Current Results from the NOνA Experiment

Alec Habig, for the NOνA collaboration

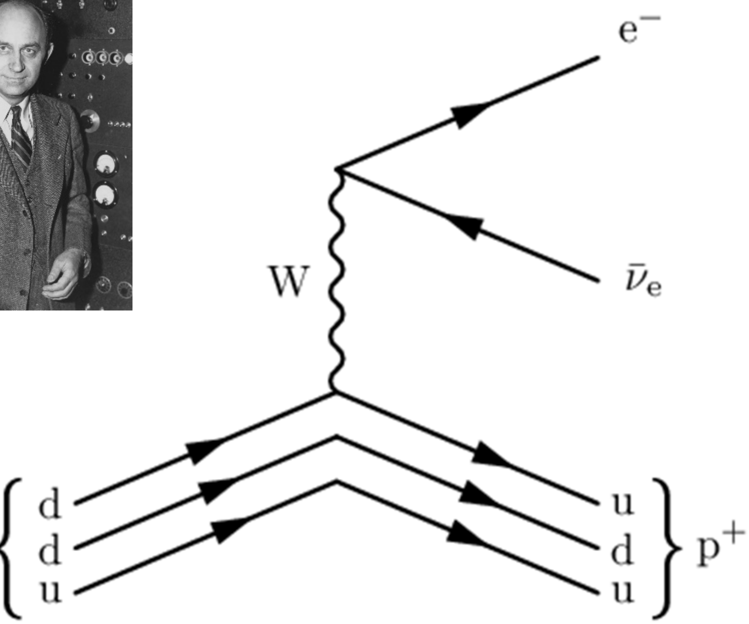
WIN2023, Zhuhai, Tuesday, July 4, 2023

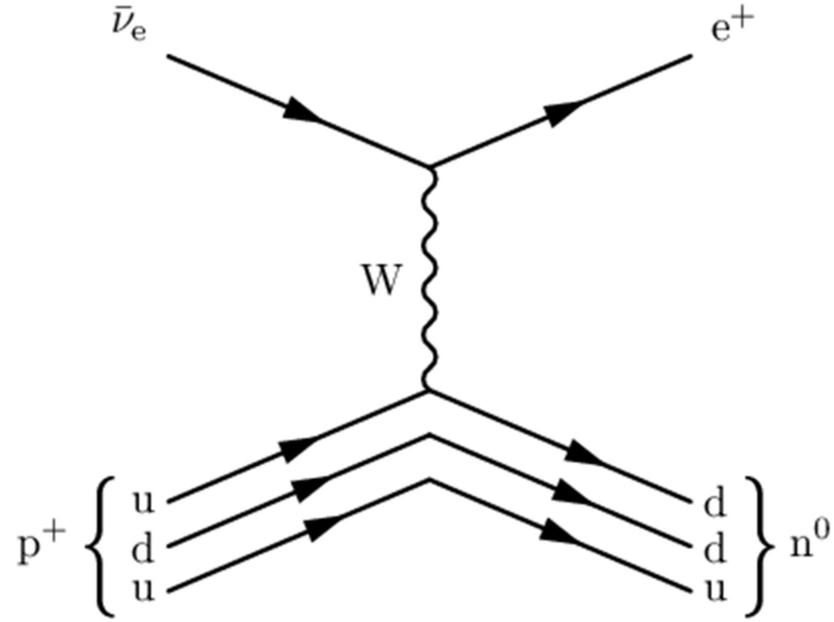
The NuMI Off-axis ν_e Appearance collaboration is 266 Scientists and Engineers from 49 Institutions and 8 countries:

NOvA @Queen Mary Univ. London, 06/2023

Argonne • Atlantico • Banaras Hindu • Caltech • Cochin
Czech IOP • Charles (Prague) • Cincinnati • Colorado State
Czech Tech • Delhi • JINR Dubna • Erciyes • Fermilab
Goias • Florida State • IIT Guwahati • Harvard • Houston
IIT Hyderabad • Hyderabad • IIT • Indiana • Iowa State • Irvine
UCL • Jammu • Magdelena • Michigan State • Minn. Duluth
Minnesota • Mississippi • Panjab • Pittsburgh • QMUL
South Alabama • South Carolina • SMU • Stanford • Sussex
Syracuse • UT Austin • Tufts • Virginia • Wichita State
William & Mary • Wisconsin

ν Interact as Flavor States …





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

Beta Decay explained
(Pauli & Fermi)
1930 & 1933

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

Inverse Beta Decay observed
(Cowan & Reines)
1953

… but propagate as mass states

UMD
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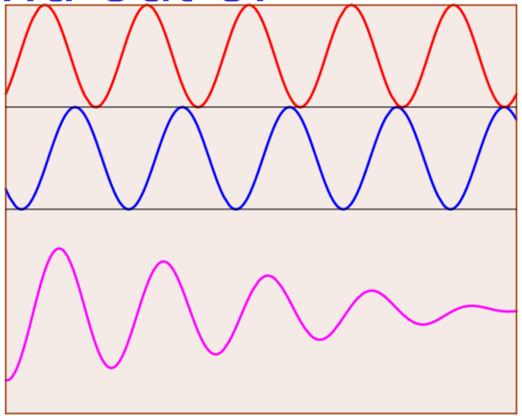
- Same energy, different mass: so wave packets have different wavelengths, slide in and out of phase
  - When you add them back up later, they might not interact as the flavor they started
- The PMNS matrix describes this:



(Exaggerated ν_2 wavelength 5% larger than ν_1)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$

$$\sin^2(2\theta_{23}) \equiv 4|U_{\mu 3}|^2\left(1-|U_{\mu 3}|^2\right)$$

Useful Approximations:

ν_μ Disappearance (2 flavors):

$P(\nu_\mu \to \nu_x) = \sin^2 2\theta_{23} \sin^2(1.27\Delta m^2_{32} L/E)$

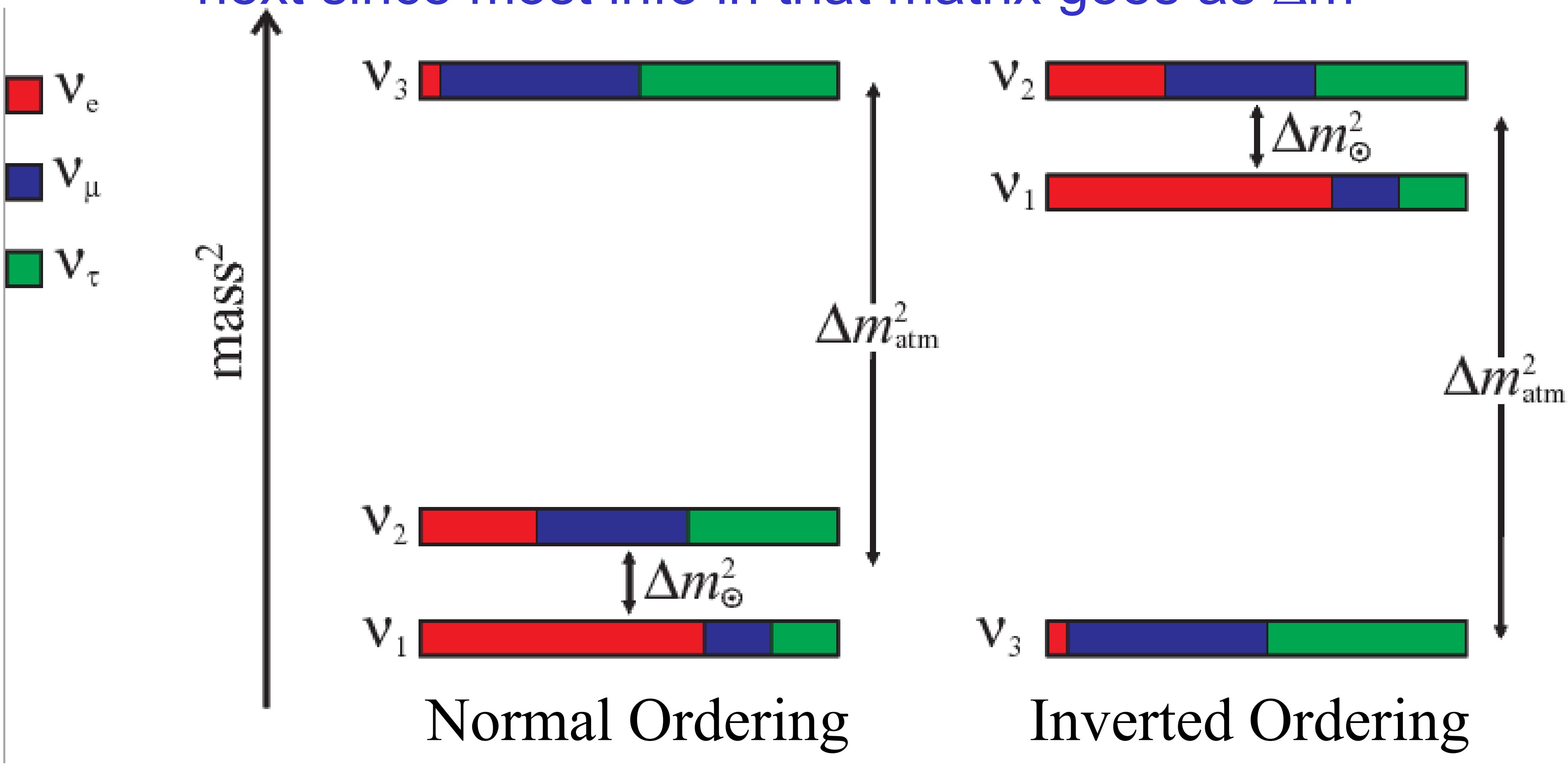
ν_e Appearance:

$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E)$

Where L, E are experimentally optimized and θ_{23}, θ_{13}, Δm^2_{32} are to be determined

Mass Ordering

- Unlike quarks and the other leptons, we do not even know which ν is more massive than the next since most info in that matrix goes as Δm^2



ν_e appearance

- Reactor experiments directly measure θ_{13} by observing ν_e disappearance
- How about starting off with no ν_e and seeing if any pop up after some L/E?
- Back to the oscillation approximations we use for ν_μ disappearance:
  - While experimentally θ_{23} is close to $\pi/4$, if it's not exactly $\pi/4$ we can't tell if it's > or <
  - … and that "≈" wipes away a lot more terms which result from multiplying out the mixing matrix properly

Useful Approximations:

ν_μ Disappearance (2 flavors):

$P(\nu_\mu \rightarrow \nu_x) = \sin^2 2\theta_{23} \sin^2(1.27\Delta m^2_{32} L/E)$

ν_e Appearance:

$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E)$

Where L, E are experimentally optimized and θ_{23}, θ_{13}, Δm^2_{32} are to be determined

ν_e appearance

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$\overset{(+)}{-}\ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$+\ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ $\Delta = \Delta m^2_{31} L/(4E)$ $A = \overset{(-)}{+} G_f n_e L/(\sqrt{2}\Delta)$

Thanks to Greg Pawloski for typesetting this beast!

- Note there are θ_{23} terms that are not squared, introducing sensitivity to $\theta_{23} > \pi/4$ or $< \pi/4$
- CP-violating δ is present
- Matter effects are in there (*30% for NOνA*), differ in sign for ν and anti-ν, so a comparison could allow sorting out the mass ordering
- But if θ_{13} is near zero, we learn nothing (all terms$\rightarrow$0)

So What Might We Learn?

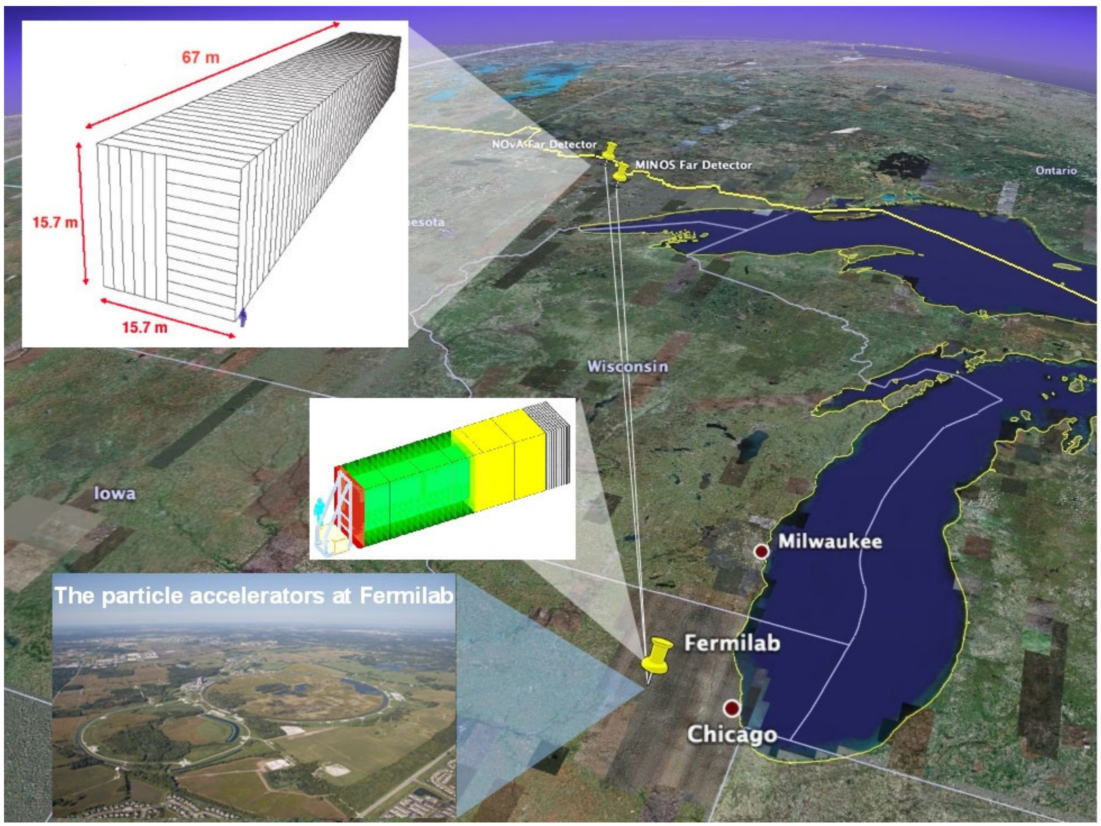
- Does the ν_3 mass state have a ν_e component?
  - Is $\theta_{13} \neq 0$? YES! (*without which nothing else works*)
- Is there CP violation in the lepton sector?
  - Is $\delta_{CP} \neq 0$?
- Is the ν_3 mass state more massive than ν_1 and ν_2 (*normal ordering*) or less massive (*inverted ordering*)?
  - Absolute mass values need β and $\beta\beta$ decay experiments to nail down
- Does the ν_3 mass state have a larger ν_μ or ν_τ component?
  - Is $\theta_{23} \neq \pi/4$?

Daya Bay, NOvA, T2K

In my biased opinion, that's 1.5 of the remaining fundamental 2 things we don't yet know about the standard model

A narrow-band, long-baseline ν_μ beam

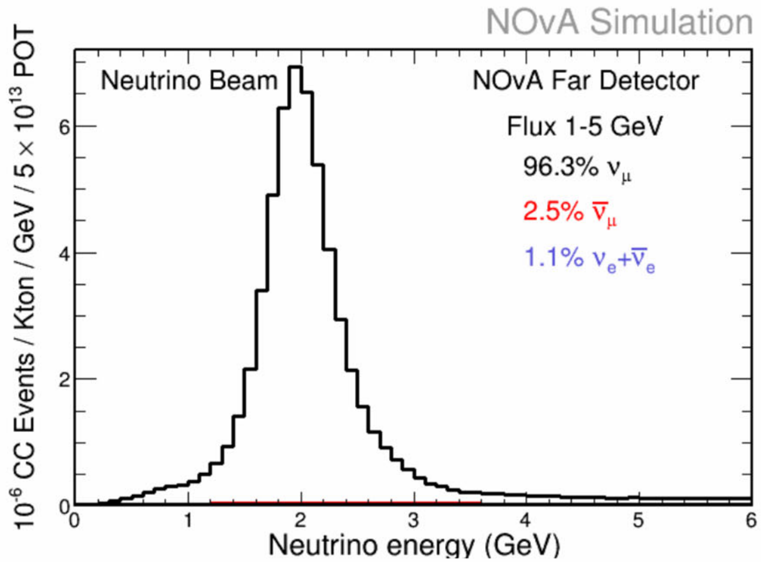
- 810 km away, 14 mrad (0.84^o) off-axis, the beam spectra is narrow and at a good L/E for oscillation physics: max ν_μ disappearance



- Two detectors: measure ν before and after the trip
- ν are from the NuMI beam at Fermilab
  - 120GeV p^+ make a π beam
  - ν born headed in right direction, from π decay in flight

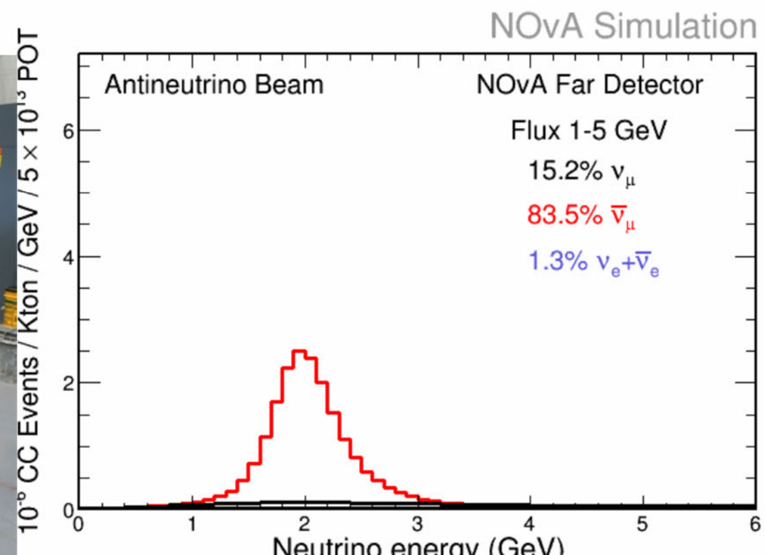
NuMI Beam

- Peaked sharply at 2 GeV, content well understood, also does $\bar{\nu}$
  - Operates routinely at around 800 kW (*record of 960MW!*)
  - Total of exposure of 41×10^{20} pot (28.5 ν, 12.5 $\bar{\nu}$)
  - 13.6 ν, 12.5 $\bar{\nu}$ analyzed and described in this talk (2022 analysis)



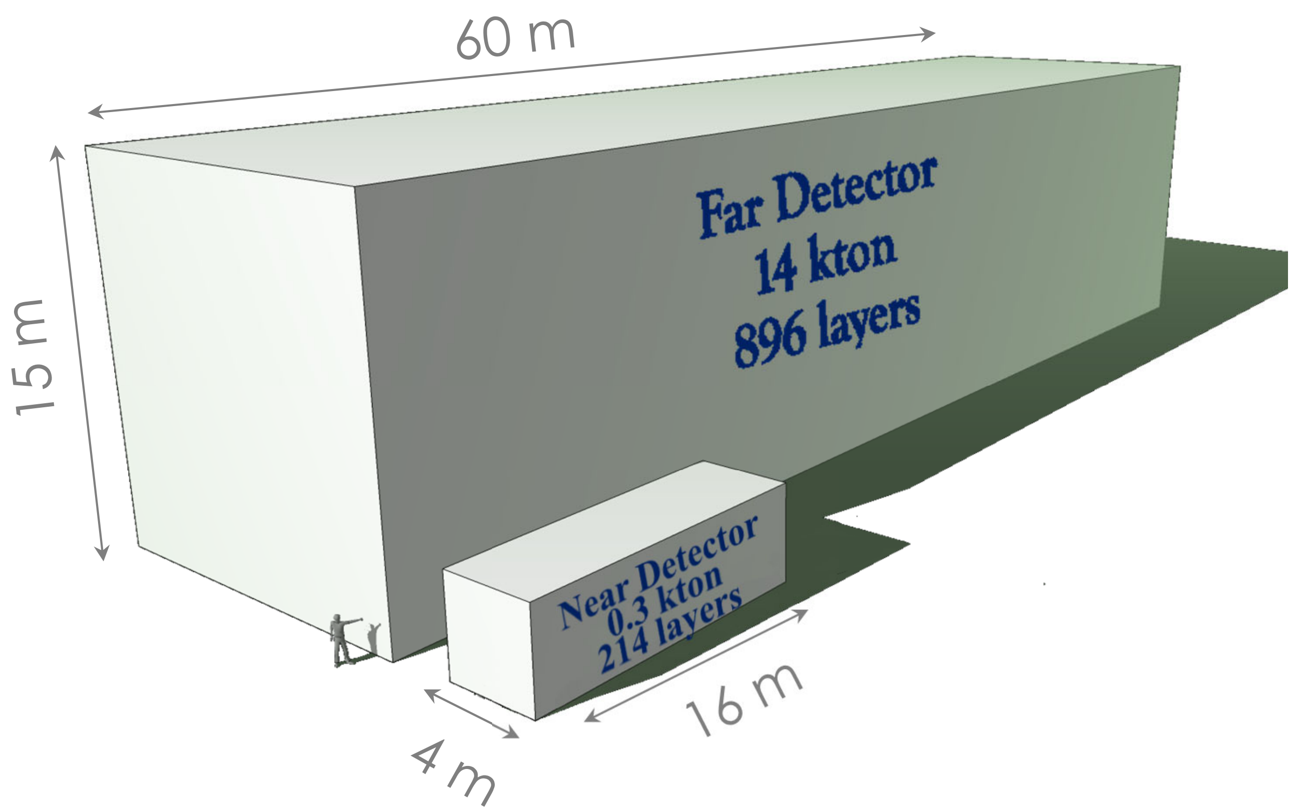
Carbon Target

1st of 2 focusing horns



Two Detectors

- Near Detector 100m underground near beam source
  - Establishes pre-oscillation expectations for Far Detector
- Both same “highly active” construction: scintillator is 60% of mass

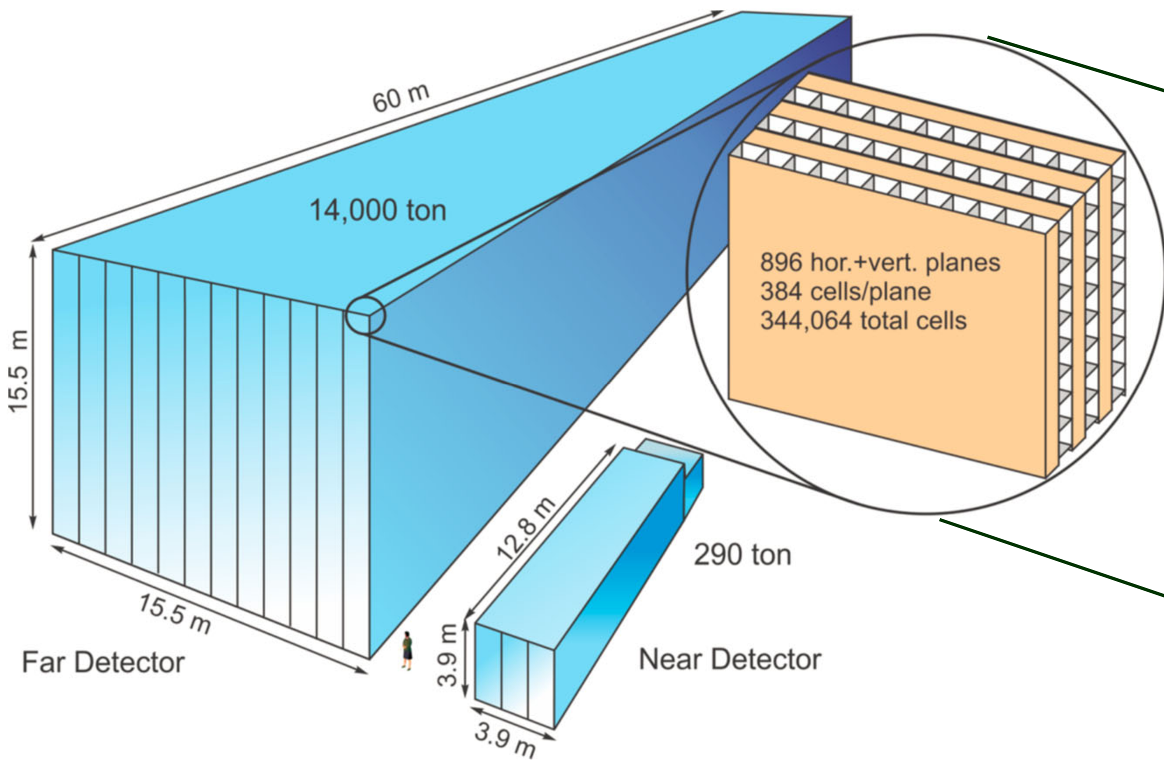


Two Detectors

- Detectors as similar as possible (*aside from size*) to minimize systematics when using large ND flux to determine the un-oscillated FD spectrum

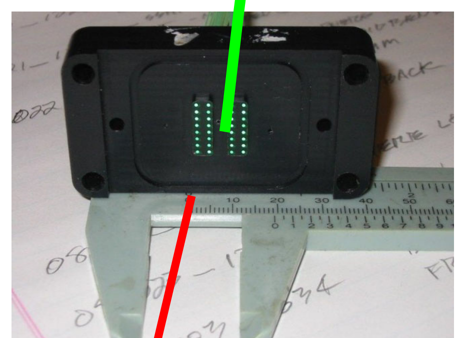
Cells

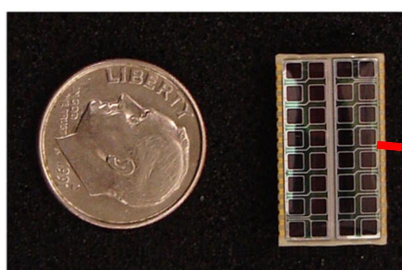
- NOνA composed of highly reflective (15% TiO_2) extruded PVC cells filled with liquid scintillator.
  - Alternating horizontal and vertical layers provide stereo views.



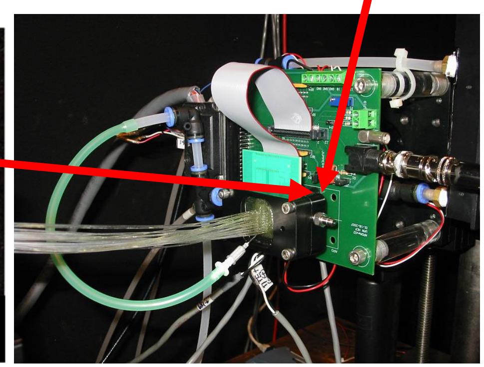
Getting the Light Out

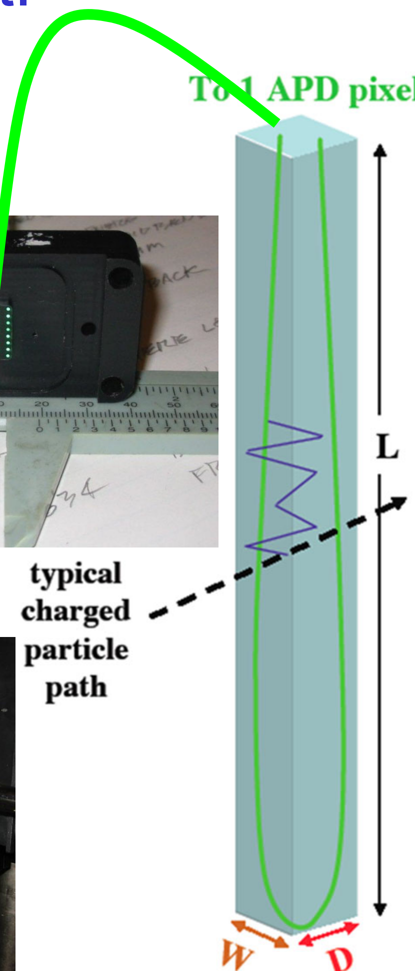
- A loop of wavelength shifting fiber in each cell pipes the scintillation light out to the readout.
- >20 photoelectrons for a muon crossing the far end (15.6m) of a cell
- How to get that much signal out?
  - Good scintillant, clear oil, looped fiber, reflective cells
- 344,000 channels: 32-pixel Avalanche Photo Diodes (APDs)
  - QE of 85%, gain of 100
  - Require low-noise amps and -15 °C



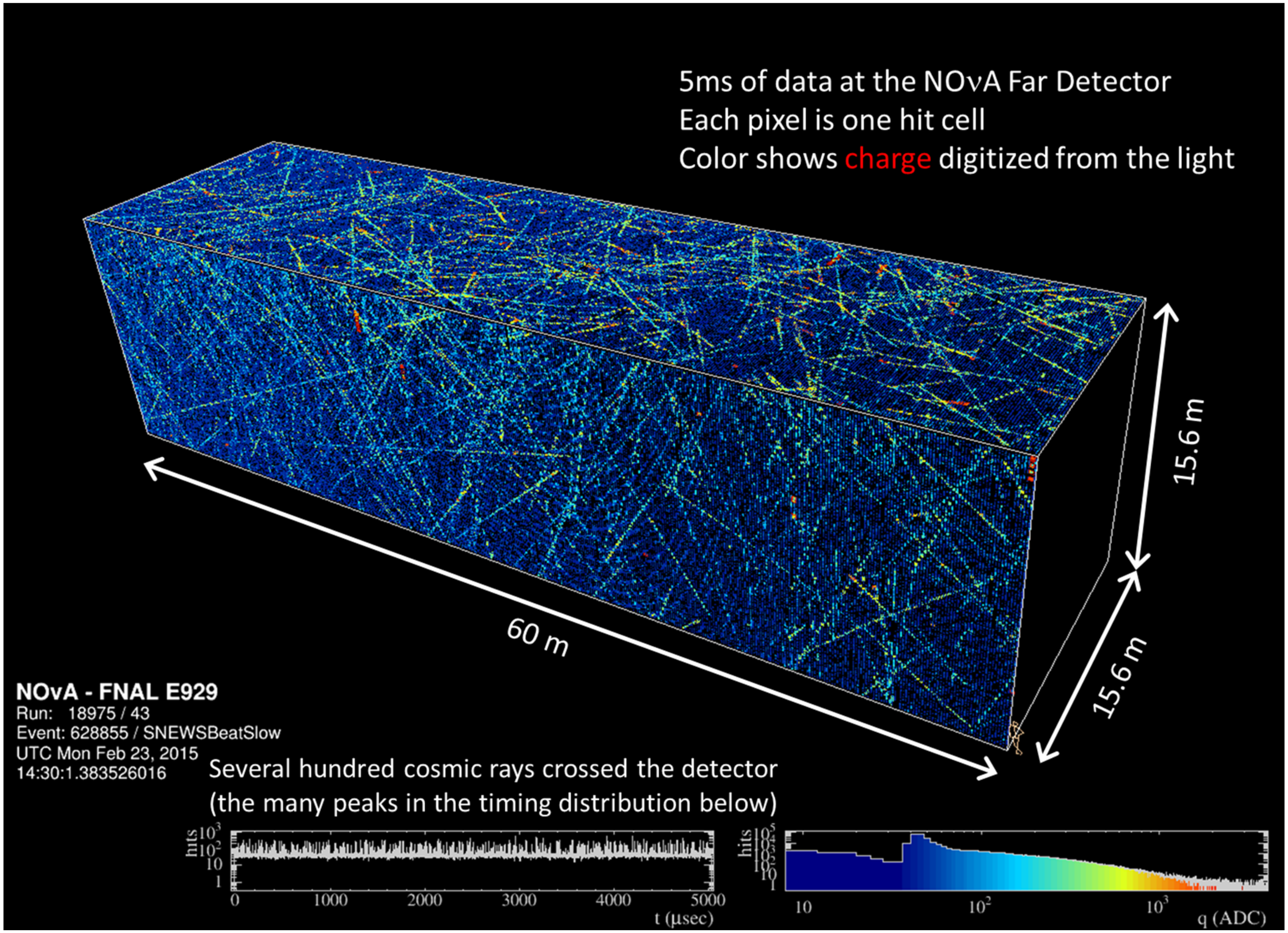


32-pixel APD

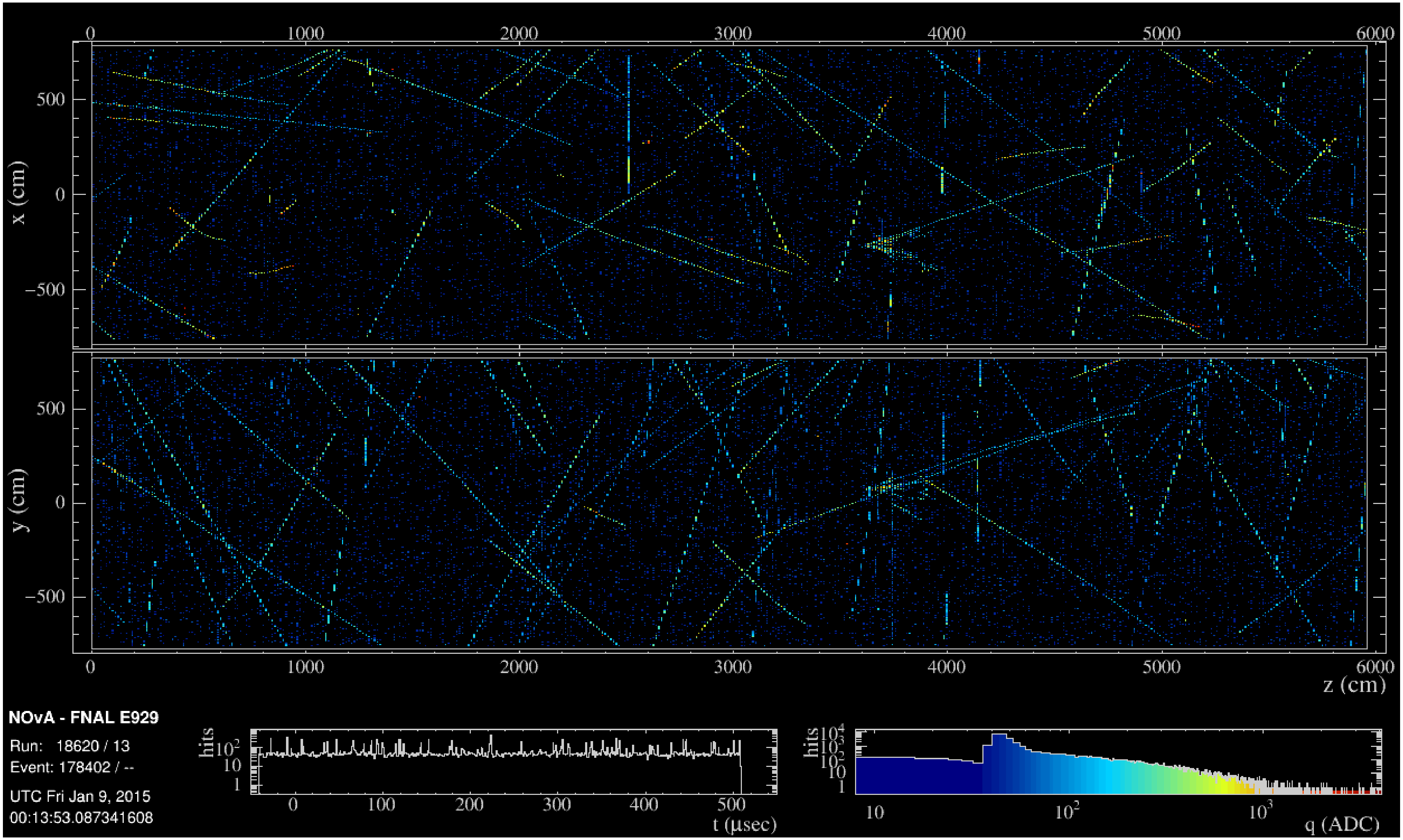




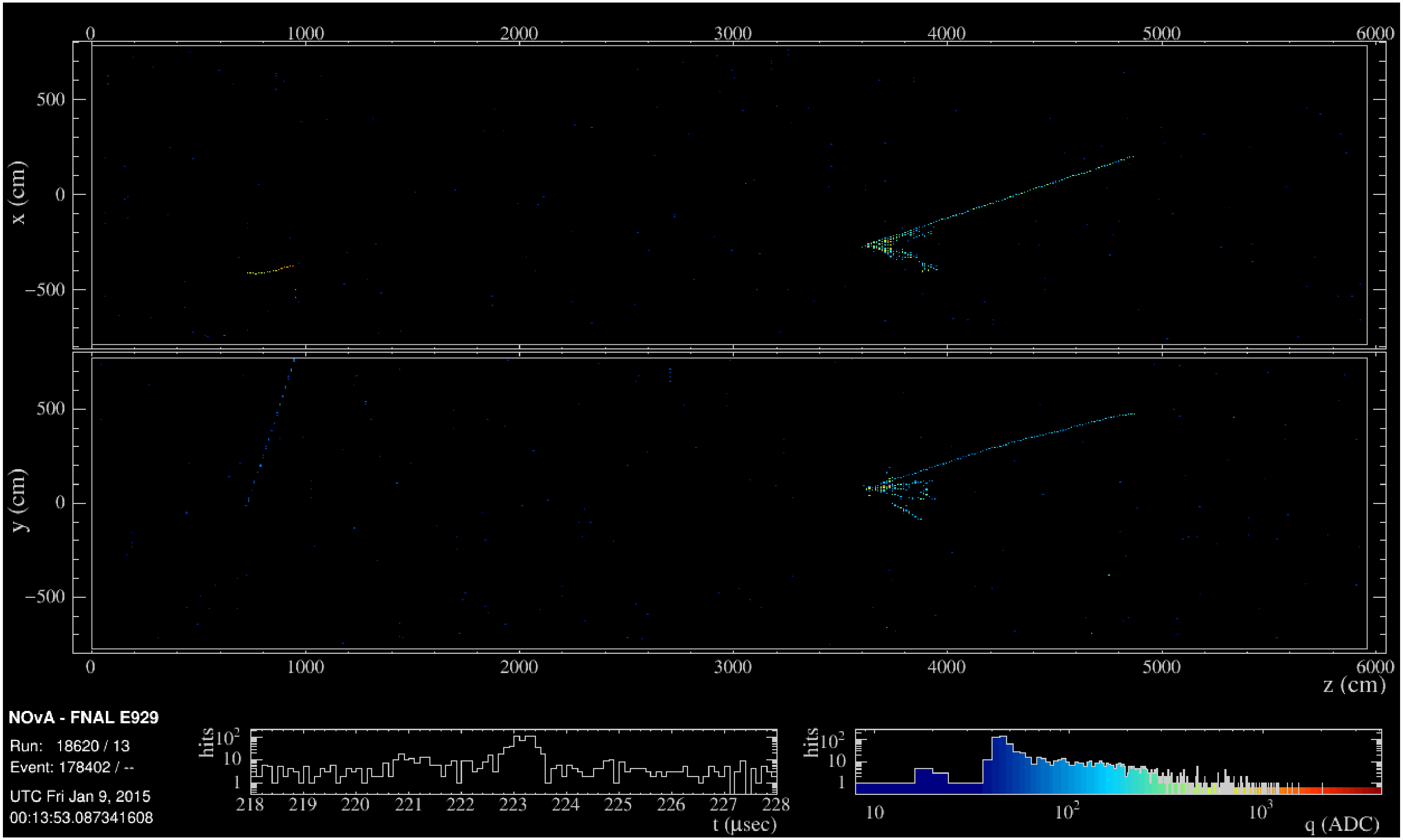
A 5ms block of Far Detector data



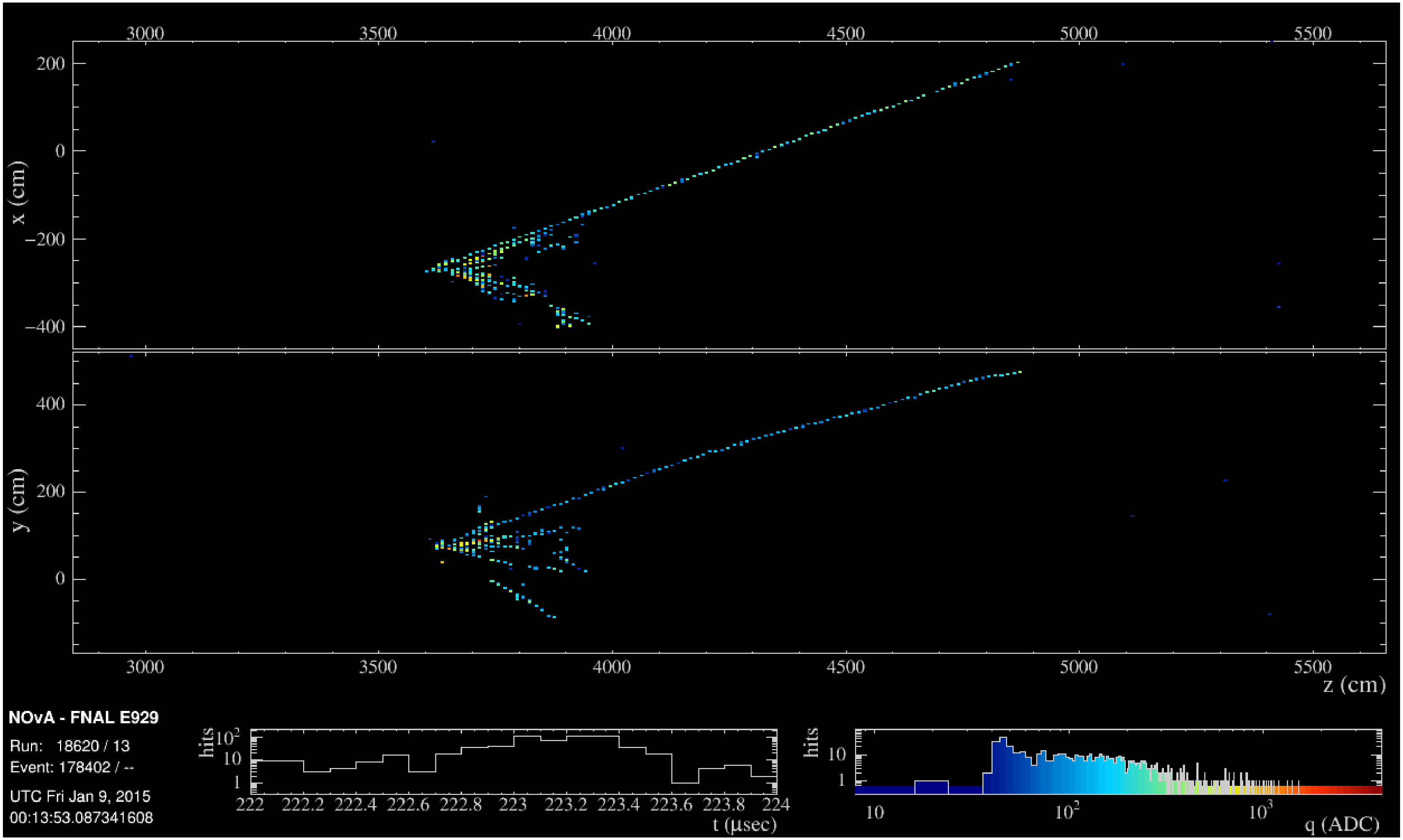
Just the 500μs around a NuMI beam spill



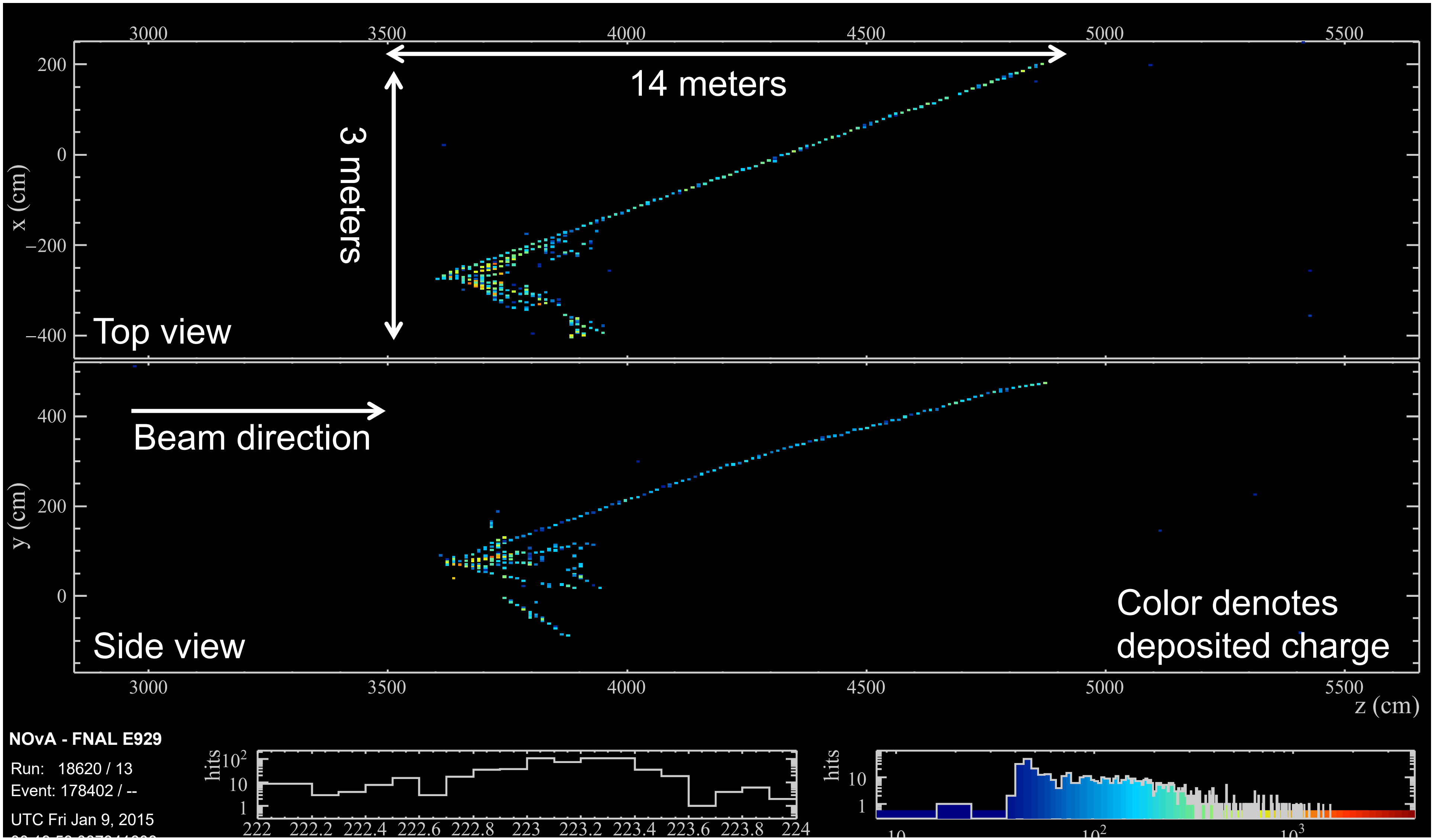
Sliced to the 10μs beam spill window



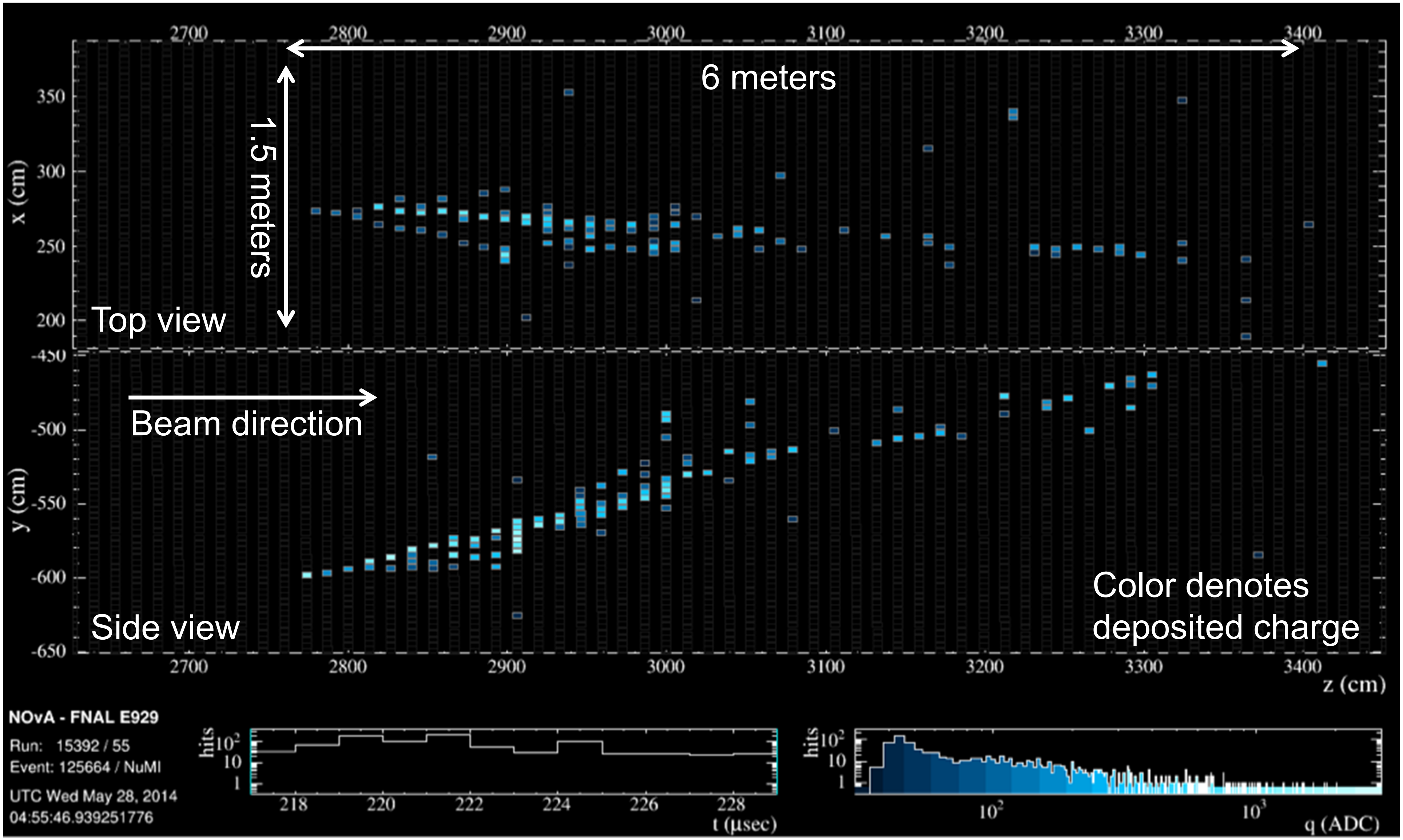
Zoomed in spatially



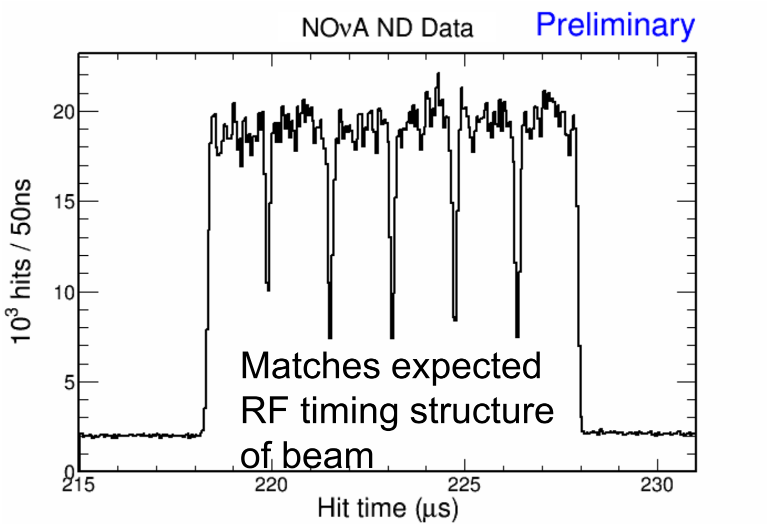
Candidate ν_μ event

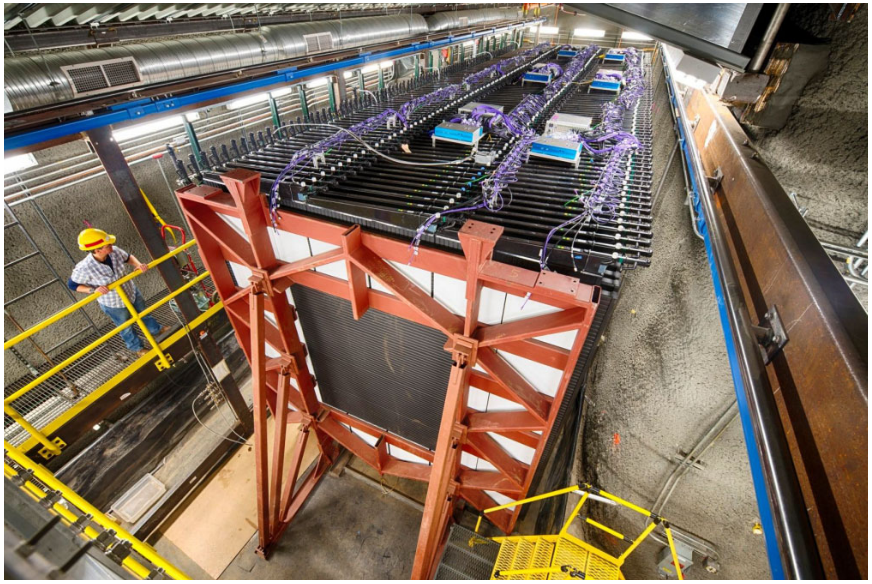


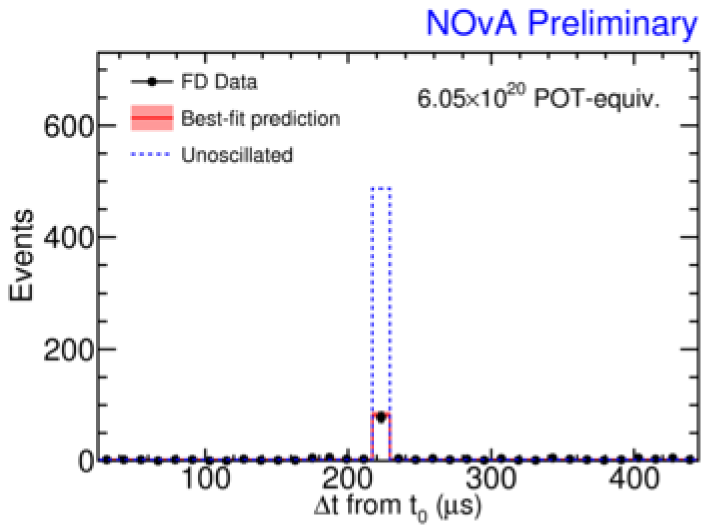
Candidate ν_e event



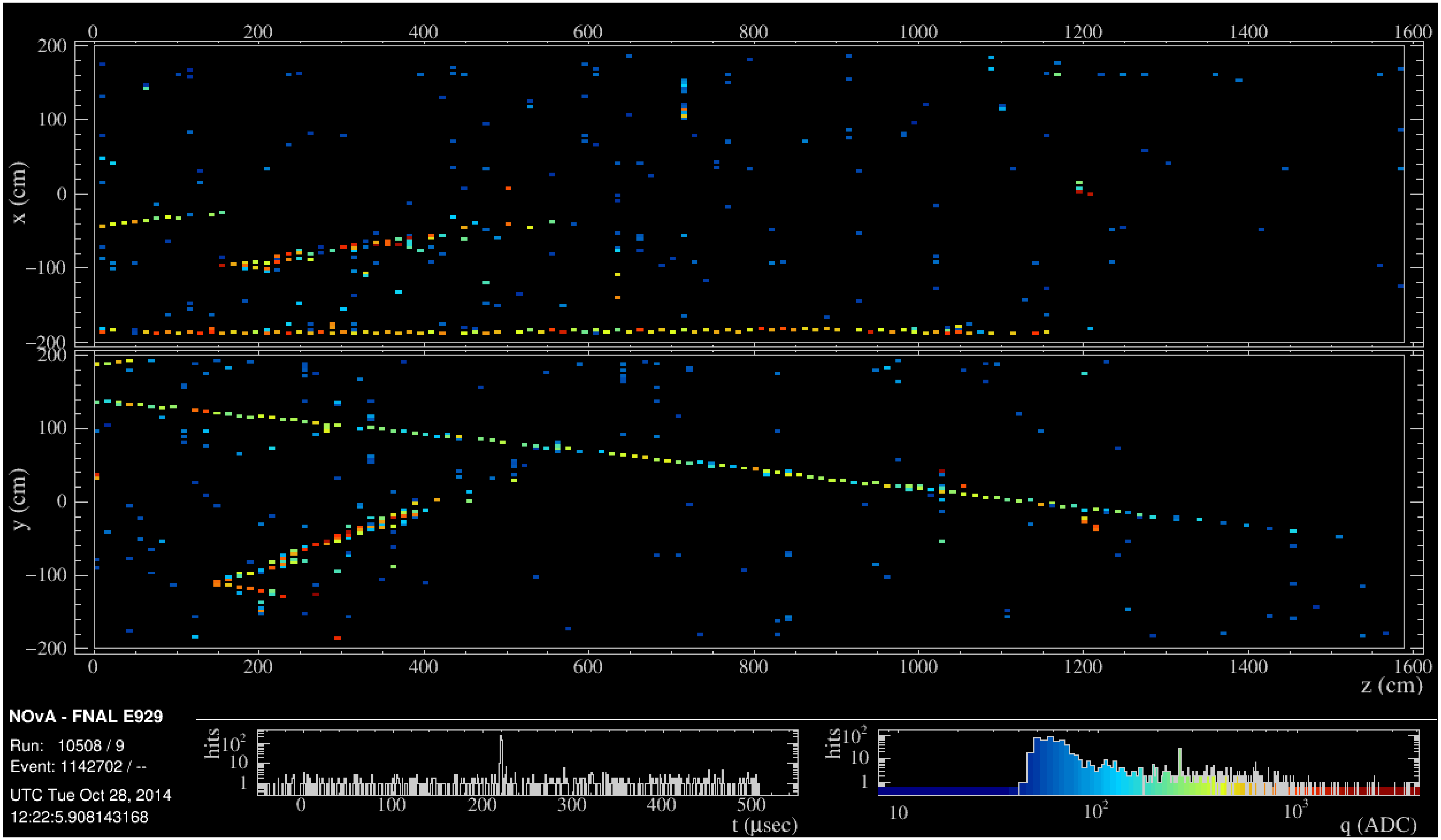
See the beam interactions by timing



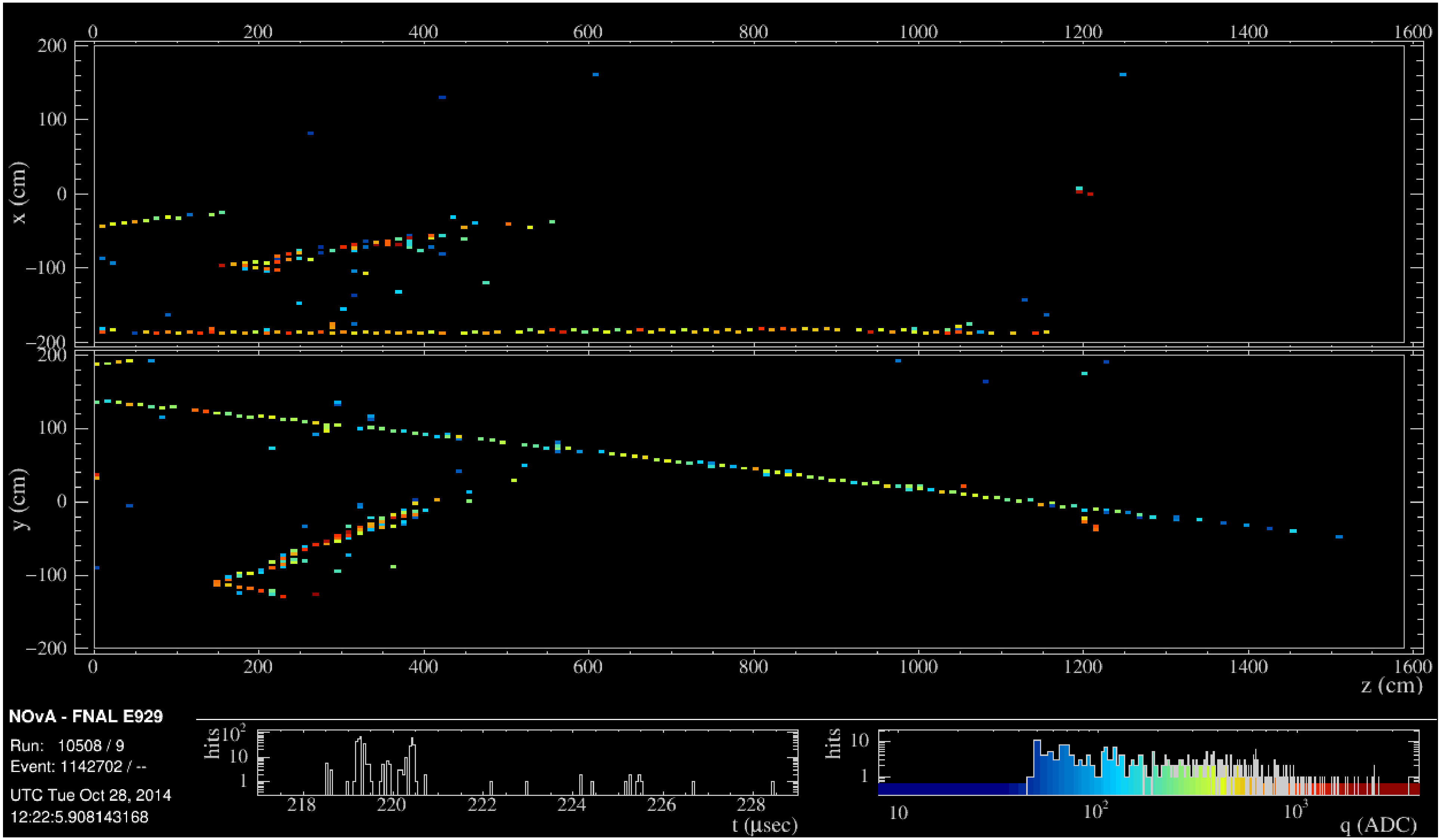




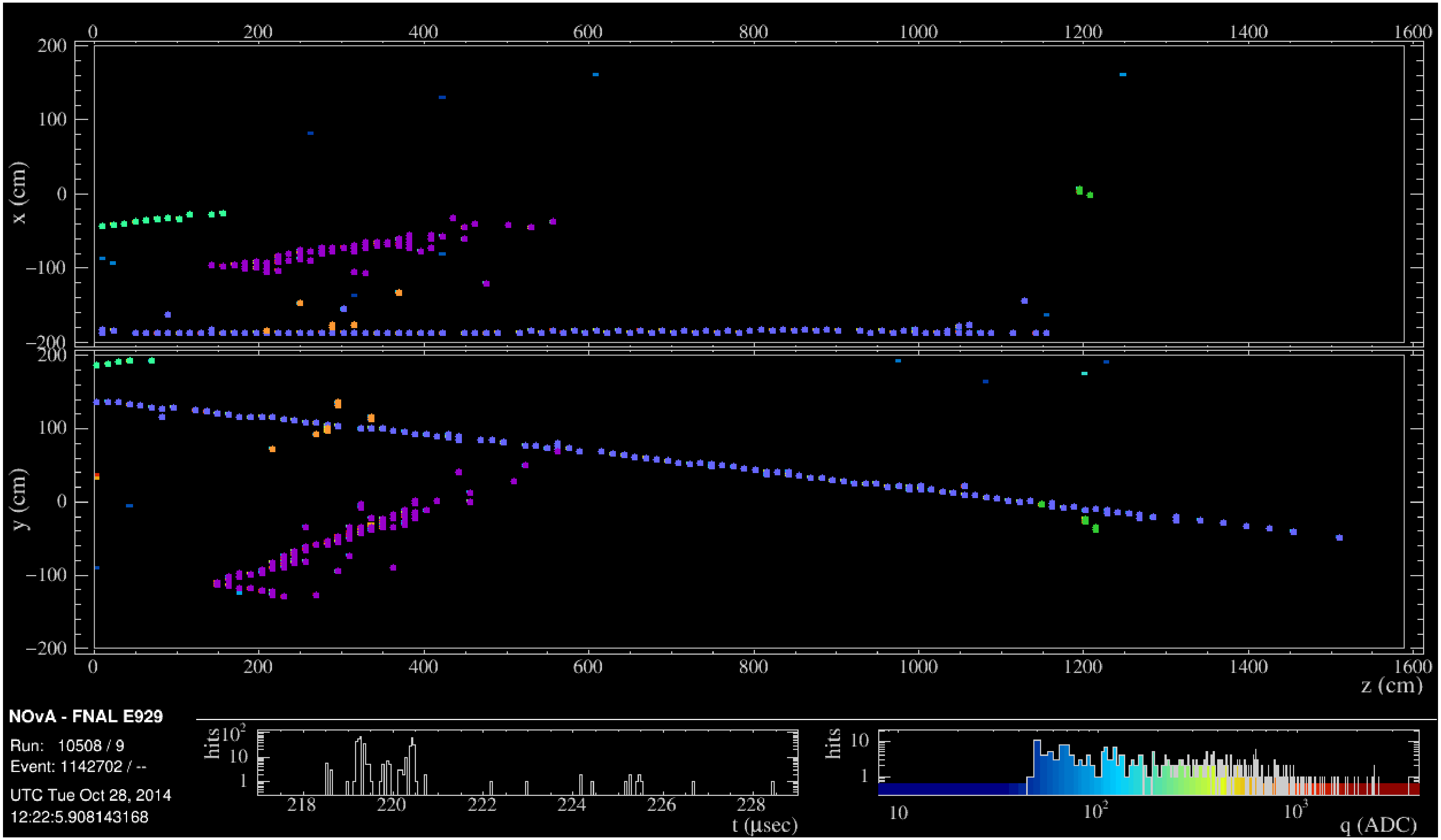
Multiple ν interactions per spill at ND



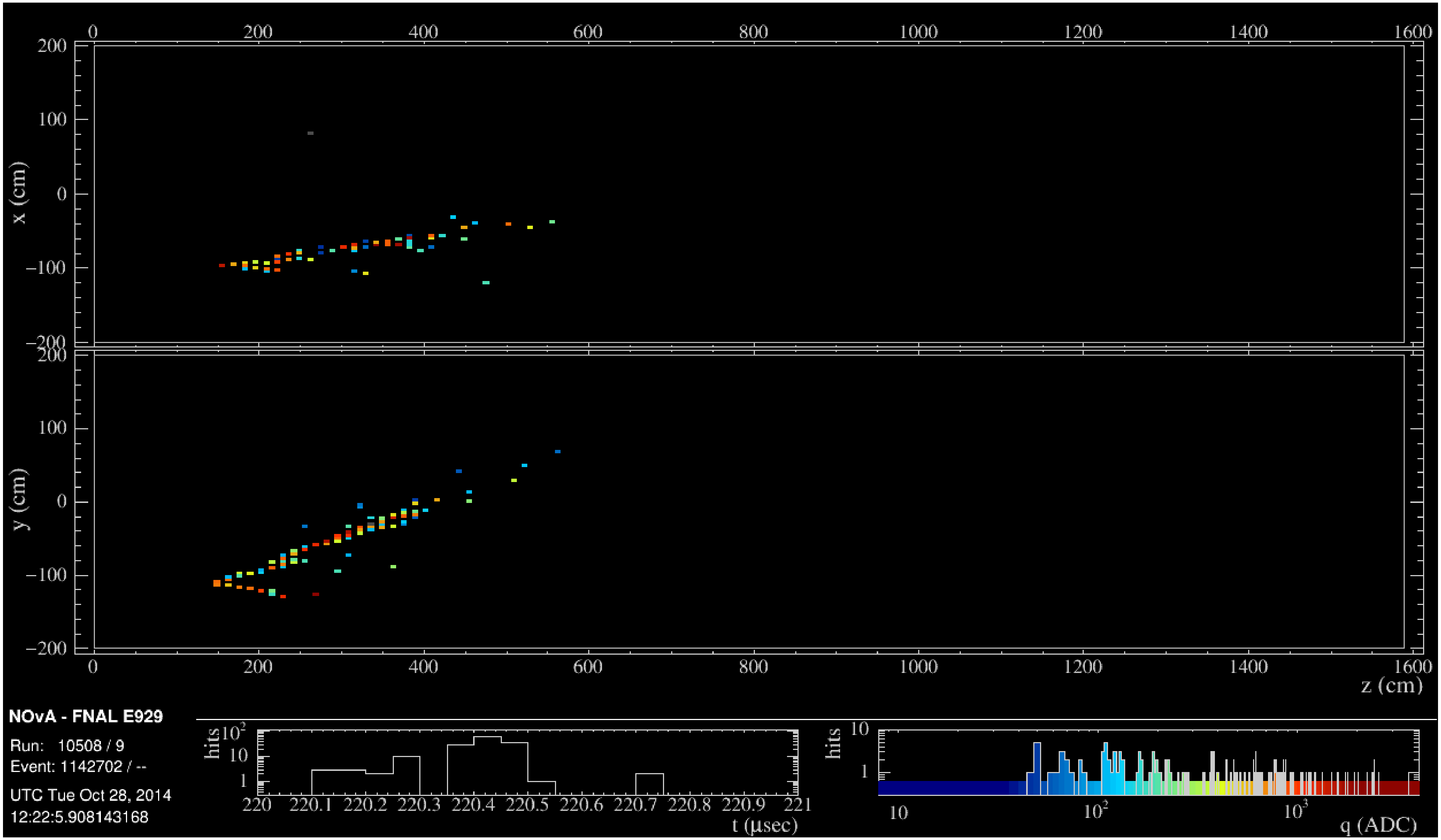
Zoom in on 10μs Beam Spill



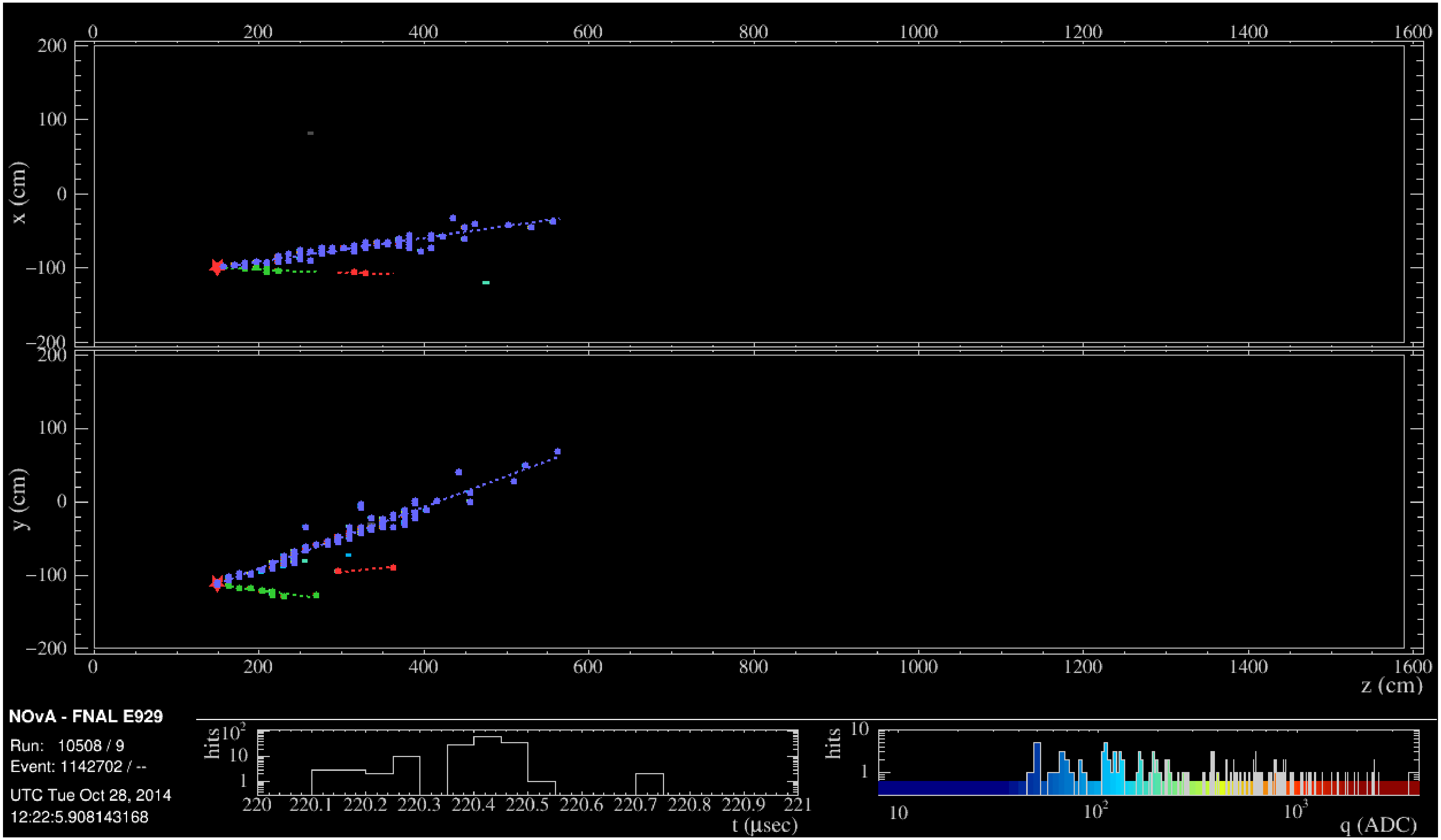
Slice by hit times



Show only one interaction

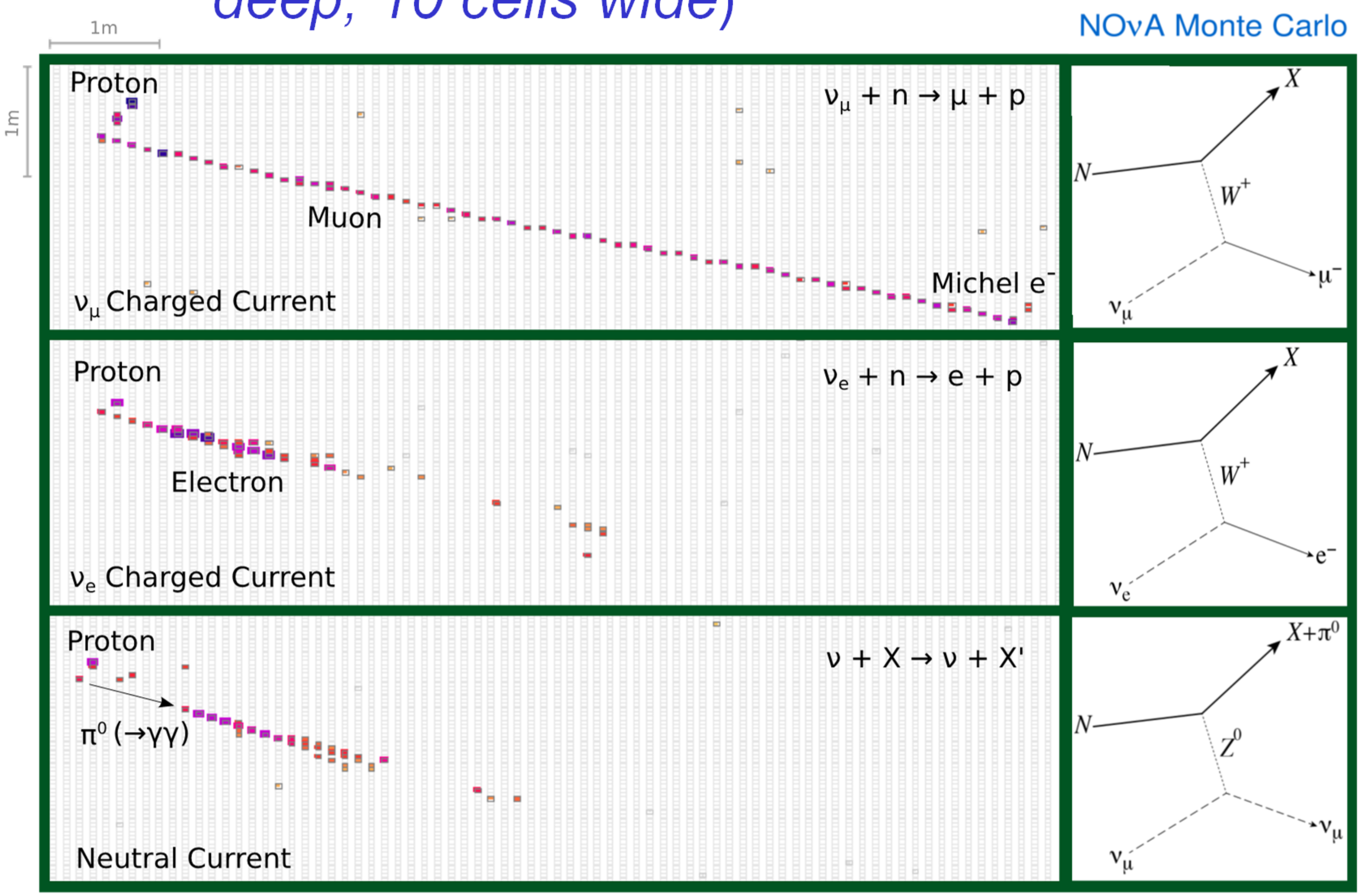


Track individual particles



How can we tell ν flavors?

- Fine granularity, radiation length is 38cm (*6 cells deep, 10 cells wide*)



muon dE/dx = 12.9 MeV/cm

Low-Z gives that long X_0, enhances γ gap between vertex and shower

What's the measurement?

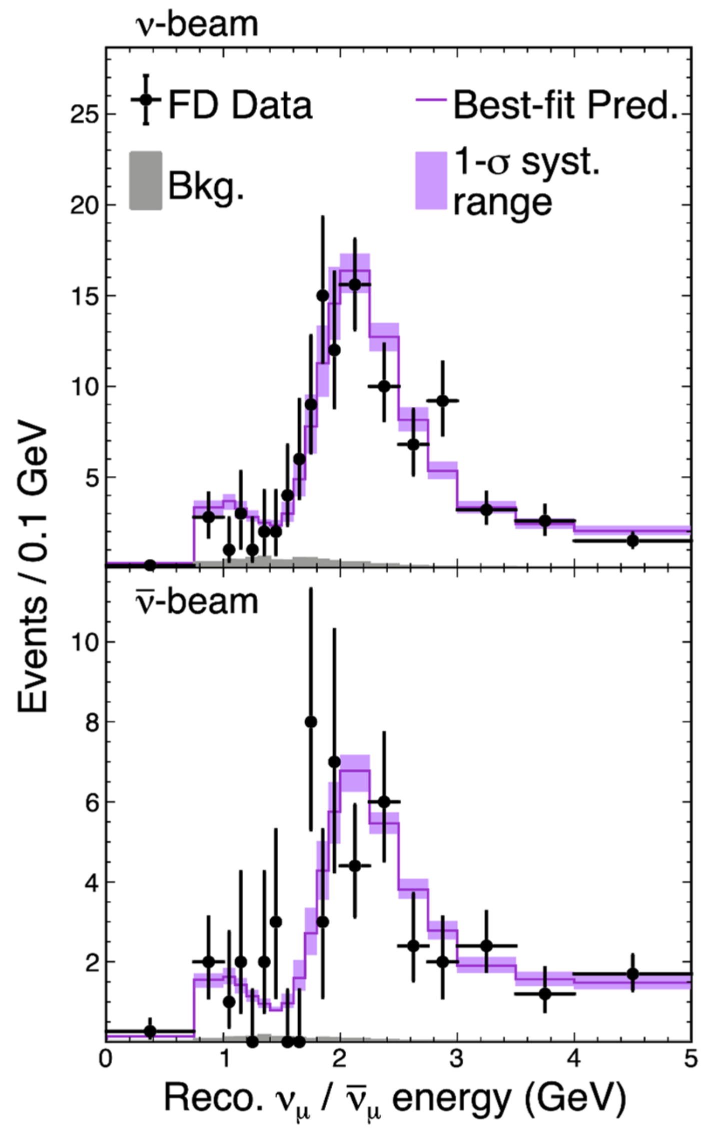
- NOνA measures $P(\nu_\mu \rightarrow \nu_e)$ and $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$ at fixed 2 GeV energy and fixed 810km baseline
  - These depend differently on the octant of θ_{23}, the sign of Δm^2, and the size of δ_{CP}
- Take data in a neutrino beam and in an anti-neutrino beam, measure the two oscillation probabilities, compare them:
  - And see what oscillation parameters the measured value best matches

3 Flavor Oscillations

- Extrapolate the high-statistics spectra observed at the Near Detector to see what you expect at the Far Detector
  - Including the "not ν_μ CC interactions" BG
  - Estimate remaining cosmic BG from data adjacent to beam spill
  - Fit for both $P(\nu_\mu \rightarrow \nu_e)$ and $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$
    - Most recently described in detail in PRD 106, 032004 (2022)

ν_μ Disappearance

- Near first disappearance maximum, so most ν_μ gone
- What's left matches the shape well with little background for both beams
  - Fit done in four energy resolution quartiles for maximum sensitivity



	Total observed	Best fit total	Signal	BG
ν_μ	211	222.3	214±14	8.2±1.9
anti-ν_μ	105	105.4	103±7	2.1±0.7

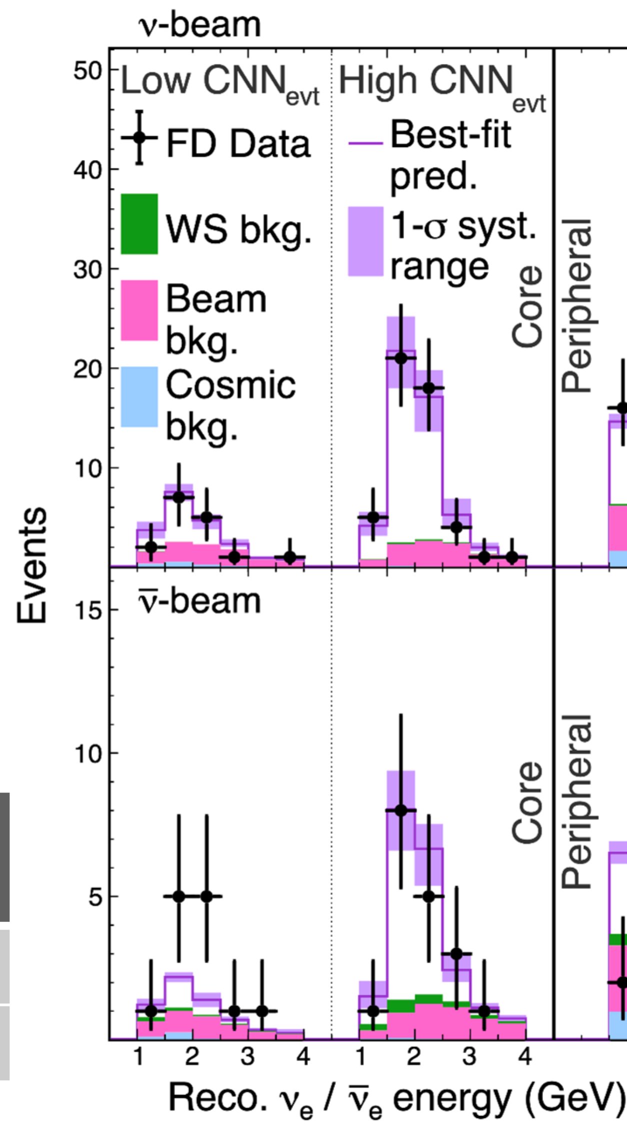
See PRD 106, 032004 (2022) Tab.III for details

ν_e appearance

- Select ν_μ and ν_e data at both ND and FD
  – Break down ND ν_e selected events into background types (*no oscillations at ND, so it's all BG!*) and extrapolate them separately to FD
  – Take observed ND ν_μ spectra, oscillate it and see which ν_e oscillation scenario best matches what's observed at the FD (broken up into resolution bins)
- Fit uses particle ID purity bins

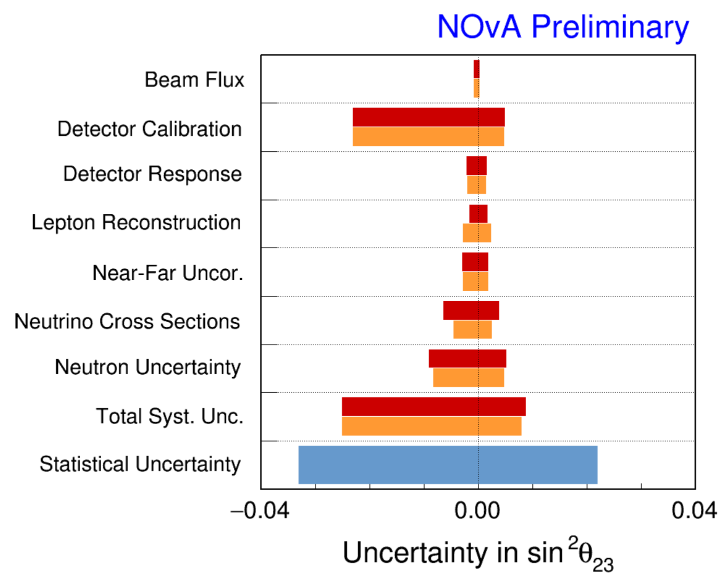
	Total observed	Best fit total	Signal	BG
ν_e	82	85.8	59±2.5	8.2±1.9
anti-ν_e	33	33.2	19.2±0.7	14.0±1.0

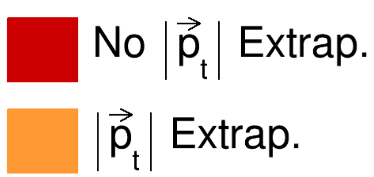
See PRD 106, 032004 (2022) Tab.III for details

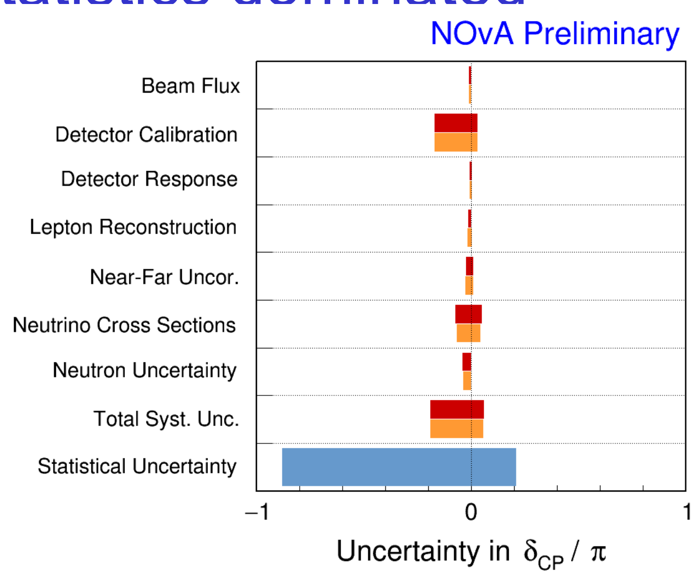


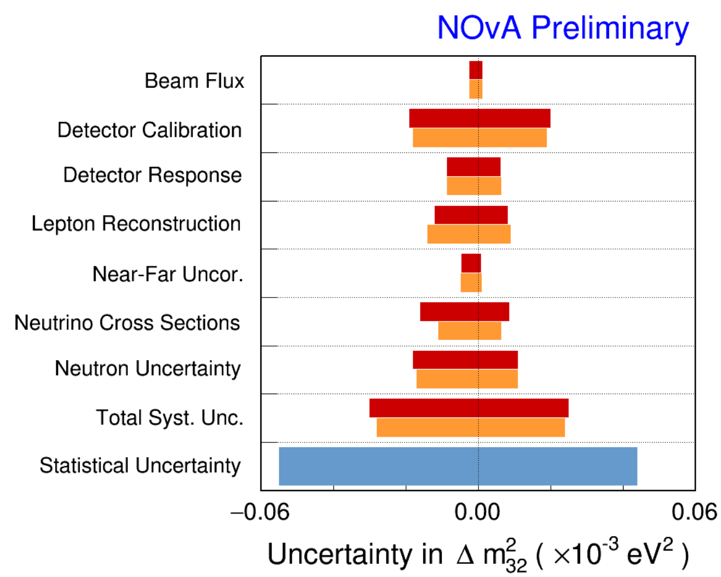
ν_μ systematics

- Systematics assessed by generating shifted sets of simulated data.
  - Can get slight improvements by extrapolating to FD in p_T bins.
  - Still statistics dominated



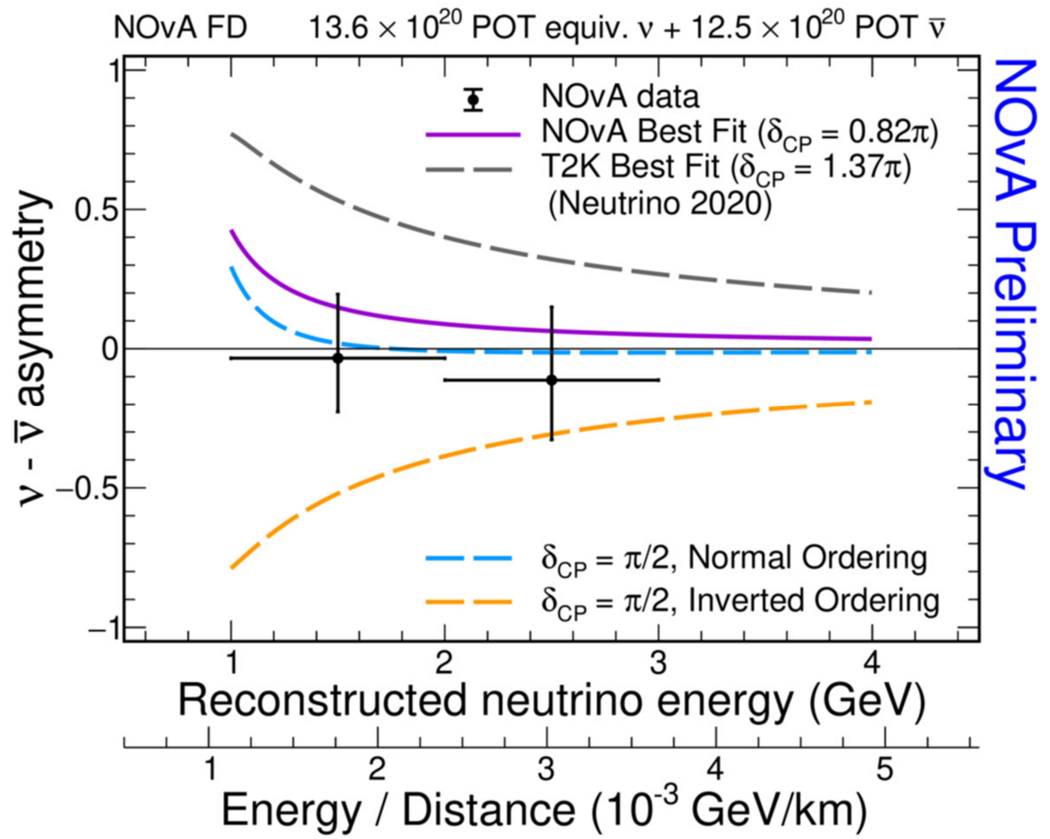






What did we learn?

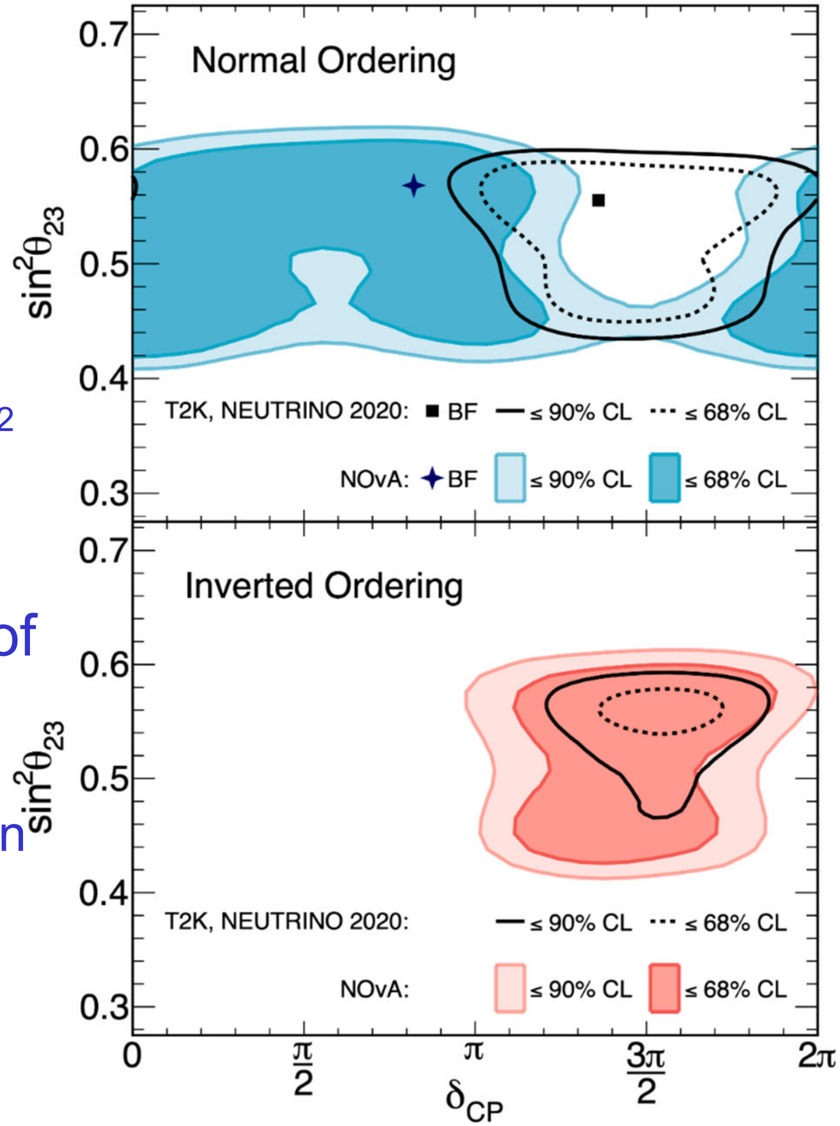
- ν_e and anti-ν_e are appearing at the same rate to 25% precision
  - Plot appearance asymmetry vs energy
  - Disfavors mass ordering/δ_{CP} combinations with large asymmetry



$$P(\nu_e) - P(\bar{\nu}_e) \;/\; P(\nu_e) \,|\!+ P(\bar{\nu}_e)$$

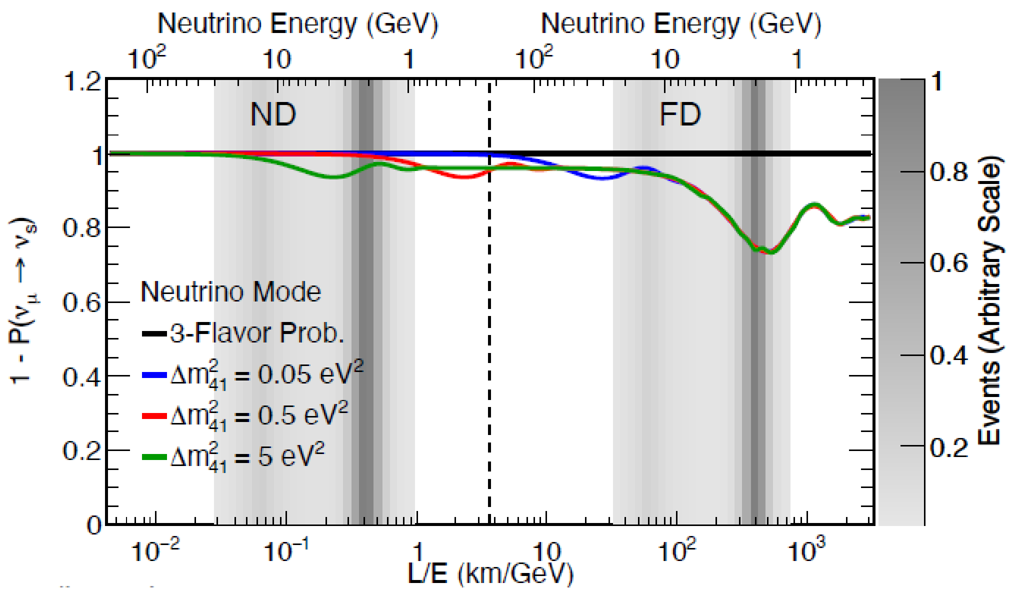
More parameters

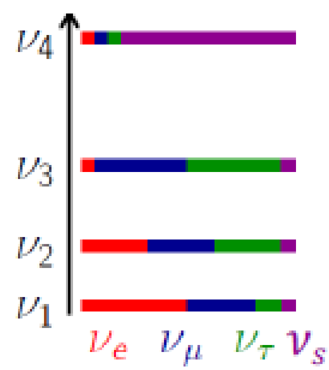
- Three-flavor frequentist approach plots of mixing amplitude vs δ_{CP} for both mass orderings
  - Best fit is NO
    - $\Delta m^2_{32}=(2.41\pm0.07)\times10^{-3}eV^2$
    - $\sin^2 2\theta=0.57^{+0.04}_{-0.03}$
    - $\delta=0.82\pi$
  - On the face of it opposite of T2K: but there's a lot of common parameter space
    - NOvA & T2K are working on a joint analysis



Sterile ν?

- Instead of extrapolating ND predictions to FD, fit both detectors simultaneously allowing for a 4th ν
  - Shape from oscillations in both detectors plus NC normalization
    - as in PRL 127 20, 201801 (2021)
  - Covariance Matrix Fit to 3+1 sterile ν model, dedicated systematics treatment ("PISCES")

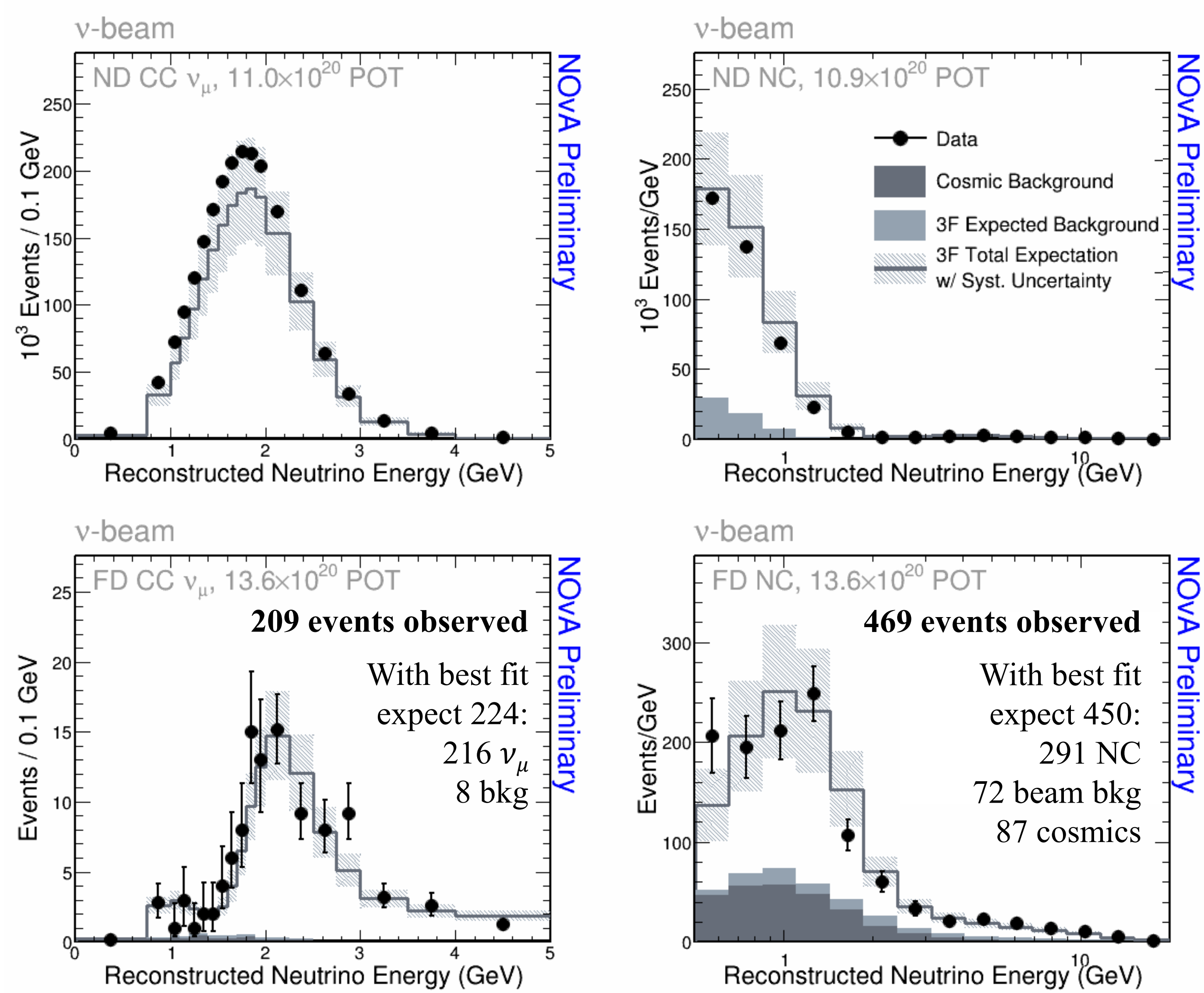




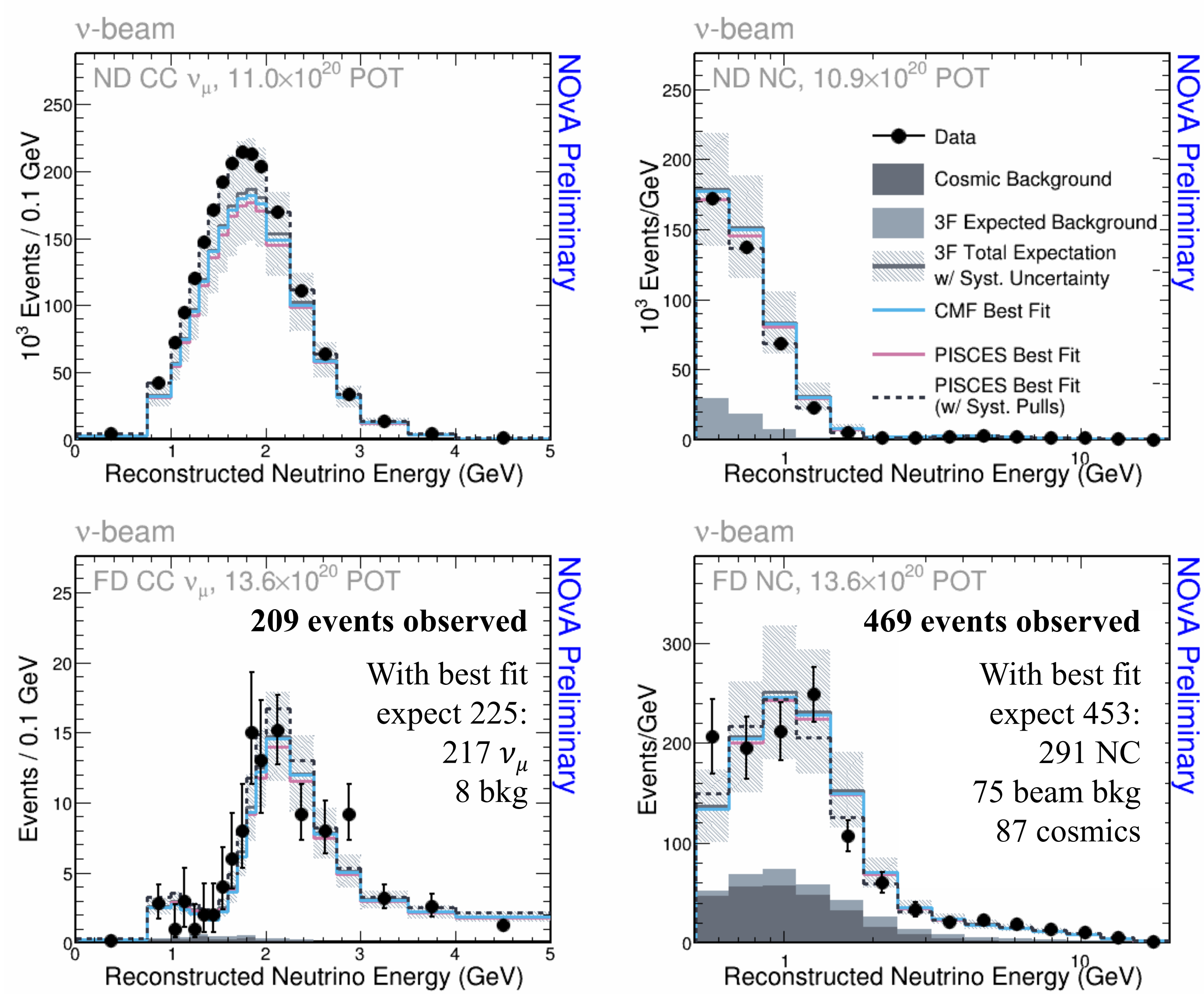
3+1 model

Add 4th mass eigenstate

Data vs. 3-flavor fit



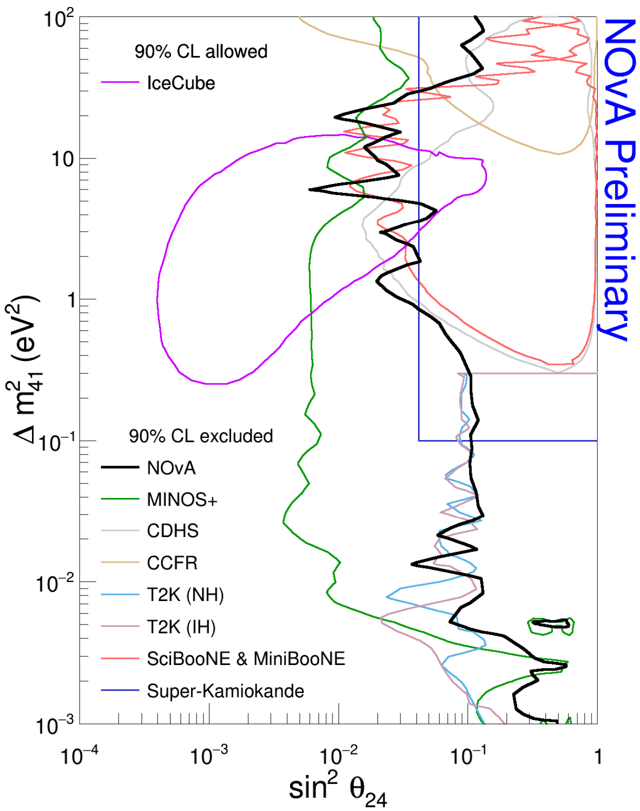
Data with best ν_s fit



ν_s exclusion plot

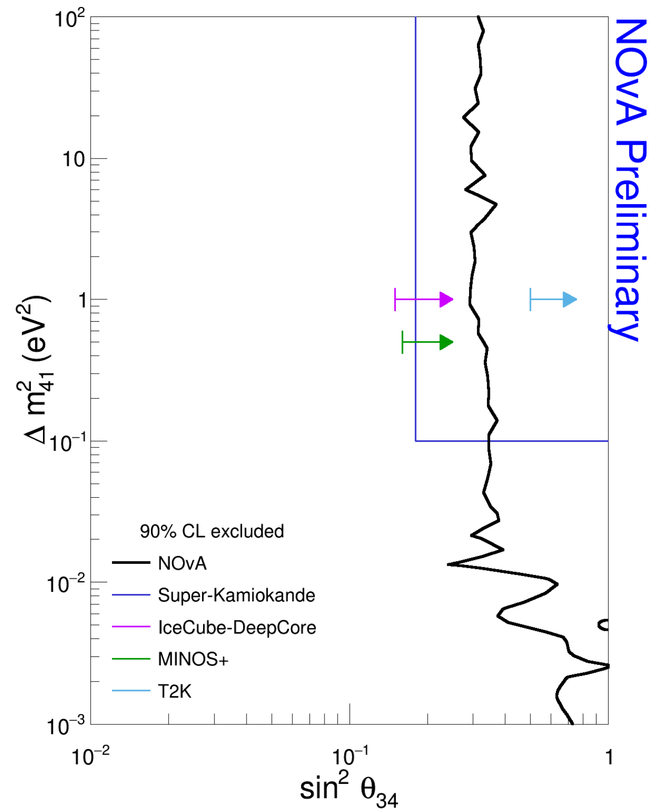
- No evidence for that sterile signal in the data
  - Doesn't fit much better than the 3-flavor version
  - Limits calculated, leading in $\sin^2\theta_{34}$, competitive at high Δm^2_{41} around 10 eV^2

Neutrino Beam



- Systematics limited at high Δm^2_{41} (high stats in ND), but FD at smaller Δm^2_{41} still stats limited

Neutrino Beam



Other Physics

- Use the high-statistics ND data set to study ν interactions:
  - ν_μ CC π^0 production Phys.Rev.D 107 (2023) 11, 112008
  - ν_e CC cross section Phys.Rev.Lett. 130 (2023) 5, 051802
  - ν_μ CC cross section Phys.Rev.D 107 (2023) 5, 052011
  - Tuning ν interaction models and evaluating uncertainties Eur.Phys.J.C 80 (2020) 12, 1119
  - ν NC π^0 production Phys.Rev.D 102 (2020) 1, 012004
- Cosmic ray production
  - multi-μ seasonal variations: in FD Phys.Rev.D 104 (2021) 1, 012014 and ND: Phys.Rev.D 99 (2019) 12, 122004
- Astrophysical:
  - Sensitive to ν from supernovae: JCAP 10 (2020) 014
  - Don't see ν from GWs: Phys.Rev.D 104 (2021) 6, 063024 and Phys.Rev.D 101 (2020) 11, 112006
- Sensitive to magnetic monopoles, DM made in NuMI target, anomalous ν MM
  - Slow Monopoles: Phys.Rev.D 103 (2021) 1, 012007
  - Rest in progress…

See Yiwen Xiao's talk #51 Wed@16:00 on $\nu \rightarrow e$ scattering

Coming Improvements

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- In addition to more exposure:
  - Test beam experiment recorded known particles of known energies in a mini-NOvA, ongoing analysis is directly addressing some of the largest systematic errors
- Old data will be reprocessed using improved reconstruction, improved ν interaction models, improved detector simulations
- NOvA/T2K continue to work on joint analysis
- Shooting for summer of 2024 for next results

Thank you!

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