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IceTop/IceCube coincidences

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Abstract: Atmospheric muons in IceCube are often accompanied by air showers seen in IceTop when their trajectories pass near the surface detectors. By selecting events in which only a single IceTop station on the surface is hit, we can identify a class of events with high probability of having a single muon in the deep detector. In this work we use this tagged sample of atmospheric muons as a calibration beam for IceCube.

Introduction

In 2006 IceCube collected data with sixteen IceTop stations and nine in-ice strings, as shown in Fig. 1. Ten more stations and thirteen more strings were deployed in 2006-07 austral summer [1]. IceTop runs with a simple multiplicity trigger that requires 6 or more digital optical modules (DOMs) to have signals above threshold. The configuration of gain settings and DOMs in tanks is such that IceTop triggers normally involve three or more stations separated from each other by 125 m. Such showers typically have energies of several hundred TeV and higher. The deep IceCube strings also have a simple multiplicity trigger of 8 or more DOMs within 5 μsec. The 8 DOMs need not be on the same IceCube string. Whenever there is an in-ice trigger, all IceTop DOMs are read out for the previous 8 μsec. This allows the possibility of identifying small, sub-threshold showers on the surface in coincidence with muons in deep IceCube.

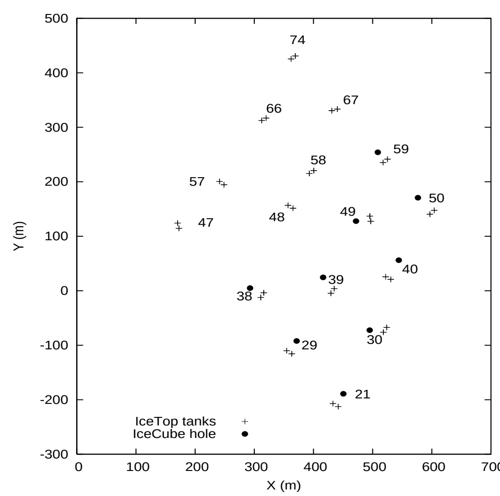

Figure 1: Surface map of IceCube in 2006. Two tanks (+) are separated from each other by 10 m at each station. Each tank has one high-gain and one low-gain DOM.

Events that trigger both the surface array and deep IceCube can be reconstructed independently by the air shower array on the surface and by the in-ice detector. Such events can be used to verify the system timing and to survey the relative position of all active detection units, i.e. IceTop tanks or in-ice DOMs. The concept has been demonstrated in the SPASE2-AMANDA experiment [2]. Verification of timing with coincident events is now a routine component of IceCube monitoring. One can also compare the two independently determined directions for the same events. Showers big enough to trigger IceTop, however, typically have several muons in the deep detector. One would also like to be able to tag single muons in IceCube to have a set of events similar to the ν_μ-induced muons that are the principal target of IceCube. In this paper we describe how a sample enriched in single muons can be tagged with IceTop, and we illustrate the use of this sample for verification of IceCube.

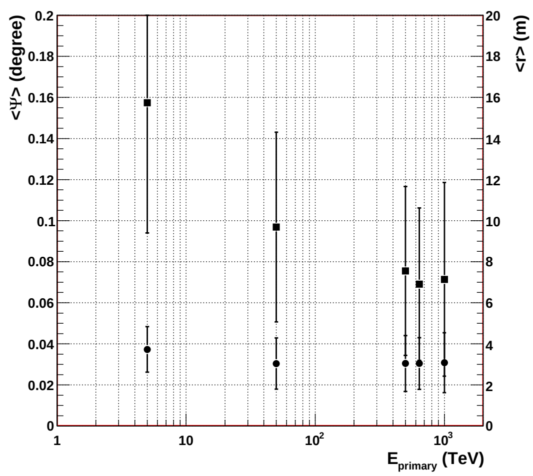

Figure 2: The average space angle Ψ between muons and air shower axis (solid circle, left vertical scale), the mean distance r of muons from air shower core (solid square, right vertical scale) as function of primary proton energy. The error bars represent the rms of Ψ and r. Only muons with energy above 460 GeV on the surface are counted. Proton showers were produced at the South-Pole altitude by CORSIKA [3] with QGSJET as the high energy hadronic model.

Muons in air showers and their energy loss in the ice

The average number of high energy muons in an air shower can be parameterized as [4]

$$N_{\mu,>E_\mu}=A\frac{0.0145TeV}{E_\mu cos(\theta)}(\frac{E_0}{AE_\mu})^{0.757}(1-\frac{AE_\mu}{E_0})^{5.25}$$

in which A, E_0 and θ are the mass, total energy and zenith angle of the primary nucleus. Muons with energy high enough to trigger the in-ice detector are also nearly parallel with the air shower axis as shown in Fig. 2.

The mean muon energy loss in matter is customarily expressed as

$$\frac{dE}{dx} = -a(E) - b(E) \cdot E,$$

where $a(E)$ stands for ionization loss and $b(E)$ for stochastic energy loss due to pair production, photo-nuclear interactions and bremsstrahlung. As an approximation, $a(E)$ and $b(E)$ can be treated as constants. For ice at the South-Pole, $a = 0.26\ GeV\, mwe^{-1}$ and $b = 3.57 \cdot 10^{-4}\, mwe^{-1}$, which are claimed with the systematic error of $\sim 3.7\%$. [5]. The least mean energy required for a muon to reach the top (1450 m) and the bottom (2450 m) of the in-ice detector is about 460 GeV and 930 GeV. For cosmic-ray protons of 500 TeV, typical of showers that trigger IceTop, $\langle N_\mu \rangle \approx 6$ at 1450 m and ≈ 2 at 2450 m.

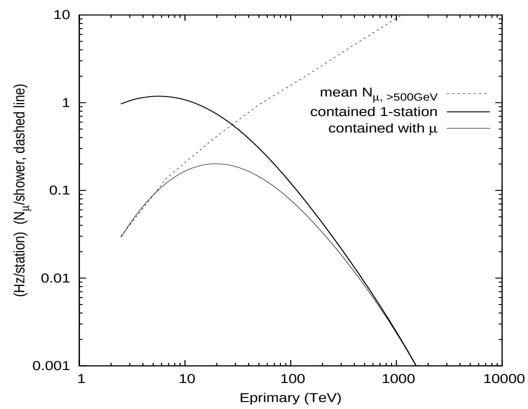

Figure 3: Response function for single station events in IceTop. Only four contained stations (39, 48, 49 and 58) were considered. The dashed line represents the number of muons above 500 GeV at production in a proton shower. The lower curve shows the response function for events with one muon in the deep detector.

We can select a sample of lower energy events by choosing in-ice triggers with both tanks hit at exactly one IceTop station. We also require the single station is not on the periphery so that events with energy high enough to hit both tanks at two or more IceTop stations are excluded from the sample. The concept is illustrated in Fig. 3 where we show an estimate of the distribution of primary cosmic-ray proton energies that give single station hits above 30MeV threshold in each tank. The lower curve shows the convolution of this response function with the probability of producing a muon with $E_\mu > 500$ GeV. This corresponds to the distribution of primary energy that gives rise to the single station coincident event sample. About ninety percent of this sample are generated by primaries with $E < 100$ TeV, and about three quarters have only a single muon with $E_\mu > 500$ GeV at production.

Verification of time synchronization and depth of the DOMs

A critical requirement for doing physics with IceCube is good time synchronization among the individual DOMs in IceCube, including IceTop together with accurate positions for the DOMs. Calibration with flashers and survey by hole logging during deployment shows that timing synchronization is at the level of 3 ns for a whole In-Ice string while the depth of individual DOMs are known with an accuracy of 50 cm [6]. By using tagged, vertical muons we can make a global check on the combination of time synchronization and depth of the DOMs over a 2.5 km baseline, from the surface to the deepest module on an IceCube string. To ensure that the single station events are not caused by tails of big air showers outside the array, only the inner stations of the IceTop array are used together with the in-ice strings directly below them. With the 16 IceTop station and 9 in-ice string array in 2006, only stations 39 and 49 fulfill this requirement.

For these two strings the muon speed has been individually calculated for each DOM relative to the time t_0 at the surface according to $v_i = d_i/(t_i - t_0)$ where d_i is the distance between the station and the i^{th} in-ice DOM. Because of scattering in the ice, there is a distribution of arrival times of photons at each DOM relative to the arrival time in the ideal case with no scattering. We represent the distribution of delays by an exponential with a characteristic delay τ. We then convolve this exponential distribution with a Gaussian resolution function to represent other uncertainties in the system. The result is a Gaussian-convoluted exponential function as shown bellow. By fitting the distribution of arrival times at each DOM, we extract a fitted value of the arrival time t_i at the ith DOM in the absence of scattering.

$$\frac{dN}{dt} = \frac{1}{2}\frac{N}{\tau}e^{-\frac{t-t_i}{\tau}}e^{\frac{\sigma^2}{2\tau^2}} \cdot \mathrm{erfc}\left(\frac{t_i - t + \frac{\sigma^2}{\tau}}{\sqrt{2}\sigma}\right)$$

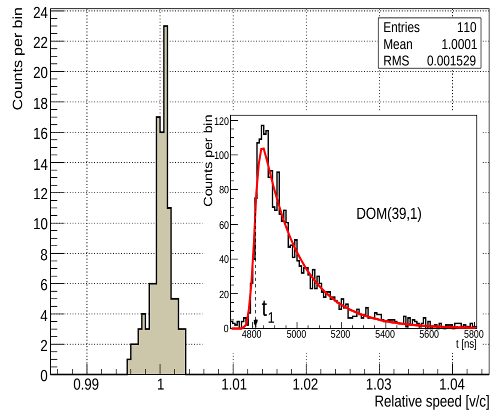

Figure 4: The distribution of muon speed (v) relative to the speed of light (c). The cut-in entry shows the time delay on one in-ice DOM and the fit. See text for details.

Other parameters here are the effective time resolution, σ, and the mean number of hits N. The expression erfc represents the complementary error function [7].

The distribution of the relative muon speed to the speed of light, v_i/c, is shown in Fig. 4, where we use the surveyed values of d_i to calculate the velocity. There are 60 DOMs on each string, 10 of which are not fitted because of insufficient data, so there are 110 entries in Fig. 4. The rms of 0.0015 of the distribution of v_i/c in Fig. 4 reflects the uncertainties in the system timing, the location of DOMs and the true muon position on the surface. This corresponds to upper limits on the uncertainty of 12 ns or 4 m over 2.5 km. Thus, although this method at present is not as precise as the standard survey and calibration techniques, it is useful to show by a complementary and independent method that there are no significant deviation from expectation.

Muons in the in-ice detector

Muon direction

Small air showers trigger a single IceTop station efficiently only when the shower core is close to the station. Since high energy muons are nearly parallel to the shower axis, the line connecting the station on the surface and the center of gravity (COG) of triggered in-ice DOMs approximates the muon trajectory closely. If we use half the string spac-

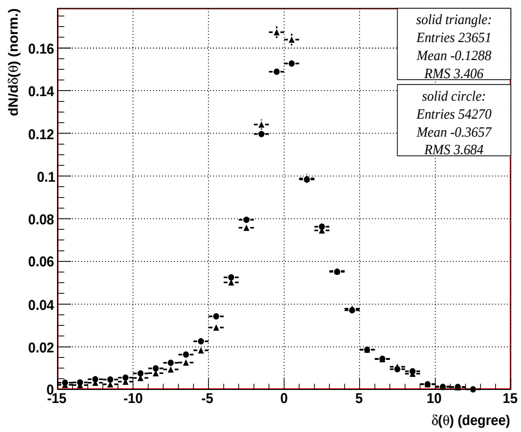

Figure 5: The difference between the zenith angle defined by the line connecting triggered IceTop station and the COG of triggered in-ice DOMs and that by the in-ice reconstruction. See text for details.

ing to estimate the accuracy of the location of the track at the surface and at 1500 m, we find that the direction of the track should be determined to an accuracy of about 3°. Fig. 5 shows a comparison between the zenith angle defined by this line and by an independent in-ice reconstruction. The events in the solid-circle histogram have charge more than 5 photo-electrons in the triggered IceTop station. Those under the solid-triangle histogram have charge more than 400 photo-electrons, indicating a core closer to the station and/or slightly higher primary energy. The mean of $\delta(\theta)$ decreased from 0.37 degree in the low-density sample to 0.13 degrees in the high density sample.The rms are about 3.7 degrees and 3.4 degrees respectively for the two groups. Given the estimated 3 ° uncertainty in the estimation of the direction by this method, the good agreement indicates that the in-ice reconstruction algorithm has an accuracy of 2° or better for events near the vertical. Nevertheless, further investigation is needed to understand these events with zenith offset larger than 6 degrees.

Uncorrelated, coincident atmospheric muons in IceCube

An important source of background for upward-moving neutrino-induced muons in IceCube is the subset of events in which two uncorrelated atmospheric muons pass through the detector in the same trigger window. Such events, which are estimated to constitute about 3% of the trigger rate in the full cubic kilometer IceCube [8], are of concern because the time sequence of hits in the combined event can easily have an upward component. It will be useful to tag a subset of such events with IceTop for study and to check that they are efficiently filtered. At present, however, with the smaller detector the fraction of accidental coincidences is much smaller, and IceTop can only tag a very small fraction of them. The rate of identified single station coincidences in 2006 was about 0.075 Hz per station, so 1.2 Hz over the sixteen station array. An estimate of the rate of tagged double uncorrelated events is therefore $\sim 10^{-5}$ Hz, somewhat about one per day. For comparison, the trigger rate of the 9-string IceCube in 2006 was 146 Hz.

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