Enhanced Starting Track RealTime Stream (ESTReS) TFT proposal for 2017/18 season

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Abstract

We present a new PnF filter stream to capture starting track events. This stream utilizes a low energy HESE style outer-layer veto in combination with a incoming muon veto used by the Enhanced Starting Events Selection(ESTES). The goal is to find down-going starting track candidates which are lower in energy than those present in the HESE real-time stream. Once running at pole, this real-time filter should find ≈ 2.4 astrophysical events per year which have a 50% purity. Additionally, the energy of these events (10-100 TeV) reaches much lower than those currently available to real-time streams. These tracks are ideal real-time candidates because they have a very high probability of being astrophysical. In this document, we will outline the physics motivation for these events, a description of the filter, the expected rate for the filter, the follow-up process once the events arrive in the north, and the modules such a filter would use.

1 Physics Motivation

There are a few starting event analyses that have been developed by IceCube. Many of them have focused on the more abundant astrophysical cascade events for diffuse spectral measurements. These selections use layer vetos which scale in from the edge of the detector uniformly since cascades have poor pointing resolution. Recently, a new starting track selection has been developed which can also obtain a neutrino pure sample. These starting track events are particularly interesting because they have a very strong veto from fact that muon neutrinos and muons are produced together in pion and kaon decays. As a

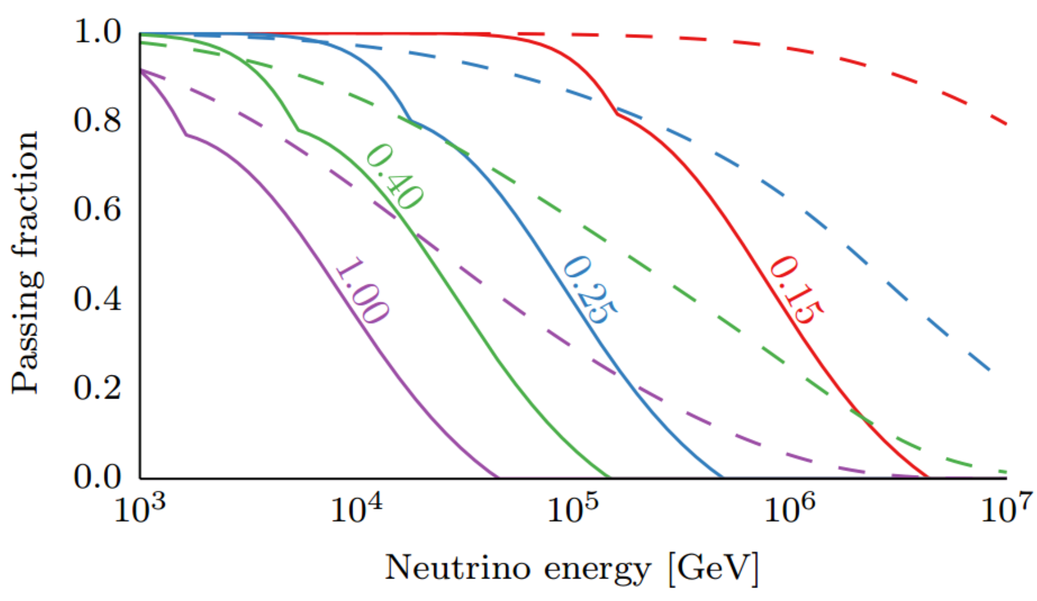

Figure 1: The fraction of atmospheric neutrinos which reach the detector with less than 1TeV of accompanying muon energy. The colored numbers provide the cosine of the zenith angle for the event while a solid or dashed line represents ν_μ and ν_e events respectively. This figure comes from [2].

result, the number of conventional atmospheric neutrinos which can pass a veto is completely suppressed at favorable angles and energies as can be seen in Figure 2. This effect when combined with a veto which suppresses muons to negligible levels as well results in a sample of events which are very likely to be astrophysical, and point with a resolution less than 1 degree.

The expectation for events per year which have an astrophysical purity of 50% or better from a $E^{-2.46}$ flux, discussed fully in Section 4, is ≈ 2.4. The majority of them come between 10 and 100 TeV. It should be noted that because the sensitive range of this filter is below the usual pivot point for IceCube quoted fluxes, it is very sensitive to changes in the spectral index. The events found by this selection, if supplied in real-time, are very valuable to the pointing component of the multi-messenger astronomy community since their directions are well known and they are likely to be signal. As a these events sent as alerts to our MOU partners and the AMON network. However, the details of whom the generated alerts would be sent to is still a topic open for discussion.

2 Filter Description

To keep the filter independent from future changes in other filters, it is proposed to run the filter on the PoleMuonLlhFit from base processing at level0. The ESTReS filter will operate by using an outer-layer veto in conjunction with a incoming muon track veto. The outer-layer veto will be identical to HESE, but with a lower total event charge and vertex charge to accommodate starting neutrinos of lower energies. The incoming muon track veto operates by taking a track hypothesis, a pulse series, and a muon photon yield table which it uses to estimate the probability of the event being incoming. The exact method is described below in steps and is accompanied by Figure 2 which depicts a muon neutrino(dashed red line) interacting in the detector and producing a muon(solid red line) and leaving hits on DOMs(filled in colored circles). The three plots on the side of the figure refer to the DOM which they are connected by a black line.

1. Given a track hypothesis, pulse series, and muon photon yield table, the hit DOMs are tested for their compatibility of the track. Hits which occur within a time window defined by the points where the photon yield is one one hundredth the peak value in that DOM are said to be compatible.
   (a) In the figure, red lines show the photon yields for the track to DOM combination they represent. Any hits on that DOM are shown as vertical blue lines at the time which they occurred The grey shaded regions are the compatible time windows.
2. With the compatible hits defined, the region where the muon was observed can be inferred by mapping the hits onto the track at the Cherenkov angle and finding those at the earliest and latest positions.
   (a) This region is visualized in the figure by the cyan lines which protrude from the track at the cherenkov angle, and the black arrow labeled "Rgeion with observed hits from muon".
3. Since the muon may be dimmer or brighter than the table's normalization, the best normalization for the event is found by maximizing the log-likelihood in Equation 1 for a which takes into account the muon and noise contributions to the obervations made by the DOMs.

$$\begin{gathered} LLH = \sum_{i}^{All\ Muon\ Compatible\ DOMs} log(p(\lambda_i, k_i)) \\ where\ p(\lambda, k) = \frac{\lambda^k e^{-\lambda}}{k!}\ and\ \lambda_i = a\,\lambda_\mu + \lambda_{noise} \end{gathered} \quad (1)$$

4. With the normalization and beginning of the event known, the un-hit DOMs which occur before the compatible region can be evaluated for the probability that they would not observe light given a muon with a light yield captured by the fit value of a. This is summarized as the probability to miss an incoming muon, or often called the p_{miss}. The definition of p_{miss} is given in Equation 2.

$$\begin{gathered} p_{miss} = \prod_{j}^{All\ In-compatible\ Non-hit\ DOMs} p(\lambda_j, 0) \\ where\ p(\lambda_j, 0)\ is\ from\ Equation\ 1\ and \\ \lambda_j\ is\ derived\ using\ the\ a\ found\ with\ Equation\ 1 \end{gathered} \quad (2)$$

Using this definition, incoming events tend to be assigned values of p_{miss} close to 1 while true starting events tend to have values of $p_{\text{miss}} < 10^{-6}$. Because the veto is defined with photon tables, tracks which pass far from DOMs in the holes of the detector naturally have values more consistent with an incoming muon than that of a starting track even in the absence of hits. This is because the expectation for hits is lower than if the event passed close to DOMs. This is one of the major strengths of this veto technique over layer vetos. Since the veto relies heavily on good track information, the proposal for the filter is to run one iteration of SplineMPE seeded with PoleMuonLlhFit from base processing. The exact settings of the filter can be tuned to obtain the desired event rate. The knobs which one can tune on are:

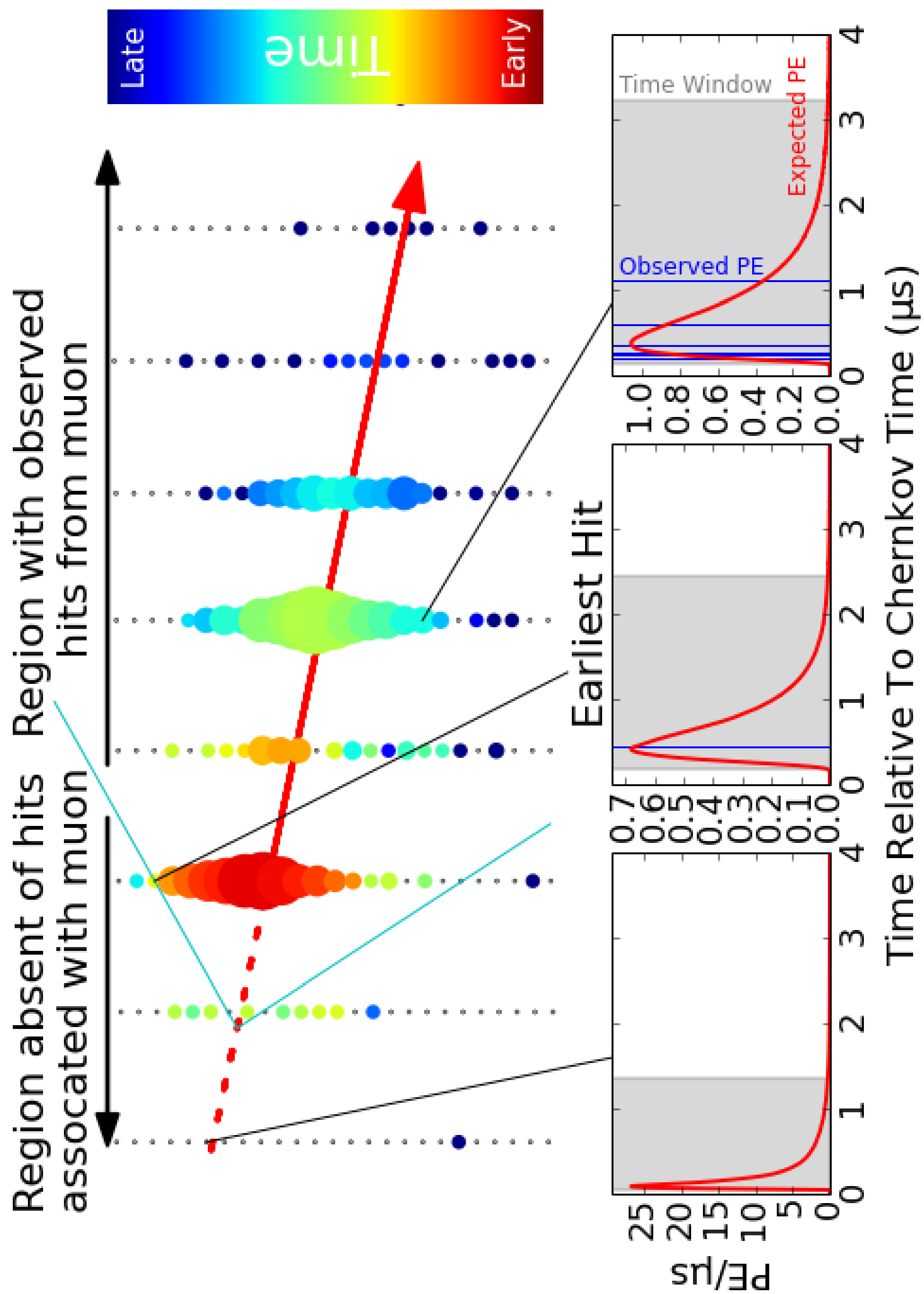

Figure 2: This figure shows how the incoming muon veto works. The figure depicts a muon neutrino(dashed red line) interacting in the detector and producing a muon(solid red line) and leaving hits on DOMs(filled in colored circles). The three plots on the side of the figure refer to the DOM which they are connected by a black line.

1. HESE veto total charge
2. Incoming muon probability (p_{miss})
3. Track length of the compatible hits region
4. SplineMPE zenith angle

Discussion of each and a table of possible settings and the resulting rates are presented in Section 4 and the demand on the pole system is discussed in Section 3.

3 Processing Requirements at Pole

Operating at level0 means this filter will encounter a high rate. However, the HESE veto which is run before reduces the rate by over a factor of 100. This reduced rate combined implies a very negligible impact on the PnF server. Going into detail of the time required to perform the processing, one can inspect Figure 3. To make this Figure I have processed 7,541,146 low energy CORSIKA events, about half had a PoleMuonLlhFit and can be used. Most of these events are rejected by the HESE 250 PE filter, which takes on average .00003s to run meaning roughly (0.0003s x 3000Hz = .9) 1 CPU will need to be committed to cut the rate by over a factor of 100. The remaining ≈21,500 events on average take 0.0012s to finish, again contributing a small amount to the CPU must be committed (0.001s x 3000Hz x .01 = .03). Only ≈440 events of the sample make it to the incoming muon veto, and almost never need >1 second to complete. From the event numbers in the figure, one can see that at each step a factor of 100 reduction in event rate is achieved.

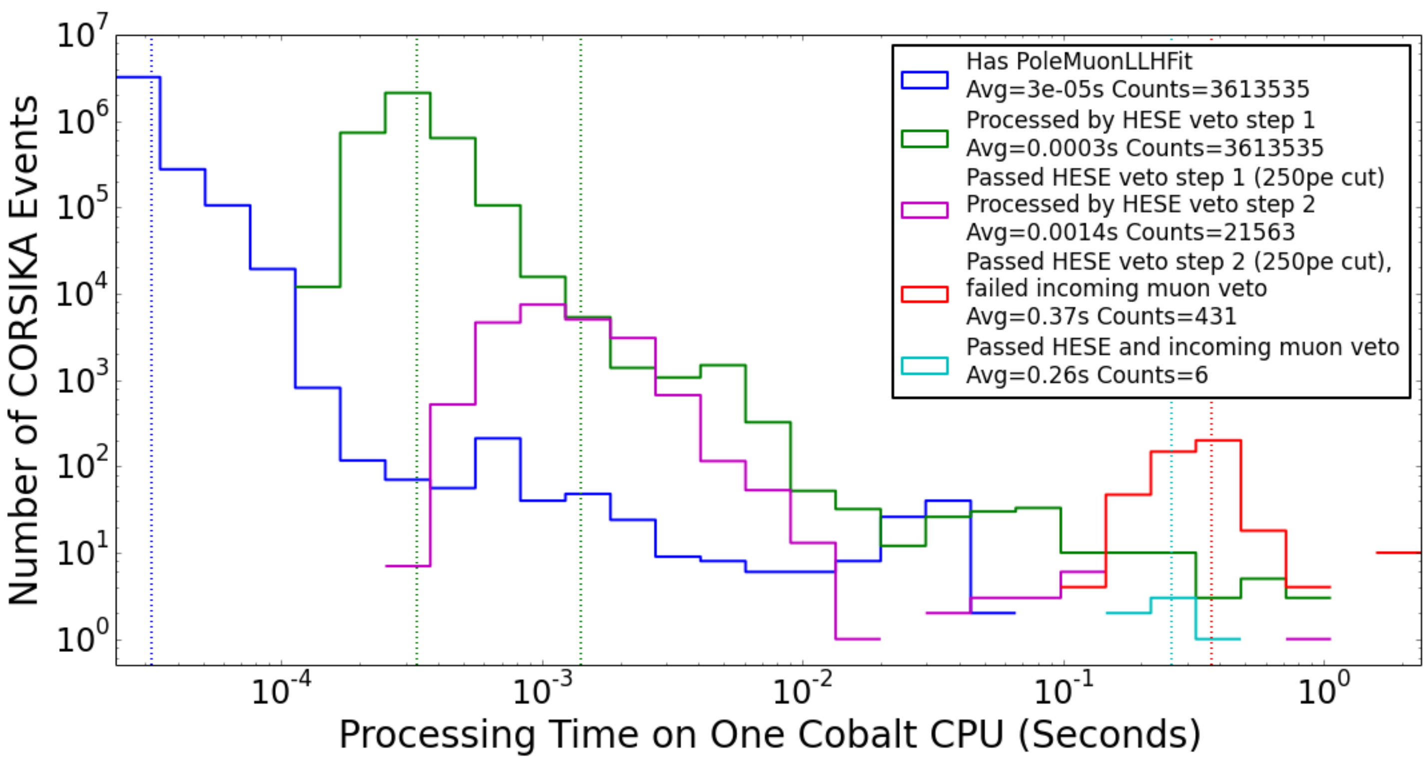

Figure 3: Time to process events to different stopping points. Most events are rejected by the HESE veto, and ≈540 make it to the incoming muon veto, with only a few events passing that selection.

4 Event Rates

Since the proposal for this filter is to do a minimal selection criterion at the pole and then send the candidate events over the I3MS Iridium link the most important rate is the total expected rate per day. Estimates from experts with the I3MS system indicate that a maximum of 4 events per day is feasible, making this a hard limit for the selection. The second most important thing to consider is the astrophysical event rate, the more astrophysical events available the better the filter can help the realtime effort. For these rate quotes, I will be using the measured flux from the MESC analysis[1]. This analysis measures an astrophysical flux normalization of $2.06 \times 10^{-18}\text{GeV}^{-1}\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$ and index 2.46. Note that ESTES and ESTReS are sensitive to the astrophysical flux almost entirely below the 100 TeV pivot point for IceCube quoted fluxes. Thus softer fluxes, like those reported by the cascade focused selections, will result in more events per year while harder fluxes, like those reported by the up-going muon selections, will result in less events per year.

With these constrains in mind I processed CORSIKA, Muon Gun, and Nugen simulation from the 2012 season to get an estimate of what event rates can be expected. The processing had cuts on the HESE veto total charge, incoming muon probability (p_{miss}), and track length of the compatible hits region set to >250pe, $< 10^{-5}$, and >300m respectively. There initially was no cut on the reconstructed SplineMPE zenith angle. However, since the atmospheric neutrino self veto is only effective for down-going events, it makes sense to explore cuts which remove events which are up-going. The initial settings yield an expectation of 47 atmospheric muons per day, 16.1 astrophysical neutrinos per year, and 298.8 atmospheric neutrinos per year. The 47 atmospheric muons is obviously far too high for the I3MS system to handle. To find compatible settings for the parameters of the filter, I investigated all combinations of the following cuts.

1. HESE veto total charge
   (a) > [250, 300, 350, 400]
2. Incoming muon probability (p_{miss})
   (a) < [10^{-5}, 5×10^{-5}, 10^{-6}, 5×10^{-6}, 10^{-7}, 10^{-8}, 10^{-9}, 10^{-10}]
3. Track length of the compatible hits region
   (a) > [300, 350, 400, 450, 500]
4. SplineMPE zenith angle
   (a) < [80, 75, 70, 65, 60]

I present in Table 1 cut combinations where the atmospheric muon rate is <4 events per day and the number of astrophysical neutrino above the 50% purity point is >2.2 per year. I should also note that these numbers are subject to change in future revisions of this proposal. Currently, limited CORSIKA has been processed and limits the statistical error on the rate to ≈15%. As I mentioned before, the cut combination whose rate can be handled by the I3MS system and yields the highest astrophysical neutrino rate should be taken. I have highlighted this option in grey in Table 1.

Zenith Cut (<)	**Charge Cut (>)**	**Prob. Cut (<)**	**Dist. Cut (>)**	**Atm. μ Rate (per Day)**	**Atm. ν Rate (Total per Year)**	**Astro. ν Rate (Total/@50% purity per Year)**
75	400	10^{-8}	450	3.5	7.5	2.8/2.4
70	400	10^{-7}	500	3.9	5.0	2.6/2.4
70	400	10^{-8}	500	2.8	4.4	2.3/2.2

Table 1: Table of event rates for atmospheric muons, atmospheric neutrinos, and astrophysical neutrinos for different cut values which roughly optimize the total rate per day and 50% pure astrophysical neutrino rate per year. The recommended cut selection is highlighted in light grey.

5 Comparison to Other Real-time Filters

There are already a few online event selections implemented to search for single astrophysical muon tracks in real-time. One is the implementation of the high energy starting event selection (HESE) on level0. Second is the implementation of the extremely high energy event selection (EHE) with a higher number of photo-electron cut at level0. There are also other selections which are implemented to search for multiplets which I will not consider here. One way to compare selections is to look at their effective area. This is presented in Figure 4. The lines for the HESE is taken, at the moment, as estimates for the selections, as they are not yet confirmed by the authors. The Online EHE Realtime line is from the filter maintainers. Also plotted is the medium energy starting tracks(MEST) selection implemented by Jake F. which now acts as the "heart-beat" for the HESE real-time stream. The events found by this heart beat are not sent to the north in full, and thus do not count as a true real-time stream. What is obvious from the plot is that ESTReS will provide access to a different neutrino energy than the existing selections, being most effective from $\approx 10^4 - 10^5$. By chance, this selection stops gaining in effective area when the other selections begin preforming better. As a result these selections and ESTReS are very complimentary to each other in their search for astrophysical tracks. Also included is the effective area for ESTES, which ESTReS events will be run through when they arrive in the north. The effective area for ESTES is a factor of 3 larger than ESTReS across all energies, but the ESTES effective area is could get larger by up to a factor of 2 depending on the performance of the final cut BDT which is still being prepared and tuned.

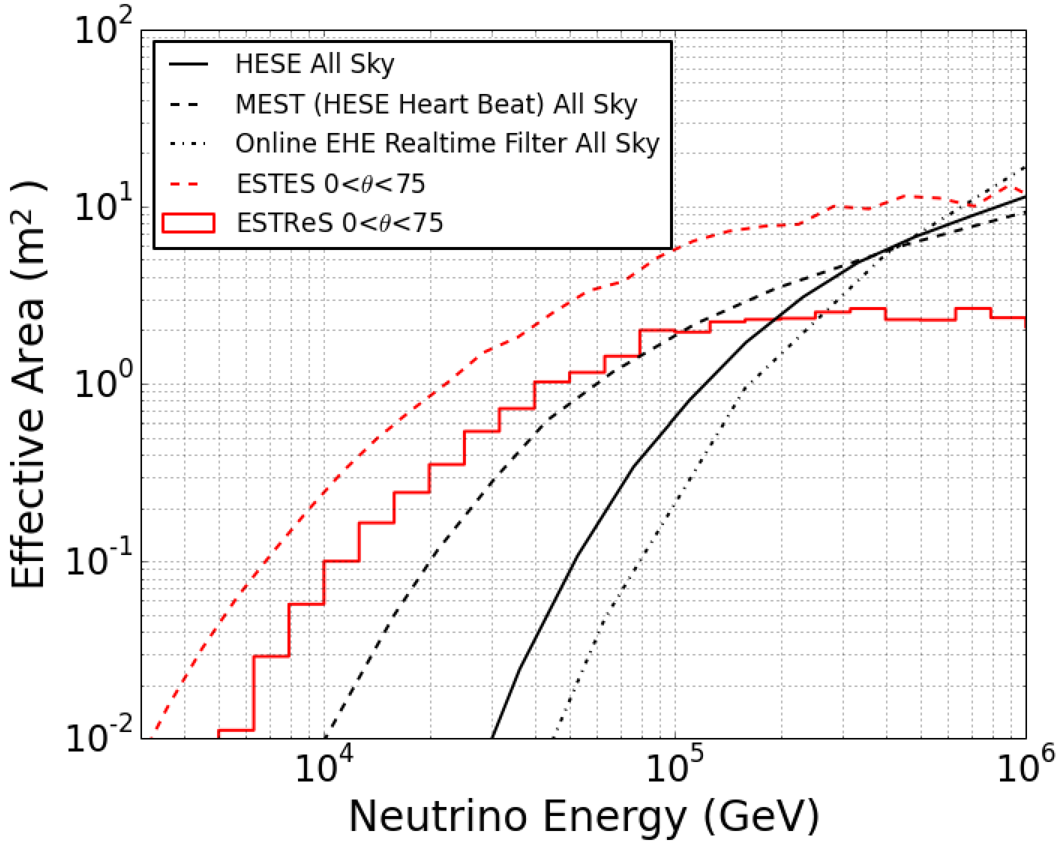

Figure 4: Effective areas for real-time streams.

6 Follow-Up

As can be seen from the results of Section 4, the stream will be dominated by atmospheric muons. In order to completely remove these, the full ESTES selection must be run. The full ESTES selection takes 30 seconds or more per signal-like event to complete and is thus too expensive to run at pole. The idea then would be to send, at a minimum, the pulse series of events identified by the ESTReS filter detailed in Section 2 and 4 over the I3MS link for further processing in the north by the ESTES processing, which will be discussed in the rest of this section.

The ESTES selection works by searching, via a brute force technique, for possible incoming event hypotheses which sneak through holes. The first stage of the selection operates by checking all regions of the detector for sneaky events. To do this, a predefined set of points in the middle of holes and lanes in the detector are computed as well as a uniform set of points above the detector. One can get a track by drawing the vector from this point to the center of gravity of the hits of the event. The predefined set of holes can be seen in Figure 6. To identify if none of the tracks defined by the holes are of interest, the track fits found at level2 processing are also included. The likelihood of every track is tested with a time-only SplineMPE fit. To save time and focus on only the most likely track hypotheses, only the best 2% of fits are checked with the incoming muon veto described in Section 2. If any reconstruction checked fails a length cut of 300m the event is rejected. If the smallest p_{miss} is smaller than the incoming muon probability cut of 10^{-5}, the event is kept, otherwise the event is rejected. Events which pass this brute force check are subject to a second brute force check which focuses closer to the best likelihood track found in the previous stage. To do this, the origin of the track is shifted 300 meters from the start of the track and then variations in +/- x, y, and z are constructed. At each of these points, angular variations in zenith and azimuth are constructed by finding the angle needed to vary the track's entry position to the detector horizontally by 25m. This, as well as variations of this angle times 2,4,6, and 8 are also hypothesized. The resulting tracks checked can be seen in Figure 6. Again, the best 2% of fits are check with the incoming muon veto described in Section 2. As with the previous stage, if any reconstruction checked fails the length cut (same as before) the event is rejected. If the smallest p_{miss} is smaller than the incoming muon probability cut (same as before), the event is kept, otherwise the event is rejected. At this stage, the events all look like good starting muons, but the penetrating atmospheric muons still outnumber the astrophysical neutrinos by 1000 to 1. It is possible to separate these events to obtain less than 1 expected atmospheric muon event per year via straight cuts or a BDT using variables like deposited energy, distance inside the detector, and other quality parameters. At the time of writing, a BDT is nearing completion to assume the role of the final "cut" in this selection. Events which pass to the final level are reconstructed with Millipede. Since these events are destined for multi-messenger partners a detailed Millipede scan such as

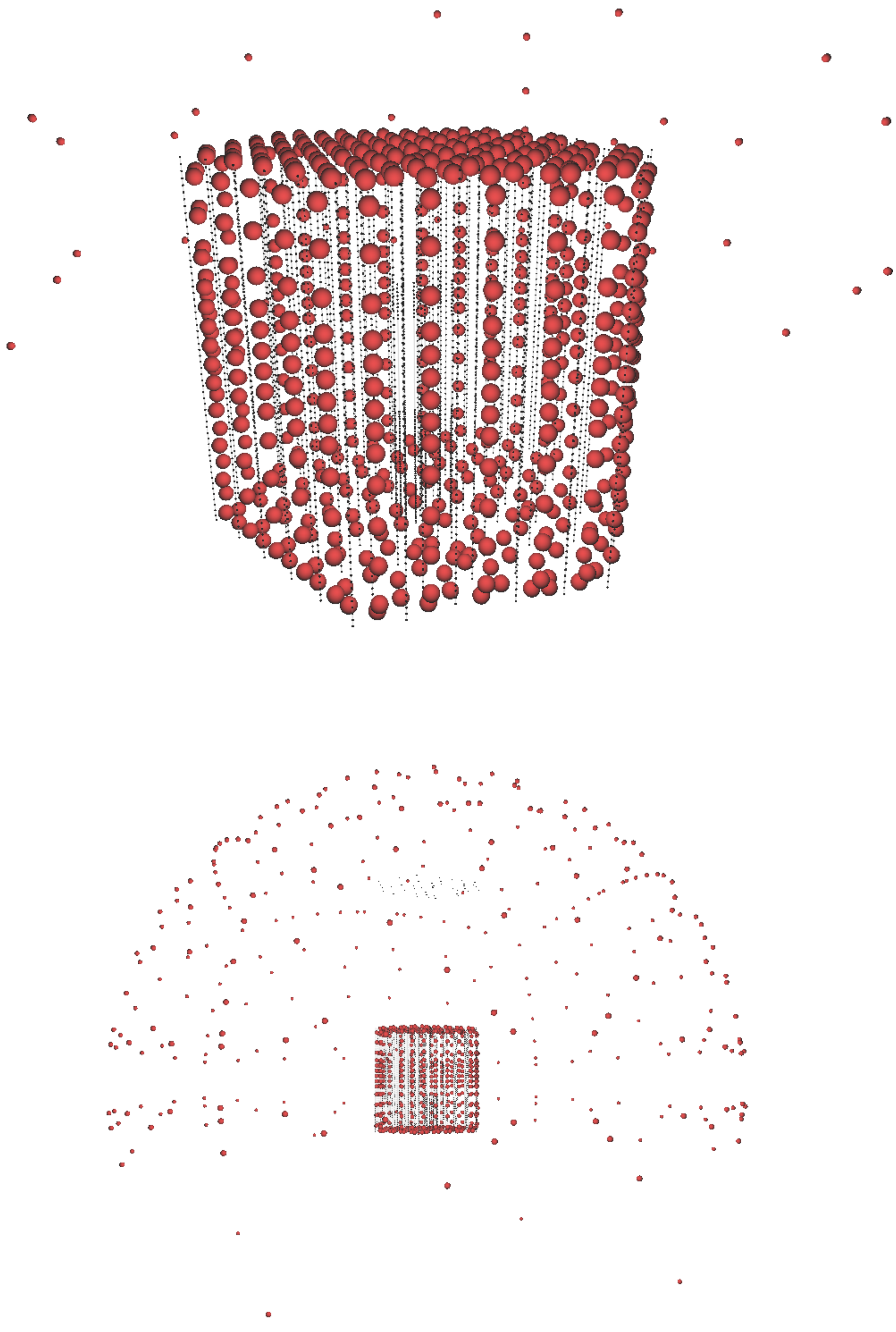

Figure 5: The top figure shows in detail the possible entrance points checked by the ESTES selection while the bottom shows the uniform points above the detector which are also checked.

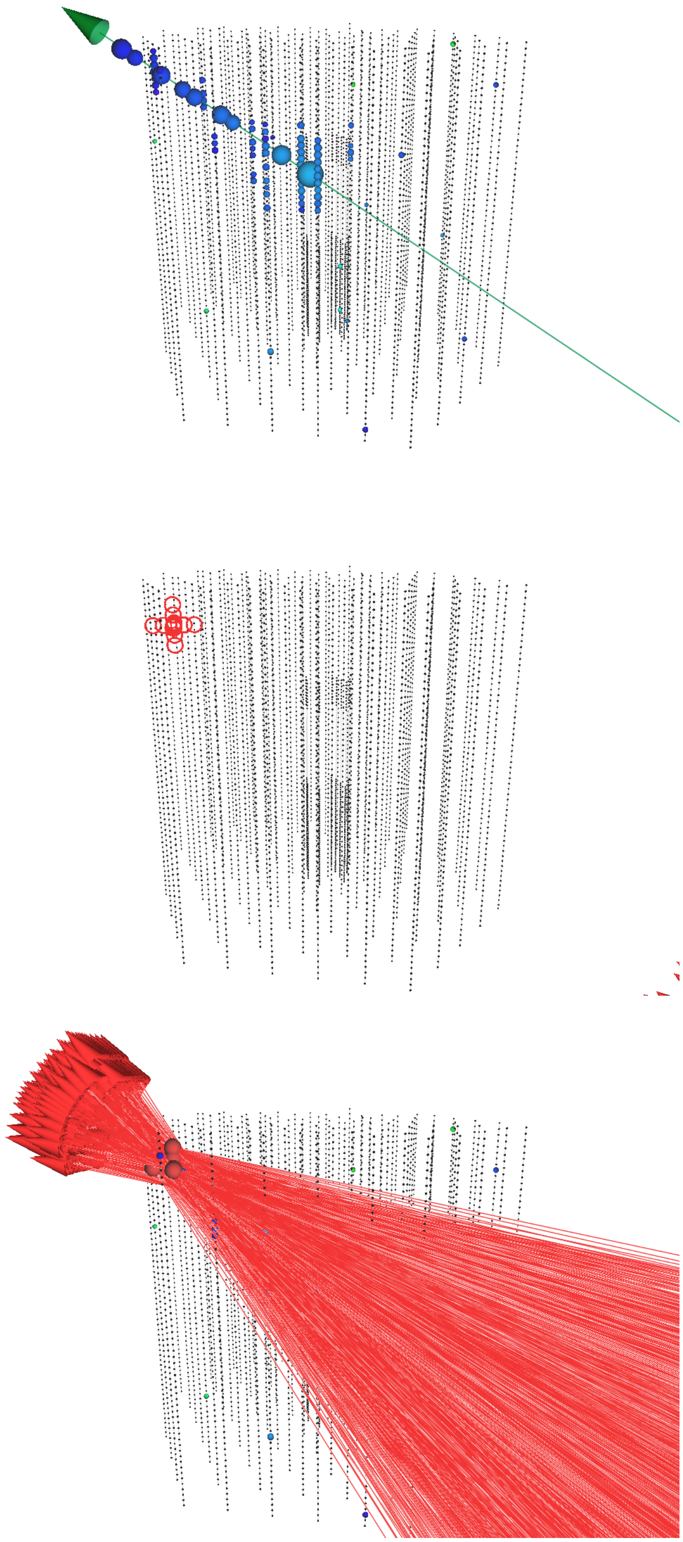

Figure 6: The top figure shows the Monte Carlo event losses and deposited charge of a starting muon neutrino. The middle figure shows the variations around the best fit track which are tested in concert with variations in the track direction. The bottom figure shows all the reconstructions which are tested. The result is very complete coverage of the local area which the event passed through.

is performed for the HESE realtime events is likely desirable in some form.

7 Required Modules

A basic implementation of the proposed filter with documentation is available at `http://code.icecube.wisc.edu/svn/sandbox/kjero/ESTReS/`. The only new segment which would need to be code reviewed and added to the appropriate meta-project is the incoming track veto. The project name is originates from a time when I mistook what the veto definition was appropriate for, it is a veto which helps find starting events, but which rejects(vetos) incoming tracks. `http://code.icecube.wisc.edu/svn/sandbox/kjero/StartingTrackVeto/`

References

[1] MG Aartsen, M Ackermann, J Adams, JA Aguilar, M Ahlers, M Ahrens, D Altmann, T Anderson, C Arguelles, TC Arlen, et al. Atmospheric and astrophysical neutrinos above 1 tev interacting in icecube. *Physical Review D*, 91(2):022001, 2015.

[2] Thomas K Gaisser, Kyle Jero, Albrecht Karle, and Jakob van Santen. Generalized self-veto probability for atmospheric neutrinos. *Physical Review D*, 90(2):023009, 2014.