OPOS Seminar:
The NOvA Experiment

Alex Himmel

April 25th, 2016

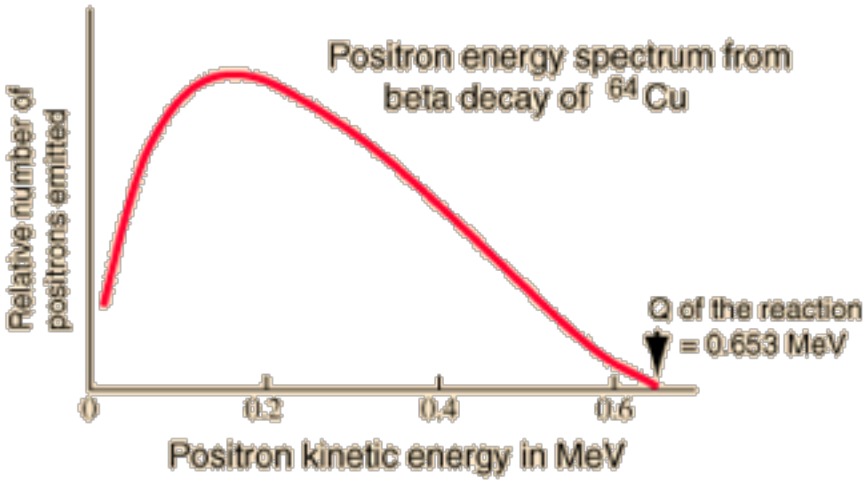
(Plus a bunch of slides I stole from Ryan Patterson's Wine & Cheese presentation last summer)

Outline

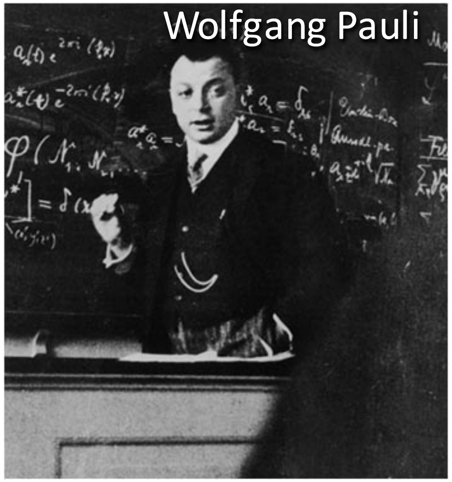
- The neutrino
  - and neutrino oscillations
- The NOvA Experiment
- Production Processing
- ν_μ Disappearance Results
- ν_e Appearance Results

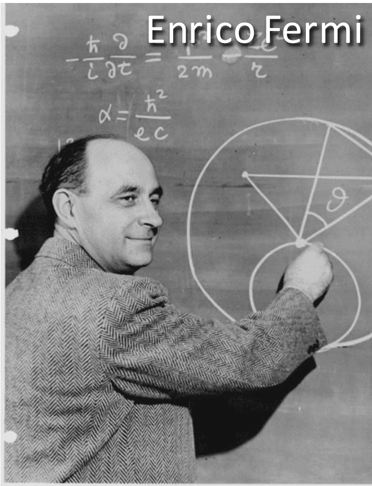
The Neutrino

$$^{60}Co \rightarrow {}^{60}Ni + e^-$$



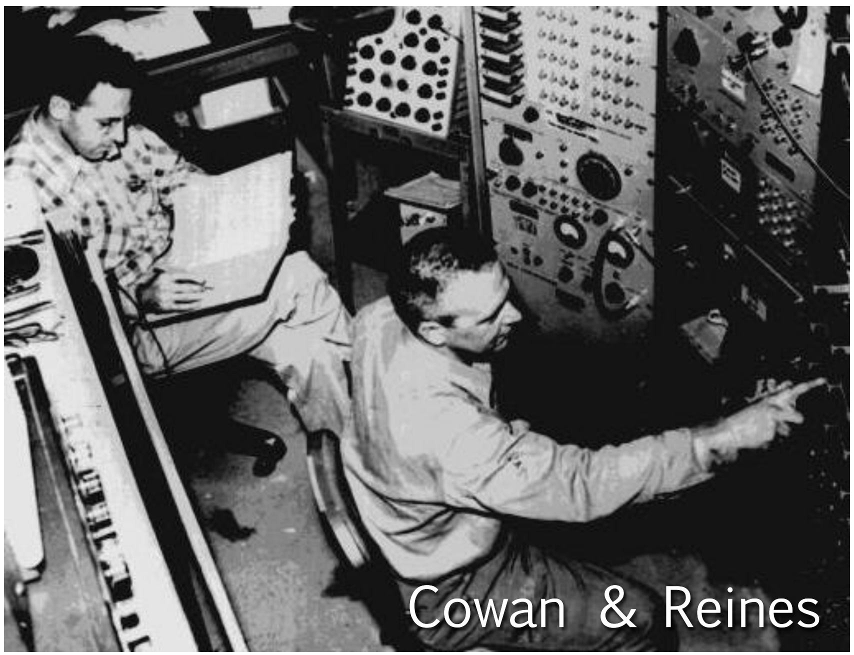
- The "little neutral one"
  - Massless, neutral particle
  - Proposed in the 1930's to save energy conservation in β decay

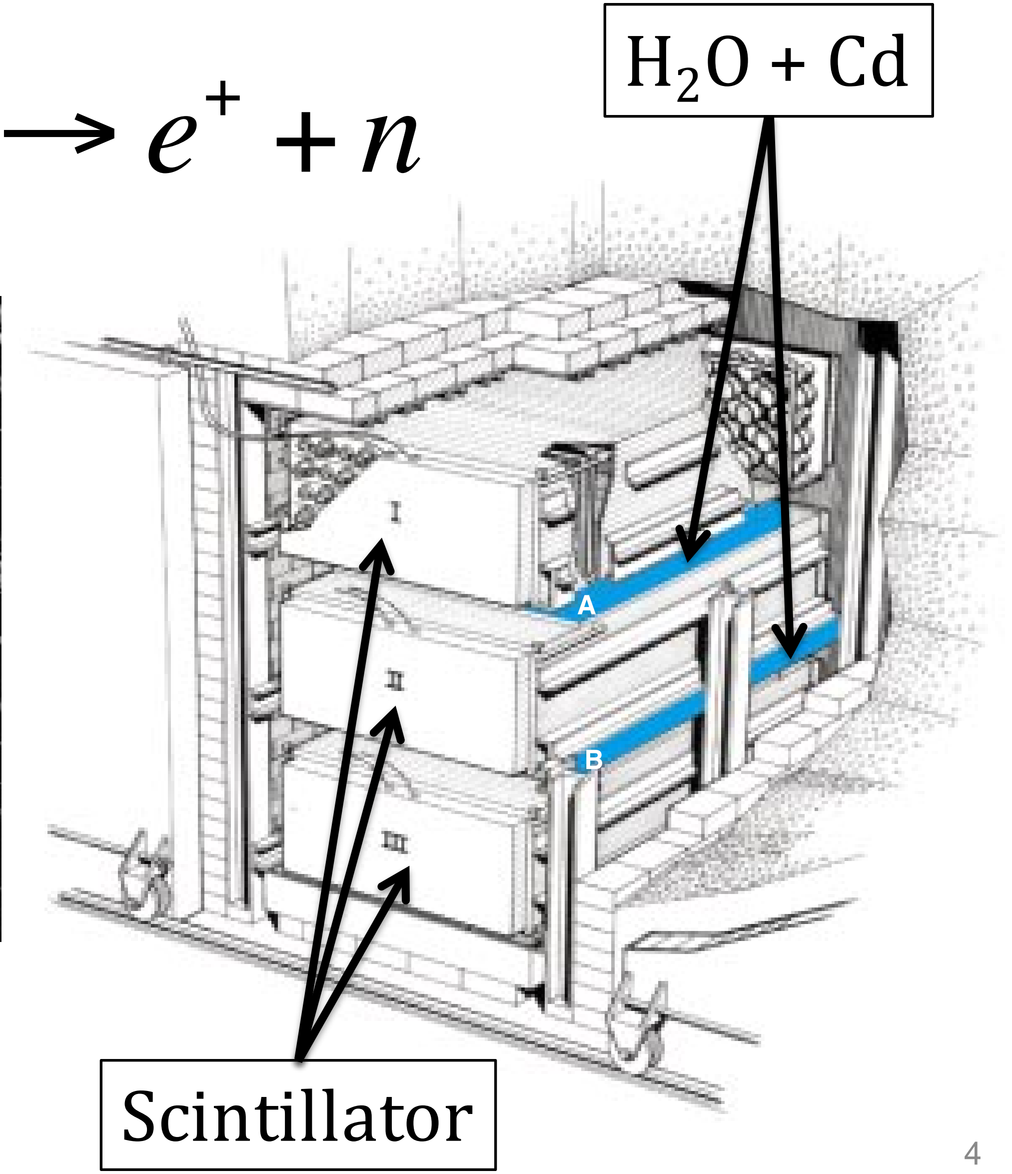




The First Detection

$$\bar{\nu} + p \rightarrow e^{+} + n$$

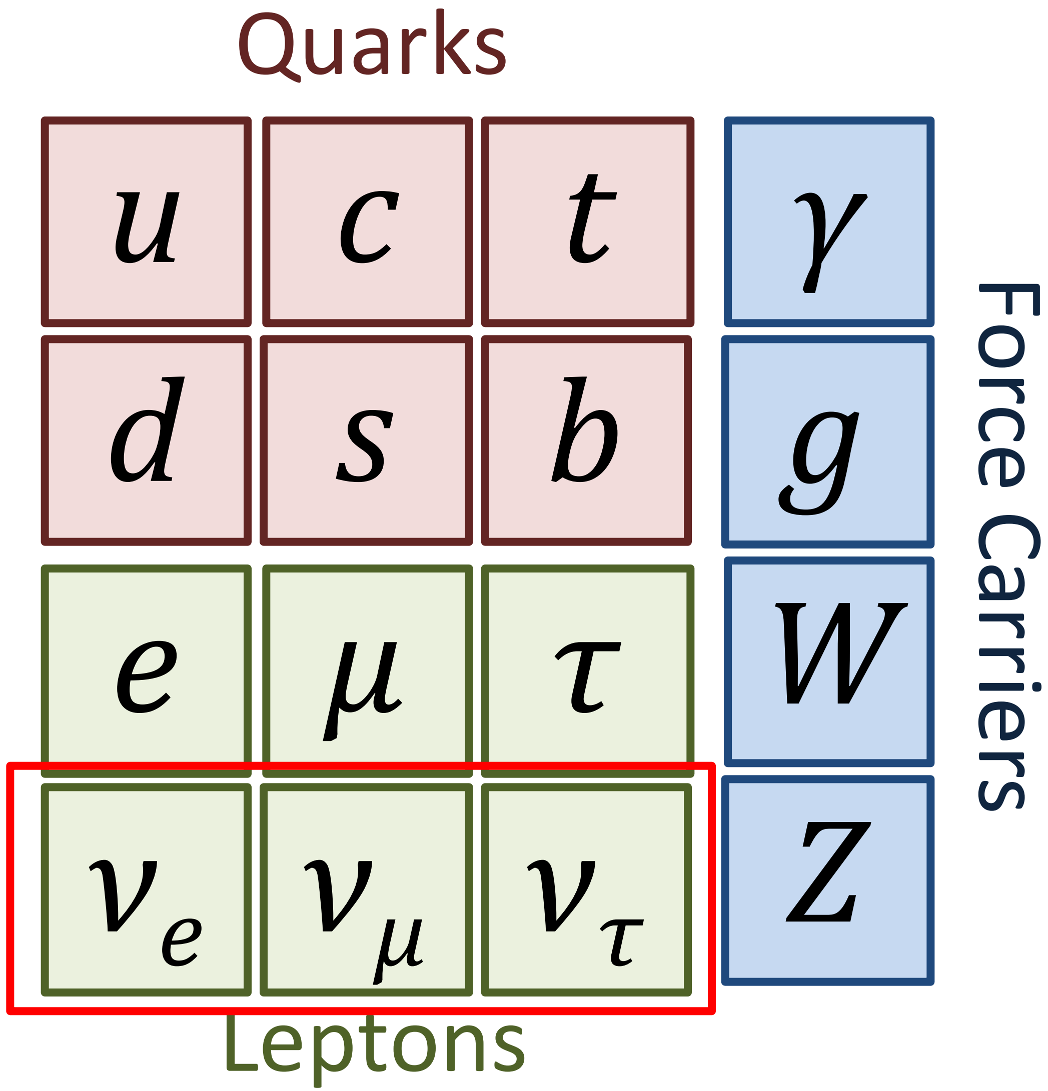




1956

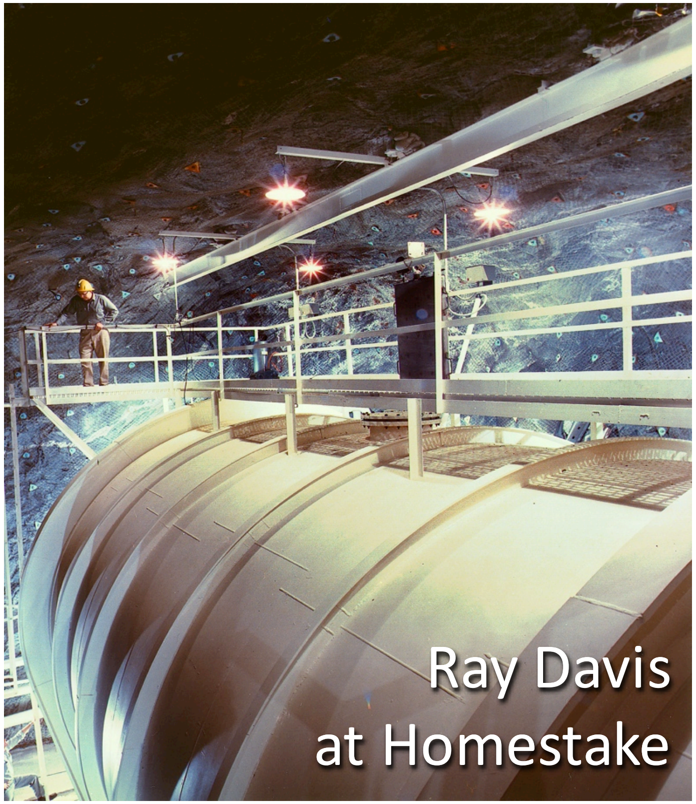
The Neutrino in the Standard Model

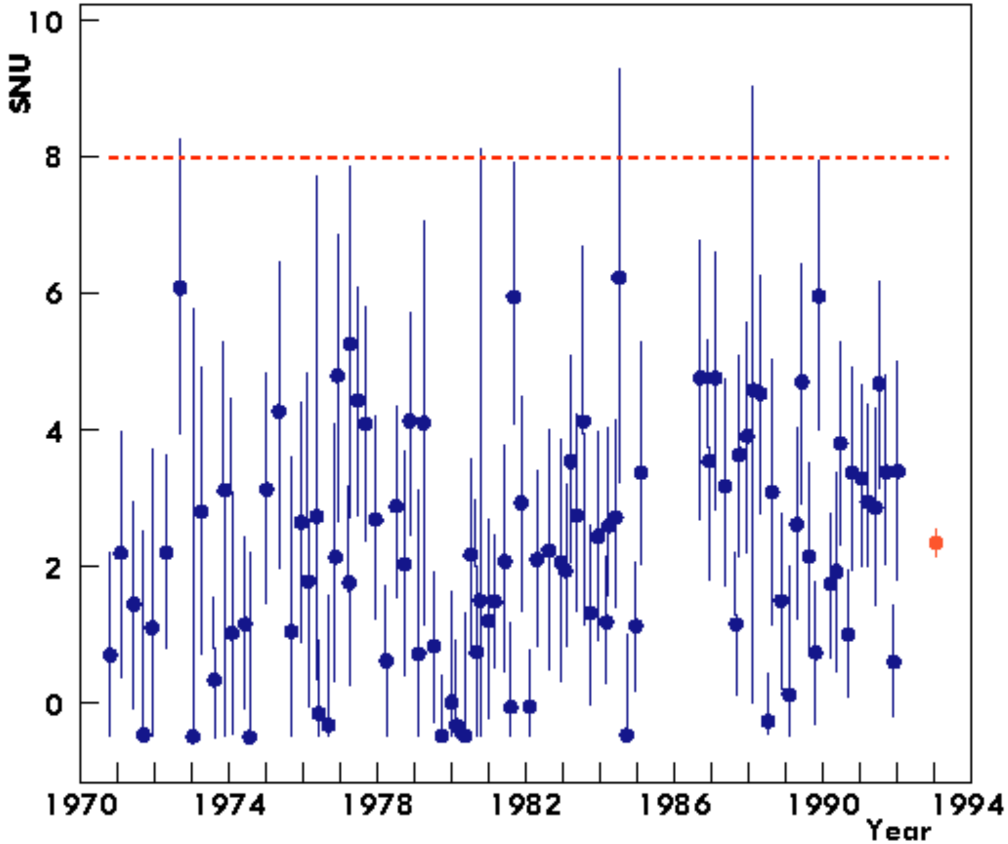
- The standard model includes 3 flavors of massless, neutral neutrinos.
  - Only weak interactions



The Solar Neutrino Problem

$$\nu_e + {}^{37}\text{Cl} \rightarrow e^- + {}^{37}\text{Ar}$$

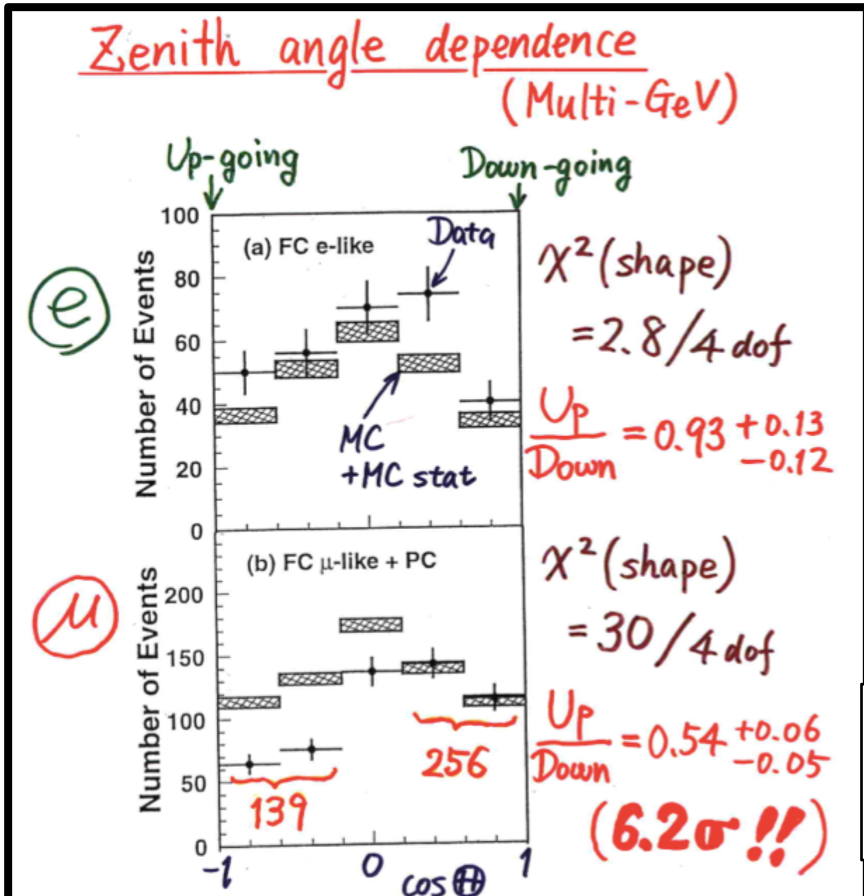


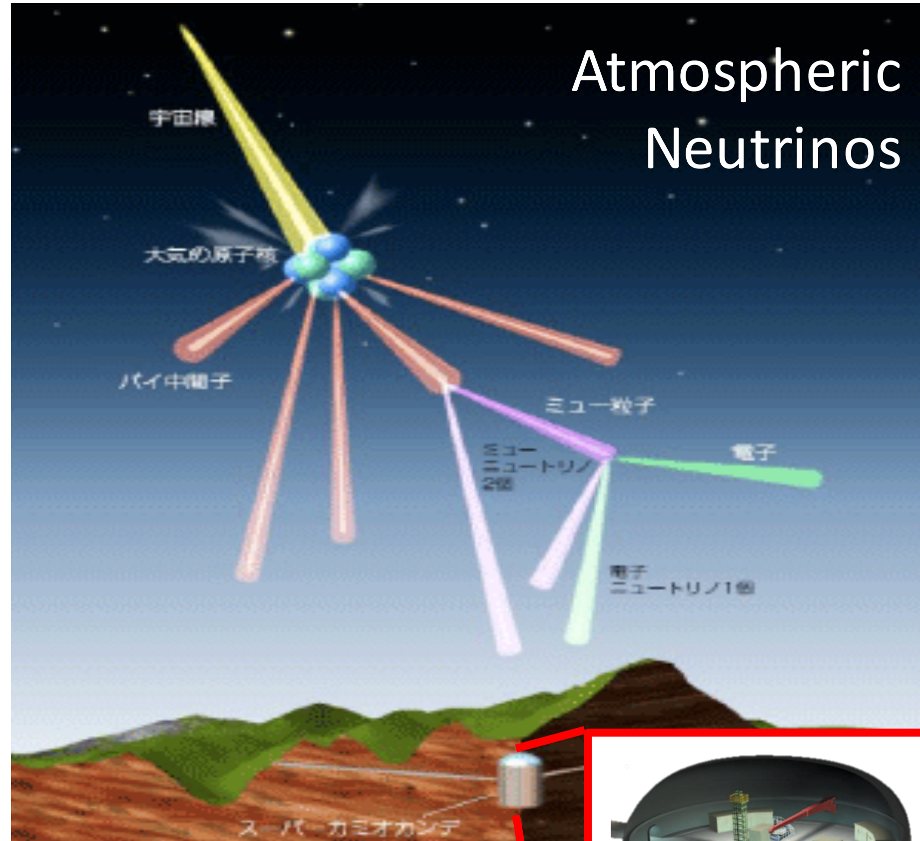


1969

The Solution: Neutrino Oscillations

Discovered in 1998 by Super-Kamiokande





T. Kajita
Neutrino 1998

Neutrino Oscillations

- Create in one flavor (ν_μ), but detect in another (ν_e)

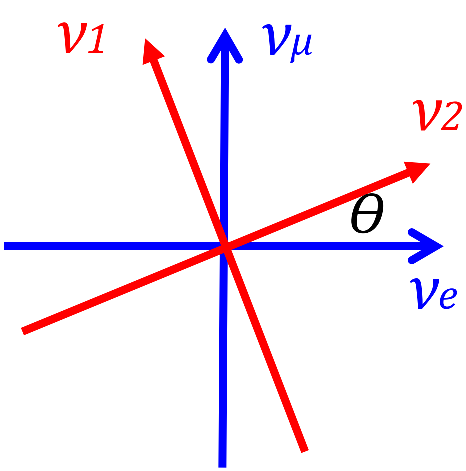
Neutrino Oscillations

- Create in one flavor (ν_μ), but detect in another (ν_e)

- Each flavor (e, μ) is a superposition of different masses (1, 2)

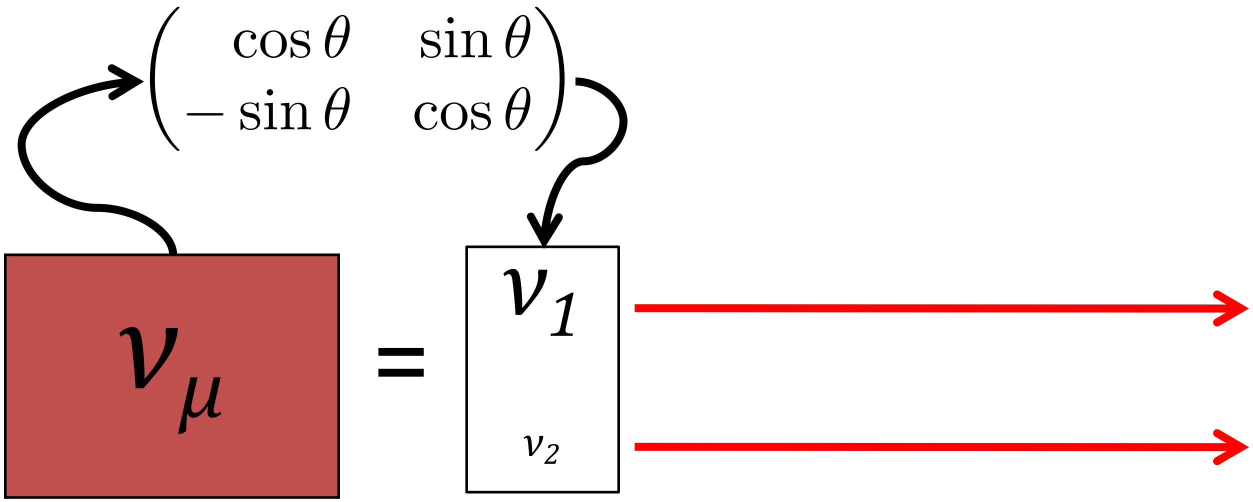
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

"Mixing Matrix"

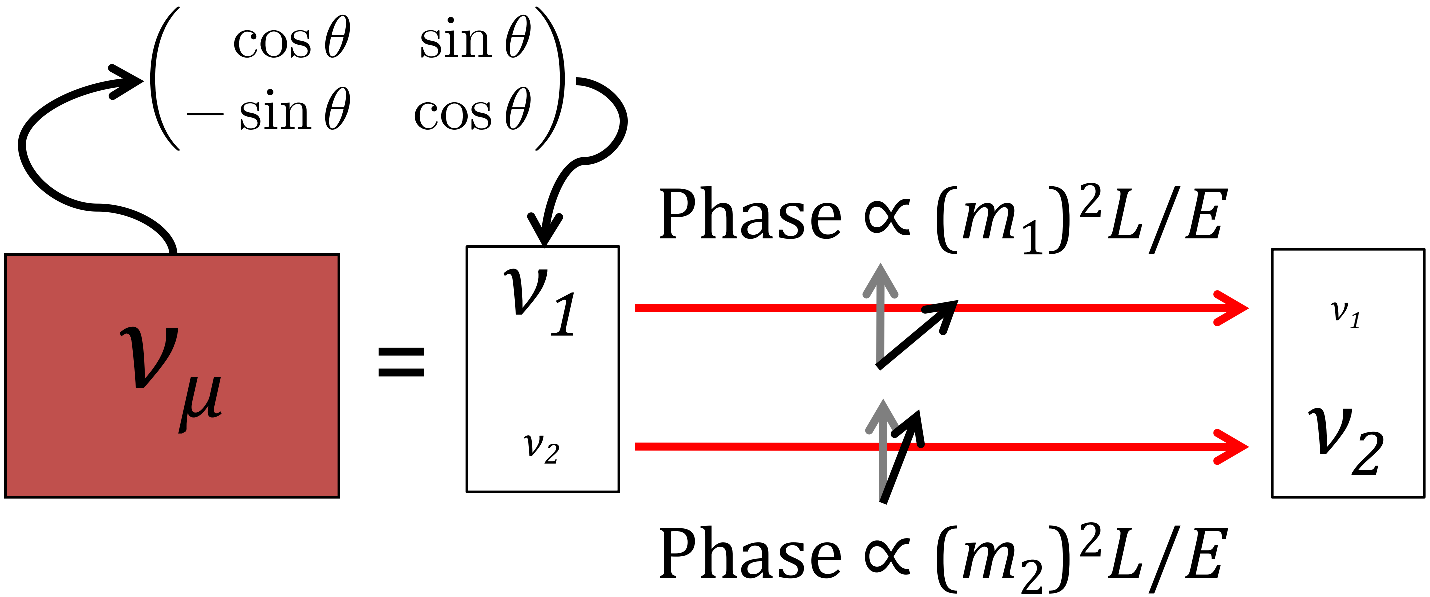


Neutrino Oscillations

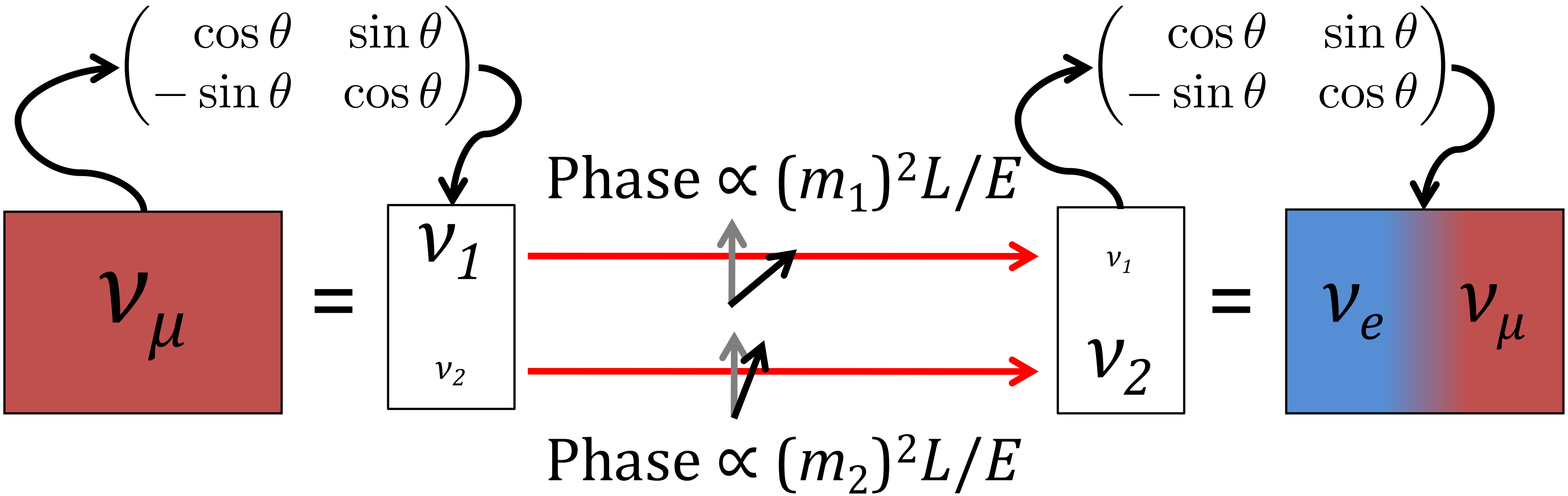
Neutrino Oscillations



Neutrino Oscillations

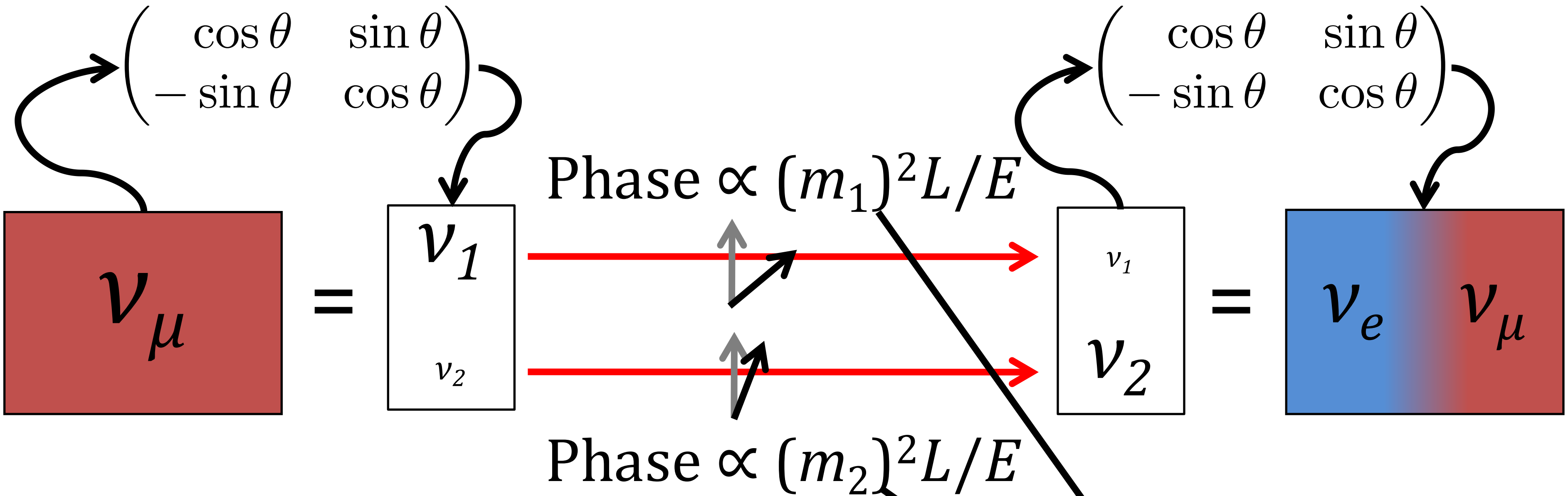


Neutrino Oscillations



Neutrino oscillations require that neutrinos have mass!

Neutrino Oscillations



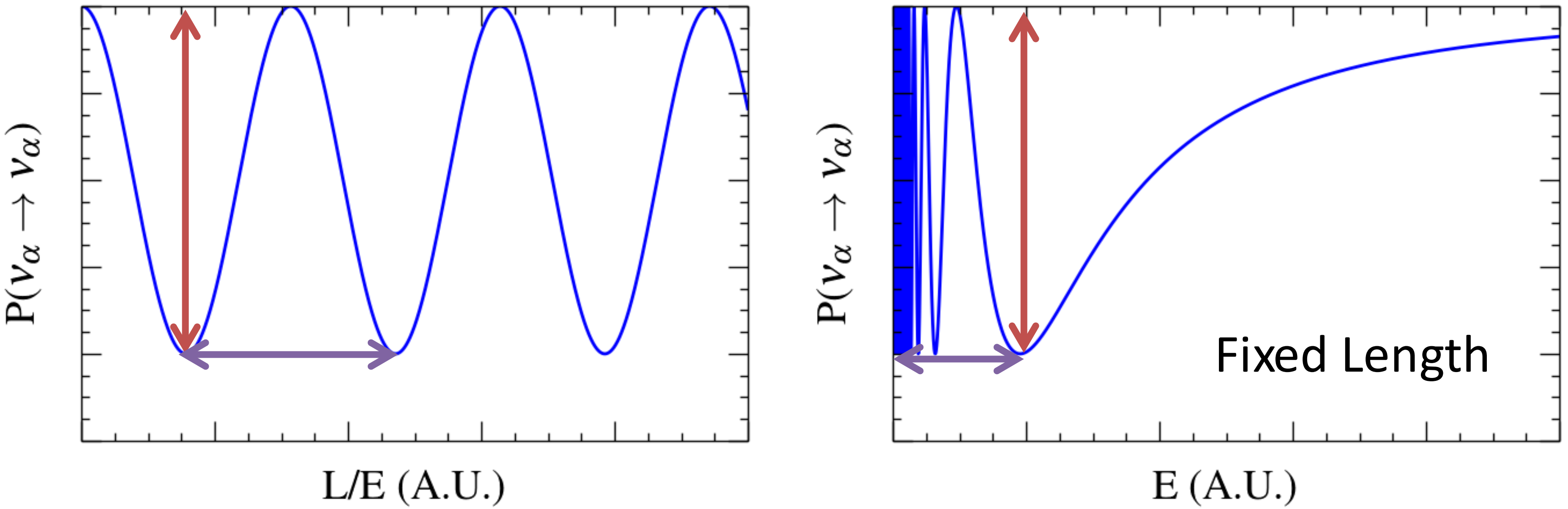
Muon Neutrino Survival Probability

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Neutrino Oscillations

- With only 2 neutrinos, the oscillation formula is simple:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

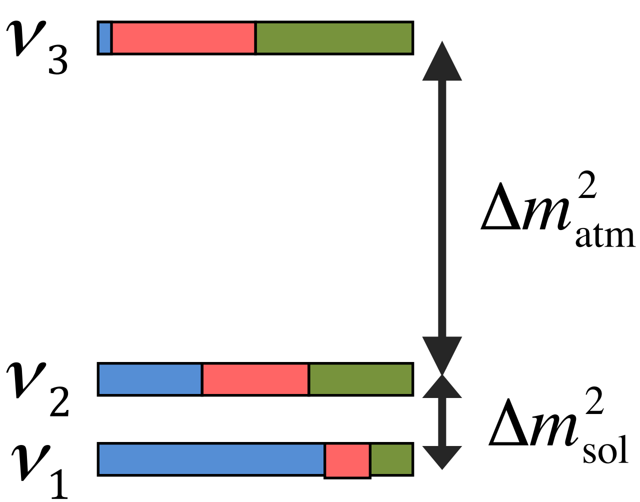


The PMNS Mixing Matrix

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass



Pontecorvo

Sov.Phys.JETP 6:429, 1957

Sov.Phys.JETP 26:984-988, 1968

Maki, Nakagawa, Sakata

Prog.Theor.Phys. 28, 870 (1962)

What We Know

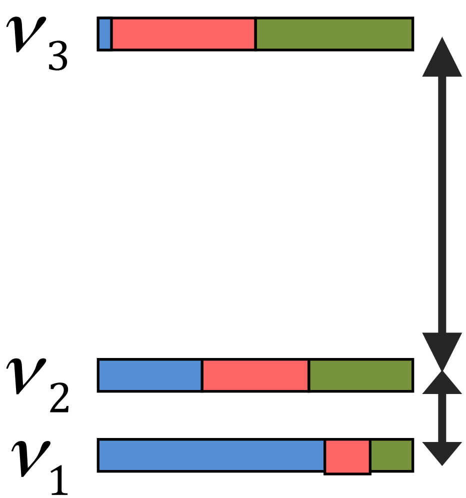
atmospheric accelerator ν_μ	short baseline reactor accelerator ν_e	solar long baseline reactor

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass

$\theta_{23} \approx 45°$ $\theta_{13} \approx 9°$ $\theta_{12} \approx 34°$



$\Delta m^2_{\mathrm{atm}} \approx 2 \times 10^{-3}\ \mathrm{eV}^2$

$\Delta m^2_{\mathrm{sol}} \approx 8 \times 10^{-5}\ \mathrm{eV}^2$

What We Don’t Know

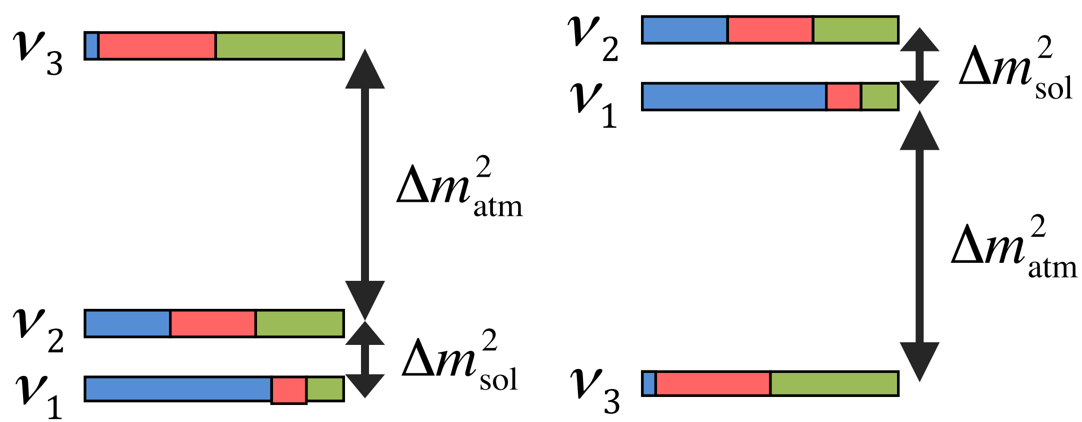
atmospheric / accelerator ν_μ — short baseline reactor / accelerator ν_e — solar / long baseline reactor

Flavor

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1&0&0\\ 0&c_{23}&s_{23}\\ 0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\ 0&1&0\\ -s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\ -s_{12}&c_{12}&0\\ 0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Mass

Phase δ_{CP}, and potentially CP violation



The “mass hierarchy,”
the sign of the atmospheric Δm^2

Oscillation Physics at NOvA

atmospheric
accelerator ν_μ

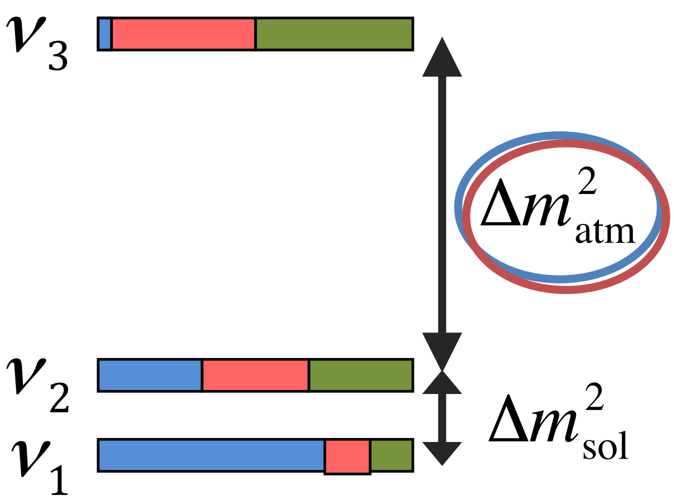
short baseline reactor
accelerator ν_e

solar
long baseline reactor

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass

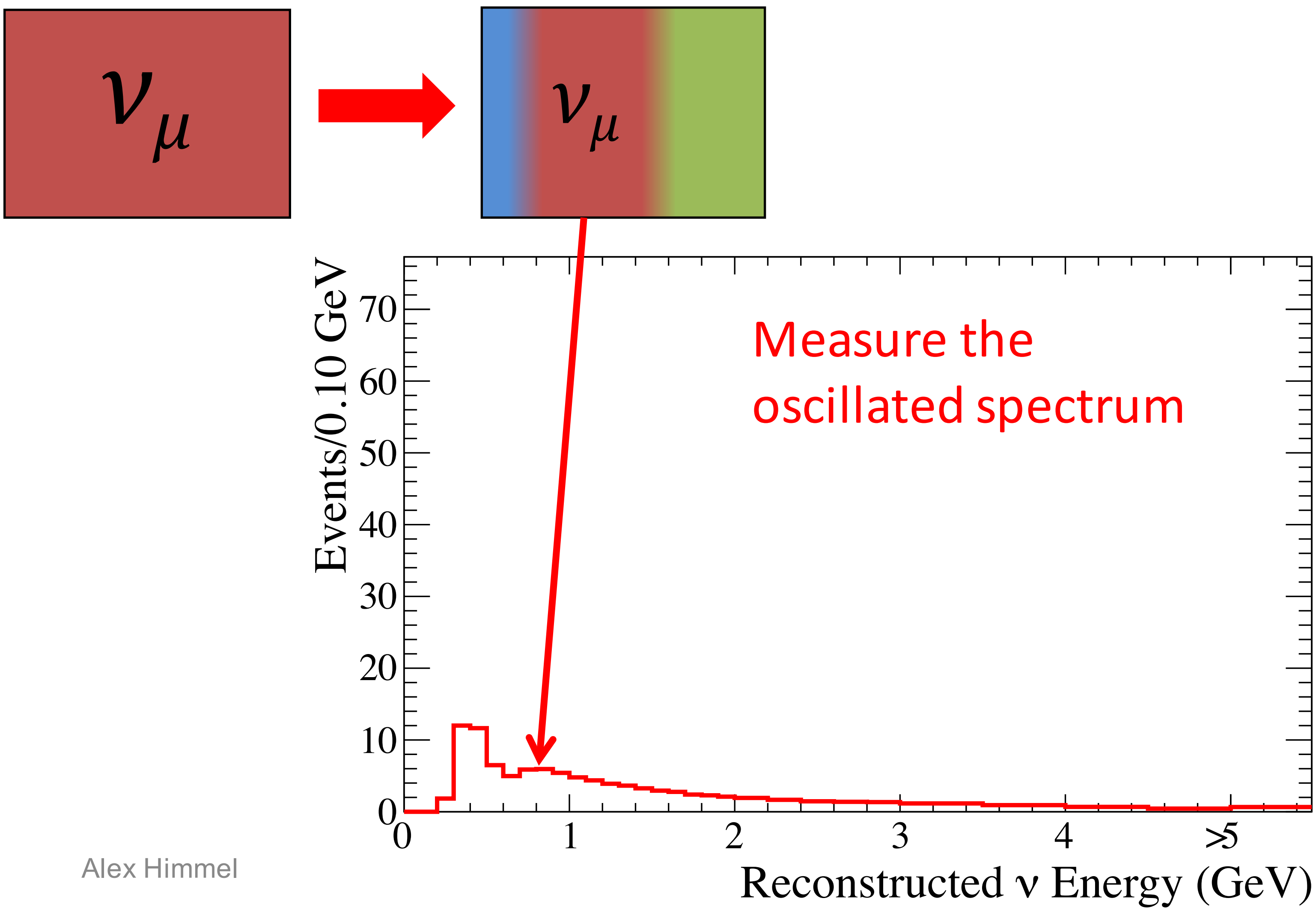


Long Baseline

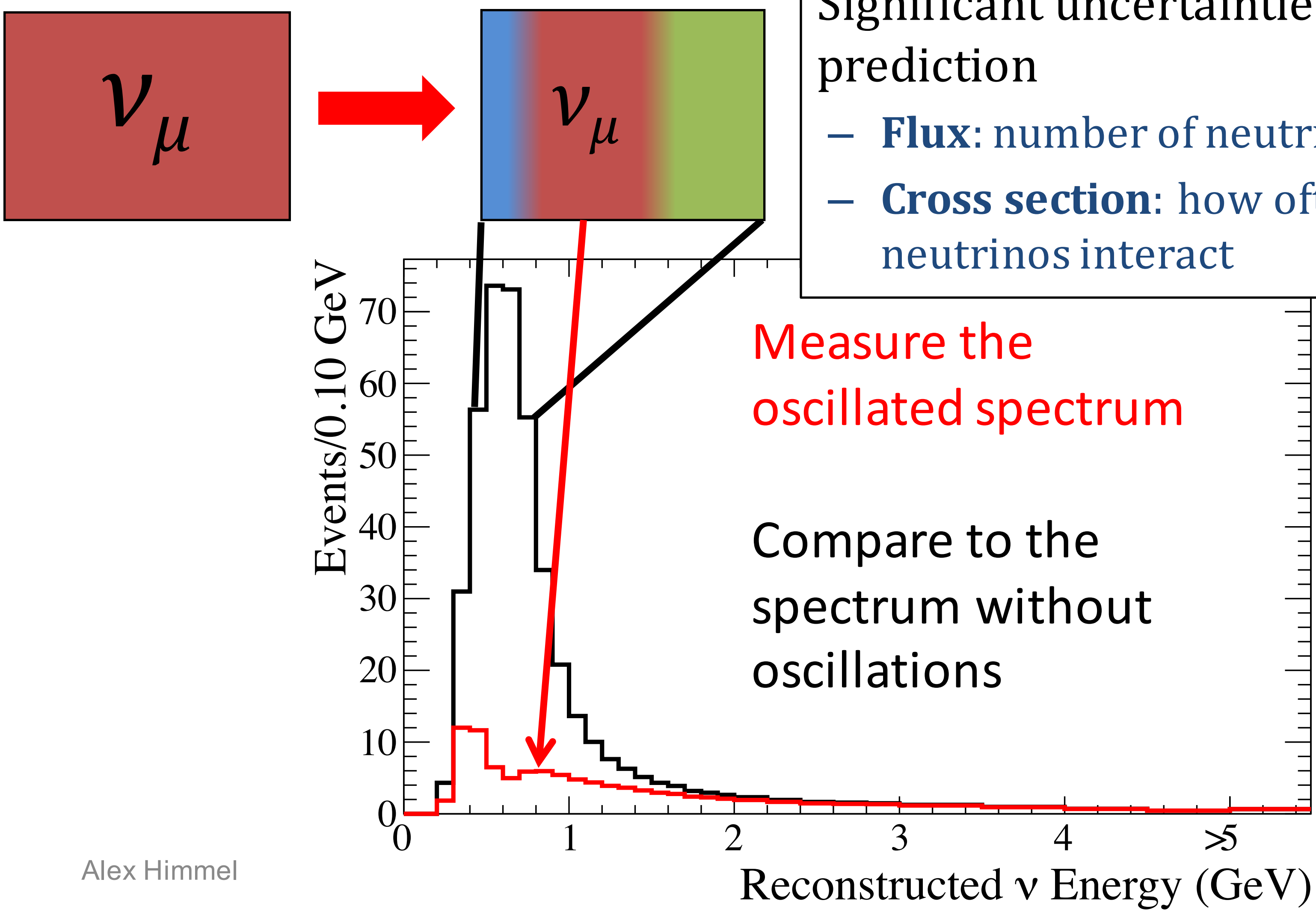
ν_μ Disappearance: θ_{23}, $|\Delta m^2{}_{\text{atm}}|$

$\nu_\mu \rightarrow \nu_e$ Appearance: θ_{13}, δ_{CP}

How We Measure Oscillations: Disappearance



How We Measure Oscillations: Disappearance



Significant uncertainties in the prediction
- **Flux**: number of neutrinos produced
- **Cross section**: how often the neutrinos interact

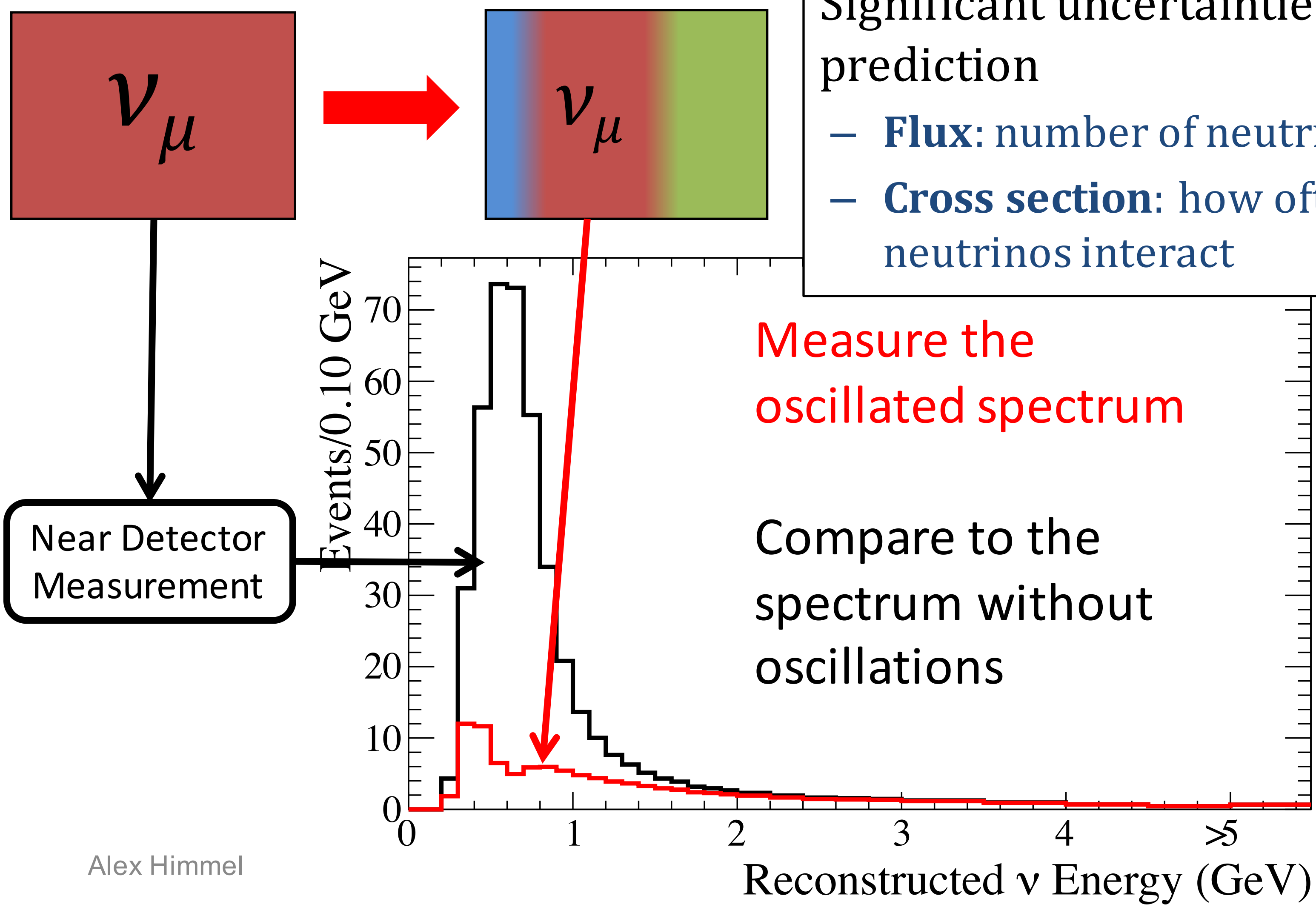
Measure the oscillated spectrum

Compare to the spectrum without oscillations

How We Measure Oscillations: Disappearance

Significant uncertainties in the prediction

- **Flux**: number of neutrinos produced
- **Cross section**: how often the neutrinos interact



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

- 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 ...

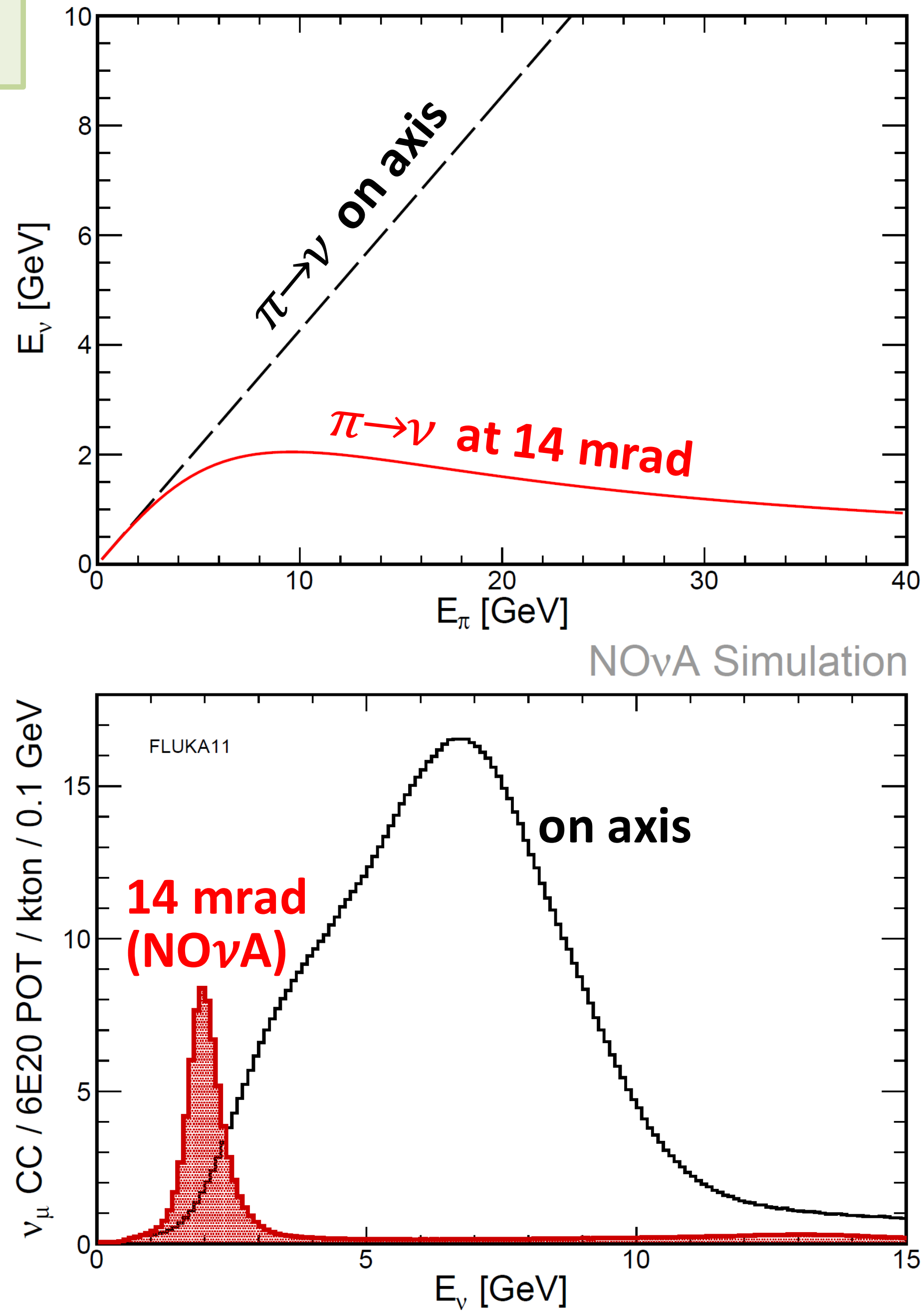
- Neutrino cross sections at the NOνA Near Detector
- Sterile neutrinos
- Supernova neutrinos
- Other exotica

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.**



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

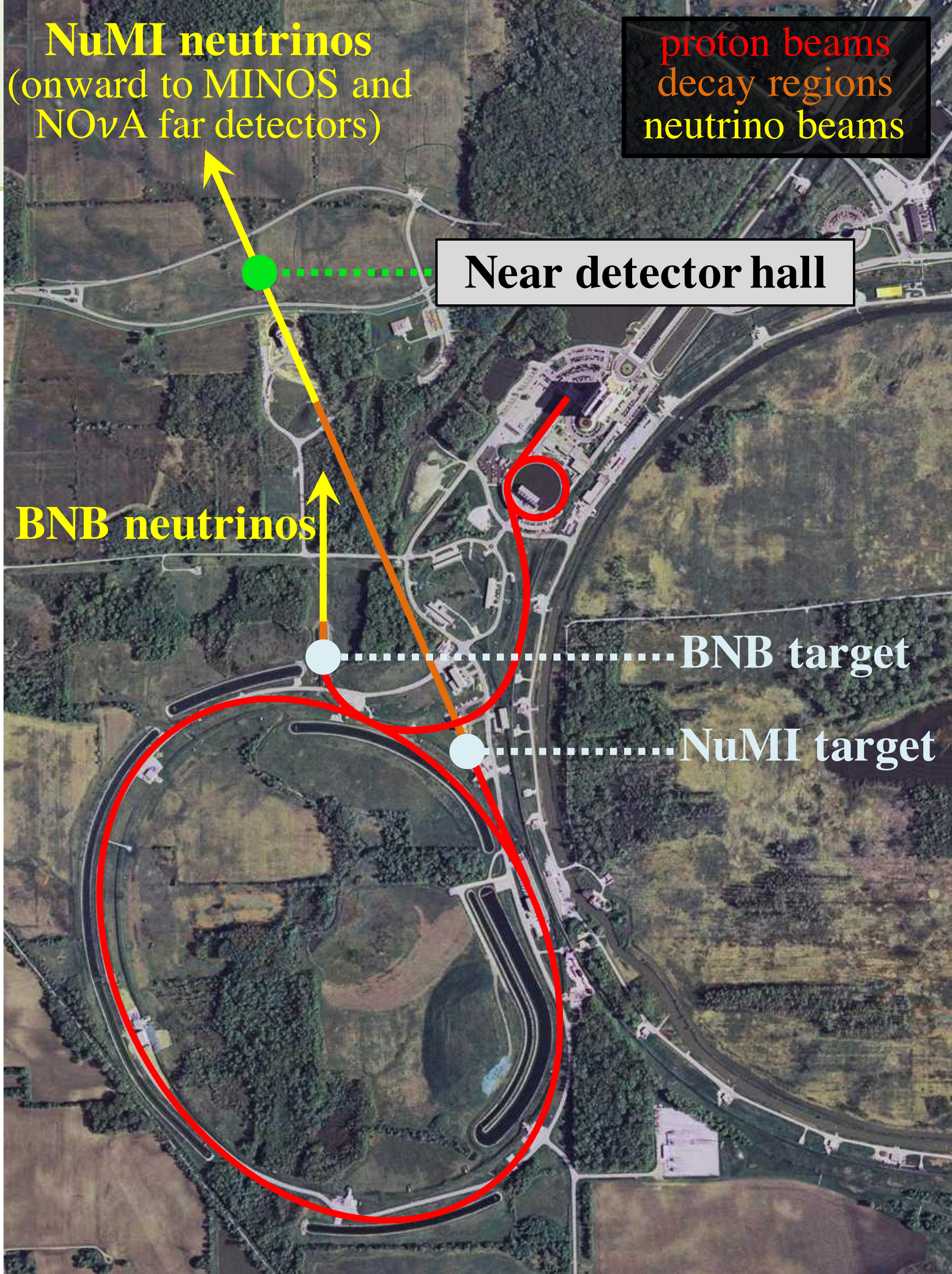
→ **Major upgrades toward 700 kW operation**

Since March 2015:

Routine slip-stacking (2+6 batches) into recycler, typically ~420 kW

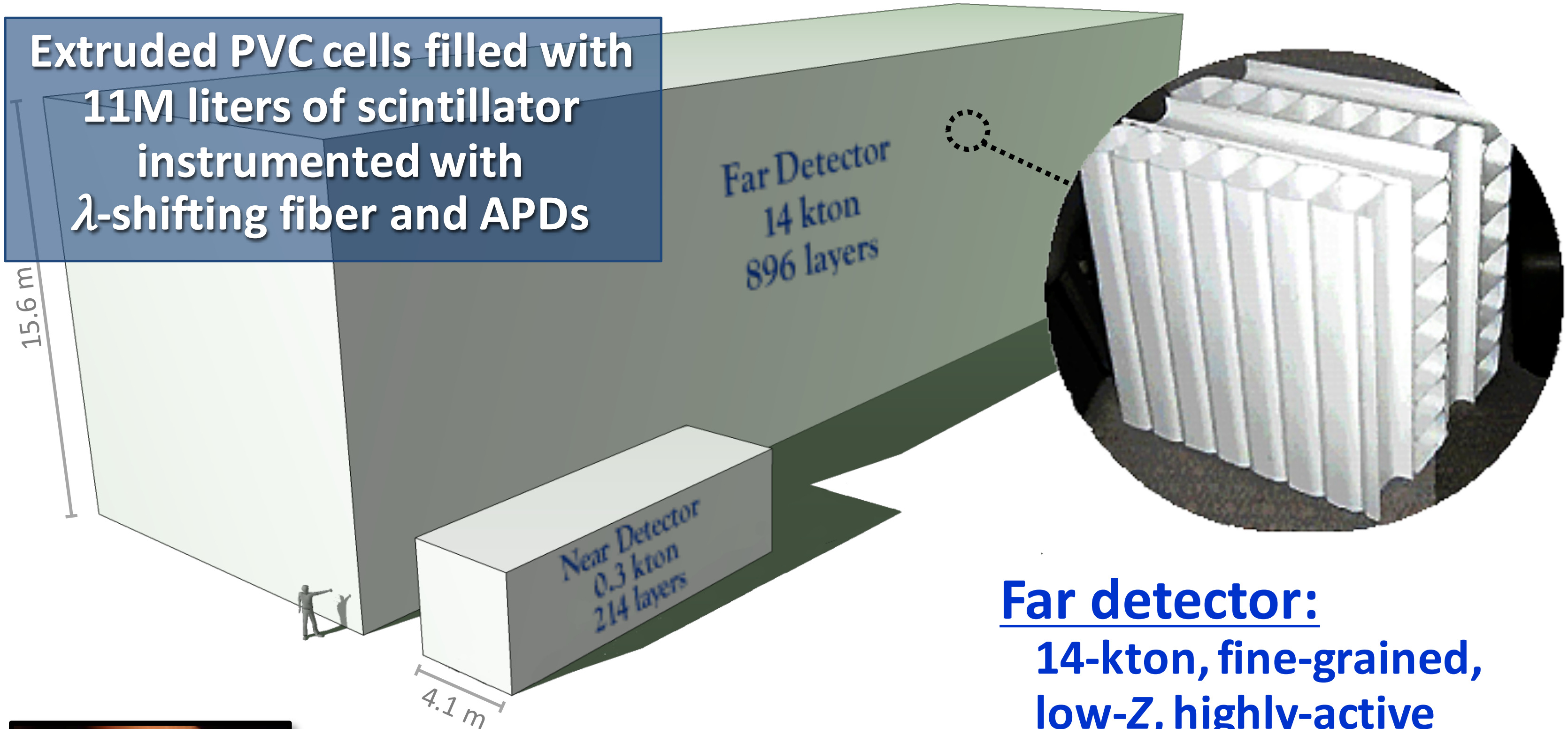
→ **Beam power record: 521 kW!**

→ **85% uptime!**

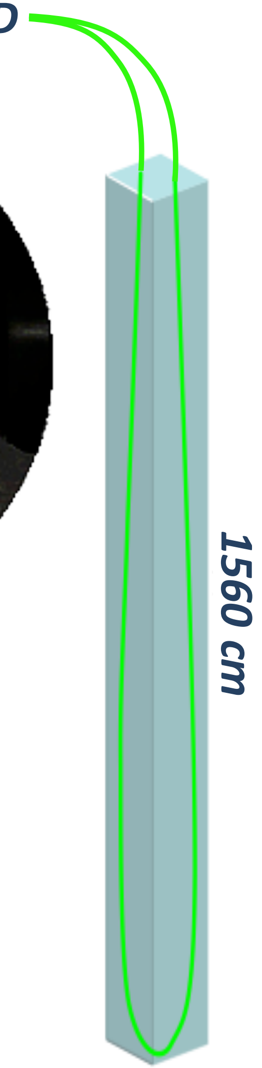


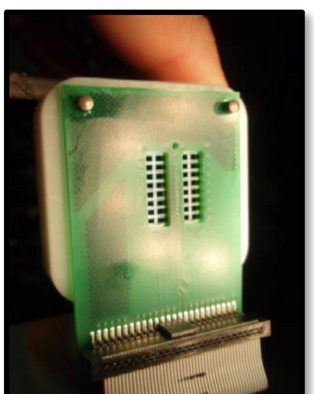
NOνA detectors

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



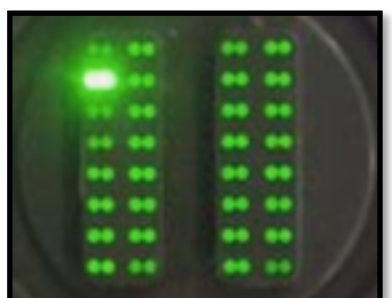
A NOνA cell





32-pixel APD ←

Fiber pairs from 32 cells →



Far detector:

14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter

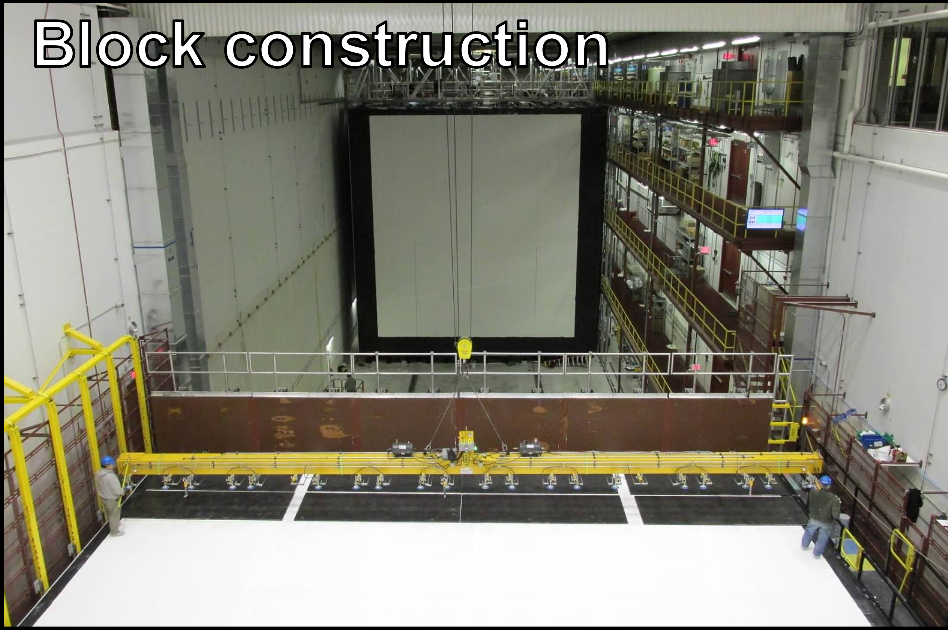
→ *344,000 channels*

Near detector:

0.3-kton version of the same

→ *20,000 channels*

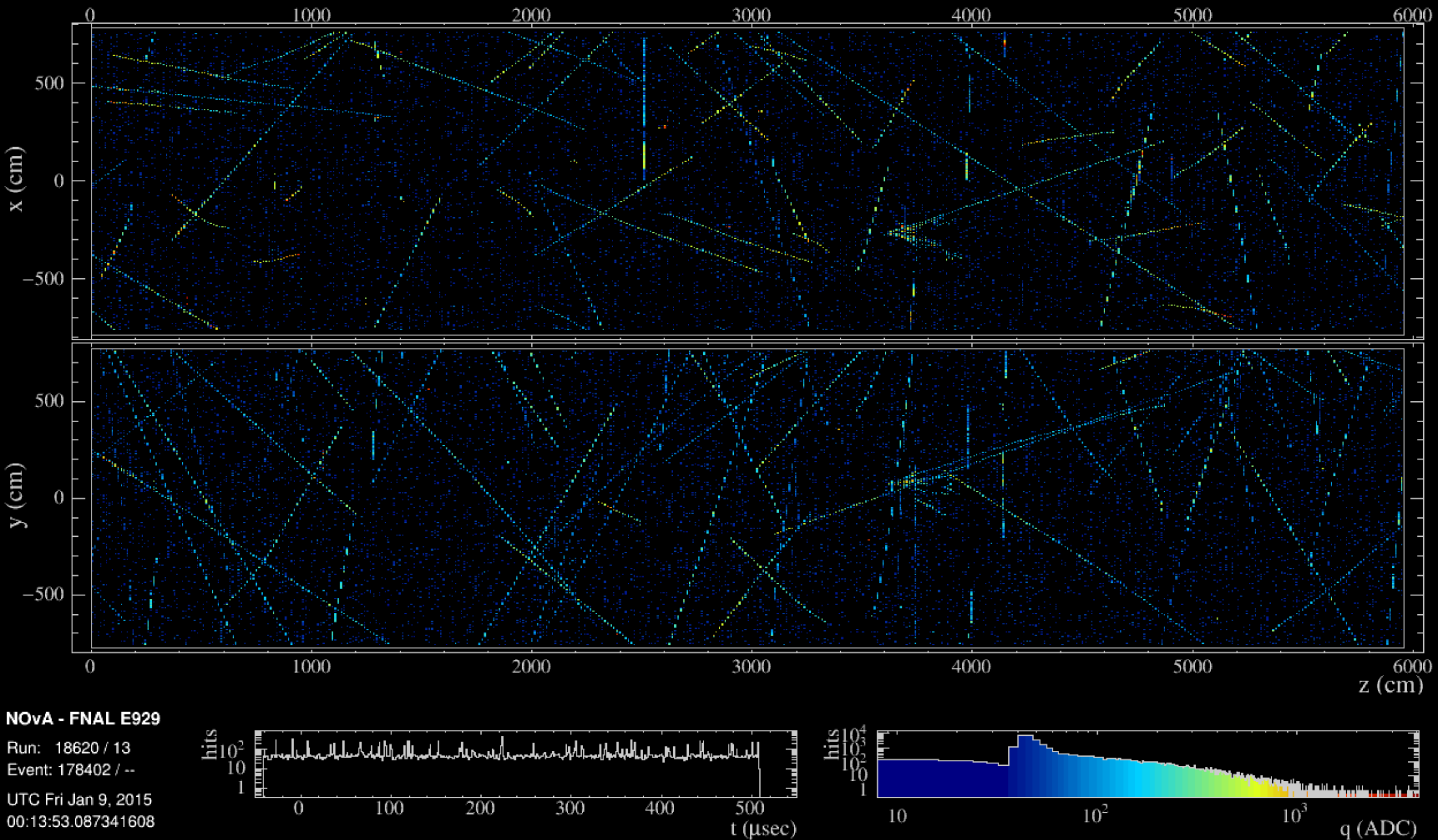

Far Detector site


Block construction

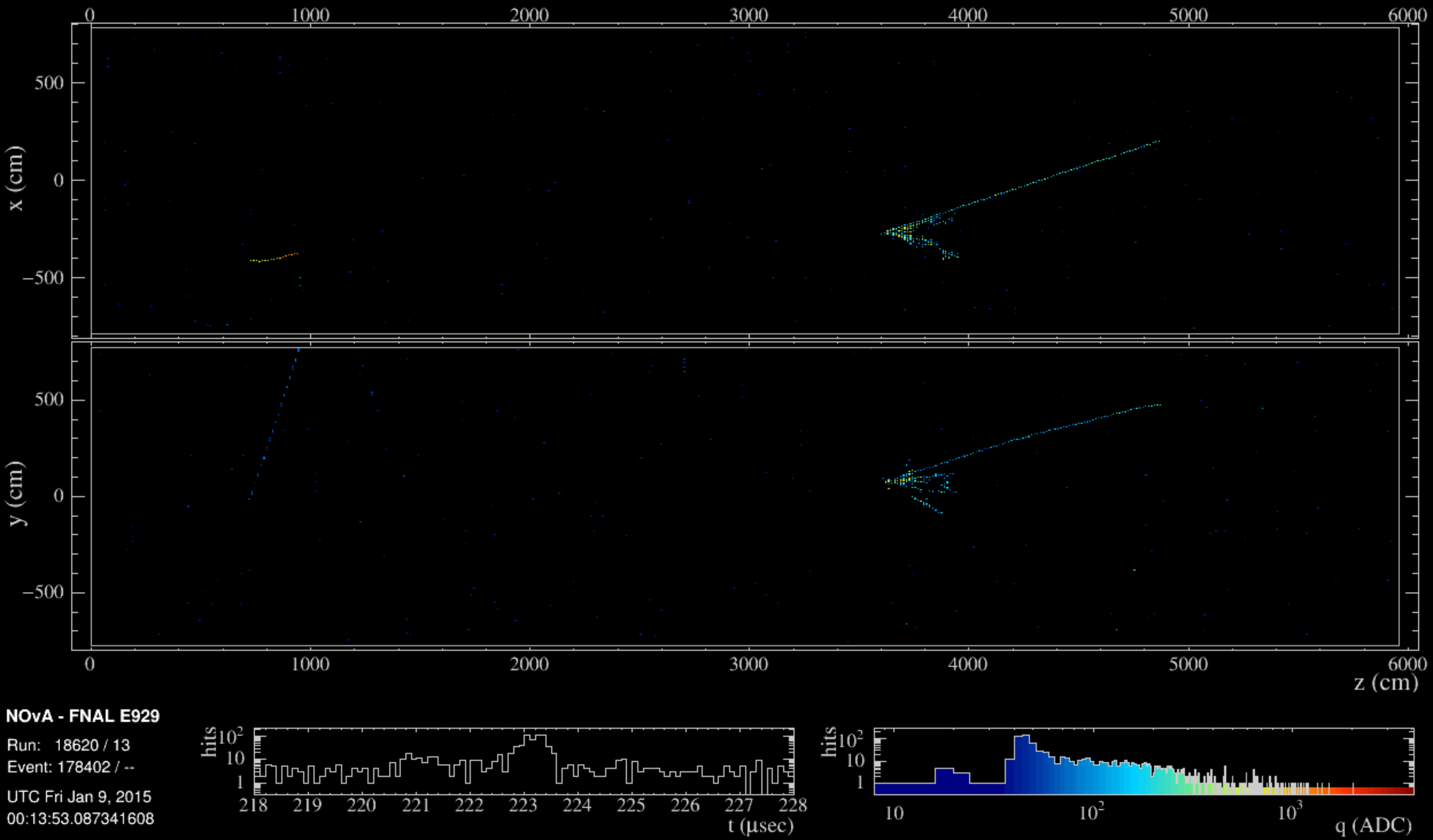

Outfitted Far Detector


Near Detector

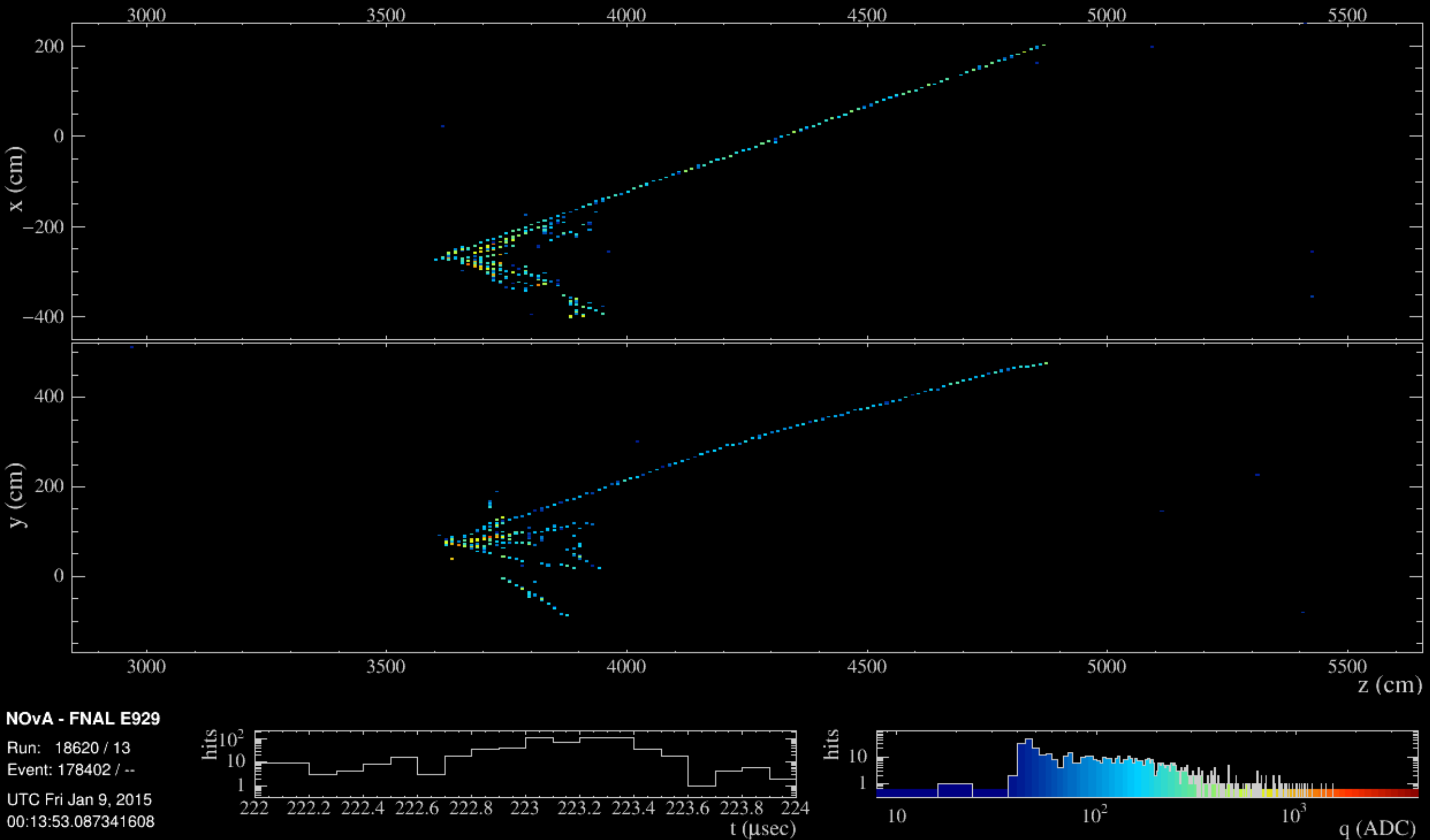
550 μs exposure of the Far Detector



Time-zoom on 10 μs interval during NuMI beam pulse

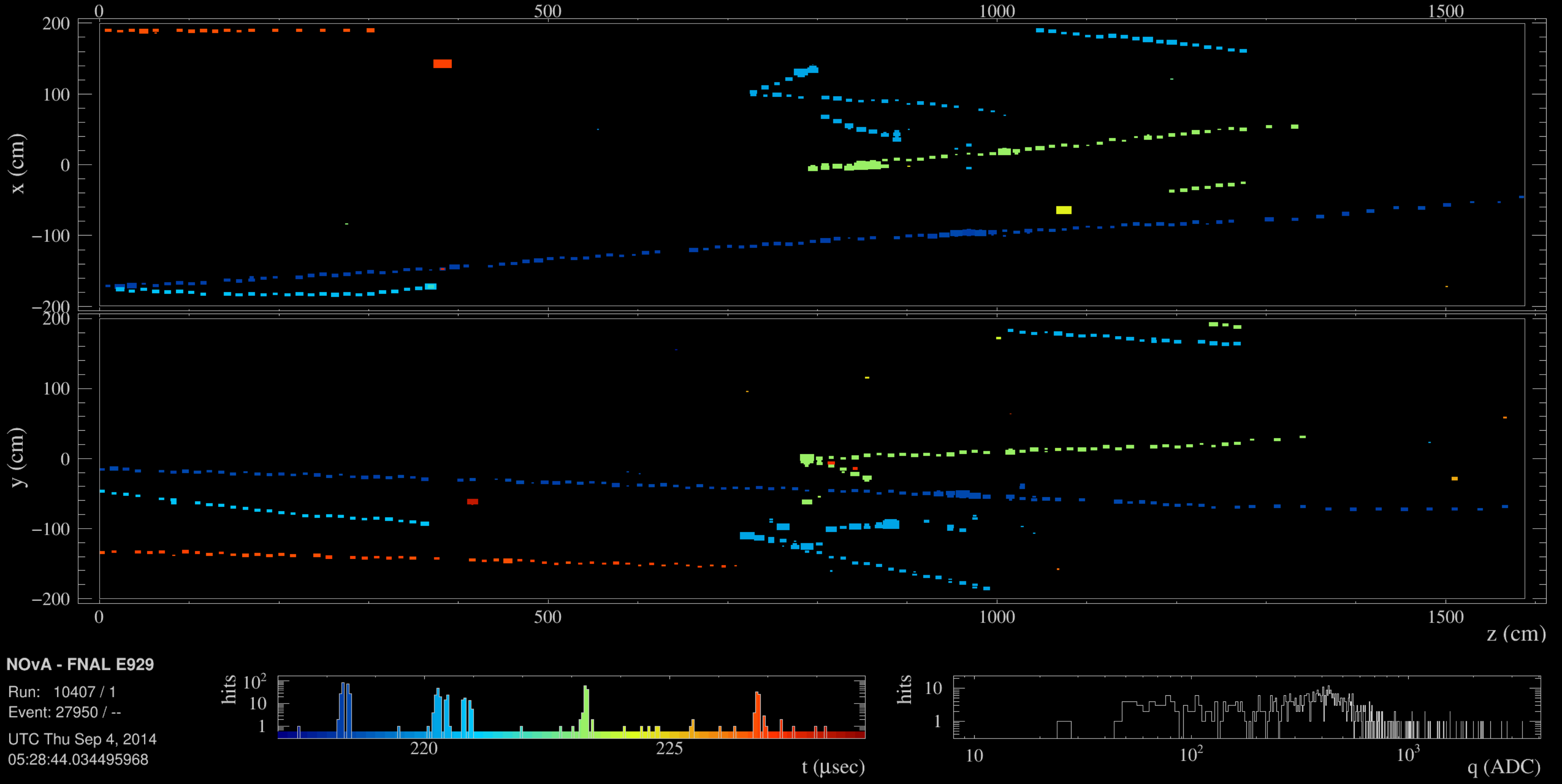


Close-up of neutrino interaction in the Far Detector



Near Detector: 10 μs of readout during NuMI beam pulse

(color ⇒ time of hit)



Near Detector: 10 μs of readout during NuMI beam pulse

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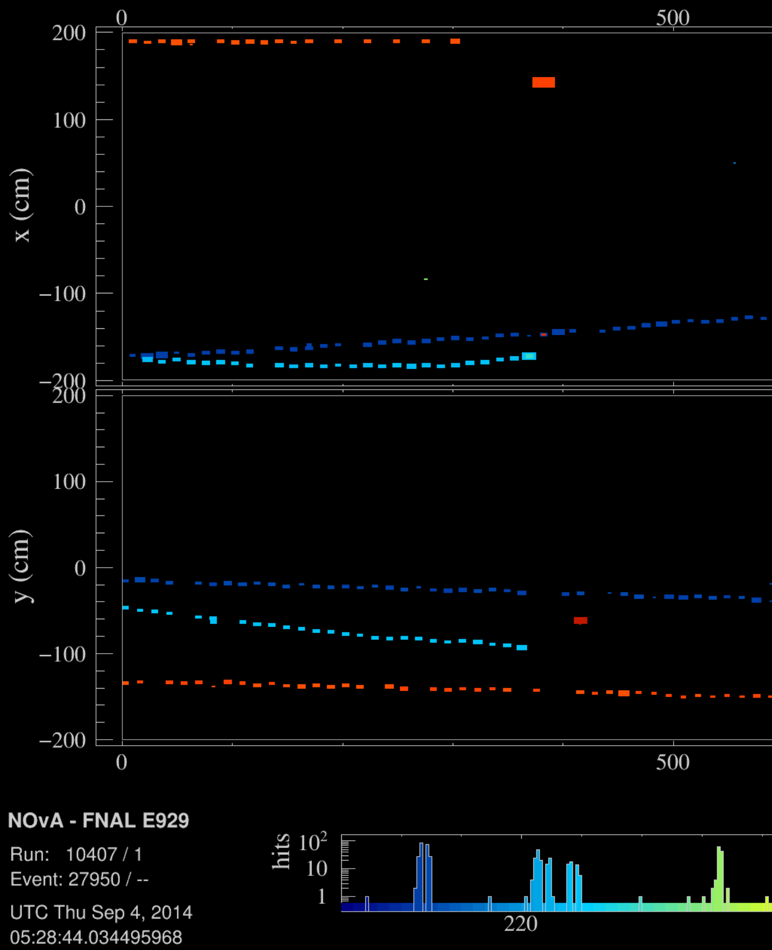
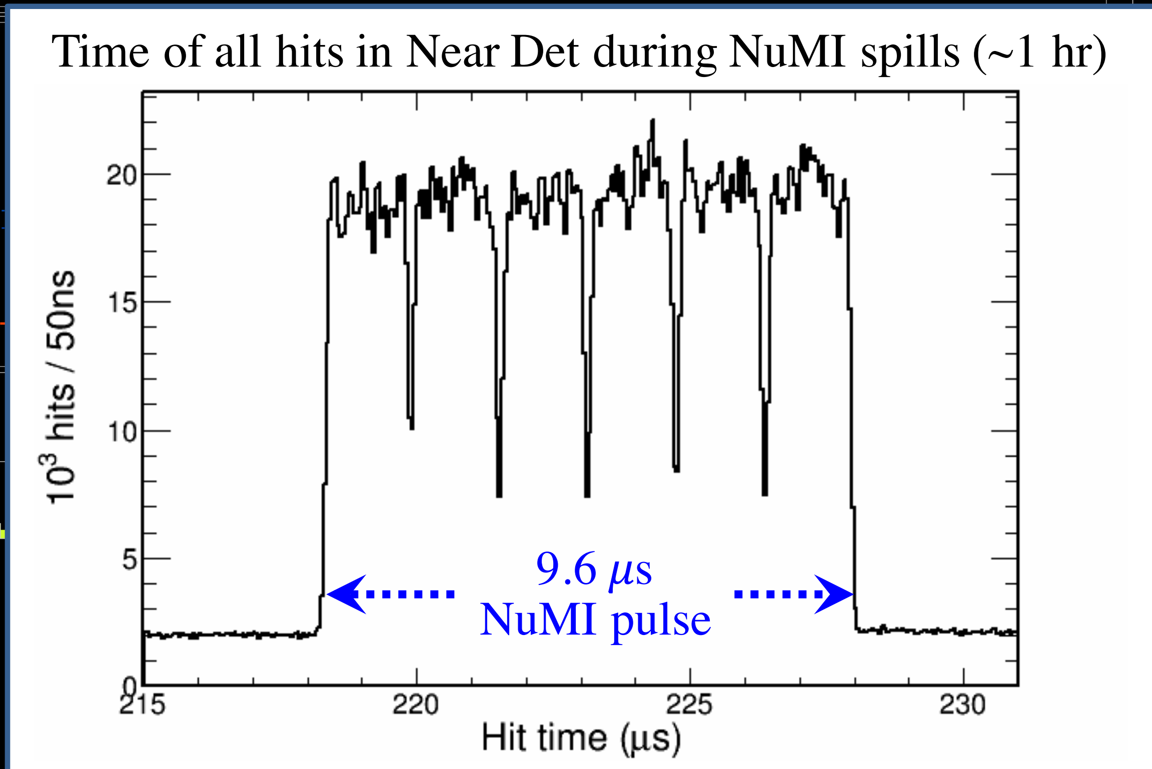
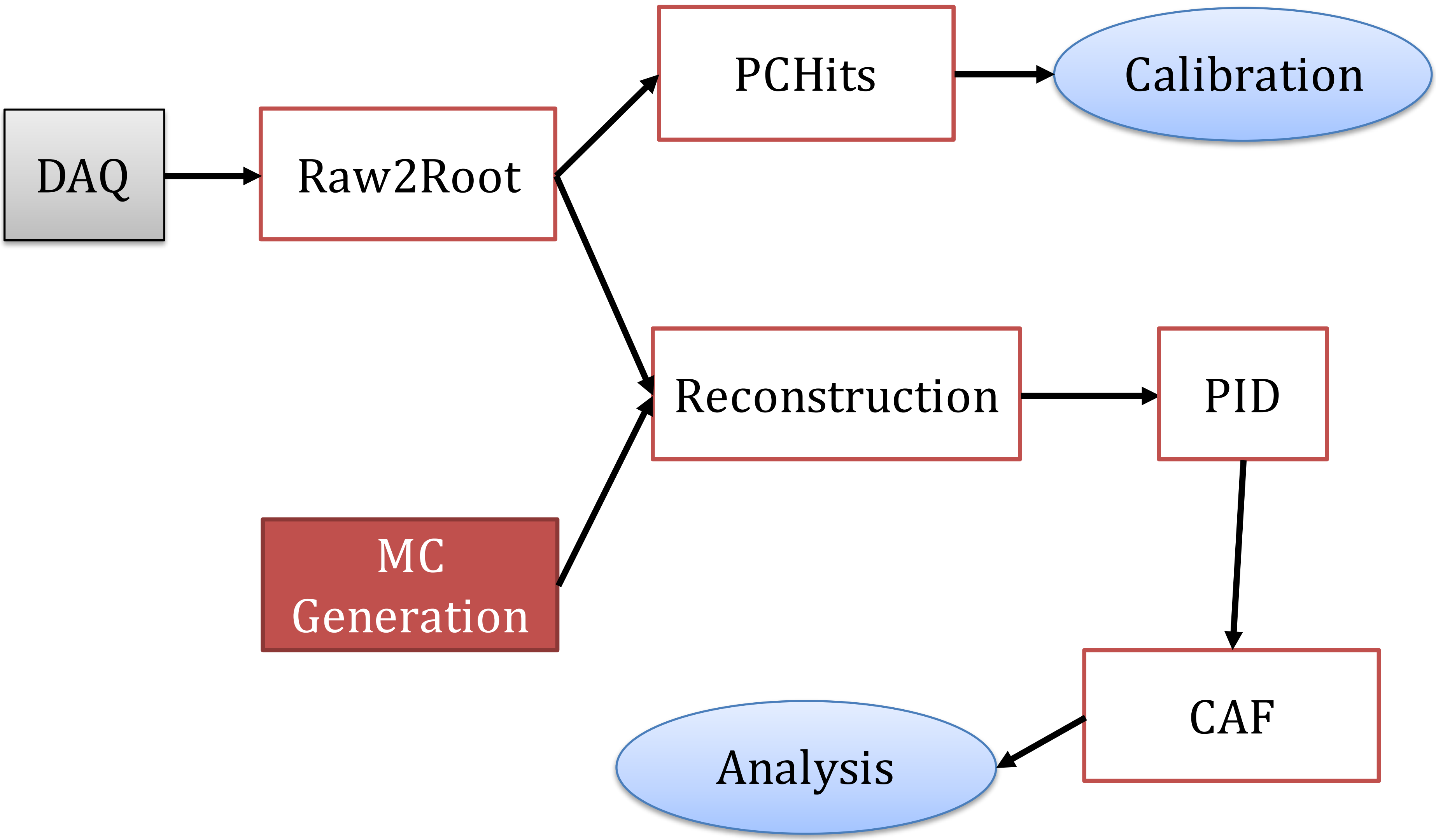
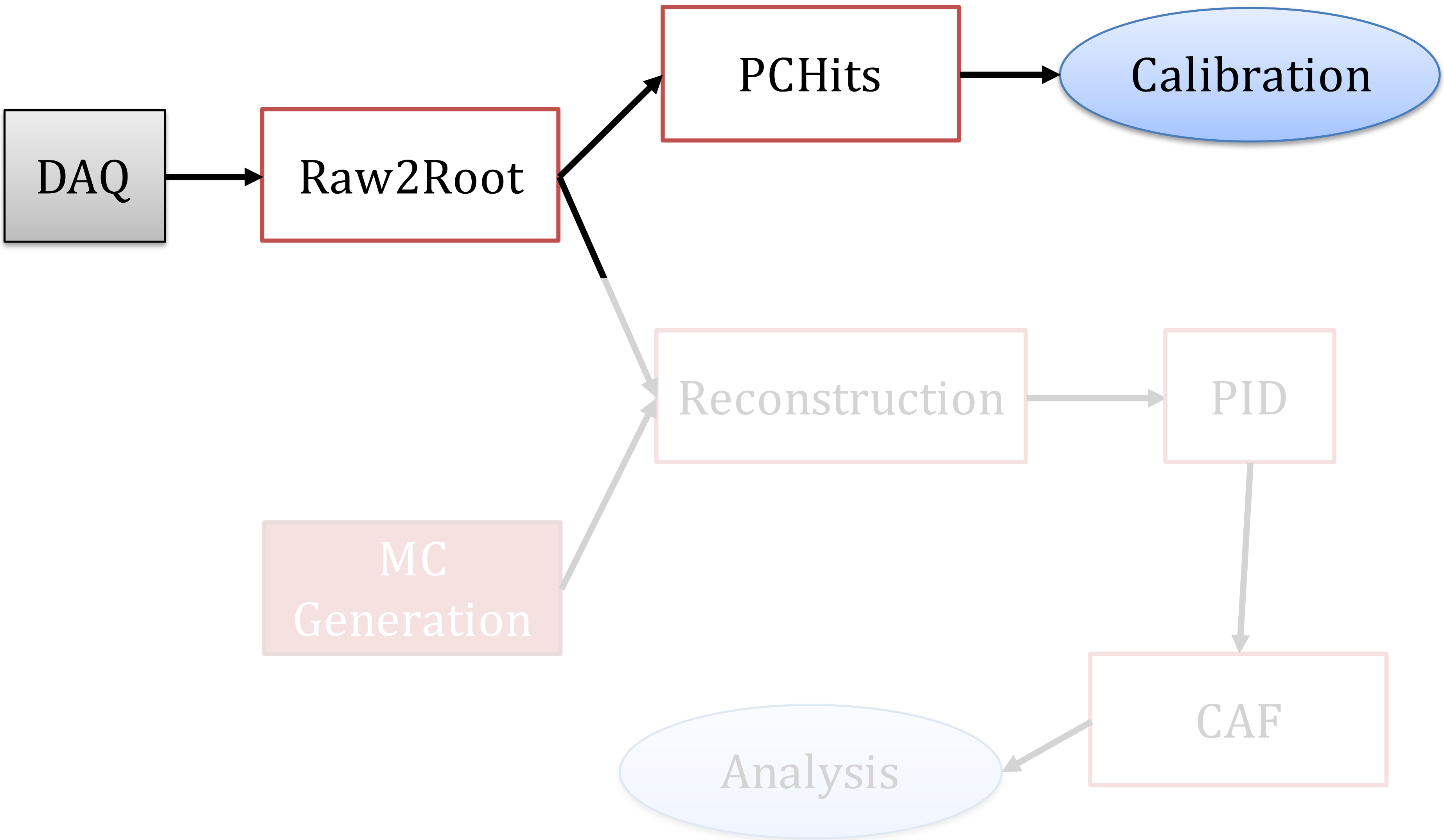




Nova Production Processing

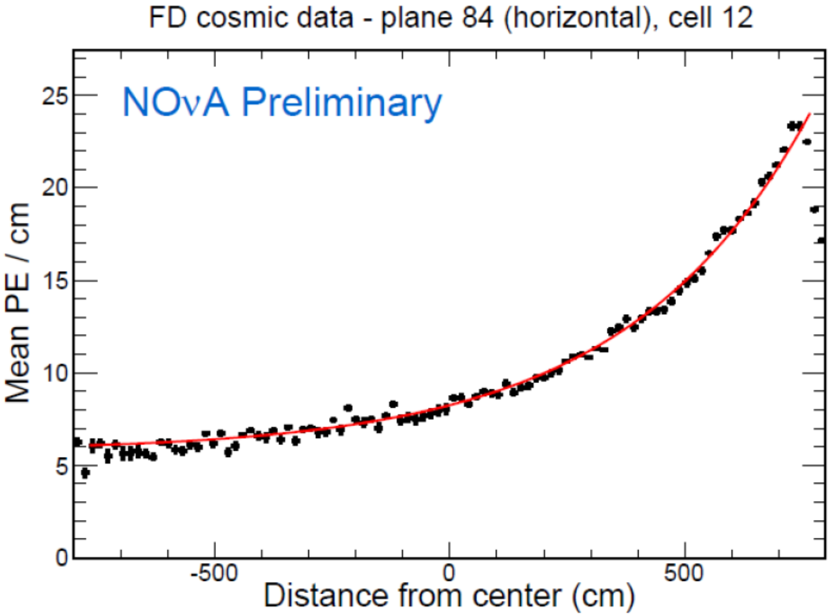


Nova Production Processing



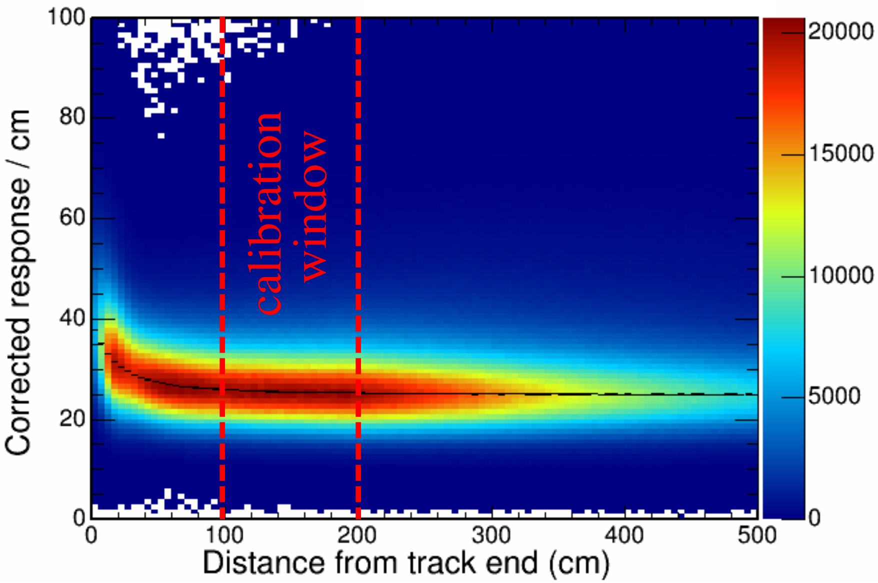
Calibration

- **Biggest effect** that needs correction is **attenuation** in the WLS fiber
  Example FD cell ⟶

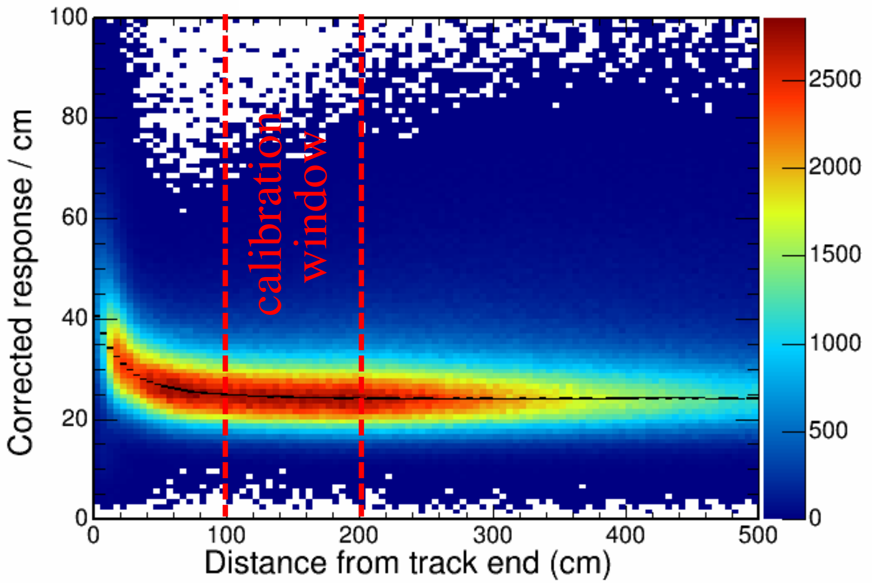


- **Stopping muons** provide a standard candle for setting absolute energy scale *(below)*

Far Detector Data



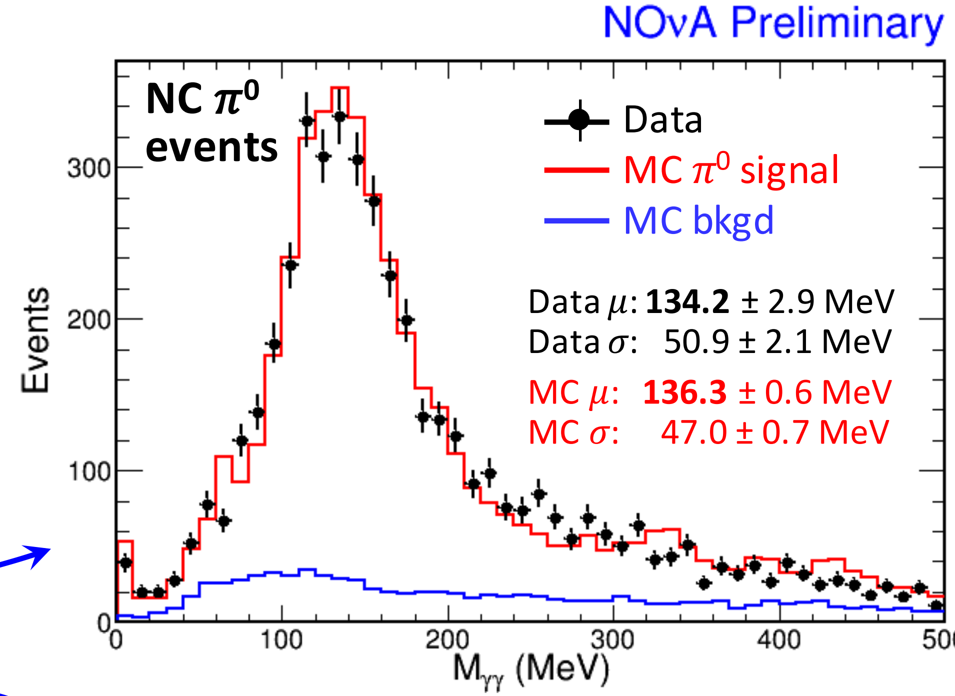
Far Detector Simulation

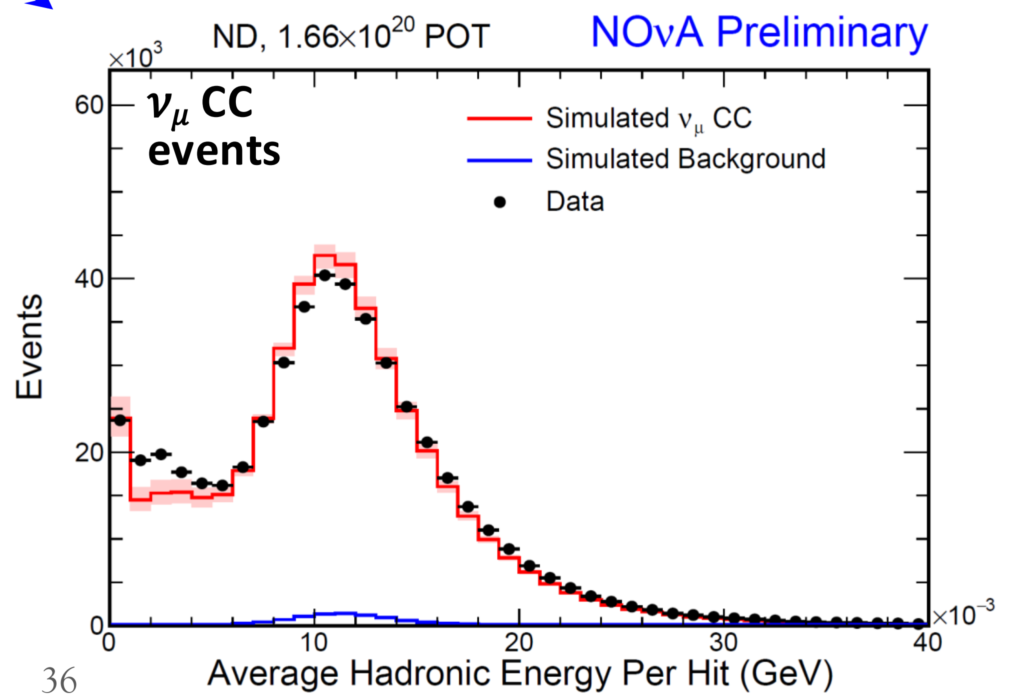


Multiple probes of energy scale

In Near Detector

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



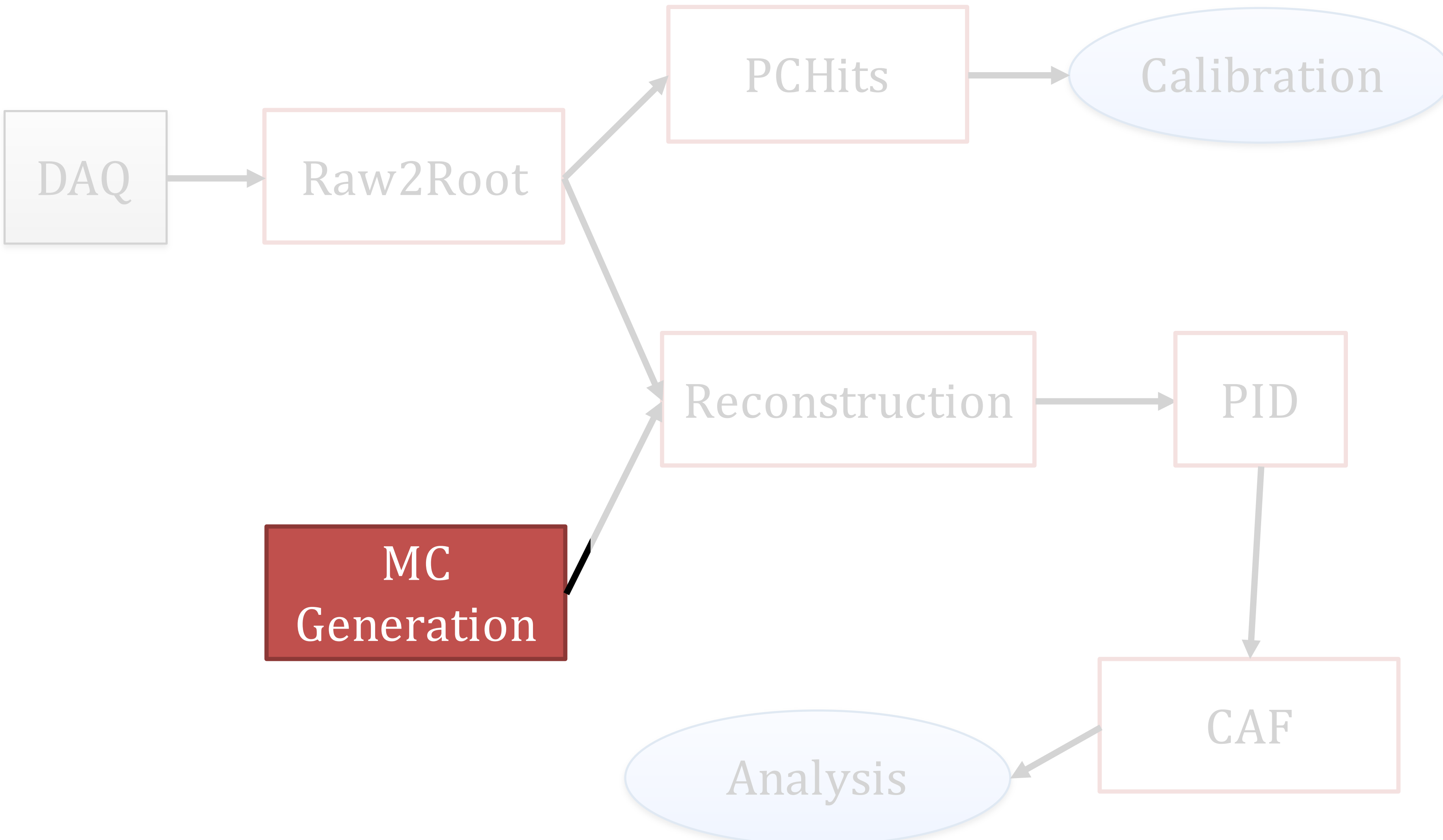


In Far Detector

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

All agree within ±5%

Nova Production Processing

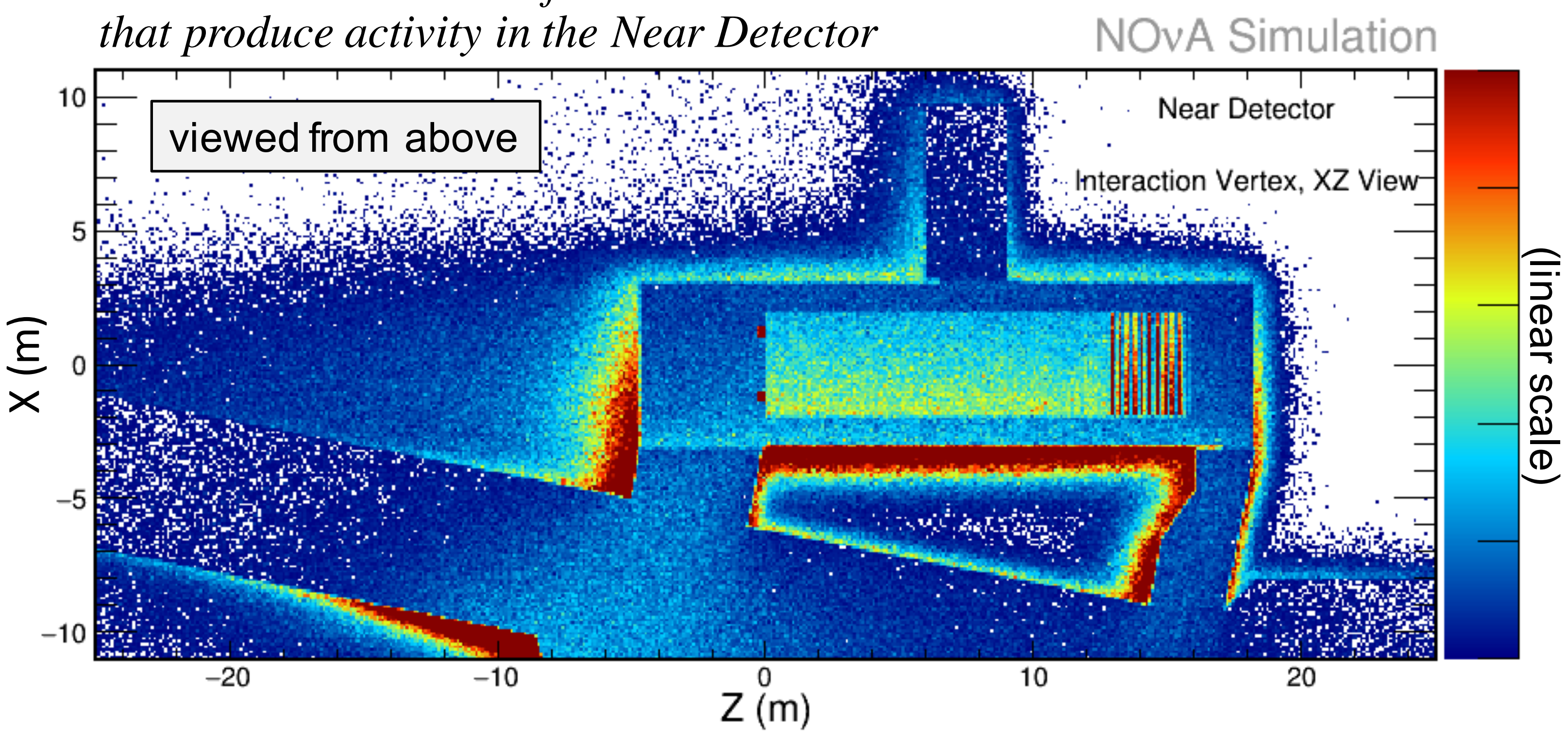


Simulation

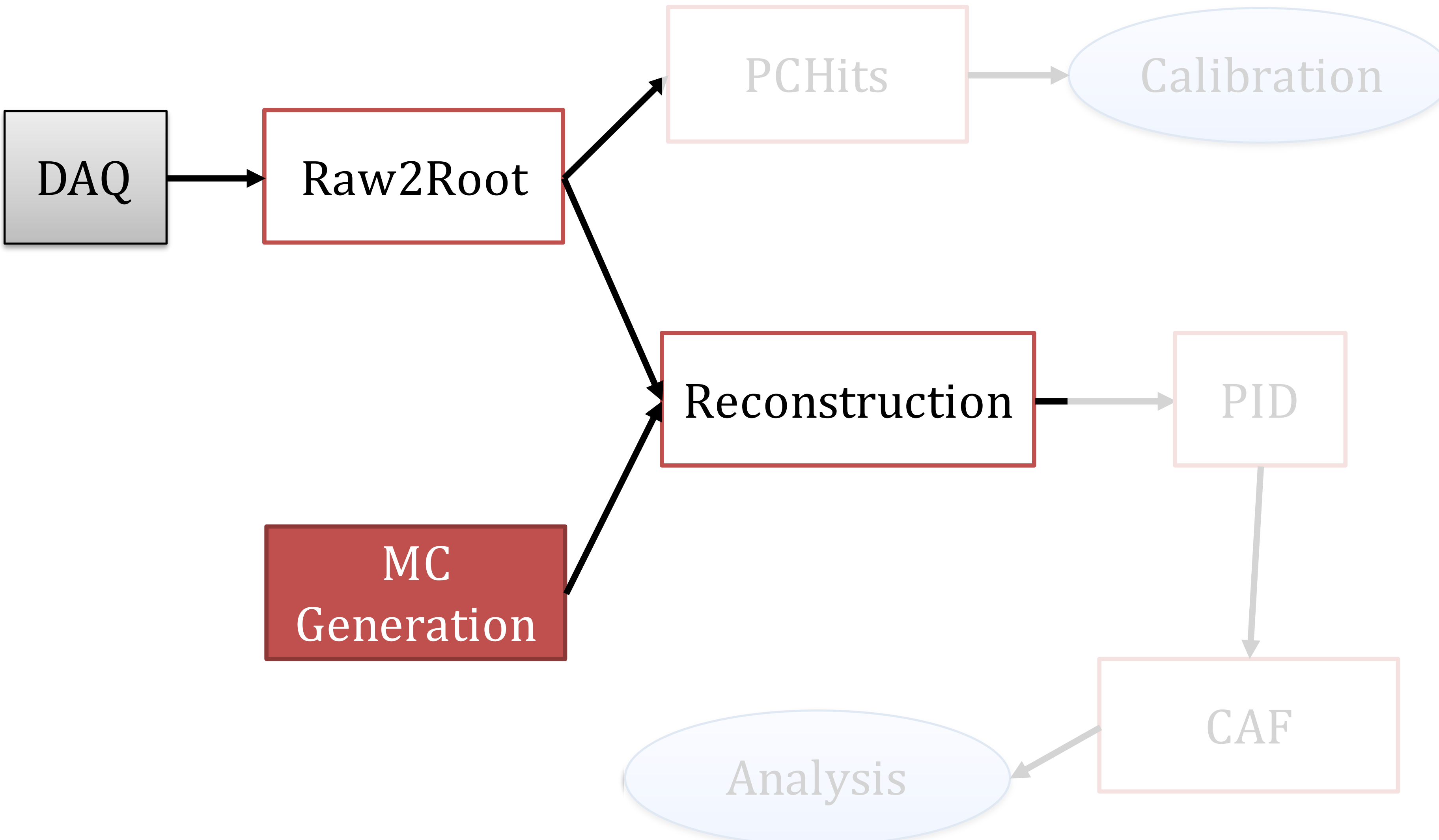
Highly detailed end-to-end simulation chain

- 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**

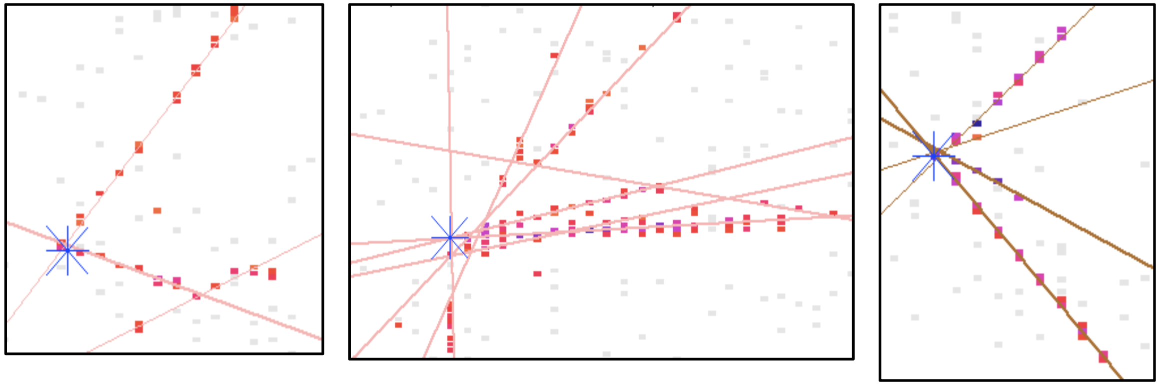
Simulation: Locations of neutrino interactions that produce activity in the Near Detector



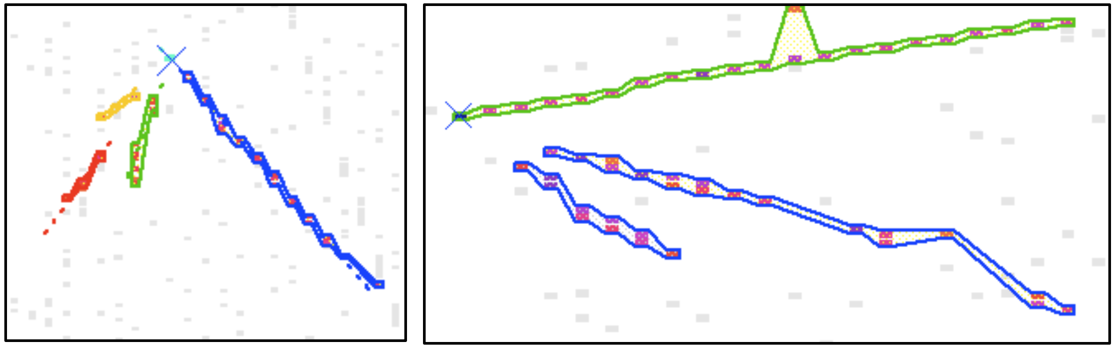
Nova Production Processing



Reconstruction

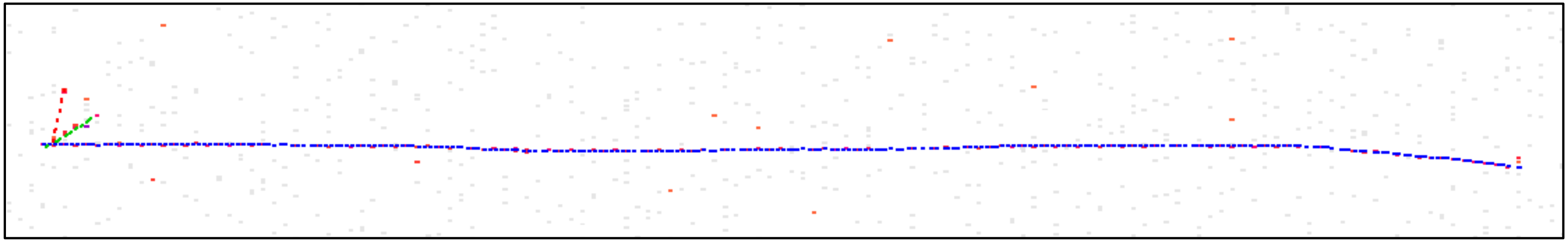


Vertexing: Find **lines of energy depositions** w/ Hough transform
CC events: 11 cm resolution

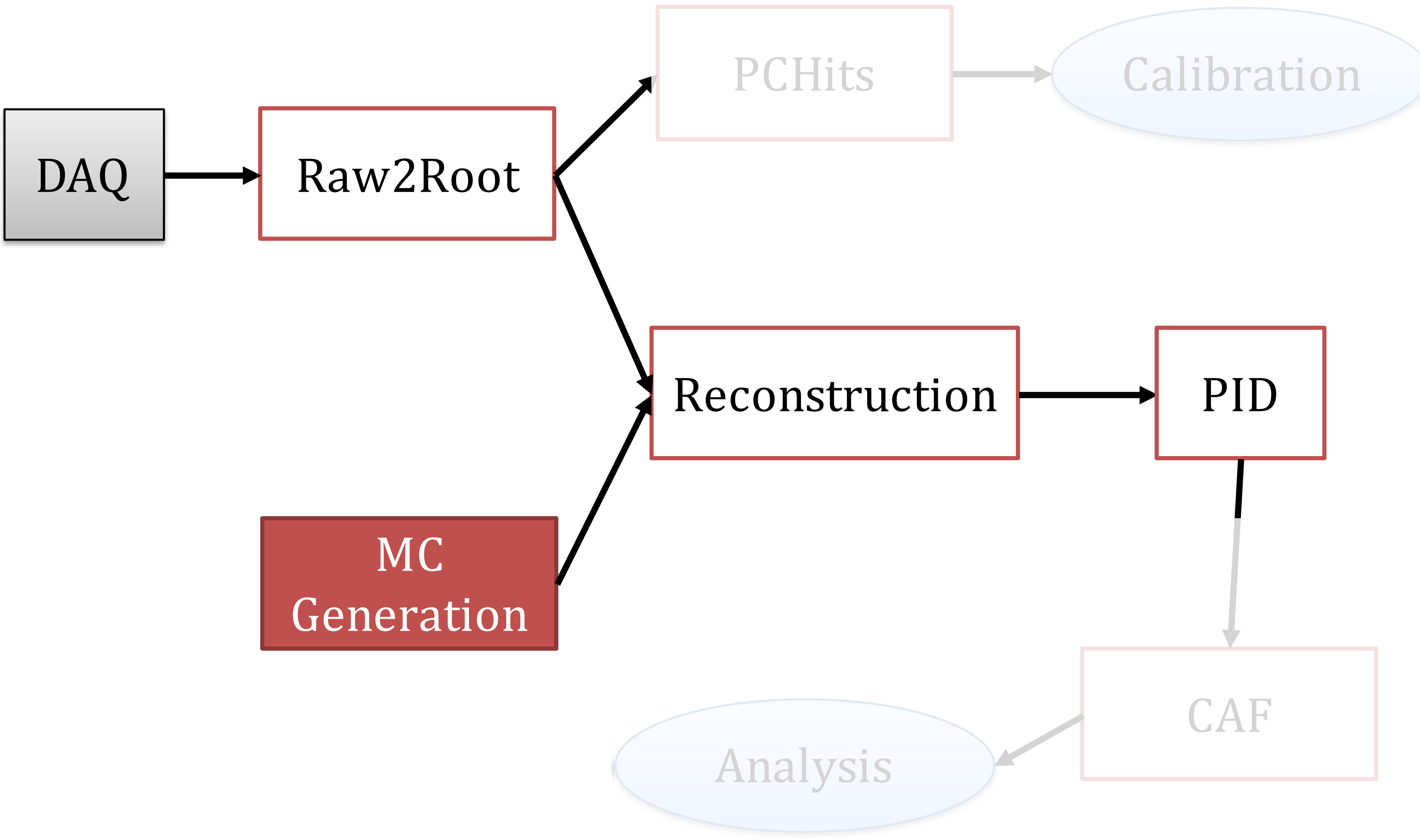


Clustering: Find **clusters in angular space** around vertex. **Merge views** via topology and prong *dE*/*dx*

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.



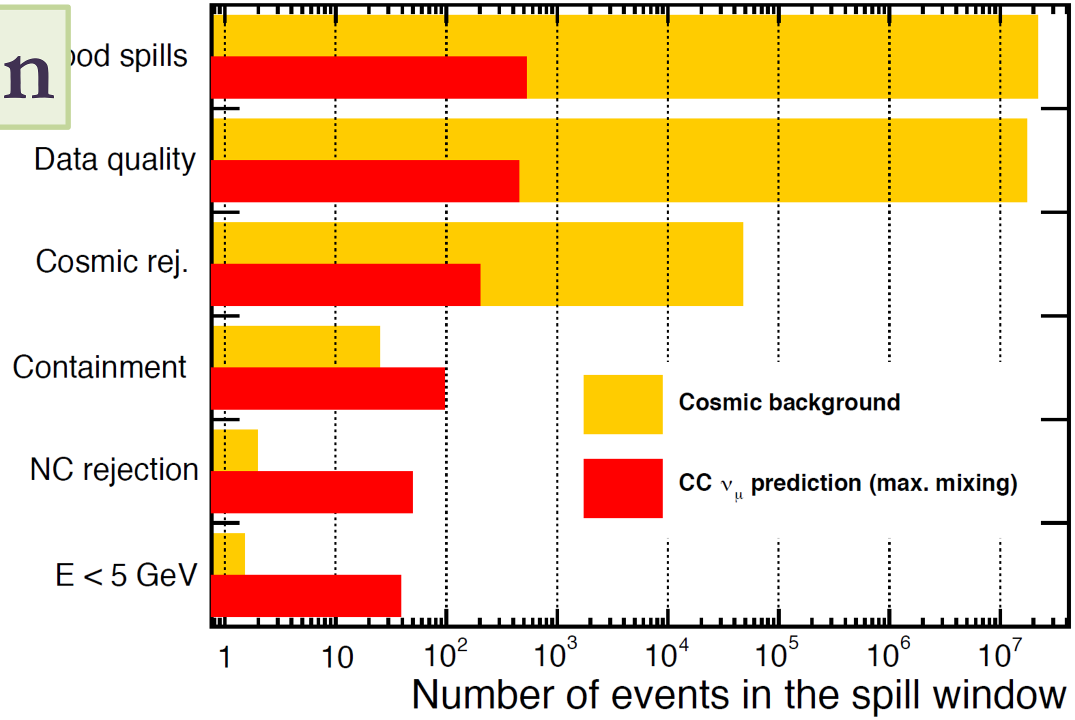
Nova Production Processing

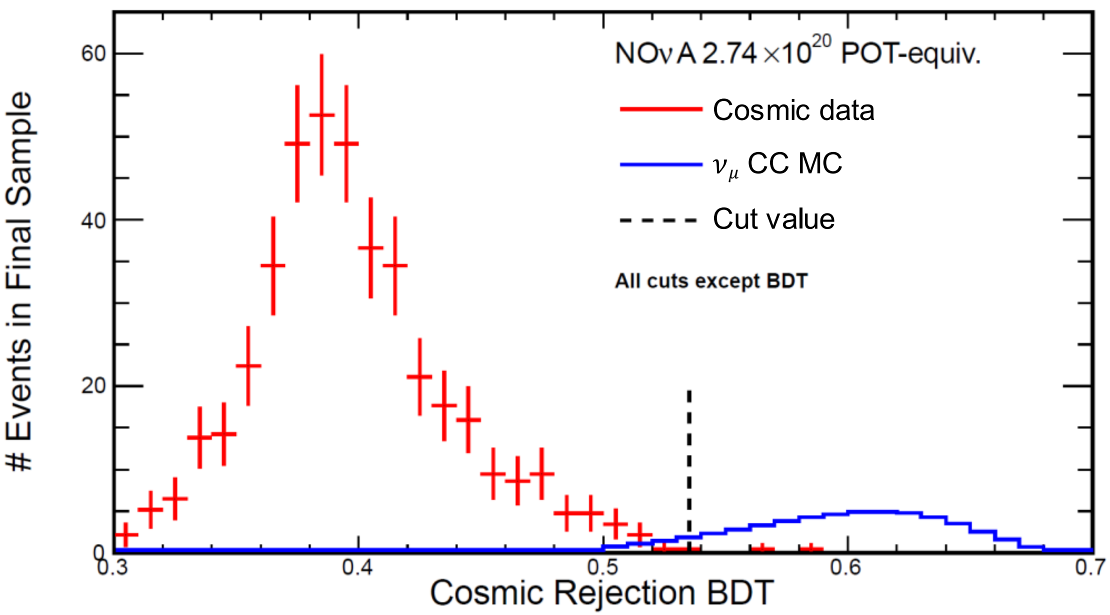


ν_μ Cosmic rejection

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

ν_μ CC selection

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

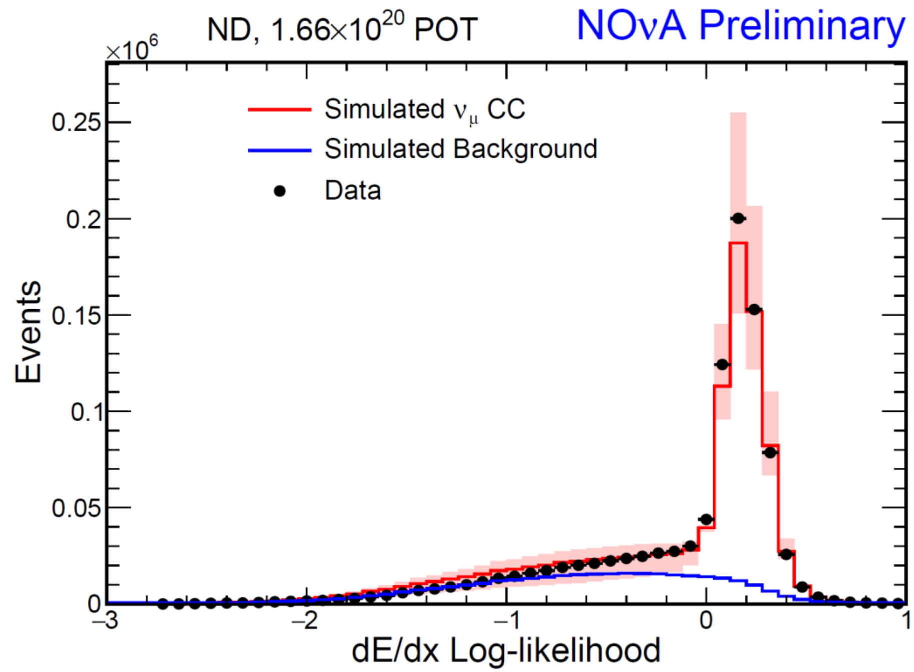
<u>Muon ID</u>

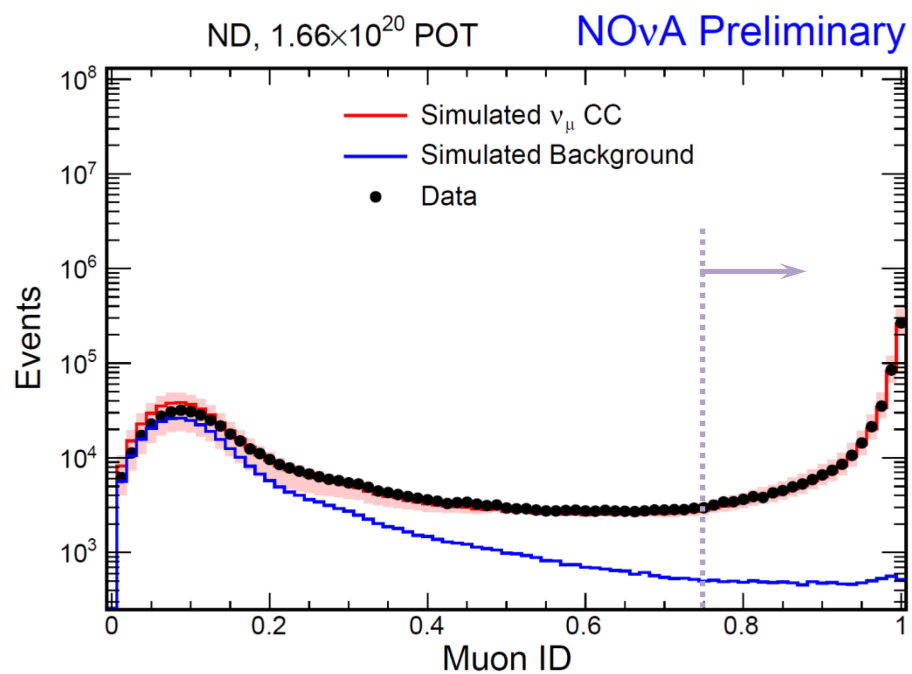
4-variable ***k*-nearest-neighbors** algorithm used to identify muons.

Inputs:

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

Keep events with μ ID > 0.75

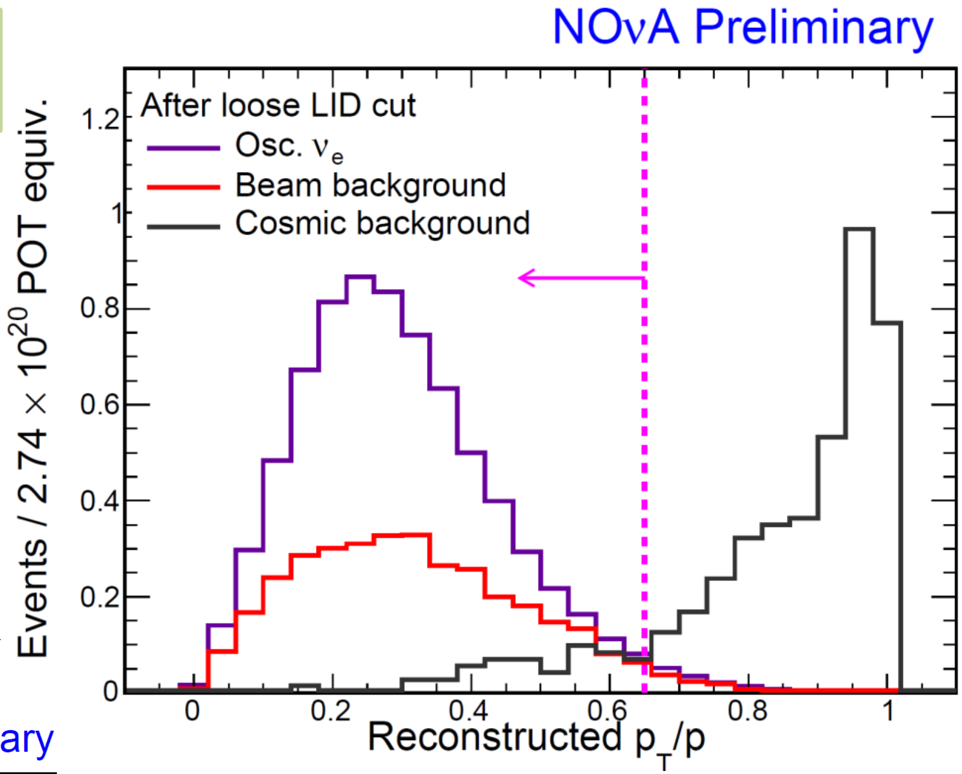




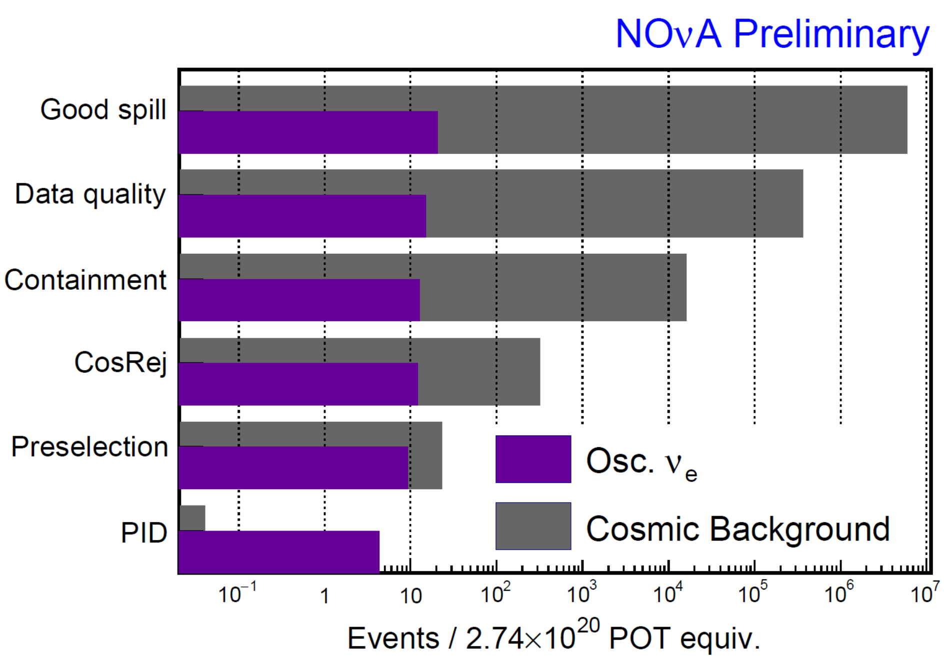
ν_e Cosmic rejection

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

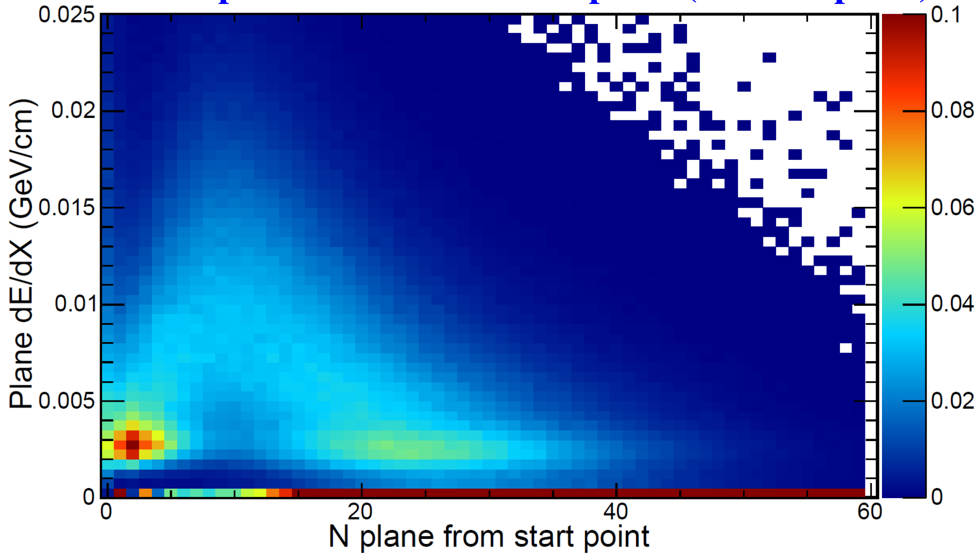
We have developed two independent ν_e CC selection algorithms
→ *Very different designs*

LID: Likelihood Identification

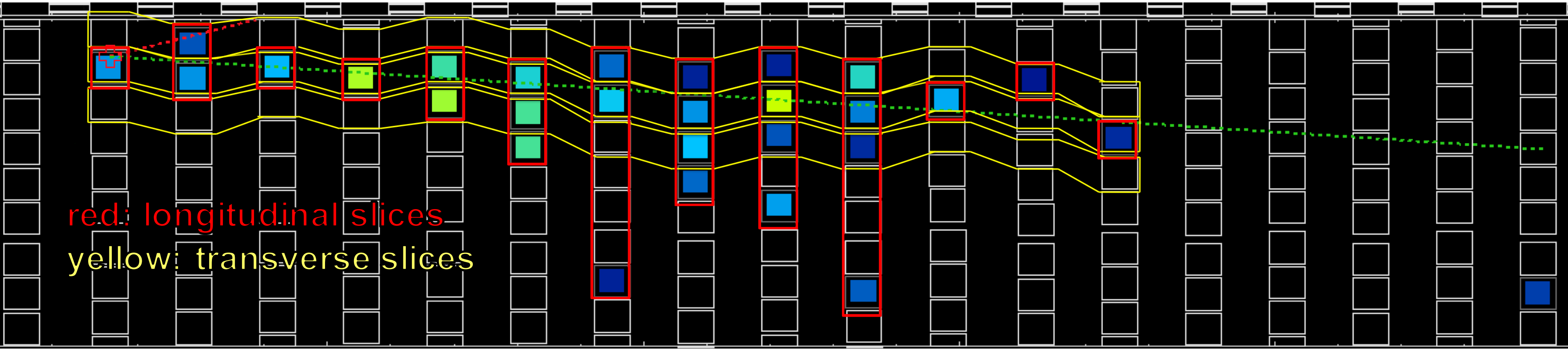
***dE/dx* likelihoods** calculated for **longitudinal and transverse** slices of leading shower under multiple particle hypotheses

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

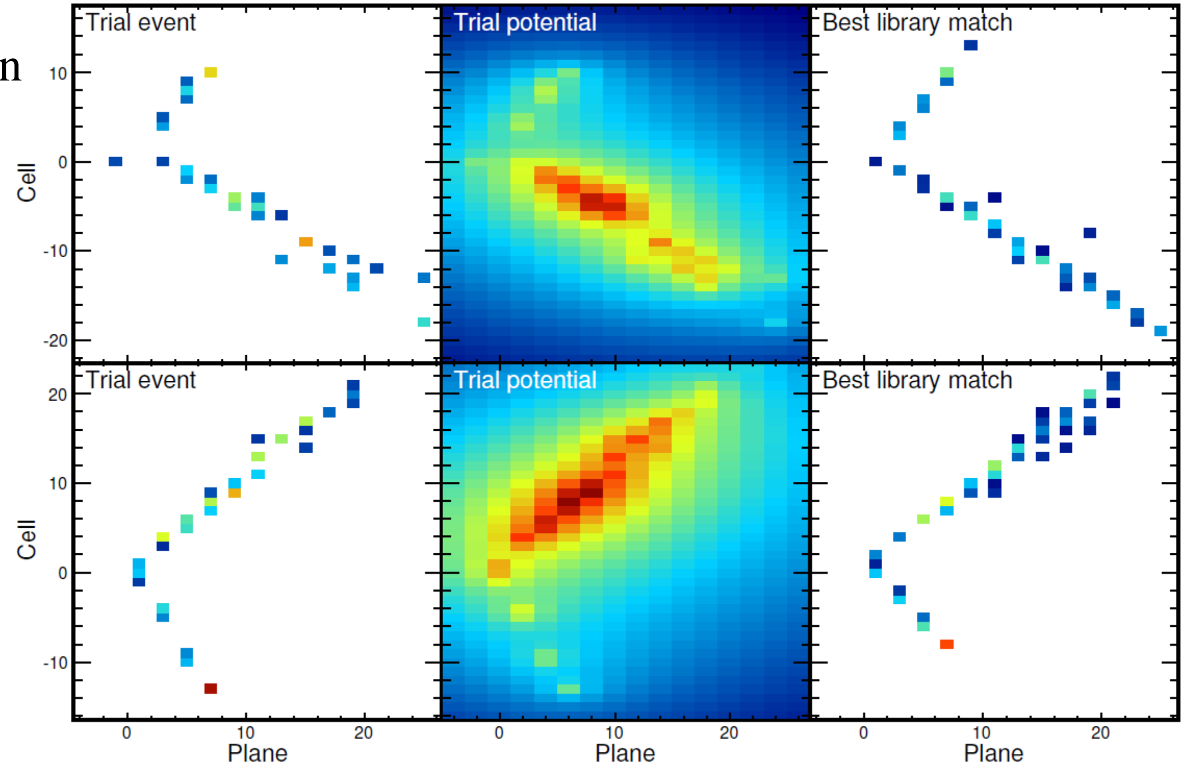


LEM: Library Event Matching

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**



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***Left panels*: candidate event, both views**
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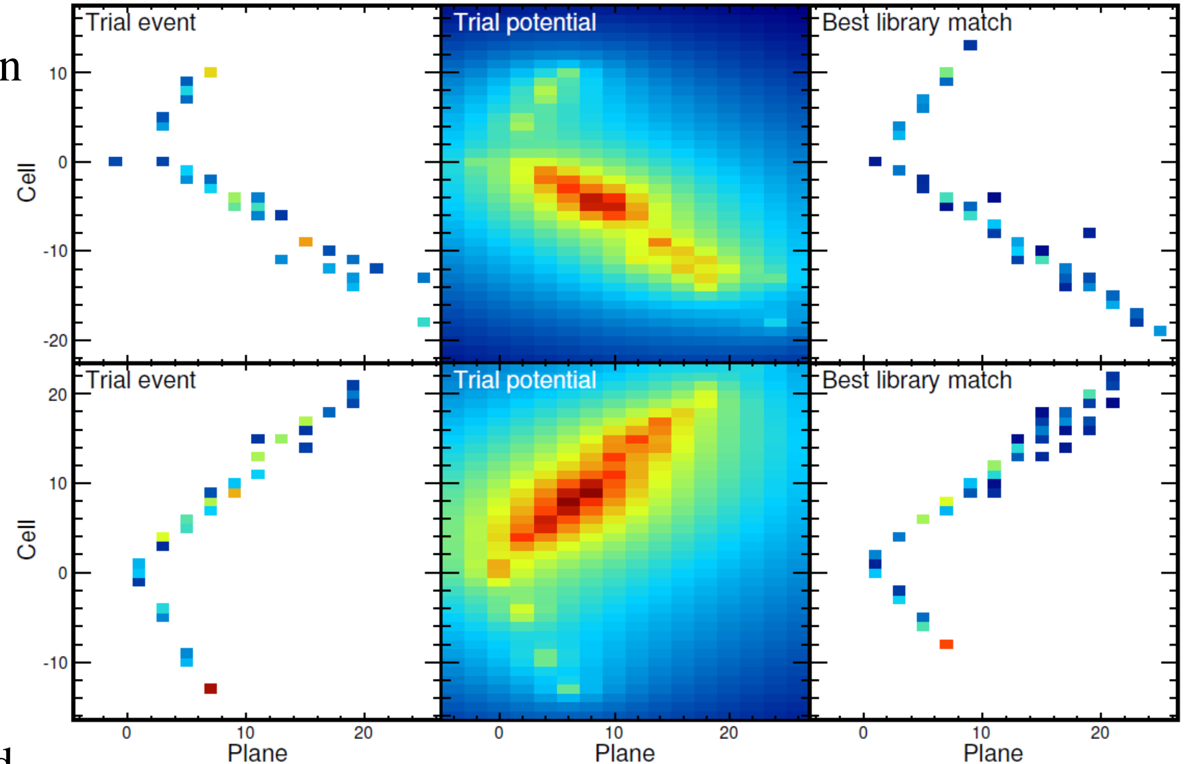
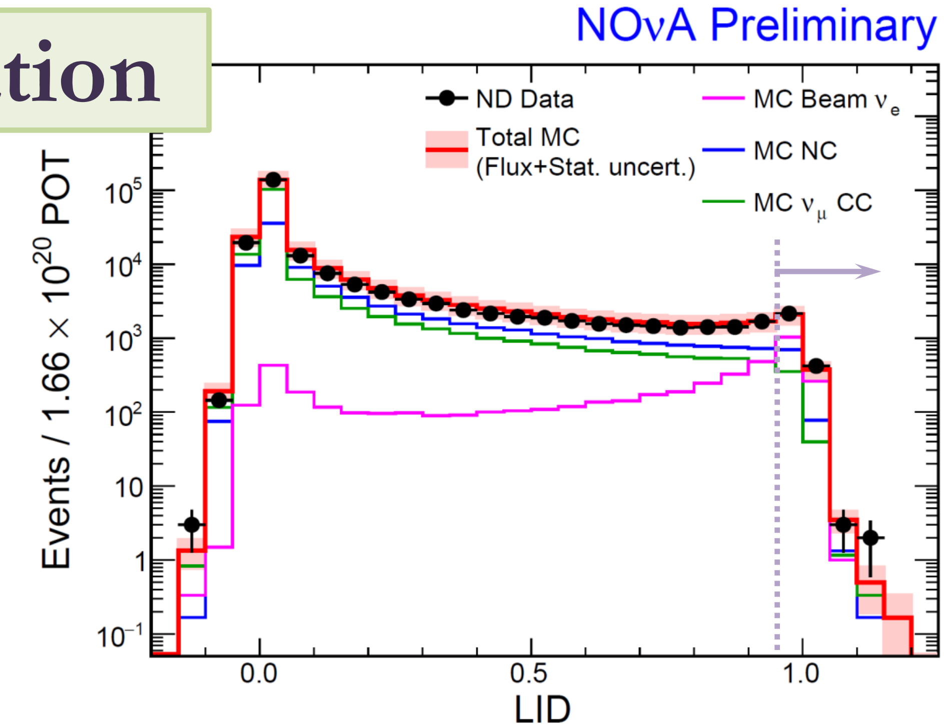


LID and LEM sensitivities

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

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

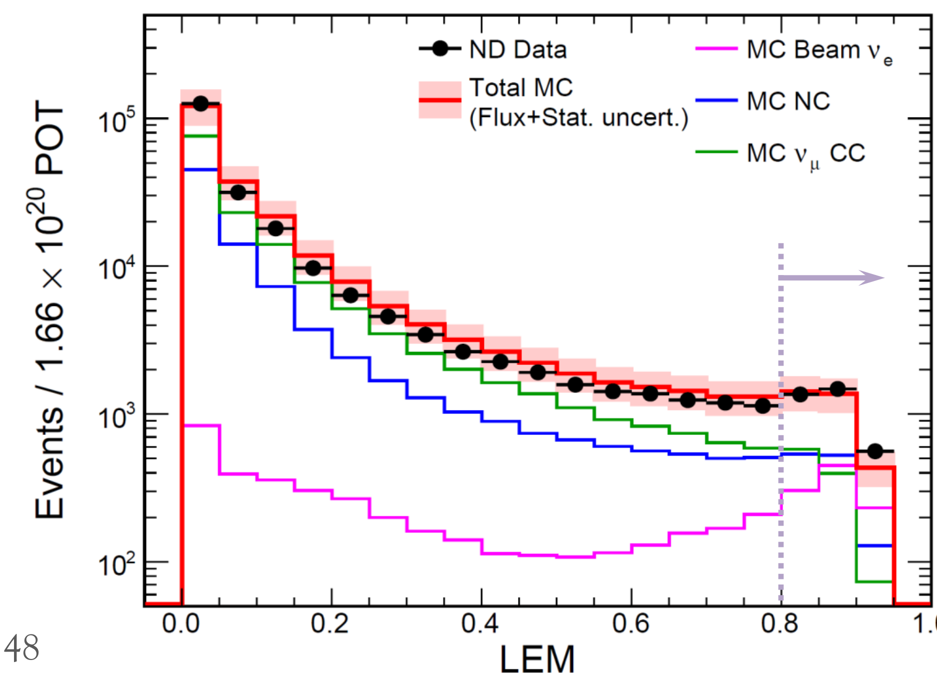
ν_e CC event identification



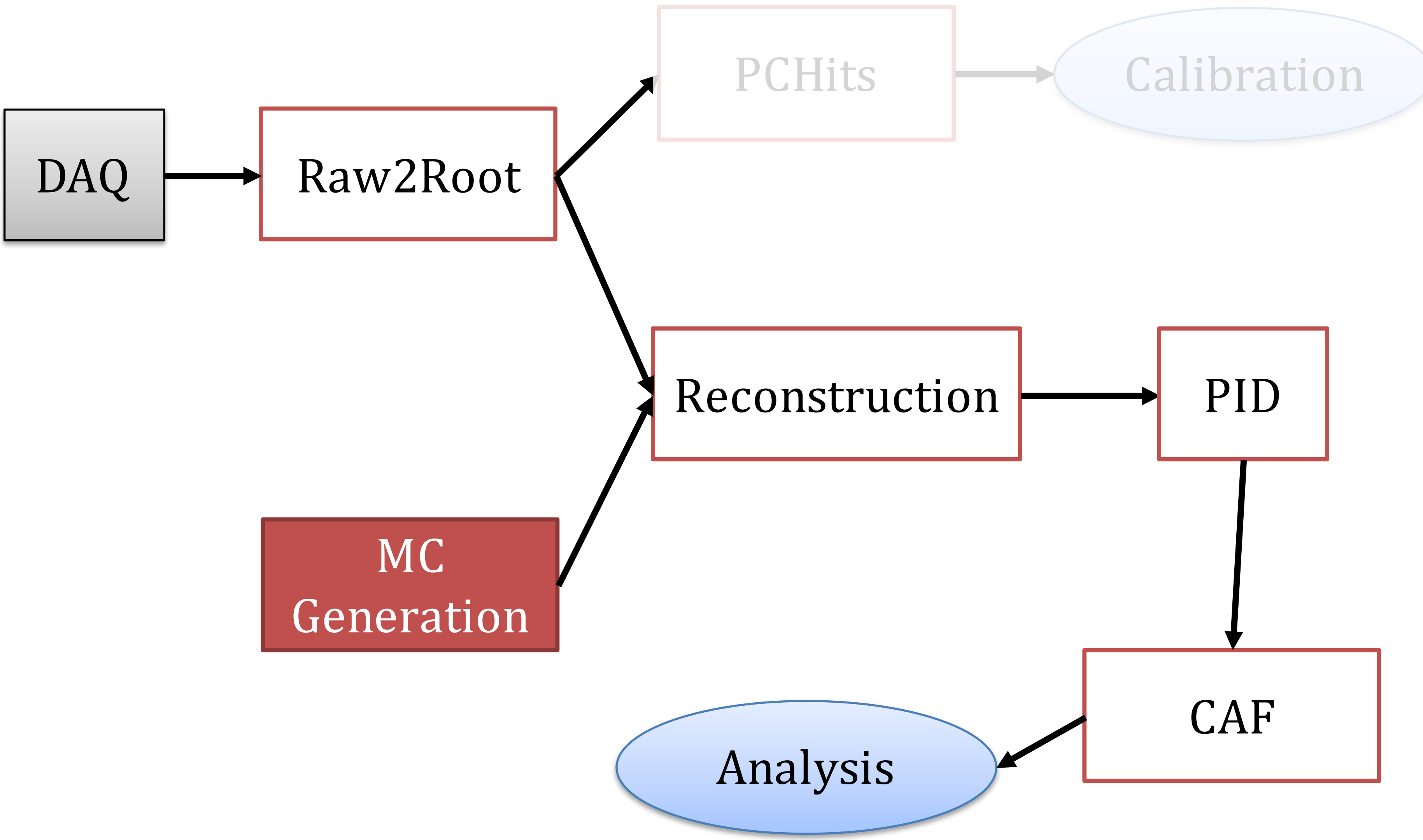
LID and **LEM** distributions for **ND data** and **simulation**

all preselection cuts applied

Good agreement over full range

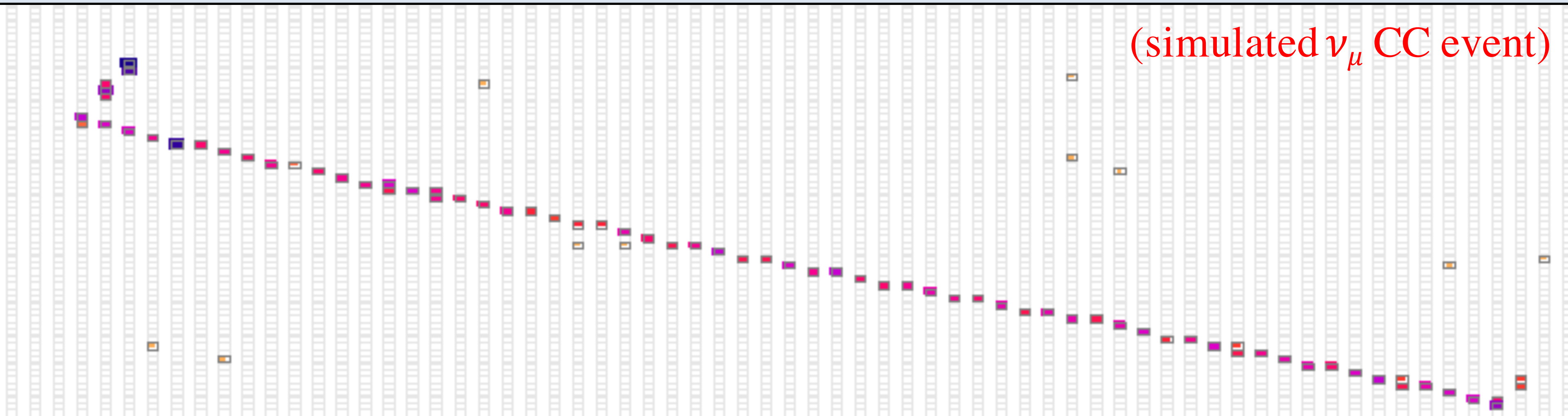


Nova Production Processing

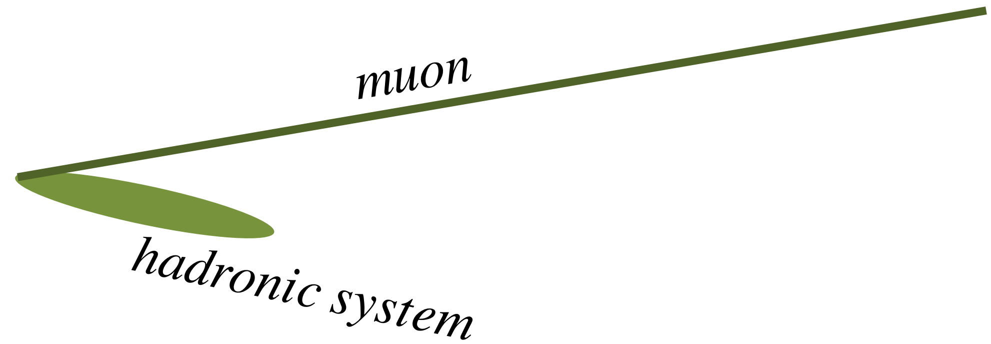


ν_μ disappearance

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



Energy estimation

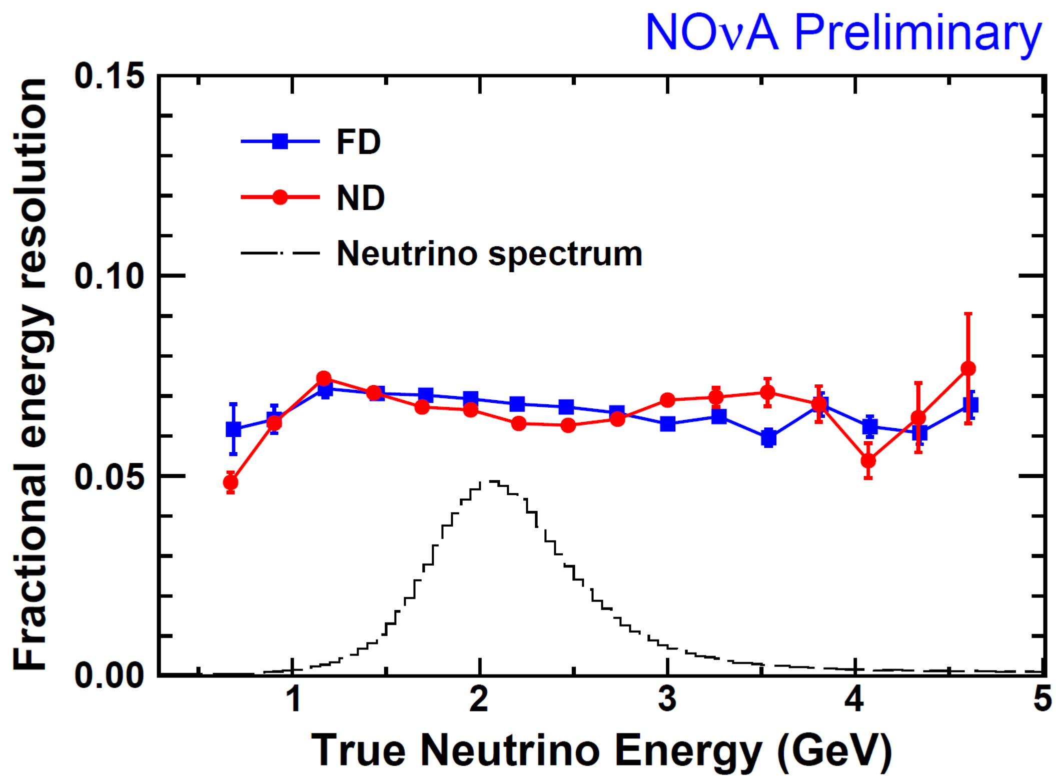


Reconstructed muon track:

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%

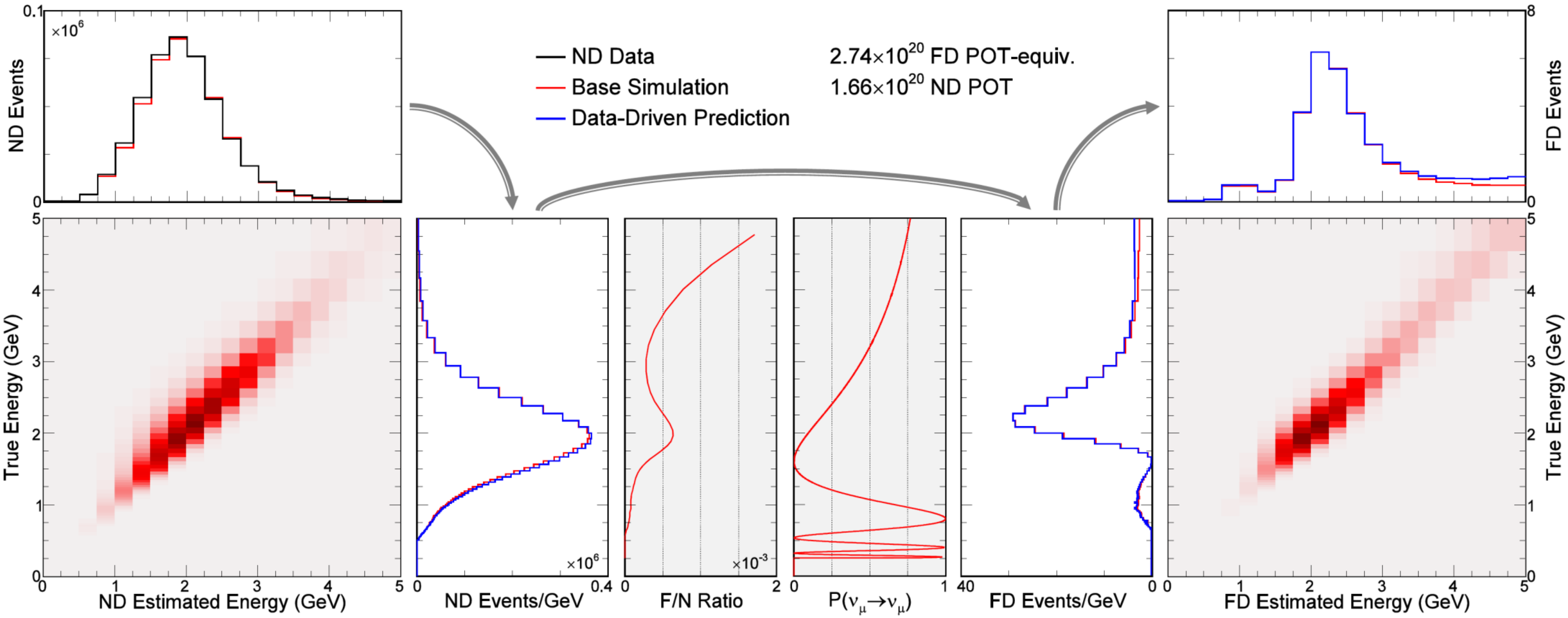
Far Detector prediction

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

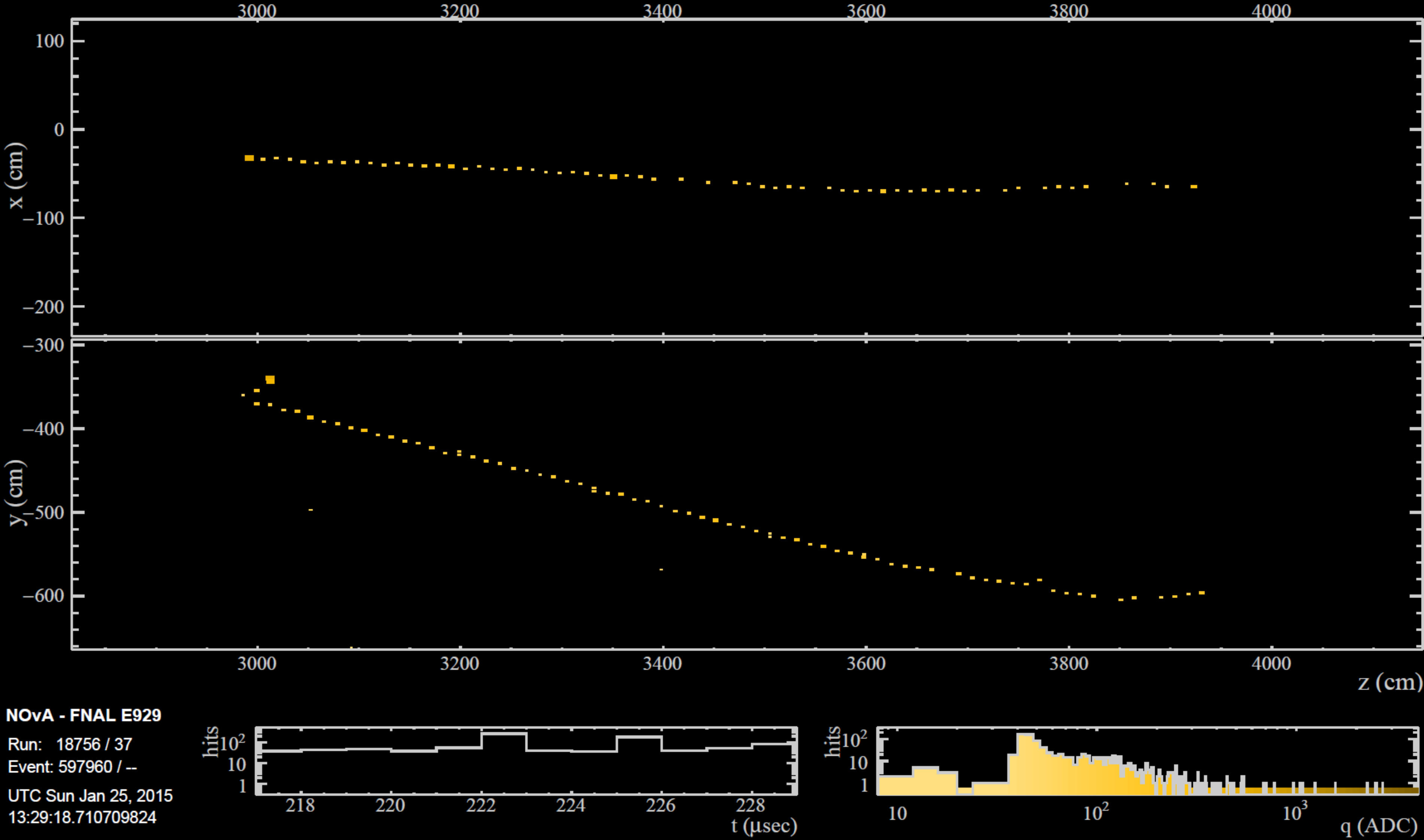
(2) Multiply by expected **Far/Near event ratio** and **$\nu_\mu \rightarrow \nu_\mu$ oscillation probability** as a function of true energy

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

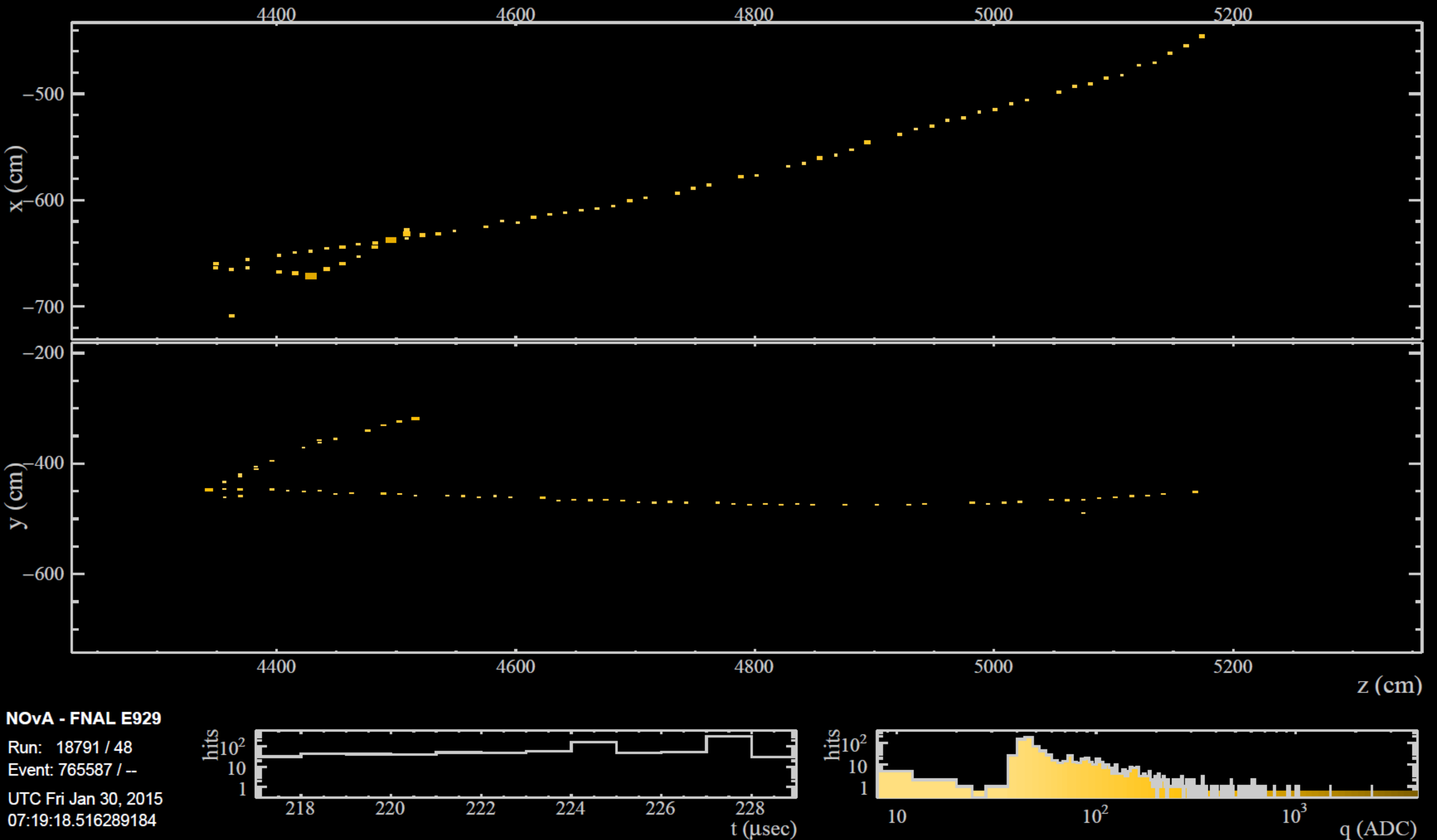
Systematic uncertainties assessed by **varying all MC-based steps**



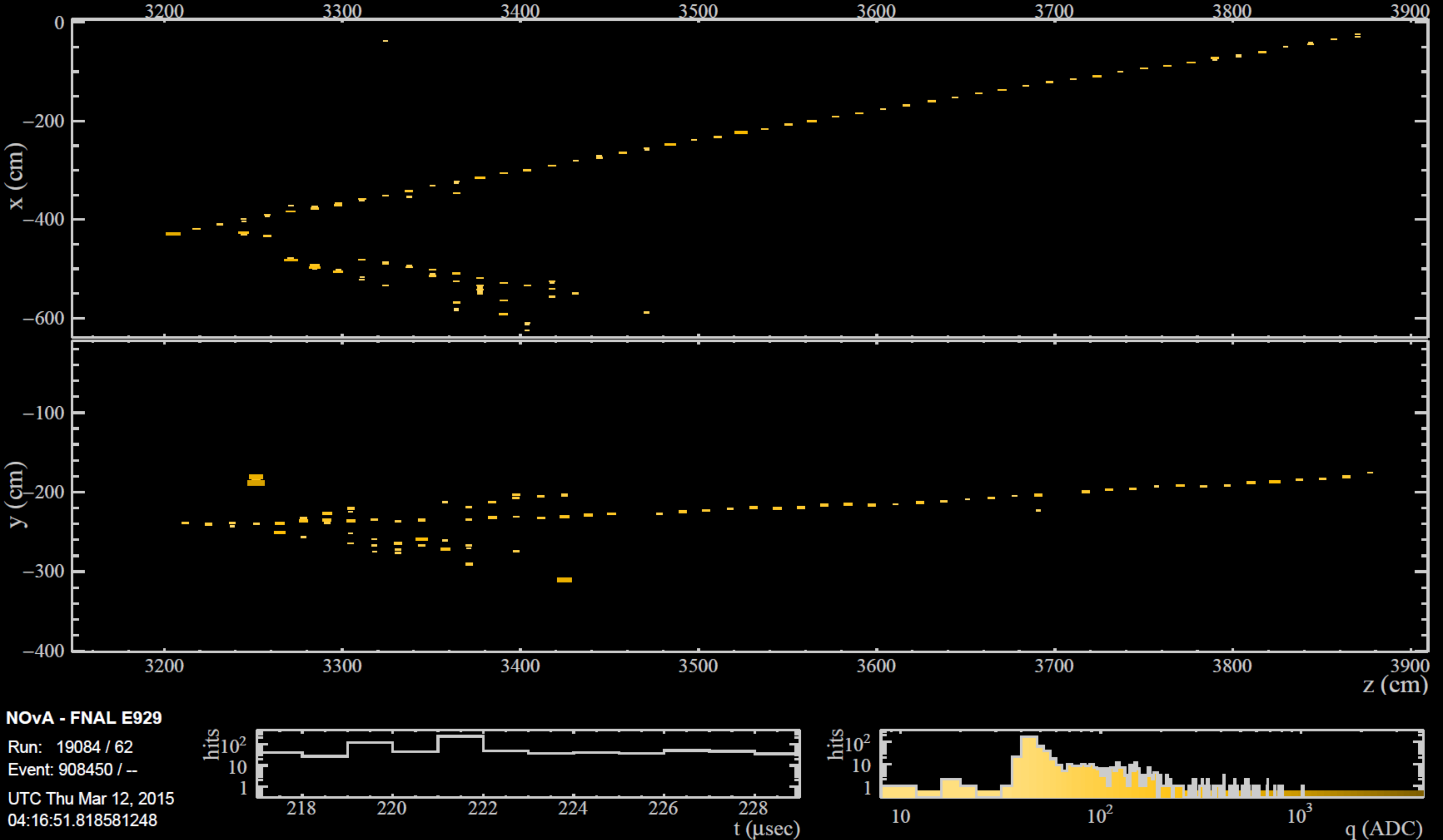
Far Detector selected ν_μ CC candidate



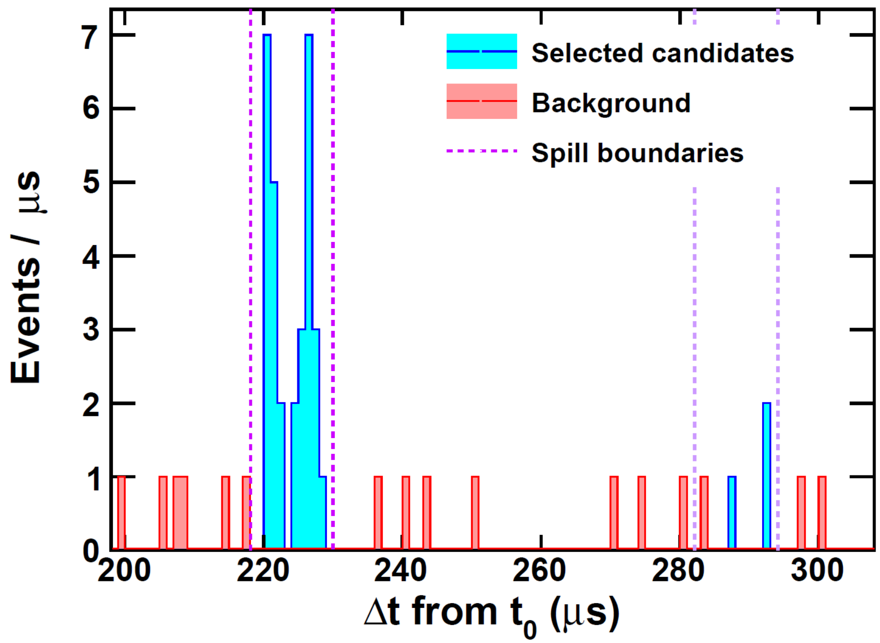
Far Detector selected ν_μ CC candidate

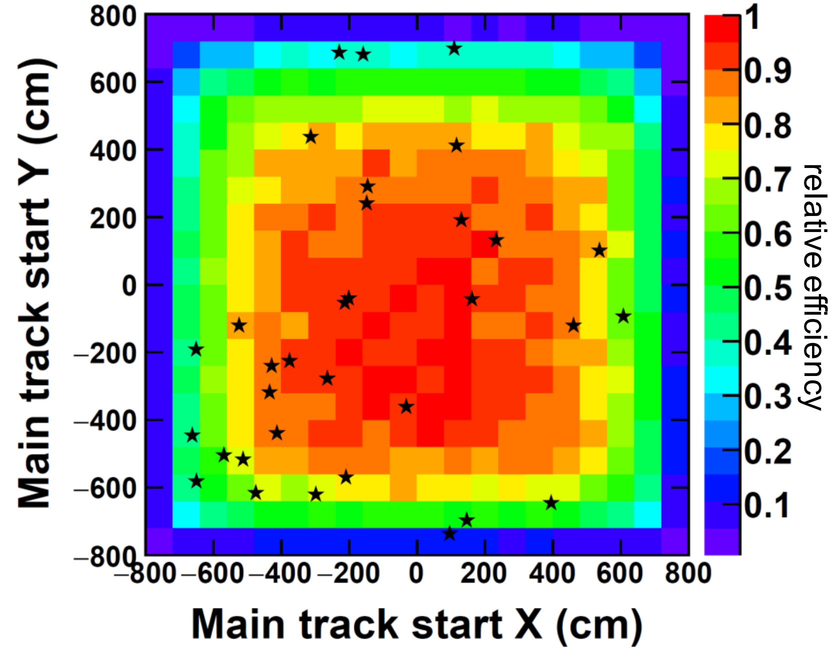


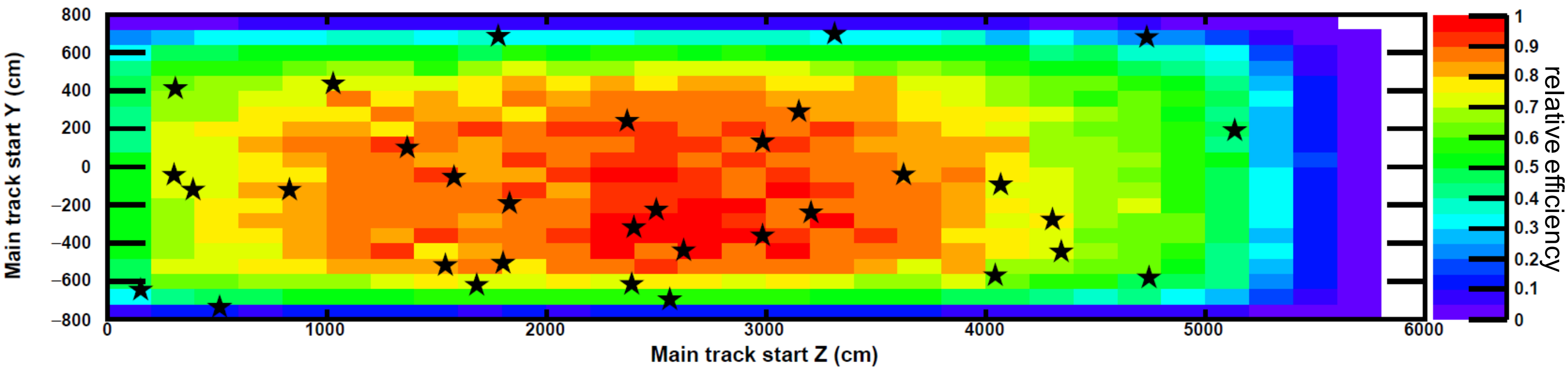
Far Detector selected ν_μ CC candidate



FD ν_μ CC candidates: when and where







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

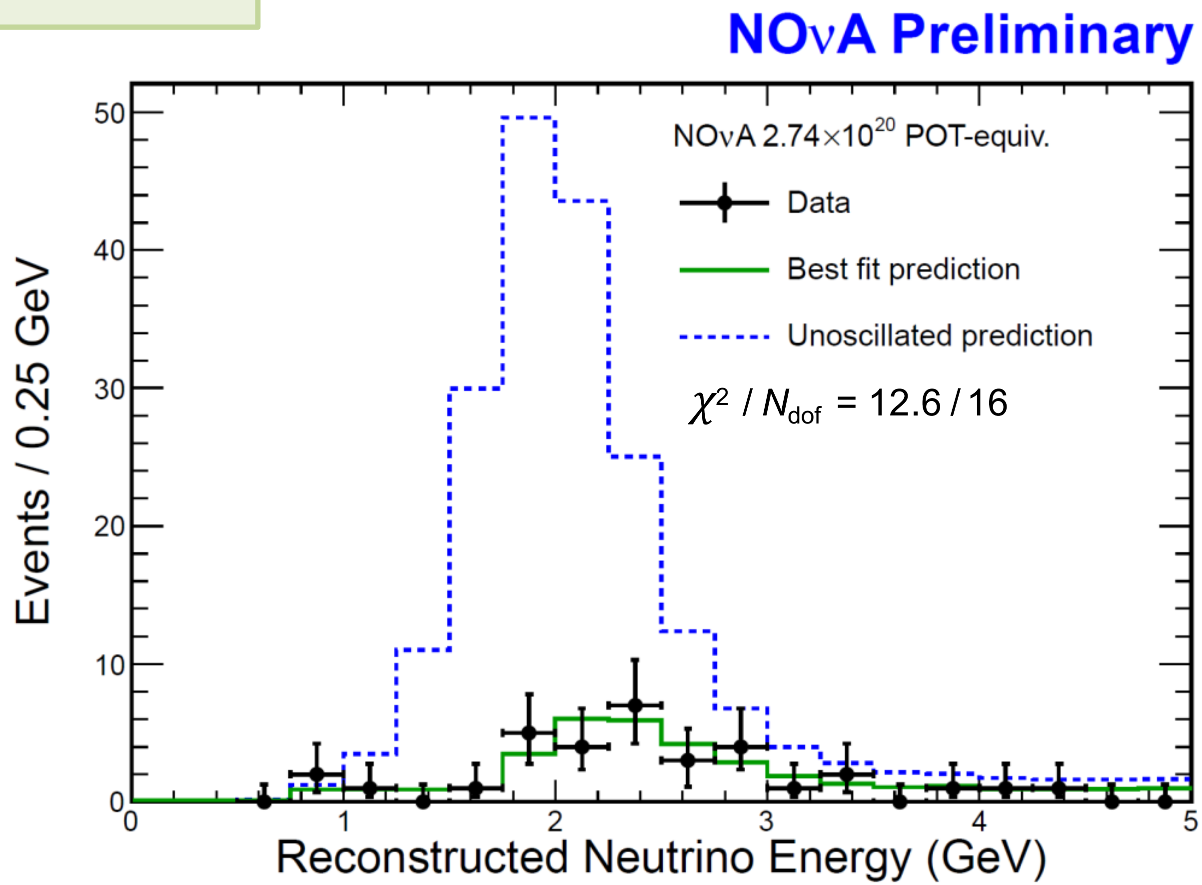
Note 2: Colors show relative efficiency. Not weighted by time variation in detector size.

FD 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

NOνA Preliminary

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

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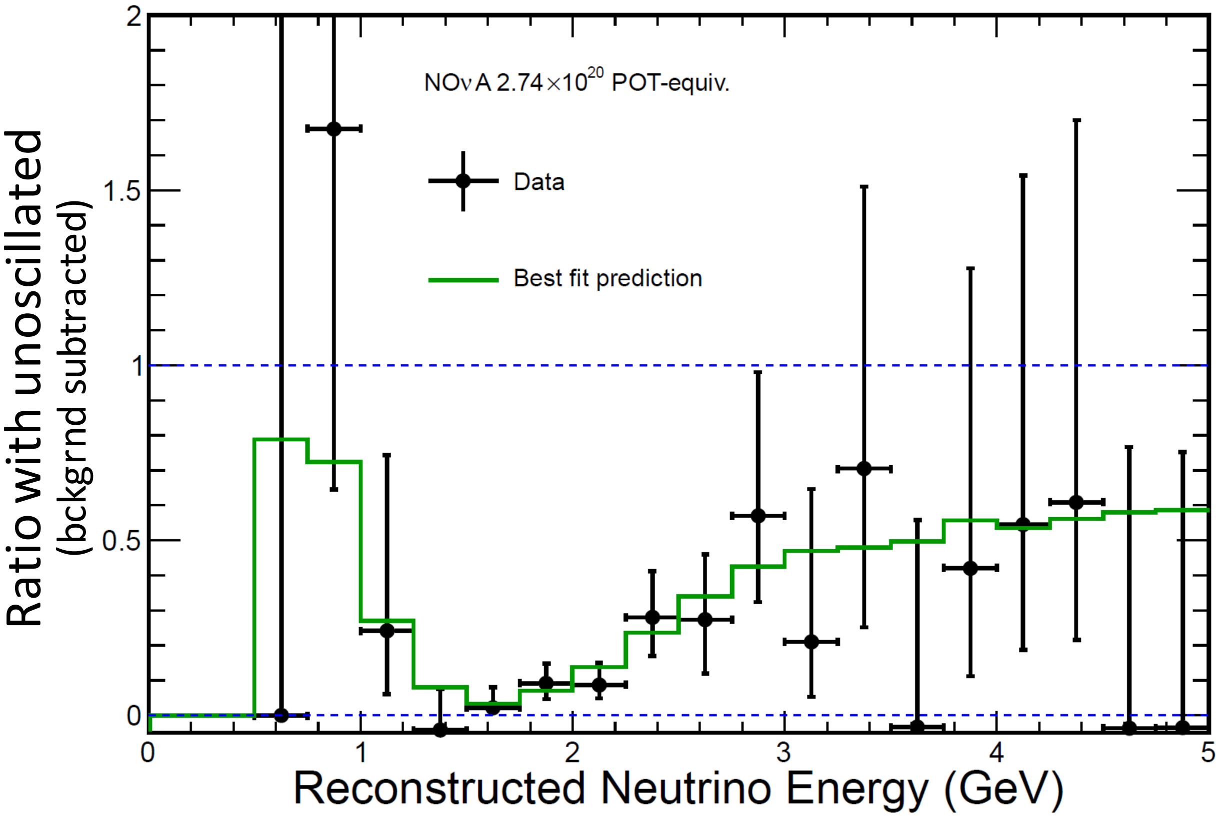


Spectrum is well matched by oscillation fit for Δm^2_{32} and θ_{23}
(syst. uncertainties included in fit via nuisance parameters)

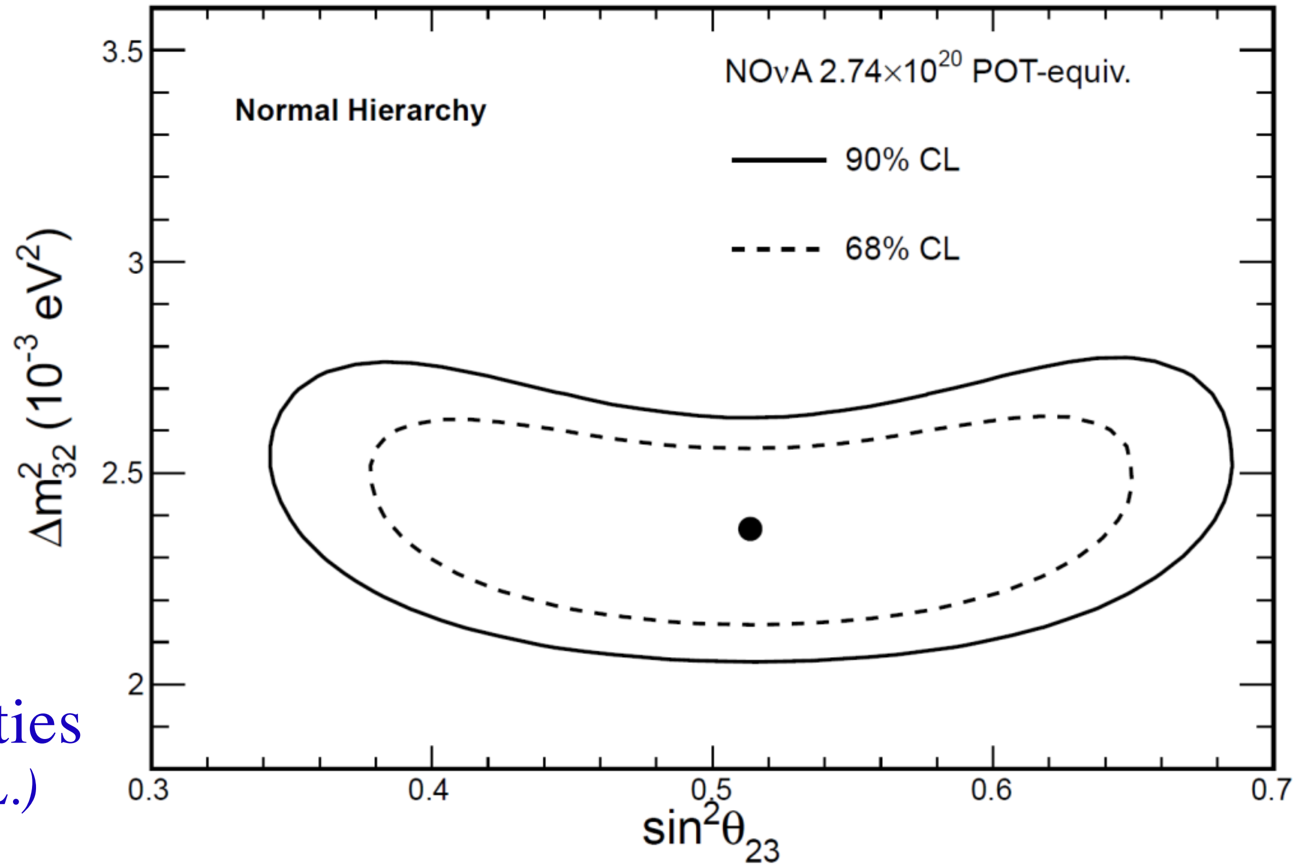
Clear observation of ν_μ disappearance

Fit result

NOνA Preliminary

At right:
NOνA allowed regions in $(\Delta m^2_{32}, \sin^2\theta_{23})$ parameter space

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



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

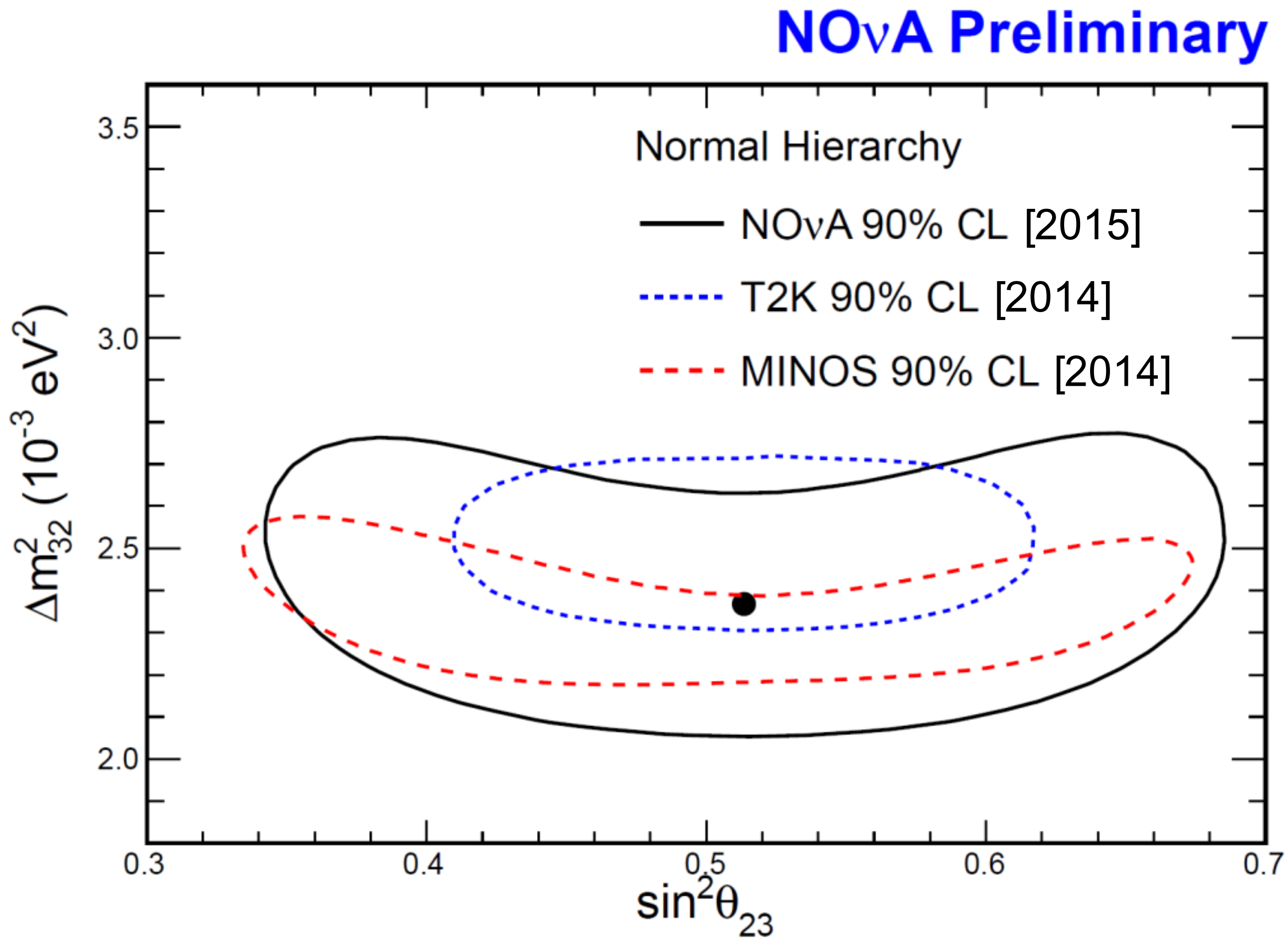
$$\sin^2(\theta_{23}) = 0.51 \pm 0.10$$

6.5% measurement uncertainty

Allowed regions are consistent with MINOS and T2K

(shown at right)

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



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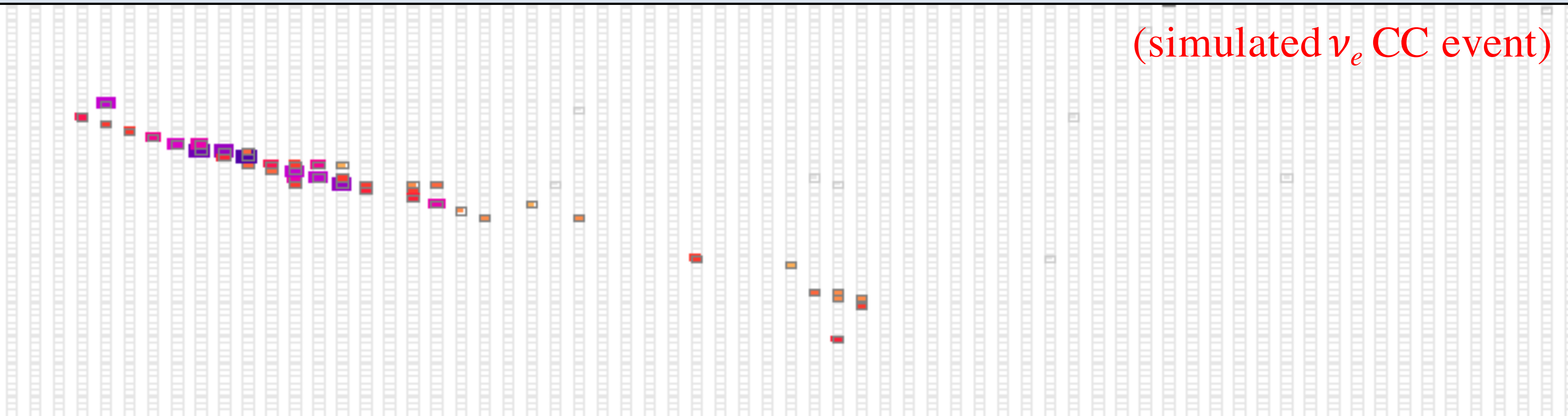
6.5% measurement uncertainty

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

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



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]

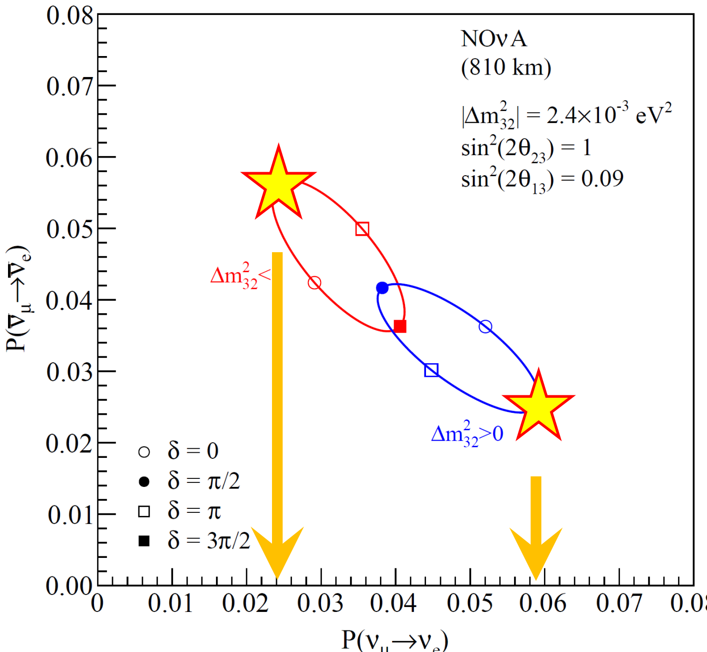
2.74×10^{20} POT equiv.

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

5.62 ± 0.72 events

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

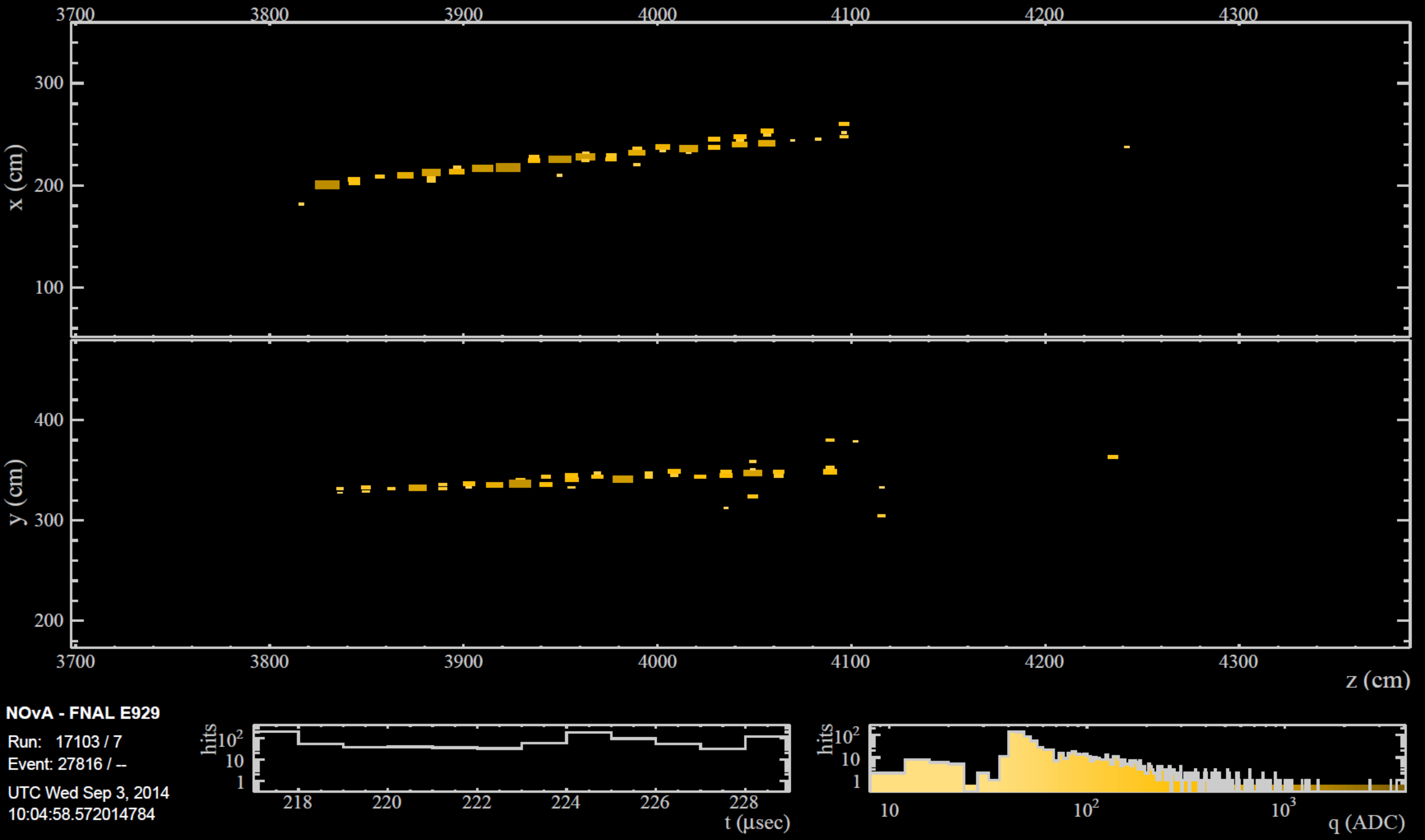
2.24 ± 0.29 events



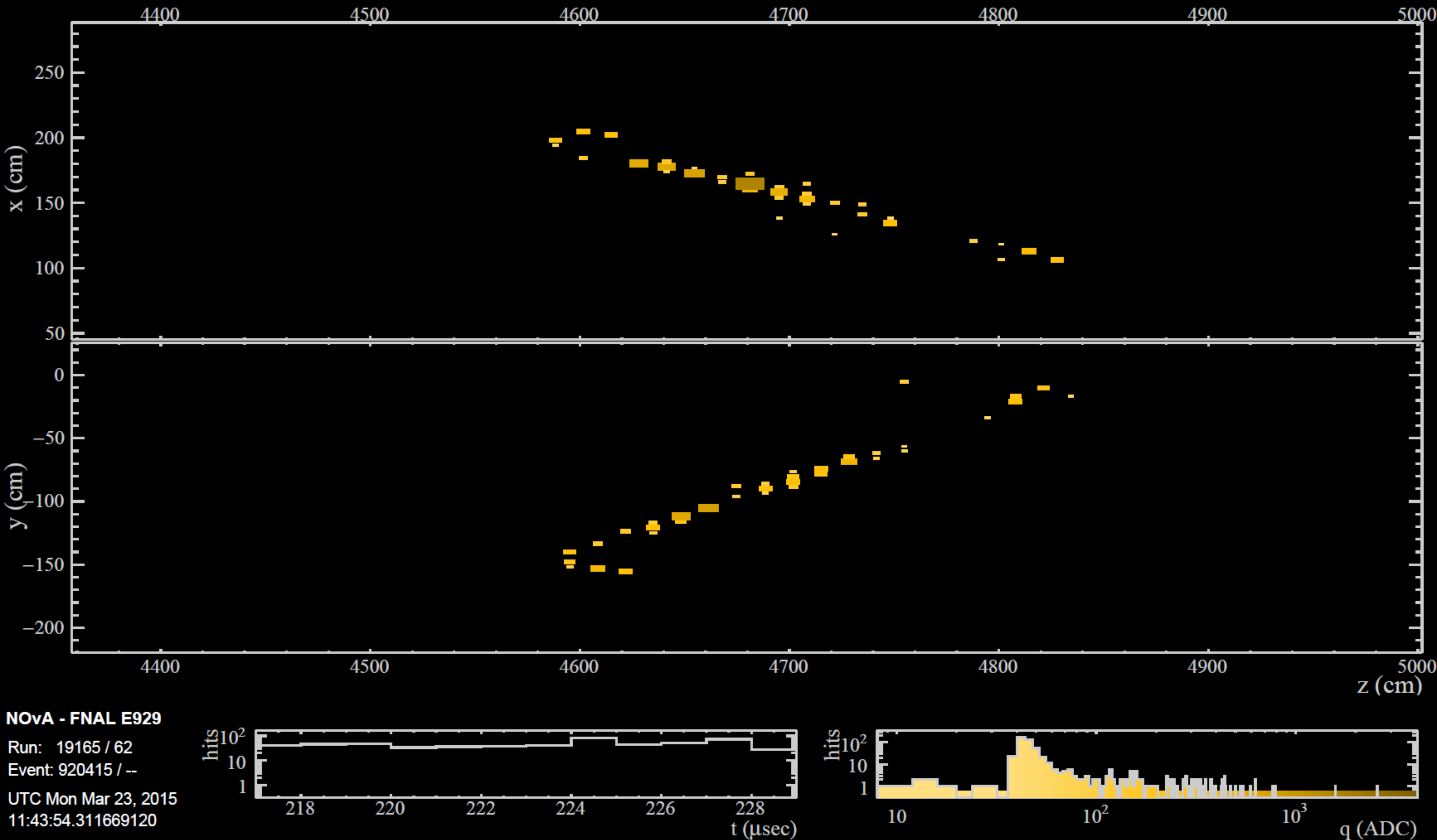
smaller ν_e rate

larger ν_e rate

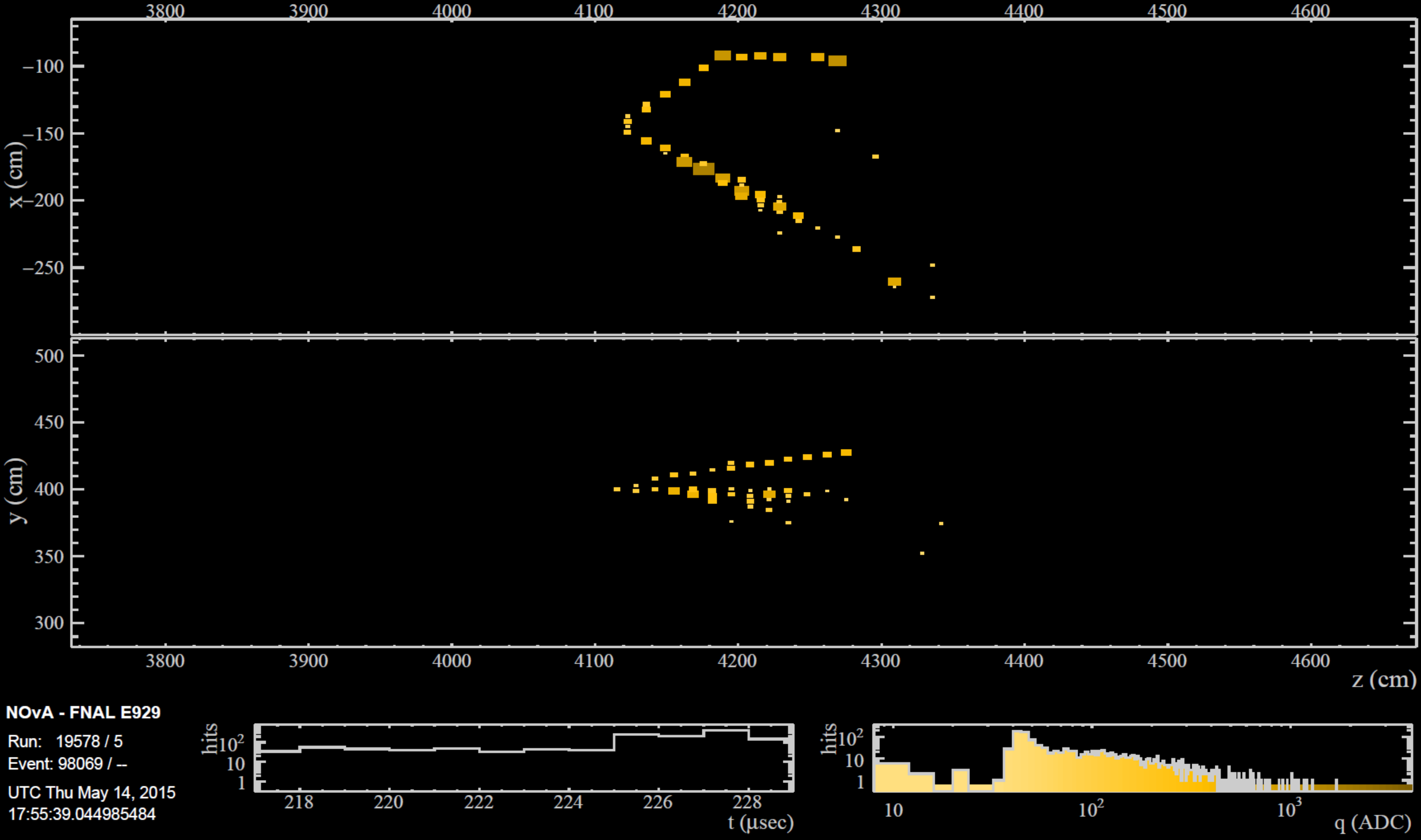
Far Detector selected ν_e CC candidate



Far Detector selected ν_e CC candidate



Far Detector selected ν_e CC candidate



Far Detector selected events

LID: 6 ν_e candidates

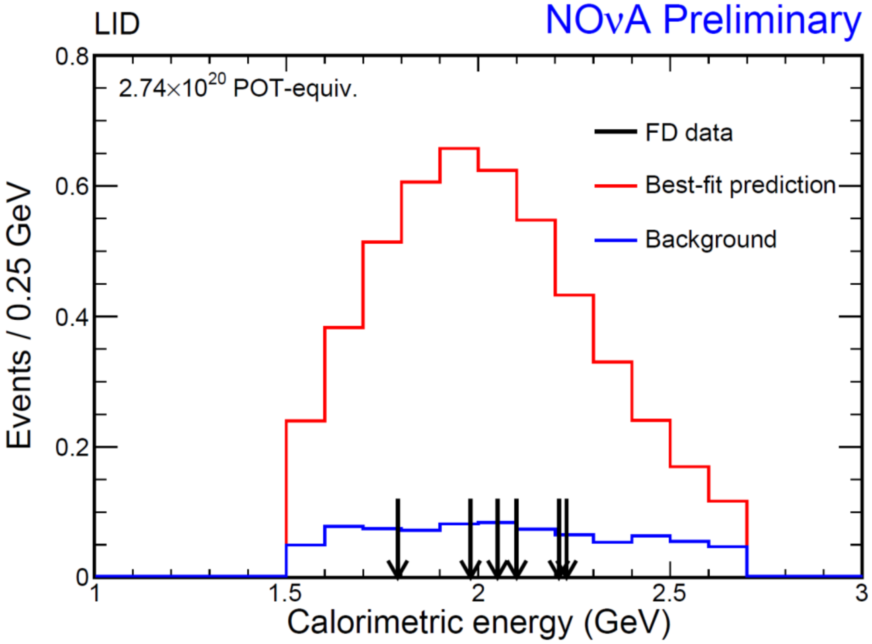
3.3σ significance for ν_e appearance

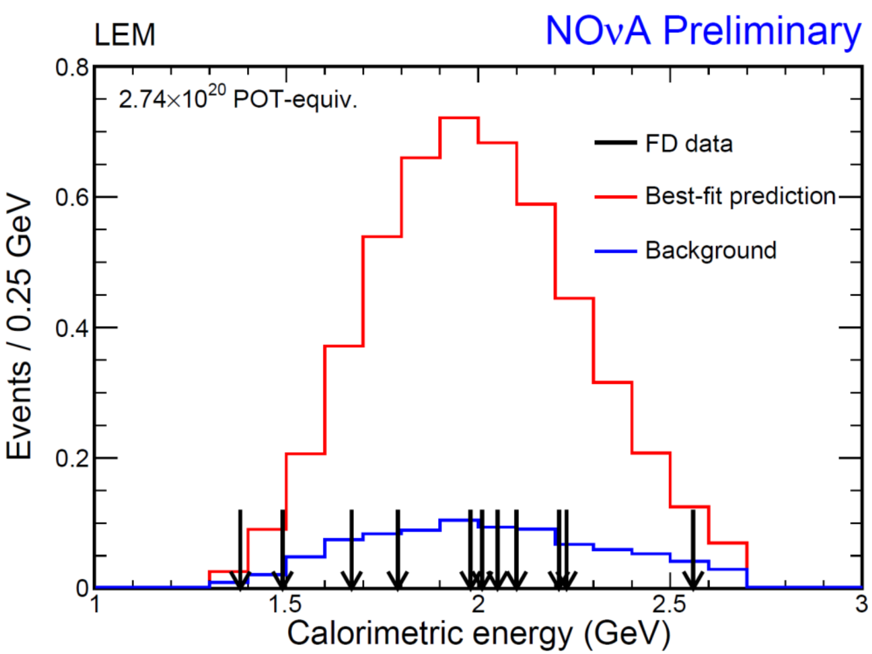
At right:
Calorimetric energy

LEM: 11 ν_e candidates

5.5σ significance for ν_e appearance

(All 6 LID events present in LEM set)



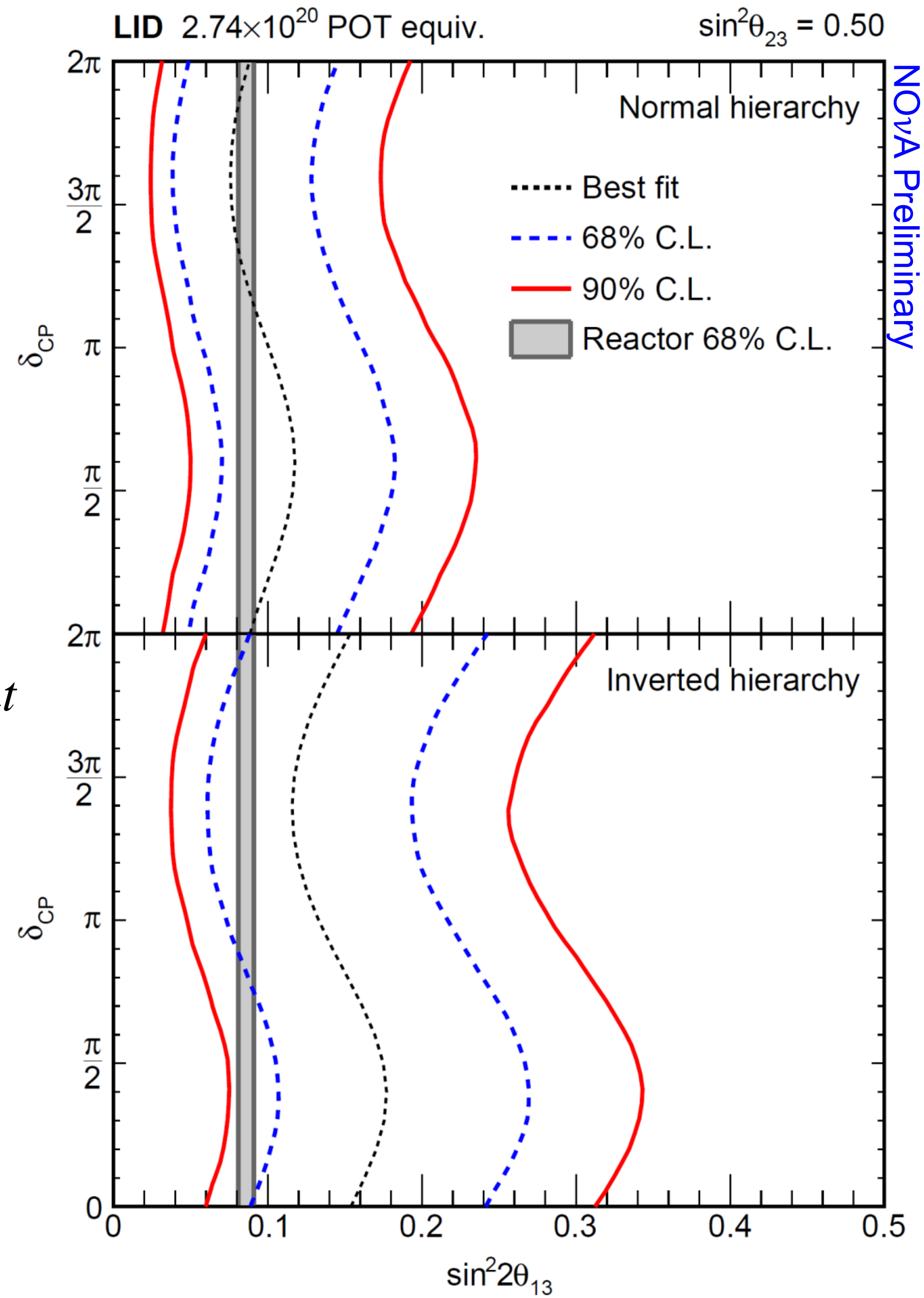


Result using LID selector

FD selection: **6 ν_e candidates**

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

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



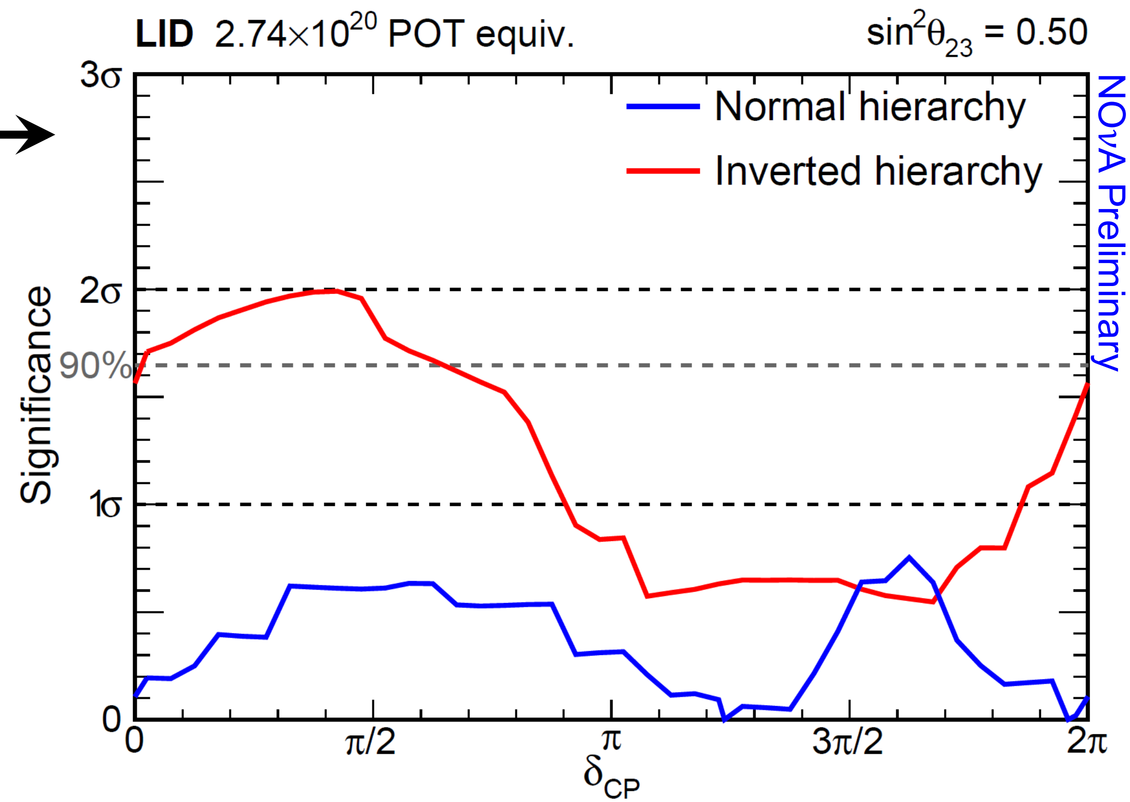
Result using LID selector

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]

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 ($>1\sigma$)

Summary

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

$$\Delta m^2_{32} = \begin{cases} +2.37^{+0.16}_{-0.15} & \text{[NH]} \\ -2.40^{+0.14}_{-0.17} & \text{[IH]} \end{cases} \times10^{-3}\ \text{eV}^2$$

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

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

- 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.**

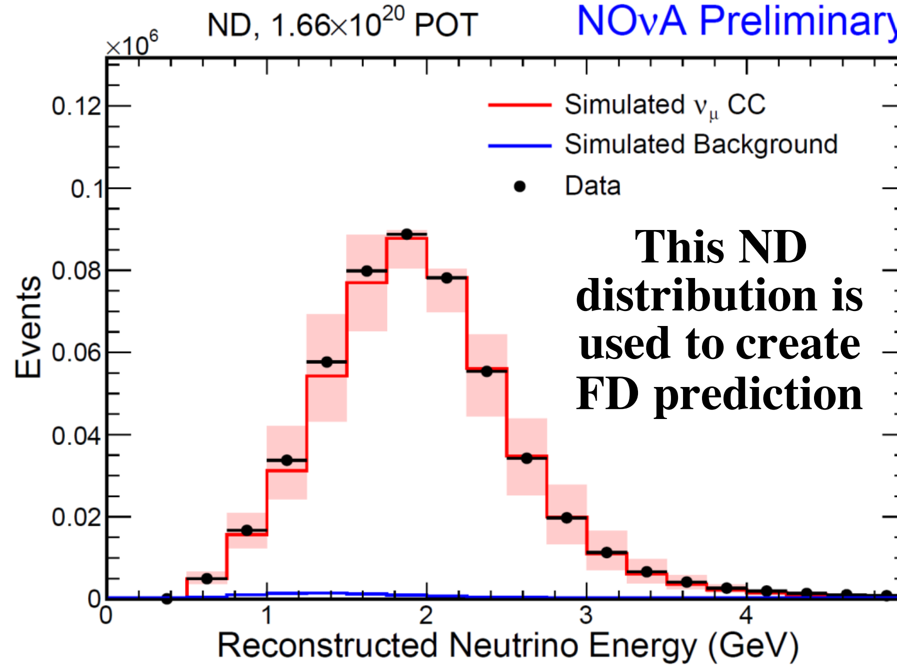
Above results obtained with 7.6% of baseline NOνA exposure.

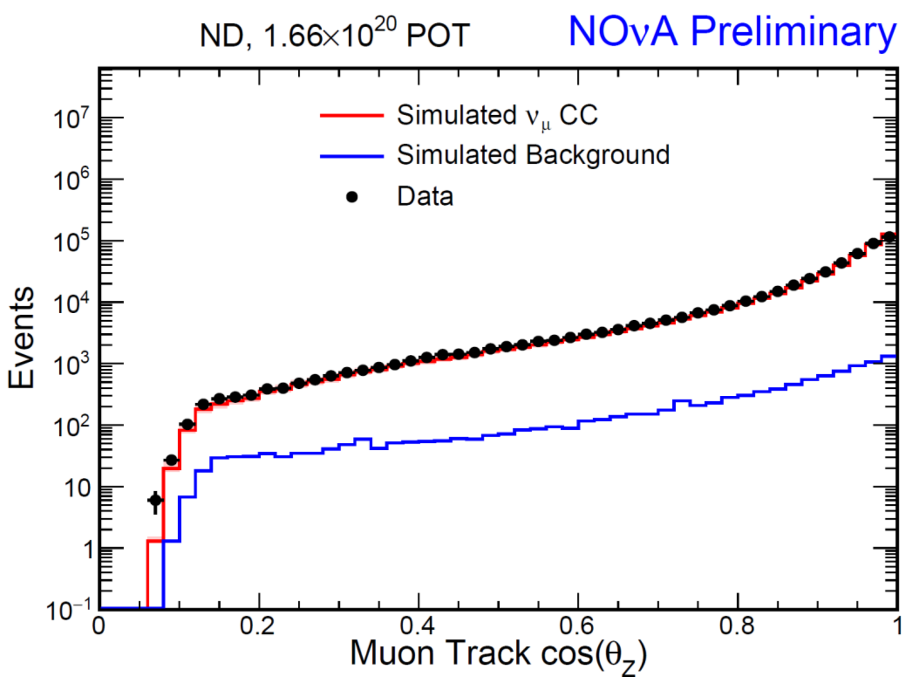
Much more to come!

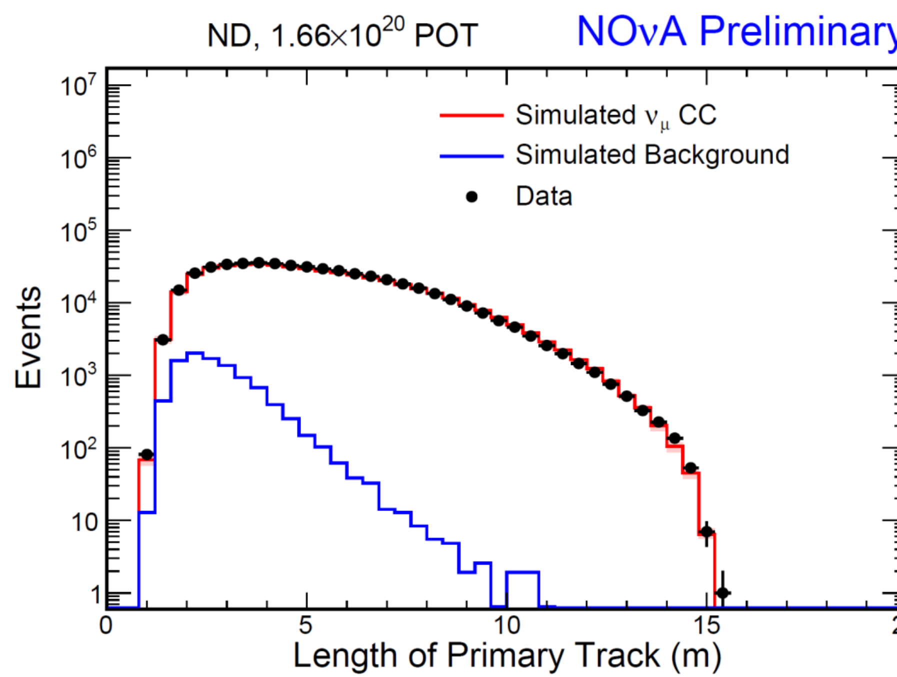
Backup Slides

Kinematic variables in Near Det. after all cuts

→ *Sample purity in ND = 98%*



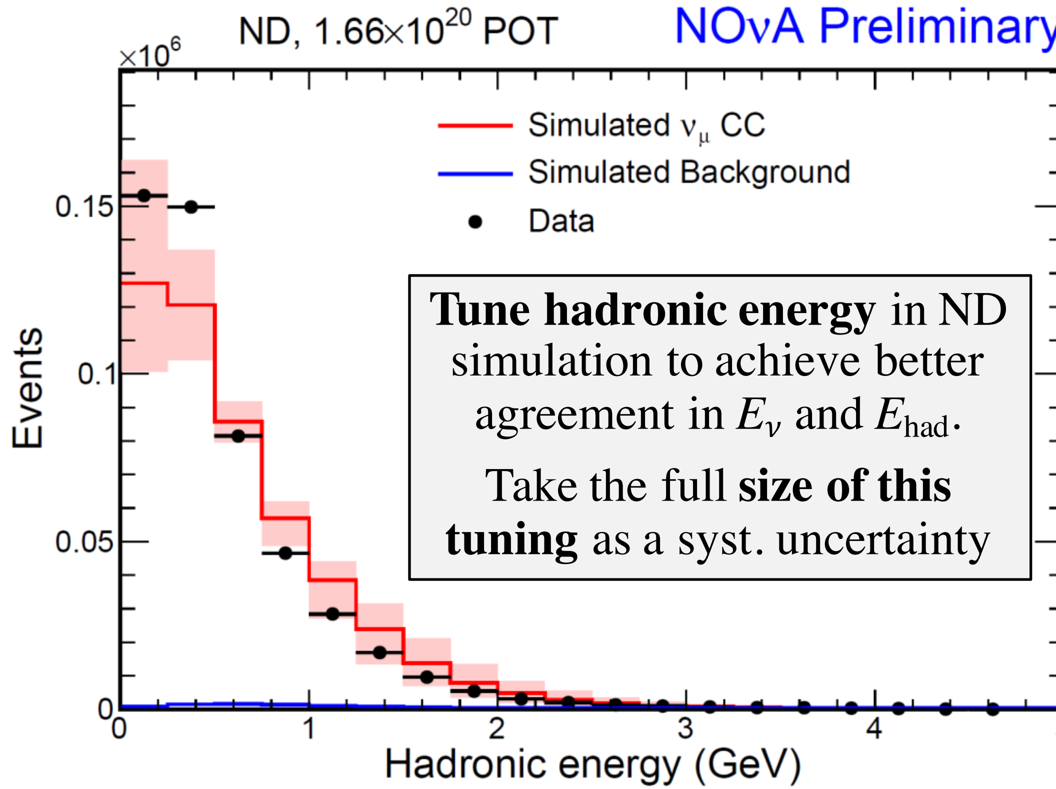




Systematics

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)

Uncertainties assessed

- 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)

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]

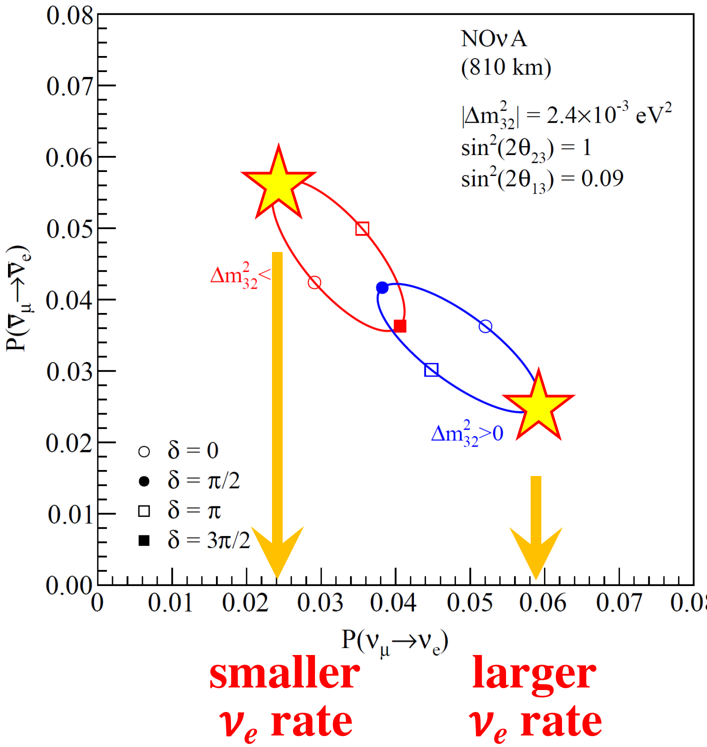
2.74×10^{20} POT equiv.

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



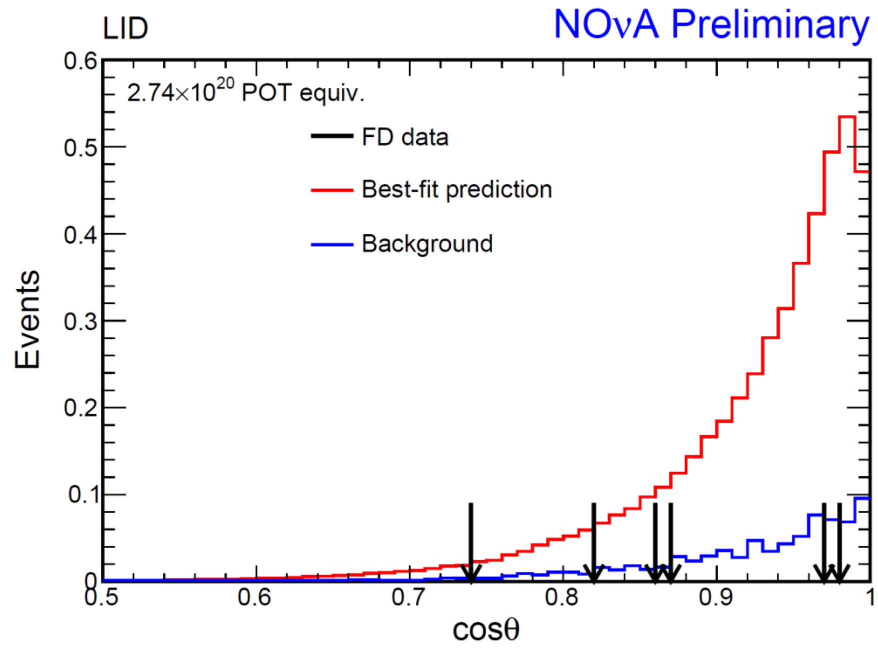
Aside: Before unblinding, **two sidebands checks** –
(1) Near-PID (LID/LEM) sideband, and
(2) High-energy sideband

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

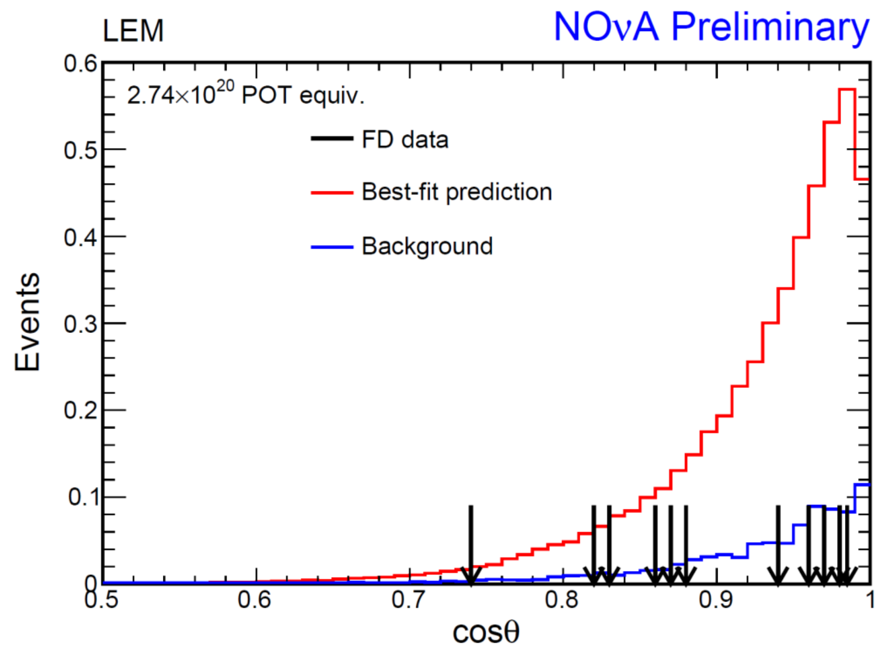
Far Detector selected events

LID: 6 ν_e candidates

3.3σ significance for ν_e appearance



At right:
Reconstructed direction of leading shower



LEM: 11 ν_e candidates

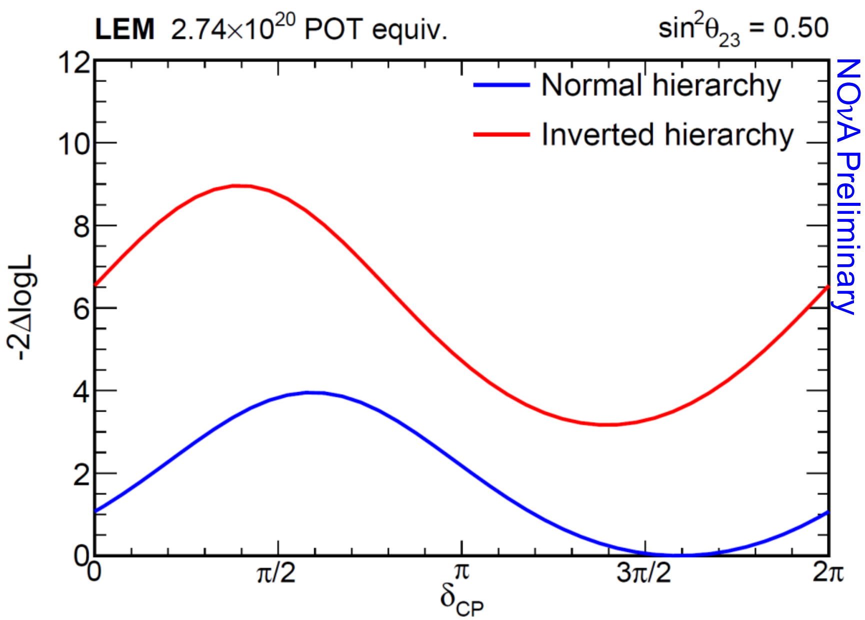
5.5σ significance for ν_e appearance

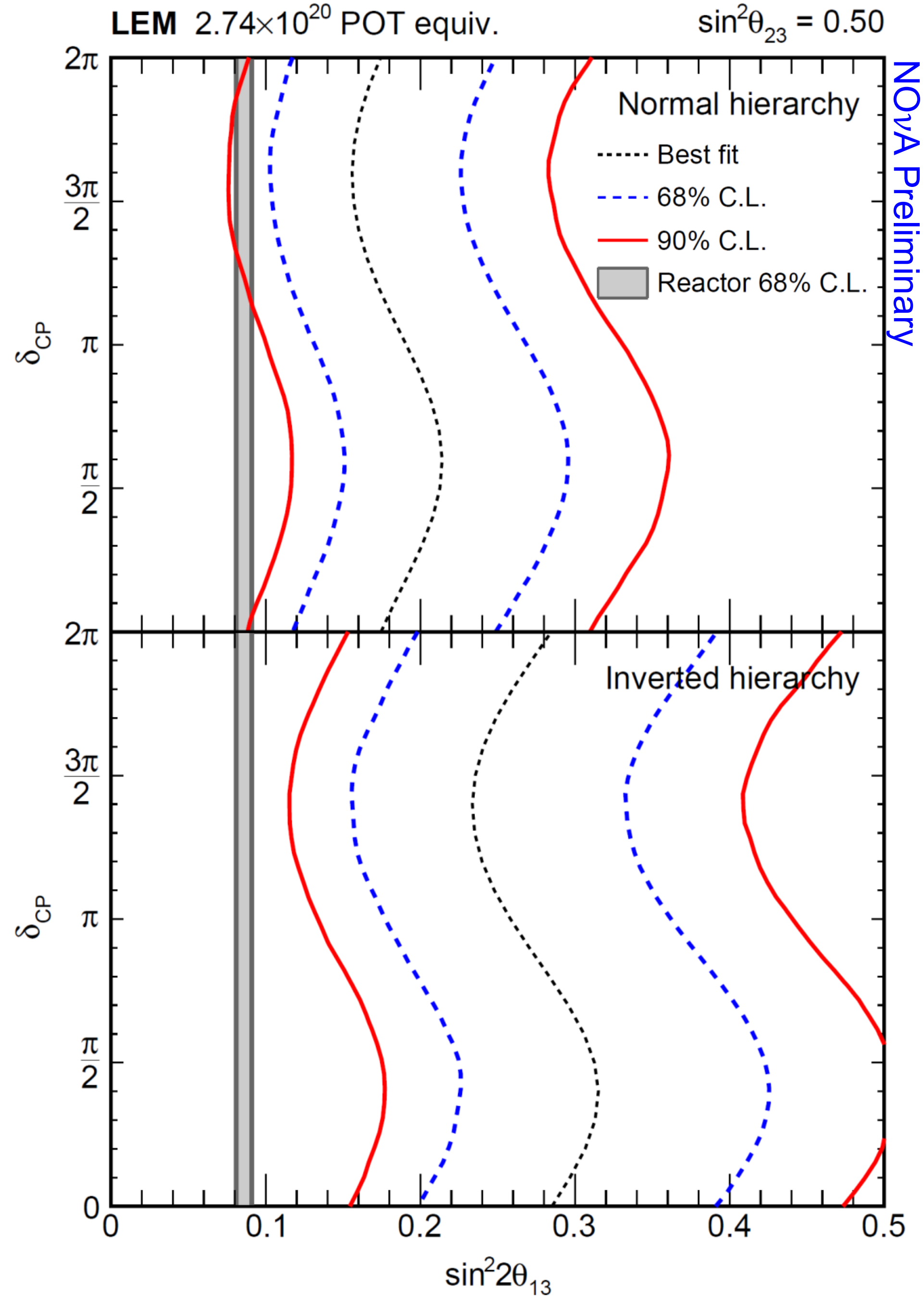
(All 6 LID events present in LEM set)

Result using LEM selector

FD selection: **11 ν_e candidates**

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





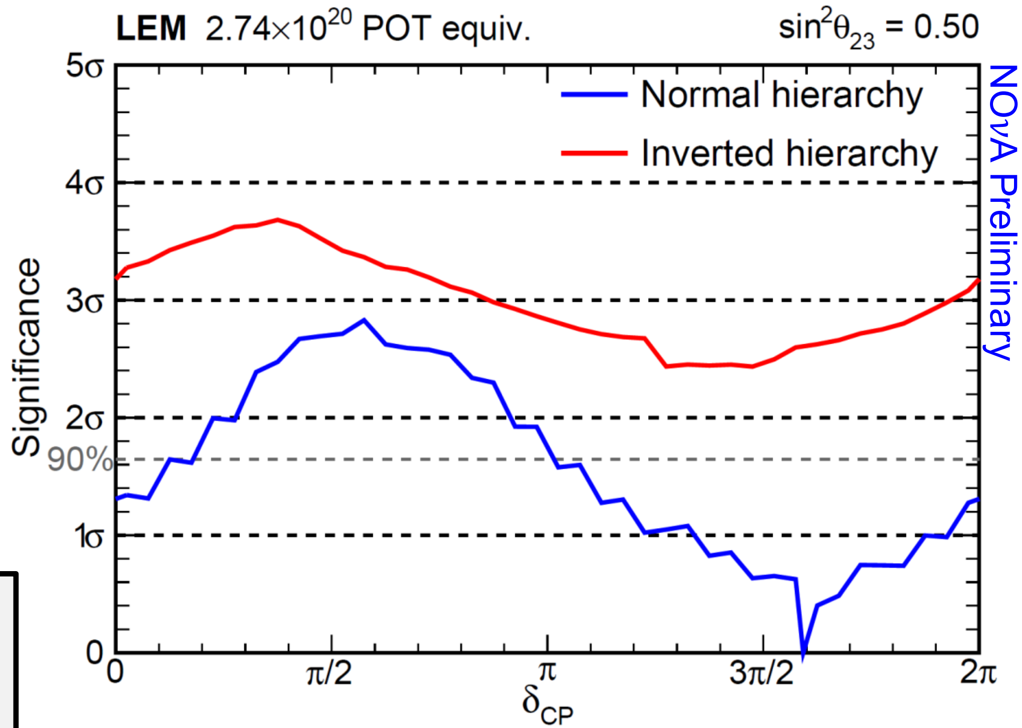
Result using LEM selector

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

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

IH is disfavored at **$>2.2\sigma$**

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



LID, LEM Consistency

- Both prefer **normal hierarchy**
- Both prefer **δ near $3\pi/2$**
- 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]**