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Implementation of IceTop data in the IceCube Realtime Alert System

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Implementation of IceTop data in the IceCube Realtime Alert System

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Abstract. The IceCube Neutrino Observatory is a cubic-kilometer detector at the geographic South Pole searching for astrophysical neutrinos. The main background for astrophysical neutrinos is leptons produced by cosmic ray air showers: neutrinos from the northern hemisphere and muons from the southern hemisphere. These atmospheric backgrounds are reduced using a data-driven selection based on the observed event energy and arrival direction. An array of ice-Cherenkov tanks on the surface, IceTop, detects showers of secondary particles created in cosmic ray air showers. We will show that data from IceTop can be used to further reduce the background due to atmospheric muons, and by implementing this method, we vetoed three alert events.

1. Introduction

The IceCube Neutrino Observatory is sensitive to neutrinos from the full celestial sphere. The in-ice array is buried in the ice at depths of 1450 m to 2450 m, while IceTop array is located on the ice surface. The in-ice array [1] consists of 86 strings installed in a hexagonal pattern and each string has 60 digital optical modules (DOMs) that detect the Cherenkov radiation. IceTop [2] consists of 162 ice tanks arranged in pairs at 81 stations.

Since April 2016, IceCube has identified, in real time, exceptional events of likely astrophysical origin and has issued alerts through the Gamma-ray Coordination Network (GCN) to the multimessenger community [3]. An improved version of this system has been active since June 2019 which selects track-like event with good directional reconstruction and high probability to be a muon produced by an astrophysical neutrino [4]. The main challenge is to identify these muons of astrophysical origin against a background of atmospheric leptons. Atmospheric neutrinos are an irreducible background over the full sky, limiting alert quality events to those with reconstructed energy $E_{\rm reco} \gtrsim 100$ TeV, where the astrophysical flux exceeds the steeply falling atmospheric neutrino background. At higher energies the neutrino-nucleon cross section increases with increasing energy and the high-energy up-going neutrinos are absorbed by the Earth, resulting in an upward window of $100 - 1000$ TeV where the alert system identifies the majority of its alert candidates. Downward events from the southern sky are dominated by the penetrating background of atmospheric muons. The issues are evident in Figure 1 showing the zenith angle and energy distribution of 45 alerts issued by IceCube between June 19, 2019 and December 31, 2020. Until now event by event analysis has not included IceTop data when identifying alert candidates. This contribution describes how the alert system can be improved to reduce these backgrounds for an important sample of high energy events from the southern sky by using IceTop data. It builds on previous work [5] using contained vertical events to study the veto efficiency of IceTop, but differs in that this analysis is extended to more inclined events where the reconstructed shower track is lying outside the IceTop footprint.

2. IceCube Realtime Alert System

The alert system generates alerts based on three different selection criteria: Extremely High Energy (EHE), Gamma-ray Follow-Up (GFU), and High Energy Starting Event (HESE) [4]. Both EHE and GFU streams select alert events based on zenith dependent energy thresholds and the passing sample is sent out as bronze or gold alerts depending on the probability of being originated by astrophysical neutrinos. Despite the high probability, individual events may still be of atmospheric origin, and these may be identified using IceTop data. Indeed, of the six downward events in Figure 1, three are marked as having IceTop activity, as described below.

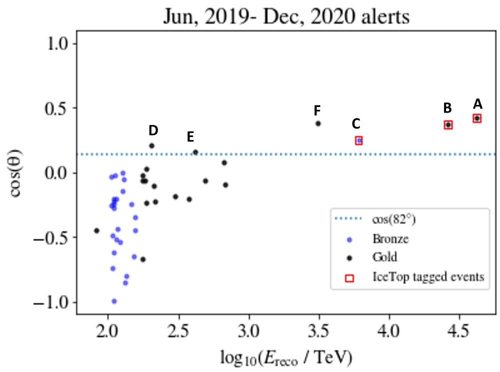

Figure 1: Estimated neutrino energy and zenith distribution for V2 alert events collected between June 2019 and December 2020. Events with significant IceTop activity are marked with a red square (see text).

3. Event rejection with IceTop

Inclined air showers create muon bundles that can hit IceCube at a slanted angle as in Figure 2. Muons pass through at a velocity nearly equal to the speed of light. A shower track is constructed from the in-ice data and extended back to the surface. The shower plane is perpendicular to the track and defines the time when a shower passes a tank, T_i. Because of the curvature and shower thickness, time residual, δt_i is positive and increases with r_i, the perpendicular distance from the shower track to the tank T_i. Time residual is calculated in a similar way for the in-ice DOMs, with the additional consideration that DOMs far from the track are further delayed by the speed of light propagation in ice. For a cosmic ray event if the shower track is properly reconstructed, IceTop and in-ice pulses will be assembled together with a small time residual after the transformation from IceCube coordinate to shower front coordinate. The candidate alert event can be rejected due to cosmic ray origin on the basis of a small number of coincident pulses, but the distribution of correlated and uncorrelated (background) pulses must be examined to determine quick, reliable, and conservative criteria to eliminate candidate events on the basis of IceTop data alone.

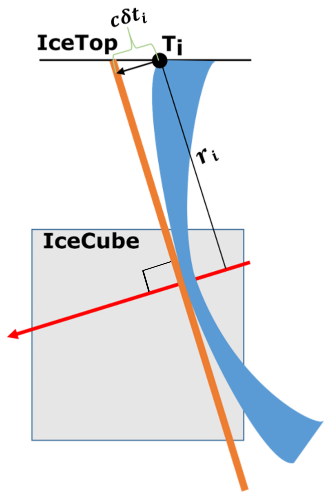

Figure 2: Geometry for calculating the time residual, δt_i. Blue area represents shower curvature and thickness.

In the IceCube data acquisition system, two coincidence conditions are defined: hard local coincidence (HLC) and soft local coincidence (SLC). For IceTop, an HLC is achieved when both tanks at a station record pulses within 1 μs; otherwise pulses are recorded as SLCs. An IceTop trigger occurs if there are 6 HLC hits within a 5 μs time window [2]. Alert events with an IceTop trigger can be trivially rejected. On the other hand, inclined events may include extended muon footprints on the surface which cause a significant number of coincident SLC pulses and these events may also be eliminated from the alert stream, even without an IceTop trigger.

In order to investigate the coincidence window and number threshold for use of in-time SLC pulses, we studied a subsample of online neutrino candidates from 2018 [6] containing $\sim$ 7500 events. This data set, which is predominantly upward atmospheric neutrinos and downward CR induced muons, provides well-reconstructed events with an angular resolution of $\lesssim 1^\circ$ above 1 TeV neutrino energy [4]. To count the number of correlated IceTop pulses with the in-ice event, pulses landing between 0 to 1 μs residual time are defined as the *in-time hits*.

Figure 3 shows the distribution of uncorrelated SLC in-time hits (from up-going events) vs the sum of uncorrelated and correlated SLC in-time hits (down-going events) in the GFU sample. The background rate is estimated to be ~ 0.2 counts/μs, assuming Poisson statistics for uncorrelated background. Cosmic ray events may have HLC pulses as well. Presence of

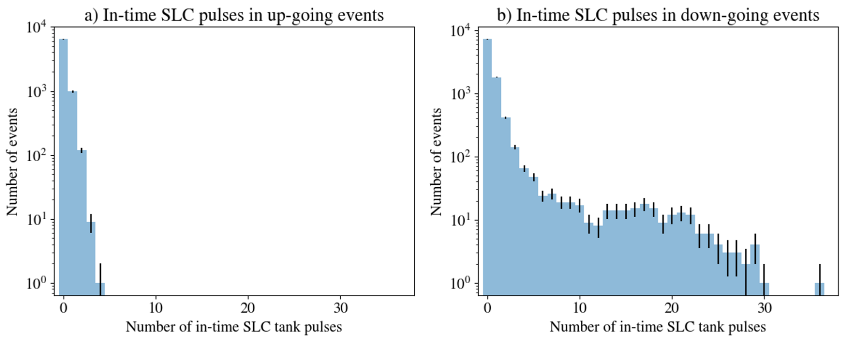

Figure 3: In-time SLC tank pulse distribution of a subsample of 2018 GFU candidate events. (a) Proxy distribution for the SLC background. Actual IceTop SLC pulses of the down-going events are replaced by SLC pulses from a near time up-going event ($> 90°$, presumably free of cosmic rays) to mimic a background of pulses uncorrelated with the in-ice reconstruction. (b) SLC tank pulses of down-going events ($< 82°$), showing contributions from two types of events. Those with a small number of coincident hits are coming primarily from the background distribution, and cosmic ray induced ones can be identified with a significant number of in-time hits correlated with the in-ice reconstruction.The black lines represent the error bars.

even a single pair of in-time HLC suggests a cosmic ray origin for an event; however, we also anticipate that for the inclined events passing the alert filters, HLC pulses in IceTop will always be accompanied by SLC pulses. In our analysis, cosmic ray activity will be marked by more than 2 in-time HLC pulses or 4 in-time SLC pulses.

4. IceTop activity in alert events of 2019-2020

Between June 19, 2019, and December 31, 2020, IceCube issued 6 down-going alerts ($\theta < 82°$) whose properties are listed in Table 1. Events A, B, C satisfy the criterion of being cosmic ray events and are marked with a red square in Figure 1. To clarify the variety of IceTop activity, time residuals are plotted in Figure 4 for three events. Event A is one of the two energetic events (A and B) that triggered IceTop. Such events with multiple in-time HLC and SLC pulses are trivially identified as cosmic rays and rejected as neutrino candidates. Follow up GCN circulars were issued to retract those alerts. Event C is a good example of the potential for this analysis

Table 1: 2019-2020 V2 down-going alerts. r is the perpendicular distance of the track to the center of IceTop, and d is the distance of the core location on the surface to the center of IceTop. $E_{\rm reco}$ is estimated assuming a single neutrino-induced muon track and is not valid for cosmic-ray events. SLC and HLC pulses are counted within the in-time window. Events with asterisks include an IceTop cosmic ray signature.

	Date	θ [°]	$E_{\rm reco}$ [TeV]	HLC	SLC	r [m]	d [m]
A*	2020/07/28	65.10	42024	38	38	1885	4461
B*	2020/11/15	68.26	26182	12	27	2335	6305
C*	2020/01/20	75.45	6055	0	9	2223	8788
D	2020/11/30	78.48	203	0	1	2387	11929
E	2020/12/09	80.01	419	0	0	2246	13068
F	2019/09/22	65.39	3114	0	1	2346	5587

to improve the realtime alert system. Although there are no HLC pulses and no Icetop trigger, there are 9 in-time SLC pulses, clearly in excess of the background, so this event may also be rejected as a neutrino candidate. At that time, the use of IceTop data was still in a preliminary stage and the follow-up GCN circular cautioned that event C was likely due to a cosmic ray, but did not retract the alert.

There is an apparent correlation between the intensity of the IceTop activity and $E_{\rm reco}$ the estimate of the in-ice energy. This should be viewed with caution, as the energy estimate assumes a neutrino origin and a single μ crossing IceCube. For events of cosmic ray origin the ratio of surface to in-ice muon intensity can be a strong function of event geometry and may experience event to event fluctuations. Even so, events D and E have lower $E_{\rm reco}$, and it is reasonable that they would have reduced IceTop activity. The single in time SLC pulse for event D is suggestive of cosmic ray origin, but is not disqualifying to the neutrino hypothesis.

The example of the last type is event F. From Table 1, one might expect a small but non-zero number of SLC pulses. However, the event clips the bottom of the detector, and the track length inside the detector is short. Uncertainty in the estimated energy and direction is higher for shorter tracks. A follow-up GCN circular cautioned that the energy estimate is not reliable and the pointing resolution is almost 3°. Although intriguing, the lack of IceTop activity cannot be considered significant without an extensive follow up analysis.

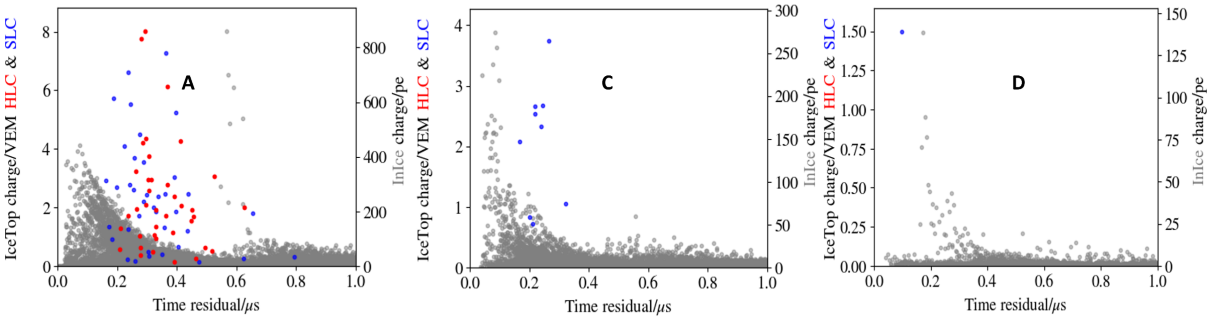

Figure 4: The coincident window (0 to 1 μs) for in-time pulses is shown for events A,C,D. Event A and C are clearly of cosmic ray origin. Event D is low energy, and is not expected to have IceTop activity. See text for an elaborated discussion.

5. Summary and Discussion

In this contribution, IceTop data were used to recognize alerts as cosmic ray background whenever a significant number of IceTop tanks record pulses in time coincidence with the event. If the in-time hit count is greater than 4 SLC or 2 HLC IceTop pulses, then the event has "IceTop activity". In this way, the three highest energy alerts were tagged as cosmic-ray initiated activity, and the alerts were retracted. To maximize the use of IceTop information, we expect to refine the use of time-residuals to include shower thickness and curvature, and to simulate rare high energy inclined events to quantify the significance of passing events.

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