NOνA Analysis Status

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NOνA Operational Readiness Review

October 28, 2014

A spin through NOνA's analysis structure

- A **distributed effort**. Organization:

NC and ν_e CC
ν_μ CC
Exotics

} **Interaction "channels"** *(multiple physics topics in each)*

Reconstruction
Detector simulation
Beam data and simulation
Calibration and alignment
Computing, production, software

} **Support and infrastructure**

Data quality
Triggers

} **Data collection**

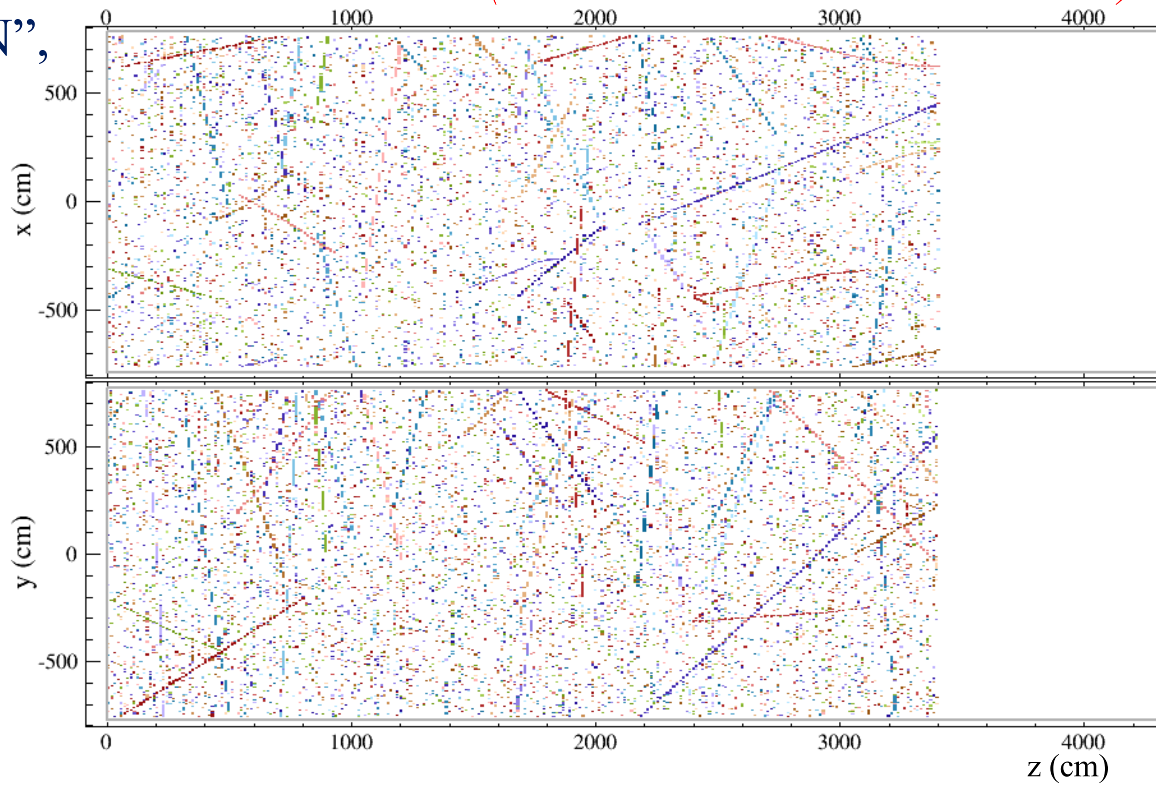
- Plus lots of **activity at the group boundaries**
- Focusing here on items directed at the **3-flavor $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ analyses**

Isolating individual interactions

- A standard trigger in the Far Detector (FD) records 550 μs of activity:
  - *hundreds of **noise hits** (since we keep the DAQ thresholds as low as possible)*
  - *about **50 cosmic rays***
  - *and rarely, a **neutrino interaction***
- **Isolating these components** is the first step of the offline analysis sequence
- Algorithm based on "DBSCAN", **M. Ester *et al.*** (1996)
- Looks for causally connect-able **clusters in space/time**, also using knowledge of how noise hits behave
- *According to FD simulation:*
  Avg. completeness: 99.3%
  Avg. purity: 99.5%

(Actually improved beyond this now…)

A NuMI trigger recorded in April
(detector still under construction)



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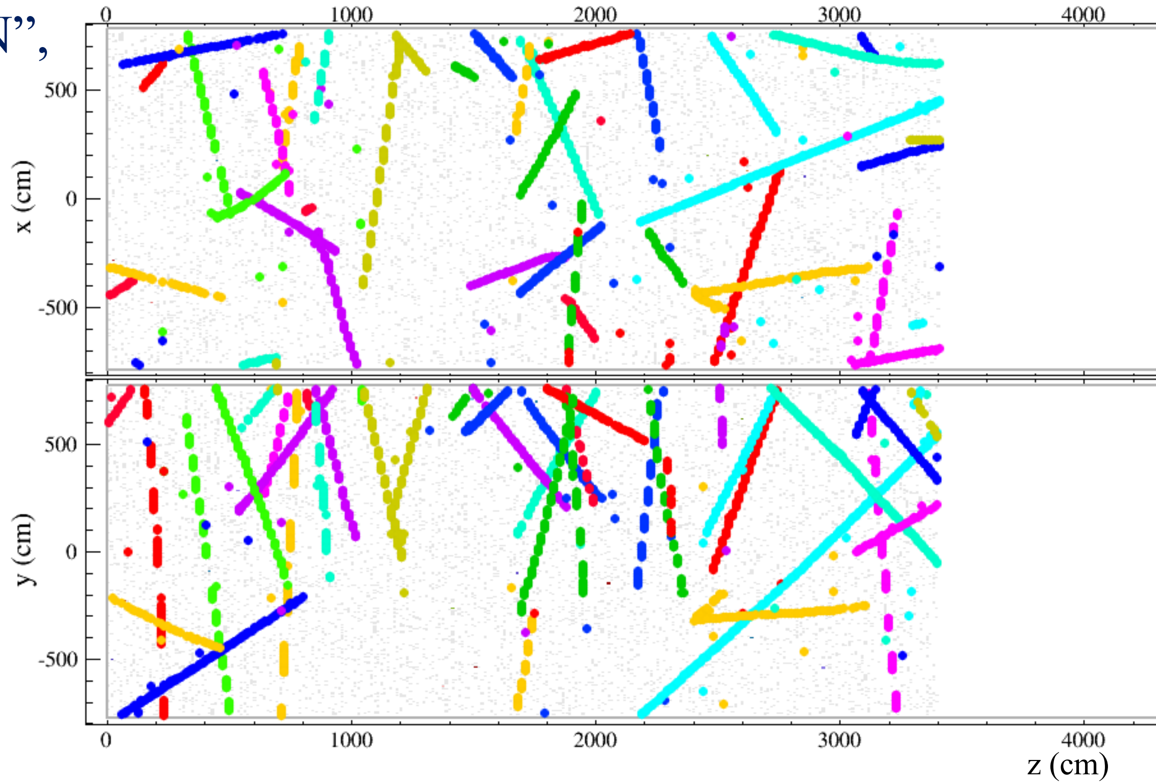
Individual physics events isolated



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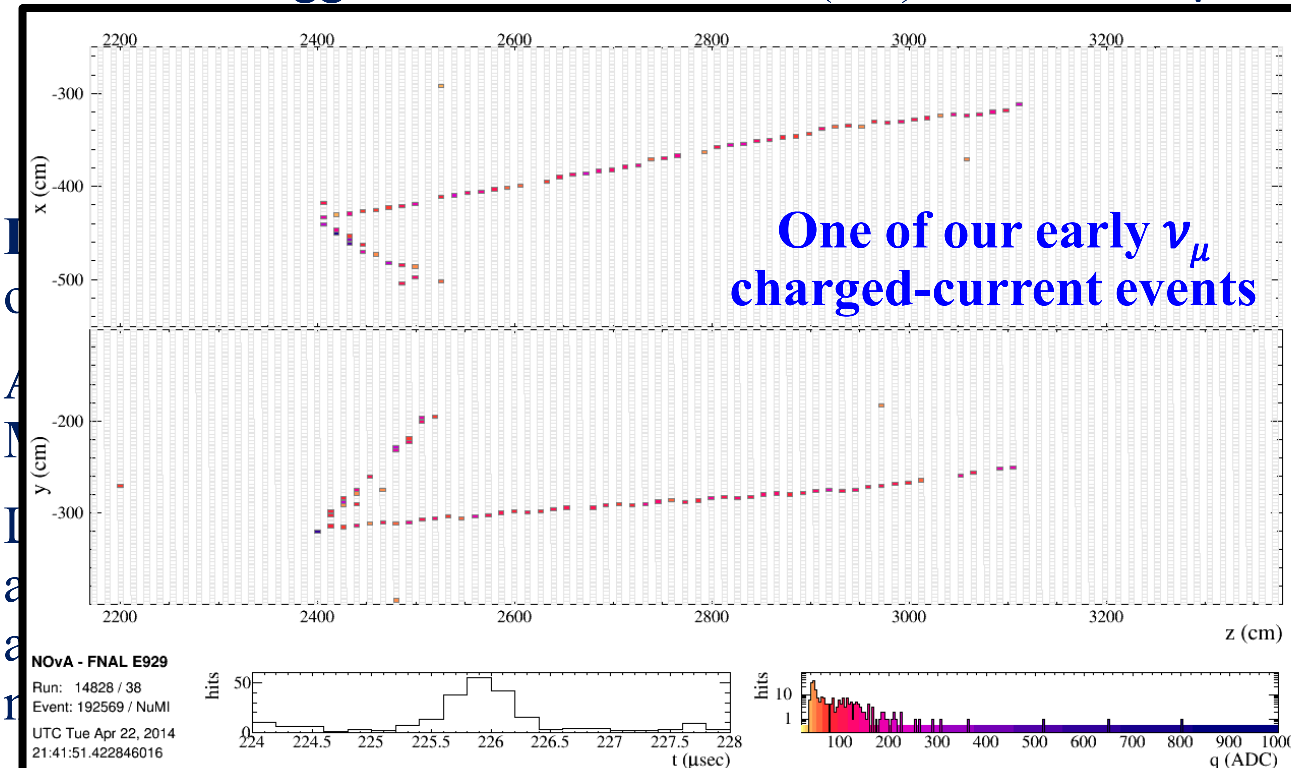
- I... c...
- A... N...
- I... a... a... r...



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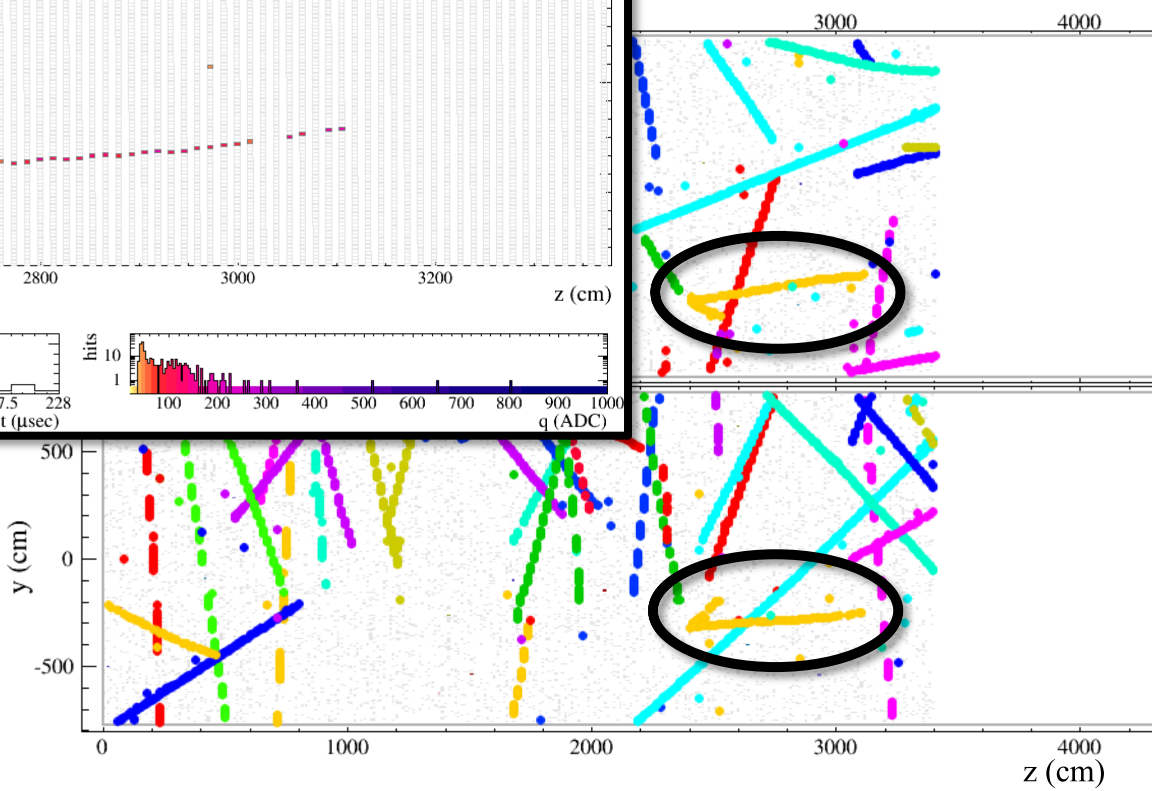

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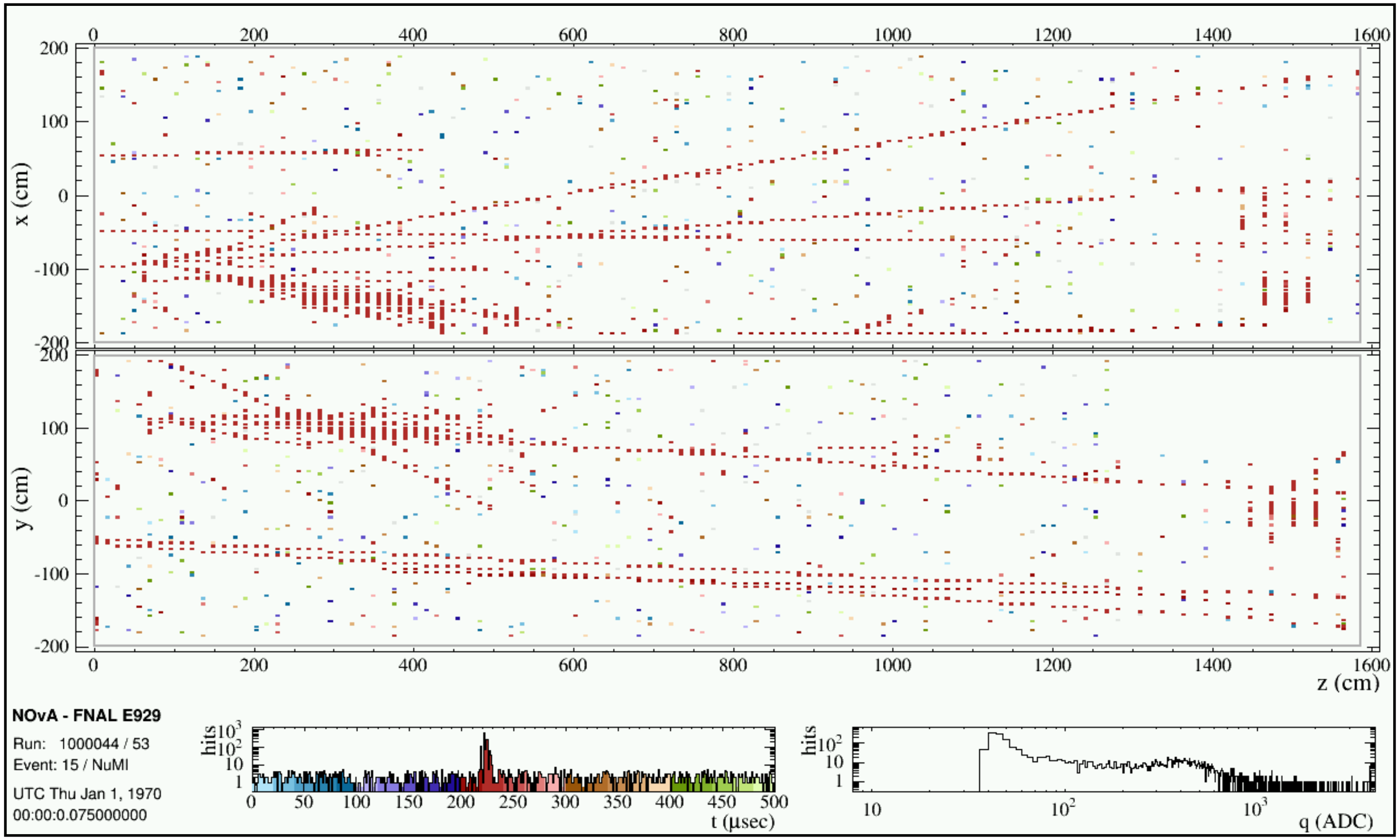
And in the ND…

- **ND event pile-up easily handled**
- **Cosmic ray rate much reduced** (50 Hz in ND vs. 100,000 Hz in FD)
  Instead, neutrino interactions in the rock send particles (mostly muons) into the detector

5×10^{13} ppp ND event (i.e., design intensity) shown here, from simulation



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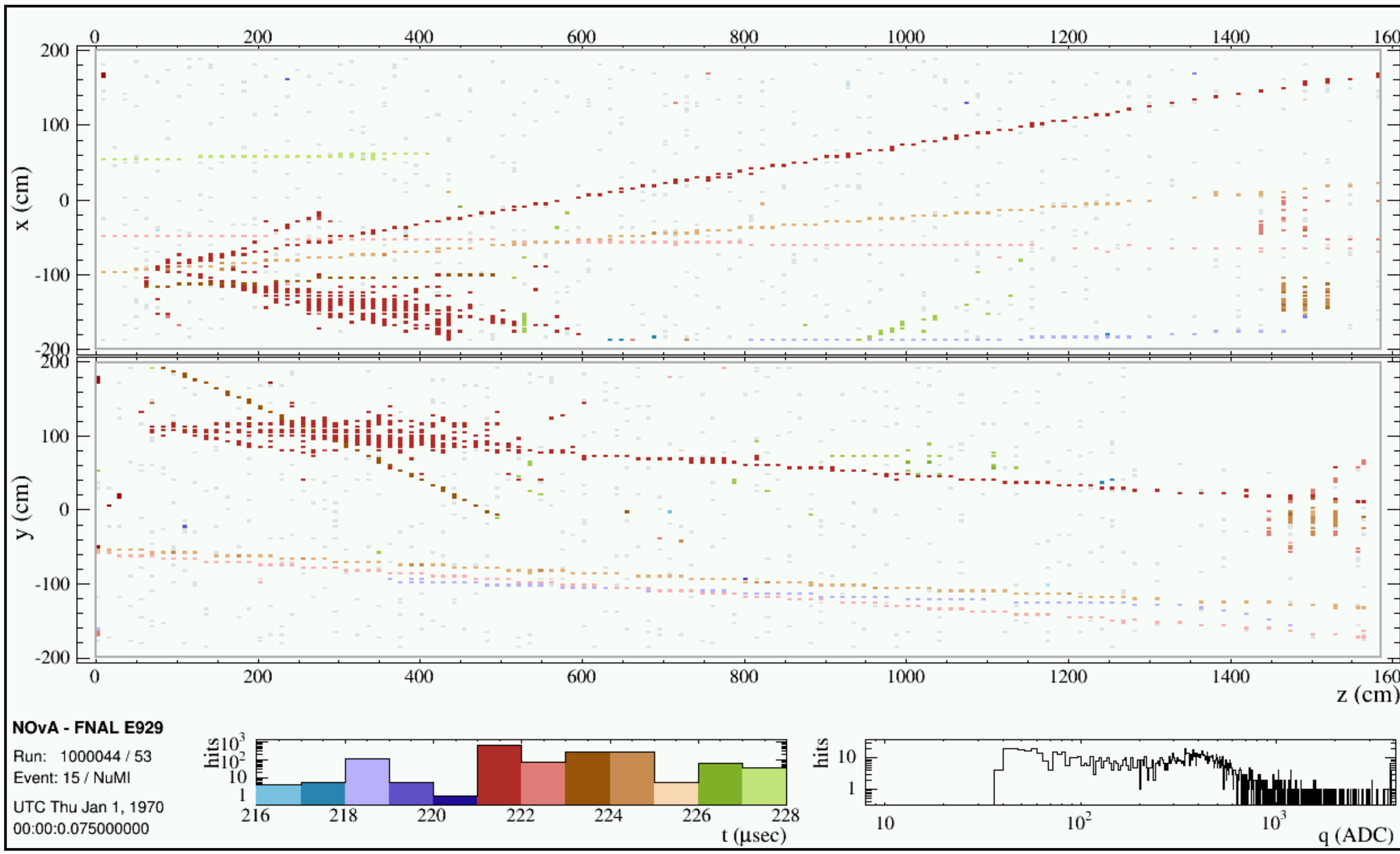

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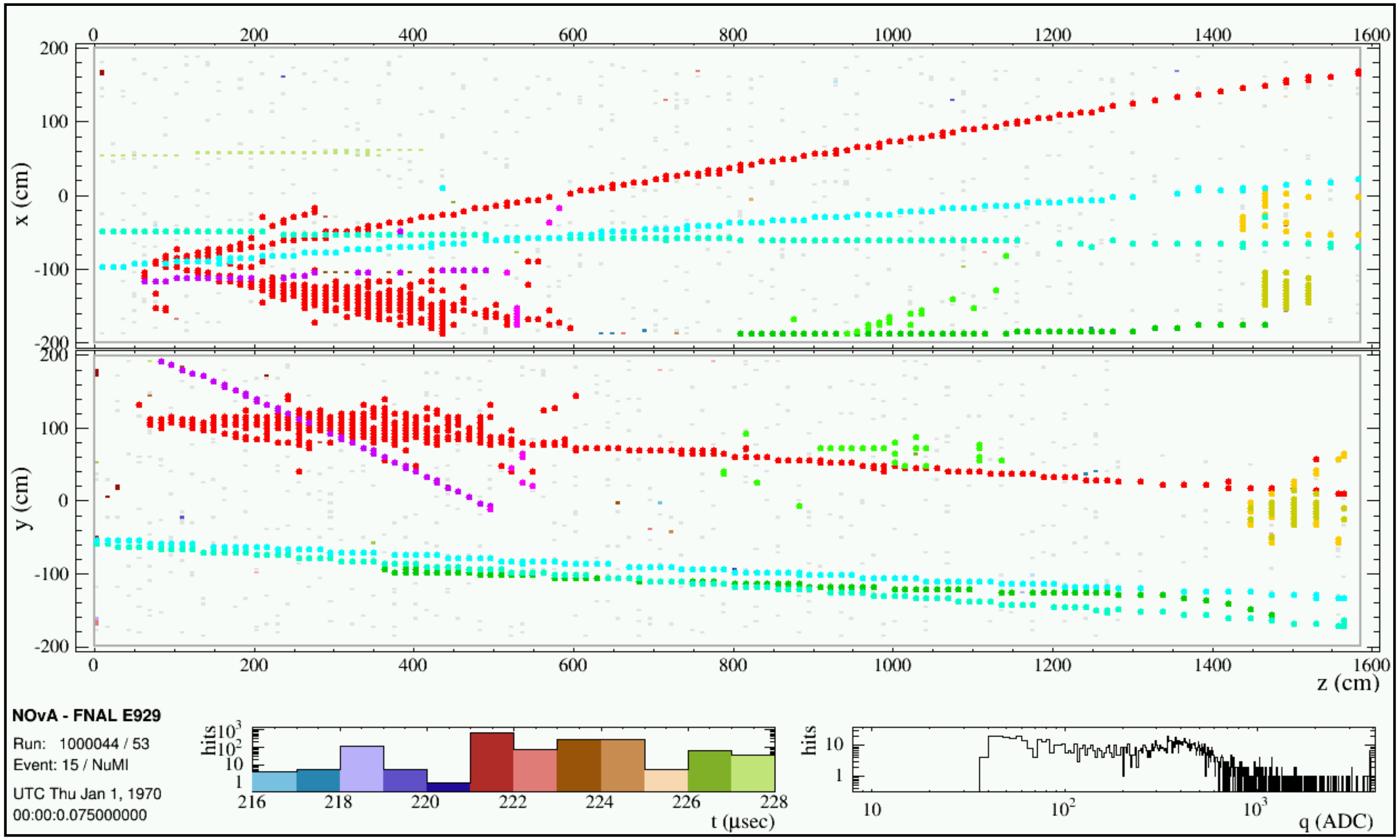

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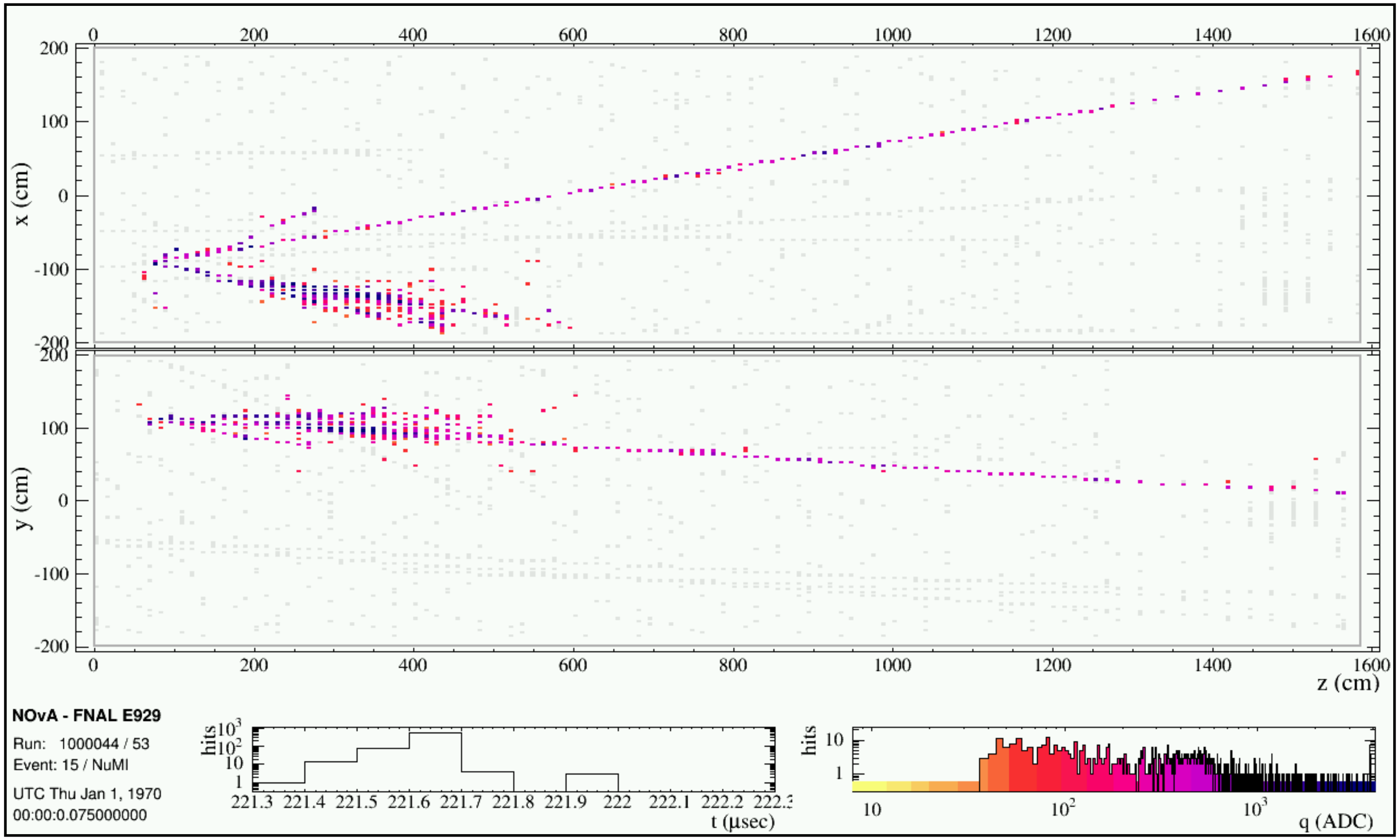
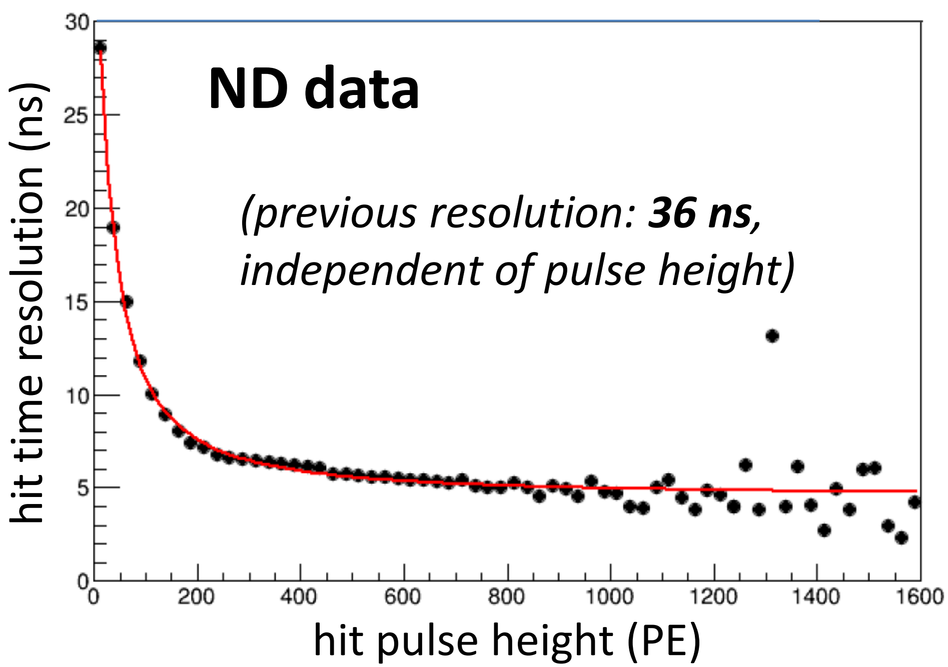
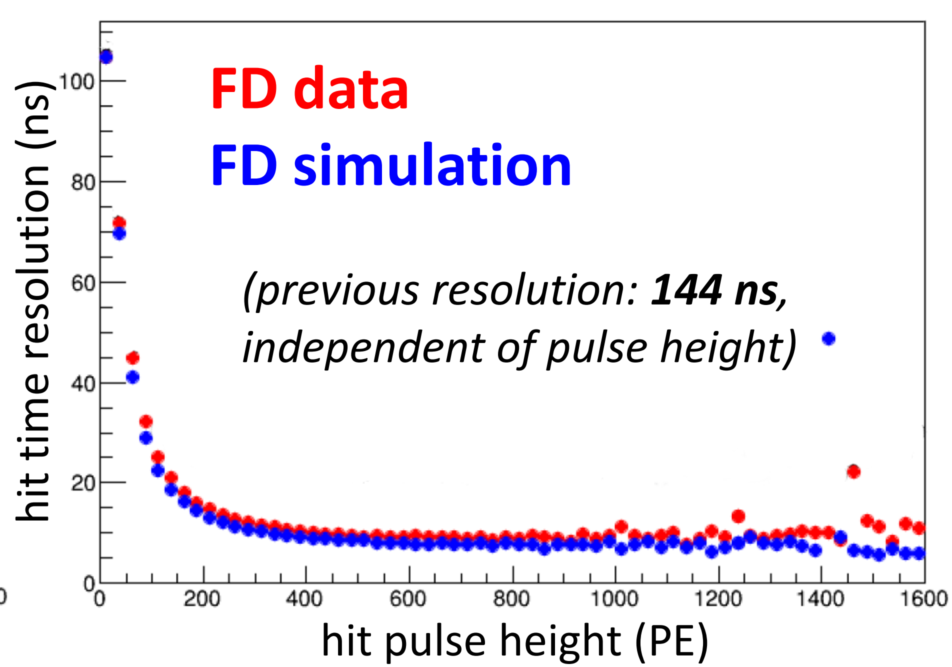


Timing resolution

- **Newly deployed firmware** leads to substantial improvement in timing resolution
- **Fully incorporated** into calibration procedures, simulation packages, and analysis software
- Benefitting event clustering and opening new lines of analysis





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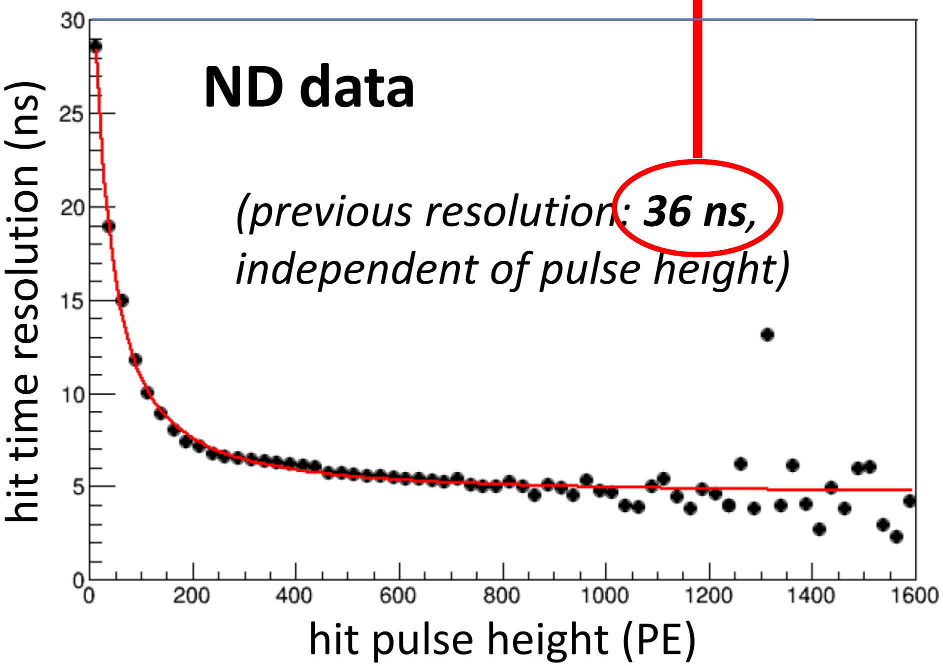
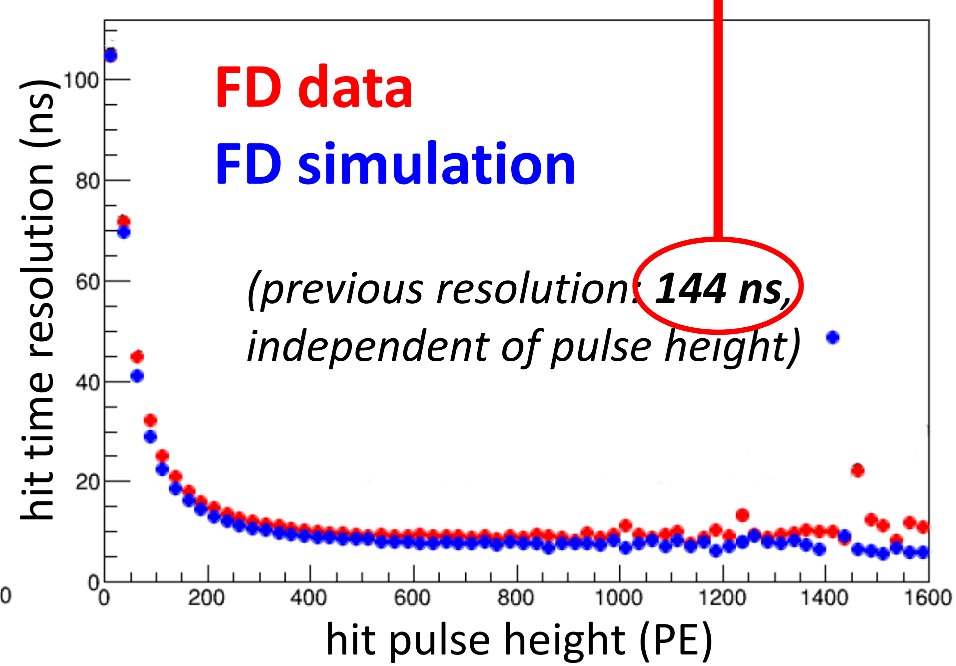
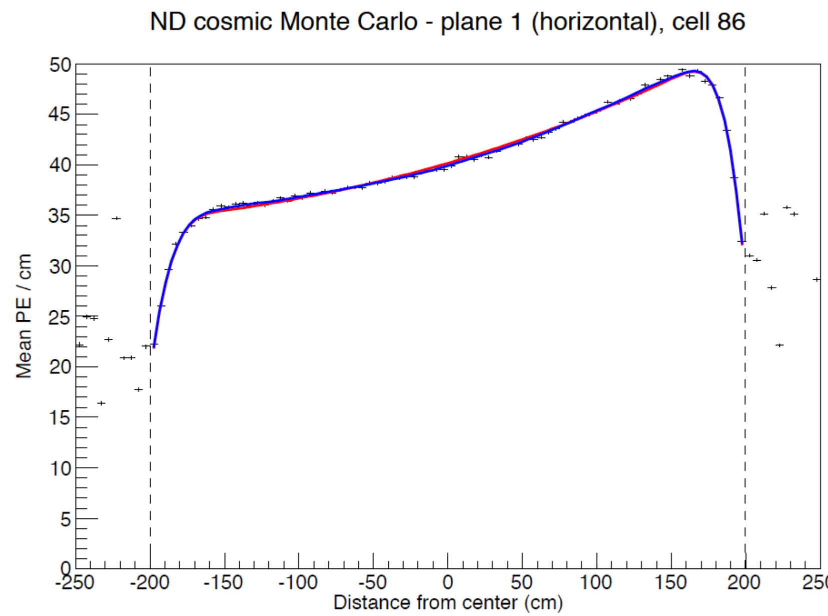
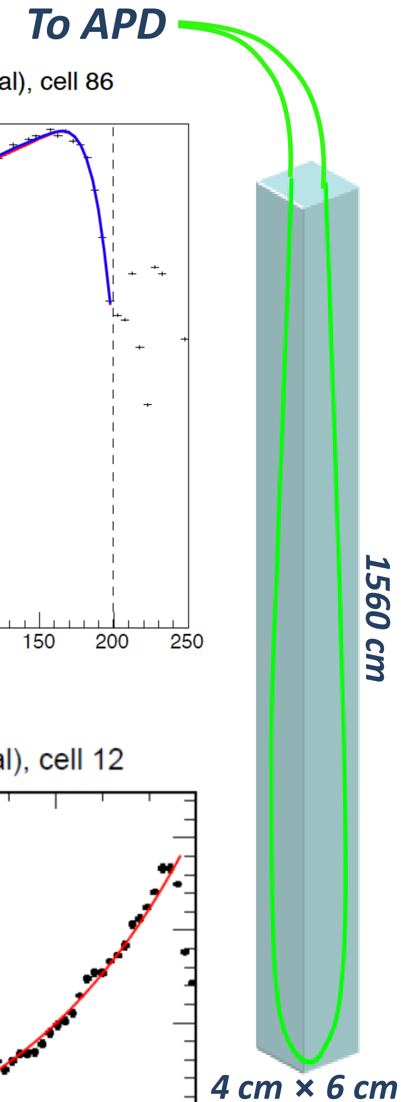


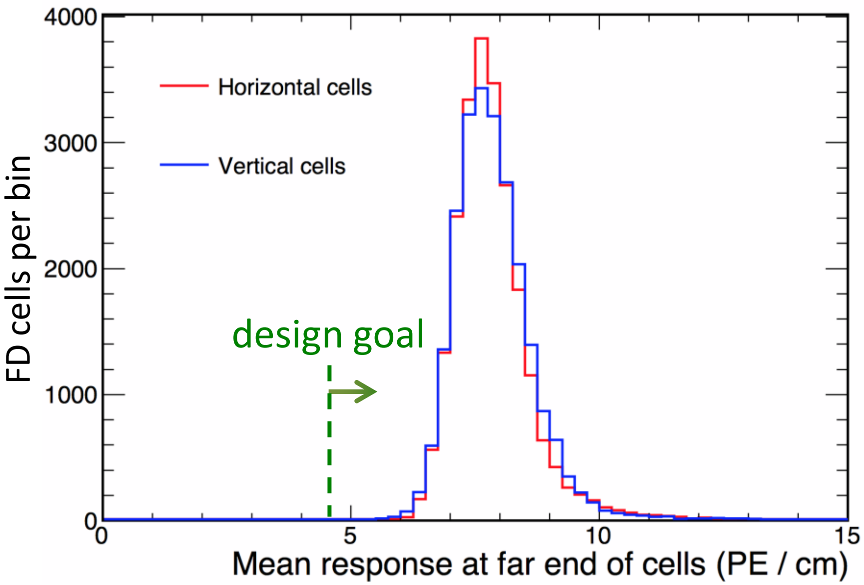


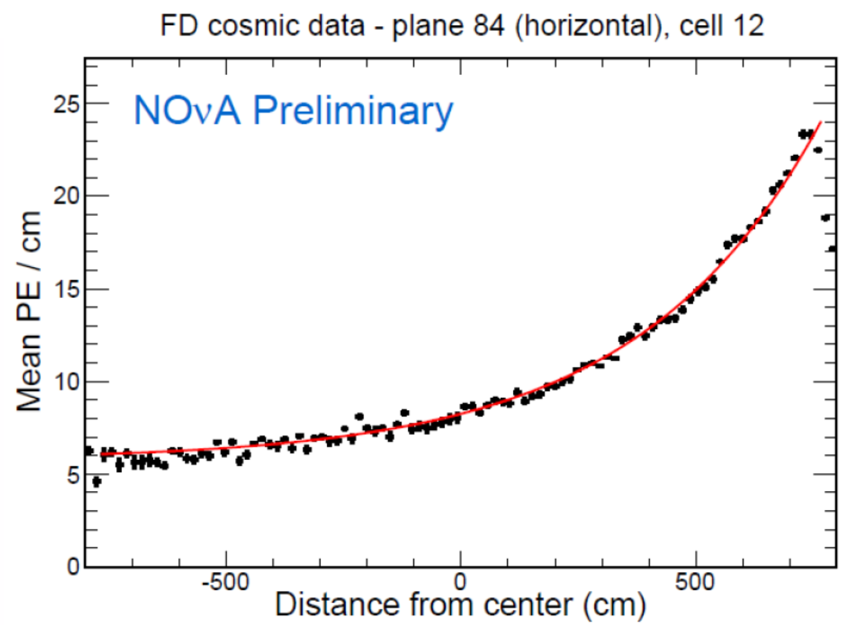
Energy calibration

- **Biggest effect** that needs correction is **attenuation** in the WLS fiber
- A local regression **corrects any residuals** beyond the basic functional form
- **Light level requirements** at end of cell **are well met**



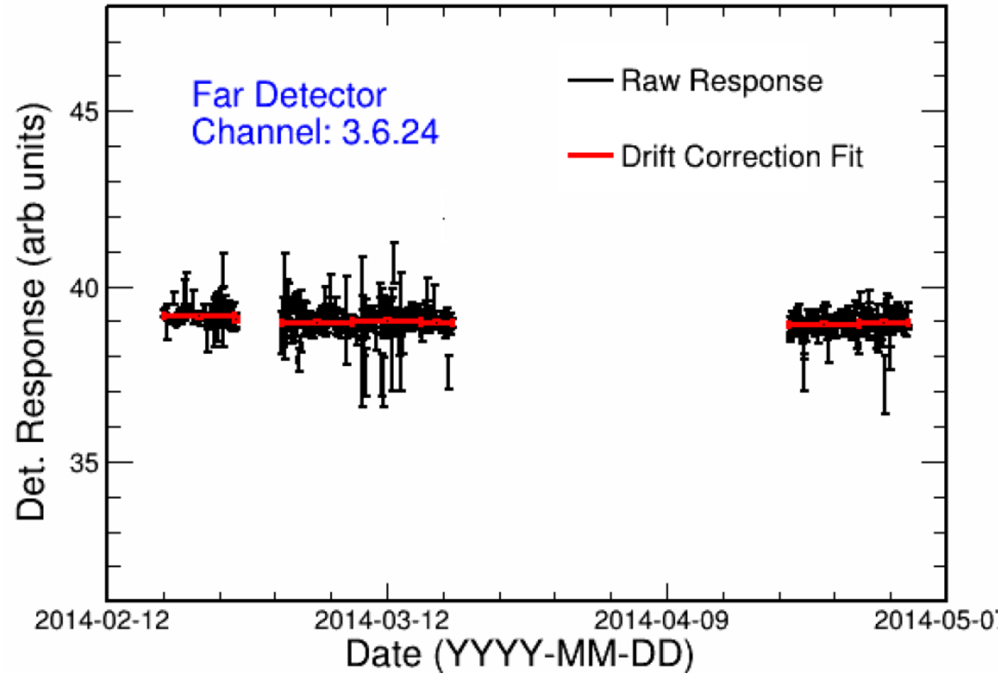




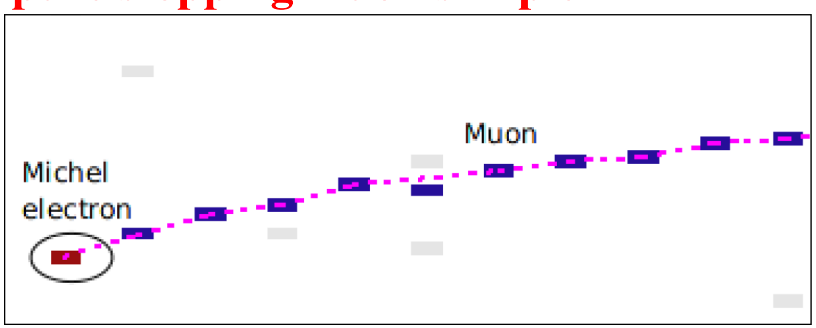


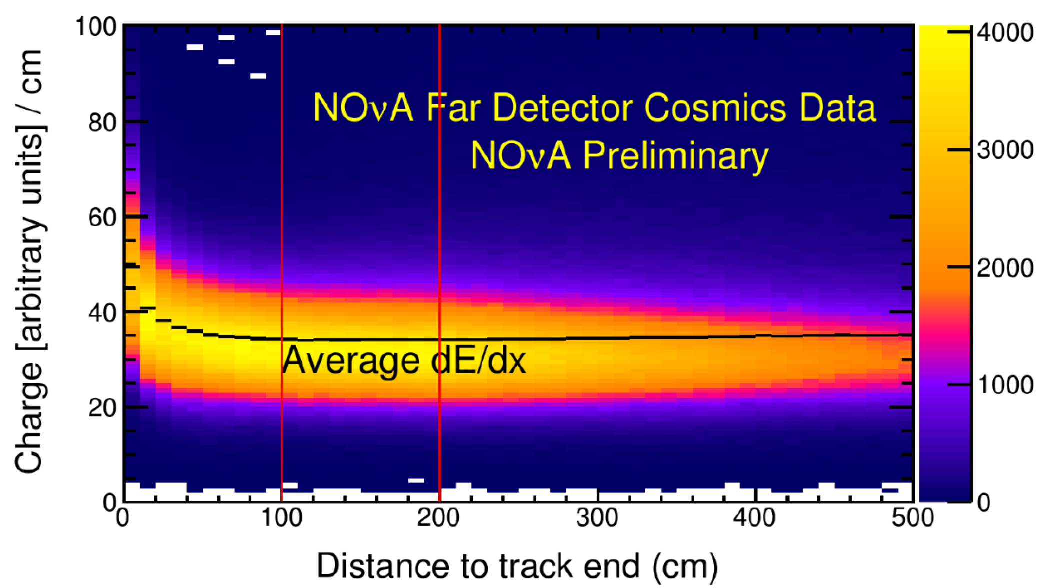
Energy calibration

- A **drift correction** handles changes in charge response over time (included that due to swapped hardware)
- **Stopping muons** provide a standard candle for setting the **absolute energy scale**



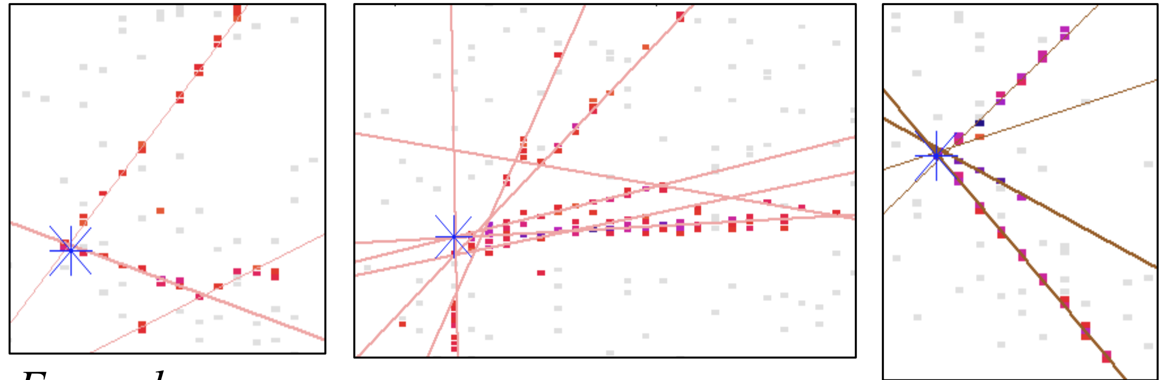
Michel electron tag yields very pure stopping muon sample



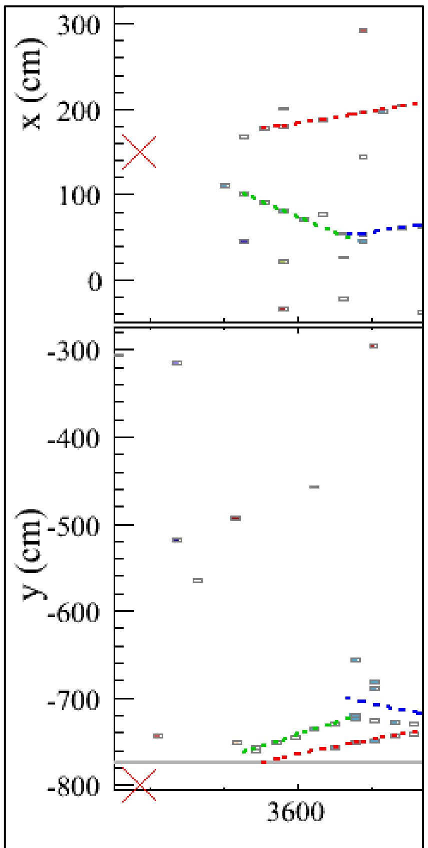


Event vertexing

- Find **lines of energy depositions** using a Hough transform.

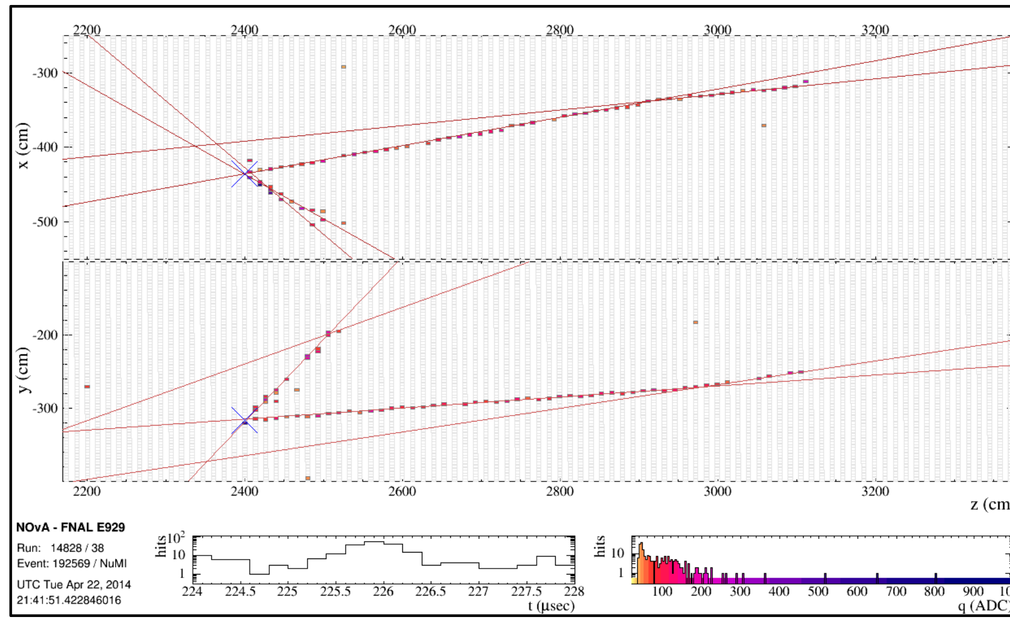


Examples…



A vertex outside the detector ←

The FD ν_μ CC data event from earlier →

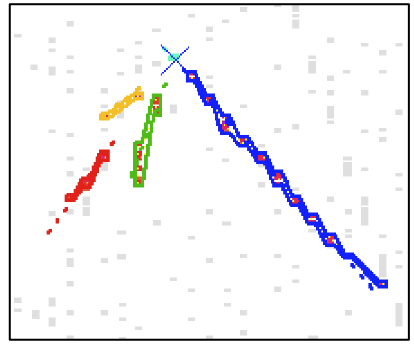


Vertex resolution for **charged-current events: 11 cm**
Vertex resolution for **neutral-current events: 29 cm**

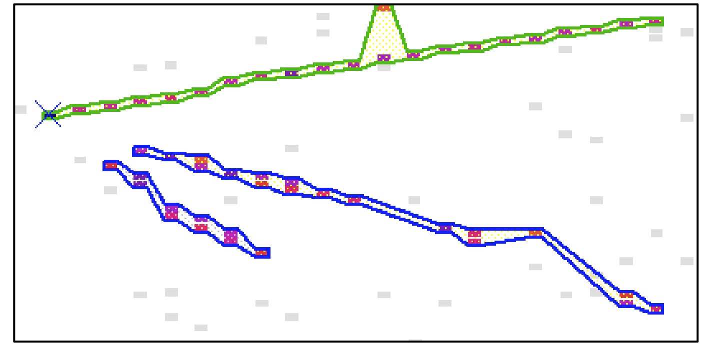
→ *Note: this is one of **several vertexing algorithms** implemented*

Prong clustering

- Given a seed vertex, look for **clusters in angular space** around it.
- Energy depositions are also used in the clustering metric, and hits can be shared between the resulting "prongs".
- Prongs in each view are matched based on topology and *dE*/*dx* to form 3D objects.

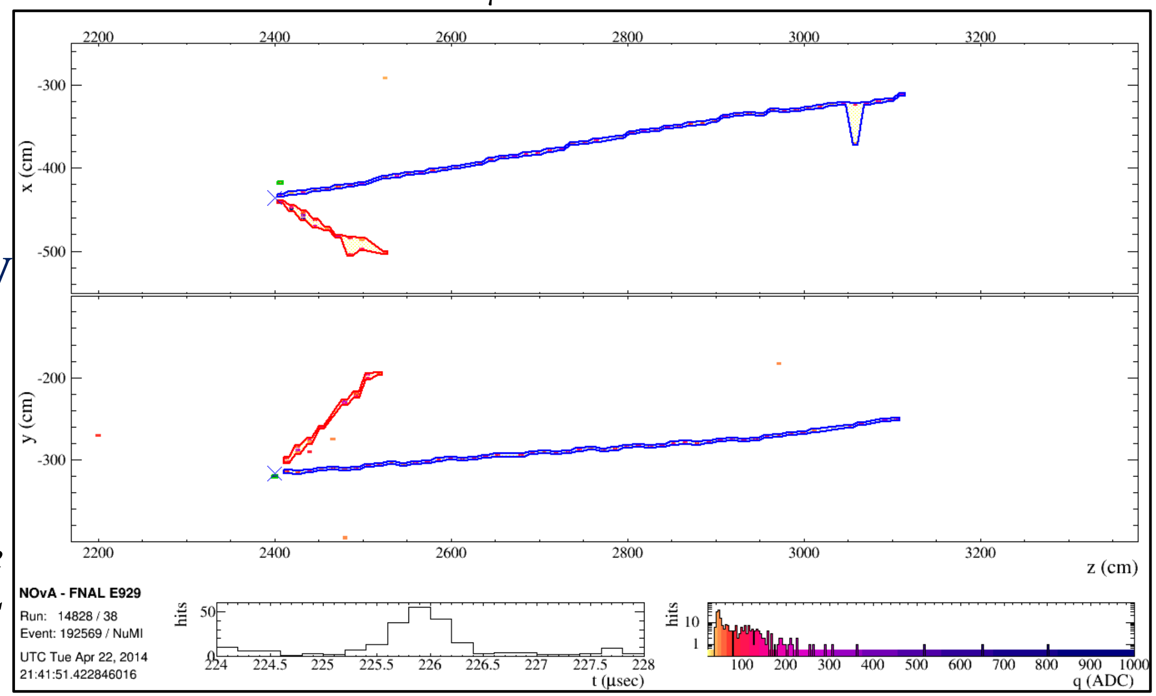


Cosmic ray neutron event in the FD data



Simulated ν_μ CC event

FD ν_μ CC data event



Prongs are drawn here by outlining the cells that belong to them.

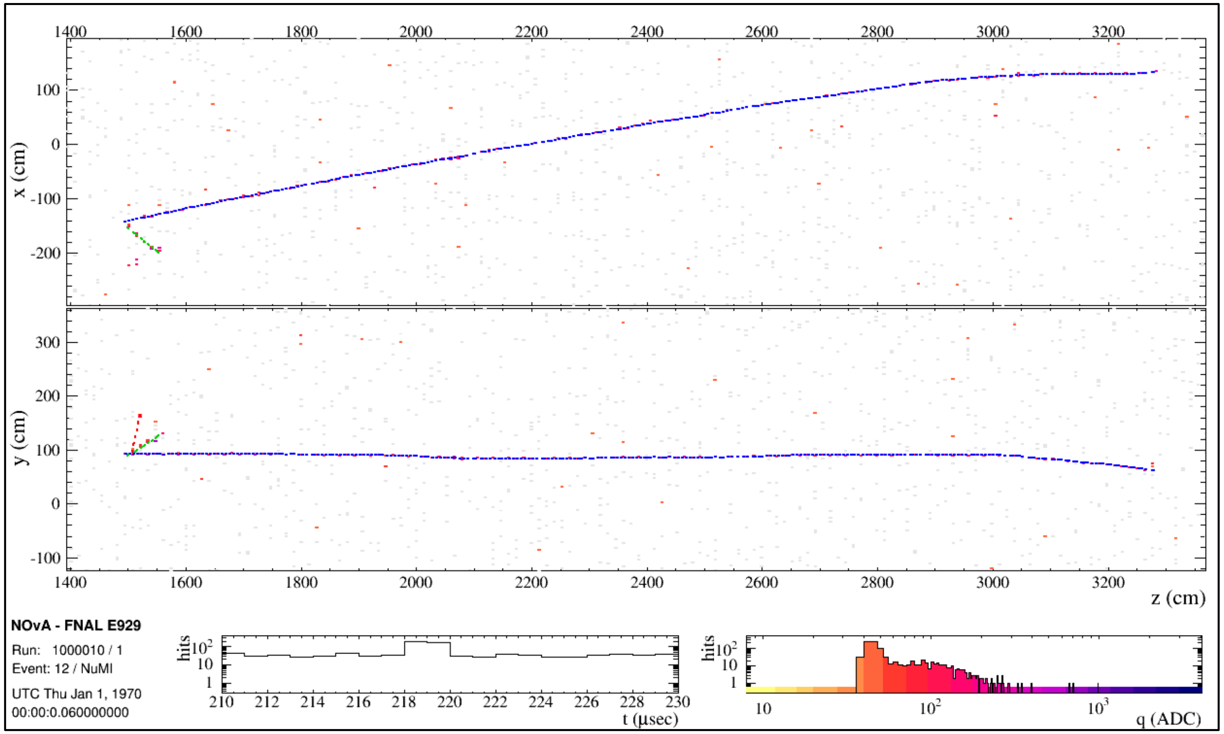
Tracking

- **Multiple trackers** developed and in use. *Two primary trackers:*
  - ***Cosmic ray tracker:*** lightweight, very fast, good for large calibration samples and online tools
  - ***Kalman filter tracker:*** more detailed, traces scattering for accurate energy, direction measurement.

(simulated event)

Resulting **energy resolution** for ν_μ CC events (driven in large part by the track energy)

quasielastic: 4.5%
non-quasielastic: 6.0%



Reconstructed tracks are drawn here as colored lines.

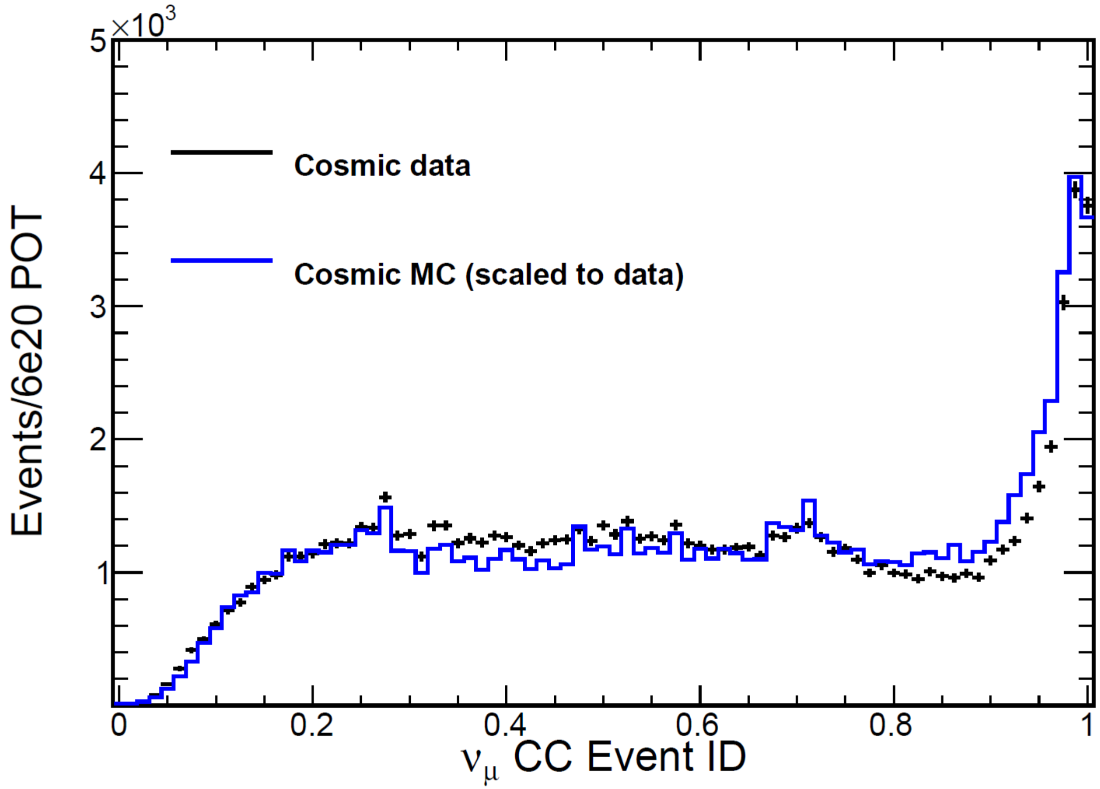
Identifying ν_μ CC events

- PID the **muon track candidate** using a ***k*NN classifier** that considers: *dE/dx, track scattering, track length, extent of hadronic activity*
- Further classify into quasielastic and non-quasielastic samples based on track multiplicity and kinematics

QE and non-QE samples fitted separately in the analysis

ν_μ CC event ID for cosmic rays, *FD data and MC*

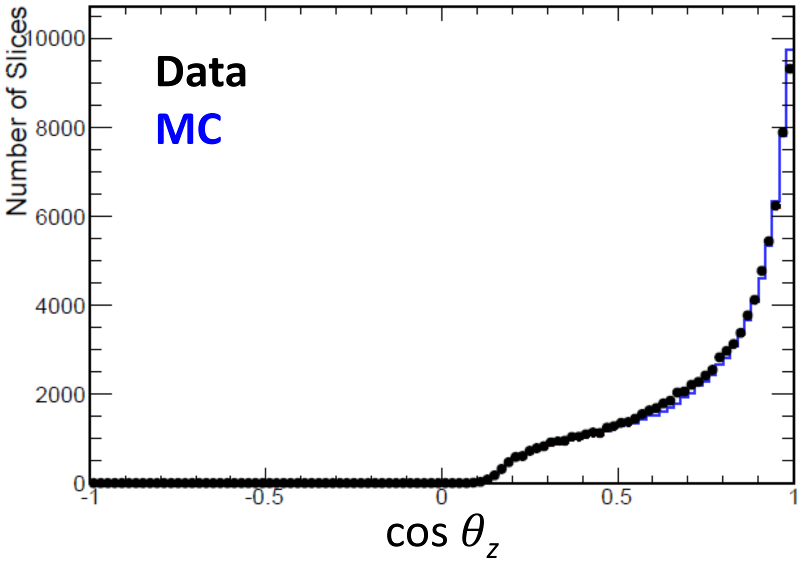
Current MC tuning already shows good agreement

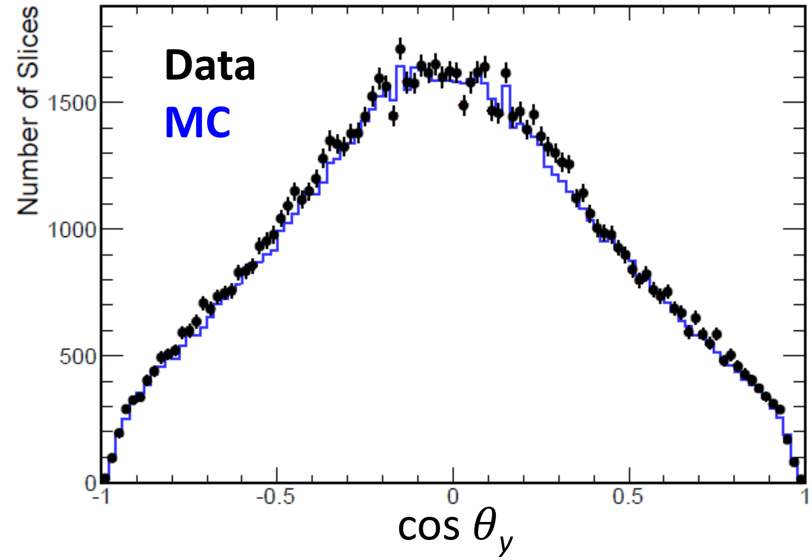


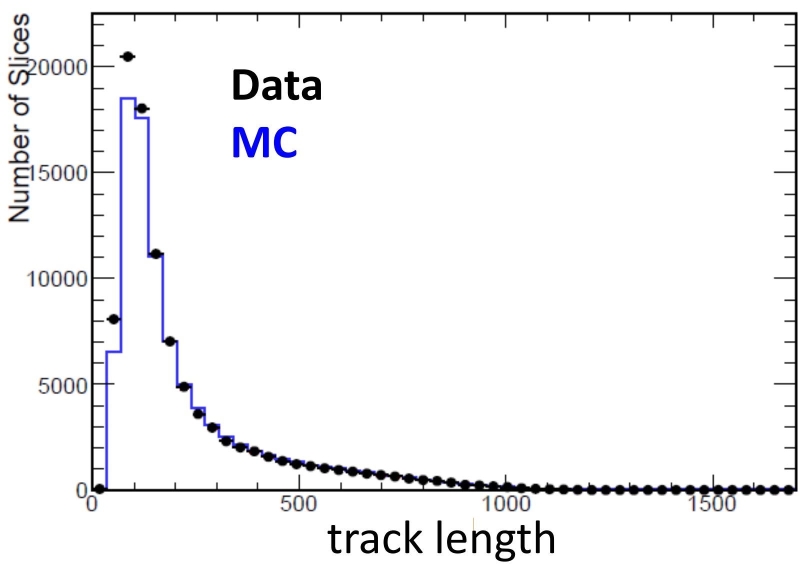
ν_μ CC tracking & event ID distributions, ***ND beam data*** *and MC*

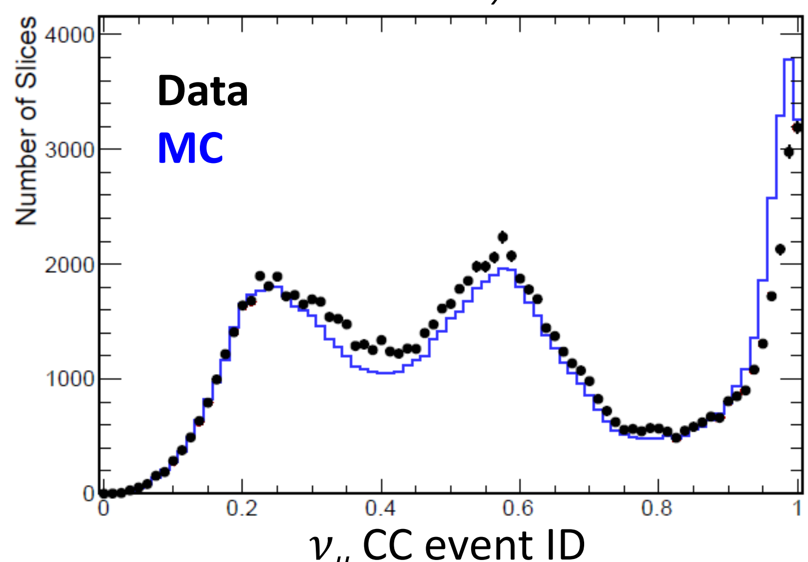
Again, good level of agreement from the current tuning of MC.

(Investigating residual differences is a central part of current activity.)









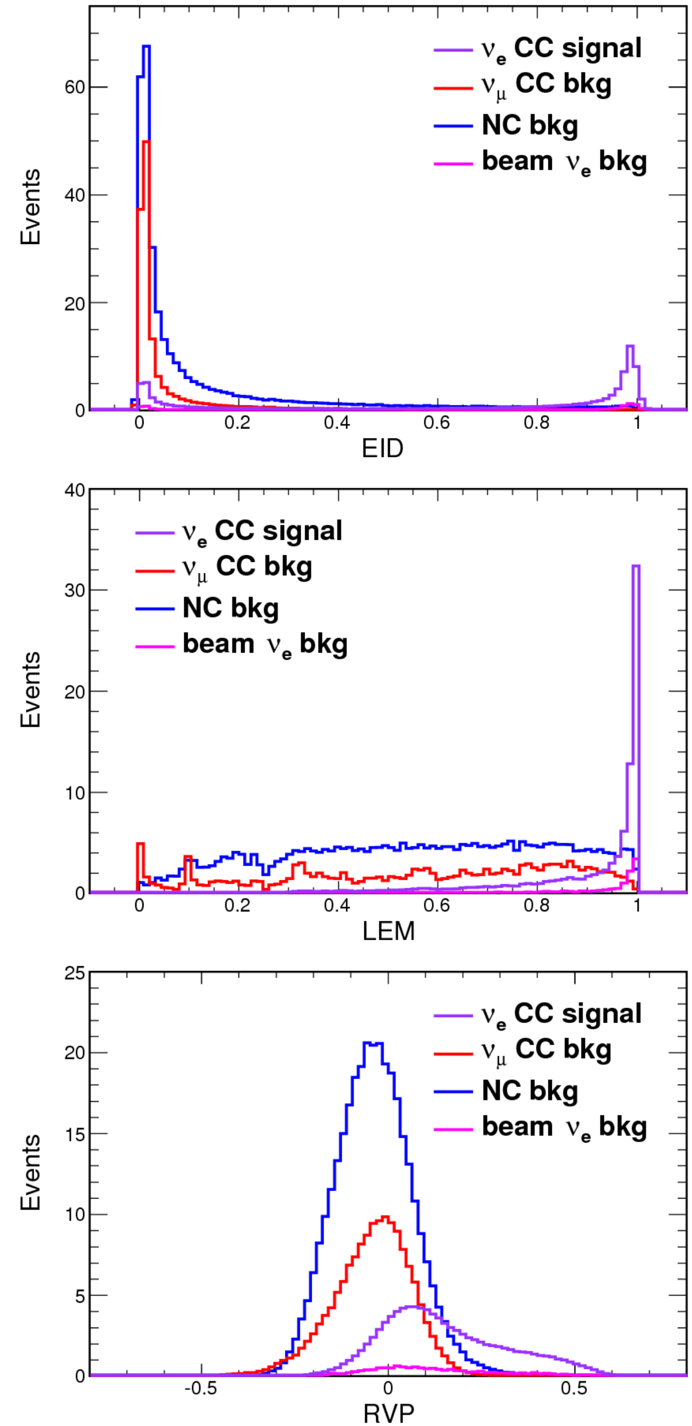
Identifying ν_e CC events

Three **very different approaches** implemented and supported

EID: **Neural network** that uses as input EM shower likelihoods, vertex activity, event kinematics, and topology variables

LEM: **Library event matching** algorithm that compares events to a large library of known events, with the comparisons based directly on the pattern of detector hits

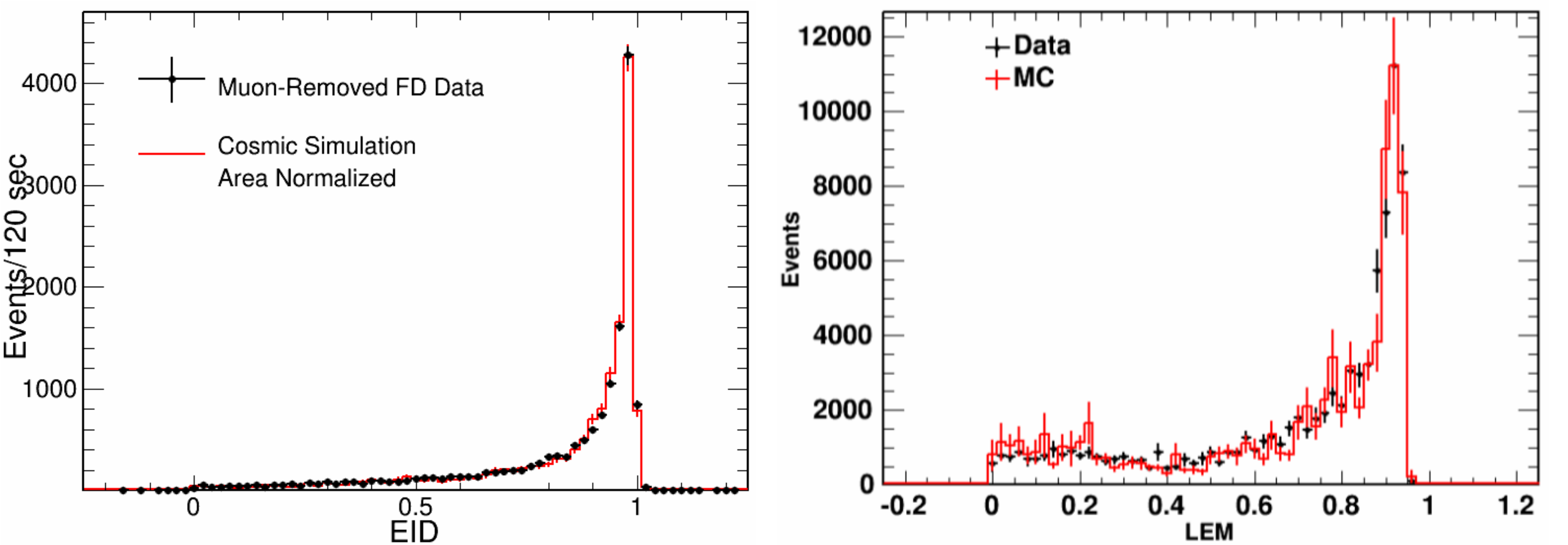
RVP: **Boosted decision tree** that uses as input a selection of topological and kinematic variables. (Serves as the "simple" ID algorithm.)



EM shower sample

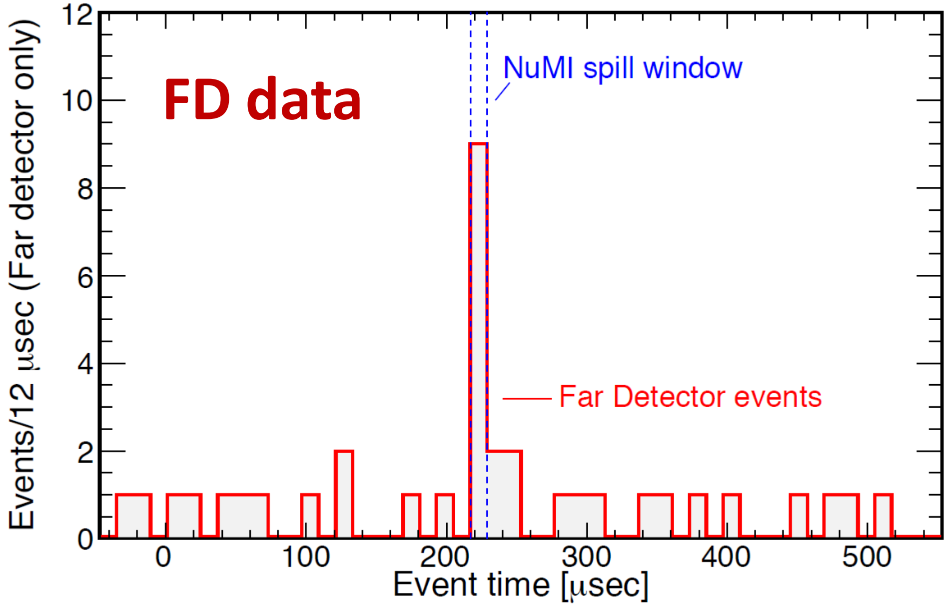
- As a check of **EM shower modeling** and **PID performance**, isolate cosmic ray **bremsstrahlung showers** by removing the parent muon hits
- Data / MC **agreement is excellent**
- **Primary ν_e CC PID distributions** shown below

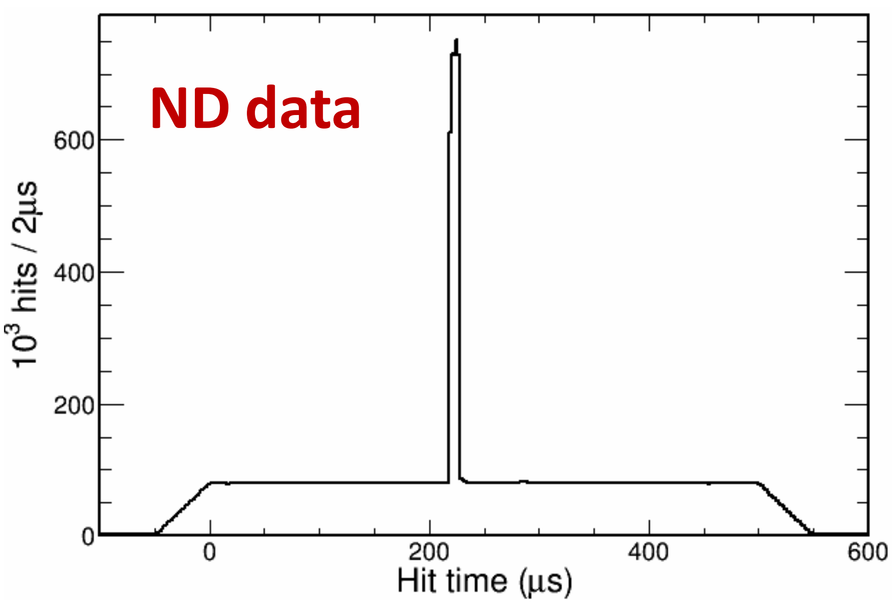
PID distributions from <u>FD data</u> EM showers and equivalent MC

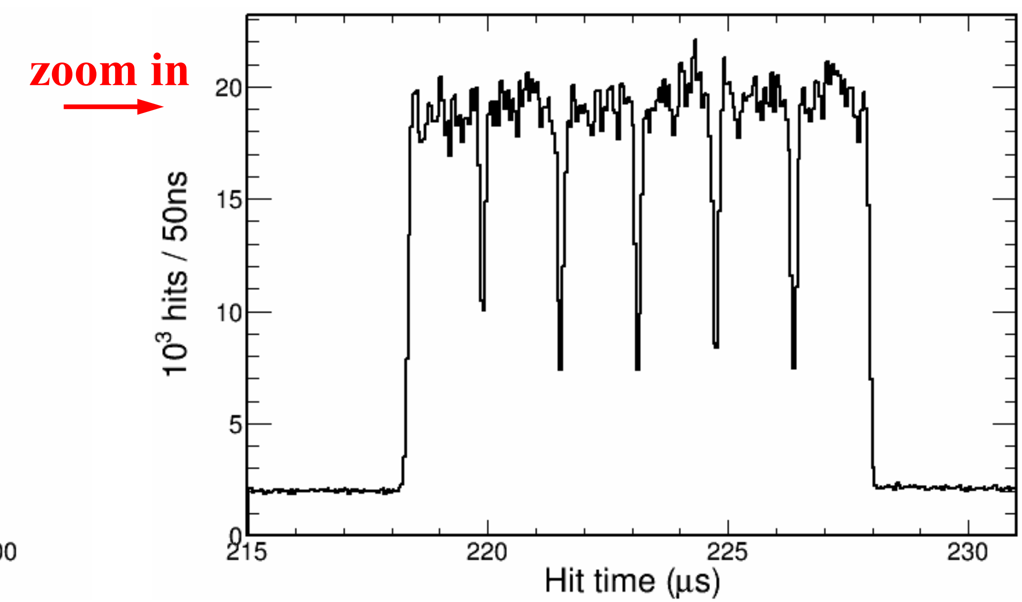


Rejecting cosmic rays in the FD

- **Beam timing** gives us a 10^5 head start (10 μs spill every 1.3 s)
- *At right:* **FD neutrino peak**
- *Below:* **ND neutrino peak**
  Spill structure visible in zoomed version.







An additional 10^7 rejection from…

ν_e CC case: Cut events…

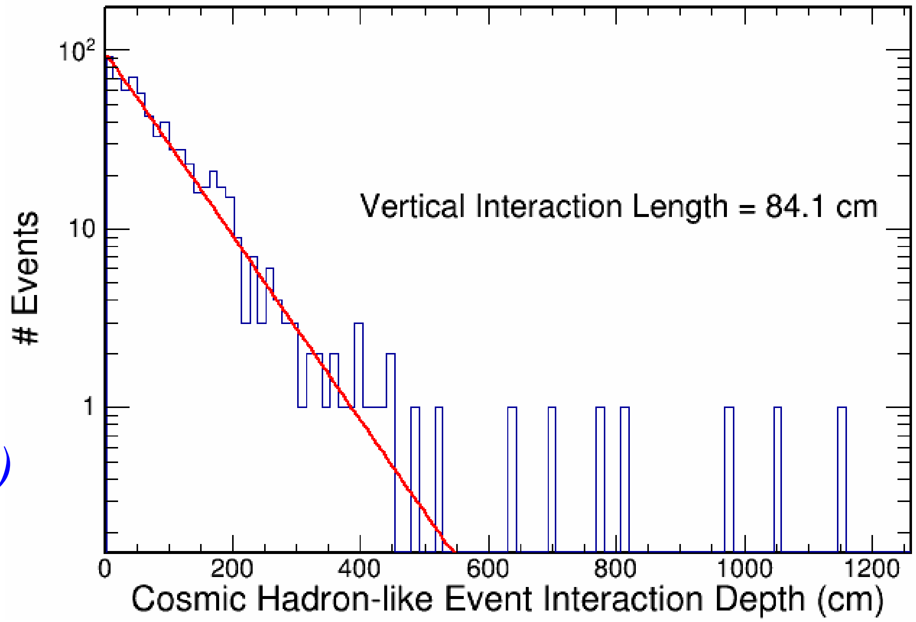
- ***…too near the detector edges***
- ***…with high p_T/p***
- ***…with poor ν_e CC PID values***

For nominal **1-yr exposure** (6×10^{20} p.o.t. at 700 kW), **expect:**

14 signal
6 beam bkg.
<1 cosmic bkg.

("avg." osc. pars)

40M-to-1 cosmic rejection ***demonstrated*** with FD data



Above: penetration of neutrons into the top of the detector (largely removed by p_T/p cut)

ν_μ CC case: Cut events…

- ***…whose tracks project too near to the detector edges***
- ***…with cosmic-like muon directions***

For nominal **1-yr exposure, expect:**

75 signal
4 beam bkg.
~1 cosmic bkg.

(after disappearance)

20M-to-1 cosmic rejection ***demonstrated*** with FD data

Treatment of detector variations

- **If a portion of the detector is down** for some reason (*in the past:* initial detector construction; *in the future:* hardware swaps, etc.), the **rest of the detector continues to operate** thanks to DAQ "partitioning".
  → *The analysis code responds appropriately to this (for example, geometry functions report dynamically where the effective edges of the detector are.)*
- A **table of misbehaving channels** is updated on a subrun basis
  → *Event reconstruction code references this table*
- Our large **MC samples** use a **run-by-run matched suite** of bad channel tables, detector configurations (*i.e.*, live portions), and exposures.

Putting all the pieces together

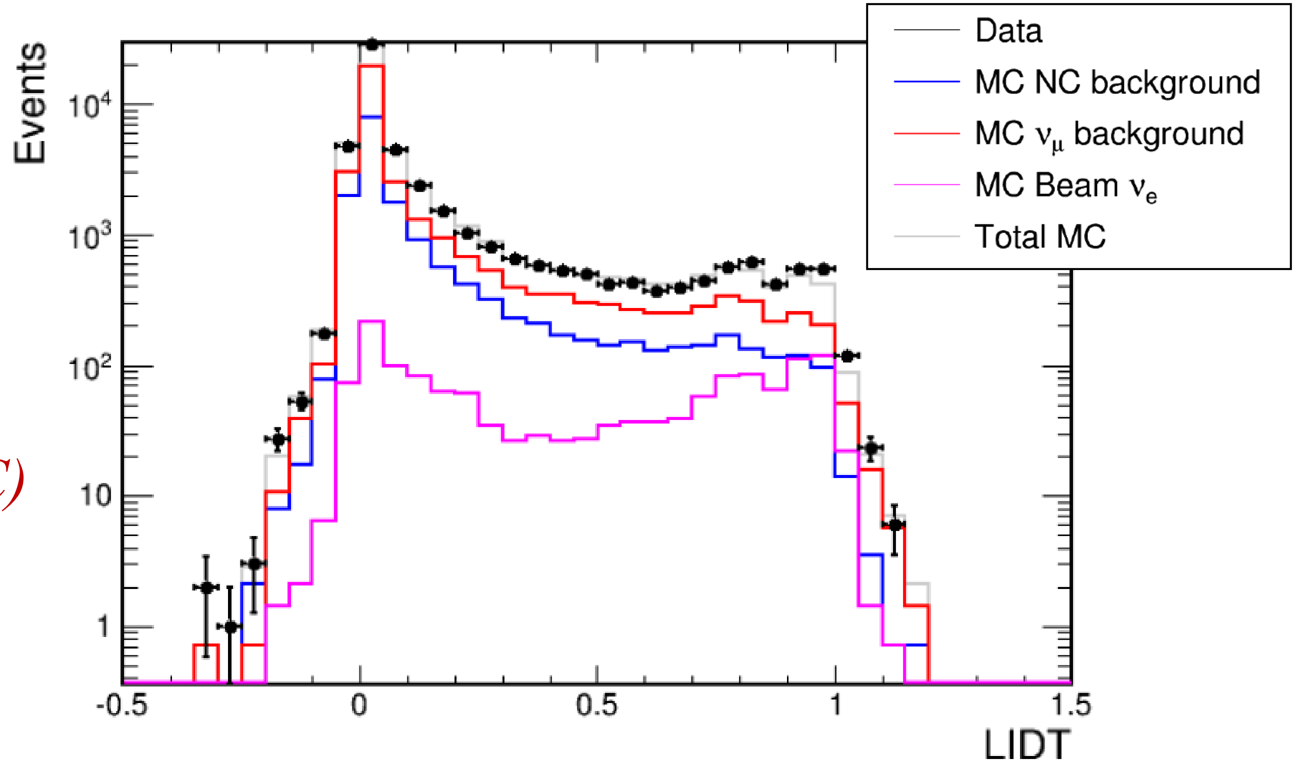
- File production concludes with **Common Analysis Files (CAFs)**
  → *Light-weight ROOT files for end-game analysis work.*
- **CAFAna**: a suite of utilities both for **executing common tasks** with CAFs and for **constructing full oscillation analyses**.
  → *In use throughout collaboration*
- **Uniform treatment** of systematic uncertainties, cuts, protons-on-target accounting, spectrum comparisons, oscillation weighting, …
- The CAF/CAFAna infrastructure is well-documented, well-supported
  → *Including a live tutorial session that was recorded and posted (audio and screen capture), plus demo exercises to follow along. Great for getting new folks up to speed quickly.*

Brief examples of the end-game tools

- **Apply selection to the ND** to determine: $\Sigma_{\text{flavors}}(flux \times \sigma \times eff.)$

ν_e* CC event selection applied to *<u>ND data</u> and MC

(Great agreement in MC)

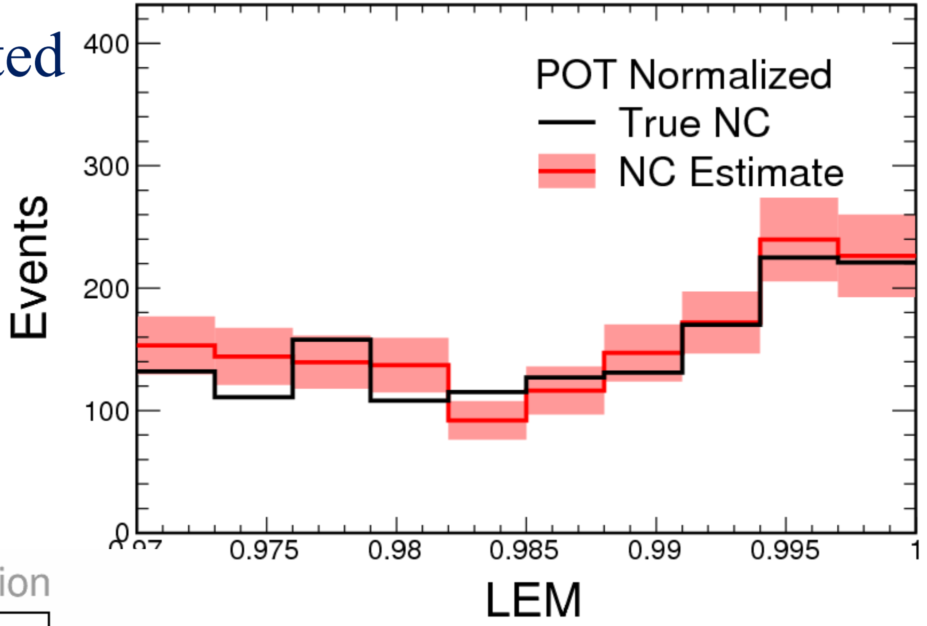


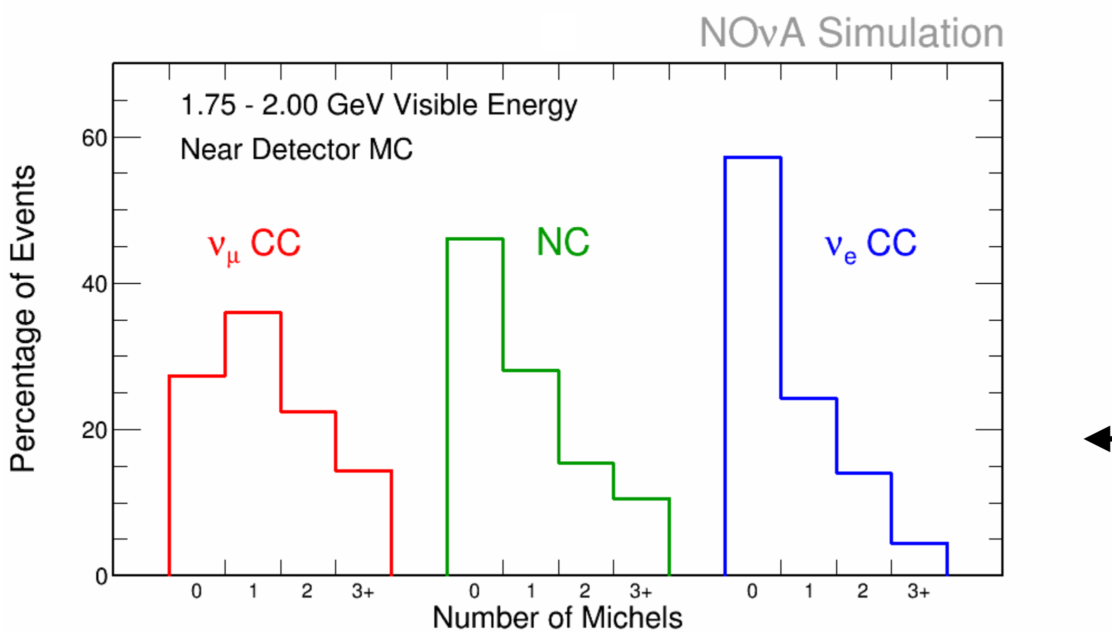
- Use "**decomposition**" techniques to break apart the summed sample
  → *Need to flavor-separate sample since oscillations affect each piece differently when converting from ND to FD prediction.*

ND decomposition in the ν_e analysis

- **Two primary methods** implemented in the CAFAna framework

Muon-removal: *Remove μ's from ν_μ CC events to form an NC-like events. From these, infer NC mis-ID contribution in selected sample.*





Michel electrons: *Statistically decompose the ND sample based on differences in Michel electron rates among ν_μ CC, ν_e CC, and NC events.*

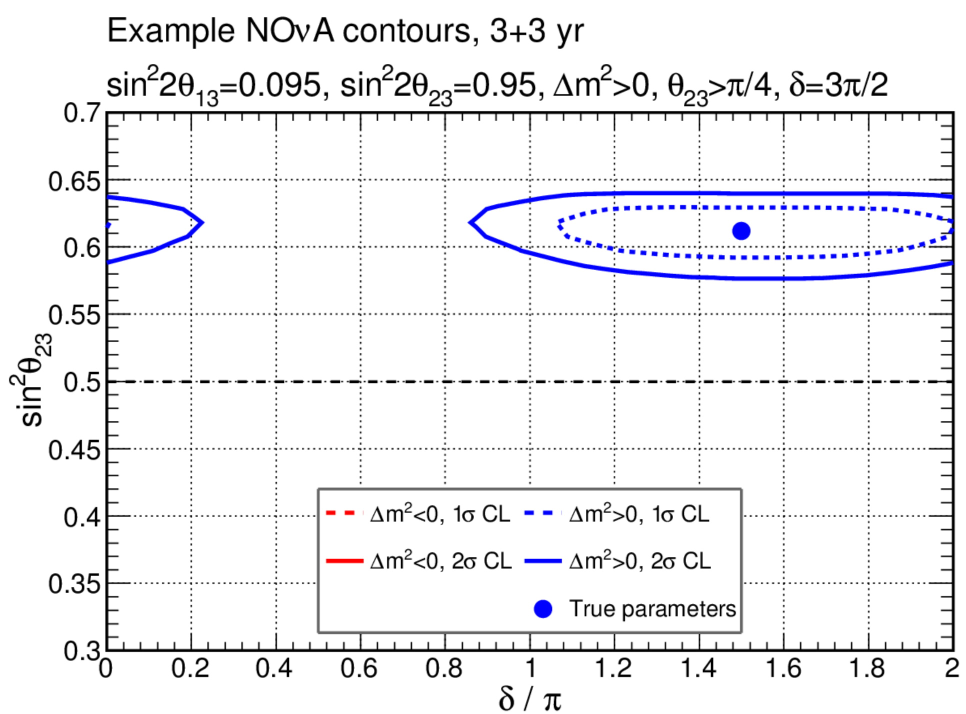
Final fits

- A flexible **ND-to-FD extrapolation** toolkit is built in CAFAna
- The resulting FD predictions feed an **oscillation fitting framework**
- ***A few noteworthy features:***
  - Seamlessly **float, freeze, or marginalize any oscillation parameters**, with or without penalty terms
  - Seamlessly **combine NOνA analyses and/or external results**. Important for folding in known constraints (*e.g.*, reactor, T2K)
  - Statistically **rigorous contours** via Feldman-Cousins unified approach
  - Systematics via **nuisance parameters**

At right: example contours from CAFAna for one point in parameter space

Simultaneously break **ν_3 flavor degeneracy** (θ_{23} octant), determine **mass hierarchy**, and constrain **CP phase δ**.

(Full TDR exposure of 36×10^{20} p.o.t.)



Summary

- **End-to-end analysis tools in place**
- Calibration, reconstruction, particle ID, fitting tools are **operational on ND and FD data**
- Surface operation: cosmic ray rejection **demonstrated with FD data**
- ***Current analysis frontiers include:***
  - Understanding residual data/MC differences
    Several MC improvements already developed
  - Assessing systematic uncertainties
    Should not a major factor until we gain significant exposure
  - Most critical: **integrating protons-on-target !!**

NO*ν*A is ready to produce the next round of significant results in neutrino physics.

The world is watching, waiting.

Extras

NOνA

A broad physics scope

Using $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ ...

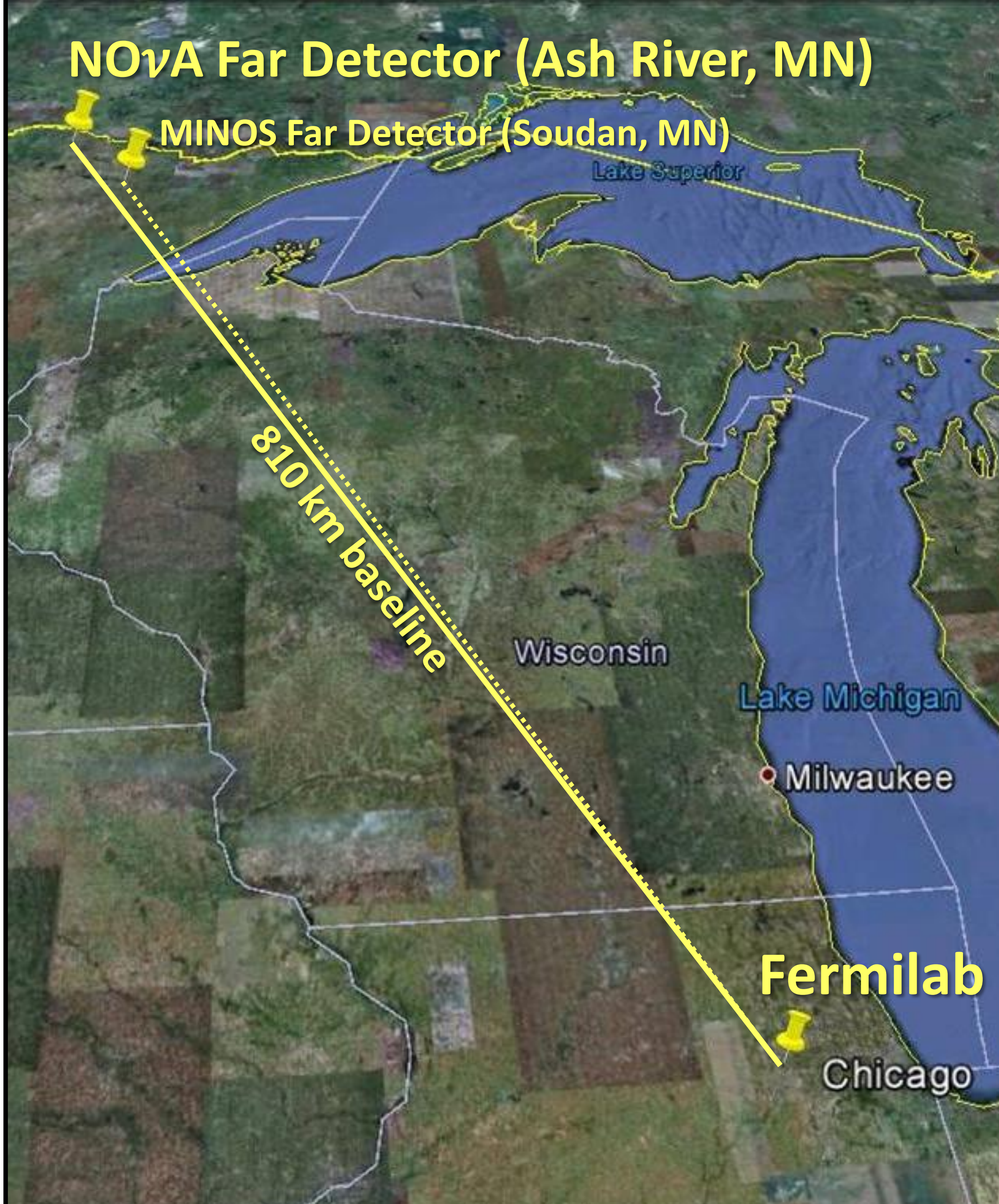
- Determine the **ν mass hierarchy**
- Determine the **θ_{23} octant**
- Constrain δ_{CP}

Using $\nu_\mu \to \nu_\mu$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$ ...

- **Atmospheric parameters:** precision measurements of θ_{23} , Δm^2_{32}. (*Exclude* $\theta_{23}=\pi/4$?)
- **Over-constrain** the atmos. sector (*four oscillation channels*)

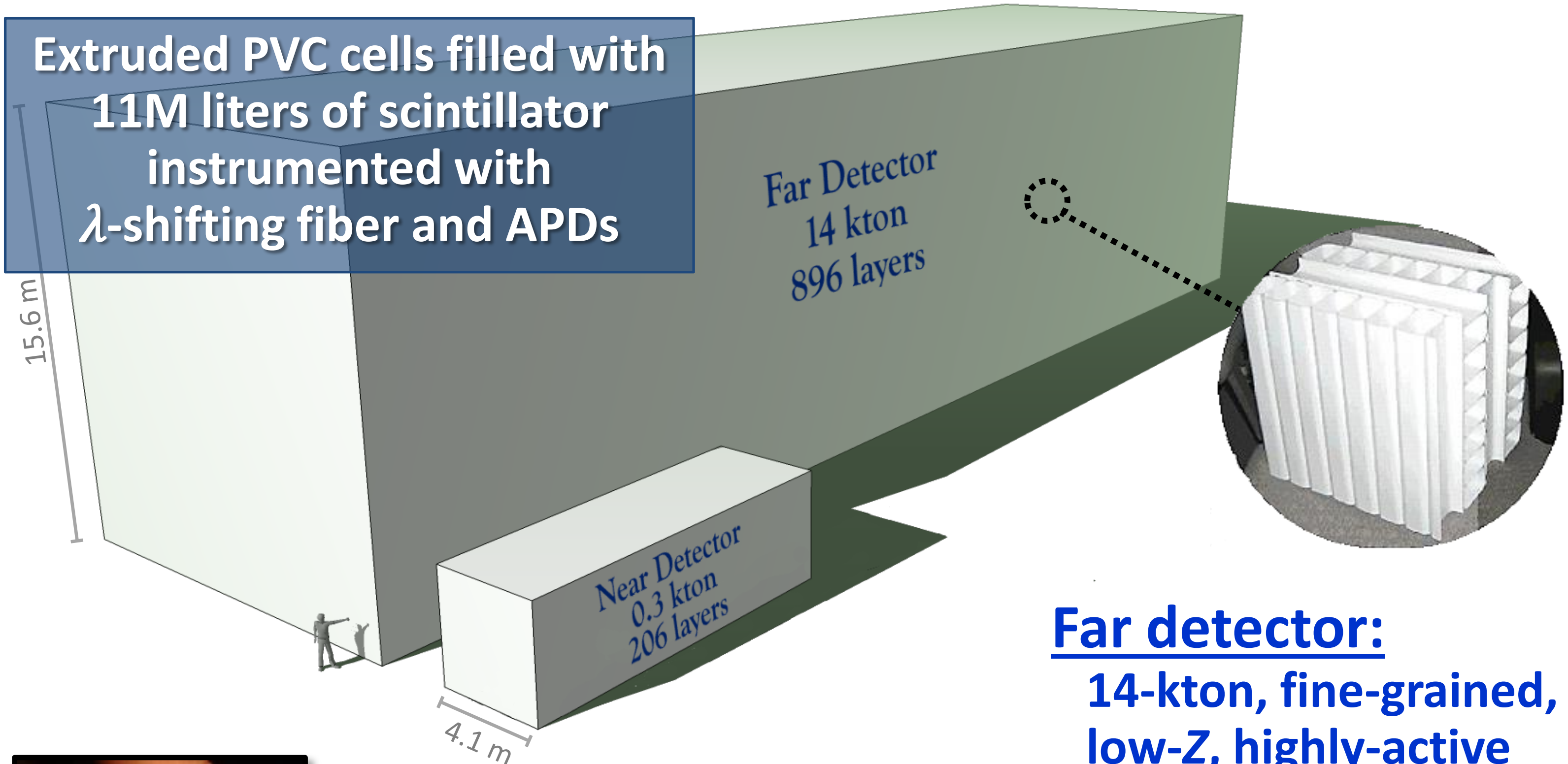
Also ...

- Neutrino cross sections at the NOνA Near Detector
- Sterile neutrinos
- Supernova neutrinos
- Other exotica

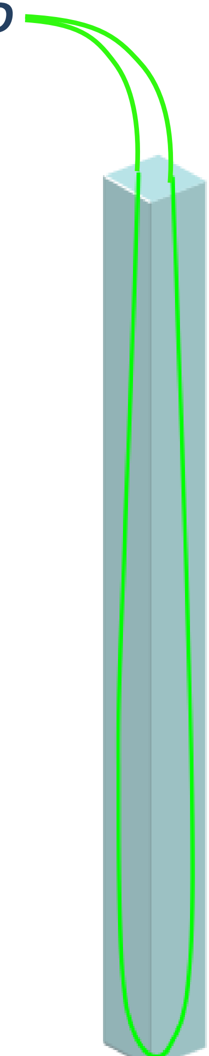


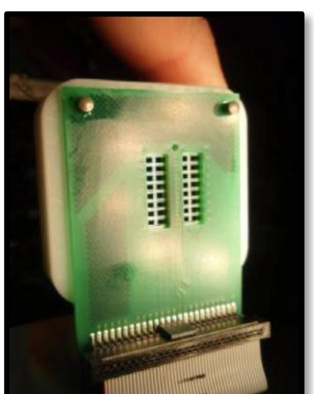
NOνA detectors

Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs



A NOνA cell





32-pixel APD ←

Fiber pairs from 32 cells →

Far detector:

14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter
→ ***344,000 channels***

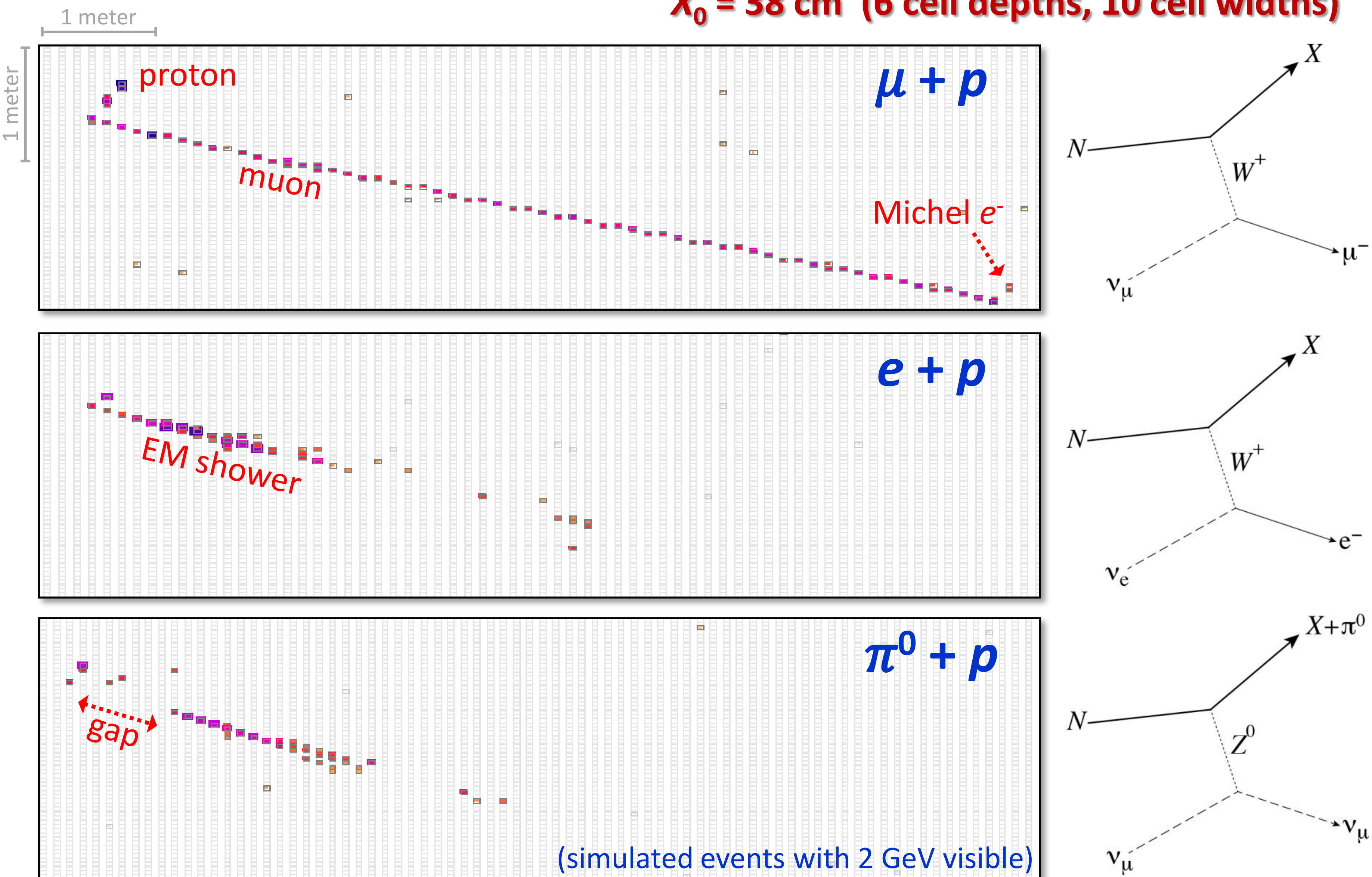
Near detector:

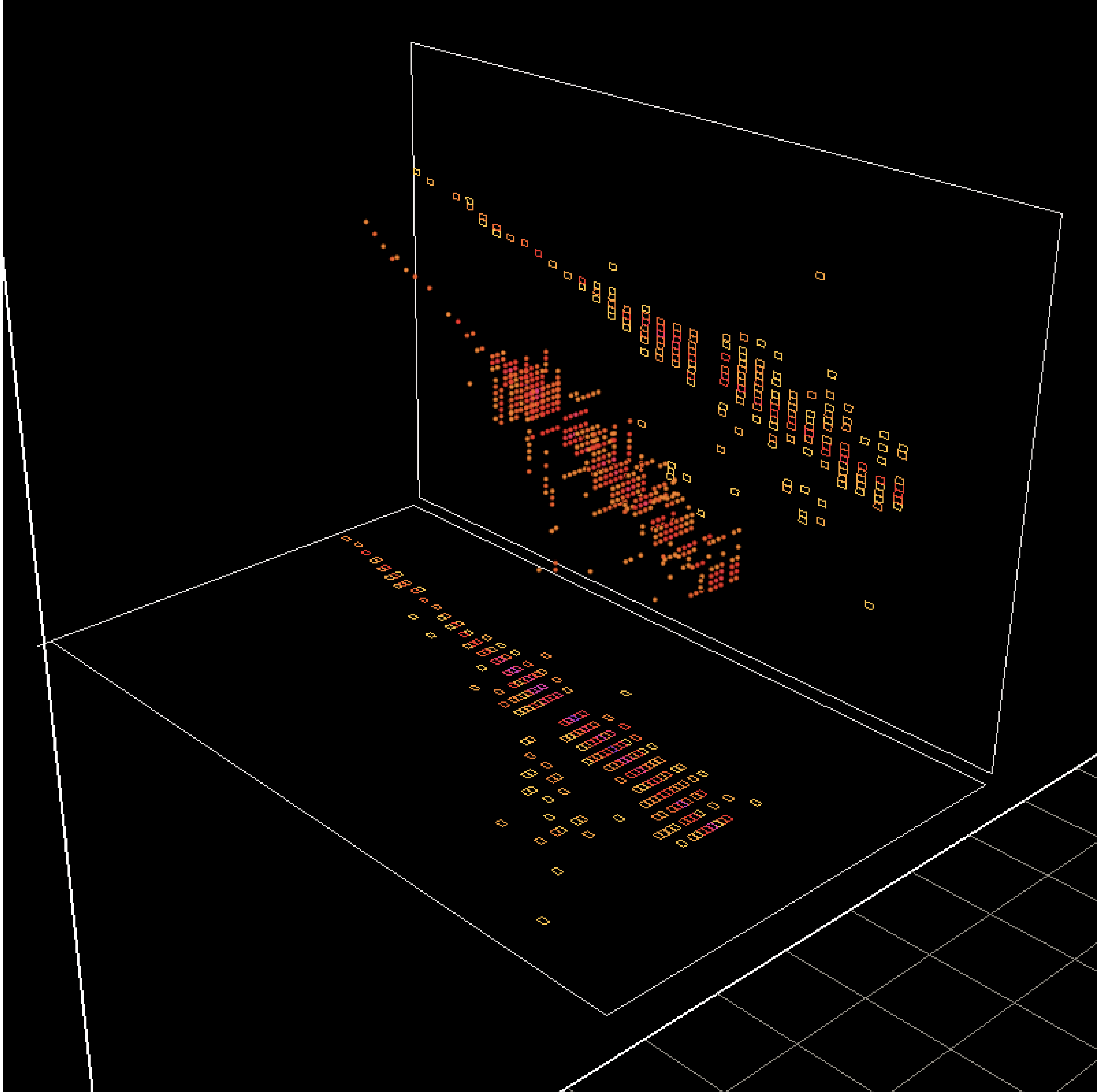
0.3-kton version of the same
→ ***18,000 channels***

Events in NOνA

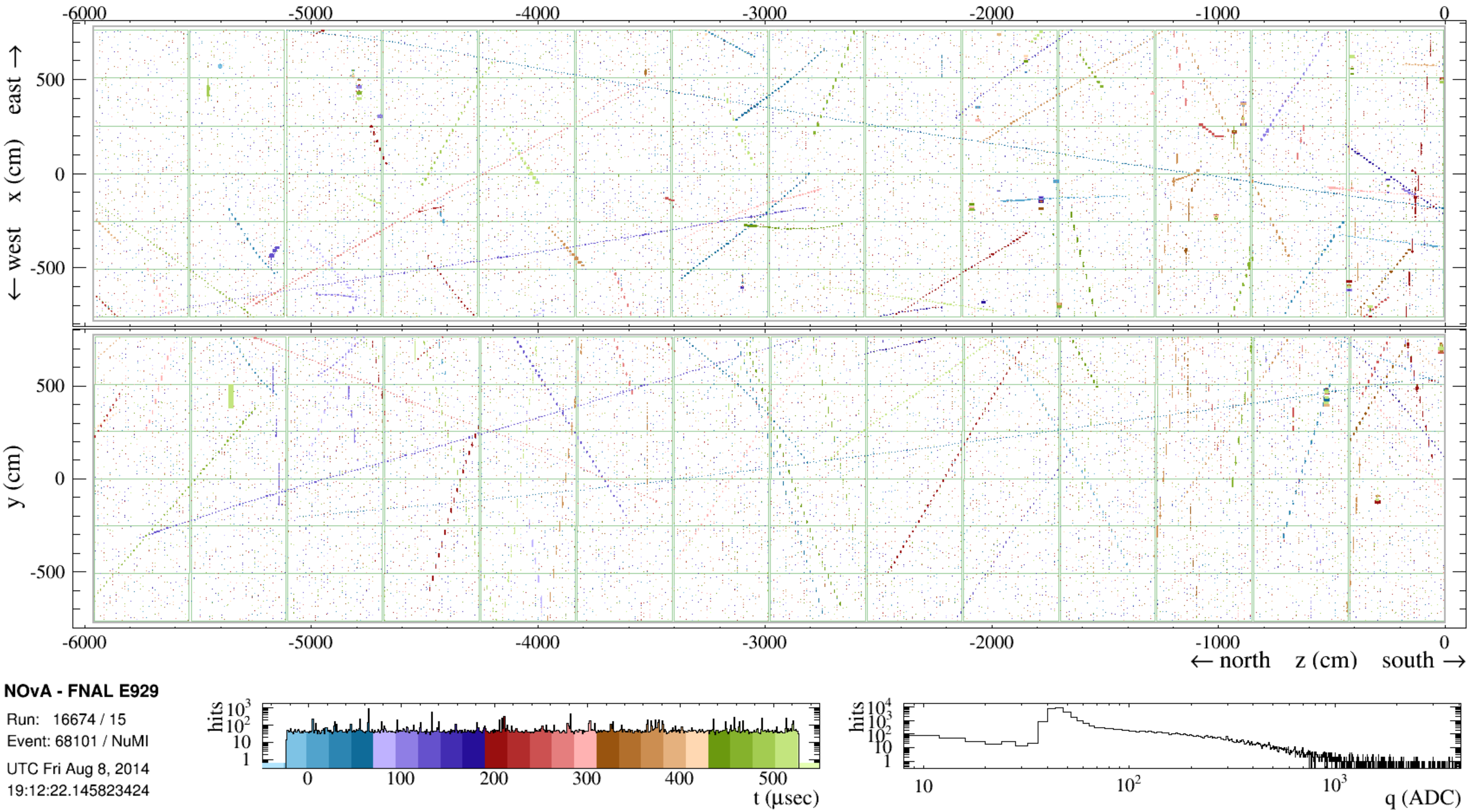
Superb spatial granularity for a detector of this scale

X_0 = 38 cm (6 cell depths, 10 cell widths)

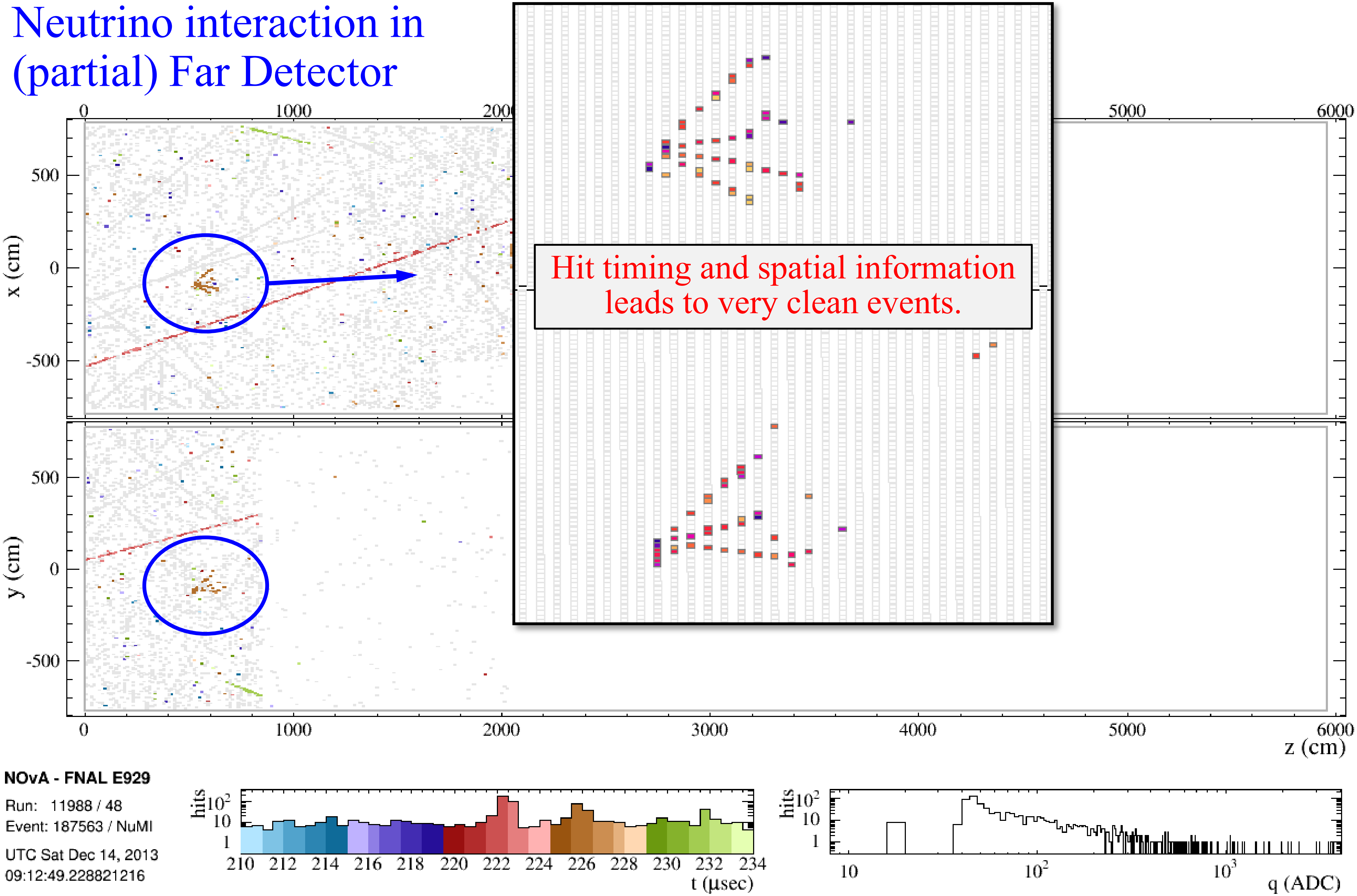




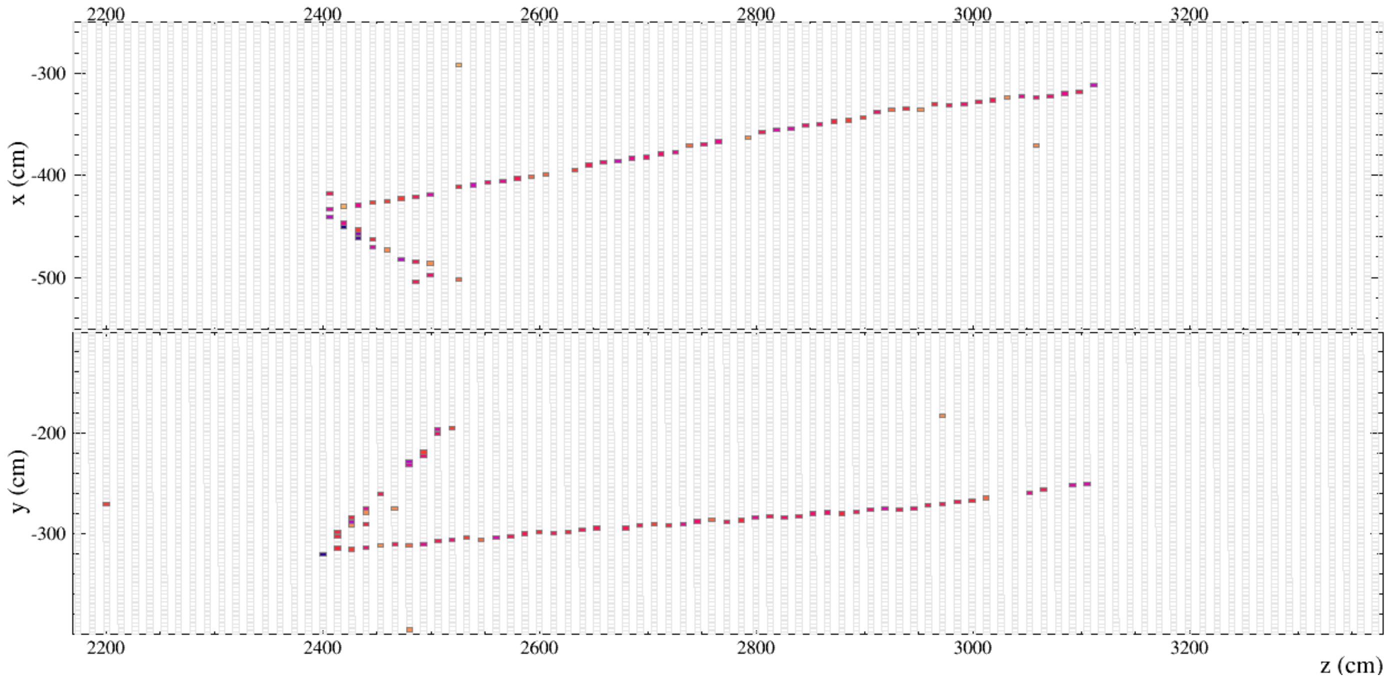
Raw data from 500 μs of Far Detector activity

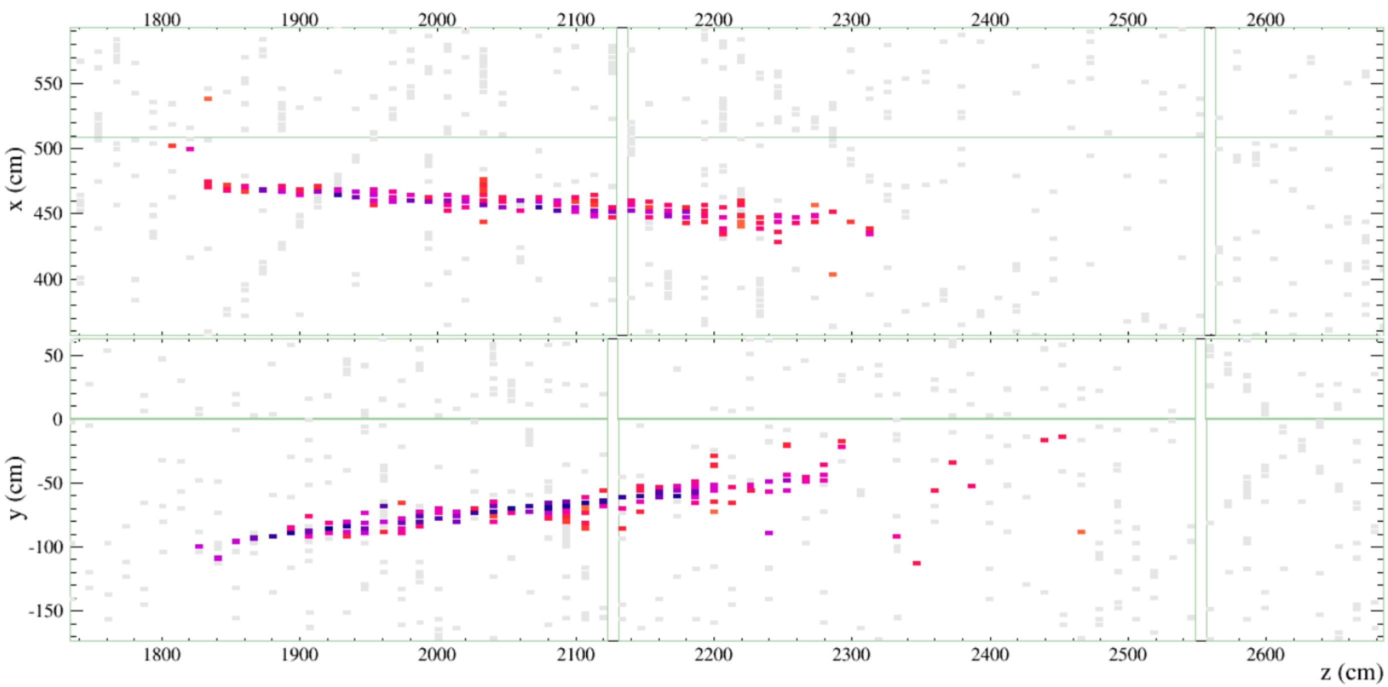


Neutrino interaction in (partial) Far Detector

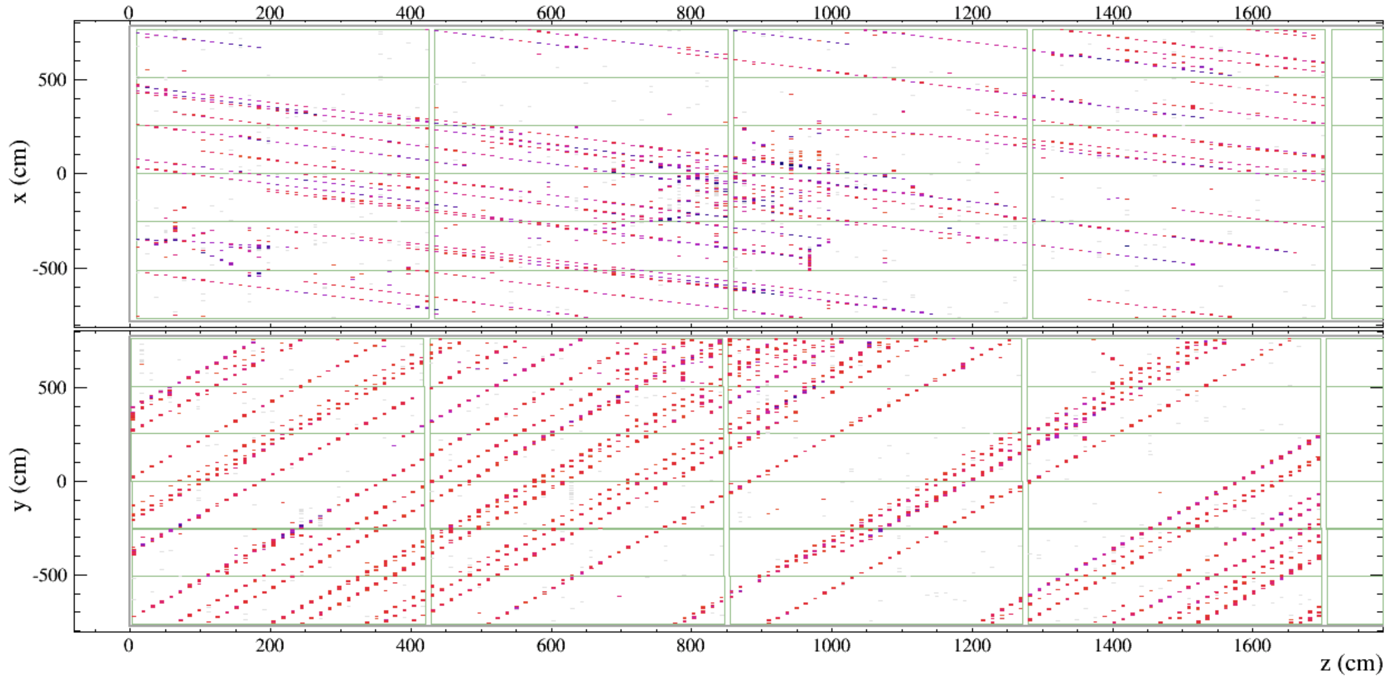


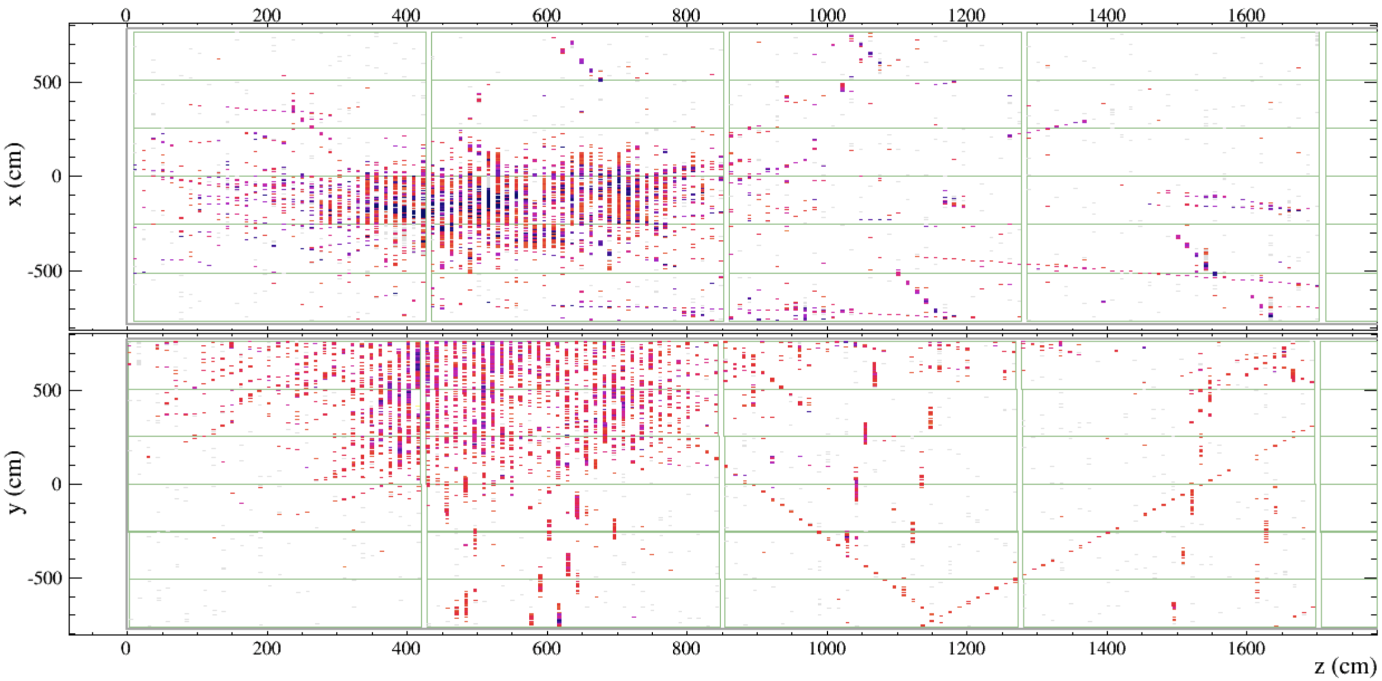
Charged-current candidates in the Far Detector



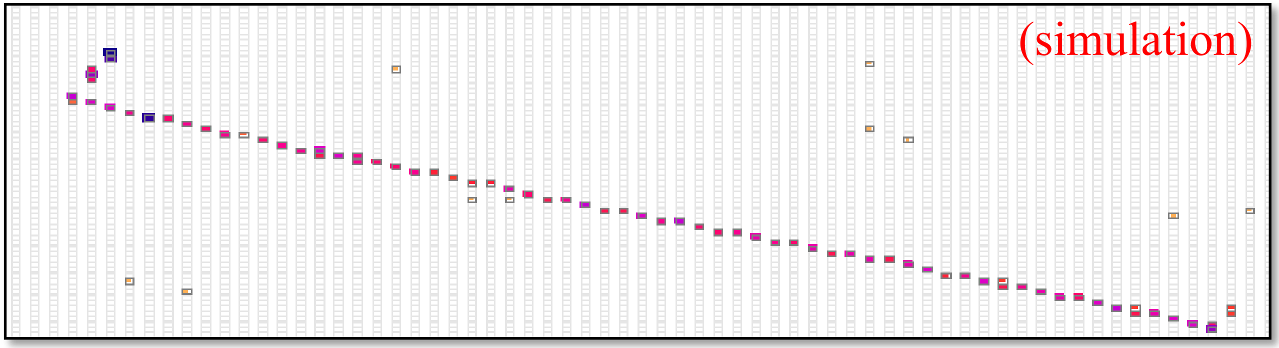


Air shower and high-energy cosmic event

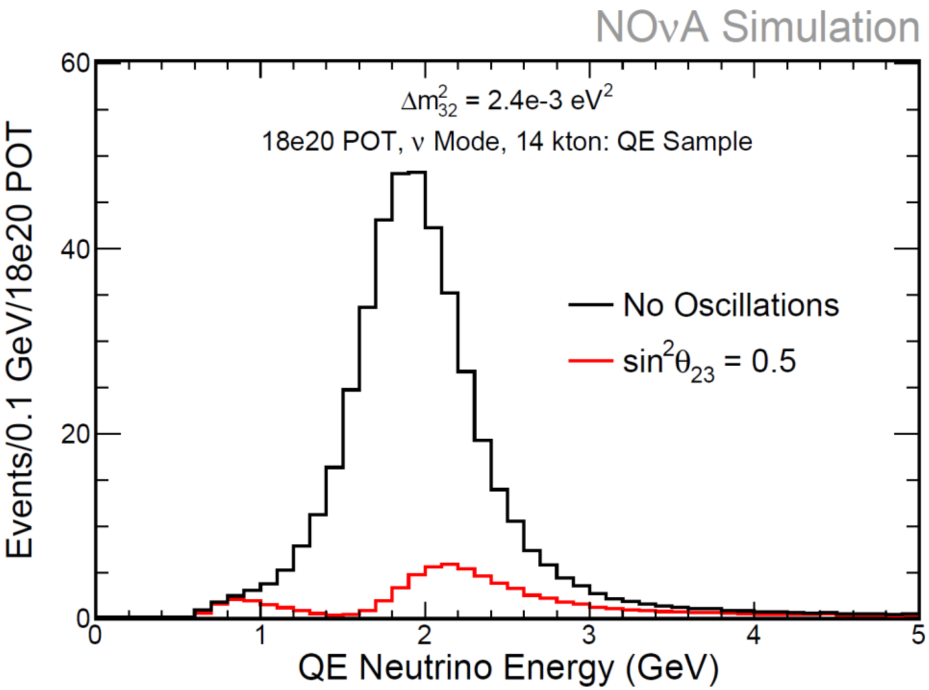


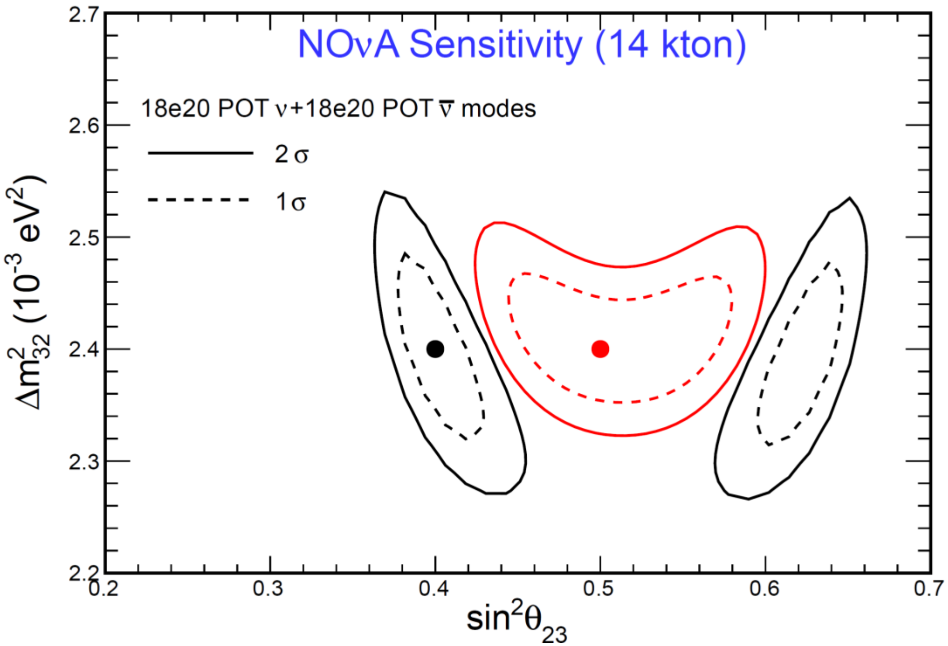


$\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$



- **Below:** Oscillated and non-oscillated spectra (reconstructed energy) for ν_μ CC QE candidates
  Non-QE candidates fitted separately.
  6% vs. 4.5% energy resolution using current techniques.)
- **Right:** example contours for a nominal 6-year run at two test points
  Requirements of cosmic rejection now included (small change)

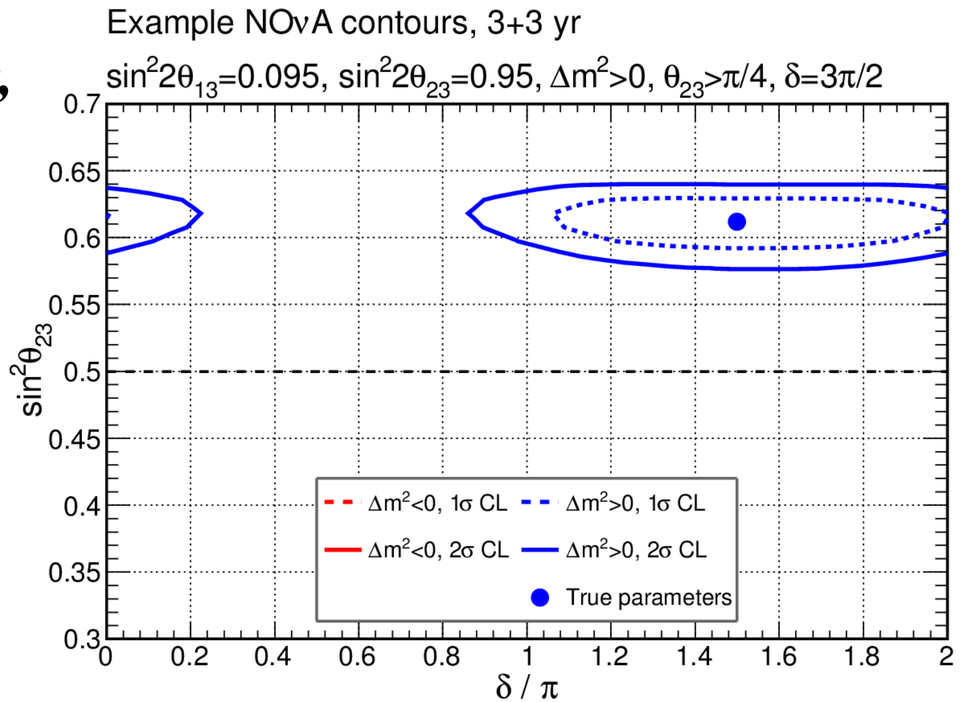




Long baseline → hierarchy sensitivity,
along with rest of oscillation reach

Example point in ν parameter space

Simultaneously break ***ν*$_3$ flavor degeneracy** (θ_{23} octant), determine **mass hierarchy**, and constrain **CP phase *δ***.



And a "degenerate" point…

Hierarchy and ***δ*** information now correlated. **Octant preference** still established.