The NOvA Upward-going Muon Trigger

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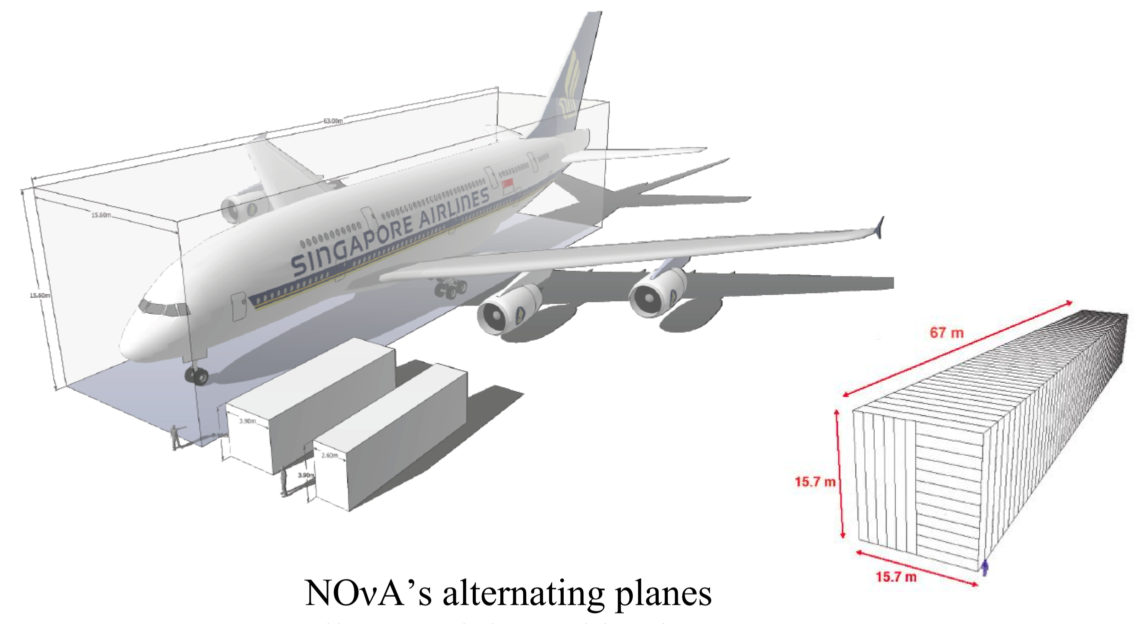
Introduction - NOvA experiment

★ The NOvA far detector is a 14 kTon, fine-grained, low-Z, liquid scintillator tracking calorimeter.
★ Cellular design allows 3D particle tracking.
★ Located in Ash River, MN
★ Designed to do neutrino oscillation physics - but there's potential for much more!



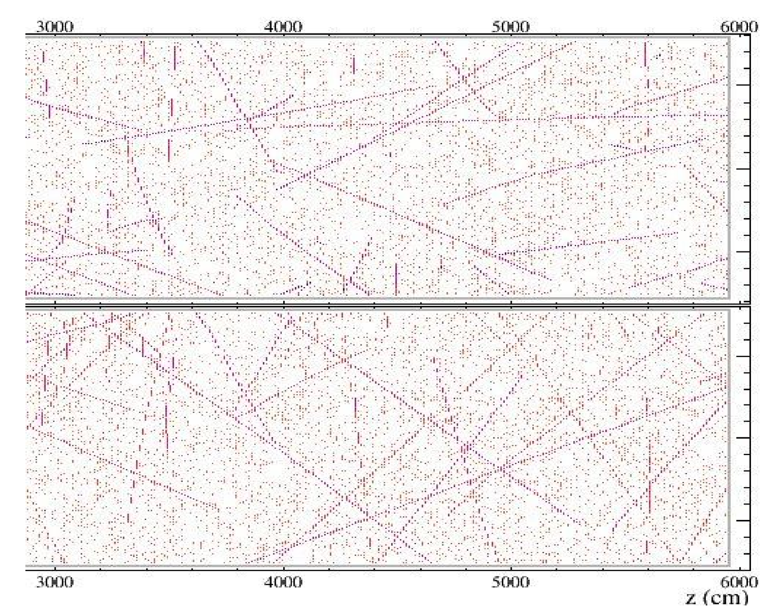
NOvA's alternating planes allow particle tracking in 3D.

Anticipated Signal - WIMP annihilations

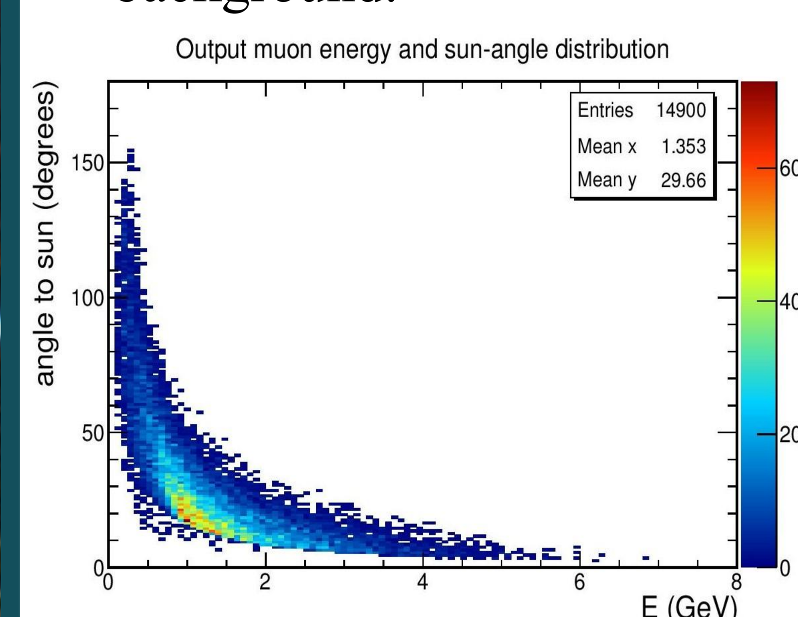
★ WIMPs (Weakly Interacting Massive Particles) are a leading theoretical candidate for dark matter.
★ As gravity wells, like the Sun, travel through space, they trap the slow-moving WIMPs.
★ At equilibrium, WIMPs in these gravity wells annihilate with their antimatter partners, producing a variety of products *including neutrinos*.
★ The annihilation rate equals the capture rate, so it is proportional to the overall abundance of WIMPs.
★ Sufficiently sensitive Earth-bound neutrino detectors should see an excess of neutrinos coming from the gravity wells.

Practical Complications - cosmic ray muons and directionality

★ Cosmic rays interact in the atmosphere producing a number of energetic particles including muons and neutrinos.
★ The muons produced around the detector travel through it, leaving about 100,000 downward-going tracks per second.
★ Neutrinos travel through the Earth to the detector, forming an irreducible background.



The far detector is highly active! This is a 500 µsec exposure of about half the detector mass.

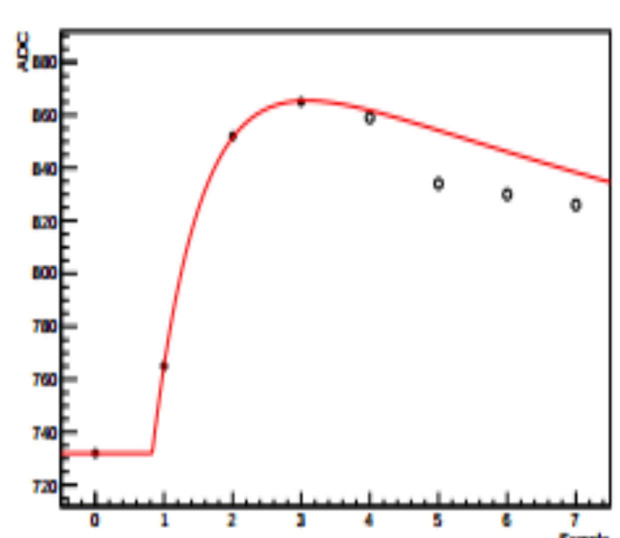


Secondary products that deposit energy in the detector no longer point directly to the source.

★ When signal neutrinos (which point directly back to the Sun) interact in or around the detector, they unfortunately leave no track with clearly-defined trajectory.
★ Only the secondary products leave tracks, but they do not point exactly in the same direction as the source neutrinos.

"Under-the-hood" Improvement - fine timing

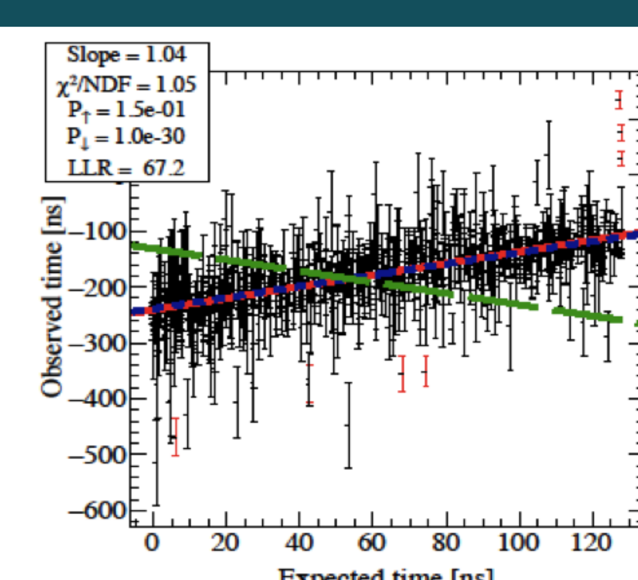
★ Previously, the resolution on timing determinations for single hits in the detector was ~120 ns.
★ Muons travel through the detector in about 50 ns.
★ By fitting to multiple channel readouts and storing results in a lookup table, single-hit timing resolution was improved efficiently to ~10 ns.



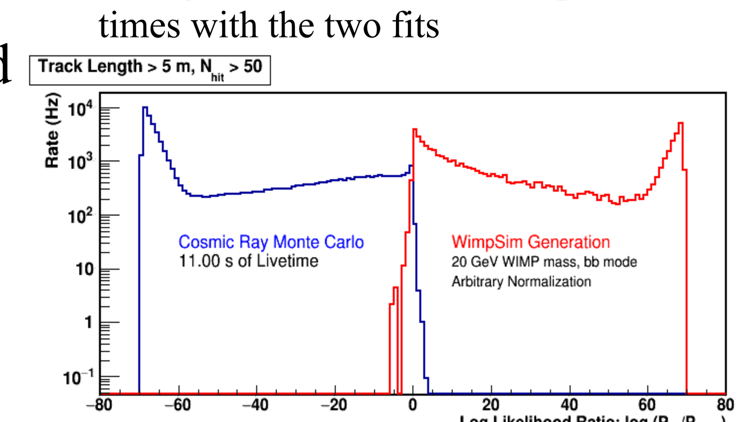
By fitting a known response curve to multiple read-outs from a single channel, a more precise timing determination is possible.

The Algorithm - log likelihood ratio

★ The Data-Driven Trigger is a software trigger that analyzes each block of live data in order to identify and record "interesting" events.
★ After tracking, the UpMu trigger searches for muon tracks that appear to be moving upward through the detector.
★ Assuming the track is going upward, each cell-hit is assigned an expected time (muons are assumed to be travelling at c).
★ Two linear fits are then done to the measured time vs the expected time for all hits in the track:
  ➢ Assuming upward-going (slope of 1)
  ➢ Assuming downward-going (slope of -1)
★ A likelihood is assigned to each fit. Then the log of the ratio of likelihoods is taken.
★ If this value is positive, it indicates an upward-going track!



A single track measured vs expected times with the two fits

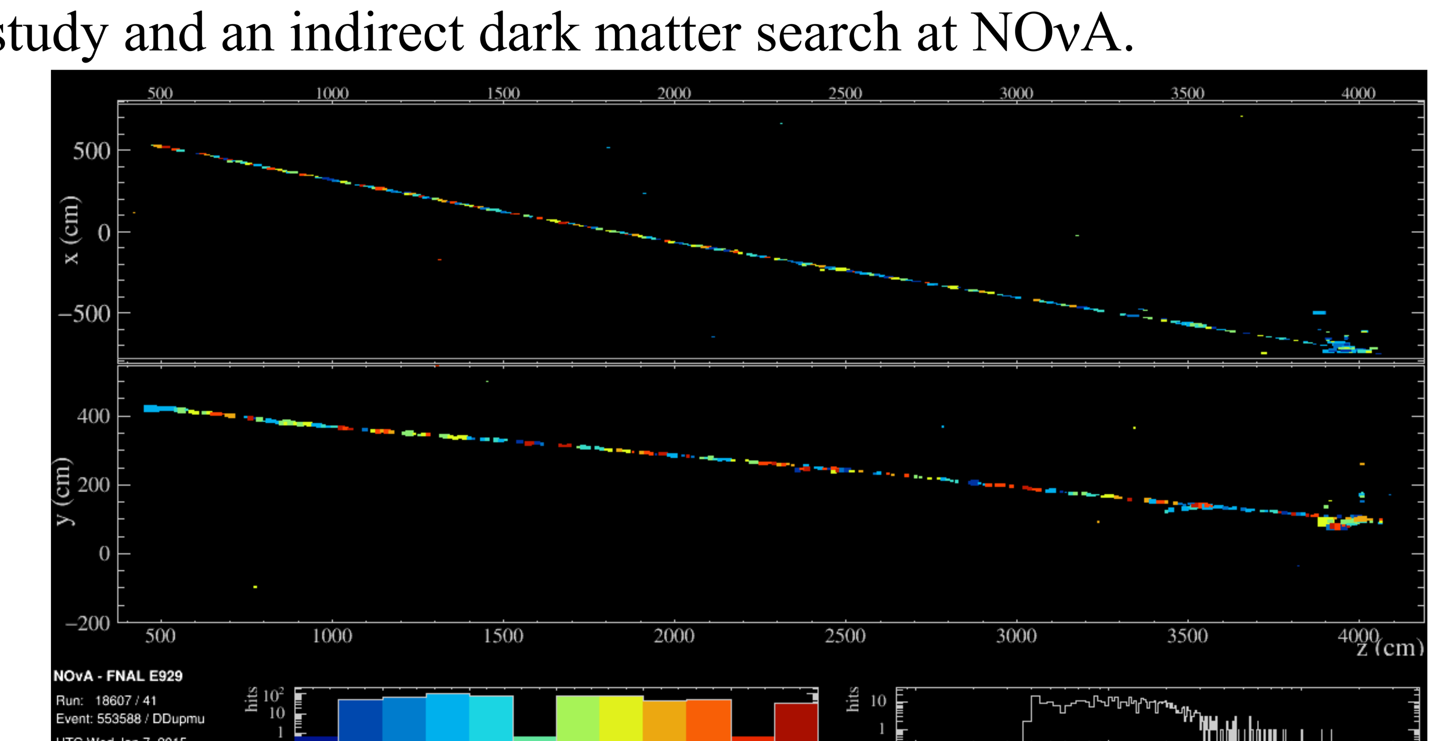


The LLR is a robust discriminator for simulated muon tracks in the detector.

$$LLR = ln(\frac{likelihood_{up}}{likelihood_{down}})$$

Conclusions - trigger effectiveness

★ An upward-going muon trigger has been implemented for the NOvA far detector, and has been running since November 2014.
★ Events with Michel electrons and contained vertices have been used to confirm upward-going muons in the triggered event sample.
★ Using individual hit timing information and the LLR, the trigger suppresses cosmic ray muons by five orders of magnitude.
★ Finally, this new trigger opens to door to an atmospheric neutrino study and an indirect dark matter search at NOvA.



This triggered event is a strong candidate for an upward-going muon, based on the topology. The activity at the bottom right indicates a charged current scattering interaction, the long track is almost certainly from a muon, and the curving towards the end probably indicates the muon ranging out. There is evidence for a Michel electron, based on hit timing. With an LLR of 67.2, this track demonstrates that the trigger is correctly identifying upward-going muons.

WIMP annihilation