A first look at NOvA's upward-going muon trigger data

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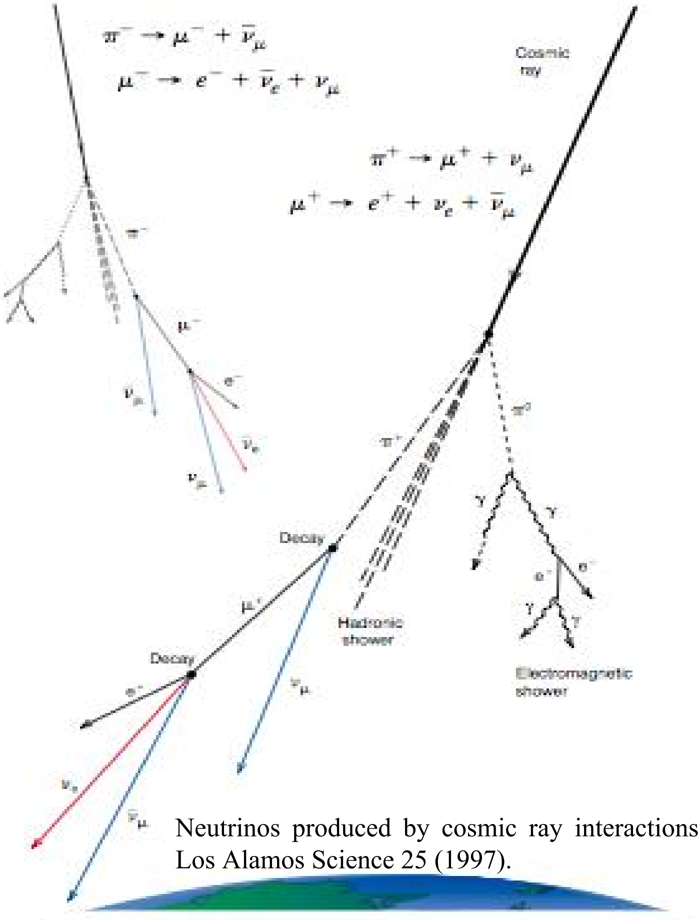
The NOvA Program

- NOvA (NuMI Off-axis ν_e Appearance) is a two-detector accelerator neutrino oscillation experiment that uses Fermilab's NuMI, the most intense high-energy neutrino beam on the planet.
- It will say something about the θ_{23} octant, Δm^2_{23}, and δ_{cp}.
- But I'm going to talk about **something else entirely**.

Atmospheric neutrinos

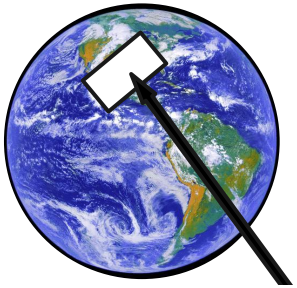


Neutrinos produced by cosmic ray interactions, from Los Alamos Science 25 (1997).

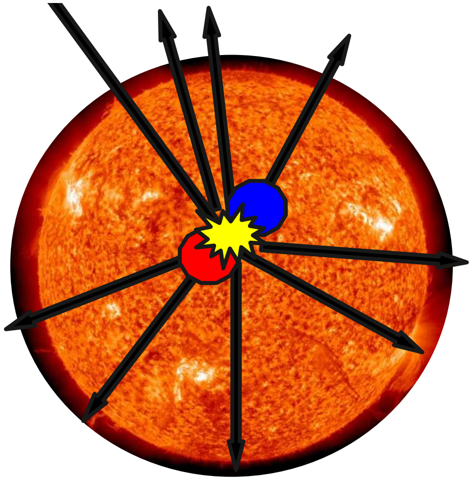
High-energy cosmic rays interact in Earth’s atmosphere and produce particles that decay into neutrinos (among other things).

It is well established that atmospheric neutrinos oscillate[1]. We should see this oscillation in NOvA.

WIMPs



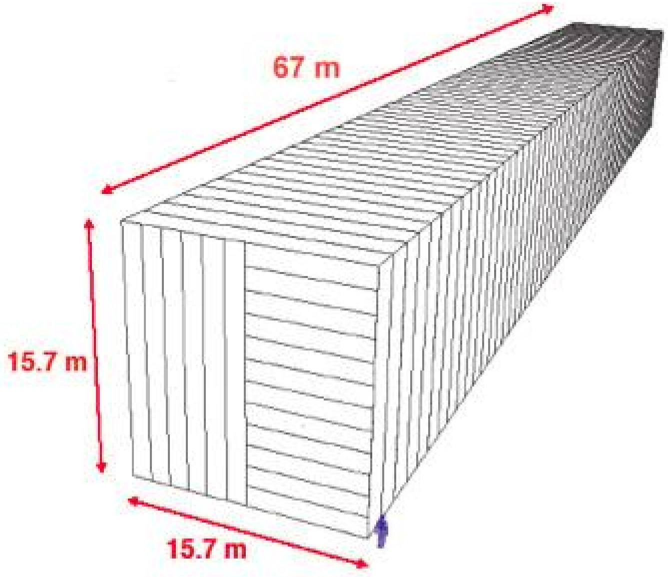
WIMPs annihilate in the Sun, producing neutrinos, some of which may be detectable on Earth.



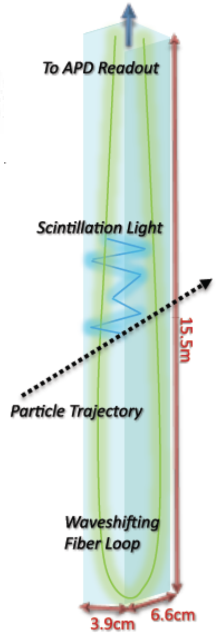
- Dark matter contributes about 25% to the energy density of the observable universe, while “normal” (Standard Model) matter contributes only about 4%[2].
- One important class of theoretical candidate particles for Dark Matter is the Weakly Interacting Massive Particle (WIMP).
- WIMPs can become trapped in the gravitational well of the Sun, where they annihilate at a rate equal to the capture rate. These annihilations produce a neutrino signal to which NOvA may be sensitive.

The NOvA Far Detector

- Located 14 mrad off-axis of the beam, 810 km from the source, in Ash River, MN.
- Large - 14 kTon - highly active scintillating tracking calorimeter.
- Fine spatial granularity (~3cm) and time resolution (~10ns) → an **excellent muon tracker** (among other things).
- > 300,000 independently active channels, each read out at 2×10^6Hz → **very high data throughput**.

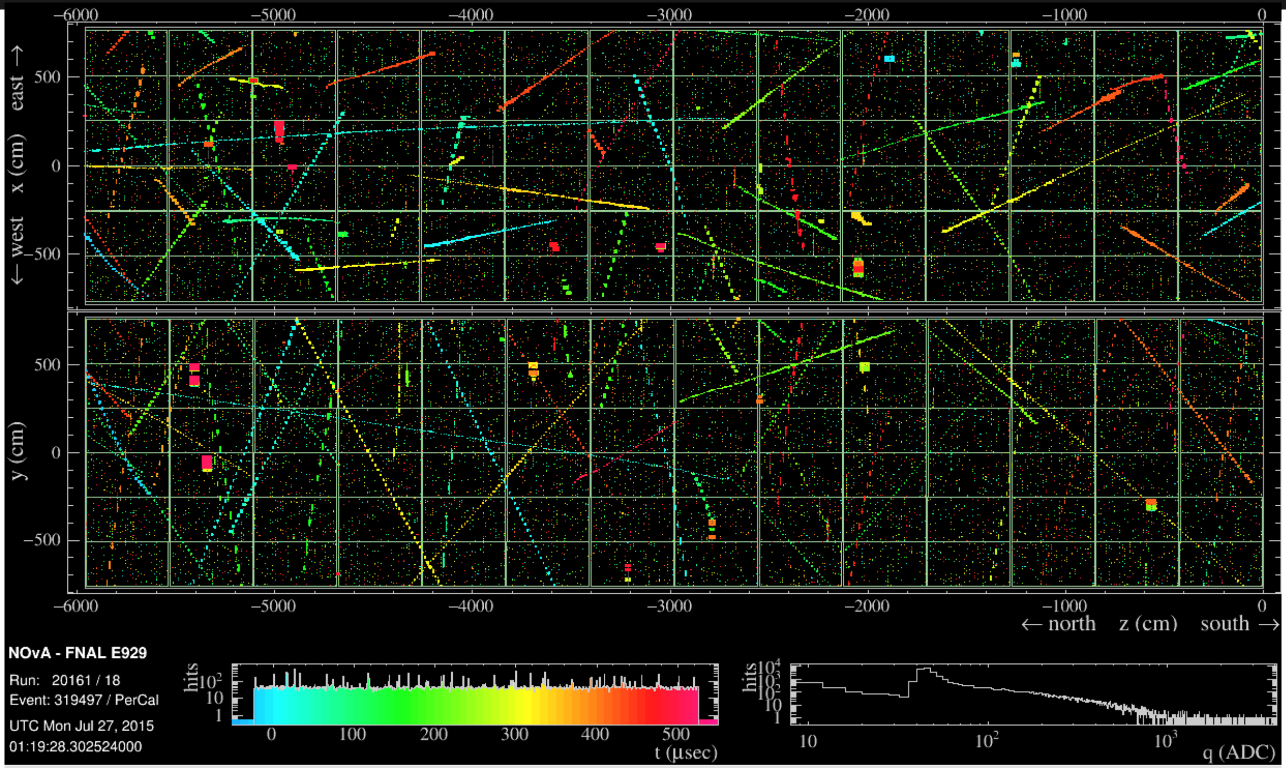


NOvA's alternating planes allow particle tracking in 3D.



A NOvA cell

The NOvA UpMu Trigger



A 550 μsec exposure of the far detector showing the high rate of cosmic ray muons.

- The rate of downward-going muons from cosmic ray interactions is very high (~100kHz) in the far detector because it is on the surface.
- **Upward-going muons are relatively rare.** The expected rate of upward-going muons from cosmic ray-induced neutrinos is ~1 per day.

The NOvA UpMu Trigger

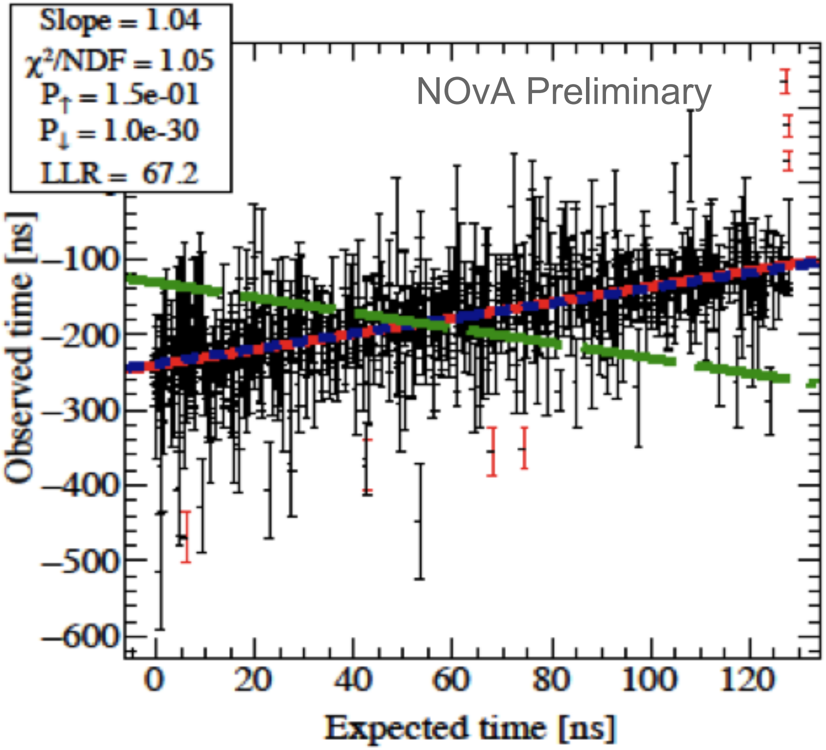
- To say anything about these atmospheric neutrinos, NOvA must overcome this (cosmic) **background-to-signal ratio of ~10^{10}**.
- Predictions of the WIMP neutrino flux are often quite small even compared to the atmospheric neutrino flux (which is a background in the indirect dark matter search).
- Data storage and processing is expensive, so we can't afford to record every muon track.
- We have written two upward-going muon triggers to produce signal-enriched samples:
  - *The "through-going" trigger is optimized to search for through-going muons from interactions in the rock surrounding the detector.*
  - The "contained" trigger searches for muon tracks from neutrino interactions within the detector.

General strategies for reducing cosmic background

Neutrino experiments employ several methods to select “interesting” upward-going muons:

- geometric veto - Cosmic ray muons originating outside the detector must travel through the top or sides. Vetoing events with activity near the edges of the detector will eliminate this class of background. The contained trigger searches for fully contained events, but **the through-going trigger can’t use this**.
- topology - particular signal interactions often produce distinctive event topologies in detectors. This search can benefit especially from vertex-finding and Michel electron identification. **Work is ongoing to exploit these features.**
- **timing** - a finely segmented detector with sufficiently small hit time resolution (eg. NOvA) can use hit timing along a track to infer the direction of the particle. **This is the primary strategy used in this search.**

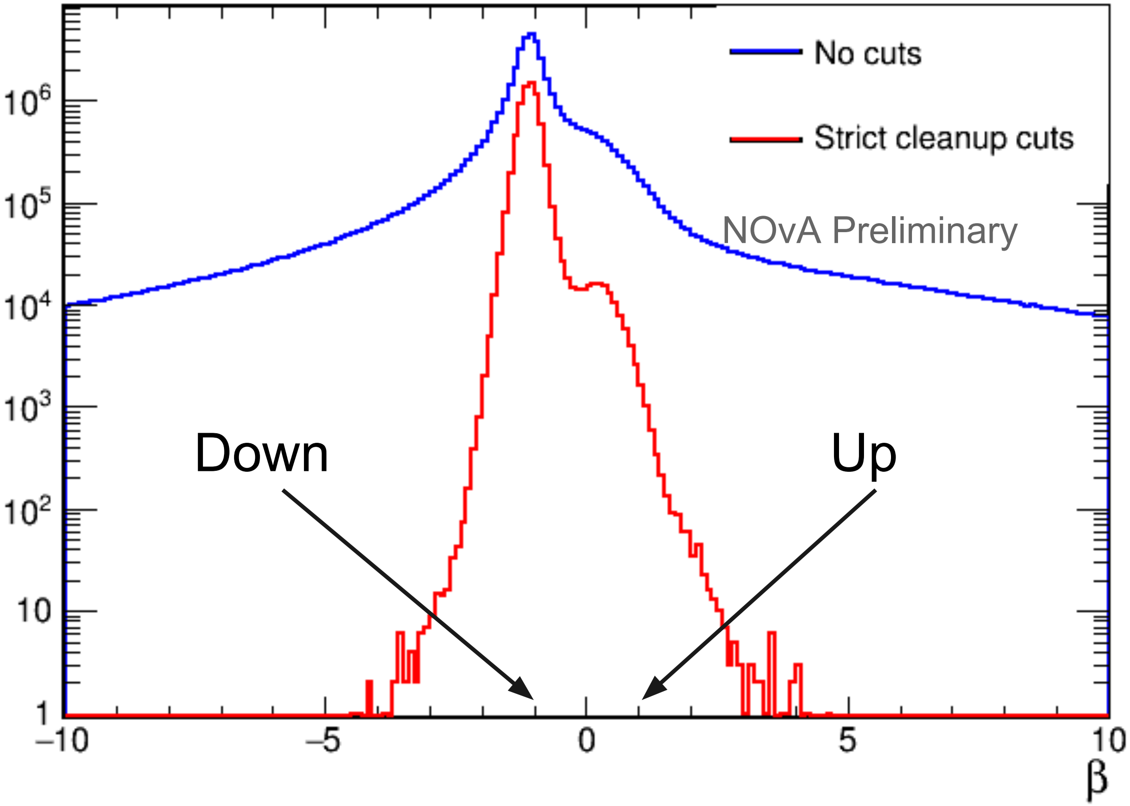
β



The measured times vs expected times for cell hits along a promising upward-going muon candidate. Uncertainties are taken from a parameterization of single-hit timing resolution as a function of energy.The best-fit slope (β, red line) of 1.04 indicates a likely upward-going particle.

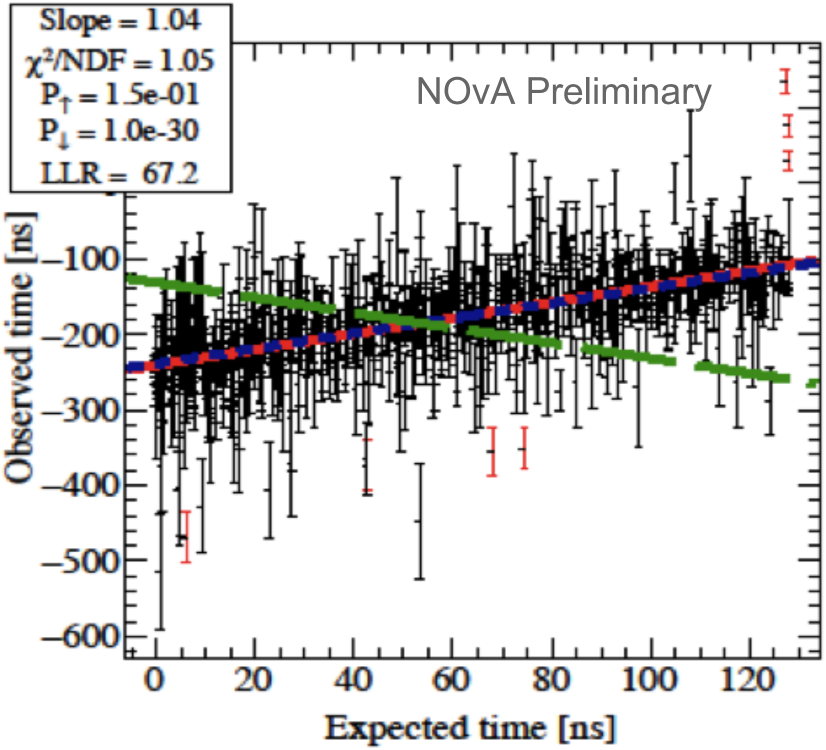
- To determine directionality, we calculate a speed, *β,* for each muon-like (linear) track, normalized by *c*. 1.0 means upward-going and -1.0 means downward-going.
- This is simply the slope from a linear fit to the measured times of the track cell hits vs the expected times assuming an upward-going relativistic particle.

β



Even with strict cleanup cuts designed to maximize the discriminating power of *β*, we cannot achieve separation between downward- and upward-going muons in the data. A more powerful discriminator is needed.

Log Likelihood Ratio



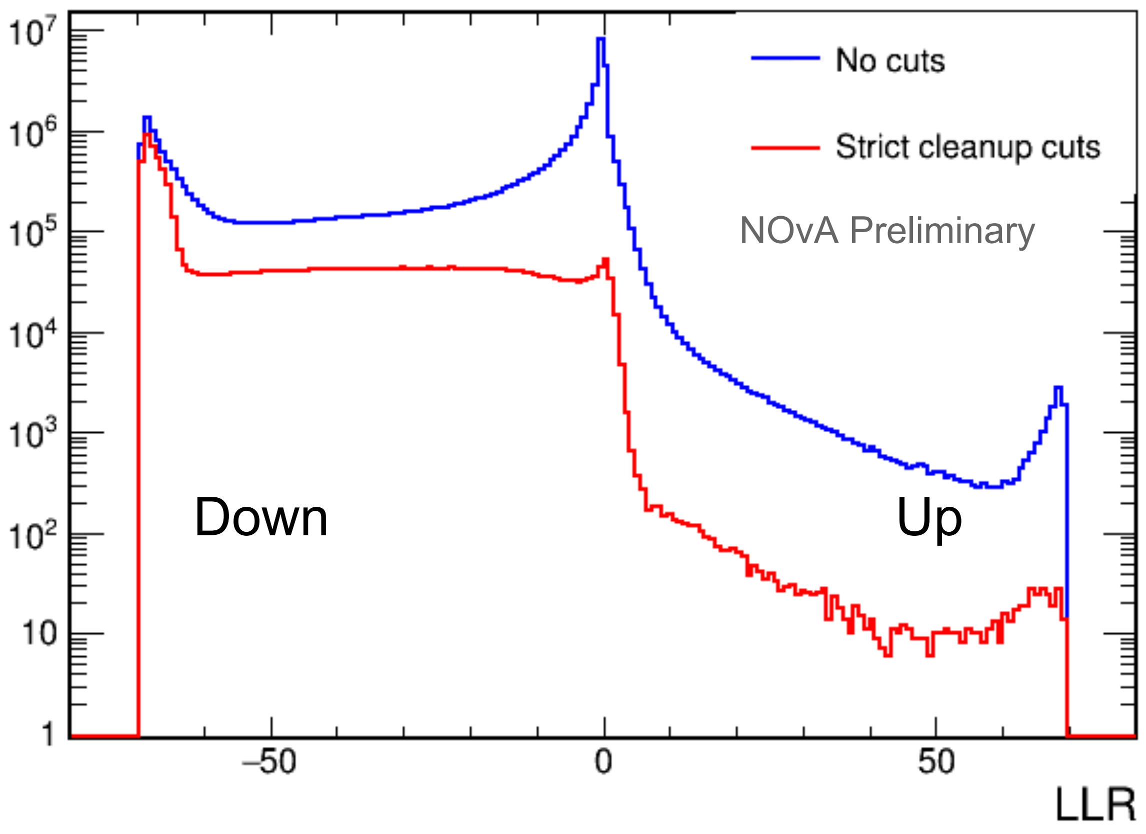
The measured times vs expected times for cell hits along a promising upward-going muon candidate. The fit with slope 1 is in blue and that with slope -1 is in green. The LLR of 67.2 indicates a likely upward-going particle.

If a track is not perfectly horizontal (we place a minimum on the absolute value of ΔY), then the true value of β is either 1 or -1.

We leverage this simplifying constraint using the LLR:

- Perform a linear fit to the measured vs expected times with a fixed slope of 1
- Perform another fit with a fixed slope of -1
- Calculate the probability of each fit using the χ^2. Set a nonzero minimum for the probabilities (10^{-30}).
- LLR = $\ln(\text{Prob}_{up} / \text{Prob}_{dn})$
- LLR close to 0 means the track was neither conclusively upward- nor downward-going.

LLR



Combined with cleanup cuts, the LLR provides a powerful discriminator for track directionality. The drop of 3 orders of magnitude between tracks with negative (downward-going) and positive (upward-going) LLR reflects this.

UpMu sample

Today we’ll take a first look at some of the data taken by the “through-going” trigger, which fires at ~1 Hz, thus reducing the background in the triggered sample by ~5 orders of magnitude.

The sample consists of 695 runs spanning a period of 164 days with total livetime 83.98 days.

Selecting candidates

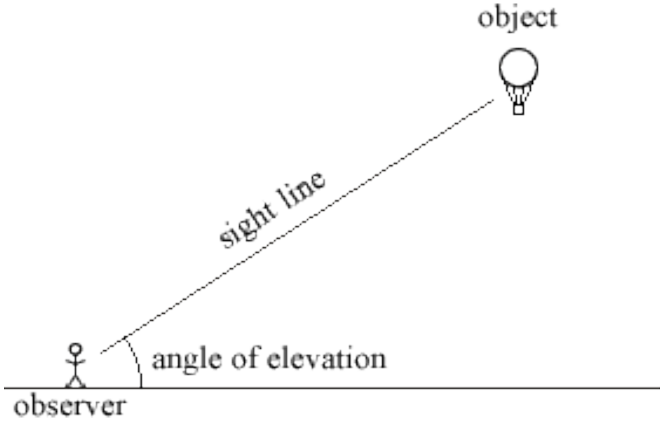
To select upward-going candidates from this sample (which contains ~43 million tracks), I began with cuts used in the trigger, and tightened the requirement on LLR:

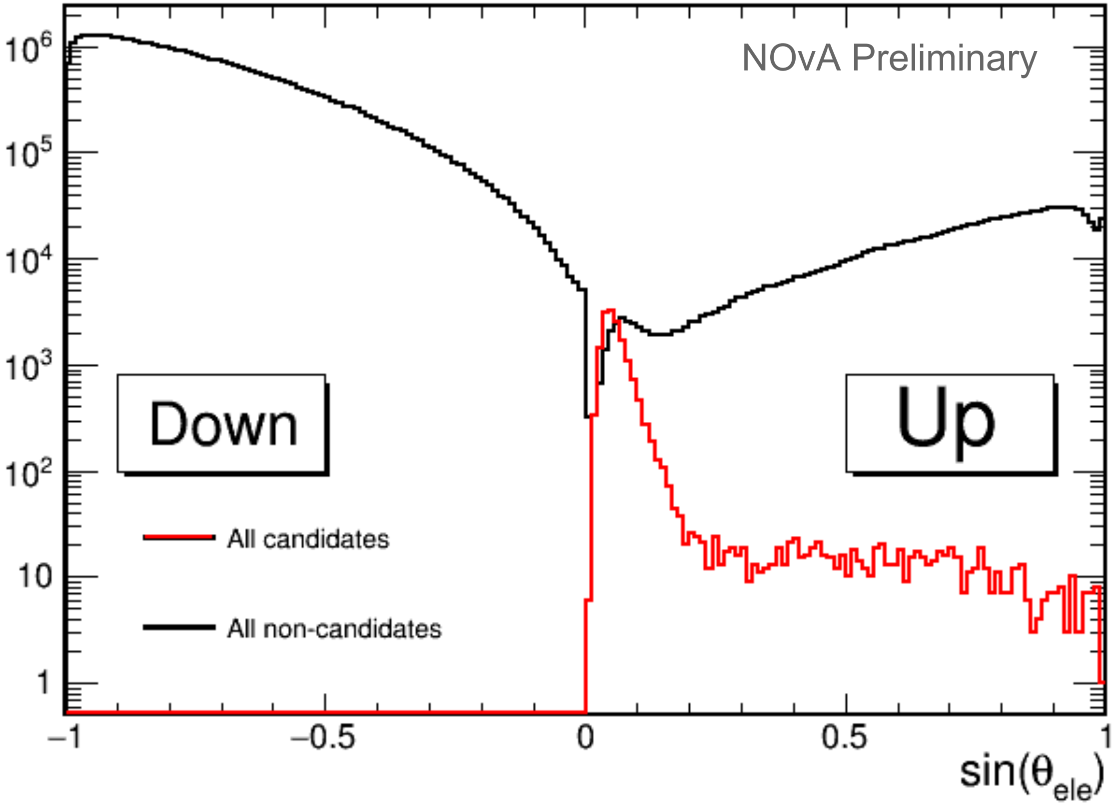
- Length > 5m
- ΔX > 5 cell widths
- ΔY > 10 cell widths
- ΔZ > 5 plane widths
- LLR > 10
- LLR per view > 5
- 0 < best-fit β < 2
- χ^2 of linear fit mT vs eT < 1.5
- R^2 of linear fit to X, Y vs Z per view > 0.99
- Number of hits used in timing fits > 60
- Number of hits per view used in timing fits > 15

Elevation angle

Most of the candidate tracks are horizontal.

Cosmic ray muons travelling slightly upward but mostly horizontally pass the timing cuts. This is the primary component of the candidate pool with elevation angles below 10°. The “interesting” signal should be easier to extract in the region with higher elevation angle.

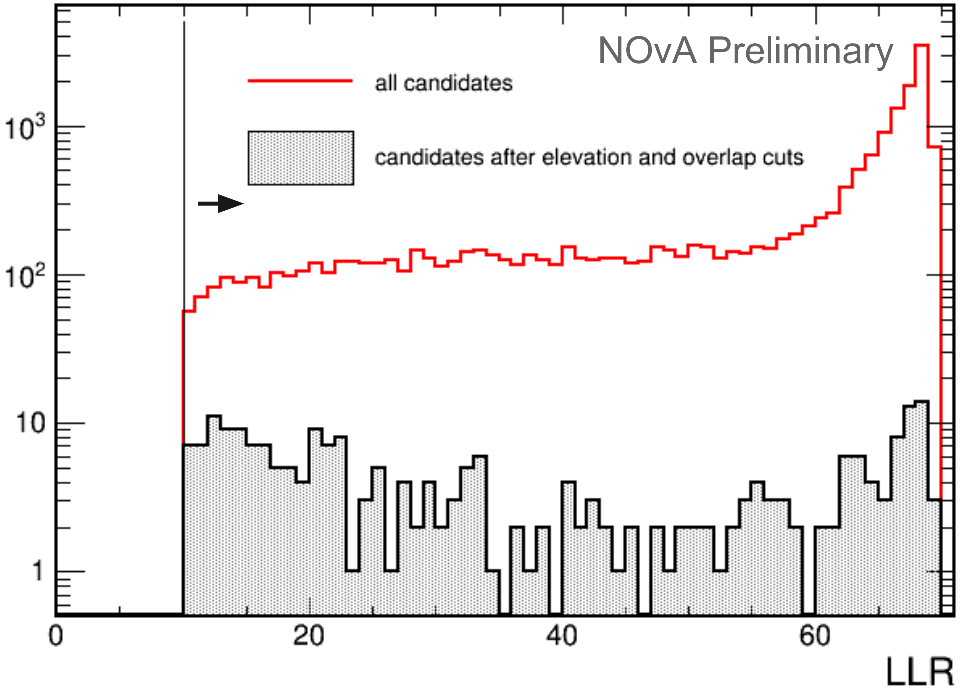




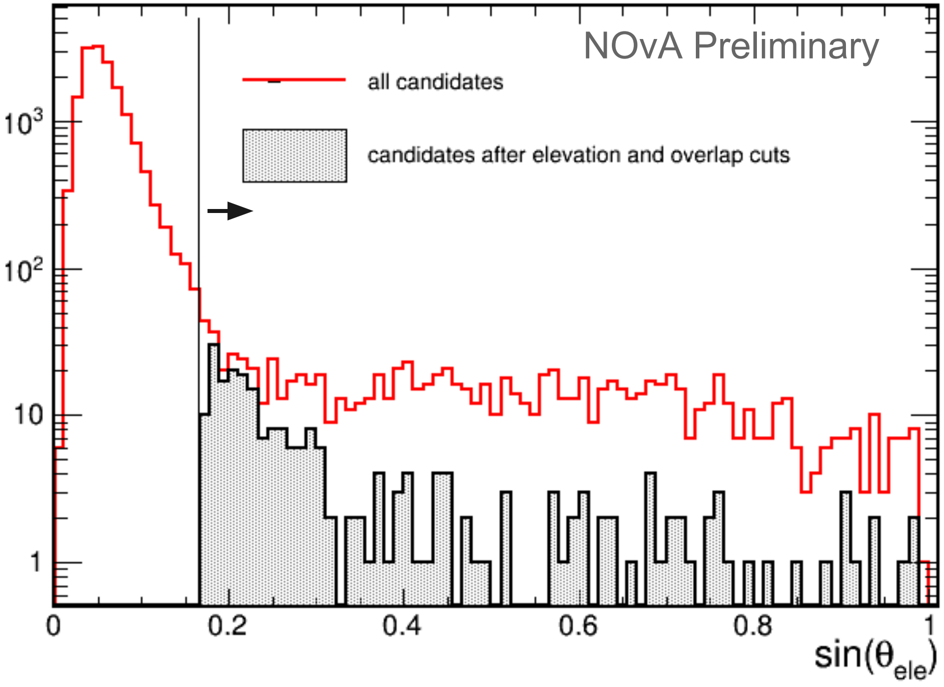
Timing + Geometry

Combining the timing information from the LLR with a cut on elevation angle, I further reduced the pool to 1,051 tracks. Of those that remain, ~75% are not conclusively upward-going due to a misreconstruction in which two unrelated overlapping muon tracks make reconstruction tricky.

This class of misreconstruction was mostly eliminated using a simple “overlap” cut, leaving 255 tracks. This represents a reduction of ~3 billion to 1 in the number of muons, with the trigger and these cuts combined.


NOvA Preliminary
all candidates
candidates after elevation and overlap cuts
10^3
10^2
10
1
0
20
40
60
LLR

[redacted]


NOvA Preliminary
all candidates
candidates after elevation and overlap cuts
10^3
10^2
10
1
0
0.2
0.4
0.6
0.8
1
$\sin(\theta_{ele})$

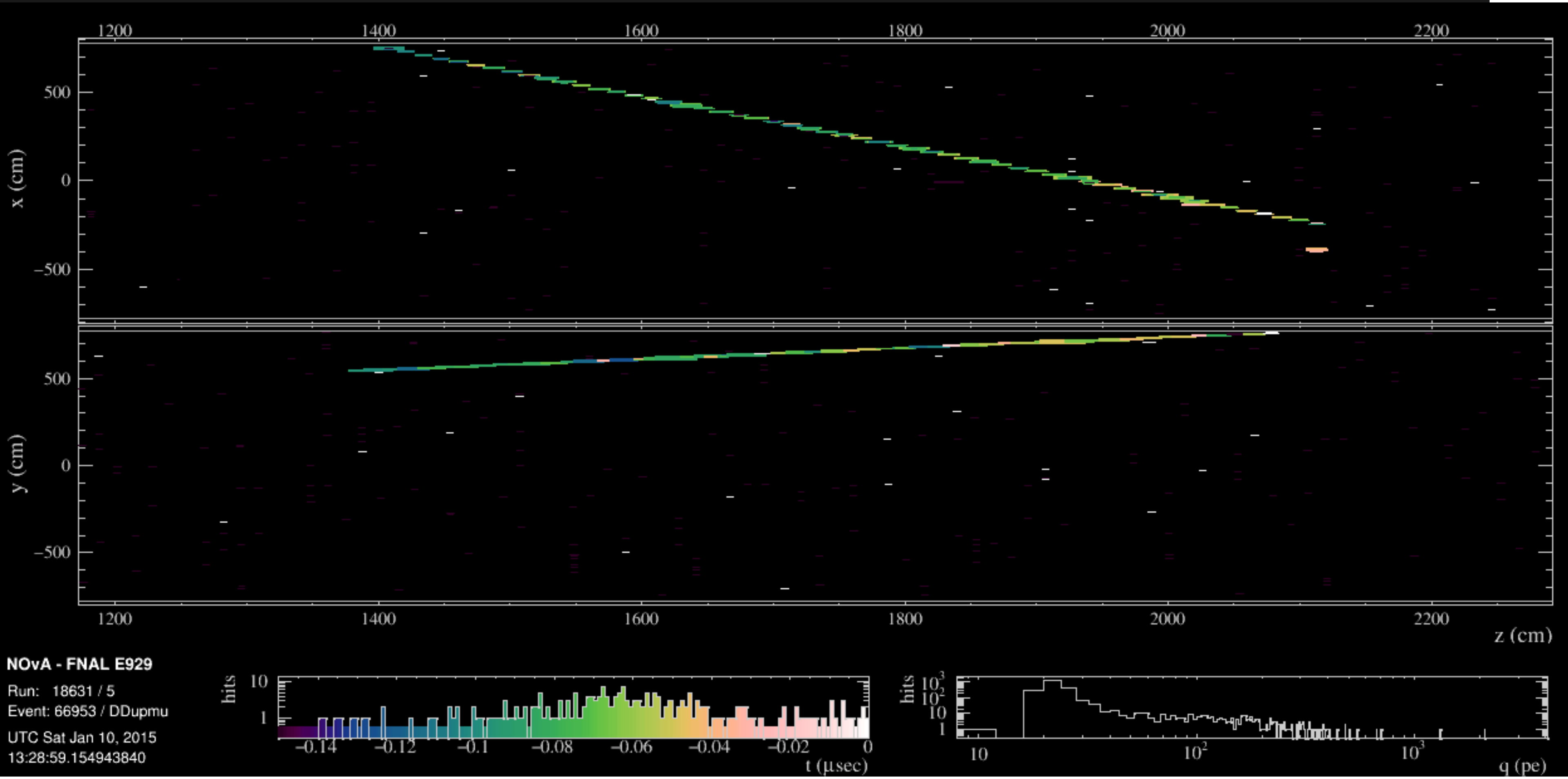
Visual search

I visually examined each of these candidate events, categorizing them:

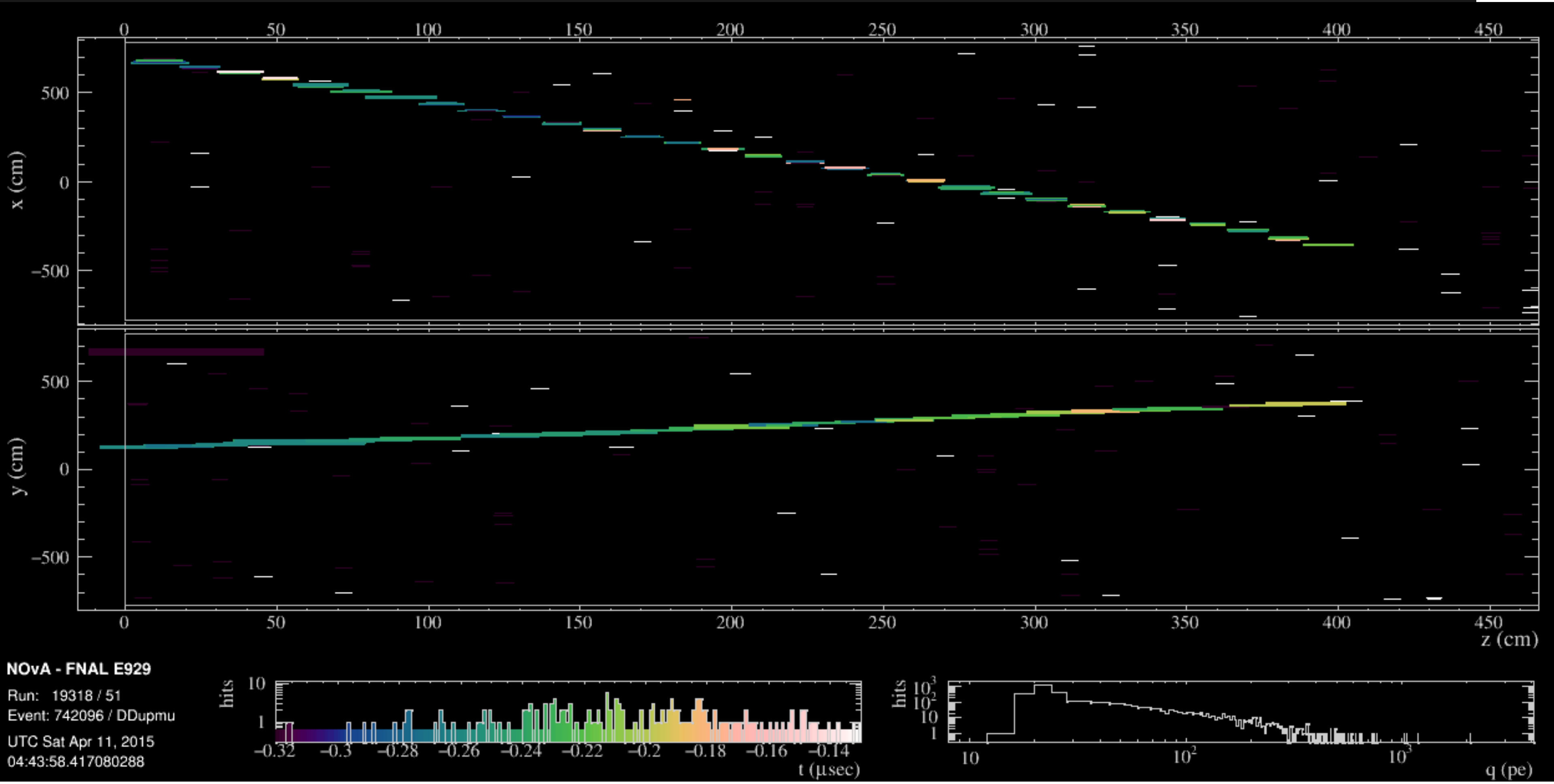
Through-going:	105
Stopping (seemingly upward-going):	75
Overlapping muons:	34
Up-scattered (within the detector) cosmics:	23
Likely downward-going (backup):	1
In-produced:	1
Likely caused by a temporary timing miscalibration:	14*
Uncategorized (backup):	2

* do not appear in the following plot

Through-going

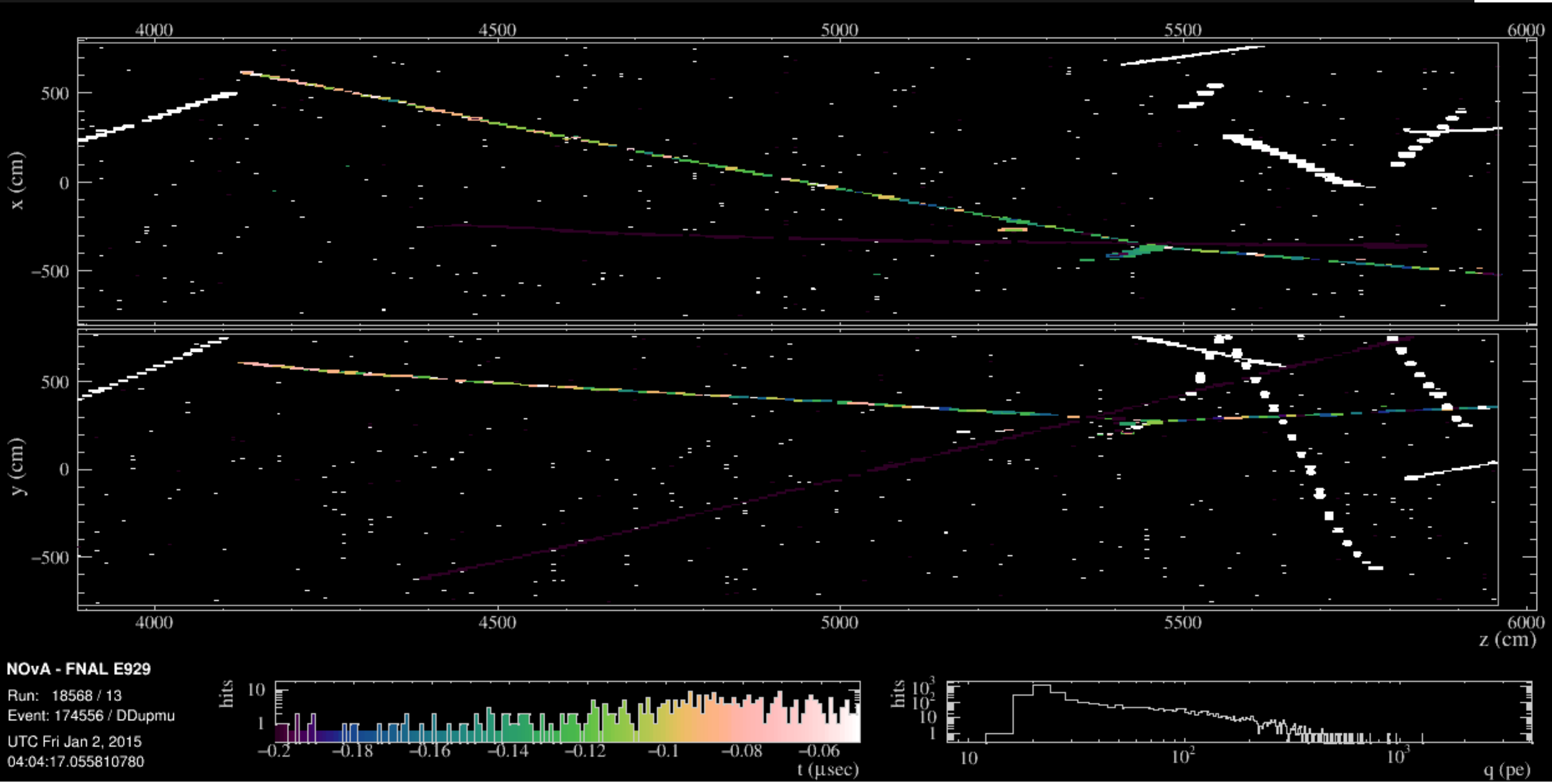


Stopping



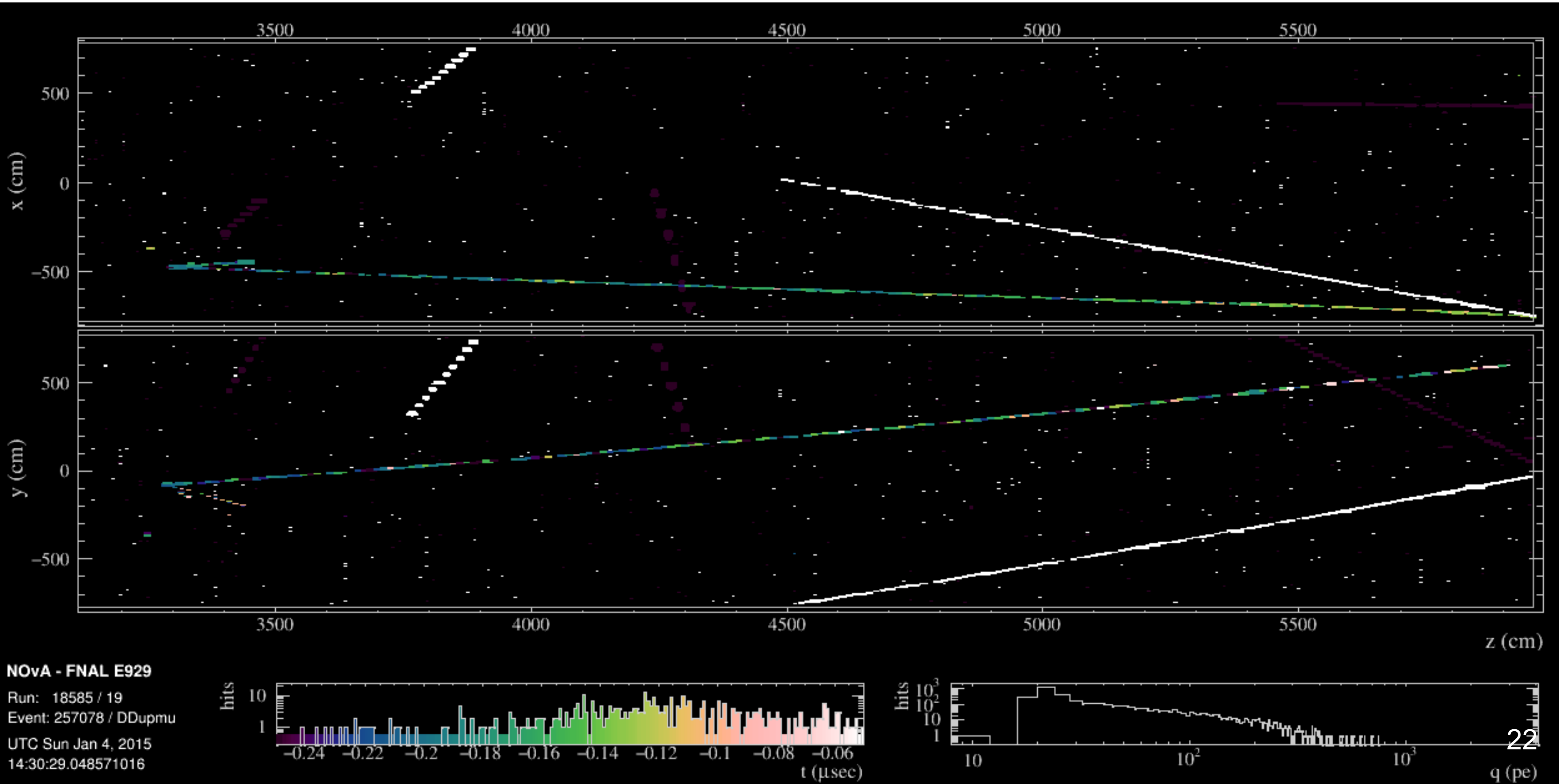
x (cm)
y (cm)
z (cm)
0
50
100
150
200
250
300
350
400
450
500
−500
NOvA - FNAL E929
Run: 19318 / 51
Event: 742096 / DDupmu
UTC Sat Apr 11, 2015
04:43:58.417080288
hits
t (μsec)
−0.32
−0.3
−0.28
−0.26
−0.24
−0.22
−0.2
−0.18
−0.16
−0.14
q (pe)
10
10^2
10^3
1

Up-scattered cosmics

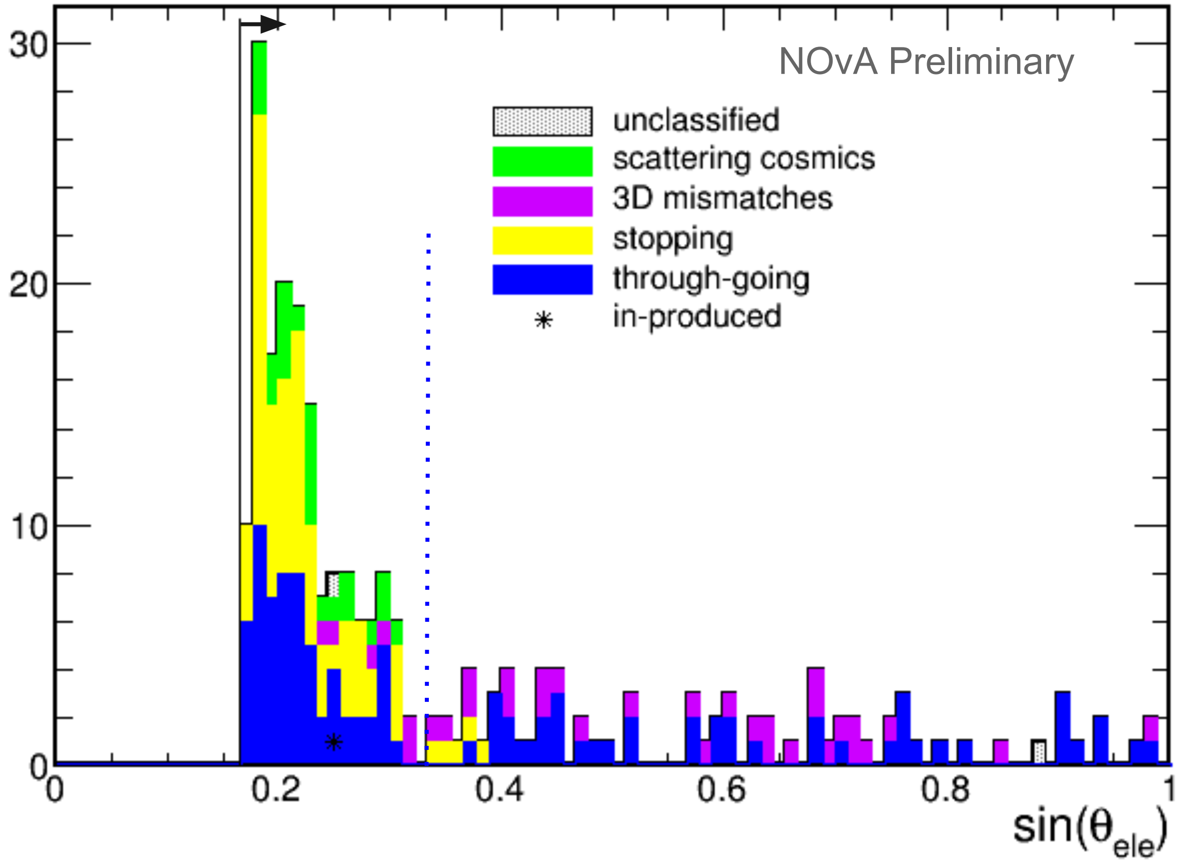


In-produced

Beam?



Elevation angle revisited



Cutting at 20° ($\sin(\theta)$~0.35) should eliminate almost all the background from cosmics scattering in or around the detector.

* 14 tracks that seem to be caused by a temporary timing miscalibration are not included

Summary

- NOvA has a working upward-going muon trigger.
- We can reduce the cosmic ray muon background by nine orders of magnitude, using timing and geometry, to produce a sample sufficiently small to allow visual scanning.
- These techniques will allow an atmospheric neutrino oscillation study and potentially an indirect Dark Matter search.
- Stay tuned for an update on the contained-event sample.

References

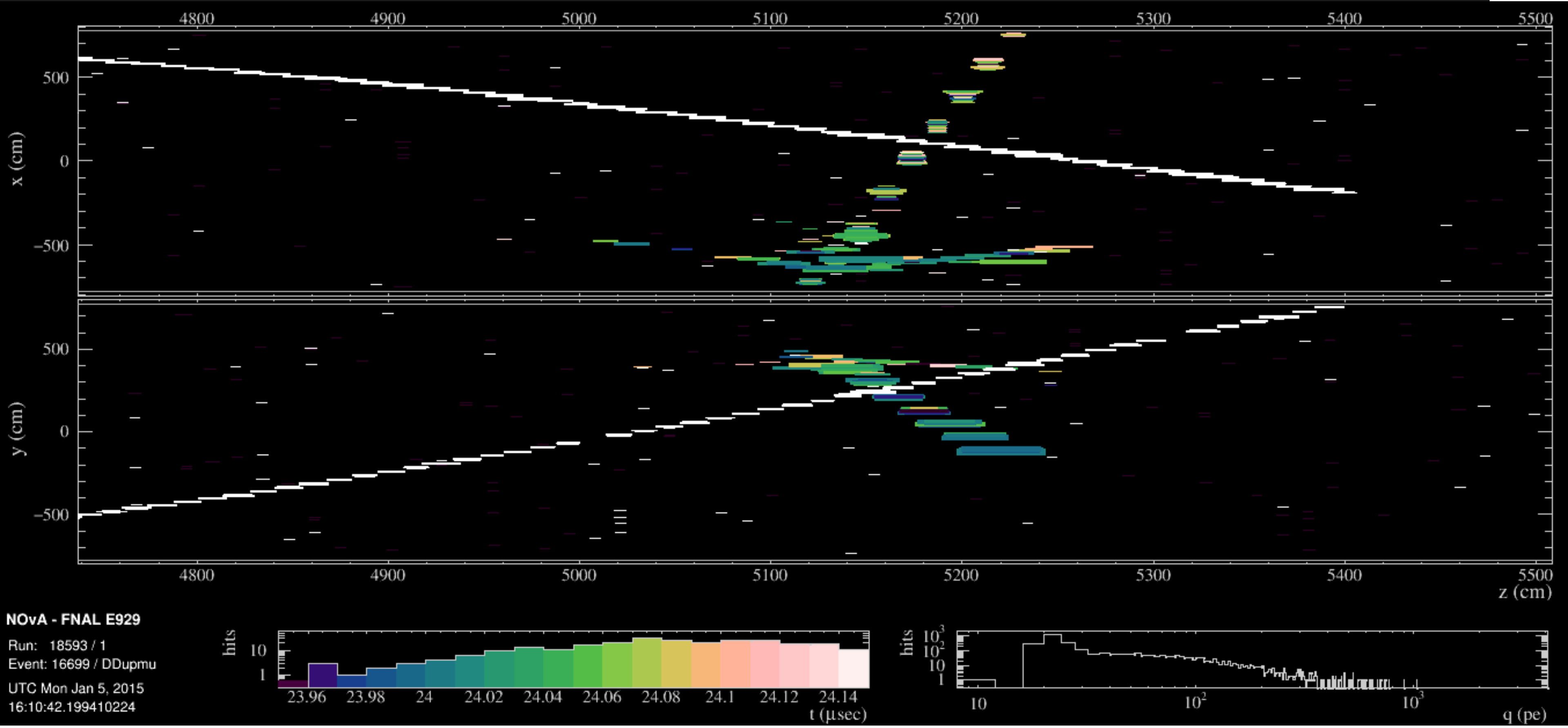
[1] The Super-Kamiokande Collaboration, “Measurement of the flux and zenith-angle distribution of upward through-going muons by Super-Kamiokande.” arXiv:hep-ex/9812014

The Super-Kamiokande Collaboration, “Neutrino-induced upward-going stopping muons in Super-Kamiokande.” arXiv:hep-ex/9908049

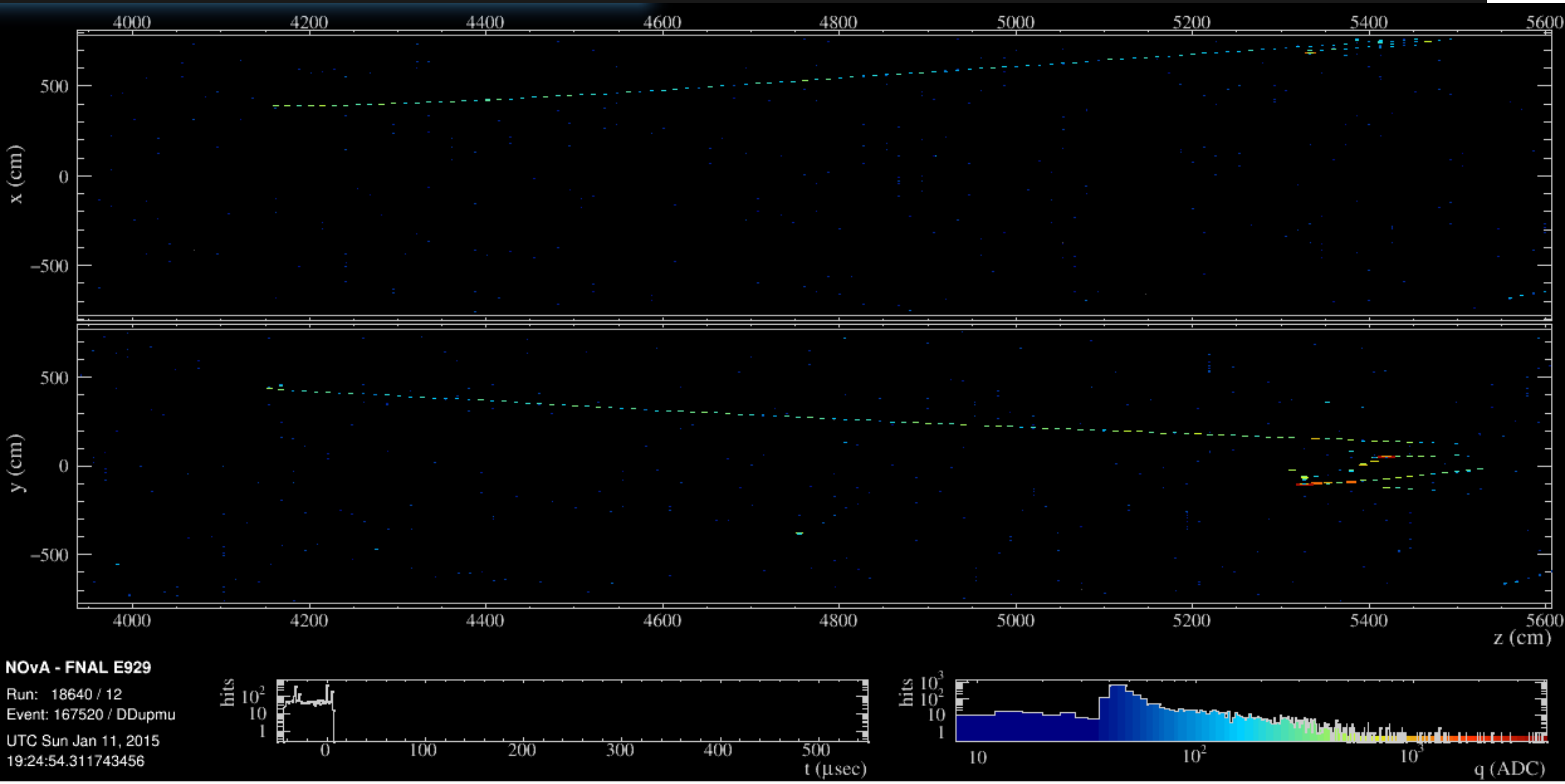
[2] C. L. Bennett et al., “Nine Year WMAP Observations: Final Maps and Results.” **arXiv:1212.5225 [astro-ph.CO]**

Backup slides

Likely downward-going



Uncategorized candidate 1

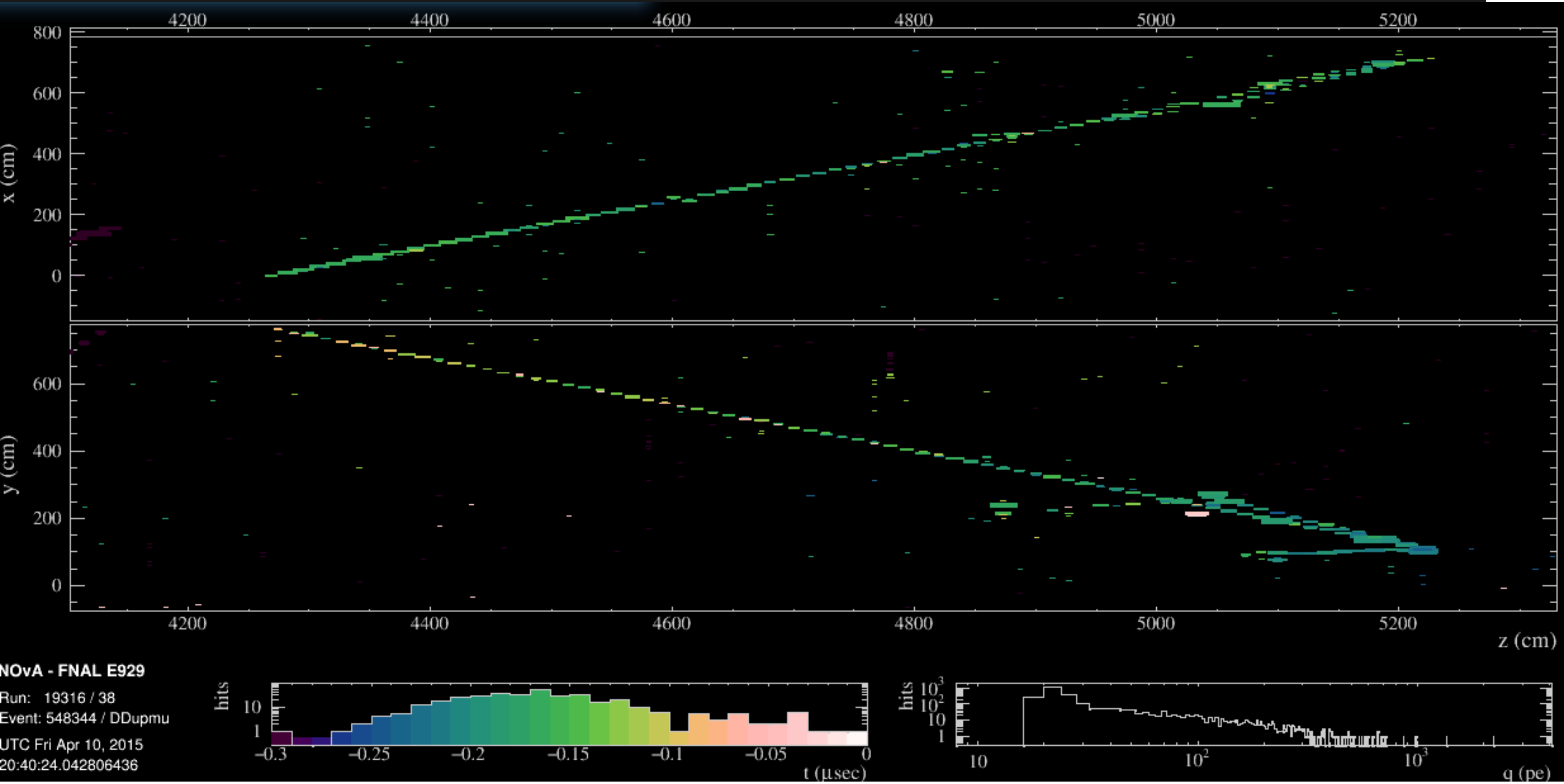


NOvA - FNAL E929

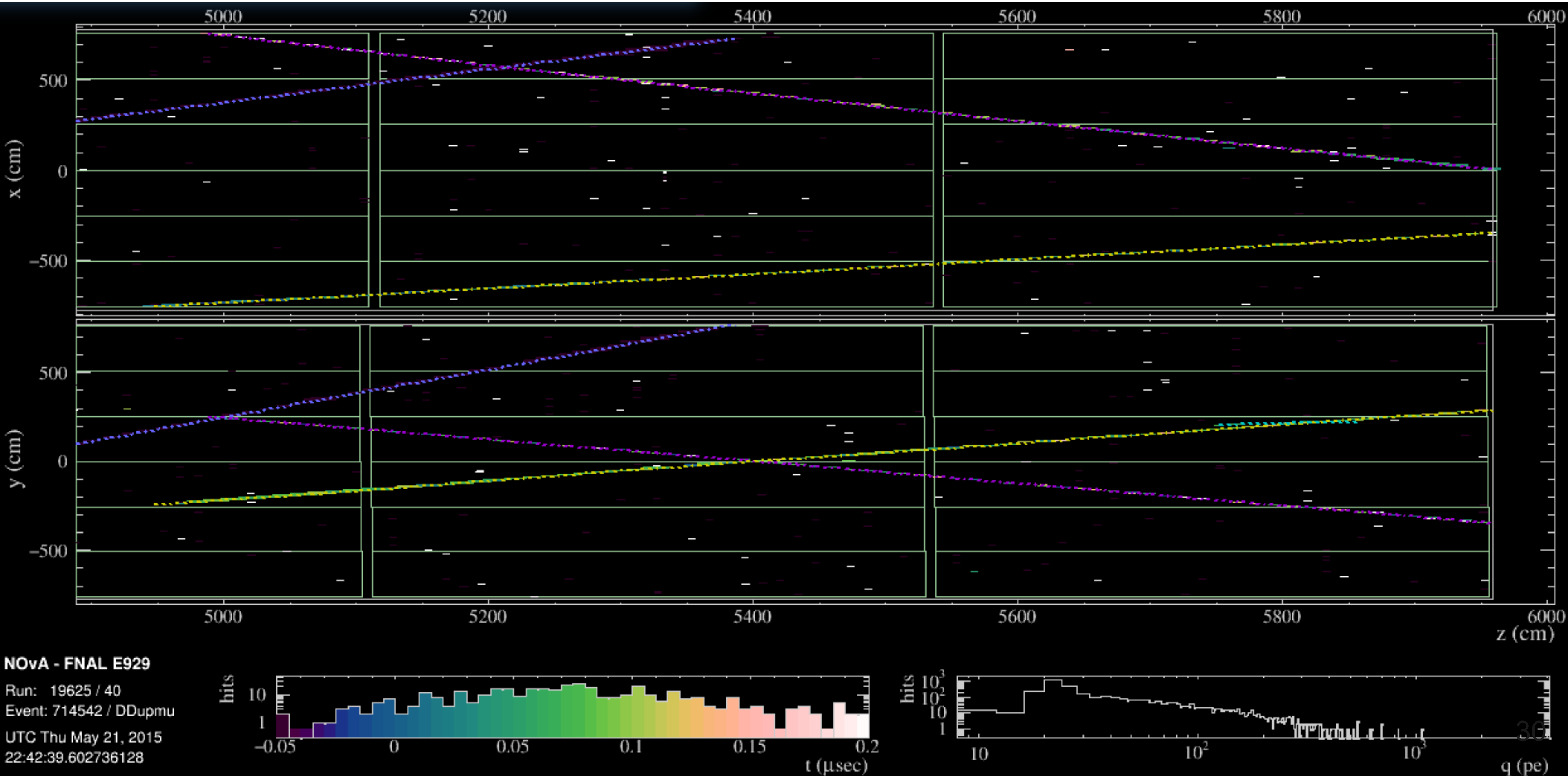
Run: 18640 / 12
Event: 167520 / DDupmu

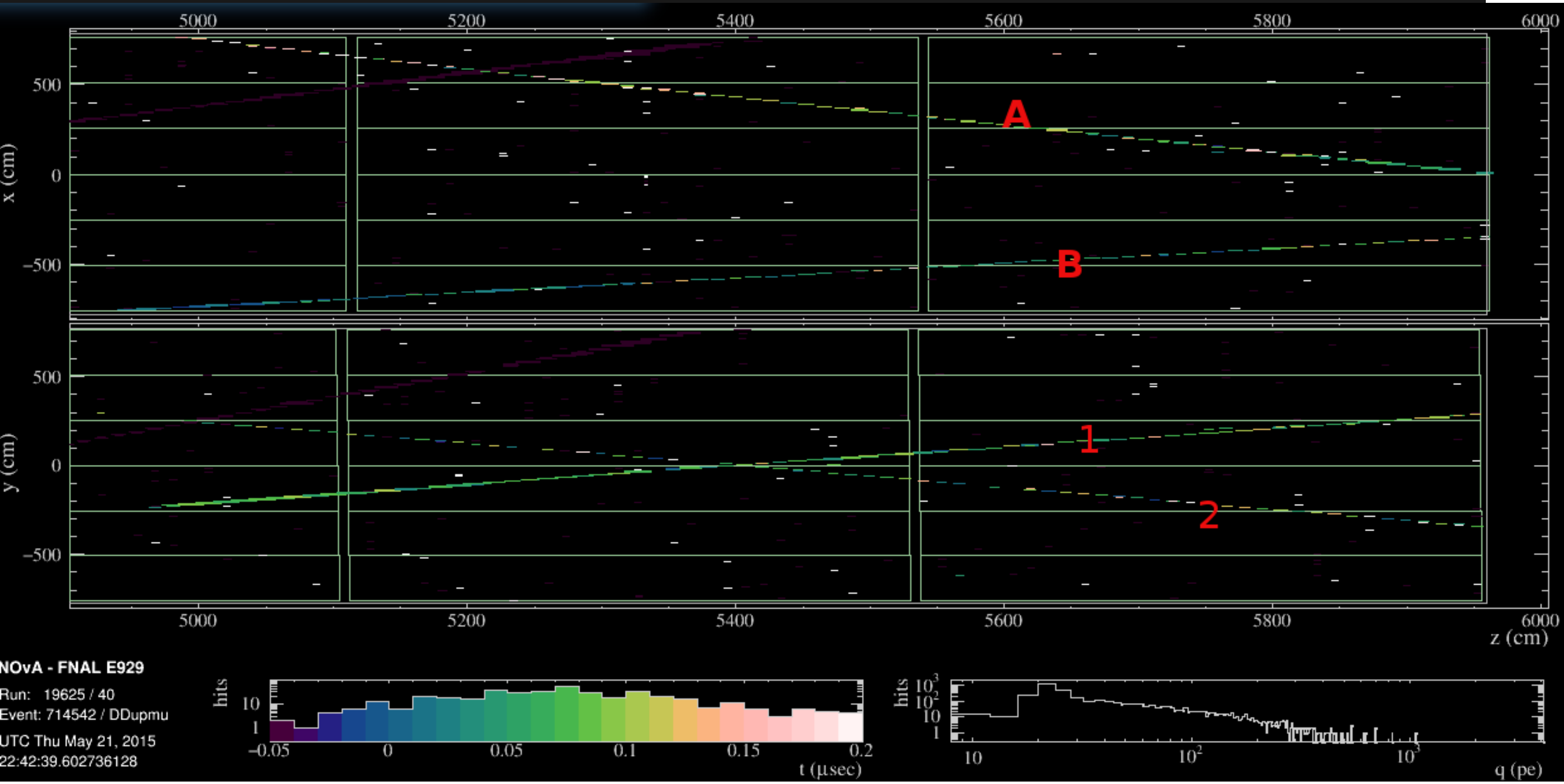
UTC Sun Jan 11, 2015
19:24:54.311743456

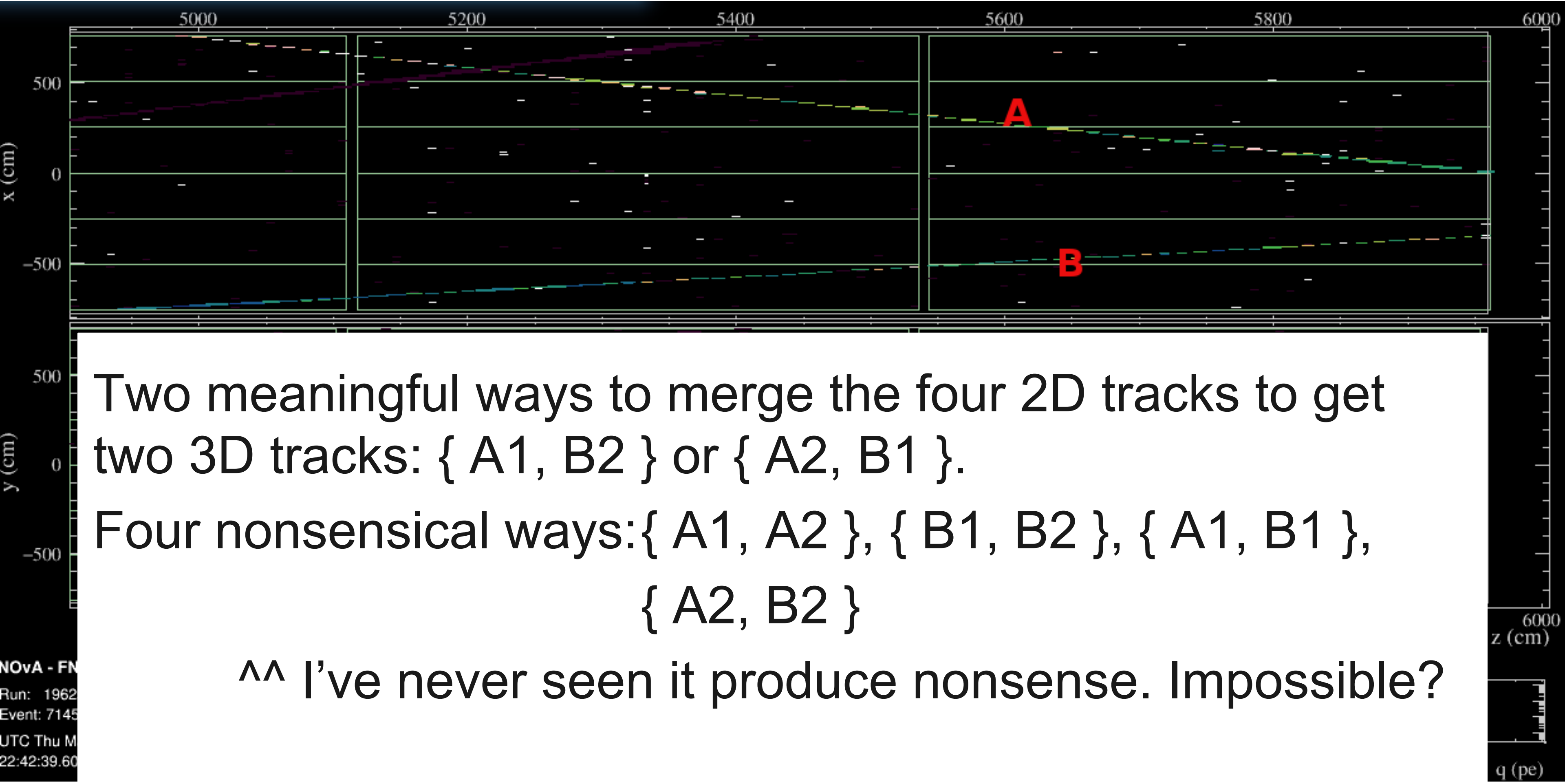
Uncategorized candidate 2



3D track mismatch... What is it?



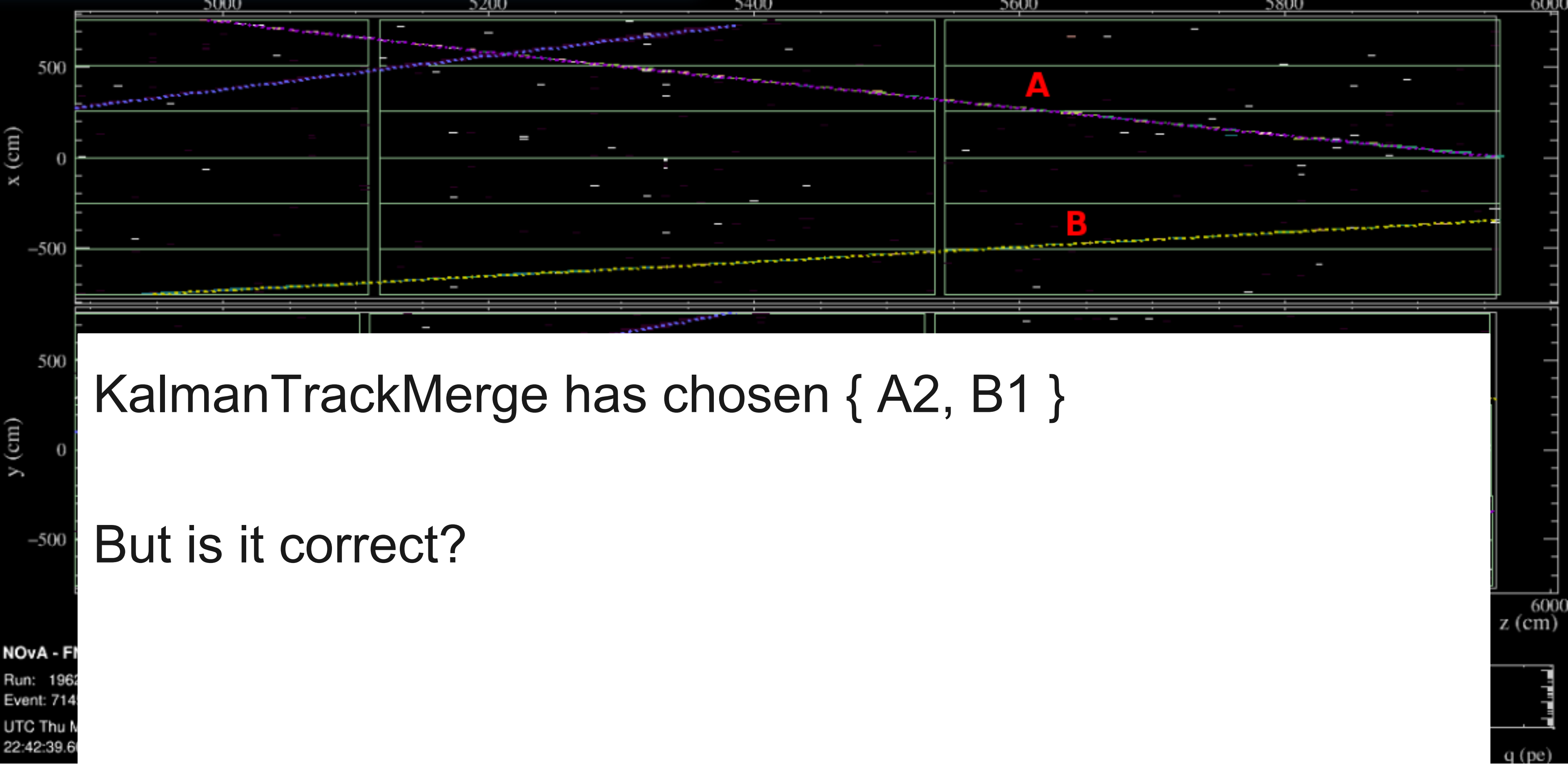

5000
5200
5400
5600
5800
6000
x (cm)
500
0
−500
A
B
y (cm)
1
2
z (cm)
NOvA - FNAL E929
Run: 19625 / 40
Event: 714542 / DDupmu
UTC Thu May 21, 2015
22:42:39.602736128
hits
10
1
−0.05
0
0.05
0.1
0.15
0.2
t (µsec)
10^3
10^2
10
1
10
10^2
10^3
q (pe)



Two meaningful ways to merge the four 2D tracks to get two 3D tracks: { A1, B2 } or { A2, B1 }.

Four nonsensical ways:{ A1, A2 }, { B1, B2 }, { A1, B1 }, { A2, B2 }

^^ I've never seen it produce nonsense. Impossible?



KalmanTrackMerge has chosen { A2, B1 }

But is it correct?

The trickiness with timing

- The last step in the calibration of hit time for a single cell hit is to estimate the time of propagation of the scintillation light down the fiber to the readout.
- That is: real_time = apparent_time - (distance_from _readout / speed _of_propagation)
- See docdb 12570, page 19, item 1

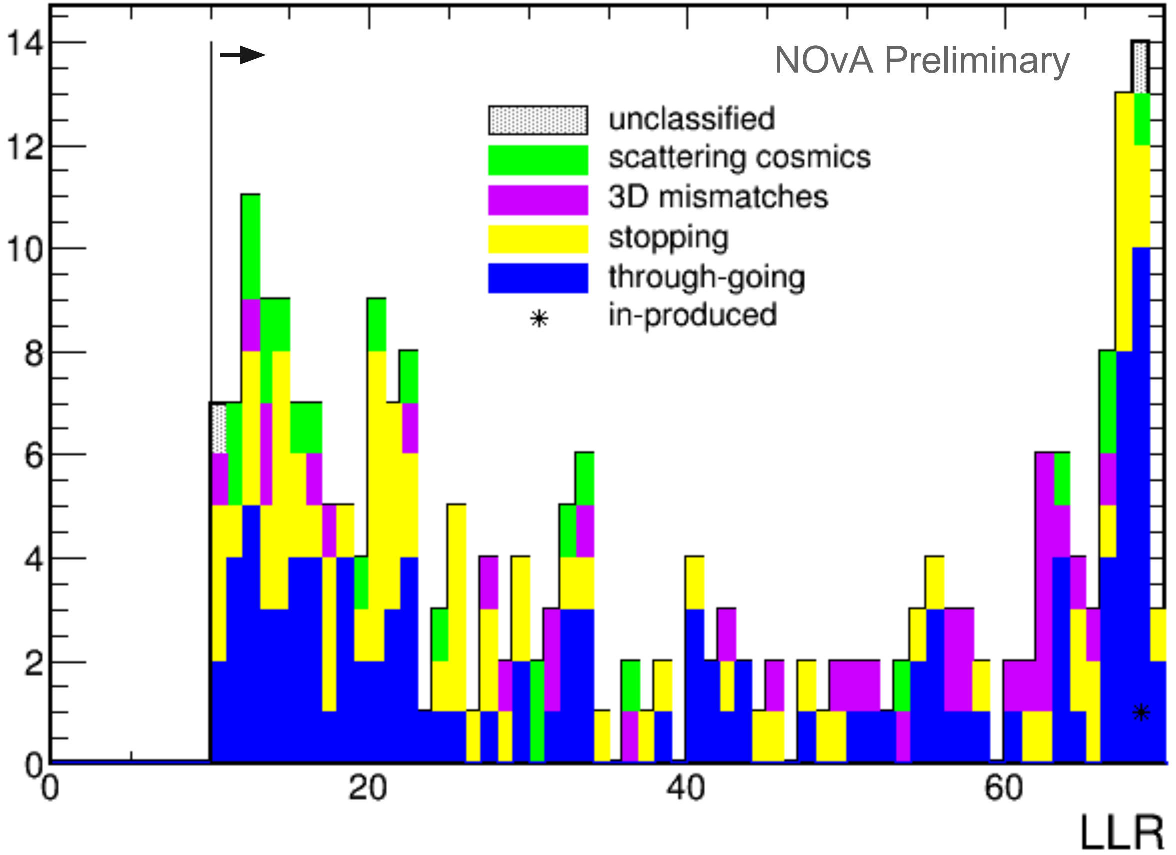
The trickiness with timing

- The distance to the readout for a hit can only come from 3D track information, so the reconstructed times of the hits in these tracks depend on which pairing the track merger makes.
- The maximum size of this effect is 16 meters (detector width/height) / 15.3 cm/ns = ~100 ns. Most cosmic muons travel through the detector in less than this much time.
- This is why these tracks are the dominant misreconstruction in the UpMu sample after cuts have eliminated almost all cosmics.

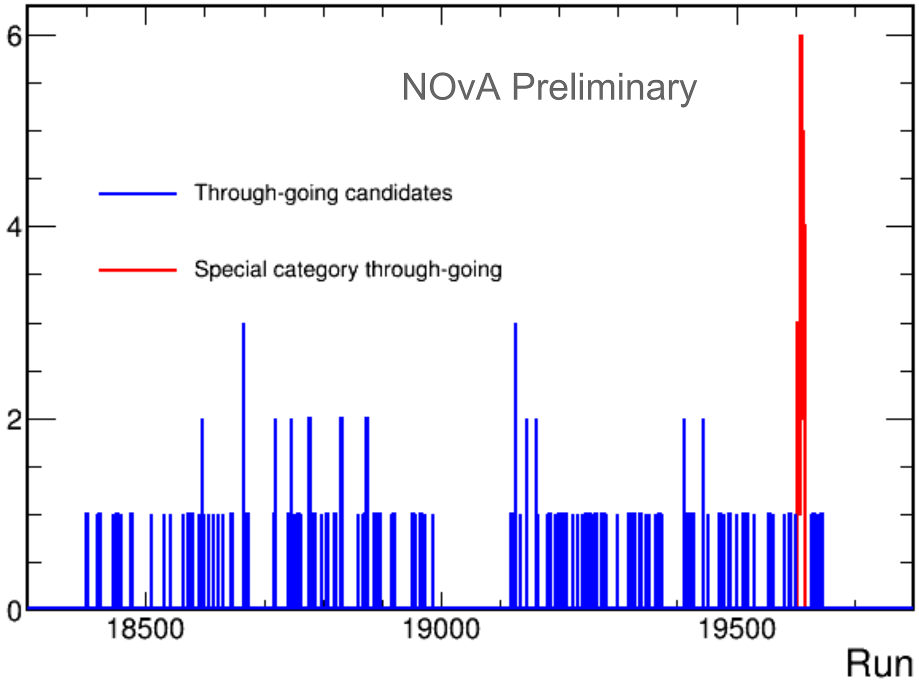
What are we doing about it?

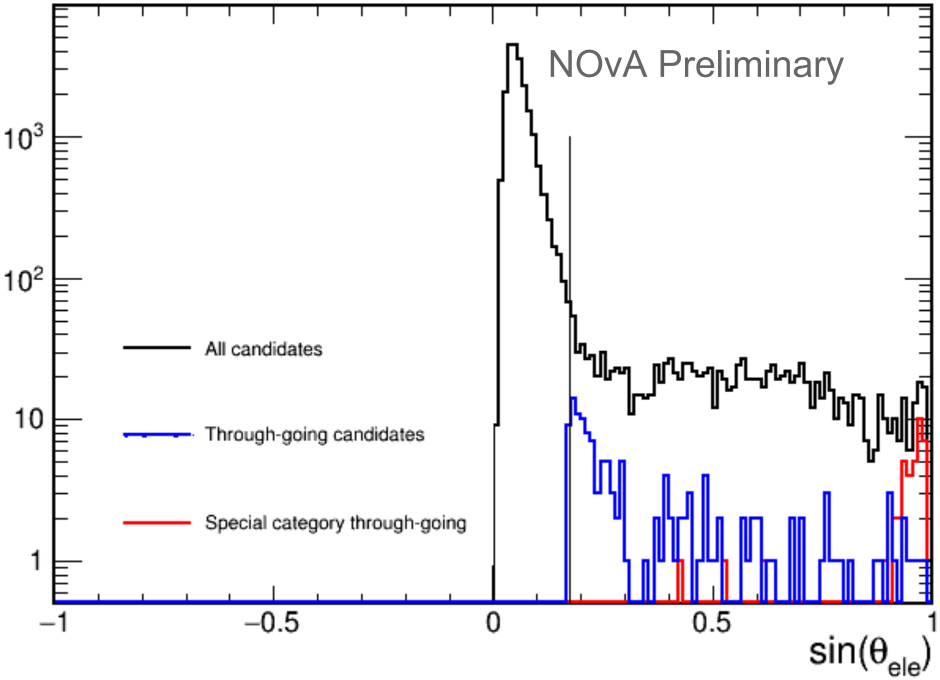
- For the ddupmu sample, I designed a slice-level cut that eliminates most of this contamination without losing much signal efficiency:
  - Pass all slices with 1 or > 3 tracks (in order not to cut contained-vertex events)
  - For each track in a slice with 2 or 3 tracks, compute the differences in Z between the candidate track's start and end and that of the other track. If *both* the start and end differ by less than 5 plane widths, call this a match. Cut slices with more than 1 match.
  - Count the number of tracks in the slice with length > 8m. Cut slices with more than 1 such track.
- For the ddcontained sample, the track containment requirement should eliminate almost all of these events.

LLR revisited

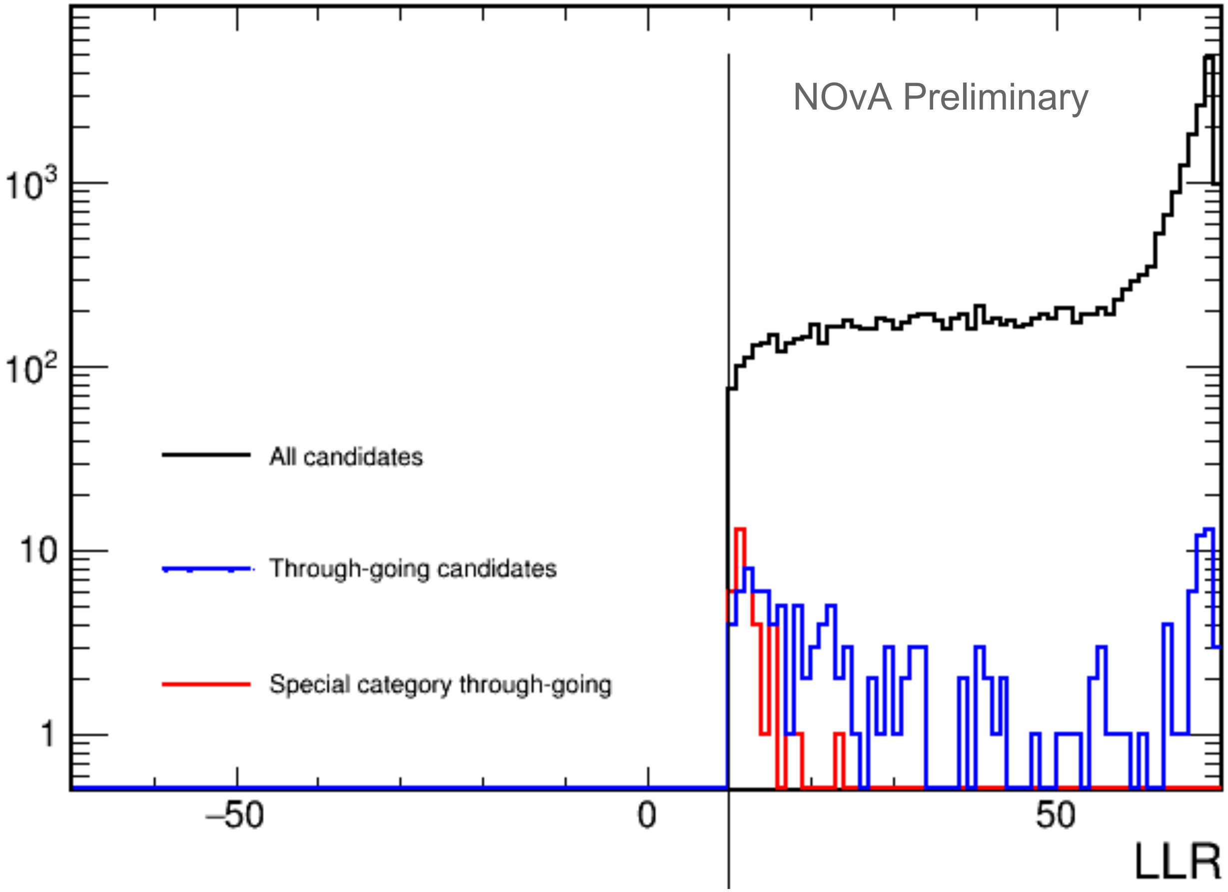


Separate "special" through-going sample





Separate "special" through-going sample



- High rate per run
- Highly vertical
- Low LLR compared to other candidates
- (not pictured) contained in Diblock 14