First Results from NOvA

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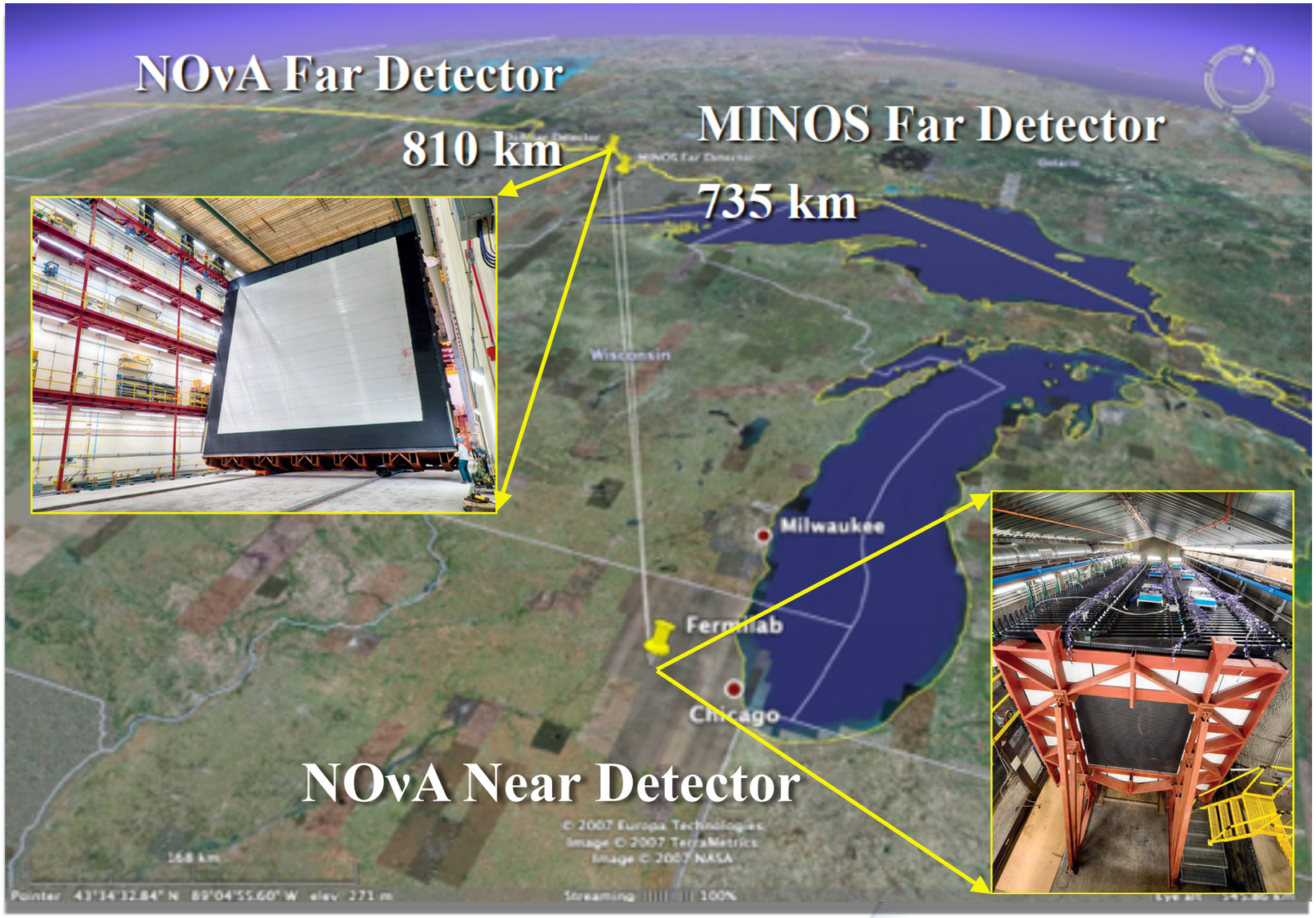
The NOvA Experiment

NuMI Off-Axis ν_e Appearance Experiment

- 810 km baseline from Fermilab to Ash River, MN
- 700 kW NuMI neutrino beam at Fermilab
- Near and Far Detectors placed 14 mrad off the NuMI beam axis
- Measure $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ to:
  - Determine ν mass hierarchy
  - Determine the θ_{23} octant
  - Constrain δ_{CP}
- Use $\nu_\mu \rightarrow \nu_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ to:
  - make precise measurements of θ_{23} and Δm^2_{32}
- Many other physics topics:
  - ν cross sections at the ND
  - Sterile neutrinos
  - Supernova neutrinos
  - ...



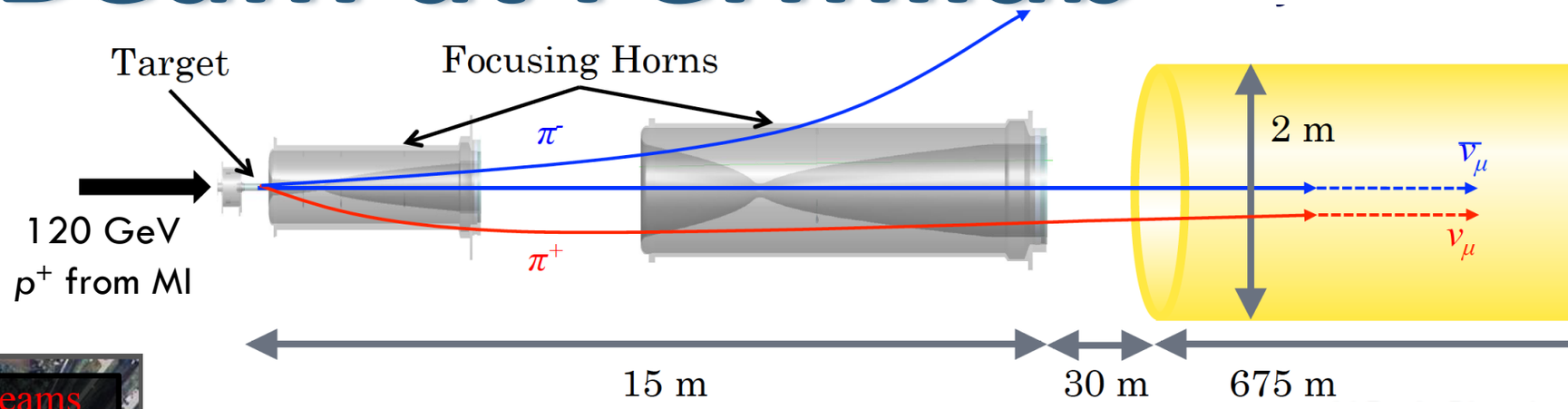
200+ Collaborators
42 Institutions
8 Countries

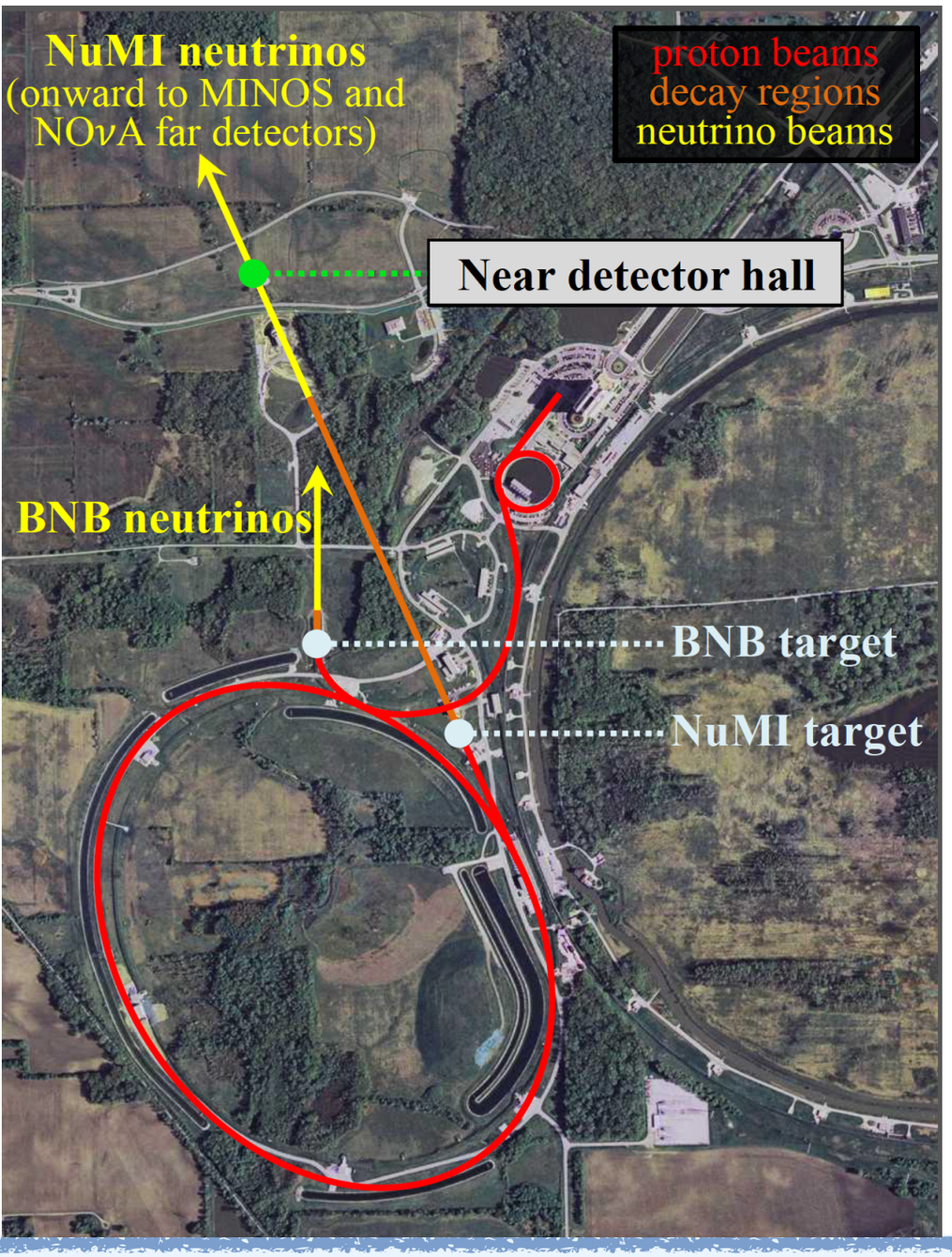
Argonne, Atlantico, Athens, Banaras Hindu University, Caltech, Institute of Physics of the Academy of Sciences of the Czech Republic, Charles University, Cincinnati, Czech Technical University, Delhi, Fermilab,Goiás, Guwahati, Harvard, Indian Institute of Technology, Hyderabad, Indiana, Iowa State, Jammu, Lebedev Physical Institute, Michigan State, Minnesota-Twin Cities, Minnesota-Crookston, Minnesota-Duluth, INR Moscow, Punjab, South Carolina, SMU, Stanford, Sussex, Tennessee, Texas-Austin, Tufts, UCL,Virginia, Wichita State, William and Mary

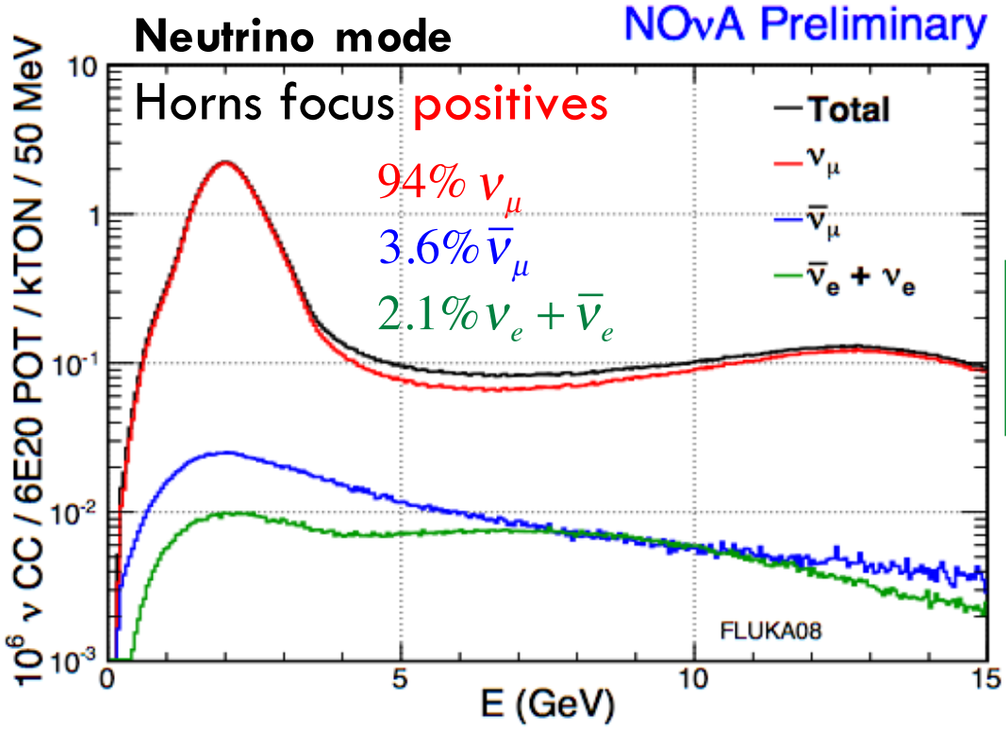
The NOvA Collaboration

NuMI Beam at Fermilab

- Neutrinos from the Main Injector (**NuMI**) beam at Fermilab





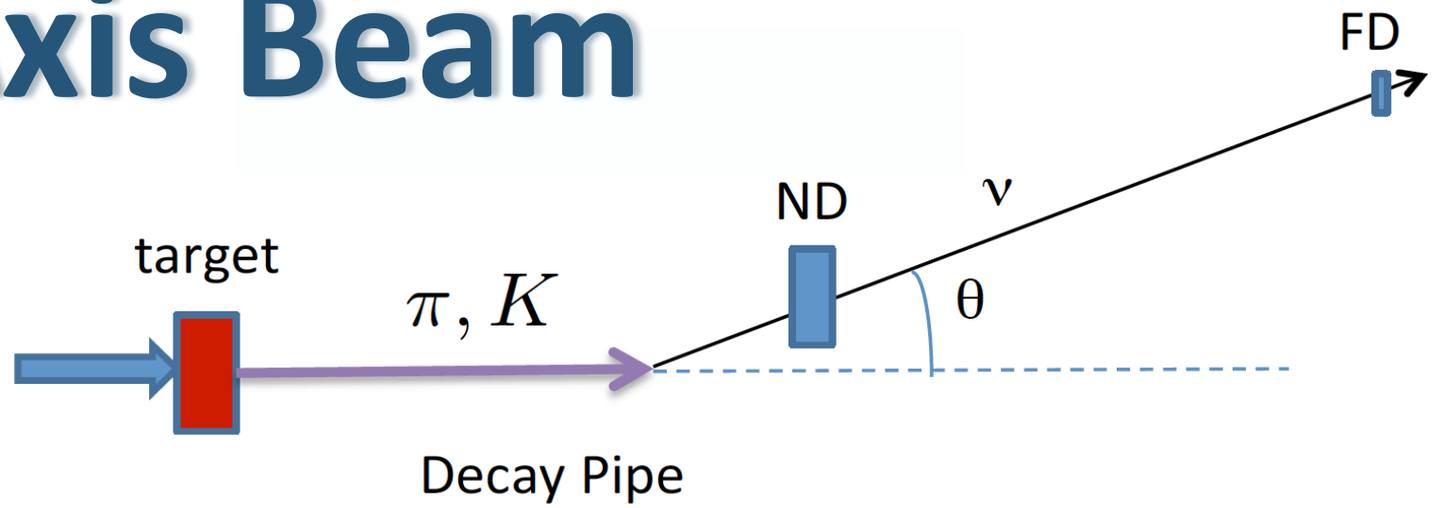


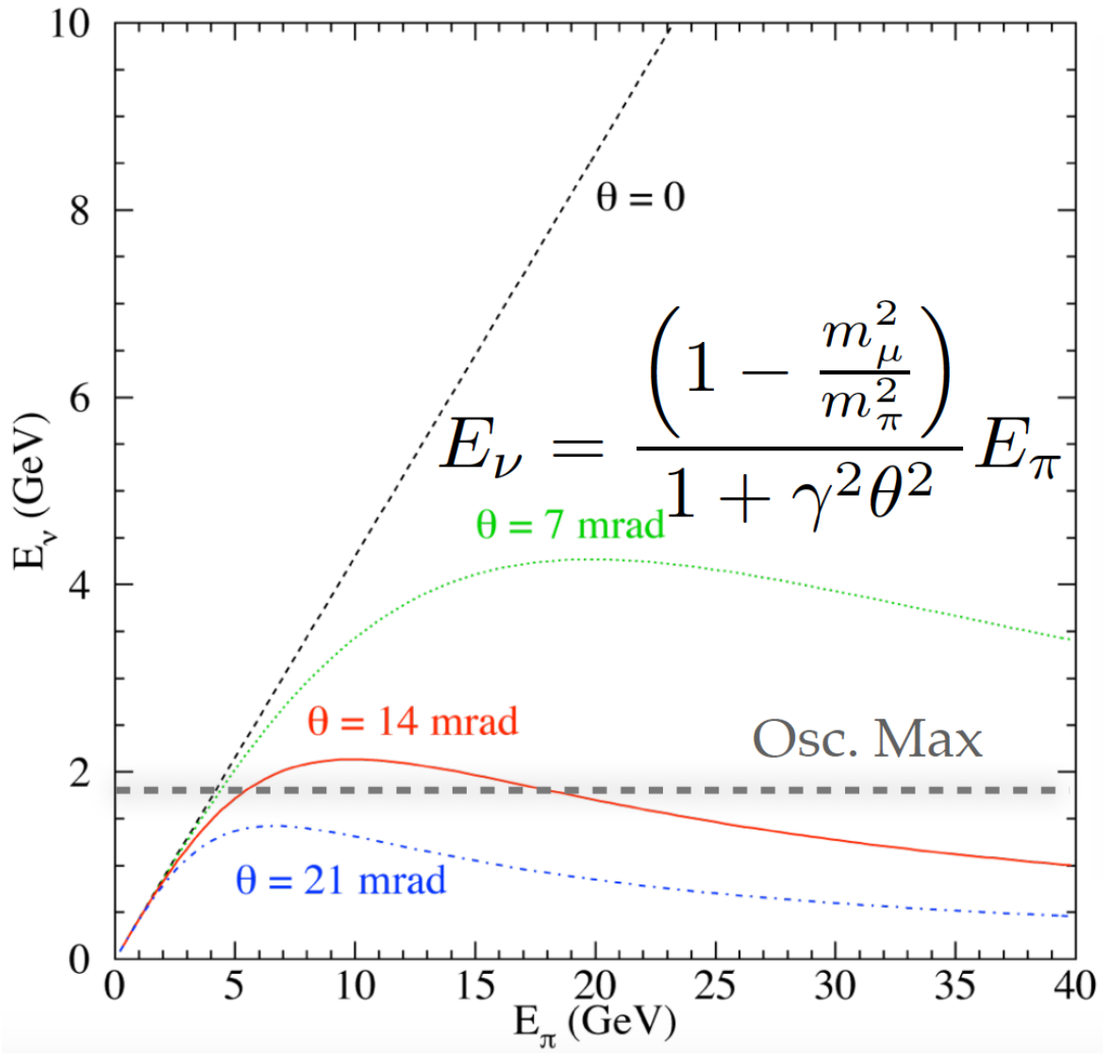
Poster:
Kuldeep Kaur Maan

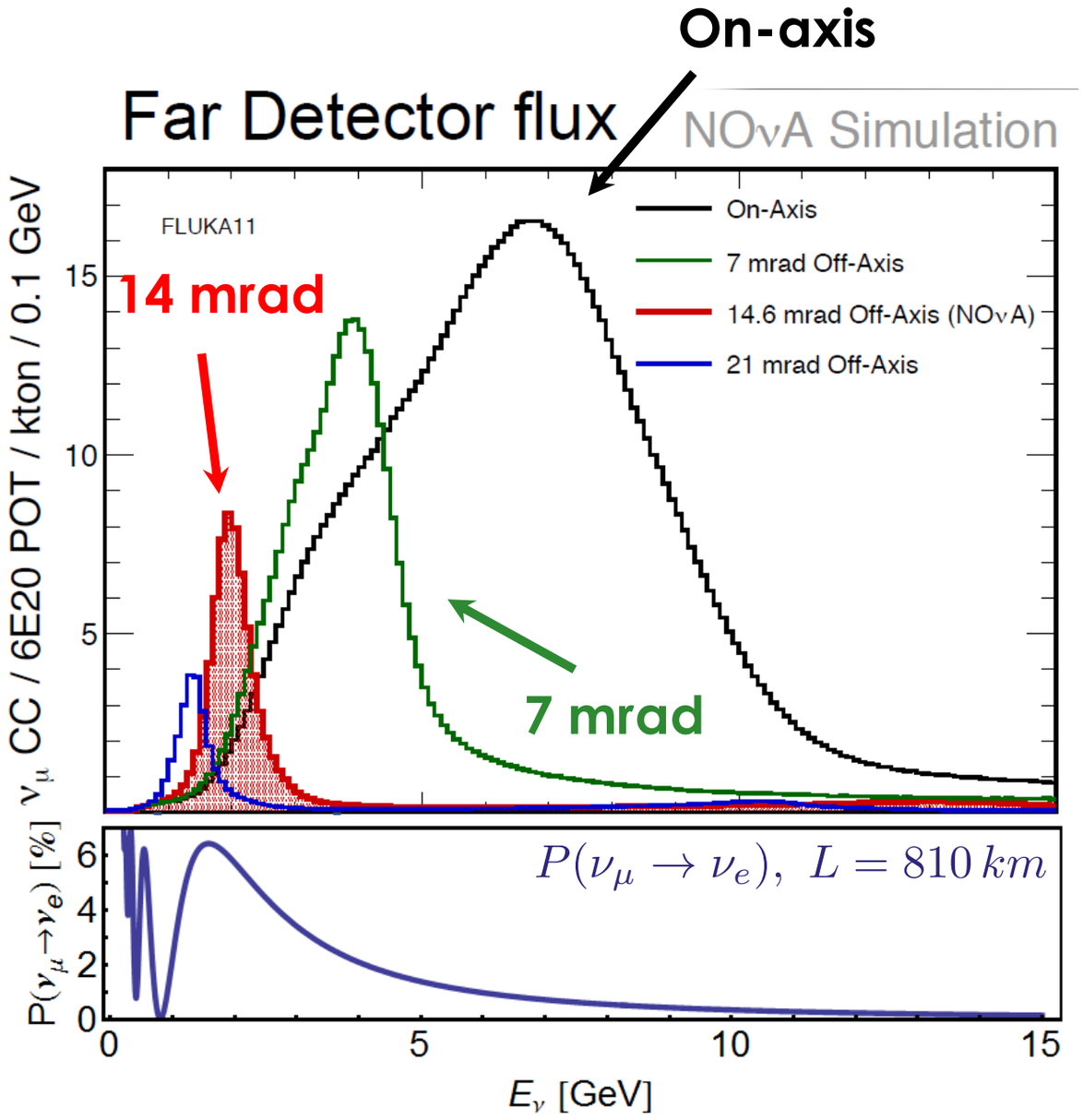
- Long shutdown in 2012-2013 to prepare for NOvA operations at 700 kW beam power
  - 5×10^{13} protons-on-target (POT) in 10 μs pulse every 1.33 s
  - Routine operation at 400 kW during FY15
  - 85% uptime
  - Neutrino beam power World Record: **521 kW**!
  - 700 kW operation expected in Spring 2016

Off-Axis Beam

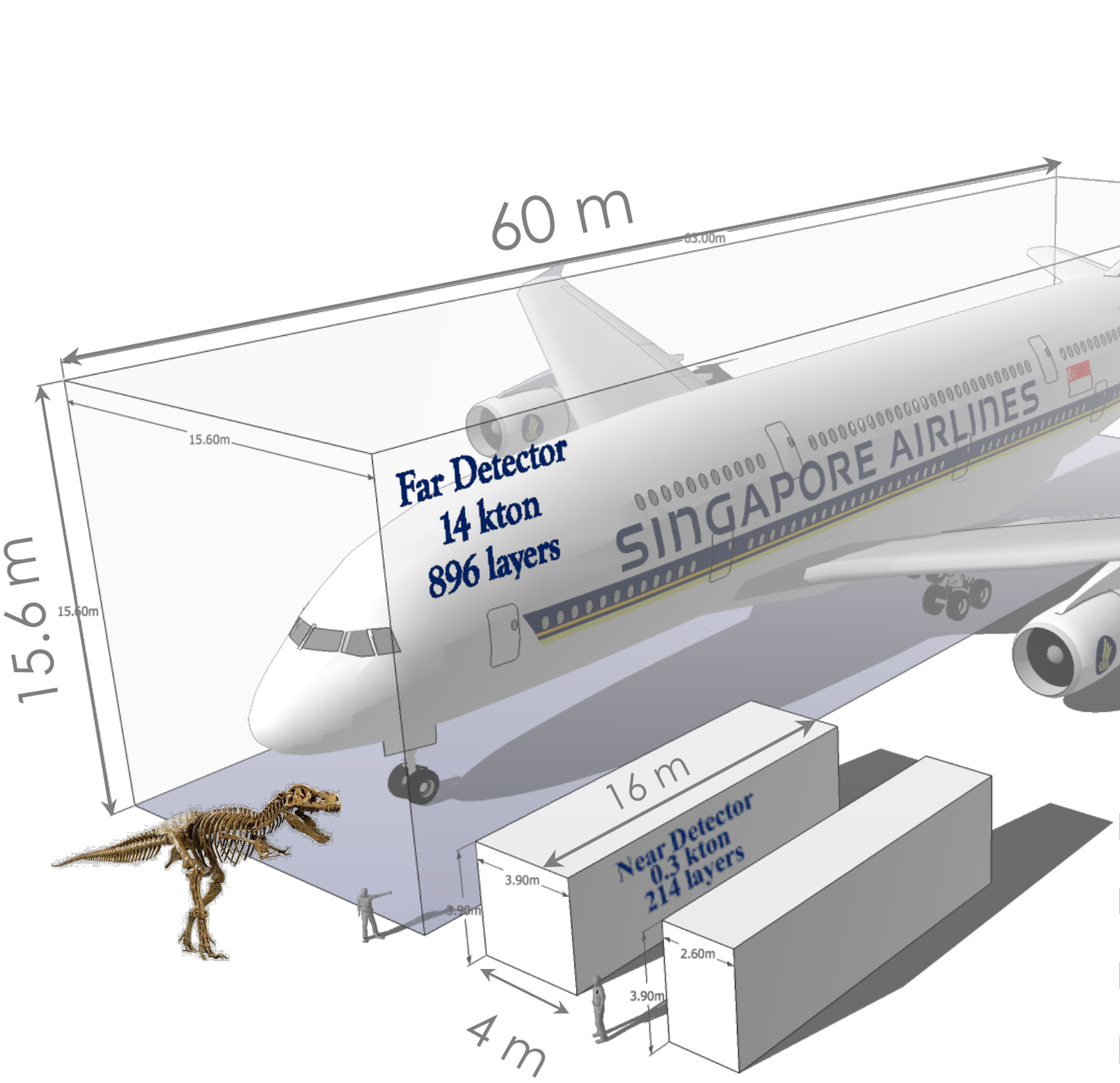
- At 14 mrad off-axis, narrow band beam peaked at 2 GeV
- Near oscillation maximum at 810 km
- Drastic reduction of feed-down background from high energy events







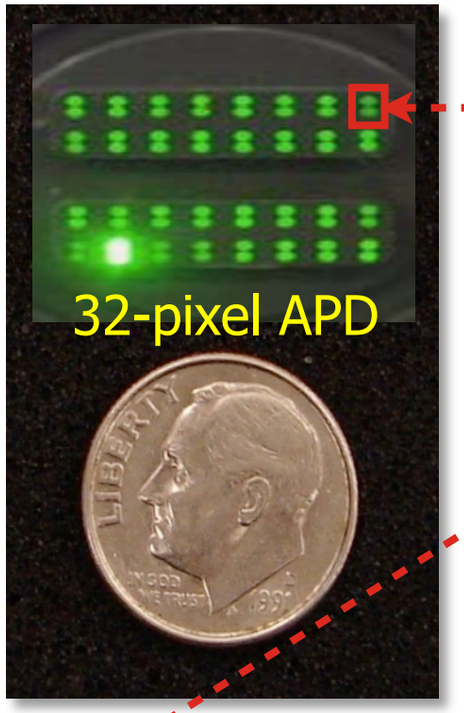
The NOvA Detectors

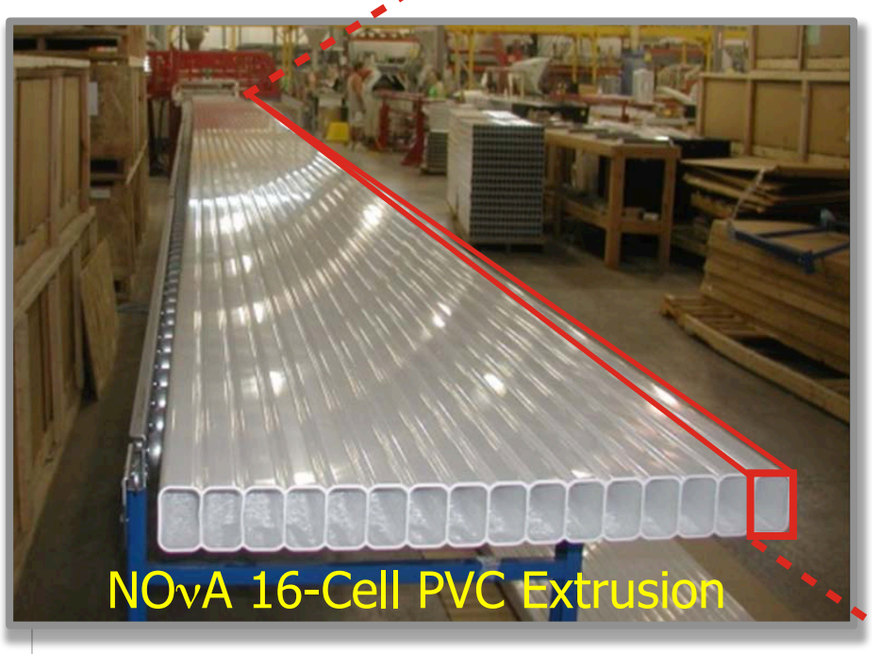


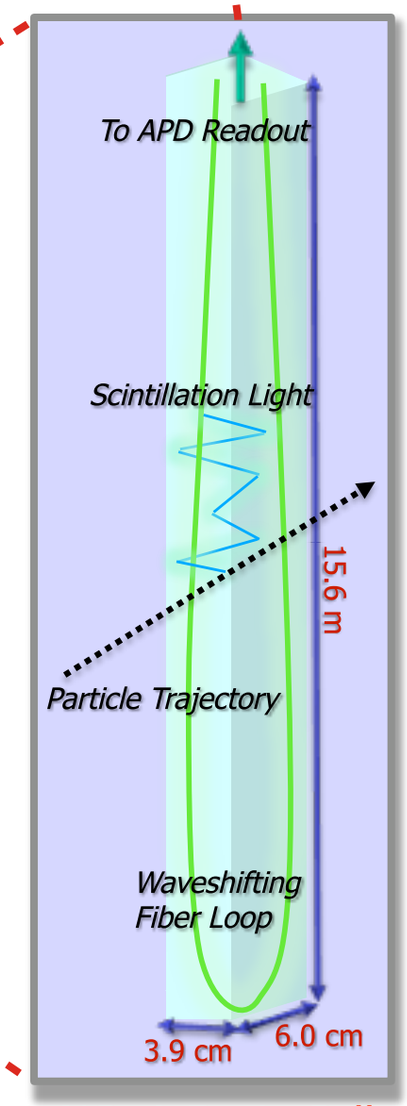
- Optimized for electron identification
- Fine segmentation
- Low-Z, 65% active
- ND: 300 ton, 1 km from source, 100 m depth
- FD: 14 kton, 810 km from source, on the surface, 3 m.w.e. overburden

Detector Technology

- PVC extrusion + Liquid Scintillator
  - 11M liters of mineral oil + 5% pseudocumene
- Read out via WLS fiber to 32-pixel APD
  - FD has 344,064 channels
  - ND has 18,000 channels
  - muon crossing far end at FD~25 PE
- Layered planes of orthogonal views
- 0.15 X_0 per layer, excellent for e^- identification

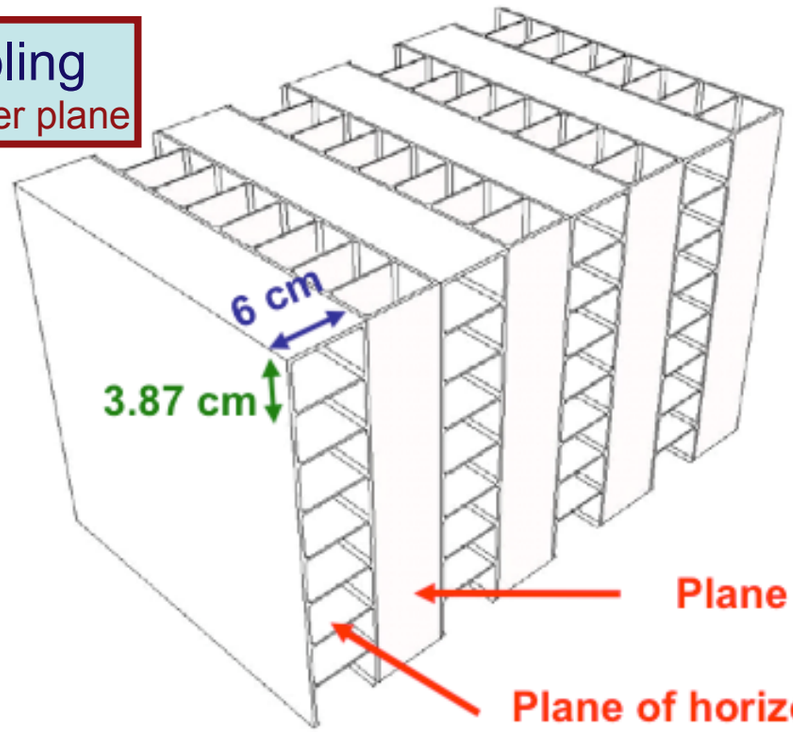






NOνA Basic Cell

Sampling
0.15 X_0 per plane

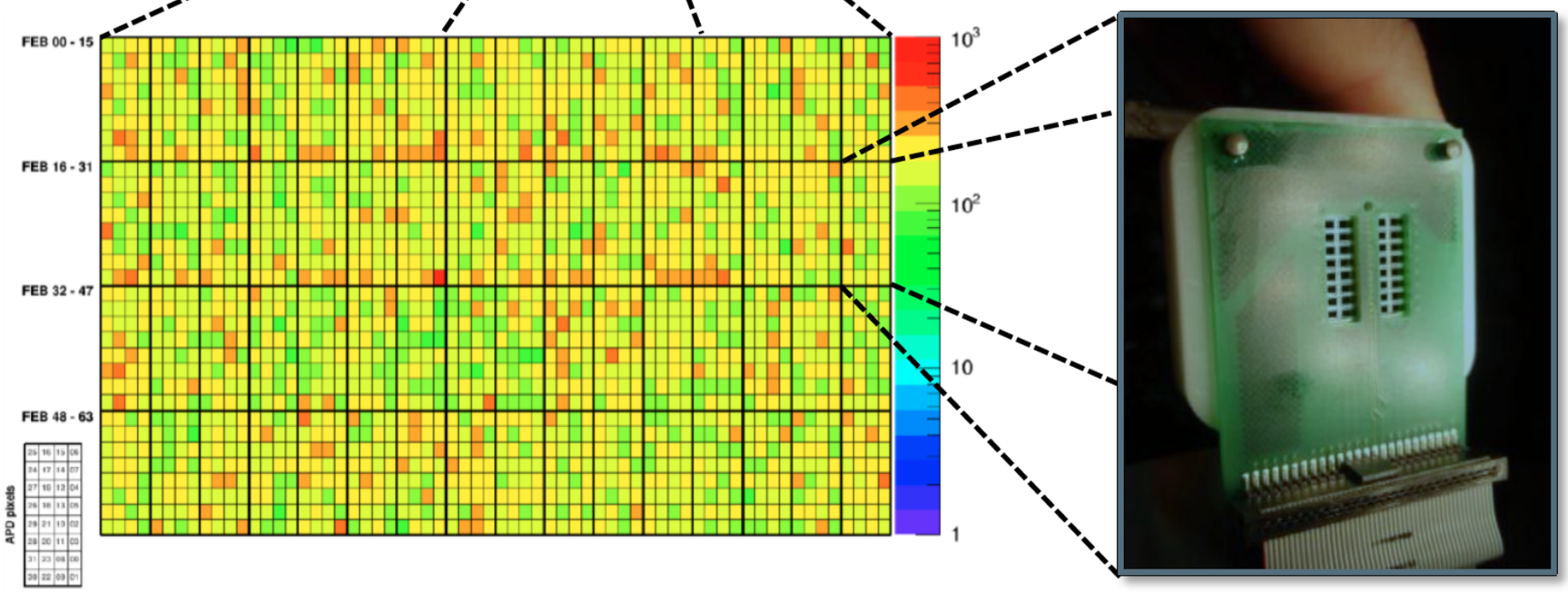


DB14 DB13 DB12 DB11 DB10 DB09 DB08 DB07 DB06 DB05 DB04 DB03 DB02 DB01

DCM01 DCM02 DCM03 DCM04 DCM05 DCM06 DCM07 DCM08 DCM09 DCM10 DCM11 DCM12

10^4

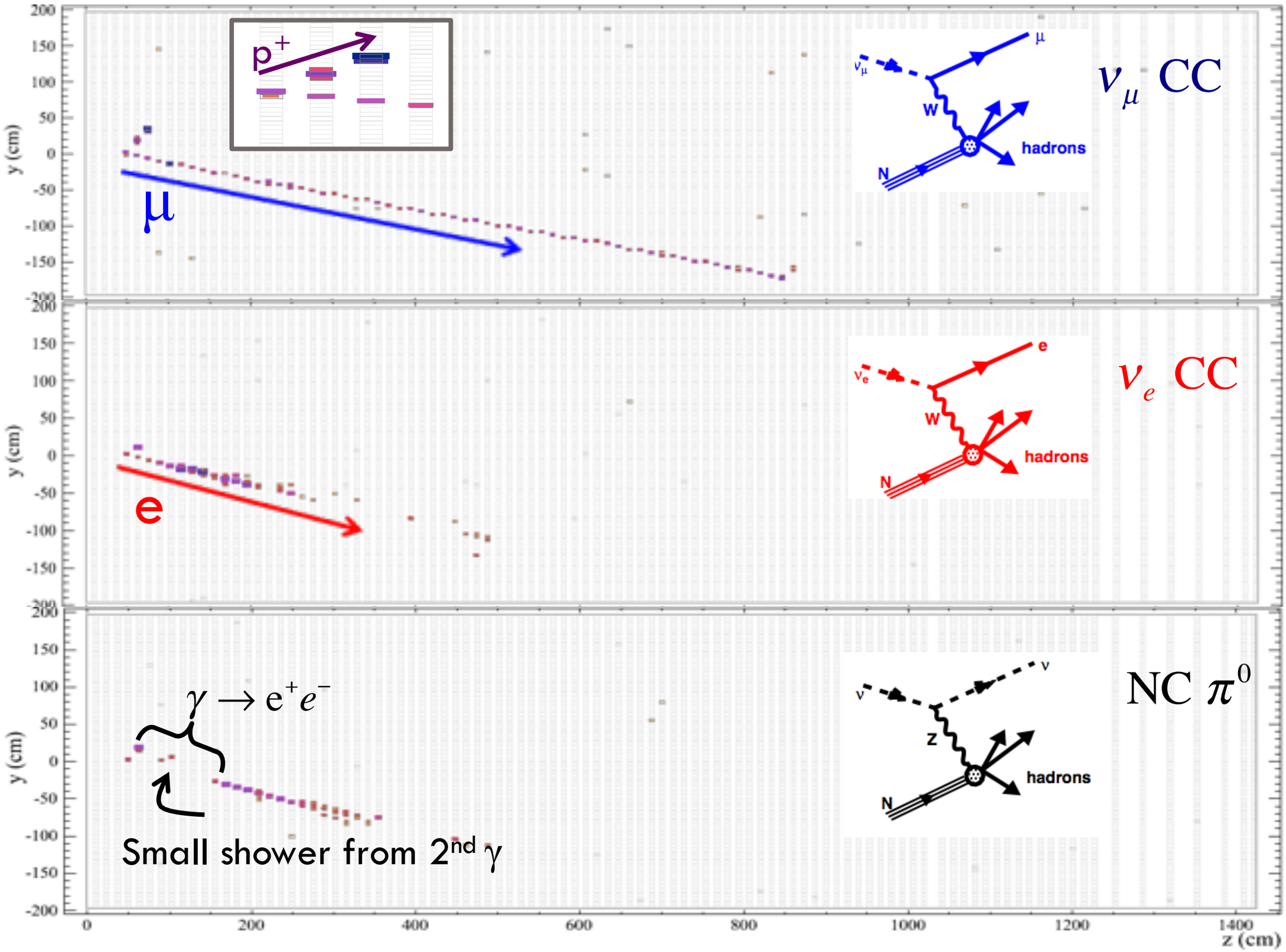
10^3



344,064 channels!

99.5% operational

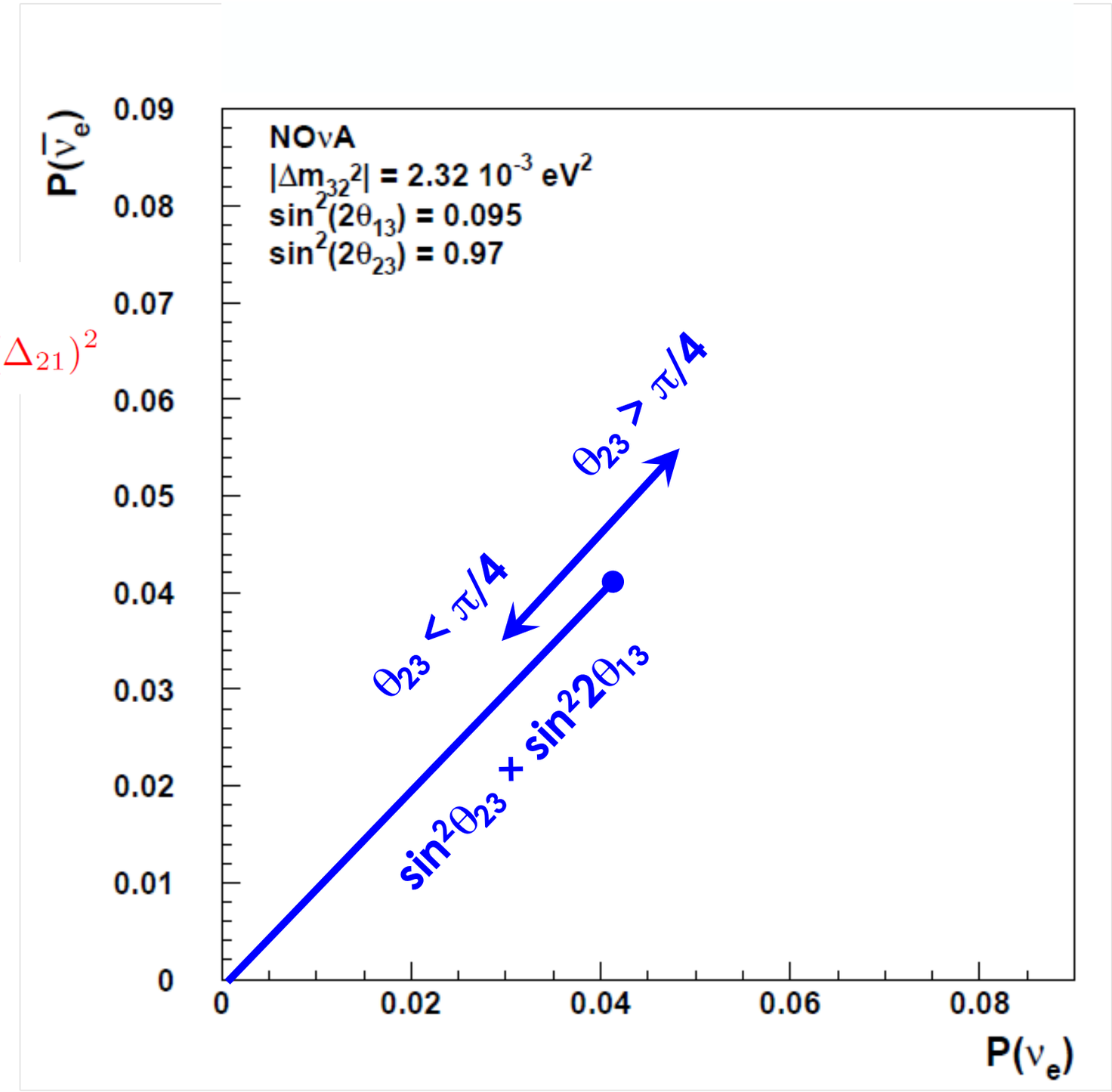
Simulated Events in the Detectors



Measuring mixing parameters with NOvA

- Measuring ν_e and $\overline{\nu}_e$ appearance in the ν_μ and $\overline{\nu}_\mu$ beam is key

$$\mathcal{P}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2(2\theta_{13})\sin^2\Delta_{\mu e} \pm \tilde{J}\sin\delta\sin\Delta_{21}\sin^2\Delta_{\mu e} + \mathcal{O}(\Delta_{21})^2$$



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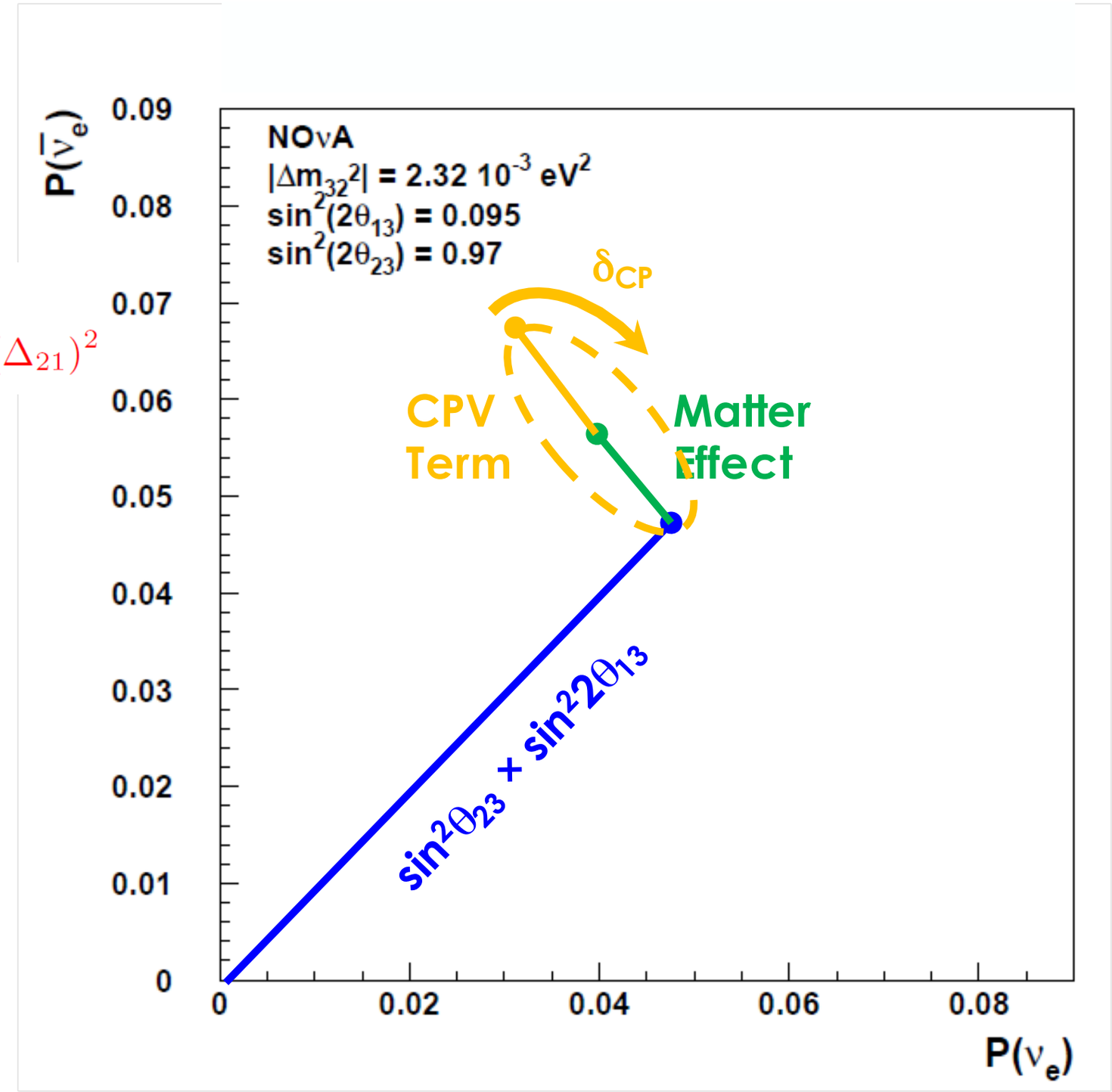
$$A \equiv \frac{\sqrt{2}G_F n_e}{\Delta m^2_{32}/2E} \sim \frac{E}{11.5\ \text{GeV}}$$

$$\tan(2\tilde{\theta}_{13}) \equiv \frac{\sin(2\theta_{13})}{\cos(2\theta_{13}) - A}$$

- Matter effects change osc. prob. by
  30% for NOvA (810 km),
  11% for T2K (295 km)



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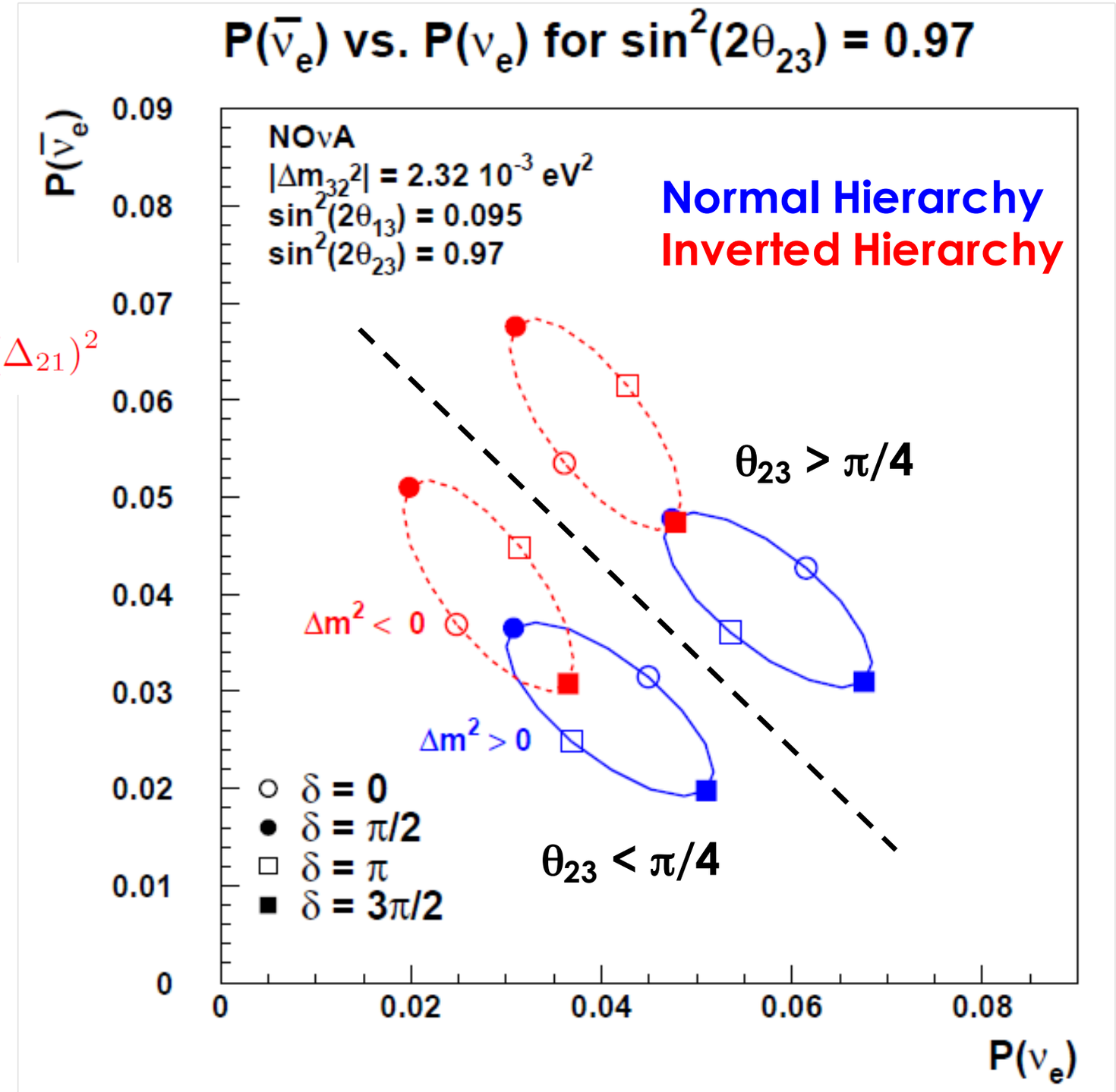

Measuring mixing parameters with NOvA

- Measuring ν_e and $\bar{\nu}_e$ appearance in the ν_μ and $\bar{\nu}_\mu$ beam is key
- Showing expected 1σ and 2σ allowed regions around most favorable case for NOvA

$$\mathcal{P}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2(2\theta_{13})\sin^2\Delta_{\mu e} \pm \tilde{J}\sin\delta\sin\Delta_{21}\sin^2\Delta_{\mu e} + \mathcal{O}(\Delta_{21})^2$$

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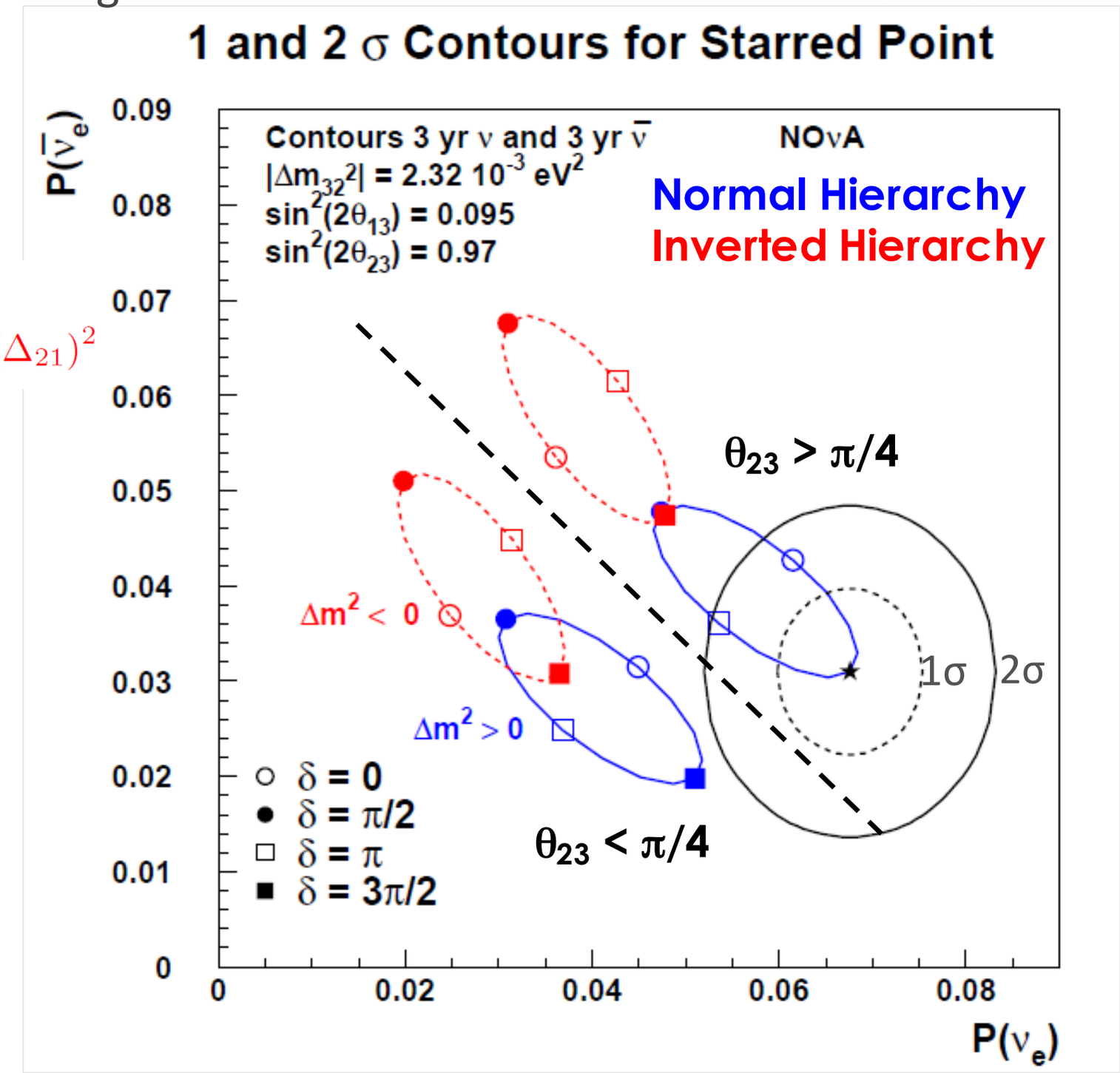
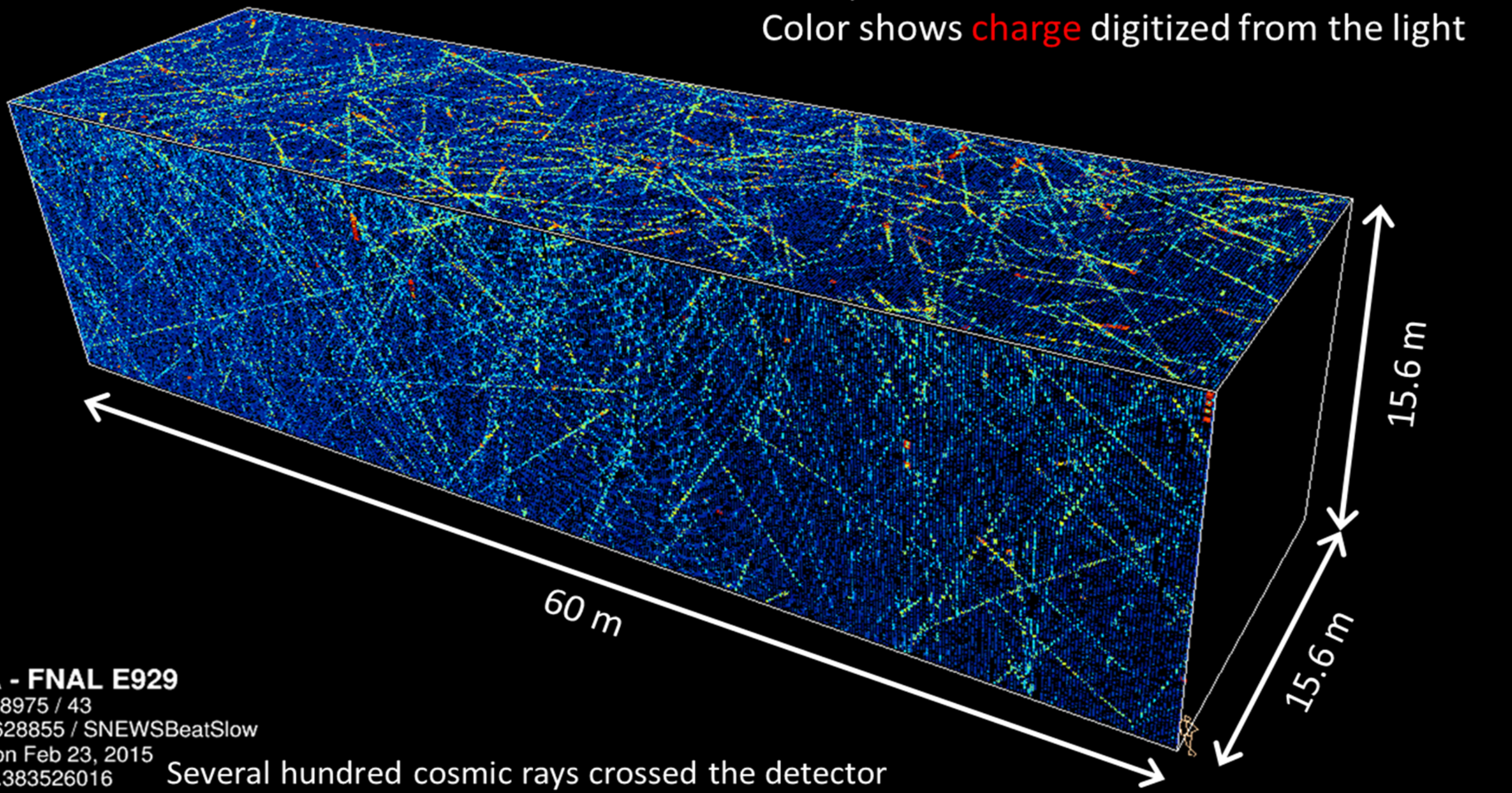


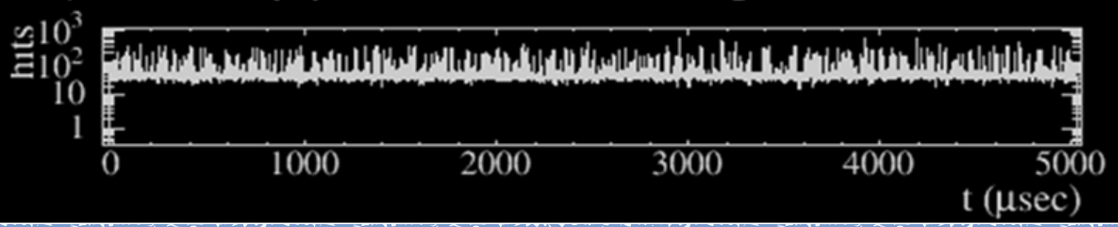
A Cosmic Challenge

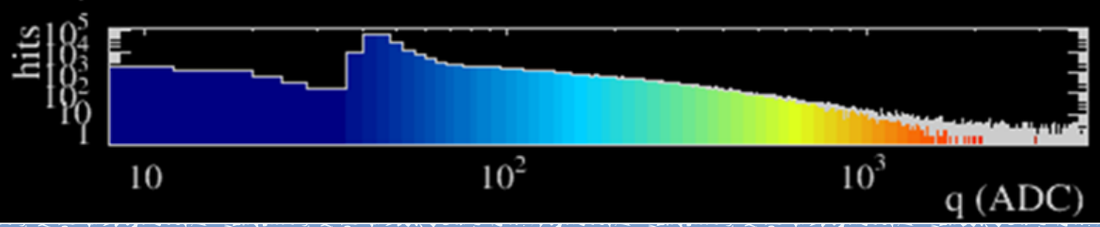
5ms of data at the NOνA Far Detector
Each pixel is one hit cell
Color shows charge digitized from the light



NOvA - FNAL E929
Run: 18975 / 43
Event: 628855 / SNEWSBeatSlow
UTC Mon Feb 23, 2015
14:30:1.383526016

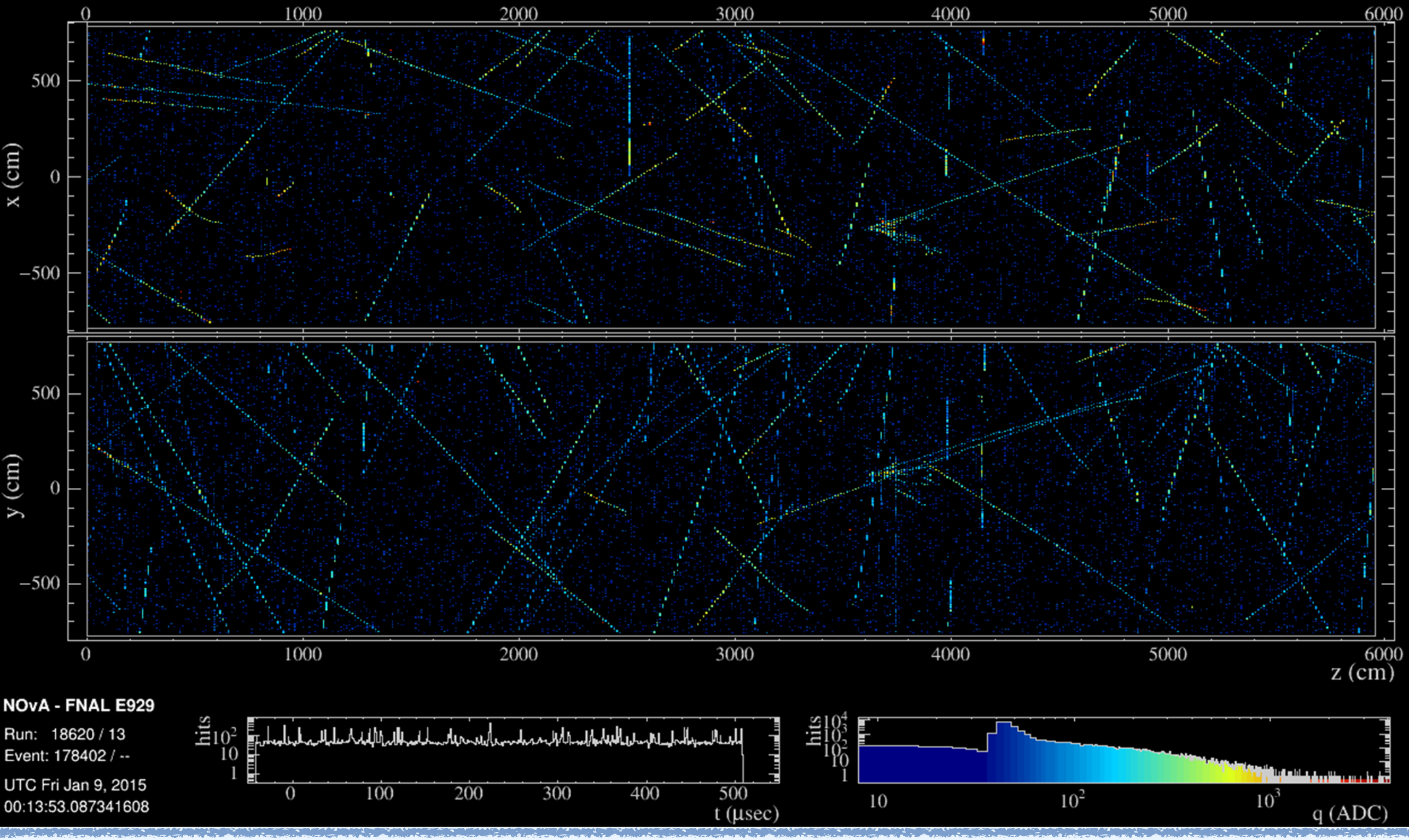
Several hundred cosmic rays crossed the detector
(the many peaks in the timing distribution below)





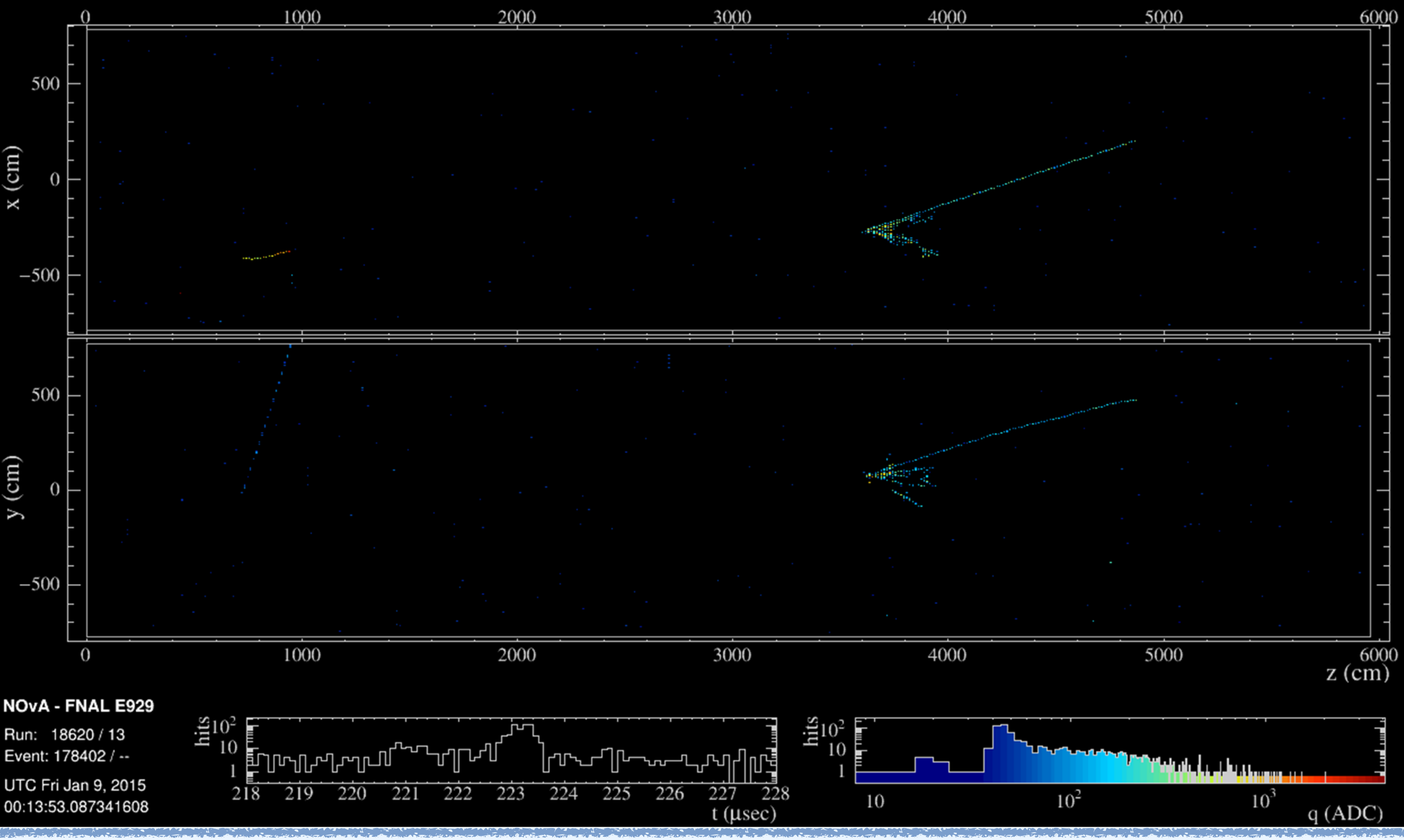
A Cosmic Challenge

Just the 550 μs around the NuMI beam trigger



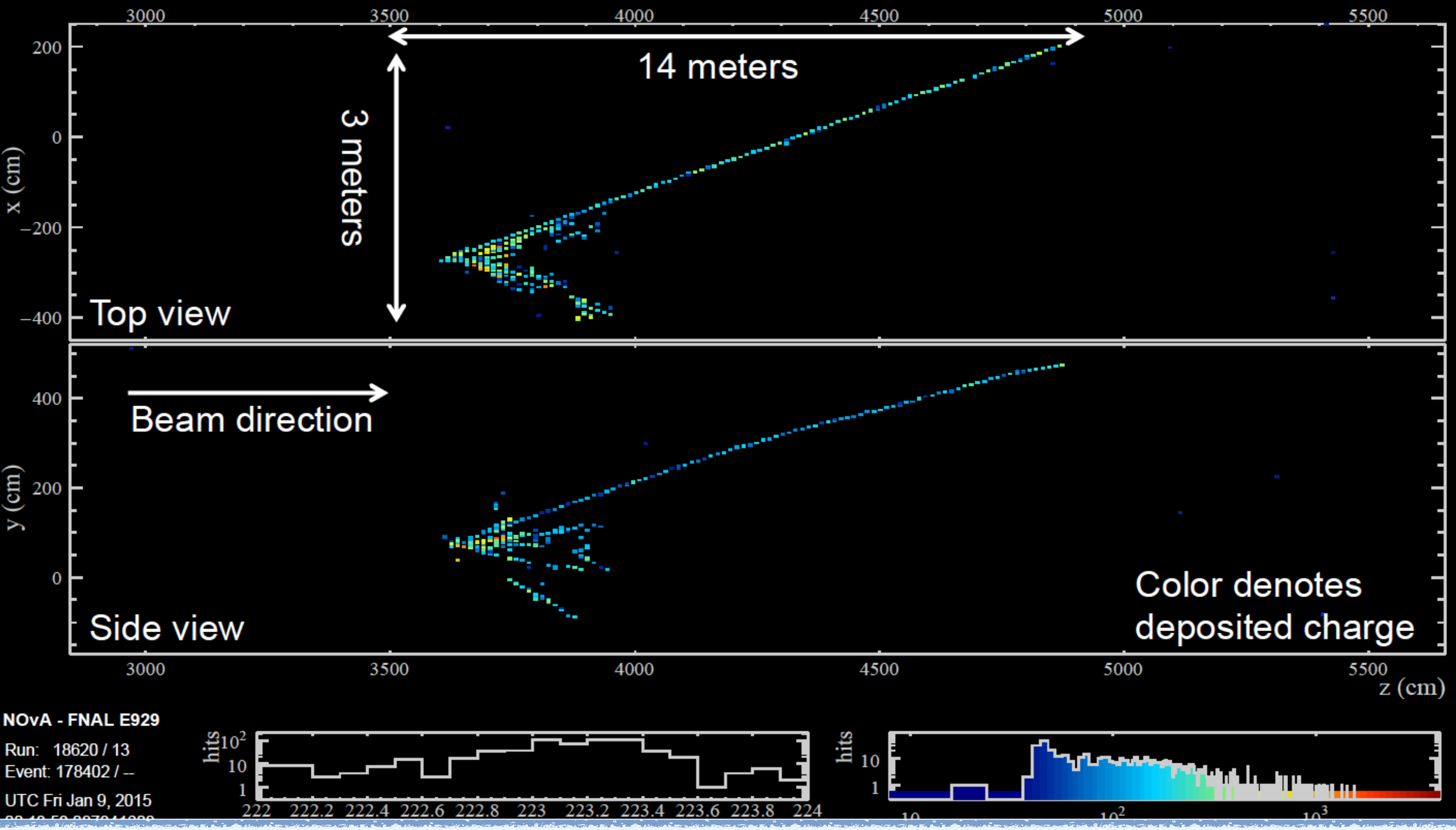
A Cosmic Challenge

Sliced to the 10 μs NuMI beam spill window



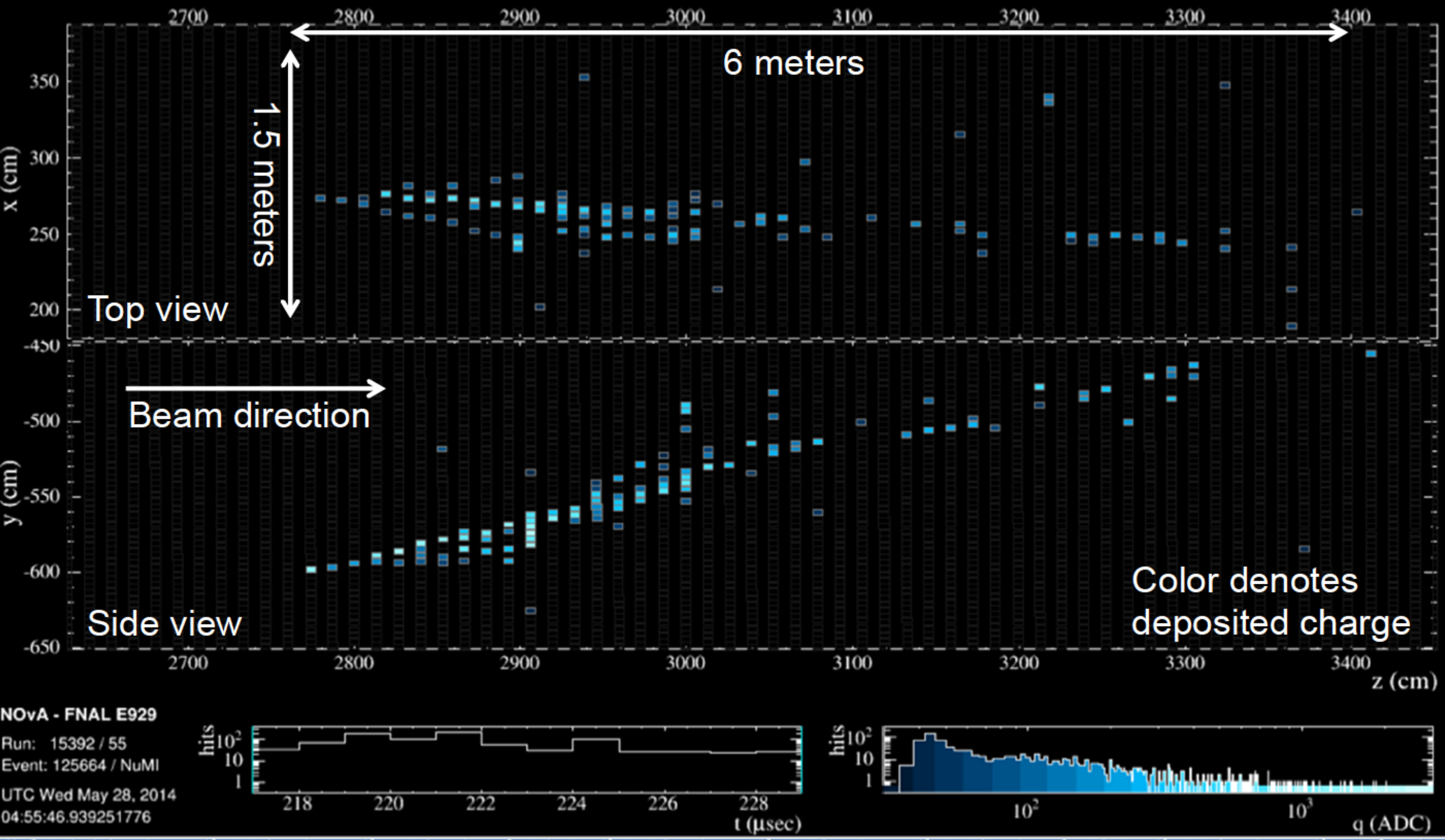
ν_μ CC Candidate

Zoomed in spatially



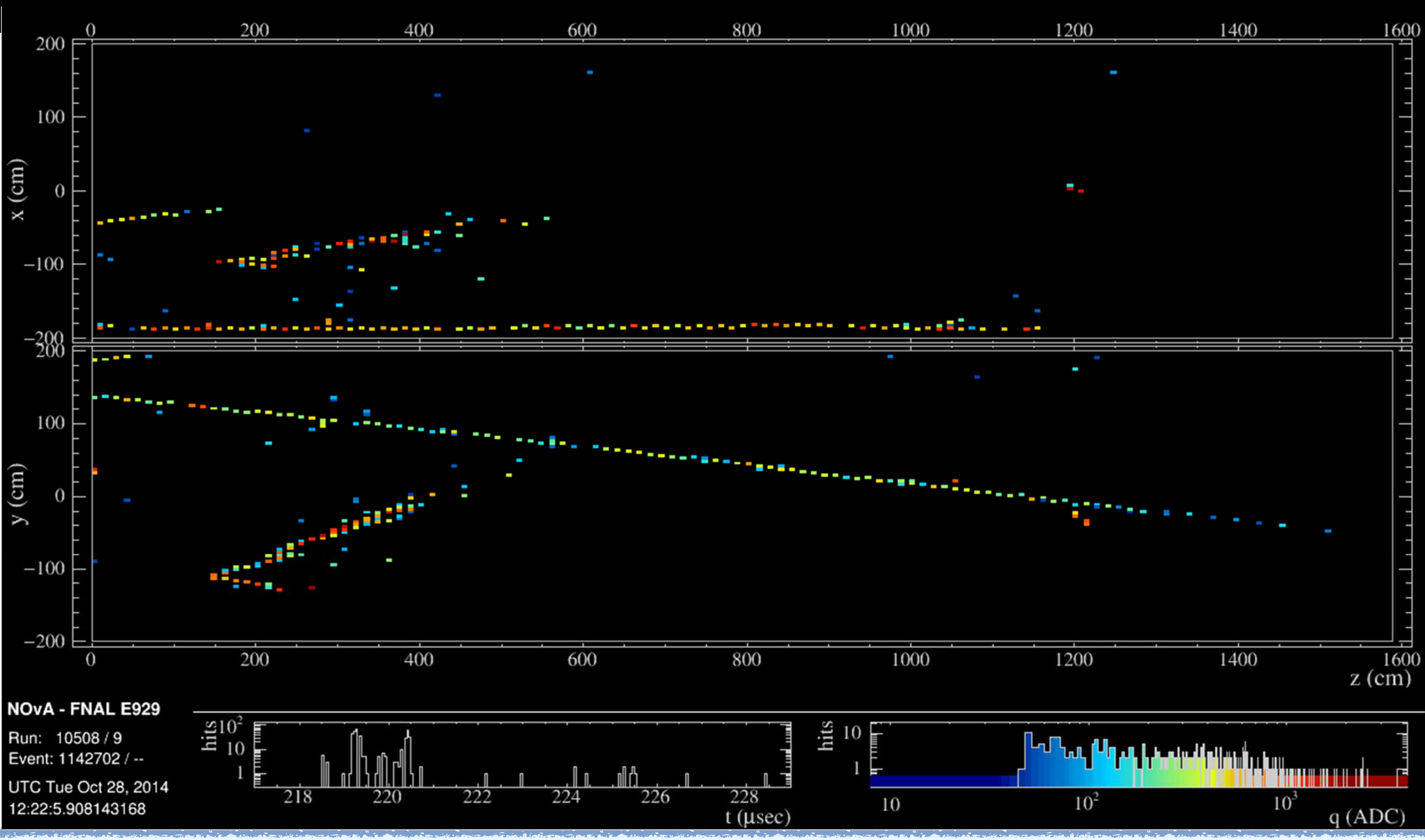
ν_e CC Candidate

Zoomed in spatially



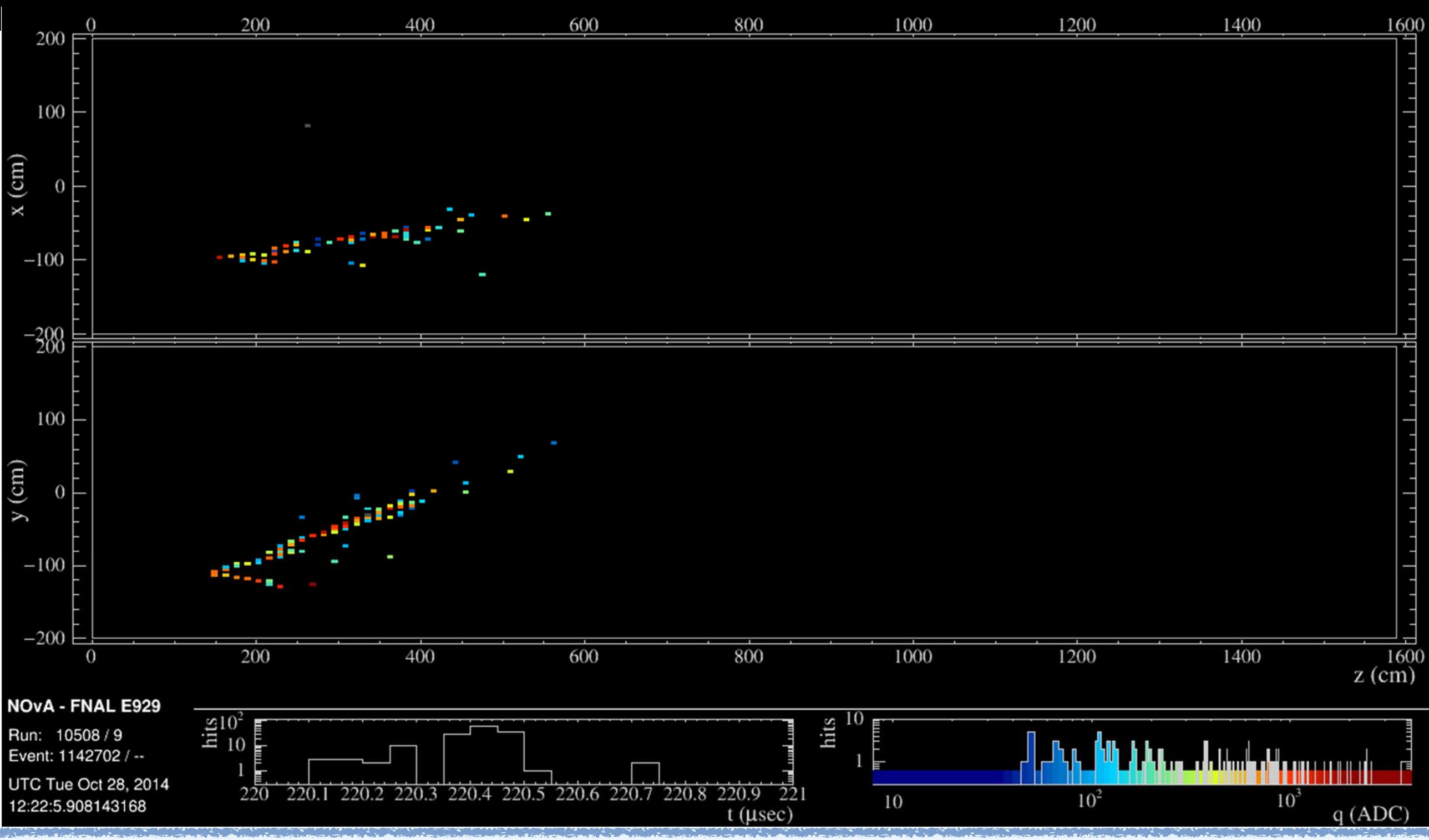
Beam Spill in the Near Detector

10 μs beam pulse in Near Detector



Beam Spill in the Near Detector

Pick one of the neutrino interactions



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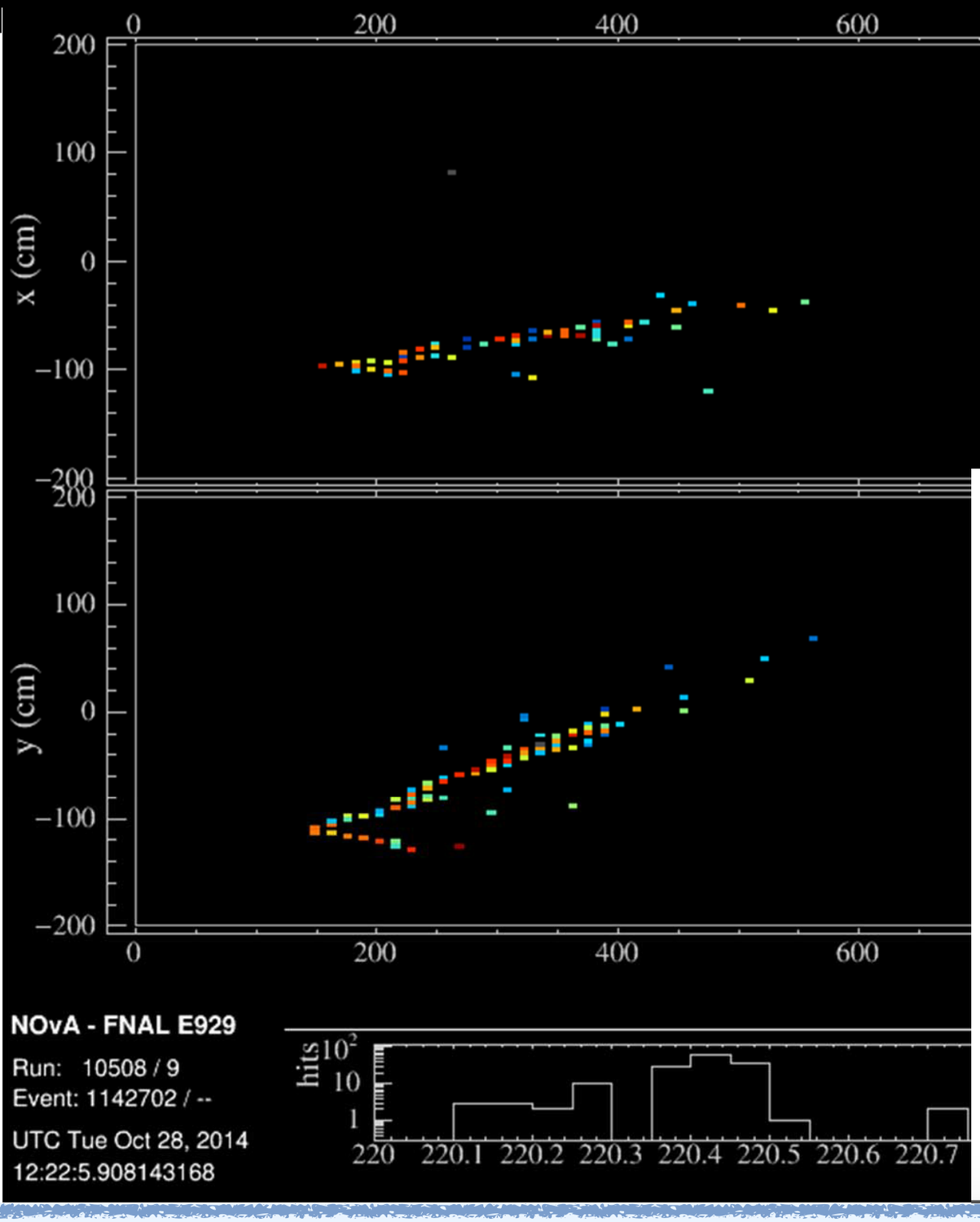
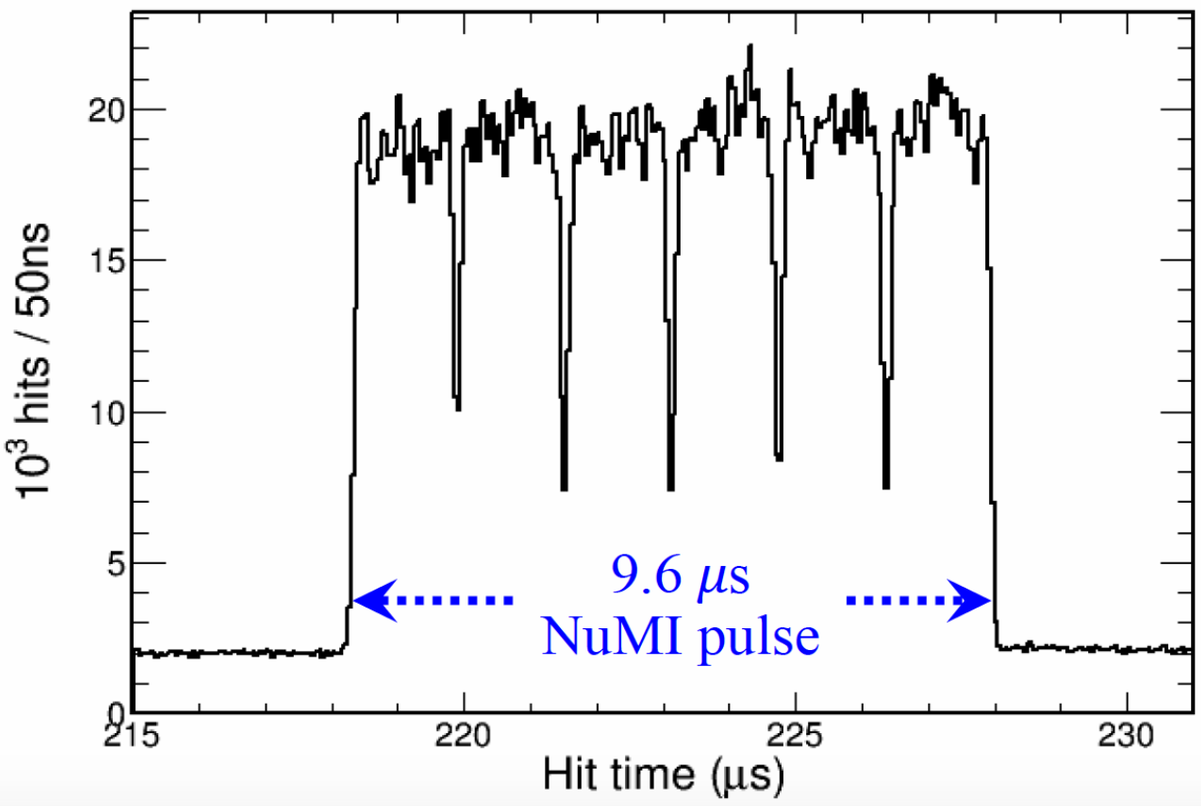
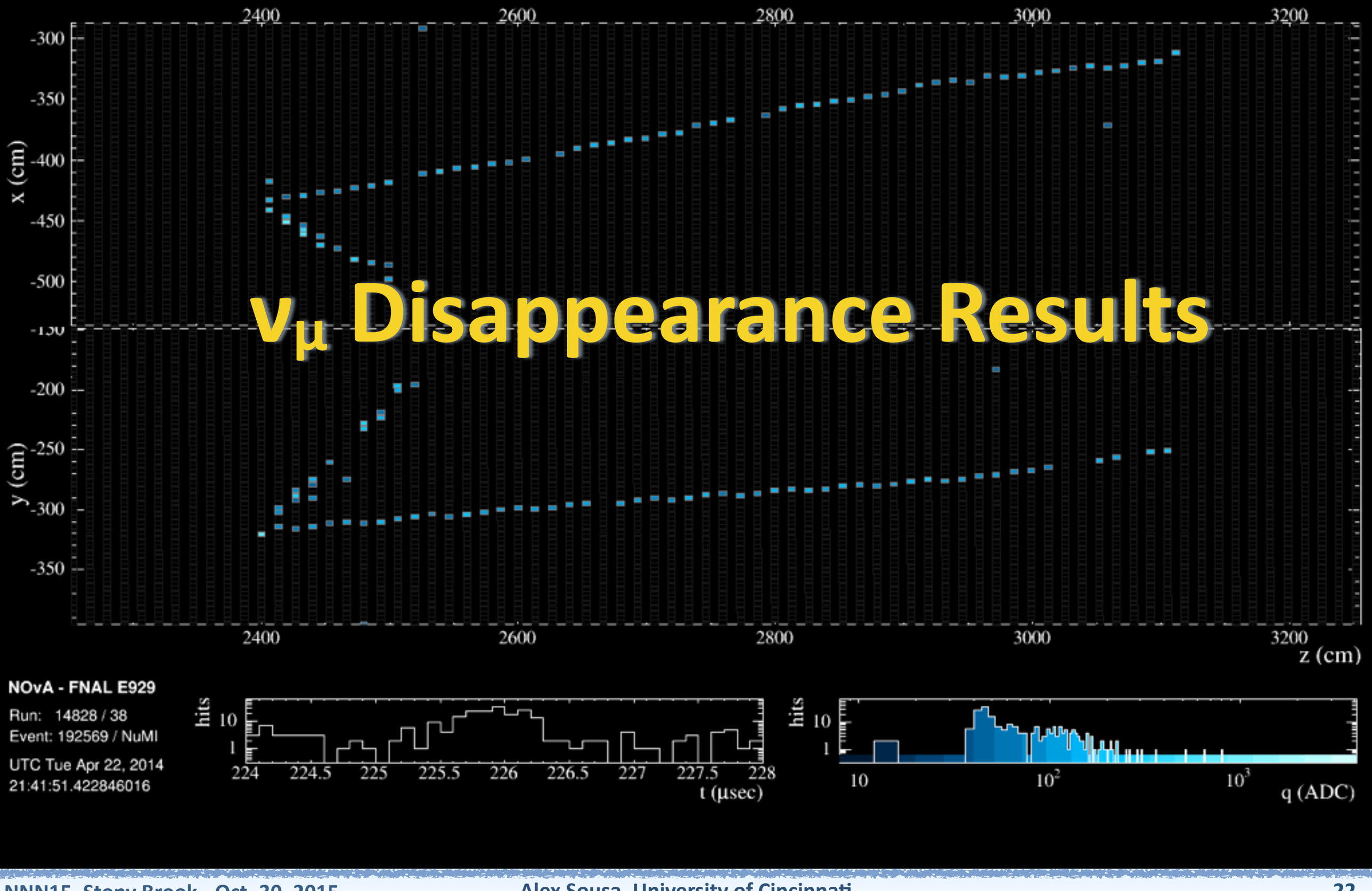


Time of all hits in Near Det during NuMI spills (~1 hr)

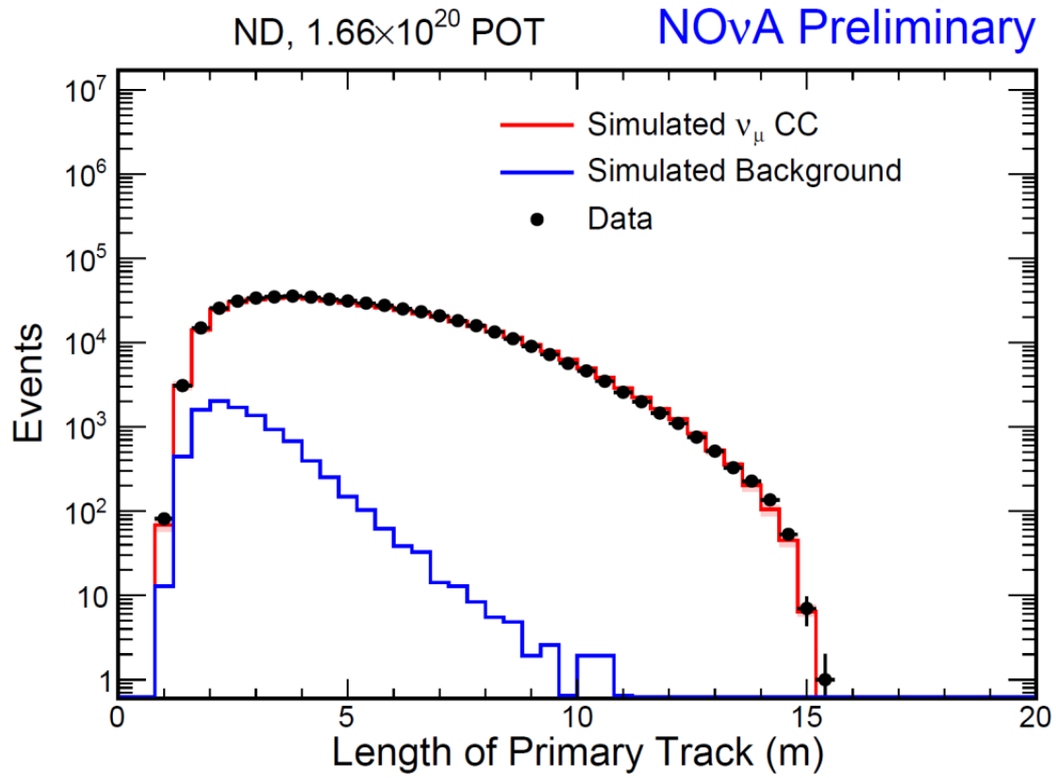


ν_μ Disappearance Results

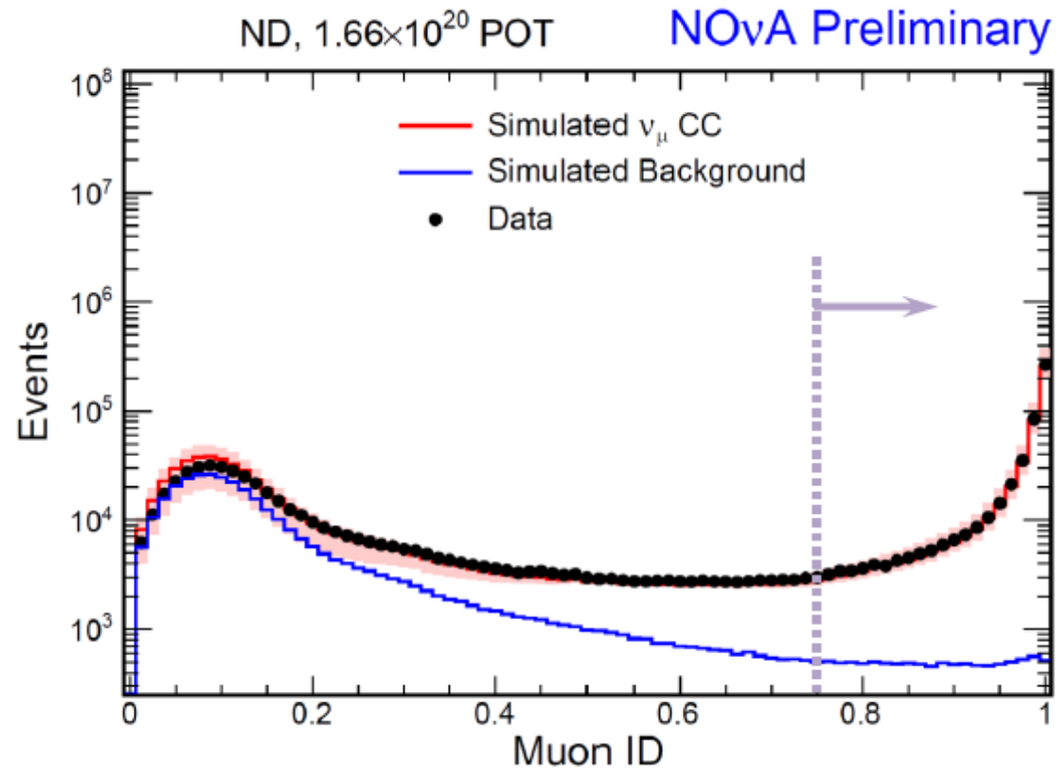


Selecting Muon Neutrinos

- Isolate a pure sample of ν_μ CC events
  - Select events with long tracks
  - Suppress neutral-current and cosmic backgrounds
- Containment cuts: require a buffer of no-cell activity around the event



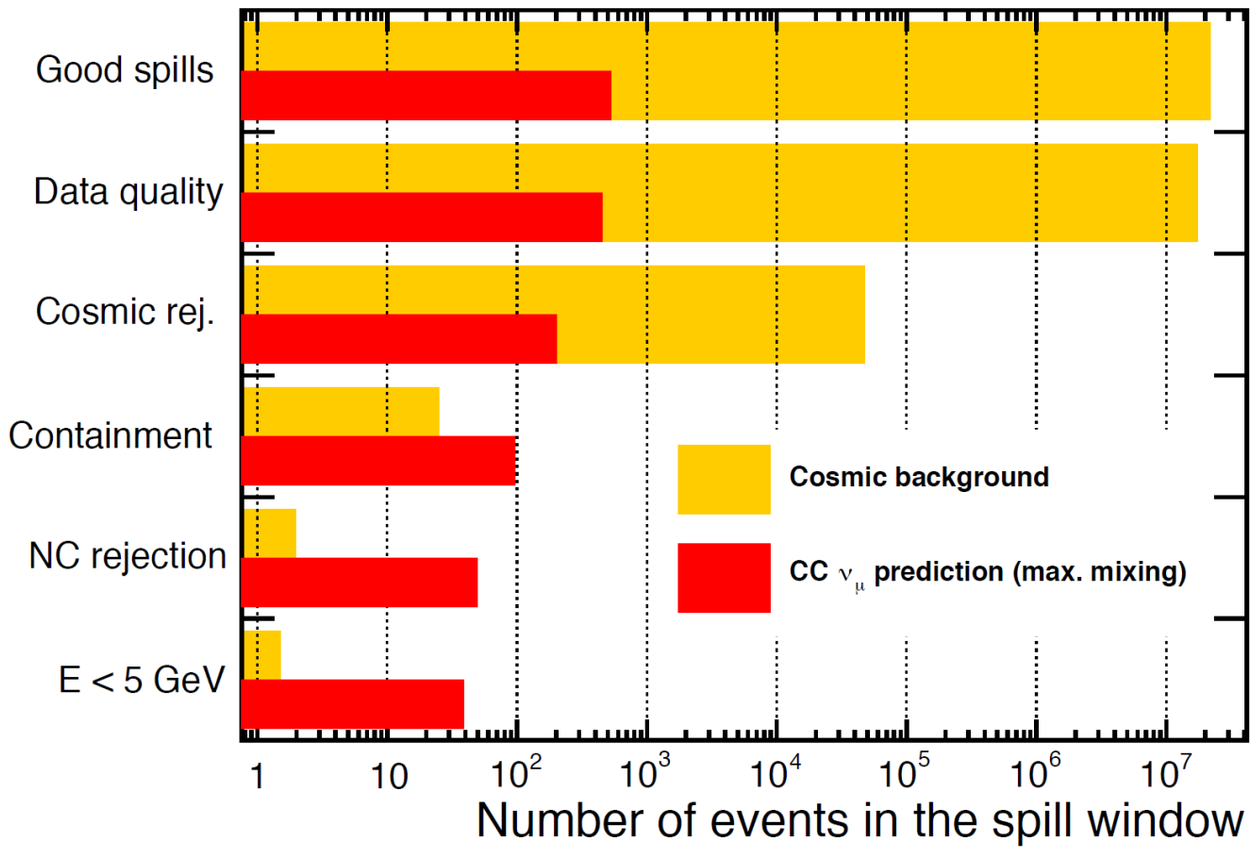
- 4-variable k-Nearest-Neighbor algorithm used to identify muons
  - Track Length
  - dE/dx along track
  - scattering along track
  - track-only fraction of planes
- ND Data matches simulation well for selection variables
- **Keep events with Muon ID>0.75**

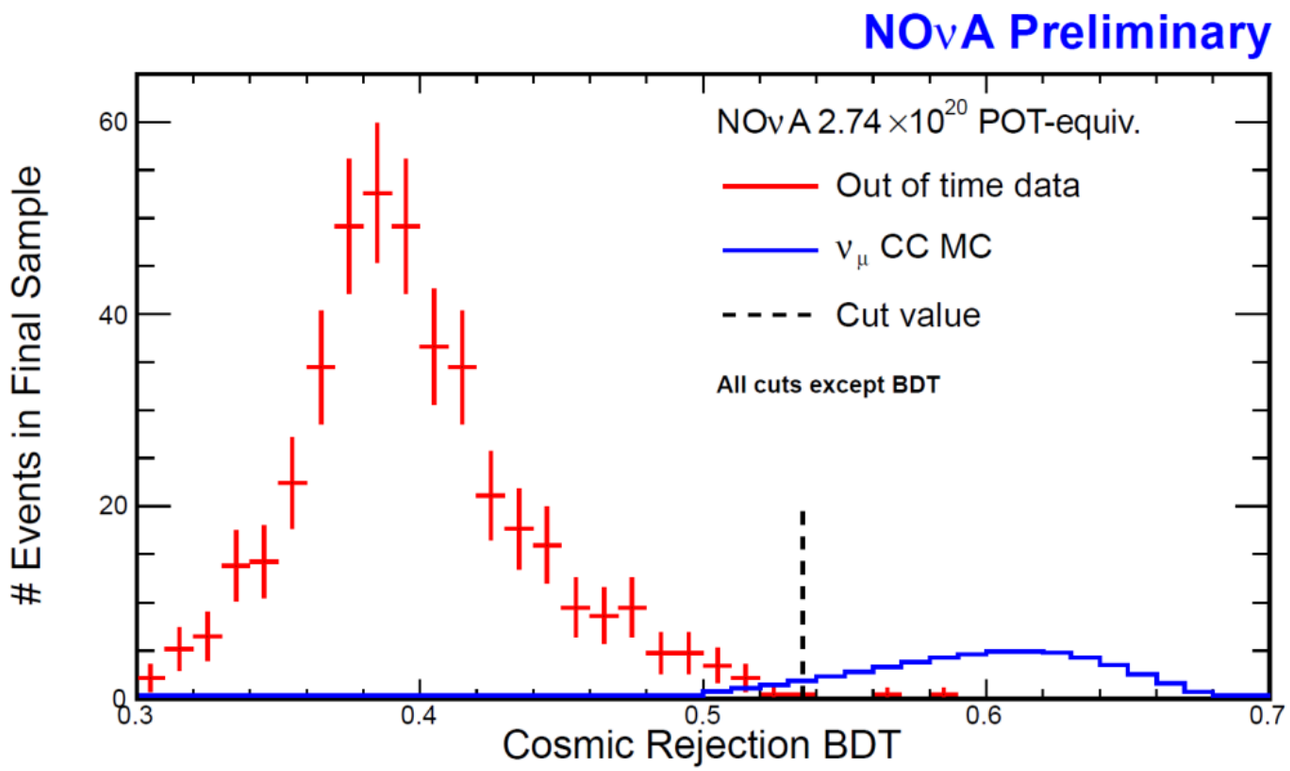


Cosmic Rejection

- Cosmic rejection factor from
  - beam timing: **10^5**
  - event topology: **10^7**

- Final cosmic background rate measured directly with beam-off FD data



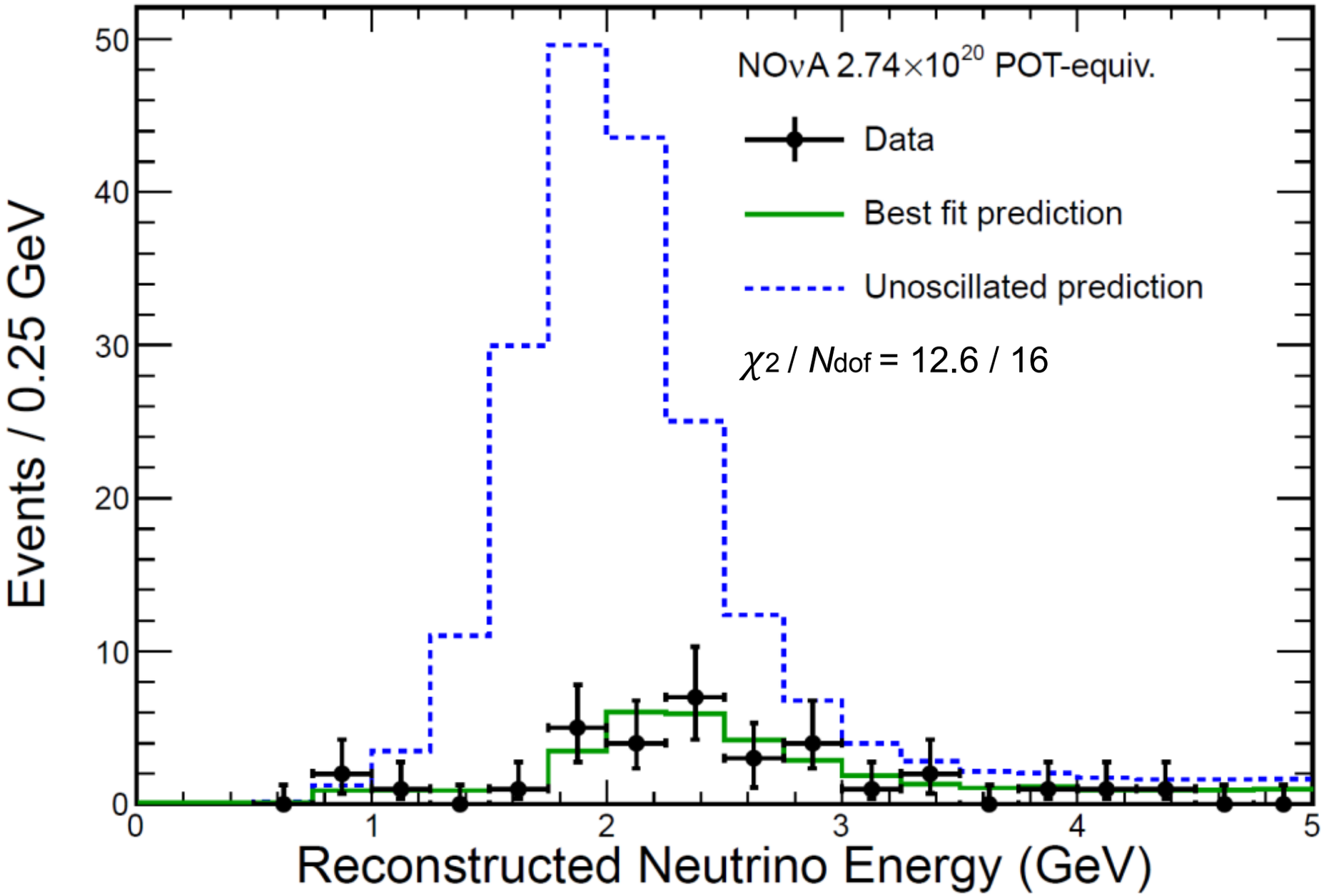


- Use boosted decision tree algorithm based on track direction, position, length, energy, and number of hits to reach **10^7** cosmic rejection factor
- Output of BDT algorithm after all other cuts applied

- **Purity of ν_μ CC-selected sample = 98%**

ν_μ CC Energy Spectrum

NOνA Preliminary



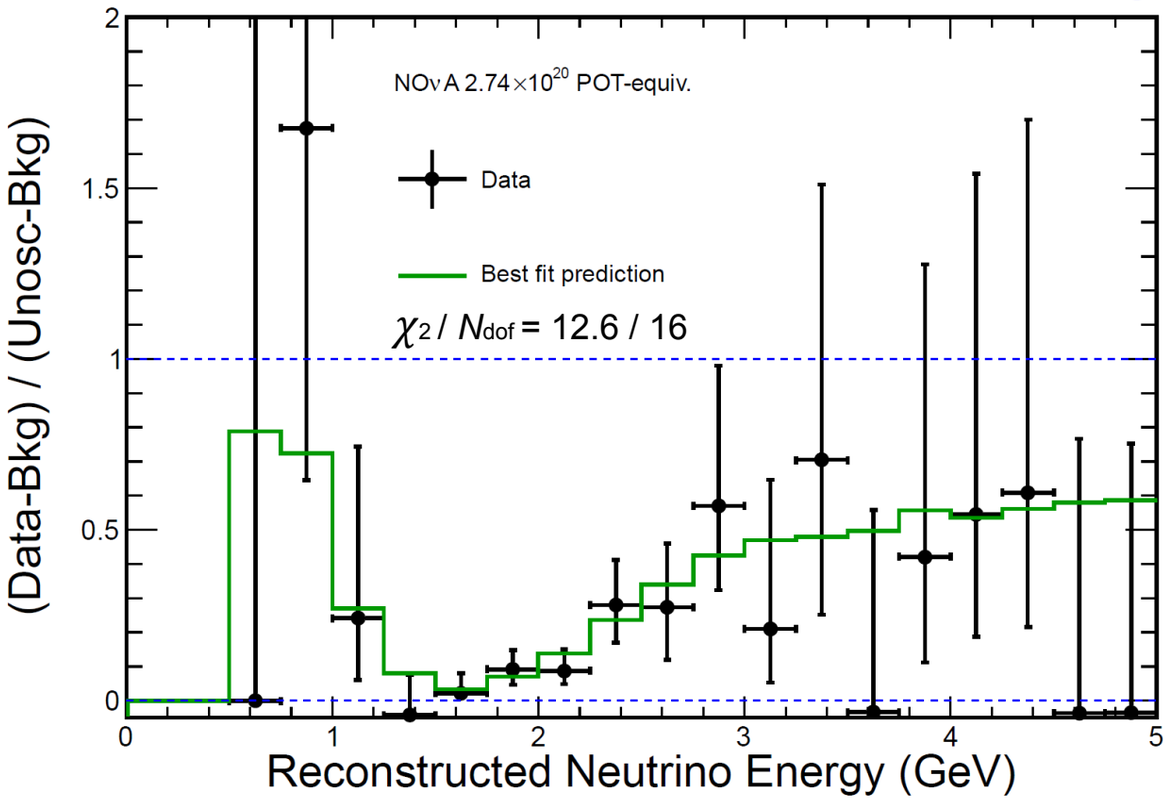
- **201 events predicted** without neutrino oscillations (including 2.0 beam bkgnd and 1.4 cosmic bkgnd)

33 events observed

NOvA sees ν_μ disappearance consistent with oscillations

ν_μ Disappearance Allowed Regions

NOνA Preliminary



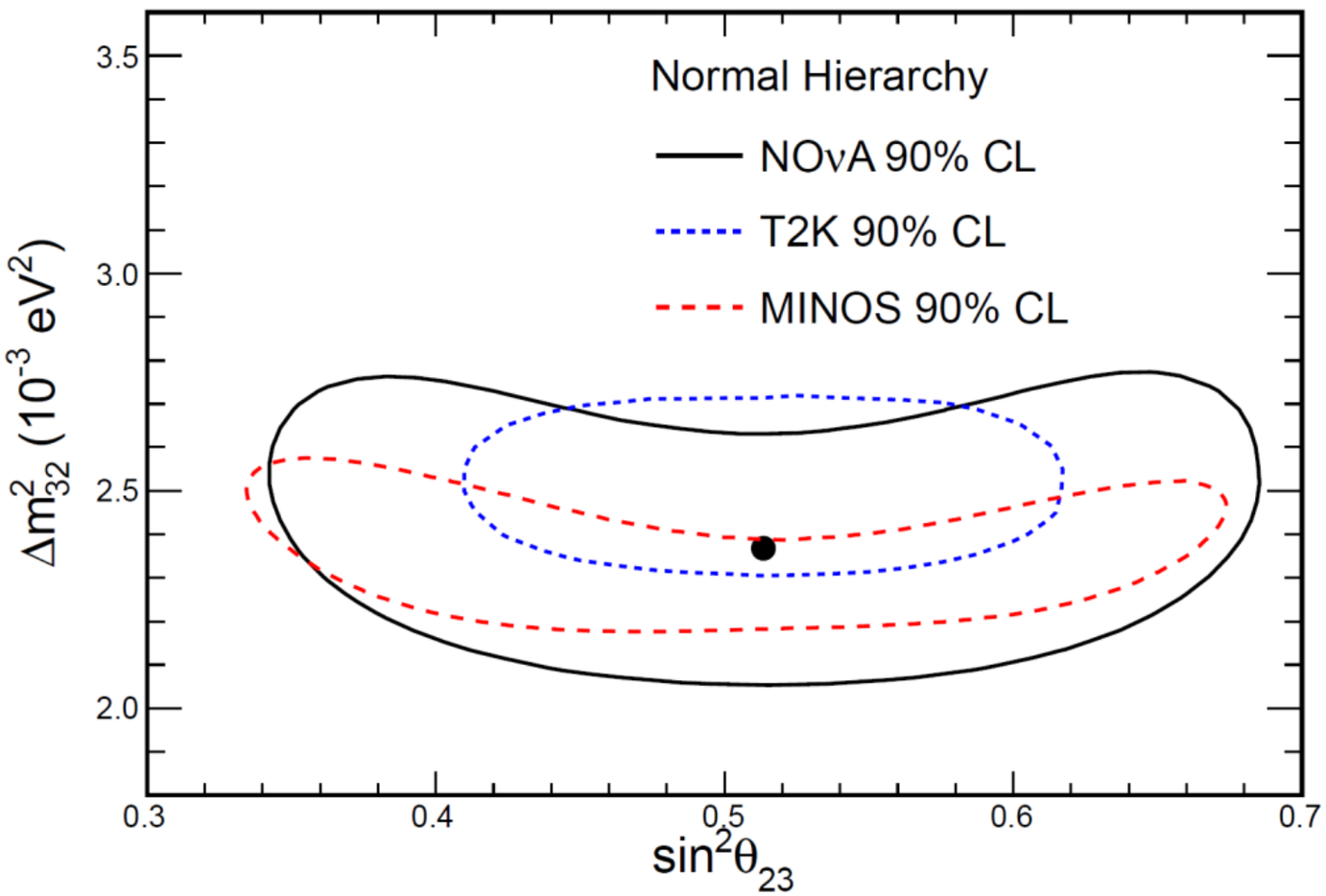
$$\Delta m^2_{32} = \begin{cases} +2.37\ ^{+0.16}_{-0.15}\ [\text{NH}] \\ -2.40\ ^{+0.14}_{-0.17}\ [\text{IH}] \end{cases} \times 10^{-3}\ \text{eV}^2$$

6.5% measurement uncertainty

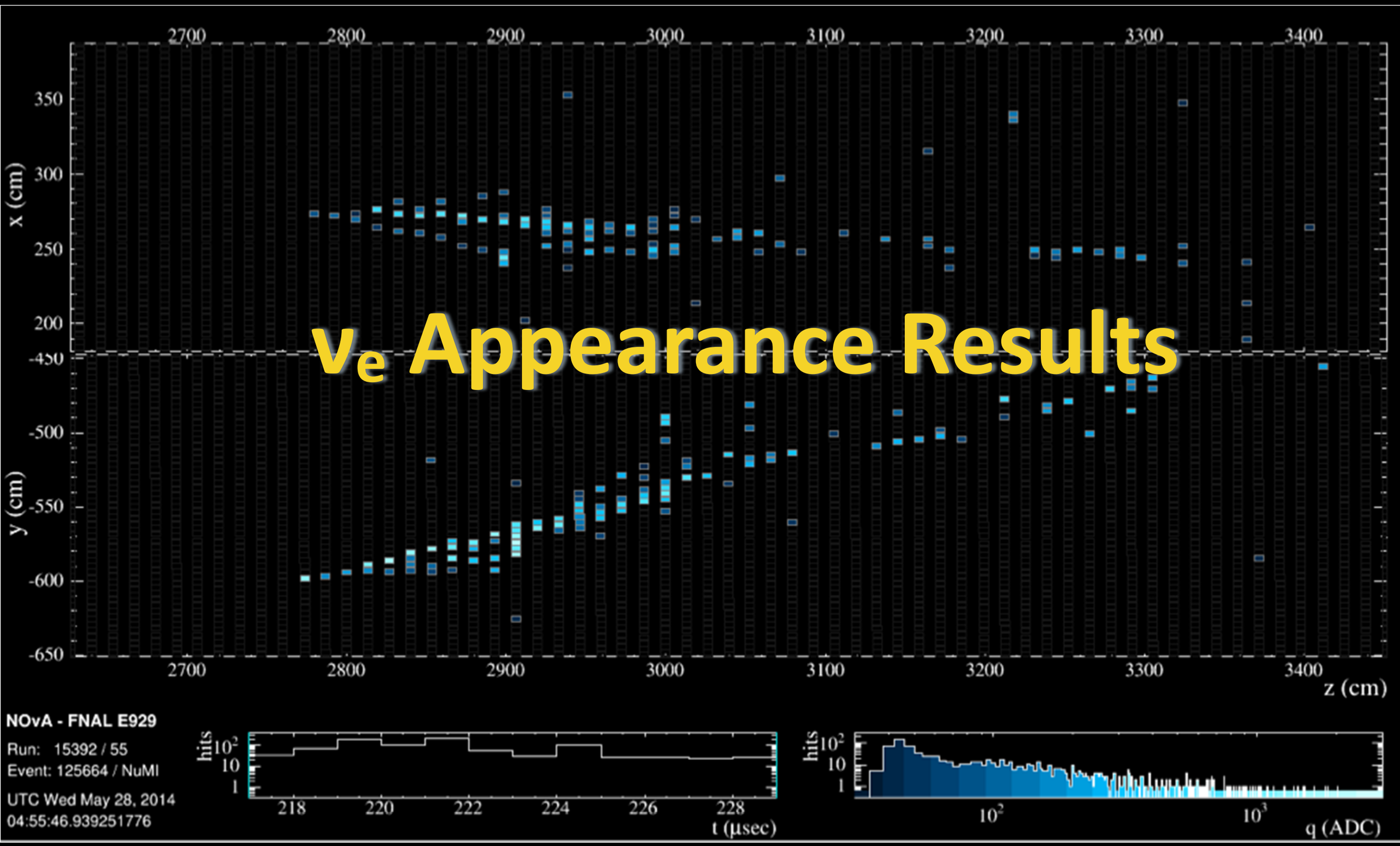
$$\sin^2(\theta_{23}) = 0.51 \pm 0.10$$

- Consistent with maximal mixing
- Allowed regions compatible with MINOS and T2K
- With just 7.6% of nominal exposure, NOvA is already competitive with other running experiments!

NOνA Preliminary



ν_e Appearance Results

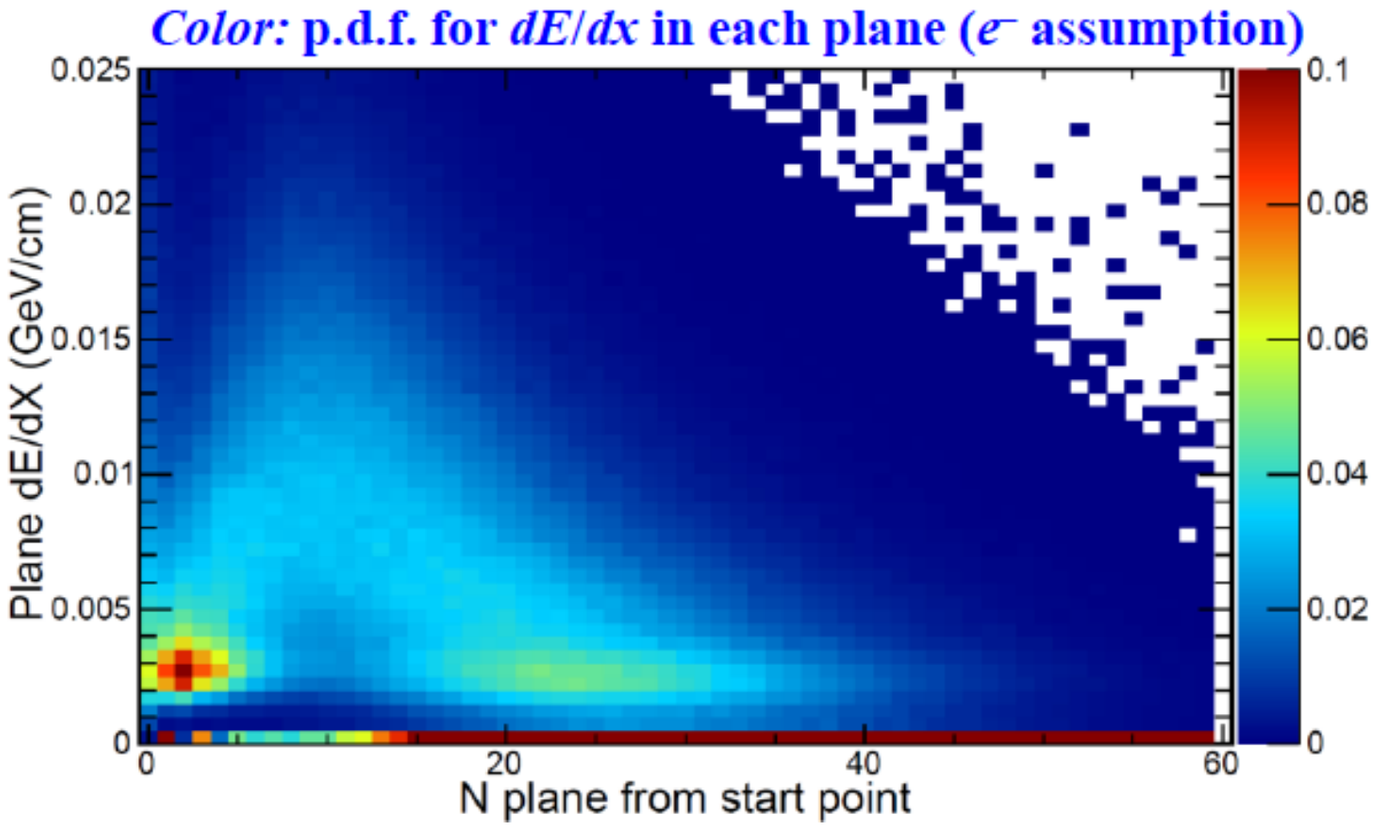


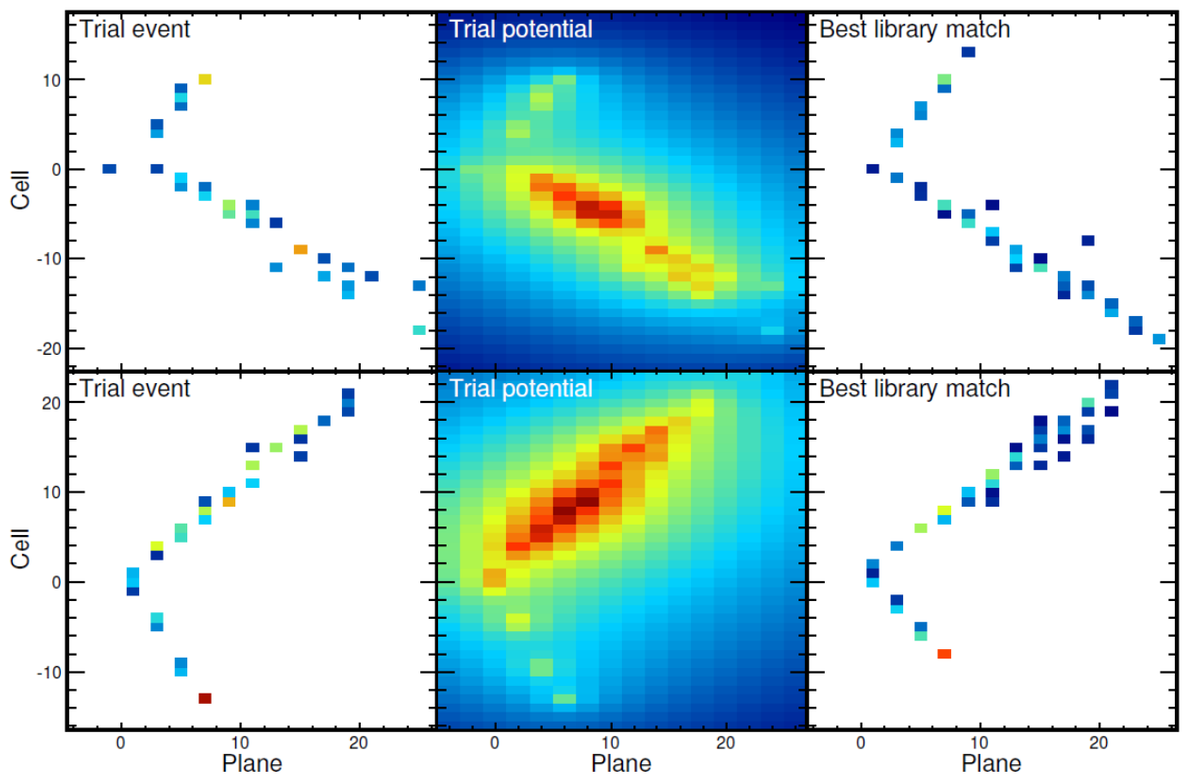
Selecting Electron Neutrinos

- Isolate a pure sample of ν_e CC events
  - Select events with EM showers
  - Suppress NC, ν_μ CC, beam ν_e, and cosmic backgrounds
  - Used two independent multivariate methods

- 1) Likelihood Identification Method (**LID**)
  - Compare dE/dx in transverse and longitudinal slices to simulated e/μ/π/p distributions
  - Combine likelihoods with topology information in an ANN

- 2) Library Event Matching (**LEM**)
  - Compare pattern of energy deposition of entire event to a very large simulated event library (10^8 events!)
  - Properties of the best matched events input into a decision tree

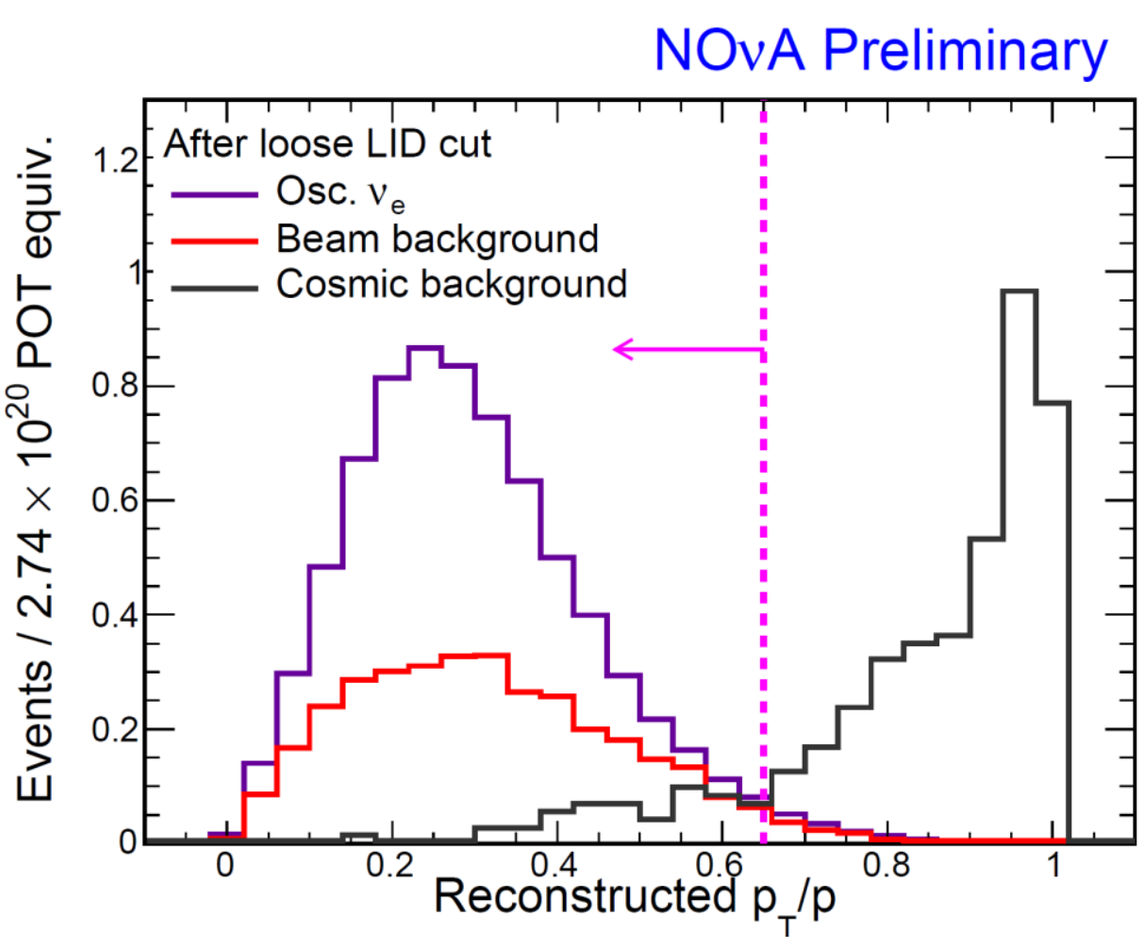


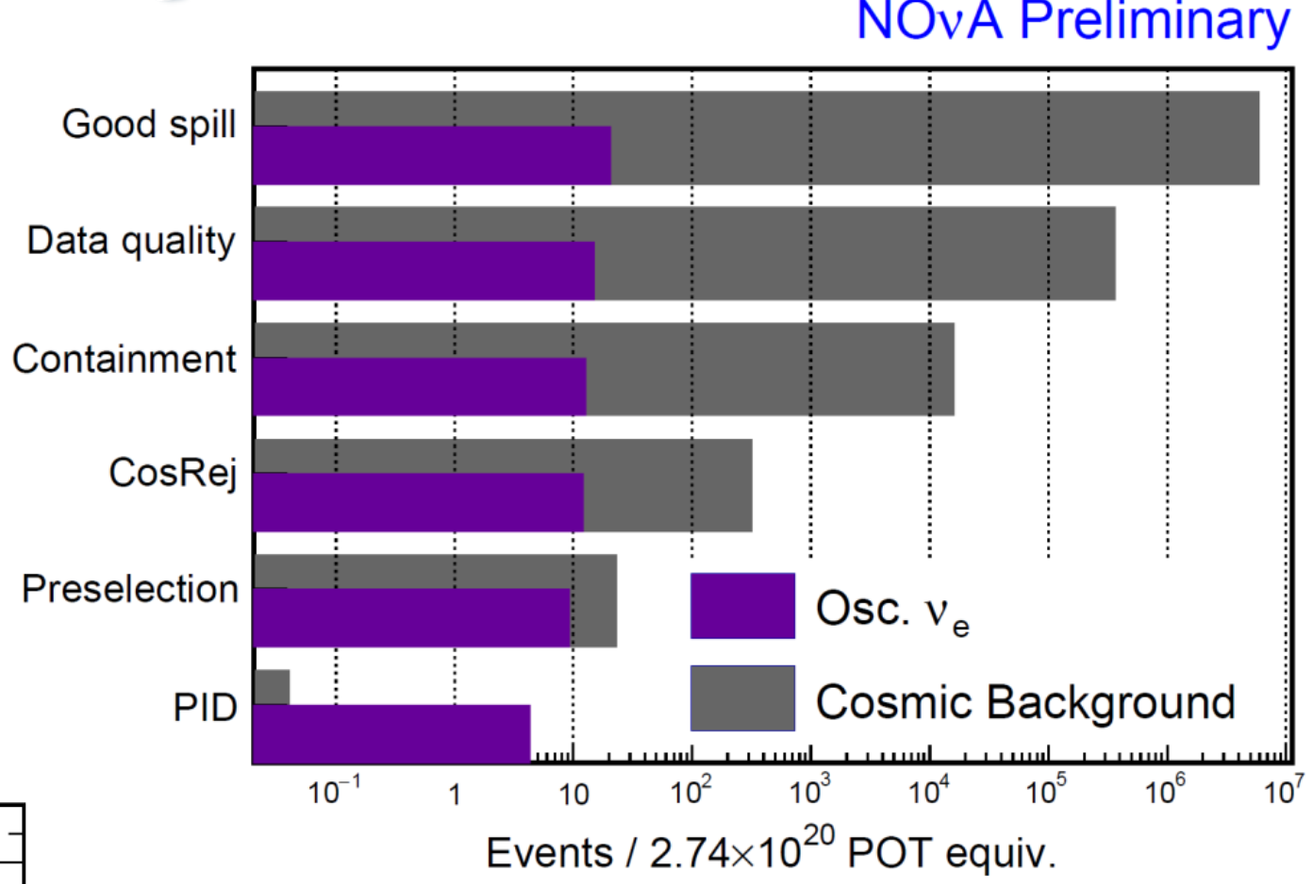


Cosmic Rejection

- ν_e PIDs themselves provide strong cosmic rejection

- Make additional cut on p_T/p to reject downward-directed cosmic showers

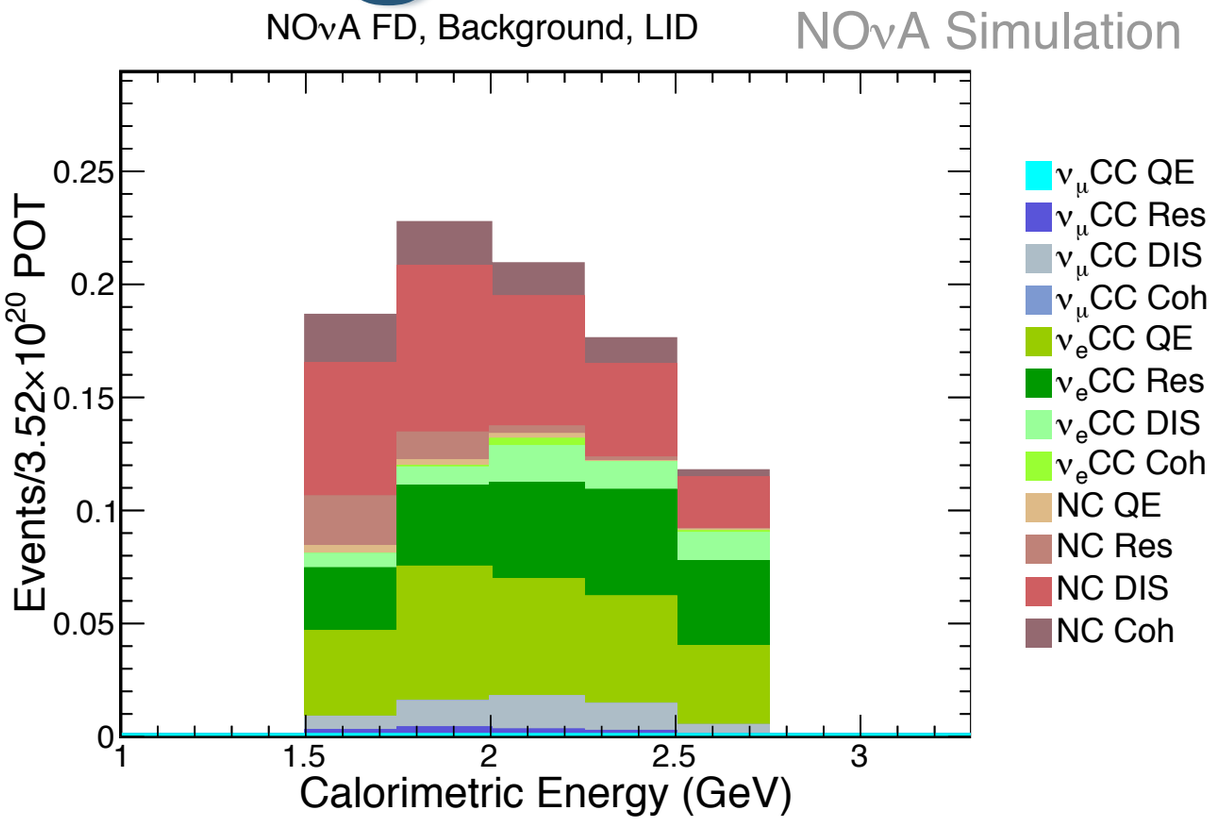


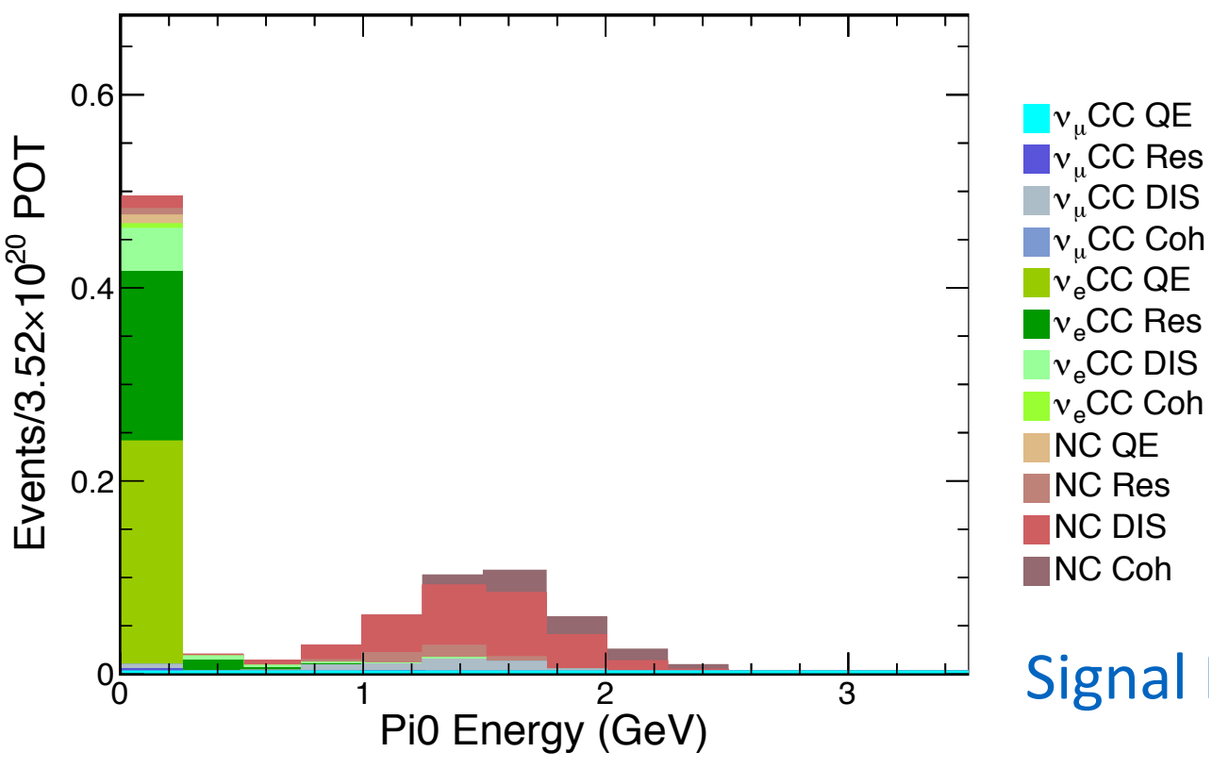


- Cosmic rejection factor from
  - beam timing: **10^5**
  - PIDs + pT/p cut: **10^8**

Expected cosmic background:
0.06 events

Background and Signal Predictions





- Both selection methods achieve good sensitivity to ν_e appearance
  - 40% signal selection efficiency
  - Reject 99.7% of NC backgrounds
  - 62% expected overlap of the signal events
  - better than 1 in 10^8 cosmic rejection
- Selected BG dominated by beam ν_e and NC events with π^0 production
  - Most selected NC events have an energetic π^0
- Before unblinding FD data, chose the more traditional **LID method as the primary selection**

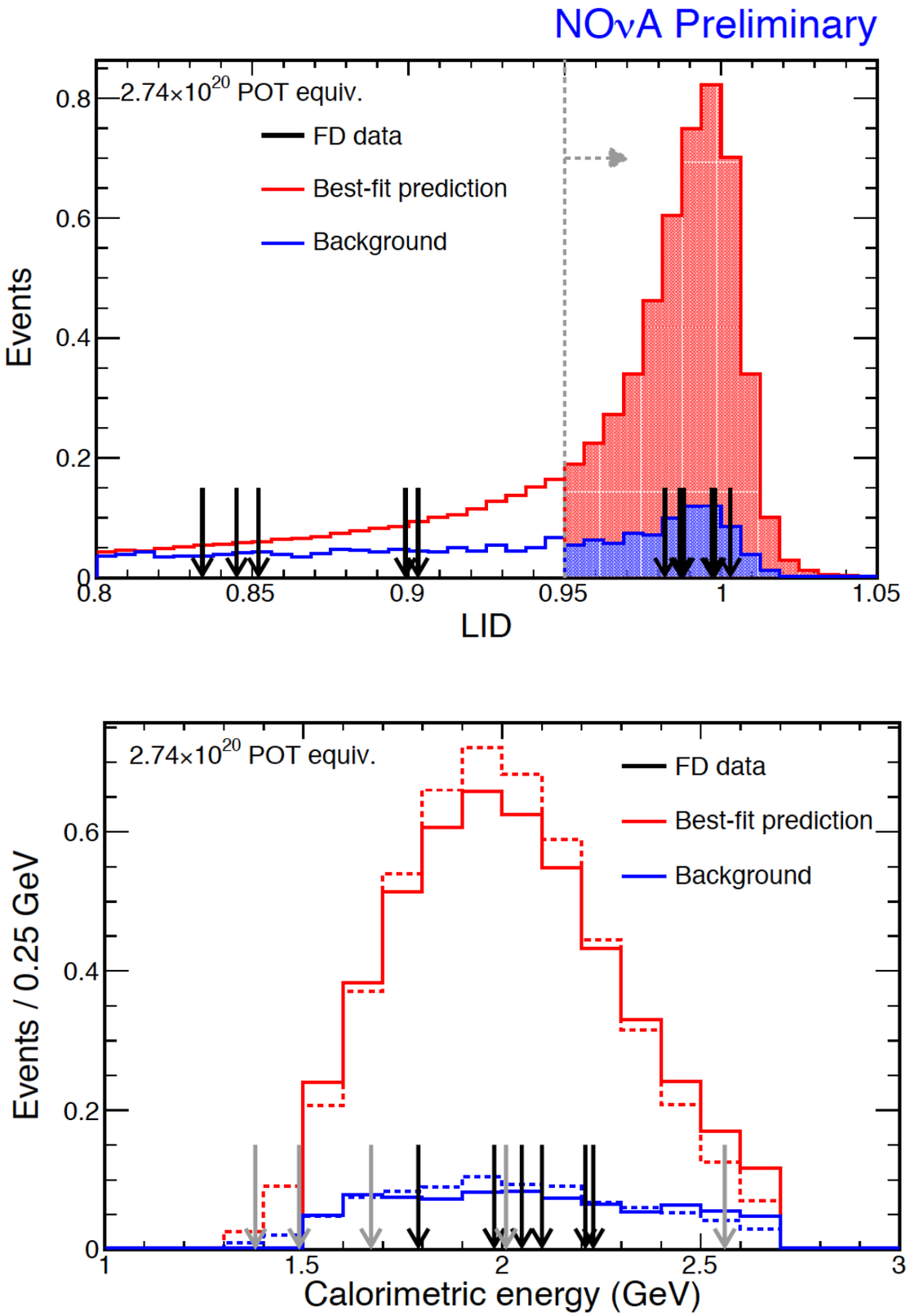
	Total Bkg	Beam ν_e	NC	ν_μ CC	ν_τ CC	Cosmic
LID	**0.94 ± 0.09**	**0.47**	**0.36**	**0.05**	**0.02**	**0.06**
LEM	1.00 ± 0.11	0.46	0.40	0.07	0.02	0.06

Signal Prediction →

	NH $\delta_{CP}=3\pi/2$	IH $\delta_{CP}=\pi/2$
LID	**5.62 ± 0.72**	**2.24 ± 0.29**
LEM	5.91 ± 0.59	2.34 ± 0.23

ν_e CC Selected Events

Poster:
Jianming Bian



- LID:
  - **Select 6 events**
  - **3.3σ evidence for ν_e appearance**
- LEM:
  - **Select 11 events**
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- All 6 LID-selected events are also selected by LEM
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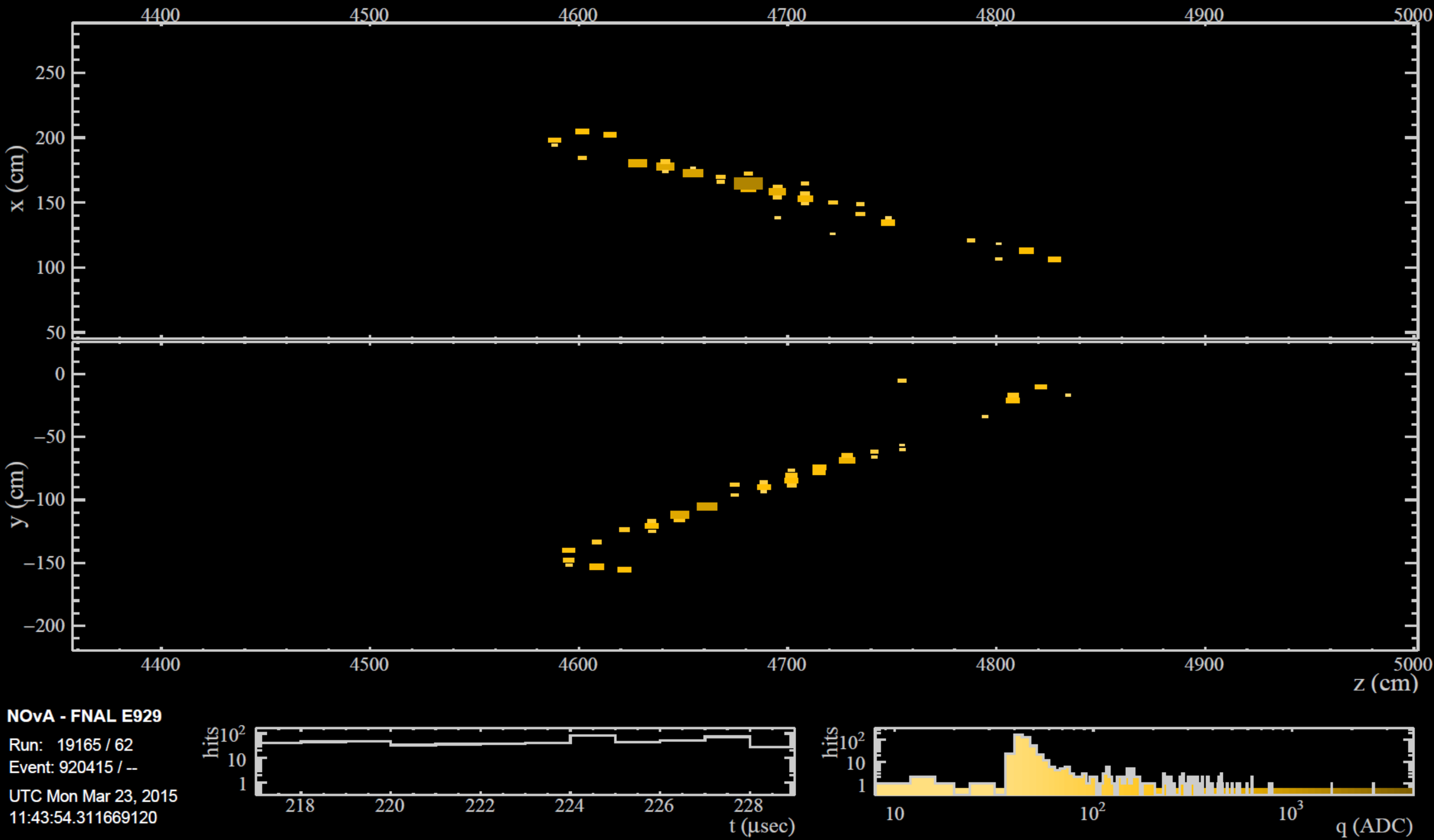
ν_e CC Candidate



NOvA - FNAL E929

Run: 19165 / 62
Event: 920415 / --

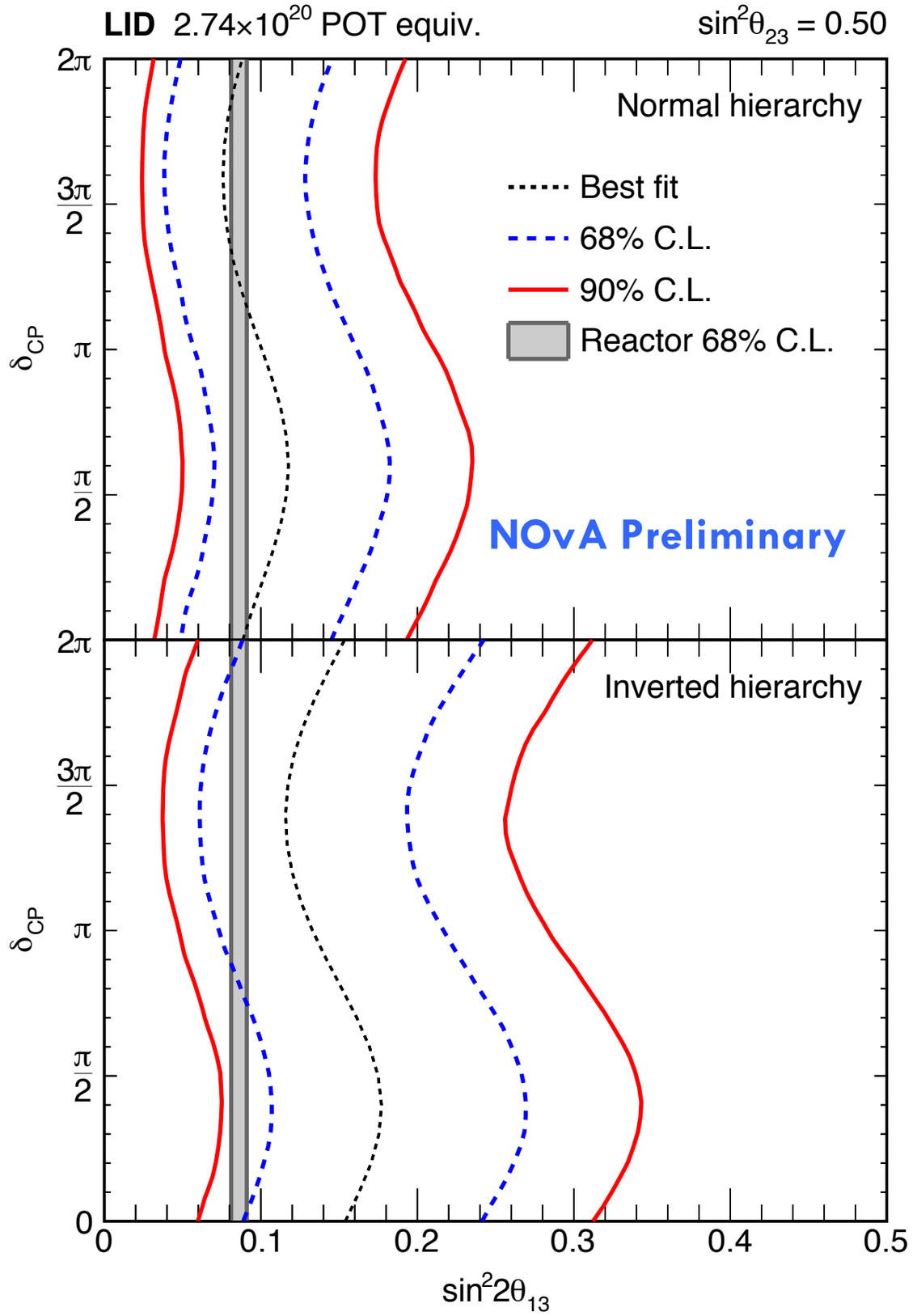
UTC Mon Mar 23, 2015
11:43:54.311669120

ν_e Appearance Allowed Regions - LID

- LID results in good agreement with reactor measurements (gray band) for normal (top) and inverted (bottom) hierarchy

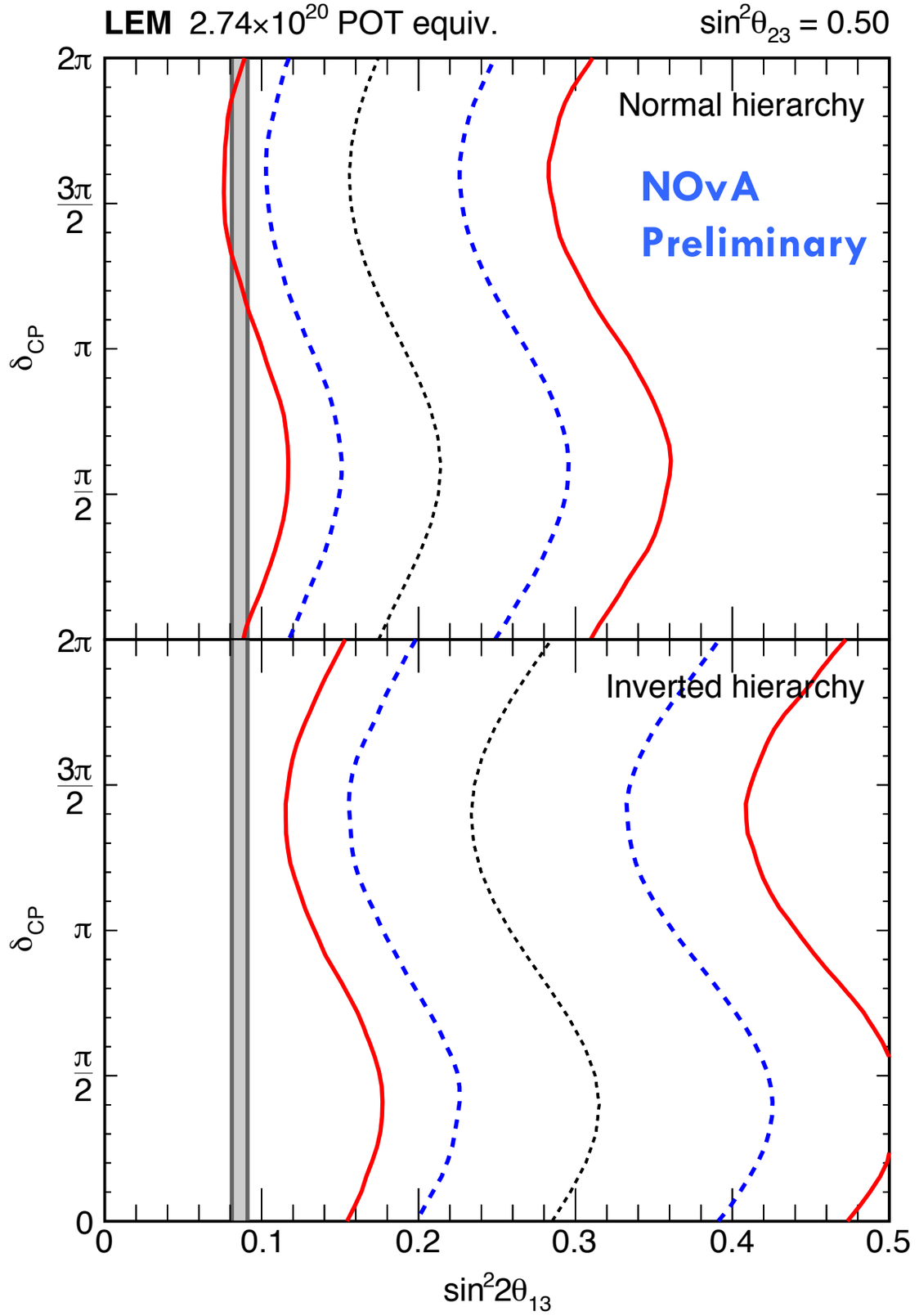
- Agreement is ~1σ better for normal hierarchy

- **(δ_{CP}, $\sin^2\theta_{13}$)** contours include:
  - errors on solar parameters
  - Δm^2_{32} varied within errors of NOvA's new result
  - $\sin^2\theta_{23} = 0.5$



ν_e Appearance Allowed Regions - LEM

- LEM results shift contours to the right by almost (x2)
- Some tension with reactor results, in particular for inverted hierarchy

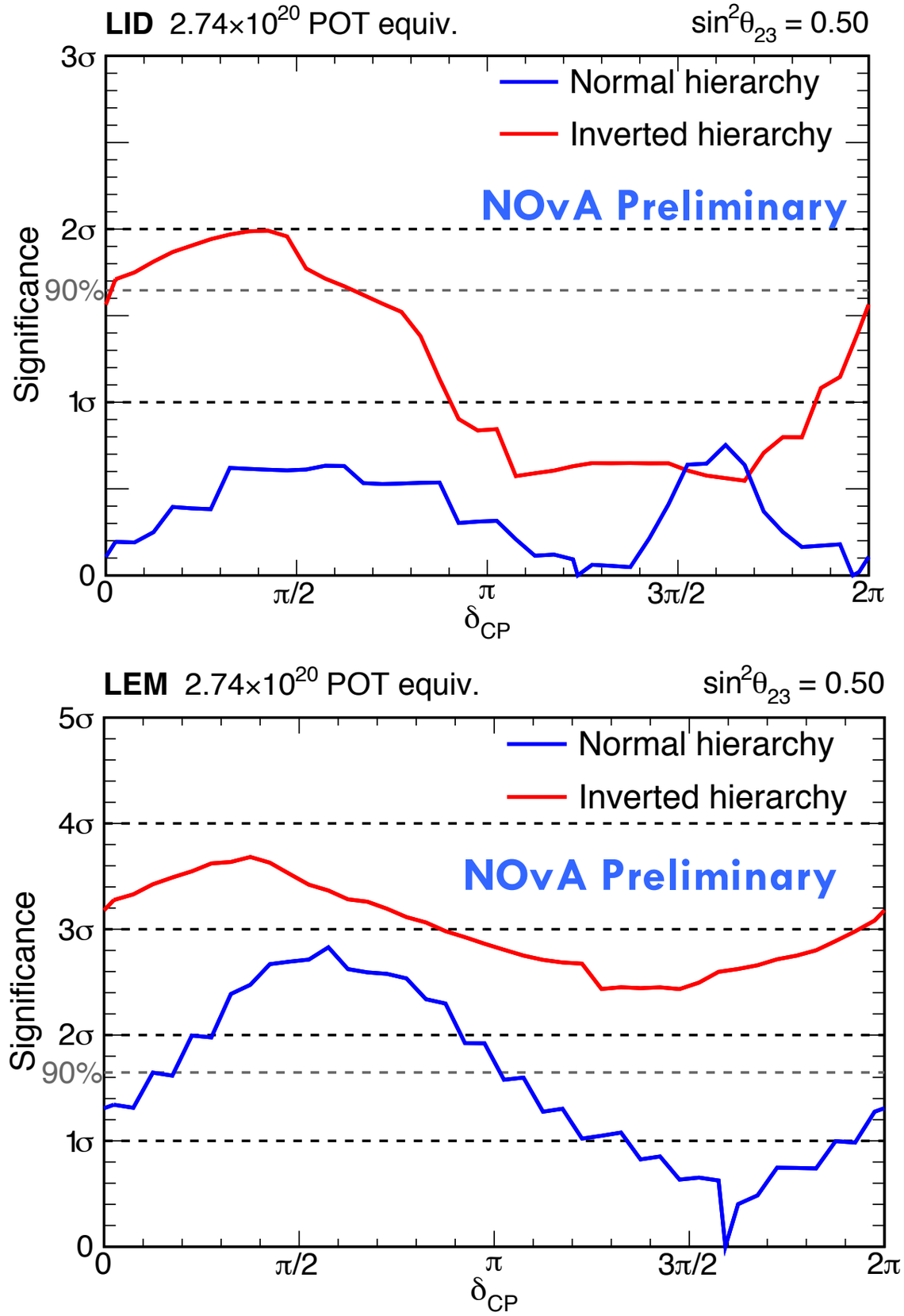


Significance of ν_e Appearance Results

- Use reactor measurement of
  $\sin^2 2\theta_{13}$=0.086±0.05
  as input to understand how NOvA's results favor choices of mass hierarchy or δ_{CP}
  - Both LID and LEM prefer **NH** with δ_{CP} between π and 2π
  - LID shows some tension with **IH** for $0 < \delta_{CP} < 0.8\,\pi$
  - LEM disfavors **IH** at greater than 2σ for all values of δ_{CP}

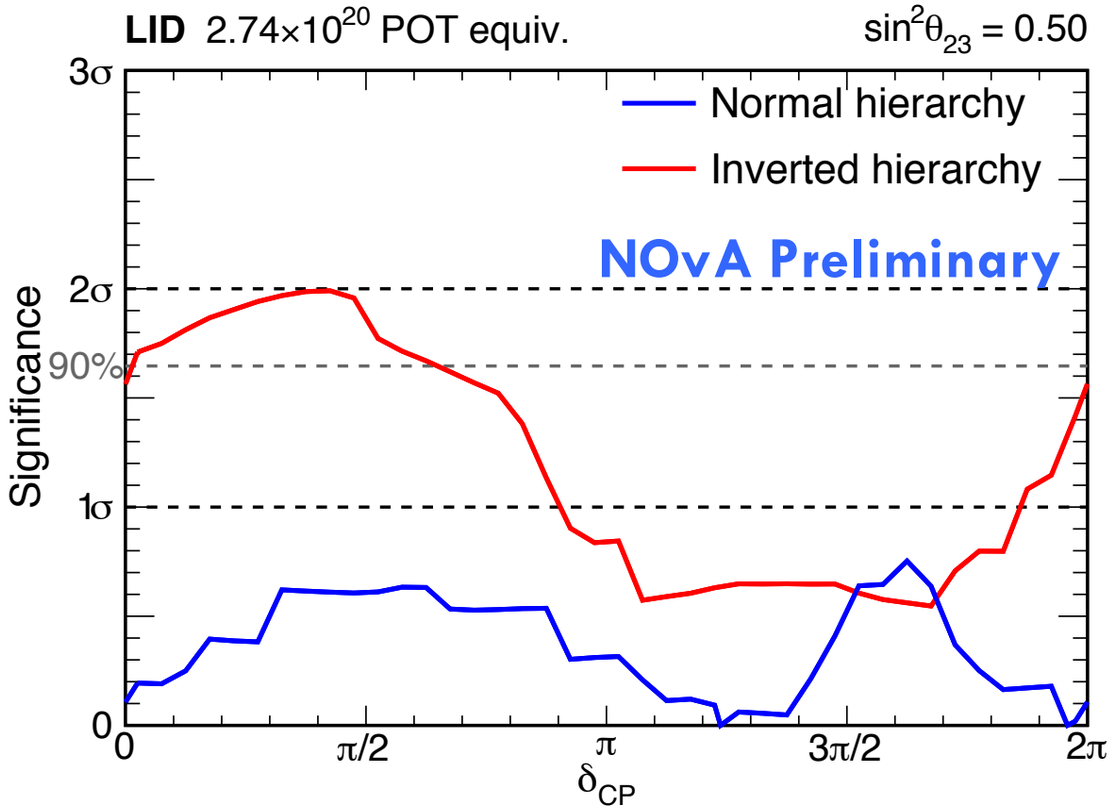
- Beware of trials factor of choosing to only look at LEM results
  - true answer is most likely somewhere in between LID and LEM results

- Note: Jagged contours are due to discrete nature of counting experiment

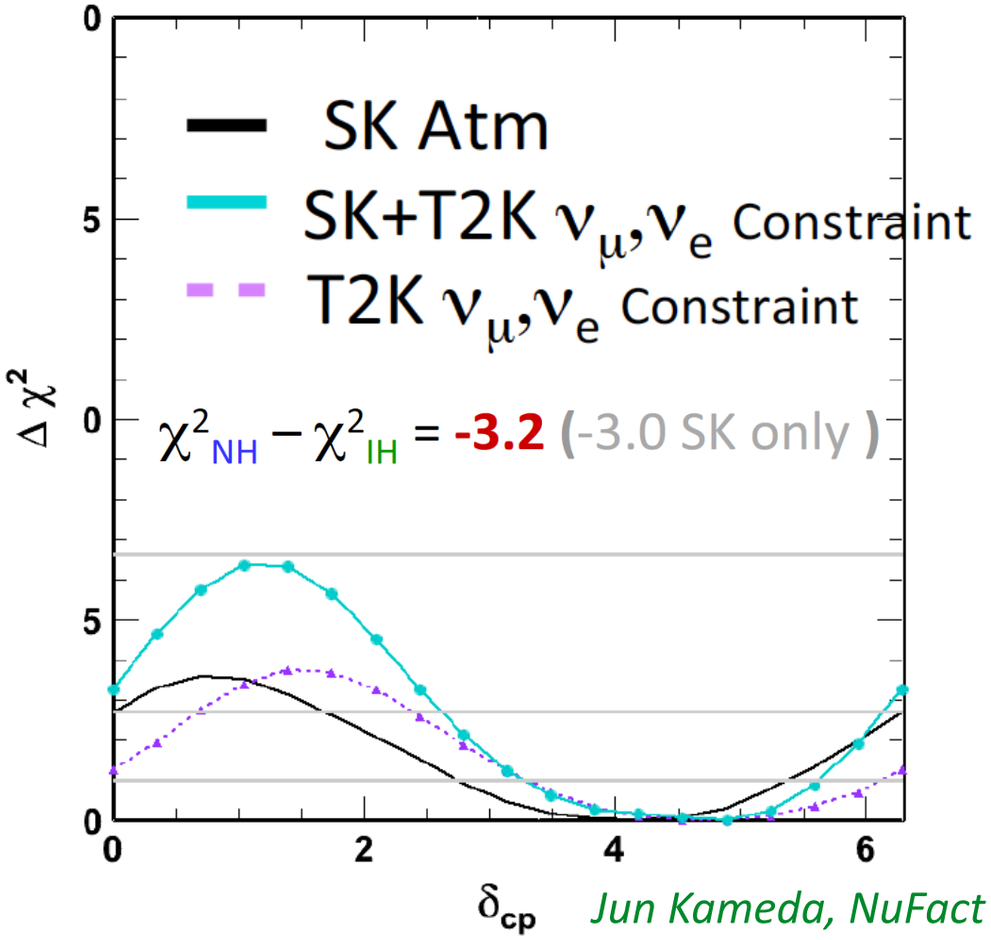


Significance of ν_e Appearance Results

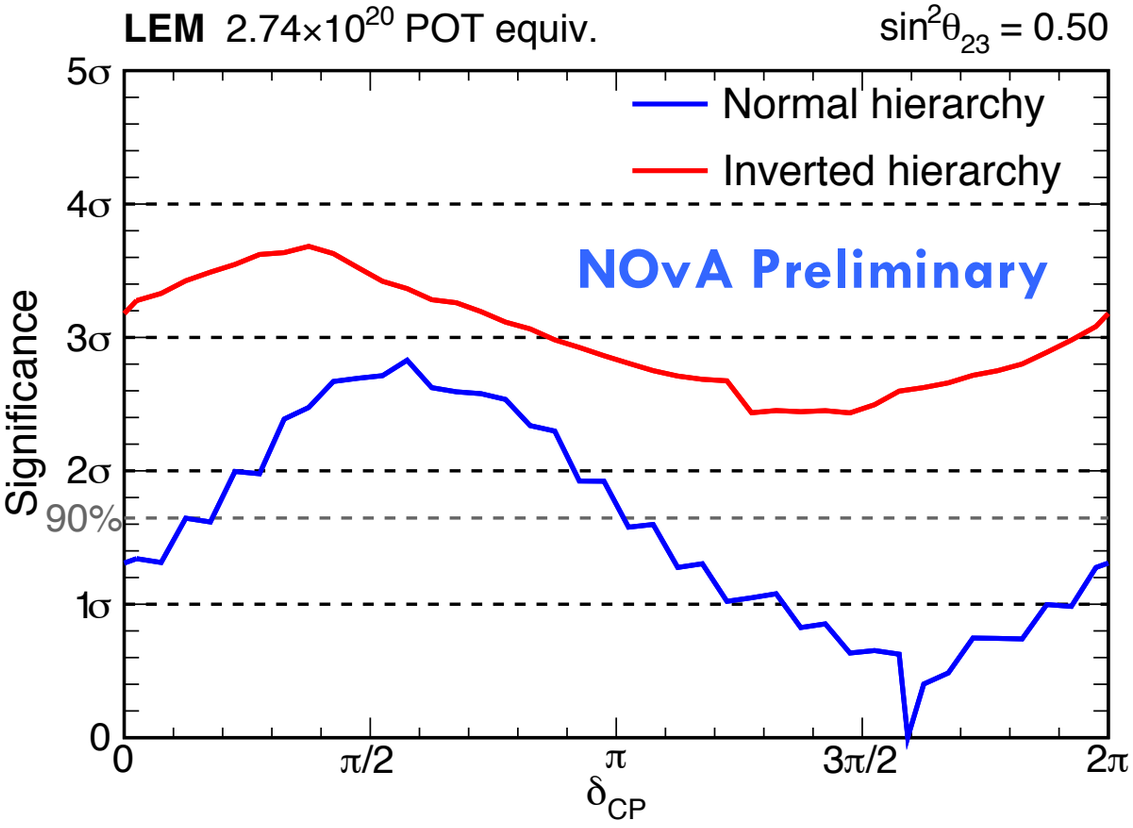
- NOvA's first results agree well with very recent results from SuperK and T2K
  - Normal hierarchy and δ_{CP} ~$3\pi/2$ is the most favorable combination of parameters for NOvA to measure the mass hierarchy
  - Will double the data sample by Summer 2016. NuMI beam has just resumed operations!



Preliminary



Jun Kameda, NuFact 2015



Summary

- NOvA has observed muon neutrino disappearance and electron neutrino appearance with just 1/13th of baseline exposure
  - **6.5% precision of the atmospheric mass splitting from ν_μ disappearance**
  - **θ_{23} measurement consistent with maximal mixing**
  - **ν_e appearance signal at 3.3σ for primary selector, 5.5σ for secondary selector.**
    - **Consistent with global data hints preferring $\pi < \delta_{CP} < 2\pi$ and Normal Hierarchy**

- Expect doubling of data sample by Summer 2016

- **New results coming soon!**

www-nova.fnal.gov

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Thank You!

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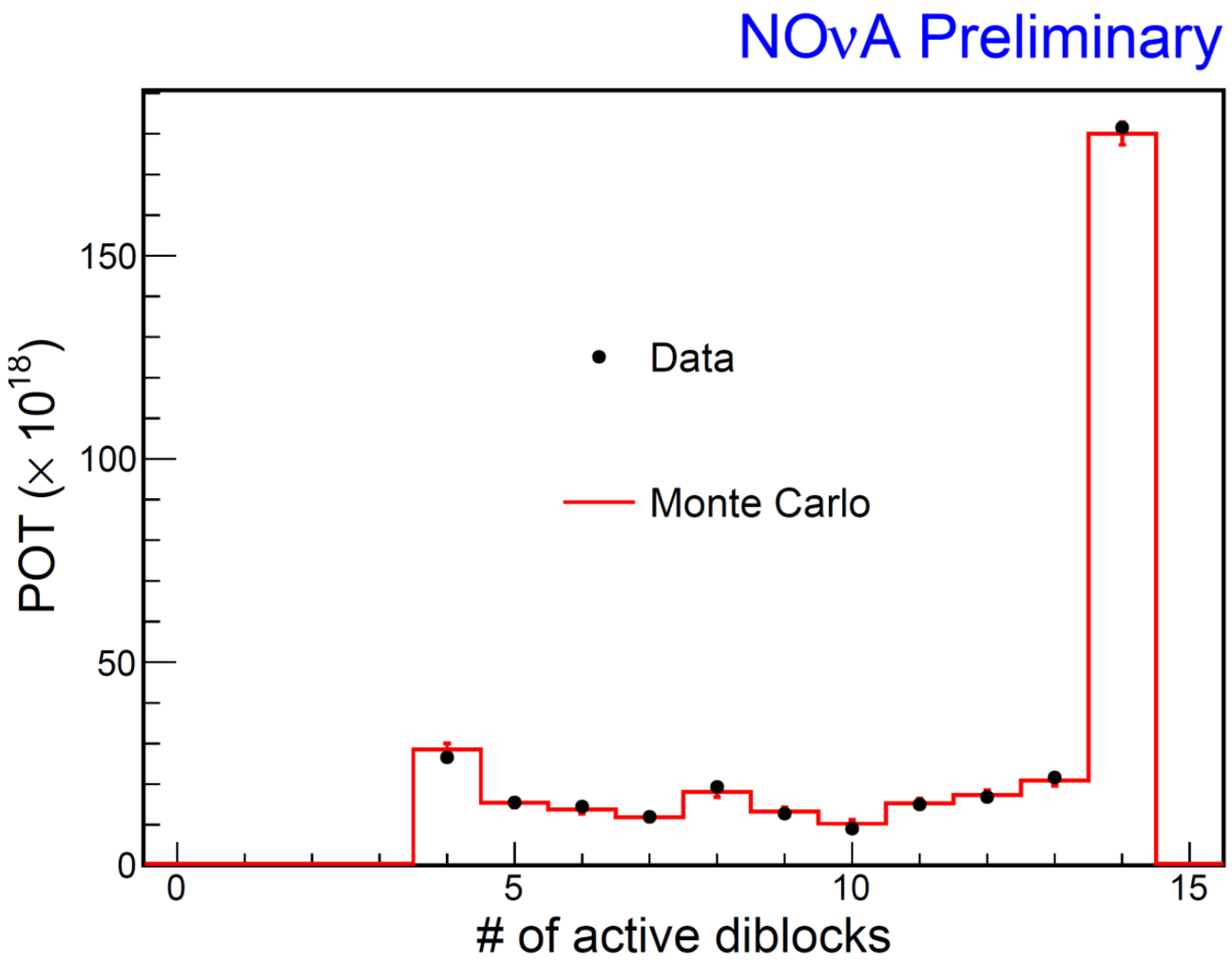
Supplements

Data Collected

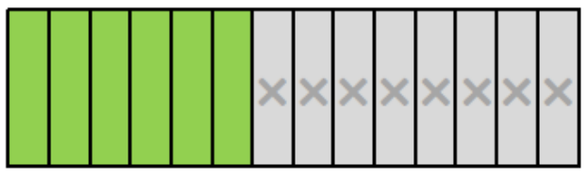
- Physics data was also collected during construction phase

- Upgraded NuMI operation started in Sept. 2013, full Far Detector ready by October 2014

- As soon as each Far Detector di-block (1kton, 64 layers) was commissioned and physics-ready it was added to the data sample



- Full suite of FD configurations is simulated for the analyses

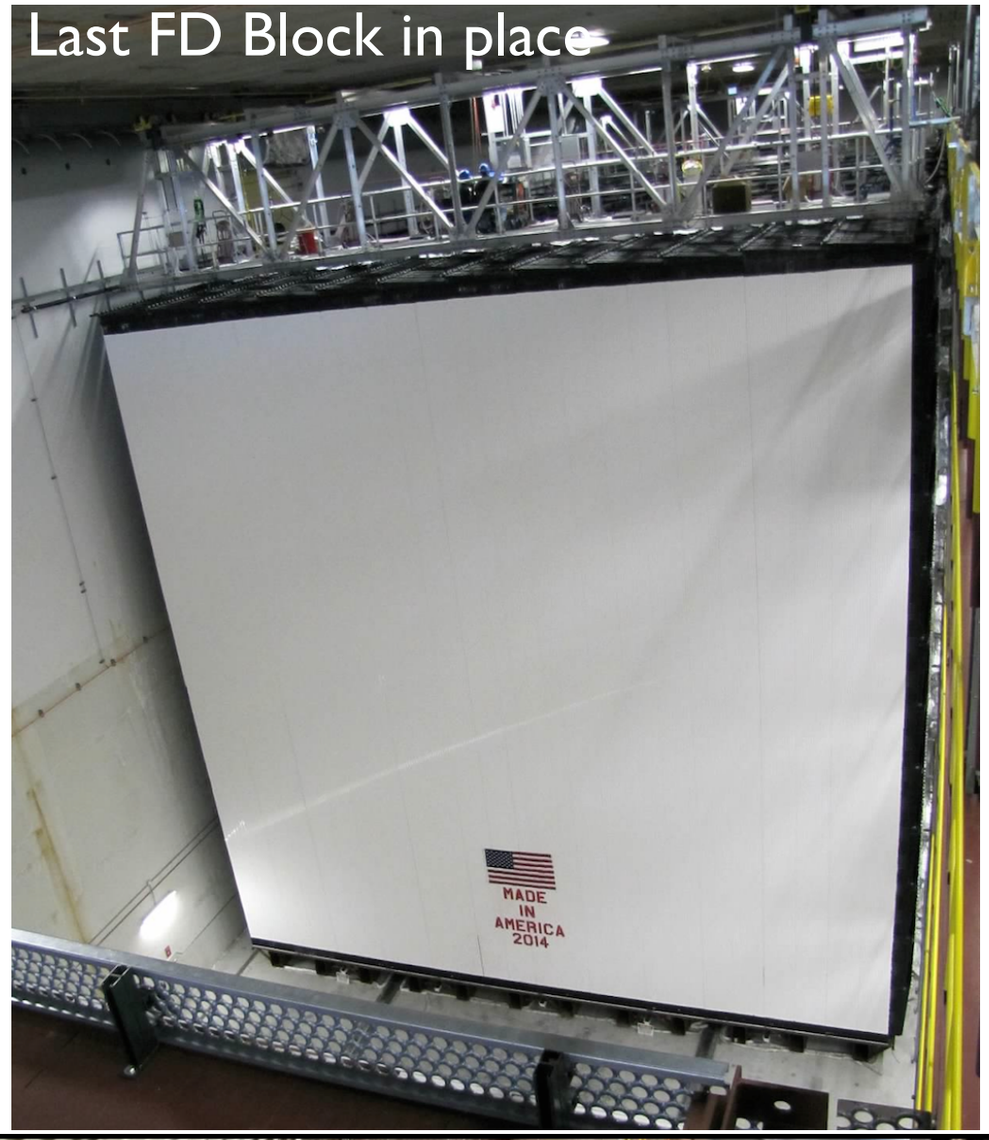


Partial Far Detector during construction
(6 diblock example)

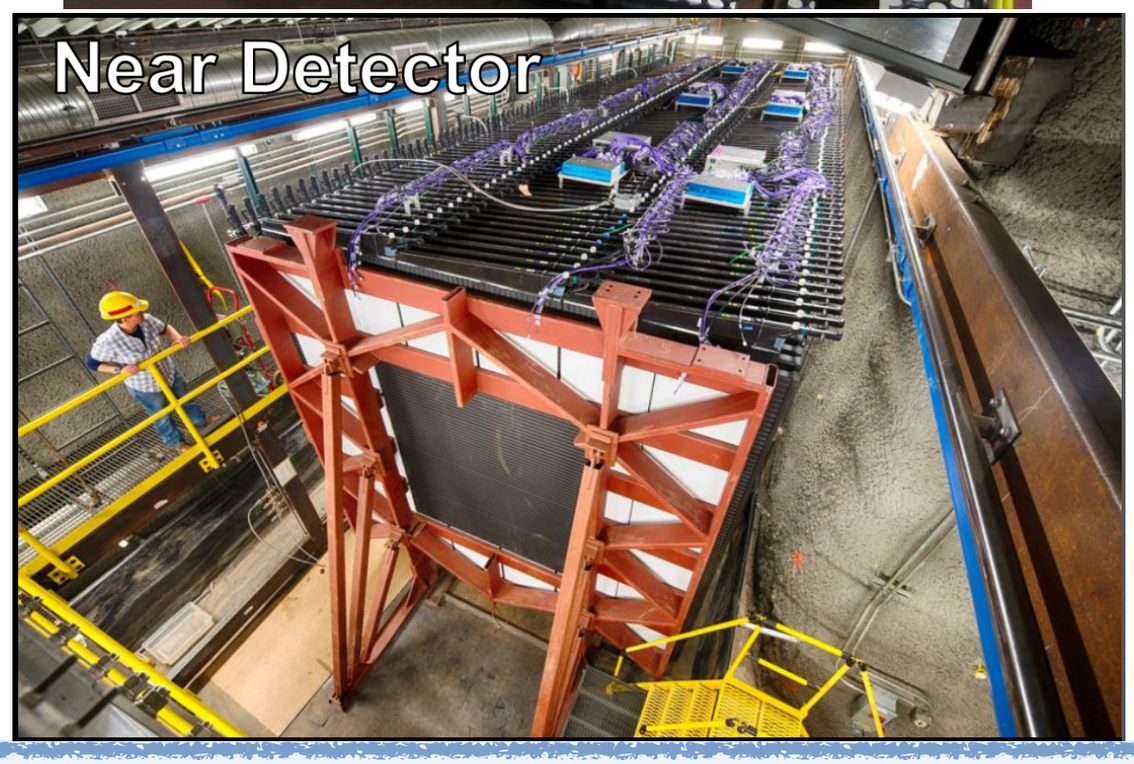
Full Far Detector
(14 diblocks)

- 3.45×10^{20} POT recorded from NuMI
- Average 79.4% of full detector mass
- **2.74×10^{20} POT-equivalent**


Far Detector site

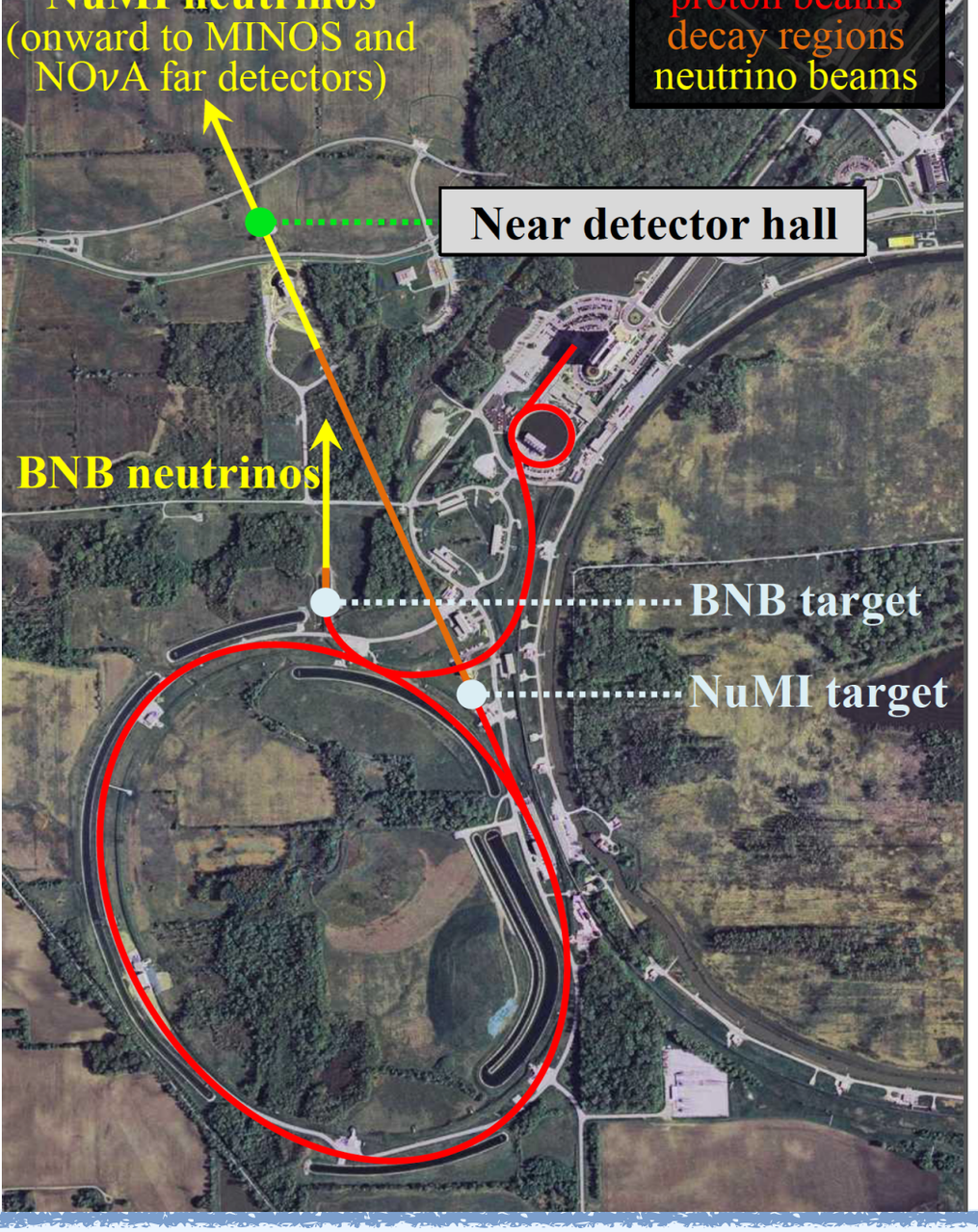

Last FD Block in place
MADE
IN
AMERICA
2014

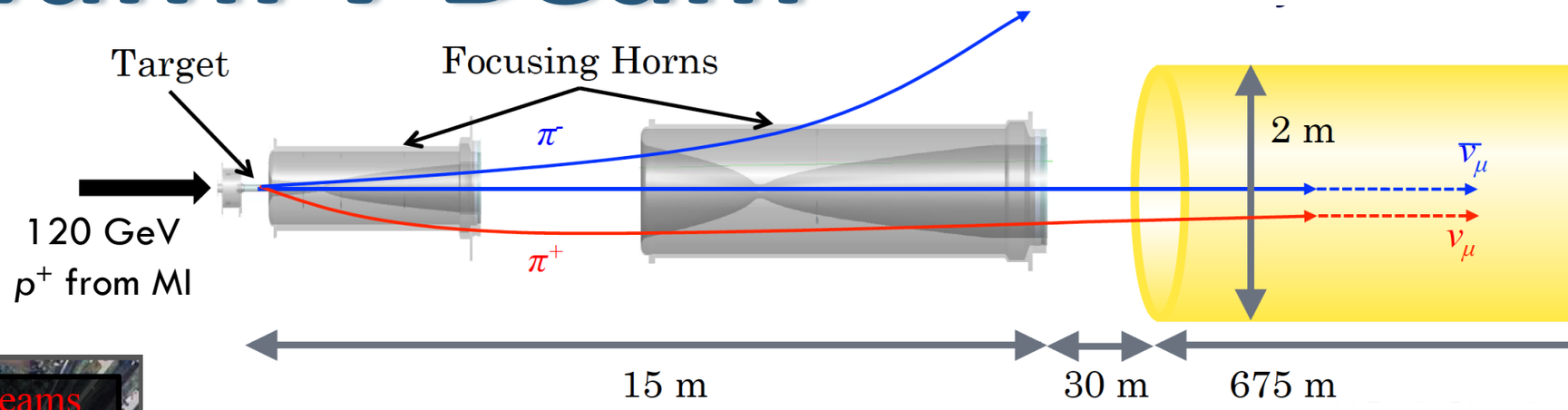

Outfitted Far Detector

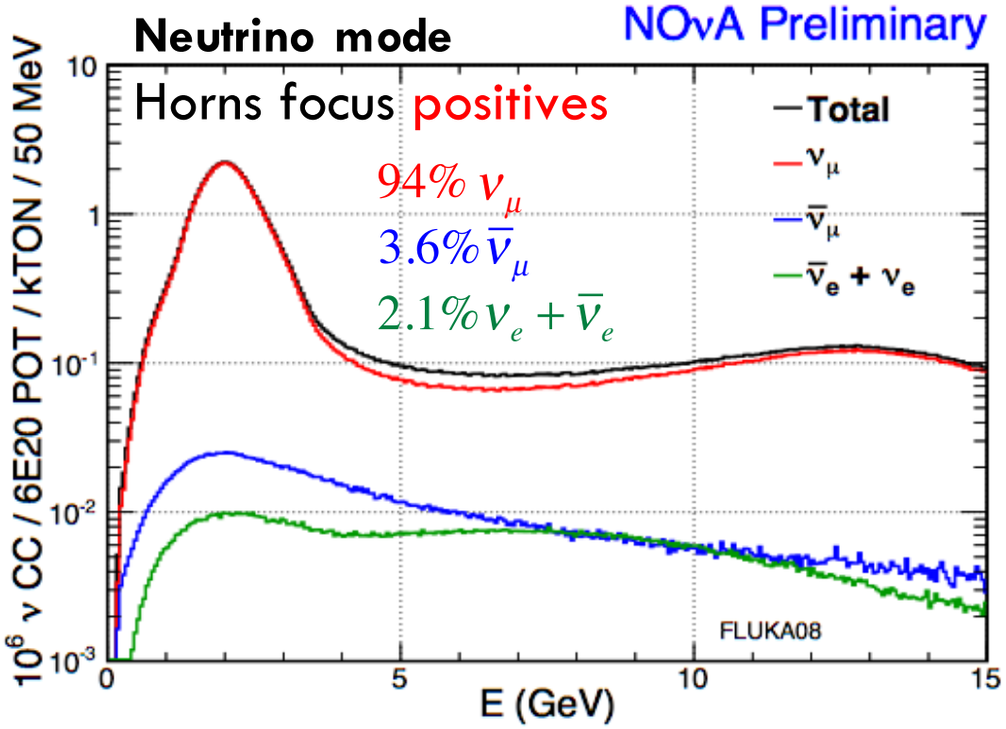

Near Detector

NuMI ν Beam

- Neutrinos from the Main Injector (**NuMI**) beam at Fermilab







- Operating since 2005. Long shutdown in 2012-2013 to prepare for NOvA operations at 700 kW beam power
  - 5×10^{13} protons-on-target (POT) in 10 μs pulse every 1.33 s
- Since March 2015:
  - Neutrino beam power World Record: **521 kW**!
  - 85% uptime
  - 700 kW operation expected in Spring 2016

NuMI $\bar{\nu}$ Beam

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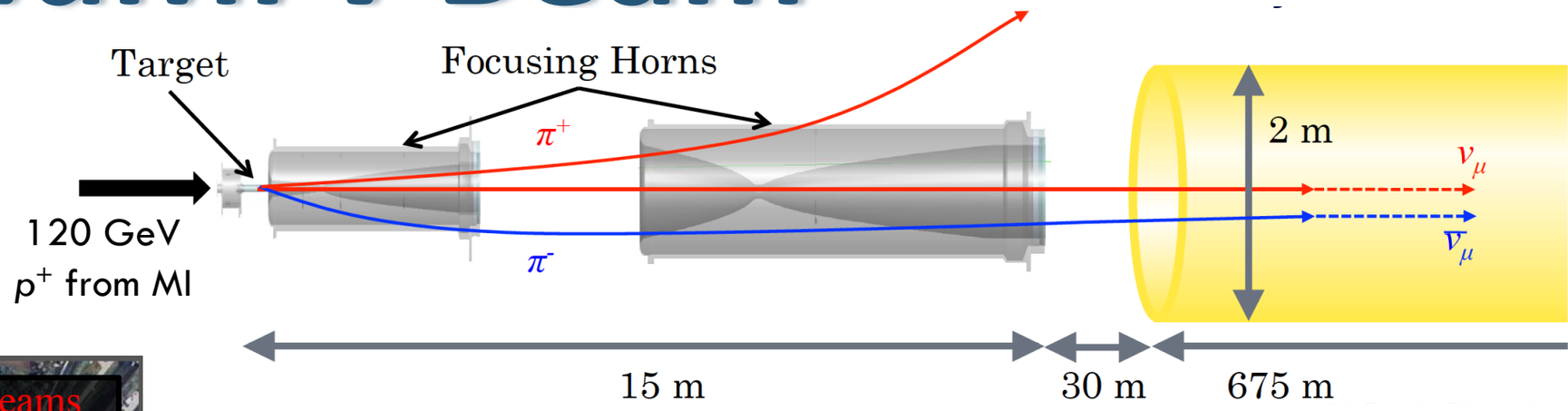
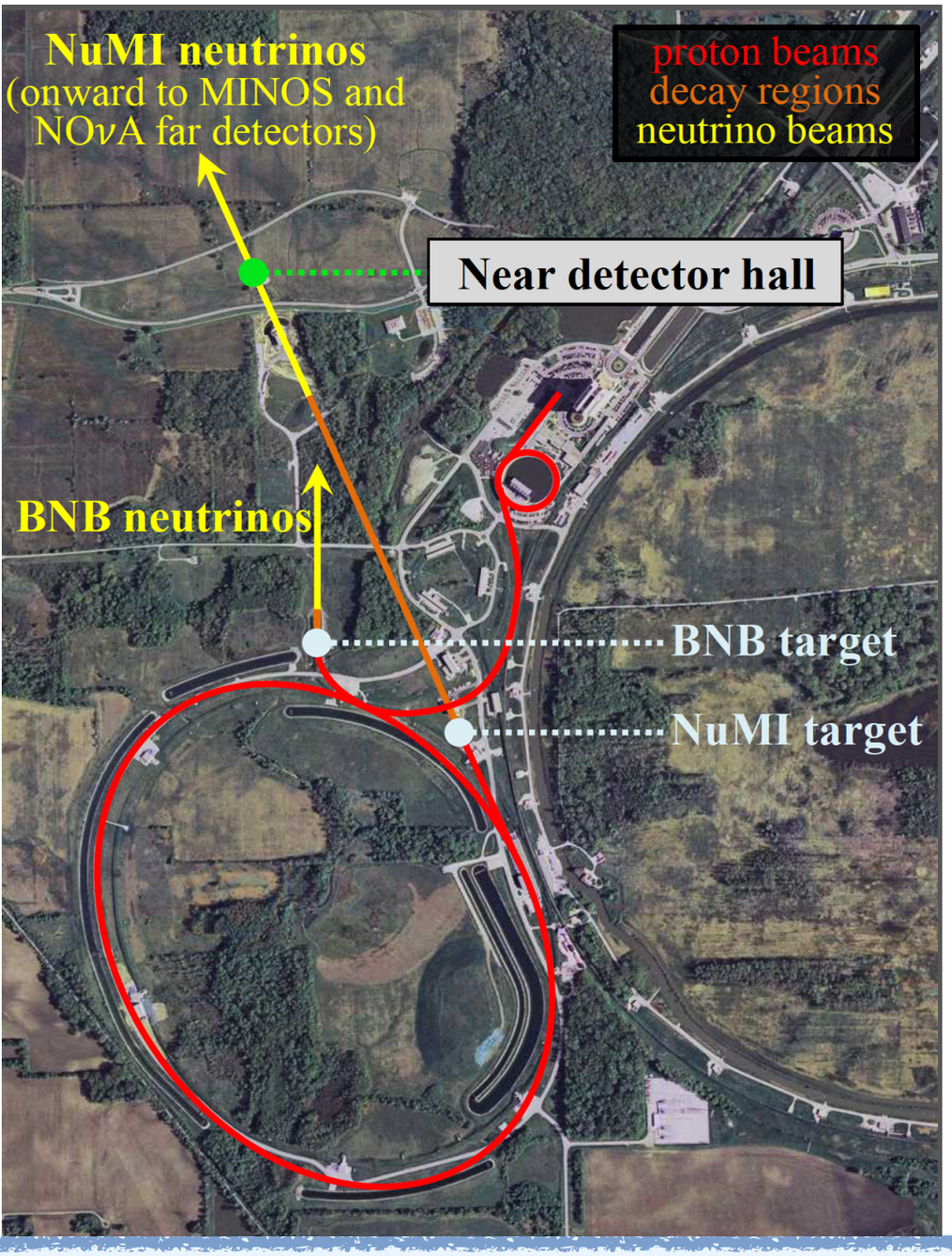
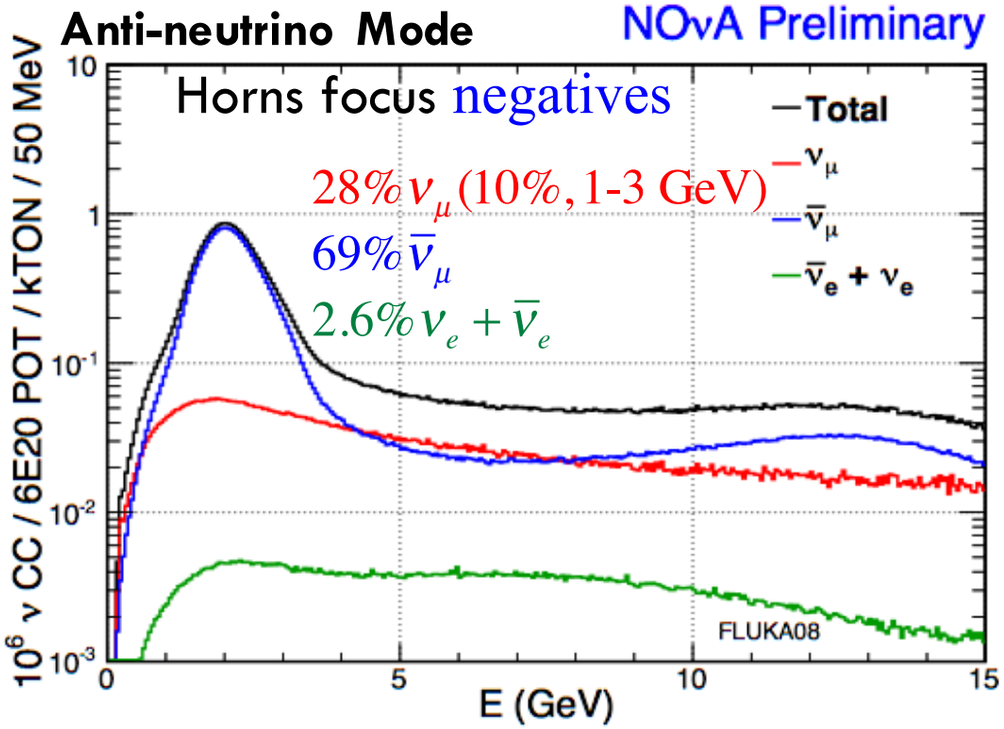






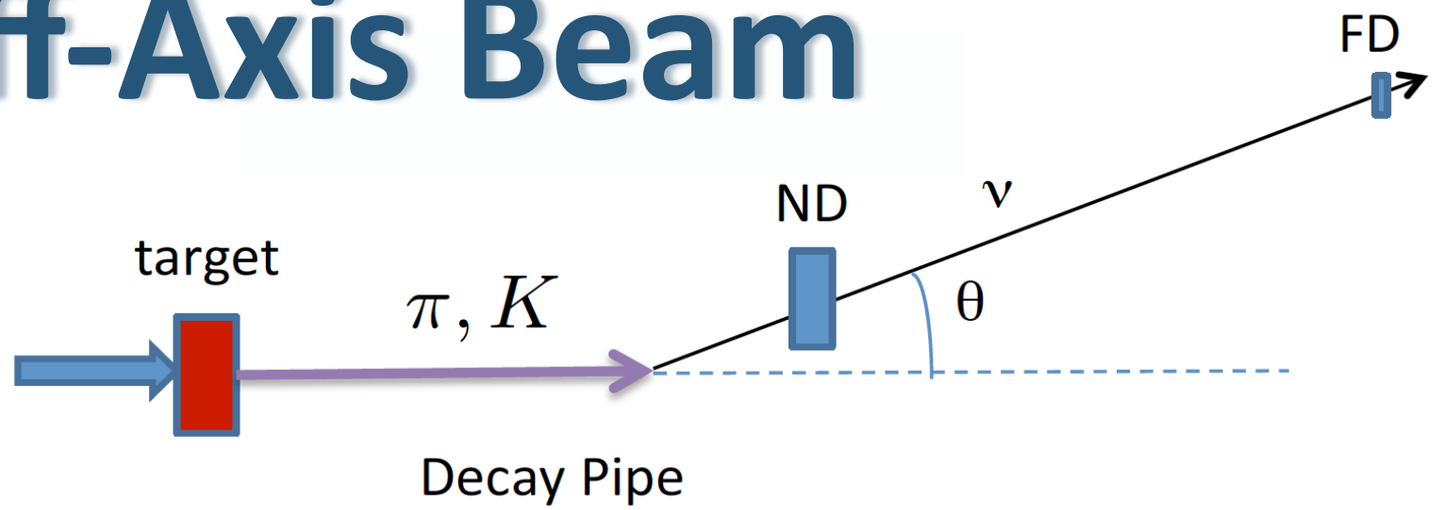
- Antineutrino running essential to check if:

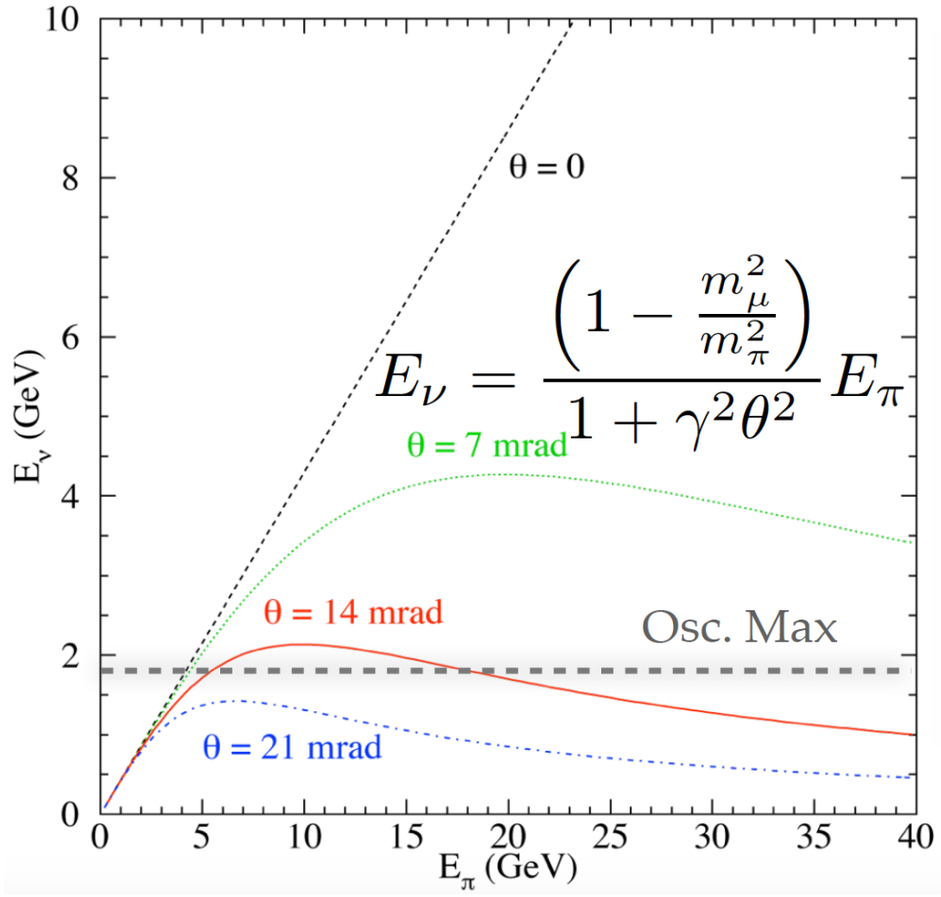
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \neq P(\nu_\mu \to \nu_e)$$

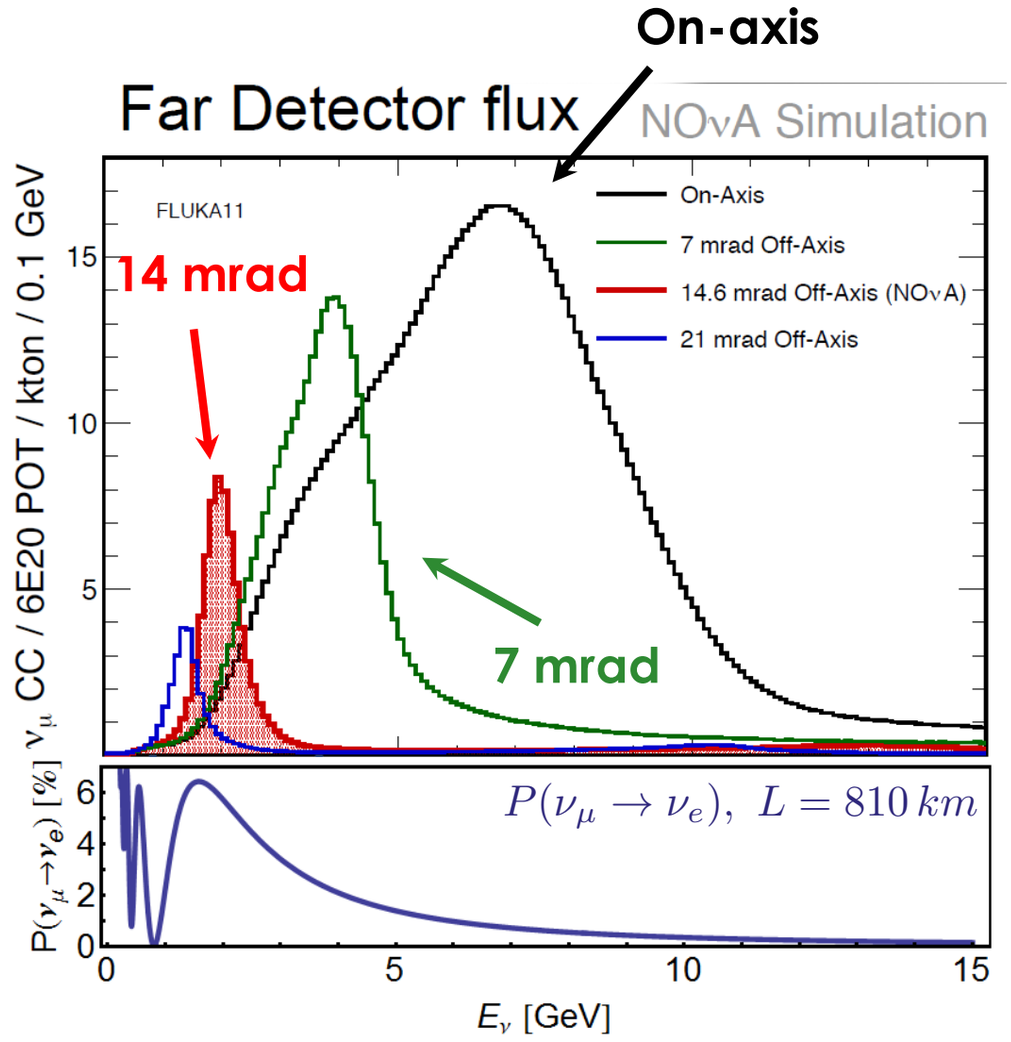
- Planning to run for 6 years, with 3 years each of neutrino, and antineutrino running, for a total of 36×10^{20} POT
- So far, have collected 2.74×10^{20} POT, 7.6% of expected total beam exposure for NOvA

NuMI Off-Axis Beam

- At 14 mrad off-axis, narrow band beam peaked at 2 GeV
- Near oscillation maximum at 810 km
- Drastic reduction of feed-down background from high energy NC events





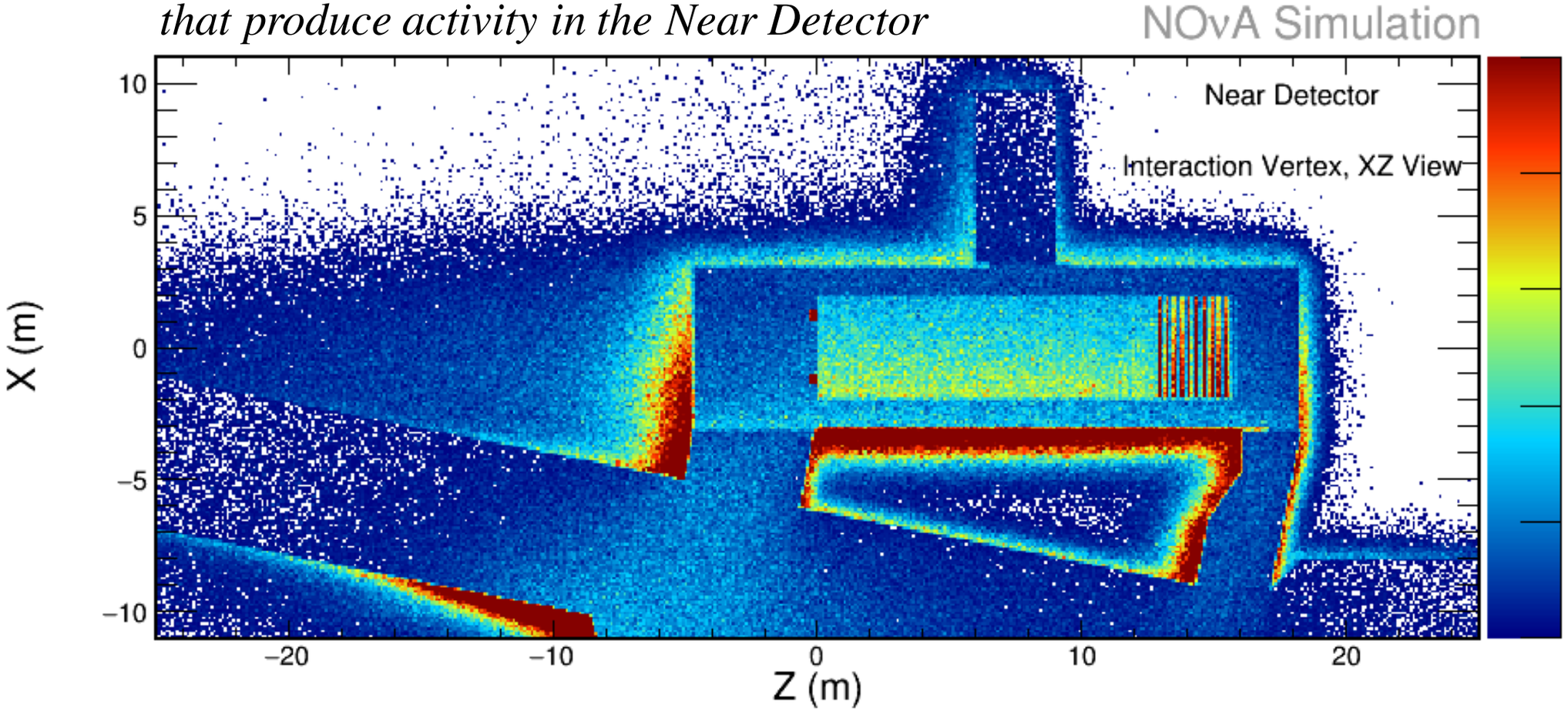


Simulating Neutrinos in NOvA

Highly detailed end-to-end simulation chain

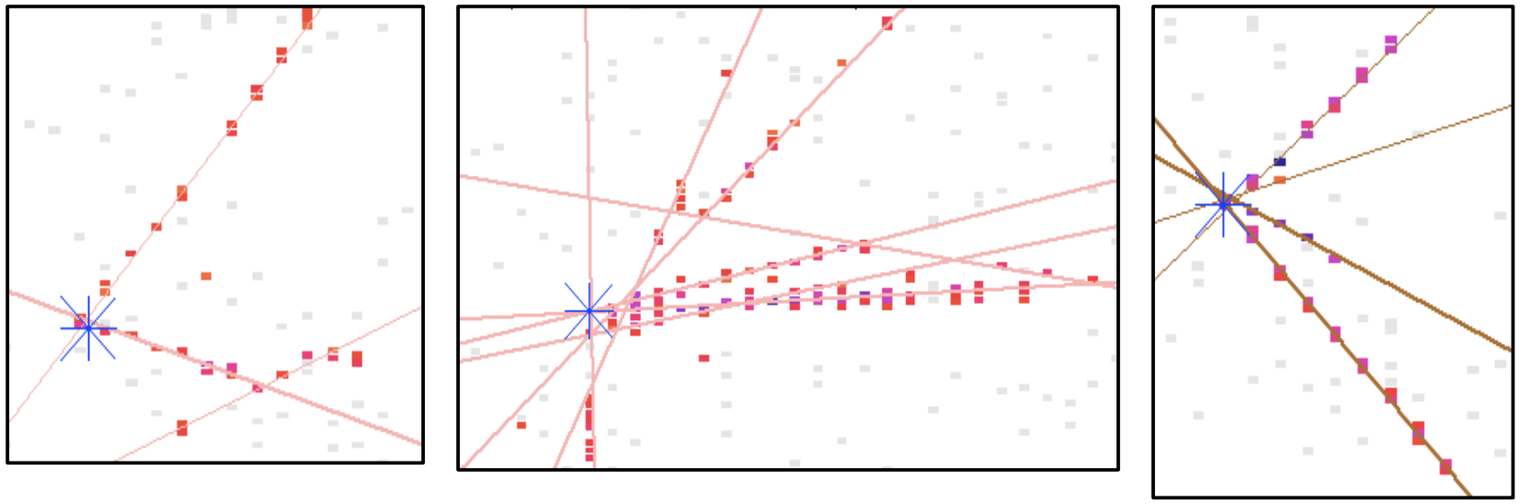
- Beam hadron production, propagation; neutrino flux: **FLUKA/FLUGG**
- Cosmic ray flux: **CRY**
- Neutrino interactions modeling: **GENIE**
- Detector simulation: **GEANT4**
- Light Transport in Fiber, APD Readout and Electronics: **Custom simulation routines**

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

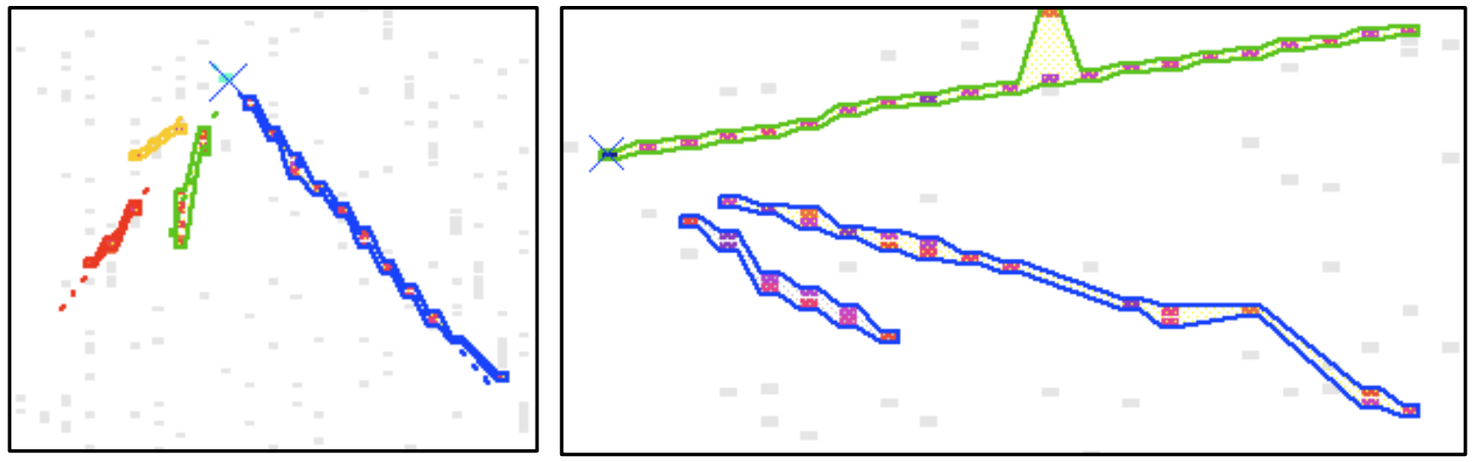


Event Reconstruction

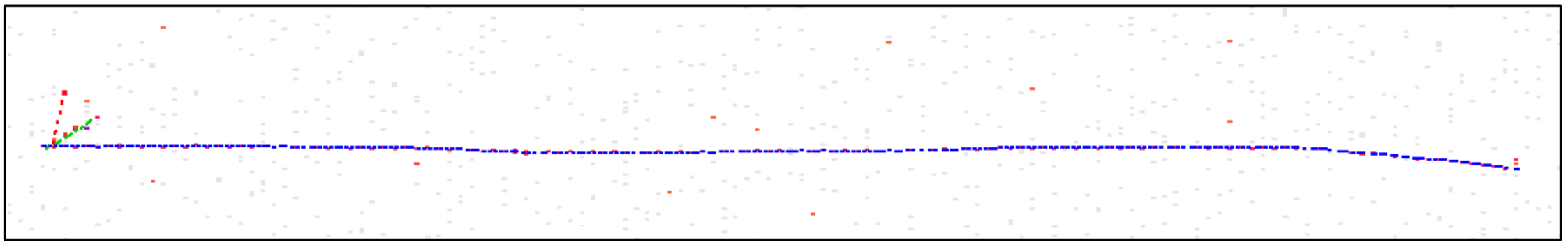
<u>Vertexing:</u> Find **lines of energy depositions** w/ Hough transform
CC events: 11 cm resolution



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

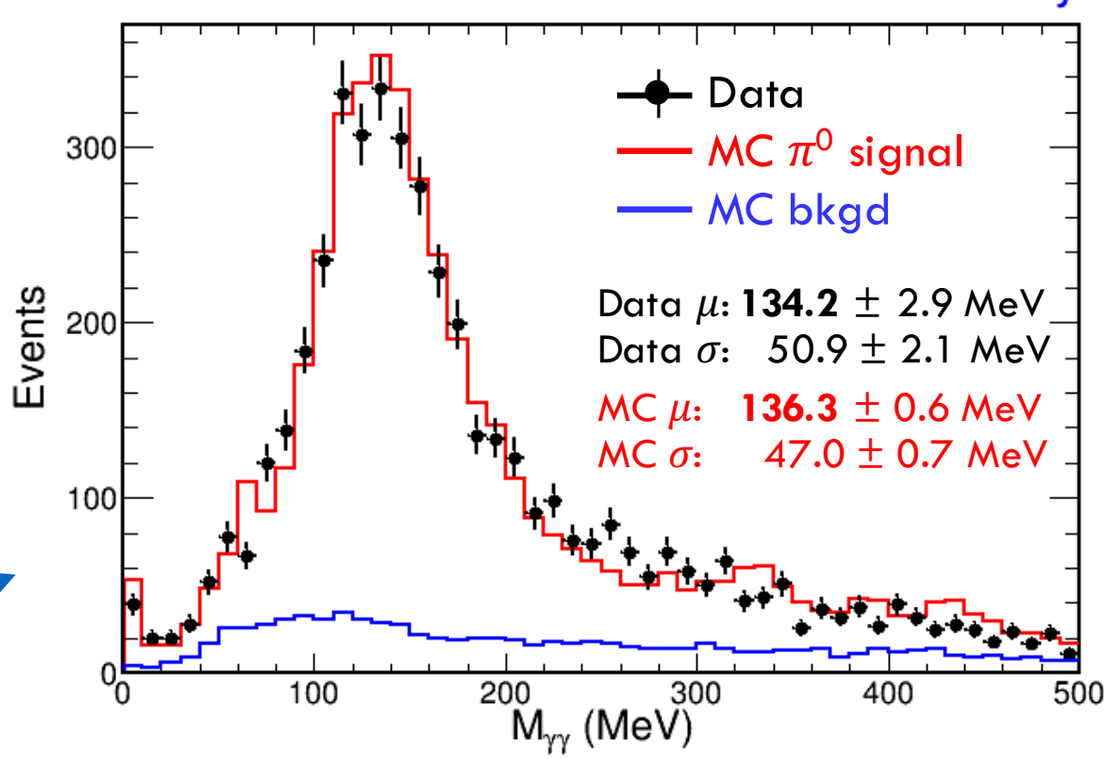


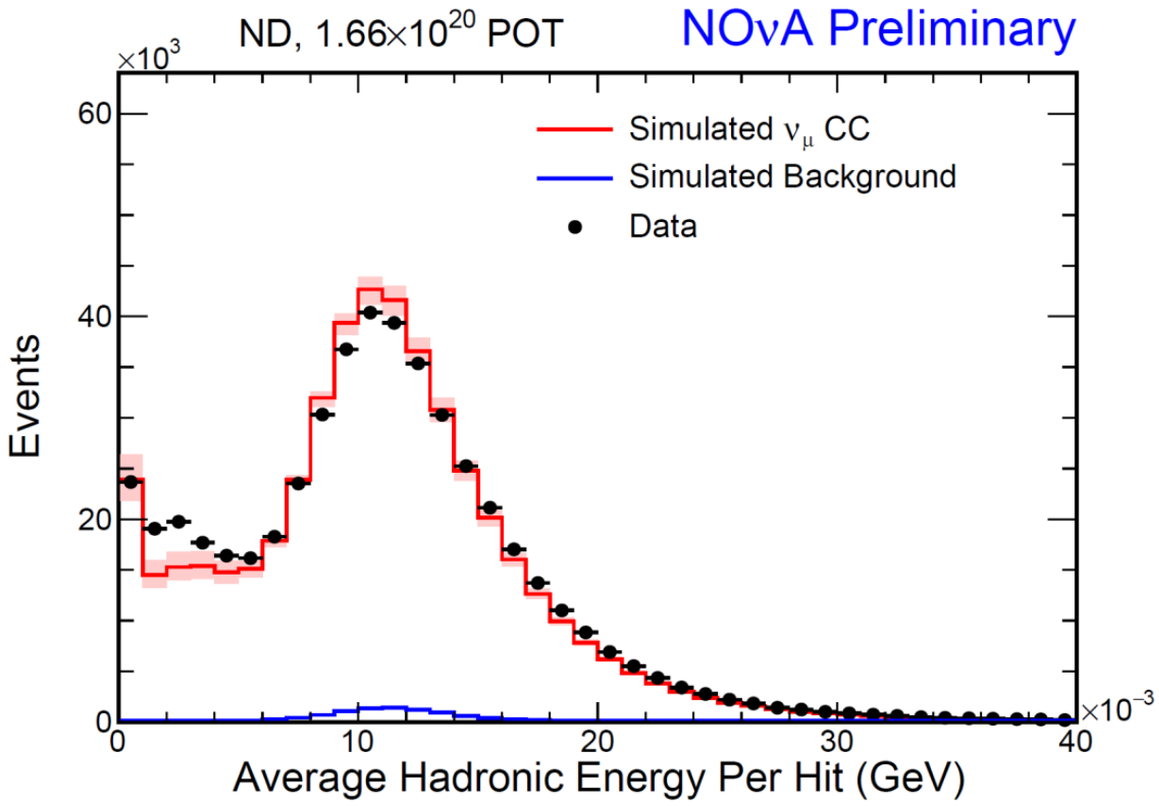
<u>Tracking:</u> Trace particle trajectories with **Kalman filter** tracker (below).
Also have a **cosmic ray tracker**: lightweight, very fast, and useful for large calibration samples and online monitoring tools.



Detector Calibration and Energy Scale

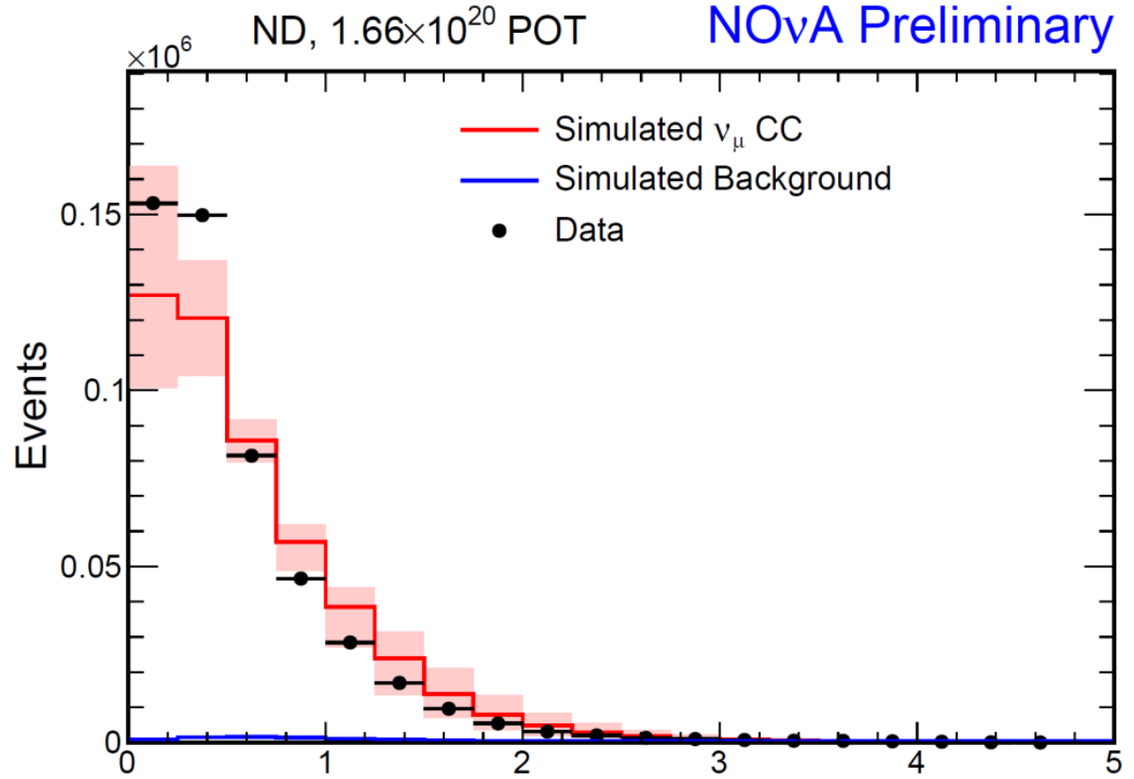
- Calibration uses beam and cosmic muons traversing the Far detector and stopping muons as standard candles
- Near Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e- spectrum
  - π^0 mass
  - hadronic shower E-per-hit
- Far Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e- spectrum
- All agree to within ±5%





ν_μ Disappearance Energy Estimation

- While the muon simulation matches data, the simulated hadronic system has 21% more energy than seen in data.
- The hadronic energy scale is recalibrated so the total energy peak of the data matches the MC.
- Correction taken as a systematic on the absolute energy scale
- This results in 6% overall neutrino energy scale uncertainty.
- ND reconstructed energy distribution is used to produce a data driven prediction of the FD spectrum



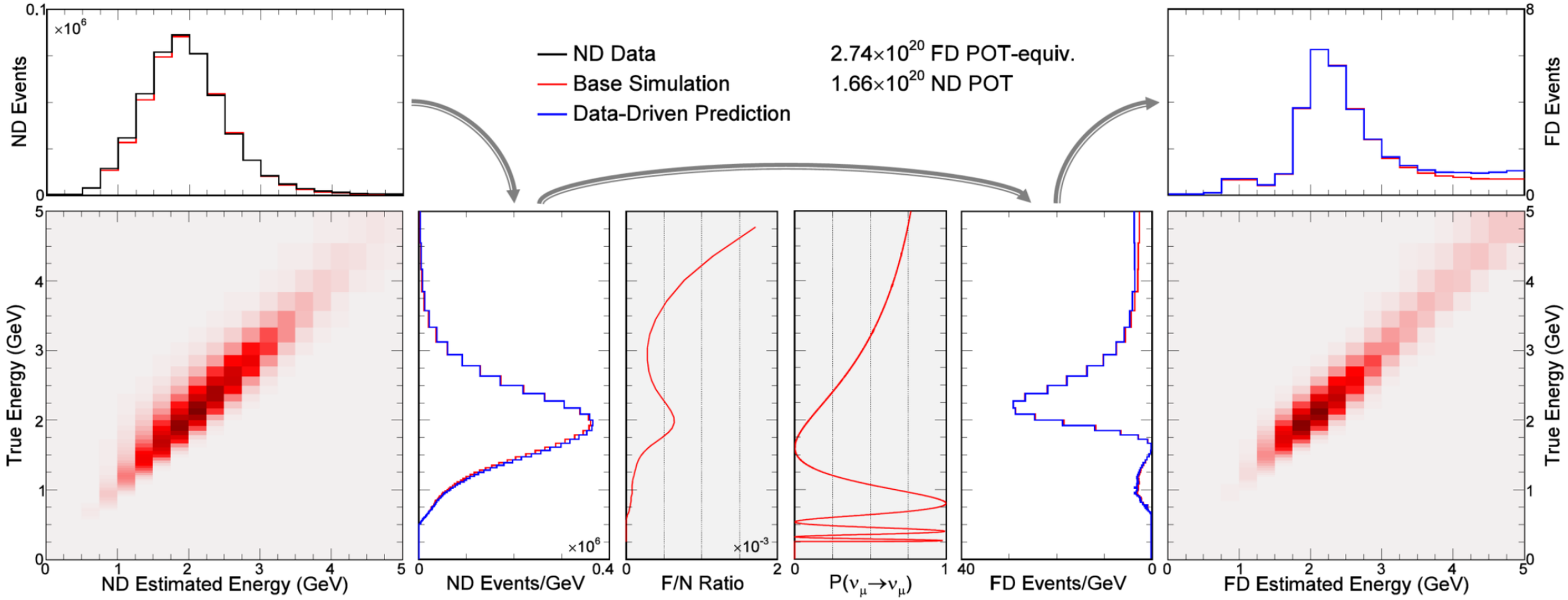
Near to Far Prediction

(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**



ν_e Disappearance Systematics

Source	$\delta(\sin^2\theta_{23})$ (±%)	$\delta(\Delta m^2)$ (±%)
Absolute Calorimetric Energy Calibration [±22%]	7.7	3.1
Relative Calorimetric Energy Calibration [±5.4%]	3.7	0.8
Cross Sections and FSI [±(15-25)%]	0.6	0.7
NC and CC Backgrounds	3.2	0.7
Detector Response	1.3	0.7
Flux [±21%]	1.6	0.4
Exposure [<±2%]	0.3	0.2
Oscillation Parameters	2.1	2.2
Total Systematic	9.2	4.1
Statistical	19	5.0

- Systematics assessed by modifying the simulation used in the signal and background predictions.
- Variation in the BG and signal prediction taken as the size of the systematic

ν_μ Appearance Systematics

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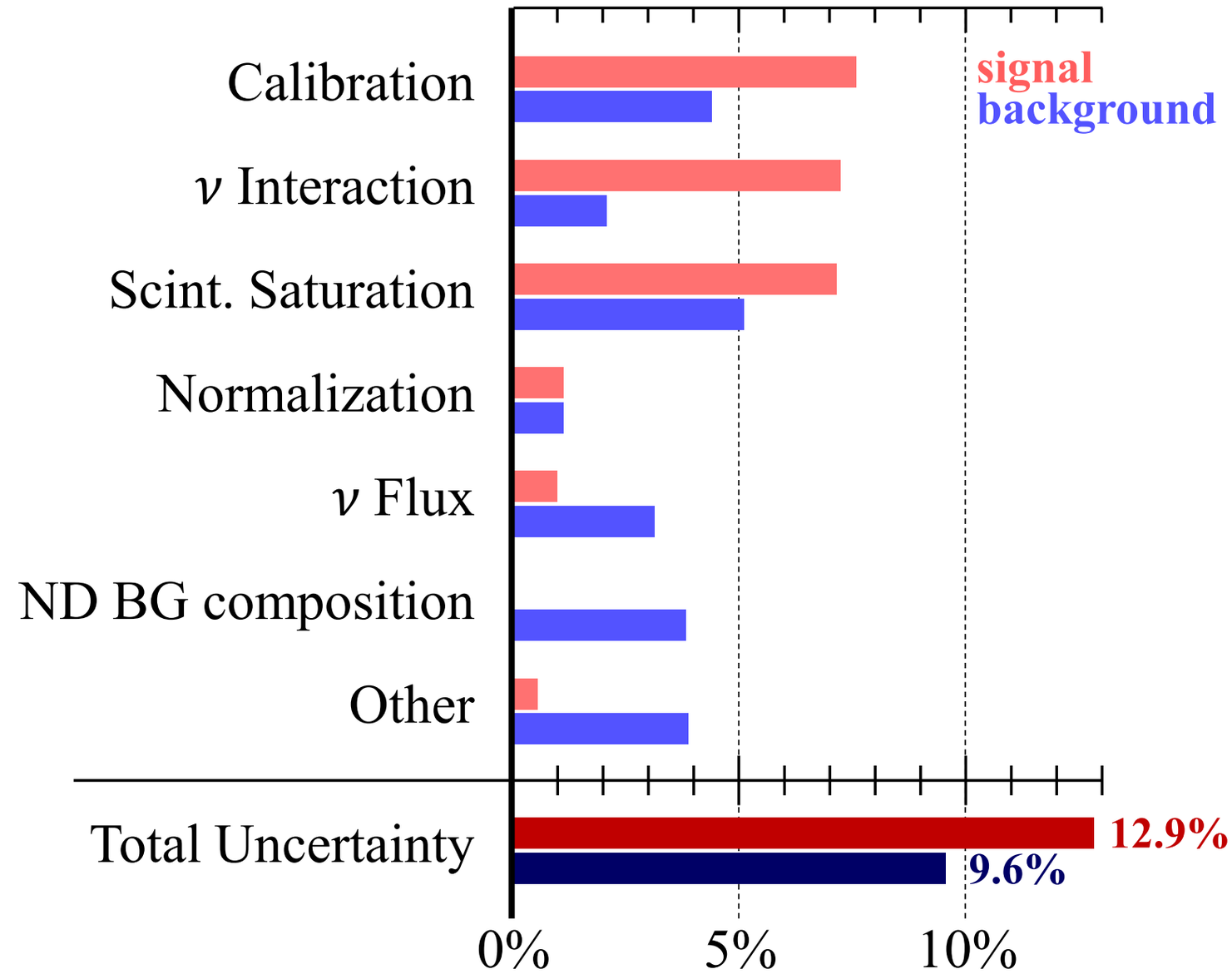
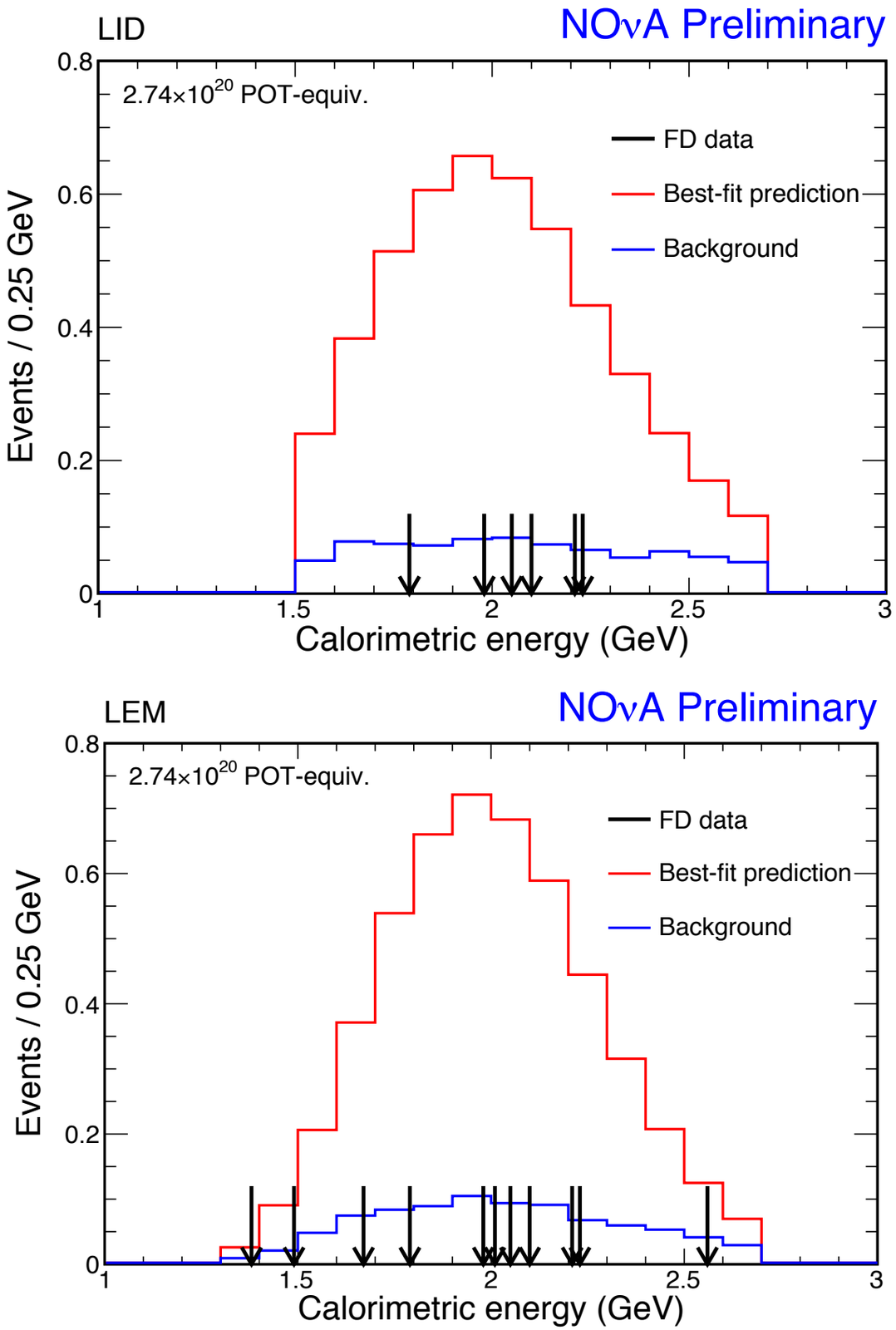


ν_e CC Selected Events



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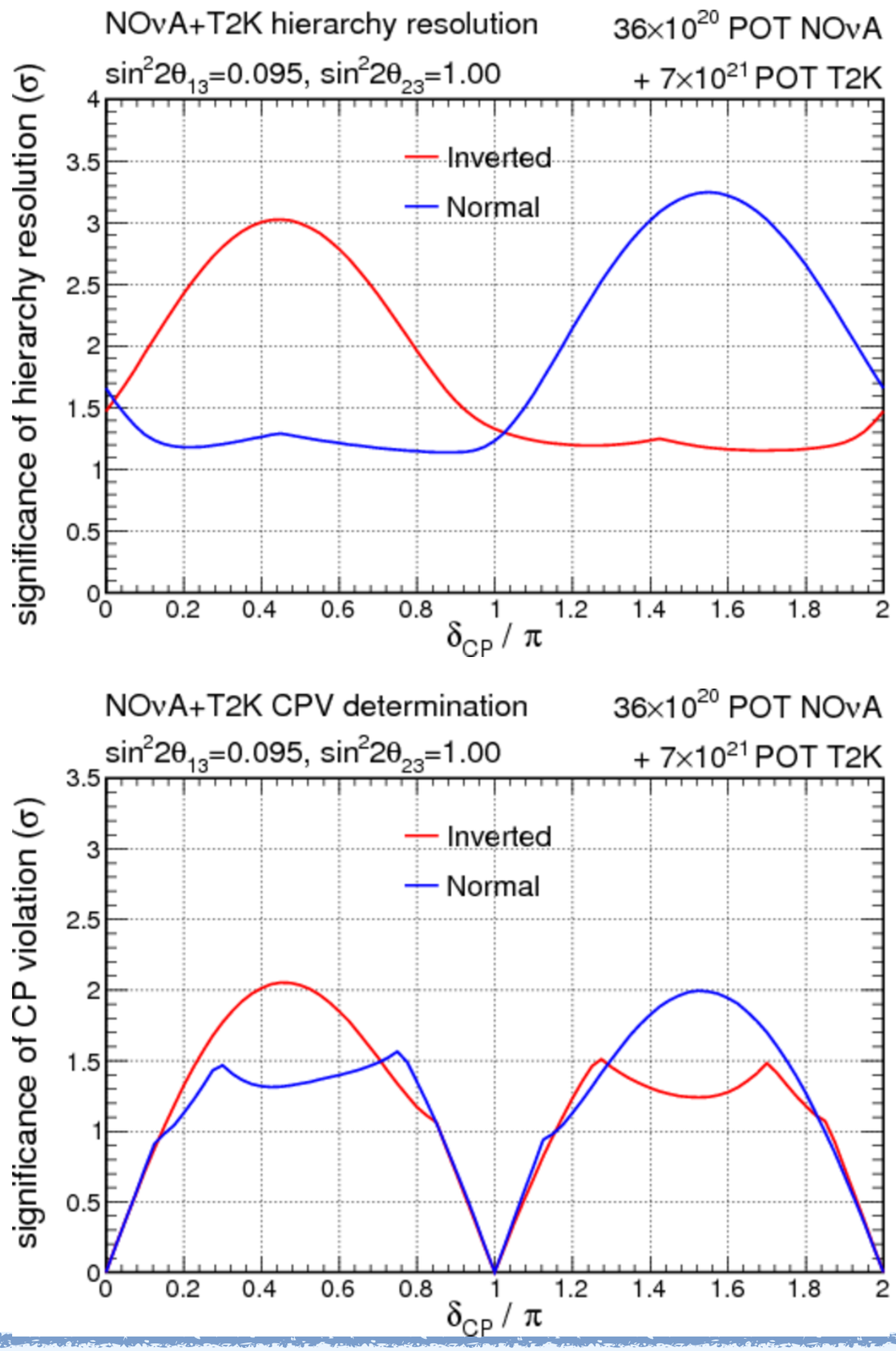
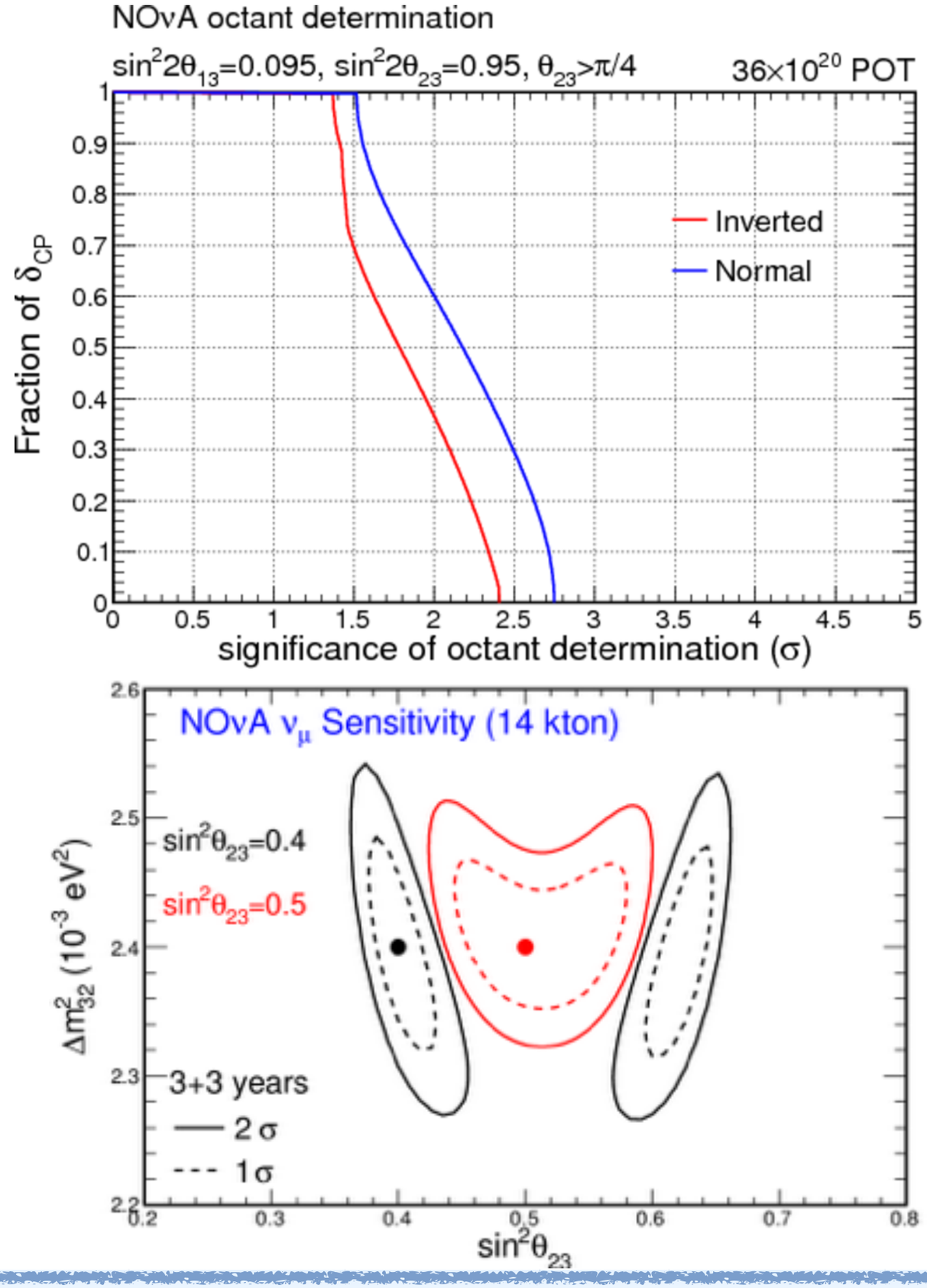
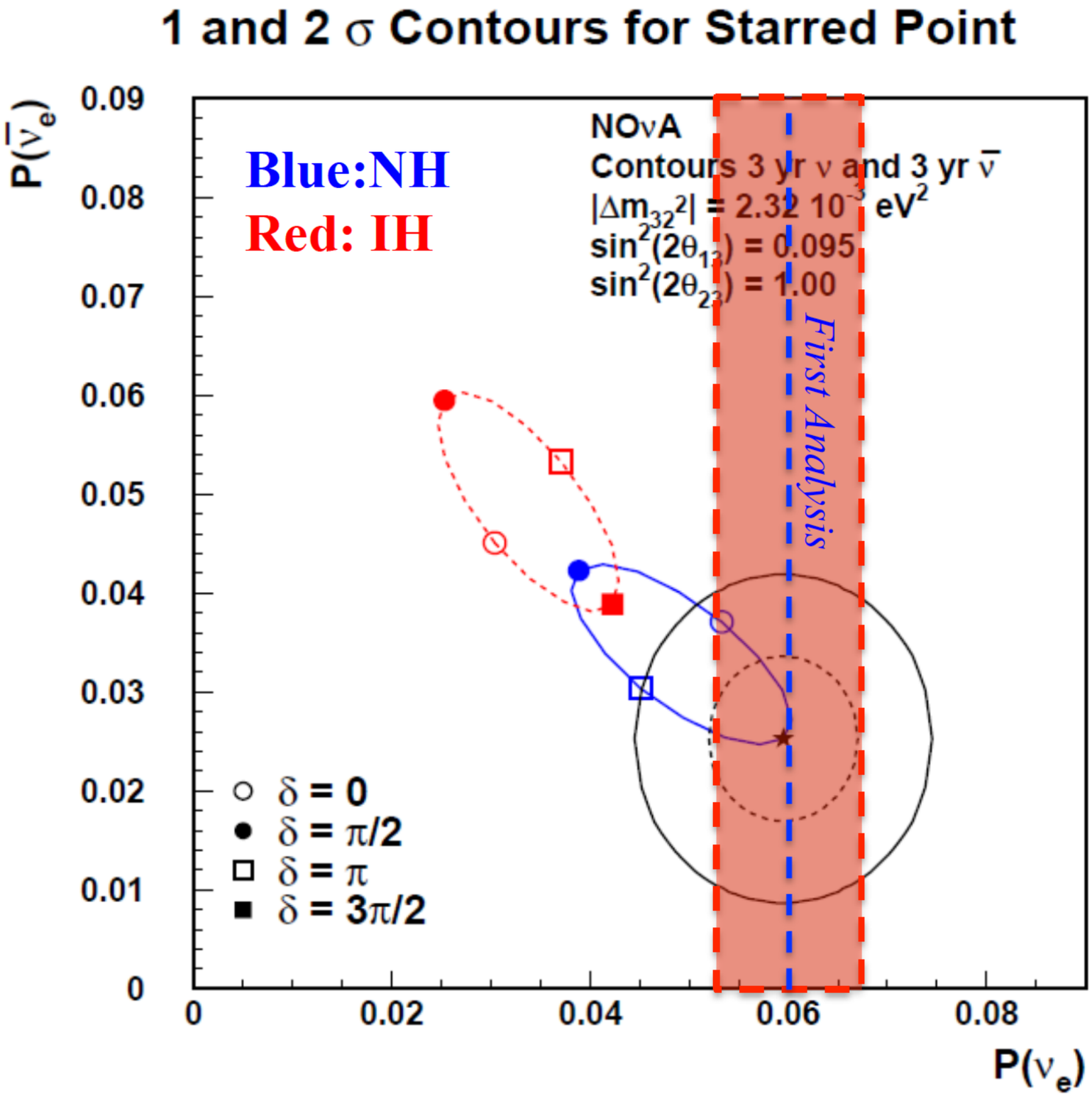
NOvA Sensitivities

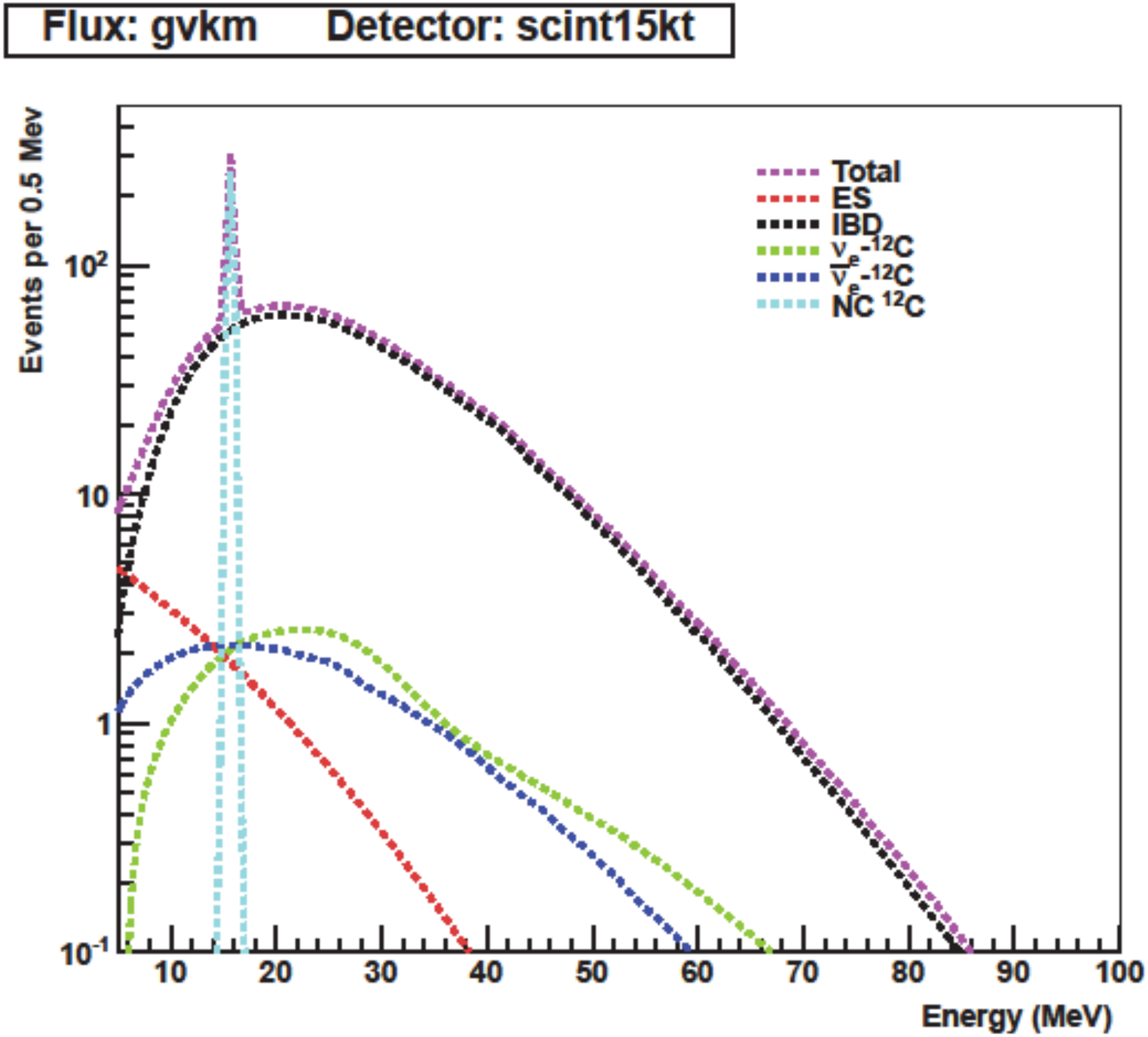




A possible first analysis result

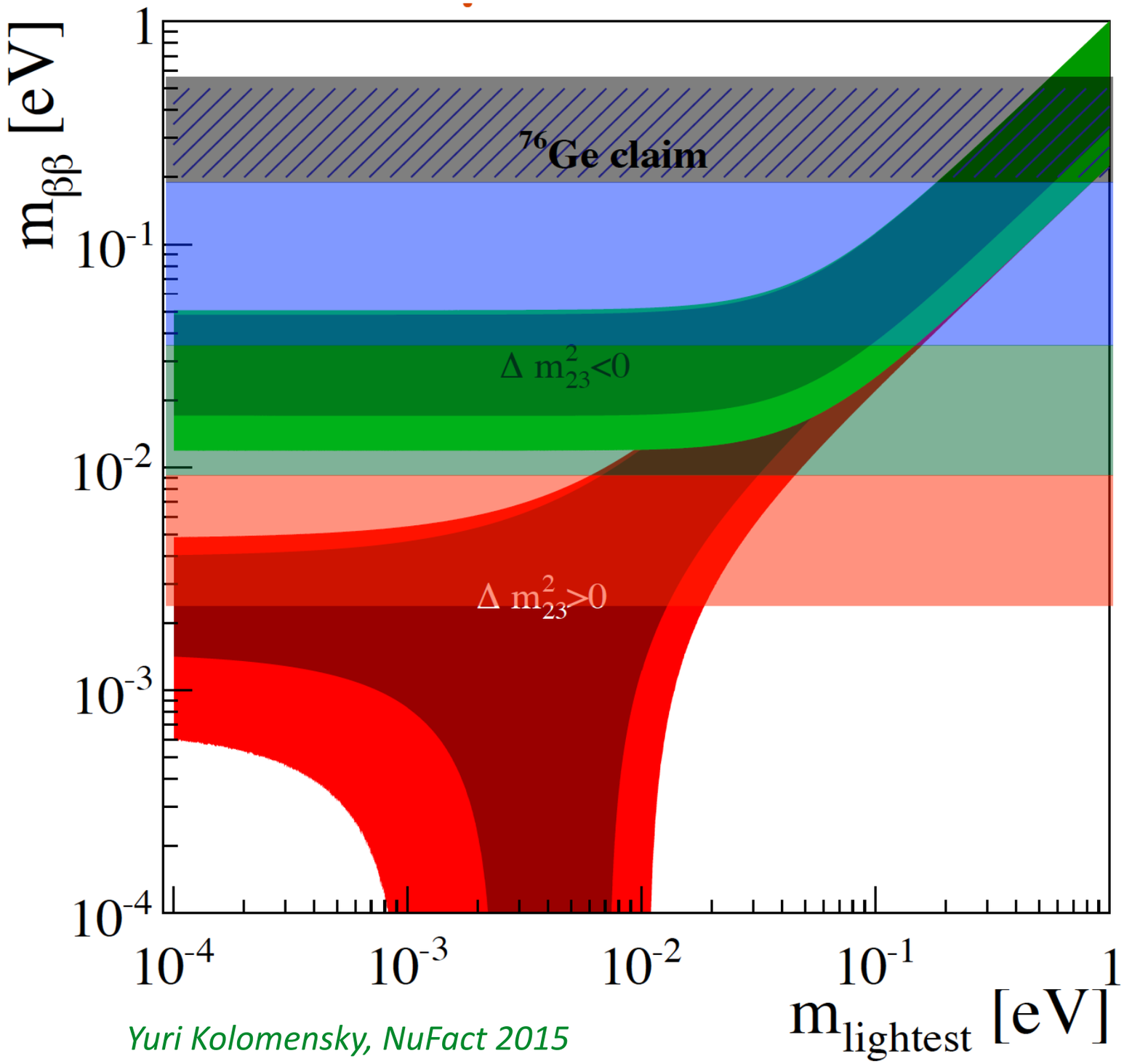


Supernova signal in NOvA



- For galactic SN expect O(1000) events above background over 10-20 seconds

Neutrinoless Double Beta Decay



Yuri Kolomensky, NuFact 2015

Past and present (~10 kg)

Present and near future (~100 kg)

Future (~1000 kg)

Dreams ? (~10000+ kg?)

$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$