First oscillation results from NOνA

Ryan Patterson
Caltech

for the NOνA Collaboration

Joint Experimental-Theoretical Seminar, Fermilab
August 6, 2015

Long-baseline neutrino oscillations

ν_μ disappearance:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(\Delta m^2_{32} L/4E)$$

experimental data are **consistent with unity** ("maximal mixing")

...to leading order

➜ **Need a leap in precision on θ_{23} (and Δm^2_{32})**

ν_e appearance:

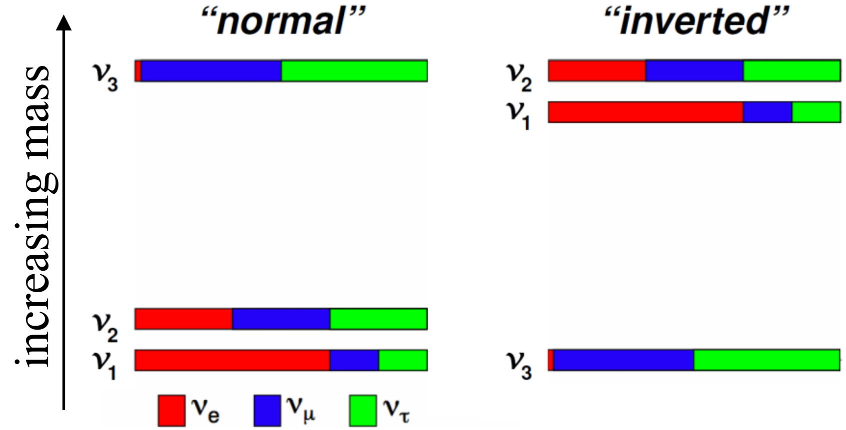
$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(\Delta m^2_{32} L/4E)$$

Daya Bay reactor experiment:
$\mathbf{\sin^2(2\theta_{13}) = 0.084 \pm 0.005}$

*...plus potentially large **CPv** and **matter effect** modifications!*

➜ **Non-zero θ_{13} opens the long-baseline appearance channel, and…**

$\theta_{13} > 0 \;\Rightarrow\; \nu_\mu \to \nu_e$



Makes feasible long-baseline measurements of…

neutrino mass hierarchy

via matter effects that modify $P(\nu_\mu \to \nu_e)$

Implications for: $0\nu\beta\beta$ data and Majorana nature of ν; approach to m_β; cosmology; astrophysics; theoretical frameworks for mass generation, quark/lepton unification; Is the lightest charged lepton associated with the heaviest light neutrino?

CP violation

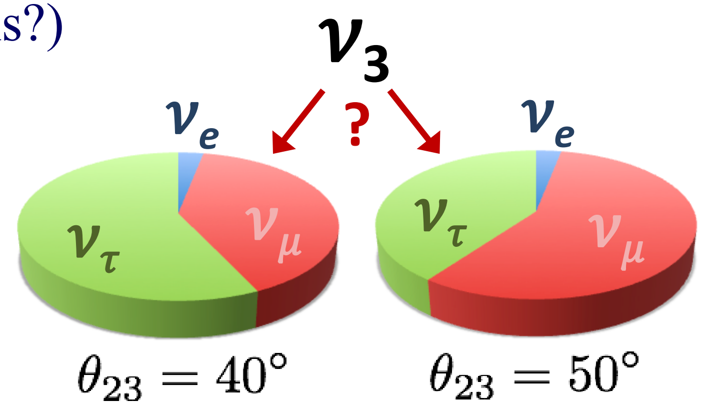
via dependence of $P(\nu_\mu \to \nu_e)$ on *CP* phase δ. Amplified by $\nu/\bar{\nu}$ comparisons.

baryon asymmetry through see-saw/leptogenesis; fundamental question in the Standard Model (is *CP* respected by leptons?)

ν_3 flavor mixing

via leading-order factor $\sin^2(\theta_{23})$

Is ν_3 more strongly coupled to μ or τ flavor?; frameworks for mass generation, unification



Long-baseline $\nu_\mu \rightarrow \nu_e$

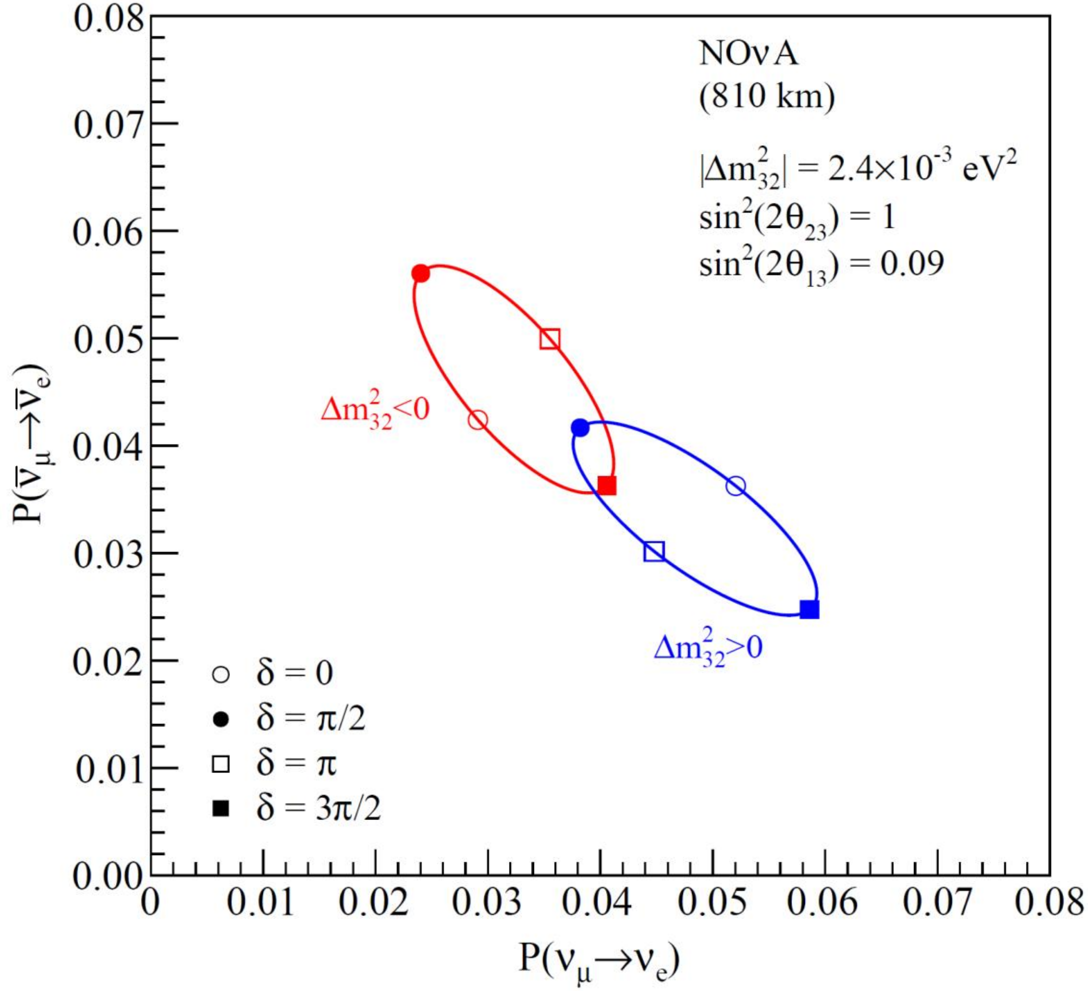
A more quantitative sketch…

At right:

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs. $P(\nu_\mu \rightarrow \nu_e)$

plotted for a single neutrino energy and baseline

For fixed L/E = 0.4 km/MeV



Long-baseline $\nu_\mu \rightarrow \nu_e$

A more quantitative sketch…

At right:

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs. $P(\nu_\mu \rightarrow \nu_e)$

plotted for a single neutrino energy and baseline

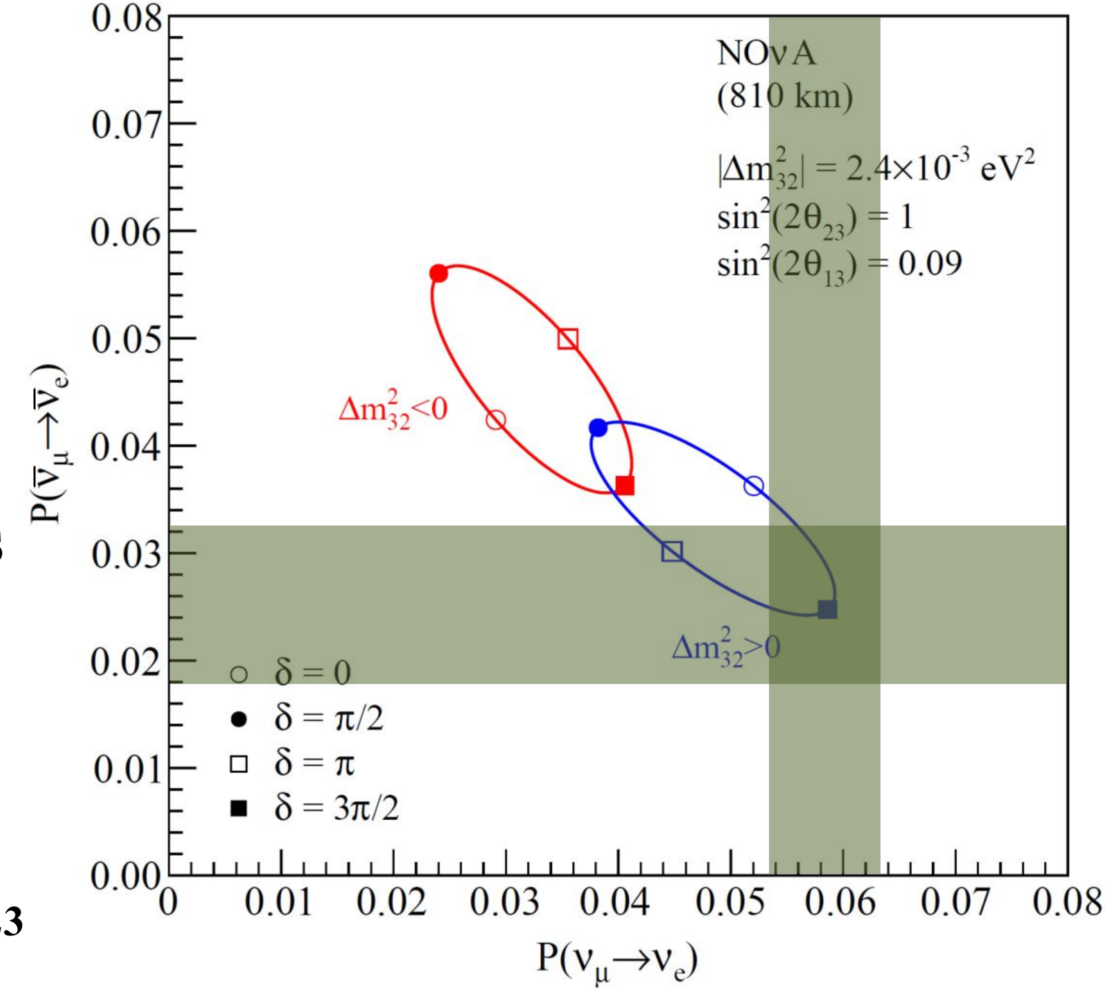
Measure these probabilities

(an example measurement of each shown)

Also:

Both probabilities $\propto \sin^2\theta_{23}$

For fixed L/E = 0.4 km/MeV



NOνA

A broad physics scope

Using $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ …

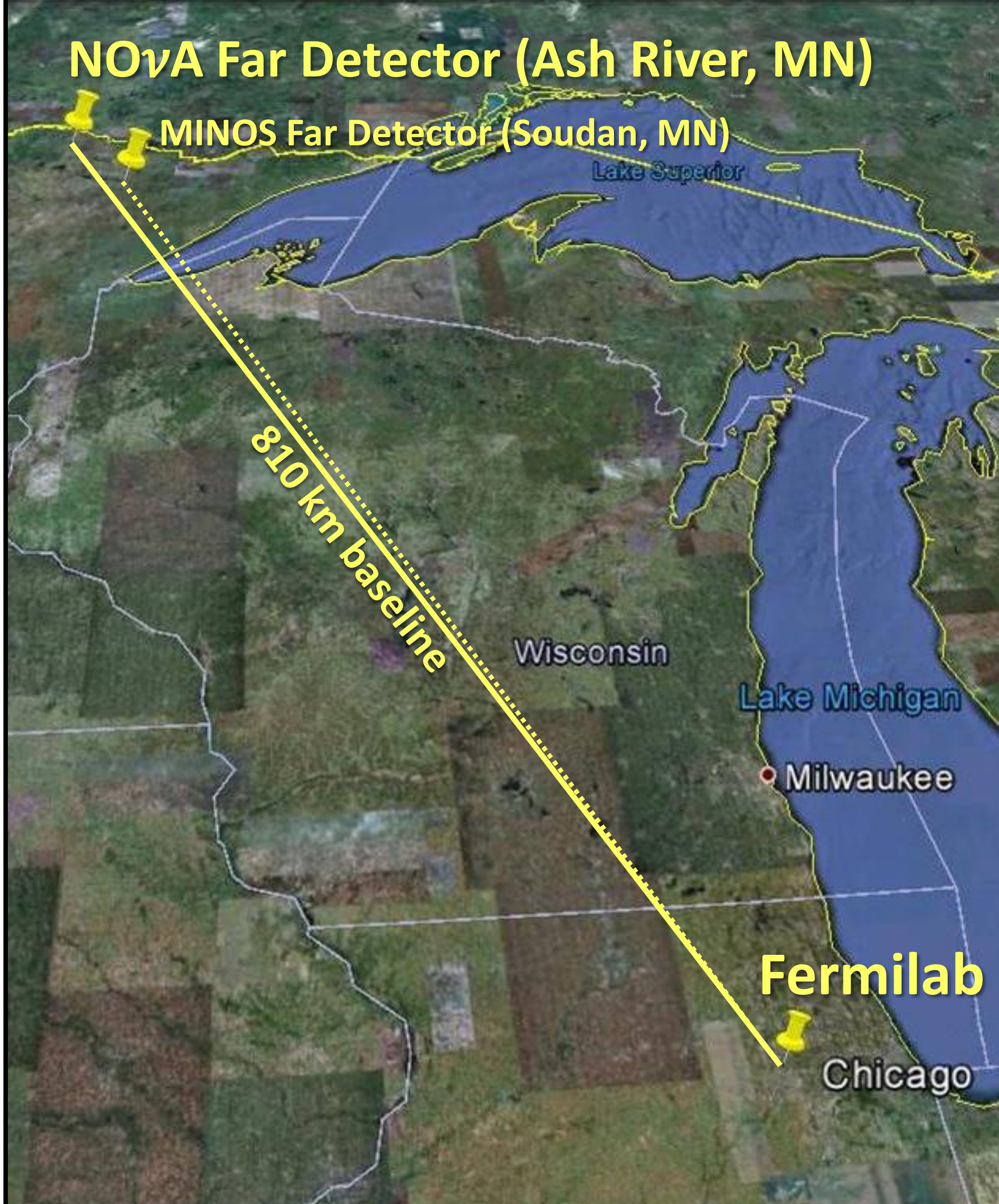
- Determine the **ν mass hierarchy**
- Determine the **θ_{23} octant**
- Constrain **δ_{CP}**

Using $\nu_\mu \rightarrow \nu_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ …

- Precision measurements of **$\sin^2 2\theta_{23}$** and **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

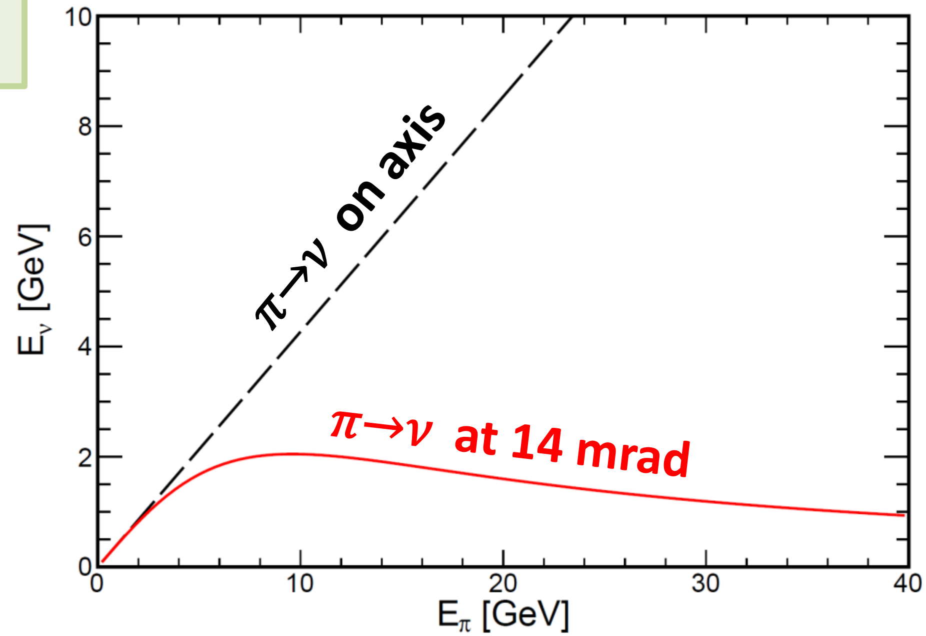


NuMI off-axis beam

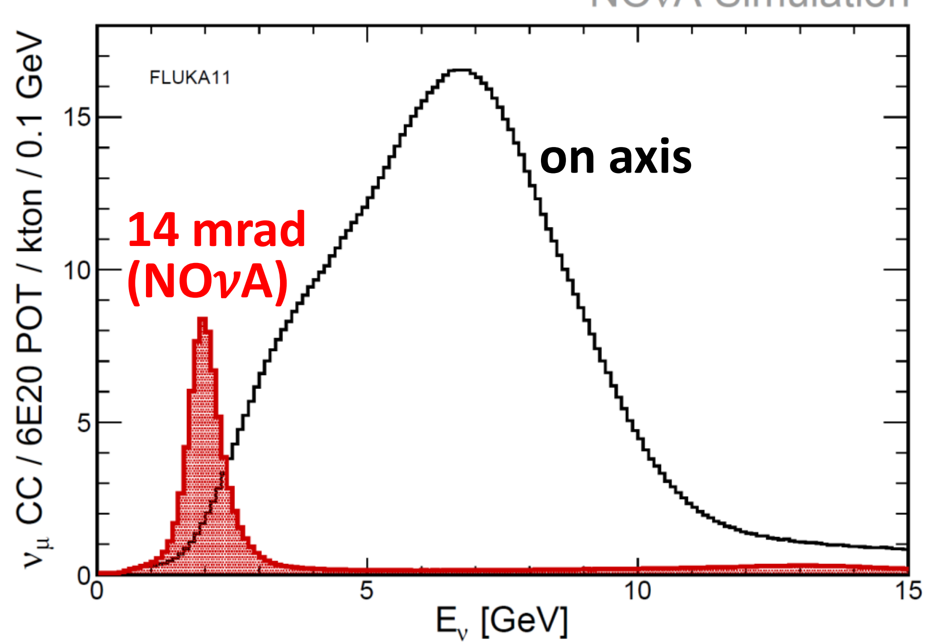
NOνA detectors are sited **14 mrad** off the NuMI beam axis

With the **medium-energy NuMI** tune, yields a narrow 2-GeV spectrum at the NOνA detectors

→ **Reduces NC and ν_e CC backgrounds** in the oscillation analyses while maintaining **high ν_μ flux at 2 GeV.**



NOνA Simulation



Fermilab Neutrino Complex

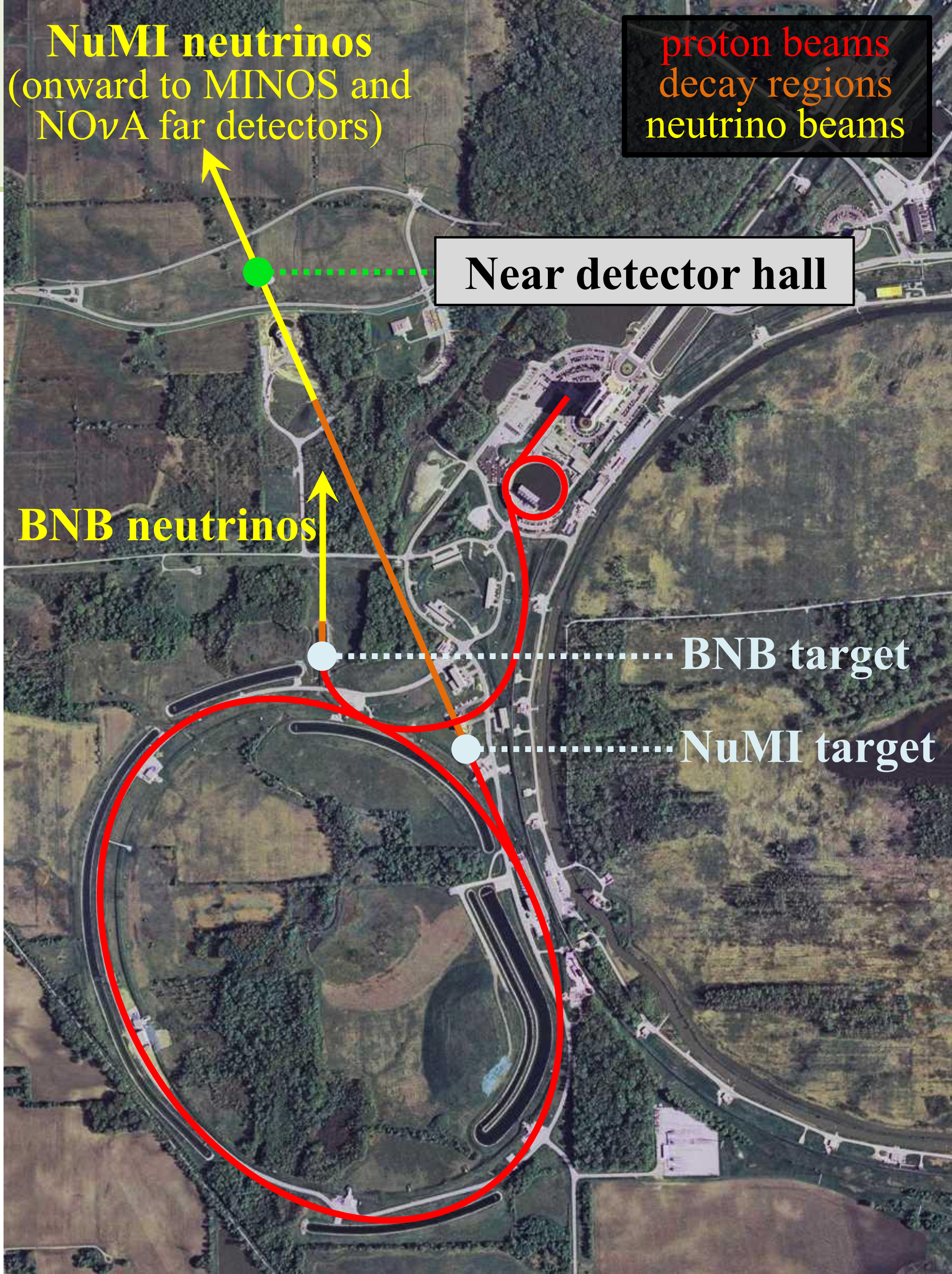
NuMI =
Neutrinos from the Main Injector

Long shutdown in 2012–2013

- Repurpose recycler for injection
- Add associated kickers and instrumentation
- RF, power supply upgrades
- Overhaul of NuMI target station

→ **Major upgrades toward 700 kW operation**

Since March 2015:
Routine slip-stacking (2+6 batches) into recycler, typically ~420 kW
→ **Beam power record: 521 kW!**
→ **85% uptime!**



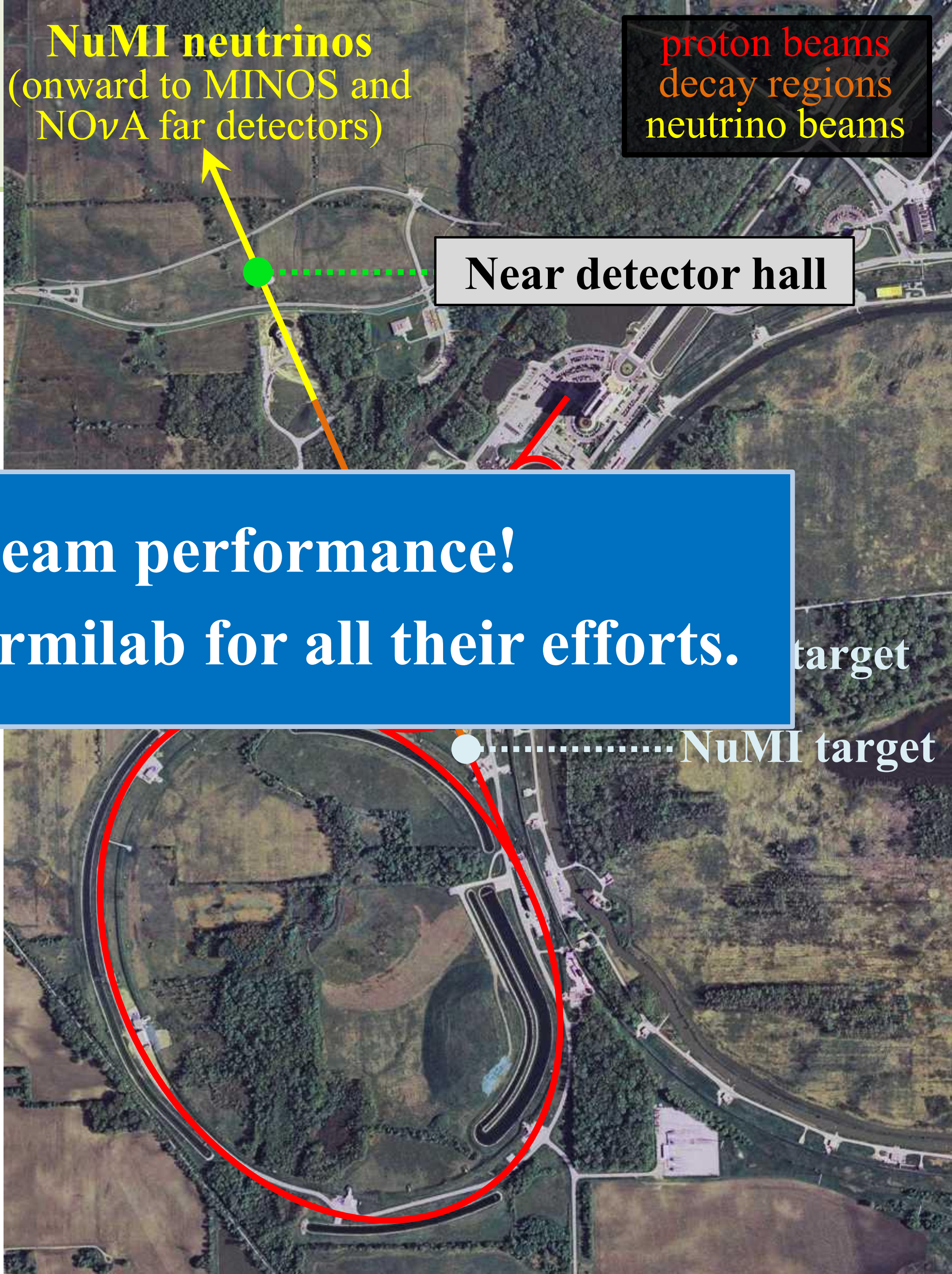
Fermilab Neutrino Complex

NuMI =
Neutrinos from the Main Injector

Long sh

- Repu
- Add
  ins
- RF, p
- Overhaul of NuMI target station
  → **Major upgrades toward 700 kW operation**

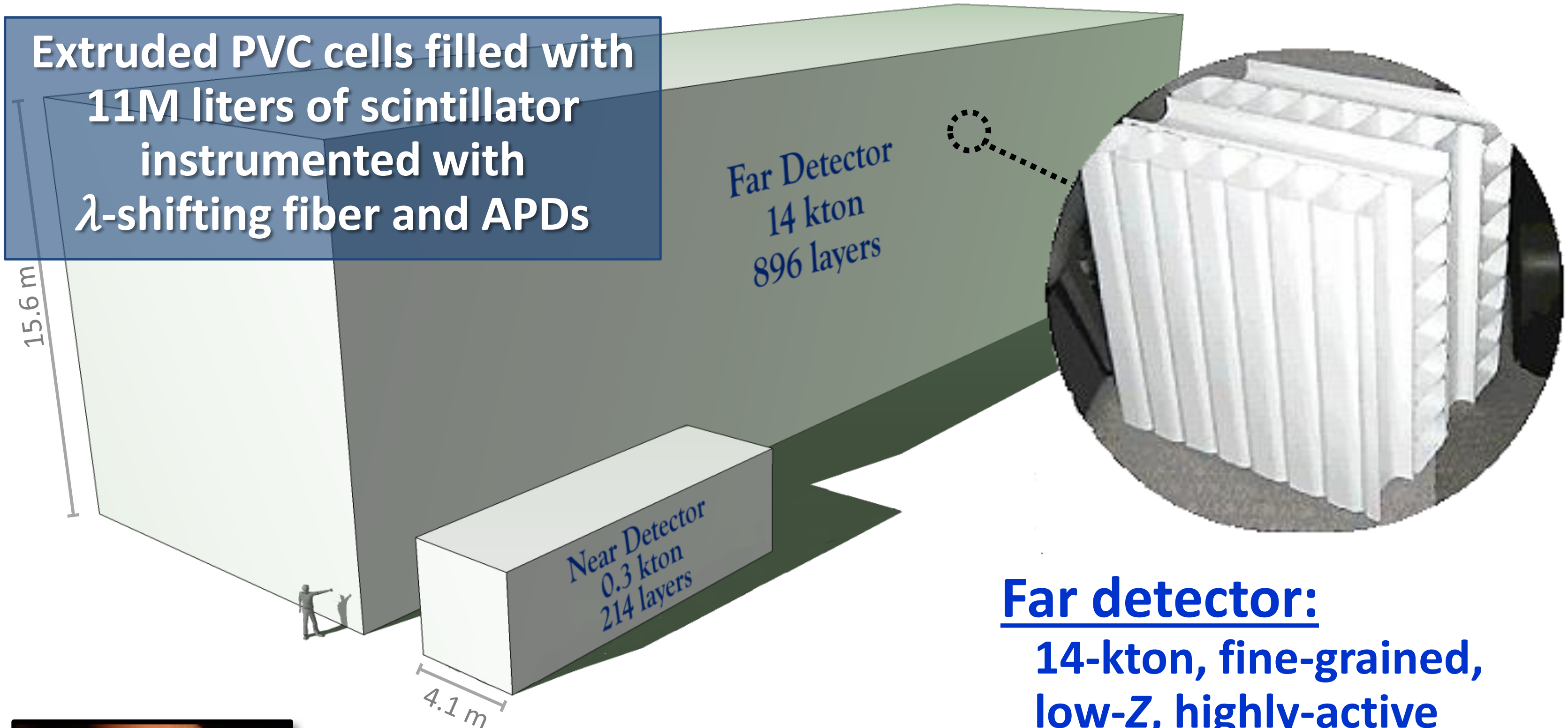
Since March 2015:
Routine slip-stacking (2+6 batches) into recycler, typically ~420 kW
→ **Beam power record: 521 kW!**
→ **85% uptime!**



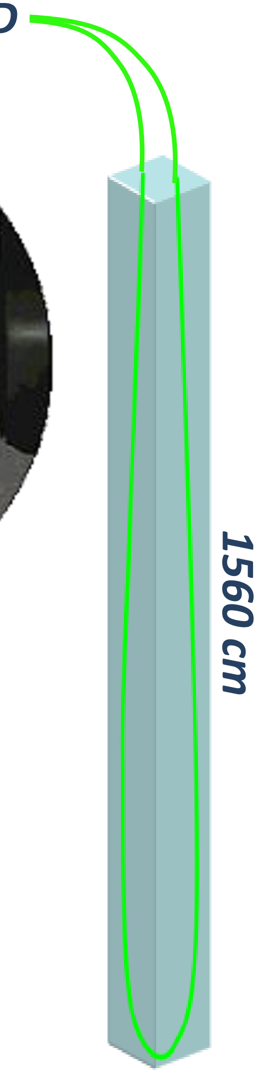
Fantastic beam performance!
Many thanks to Fermilab for all their efforts.

NOνA detectors

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



A NOνA cell

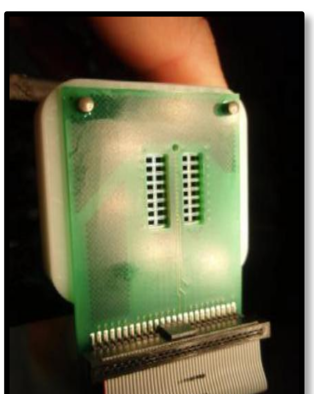


Far detector:

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

Near detector:

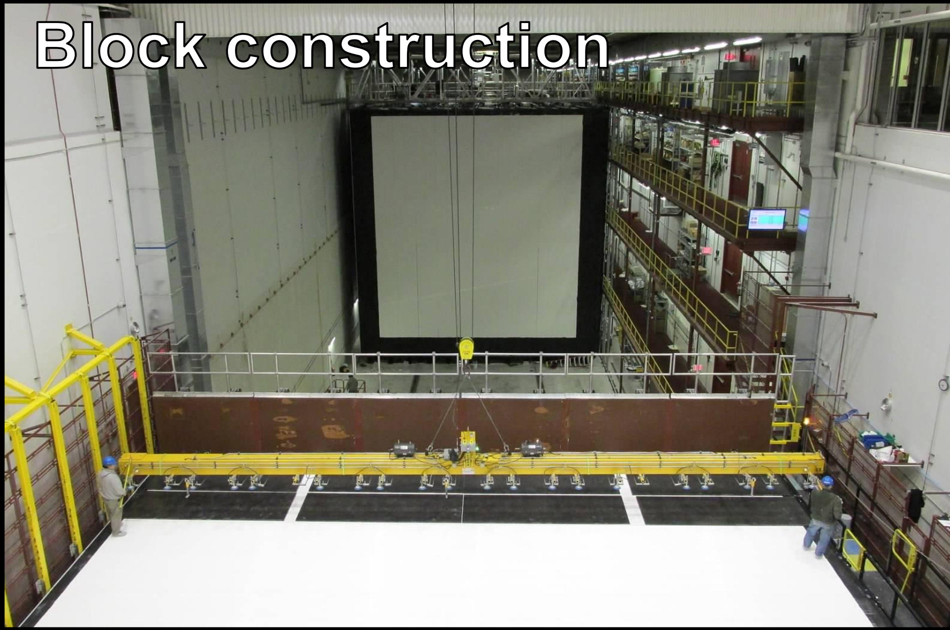
0.3-kton version of the same
→ ***20,000 channels***



32-pixel APD ←

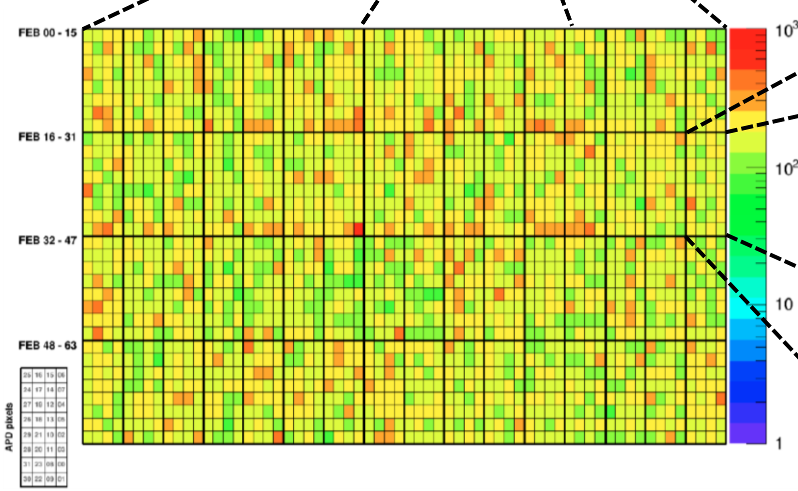
Fiber pairs from 32 cells →

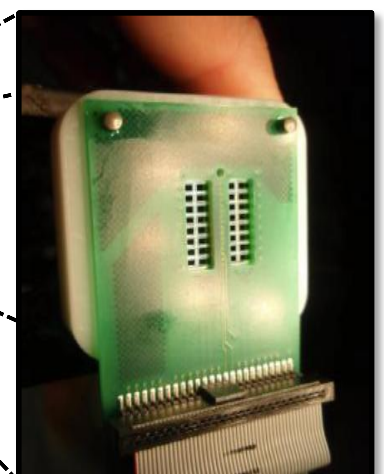

Far Detector site


Block construction


Outfitted Far Detector


Near Detector

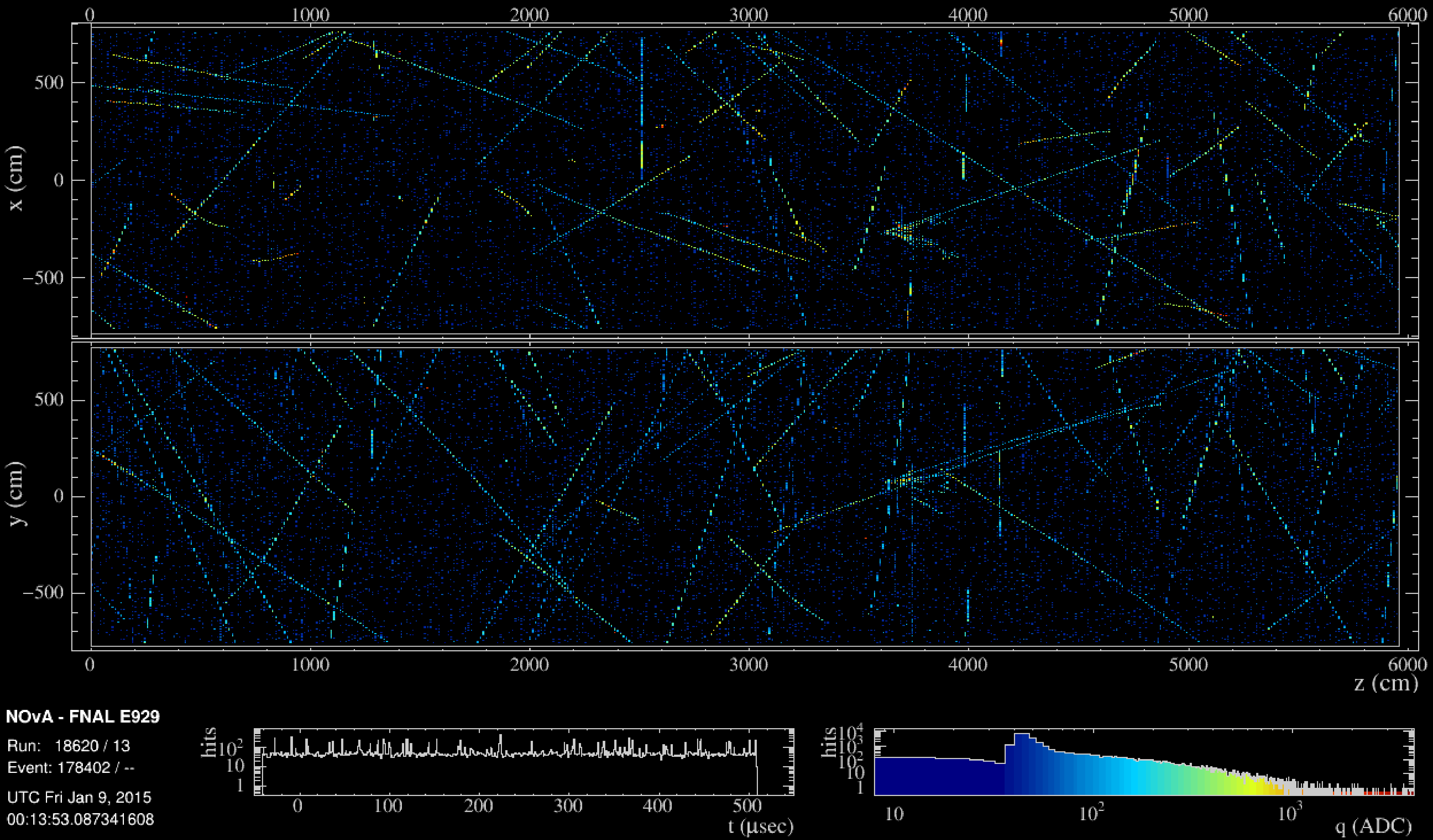




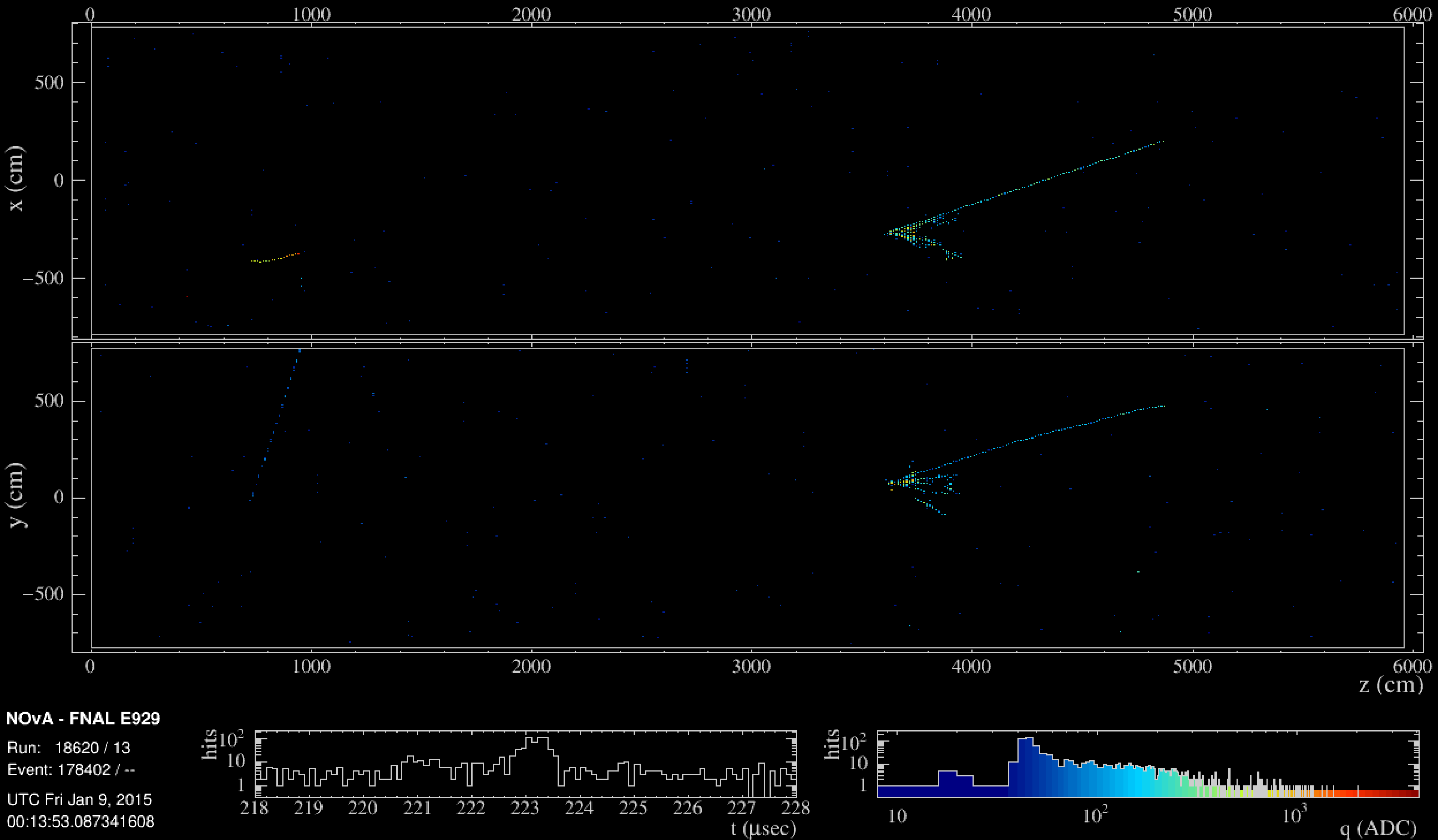
344,064 channels!

99.5% operational

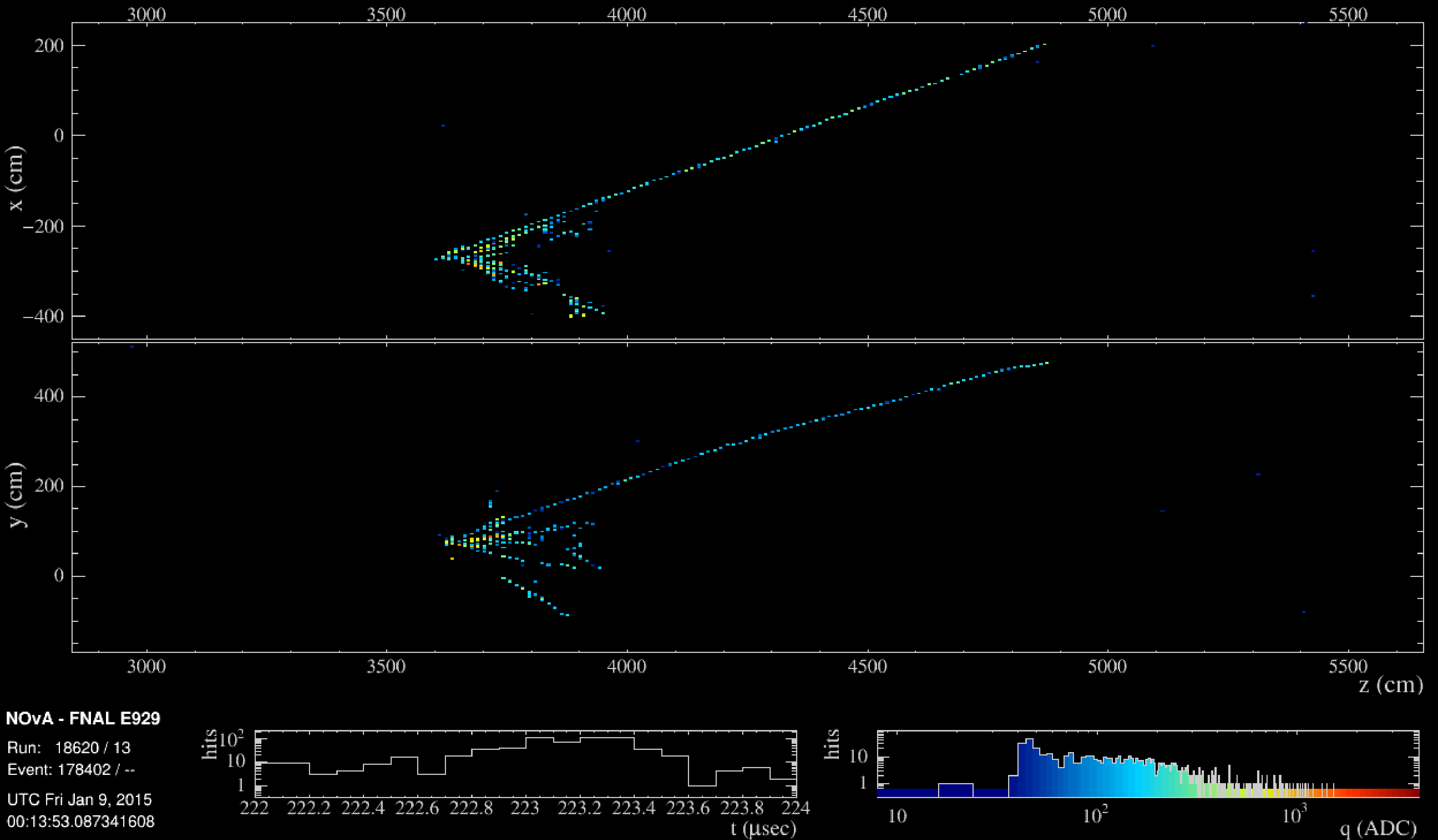
550 μs exposure of the Far Detector



Time-zoom on 10 μs interval during NuMI beam pulse

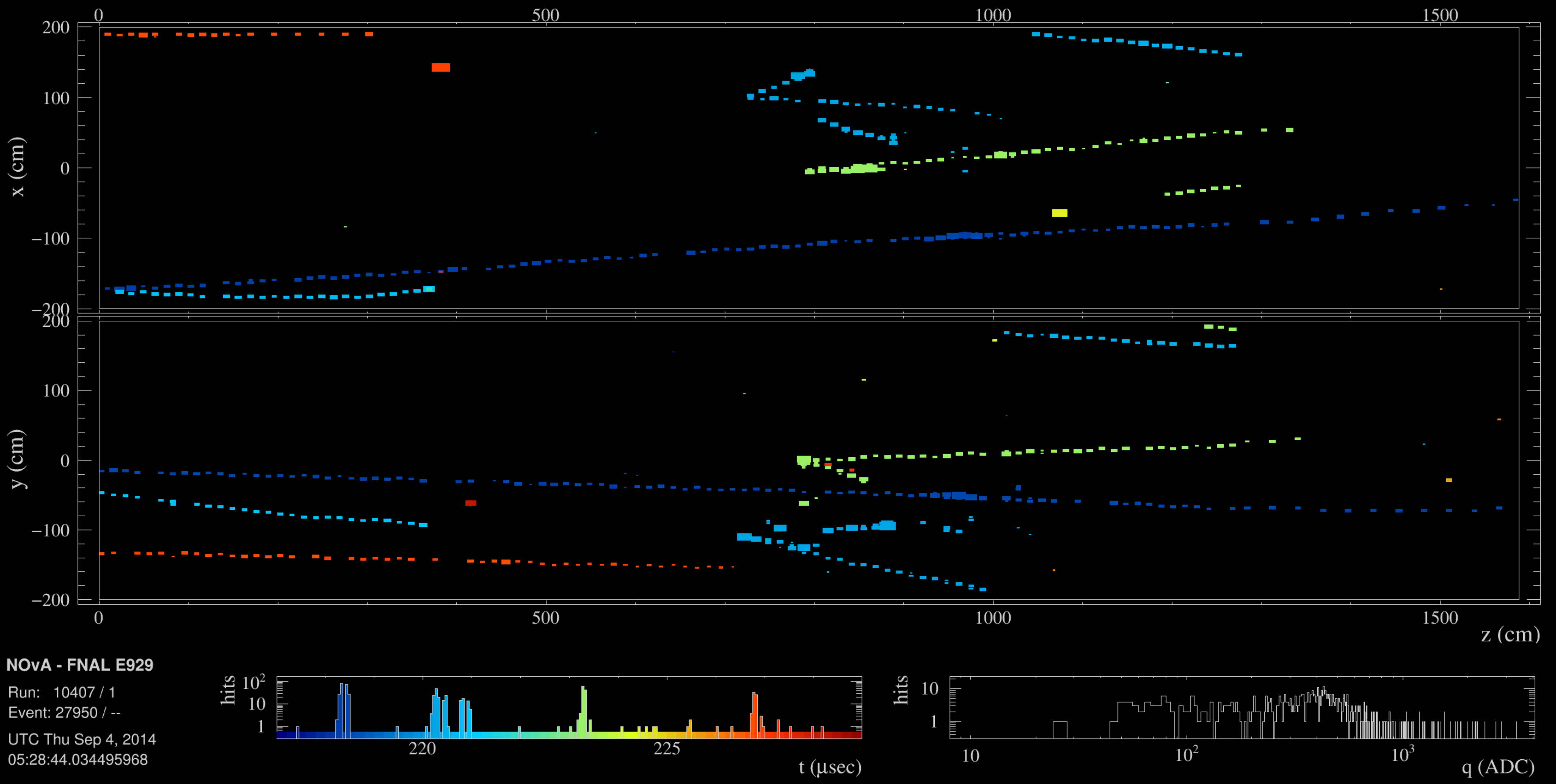


Close-up of neutrino interaction in the Far Detector



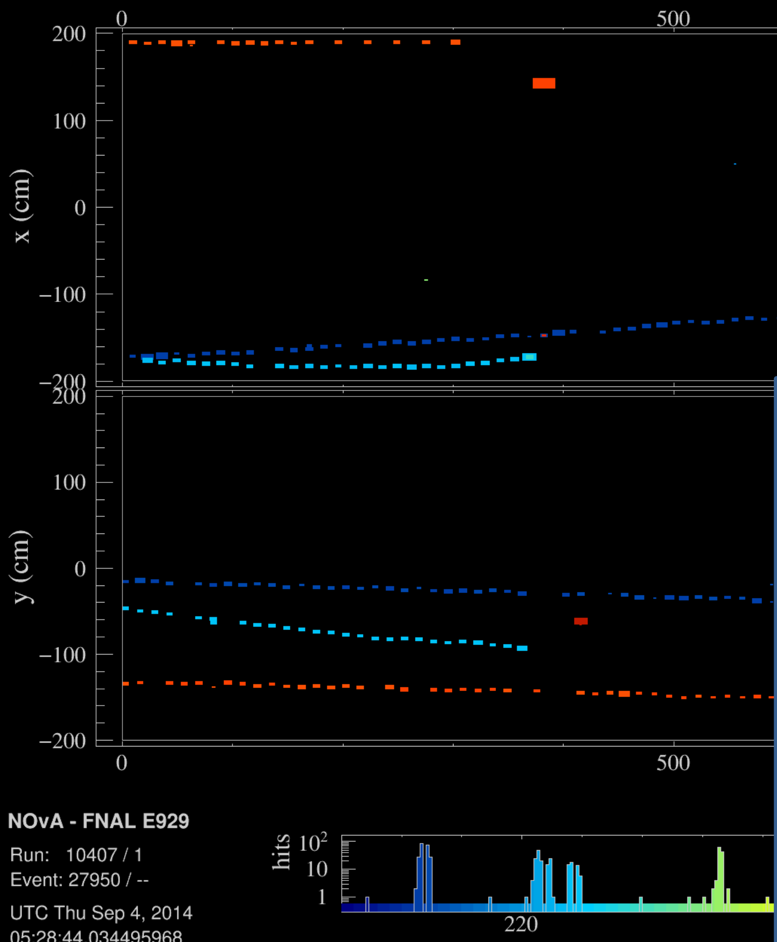
Near Detector: 10 μs of readout during NuMI beam pulse

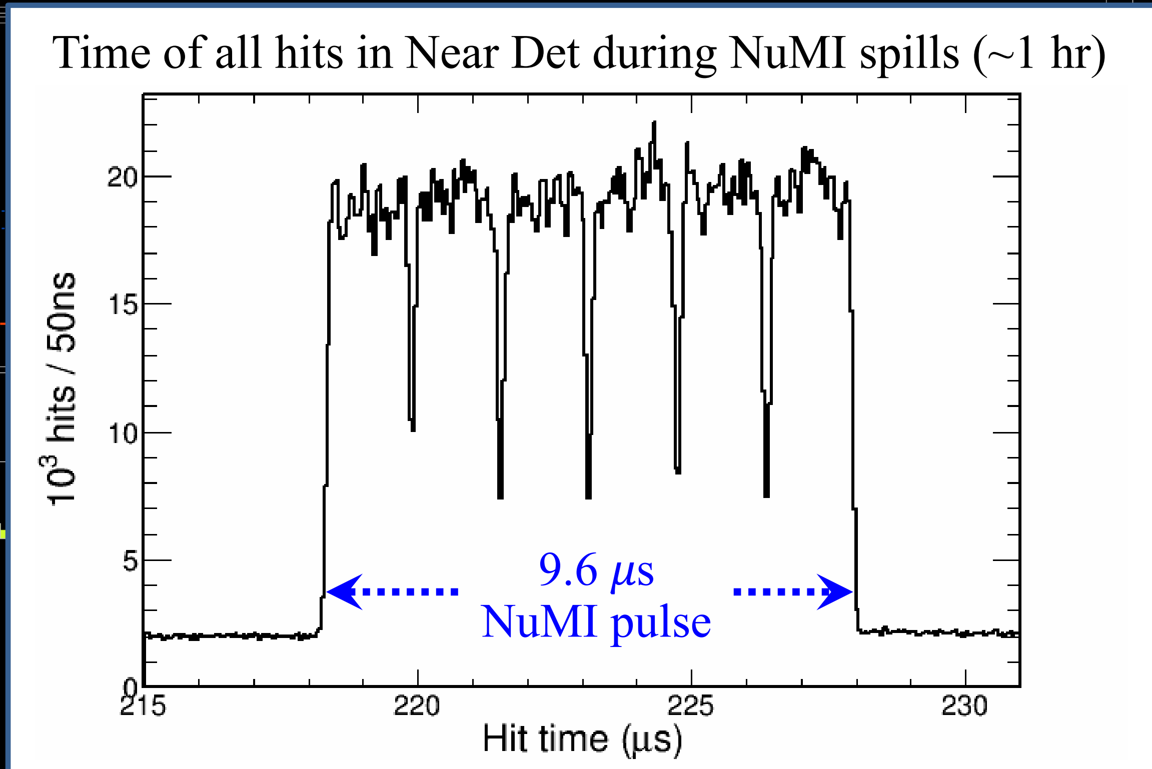
(color ⇒ time of hit)



Near Detector: 10 μs of readout during NuMI beam pulse

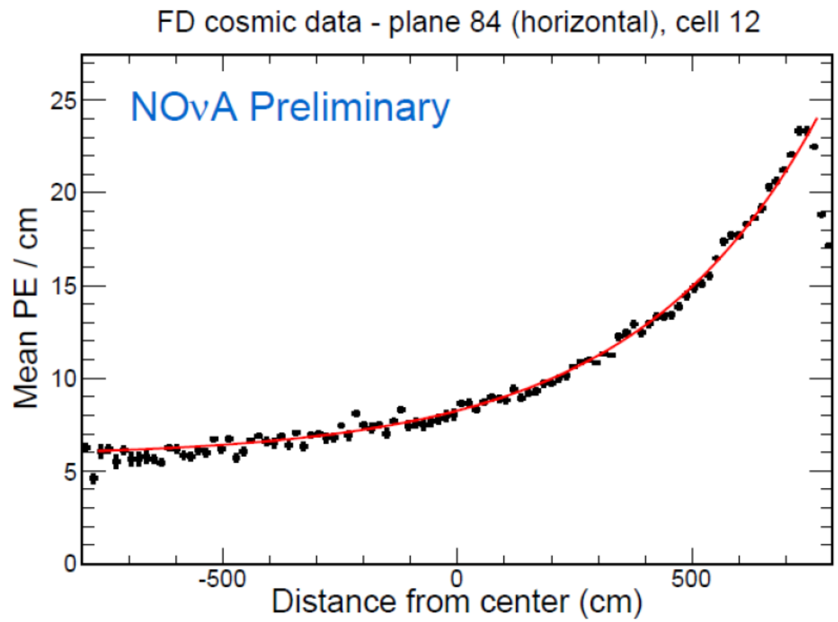
(color ⇒ time of hit)

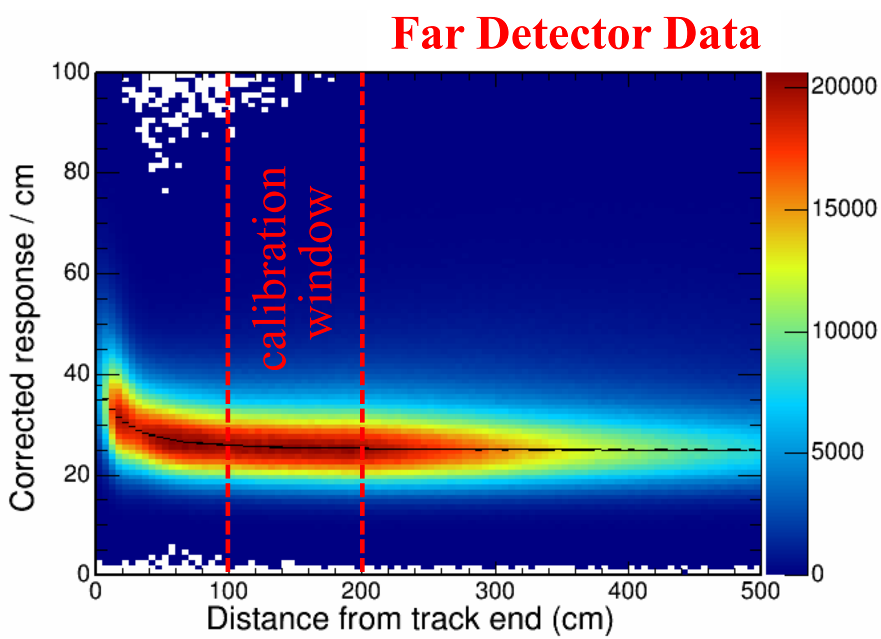


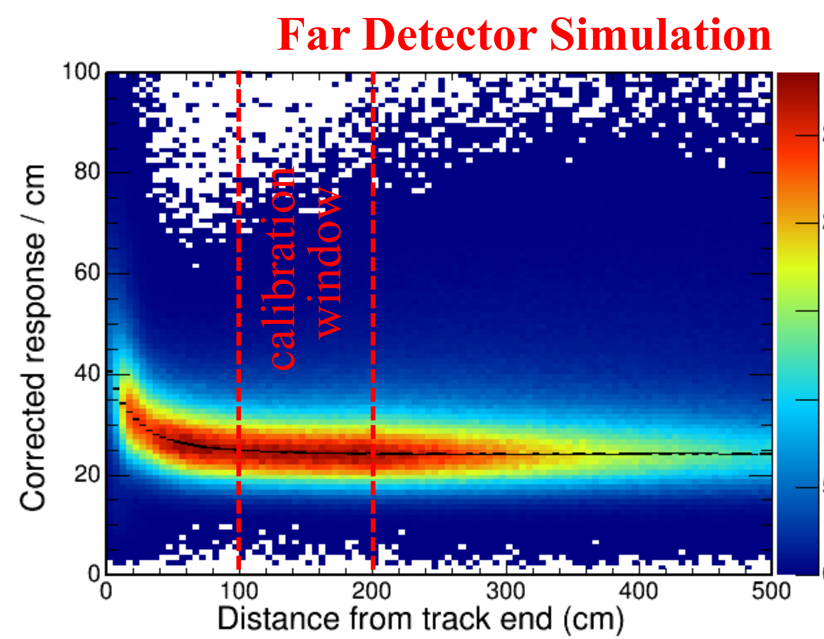


Calibration

- **Biggest effect** that needs correction is **attenuation** in the WLS fiber
  Example FD cell ⟶
- **Stopping muons** provide a standard candle for setting absolute energy scale *(below)*



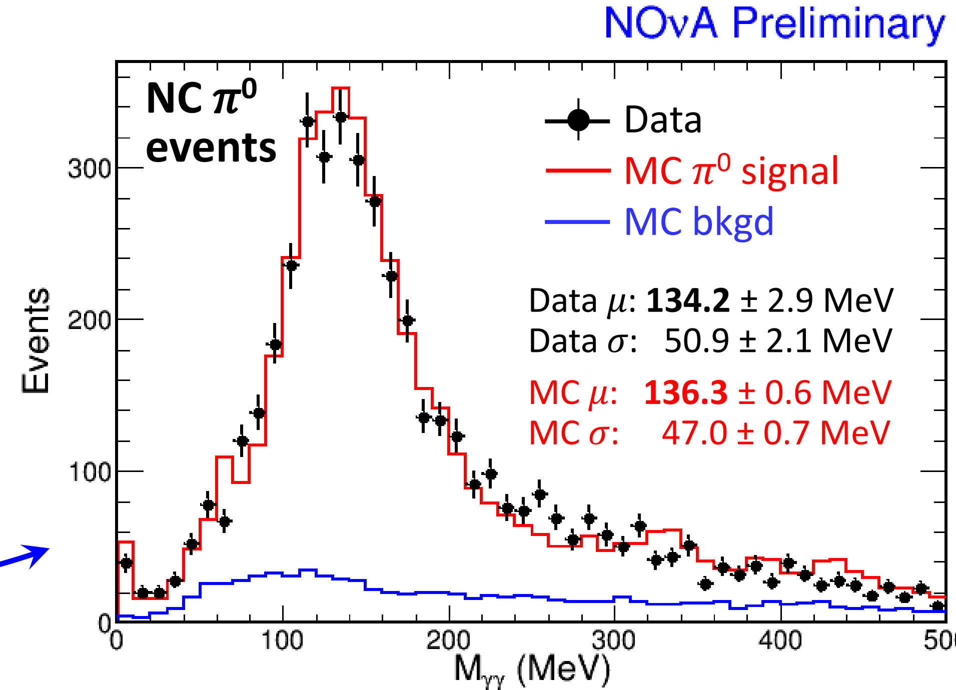


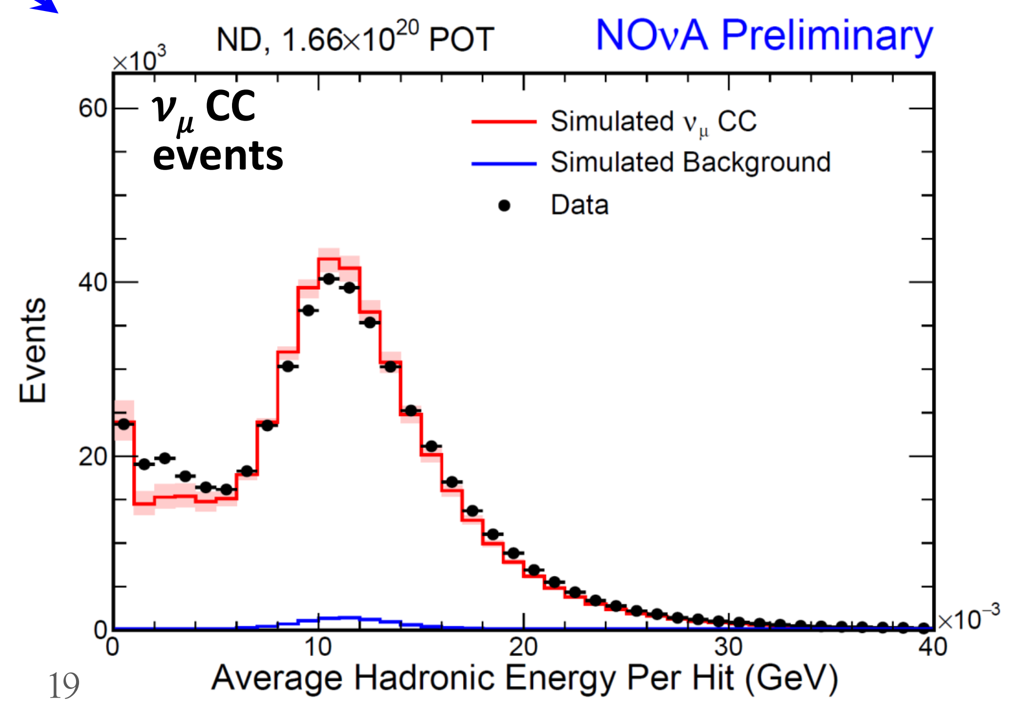


Multiple probes of energy scale

In Near Detector

- cosmic μ dE/dx [~vertical]
- beam μ dE/dx [~horizontal]
- Michel e^- spectrum
- π^0 mass
- hadronic shower E-per-hit





In Far Detector

- cosmic μ dE/dx [~vertical]
- beam μ dE/dx [~horizontal]
- Michel e^- spectrum

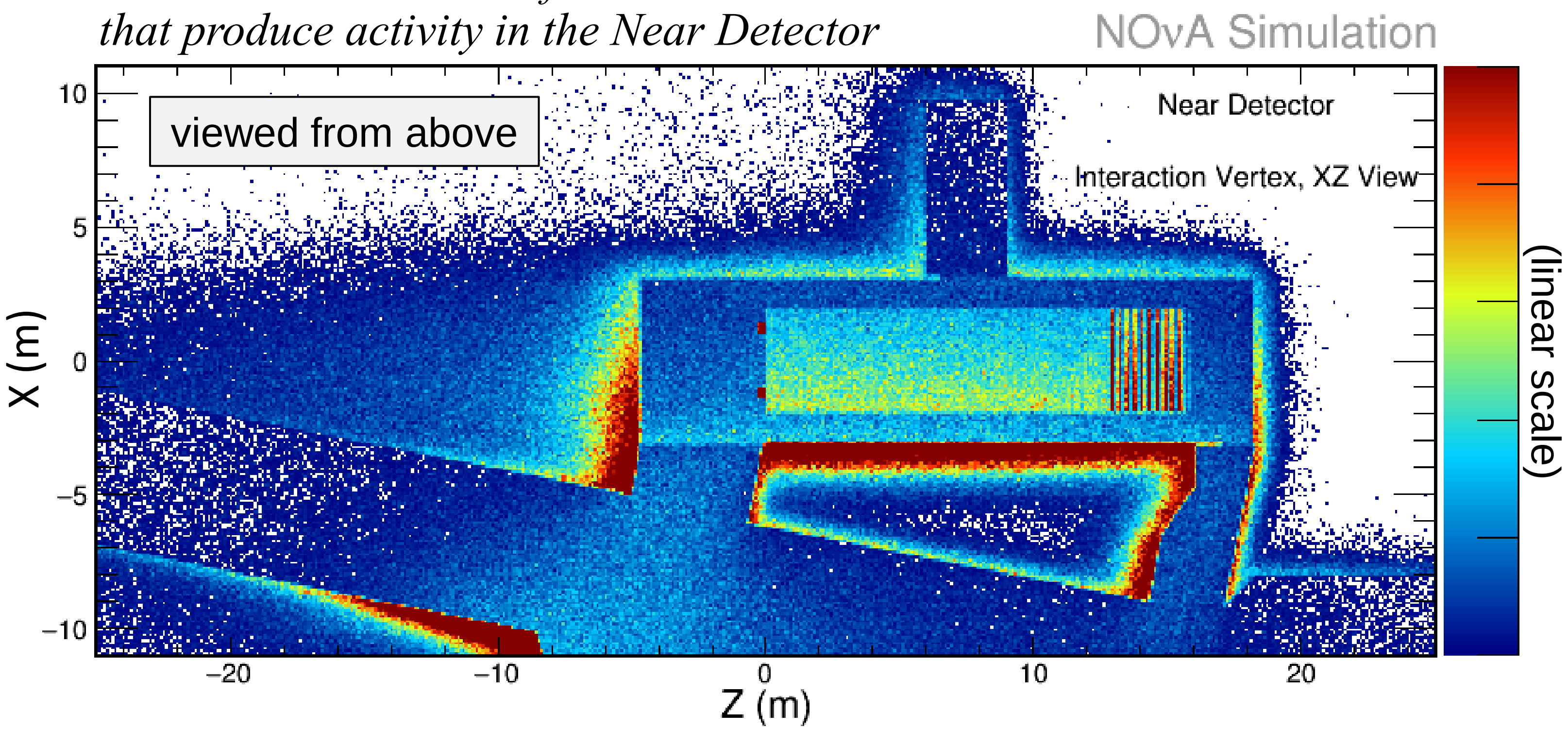
All agree within ±5%

Simulation

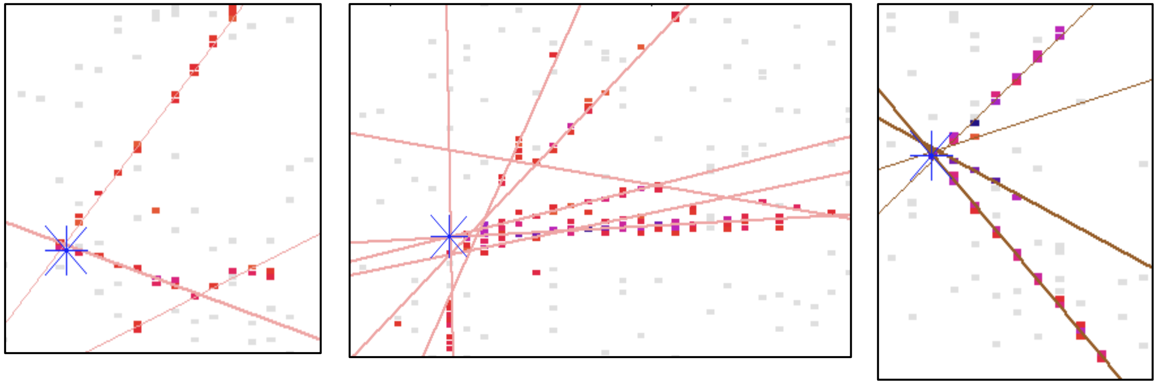
Highly detailed end-to-end simulation chain

- Beam hadron production, propagation; neutrino flux: **FLUKA/FLUGG**
- Cosmic ray flux: **CRY**
- Neutrino interactions and FSI modeling: **GENIE**
- Detector simulation: **GEANT4**
- Readout electronics and DAQ: **Custom simulation routines**

Simulation: Locations of neutrino interactions that produce activity in the Near Detector

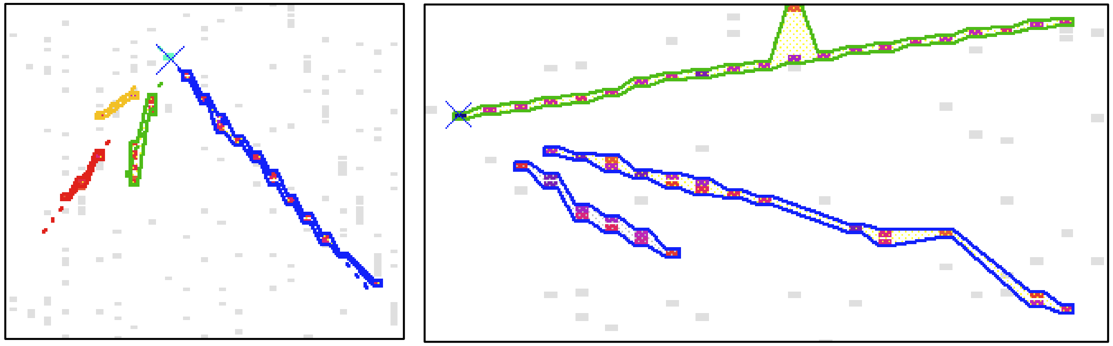


Reconstruction



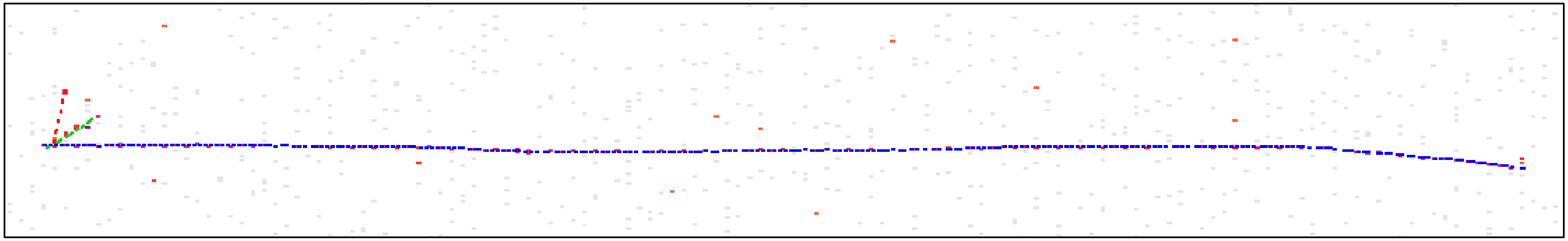
Vertexing: Find **lines of energy depositions** w/ Hough transform

CC events: 11 cm resolution



Clustering: Find **clusters in angular space** around vertex. **Merge views** via topology and prong *dE*/*dx*

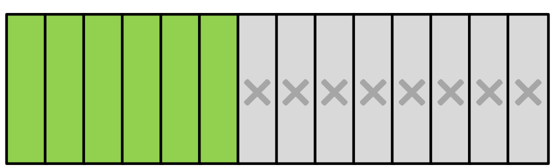
Tracking: Trace particle trajectories with **Kalman filter** tracker (below). Also have a **cosmic ray tracker**: lightweight, very fast, and useful for large calibration samples and online monitoring tools.



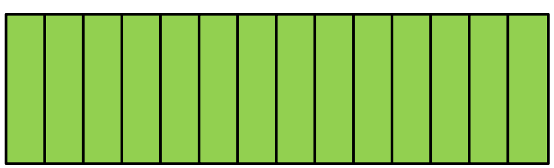
Far Detector data set

- During the construction era, we **began collecting physics data** with each Far Detector "diblock" (64 detector planes) as soon as it was **fully commissioned and physics-ready**
- Thus, FD size is **not static** throughout our data set

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**



Partial Far Detector during construction
(6 diblock example)



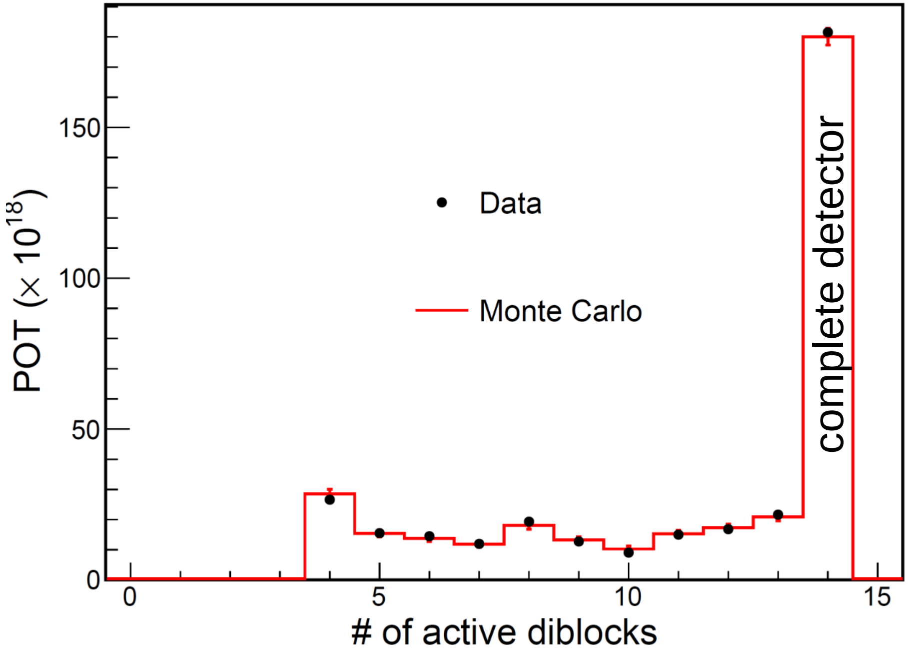
Full Far Detector
(14 diblocks)

Far Detector data set

- During the construction era, we **began collecting physics data** with each Far Detector "diblock" (64 detector planes) as soon as it was **fully commissioned and physics-ready**
- Thus, FD size is **not static** throughout our data set

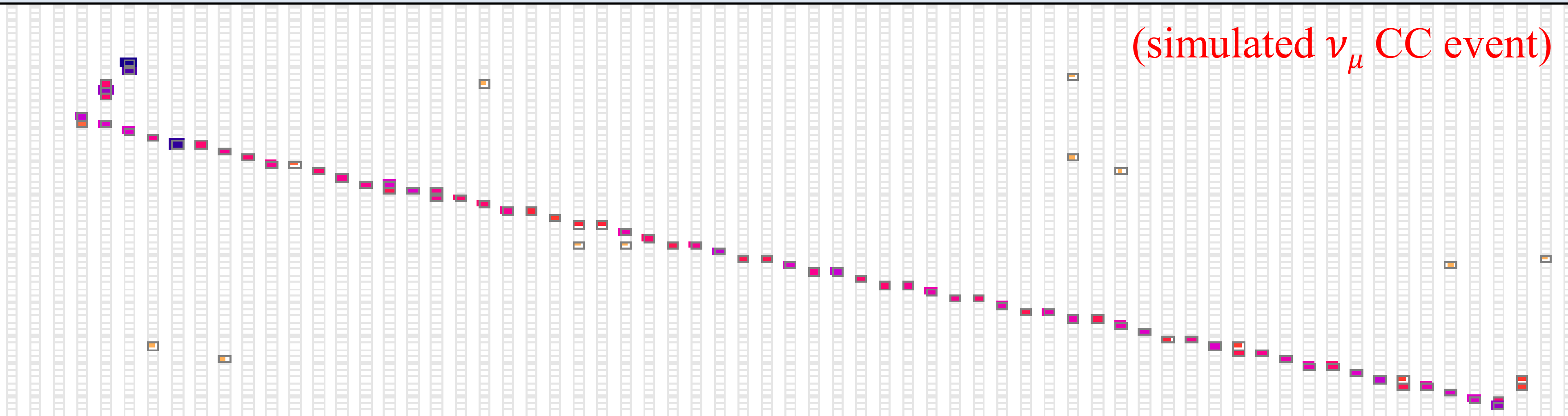
Protons-on-target in data set:	3.45×10^{20} POT
Fraction of detector operational:	79.4% (POT-weighted average)
Full-detector-equivalent exposure:	**2.74×10^{20} POT-equiv**

- *Aside:* We simulate the full suite of FD configurations in our analyses



ν_μ disappearance

- Identify **contained ν_μ CC events** in each detector
- Measure their **energies**
- Extract oscillation information from differences between the **Far and Near energy spectra**



ν_μ CC selection

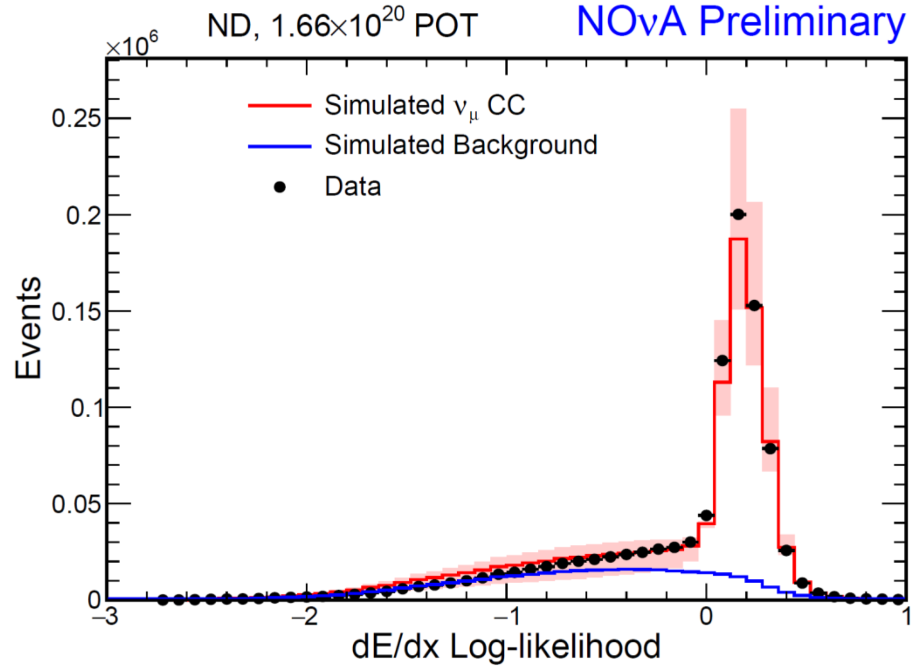
First, basic containment cuts require a buffer of no cell activity around the event. Then…

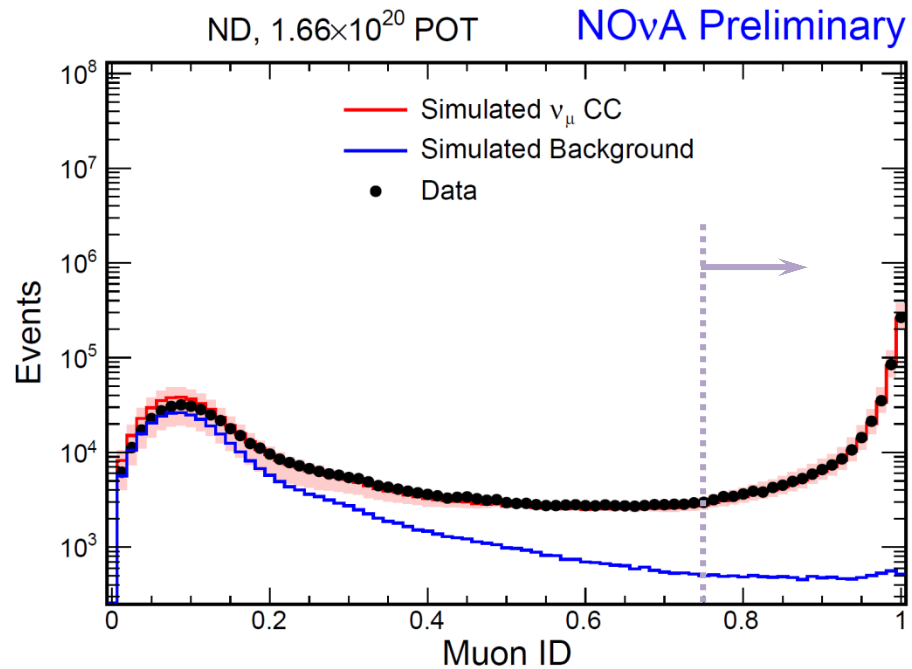
<u>Muon ID</u>
4-variable ***k*-nearest-neighbors** algorithm used to identify muons.

Inputs:

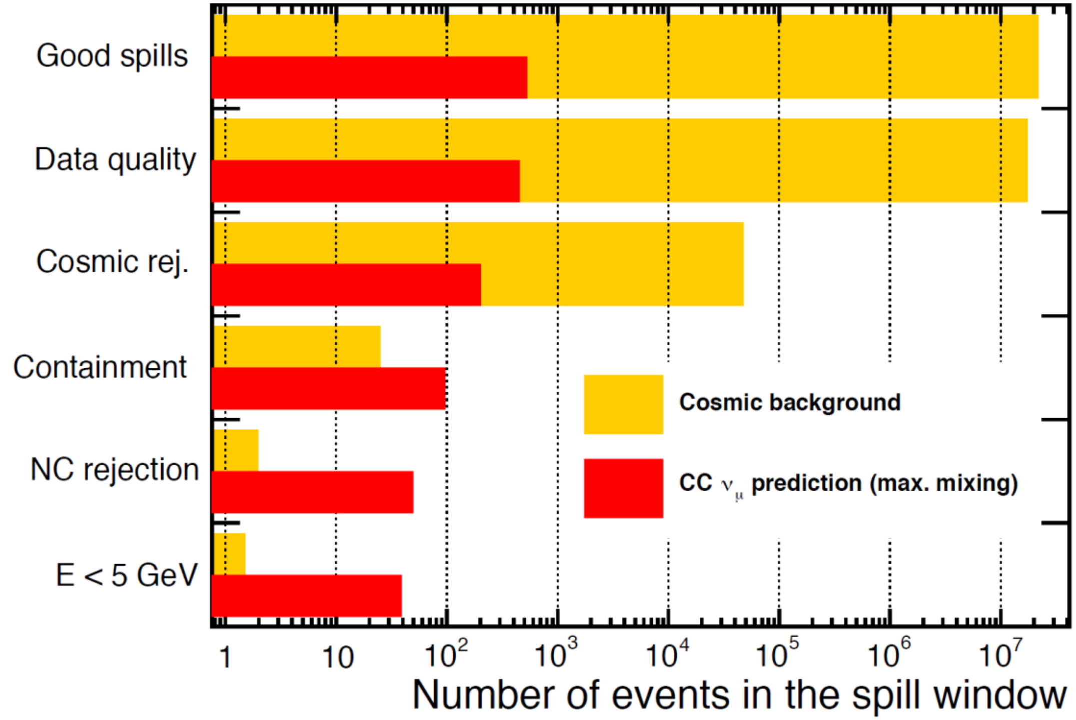
- track length
- *dE*/*dx* along track
- scattering along track
- track-only plane fraction

Keep events with μ ID > 0.75





Cosmic rejection

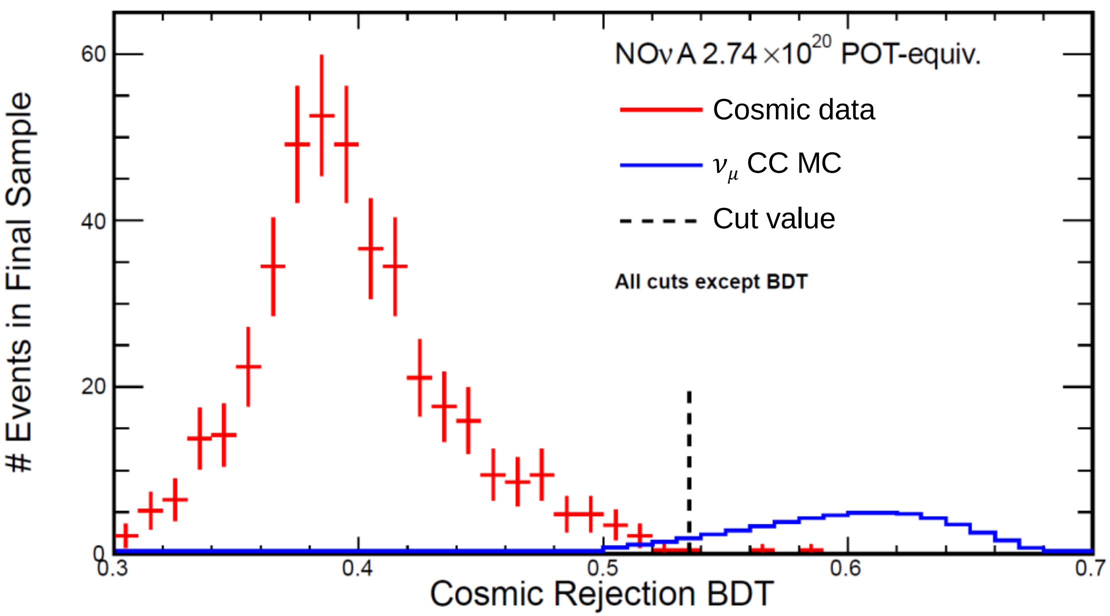


Rejection factor from

beam timing: **10^5**

event topology: **10^7 (!)**

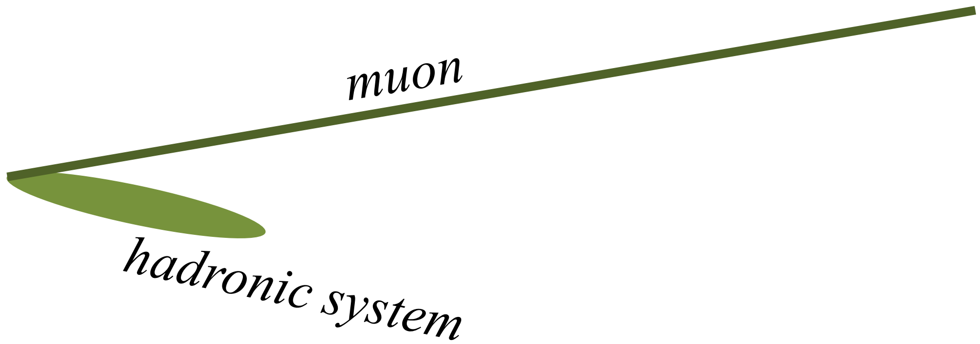
Final cosmic bkgnd rate **measured directly** with beam-off FD data.



← Output of **cosmic rejection decision tree** after all other cuts

Based on reconstructed track direction, position, and length; and energy and number of hits in event

Energy estimation



Reconstructed muon track:

length $\Rightarrow E_\mu$

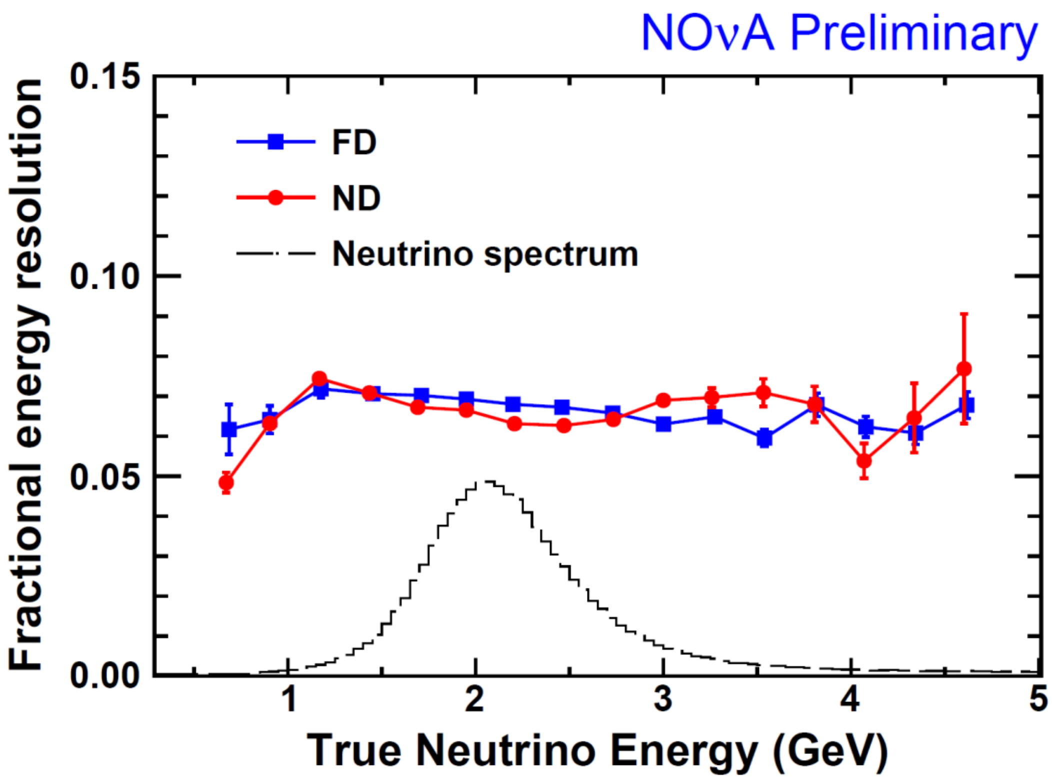
Hadronic system:

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

Reconstructed ν_μ energy is the sum of these two:

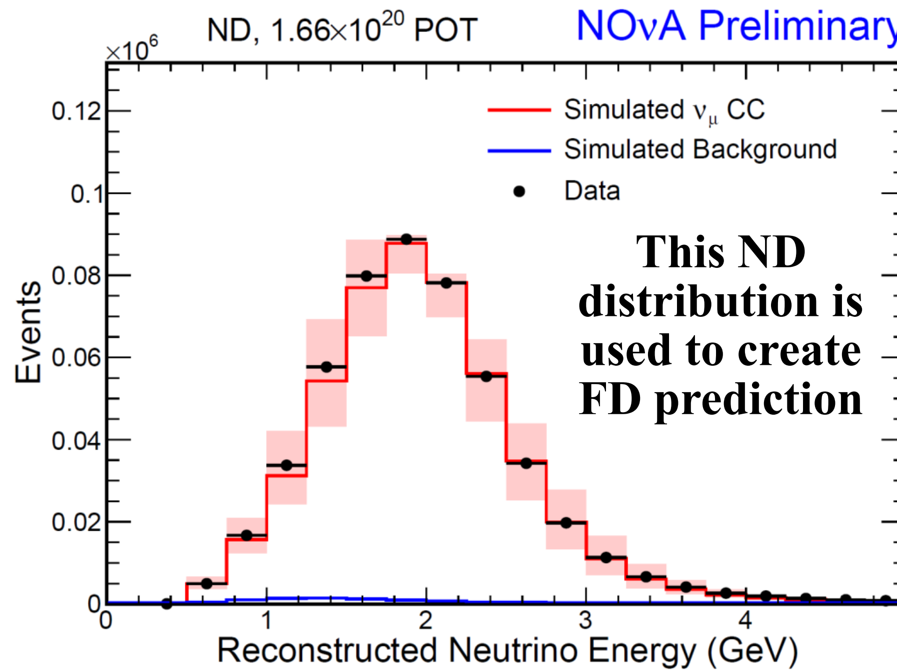
$$E_\nu = E_\mu + E_{\text{had}}$$

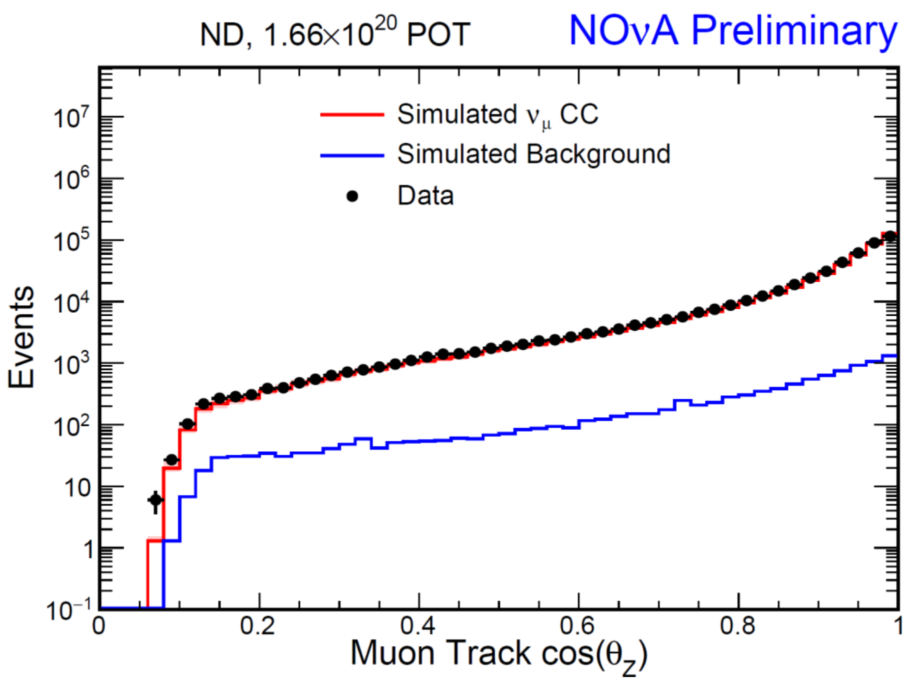
Energy resolution at beam peak ~7%

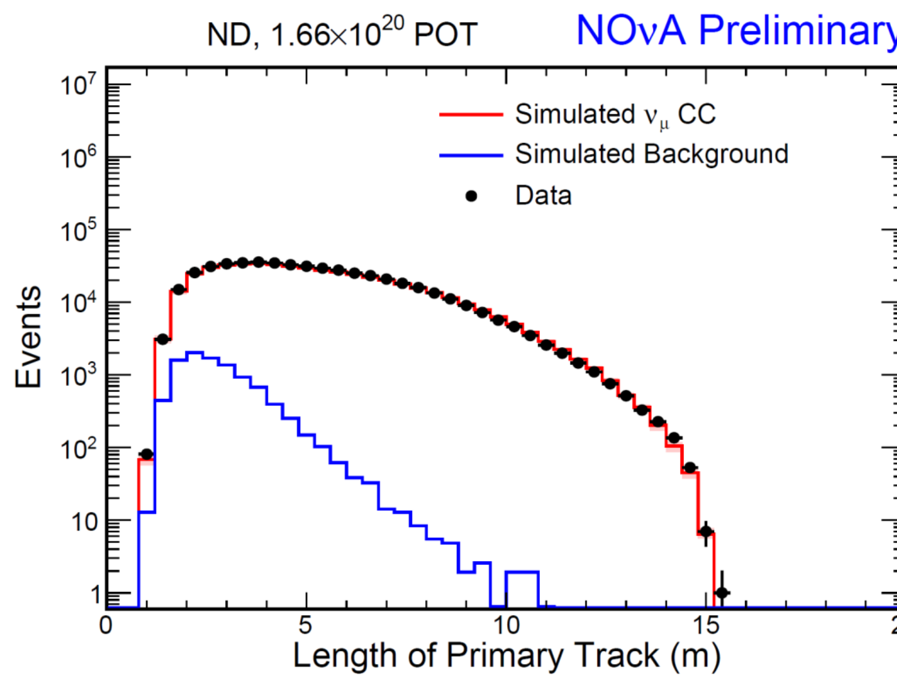


Kinematic variables in Near Det. after all cuts

→ *Sample purity in ND = 98%*







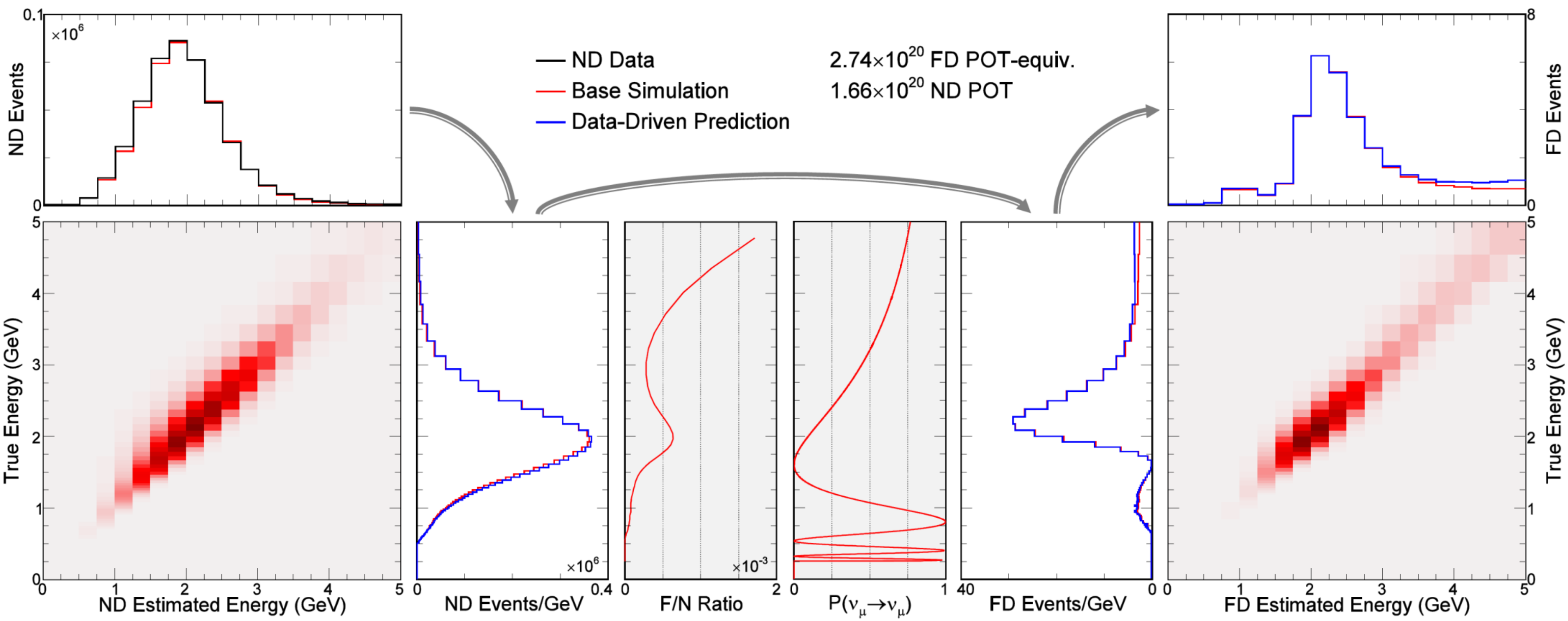
Far Detector prediction

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

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

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

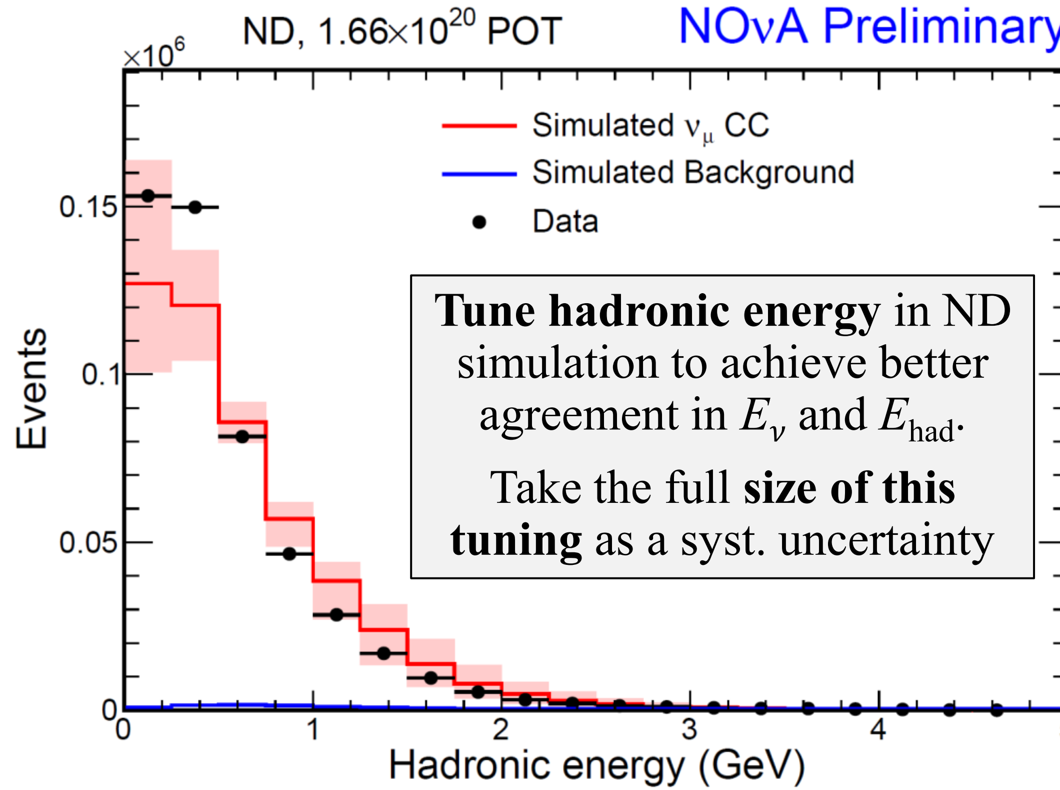
Systematic uncertainties assessed by **varying all MC-based steps**



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)

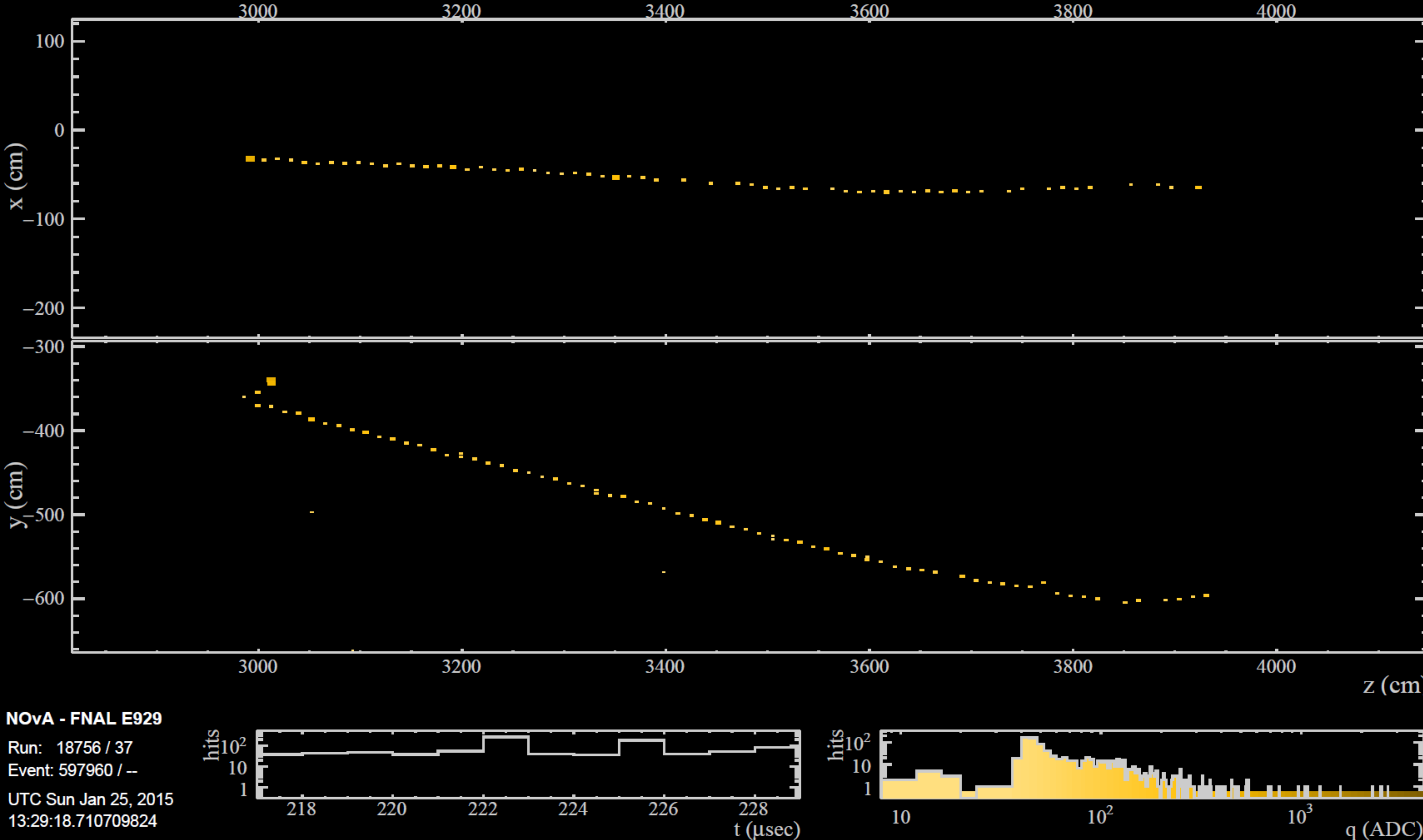


(before tuning)

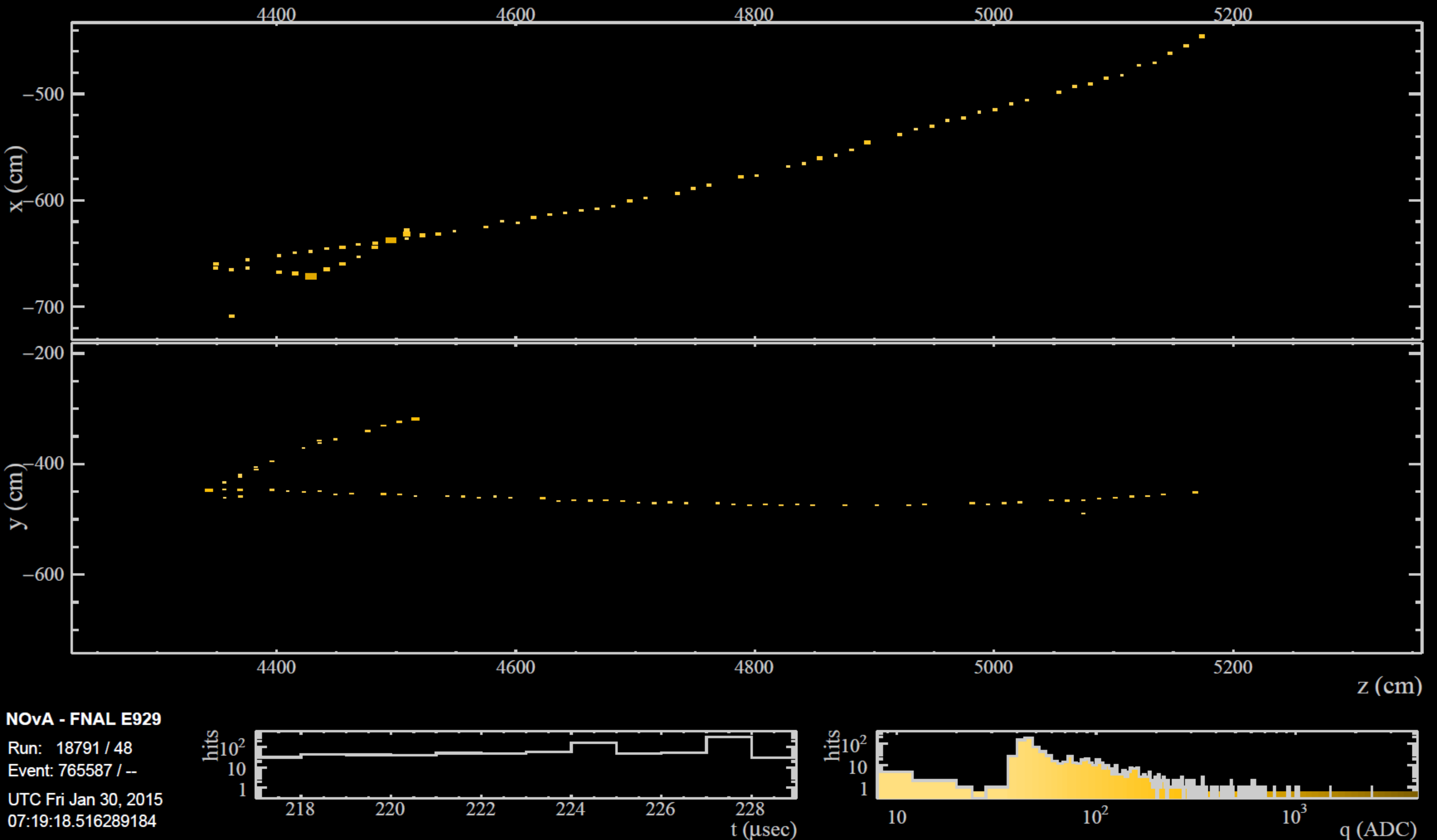
<u>Uncertainties assessed</u>

- Hadronic energy
  (21%, ~equiv. to 6% on E_ν)
- Neutrino flux
  (NA49 + beam transport model)
- Absolute, relative normalization
  (1%, 2%)
- Neutrino interactions
  (GENIE / Intranuke model)
- NC and ν_τ CC background rate
  (100% each)
- Multiple calibration and light-level systematics
  (Hit energy, fiber attenuation, threshold effects)
- Oscillation parameter uncertainties
  (current world knowledge)

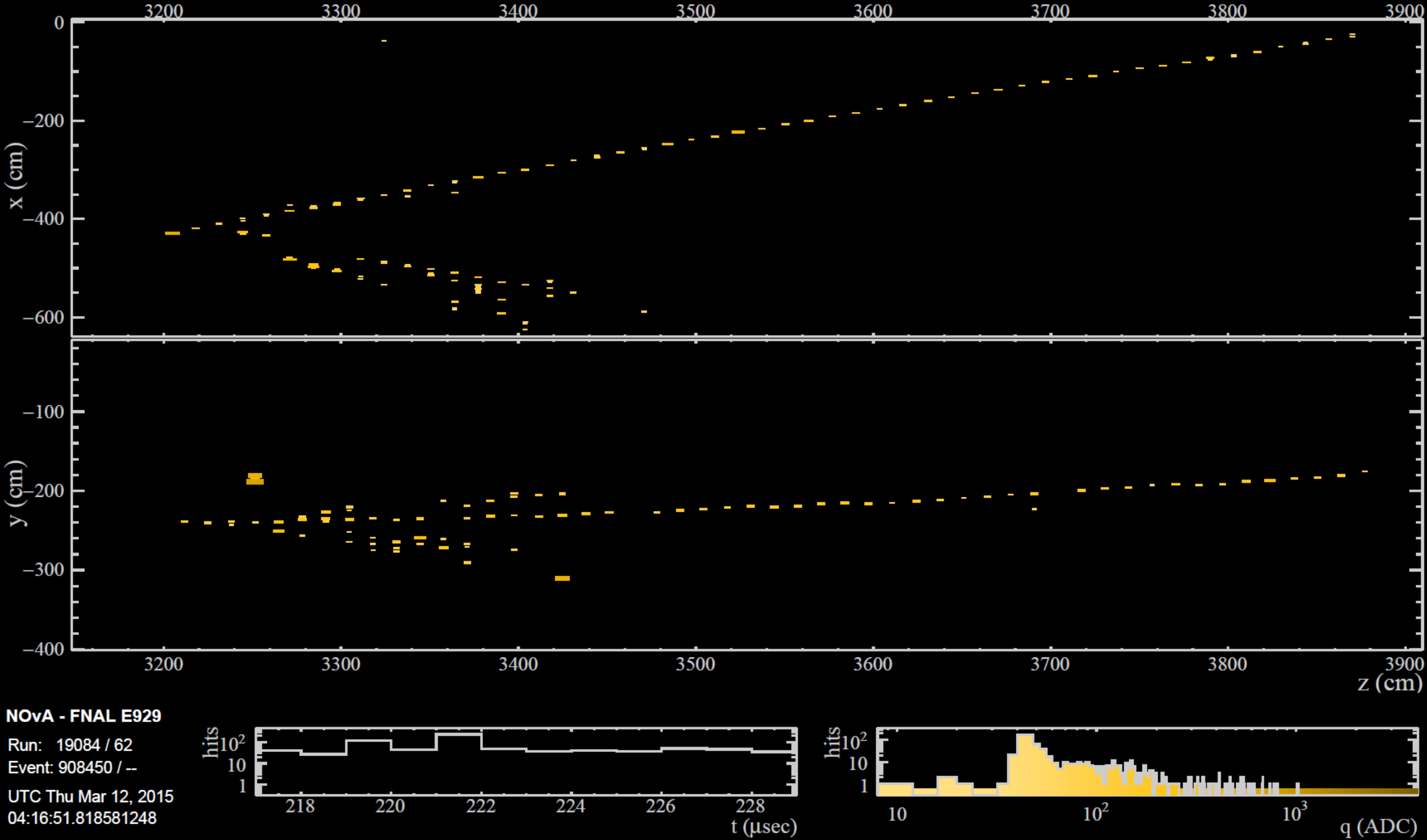
Far Detector selected ν_μ CC candidate



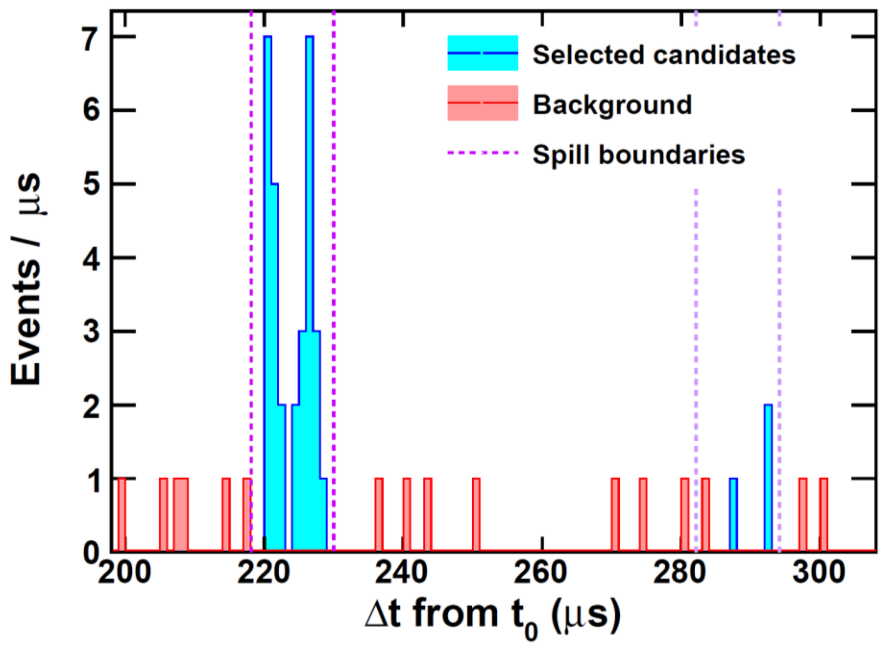
Far Detector selected ν_μ CC candidate

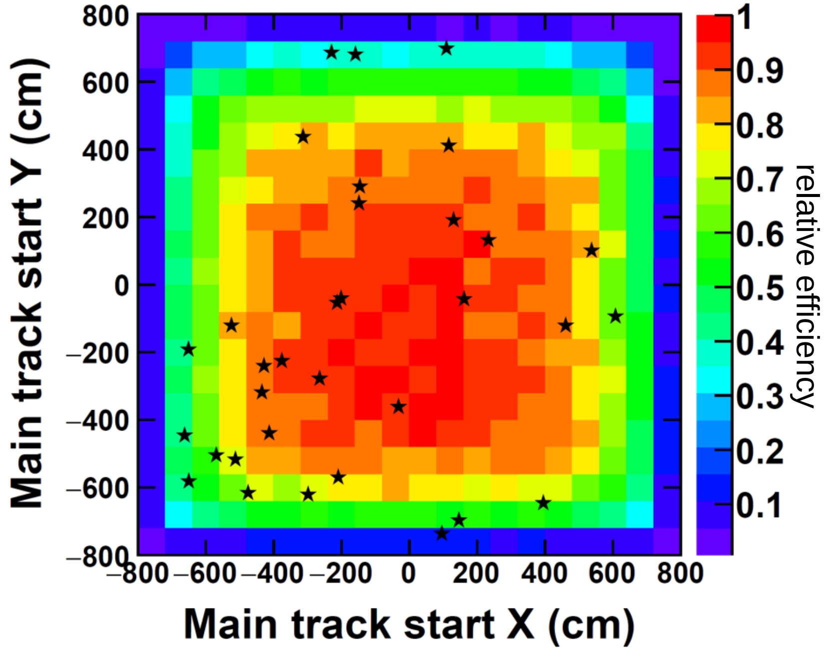


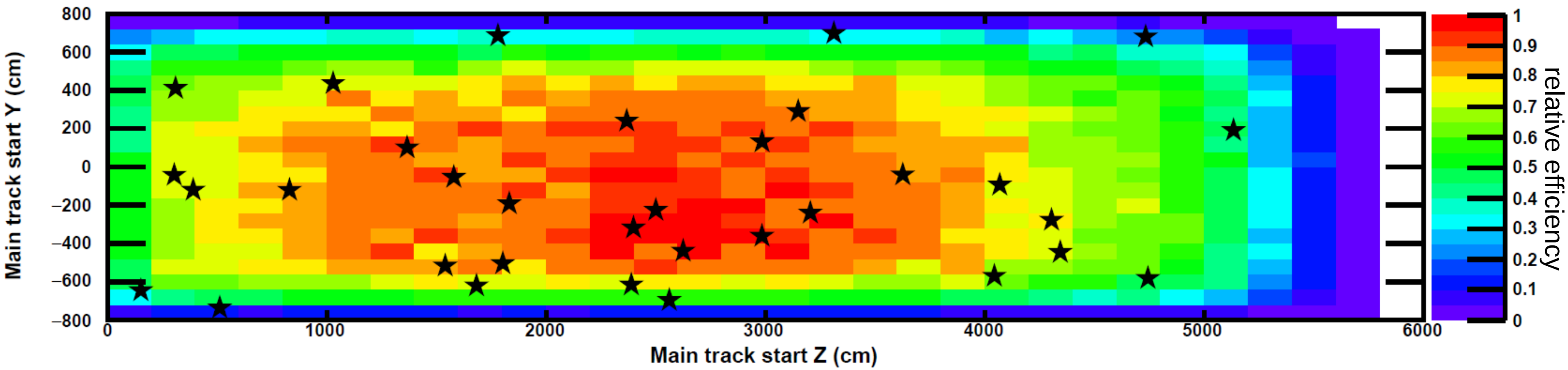
Far Detector selected ν_μ CC candidate



FD ν_μ CC candidates: when and where





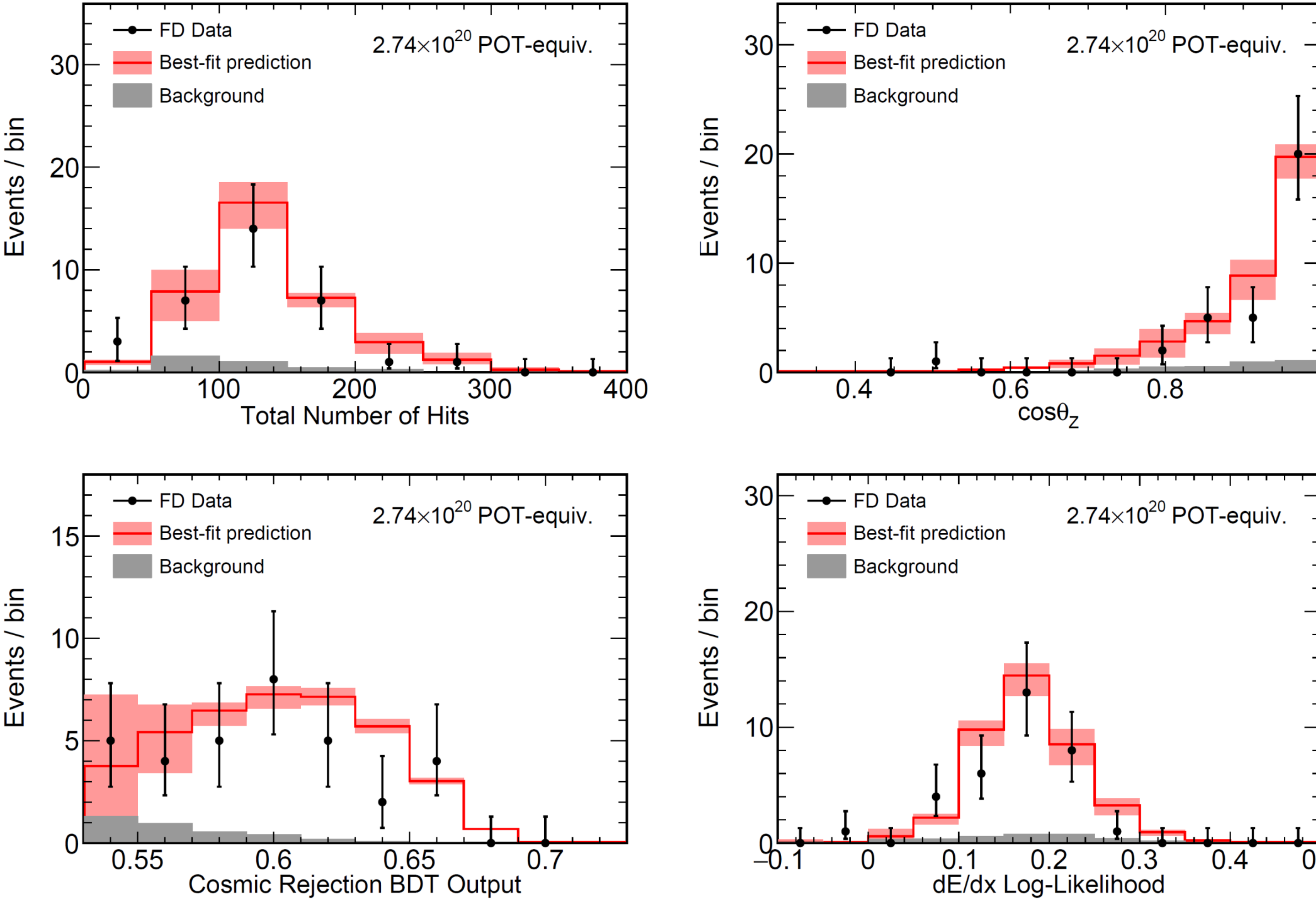


Note 1: Second timing window at +64 μs required for some of the early data

Note 2: Colors show relative efficiency. Not weighted by time variation in detector size.

FD ν_μ CC candidates: event distributions

All NOνA Preliminary

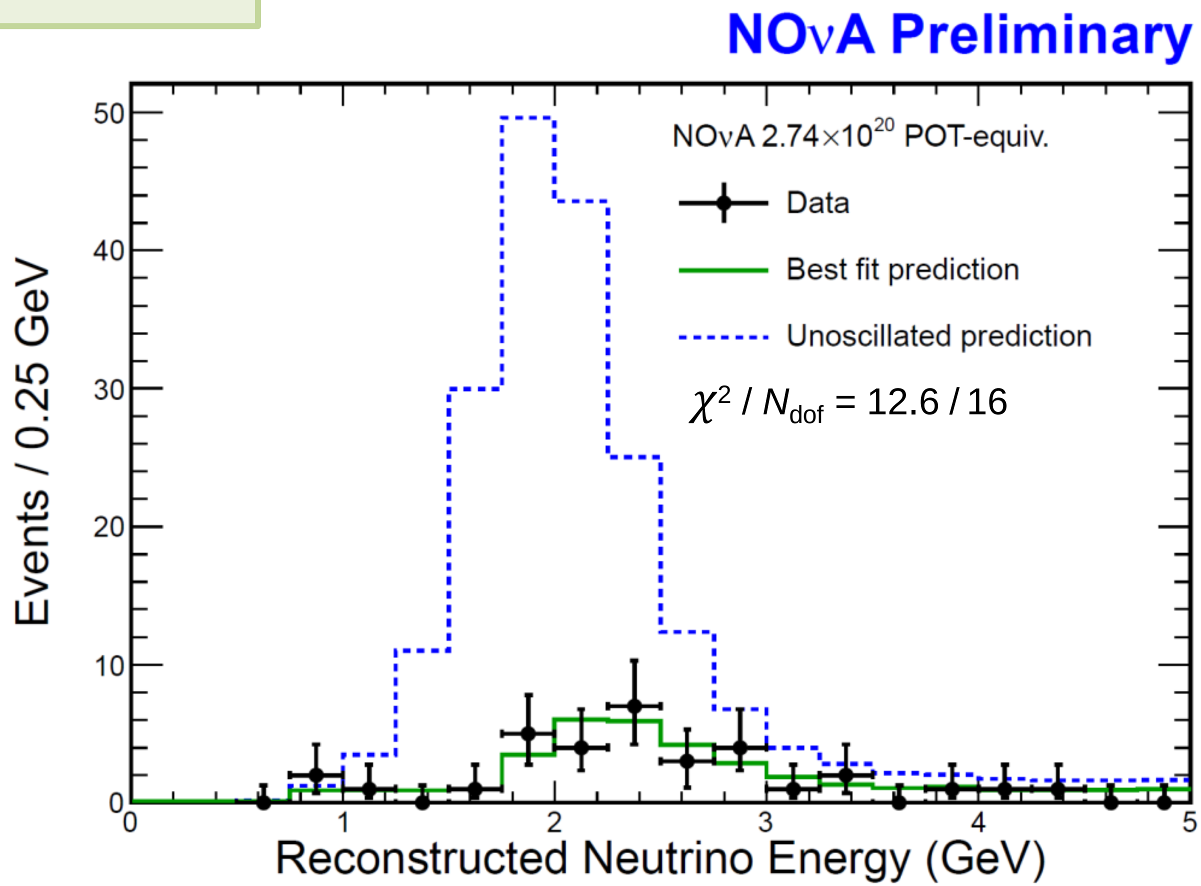


FD energy spectrum

33 events selected in Far Detector
(0 – 5 GeV)

In the absence of oscillations, would expect **201 events**

(including 2.0 beam bkgnd and 1.4 cosmic bkgnd)



Spectrum is well matched by oscillation fit for Δm^2_{32} and θ_{23}
(syst. uncertainties included in fit via nuisance parameters)

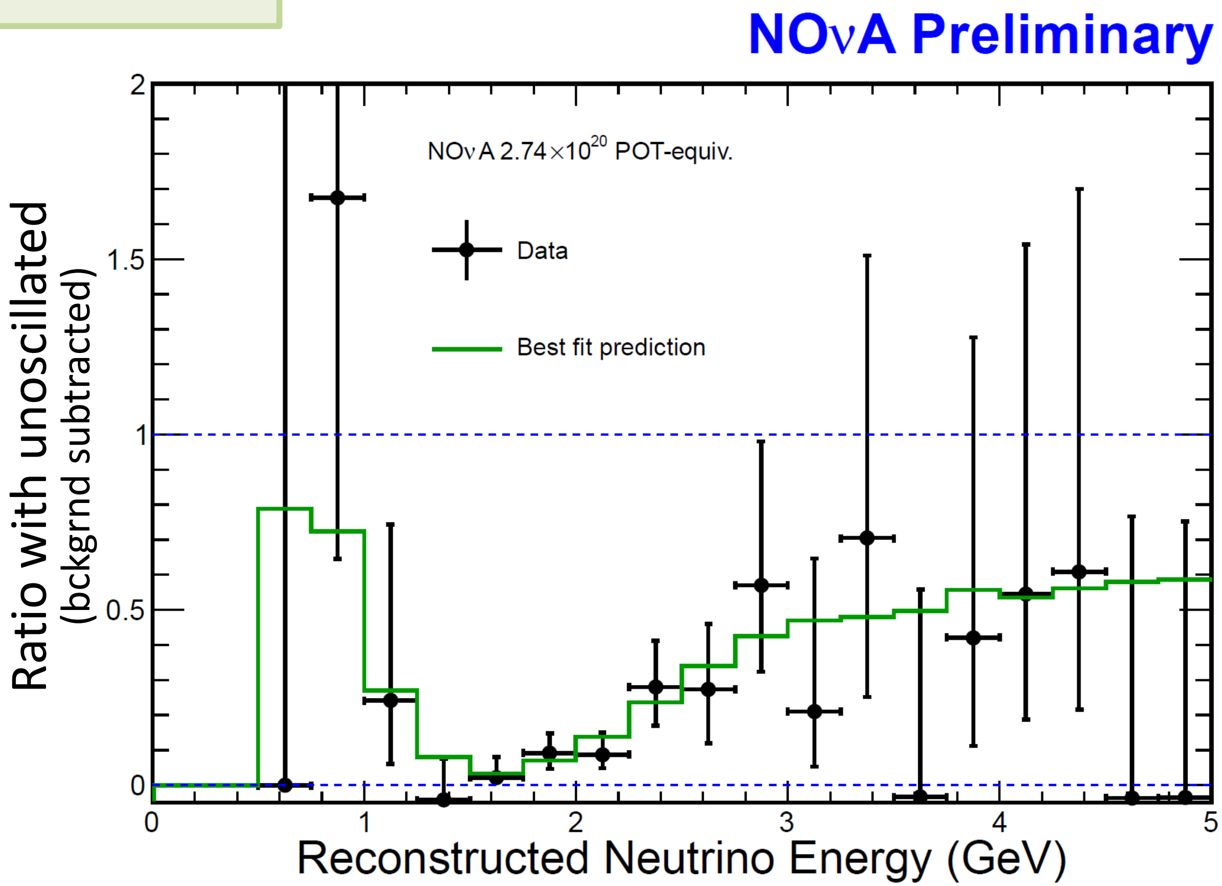
Clear observation of ν_μ disappearance

FD energy spectrum

33 events selected in Far Detector
(0 – 5 GeV)

In the absence of oscillations, would expect **201 events**

(including 2.0 beam bkgnd and 1.4 cosmic bkgnd)

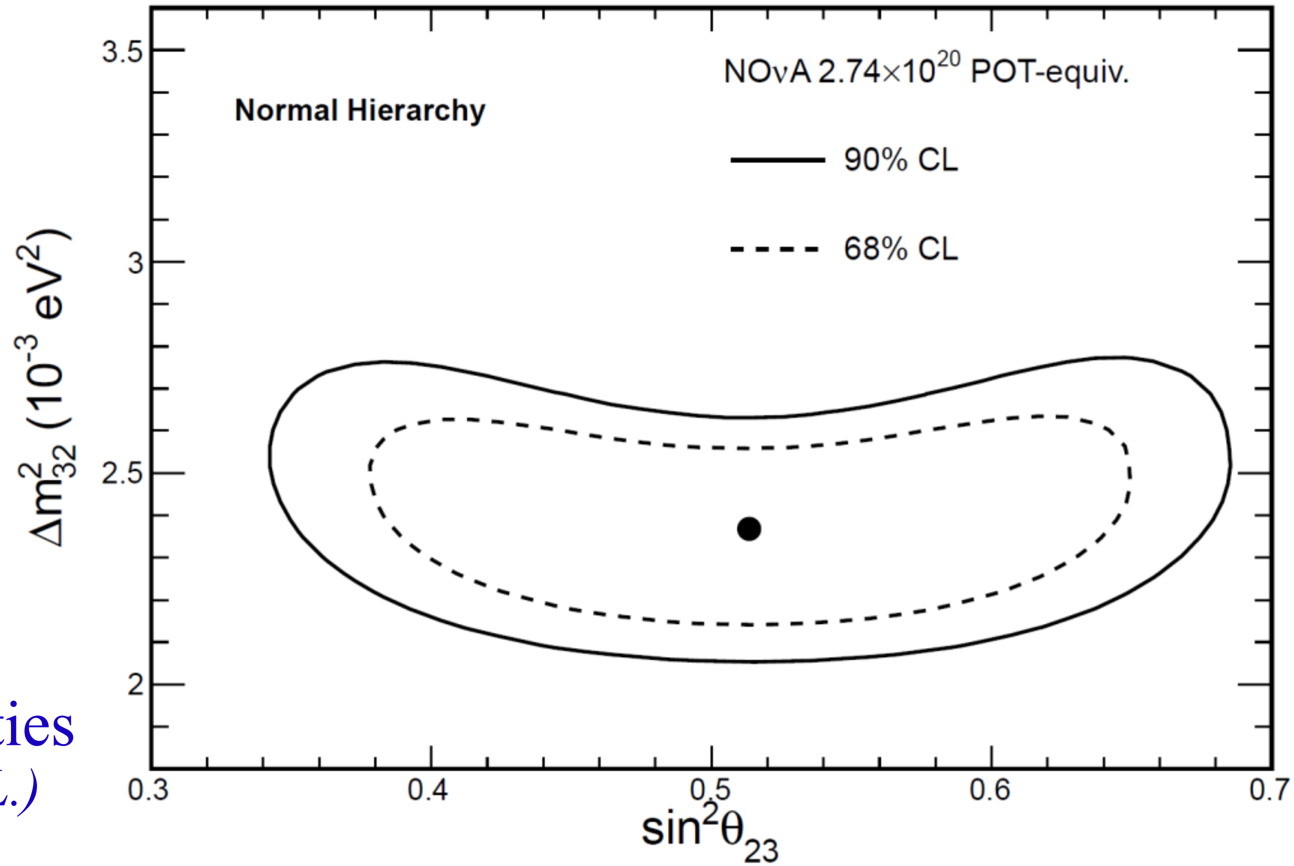


Spectrum is well matched by oscillation fit for Δm^2_{32} and θ_{23}
(syst. uncertainties included in fit via nuisance parameters)

Clear observation of ν_μ disappearance

Fit result

NOvA Preliminary



At right:

NOνA allowed regions in **(Δm^2_{32}, $\sin^2\theta_{23}$)** parameter space

Below:

Extracted parameter values and uncertainties *(1D profiles at 68% C.L.)*

$$\Delta m^2_{32} = \begin{cases} +2.37^{+0.16}_{-0.15} \text{ [NH]} \\ -2.40^{+0.14}_{-0.17} \text{ [IH]} \end{cases} \times 10^{-3}\ \text{eV}^2$$

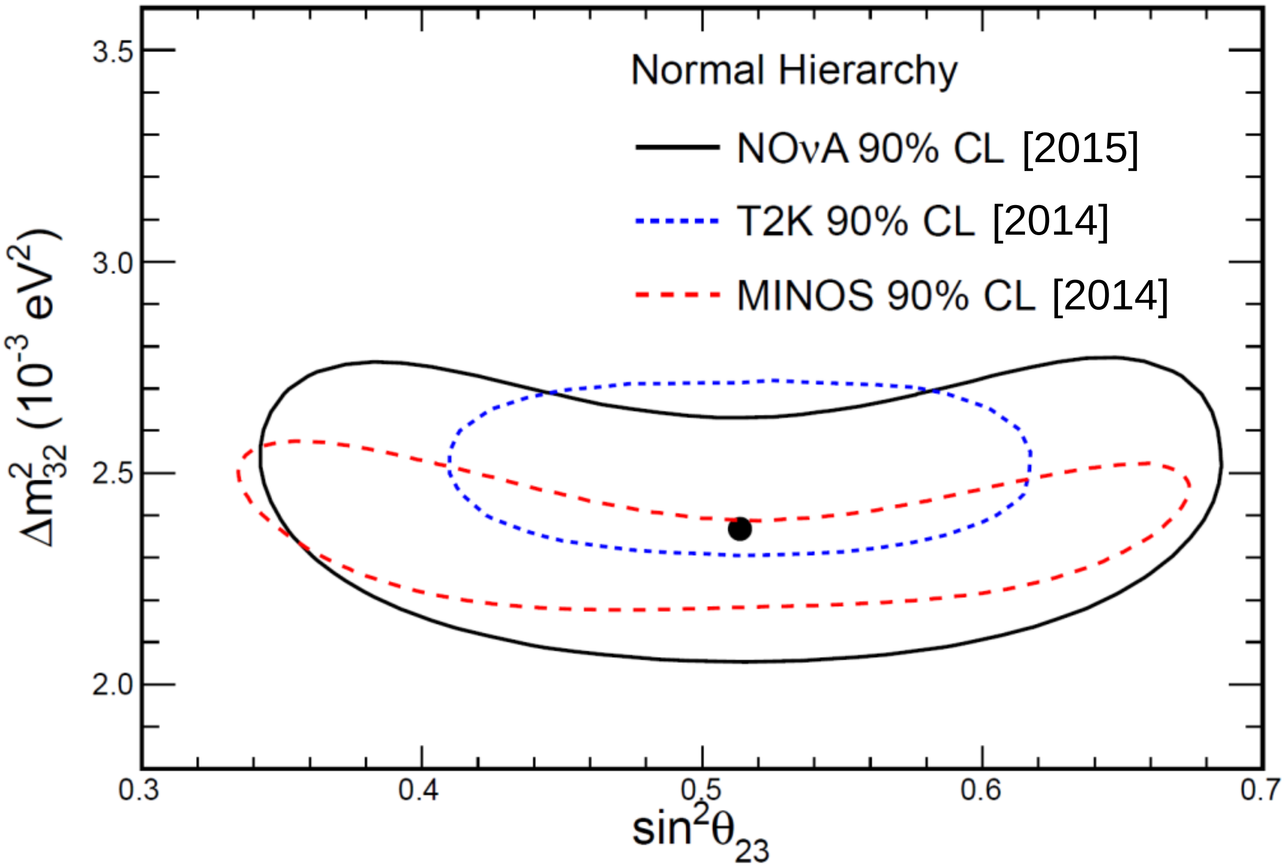
6.5% measurement uncertainty

$$\sin^2(\theta_{23}) = 0.51 \pm 0.10$$

NOνA Preliminary

Allowed regions are consistent with MINOS and T2K

(shown at right)



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

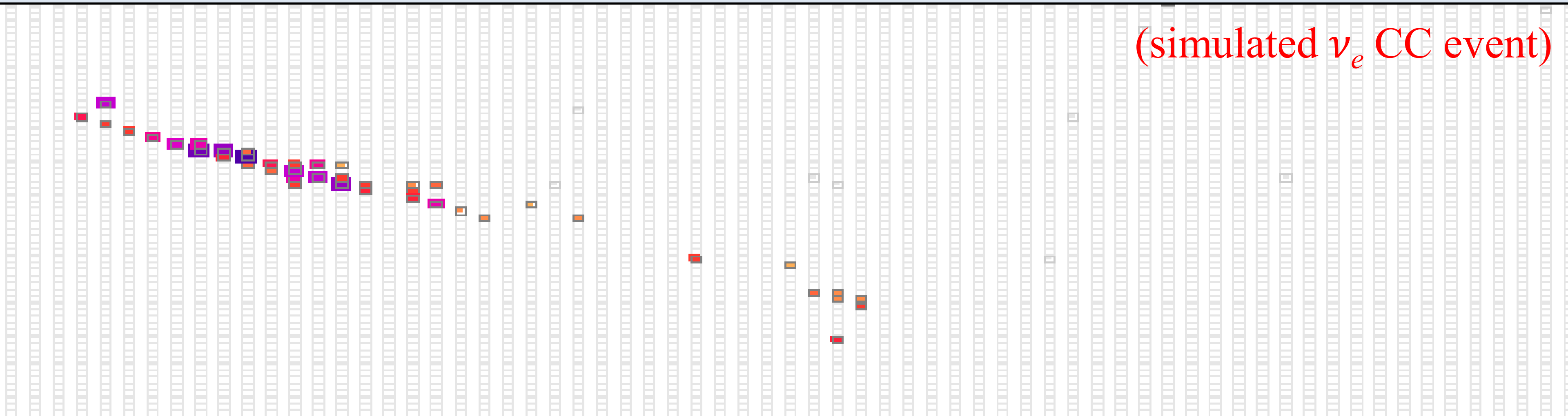
$$\Delta m^2_{32} = \begin{cases} +2.37^{+0.16}_{-0.15} \text{ [NH]} \\ -2.40^{+0.14}_{-0.17} \text{ [IH]} \end{cases} \times 10^{-3}\ \text{eV}^2$$

6.5% measurement uncertainty

$$\sin^2(\theta_{23}) = 0.51 \pm 0.10$$

ν_e appearance

- Identify **contained ν_e CC candidates** in each detector
- Use Near Det. candidates to **predict beam backgrounds** in the Far Detector
- Interpret any **Far Det. excess** over predicted backgrounds as ν_e appearance



Pre-selection

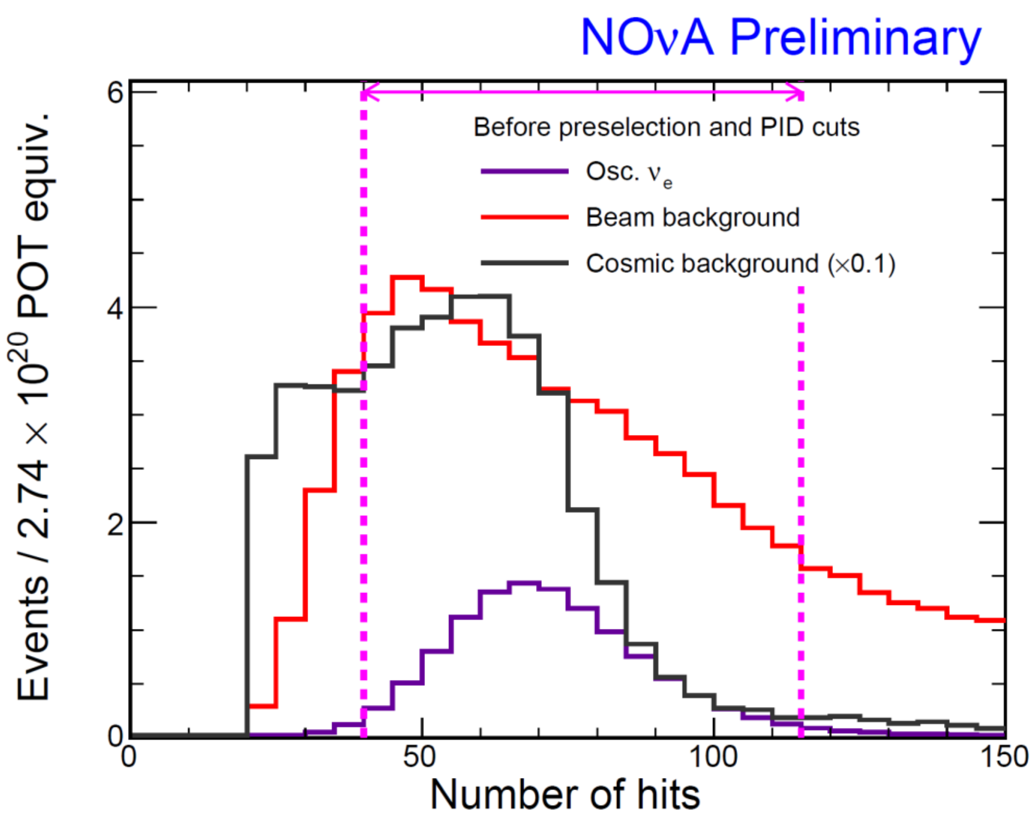
First, basic containment cuts require sufficient distance from the largest reconstructed shower to the walls.

Then, cuts applied to:

- shower length
- number of hits in event
- calorimetric energy

All three related to the "size" of the event

We know well the range of energies any appearing ν_e might have

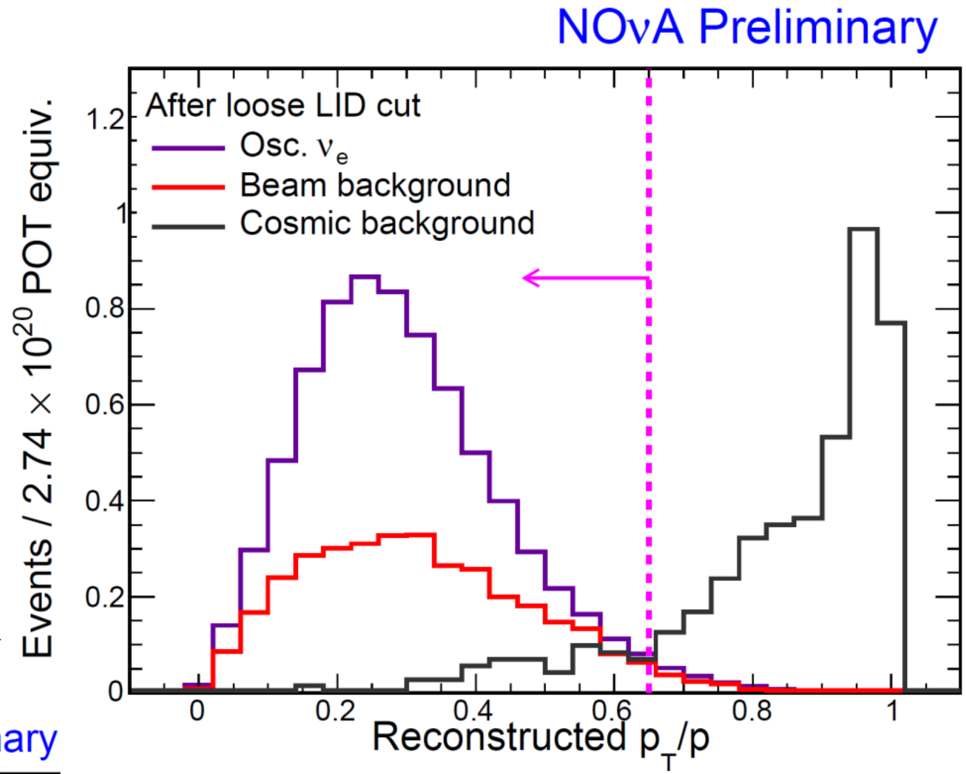


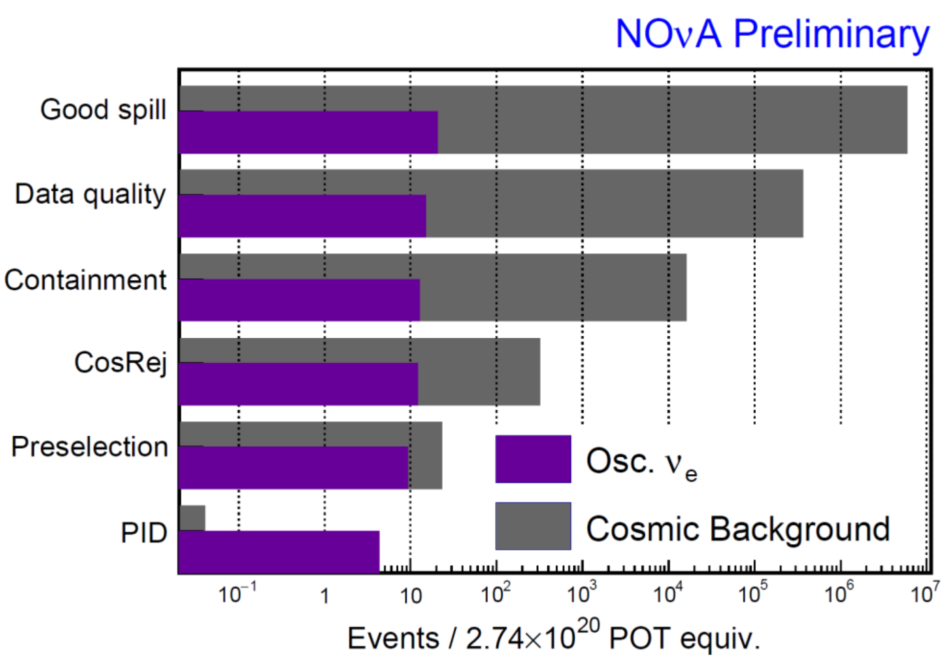
Cosmic rejection

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 identification

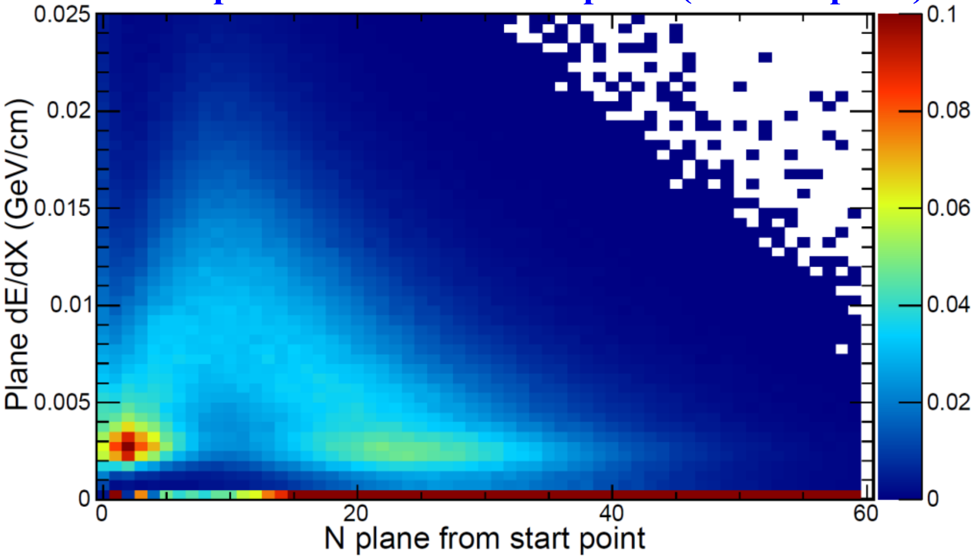
We have developed two independent ν_e CC selection algorithms
→ *Very different designs*

LID: Likelihood Identification

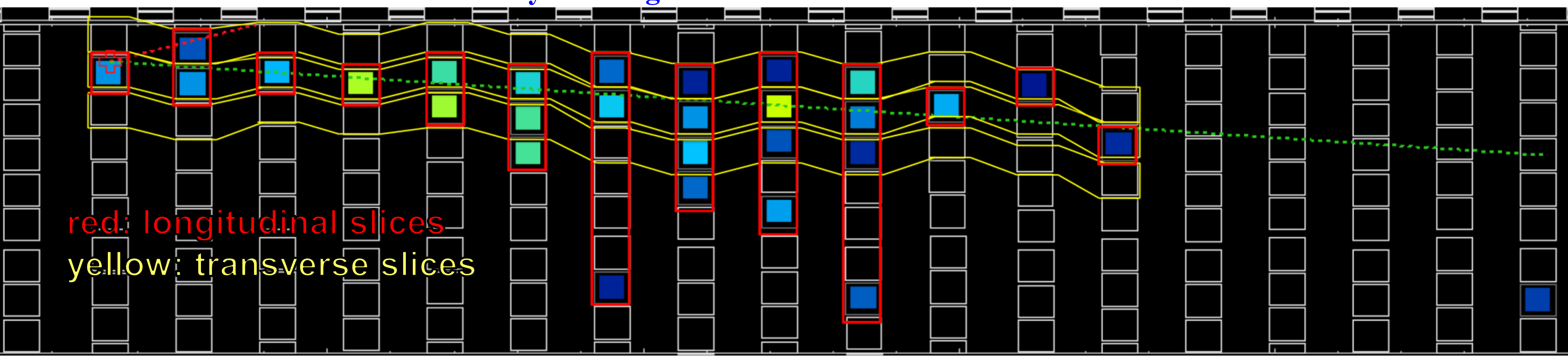
***dE/dx* likelihoods** calculated for **longitudinal and transverse** slices of leading shower under multiple particle hypotheses

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

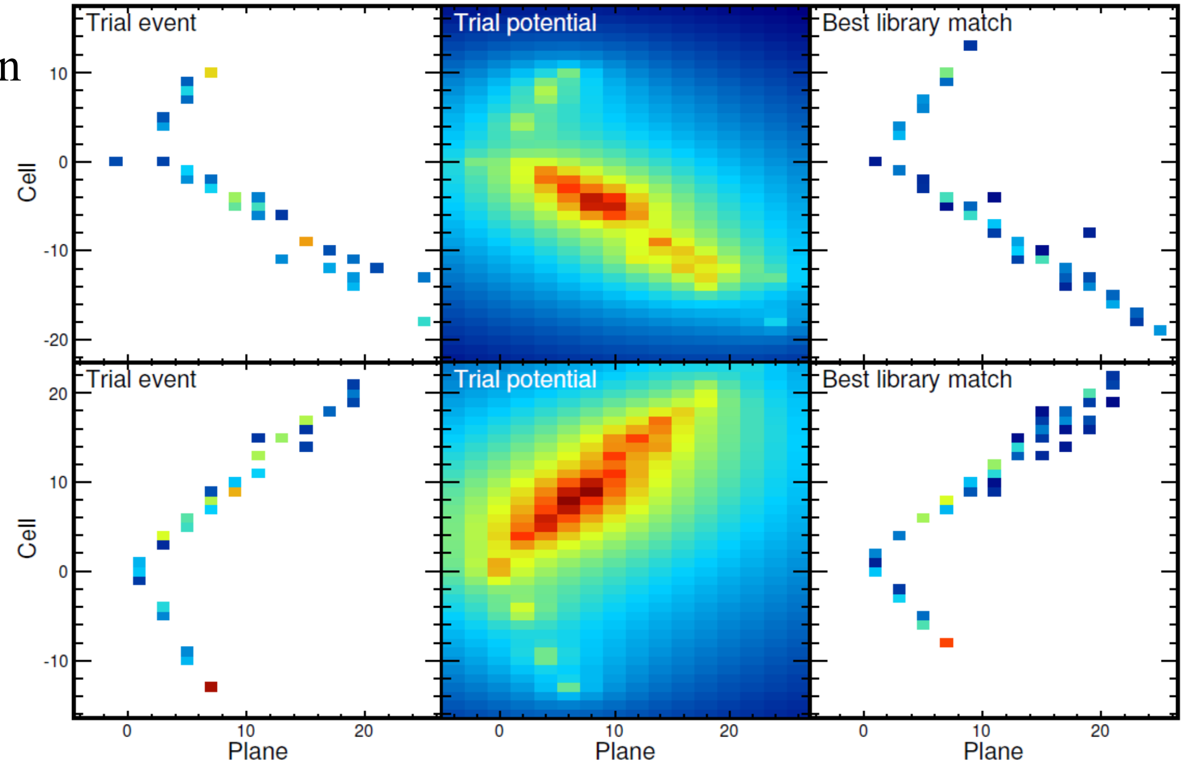


LEM: Library Event Matching

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

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

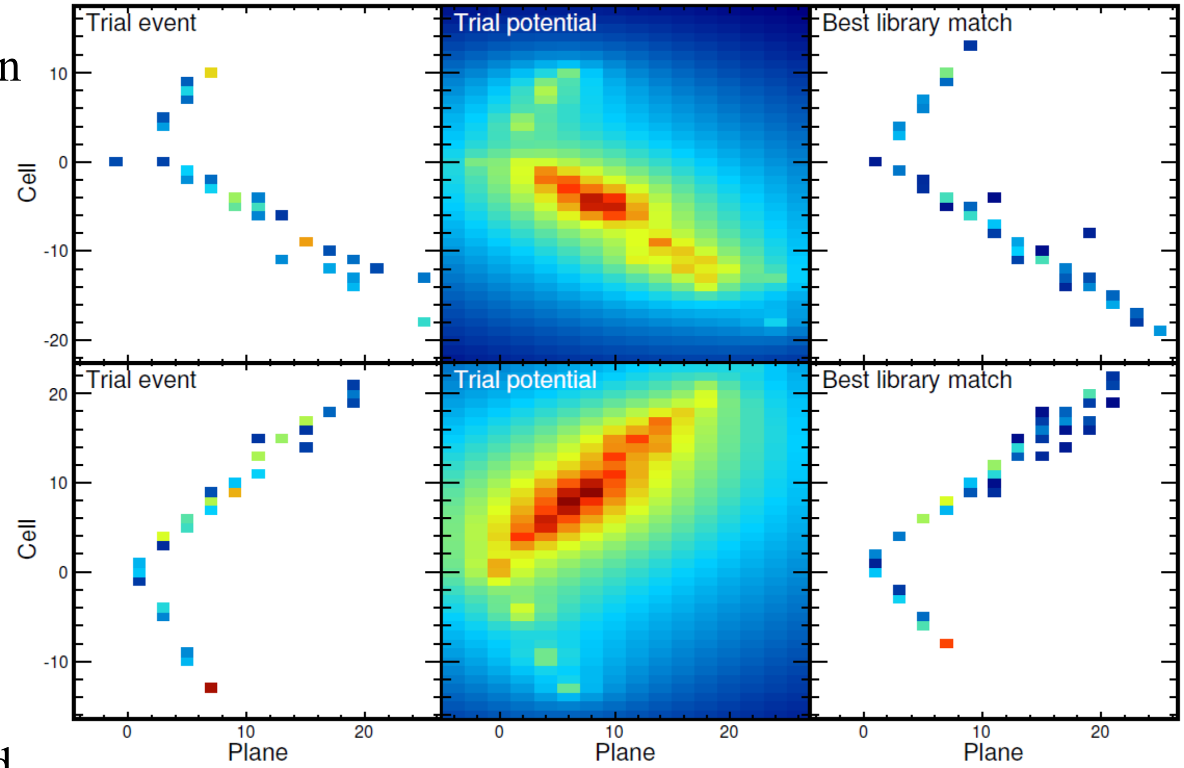


Left panels: candidate event, both views
Right panels: best-matched library event, both views
Middle panels: an intermediate step in calculating the match quality

LEM: Library Event Matching

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

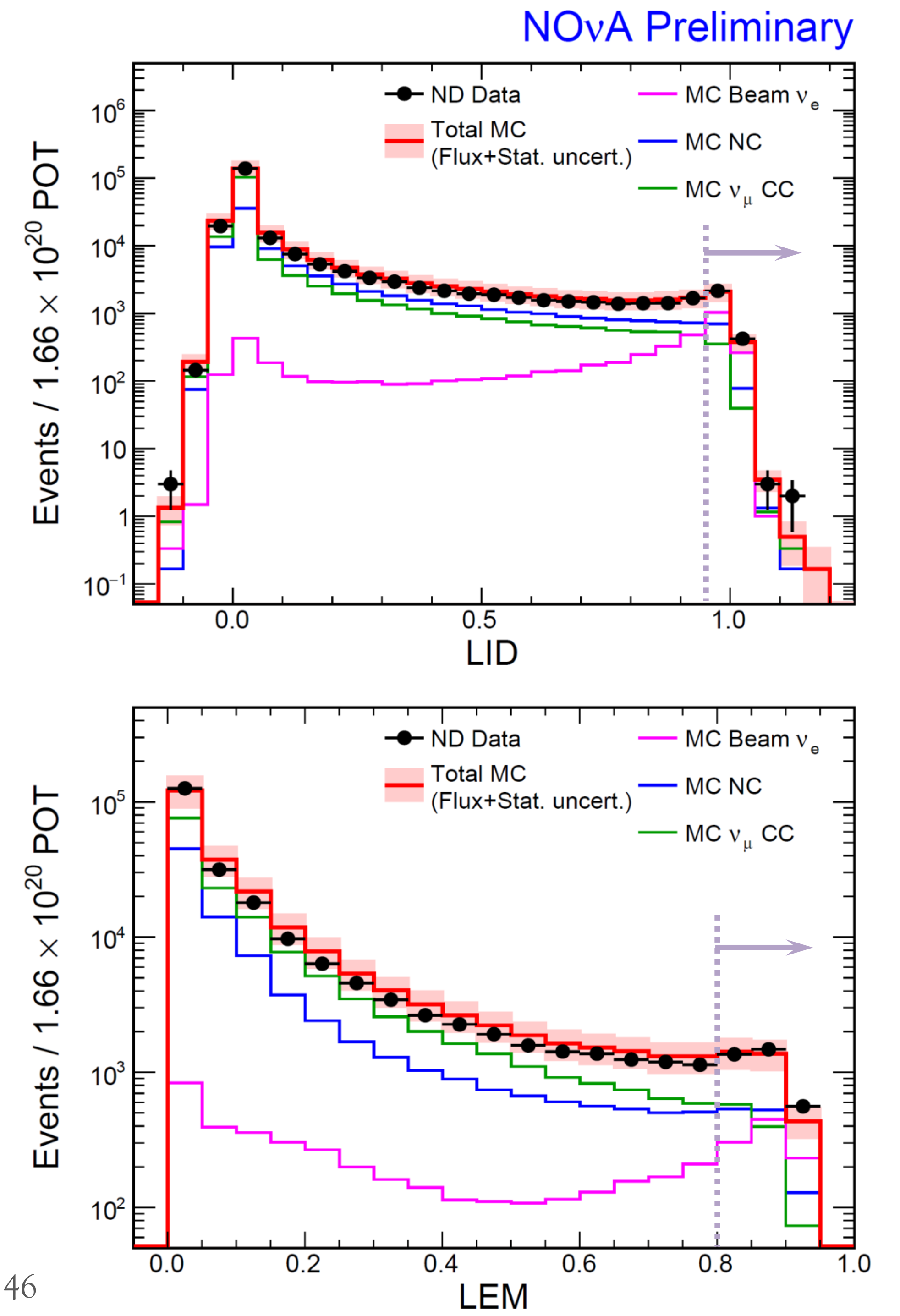
Key properties of the **best-matched library events** (*e.g.*, fraction that are signal events) are input into a decision tree to form discriminant



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.



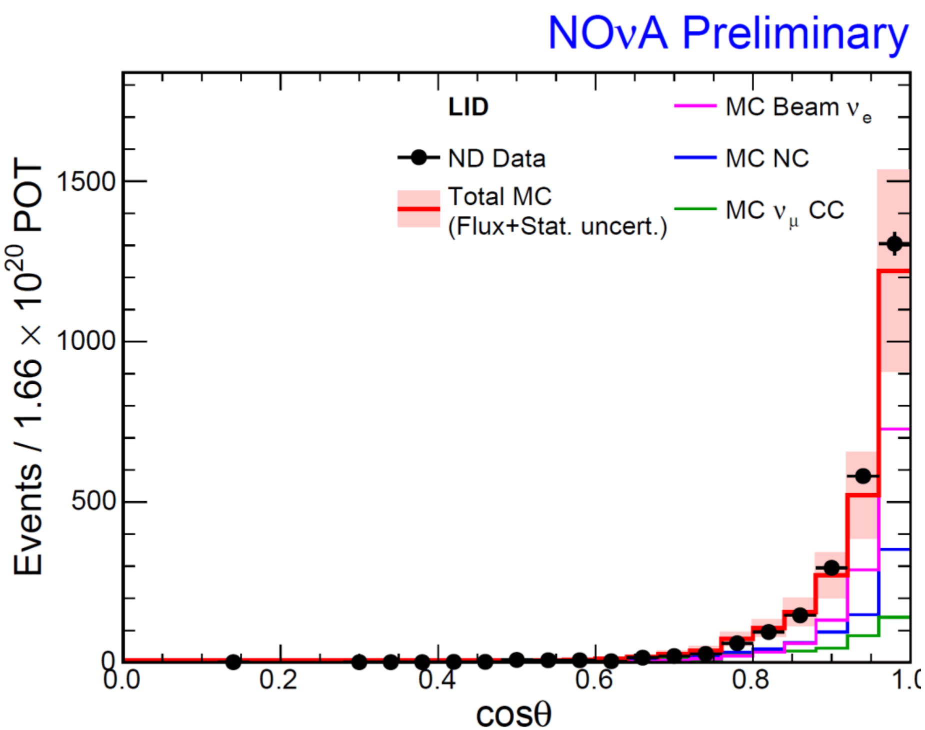
LID and **LEM** distributions for **ND data** and **simulation**

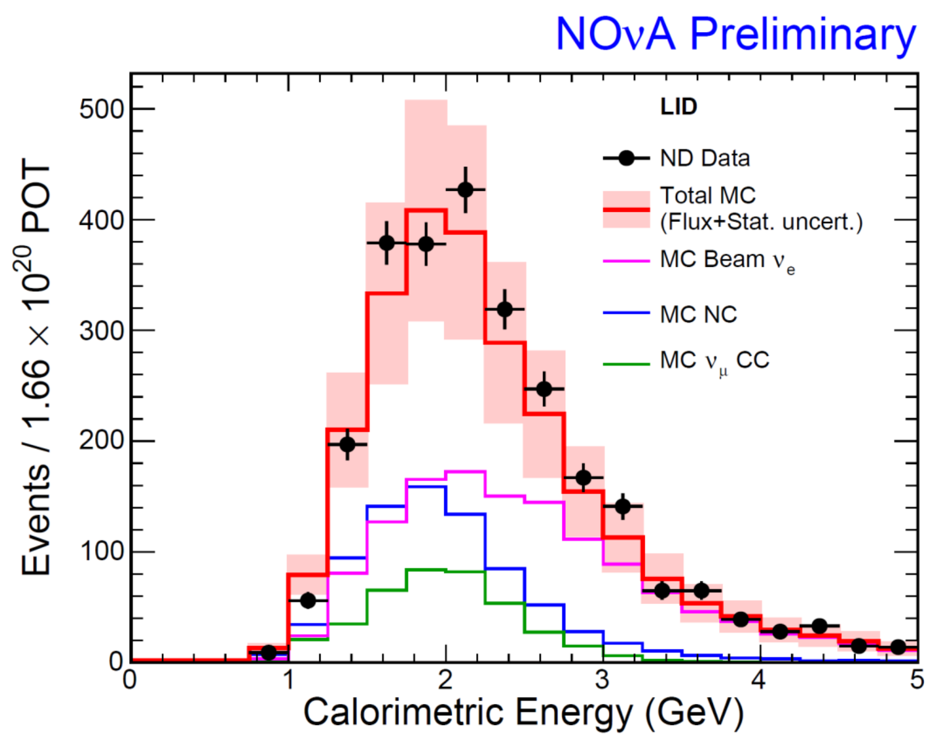
all preselection cuts applied

Good agreement over full range

Shower direction and **event energy** distributions for **ND data** and **simulation**, *after all cuts*

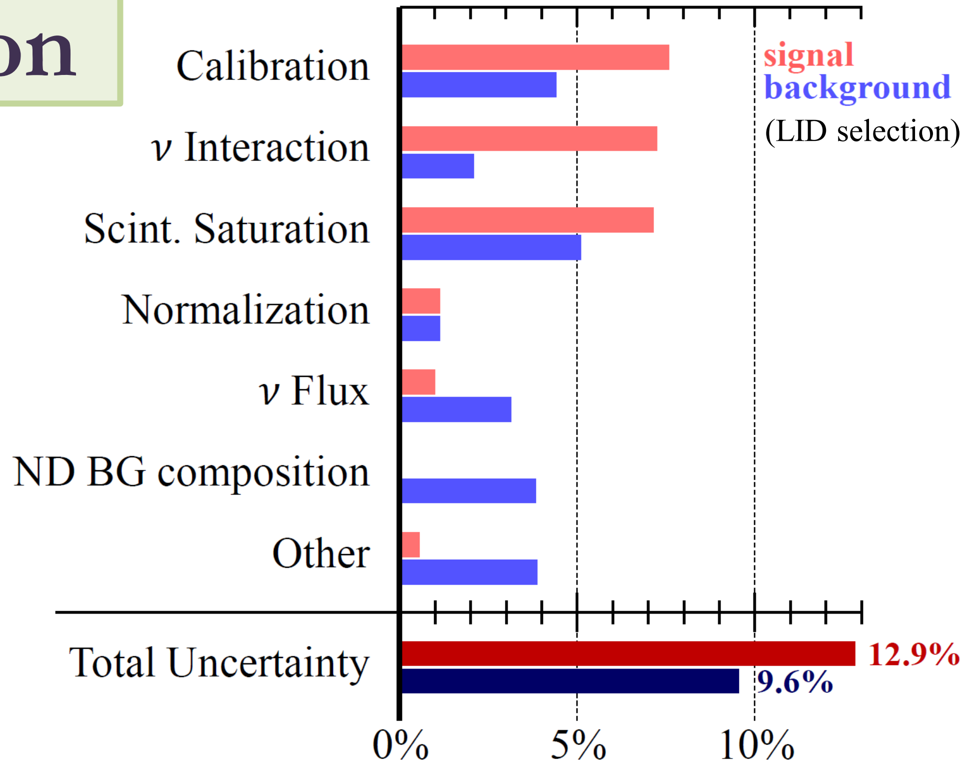
This ND distribution is used to create FD background prediction





Far Detector prediction

- **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*

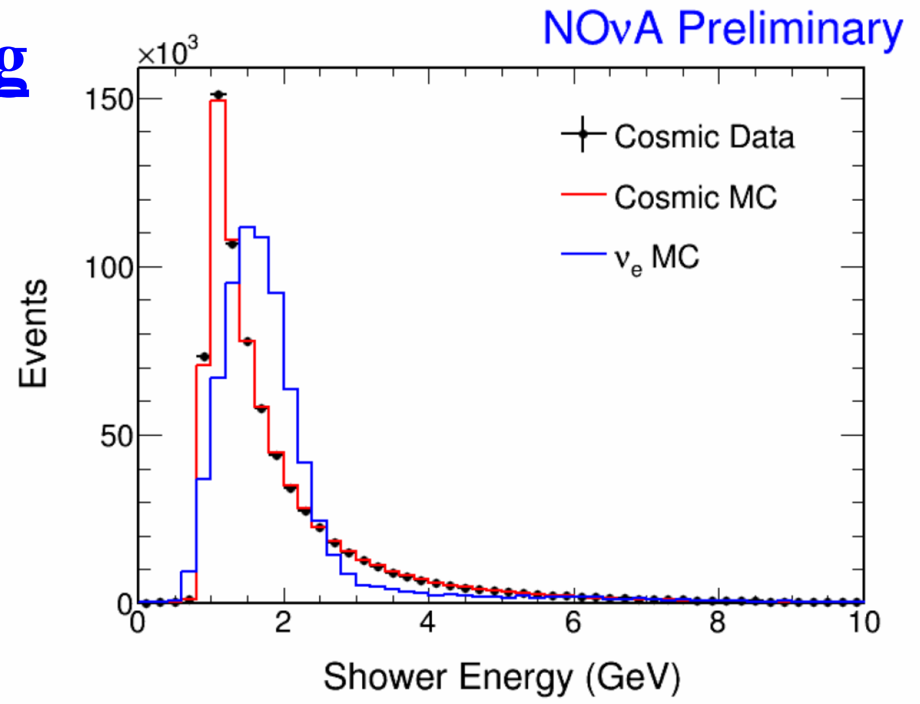
After all selection, **0.7% of NC events** remain, relative to those after containment

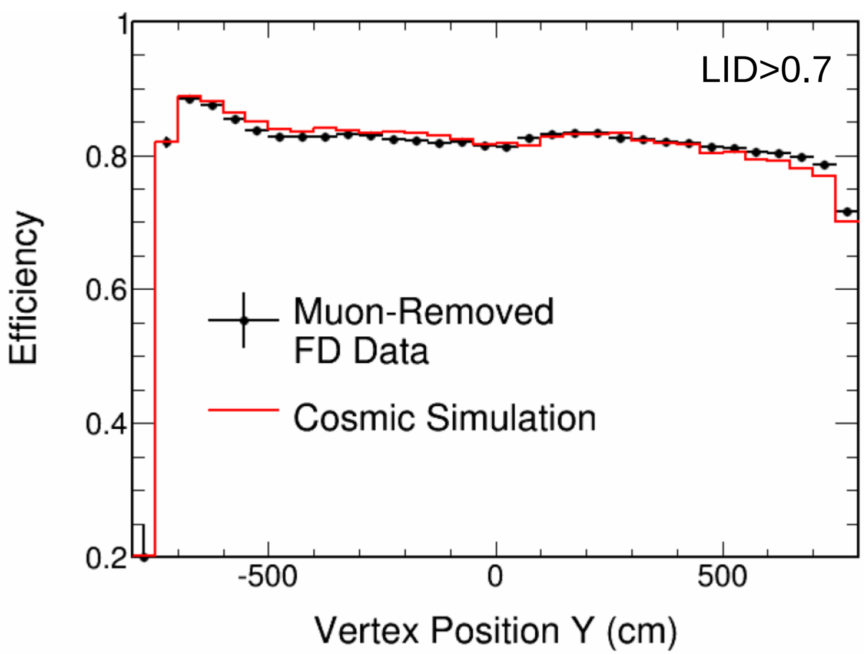
Checks of EM shower modeling

In addition to π^0 in the ND, we have **bremsstrahlung photons in ND and FD**

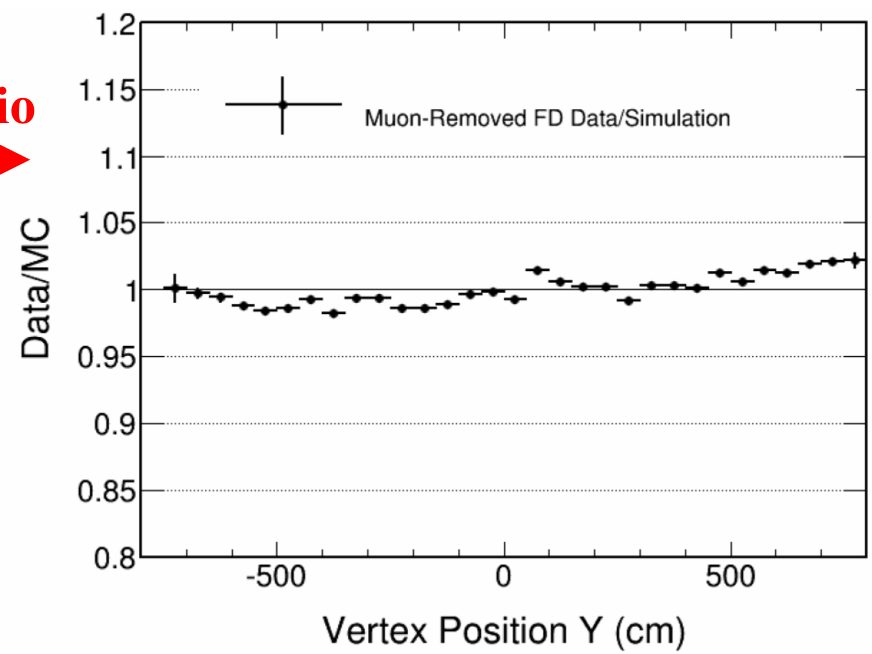
Right: **energies of brem showers** in FD
- *Excellent data/MC agreement*
- *Probes relevant E range (blue curve)*

Below: **selection efficiency** varies a bit across the large Far Detector
- ***Well modeled by simulation***





ratio →



FD predictions with systematic uncertainties indicated

LID selector

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

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

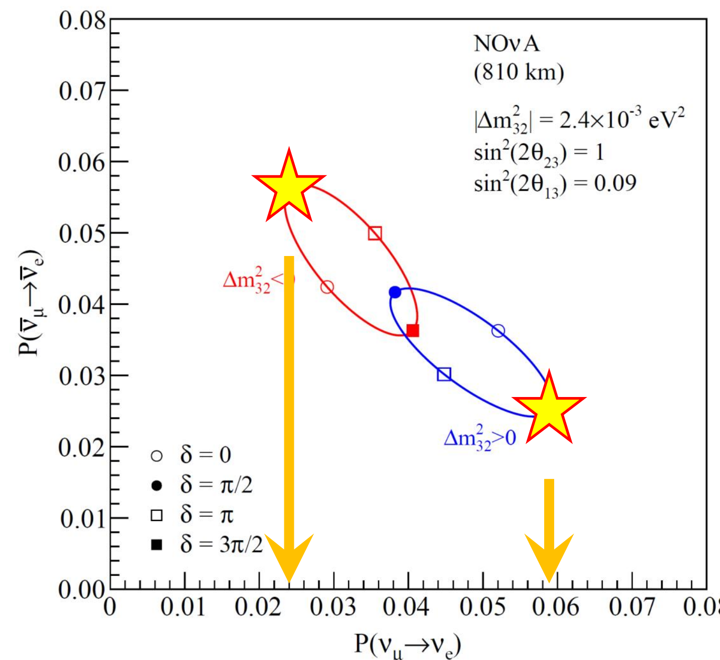
2.74×10^{20} POT equiv.

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

FD predictions with systematic uncertainties indicated

LEM selector

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

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

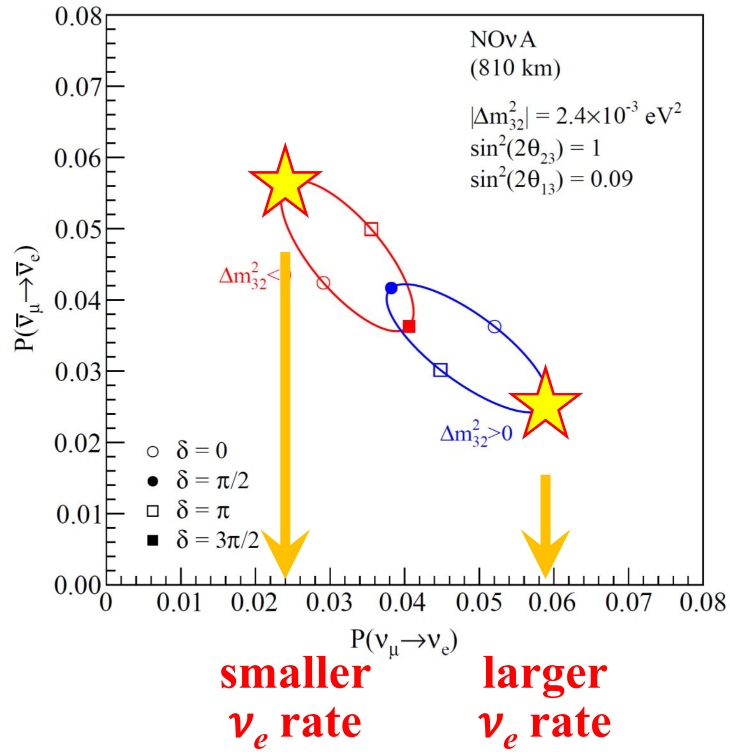
2.74×10^{20} POT equiv.

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



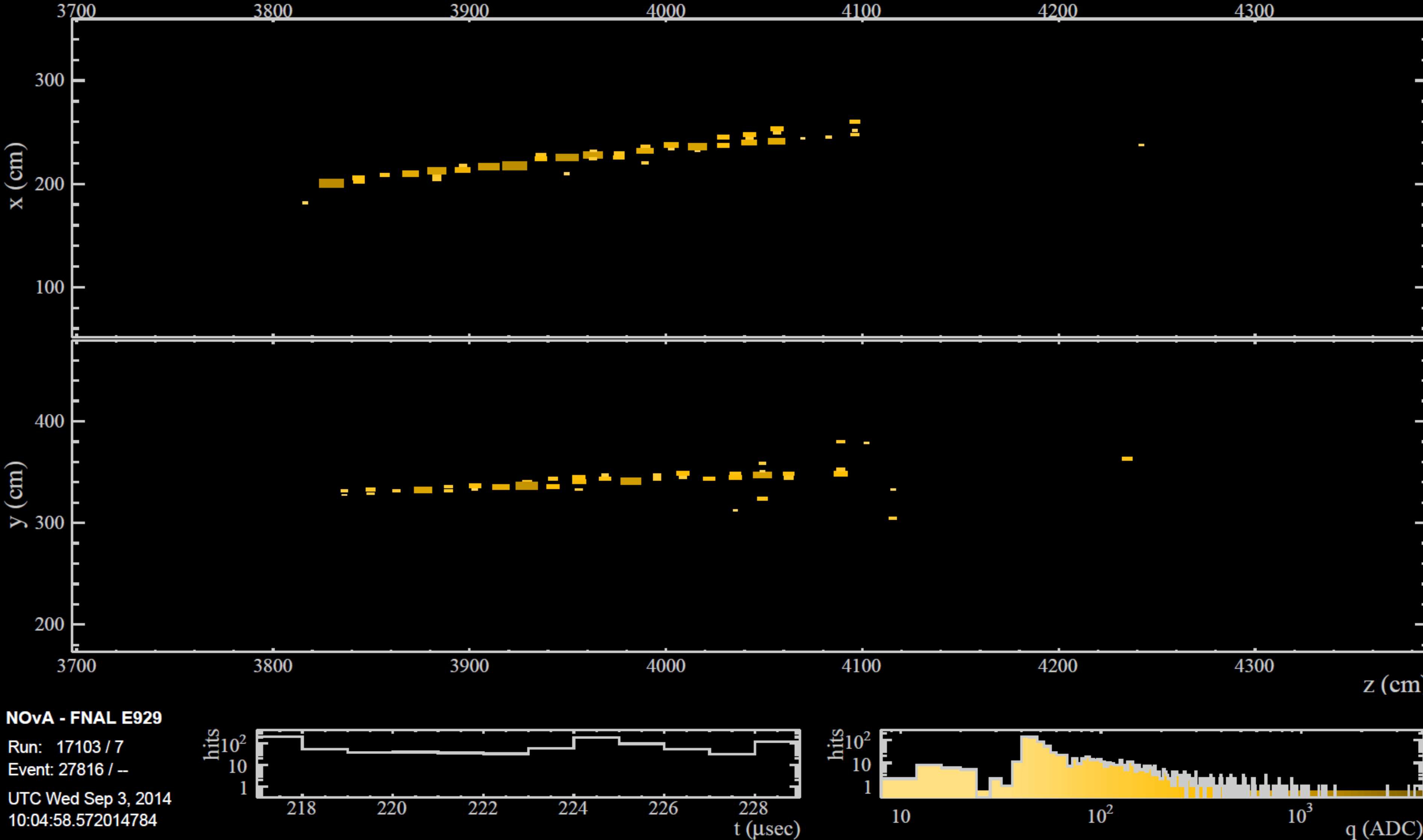
Aside: Before unblinding, **two sidebands checks** –

(1) Near-PID (LID/LEM) sideband, and

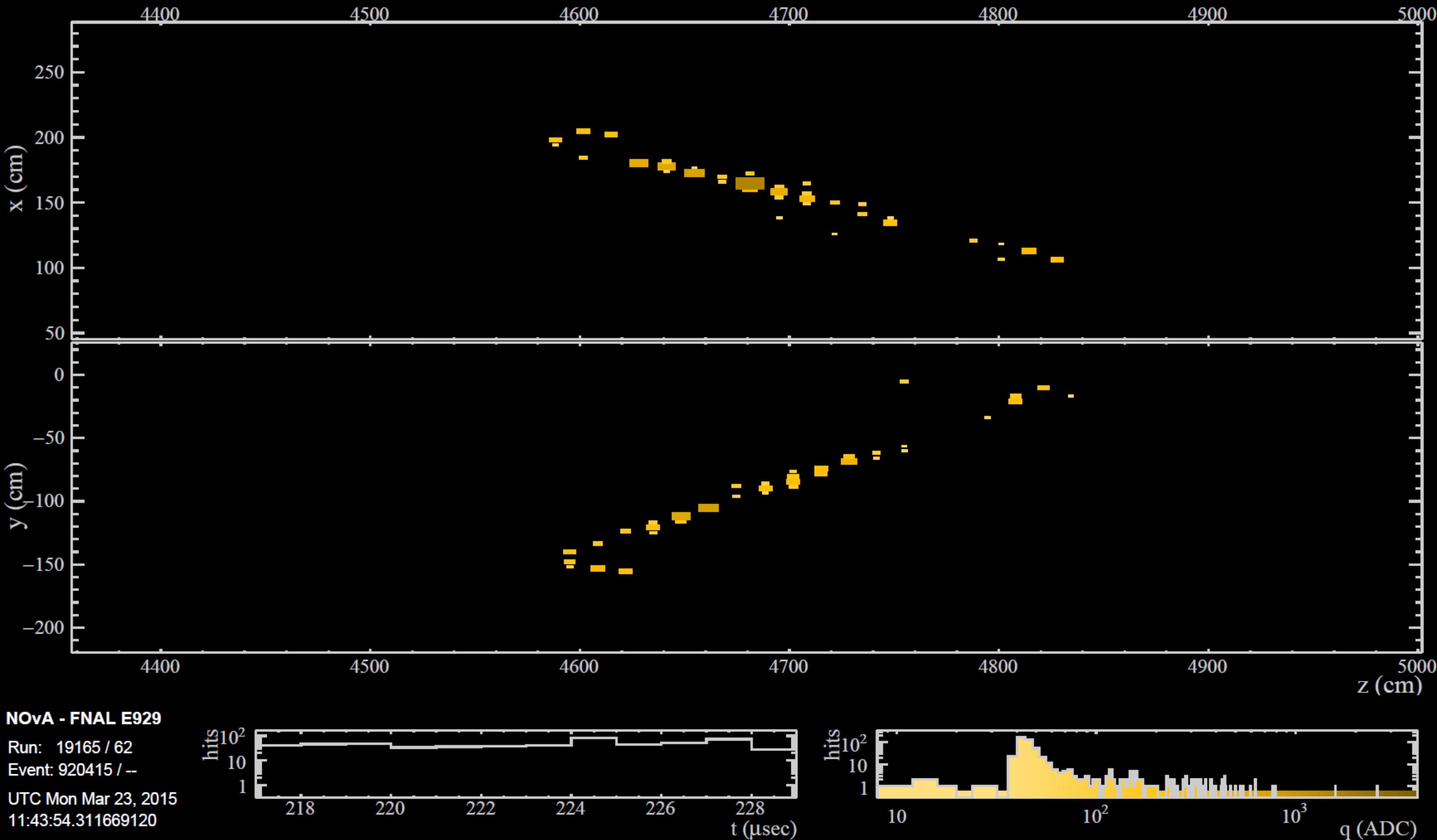
(2) High-energy sideband

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

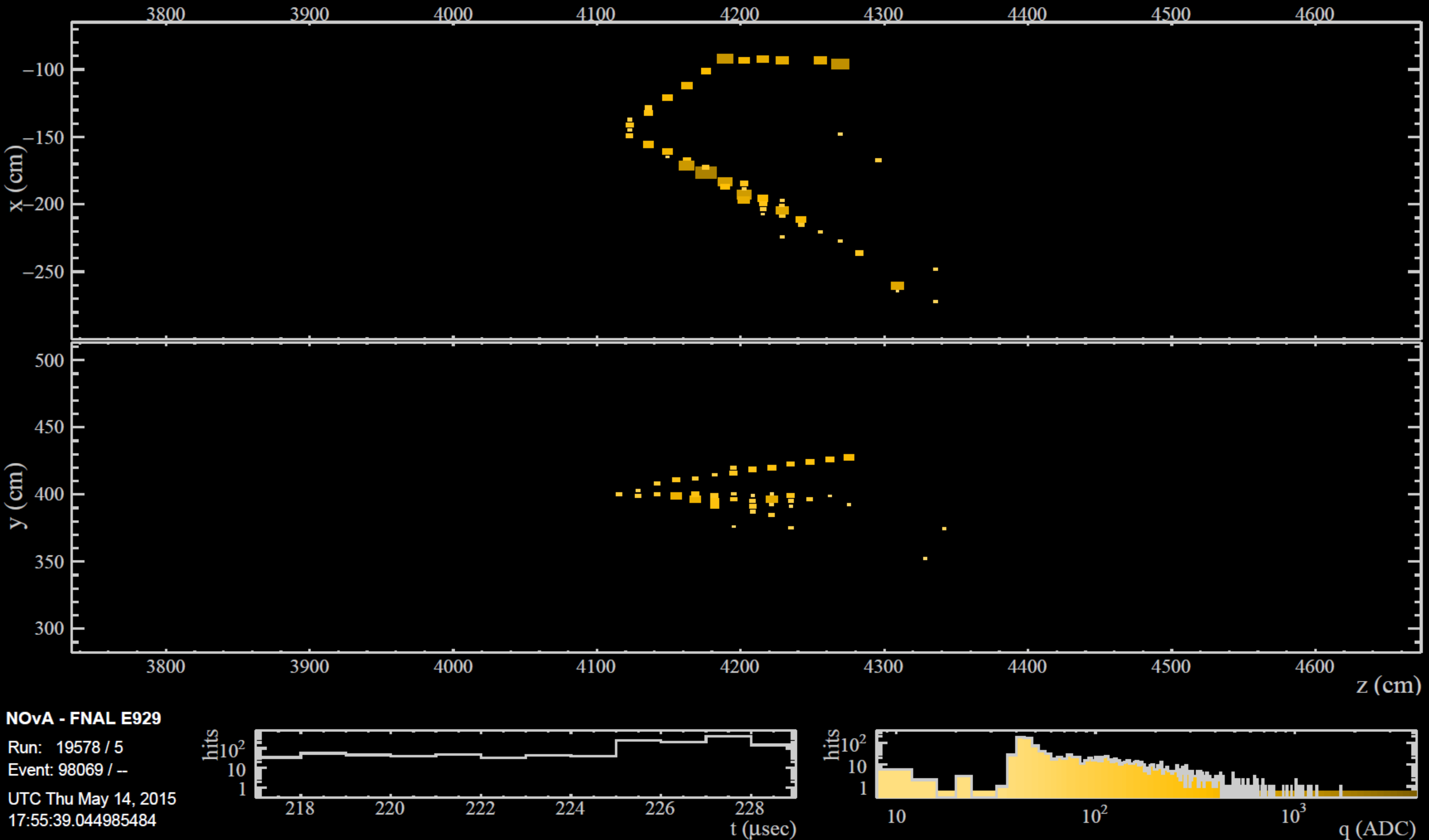
Far Detector selected ν_e CC candidate



Far Detector selected ν_e CC candidate



Far Detector selected ν_e CC candidate



Far Detector selected events

LID: 6 ν_e candidates

3.3σ significance for ν_e appearance

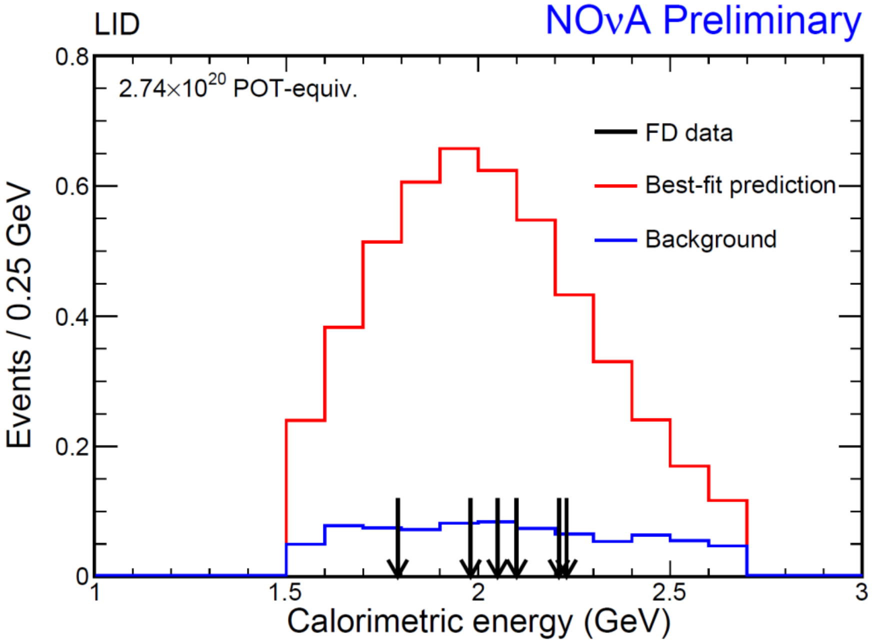
At right:

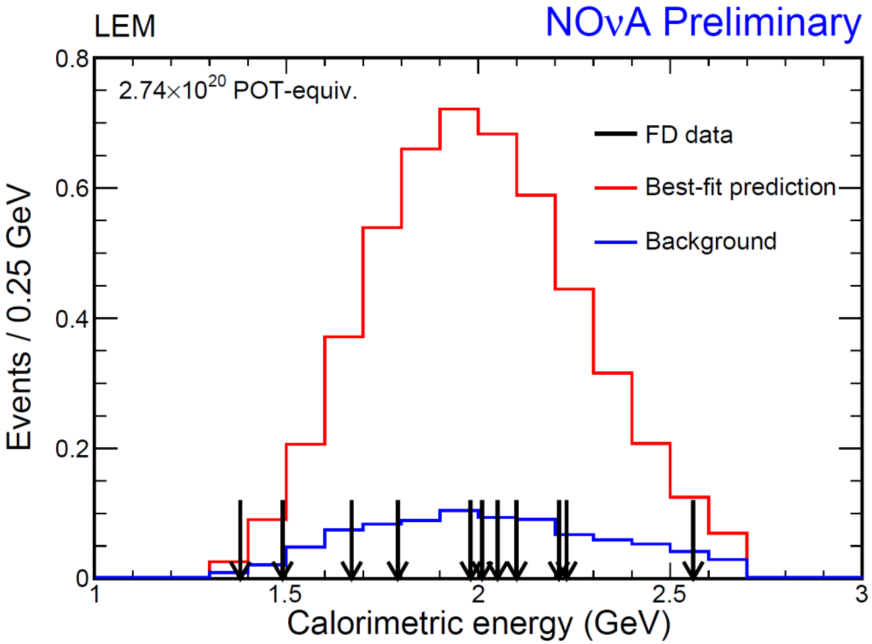
Calorimetric energy

LEM: 11 ν_e candidates

5.5σ significance for ν_e appearance

(All 6 LID events present in LEM set)

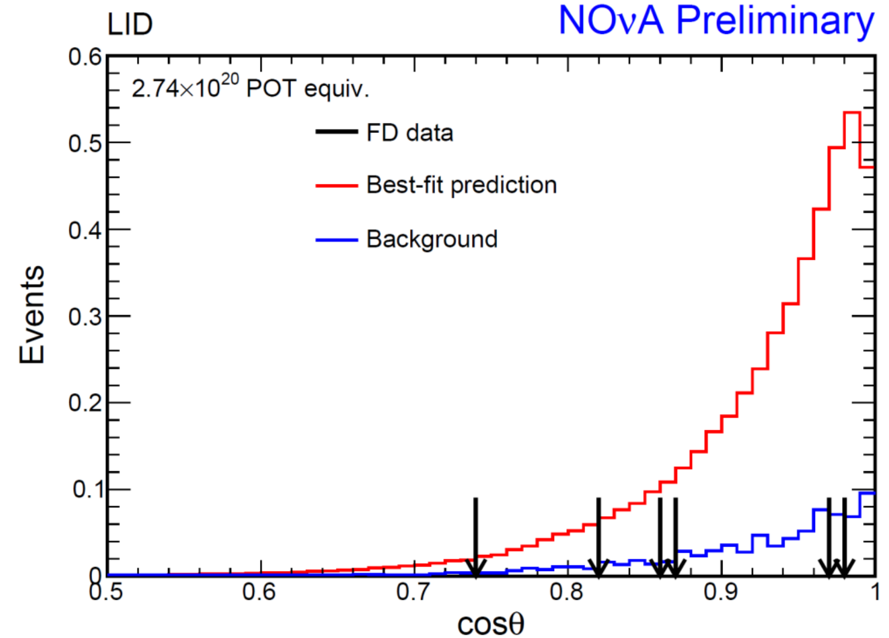




Far Detector selected events

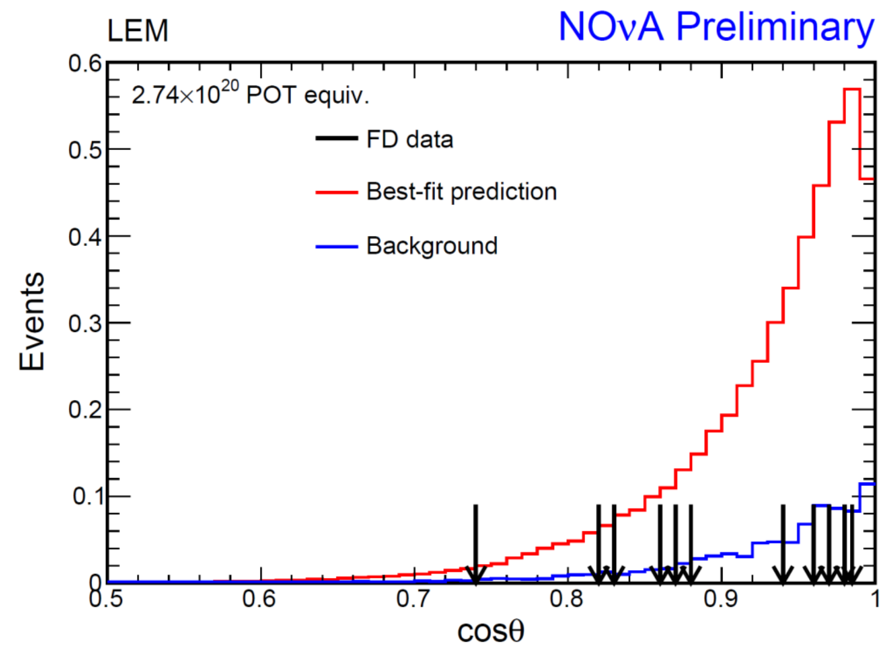
LID: **6 ν_e candidates**

3.3σ significance for ν_e appearance



At right:

Reconstructed direction of leading shower



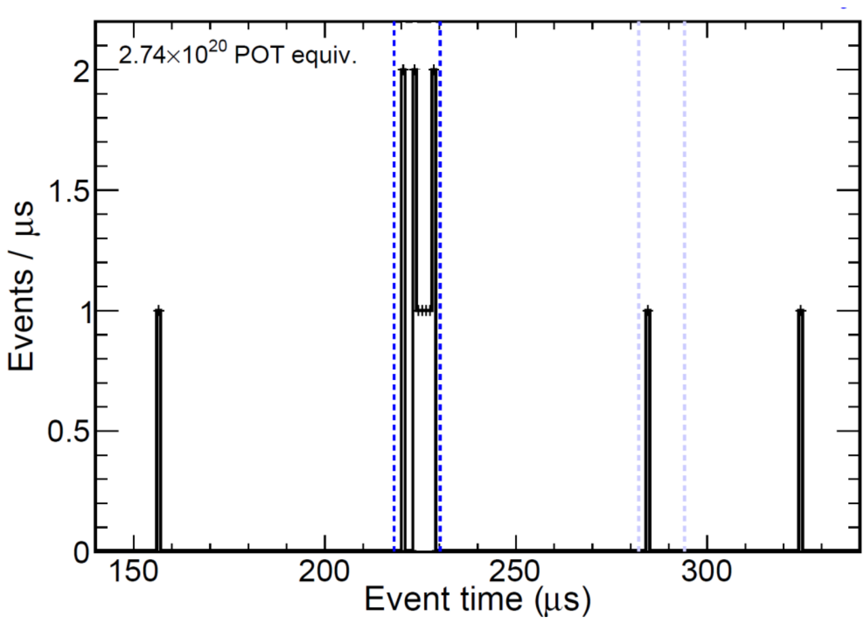
LEM: **11 ν_e candidates**

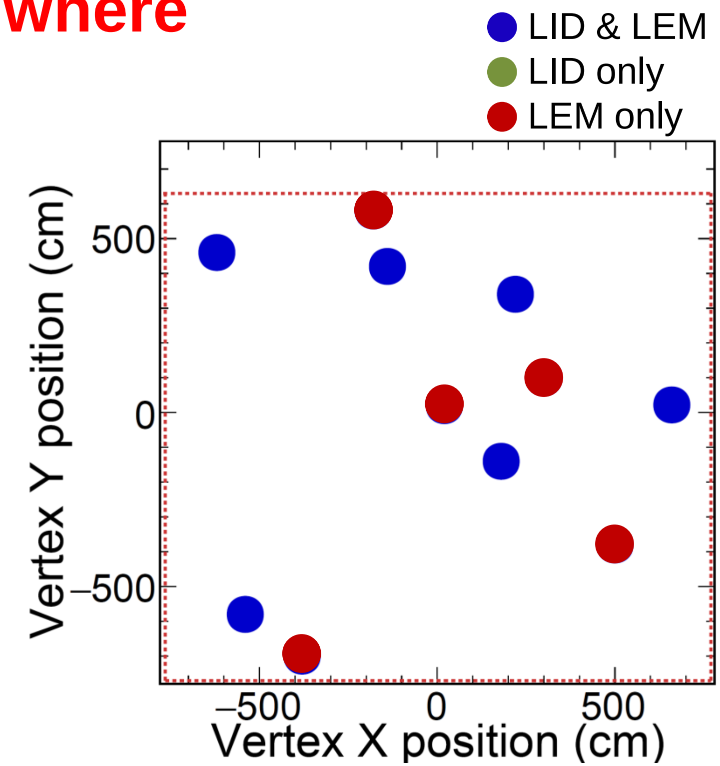
5.5σ significance for ν_e appearance

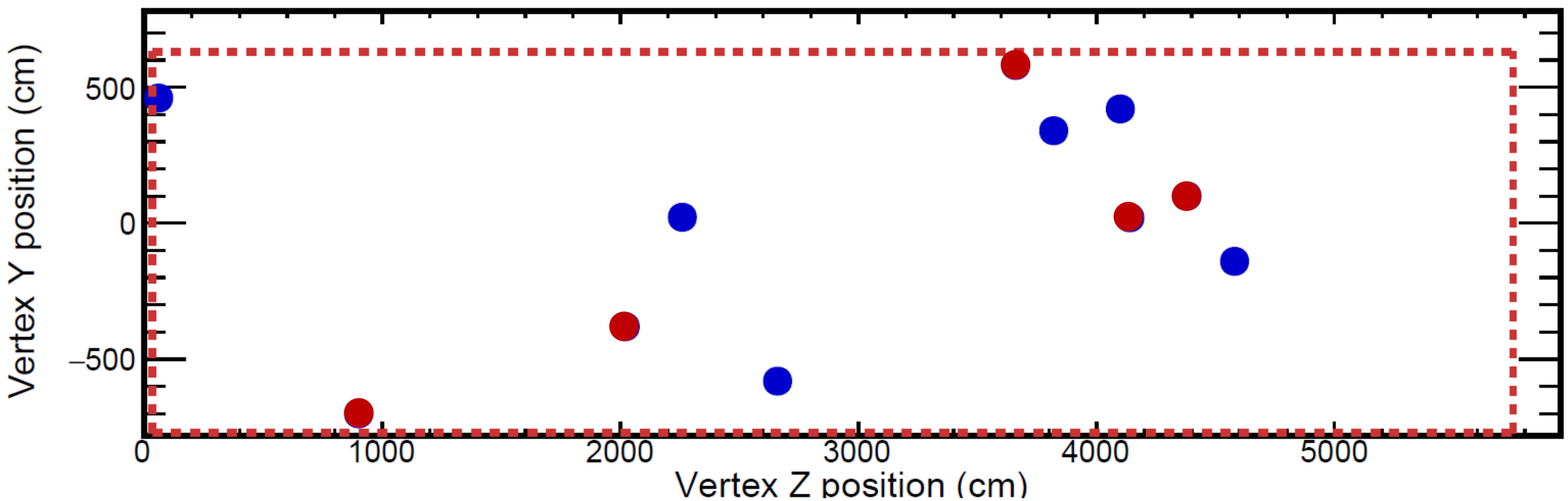
(All 6 LID events present in LEM set)

FD ν_e CC candidates: when and where

(LID + LEM events)







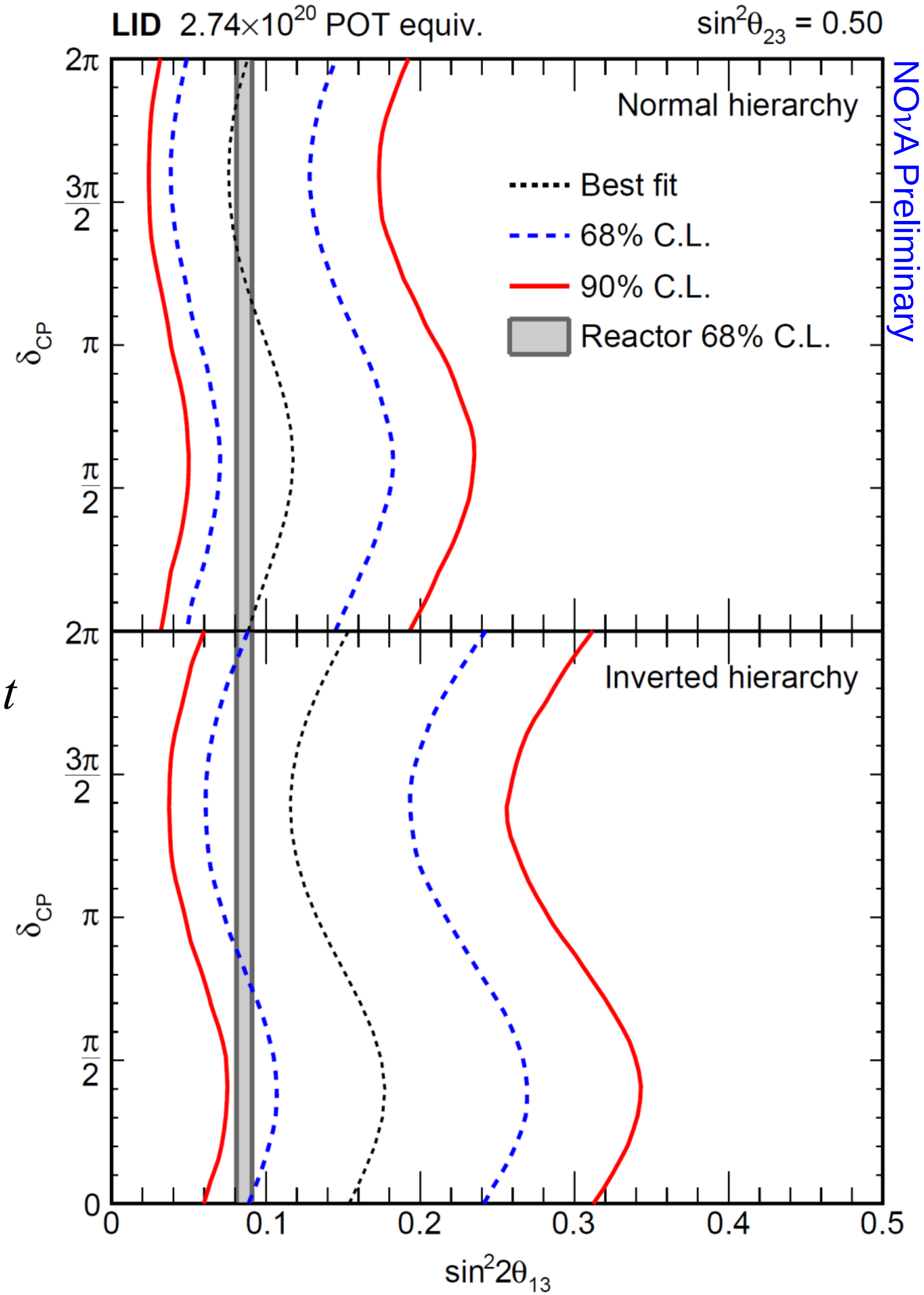
Note: Second timing window at +64 μs required for some of the early data.

Result using LID selector

FD selection: **6 ν_e candidates**

For **(δ_{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

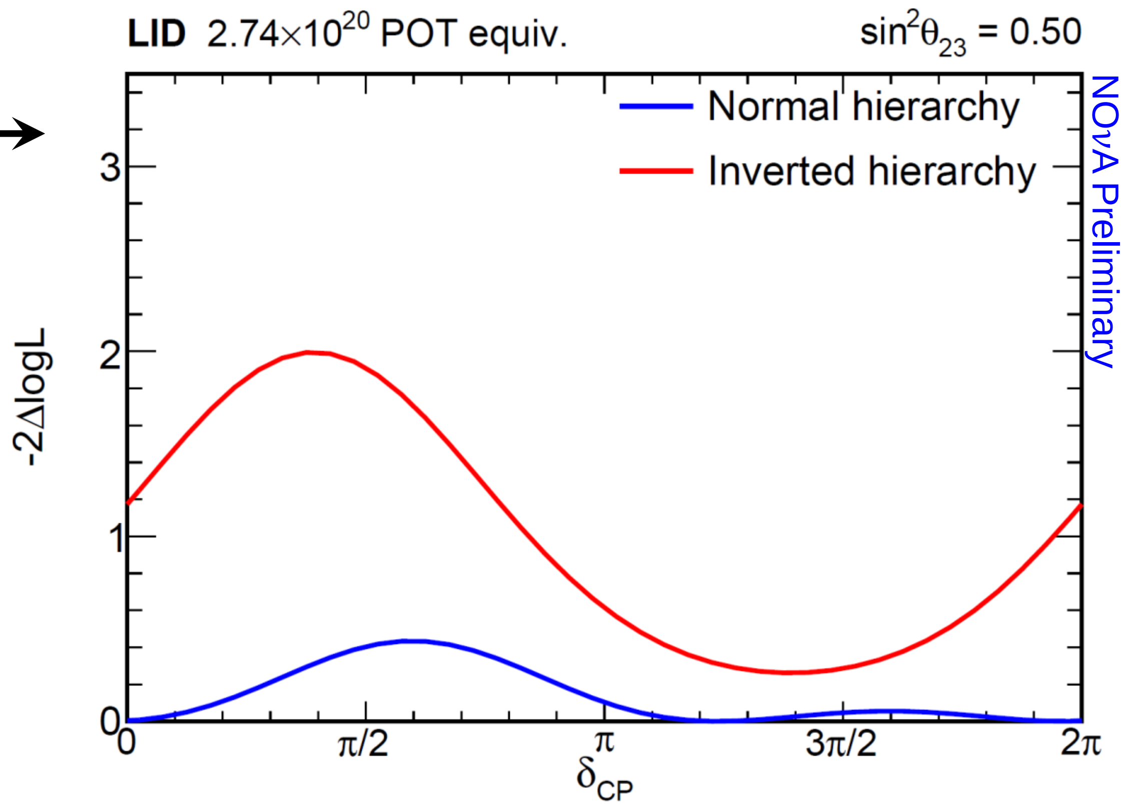


Result using LID selector

Applying **global reactor constraint** of $\sin^2 2\theta_{13} = 0.086 \pm 0.005$

- Again apply Feldman-Cousins procedure to interpret $-2\Delta\log L$
  Note: noticeable deviations from simple interpretation expected in this case
  [*e.g.*, Elevant and Schwetz, arxiv:1506.07685]

First, $-2\Delta\log L$ itself ⟶



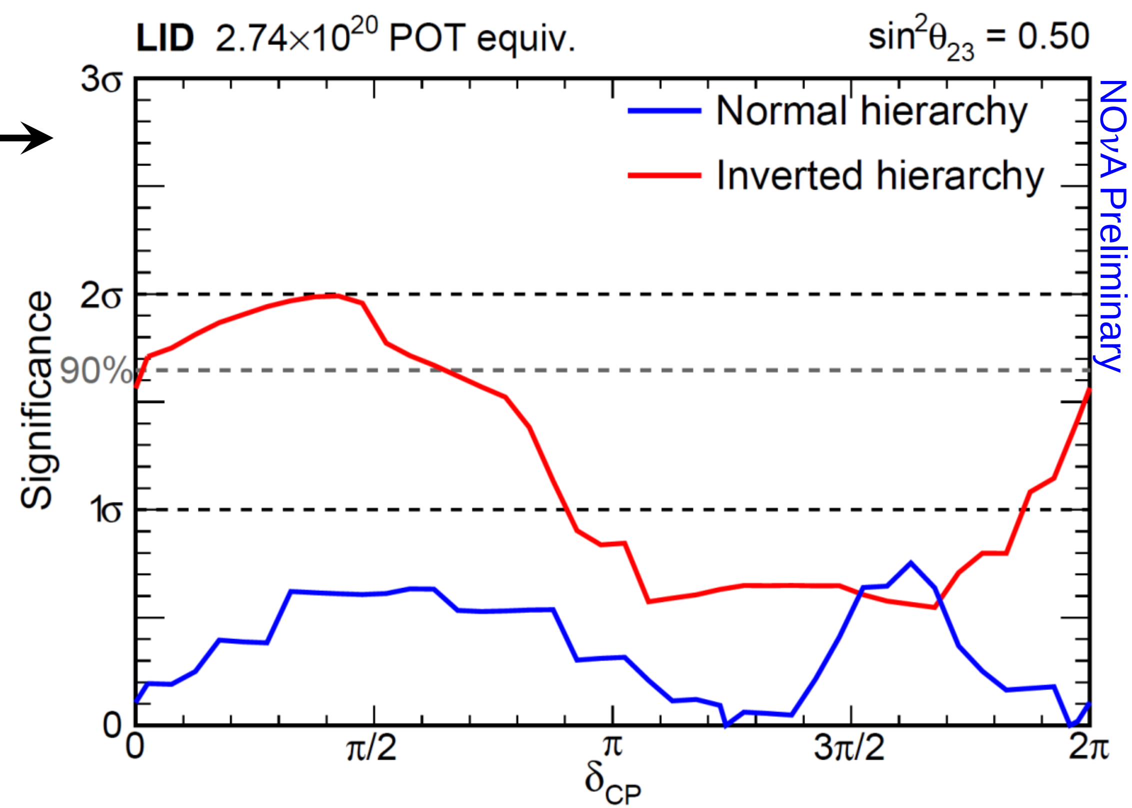
Result using LID selector

Applying **global reactor constraint** of $\sin^2 2\theta_{13} = 0.086 \pm 0.005$

- Again apply Feldman-Cousins procedure to interpret $-2\Delta\log L$
  Note: noticeable deviations from simple interpretation expected in this case
  [*e.g.*, Elevant and Schwetz, arxiv:1506.07685]

Other assumptions for $\sin^2\theta_{23}$ shown in backup

Converted into significance →
[steps due to discrete nature of counting expt.]



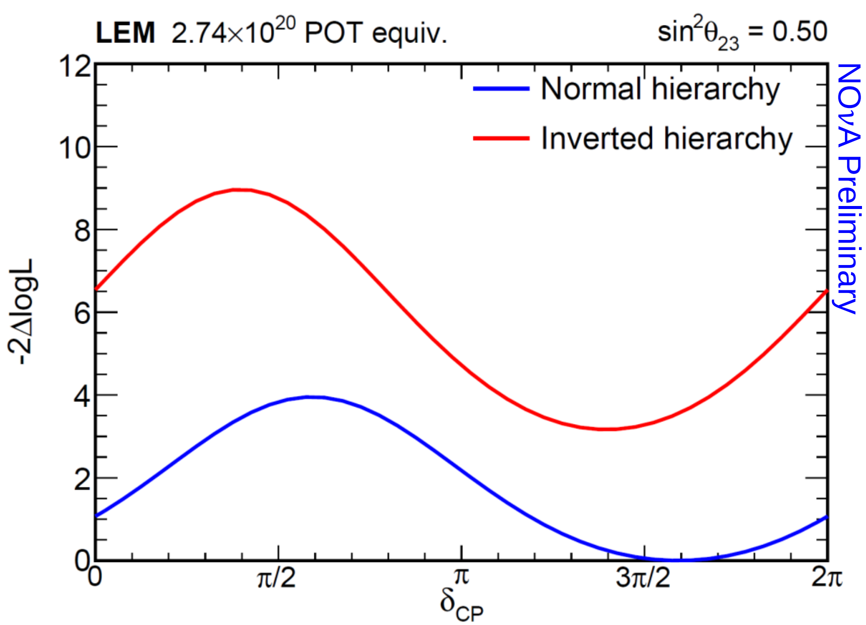
For all $\sin^2\theta_{23}$ in [0.4, 0.6]

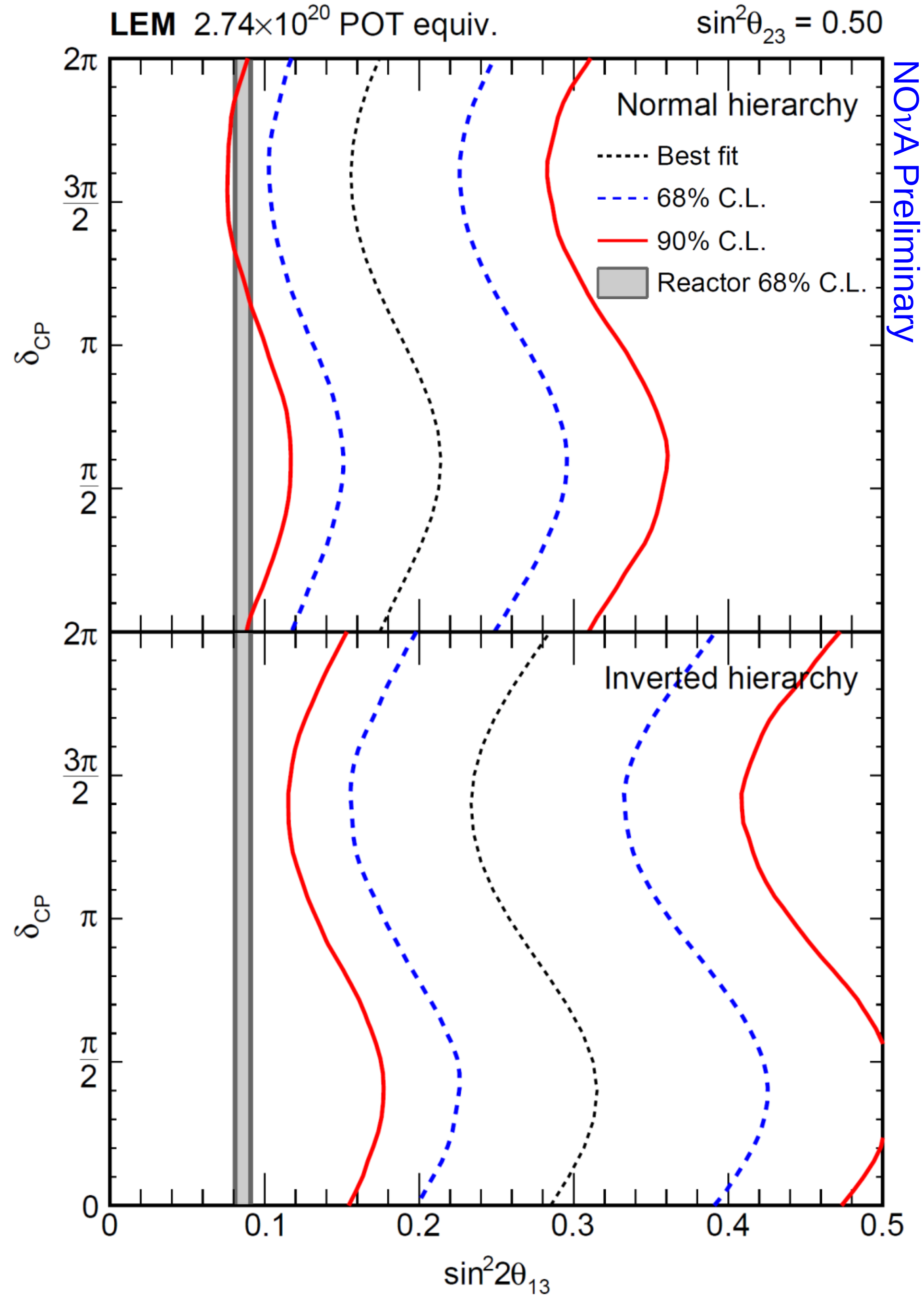
IH for $\boldsymbol{\delta \in [\,0, 0.8\pi\,]}$ is mildly disfavored ($>1\sigma$)

Result using LEM selector

FD selection: **11 ν_e candidates**

***Below:* With reactor constraint applied**
(significance on next page)





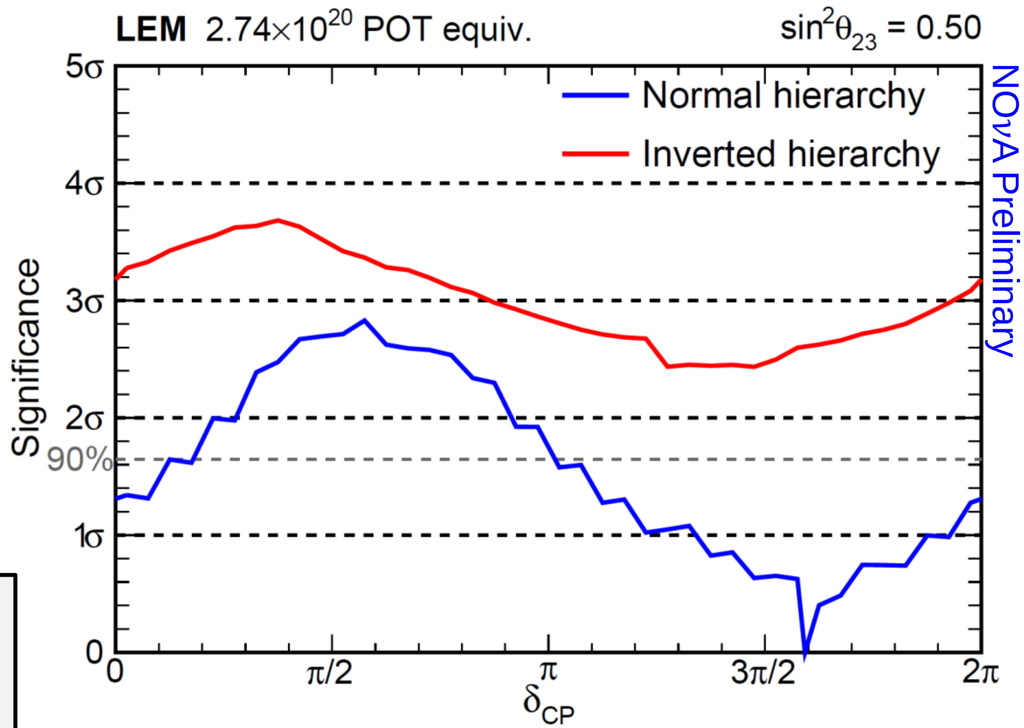
Other assumptions for $\sin^2\theta_{23}$ shown in backup

Result using LEM selector

For all $\sin^2\theta_{23}$ in [0.4, 0.6]

IH is disfavored at **>2.2σ**

NH for **$\delta \in$ [0, π]** is mildly disfavored **(>1σ)**



LID, LEM Consistency

- Both prefer **normal hierarchy**
- Both prefer **δ near 3π/2**
- Given expected correlations, the observed event counts yield a reasonable **mutual *p*-value of 10%.**

The specific point **IH, $\delta=\pi/2$** is disfavored at

1.6σ [LID], **3.2σ** [LEM]

for all **$\sin^2\theta_{23}$ in [0.4, 0.6]**

What's next?

- **We are currently in a scheduled beam shutdown**
  - Beam returns **early October.**
  - Rapid commissioning **toward 700 kW**
    (increased Booster rep rate, 4(6)+6 slip-stacking)

- ***FD exposure:* expect sizeable increase in short time**
  - Full FD, higher beam powers $\Rightarrow$ **>2× data set next summer**

- **Other NOνA physics: *Program underway***
  - Neutrino cross sections
    (millions of ND interactions already in-hand)
  - Sterile neutrinos, non-standard interactions, *CPT* tests
  - Supernova neutrinos
  - Dark matter and monopole searches
  - *and more…*

Summary

$$\Delta m^2_{32} = \begin{cases} +2.37^{+0.16}_{-0.15} & \text{[NH]} \\ -2.40^{+0.14}_{-0.17} & \text{[IH]} \end{cases} \times 10^{-3}\ \text{eV}^2$$

With **2.74×10^20 POT-equiv. exposure**…

$$\sin^2(\theta_{23}) = 0.51 \pm 0.10$$

$\nu_\mu \to \nu_\mu$

- Unambiguous **ν_μ disappearance signature**
- **6.5% measurement** of atm. mass splitting, and θ_{23} measurement consistent with **maximal mixing**

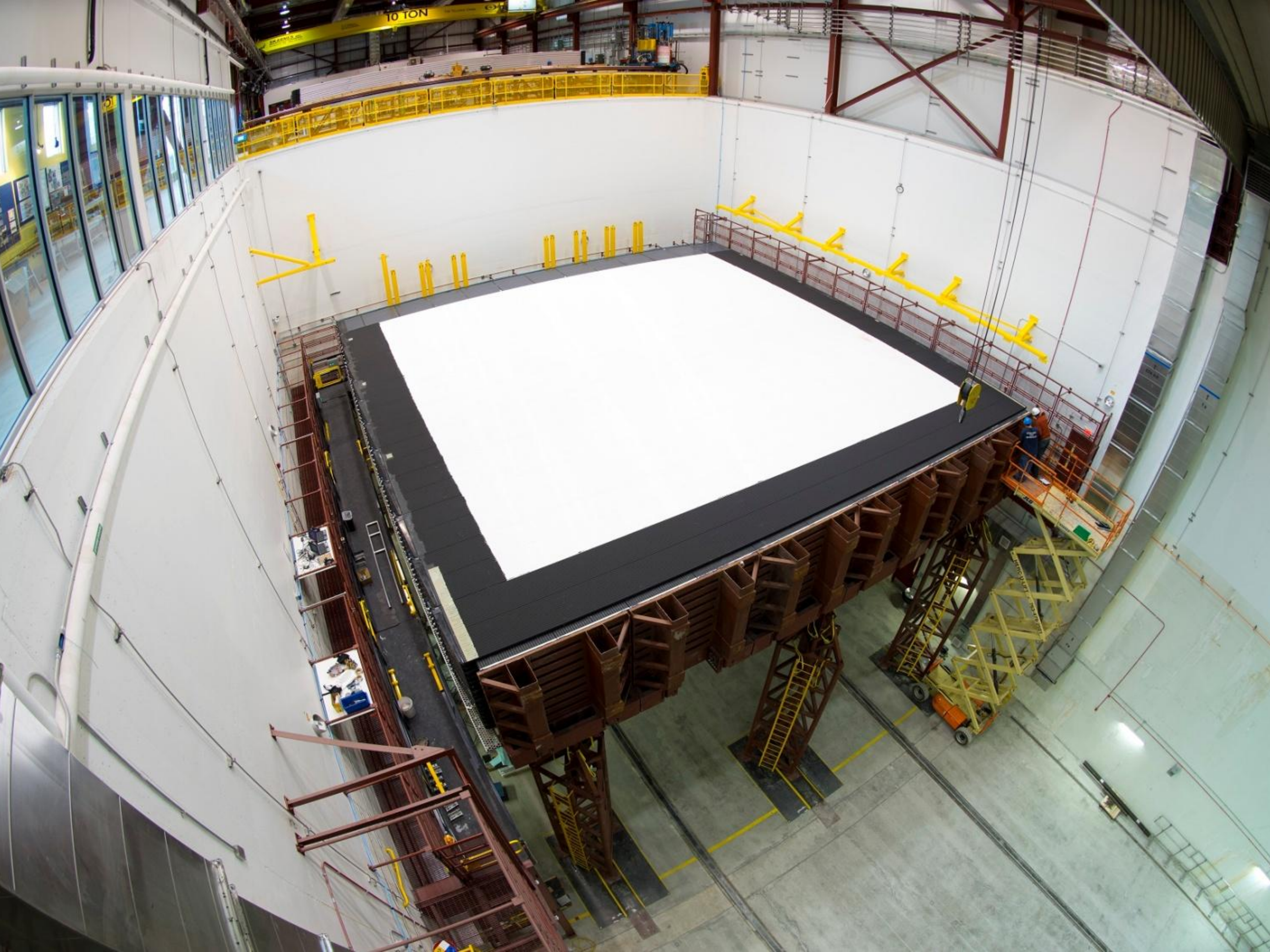
$\nu_\mu \to \nu_e$

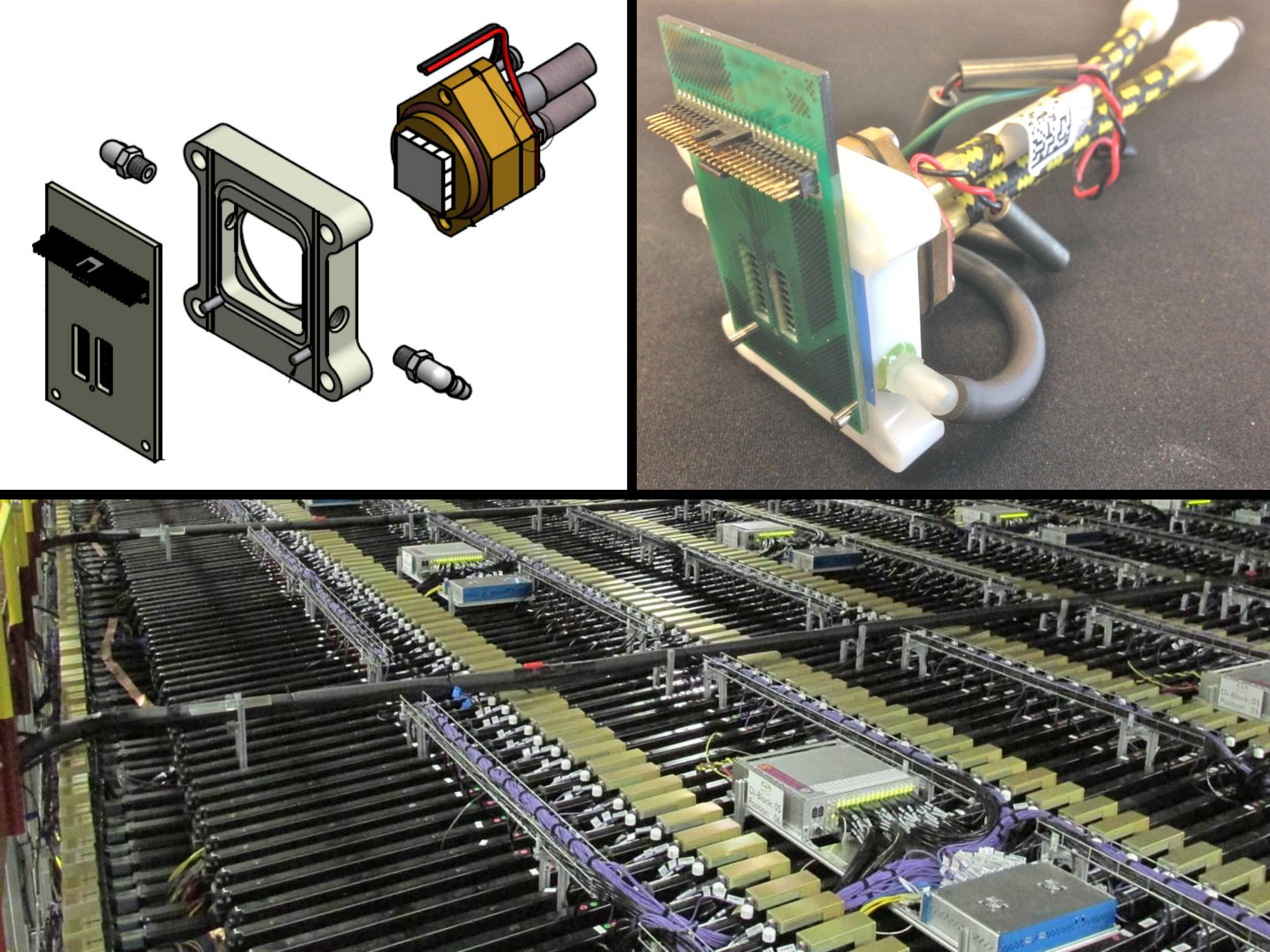
- **ν_e appearance** signal at **3.3σ** for primary ν_e selector, **5.5σ** for secondary selector.
- At max. mixing, **disfavor IH** for **$\delta \in [\ 0, 0.6\pi\ ]$** at 90% C.L. w/ primary selector. With secondary selector, further **preference for NH.**

Above results obtained with 7.6% of baseline NOνA exposure.

Much more to come!

Extras

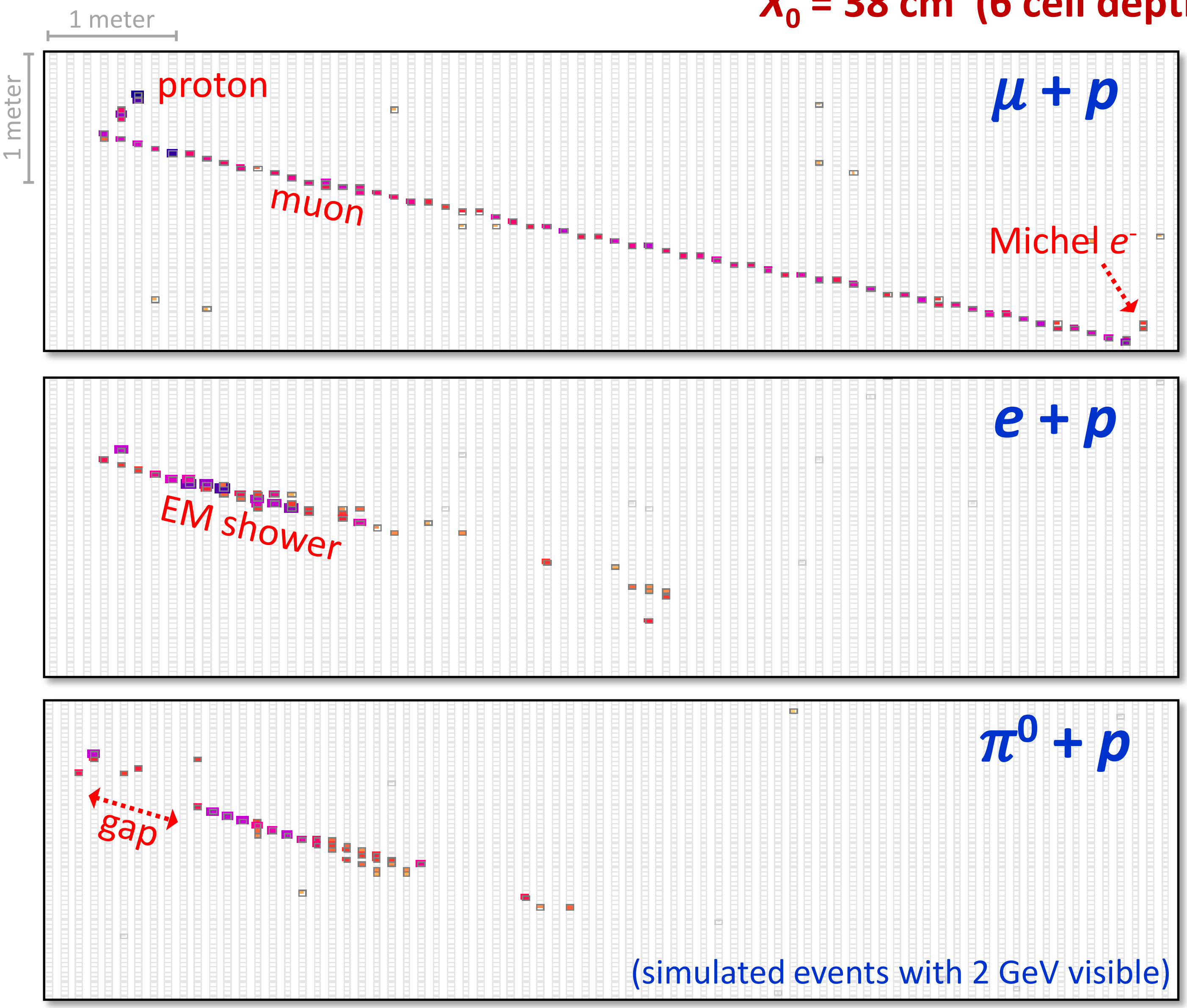

10 TON

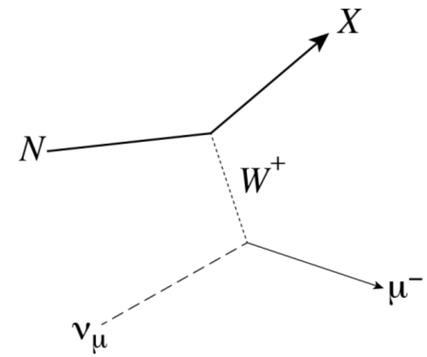


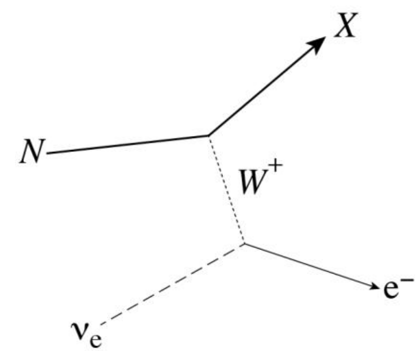
Events in NOνA

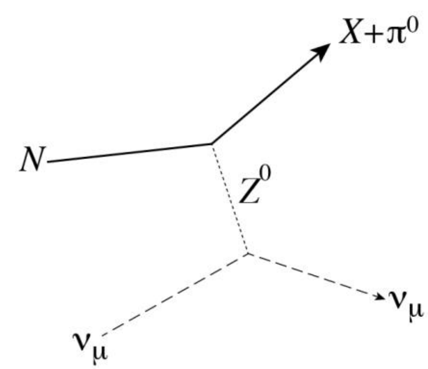
Superb spatial granularity for a detector of this scale

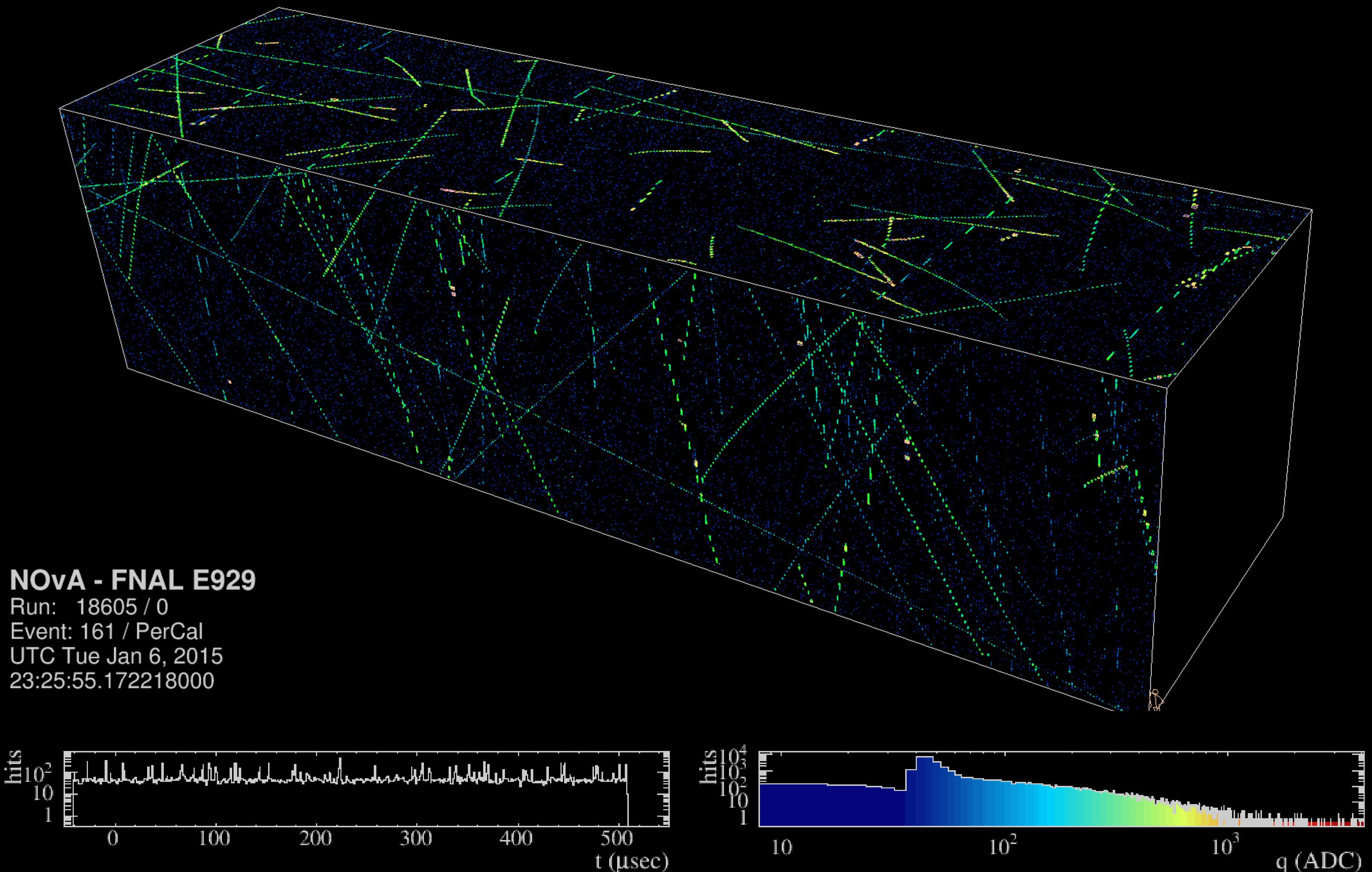
X_0 = 38 cm (6 cell depths, 10 cell widths)

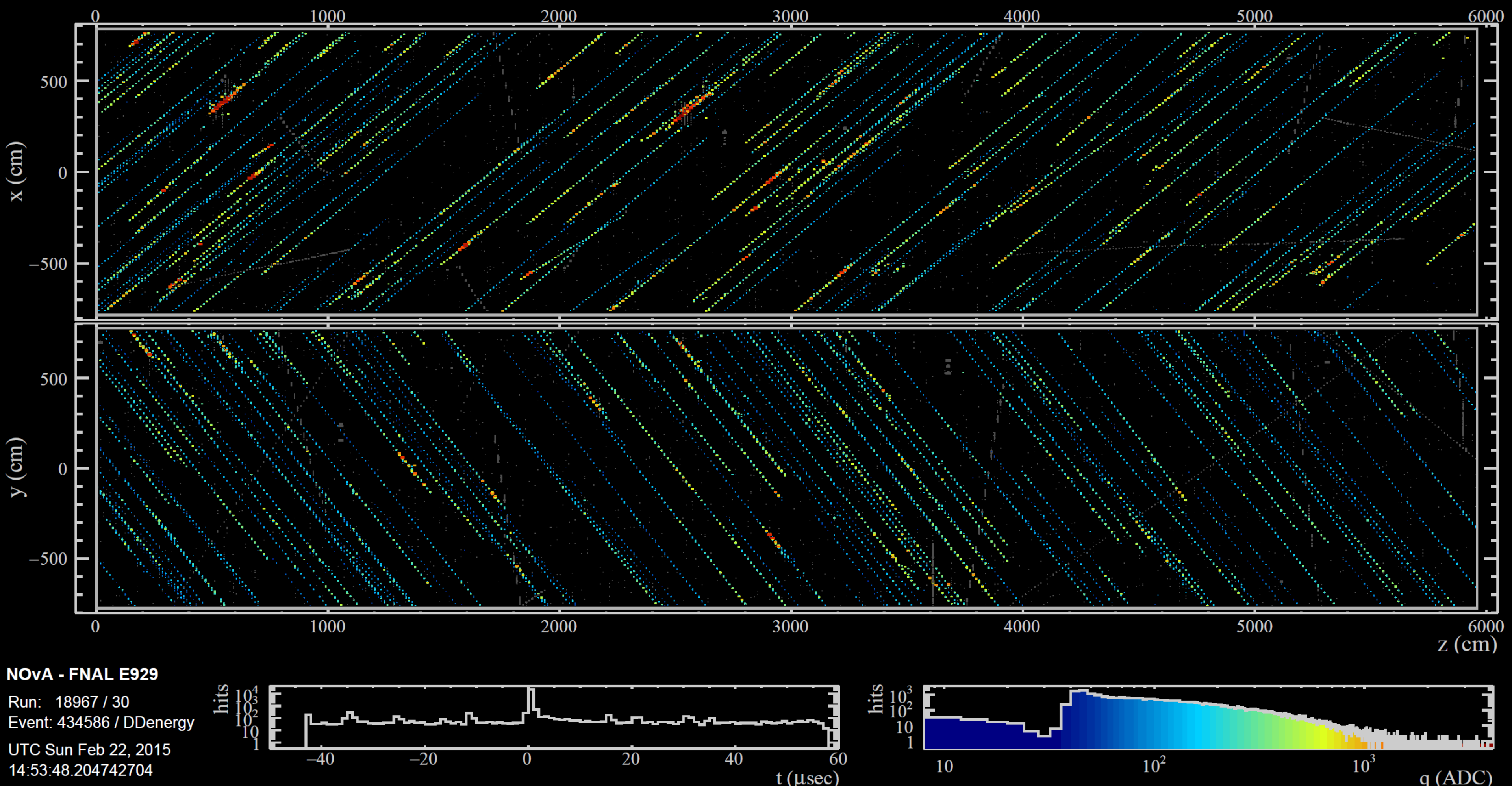






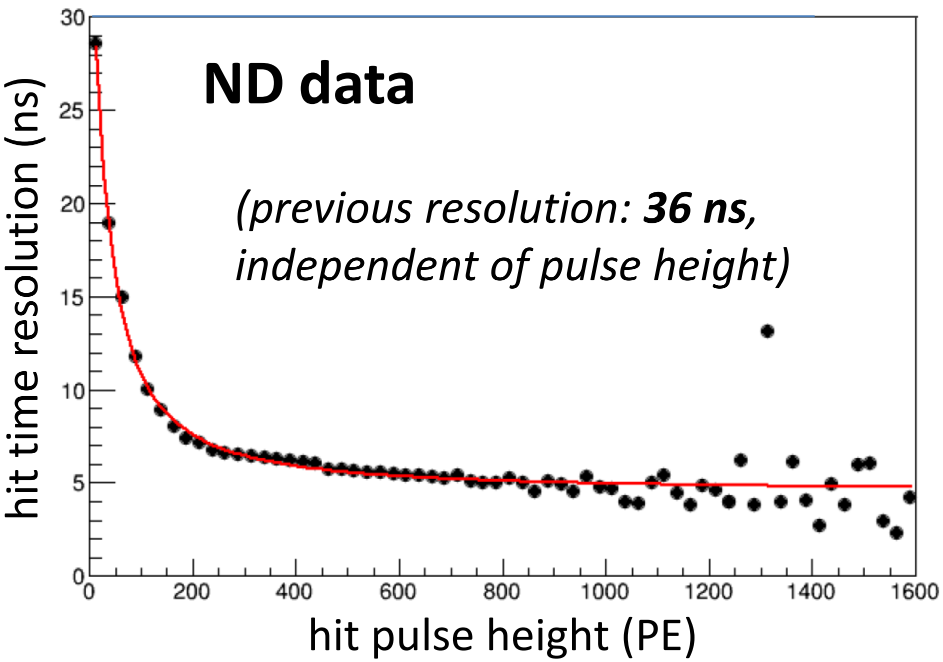


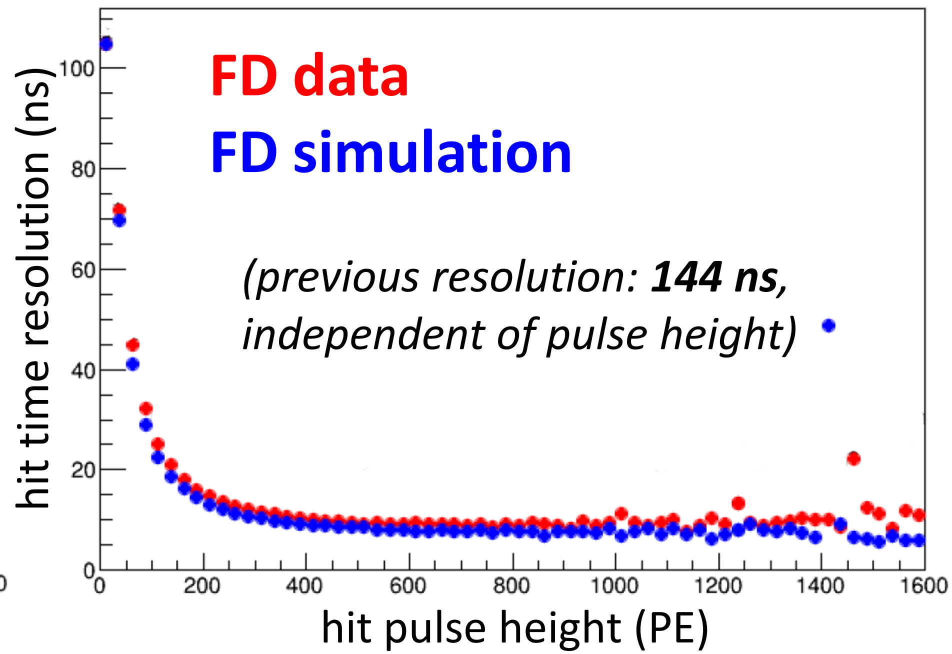

NOvA - FNAL E929
Run: 18605 / 0
Event: 161 / PerCal
UTC Tue Jan 6, 2015
23:25:55.172218000
hits
t (μsec)
q (ADC)


0
1000
2000
3000
4000
5000
6000
500
0
−500
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18967 / 30
Event: 434586 / DDenergy
UTC Sun Feb 22, 2015
14:53:48.204742704
hits
t (μsec)
−40
−20
0
20
40
60
q (ADC)
10
10^2
10^3

Timing resolution

- **Recently 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





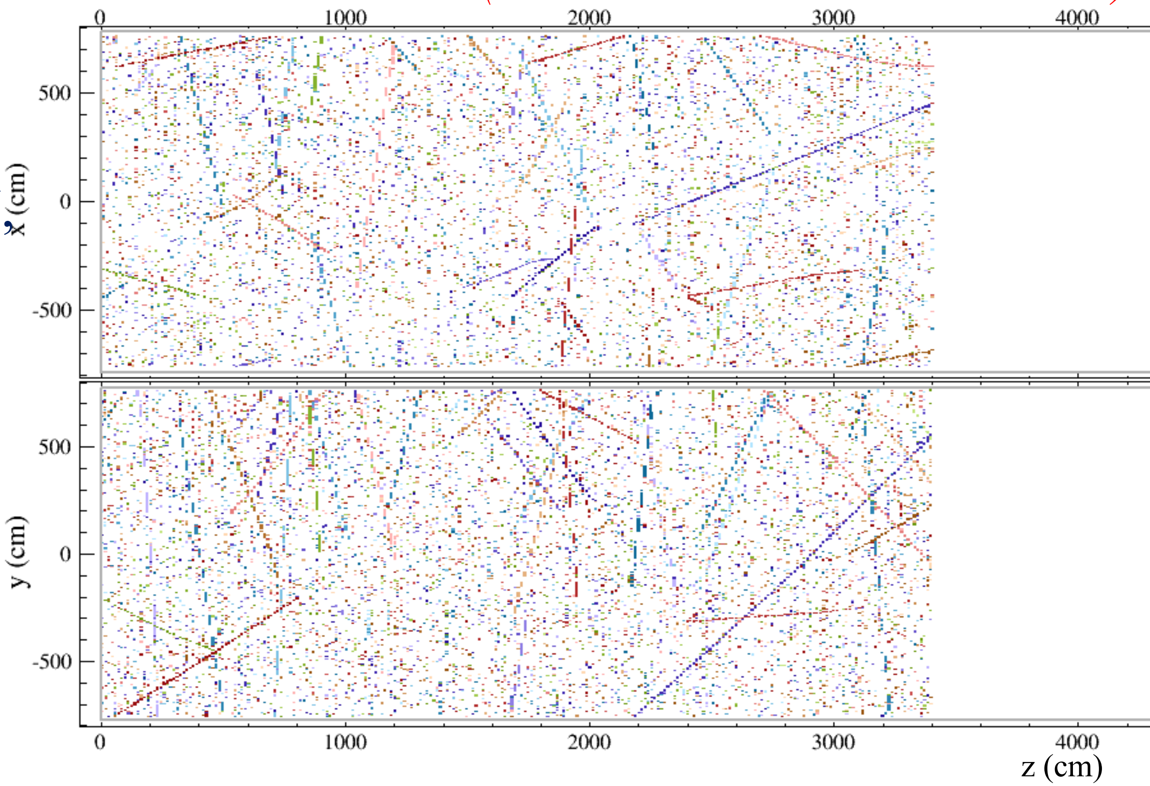
Isolating individual interactions

- 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***

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

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

- Algorithm inspired by DBSCAN, **M. Ester *et al.*** (1996)



According to FD simulation:
Avg. completeness: 99.3%
Avg. purity: 99.5%

(Actually improved beyond this now…)

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***

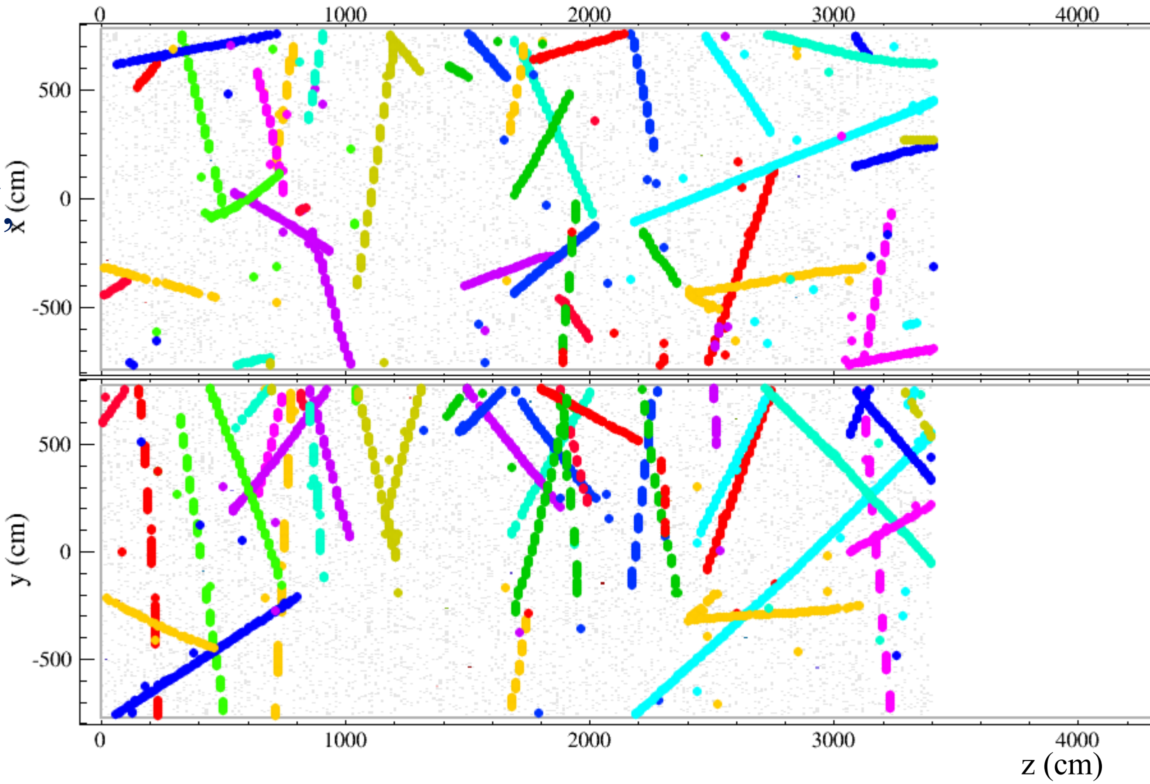
- Look for causally connectable **clusters in space/time**

- Algorithm inspired by DBSCAN, **M. Ester *et al.*** (1996)

According to FD simulation:
Avg. completeness: 99.3%
Avg. purity: 99.5%

(Actually improved beyond this now…)

Individual physics events isolated



Isolating individual interactions

- A standard trigger in the Far Detector (FD) records 550 μs of activity:

as low as possible)

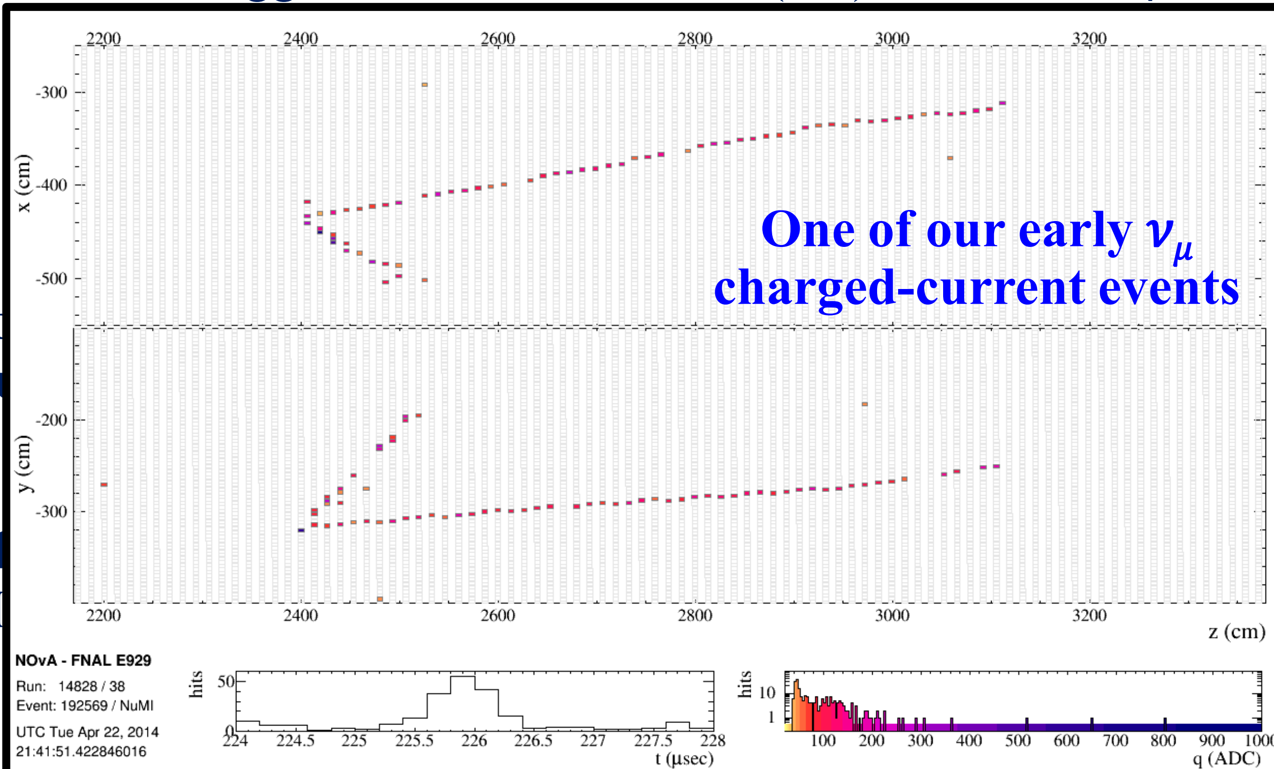
- Lo

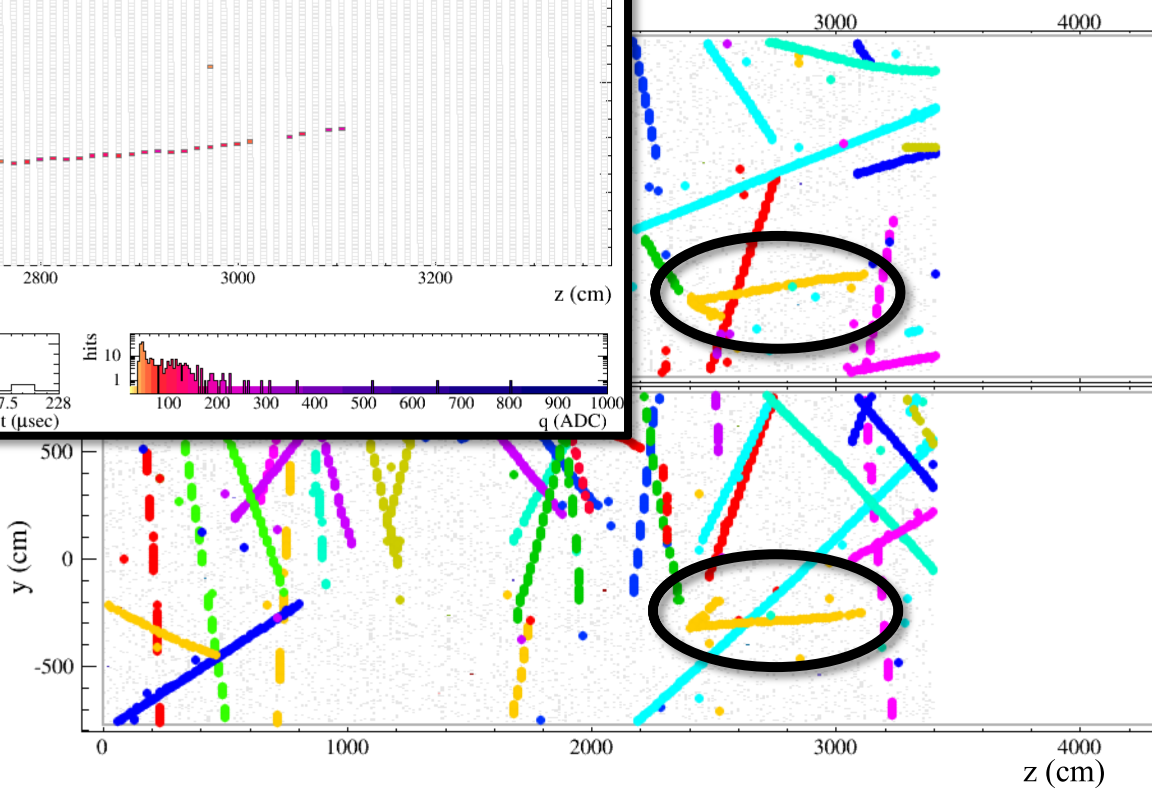
cl

physics events isolated

- Al

M





According to FD simulation:

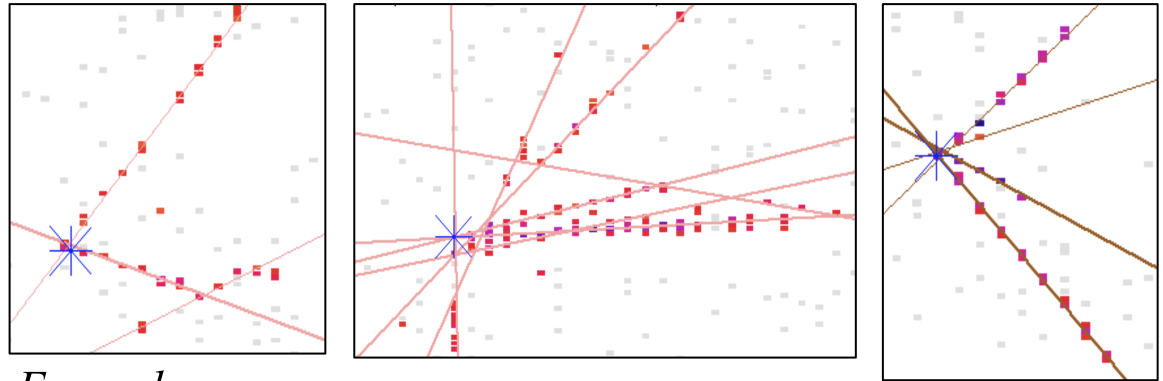
Avg. completeness: 99.3%

Avg. purity: 99.5%

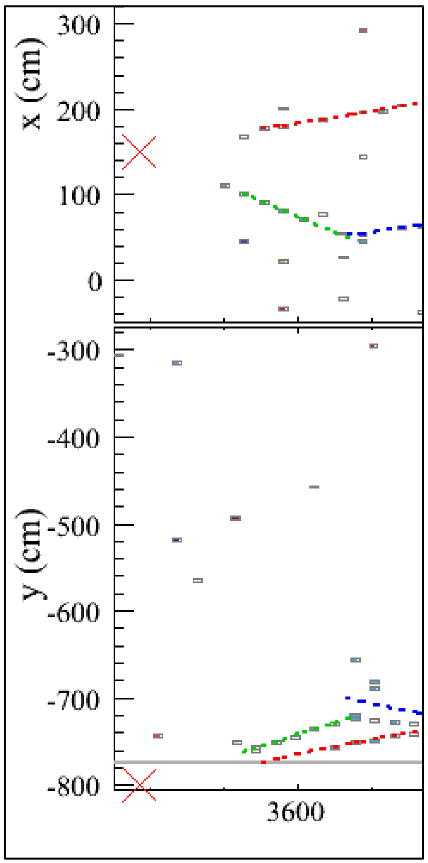
(Actually improved beyond this now…)

Event vertexing

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

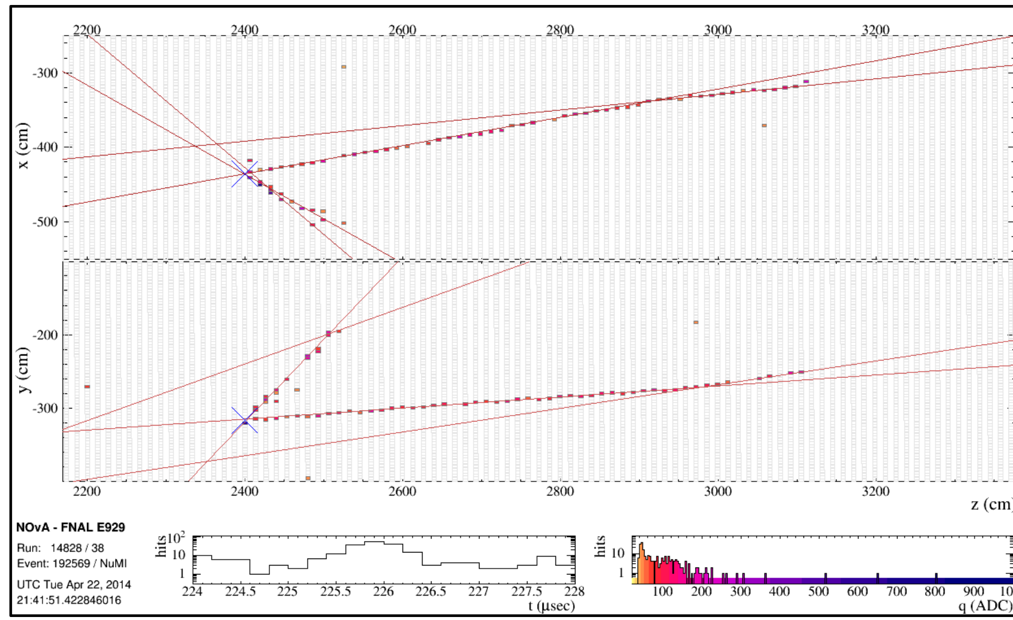


Examples…



A vertex outside the detector ←

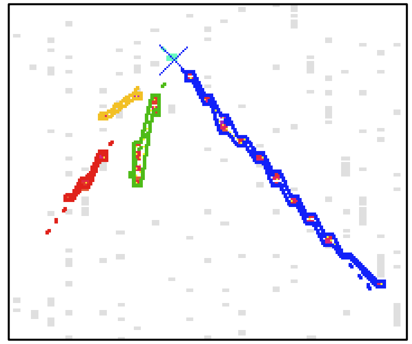
The FD ν_μ CC data event from earlier →



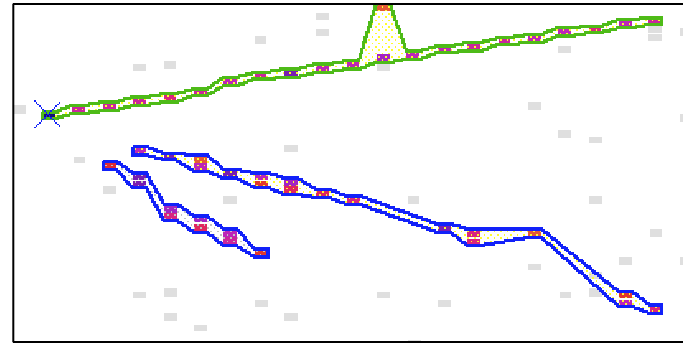
Vertex resolution for **charged-current events: 11 cm**
Vertex resolution for **neutral-current events: 29 cm**

Prong clustering

- Given a seed vertex, look for **clusters in angular space** around it.



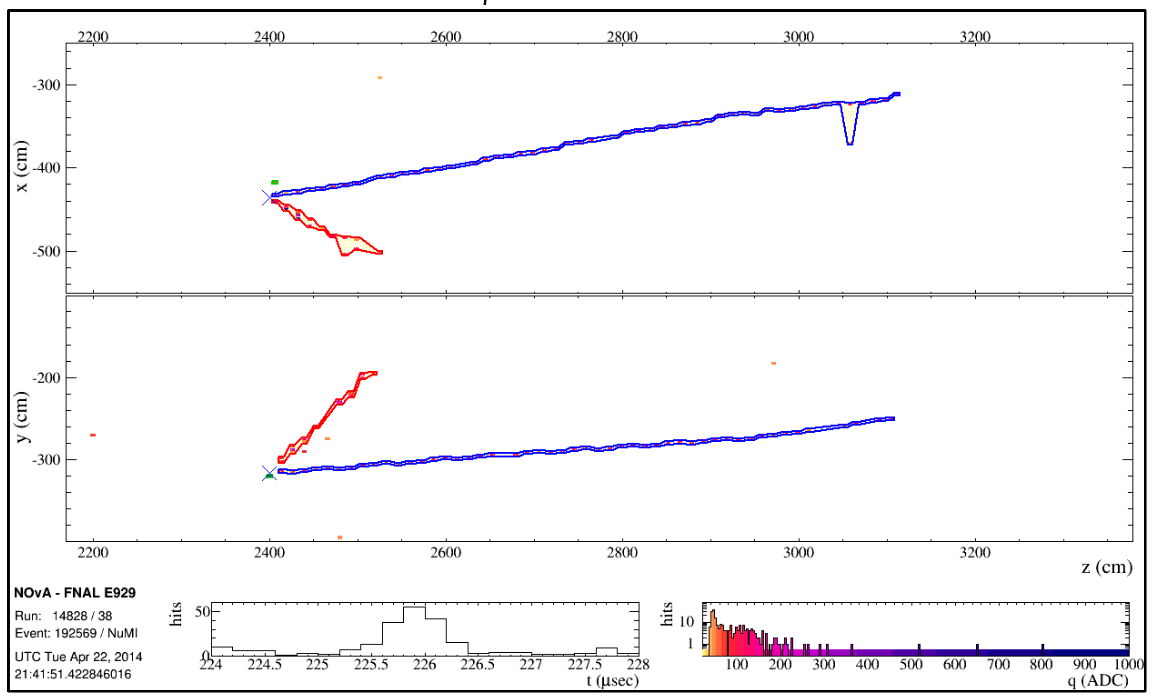
Cosmic ray neutron event in the FD data



Simulated ν_μ CC event

- Prongs in each view are matched based on topology and *dE*/*dx* to form 3D objects.

FD ν_μ CC data event

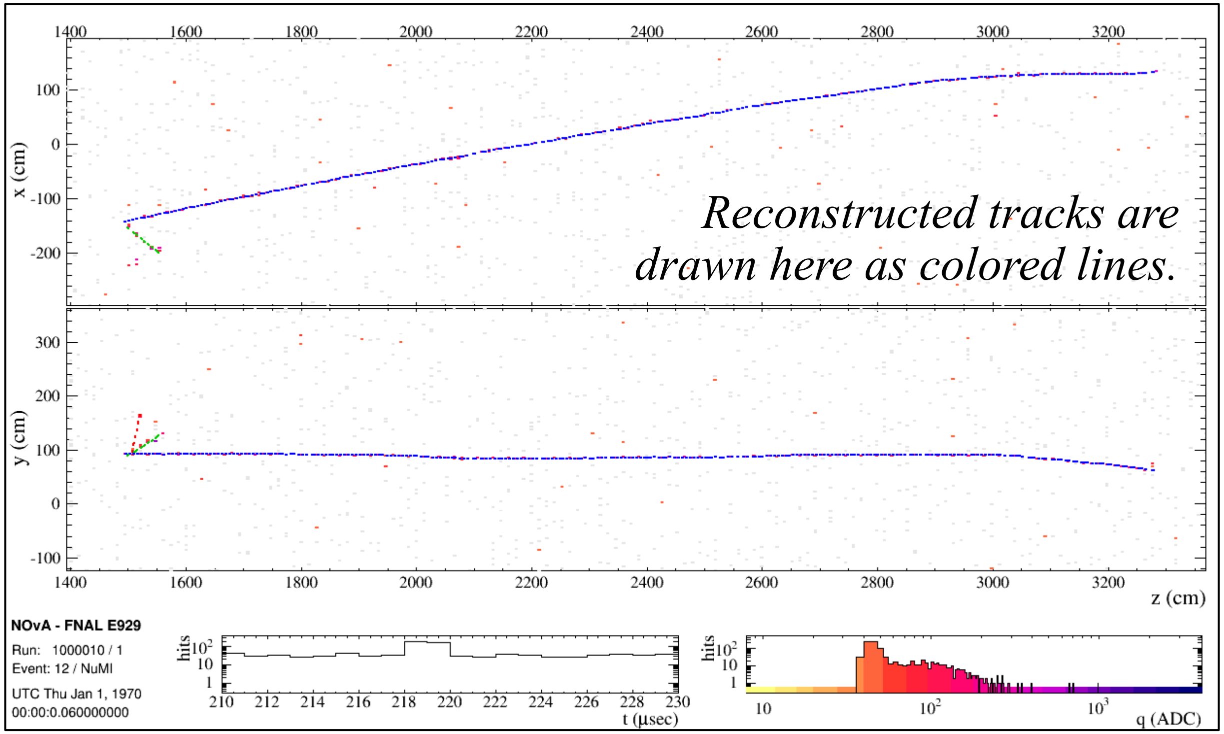


Prongs are drawn here by outlining the cells that belong to them.

Tracking

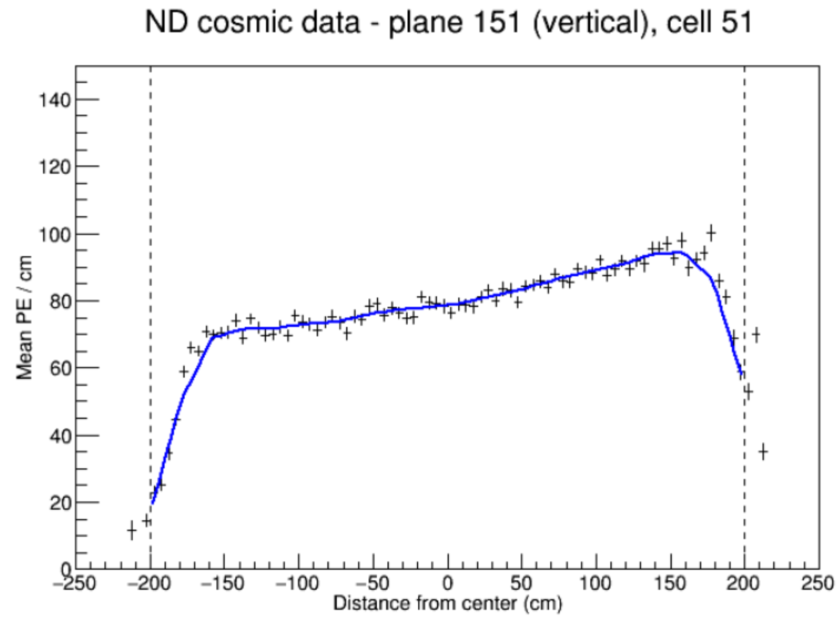
- **Two primary trackers** in use:
  - ***Cosmic ray tracker:*** lightweight, very fast, good for large calibration samples and online tools
  - ***Kalman filter tracker:*** more detailed, traces scattering for accurate energy, direction measurement.

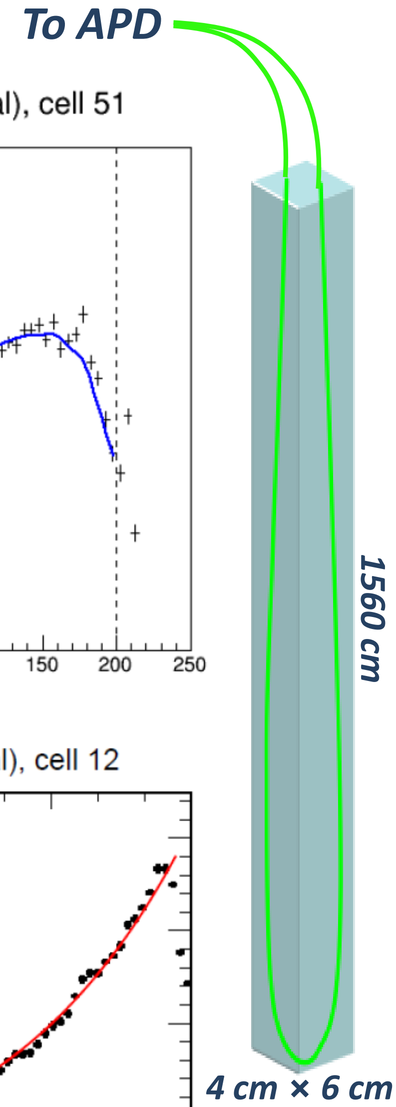
(simulated event)

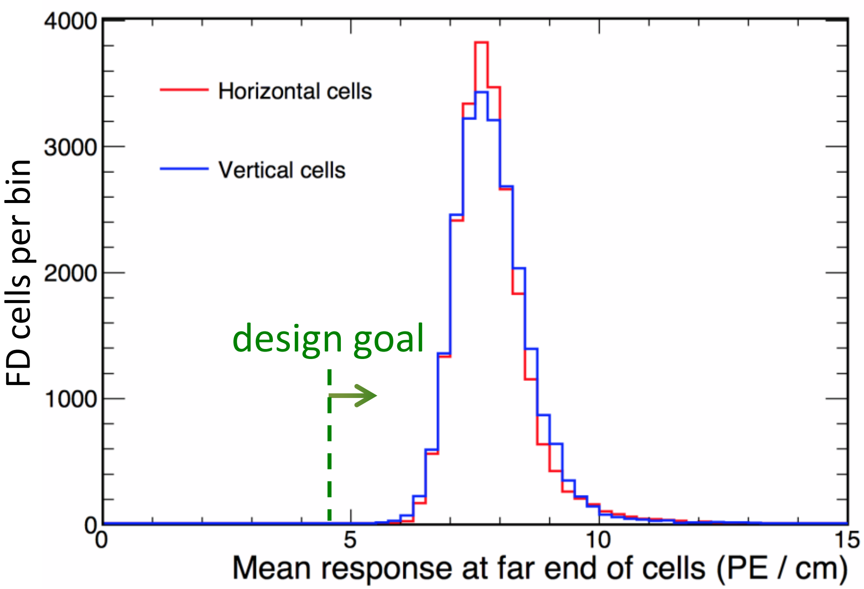


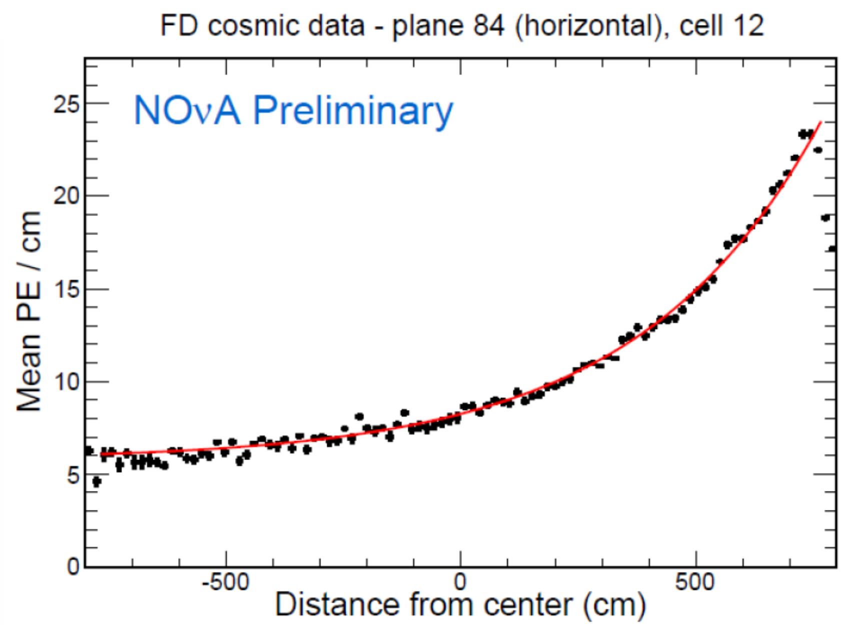
Calibration

- **Biggest effect** that needs correction is **attenuation** in the WLS fiber
- **Muons** (cosmic or ν-induced) used to probe detector response
- **Light level requirements** at end of cell **are well met**



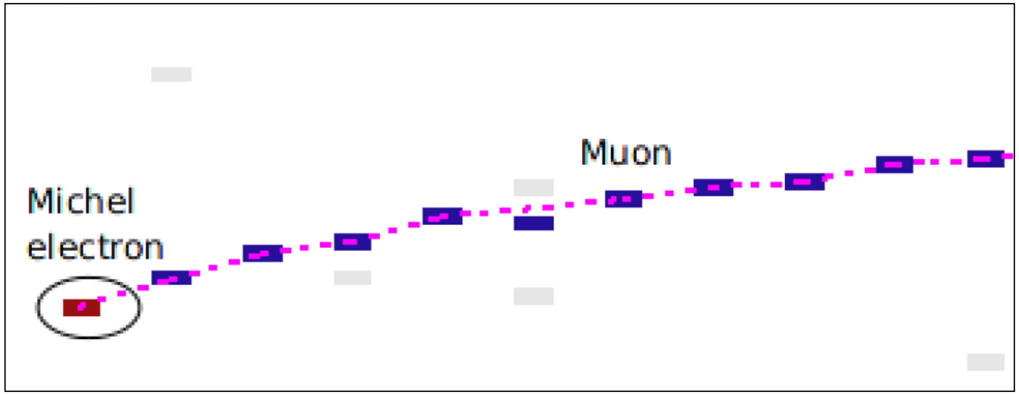


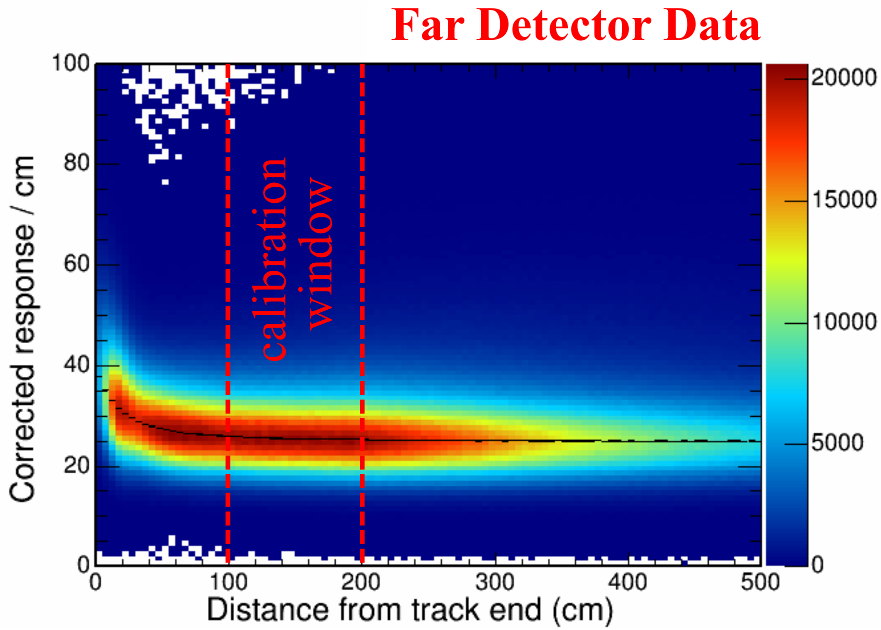


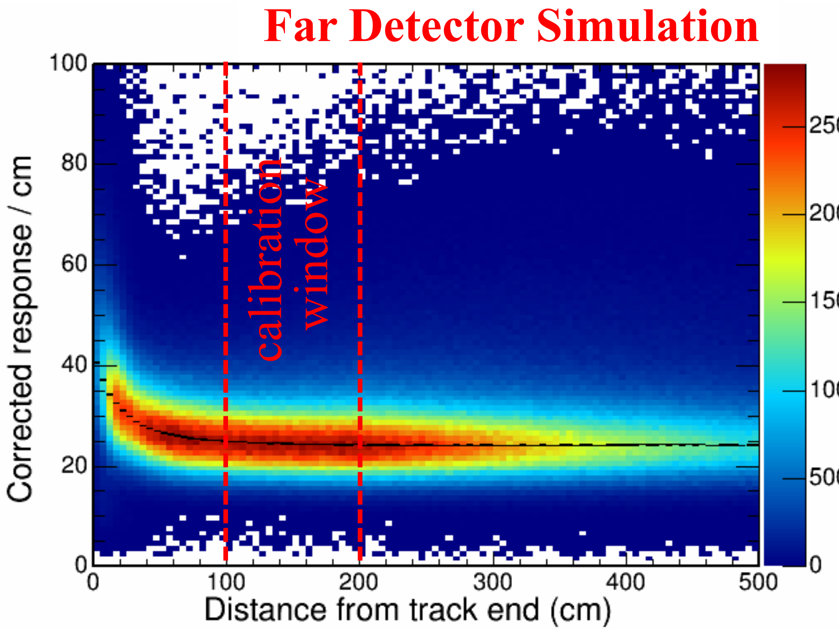


- **Stopping muons** provide a standard candle for setting the **absolute energy scale**
- Energy scale set using hits between **100 cm and 200 cm** from end of muon tracks

Michel electron tag yields very pure stopping muon sample





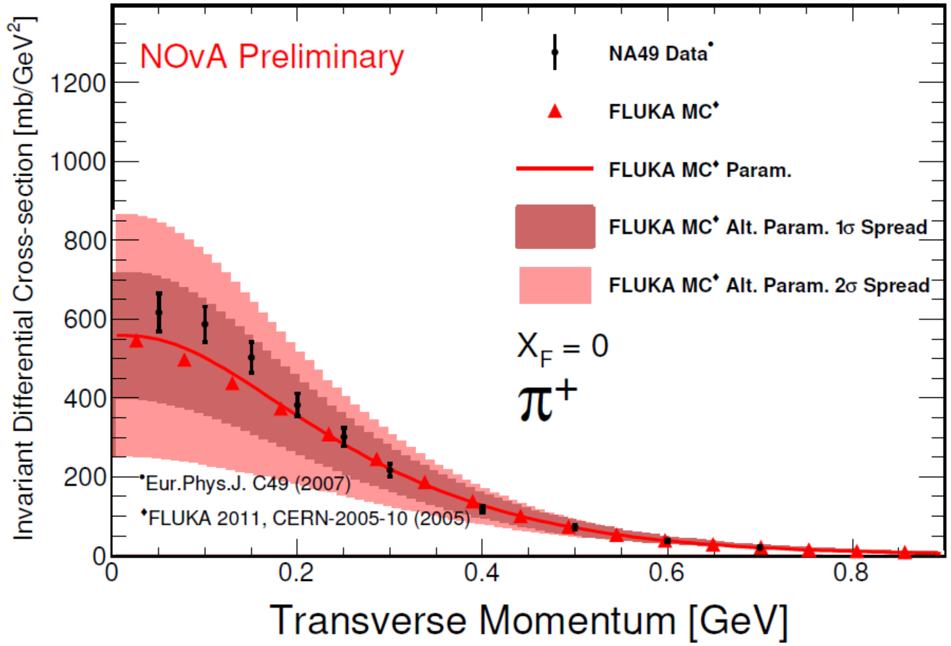


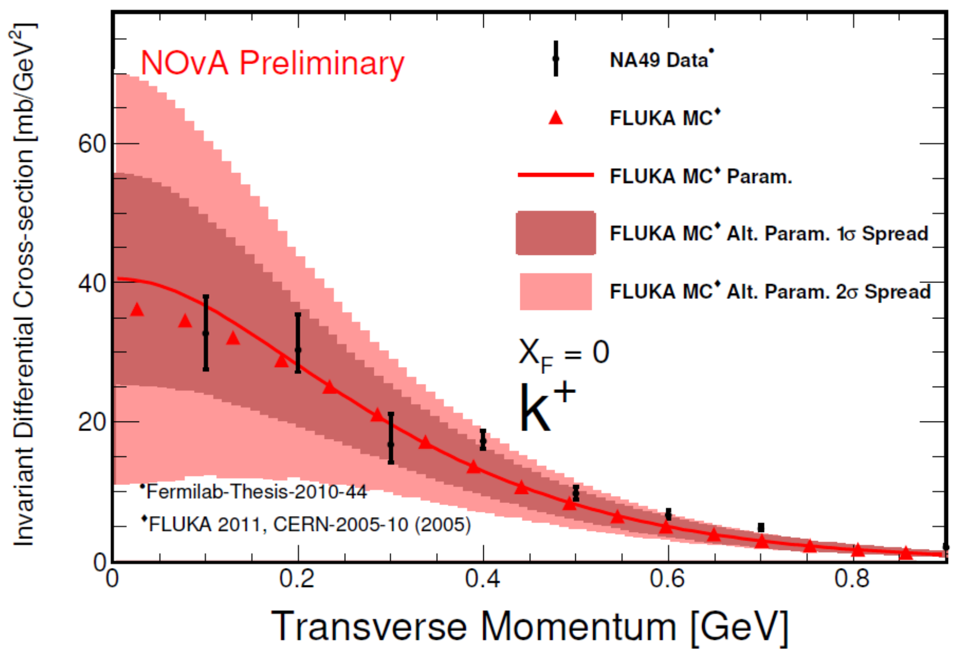
NuMI flux simulation

Full beamline geometry implemented in FLUKA (11.2c.0) and FLUGG (2009_3)

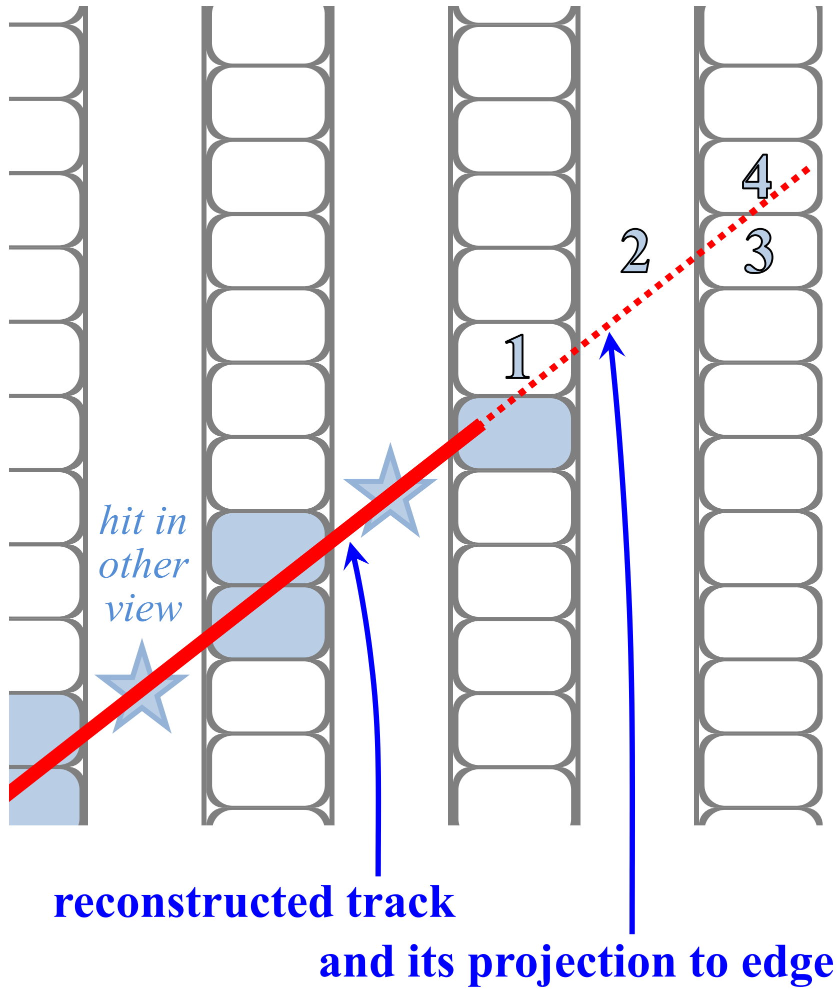
Uncertainties in hadron production based on NA49 data *(examples at right)*

Additional, lesser uncertainties assessed on beam transport model:
horn current, horn position, skin depth,
beam position, beam spot size,
target position





ν_μ CC containment



Purpose:

- ensure all **energy is recorded**
- (ND) exclude muons from neutrino interactions in the **surrounding rock**
- (FD) remove most obvious incoming **cosmic rays**

Require…

- no activity in **outermost two cells/planes**, and
- a minimum number of **un-hit cells along projection** to the wall
  → 10 cells in Far Det., 4 (fwd) or 8 (bck) in Near Det.

ν_e CC containment

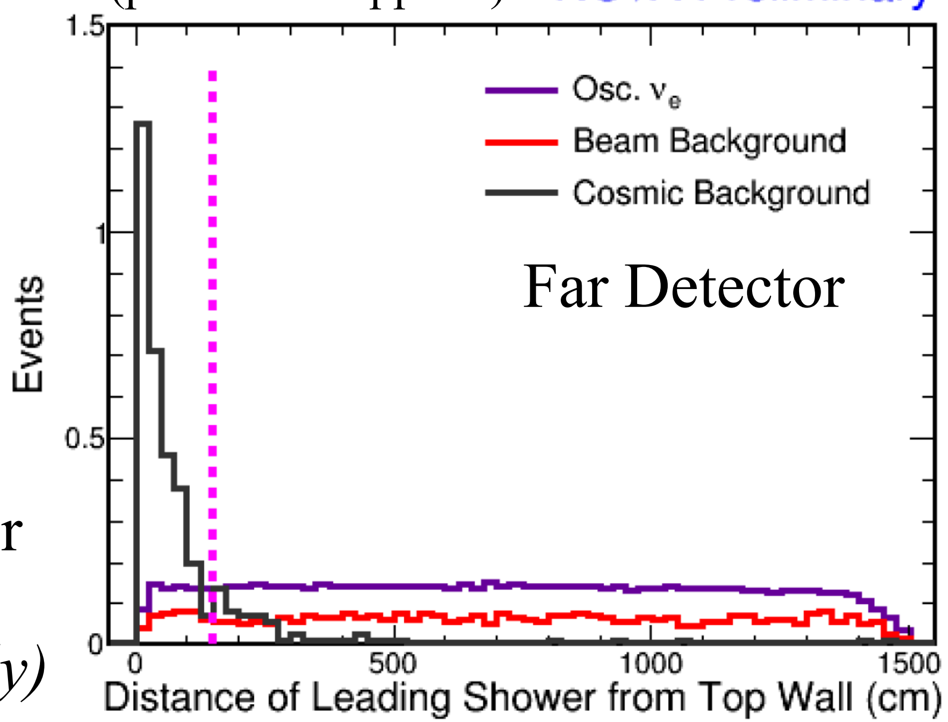
Require…

- Event vertex in fiducial region
- Leading shower's endpoints not too close to walls

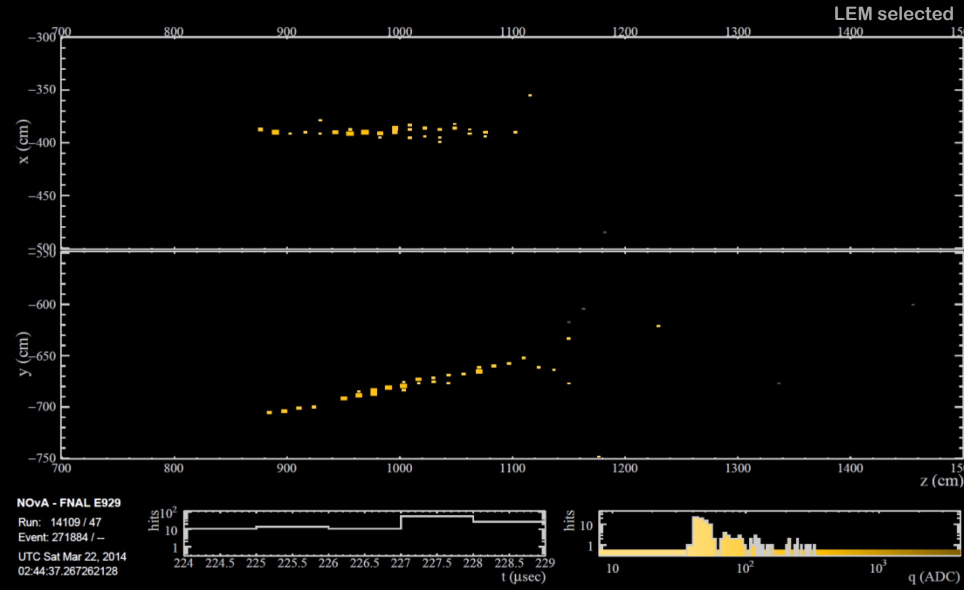
Top and back walls of Far Detector have largest required buffers

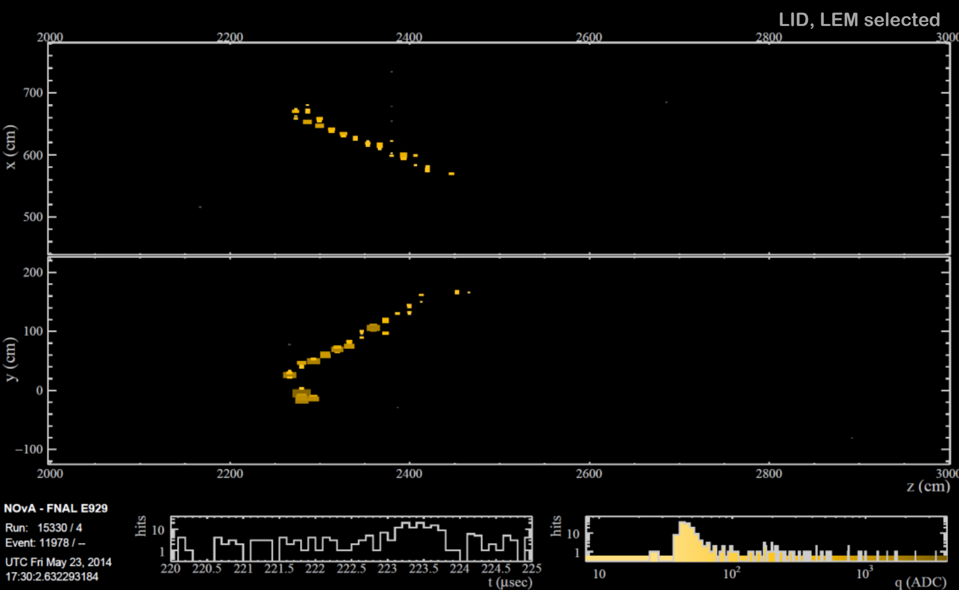
(150 cm and 200 cm, respectively)

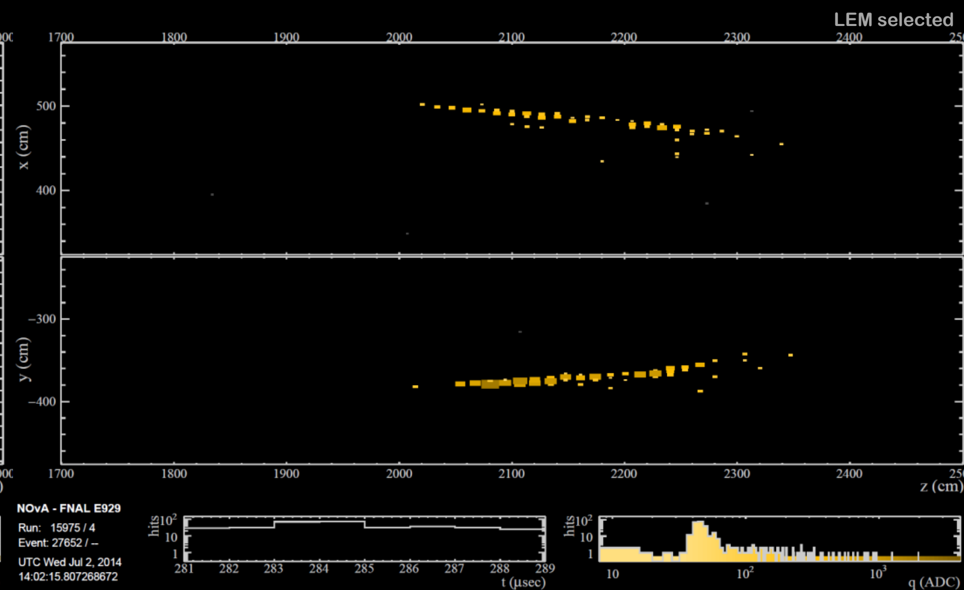
(partial cuts applied)

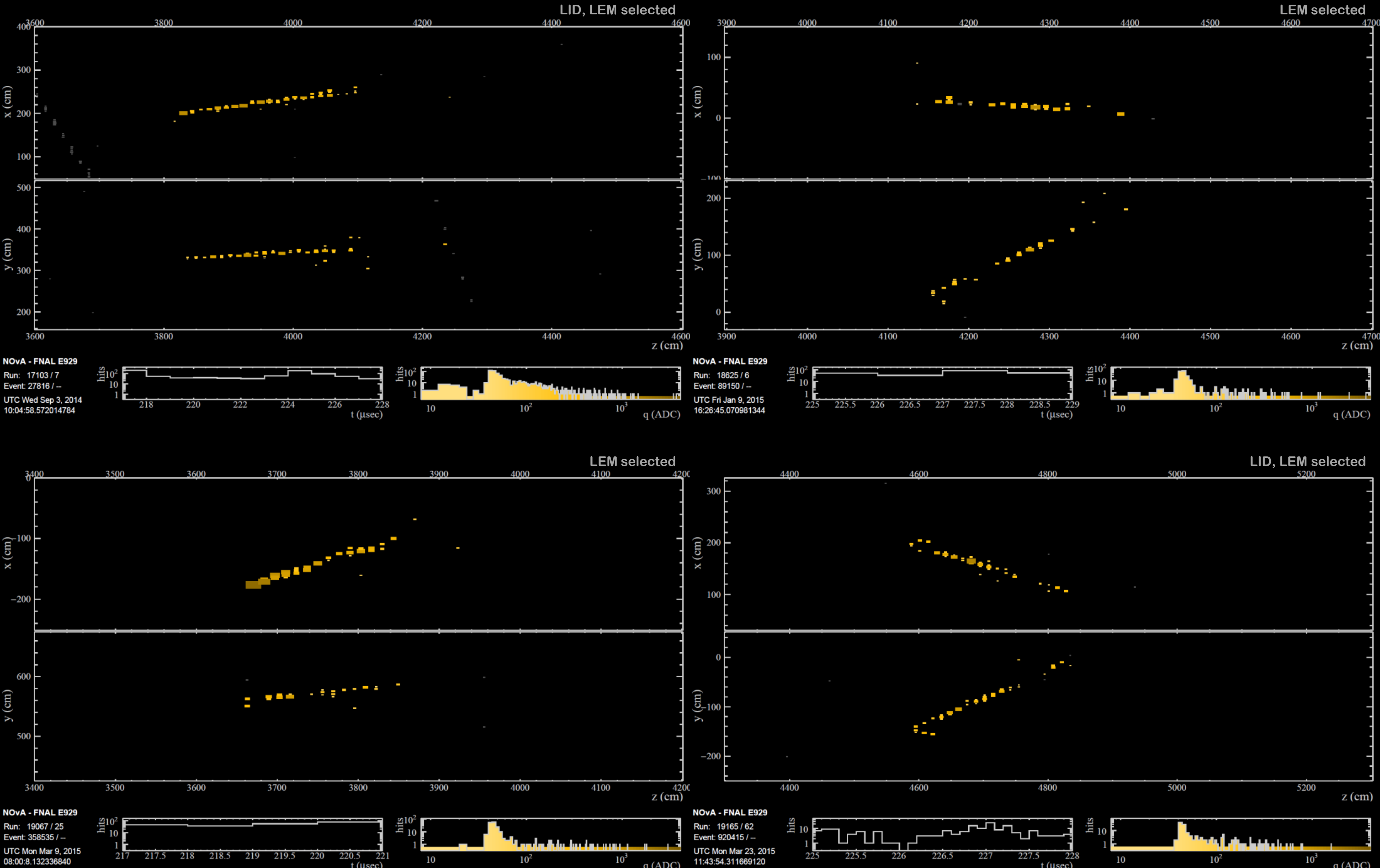


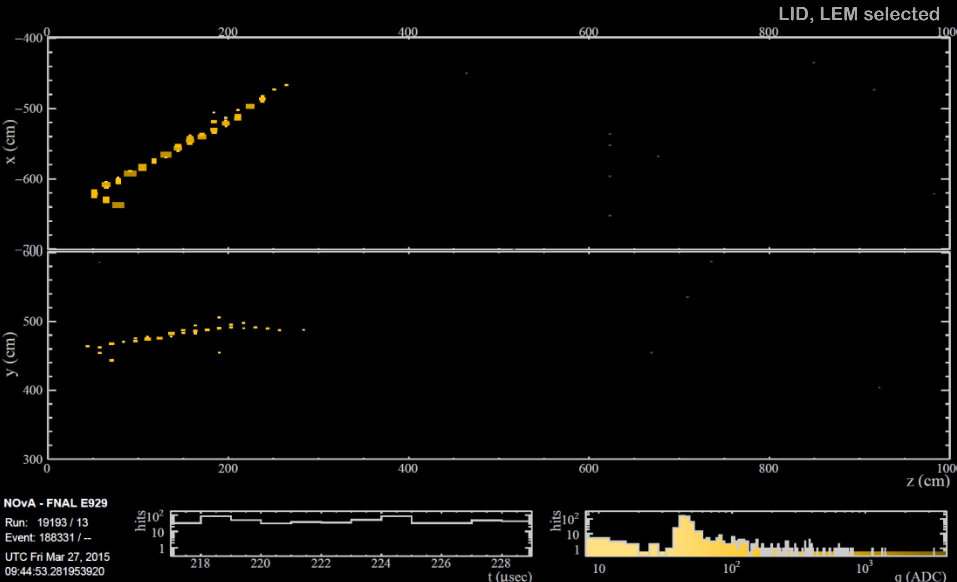
elevation view of Near Det.

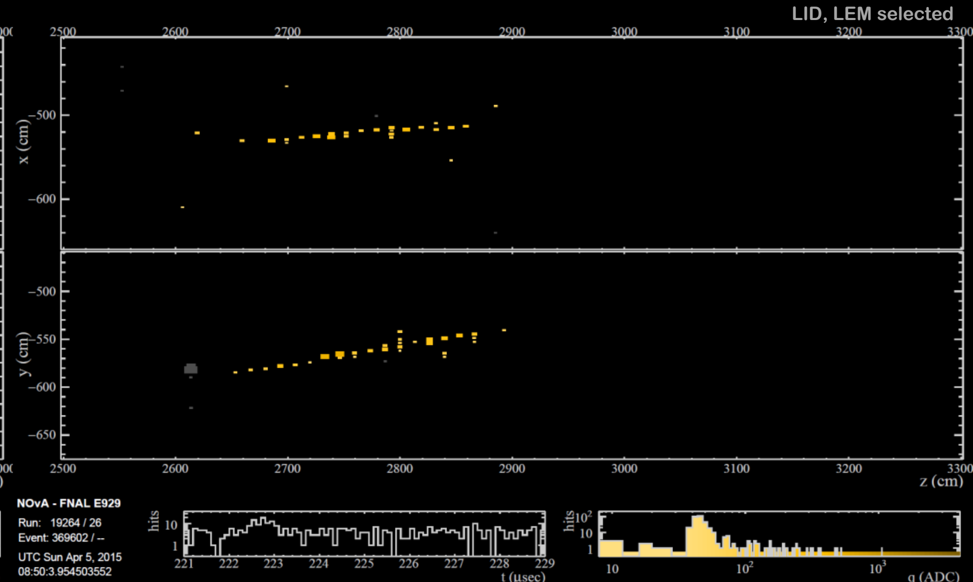

LEM selected
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 14109 / 47
Event: 271884 / --
UTC Sat Mar 22, 2014
02:44:37.267262128
hits
t (μsec)
q (ADC)

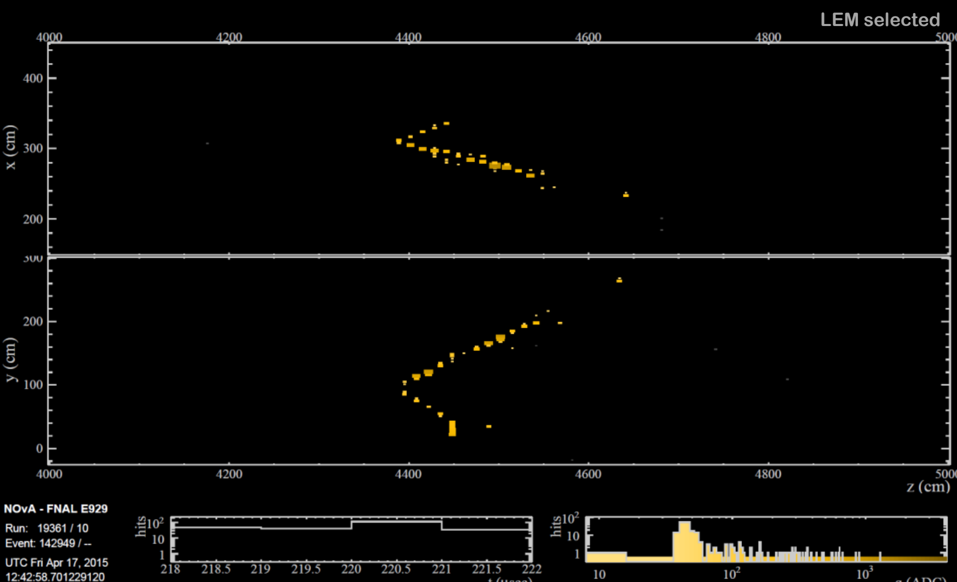

LID, LEM selected
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 15330 / 4
Event: 11978 / --
UTC Fri May 23, 2014
17:30:2.632293184
hits
t (μsec)
q (ADC)

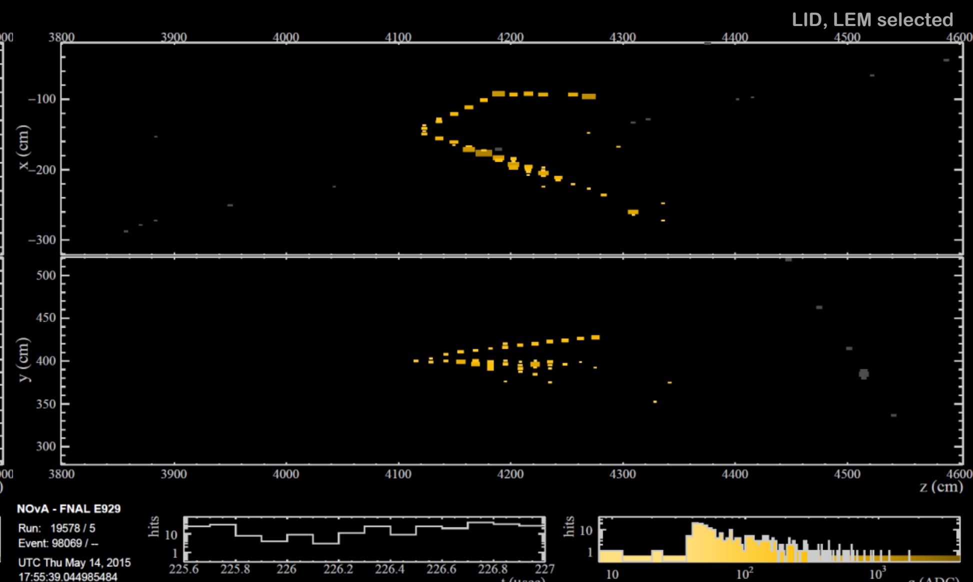

LEM selected
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 15975 / 4
Event: 27652 / --
UTC Wed Jul 2, 2014
14:02:15.807268672
hits
t (μsec)
q (ADC)


LID, LEM selected
LEM selected
LEM selected
LID, LEM selected
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)
NOvA - FNAL E929
Run: 17103 / 7
Event: 27816 / --
UTC Wed Sep 3, 2014
10:04:58.572014784
NOvA - FNAL E929
Run: 18625 / 6
Event: 89150 / --
UTC Fri Jan 9, 2015
16:26:45.070981344
NOvA - FNAL E929
Run: 19067 / 25
Event: 358535 / --
UTC Mon Mar 9, 2015
08:00:8.132336840
NOvA - FNAL E929
Run: 19165 / 62
Event: 920415 / --
UTC Mon Mar 23, 2015
11:43:54.311669120

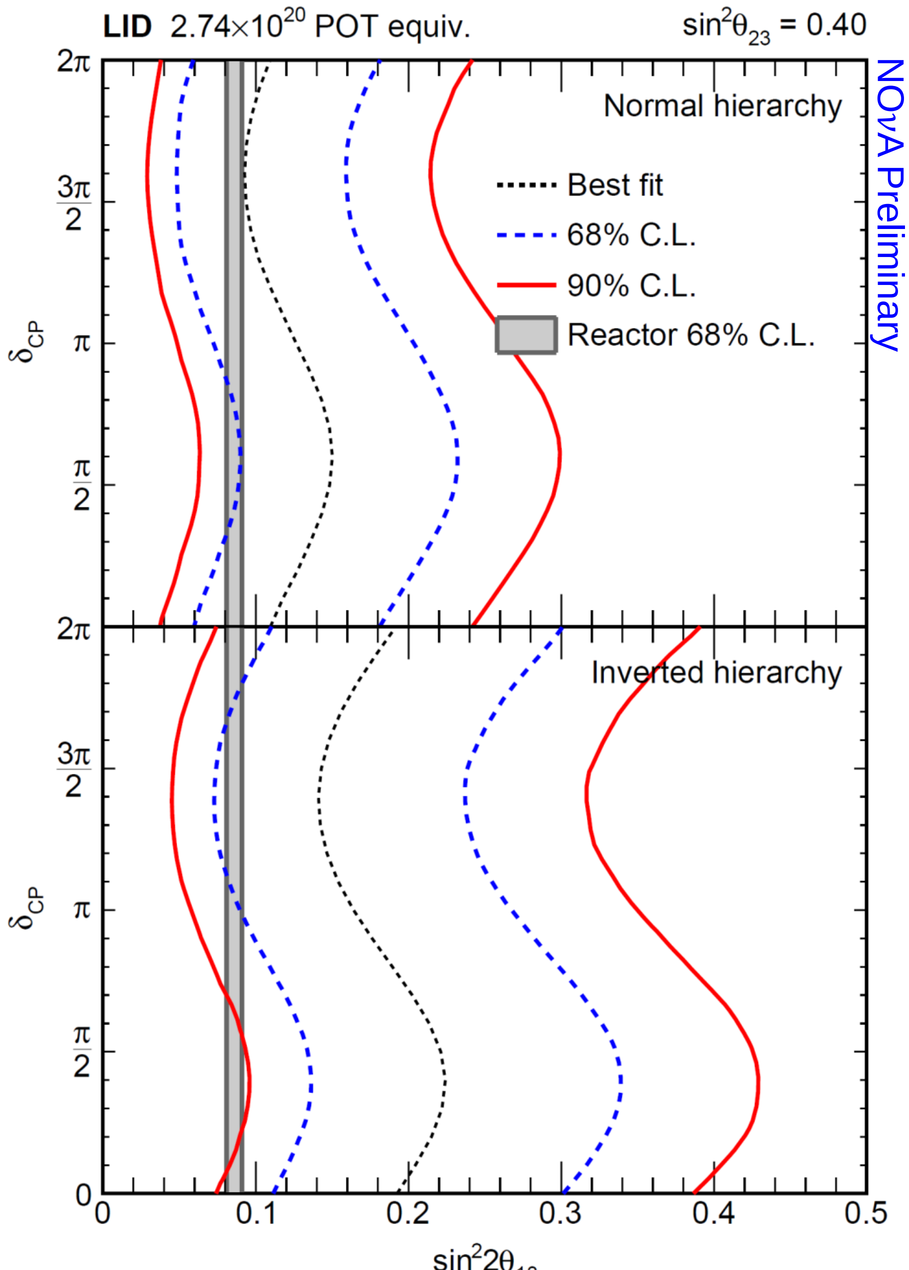

LID, LEM selected
NOvA - FNAL E929
Run: 19193 / 13
Event: 188331 / --
UTC Fri Mar 27, 2015
09:44:53.281953920
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)

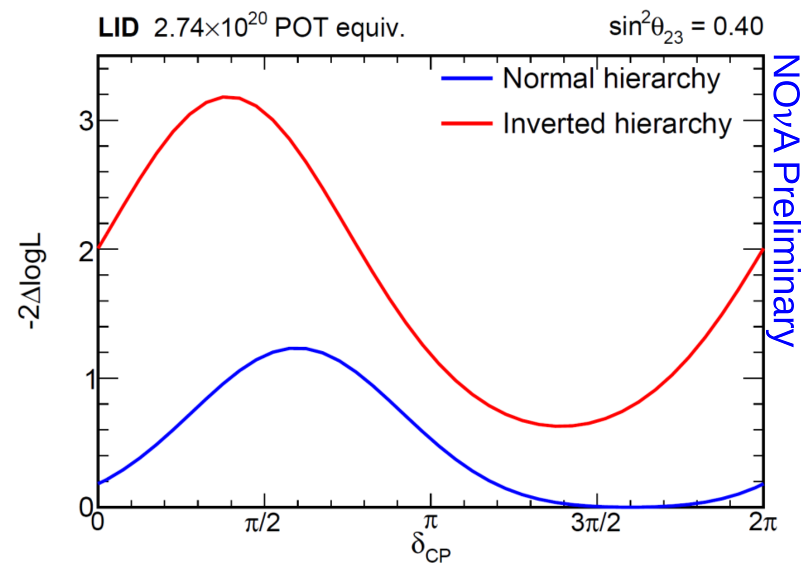

LID, LEM selected
NOvA - FNAL E929
Run: 19264 / 26
Event: 369602 / --
UTC Sun Apr 5, 2015
08:50:3.954503552
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)

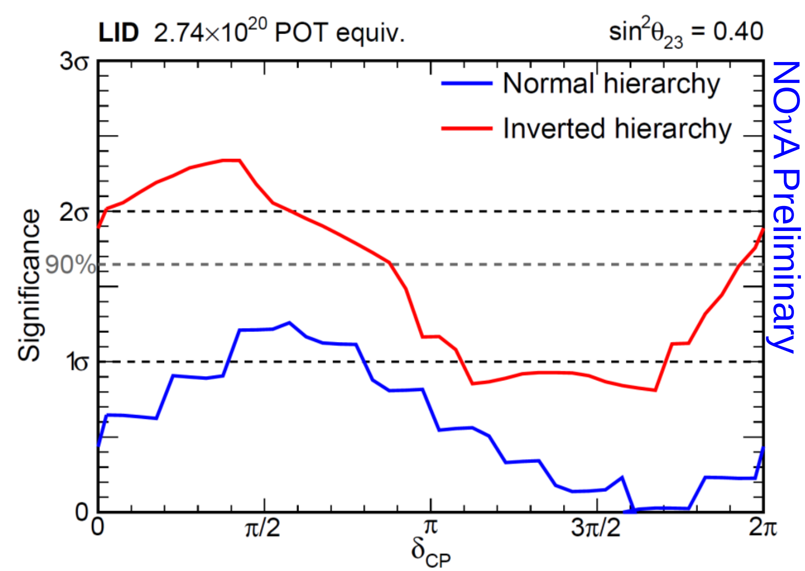

LEM selected
NOvA - FNAL E929
Run: 19361 / 10
Event: 142949 / --
UTC Fri Apr 17, 2015
12:42:58.701229120
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)


LID, LEM selected
NOvA - FNAL E929
Run: 19578 / 5
Event: 98069 / --
UTC Thu May 14, 2015
17:55:39.044985484
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)

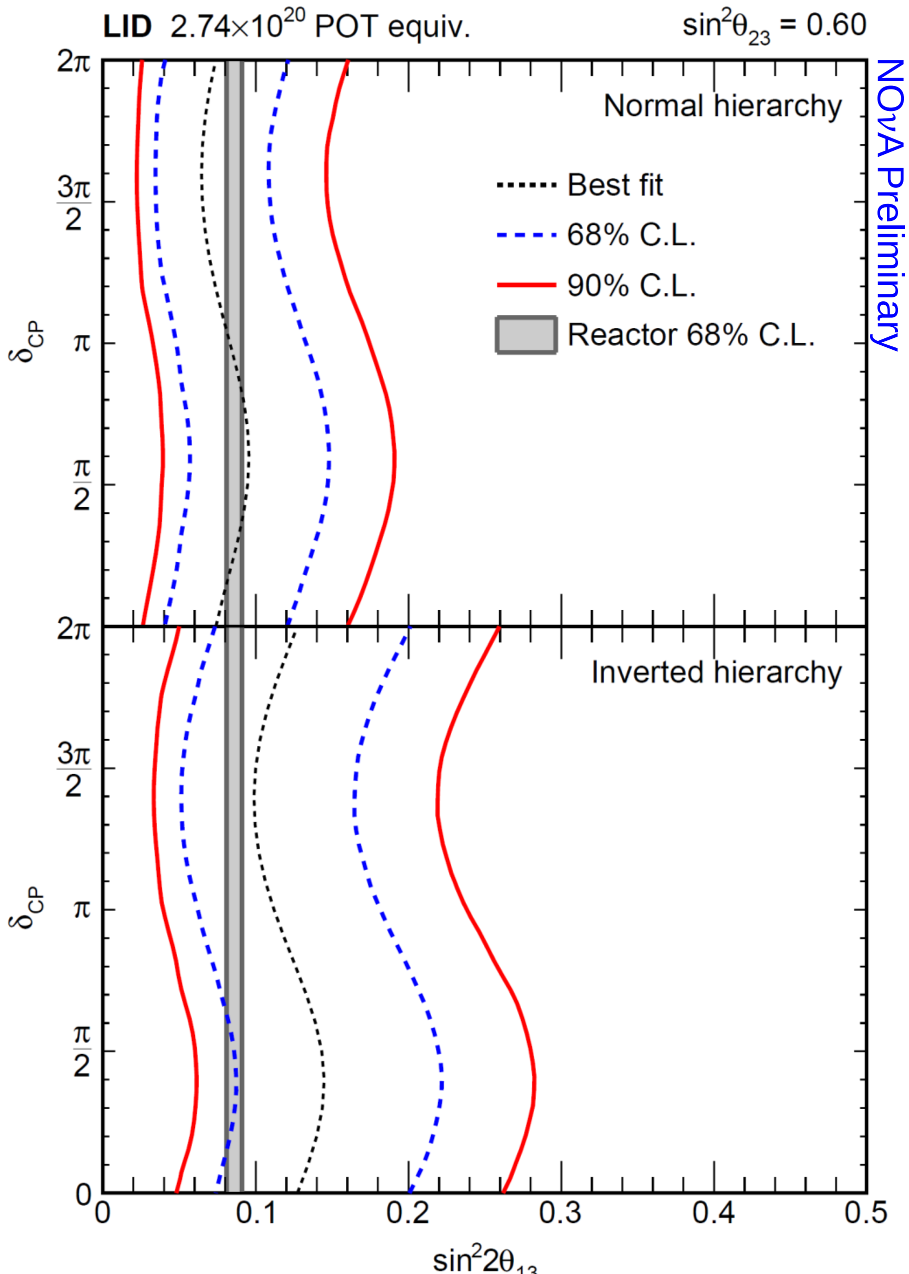
LID: Fixing $\sin^2\theta_{23} = 0.4$

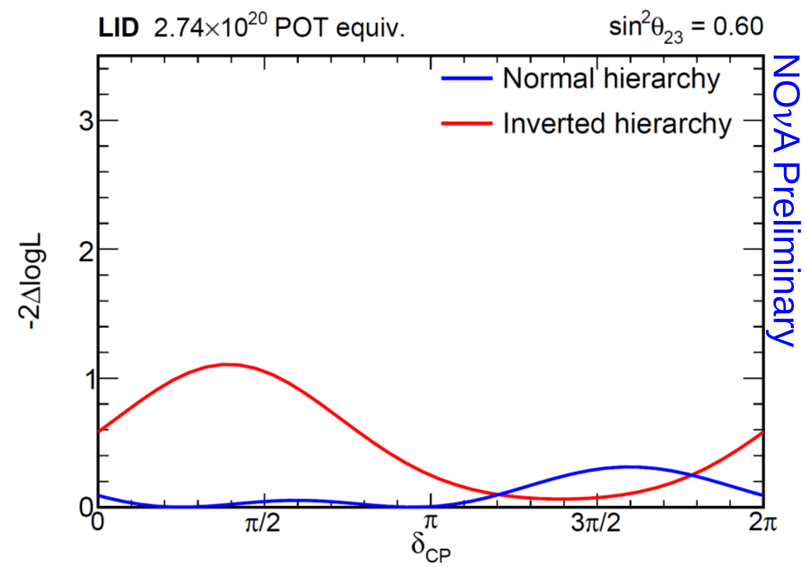


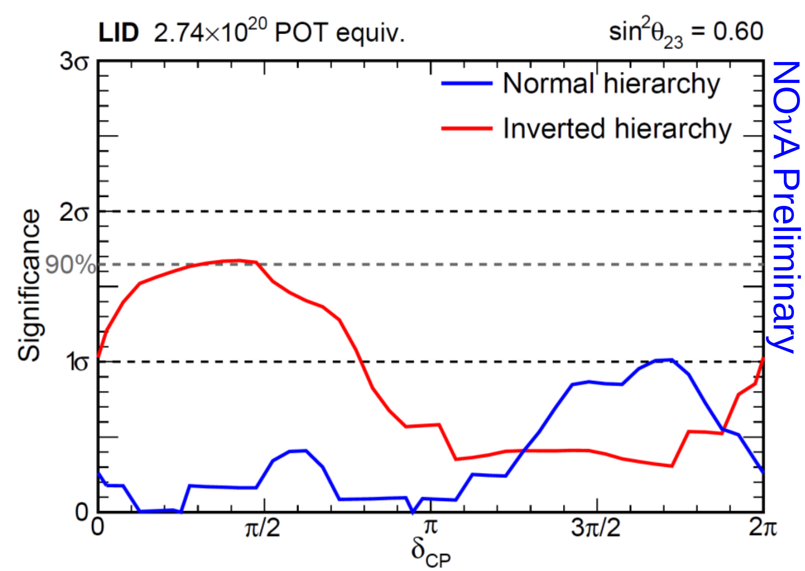




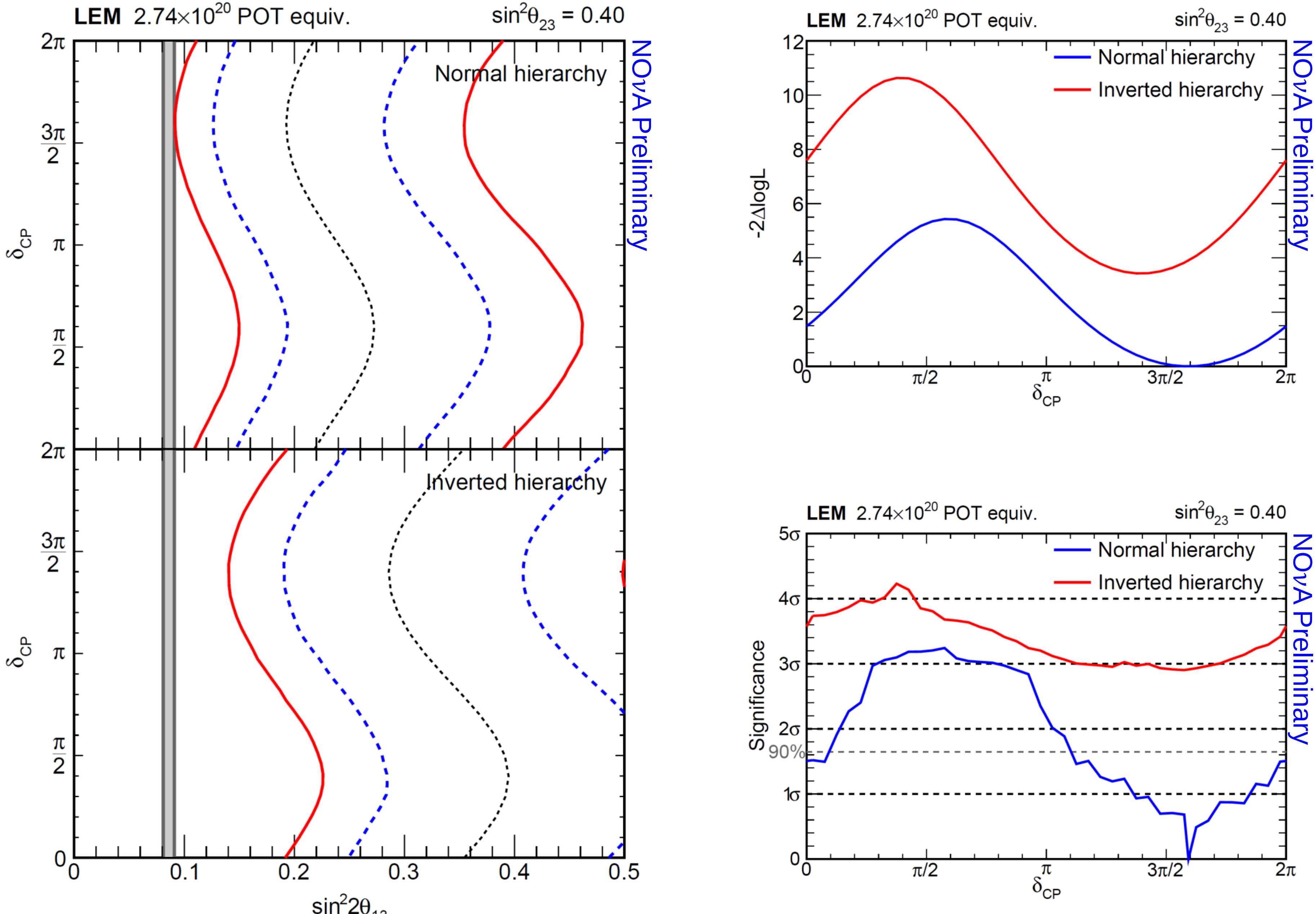
LID: Fixing $\sin^2\theta_{23} = 0.6$



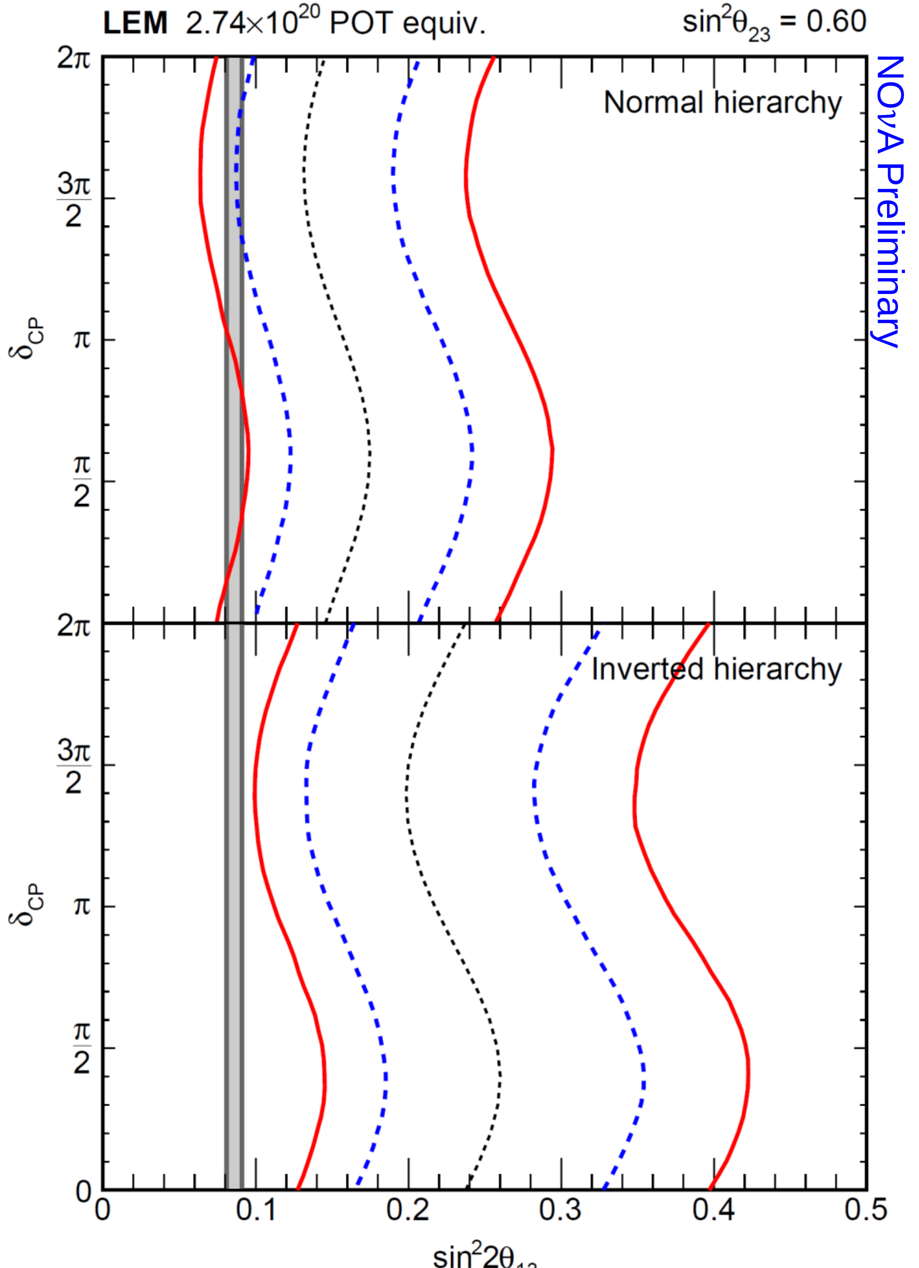


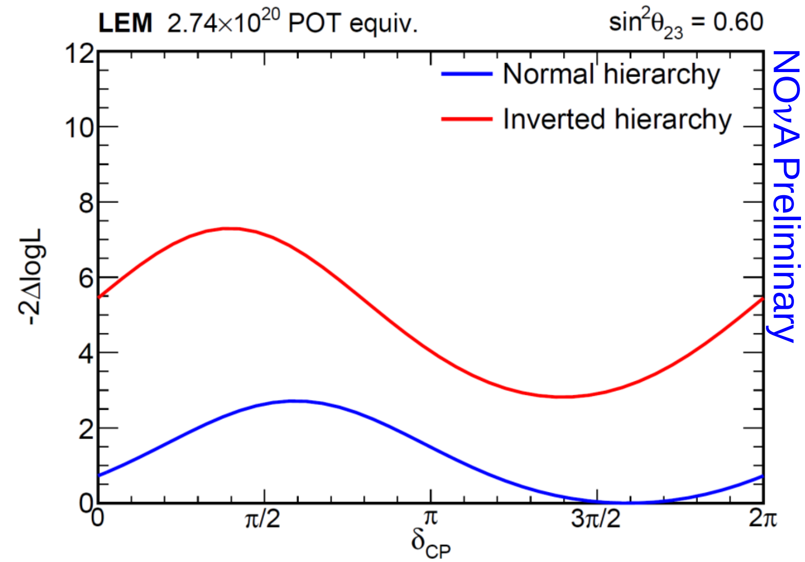


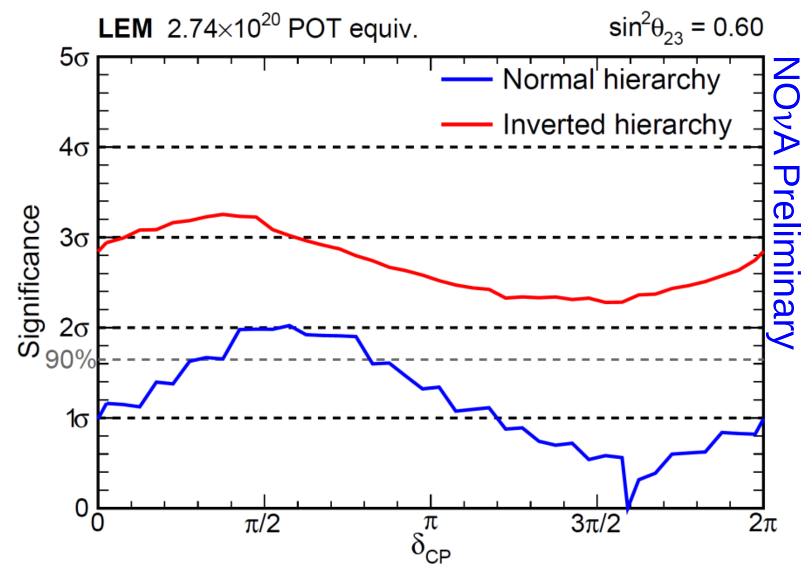
LEM: Fixing $\sin^2\theta_{23} = 0.4$



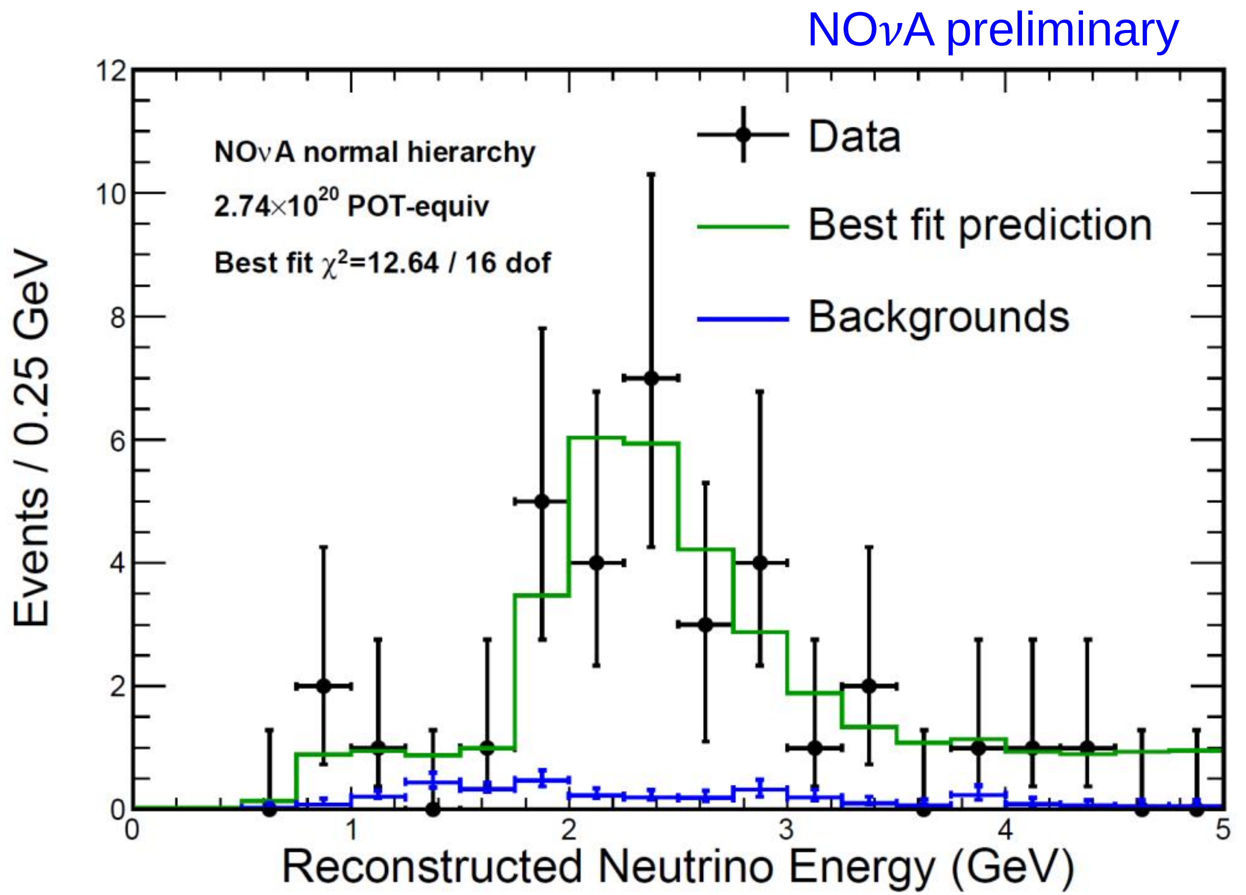
LEM: Fixing $\sin^2\theta_{23} = 0.6$

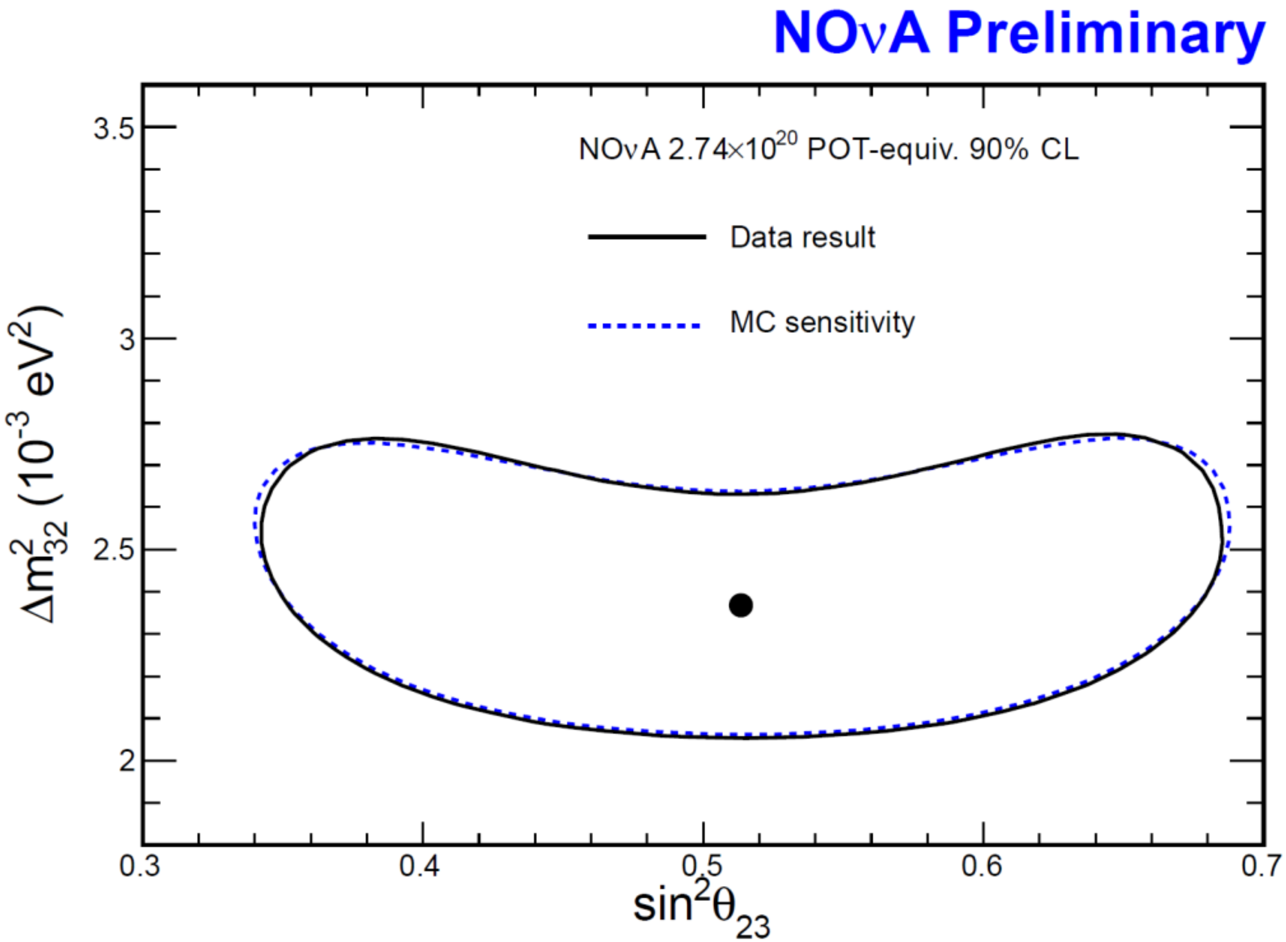






Zoomed view of Far Det. ν_μ CC energy spectrum





Comparison of NOνA disppearance result to the expected sensitivity for the same best-fit parameters.

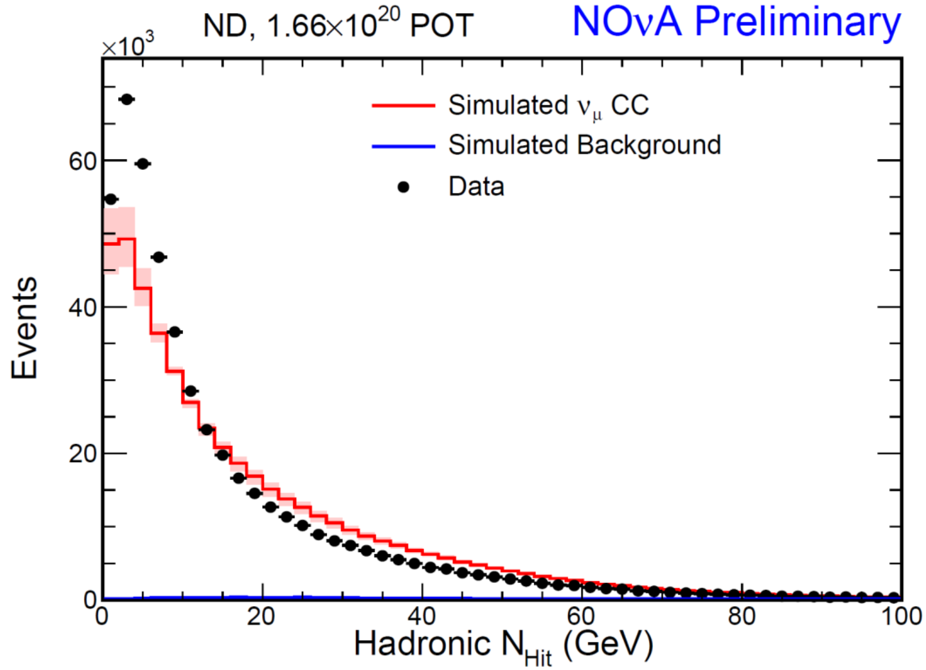
E_{had} modeling

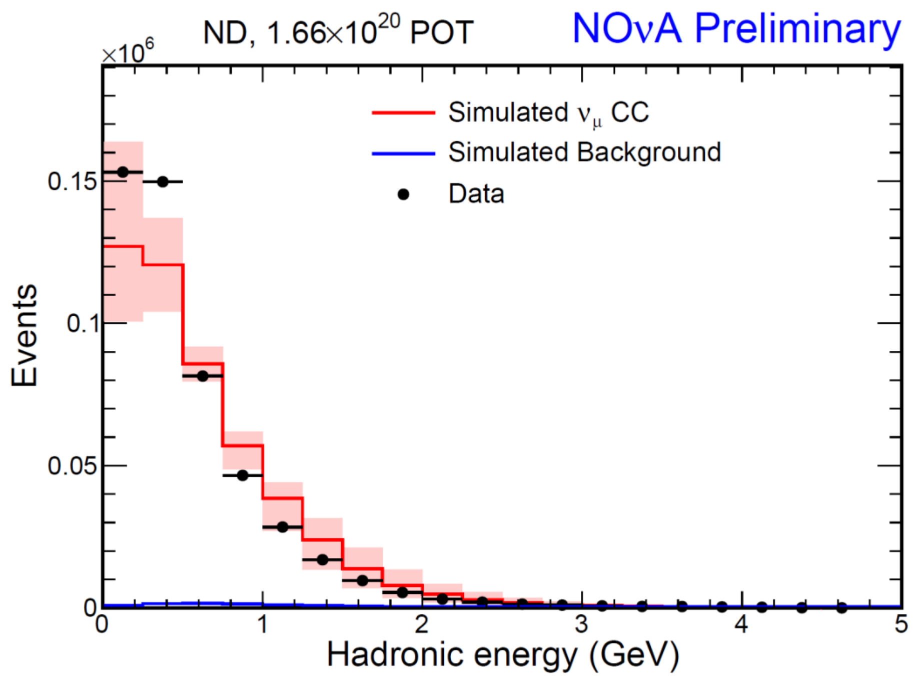
Right: **Number of hits in hadronic showers** for ν_μ CC candidates
→ *Too much activity in MC showers*

Discrepancy enters analysis ~only through E_{had} (and then E_ν)

Long term: Improve end-to-end modeling of hadronic shower production and propagation

Short term: Correct discrepancy directly via a shift in reconstructed E_{had}, and take the full shift as a systematic.

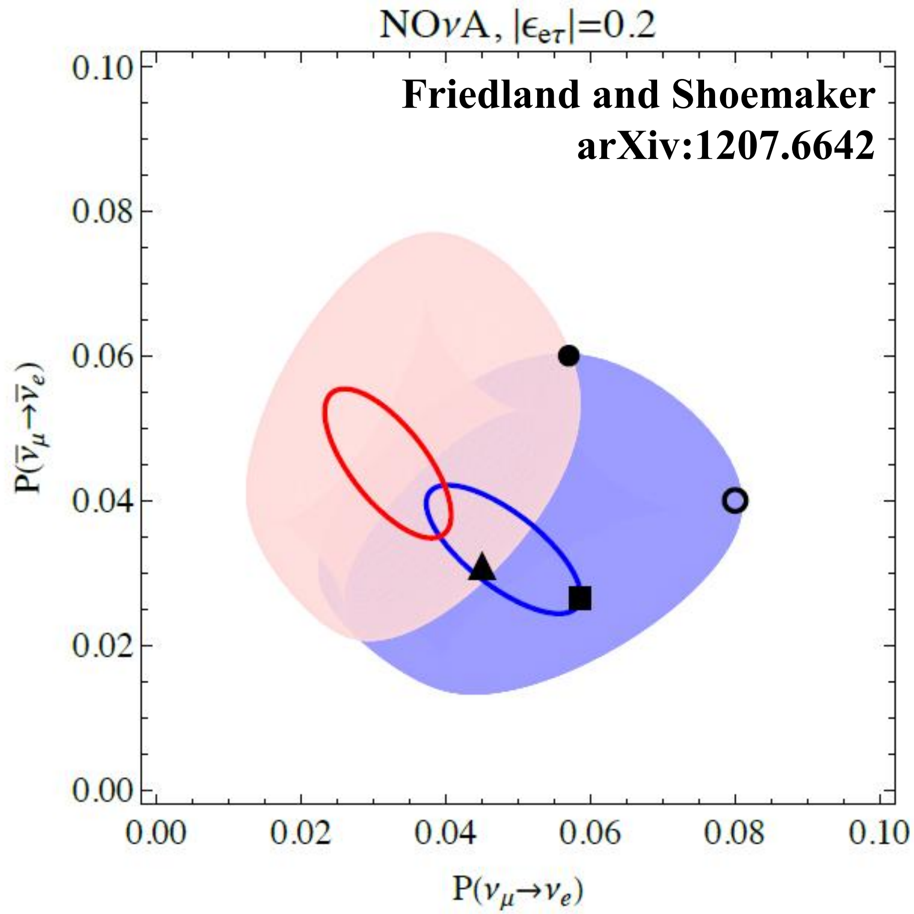




Other physics

A selection of measurements possible with NOvA outside of precision 3-flavor oscillation physics…

- **Non-standard interactions**
  NOνA's long baseline provides new sensitivity, and appearance-mode couplings are largely unconstrained.

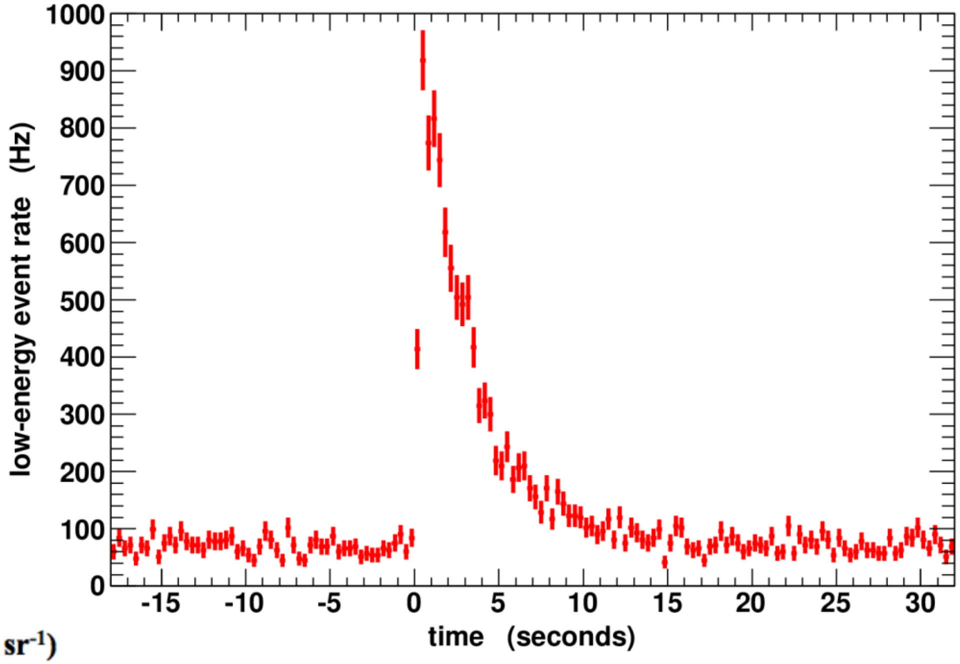


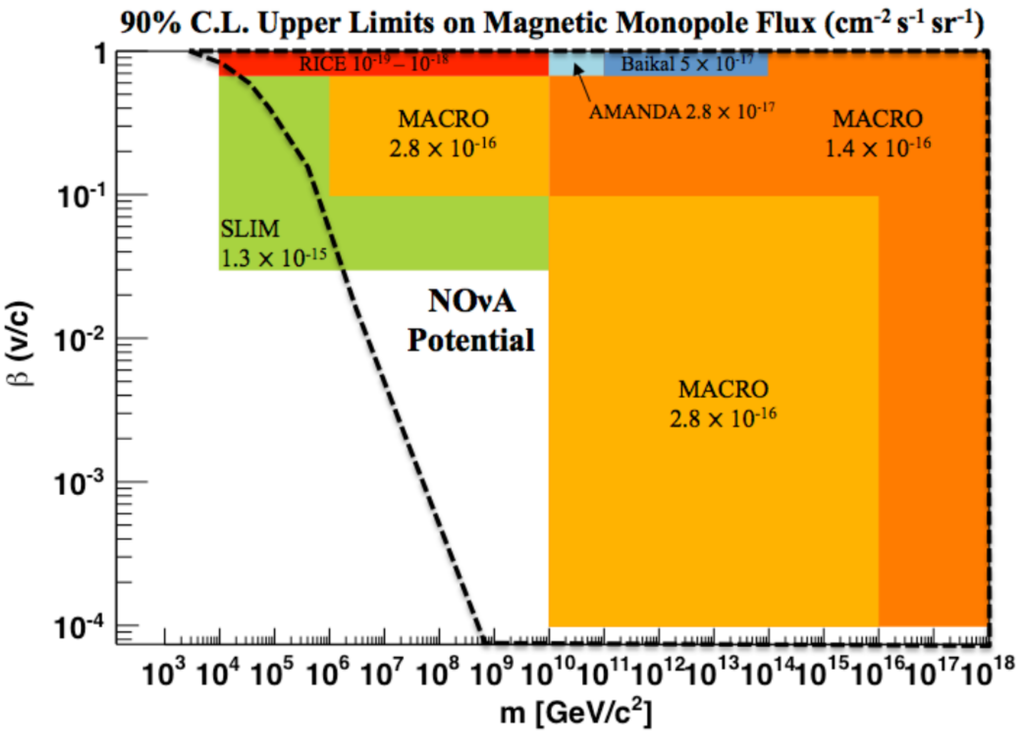
- **Neutrino/antineutrino disappearance comparisons**
  Search for few-percent differences in atmospheric oscillation parameters

- **Cross section measurements**
  ~10^8 events in full exposure in the ND. ND analyses underway. (Two NDOS analyses already out.)

Supernova neutrinos

Several thousand events in NOνA for a supernova in our galaxy. (Some DAQ development still on-going for this.)





Monopole searches

Strong ionization signal from any magnetic monopoles that might pass through. (Trigger is operational.)

From T2K Phys. Rev. **D** 91, 072010 (2015)

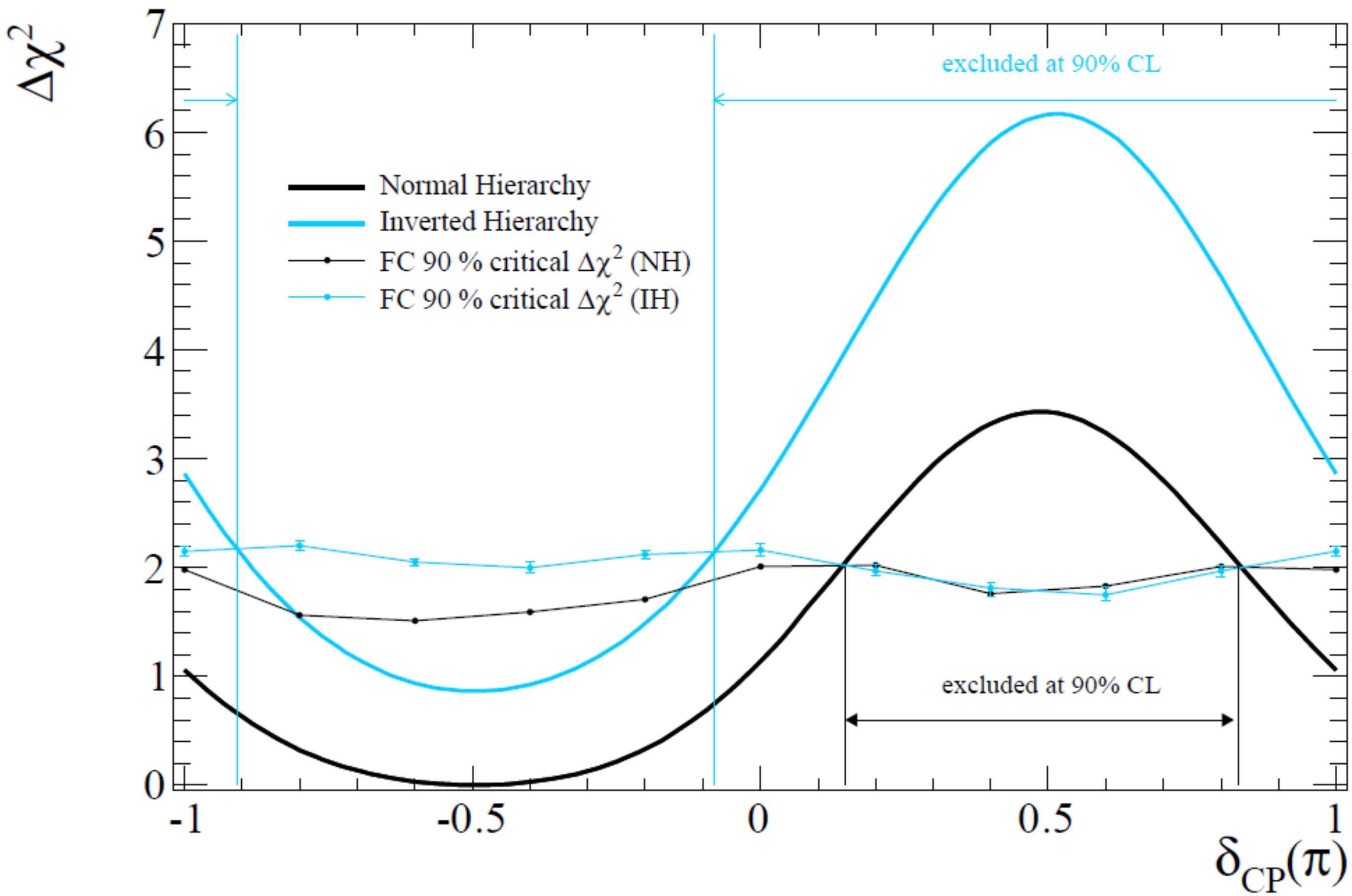


FIG. 37: Profiled $\Delta\chi^2$ as a function of δ_{CP} with the results of the critical $\Delta\chi^2$ values for the normal and inverted hierarchies for the joint fit with reactor constraint, with the excluded regions found overlaid.