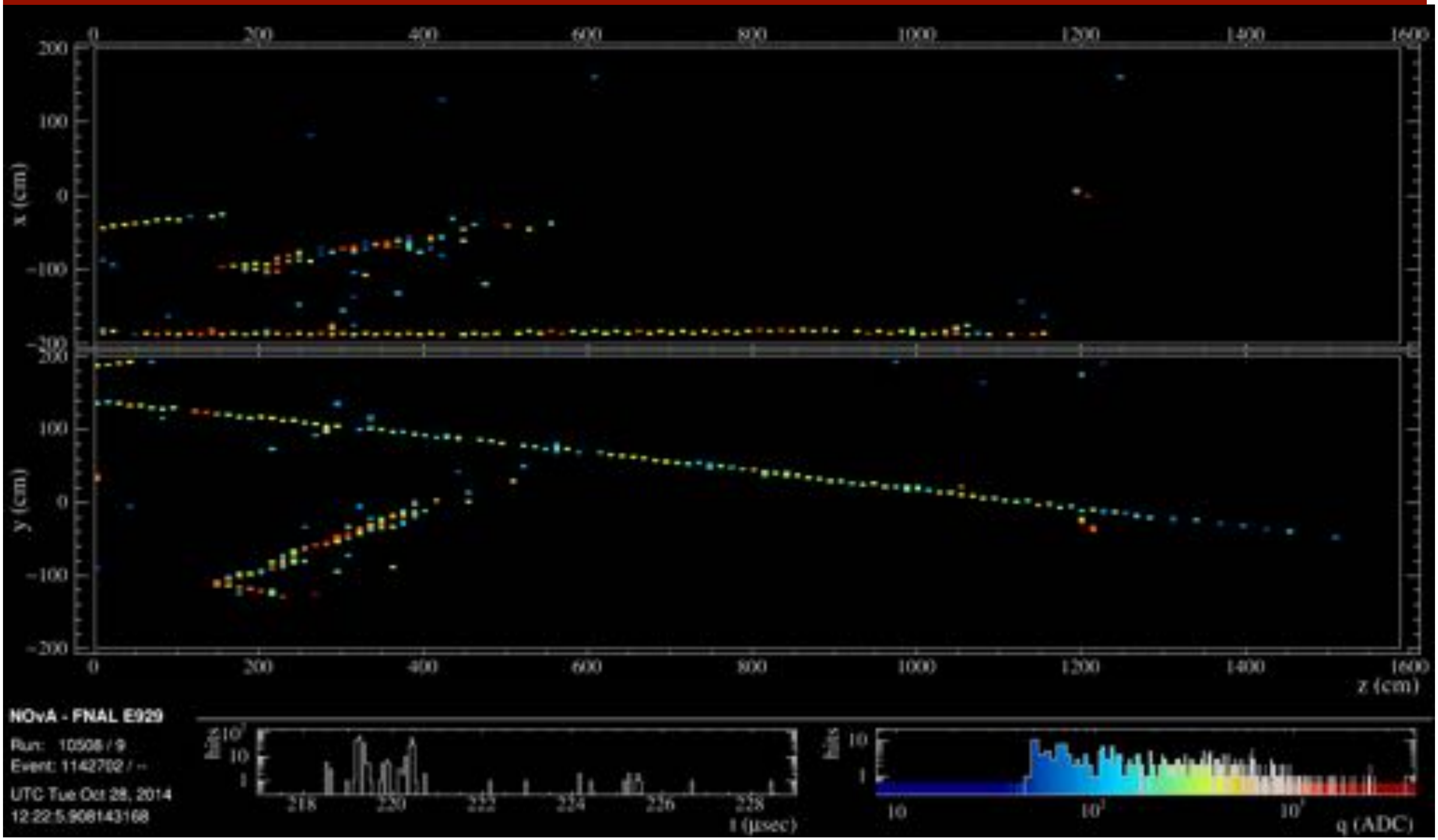


The muon is a long minimum ionizing particle (MIP) track, the electron ionizes in the first few planes then starts a shower and the photon is a shower with a gap in the first few planes.

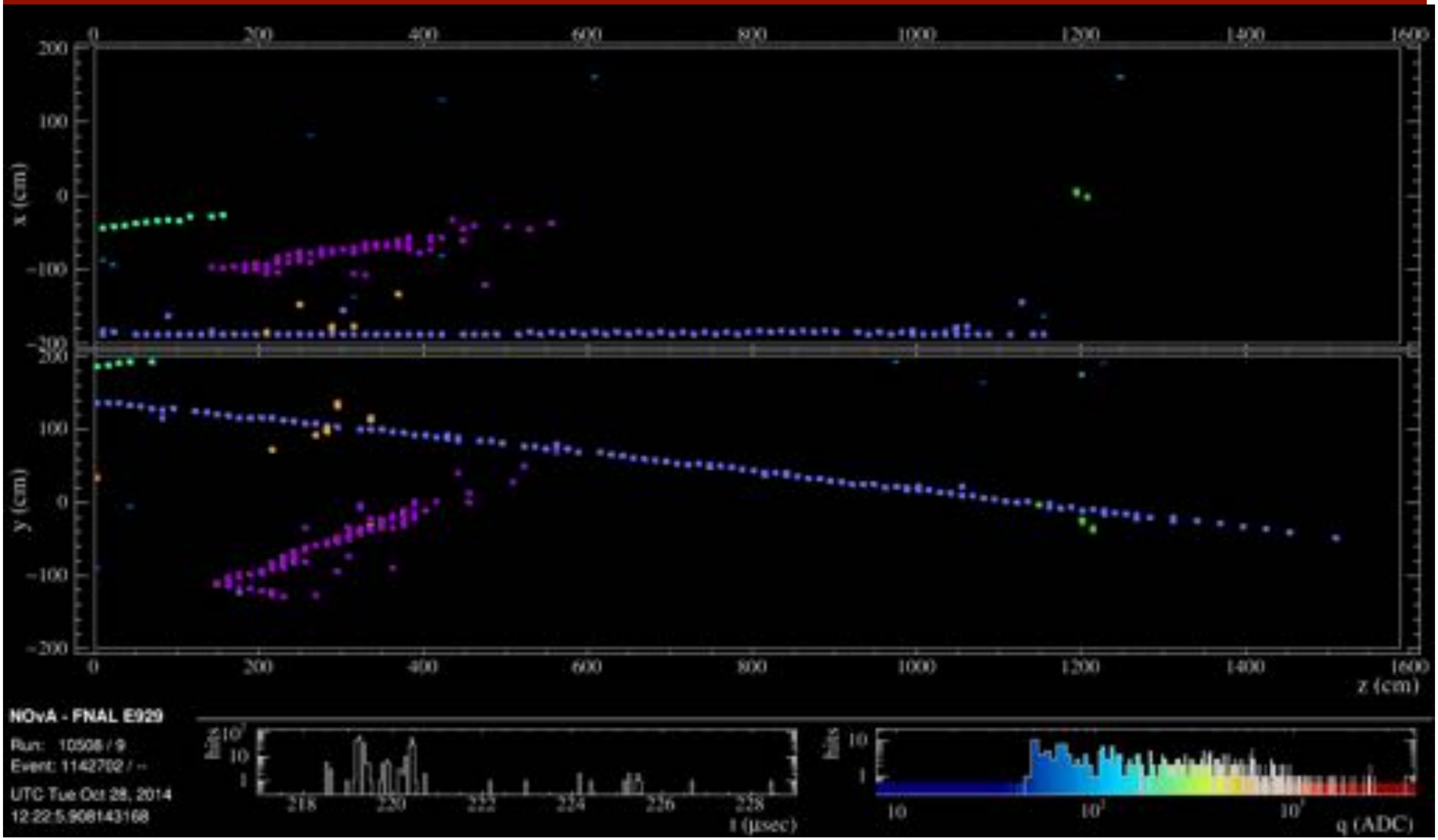
550 μs Near Detector readout window



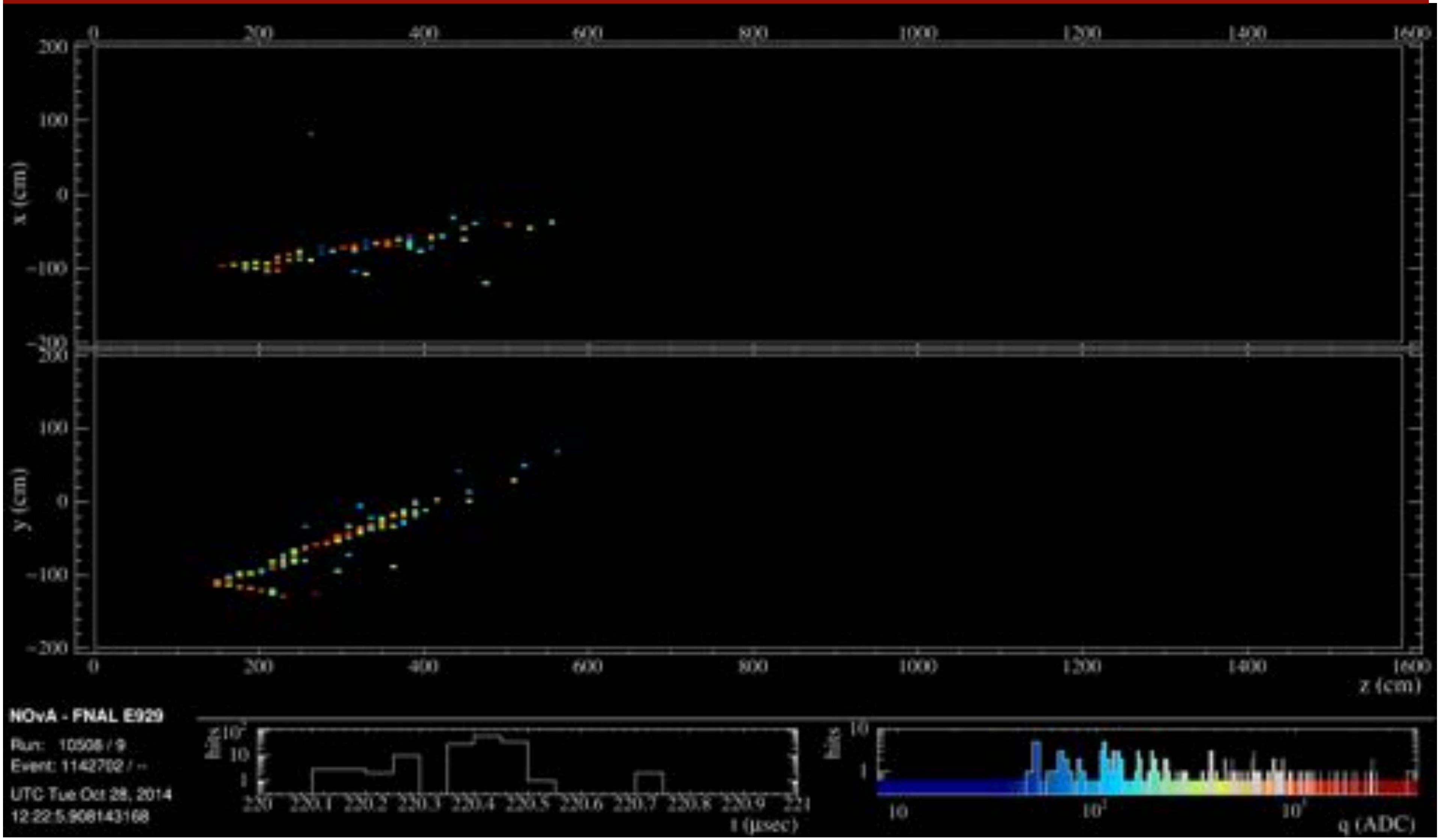
Zooming in on 10 μs beam window



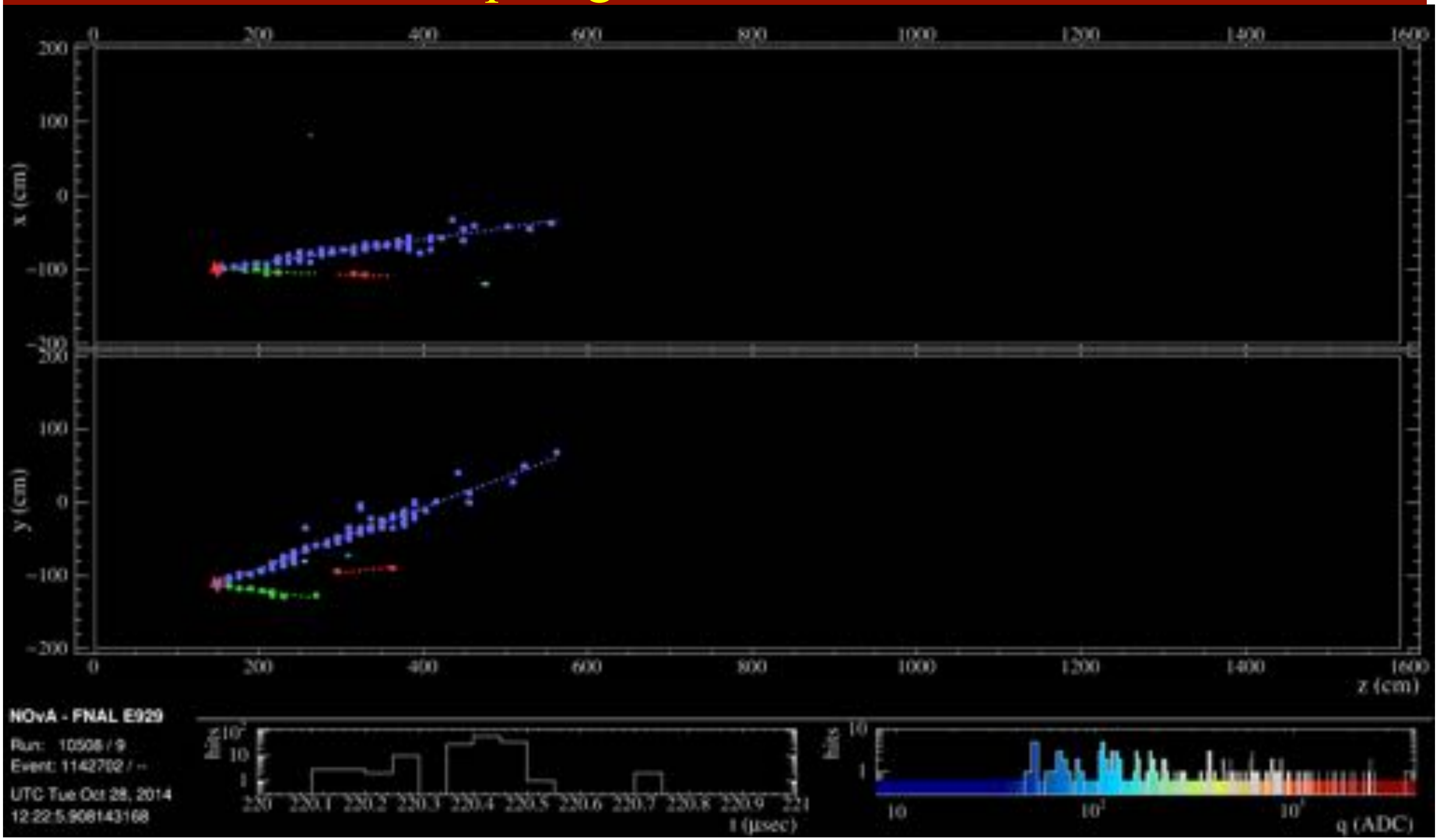
Separating event into slices



One slice before vertex and prong reconstruction

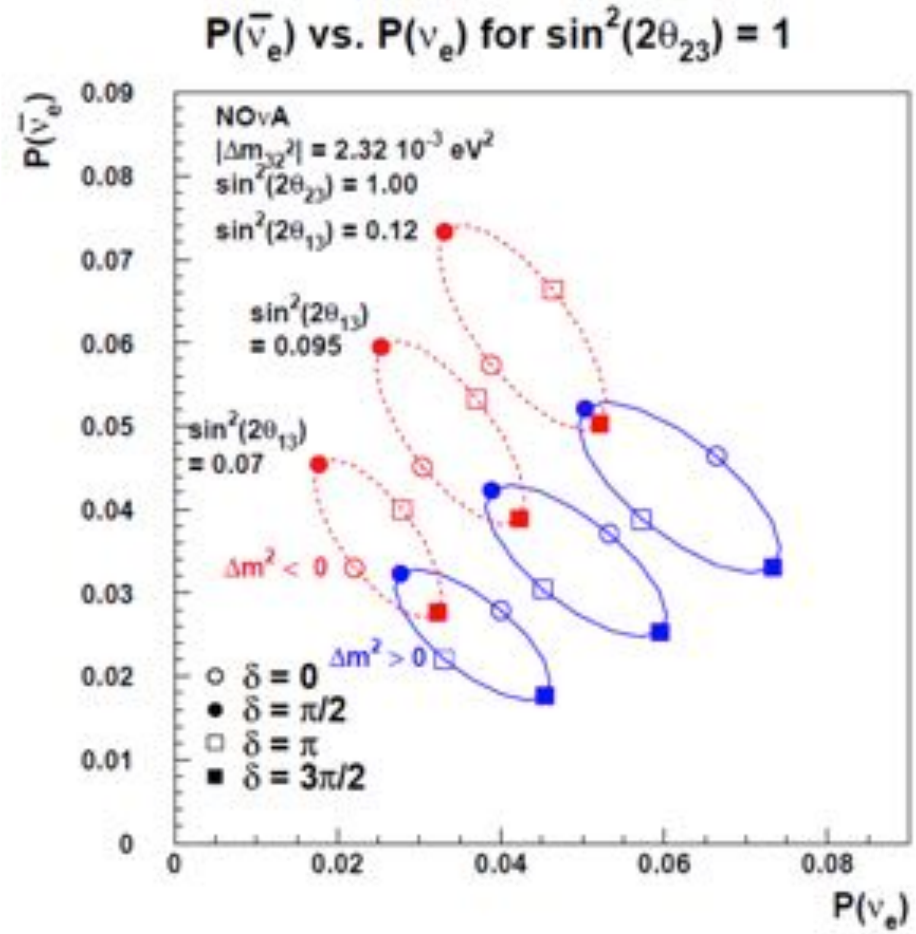


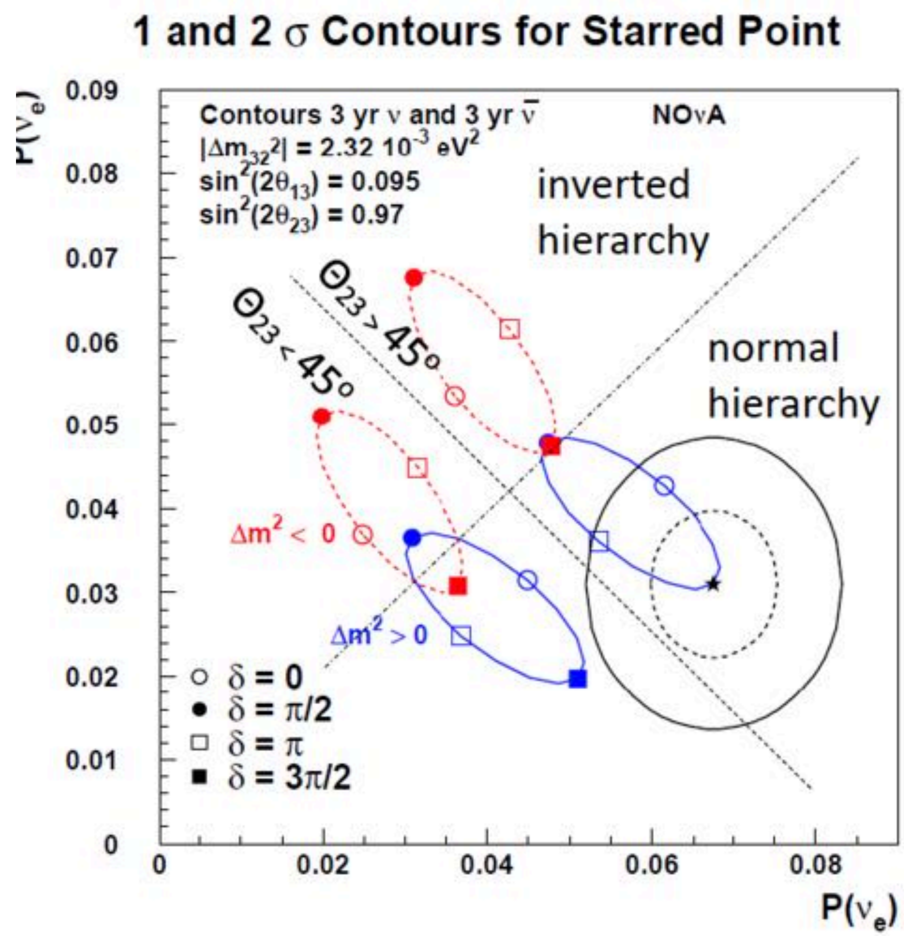
Near Detector Near Detector ν_e candidate after vertex and prong reconstruction



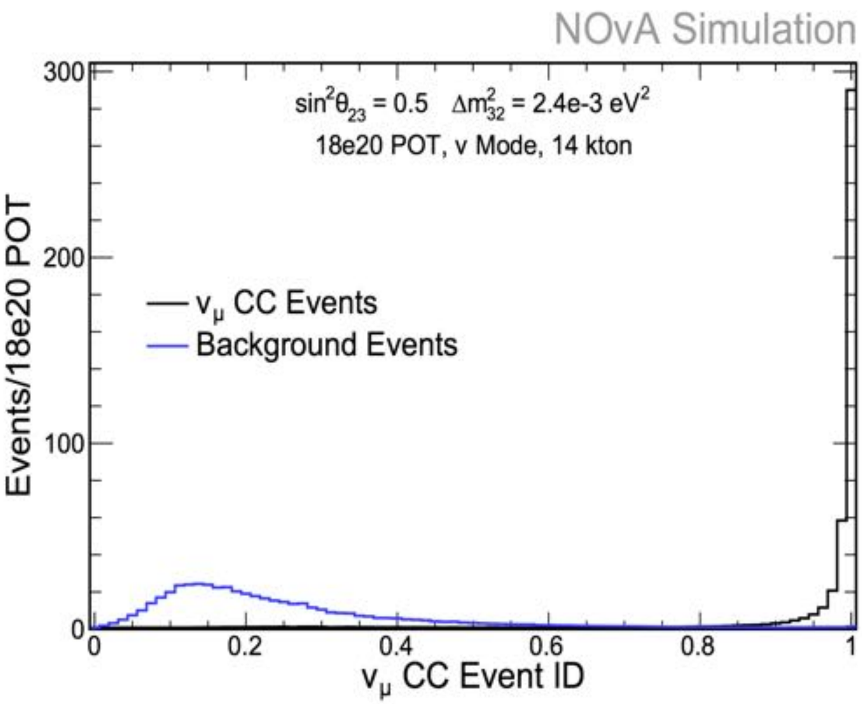
$P(\nu_e)$ vs. $P(\overline{\nu}_e)$ with different θ_{13} values and θ_{23} octant assumptions

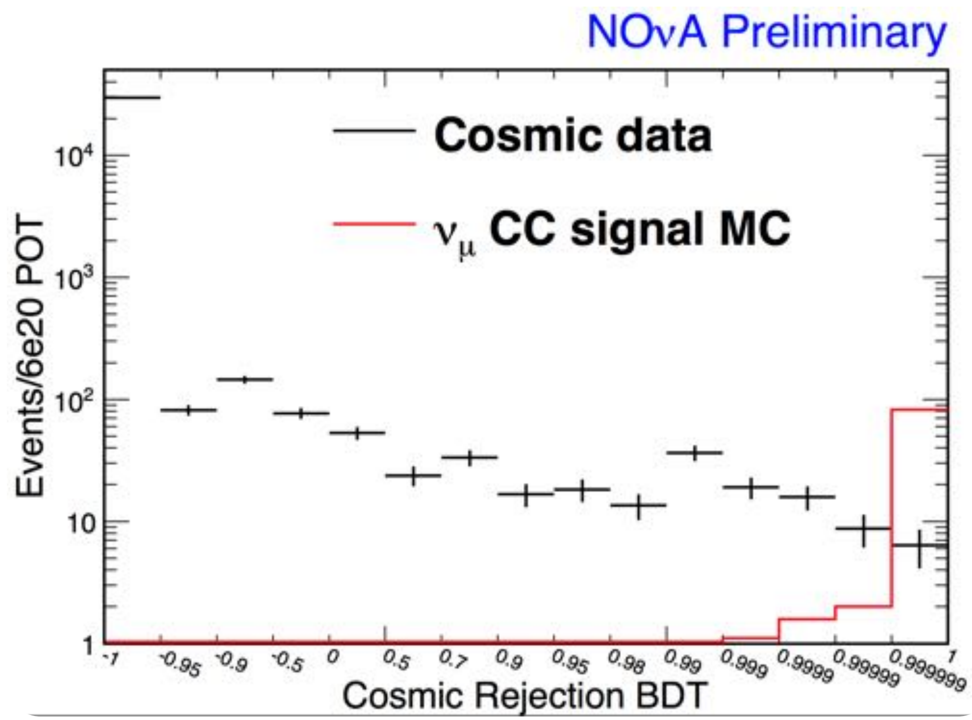
Blue:NMH
Red: IMH





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**

$\nu_e + \nu_\mu$ combined analysis