# Progress in the Search for Dark Matter Using Upward-going Muons in NOvA

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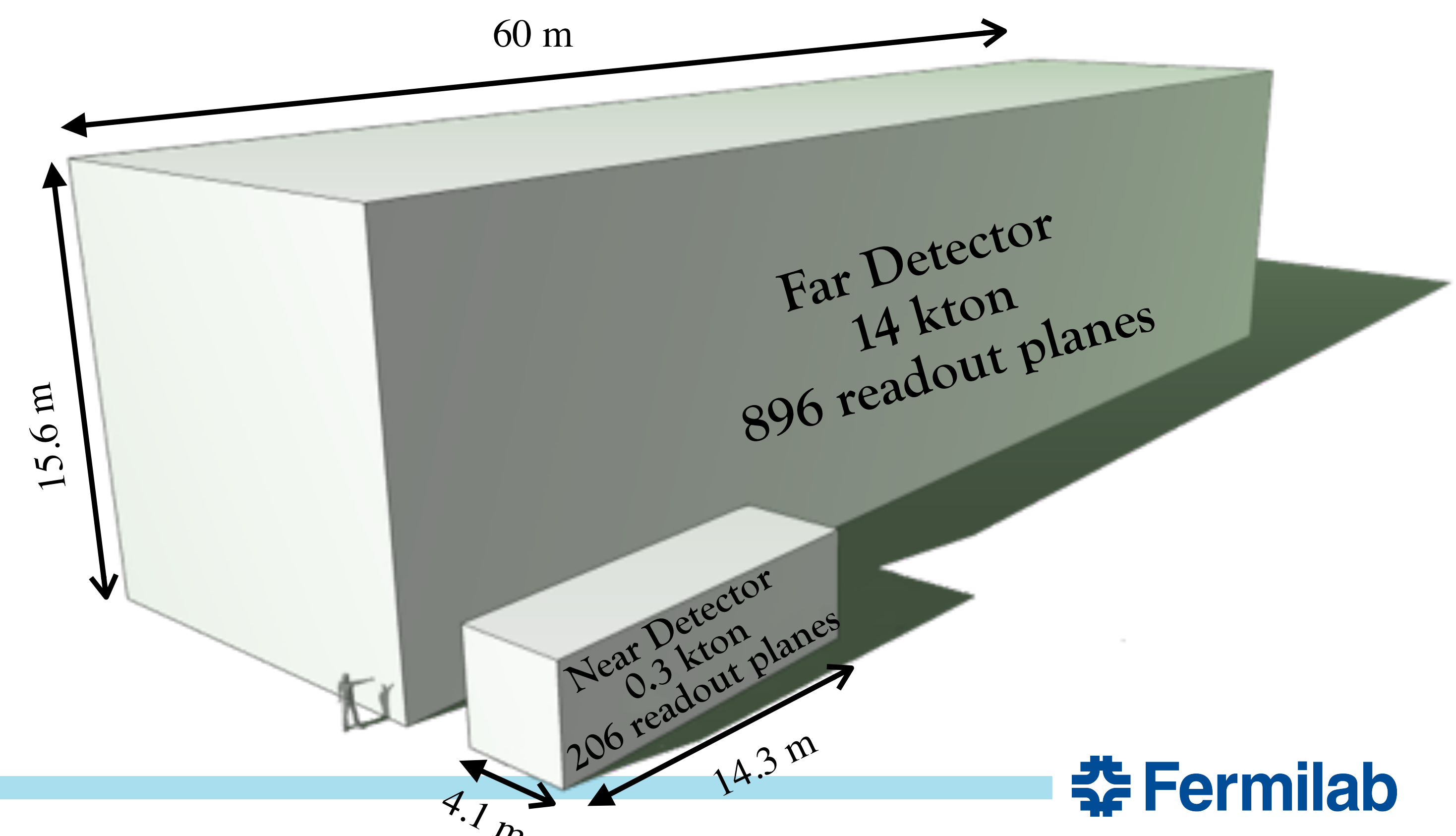
# NOvA Overview

NOvA (NuMI Off-axis $\nu_e$ Appearance) is a long baseline neutrino oscillation experiment that uses two functionally identical detectors to measure:

$\nu_e$ ***appearence*** $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

$\nu_\mu$ ***disappearance*** $P(\nu_\mu \to \nu_\mu)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$

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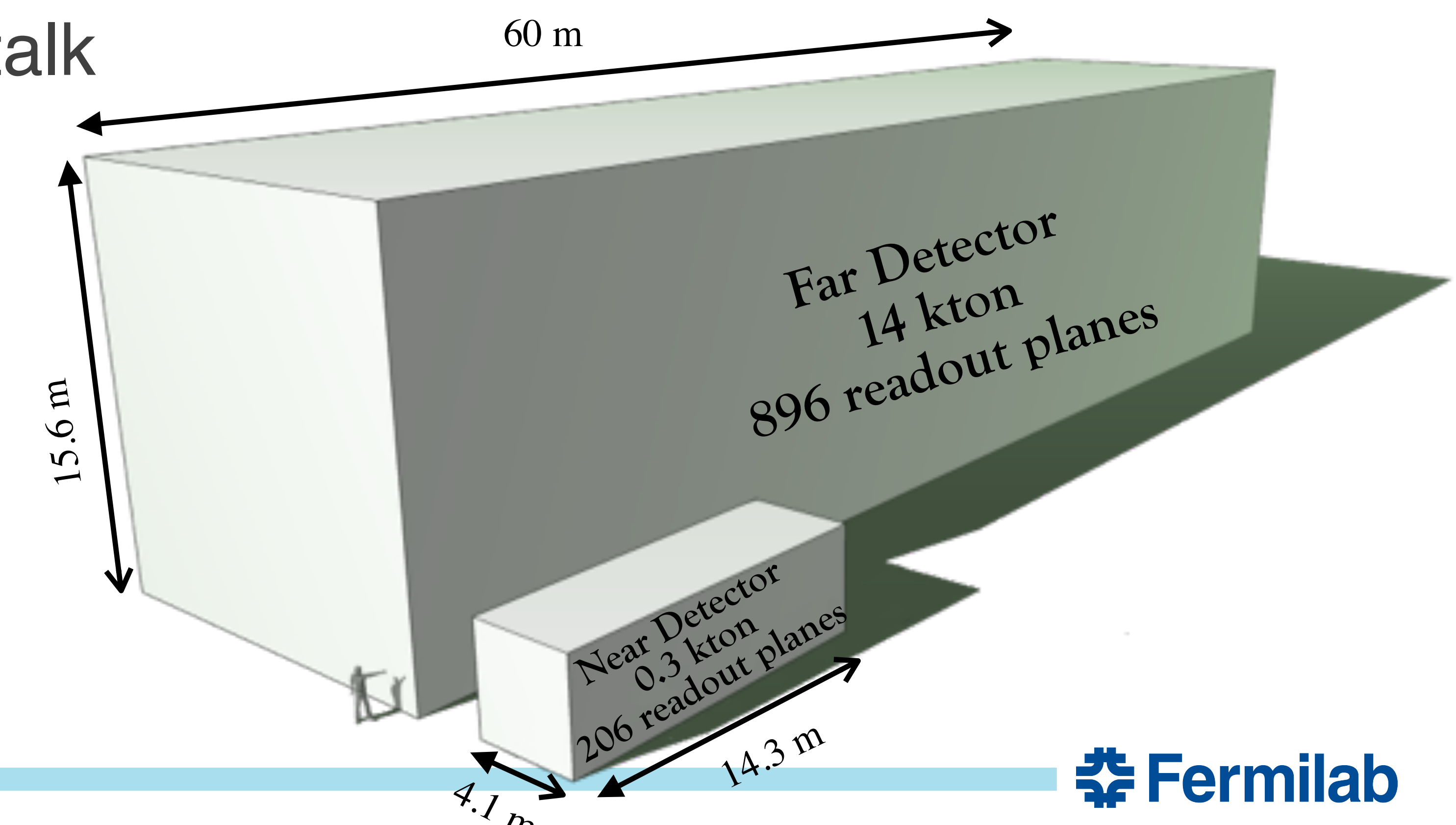
See Electron-Neutrino Appearance talk by Jianming Bian (6 Aug 2016, 14:20)

$\nu_\mu$ ***disappearance*** $P(\nu_\mu \to \nu_\mu)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$

See Muon-Neutrino Disappearance talk by Keith Matera(6 Aug 2016, 14:00)

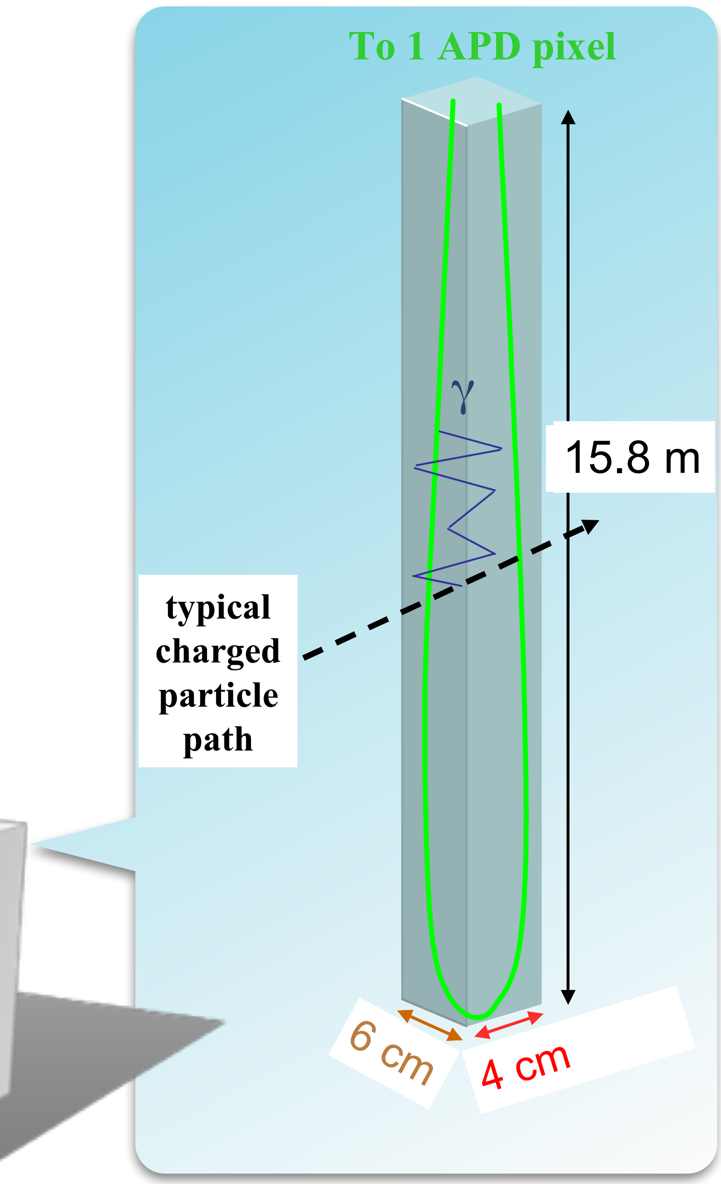
» **Search for Dark Matter using upward going muons.**

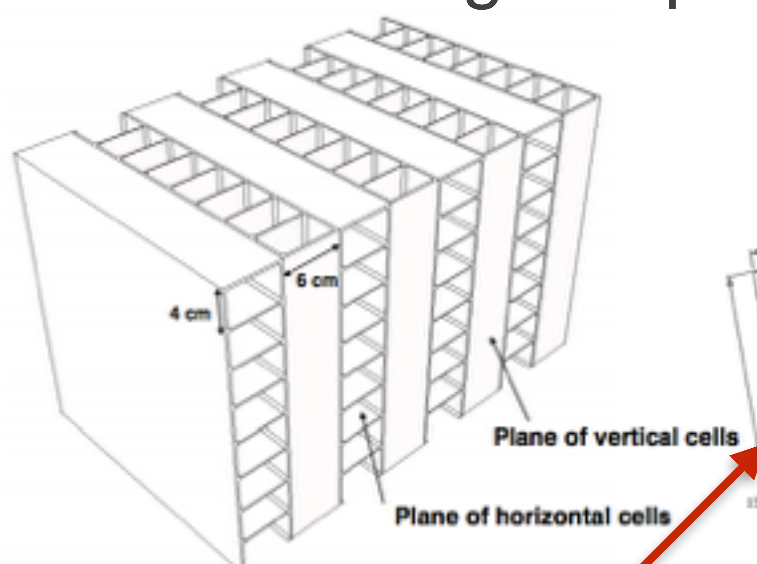


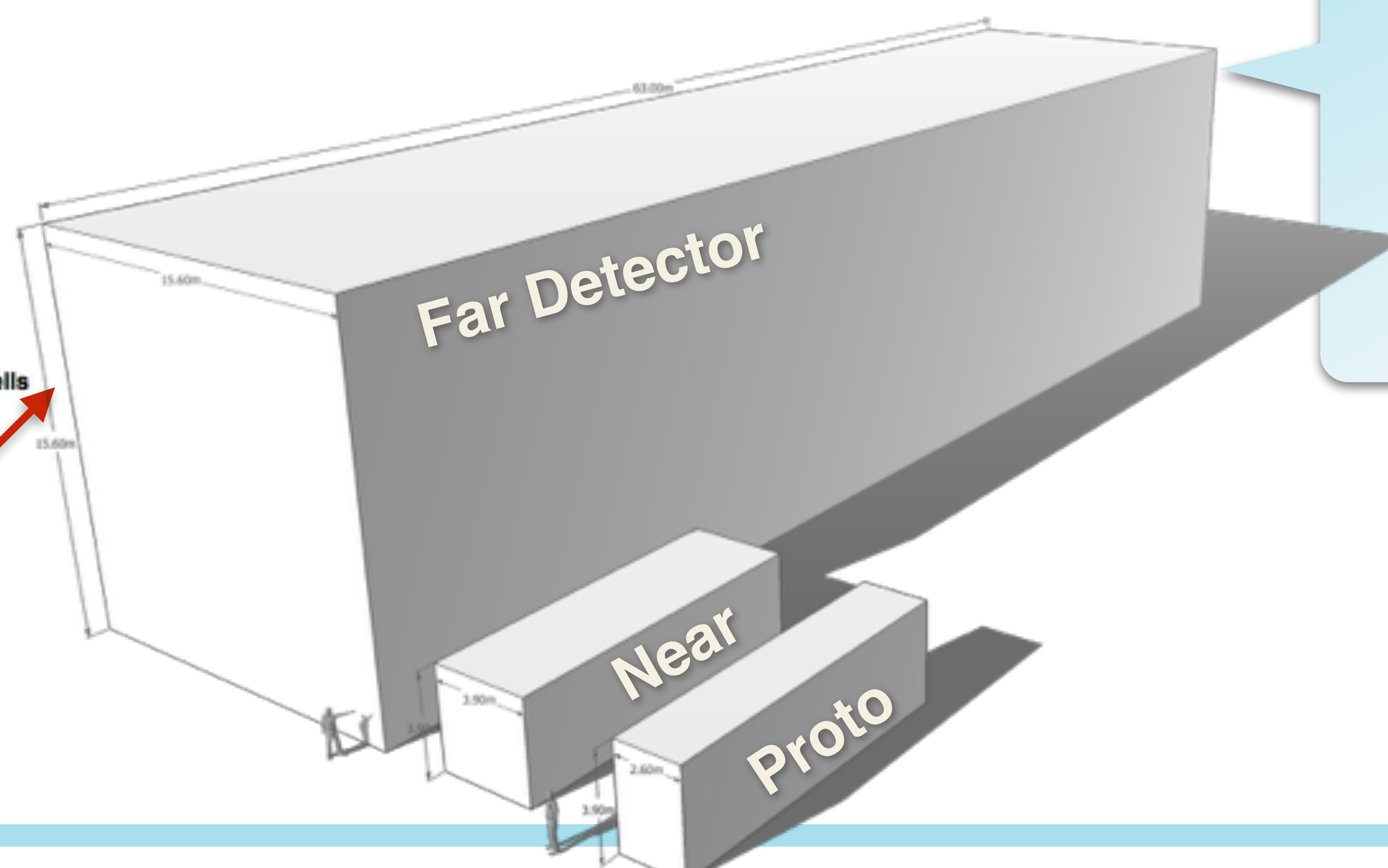
# The NOvA Far Detector

» Detector on the surface
» 3 meter earth equivalent overburden.
» Highly segmented low Z tracking calorimeter.
» Liquid scintillator with wave shifting fiber readout.
» 65% active by volume
» Detection with avalanche photo diodes.
» Alternating X/Y planar geometry.

**Building block of NOvA**




**Far Detector, on surface**
**14 kTons**
**896 readout planes**
**344,064 pixels**

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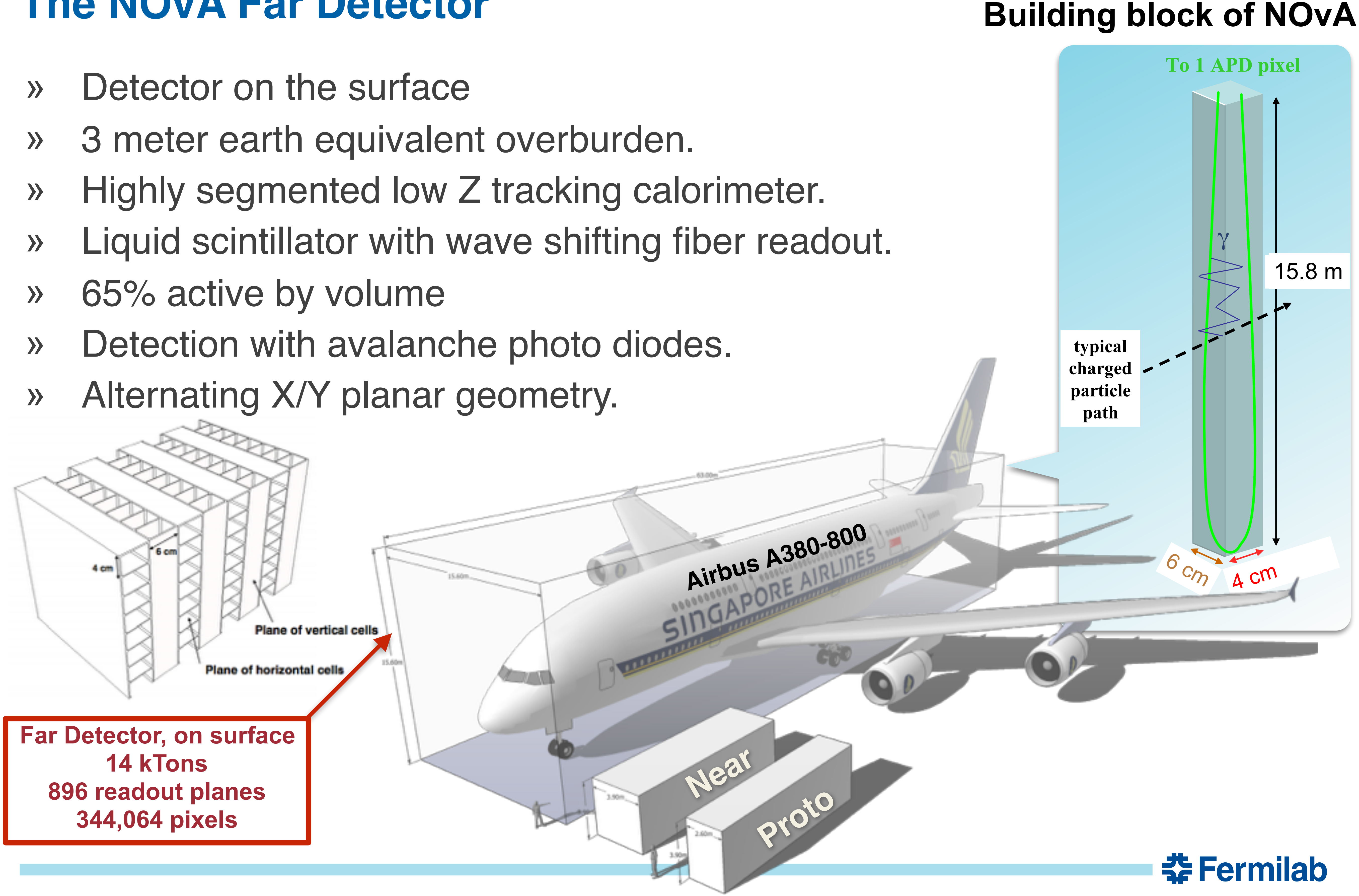
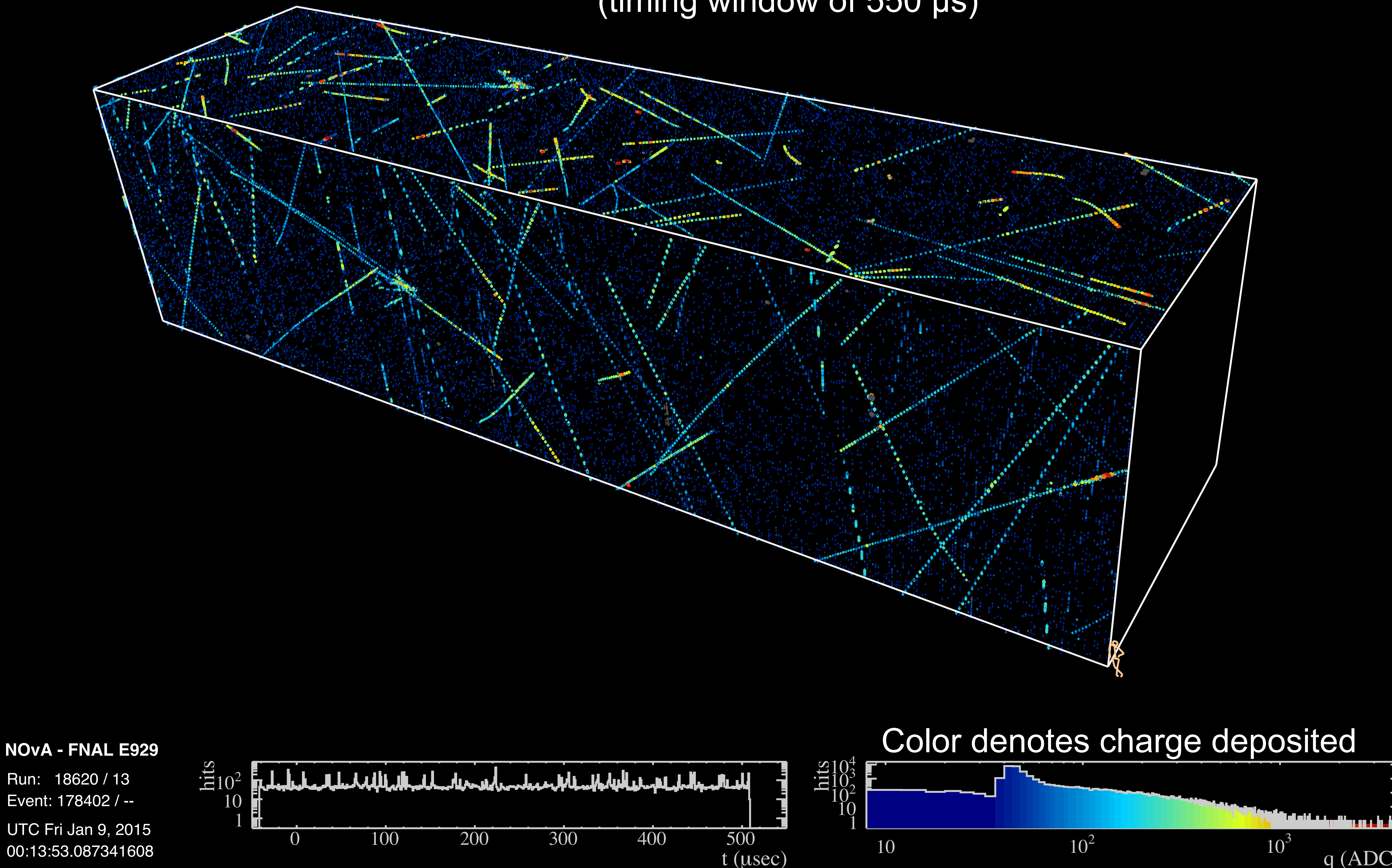


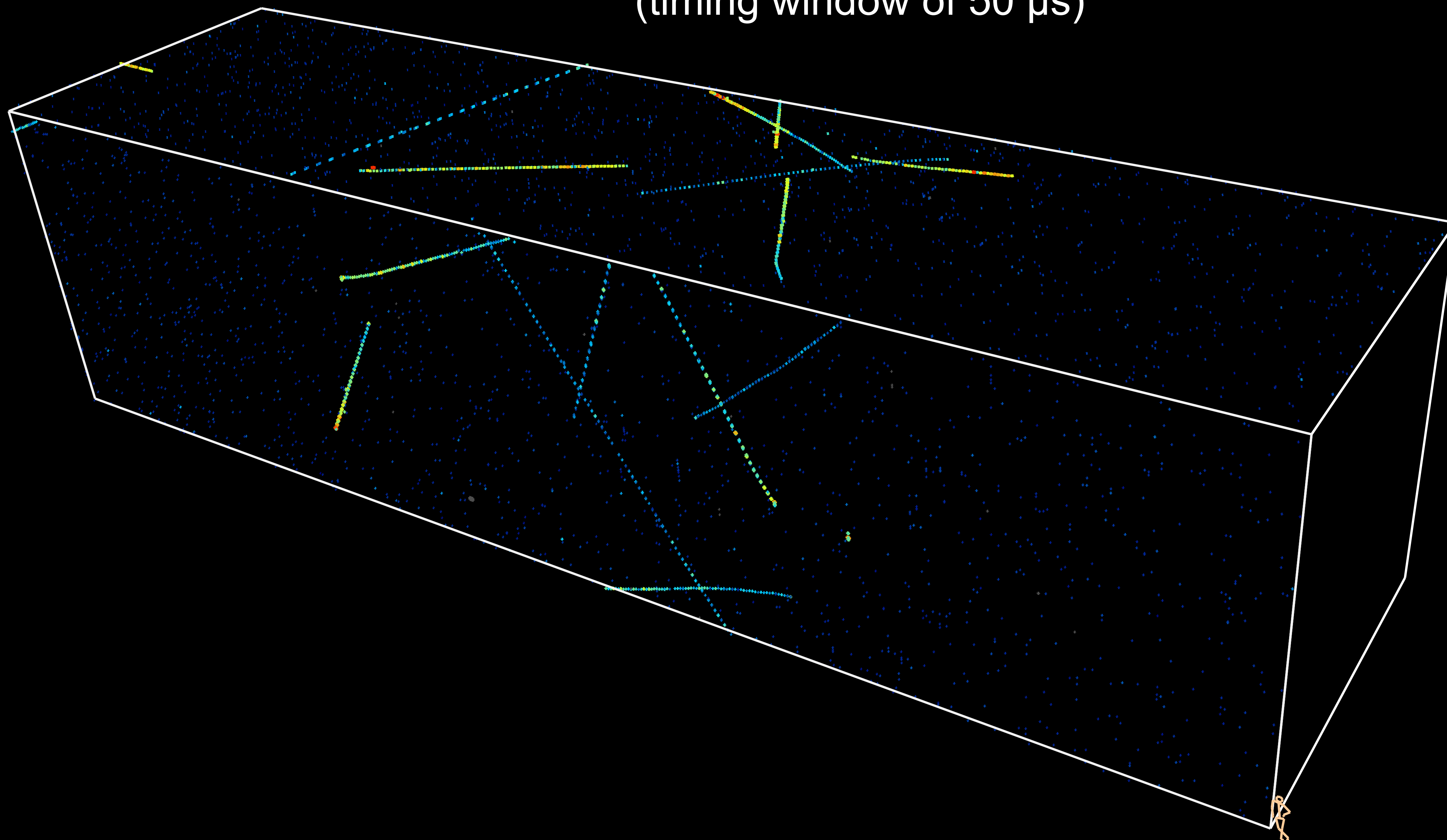
# The NOvA Far Detector

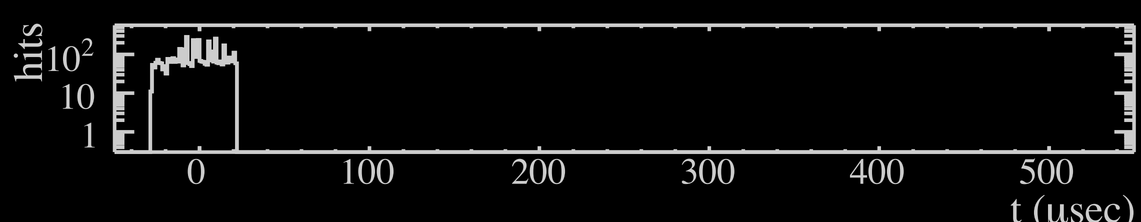
Surface far detector, rate is driven by cosmic muons (timing window of 550 μs)



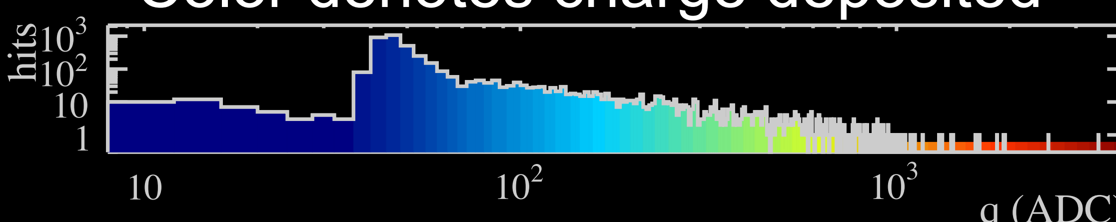
# The NOvA Far Detector

Upward-going muon trigger event
(timing window of 50 μs)






Color denotes charge deposited

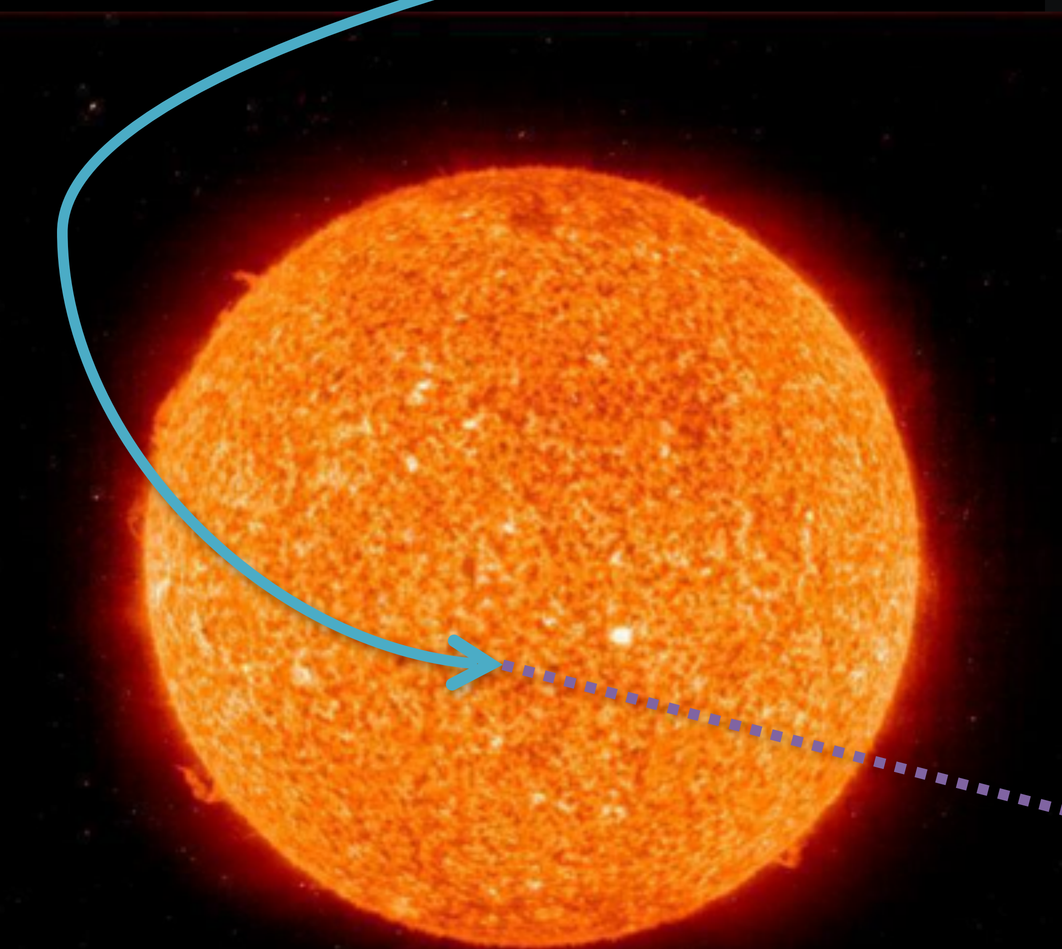


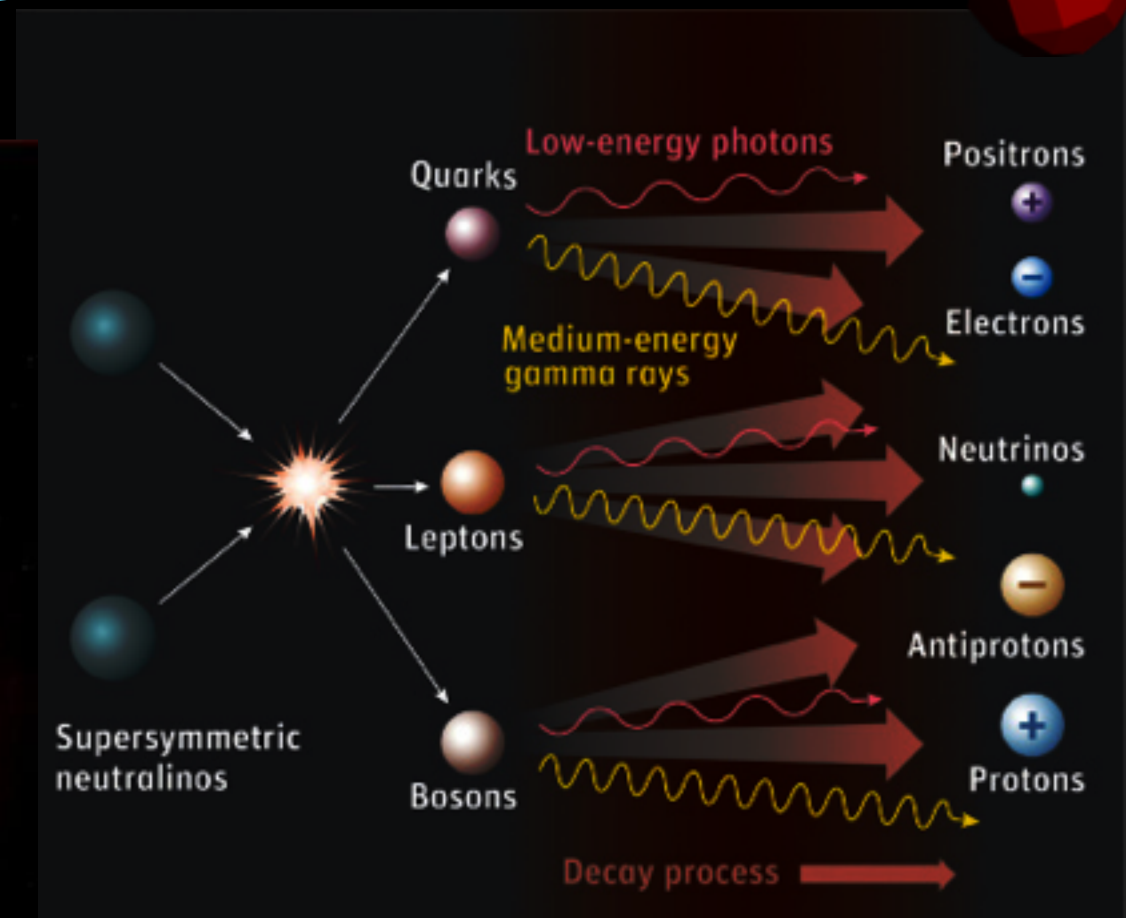
# WIMP Detection
## using Upward-going Muons

WIMP Candidate

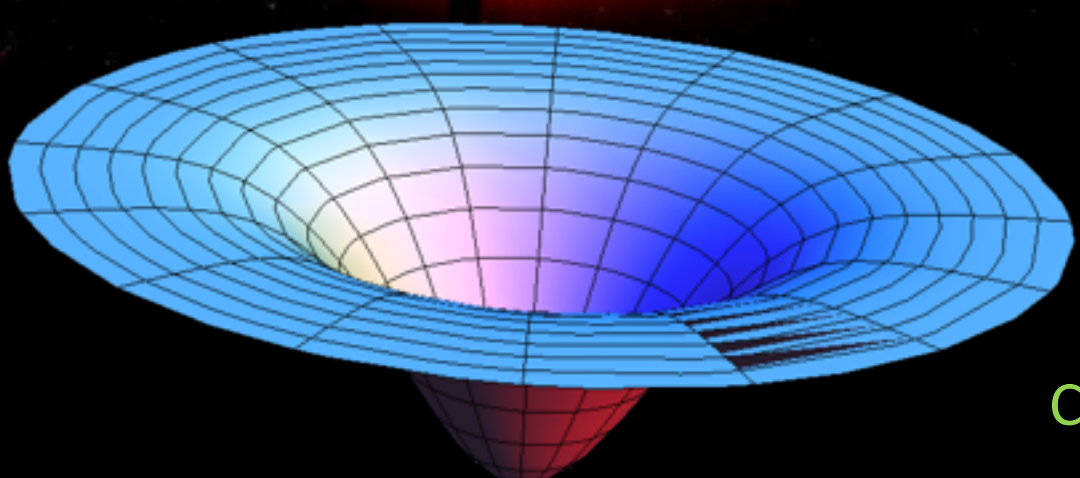
- Γ(capture)
- Γ(annihilation)
- σ(scatter)
- ν interactions

Results in ejection of high energy neutrino



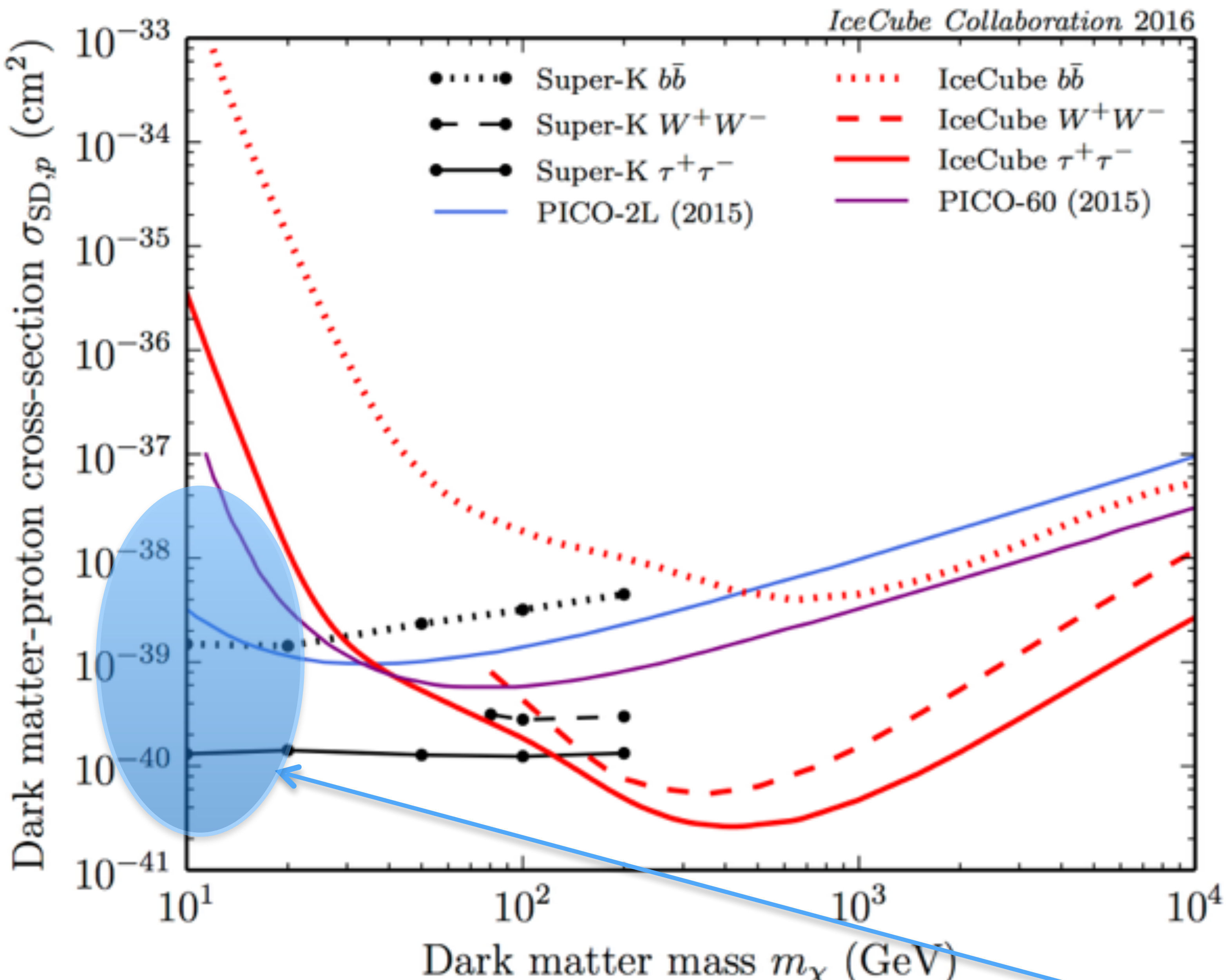



$E_\nu >> E_{\nu\text{-solar}}$




Detect CC Interaction
Correlated to Solar Position

# Limits on the Spin-Dependent Interaction Cross Section




**Improved limits on dark matter annihilation in the Sun with the 79-string IceCube detector and implications for supersymmetry**

**arXiv:1601.00653 [hep-ph]**

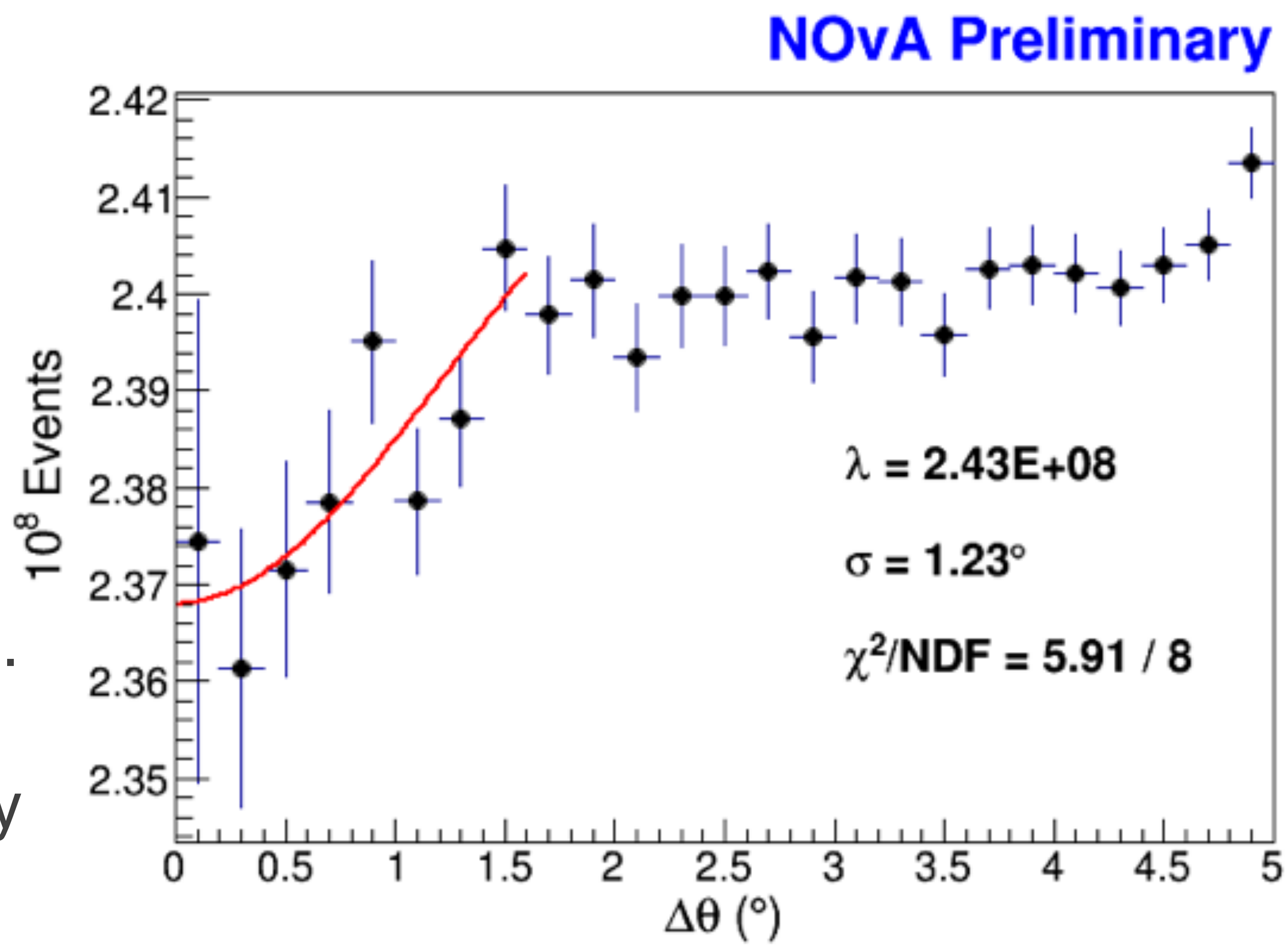
**NOvA is unique:**

- » Relative low energy muon threshold.
- » Large for its excellent granularity.
- » Previous measurements primarily looked with Cherenkov detectors.
- » The NOvA technology is different (liquid scintillator).
- » NOvA may have sensitivity in unexplored regions of phase space.

**NOvA may be sensitive here!**
**(Mass of DM<20GeV)**

# Pointing Resolution

- **We check the pointing resolution by point to the moon**
- Tracks within 5 deg. from the position of the Moon were selected.
- Tracks with at least 15 m length.
- Performed time slewing and look elsewhere analysis to verify signal significance.

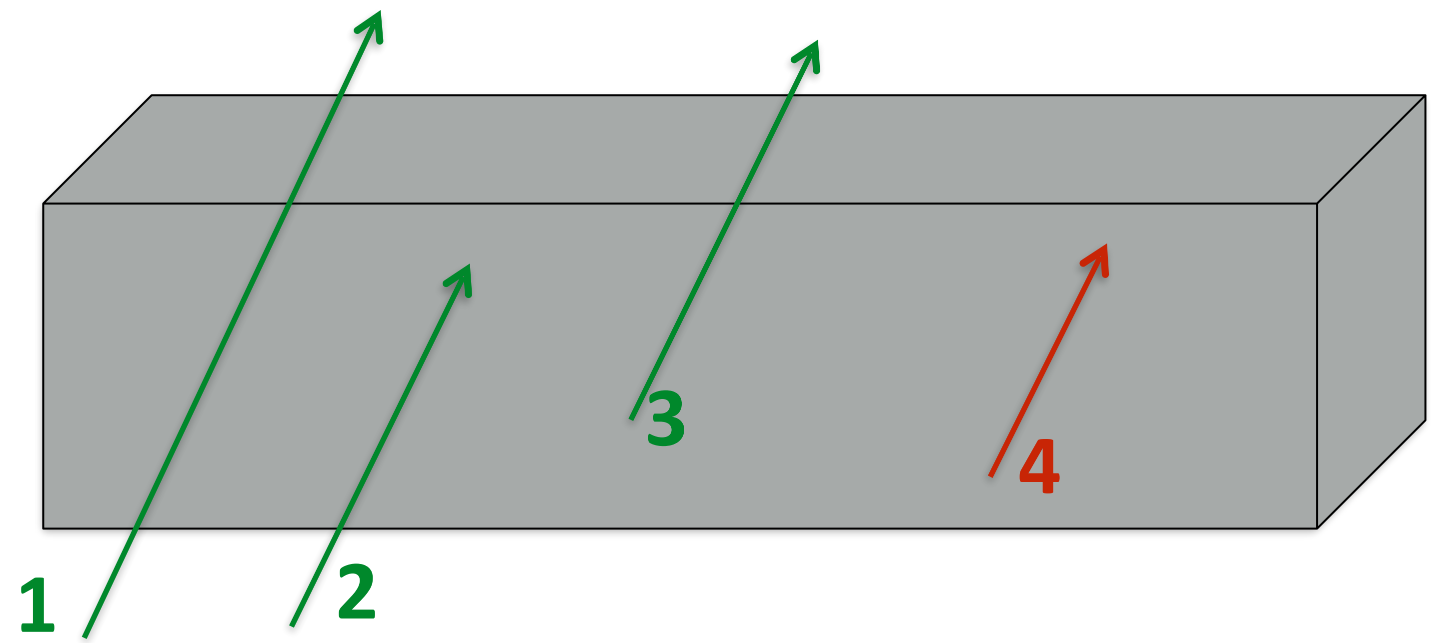



**Procedure followed by MINOS observation**
**arXiv:1008.1719 [hep-ex]**

**From moon shadow measurement estimate pointing resolution better than 1.2 deg. (dominated by Coulomb scattering and magnetic deflection)**

# The Upward-going Muon Trigger

» Two upward-going muon triggers are running since December 2014 base on timing:
  » **Through-going (1, 2, 3):** long tracks that appear to be upward going.
  » **Contained (4):** shorter tracks that appear to be upward going and pass some simple containment requirements.




**A First Look at Data from the NOVA Upward-Going Muon Trigger**
arXiv:1511.00155 [hep-ex]

**~500 days of live time have been collected.**

**For this analysis 275 days of live time were used from the through-going sample.**

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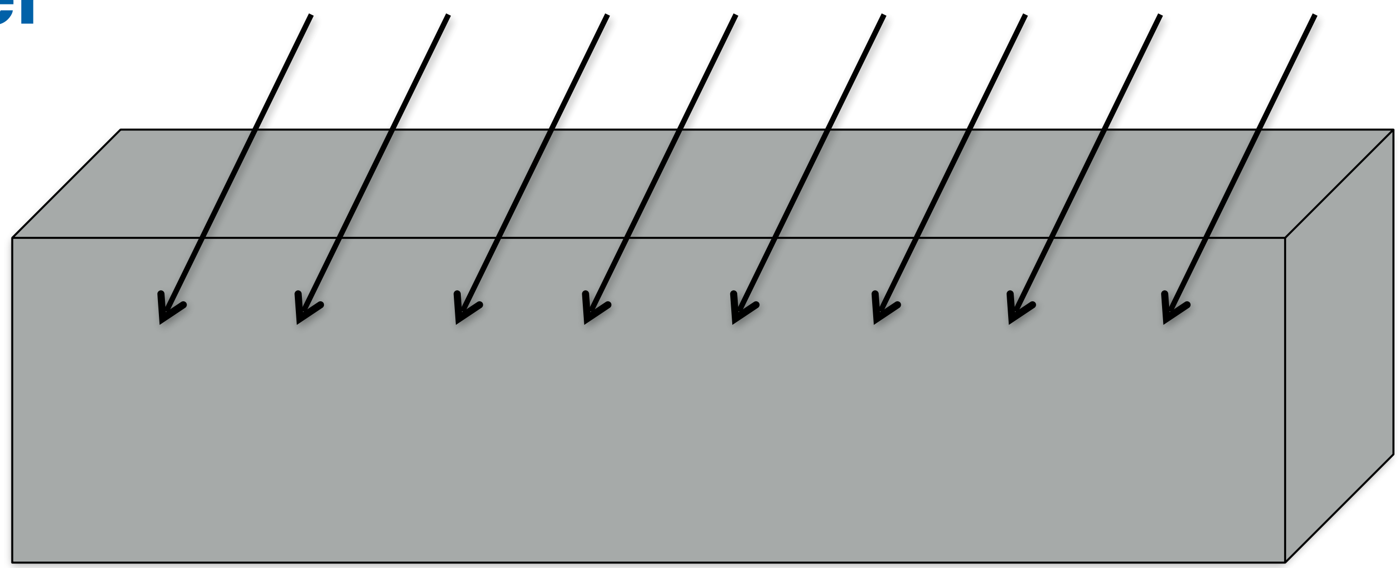

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» Note that by firing at 1Hz, this trigger already reduces the cosmic background by a factor of $10^5$ (cosmic trigger fires at ~100 kHz).

# The Upward-going Muon Trigger: Log Likelihood Ratio (LLR)

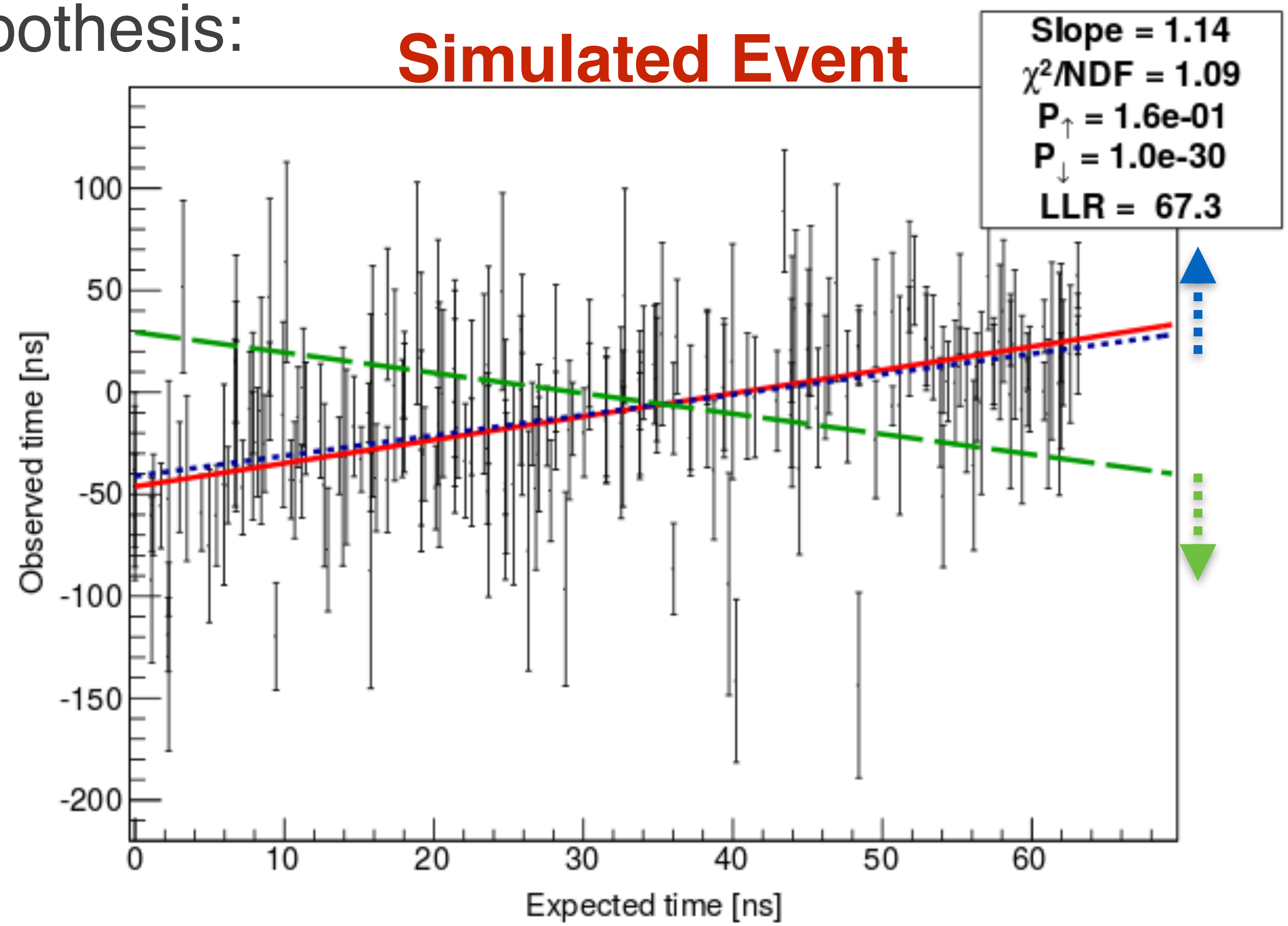
The LLR is calculated based on the upward-going and downward-going hypothesis:

- » Three linear fits to the expected v/s observed times of all hits in the track.
  - » With unconstrained slope.
  - » Independently for each hypothesis (up, down)
- » Form LLR based on the chi-square probability:

$$LLR = \ln\left(\frac{Prob_{UP}}{Prob_{DOWN}}\right)$$

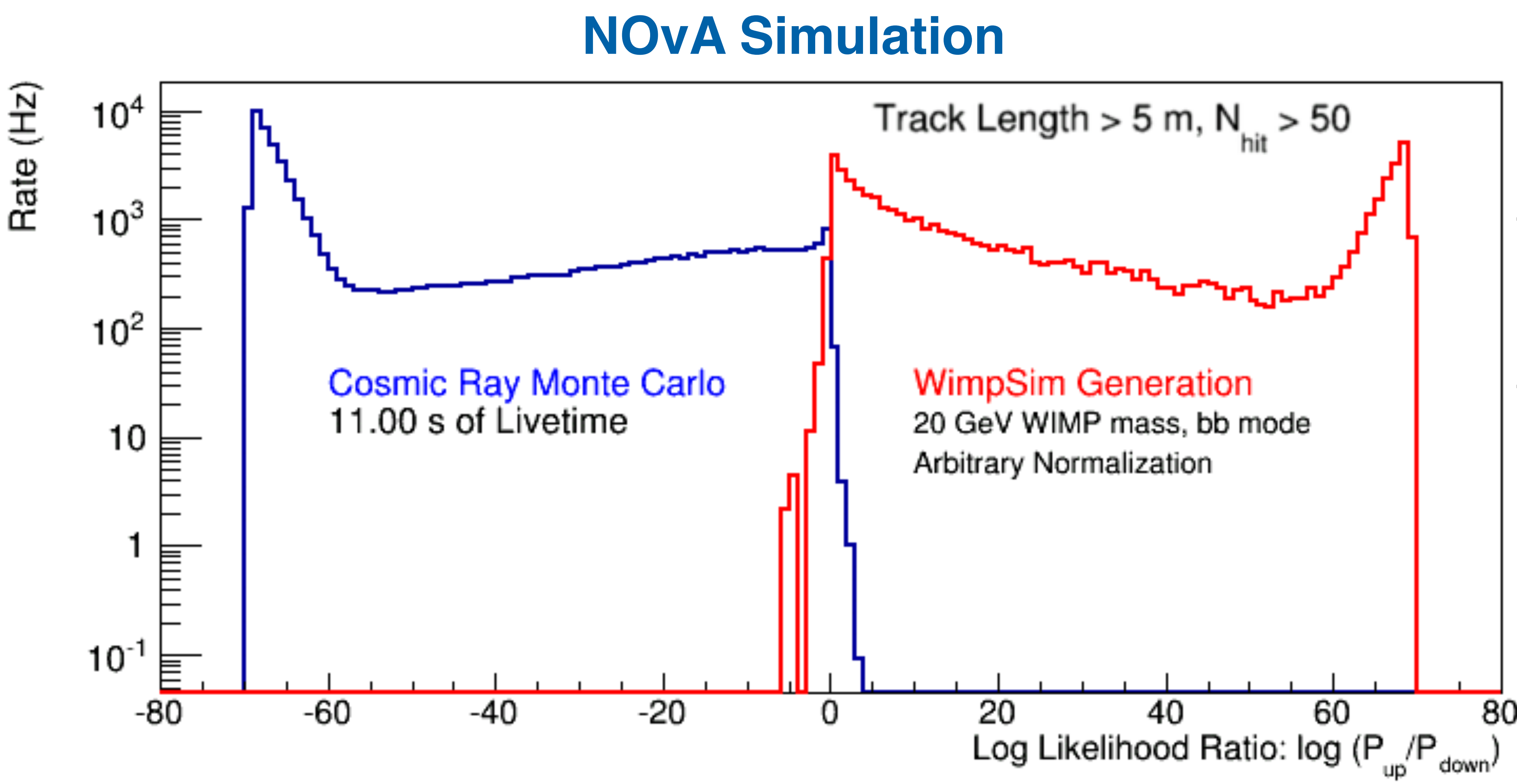
**The time resolution in the NOvA FD is ~10 ns for high energy hits.**

**(See Poster 1322 by C. Principato).**




Fitted with an upward-going (blue-dashed line) and downward-going (green-dashed line) hypothesis (assuming β=1)

# LLR is Very Effective for Long Tracks



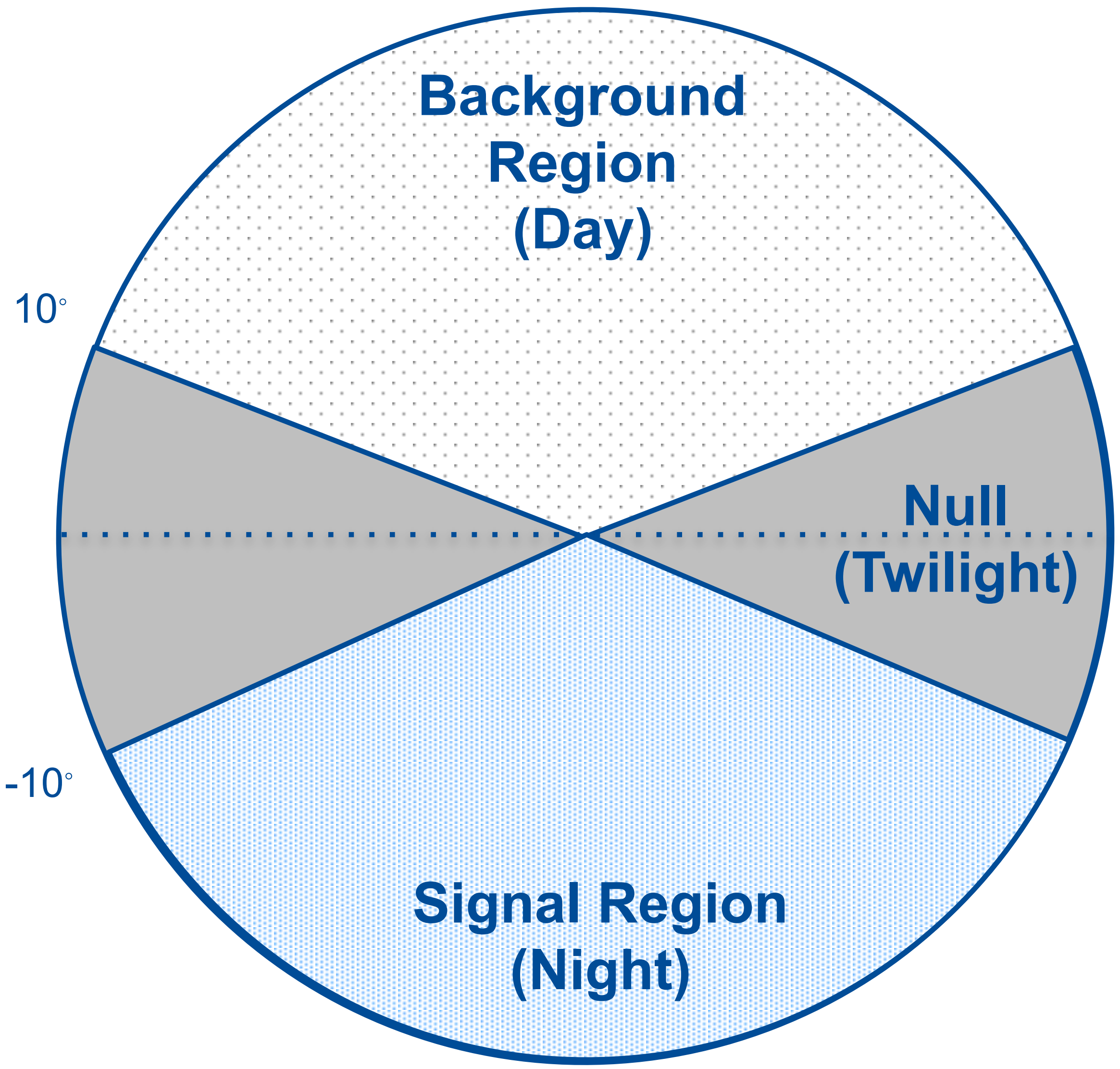

Combined with kinematic cuts, the LLR provides a powerful discriminator for track directionality.

The LLR distributions for cosmics (blue) and WIMPSIM (red) MC samples.

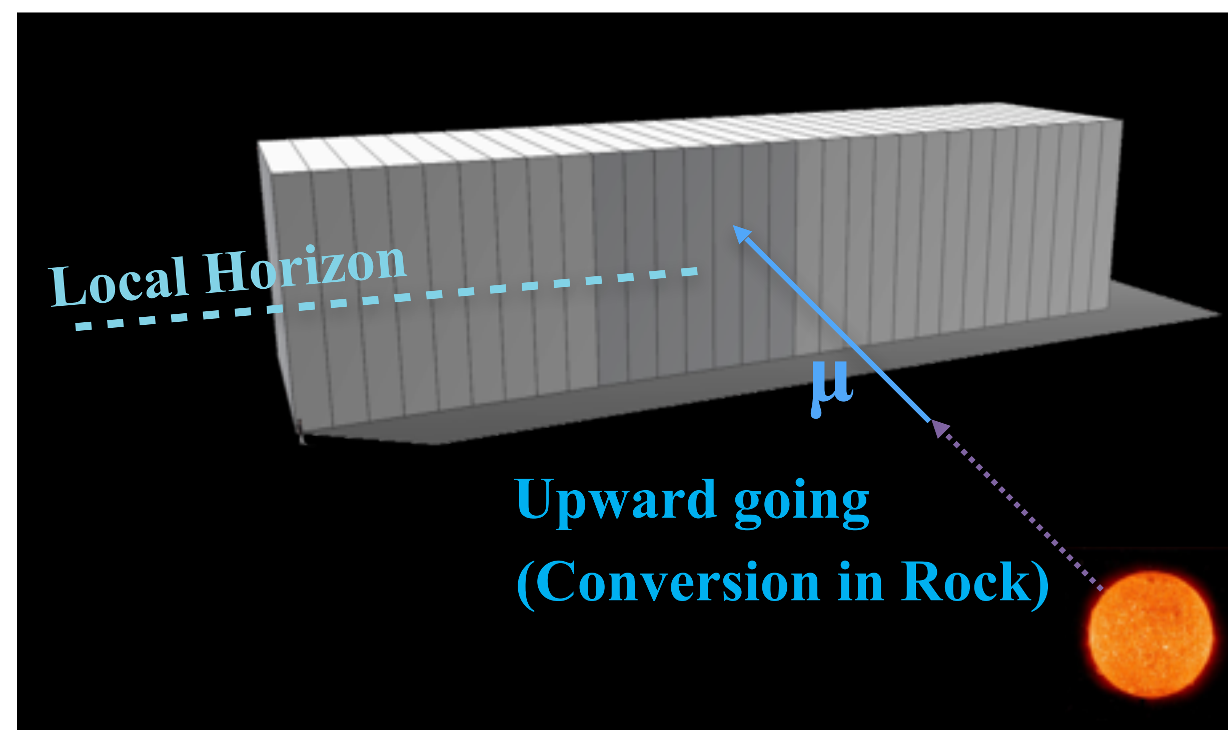
**Implementation of an upward-going muon trigger for indirect dark matter searches at the NOvA far detector**
[arXiv:1510.07571v1](https://arxiv.org/abs/1510.07571v1) **[physics.ins-det]**

# Analysis Regions and Blinding

**Sun Altitude (Ash River)**

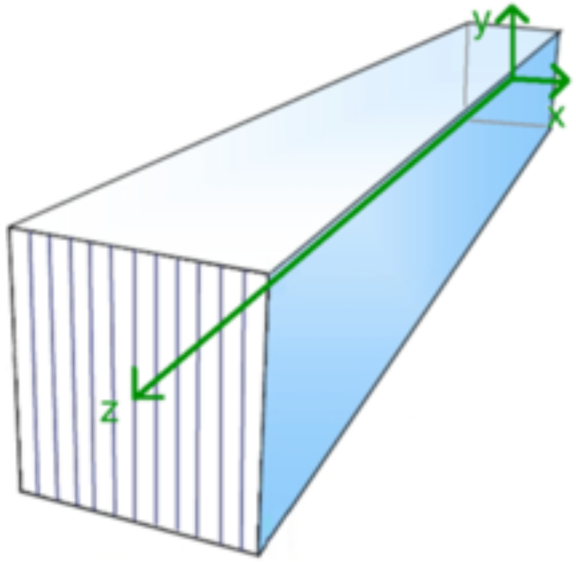


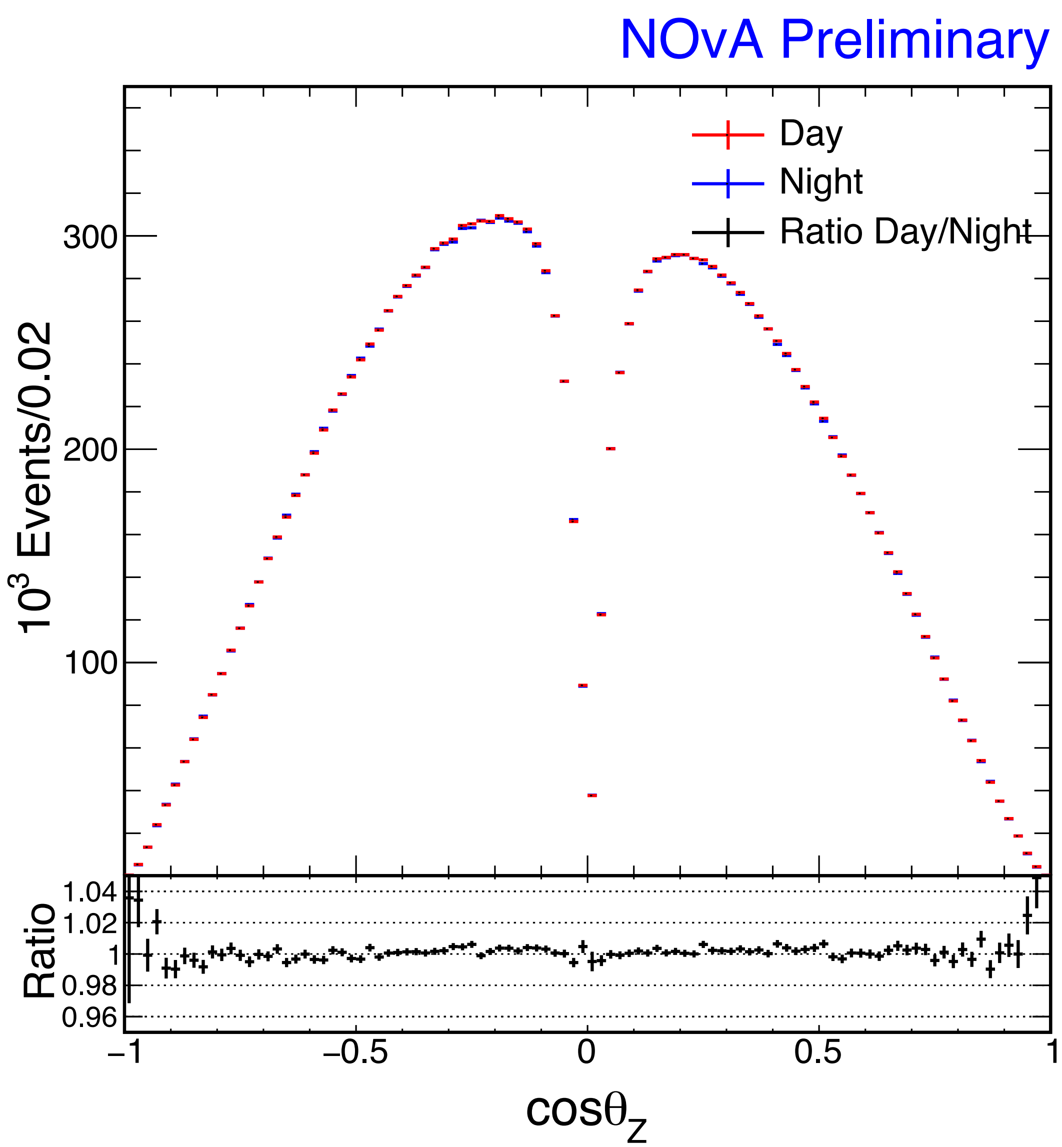

- We blind the samples based on the day/night altitude of the sun.
- No blinding is performed on the track angle.
- Measure the background during the Day and collect the signal during the Night

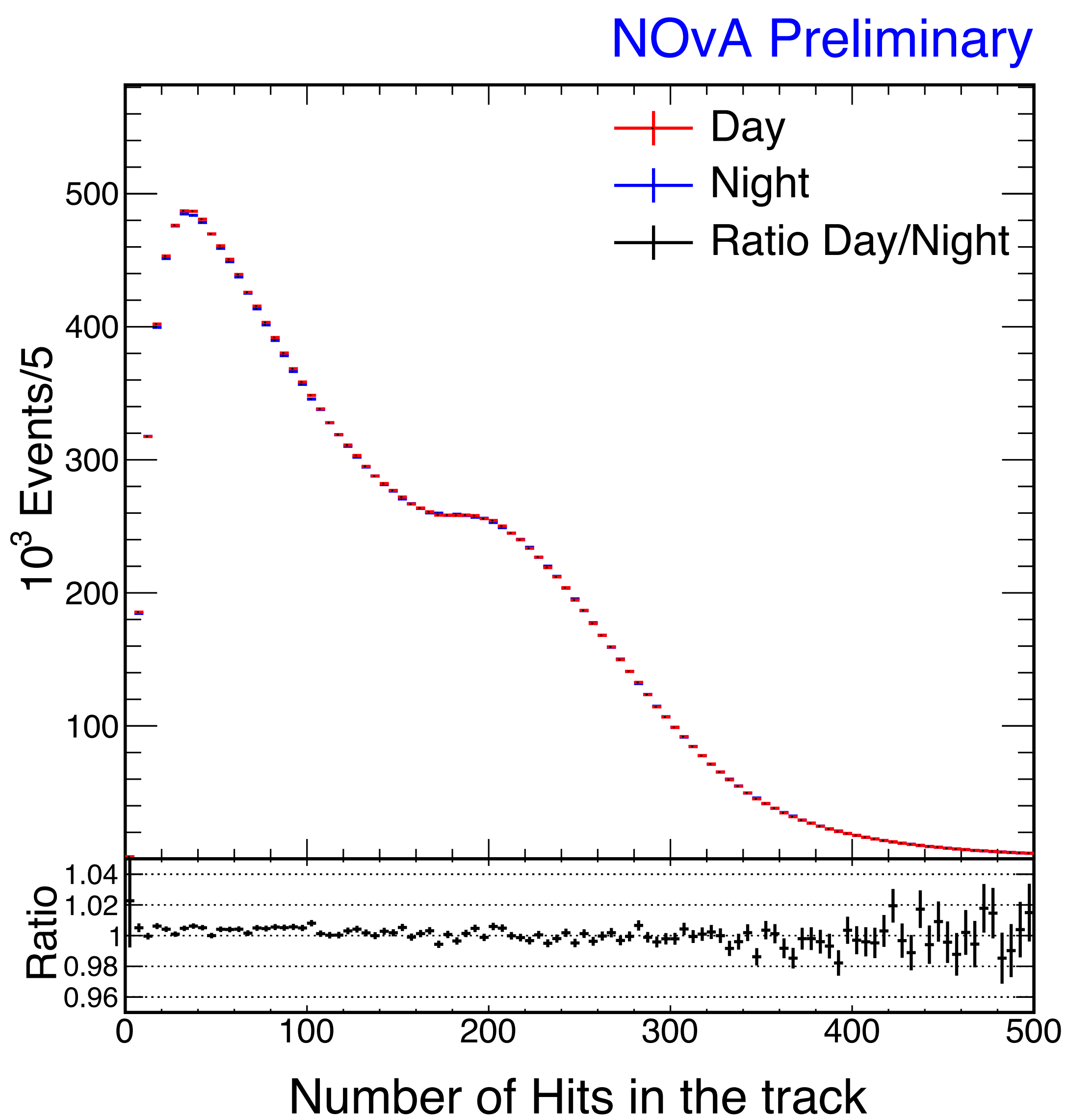


# Day Vs Night Consistency (Cosmic Events)

Sanity Check: Detector observables are stable between the day and the night.





Fermilab

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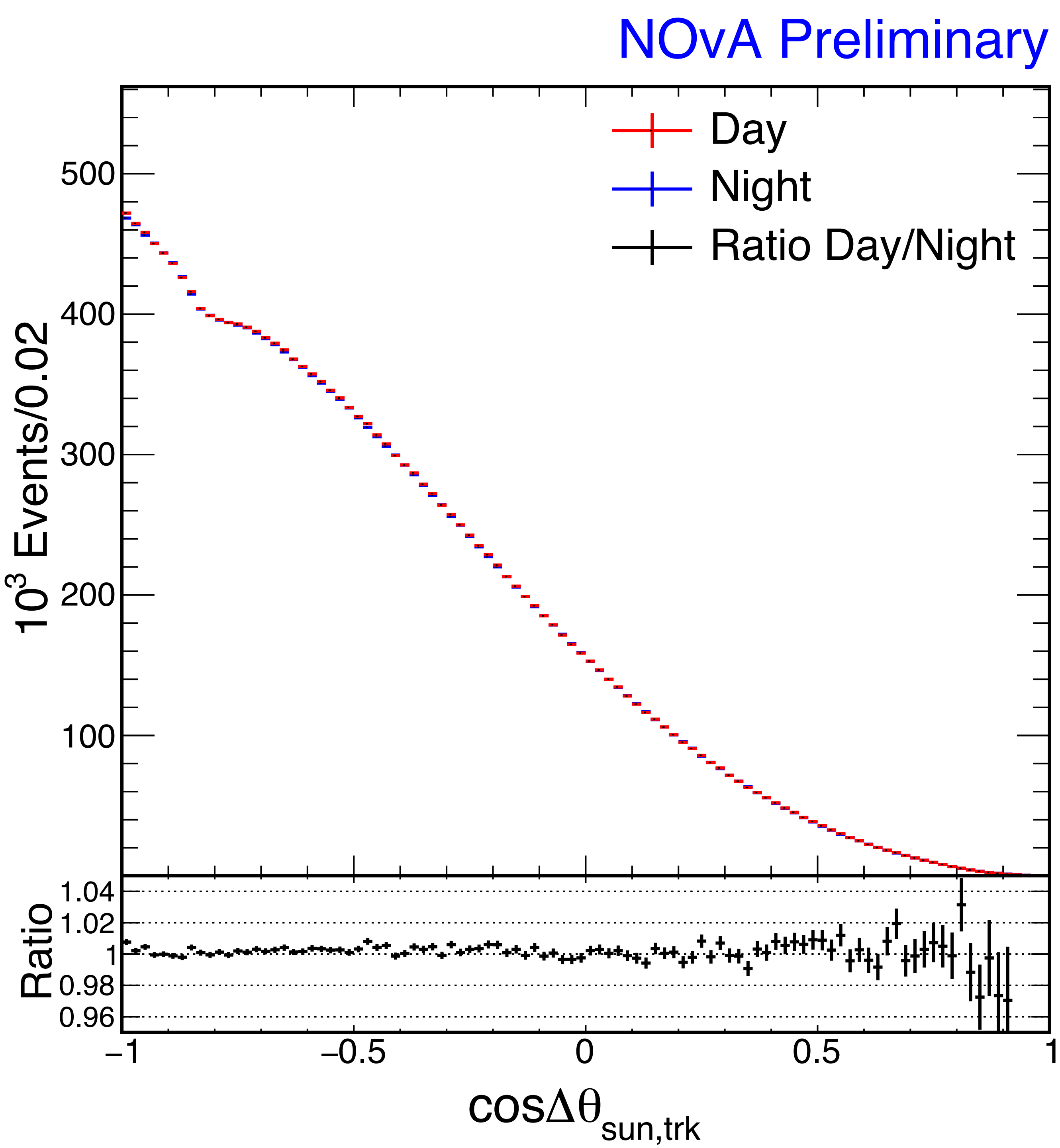
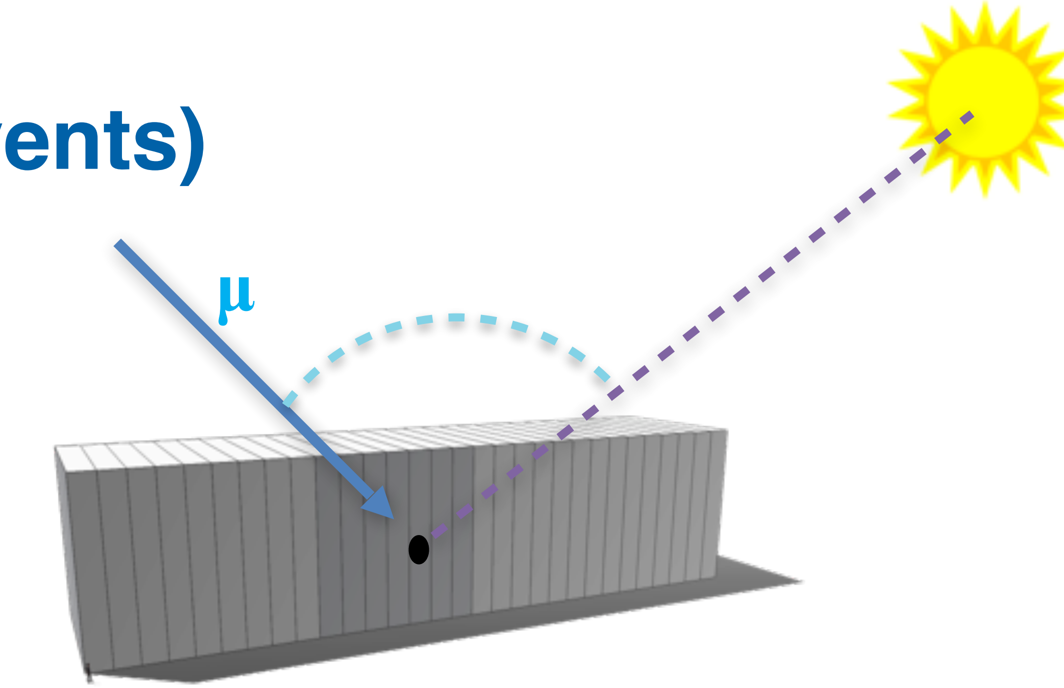
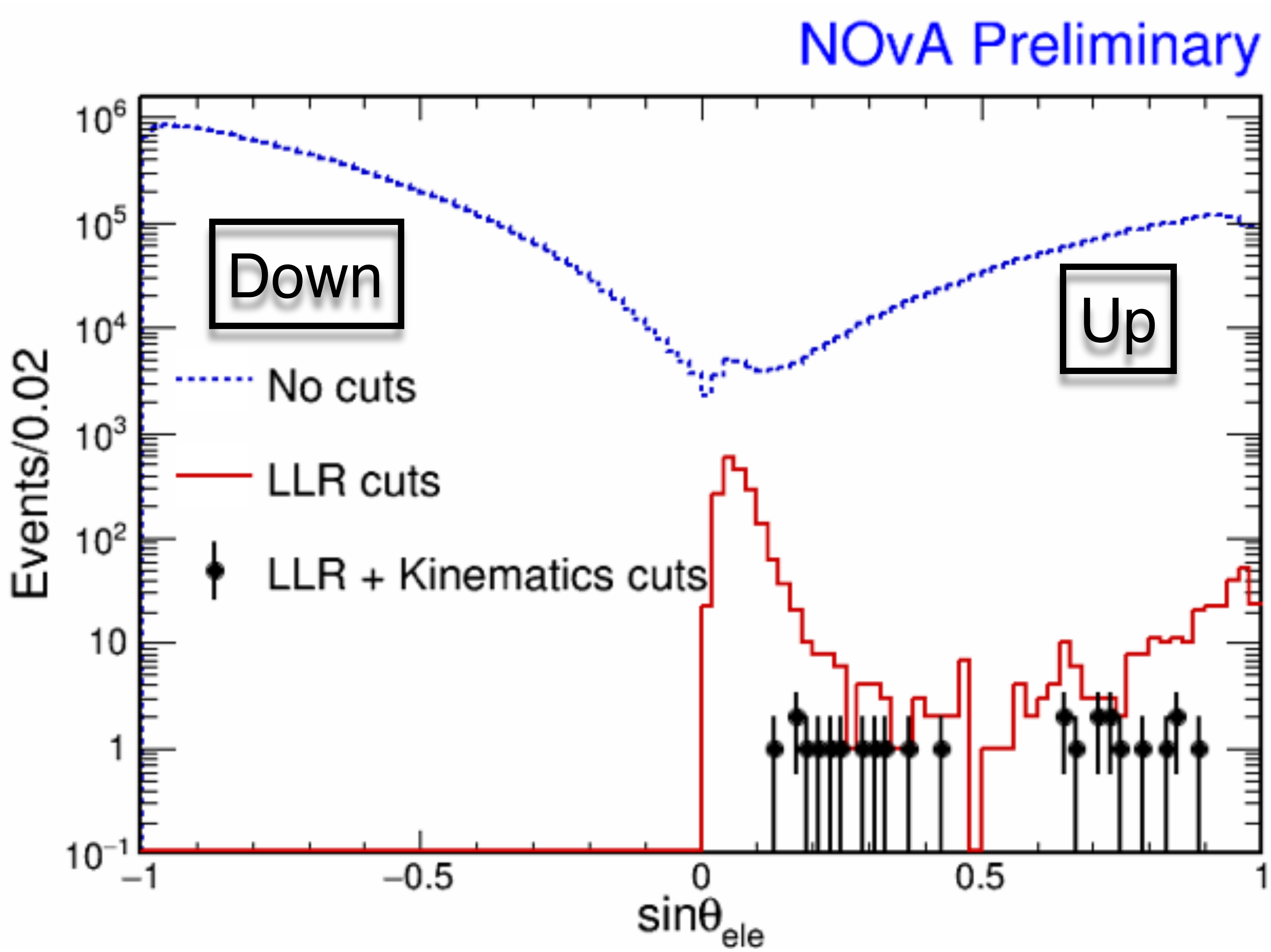


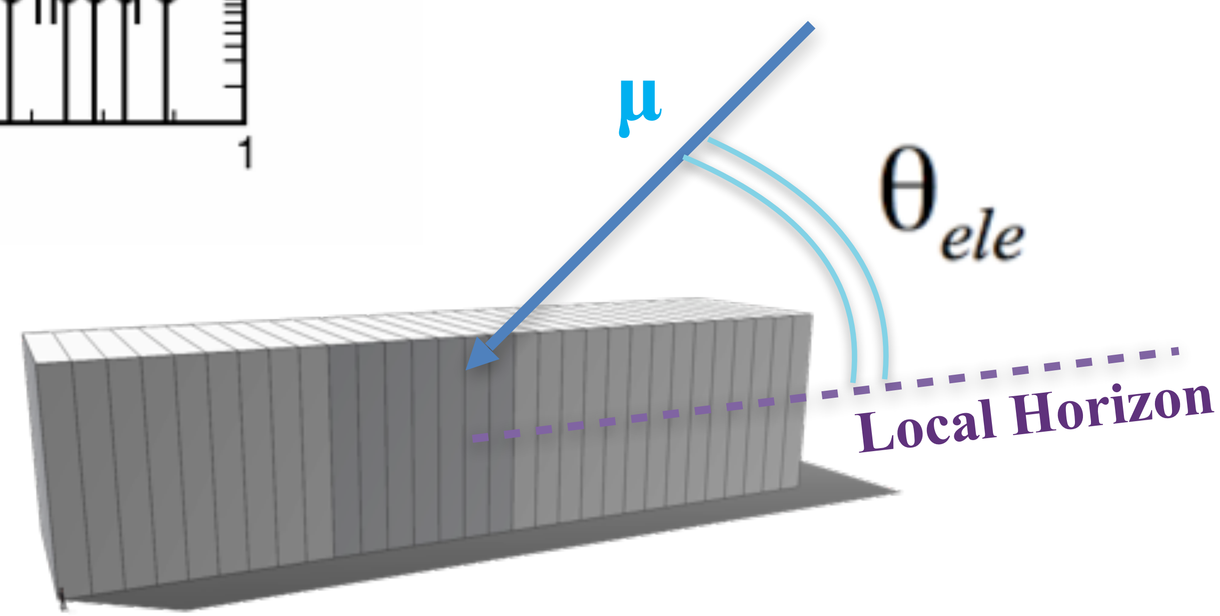




The shape of the day/night distributions for track angle to sun position match to within 2%. This deviation is taken as a systematic uncertainty in the full analysis.

# Data Driven Background Estimates (Elevation Angle)




- Cosmic-ray muons traveling slightly upwards can be scattered or penetrate though the thin layer of the Earth.
- The fall-off at steeper angles is due to shielding from the Earth.



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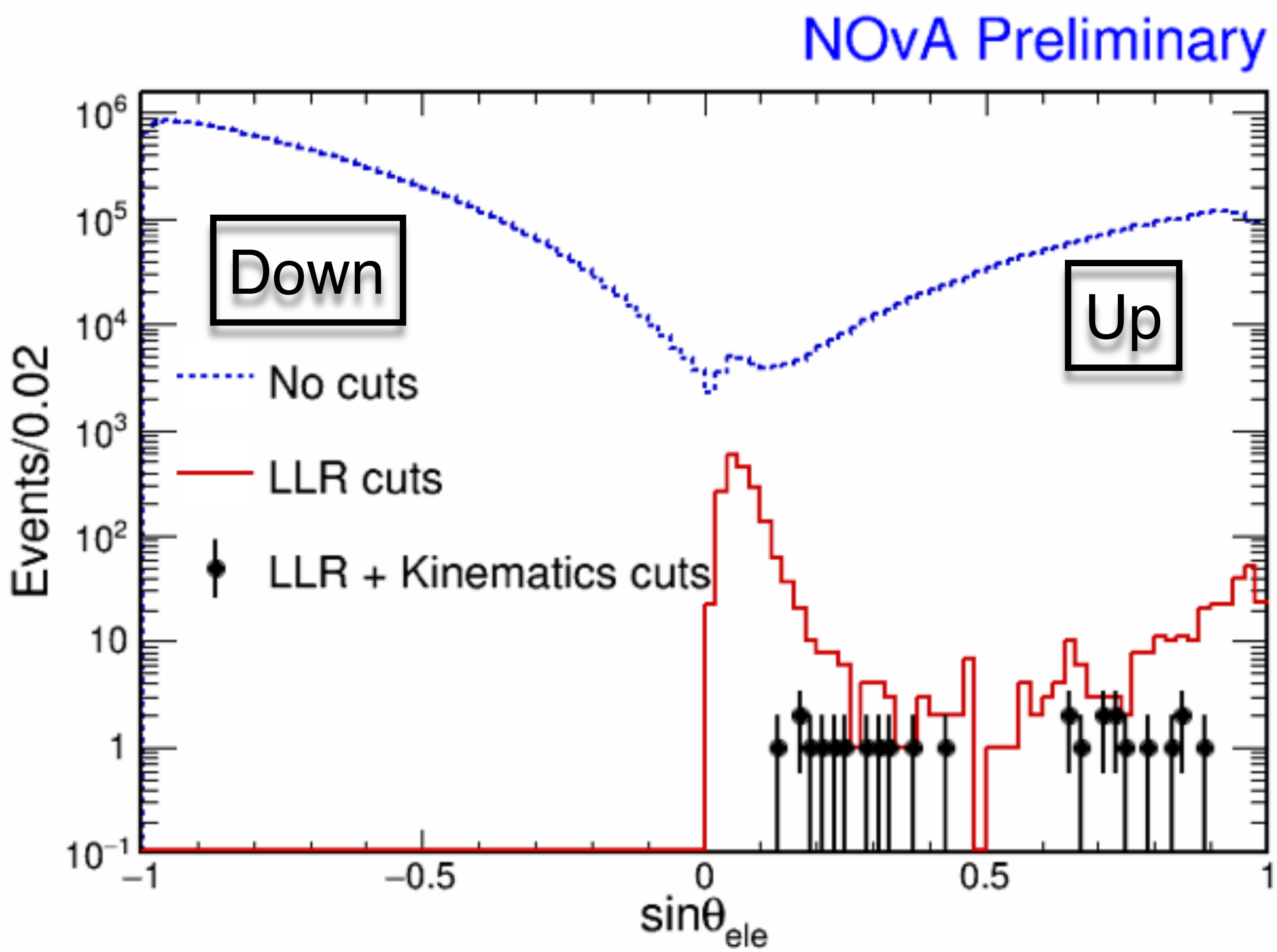


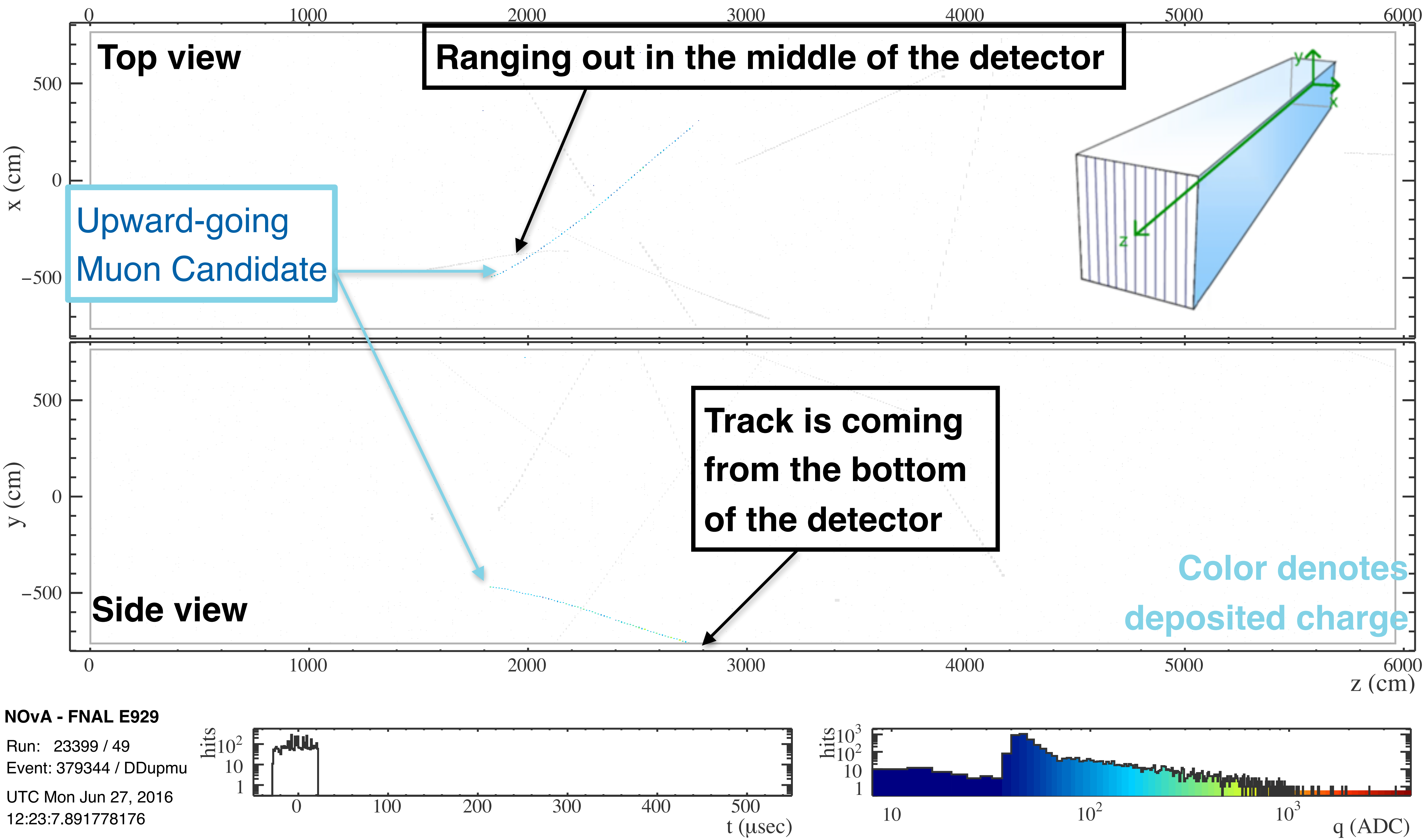

- The signal efficiency is ~30%

- For this analysis the live time exposure is:
  - **Above horizon:** 77 days
  - **Below horizon:** 147 days
  - **Twilight:** 54 days

- Events passed selections:
- **33 above horizon.**
- **Expect 23 for twilight we found 24.**
- **When unblinding the signal region we expect 63 background events**

**Every day ~$10^{10}$ events go through the detector and we are looking for < 1 per day**

# Upward-going Muon Candidate



# Summary and Future Plans

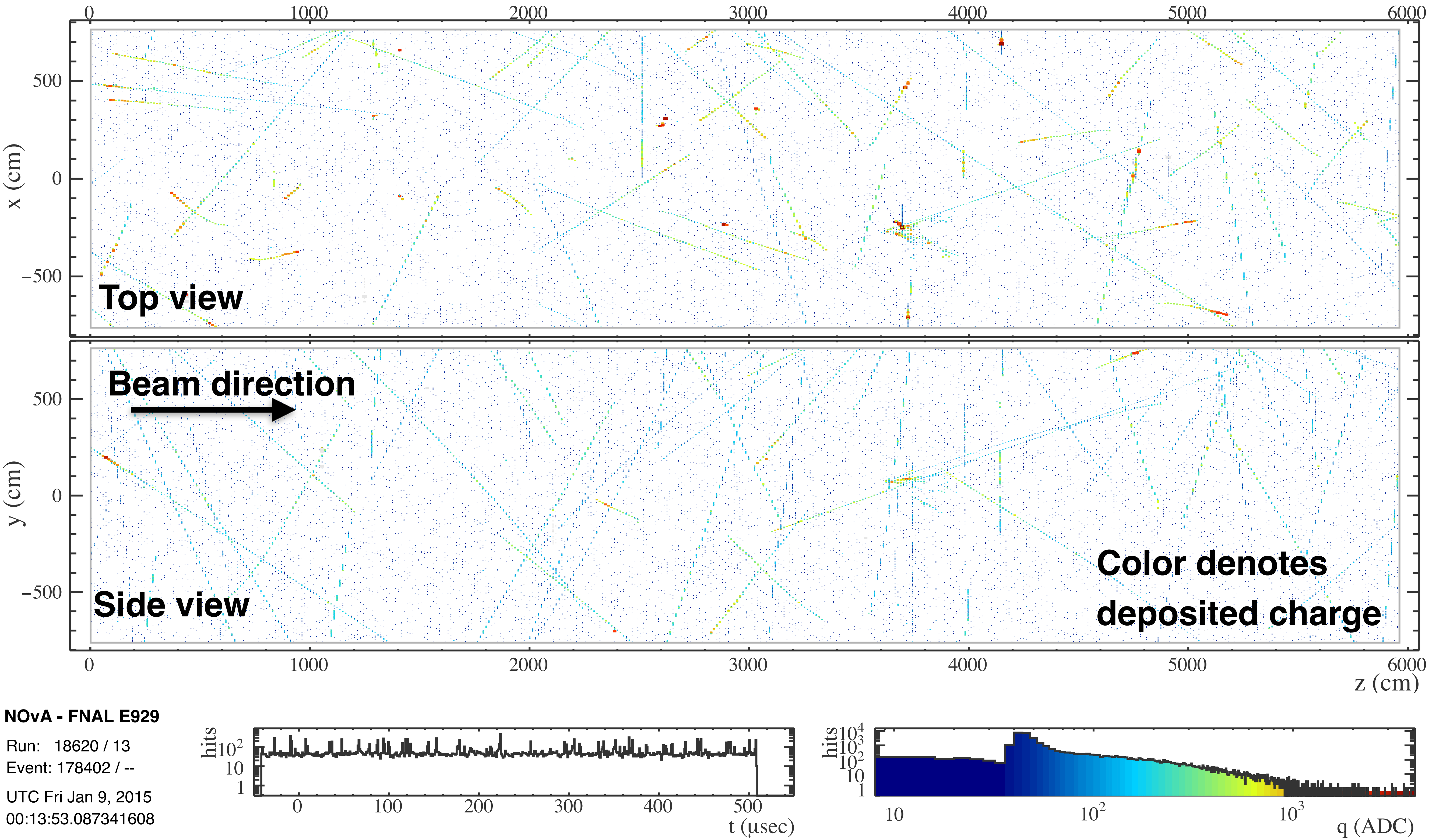
- Main goal of this analysis is to look for an excess of events coming from the sun.
- We can point to celestial objects with the NOvA detector:
  - Preliminary shape of deficit yields Gaussian pointing resolution ~1.2 deg.
- We can use the day sample as a control region to measure the background during the day
  - The several observables that were checked showed that their shape is consistent in the day and night sample.
- Continue the MC studies to predict the number of events in the signal region prior of unblinding the night sample.
- Further understanding of the background by looking the full day sample collected by the upward-going muon trigger.
- Set Limits for the WIMP detection.

# NOvA Posters

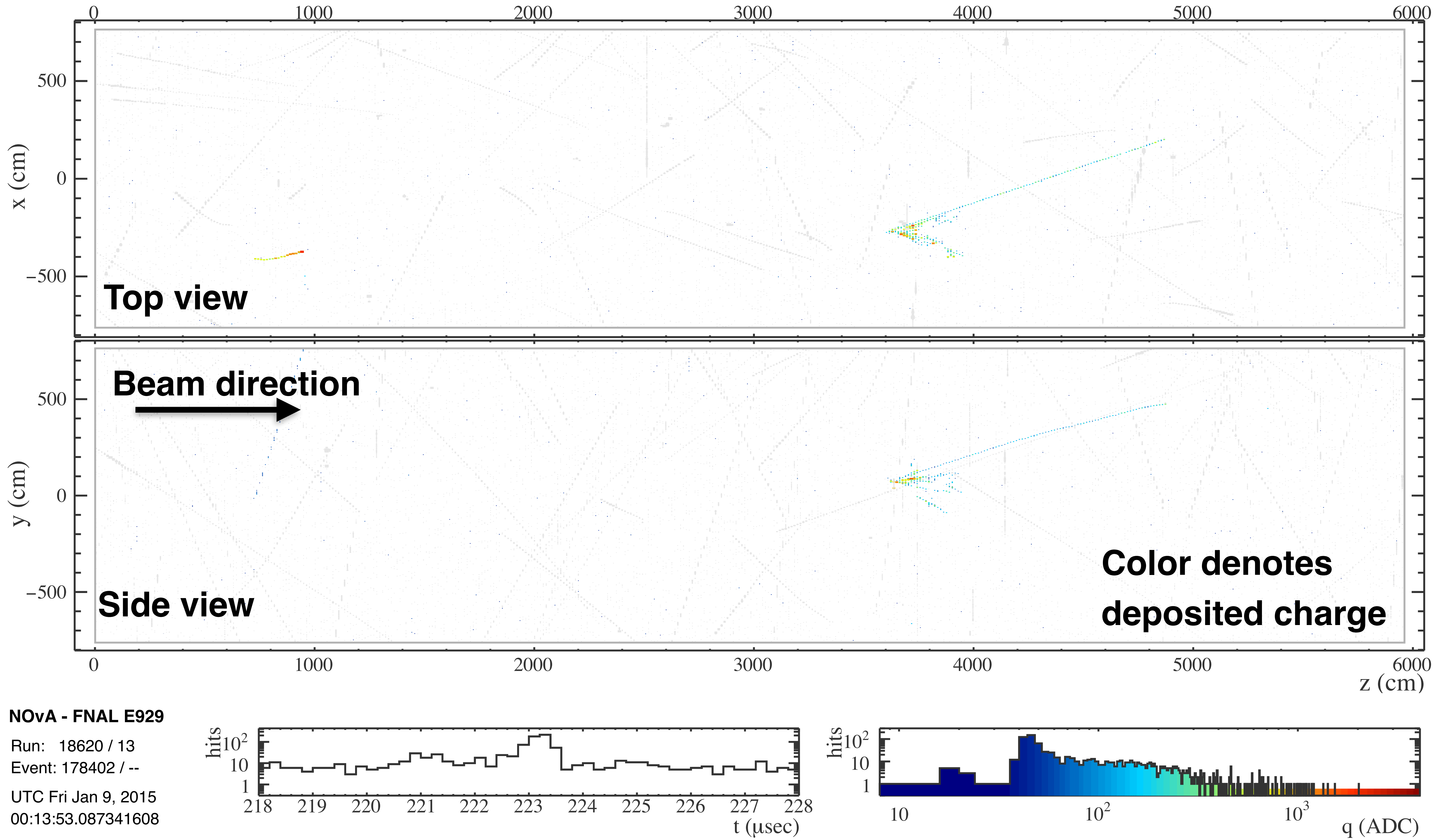
- H. Duyang: Neutrino Induced Neutral Current Coherent $\pi^0$ Production in The NOvA Near Detector.
- F. Jediny: Looking amongst the neutrinos for lightweight dark matter in the NOvA Near Detector.
- J. Lozier: Extrapolation, Systematics and Results for the NOvA Disappearance Analysis.
- K. Maan: Constraints on the Neutrino Flux in NOvA using the Near Detector Data.
- E. Niner: Systematic Uncertainties in the NOvA Electron Neutrino Appearance Analysis.
- C. Principato: Searching for Dark Matter using the NOvA upward-going muon trigger.
- K. Sachdev: Cross-section Measurements with the NOvA ND.
- A. Radovic: Neutrino Identification with a Convolutional Neural Network in the NOvA Detectors.
- P. Singh: Attenuation Calibration of the NOvA Detectors.
- E. Song: Search for Magnetic Monopoles with the NOvA Far Detector.
- S. Yang: Looking for Sterile Neutrinos with NOvA
- V. Bychkov and L. Corwin: NOvA Muon Neutrino Selection
- N. Yadav: Cosmic Electromagnetic Showers in NOvA Detector

Thank you

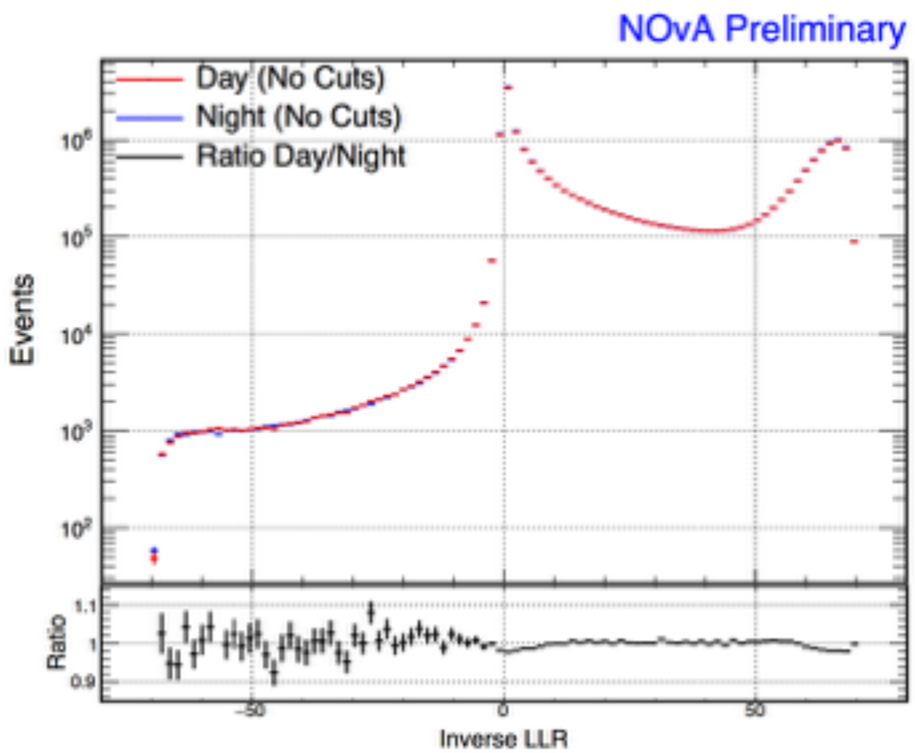
# Far Detector 550μs NOvA event



# Zoomed Far Detector 10μs NOvA Event

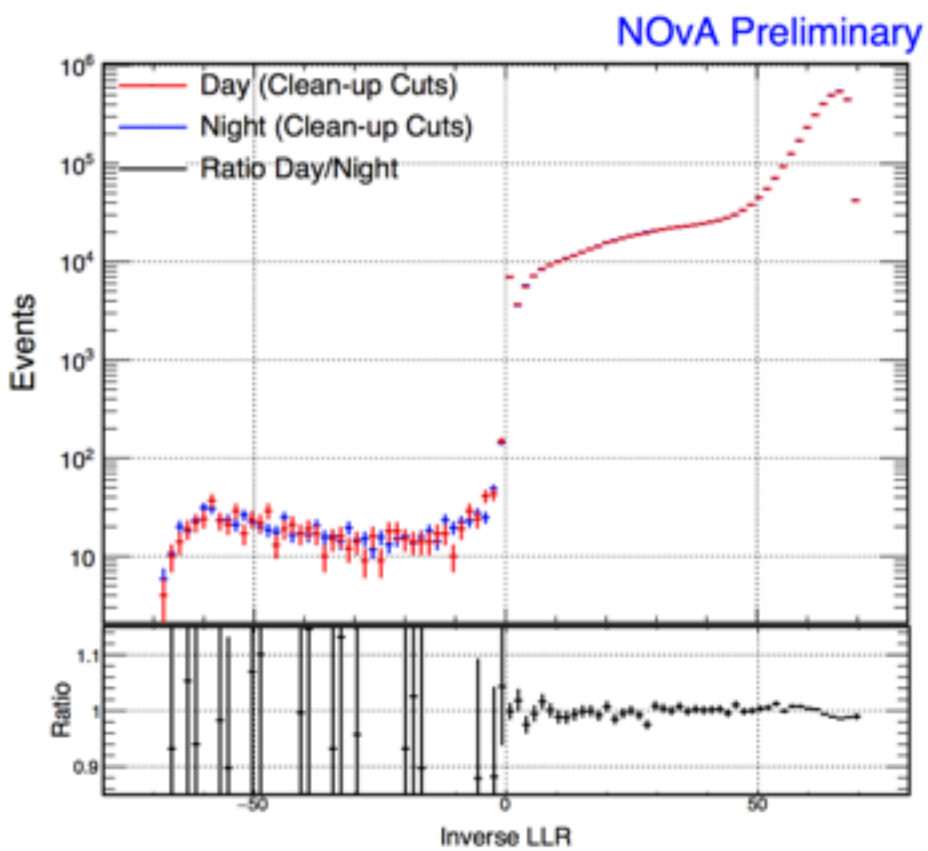


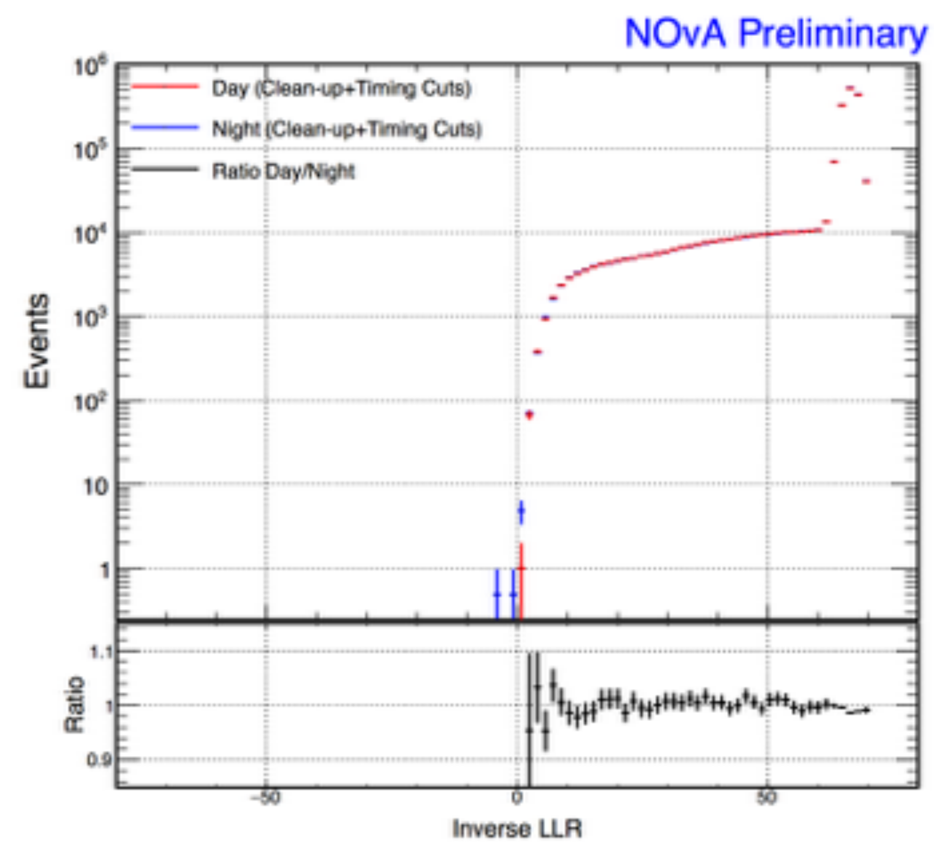
# Effect of the Selection Criteria in the Cosmic Sample




Effect of the cuts between day night in the cosmic sample
The selection criteria do not bias the day/night sample.

$$Inverse\ LLR = \ln\left(\frac{Prob_{DOWN}}{Prob_{UP}}\right)$$



# Selection Criteria used in the Upward-going Muon Trigger

| Variable | Cut Value | Description |
|---|---|---|
| TrackLen | 500.0 cm | 3 dimensional reconstructed track length |
| TrackHitsXY | 60 | total number of hits associated with 3D track |
| TrackHitsX | 15 | number of hits associated with XZ projection of track |
| TrackHitsY | 15 | number of hits associated with YZ projection of track |
| dX | 15 | Track cell length in XZ view |
| dY | 3 m | Track cell length in yz view |
| dZ | 3 m | Track plane length |
| R2X | 0.99 | Coefficient of determination for fit in XZ view |
| R2Y | 0.99 | Coefficient of determination for fit in YZ view |
| Chi2 | 2.0 | Fit $\chi^2$/NDF of time distribution |
| LLR | 3.0 | LLR of time distribution |

Table 1: Selection criteria used by the upward-going through-going muon trigger. These cuts are designed to select muon tracks with lengths and numbers of hits sufficient to compute reliable likelihood values for track direction.