

Implementation of an upward-going muon trigger for indirect dark matter searches at the NO ν A far detector

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Abstract. The NO ν 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 an efficient upward-going muon trigger with sufficient cosmic ray background rejection can be demonstrated, NO ν A will be capable of a competitive indirect dark matter search for low-mass WIMPs. The cosmic ray muon rate at the NO ν A far detector is about 100 kHz and provides the primary challenge for triggering and optimizing such a search analysis. The status of the NO ν A upward-going muon trigger 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 [1, 2]. The cleanest signature at NO ν A will be from ν_μ CC events producing upward-going muons that can be reconstructed in the NO ν A detector. The large and unique NO ν A 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.

At NO ν A, the neutrino analyses simply store events synchronous with the NuMI beam. For non-beam exotic physics searches, so-called data-driven triggers [3] are required to select events of interest.

Only the upward-going flux will be considered in order to suppress the cosmic-ray background. The downward-going muon rate in the NO ν A far detector is approximately 100,000 Hz. We expect to keep the upward-going muon trigger rate to about 10 Hz or less, so a rejection of at least four orders of magnitude is required by the trigger. Of course, this rejection must be accomplished while keeping the acceptance for upward-going muons relatively high.

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



hypothesis, NO ν A will not be able to compete with the high acceptance of the IceCube detector [4]. For lower-mass scenarios (below ~ 20 GeV) the Super-Kamiokande experiment currently has the best sensitivity [5, 6]. If an efficient upward-going muon trigger and sufficient cosmic ray background rejection can be achieved, NO ν A will be competitive with Super-Kamiokande for WIMP mass hypotheses below 20 GeV/ c^2 .

One advantage that NO ν A has compared to past experiments that performed similar searches for dark matter annihilation is the relatively low energy threshold for muons. A 1 GeV muon track travels approximately 5 meters in the NO ν A detector resulting in an energy threshold well below 1 GeV. The challenge for the dark matter search is triggering efficiently on these low-energy muons. For shorter track lengths, the timing information will not be as powerful for rejecting downward-going backgrounds. Using stopping or fully-contained events and using the top and sides of the detector to veto downward-going events can provide an additional two orders of magnitude rejection.

In this note we focus on using the timing information from all of the hits on a track to reject the downward-going muon background and efficiently select upward-going events.

2. Hit time estimates

A trigger for upward-going muons based on timing information required a minor upgrade to the readout of the NO ν A far detector. This upgrade to the so-called “multipoint” readout occurred on September 11, 2014, and resulted immediately in a single-hit timing resolution of about 25 ns (note that the timing resolution with the previous algorithm was about 125 ns, so this is a significant improvement). With dozens of hits per track, it is possible to reject downward-going muons by many orders of magnitude using hit timing information alone.

To resolve the directionality of the muon track, the upward-going muon trigger takes advantage of the timing information from each individual hit in the reconstructed tracks. The tracks are reconstructed using the Hough transform algorithm, and are required to match in both XZ and YZ views. We start from the hit with lowest y cell value, y_0 , in the track in the YZ view. The measured time of the corresponding hit is defined as T_0 . The observed and expected time of each hit on the track in the YZ view is therefore:

$$\begin{aligned} T_{obs} &= TDC_{y_i} \cdot 15.625 - T_0 \\ T_{exp} &= TOF_{\mu} \frac{y_i - y_0}{y_1 - y_0} \end{aligned} \quad (1)$$

Similarly, for the XZ view:

$$\begin{aligned} T_{obs} &= TDC_{x_i} \cdot 15.625 - T_0 \\ T_{exp} &= TOF_{\mu} \frac{x_i - x_0}{x_1 - x_0}, \end{aligned} \quad (2)$$

where x_i and y_i are the cell numbers in XZ and YZ view, and $TDC_{x(y)_i}$ is the time measurement in TDC units, which is converted to ns using the factor of 15.625 ns/TDC. TOF_{μ} is the time-of-flight of the muon track defined as:

$$TOF_{\mu} = L/29.97, \quad (3)$$

where L is track length in cm, and 29.97cm/ns is the expected speed assuming that the muon is relativistic.

Since we require that each track is reconstructed and matched in both views, $(x_0; y_0)$ and $(x_1; y_1)$ must correspond to the lowest and highest points of the track respectively. In addition,

we can estimate the missing coordinate for a particular hit in either view using 3D requirement. For the YZ view, track coordinates can be calculated as such:

$$\begin{aligned} x &= \frac{x_1 - x_0}{z_1 - z_0} \cdot (z - z_0) + x_0 = \frac{x_1 - x_0}{y_1 - y_0} \cdot (y - y_0) + x_0 \\ y &= c_0 + c_w \cdot c \\ z &= p_0 + p_w \cdot p \end{aligned} \quad (4)$$

Similarly, for the XZ view:

$$\begin{aligned} x &= c_0 + c_w \cdot c \\ y &= \frac{y_1 - y_0}{z_1 - z_0} \cdot (z - z_0) + y_0 = \frac{y_1 - y_0}{x_1 - x_0} \cdot (x - x_0) + y_0 \\ z &= p_0 + p_w \cdot p, \end{aligned} \quad (5)$$

where $c_w = 3.97$ cm and $p_w = 6.65$ cm are the widths of detector cells and planes. The cell and plane with id=0 have coordinates $c_0 = -759.50$ cm and $p_0 = 4.57$ cm.

Since for each hit in each view we can estimate (x; y; z) coordinates, we can calculate the distance from the hit to the APD readout end. The further the hit is located from the readout the longer it takes for the light to propagate and be detected by the APD. We are interested in the hit time of the muon passing through the extrusion, so we have to correct for the light propagation time in the fiber. The speed of light in the fiber is measured to be 15.3 cm/ns.

2.1. Multipoint fine timing

The light level in each channel in the NO ν A detector is independently sampled every 500 ns. The electronic response to an incident particle depositing energy in a cell can be parameterized in terms of two intrinsic timing values (T_F and T_R), the number of photoelectrons (p), and a timing “offset” (t_0), or the elapsed time between a read-out and the time of incidence of the particle:

$$f(t) = \alpha p e^{-(t-t_0)/T_F} (1 - e^{-(t-t_0)/T_R}) \quad (6)$$

Here, α is a proportionality factor that does not affect the timing fit. The parameters T_F and T_R correspond to the intrinsic falling and rising time of the response curve, respectively. As such, they are approximately known. For the purpose of determining hit timing, the parameter of note is t_0 . By performing a simple χ^2 minimization, the data-preferred value of t_0 can be extracted from multiple readouts on a single channel. For the purposes of the trigger, where hit processing time must be minimized, fit results were pre-calculated and tabulated such that the computationally expensive minimization need not be repeated for each individual hit.

Each time measurement has an uncertainty, which varies with the amount of energy deposited. The time uncertainty on a given hit from a reconstructed muon track affects the determination of track directionality, so a parameterization of uncertainty in terms of energy deposition is necessary for the timing-based trigger. Single-hit time resolution is plotted against energy deposition in Fig. 2. For high energy hits the Δt is measured to be approximately 10 ns in the data using the four-point readout scheme, which is consistent with that observed in simulation [7].

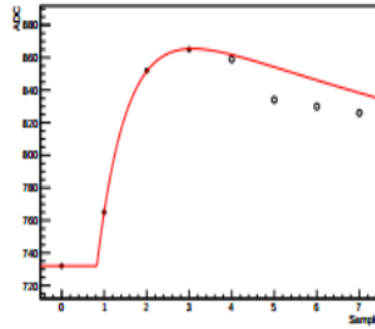


Figure 1. An example of fitting the electronics response curve to multiple readouts from a single cell hit. The time coordinate of the inflection point where the curve begins to rise is the fitted parameter t_0 .

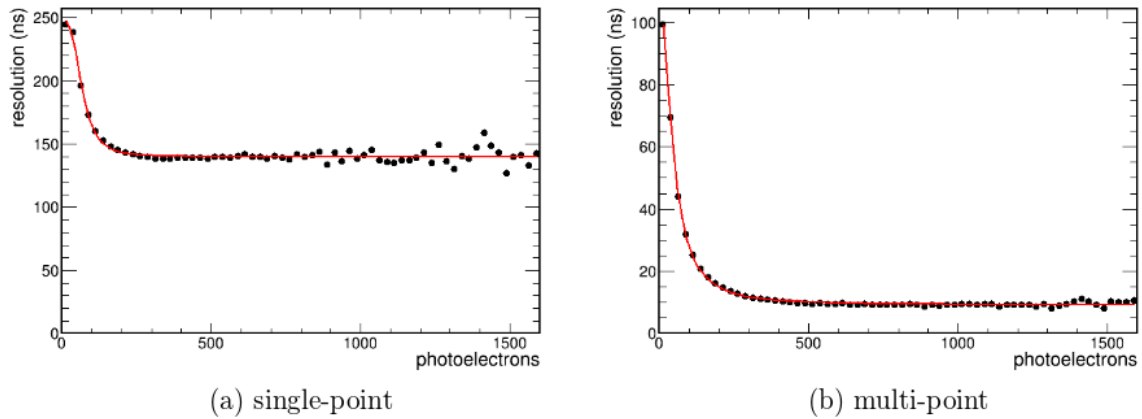


Figure 2. Single-hit timing resolution as observed in NO ν A far detector data with four-point readout, before (left) and after (right) fine timing implementation. See Ref. [7] for more details.

3. Log likelihood ratio

We can use equations 1 and 2 to produce the distribution of the expected v/s observed time for each track.

An example of expected v/s observed time distribution is shown in Fig. 3. The distribution is produced using a reconstructed upward-going muon track simulated with WIMPSIM [8, 9]. As can be seen, the points follow a rising trend with a slope value consistent with the upward-going track hypothesis. It is clear from the figure that the fitted slope value can be used to estimate the muon direction (up or down). As shown in Fig. 4, the slope values for cosmics and WIMPSIM MC samples are consistent with the downward- and upward-going hypothesis, respectively. In the relativistic limit, it is safe to assume that there are only two options for the slope values. Therefore, we can fit the time distribution on Fig. 3 with fixed values of slopes. For the upward-going track the fit with the slope constrained to “1” results in a good χ^2 probability value of the fit, P_{\uparrow} . However the fit with slope of “-1” yields a low probability value, P_{\downarrow} . Using the probability values from the fits with the fixed slope value, we can form a log-likelihood ratio (LLR):

$$LLR = \text{Log}\left(\frac{P_{\uparrow}}{P_{\downarrow}}\right) \quad (7)$$

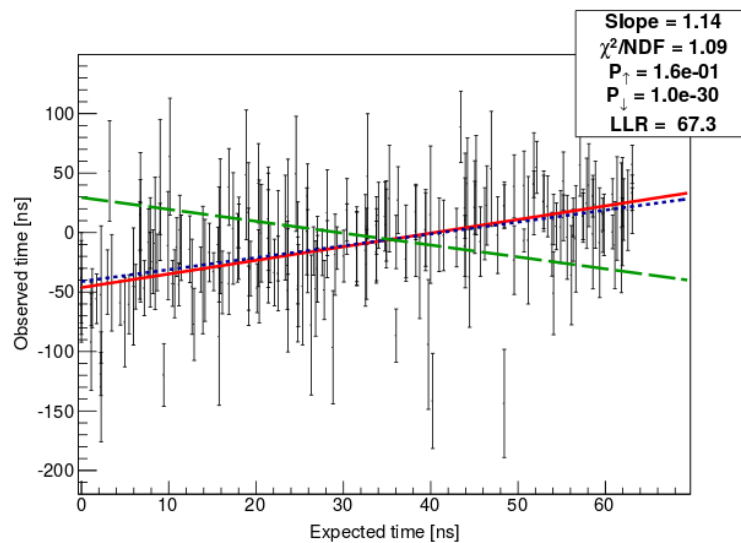


Figure 3. The expected versus observed time distribution for an upward-going muon track reconstructed in the NO ν A far detector, using fine timing. The linear unconstrained fit (red solid line) has slope value close to “1”. The fit with the upward-going track hypothesis (slope = 1) is shown as the blue-dashed line. The fit with the downward-going hypothesis is shown in the green dashed line and has a very poor probability.

The LLR distributions for the cosmic and WIMPSIM MC samples are shown in Fig. 5. From this distribution, it is clear that a cut on LLR slightly above zero will reduce the cosmic background by the desired amount while preserving a high signal acceptance. Note that the WIMPSIM sample used is for dark matter with a 20 GeV mass annihilating through the $b\bar{b}$ channel. As such the neutrinos from the b-meson decay produce muons which, on average, have a much lower energy compared to the cosmic ray muons. This explains why the LLR for the signal has a larger component close to zero than the cosmic sample.

The LLR yields better performance for cosmic background rejection for the same signal acceptance in the regime where the cosmic rejection is sufficient (at least four orders of magnitude), compared to a cut on the best-fit slope. For example, for a signal acceptance of 0.7 the background rejection is about a factor of three better for the LLR. At this point the MC predicts background rejection of close to five orders of magnitude. In addition to being a more powerful discriminator as observed in the MC studies, the LLR estimator is more robust to mis-reconstructed tracks which will be an important feature in real data. Since mis-reconstructions will result in time distributions that follow neither the upward- nor the downward-going hypothesis, the result of mis-reconstruction will yield LLR values close to “0”, and not values consistent with a high-probability for being upward-going.

4. Conclusions

A timing-based upward-going muon trigger was implemented for the NO ν A far detector and was deployed in November 2014. Triggering at < 10 Hz, the algorithm suppresses cosmic ray muons by five orders of magnitude.

As can be seen in Fig. 6, events with probable Michel electrons and contained vertices have been used to confirm upward-going muons in the triggered sample.

Atmospheric neutrinos generated on the other side of the Earth are also capable of producing upward-going muons in the detector. These events represent an irreducible background in this

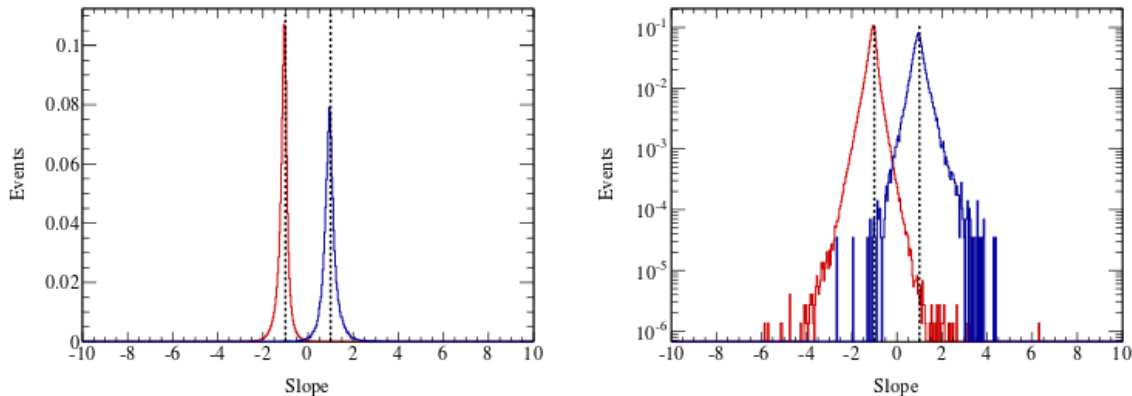


Figure 4. The slope distributions for cosmics (red) and WIMPSIM (blue) MC samples.

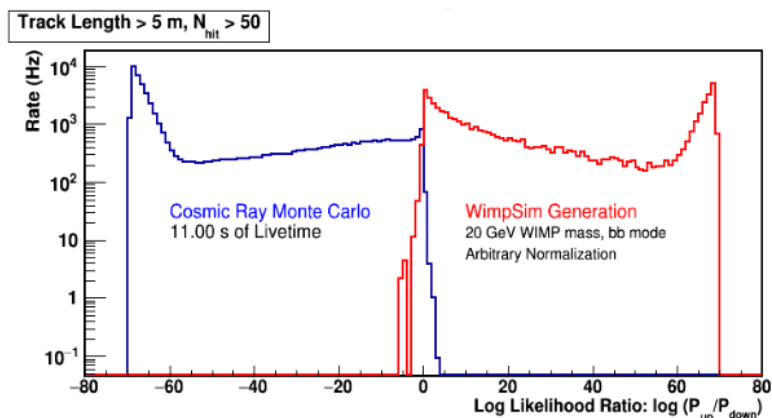


Figure 5. The LLR distributions for cosmics (red) and WIMPSIM (blue) MC samples. Note that only tracks longer than 5 m and with more than 50 hits are included.

search. The only method of discriminating atmospheric neutrino events from WIMP events is to reconstruct the directionality of the incident neutrinos, which has yet to be attempted in NO ν A.

The accumulating data sample opens the door to a program to study atmospheric neutrinos and sets the stage for a competitive dark matter search by the NO ν A experiment.

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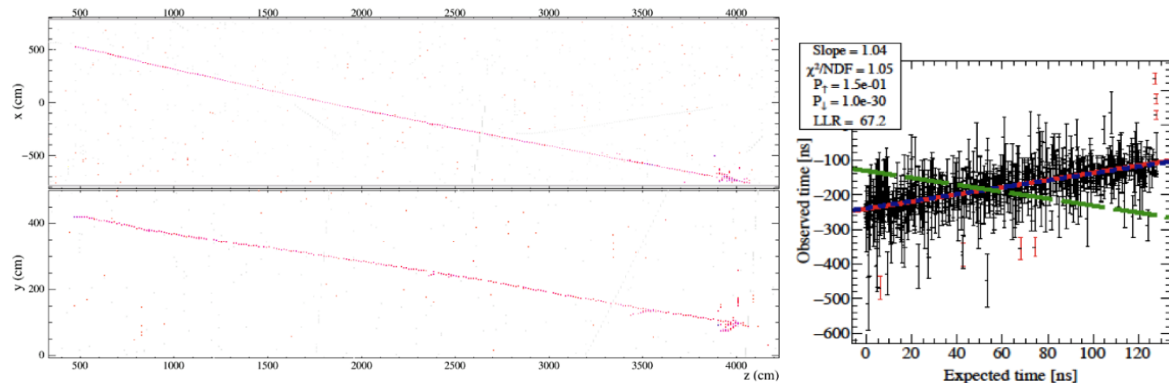


Figure 6. On the left is a display of a triggered event that is a strong candidate, based on its topology, for an upward-going muon. The activity at the bottom right indicates a CC scattering interaction. The curving at the other end probably indicates that the muon ranged out. There is also evidence for a Michel electron, based on the timing information on the right. This event confirms that the LLR algorithm is successfully selecting upward-going muons in the data.

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