A first look at data from the NO$\nu$A upward-going muon trigger

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The NO$\nu$A collaboration has constructed a 14,000 ton, fine-grained, low-Z, total absorption tracking calorimeter at an off-axis angle to an upgraded NuMI neutrino beam. This detector, with its excellent granularity and energy resolution and relatively low-energy neutrino thresholds, was designed to observe electron neutrino appearance in a muon neutrino beam, but it also has unique capabilities suitable for more exotic efforts. In fact, if sufficient cosmic ray background rejection can be demonstrated, NO$\nu$A will be capable of a competitive indirect dark matter search for low-mass Weakly-Interacting Massive Particles (WIMPs). The cosmic ray muon rate at the NO$\nu$A far detector is approximately 100 kHz and provides the primary challenge for triggering and optimizing such a search analysis. The status of the NO$\nu$A upward-going muon trigger and a first look at the triggered sample is presented.
1 Introduction

WIMPs captured by the gravitational field of the Sun that are slowed through collisions with solar matter can accumulate in the solar core. There, WIMP annihilation may produce neutrinos with much larger energy than solar neutrinos. The signal would be an excess of high-energy (> 0.5 GeV) neutrino events pointing back to the Sun. The cleanest signature at NOνA will be from νµ charged-current scattering (CC) events producing upward-going muons that can be reconstructed in the NOνA detector. The large and unique NOνA far detector, with its excellent granularity and energy resolution, and relatively low-energy neutrino thresholds, is an ideal tool for these indirect dark matter searches.

Only the upward-going flux will be considered in order to suppress the cosmic ray-induced muon background. The downward-going muon rate in the NOνA far detector is approximately 100,000 Hz.

The neutrino flux from dark matter annihilation is model dependent; however, energies from ∼0.5 GeV to many TeV should be detected with high acceptance. For high-mass signal hypotheses, NOνA will not be able to compete with the high acceptance of the IceCube detector. For lower-mass scenarios (below ∼20 GeV) the Super-Kamiokande experiment currently has the best sensitivity. If an efficient upward-going muon trigger and sufficient cosmic ray background rejection can be achieved, NOνA will be competitive with Super–Kamiokande for WIMP mass hypotheses below 20 GeV/c².

Neutrinos are produced by interactions of high-energy cosmic rays in the atmosphere, and these atmospheric neutrinos comprise the primary component of the upward-going νµ flux at the NOνA far detector. It is well known that such neutrinos undergo oscillations as they travel through the Earth. Therefore, isolating the upward-going muon signal should allow for an atmospheric neutrino oscillation study at NOνA. Since atmospheric neutrinos represent a background in the dark matter annihilation search, such a study is a natural preliminary step.

At NOνA, the neutrino analyses simply store events synchronous with the NuMI beam. For non-beam exotic physics searches, so-called data-driven triggers are required to select events of interest.

Two data-driven triggers were developed for use at the NOνA far detector: one that searches for long muon tracks originating from outside the detector, and another that searches for shorter tracks that are fully contained in the detector volume. Both triggers use timing information for detector cell hits along the length of the track to determine its direction. The effectiveness of the trigger at differentiating upward- from downward-going muons in simulated events has been demonstrated.

This note will examine data from the first trigger which searches for through-going muon tracks, and will demonstrate the effectiveness of combining hit timing with event geometry information to isolate a small, likely signal-rich component of
the triggered sample. Producing such a subsample is a necessary preliminary step to making an atmospheric neutrino oscillation measurement and to performing the indirect dark matter search.

2 Triggered Sample

The upward-going muon trigger was first implemented and tested in August 2014, but did not run in a stable configuration until December 2014. The triggered sample examined in this note covers a period of 164 days from December 2014 to May 2015. The total livetime of this sample is \(\sim 84\) days.

Over the period of this sample, the through-going trigger fired at a consistent rate of \(\sim 1\) Hz. Each triggered event is \(50\ \mu s\) in length, so that the triggered sample contains approximately 1 part in 20,000 of the total background activity during the exposure time. Activity in the NO\(\nu\)A far detector is dominated by muons from cosmic ray interactions above and around the detector [10].

NO\(\nu\)A reconstruction software was run on the triggered sample to produce the desired track and hit objects and to perform the necessary timing calibrations. The reconstructed sample contained \(4.3 \times 10^6\) track objects.

3 Hit Timing and LLR

NO\(\nu\)A’s cm-scale spatial resolution allows determination of particle direction by comparing timing for detector cell hits along a track. By applying several timing calibration techniques, single hit time resolution for the Far Detector has been improved to \(\sim 10\) ns [9]. This timing resolution is sufficient to allow effective directionality determination using a timing-based classifier called LLR [10].

Cleanup requirements including track length, track linearity, and number of hits in the track object improve the reliability of the LLR as a discriminator, and are used in the trigger to improve the determination of directionality. Applying those requirements used in the trigger to the reconstructed sample with full timing calibration produced a timing-based candidate subsample of 16,000 tracks that appear to be from upward-going muons.

4 Event Geometry

The tracks passing cleanup and timing requirements are predominantly horizontal or slightly upward-going, as shown in Fig. [1] The abundance of mostly-horizontal tracks in this subsample is explained by the position of the far detector on the surface, where energetic cosmic ray-induced muons travelling slightly upward can penetrate
the walls of the detector hall and the thin layer of the Earth’s crust surrounding it. At steeper angles the horizon provides shielding from these upward-going cosmic ray muons, explaining the fall-off in the subsample elevation angle distribution.

Placing an additional requirement on the elevation angle at 10 degrees further reduced the size of the candidate subsample to 1,051 tracks. Of those that remain, \(\sim 75\%\) are not conclusively upward-going due to a possible misreconstruction in which two unrelated but overlapping muon tracks create ambiguity in the reconstruction, as shown in Fig. 2. A simple geometric requirement was then applied to eliminate this component while preserving the neutrino-induced muon signal. 255 candidates remained after this requirement.

5 Event Categorization

| Category                                      | Count |
|----------------------------------------------|-------|
| Through-going                                | 105   |
| Stopping                                     | 75    |
| 3D mismatch                                  | 34    |
| Up-scattered cosmics                         | 23    |
| In-produced                                  | 1     |
| Likely downward-going                        | 1     |
| Likely caused by timing miscalibration       | 14    |

Table 1: Event topologies in the candidate subsample.

Each of the remaining candidate events was then examined visually and categorized. With the exception of 2 events that were difficult to categorize because they had attributes of multiple event topologies, all the events could be placed into seven categories based on event topology. The categories are summarized in Table 1.

The most common event topology was through-going tracks, indicating muons that originated outside the detector and traveled all the way through without stopping. Both tracks in Fig. 2 exemplify this topology. Stopping tracks caused by muons originating below or to the sides of the detector that stop within the detector volume are the second most abundant component. The final signal-like event in the subsample contains a track that appears to be caused by a neutrino interaction within the detector. This event is shown in Fig. 3.

The other categories correspond to events that are not signal-like. 34 events exemplifying the possible misreconstruction discussed in the previous section passed the requirements (Fig. 2). 23 events appear to contain tracks from downward-going cosmic ray muons that scattered upwards within the detector, as shown in Fig. 4. 14 of the through-going events were placed into a separate category because they share
extraordinary features that may indicate a temporary problem in the timing system for one portion of the detector; namely, they all have candidate tracks that have both ends in one particular portion of the detector, and they all occurred during an isolated, continuous running period in which the rate of through-going events was many times higher than the average. Finally, one event appears to contain a downward-going muon.

The existence of events that probably contain upward-going tracks from scattering of cosmic ray muons within the detector indicates that these cosmic ray muons are also scattering outside the detector. The through-going and stopping muon subsamples are likely contaminated by this background process, but it is not possible to distinguish between signal muons created by neutrino interactions outside the detector and those that were scattered upward in the rock around the detector. However, all of the candidate tracks from cosmic muons scattering in the detector had elevation angles below 20 degrees, so by requiring all tracks to have an elevation angle above 20 degrees, almost all contamination by up-scattering cosmic ray muons should be eliminated, as shown in Fig. 5. The remaining signal-like events after this requirement was applied were 43 through-going and 5 stopping muon events.

6 Conclusions

A first look at the triggered sample from the NOνA upward-going muon trigger showed that in its first six months of stable running, the trigger selected dozens of events with signal-like muon tracks. The extraction of this subsample from the triggered sample involved a reduction by 6 orders of magnitude in the number of tracks, and this was accomplished by combining techniques that use hit timing to determine track directionality with simple geometry-based requirements and a visual scan. This effort revealed that several backgrounds other than downward-going cosmic ray muons contaminate the sample, and new requirements were developed to minimize the acceptance of these backgrounds. These techniques will allow studies of atmospheric neutrino oscillations and, ultimately, an indirect dark matter search at NOνA.

This work demonstrates that NOνA is capable of isolating a sample that is likely rich in neutrino-induced upward-going muons for the through-going and stopping muon event topologies. A similar effort that examines data from the other upward-going muon trigger will reveal whether a signal-rich sample can be isolated for the fully-contained event topology.

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Figure 1: The distribution of sine of the elevation angle for each track in the timing-based candidate subsample (red) and all tracks excluded from the subsample (black). Almost all candidates have an elevation angle near 0, indicating they are nearly parallel with the ground. A negative elevation angle indicates a downward-going track, while a positive angle indicates an upward-going track.

Figure 2: An example of an event that is prone to a possible misreconstruction. Note the two overlapping muon tracks (the two long colored lines in each plot) with similar extent in the z-dimension (horizontal axis) and near coincidence in time (hits are colored by time). The detector produces separate two-dimensional views of each event, and the 2D track objects from each view must be merged to produce a full 3D object. Cases such as this produce ambiguity in matching the 2D components between the views; is the correct matching (A1,B2) or (A2,B1)? This class of events represents the largest component of the subsample when timing and elevation angle requirements are applied.
Figure 3: This event contains a long upward-going muon track that appears to have been caused by a $\nu_\mu$ CC interaction within the detector.

Figure 4: In this event, a slightly downward-going muon, likely originating from a cosmic ray interaction outside the detector, enters from the high-z extreme of the detector, scatters upward within it, and produces an upward-going track.
Figure 5: The distribution of sine of the elevation angle for some of the categorized candidate events. The black vertical line indicates the requirement at 10 degrees. Note that above 20 degrees (the blue vertical line), there are no events containing cosmic ray muons that scattered upward within the detector.