Summary of the First Neutrino Oscillation Results from the NOvA Experiment

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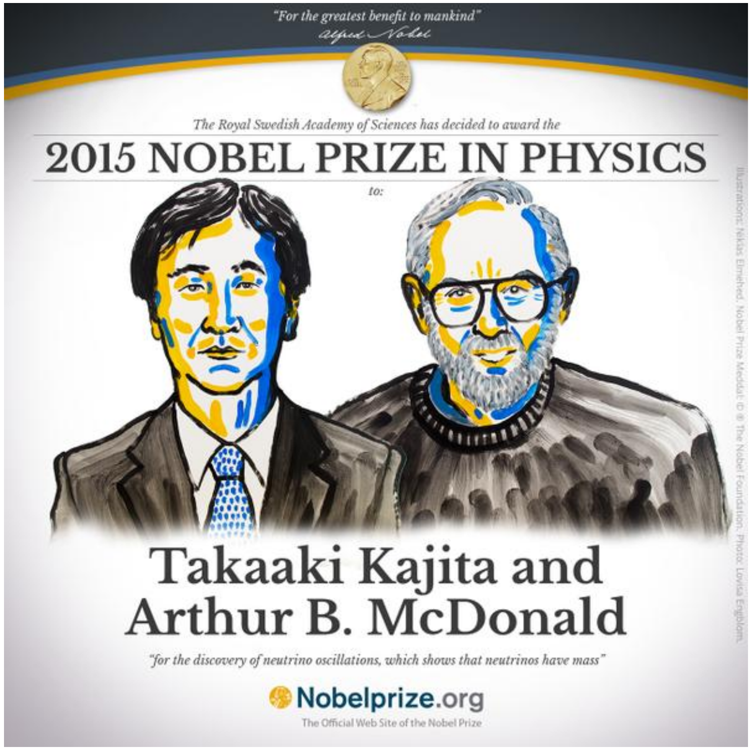
Overview:

- Neutrino Oscillations
- The NOvA Experiment
- First ν_μ Disappearance Results (arXiv:1601.05037v2)
- First ν_e Appearance Results (arXiv:1601.05022v1)

A Good Time to be in Neutrino Physics!



2015 Nobel Prize in Physics

2016 Breakthrough Prize in Physics

Neutrino Oscillations:

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$$\overbrace{\begin{pmatrix} \upsilon_e \\ \upsilon_\mu \\ \upsilon_\tau \end{pmatrix}}^{\text{flavor}} = \overbrace{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}}^{\text{PMNS}} \overbrace{\begin{pmatrix} \upsilon_1 \\ \upsilon_2 \\ \upsilon_3 \end{pmatrix}}^{\text{mass}}$$

- Neutrinos can be described in one of two different bases: flavor or mass.
- Neutrino mixing is described by 3 real rotation angles and a CP violating phase factor, δ.
- All three rotation angles have been measured, but we don't yet know what delta is.

Neutrino Oscillations:

$$\overbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}}^{\text{flavor}} = \overbrace{\begin{bmatrix} C_{12}C_{13} & S_{12}C_{13} & S_{13}e^{-i\delta} \\ -S_{12}C_{23} - C_{12}S_{23}S_{13}e^{i\delta} & C_{12}C_{23} - S_{12}S_{23}S_{13}e^{i\delta} & S_{23}C_{13} \\ S_{12}S_{23} - C_{12}C_{23}S_{13}e^{i\delta} & -C_{12}S_{23} - S_{12}C_{23}S_{13}e^{i\delta} & C_{23}C_{13} \end{bmatrix}}^{\text{PMNS}} \overbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}^{\text{mass}}$$

$$S_{ij} \equiv Sin(\theta_{ij}) \quad C_{ij} \equiv Cos(\theta_{ij})$$

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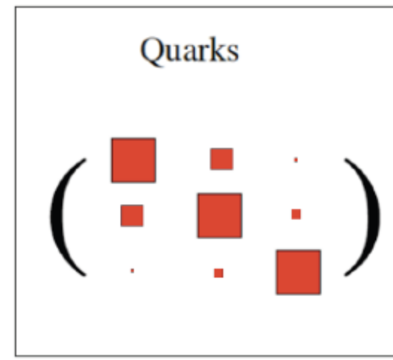

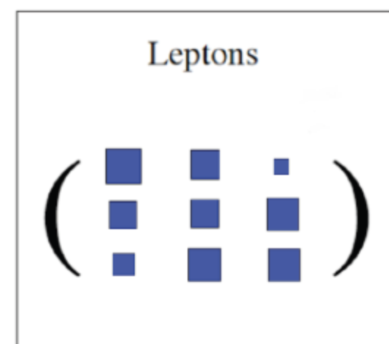

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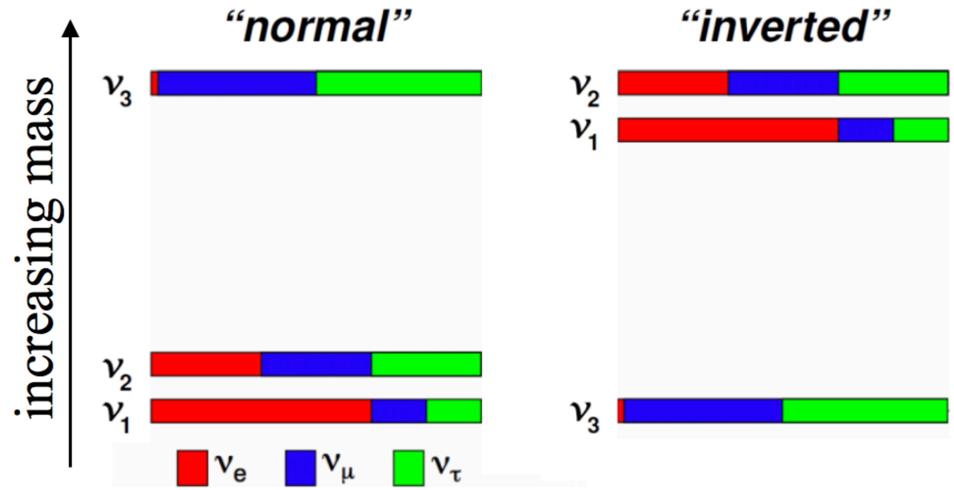
- Neutrino mixing is described by 3 real rotation angles and a CP violating phase factor, δ.
- All three rotation angles have been measured, but we don't yet know what delta is.
- The mixing is very different in the quark and lepton sectors!

Open Questions:

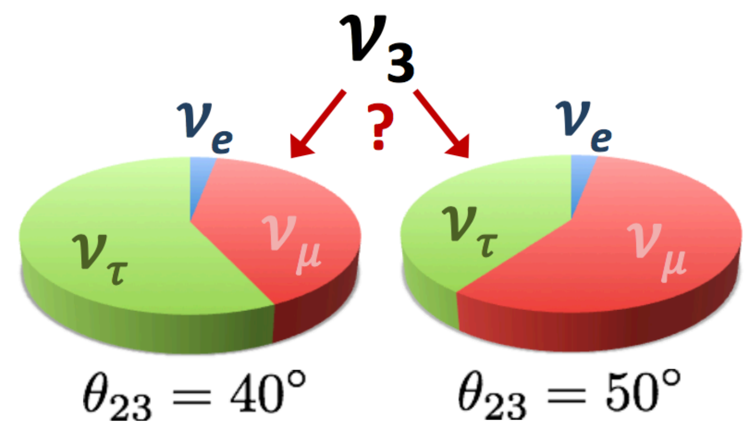
Neutrino Mass Hierarchy:

- It has not yet been determined if $m_3 > m_1, m_2$ or $m_3 < m_1, m_2$.
- Has implications for 0νββ and the Majorana nature of the neutrino.



The "octant" of θ_{23}:

- It is not known if $\theta_{23} > 45°$ or $\theta_{23} < 45°$.
- Helps determine the texture of the PMNS mixing matrix.



CP violation in the lepton sector:

- A good measurement of δ has not yet been made.
- Is related to baryon asymmetry.

Neutrino Oscillations:

Flavor oscillation in general:

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

***ν*$_\mu$ survival probability:**

$$P(\upsilon_\mu \rightarrow \upsilon_\mu) \approx 1 - sin^2(2\theta_{23}) sin^2 \underbrace{\left(\frac{1.27 \Delta m_{32}{}^2 L}{E} \right)}_{\Delta_{23}}$$

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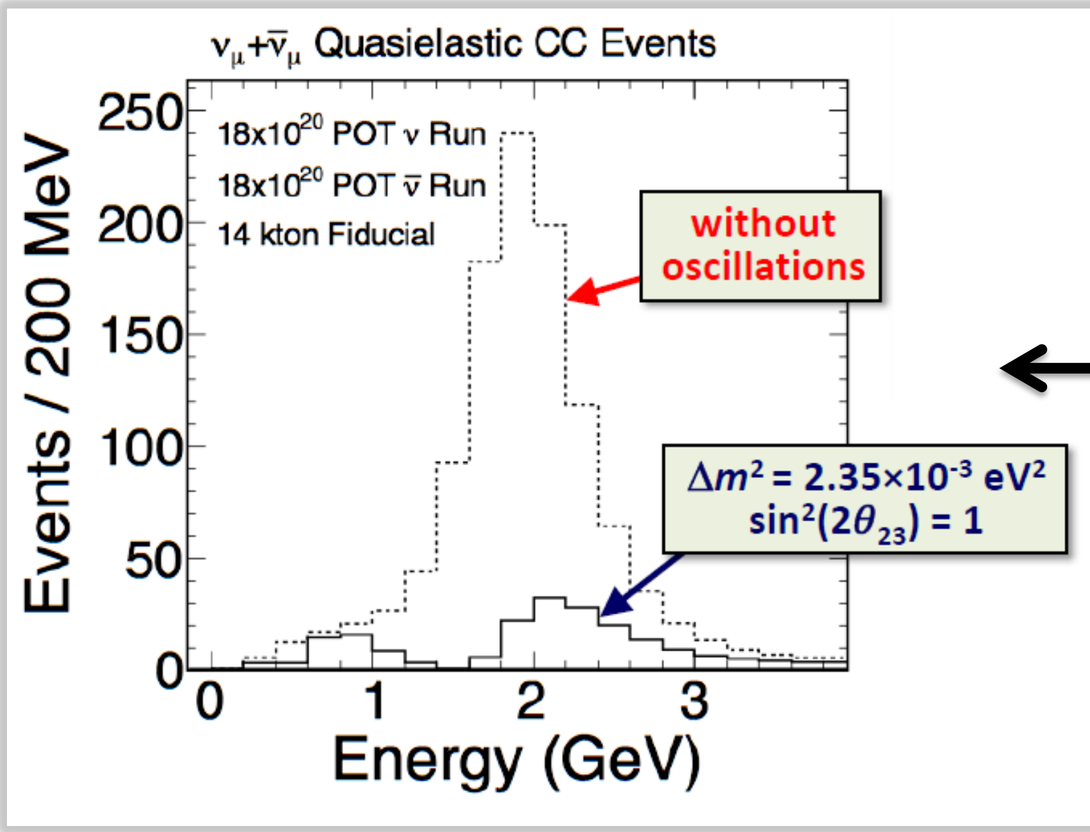

(expected NOvA Far Detector ν_μ CC spectra)

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ν_e appearance probability:

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$$"-" = neutrinos$$

$$"+" = anti-neutrinos$$

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matter effect: caused by ν_e scattering off e$^-$ as they travel through the Earth...

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octant

Is $\theta_{23} > 45°$ or $\theta_{23} < 45°$?

hierarchy

Is $m_3 > m_1$ or is $m_3 < m_1$?

CP violation

Is $\delta \neq 0$?

Neutrino Oscillations:

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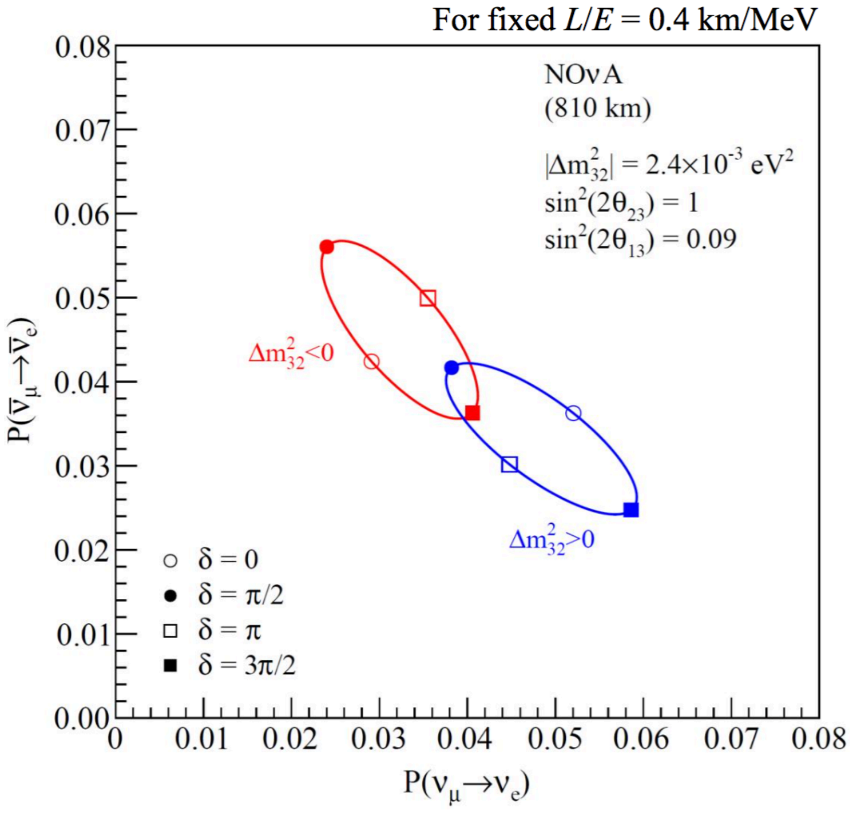

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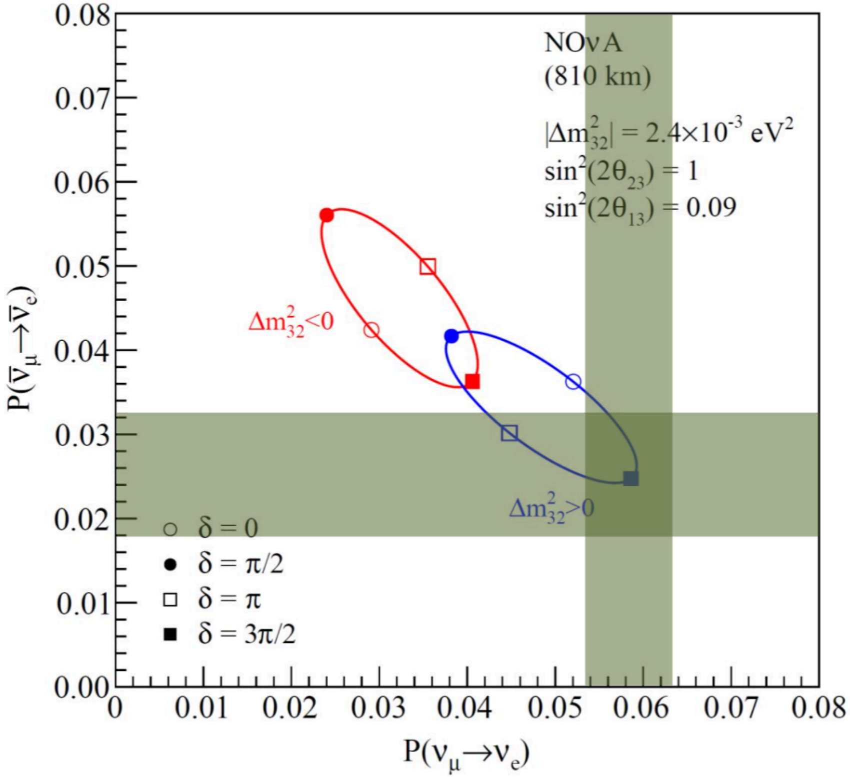
For fixed L/E = 0.4 km/MeV



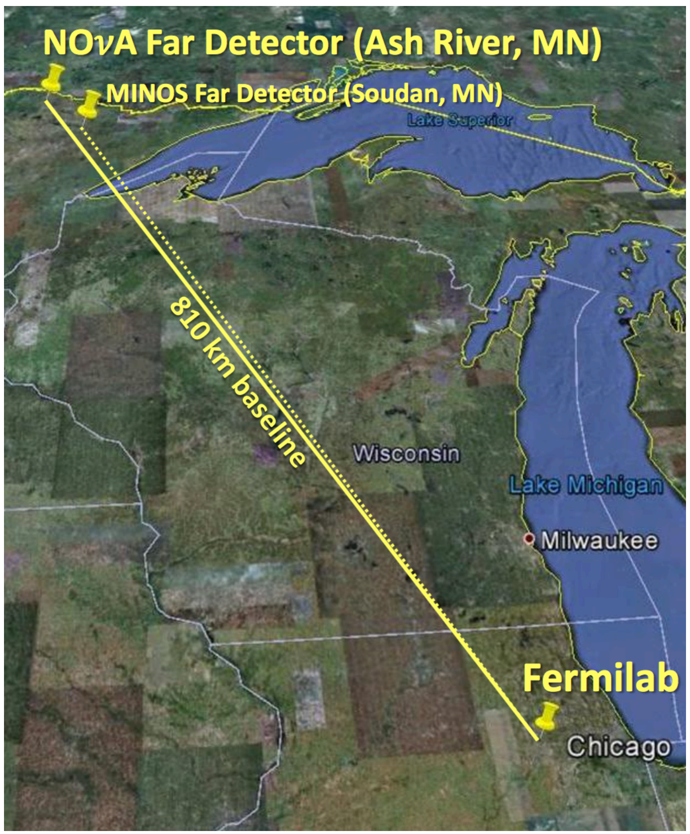
A simultaneous measurement of ν_e appearance and $\overline{\nu_e}$ appearance will help us answer these open questions!

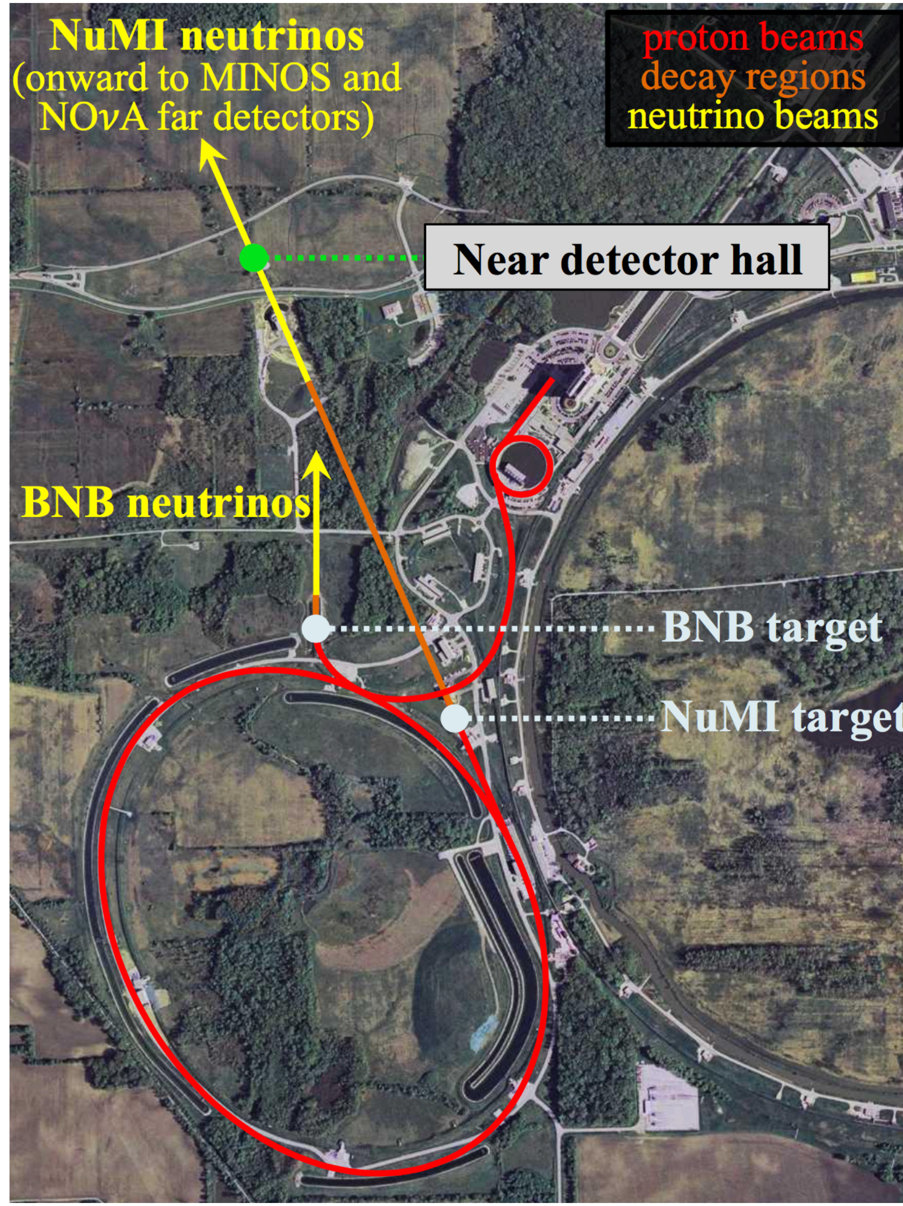
The NOvA Experiment:

The NOvA Experiment: NuMI Beam

NuMI - Neutrinos at the Main Injector

- provides a 10 μsec pulse every 1.33 sec
- currently operating at > 500 kW
- averaging 85% uptime
- expected to reach 700 kW this year

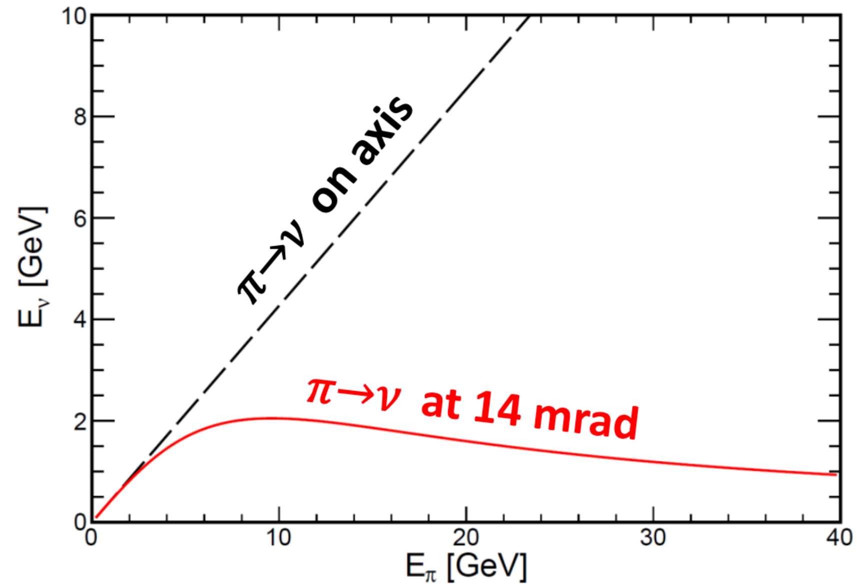


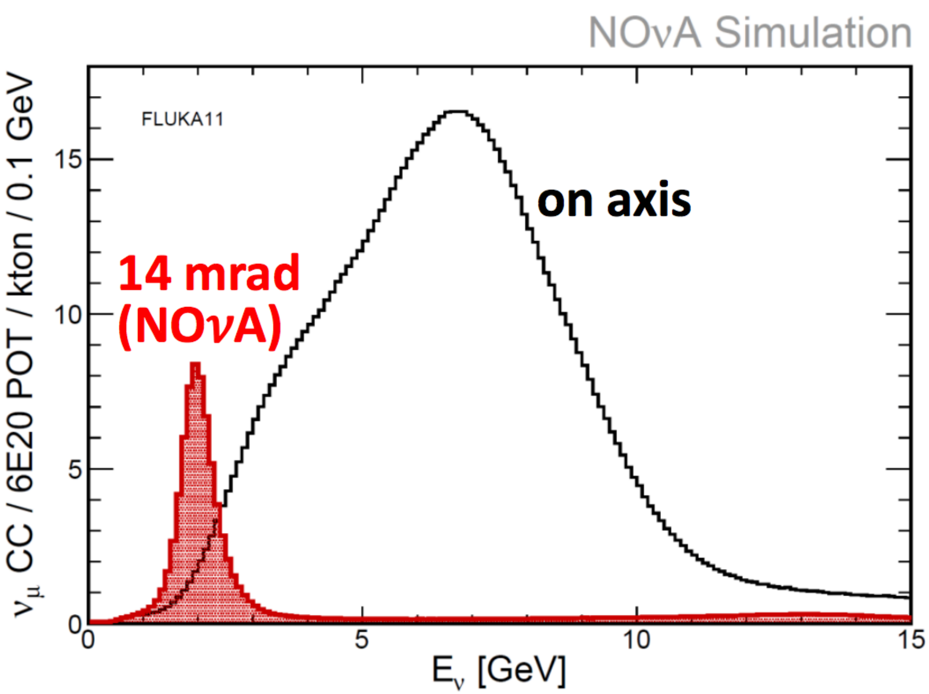


The NOvA Experiment: NuMI Beam

The NOvA experiment is 14 mrad off-axis:

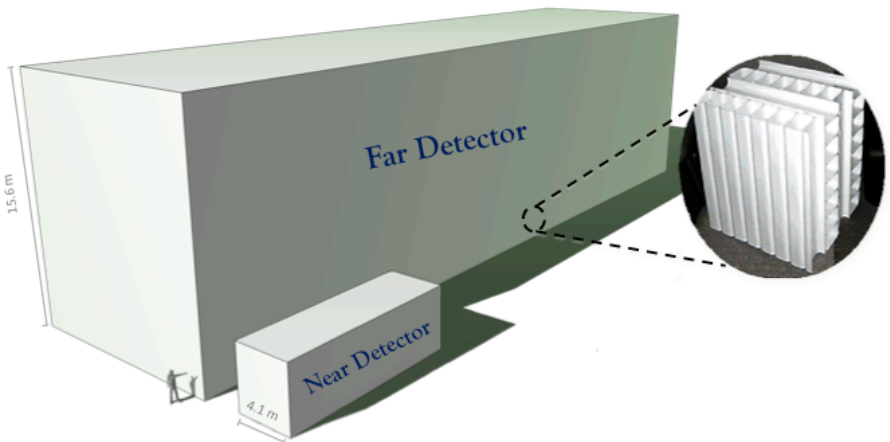
- gives us a narrowly peaked *ν* energy spectrum at 2 GeV
- 2 GeV = oscillation max for 810 km
- helps reduce NC backgrounds



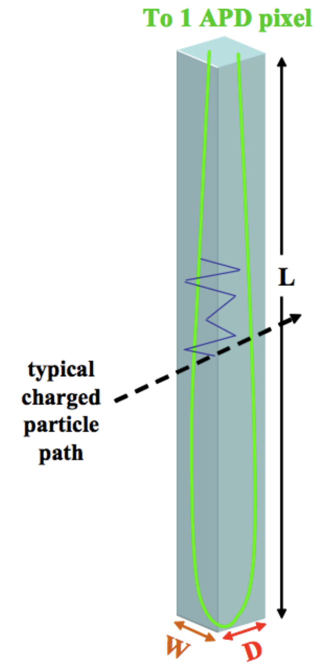


$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$

The NOvA Experiment: Detectors



Right: The NOvA cell is composed of extruded PVC filled with a liquid scintillator. A looped fiber collects scintillation light and transmits it to an avalanche photo-diode (APD.)

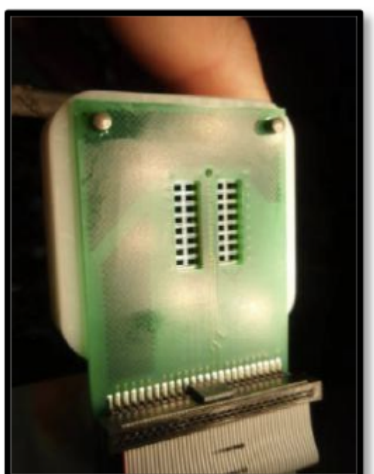


Cells are 4 cm x 6 cm and in the far detector are 15.5 m long, in the near detector, they are 4 m long.

Above: NOvA has 2 detectors, near and far. Each is composed of alternating, orthogonal planes of extruded PVC.

Far ➔ 14 kton, 810 km from Fermilab, on the surface

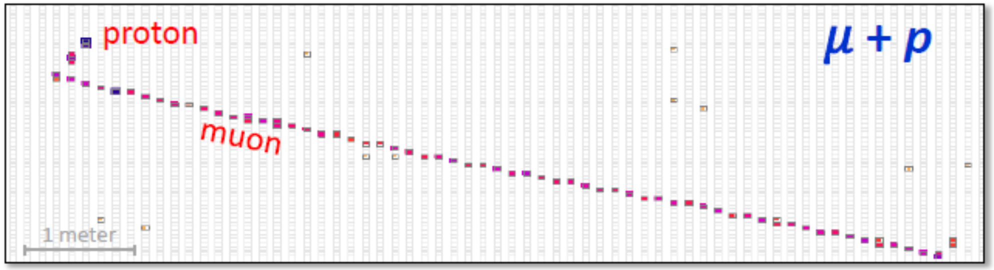
Near ➔ 300 ton, 1 km from the beam source, 105 m underground



Far Left: The NOvA APD showing the pixels used to read out 32 cells.

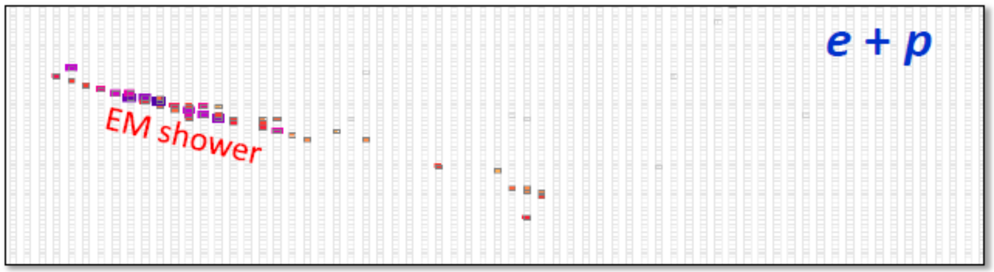
Near Left: The interface to the APD showing both ends of each of the fibers from 32 cells.

The NOvA Experiment: Detectors



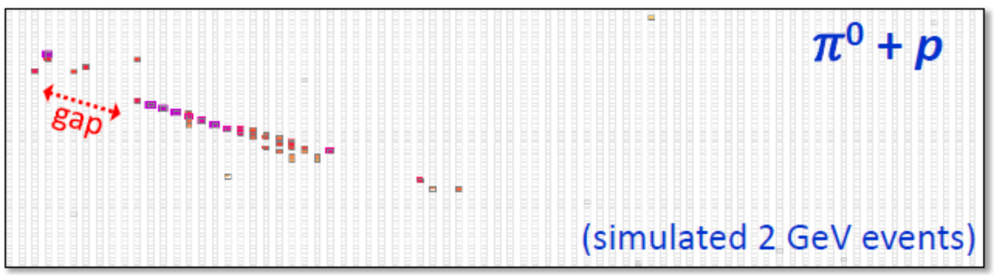
A simulated numu CC event showing a long muon track.

$$\nu_\mu + N \longrightarrow \mu + p$$



A simulated nue CC event showing an electron shower.

$$\nu_e + N \longrightarrow e + p$$

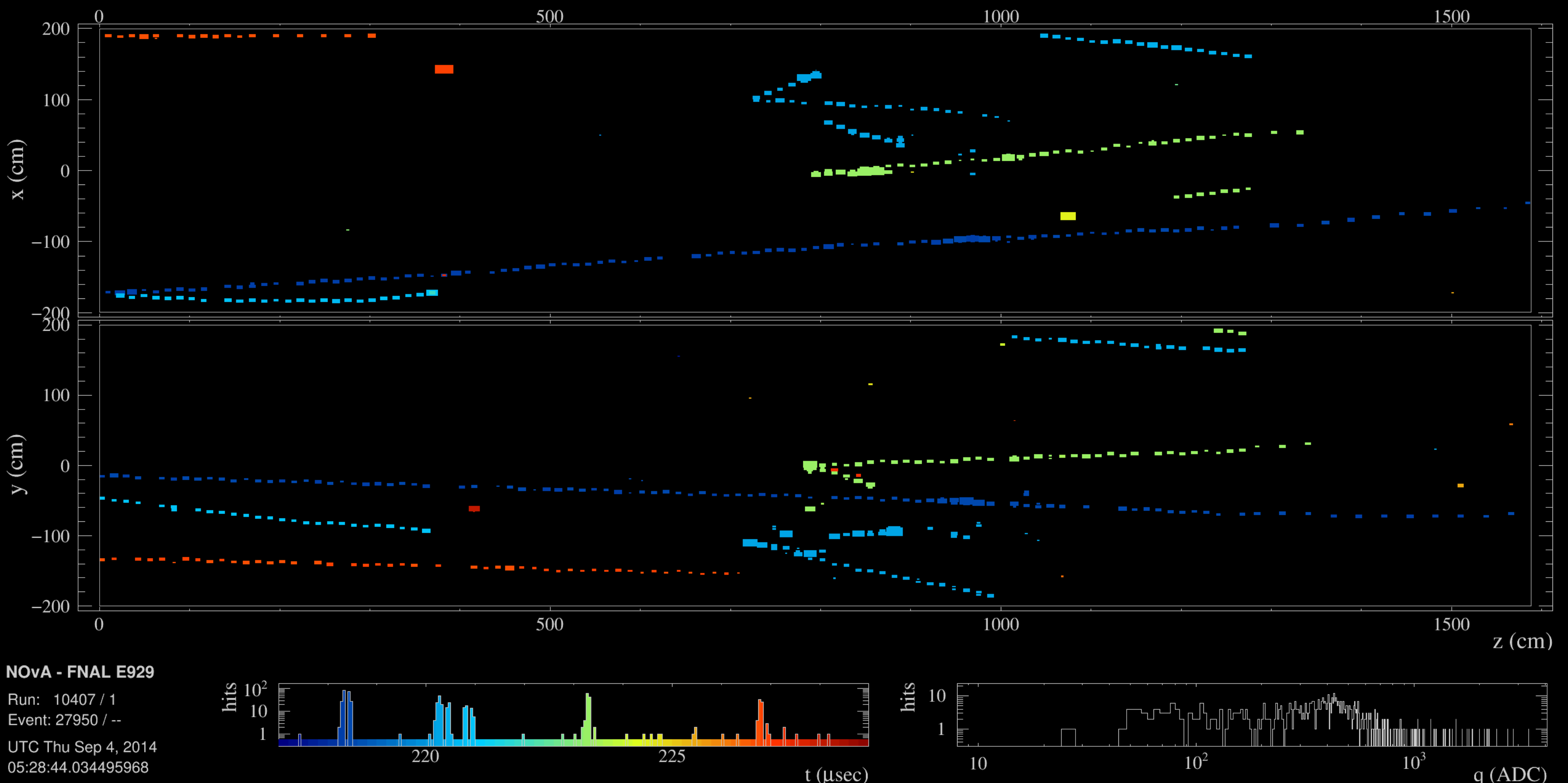


A simulated NC event with a π^0 showing an EM shower displaced from the vertex.

$$\nu_X + N \longrightarrow \pi^0 + p$$

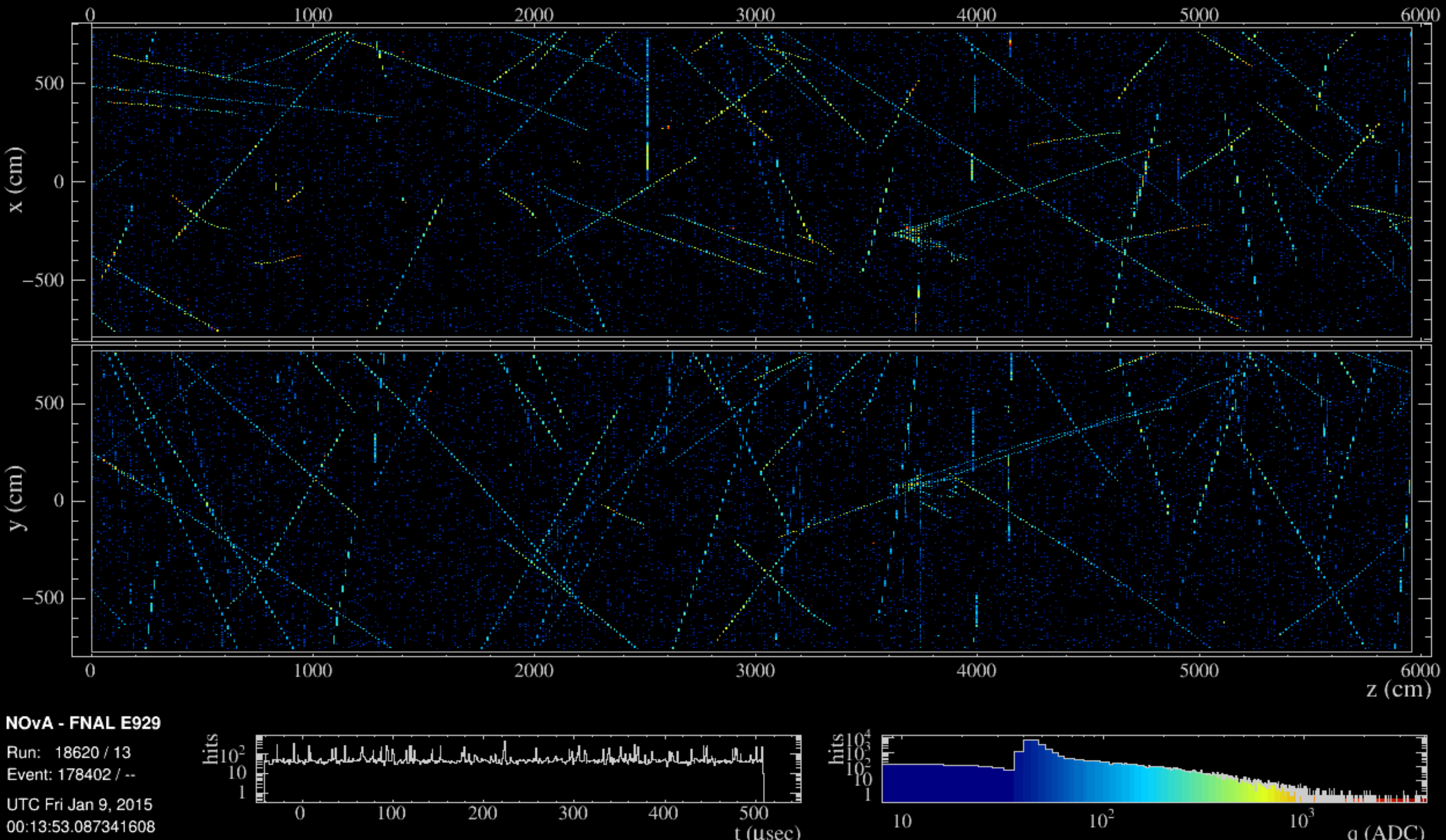
- NOvA is a totally active tracking calorimeter.
- The detectors are designed with low-Z materials (mineral oil and PVC) so as to enhance the differences between muon tracks, showers caused by electrons, and showers caused by pi-zeros.
  - Moliere radius = 11 cm
  - EM radiation length = 40 cm

Near Detector Event Display



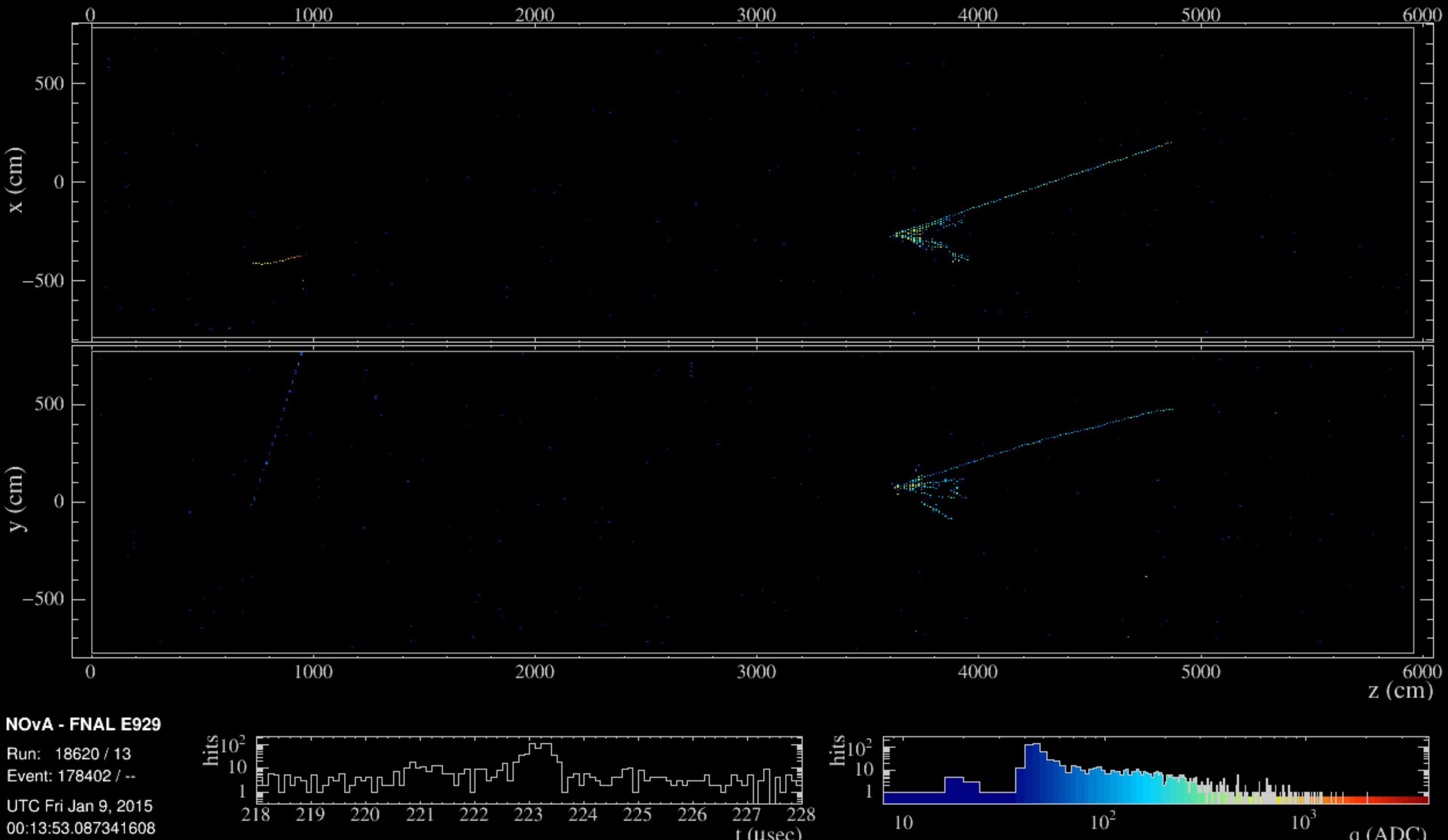
(colors show hit times)

Far Detector Event Display



(colors show charge)

Far Detector Event Display

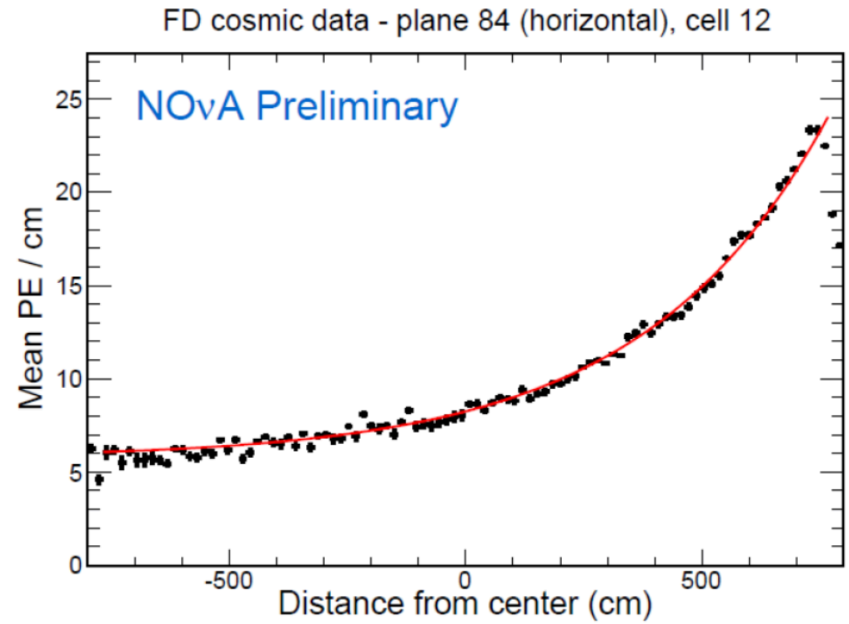


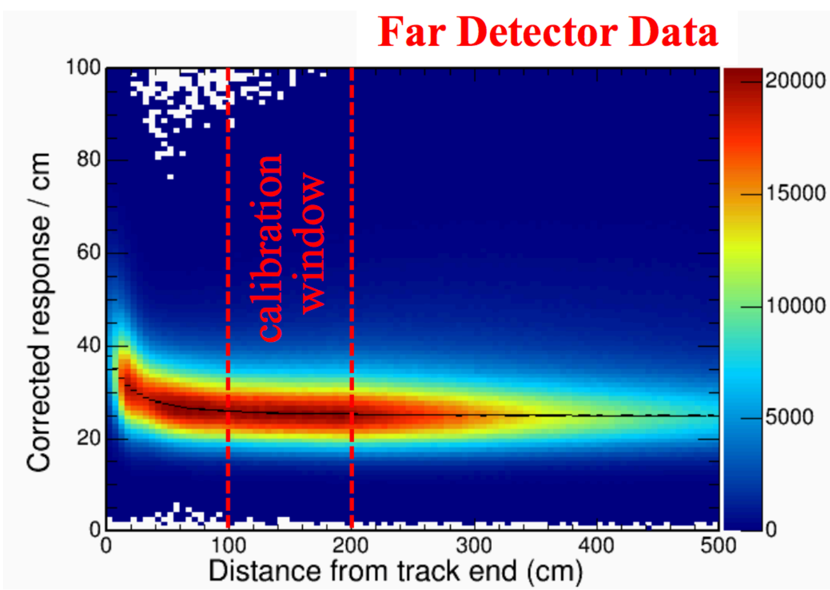
(colors show charge) zoomed in on beam window

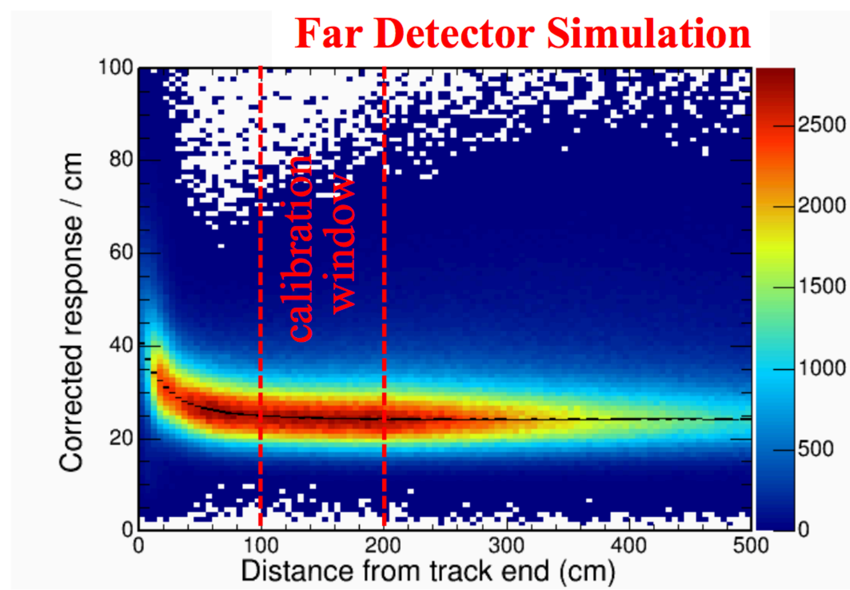
Calibration:

- Compute the attenuation curve for each fiber individually using through-going cosmic muons.

- Compute the absolute energy scale for the whole detector using stopping cosmic muons.

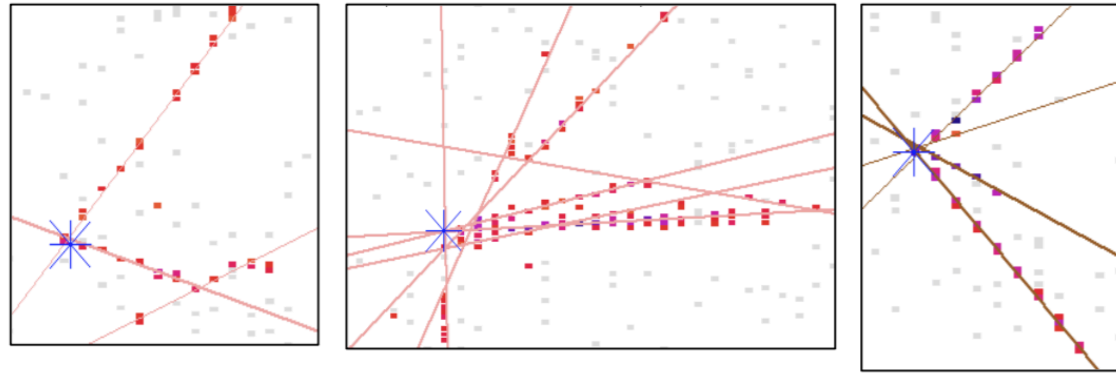




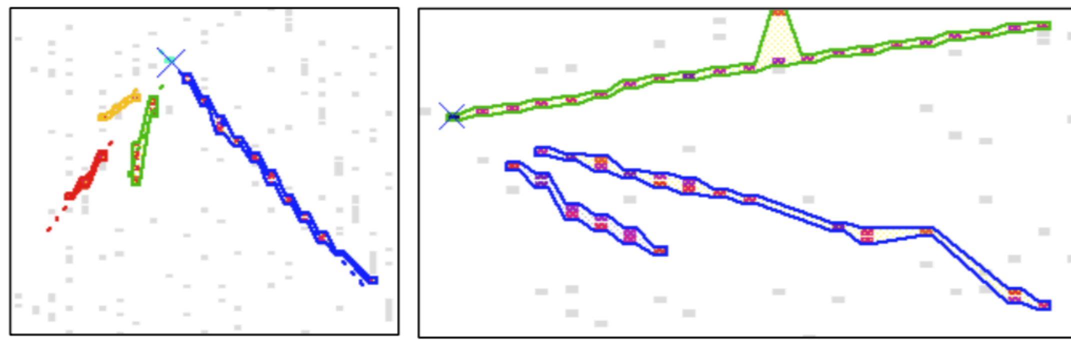


Reconstruction:

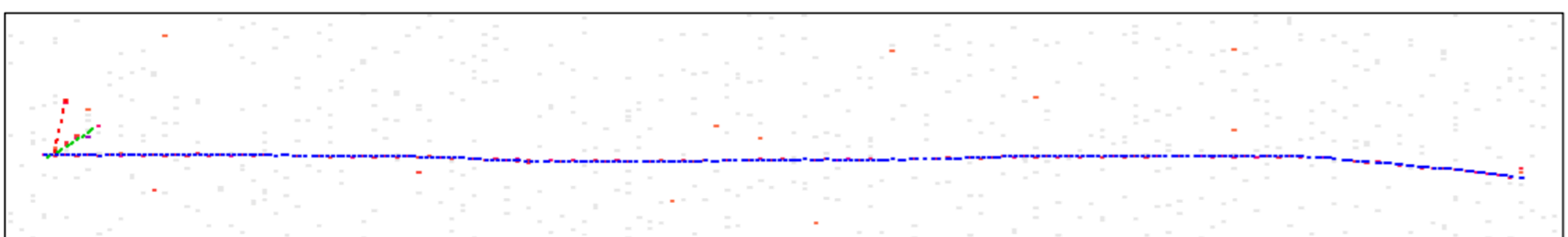
Vertexing: Identify a global event vertex using a Hough transform as guidance. **CC events: 11 cm vertex resolution**



Clustering: Find clusters in angular space around the vertex. Match clusters between views using dE/dx.



Tracking: Trace particle trajectories with a Kalman filter tracker that uses a model for multiple scattering. Also have other, faster and lighter-weight trackers for calibration and monitoring tools.



NOvA Data Collection:

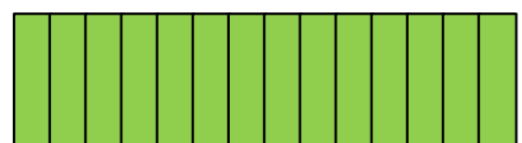
Data Summary:

- Feb 6th 2014 – May 15th 2015
- Began collecting the FD data while still under construction.
- Added each "diblock" (a unit of 64 detector planes) as soon as it was fully commissioned and physics-ready.
- The non-static detector size is also modeled in the simulations.

Protons-on-target in data set:	3.45×10^{20} POT
Fraction of detector operational:	79.4% (POT-weighted average)
Full-detector-equivalent exposure:	**2.74×10^{20} POT-equiv**

Only 7.6% of our full exposure!

Partial Far Detector during construction
(6 diblock example)

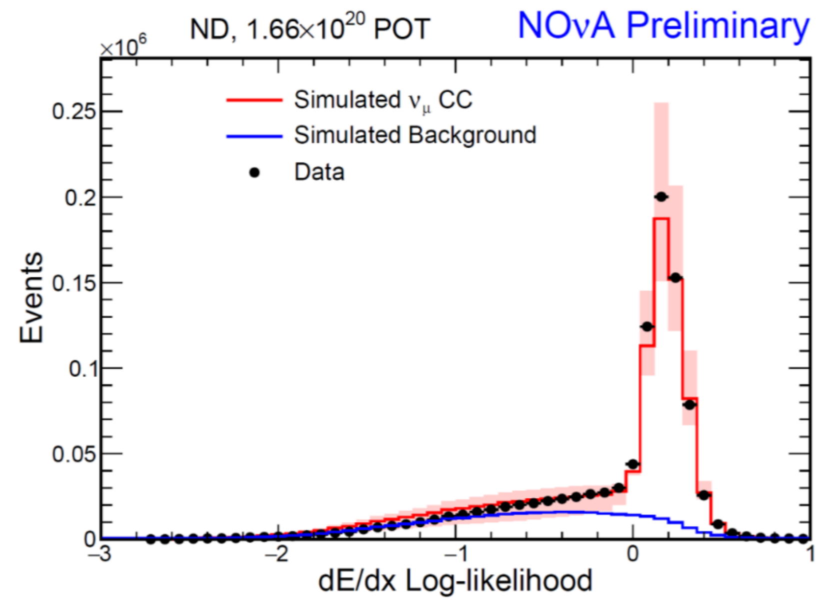


Full Far Detector
(14 diblocks)

ν_μ Disappearance Results:

ν_μ CC Event Selection:

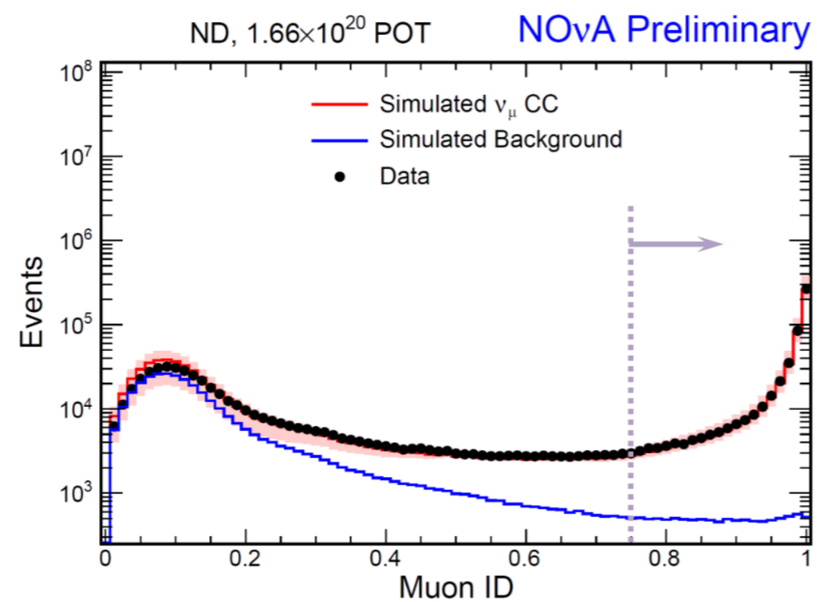
First apply basic containment cuts...



Muon ID

Use a 4-variable kNN algorithm to identify muons:

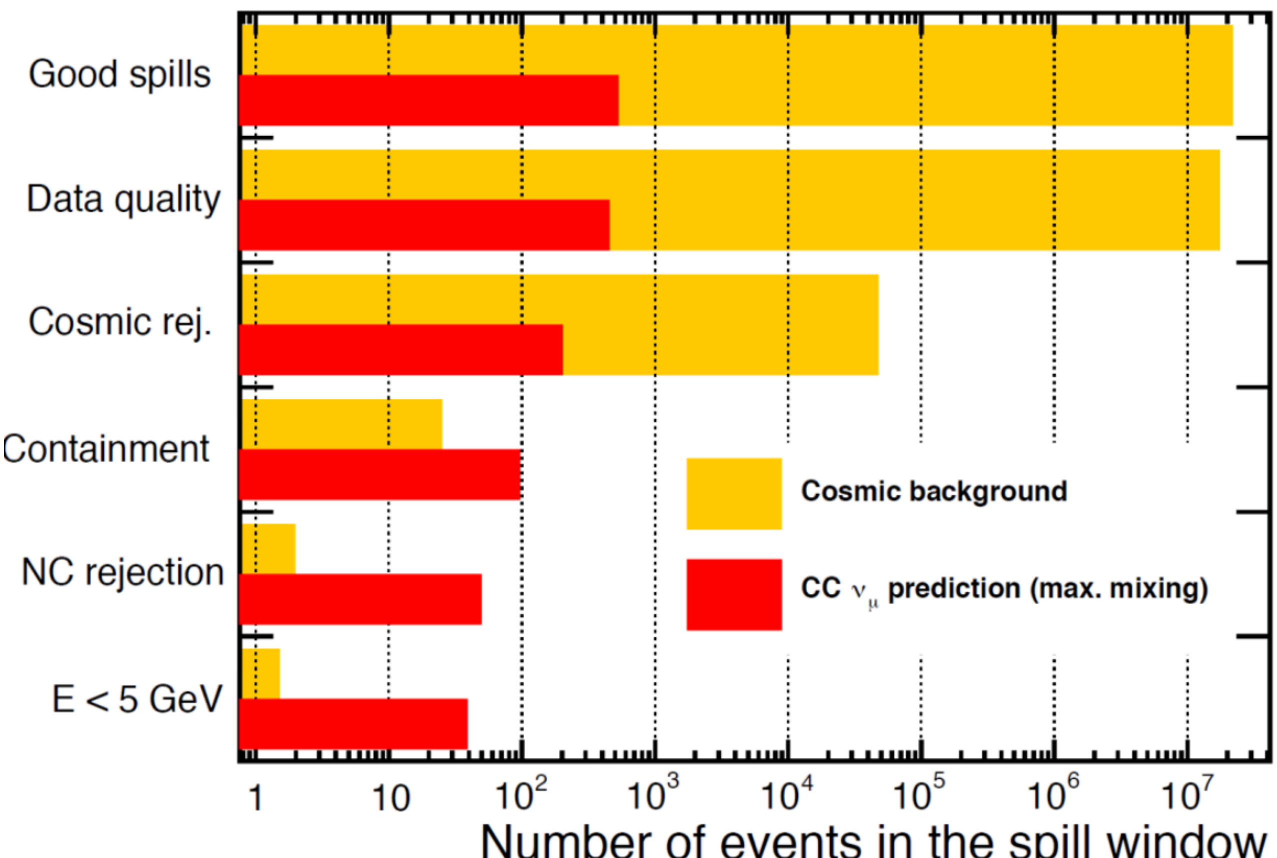
- track length
- dE/dx along track (shown top right)
- scattering along track
- proportion of lateral energy distribution consistent with muon MIP



Keep events with muon ID > 0.75.

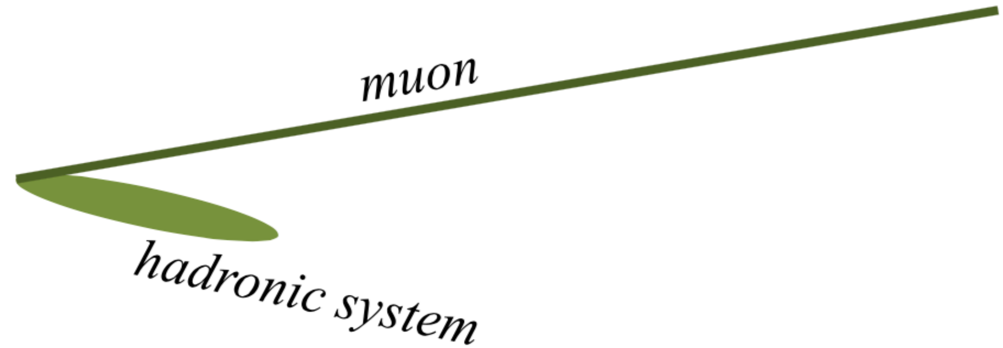
Far Detector Cosmic Rejection:

- We expect ~65,000 cosmic rays in-time with the NuMI beam spills per day. The expected number of contained ν_μ CC events per day is only a few.
- Containment cuts will remove 99% of the cosmics.



- We use a boosted-decision-tree (BDT) algorithm that takes input from reconstruction variables to reject the remaining cosmics.
- All cuts together give us > 15:1 s:b.
- Cosmics are reduced by 10^7!

Energy Estimation:



Reconstructed muon track:

length $\Rightarrow E_\mu$

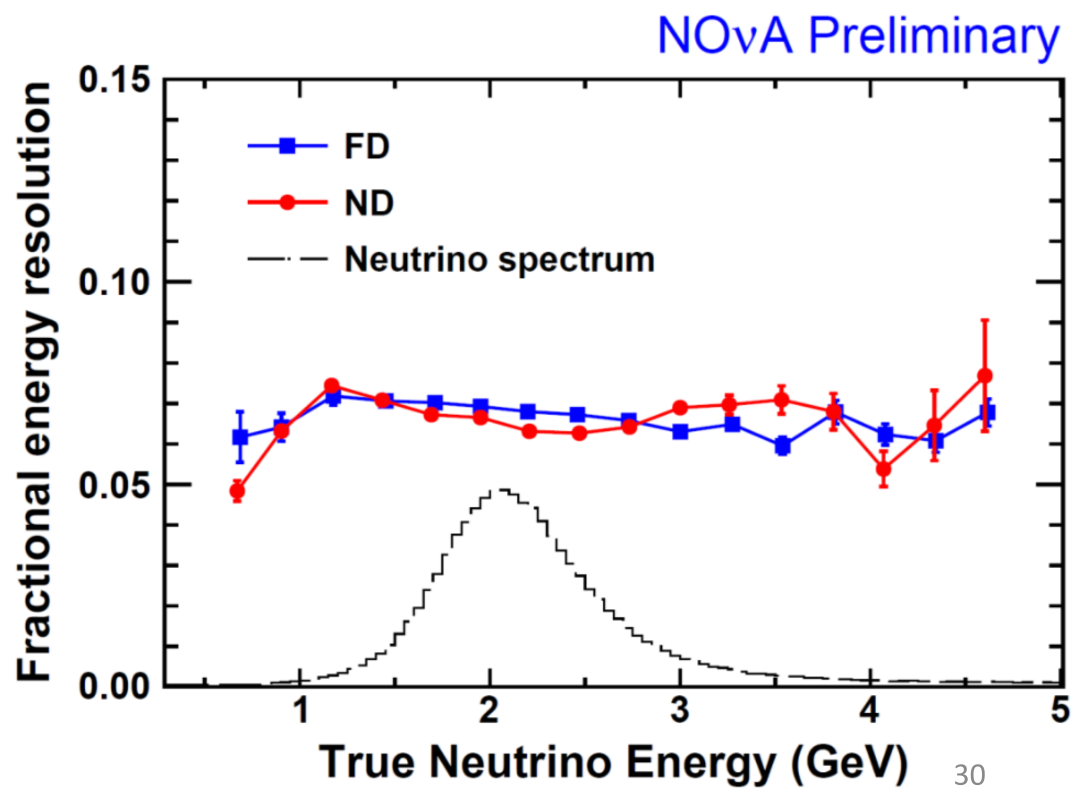
Hadronic system:

$\sum_{\text{cells}} E_{\text{visible}} \Rightarrow E_{\text{had}}$

Reconstructed ν_μ energy is the sum of these two:

$$\boldsymbol{E_\nu = E_\mu + E_{\text{had}}}$$

Energy resolution at beam peak ~7%



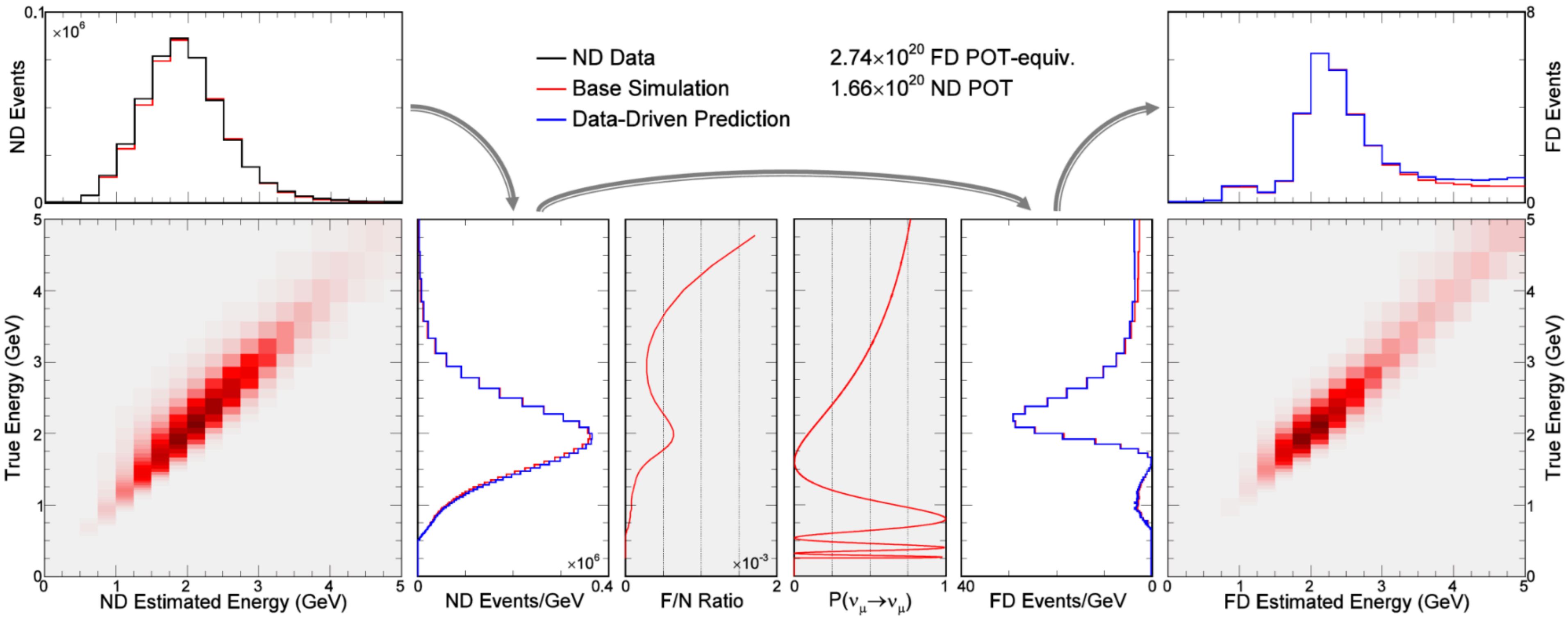
Far Detector Prediction:

(1) Estimate the underlying **true energy distribution** of selected ND events

(2) Multiply by expected **Far/Near event ratio** and $\boldsymbol{\nu_\mu \rightarrow \nu_\mu}$ **oscillation probability** as a function of true energy

(3) Convert FD true energy distribution into **predicted FD reco energy distribution**

Systematic uncertainties assessed by **varying all MC-based steps**

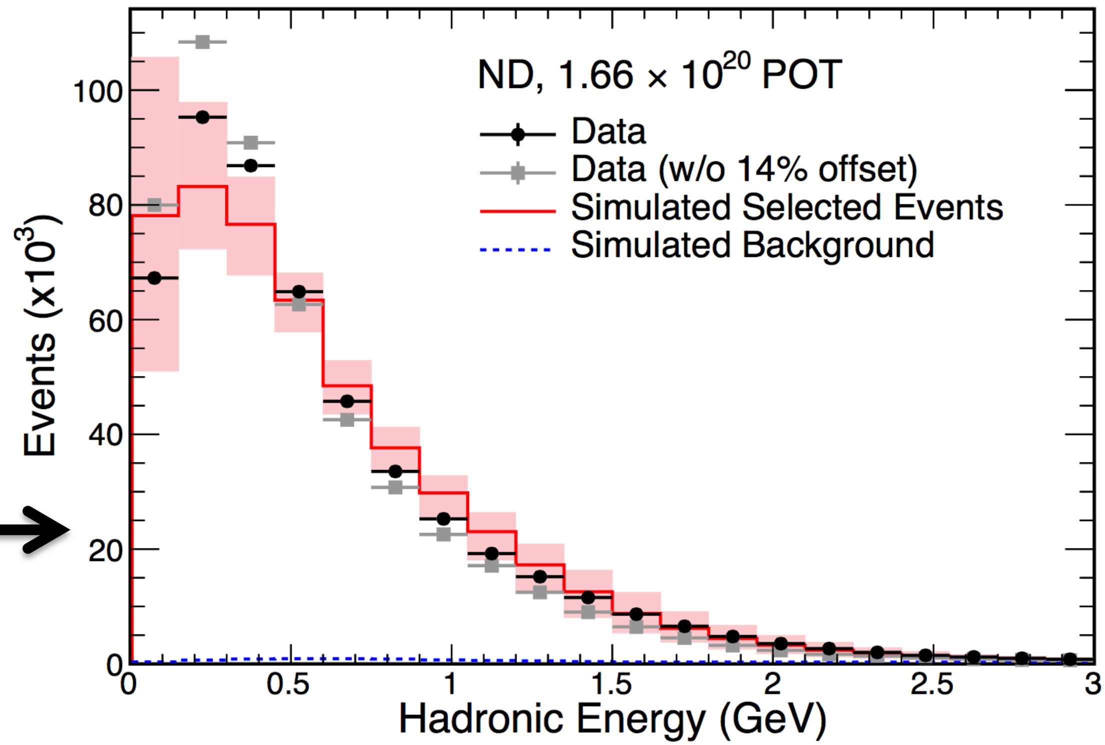


Systematics:

Most of our systematic uncertainties have **relatively little influence** on the result

Hadronic energy syst. is one with a noticeable effect

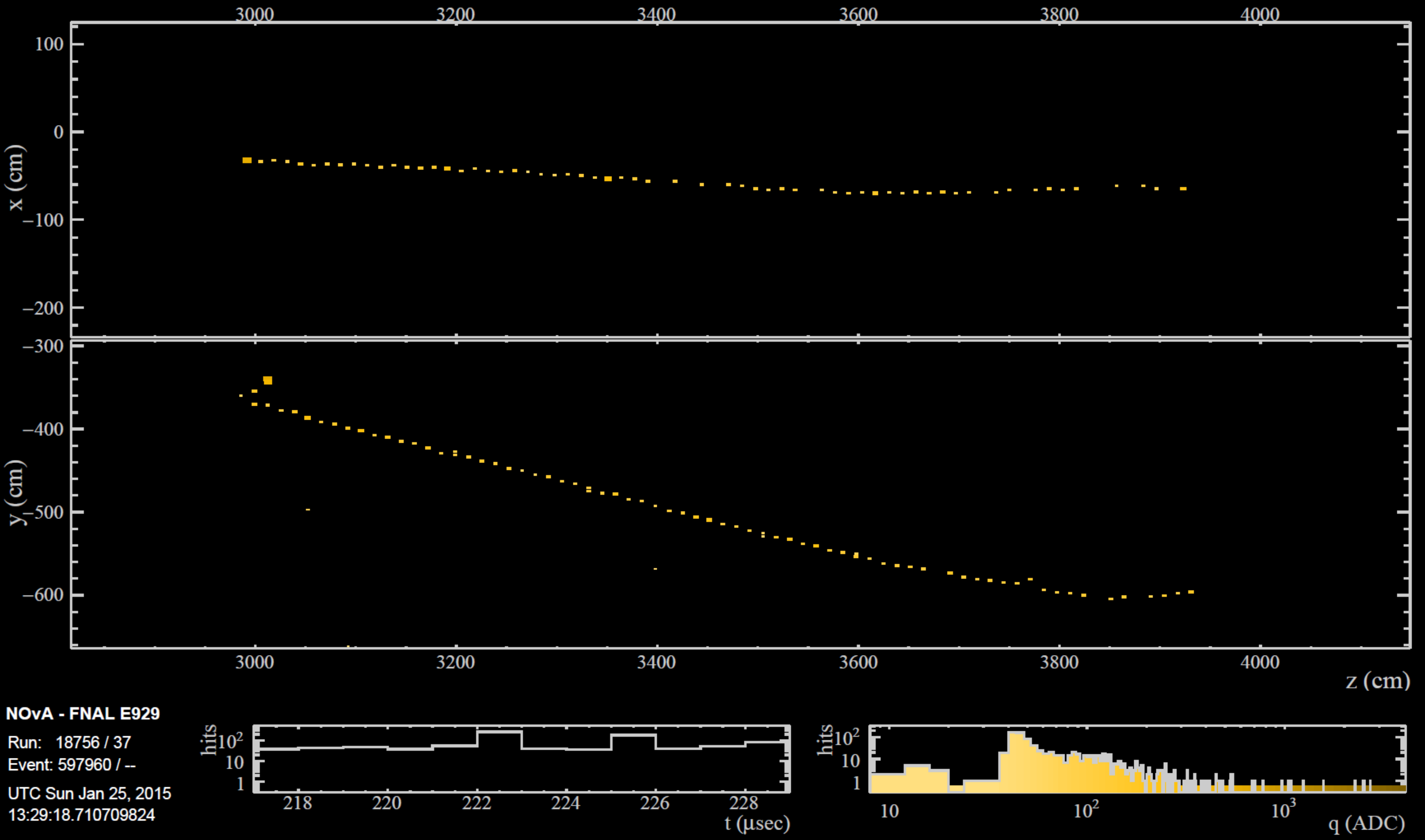
(impact reduced by ND-to-FD prediction procedure)



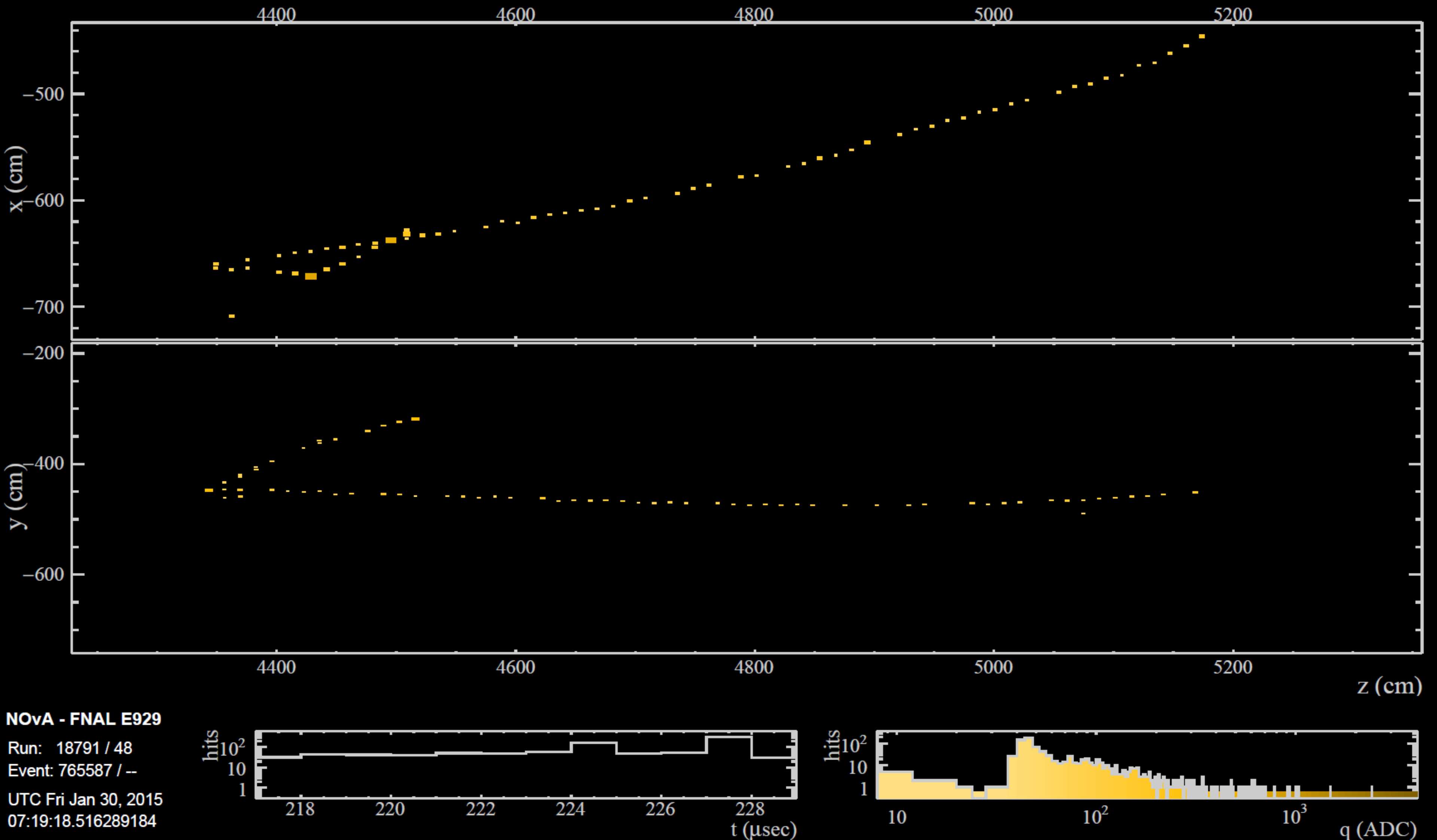
Uncertainties assessed

- Hadronic Energy
  (14% shift, equiv. to 6% shift in ν_E)
- Neutrino Flux
  (beam modeling, hadron transport)
- Absolute and Relative Normalizations
- Neutrino Interactions
  (GENIE, Intranuke modeling)
- NC and ν_τ background rates
  (100% each)
- Calibration, light-levels
  (hit energy, attenuation, thresholds)
- Oscillation parameter uncertainties
  (current world knowledge)

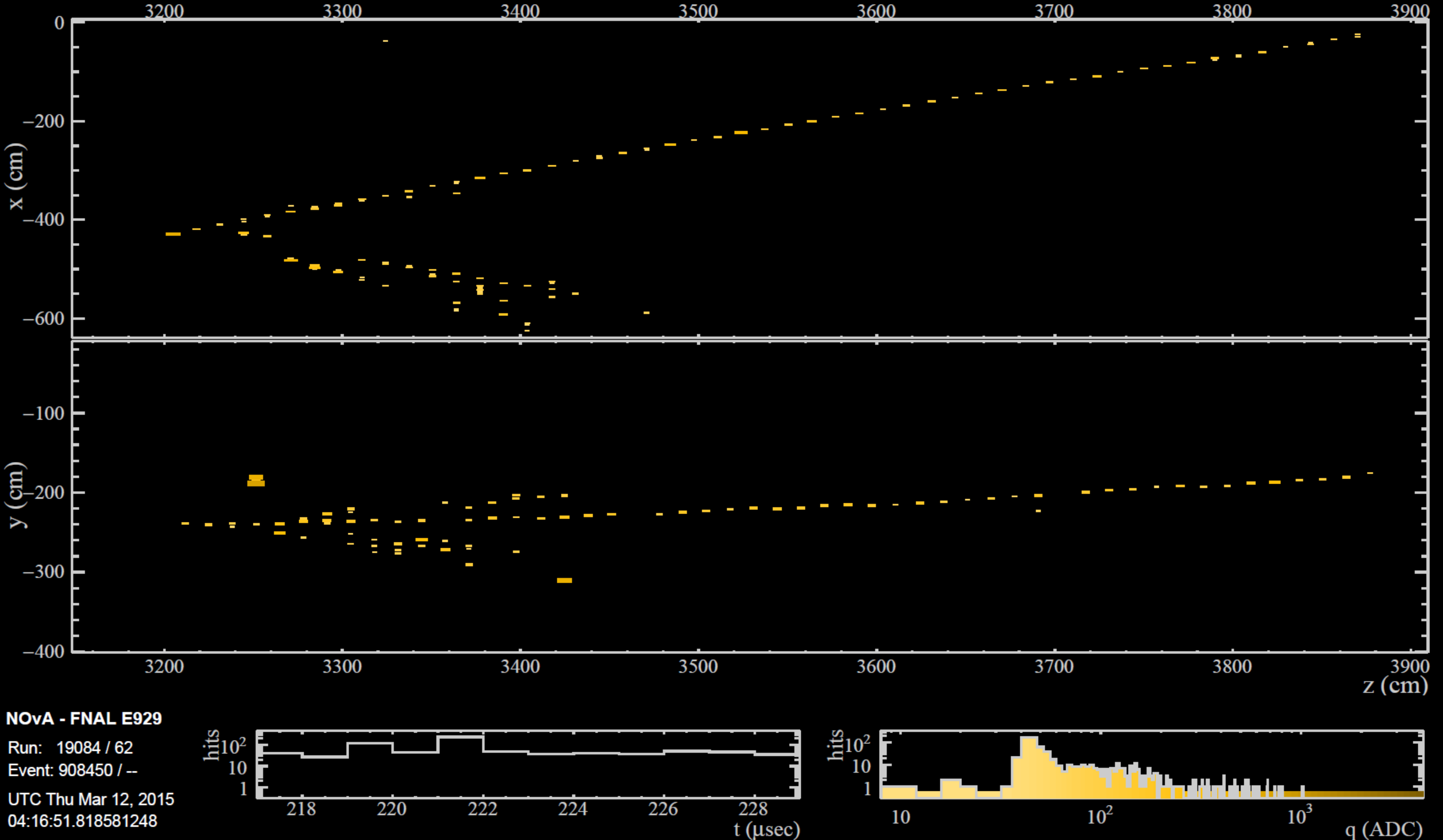
Far Detector selected ν_μ CC candidate



Far Detector selected ν_μ CC candidate



Far Detector selected ν_μ CC candidate



ν_μ CC Results:

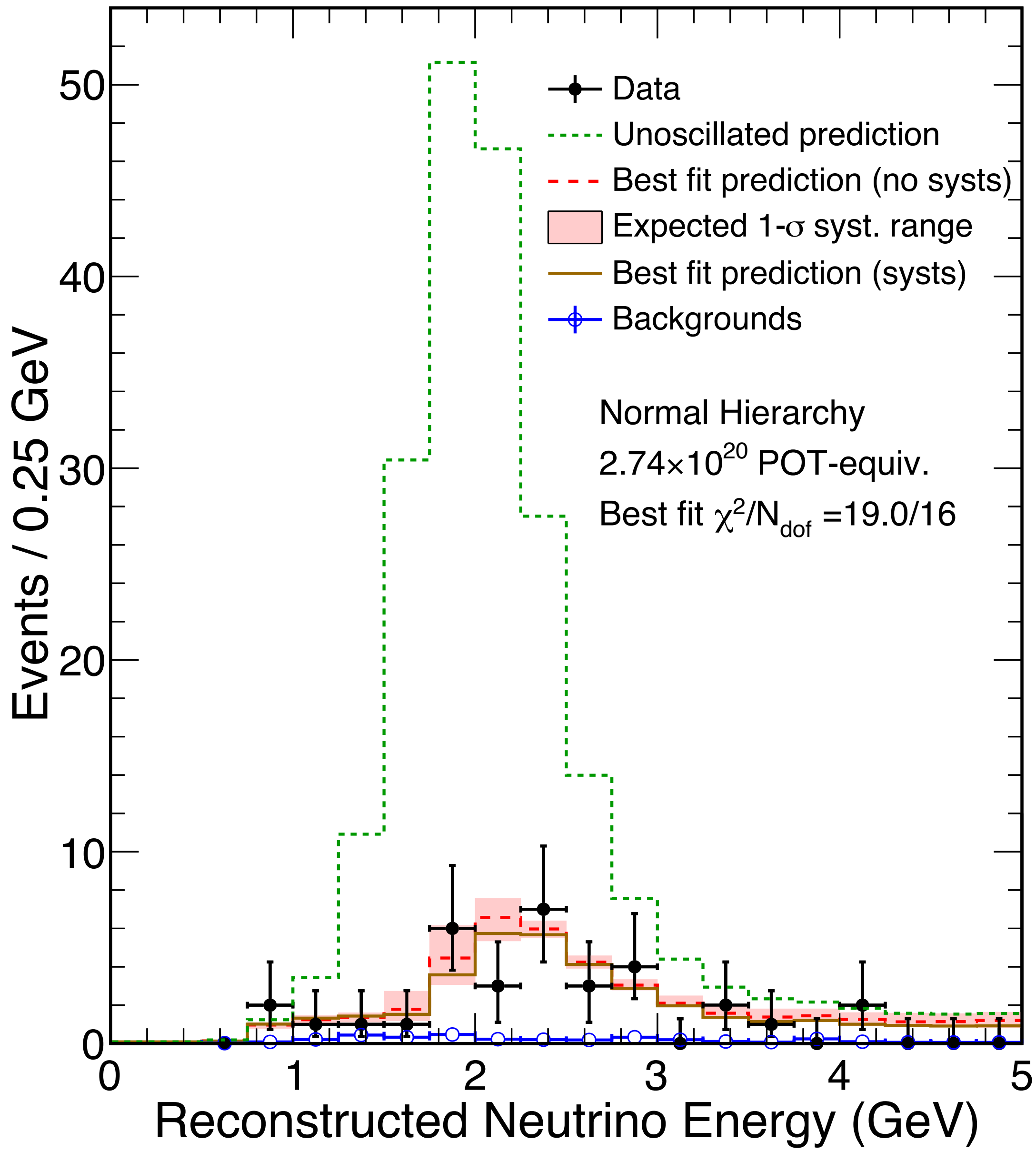
33 events selected in the FD
(0 – 5 GeV)

In the absence of oscillations, 212 events are expected.

(including 1.4 cosmic and 2.0 beam backgrounds.)

Spectrum is well matched to the oscillation parameters Δm^2_{32} and θ_{23}.

(All syst. uncertainties fit as nuisance parameters.)

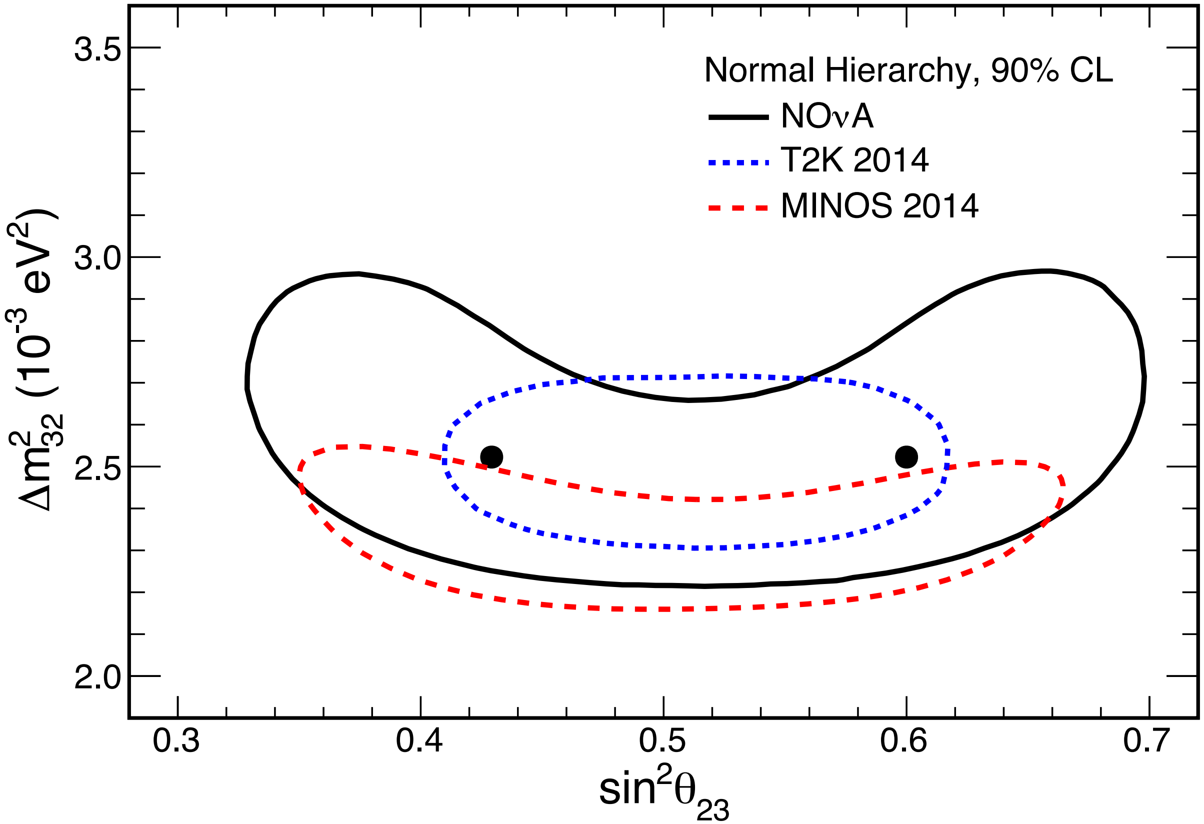


Clear observation of ν_μ disappearance!

ν_μ CC Results: (arXiv:1601.05037v2)

Allowed regions are consistent with MINOS and T2K
(shown at right)

NOνA sensitivity **already compelling** with only 7.6% of nominal exposure!



Normal Hierarchy

$$\Delta m^2_{32} = (2.52^{+0.20}_{-0.18}) \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2(\theta_{23}) = [0.38, 0.65]$$

(68% CL)

Degenerate best fit points at 0.43 and 0.60

Inverted Hierarchy

$$\Delta m^2_{32} = (-2.52 \pm 0.19) \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2(\theta_{23}) = [0.37, 0.64]$$

(68% CL)

Degenerate best fit points at 0.44 and 0.59

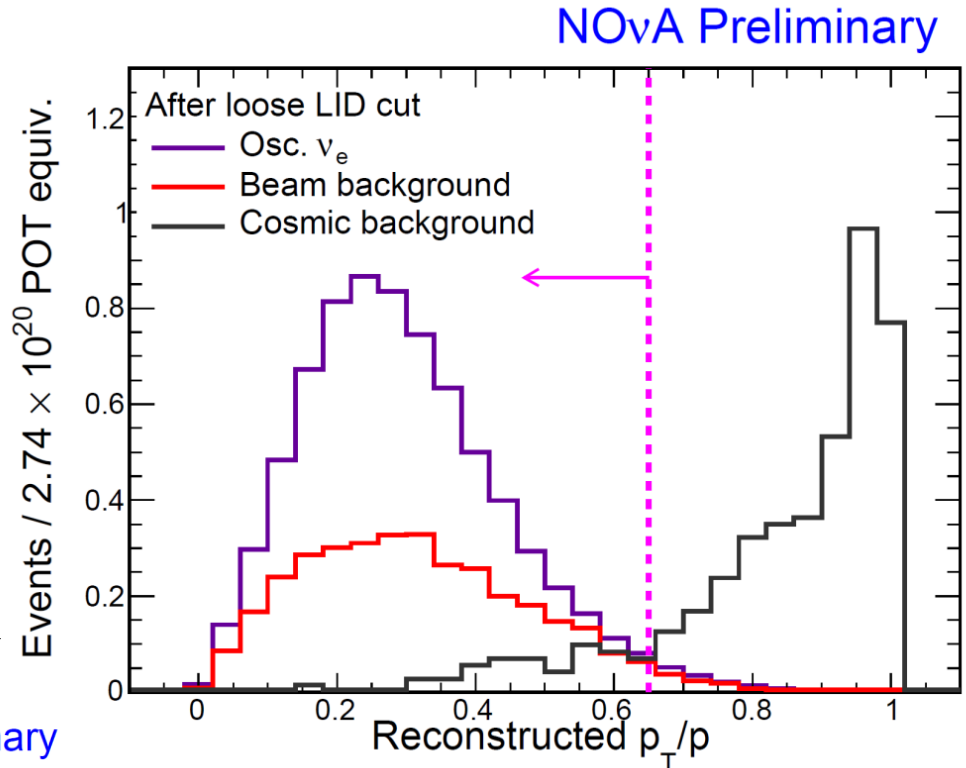
ν_e Appearance Results:

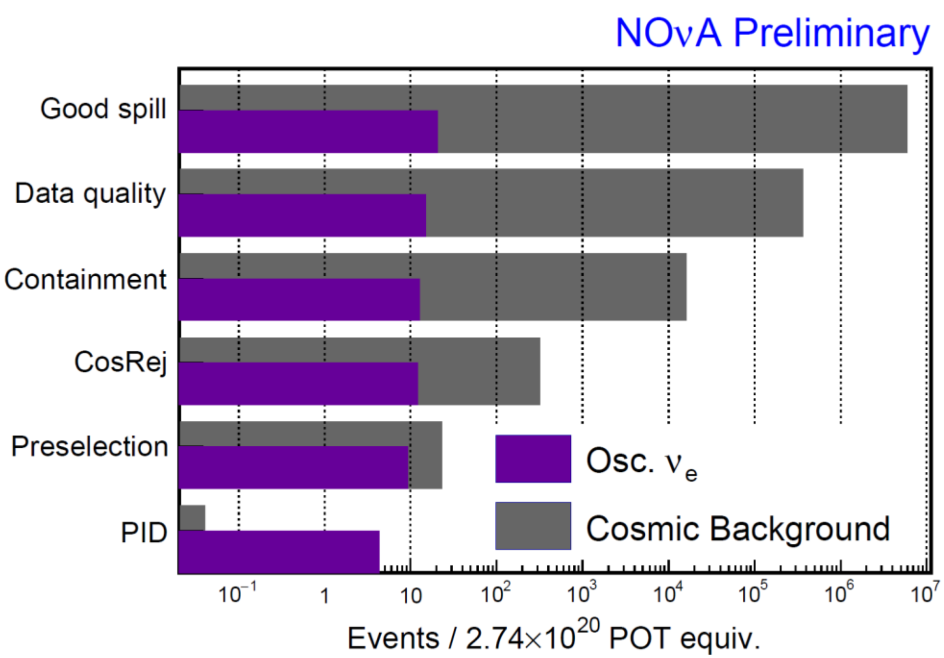
Cosmic Rejection:

Cut events with large reconstructed p_T/p

Rejects downward-directed cosmic shower

The ν_e selectors themselves provide a lot of cosmic rejection





Achieve **1 part in ~10^8** rejection of cosmic ray interactions.

Expected cosmic background: **0.06 events**

(measured with beam-off data)

ν_e CC Event Selection:

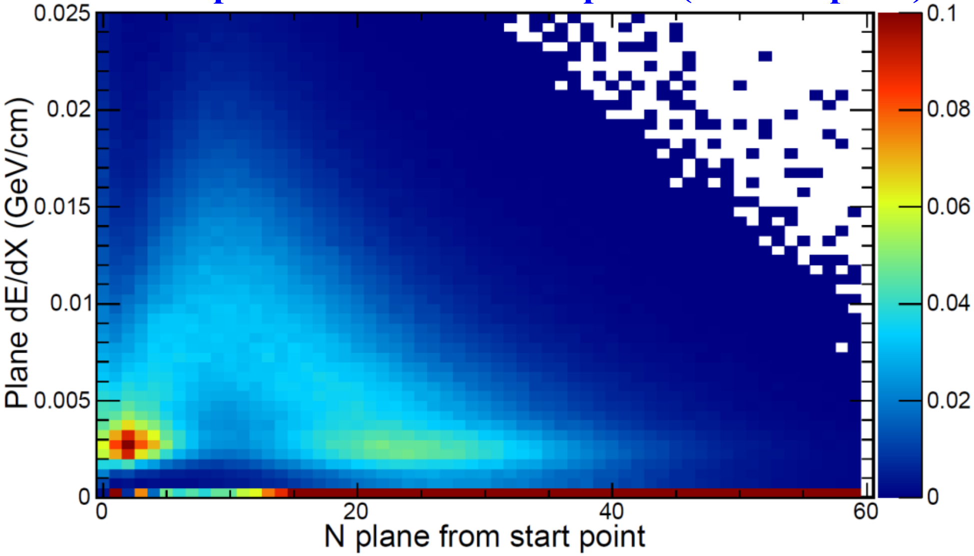
We have developed two independent ν_e CC selection algorithms
→ *Very different designs*

LID: Likelihood Identification

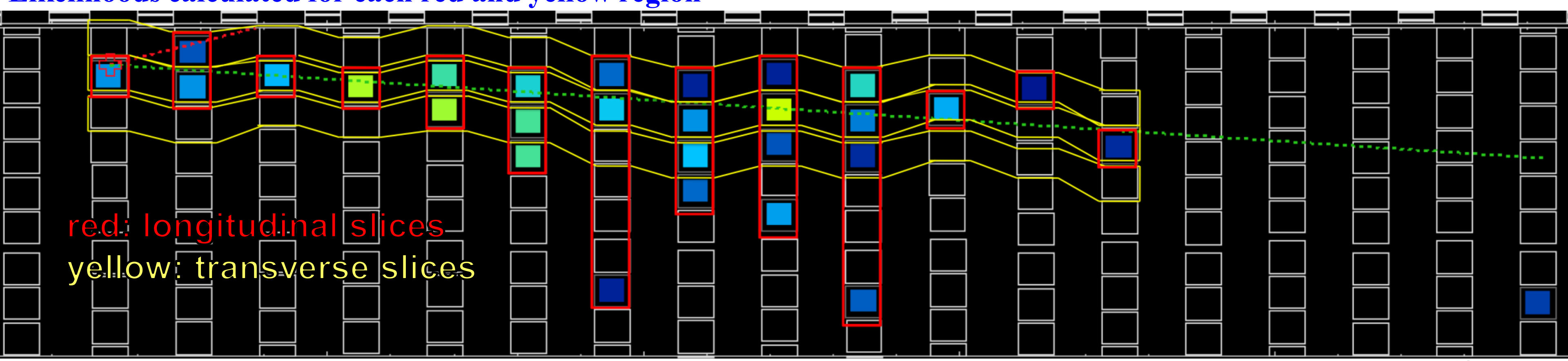
***dE/dx* likelihoods** calculated for **longitudinal and transverse** slices of leading shower under multiple particle hypotheses

Likelihoods feed an artificial neutral network along with **kinematic and topological info**:
e.g., energy near vertex, shower angle, vertex-to-shower gap

***Color:* p.d.f. for *dE/dx* in each plane (e^- assumption)**



Likelihoods calculated for each red and yellow region



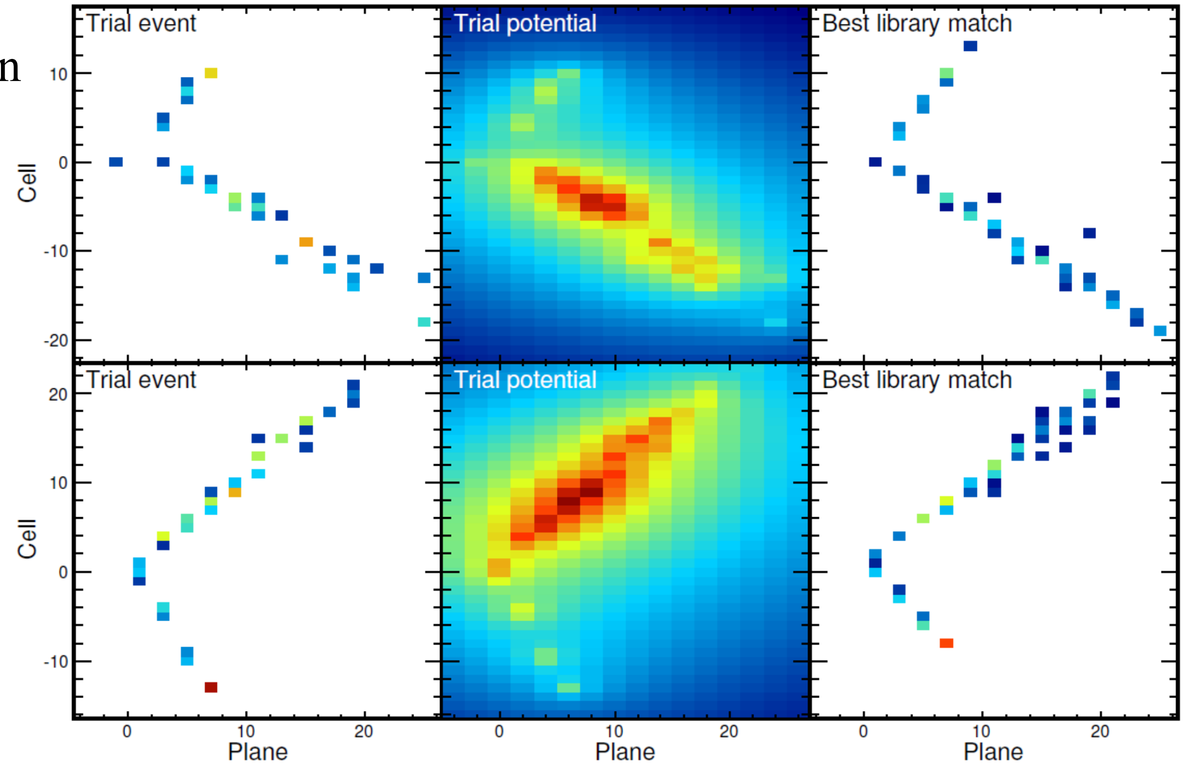
ν_e CC Event Selection:

Left panels: candidate event, both views
Right panels: best-matched library event, both views
Middle panels: an intermediate step in calculating the match quality

LEM: Library Event Matching

Spatial pattern of energy deposition is compared directly to that of ~10^8 simulated events ("library")

Key properties of the **best-matched library events** (*e.g.*, fraction that are signal events) are input into a decision tree to form discriminant



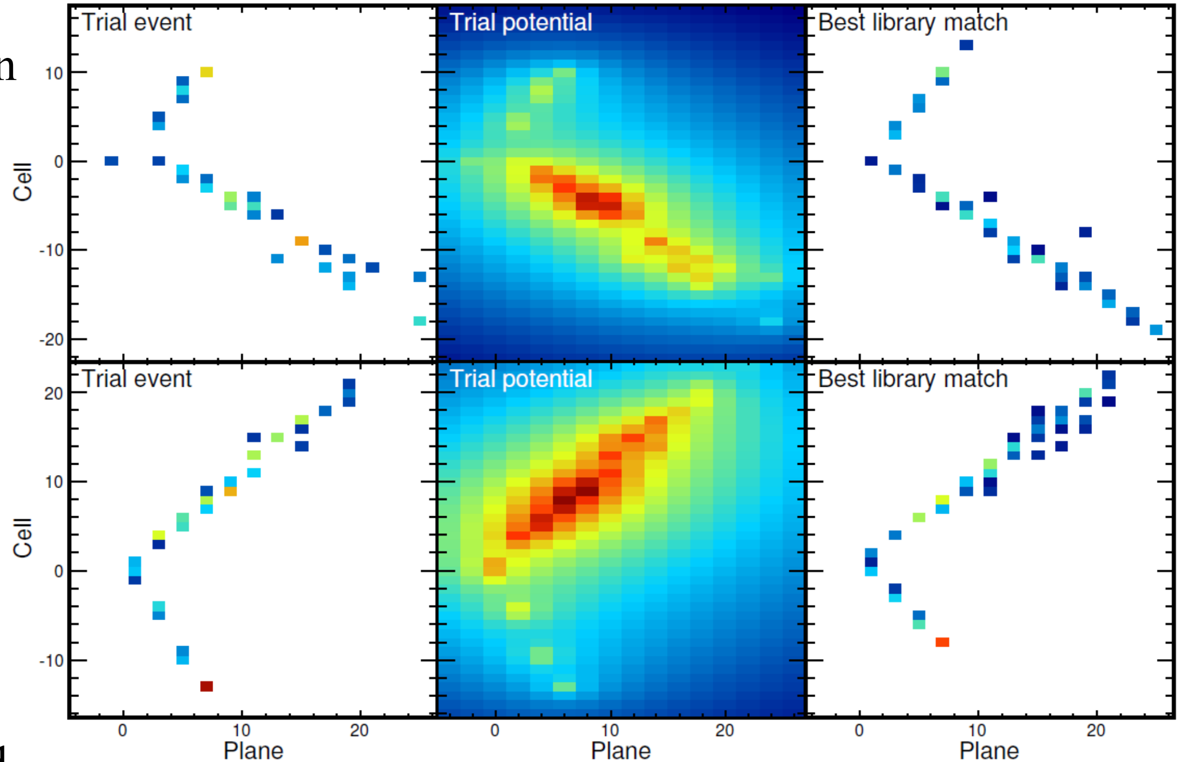
ν_e CC Event Selection:

LEM: Library Event Matching

Spatial pattern of energy deposition is compared directly to that of $\sim 10^8$ simulated events ("library")

Key properties of the **best-matched library events** (*e.g.*, fraction that are signal events) are input into a decision tree to form discriminant

***Left panels*: candidate event, both views**
***Right panels*: best-matched library event, both views**
***Middle panels:* an intermediate step in calculating the match quality**



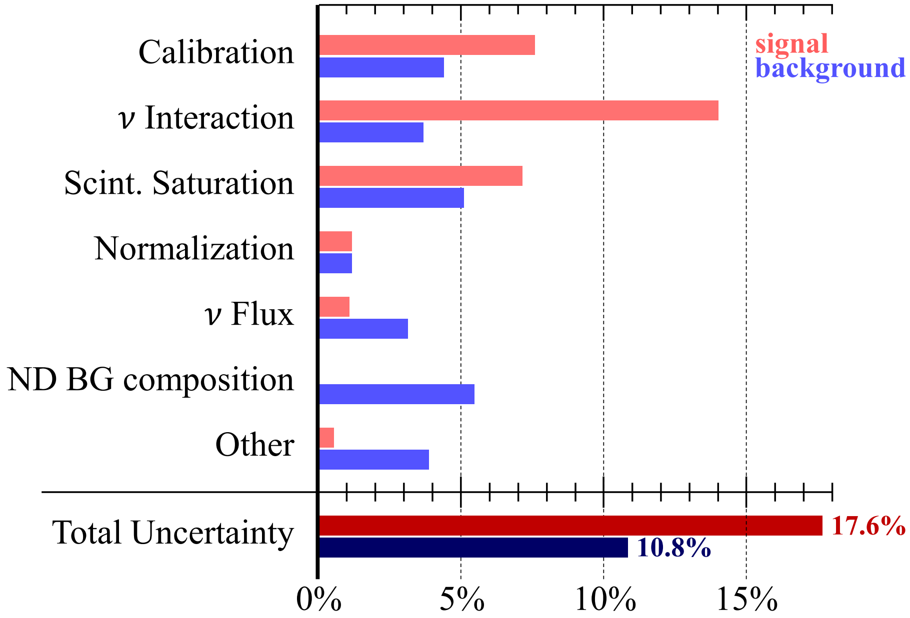
LID and LEM sensitivities

Identical performance as measured with signal efficiency, sig/bg ratio, systematic uncertainties, and overall sensitivity to ν_e appearance and oscillation parameters.

Thus, prior to unblinding, decided to **show both results** and to use the more traditional **LID technique** as the primary result where required.

ν_e CC FD Event Selection:

- **ND data** is translated to **FD bckgnd expectation** in each energy bin, using Far/Near ratios from simulation
- **FD *signal* expectation** is pinned to the ND-selected ν_μ CC spectrum
- Most **systematics** are assessed **via variations** in the Far/Near ratios



Some FD sample stats:

Signal efficiency relative to containment cuts: **35%**

Expected overlap in LID/LEM samples: **62%**

→ *Differences in which events each technique selects*

After all selection, **0.7% of NC events** remain, relative to those after containment

ν_e FD Predictions:

LID selector

Background [plus few-percent variations depending on osc. pars.]

0.94 ± 0.09 events [49% ν_e CC, 37% NC]

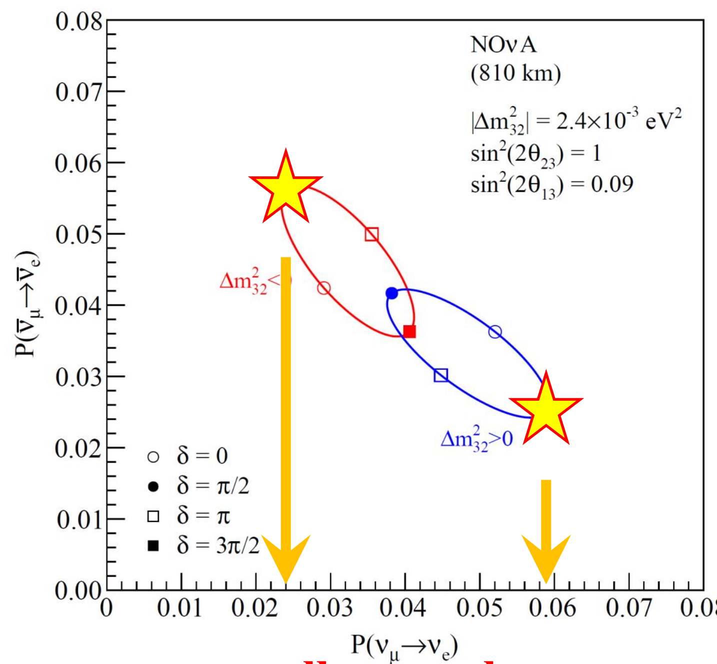
2.74×10^{20} POT equiv.

Signal [NH, $\delta = 3\pi/2$, $\theta_{23} = \pi/4$]

5.62 ± 0.72 events

Signal [IH, $\delta = \pi/2$, $\theta_{23} = \pi/4$]

2.24 ± 0.29 events



smaller ν_e rate

larger ν_e rate

ν_e FD Predictions:

LEM selector

Background [plus few-percent variations depending on osc. pars.]

1.00 ± 0.11 events [46% ν_e CC, 40% NC]

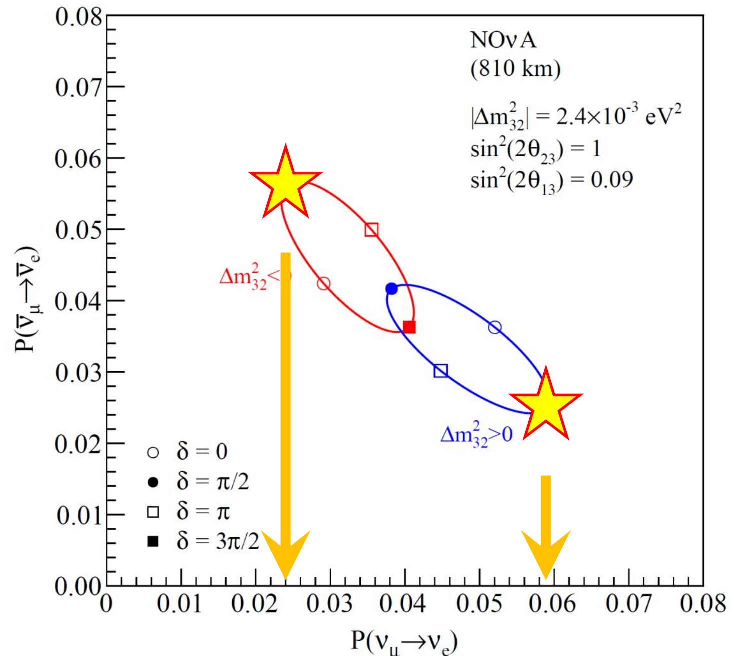
2.74×10^{20} POT equiv.

Signal [NH, $\delta = 3\pi/2$, $\theta_{23} = \pi/4$]

5.91 ± 0.65 events

Signal [IH, $\delta = \pi/2$, $\theta_{23} = \pi/4$]

2.34 ± 0.26 events

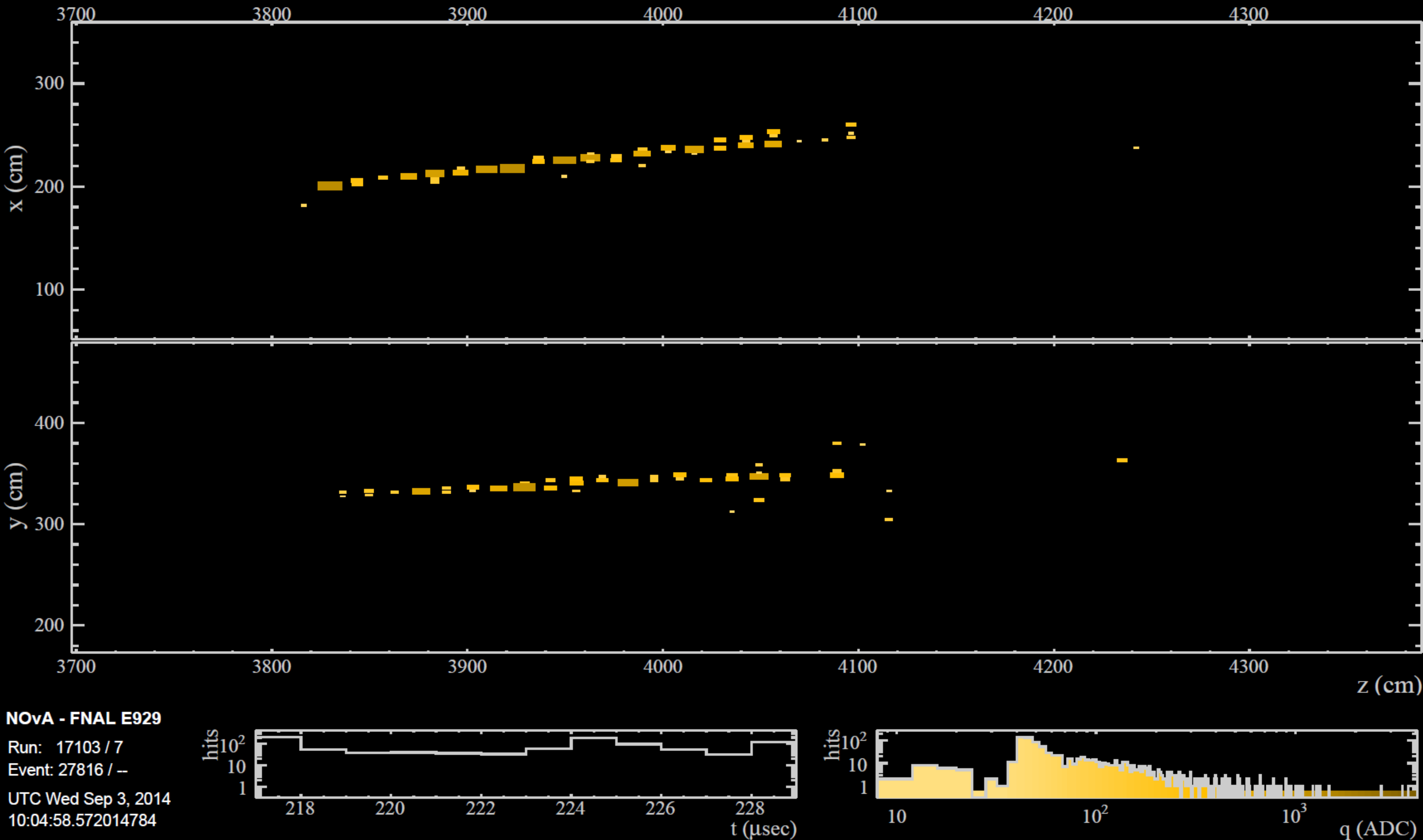


smaller ν_e rate **larger ν_e rate**

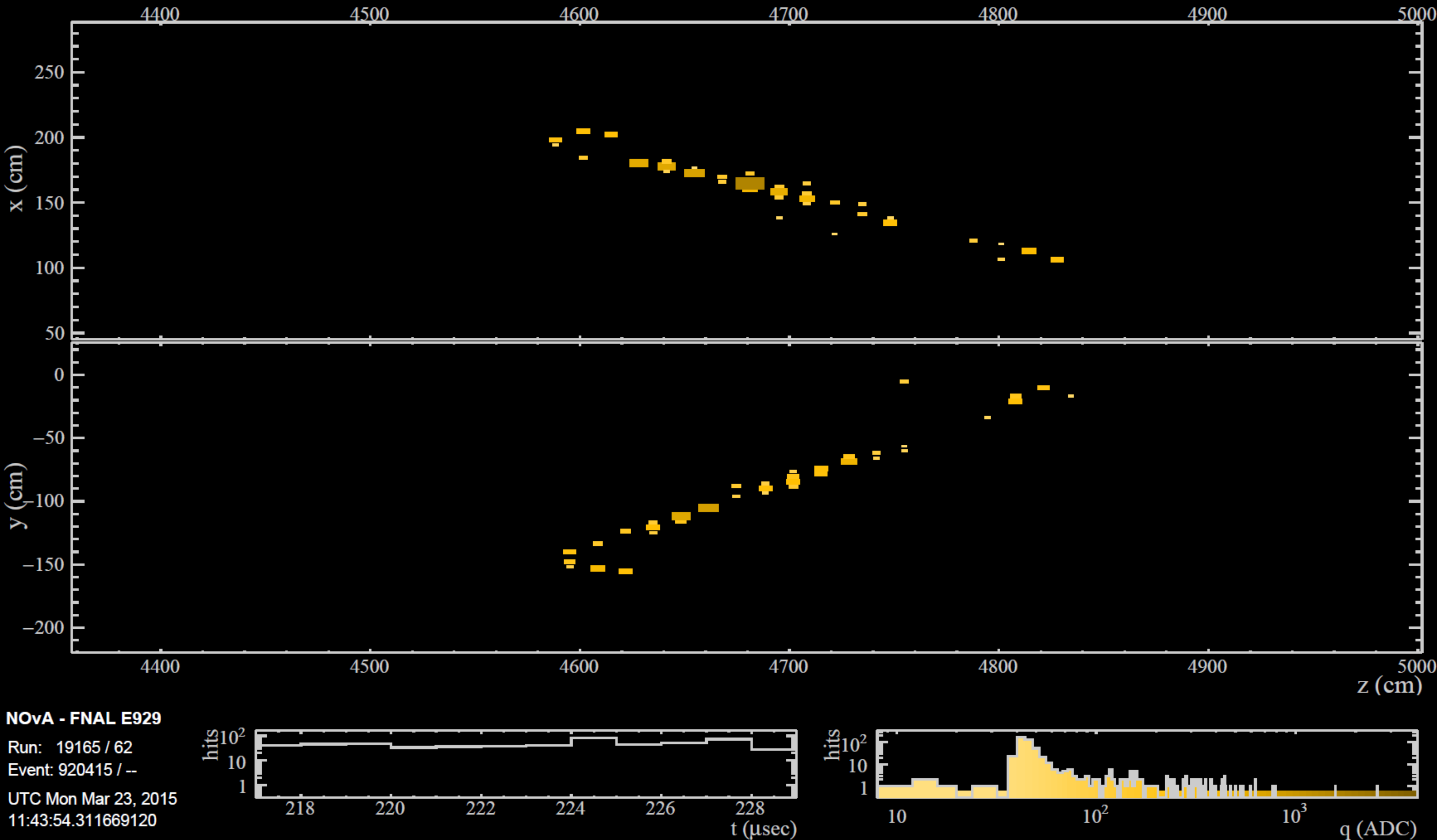
Aside: Before unblinding, **two sidebands checks** –
(1) Near-PID (LID/LEM) sideband, and
(2) High-energy sideband

Results of both were **well within expectations**.

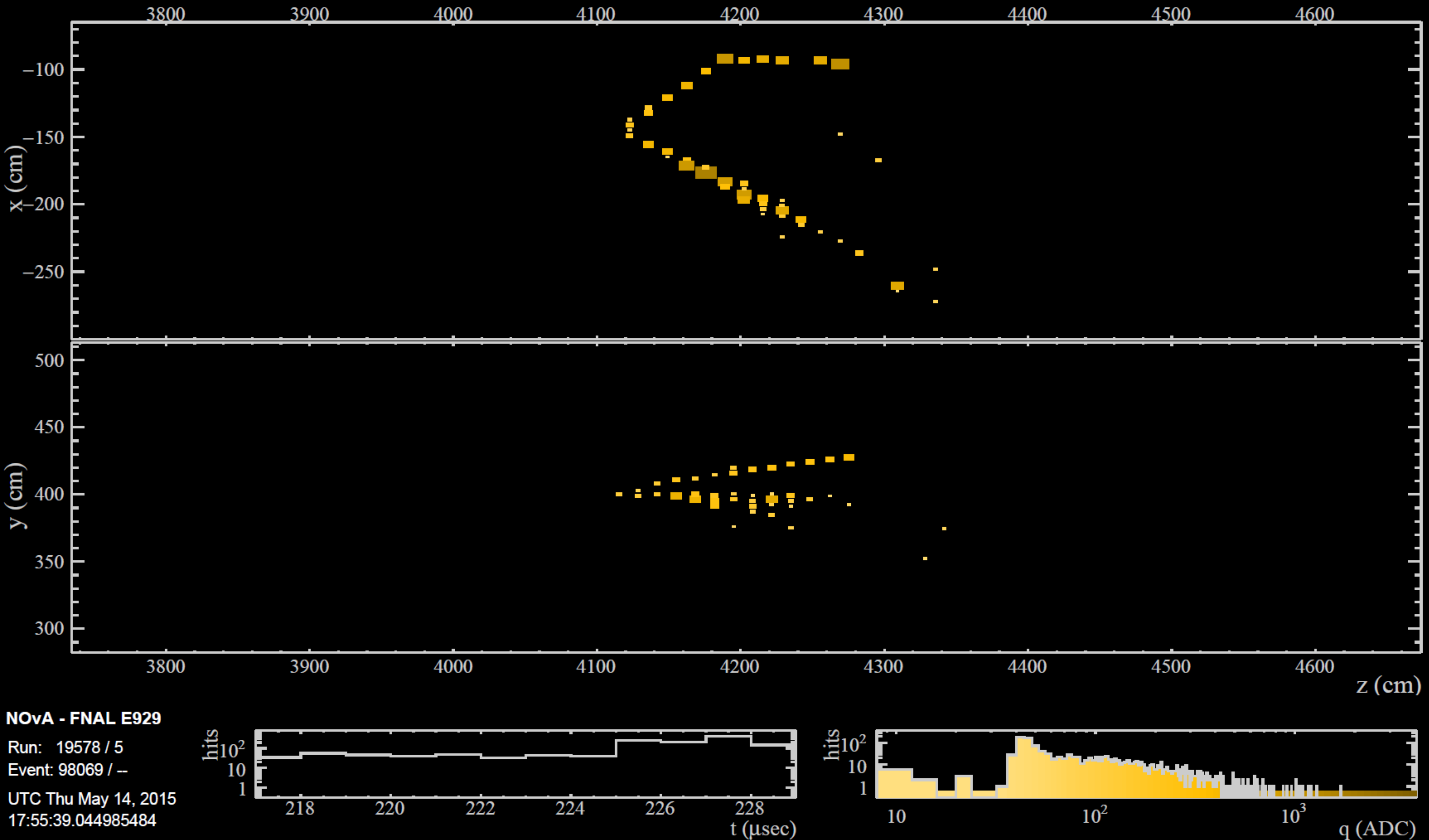
Far Detector selected ν_e CC candidate



Far Detector selected ν_e CC candidate



Far Detector selected ν_e CC candidate



ν_e FD Events:

LID: 6 ν_e candidates

3.3σ significance for ν_e appearance

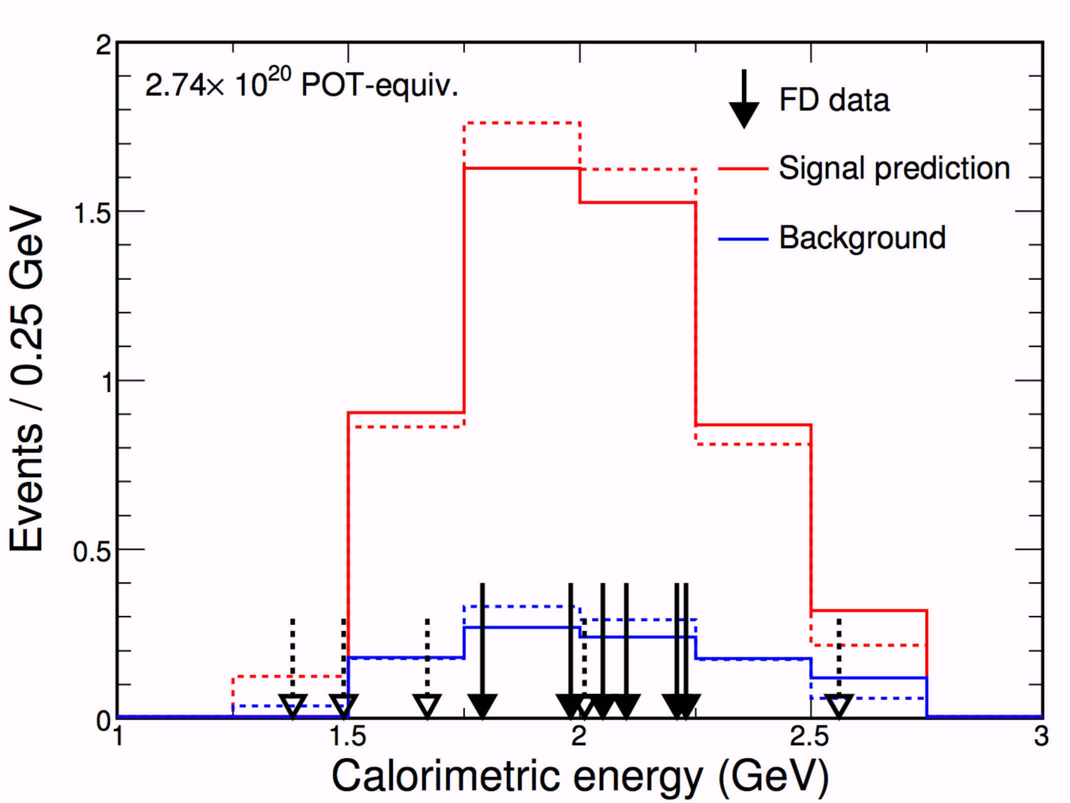
At right:

Calorimetric energy

LEM: 11 ν_e candidates

5.5σ significance for ν_e appearance

(All 6 LID events present in LEM set)



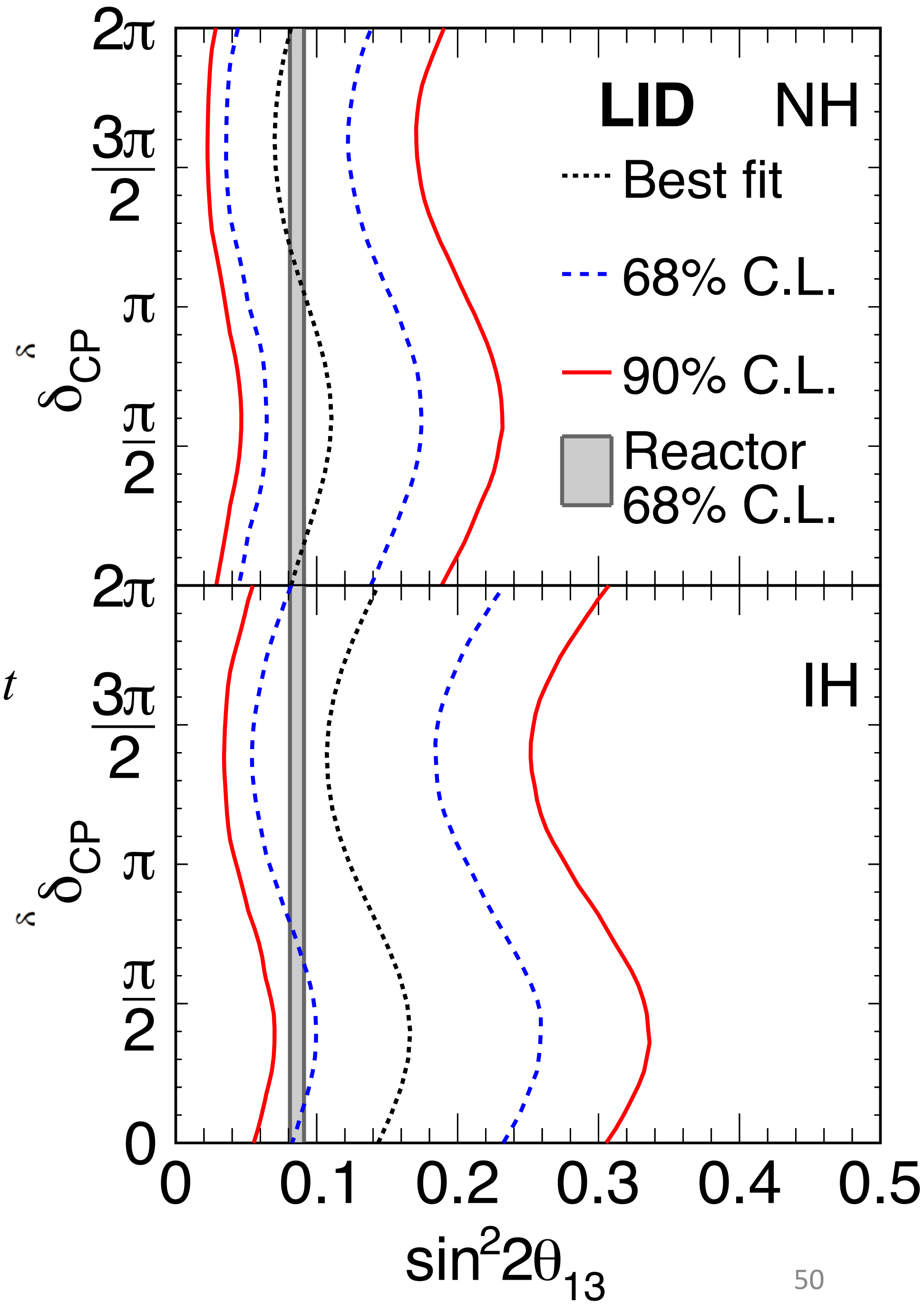
Probability of this overlap (or one less likely) is ~8%.

Result using LID selector

FD selection: **6 ν_e candidates**

For **$(\delta_{CP}, \sin^2 2\theta_{13})$** allowed regions

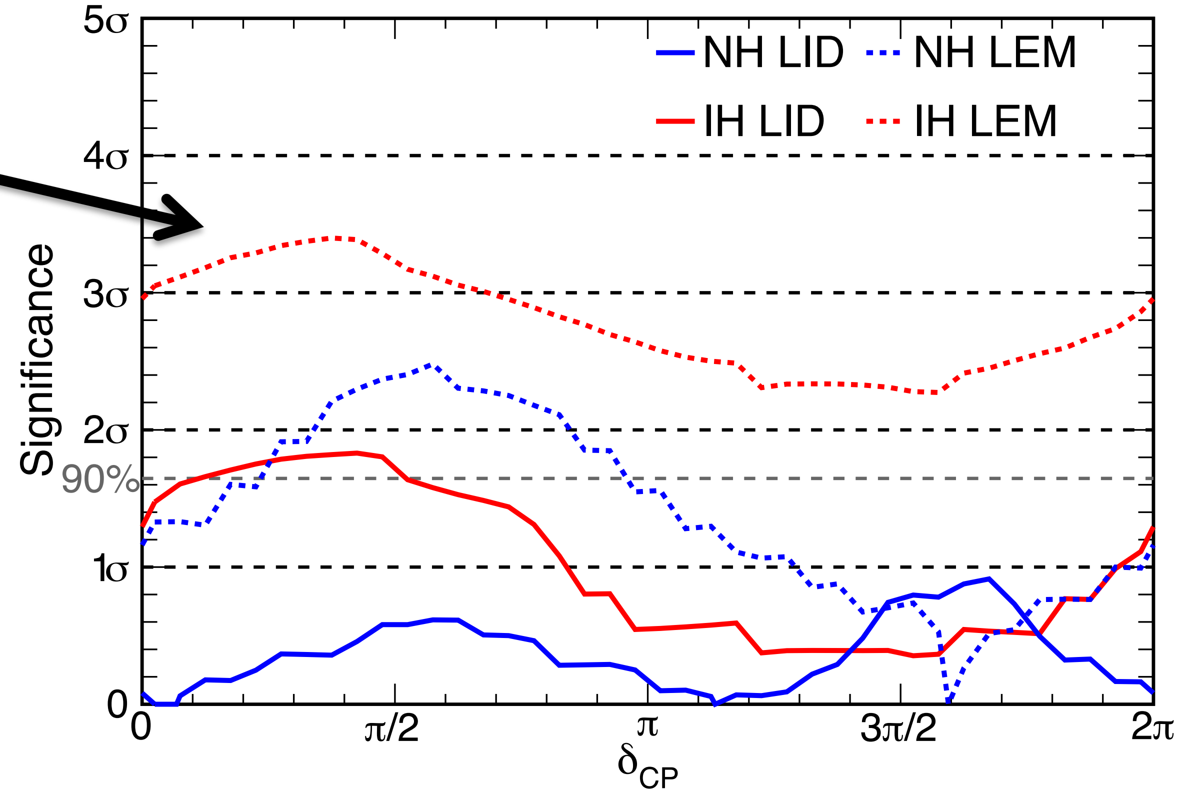
- Feldman-Cousins procedure applied
- solar osc. parameters varied
- Δm^2_{32} varied by *new NOvA measurement*
- $\sin^2\theta_{23}$=0.5



ν_e Results:

- **Applying the global reactor constraint of:** *$\sin^2 2\Theta_{13} = 0.086 \pm 0.005$*
- **Marginalizing over Θ_{23}**

Compatibility between the observed number of events and mass hierarchy / δ_{CP}.



IH for $0.1\pi < \delta_{CP} < 0.5\pi$ is disfavored at the 90% c.l.

- **Both selectors prefer the NH with $\pi < \delta_{CP} < 2\pi$.**
- **Results are consistent with T2K**

NOνA First Results Summary:

- Unambiguous observation of ν_μ disappearance (consistent with MINOS and T2K.)
- ν_e appearance observed at 3.3σ above predicted backgrounds, and suggests the NH and $\pi < \delta_{CP} < 2\pi$ (consistent with T2K.)
- Near detector X-section studies are underway (some results shown at NuINT and on the arXiv.) Look for more publications soon.
- **NOvA second analysis with double the stats is expected by this summer!**