The physics program and experimental status of NOνA

Ryan Patterson
Caltech

IceCube Particle Astrophysics Symposium 2015
Madison, Wisconsin

May 6, 2015

NOνA

A broad physics scope

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

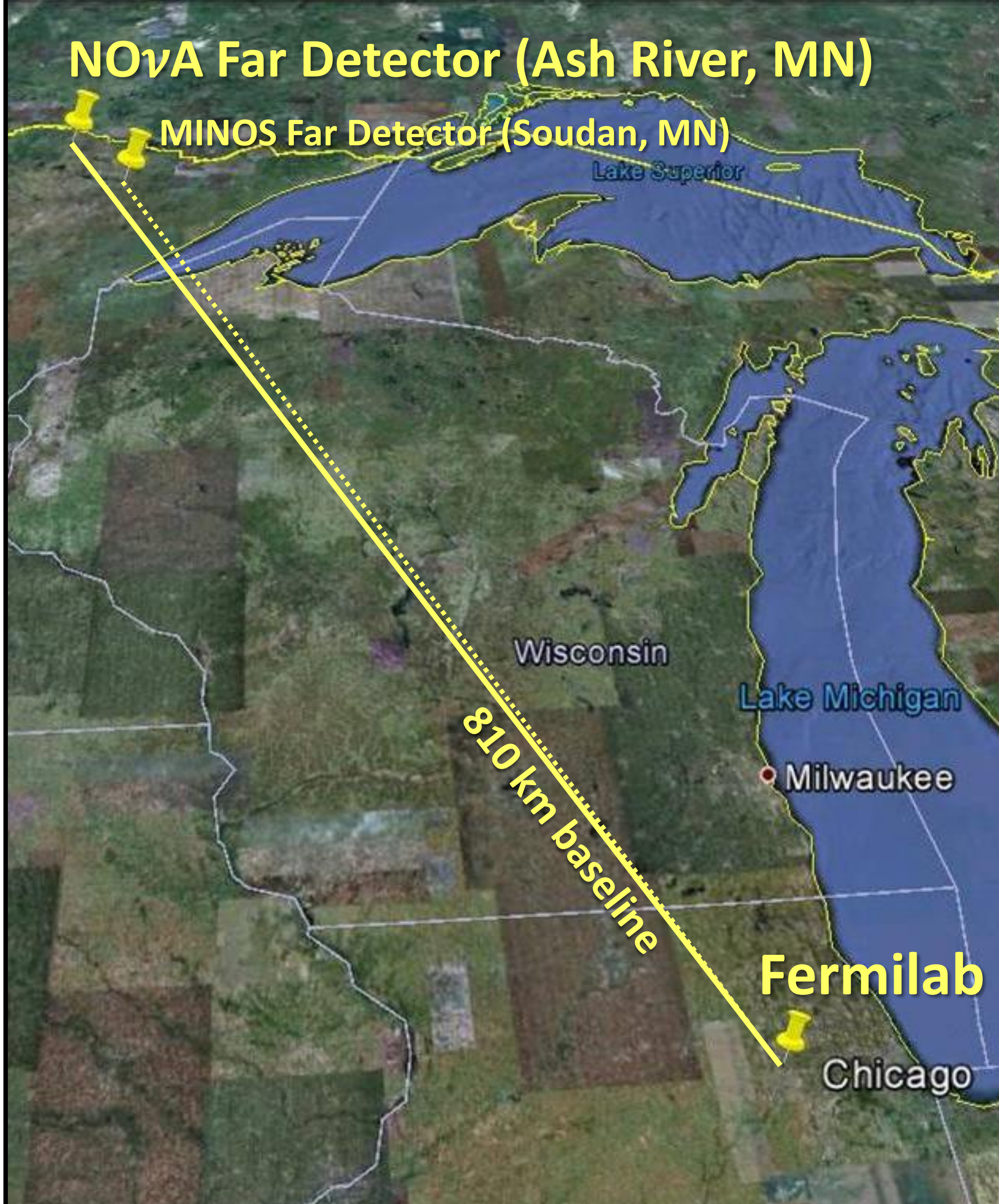
- Determine the **ν mass hierarchy**
- Determine the **θ_{23} octant**
- Constrain δ_{CP}

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
- Non-standard interactions
- Searches for monopoles and other exotica



NOνA

A broad physics scope

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

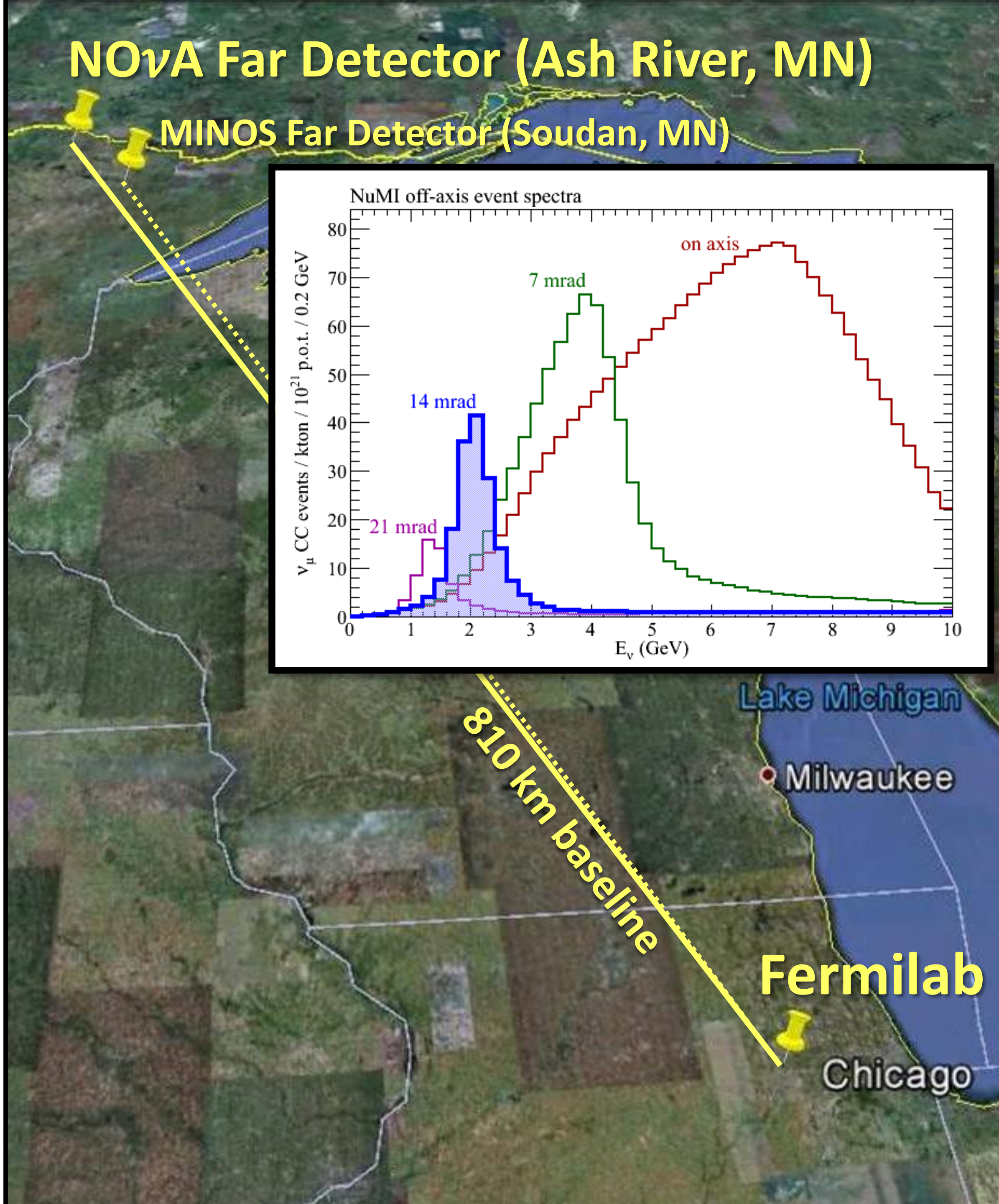
- Determine the **ν mass hierarchy**
- Determine the **θ_{23} octant**
- Constrain δ_{CP}

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
- Non-standard interactions
- Searches for monopoles and other exotica



Fermilab Neutrino Complex

NuMI =
Neutrinos from the Main Injector

2005 – 2012: MINOS "low energy" run

2012 – 2013: Long shutdown

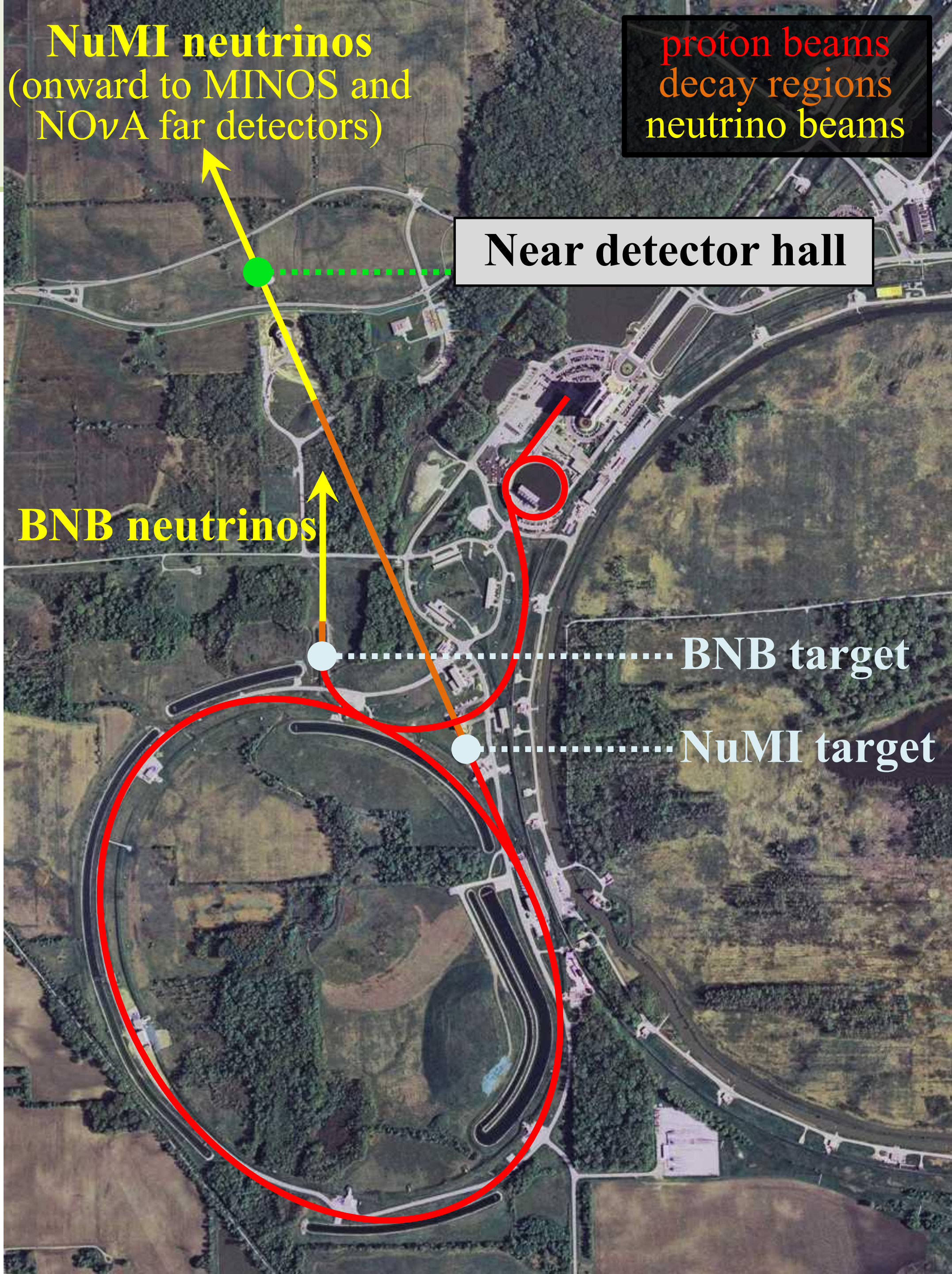
- Repurpose Recycler for injection
- Add associated kickers and instrumentation
- RF, power supply upgrades
- Overhaul of NuMI target station
  → **All toward 700 kW operation**

Today: NOνA "medium energy" run

Slip-stacking into Recycler now standard

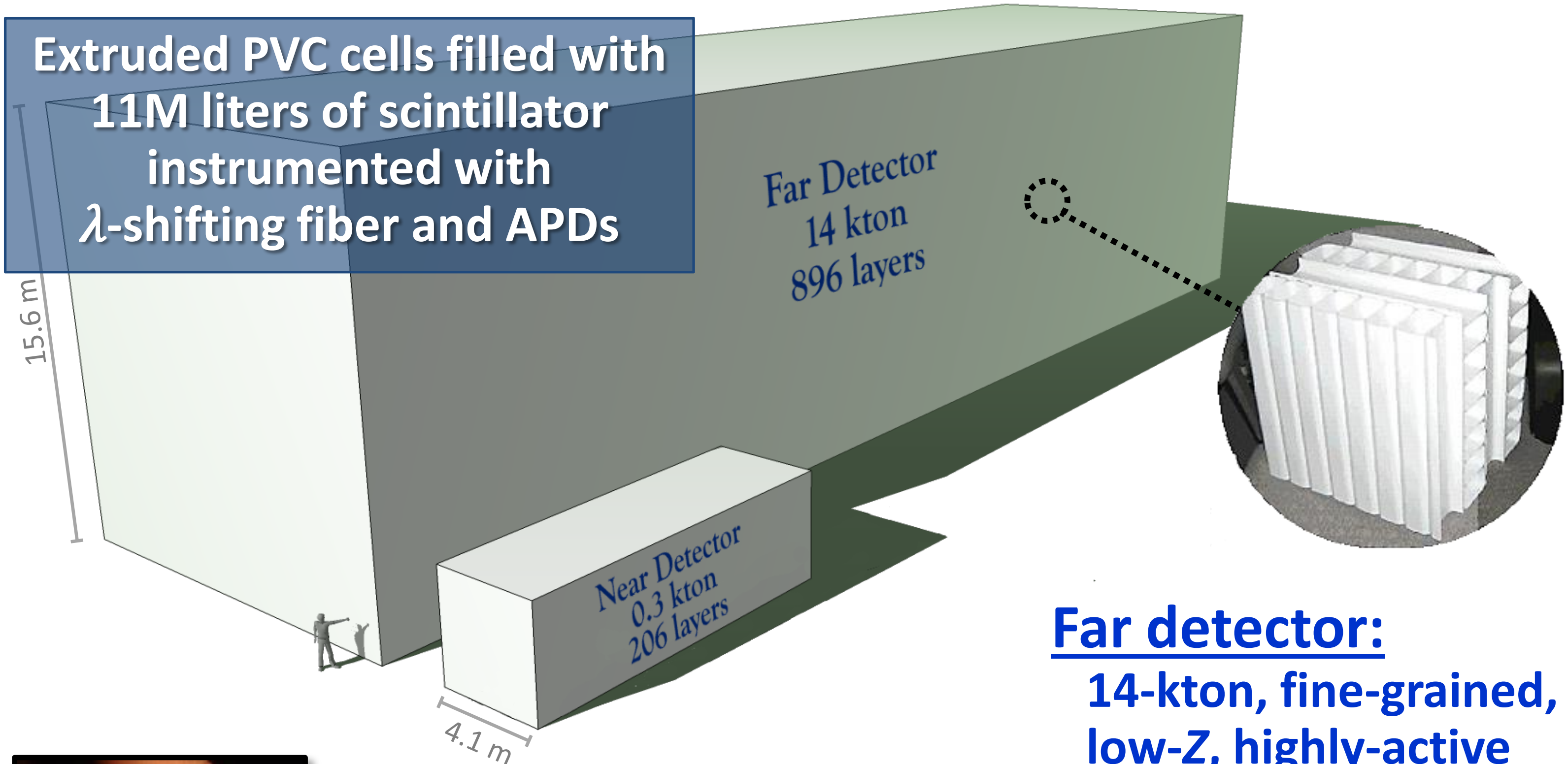
~420 kW operation now standard.
(Record so far: 474 kW)

Booster RF upgrades still underway for full 700 kW operation.

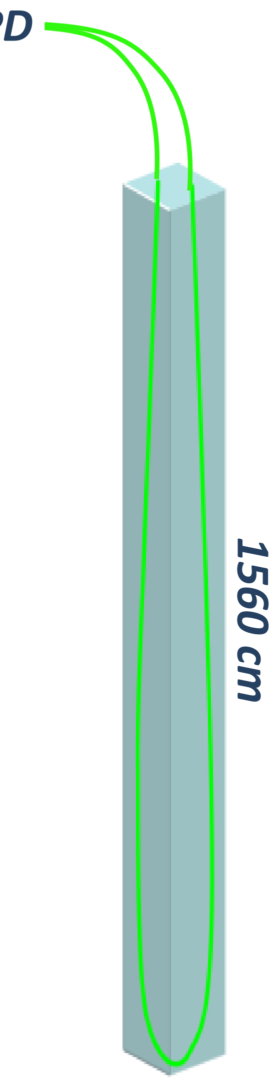


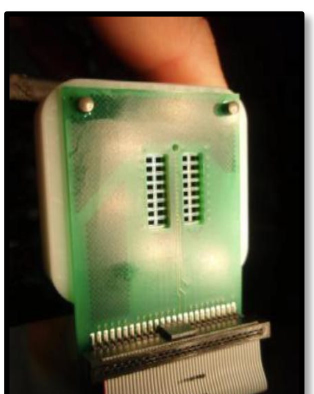
NOνA detectors

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:

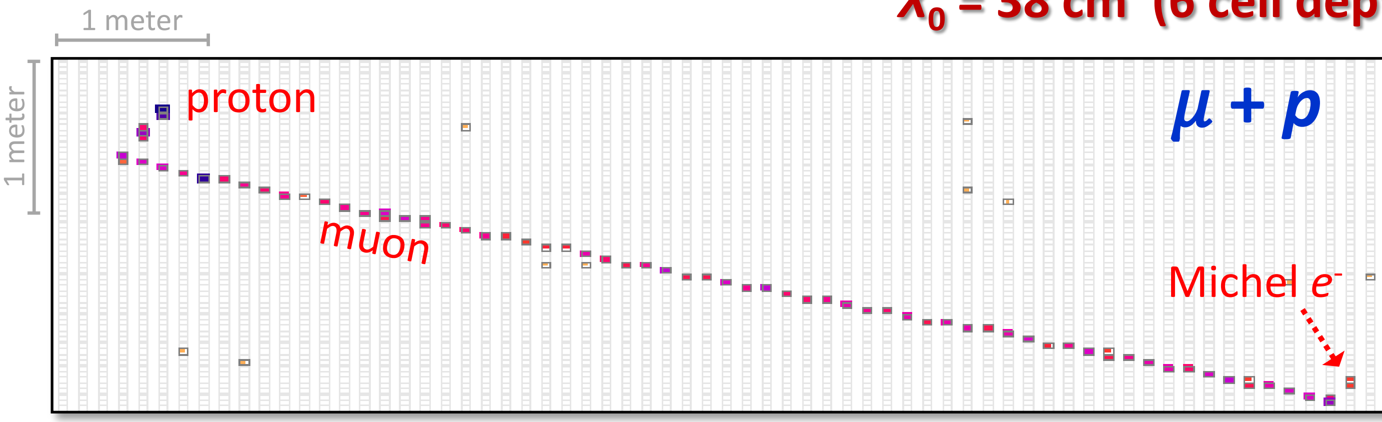
0.3-kton version of the same

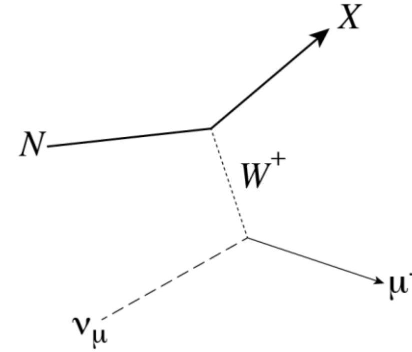
→ *18,000 channels*

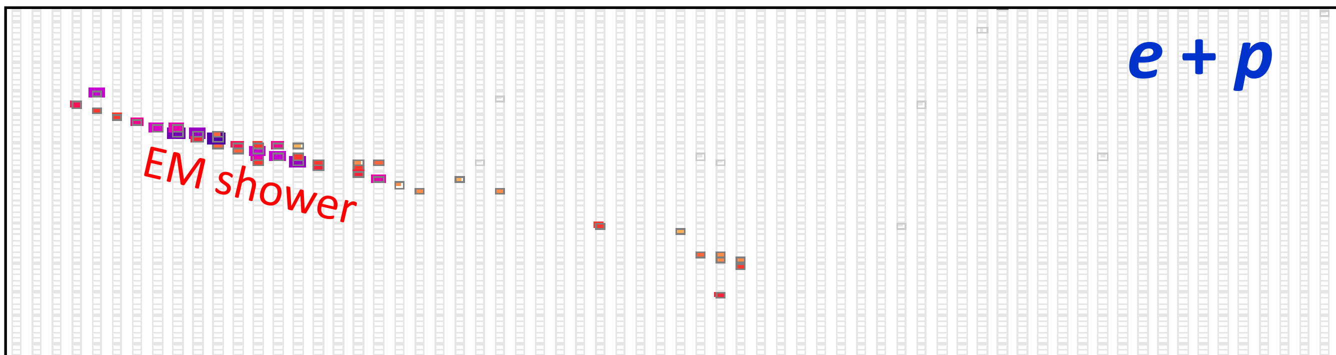
Events in NOνA

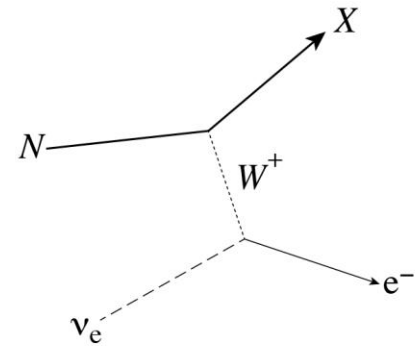
Superb spatial granularity for a detector of this scale

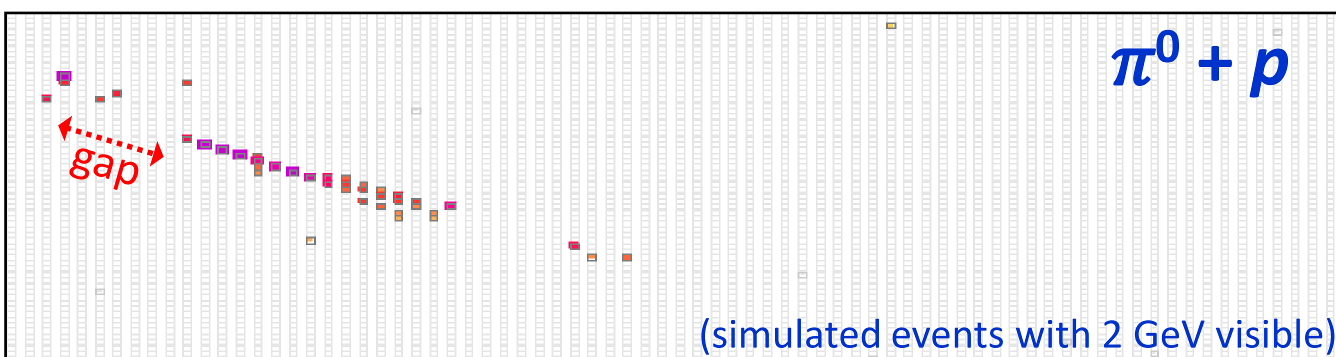
X_0 = 38 cm (6 cell depths, 10 cell widths)

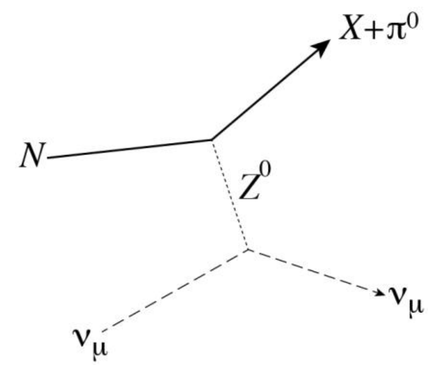








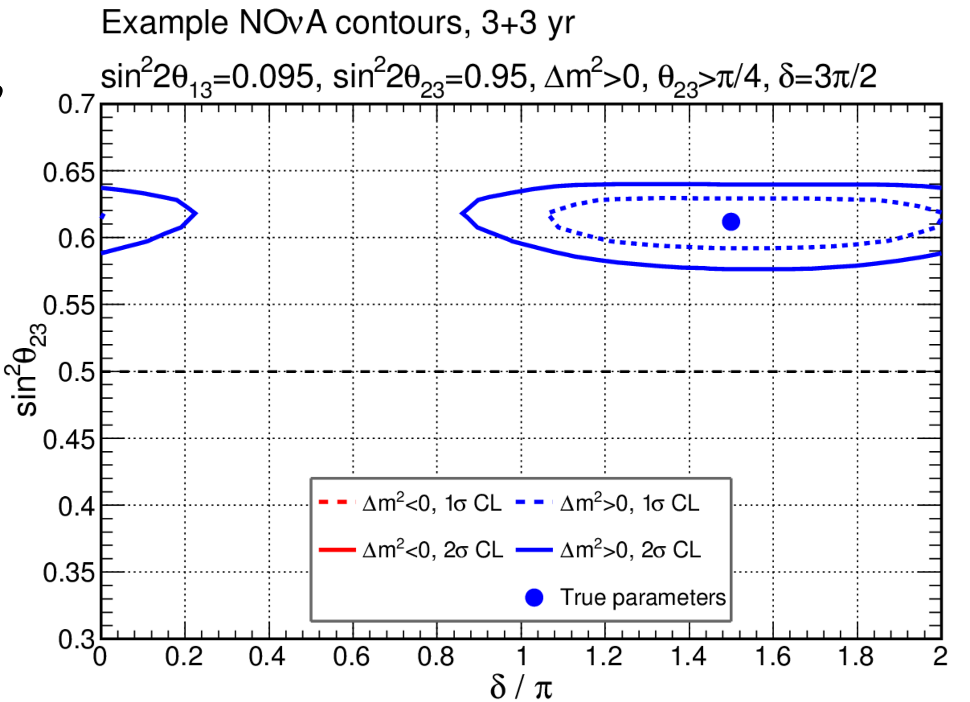




Long baseline → hierarchy sensitivity, *along with rest of oscillation reach*

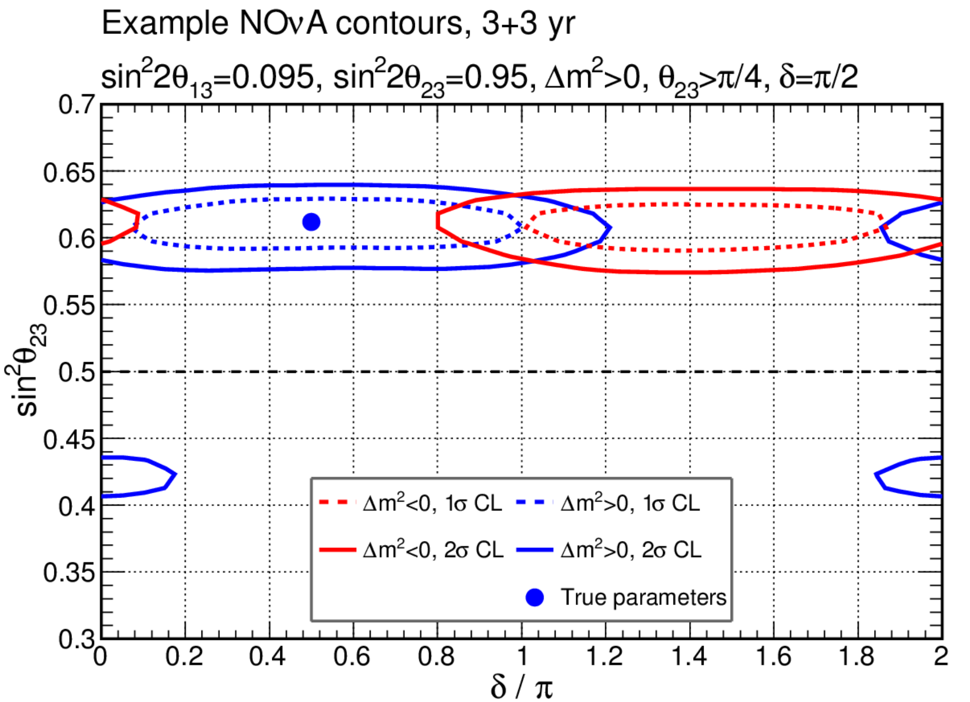
Example point in ν parameter space

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

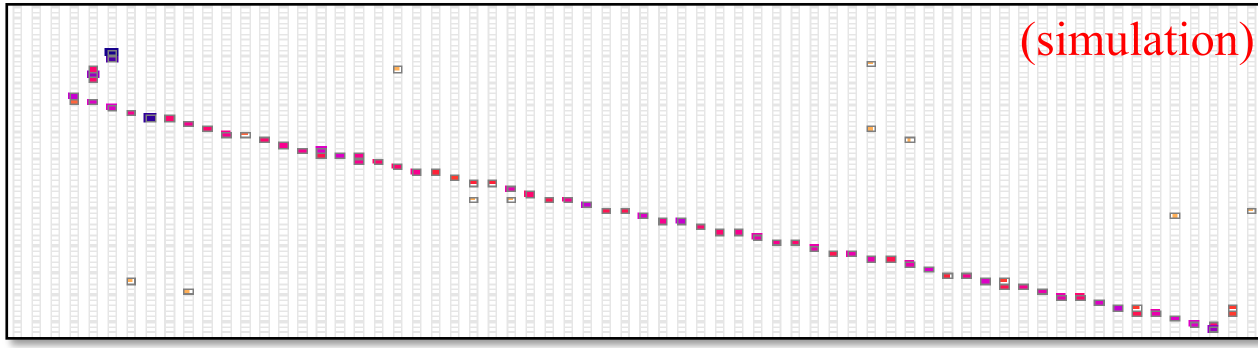


And a "degenerate" point…

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

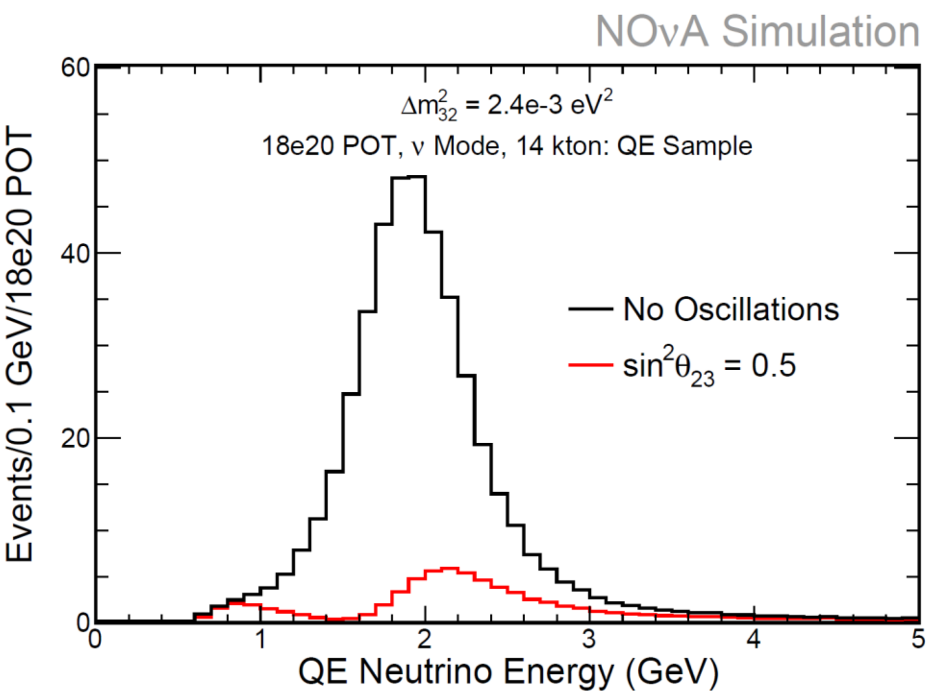


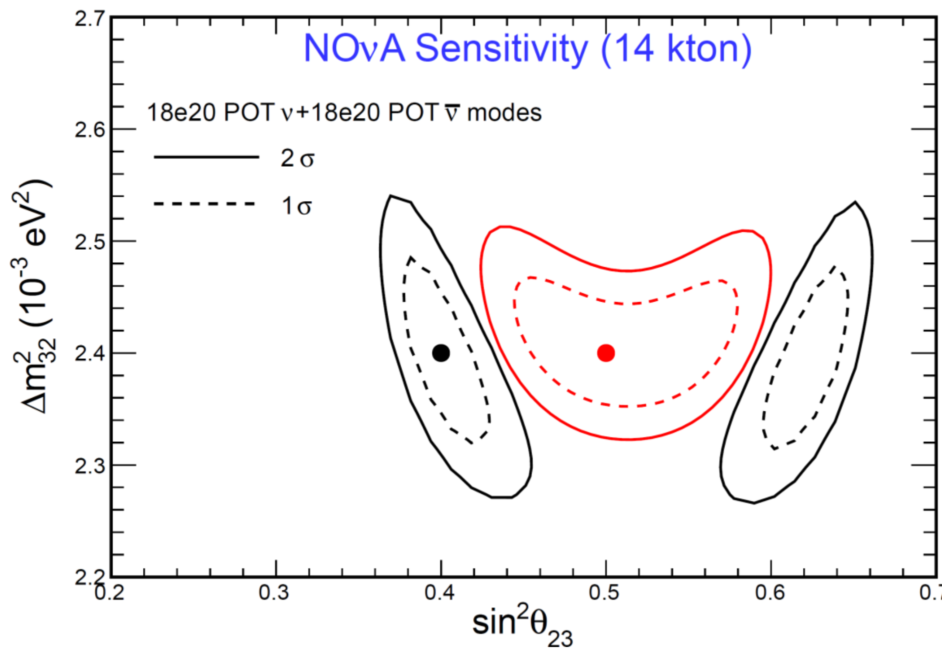
$\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$



- **<u>Below:</u>** Oscillated and non-oscillated spectra (reconstructed energy) for ν_μ CC QE candidates
  6% (non-QE) vs. 4.5% (QE) energy resolution using current techniques.

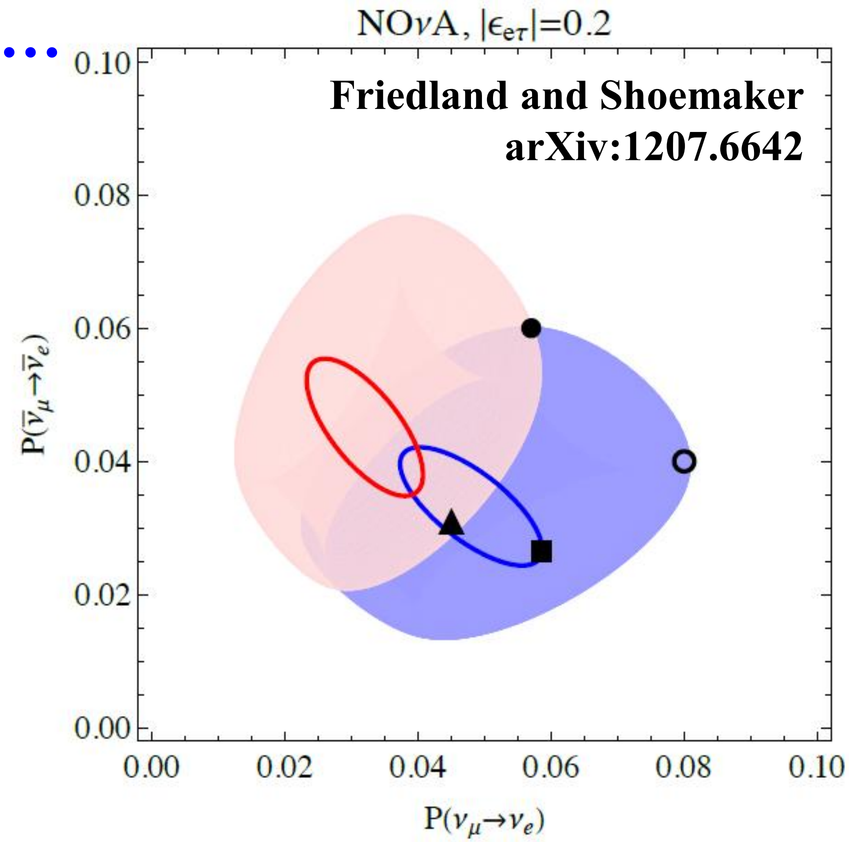
- **<u>Right:</u>** example contours at two test points

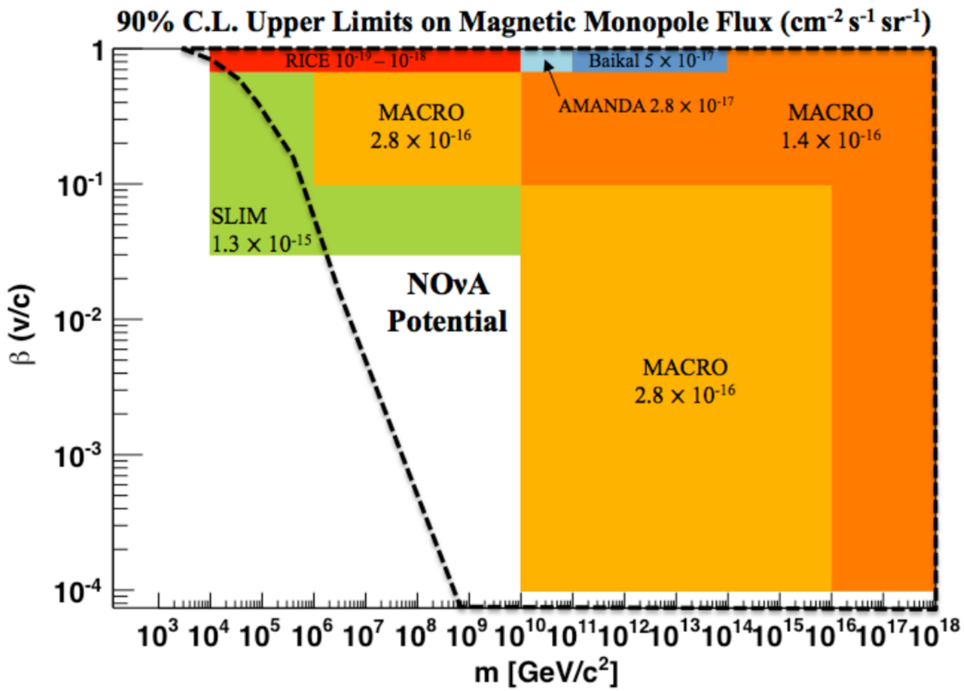




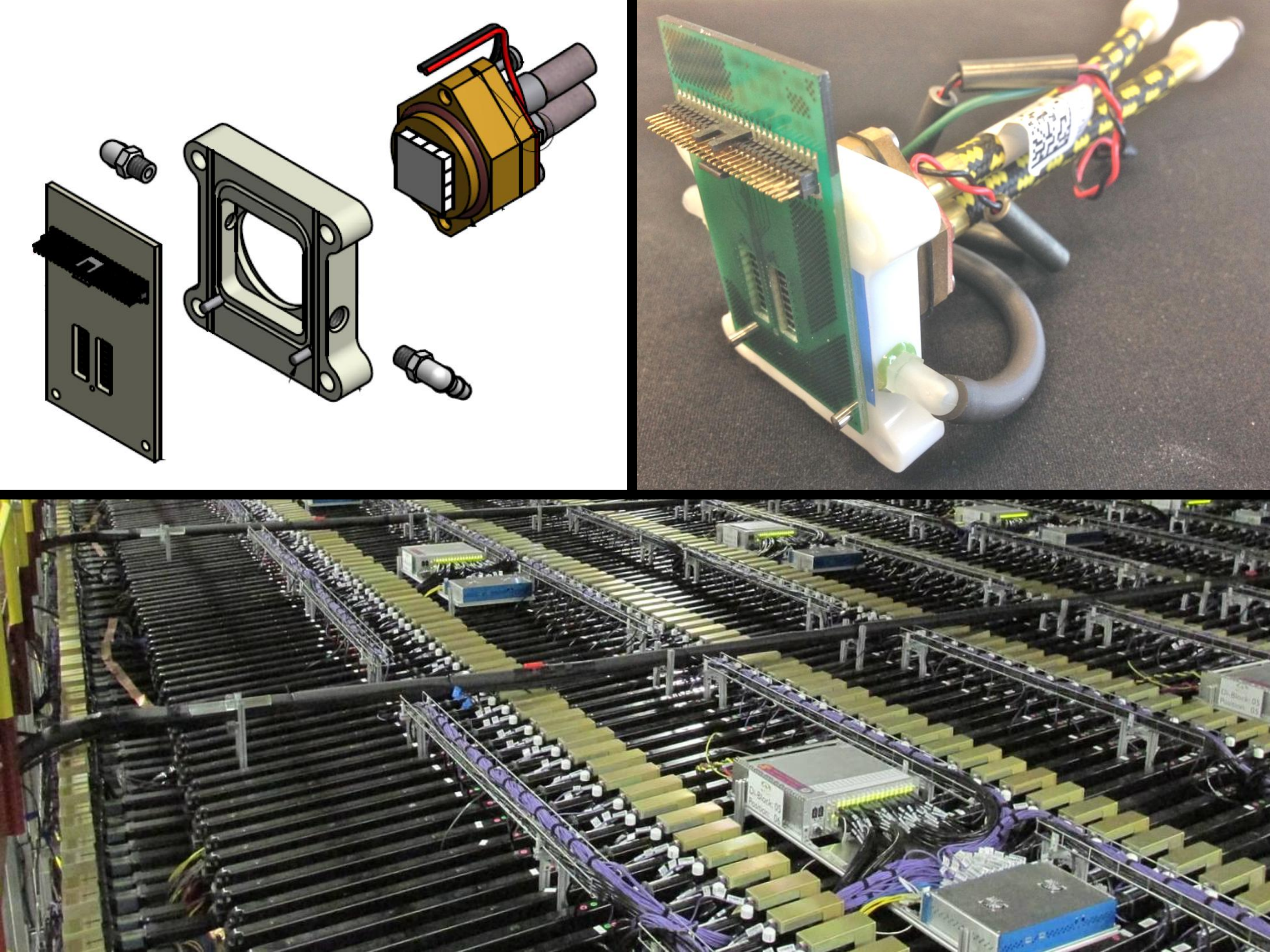
Outside of 3-flavor oscillation physics…

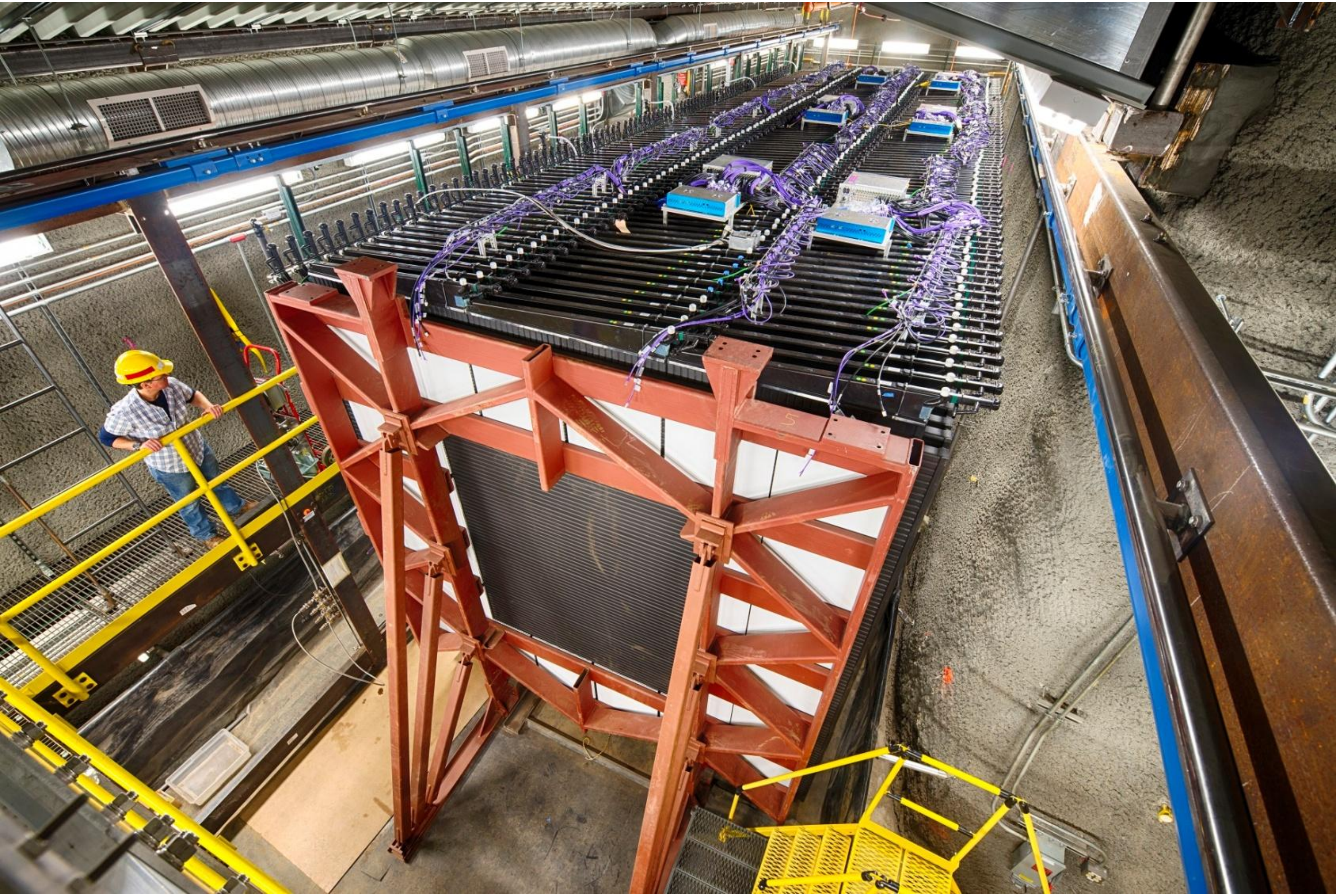
- **Non-standard interactions** *(plot at right)*
  Long baseline → new sensitivity; appearance-mode couplings largely unconstrained.
- **Neutrino/antineutrino comparisons**
- **Cross sections**
  $\sim 10^8$ events in full exposure in the ND.
  ND analyses underway.

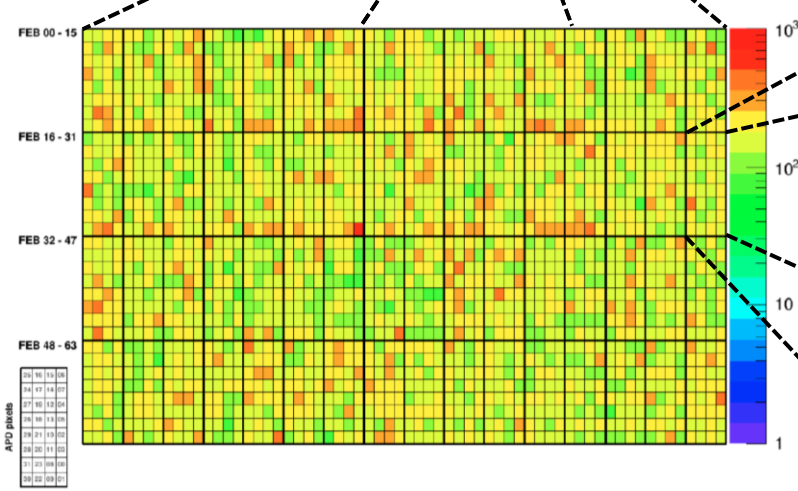


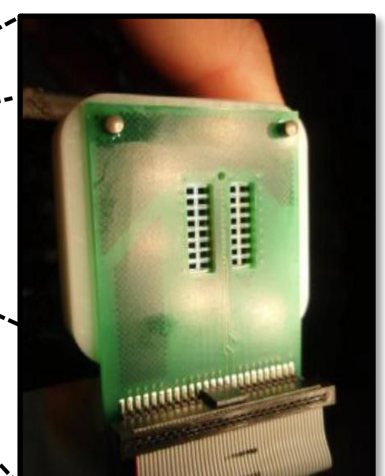


- **Monopole searches** *(plot at left)*
  Look for strong ionization signal
- **Supernova neutrinos**
  Several thousand events in NOνA for a supernova in our galaxy.
  (Some DAQ development still on-going for this.)



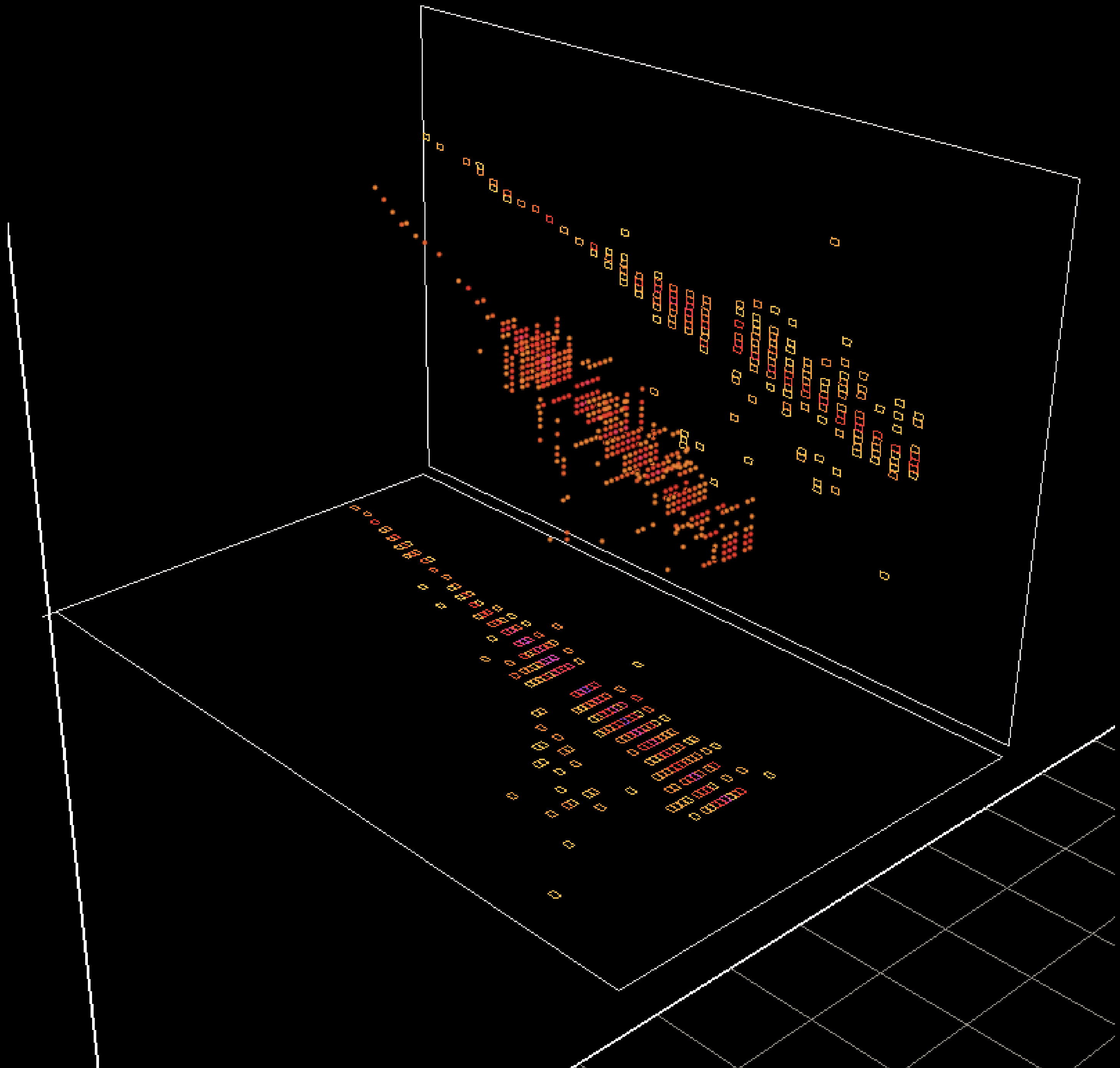






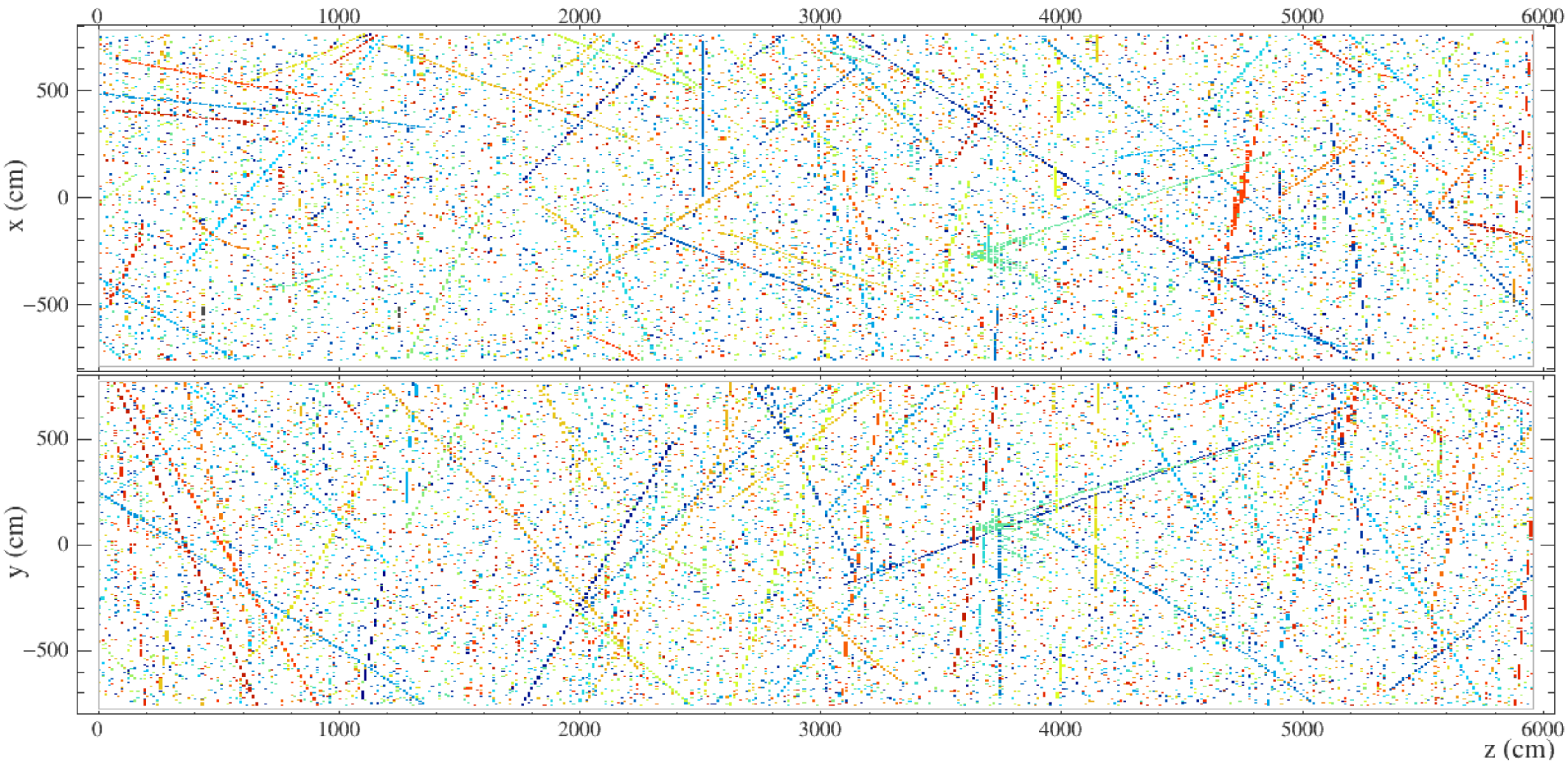
344,064 channels!

>99% operational



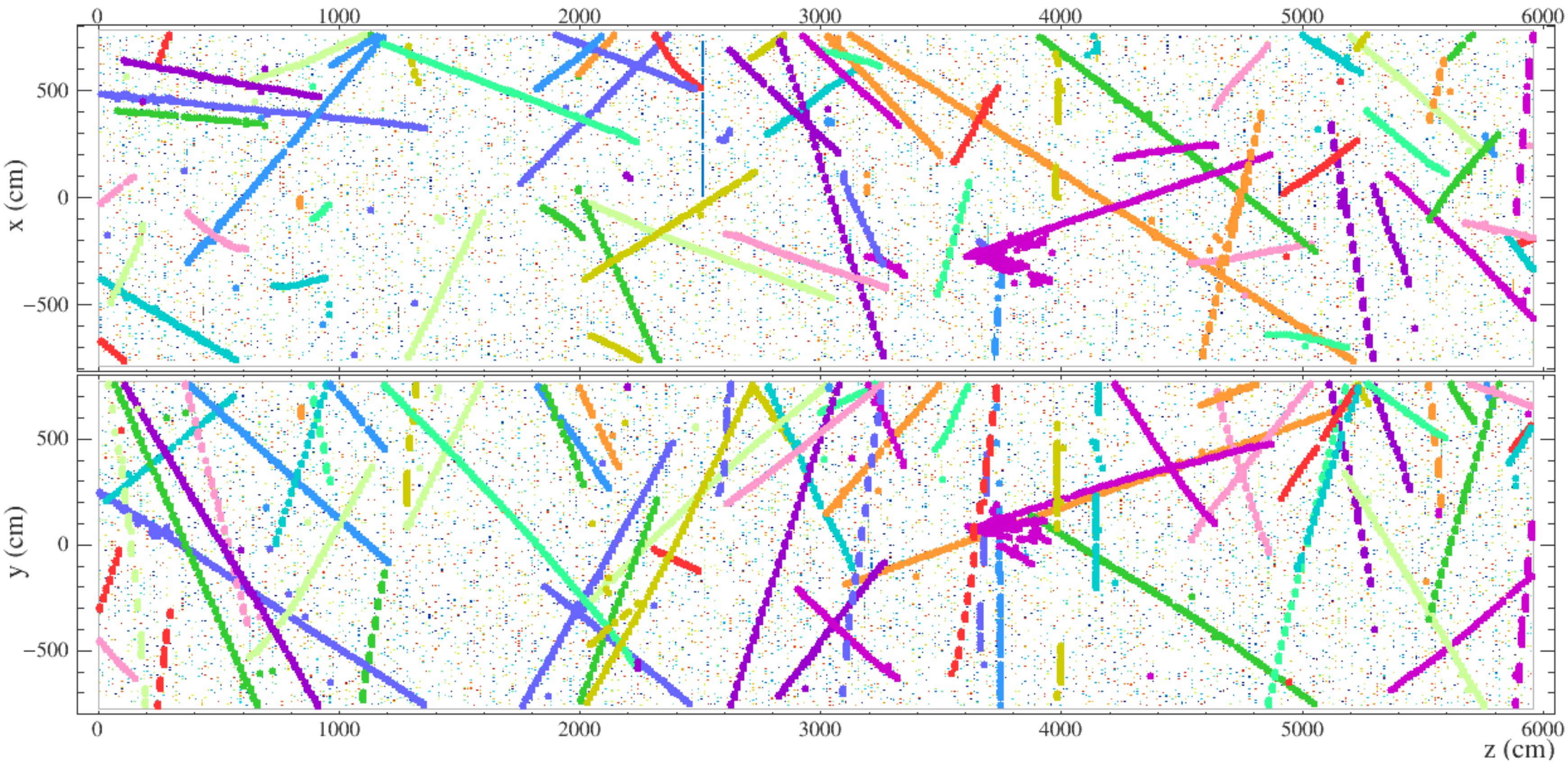
Isolating individual interactions

- 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***
- Look for causally connected **clusters in space/time**



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***
- Look for causally connected **clusters in space/time**

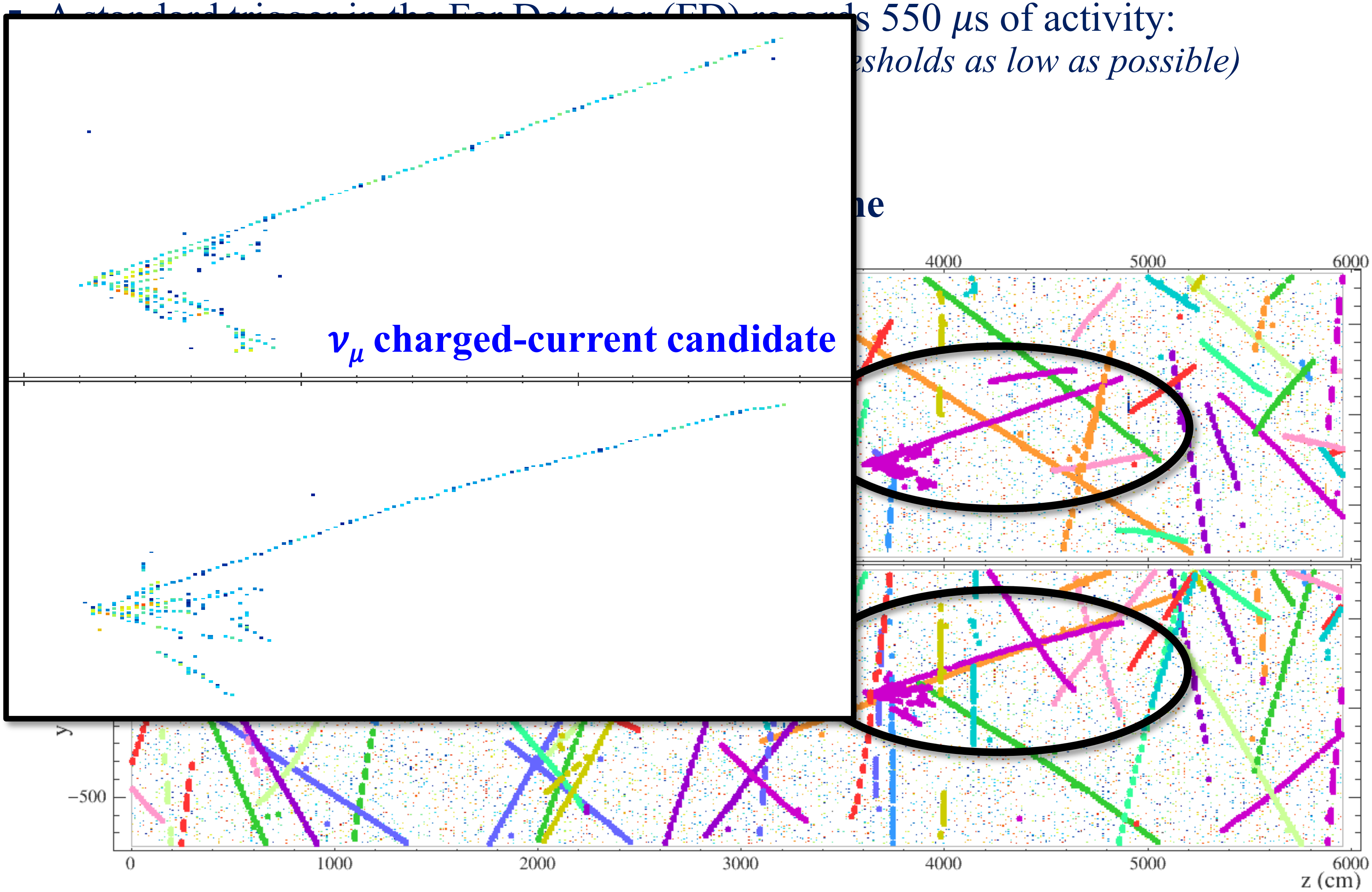


Isolating individual interactions

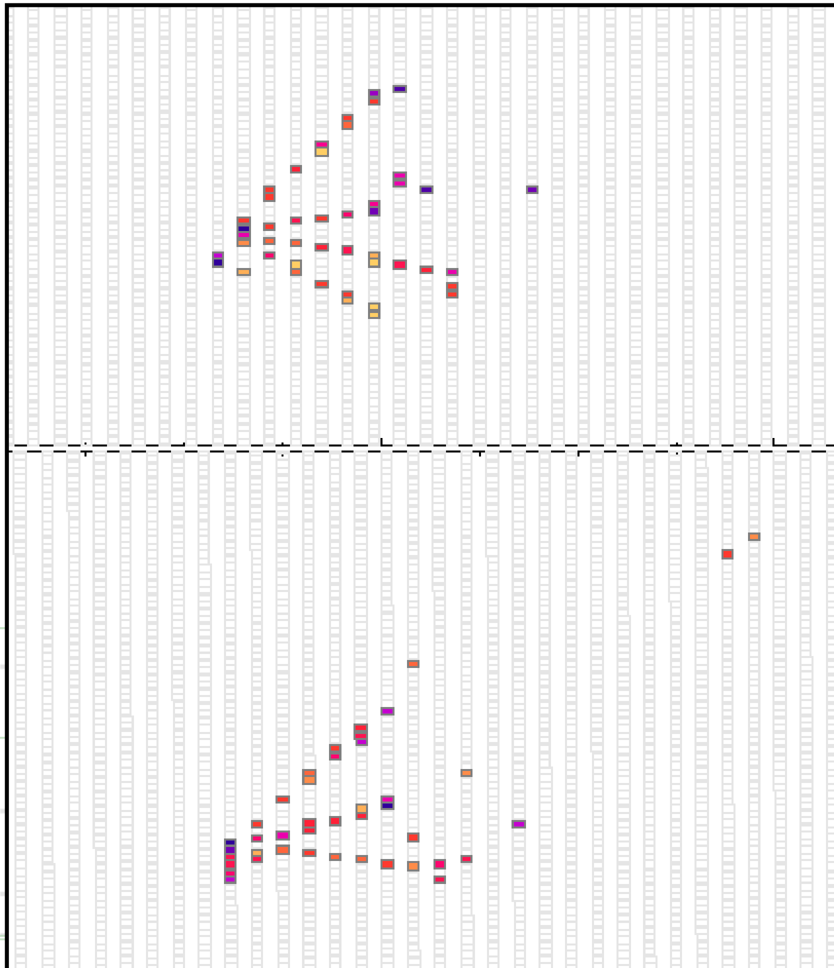
s 550 μs of activity:

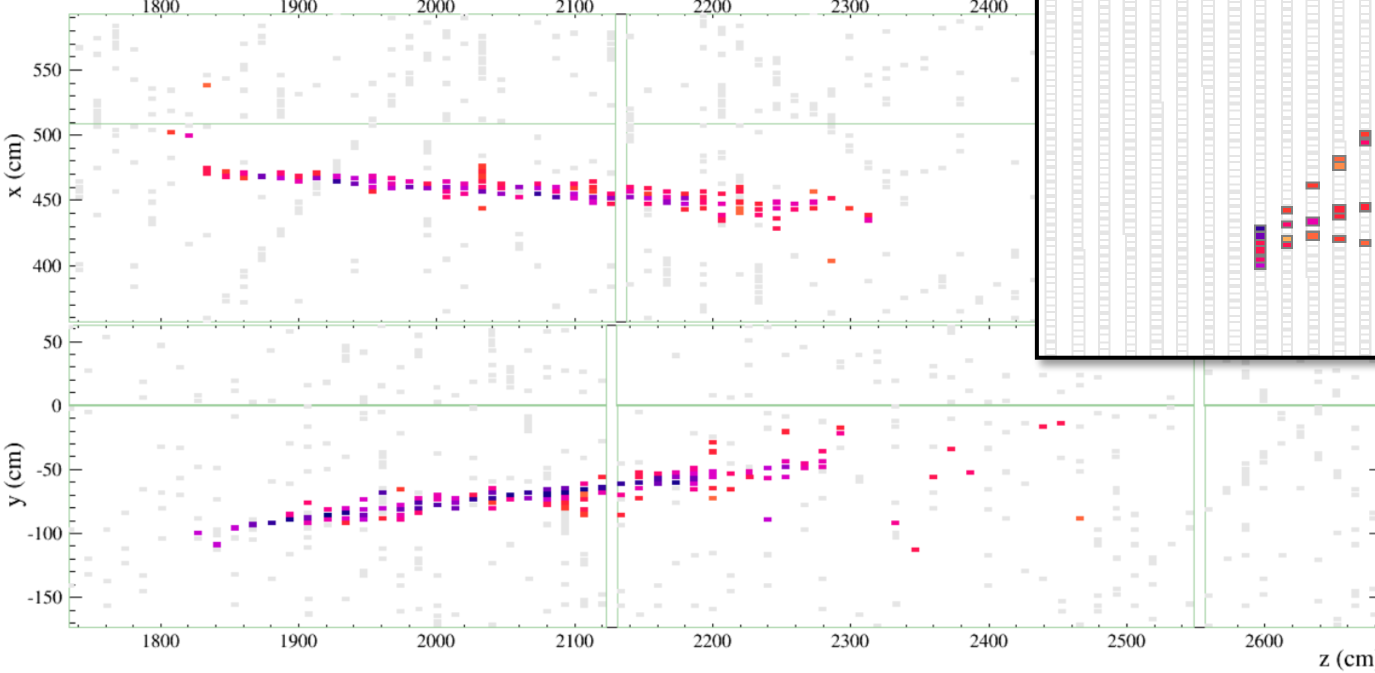
esholds as low as possible)

ne

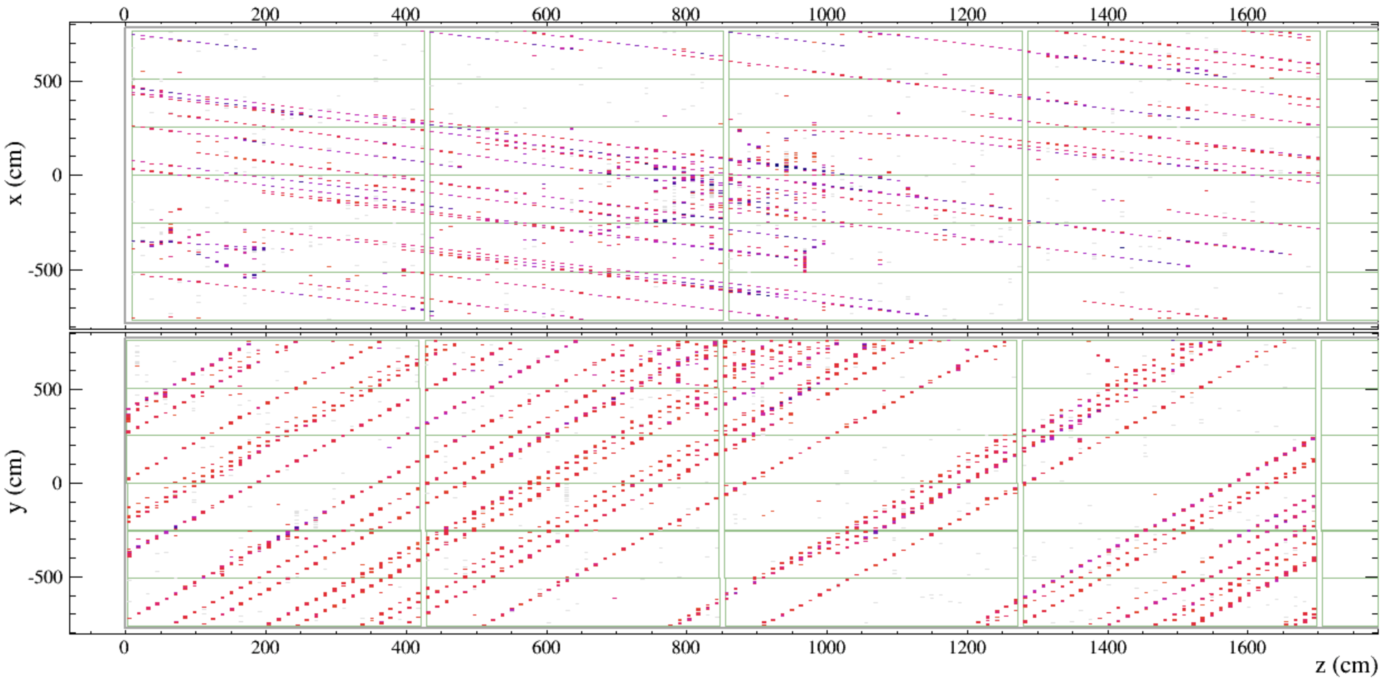


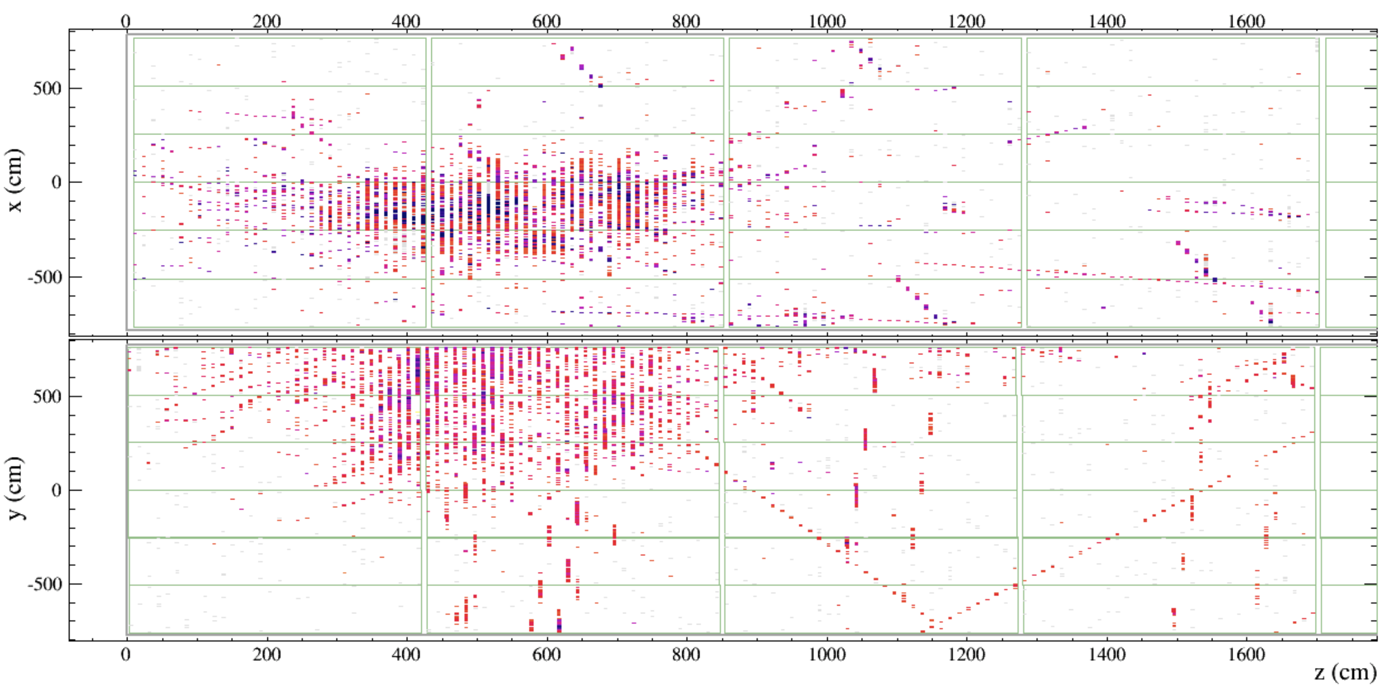
Neutral current (right)
and $\boldsymbol{\nu_e}$ **charged current** (below)
candidates in the Far Detector





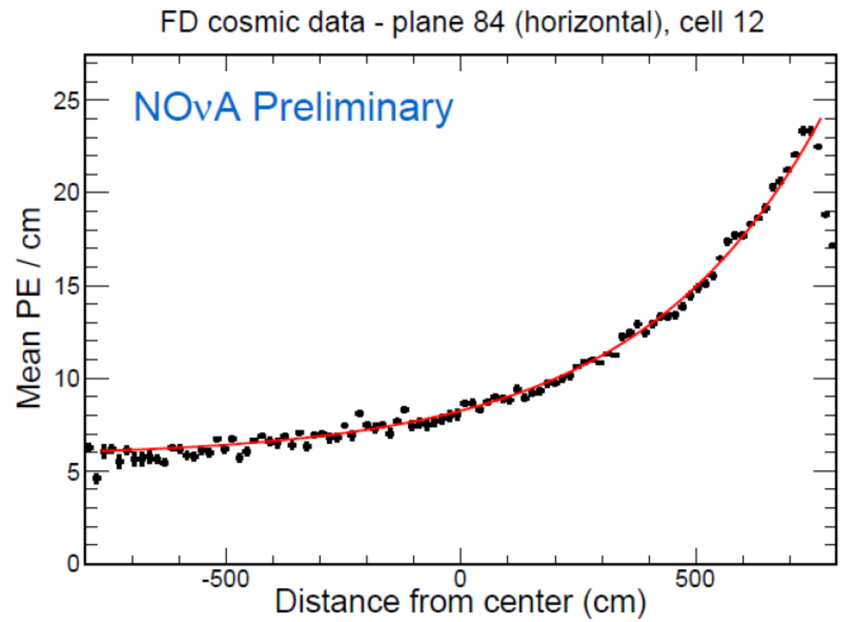
Air shower (right) and **high-energy cosmic event** (below)



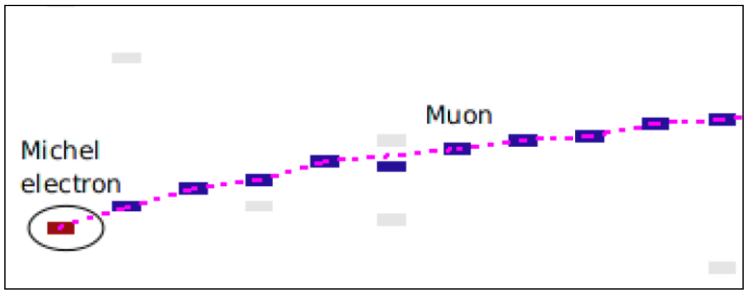


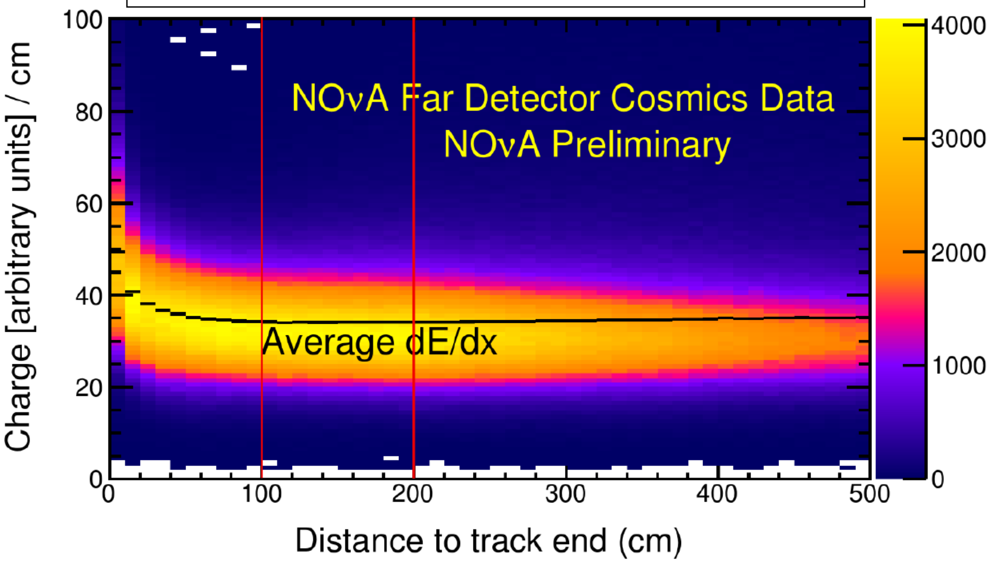
Energy calibration

- **Attenuation** in the WLS fiber →
  *A local regression **corrects any residuals** beyond the basic functional form*

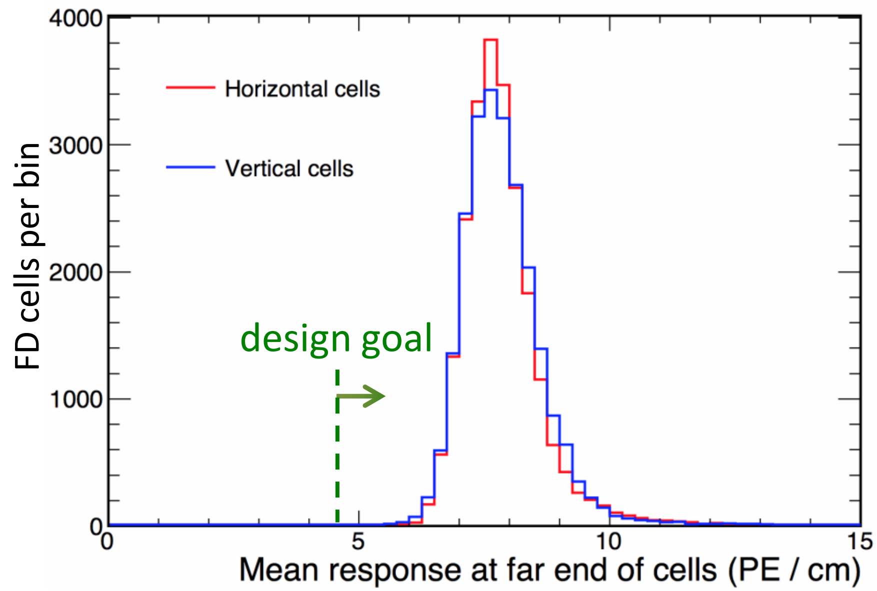


- **Stopping muons** provide standard candle for setting **absolute energy scale:**



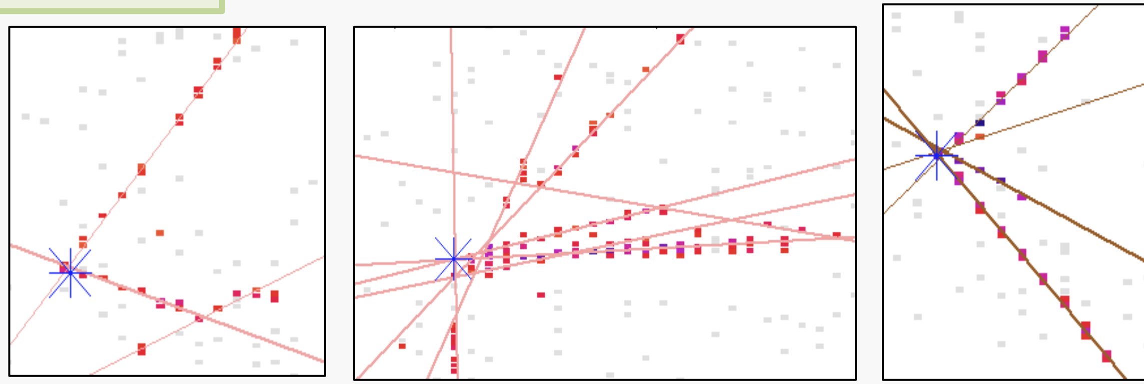


Light level requirements
at end of cell **are well met:**

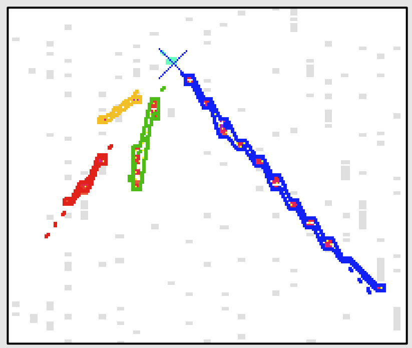


Event reconstruction

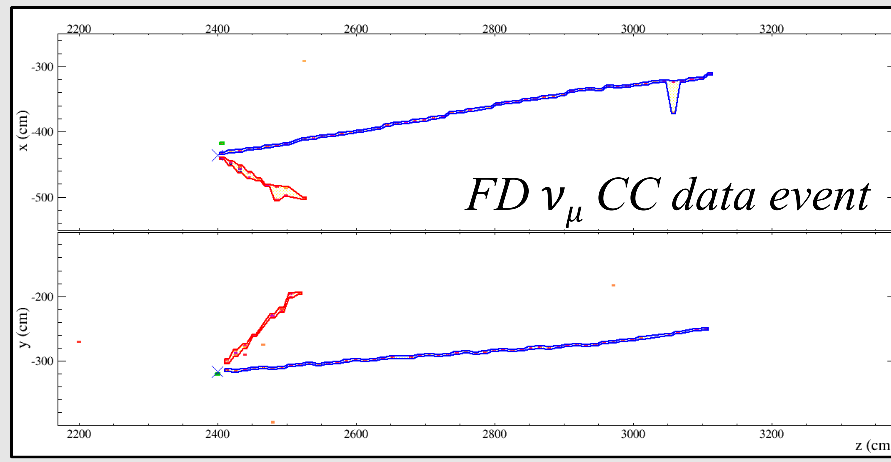
Vertexing *(11 cm resolution for charged-current events)*



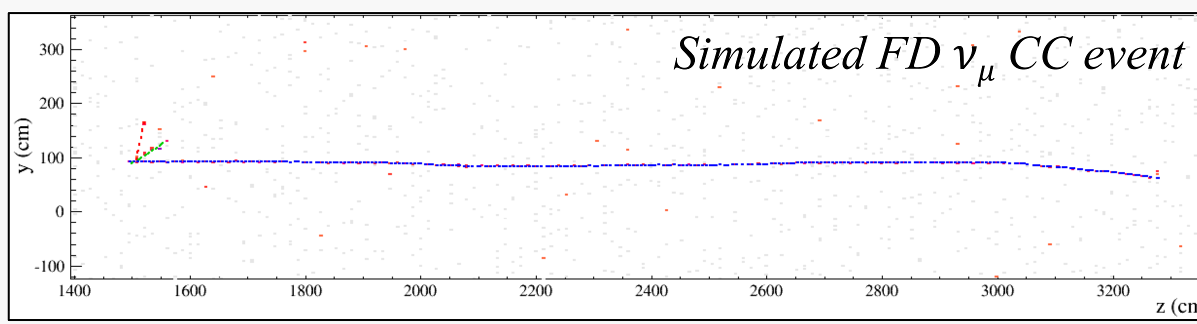
Clustering and **view maching**



Cosmic ray neutron event in the FD data



Tracking *(Kalman filter algorithm shown)*

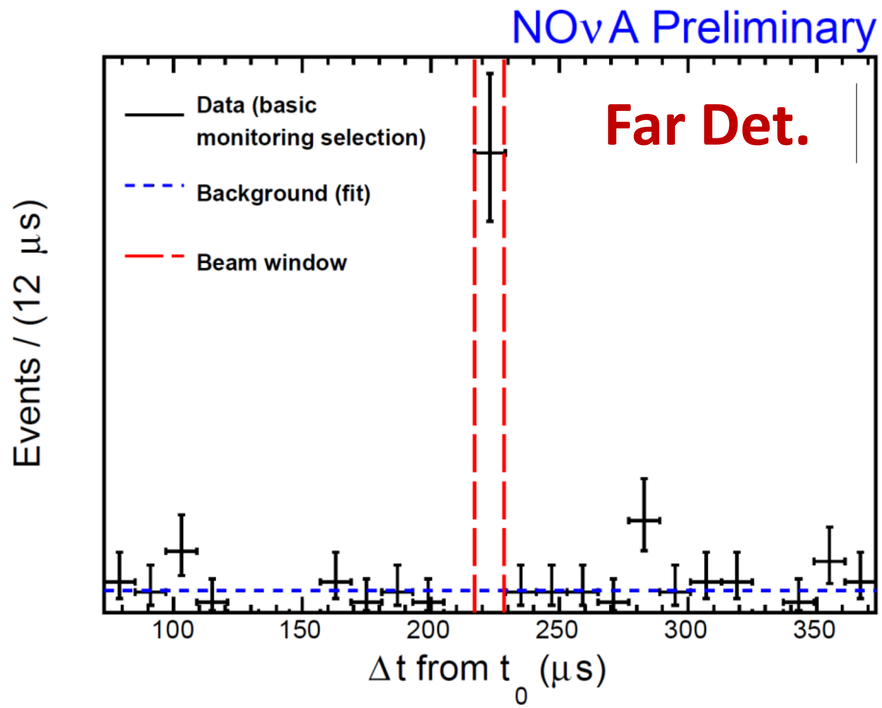


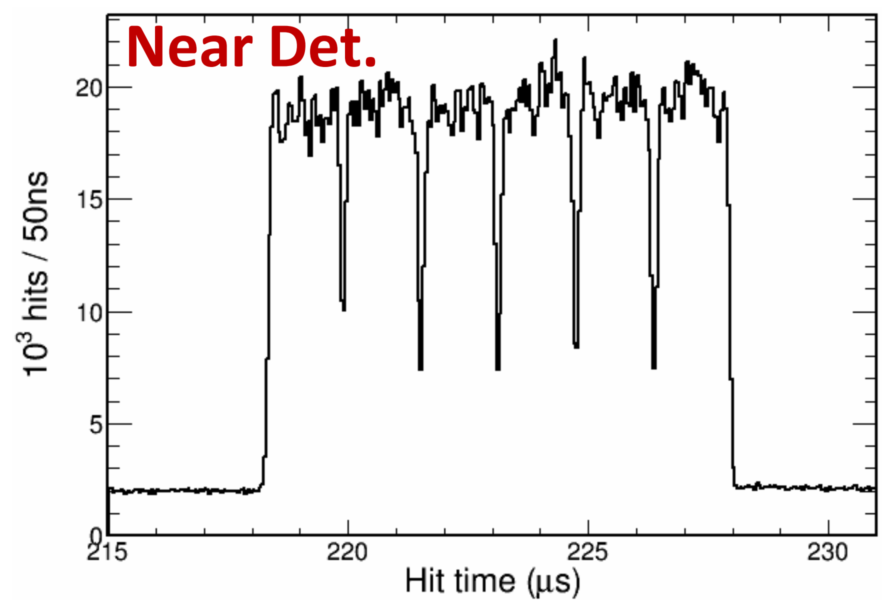
Beam timing

- *Top plot:* **FD neutrino peak**
  A basic monitoring event selection used

- *Bottom plot:* **ND neutrino peak**
  No event selection at all! Spill structure visible with minimal data.

- **Beam timing** gives us a 10^5 head start on cosmic ray rejection in the Far Detector ($10\ \mu s$ spill every 1.3 s)





An additional 10^7 rejection from…

ν_e CC case: Cut events…

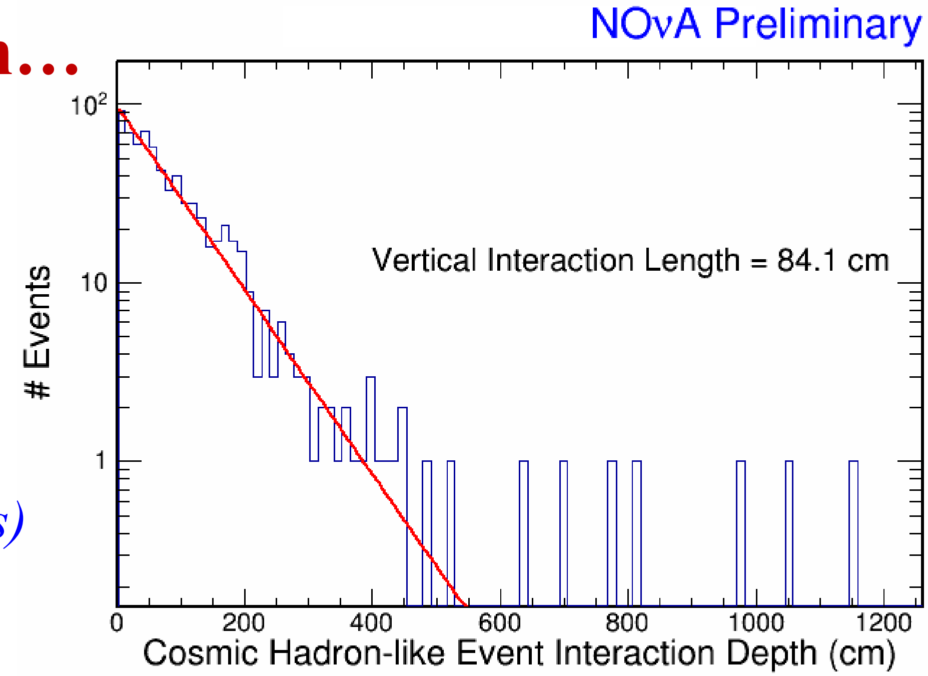
- ***…too near the detector edges***
- ***…with high p_T/p***
- ***…with poor ν_e CC PID values***

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:**

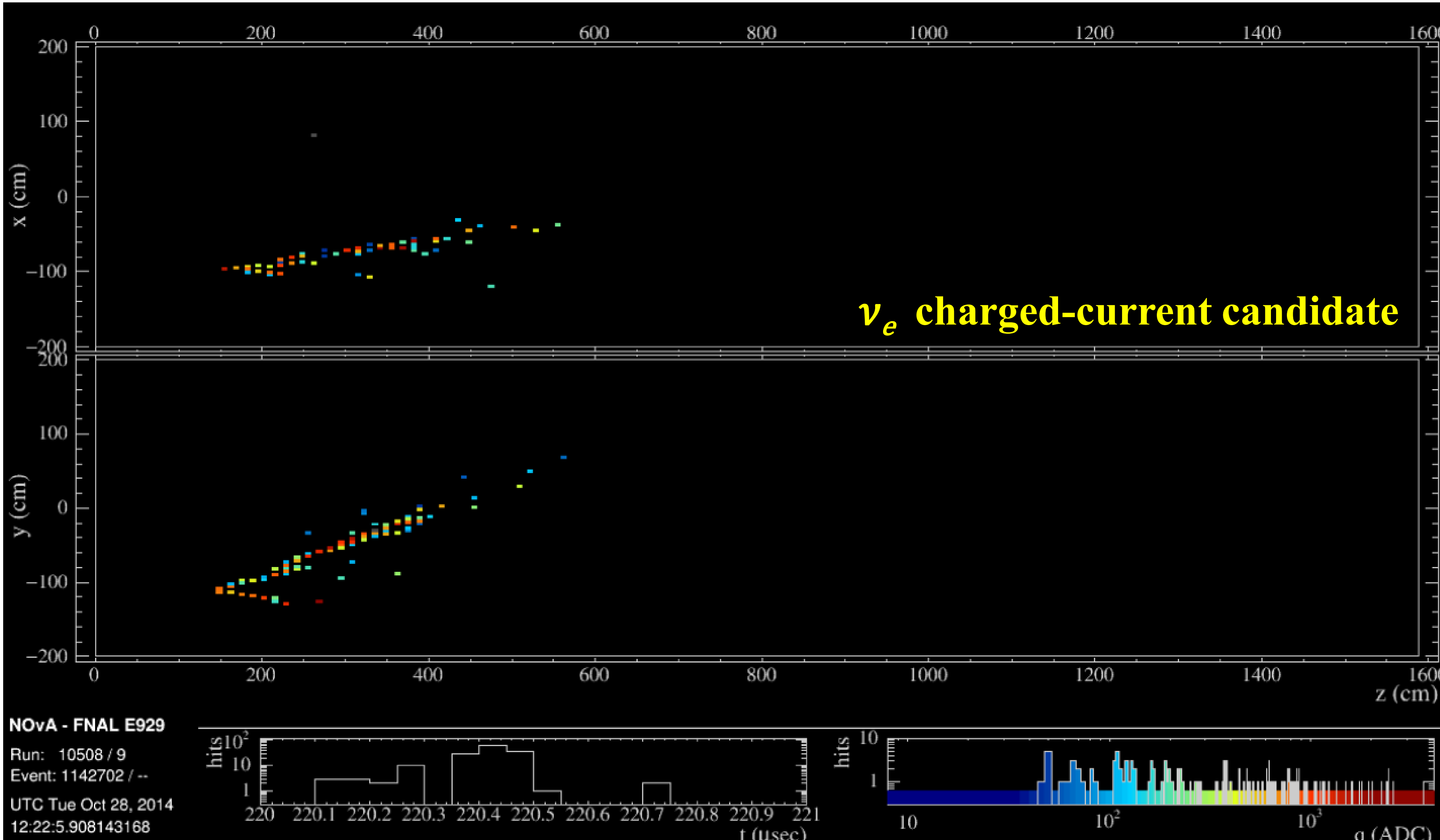
75 signal
4 beam bkg.
~1 cosmic bkg.

(after disappearance)

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

In the ND…

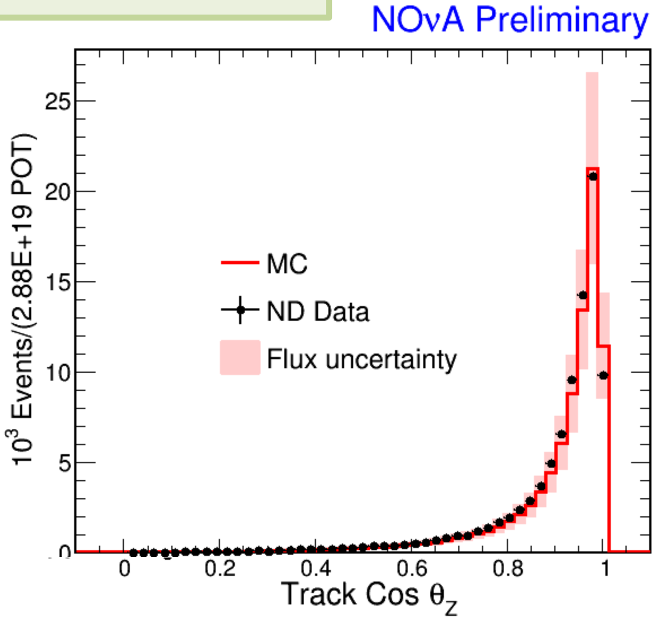
- **Cosmic ray rate much reduced** (50 Hz in ND vs. 100,000 Hz in FD)
- **ND event pile-up easily handled** given temporal and spatial resolution of detector

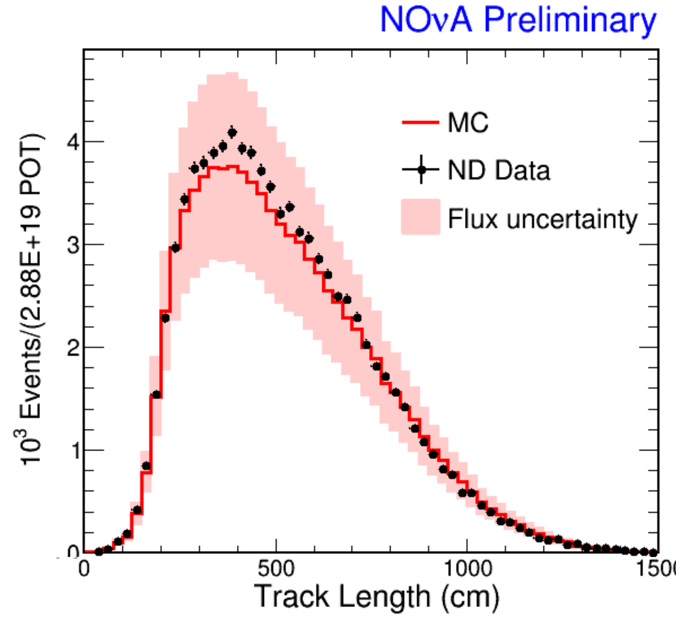


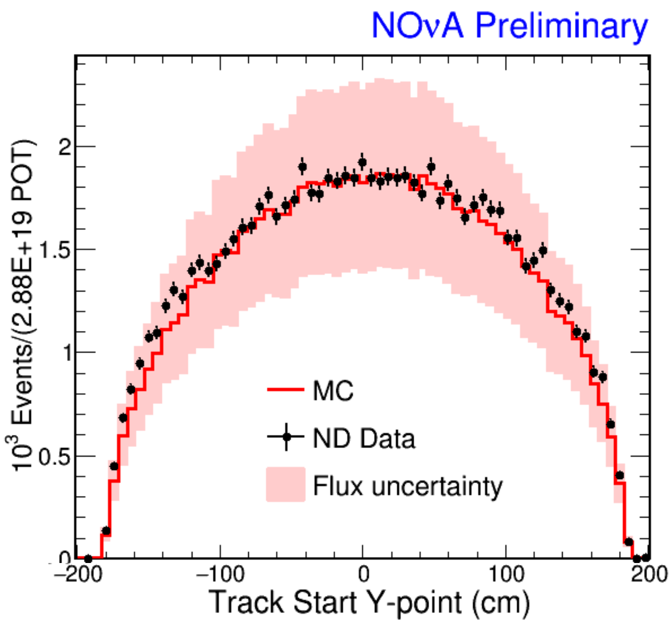
Events in the ND

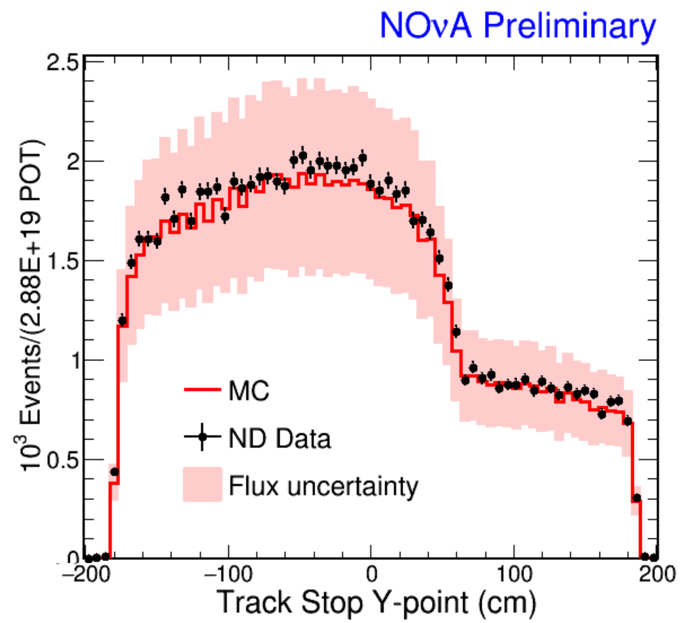
ν_μ CC events

assorted tracking variables









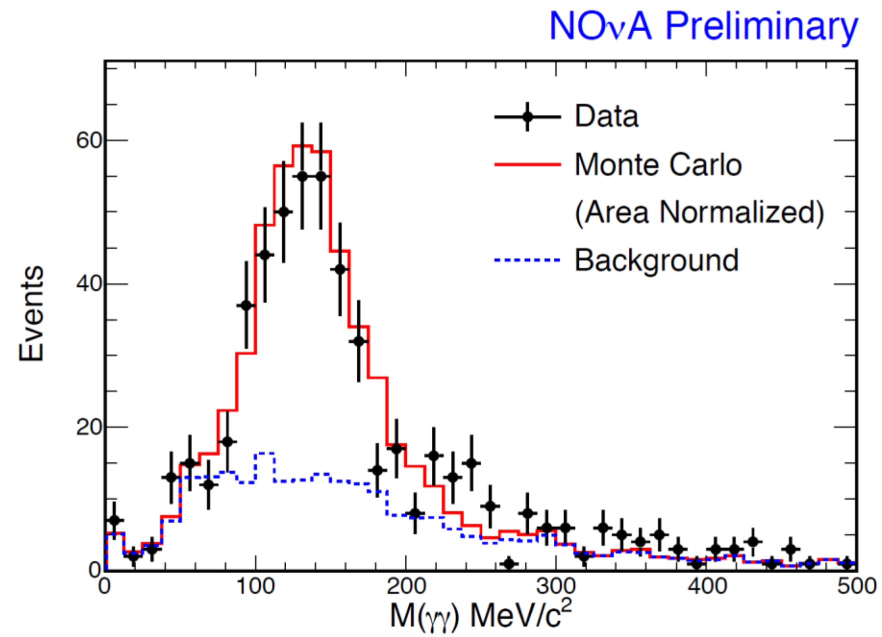
Events in the ND

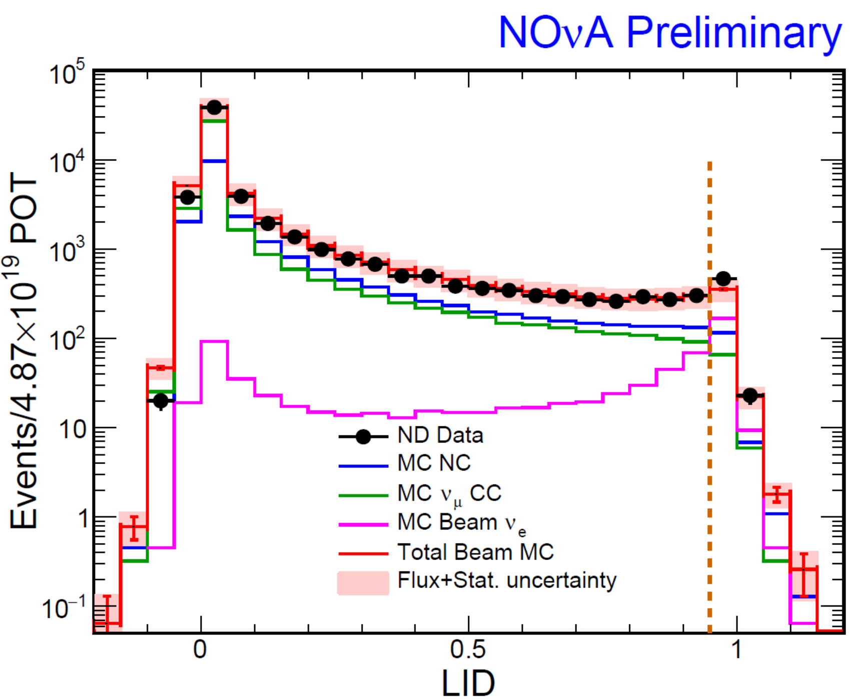
***Right:* π^0 sample**

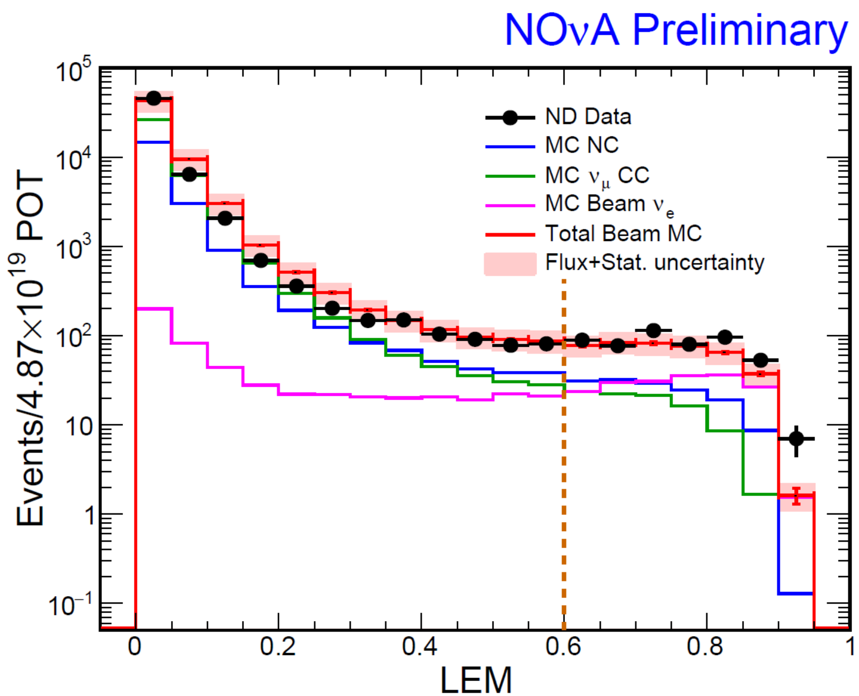
***Below:* two ν_e CC event classifiers**

LID: Shower reconstruction likelihoods

LEM: Library event matching



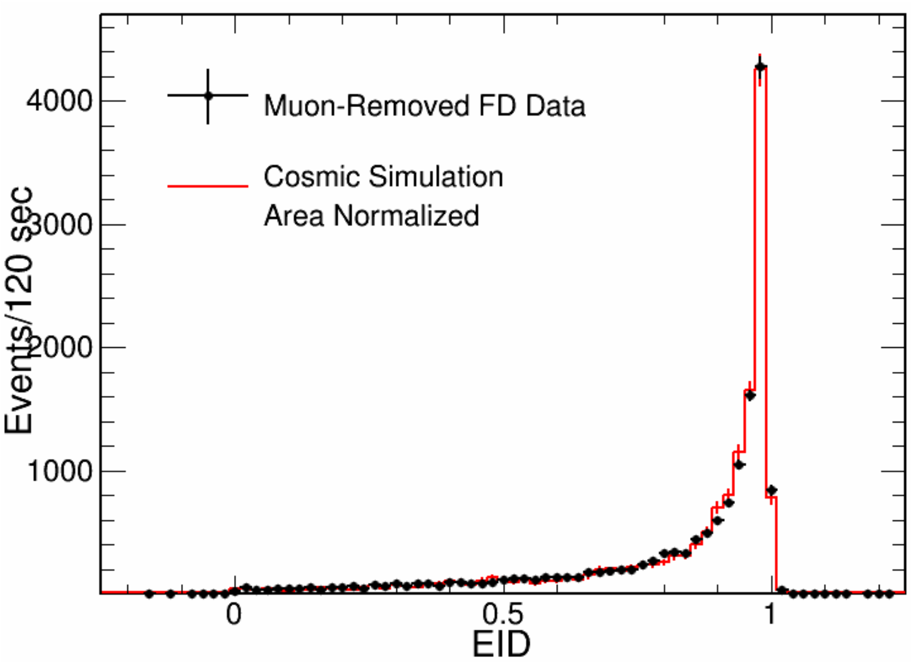


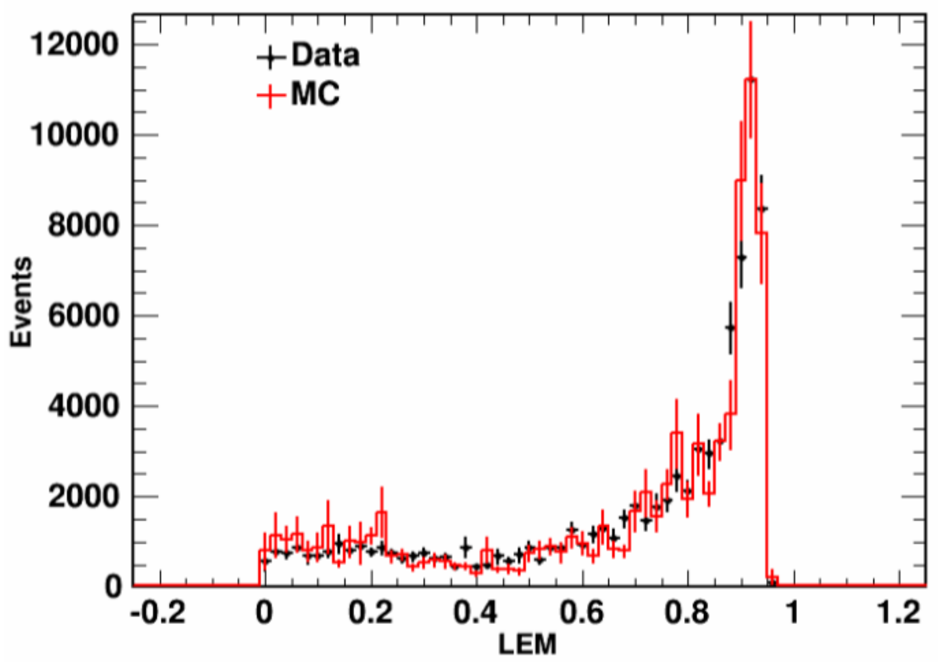


EM shower sample in the Far Detector

- As one 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 FD data EM showers and equivalent MC





Summary and Outlook

- **Taking physics data with full Near and Far Detectors!**
- Since final commissioning and outfitting, **operations have been smooth!**
- **420 kW NuMI power** now. Next major step after summer shutdown.
- **Surface operation:** cosmic ray rejection **demonstrated with FD data**
- **Calibration, reconstruction, particle ID, fitting tools** built
- **Current analysis frontiers:** *tuning of simulations and algorithms based on all this new data; assessment of systematic uncertainties; ramp-up of non-oscillation physics analysis; collecting protons-on-target!*
- **First oscillation results soon!**

  With small data set: only 5% of full planned exposure.