Air showers in a three dimensional array: Recent data from IceCube/IceTop [1]

Xinhua Bai & Thomas K. Gaisser for the IceCube Collaboration [2]
Bartol Research Institute and Department of Physics and Astronomy
University of Delaware, Newark, DE 19716 USA

E-mail: `bai@bartol.udel.edu`, `tgaisser@bartol.udel.edu`

Abstract. The next generation high energy neutrino and cosmic ray array IceCube/IceTop is under construction at the geographic South-Pole. Air showers with trajectories that pass through the surface array and near the deep strings trigger both components in coincidence. The ratio of the muon signal in the deep detectors to the shower signal on the surface is sensitive to the elemental composition of the primary cosmic radiation.

One string of 60 sensors buried between 1.5 and 2.5 km in the ice and a surface array of 4 stations were successfully deployed at the South Pole during the austral summer of 2004-05 and have been producing data since February 2005 [1]. Eight more strings and 12 more IceTop stations were deployed in the austral summer of 2005-06. Since then 16 stations and 9 strings have been operating. The full array with up to 80 strings and 80 surface stations is scheduled for completion in 2011.

Each IceTop station consists of a pair of ice Cherenkov tanks (to be referred to as tank A and B) separated by 10 m, each containing a cylinder of clear ice $2.7\,\mathrm{m}^2 \times 0.9\,\mathrm{m}$ viewed from the top by two standard IceCube digital optical modules (DOMs). The operation of a surface array over the deep IceCube neutrino telescope has three goals:

- Composition: To study the ratio of the muon signal in the deep array to the shower signal on the surface which is sensitive to the fraction of heavy nuclei in the cosmic-ray spectrum.
- Calibration: To study the angular resolution and pointing accuracy of the neutrino array by providing a sample of externally identified muon bundles.
- Filtering: To study and filter single or multiple muon background in the deep detector by tagging the associated air-shower activities on the surface.

Predecessors for operation of a surface array in conjunction with a deep underground detector sensitive to muons are SPASE-AMANDA [2] and EASTOP-MACRO [3]. With an acceptance at completion of ~ 0.3 km^{2}sr, IceTop/IceCube will have a significantly higher reach in primary energy than these earlier experiments. With a threshold of approximately 300 TeV, the experiment will be sensitive from below the knee of the cosmic-ray spectrum up to approximately 1 EeV, where it will be statistically limited by its acceptance. A significant motivation for studying the composition in this energy region is to search for the transition from a population of cosmic rays primarily of local origin in the Milky Way Galaxy to a population of extra-galactic origin [4].

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[2] The full IceCube Collaboration author list is at the end of these proceedings.

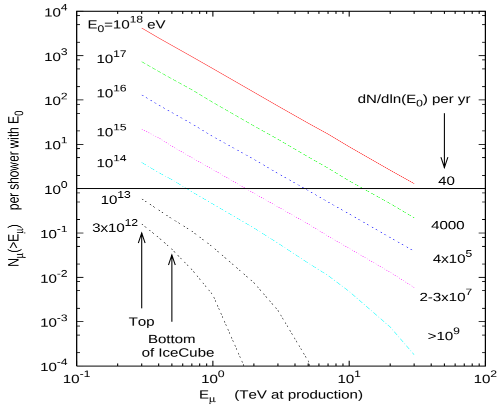

Figure 1. Integral energy spectra of muons in air showers (see text).

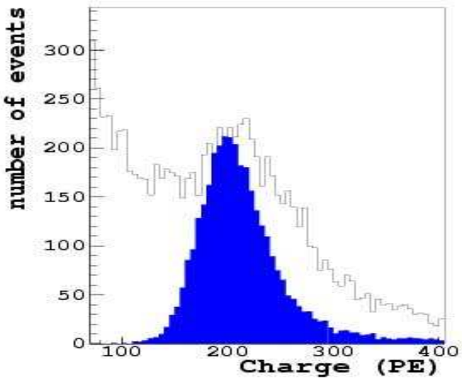

Figure 2. Charge spectrum of pulses in an IceTop tank (see text).

Figure 1 shows the integral energy spectra of muons at production in the atmosphere in proton-initiated showers of various primary energies. The two vertical arrows indicate the minimum muon energies needed to reach the top and bottom of the deep in-ice detector. Each spectrum is labeled on the right with the number of coincident events per year ($\mathrm{d}N/\mathrm{d}\ln E$) expected within the acceptance of the full detector. The currently operating array with 16 surface stations and 9 strings has approximately 0.5% of the geometrical acceptance for coincident events of the full detector and is therefore statistically limited at 10^{17} eV, where the expected number of events per year would be about 20 (as compared to 4000 for the completed detector).

Low-energy atmospheric muons (typically in the GeV range) provide a natural beam for calibrating and monitoring the response of IceTop detectors to track length above Cherenkov threshold and hence to the energy deposition in the tanks. The characteristic spectrum (shown in Fig. 2) combines the steeply falling spectrum of electrons and converting γ-rays with a peak due to muons. Small air-showers contribute to the high-energy tail. The solid histogram in Fig. 2 shows the single muon peak identified by a muon telescope in a special run. The tagged muon histogram is narrower than the muon peak in the composite spectrum and very slightly shifted toward the lower integrated charge. The vertical through going muon deposits 160 MeV and thus provides the conversion between energy deposition and integrated charge of the waveform. Special, periodic monitoring runs obtain the composite, inclusive spectrum to look for any change in shape or peak location, which would indicate a change in tank response.

In normal data taking, the IceCube data acquisition system sends data to the surface only if neighboring DOM pairs are hit. For IceTop, we require that both tanks at the same station register a hit so that only air showers are reported. Events are recorded if the hits satisfy a simple majority trigger (SMT). For IceTop, the SMT is set to 6 DOM hits within $2\mu s$; for in-ice detector, the SMT is set to 8 hits within $5\mu s$. With these settings, the in-ice trigger rate is 146 Hz and the IceTop SMT rate is 7.1 Hz. Whenever either trigger is satisfied, waveforms of all hit DOMs are recorded. Of particular interest is the subset in which both SMT triggers are satisfied. This coincident rate is measured to be 0.19 Hz in the 2006 detector configuration. These events will be the subject of the composition analysis. They also provide tagged muon beams for the calibration of in-ice array.

Figure 3 shows the lateral distribution for a typical large IceTop event, which happens to be a coincident trigger. Figure 4 shows the waveforms on the surface at two locations ($\sim$ 100 m and $\sim$ 210 m from the reconstructed shower core) and a sample waveform from an in-ice DOM in the same event. Surface waveforms have the characteristic features of large, smooth shape near the core and smaller, more uneven structure farther out. In-ice waveforms are typically a sequence of single photo-electrons.

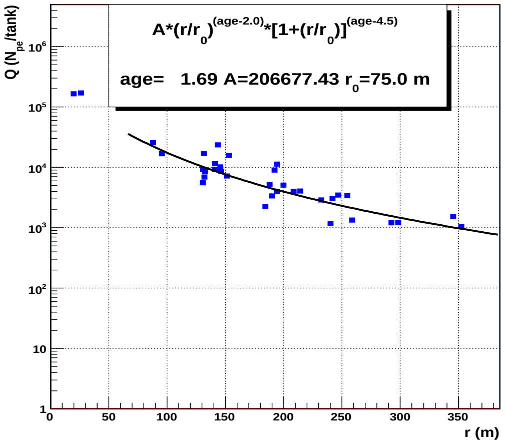

Figure 3. Lateral distribution of the charge in surface tanks fitted with an NKG distribution.

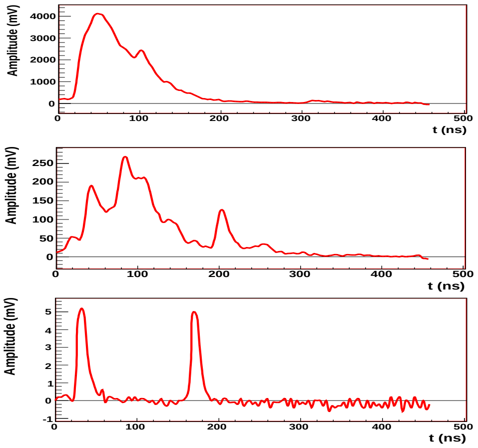

Figure 4. Waveforms in coincident events (see text).

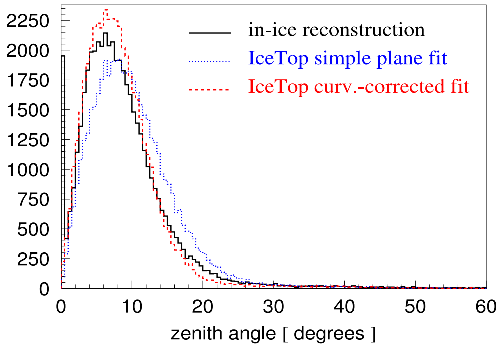

Figure 5. Zenith angle distribution of coincident events as reconstructed by in-ice alone (black histogram) and by IceTop alone with two different procedures.

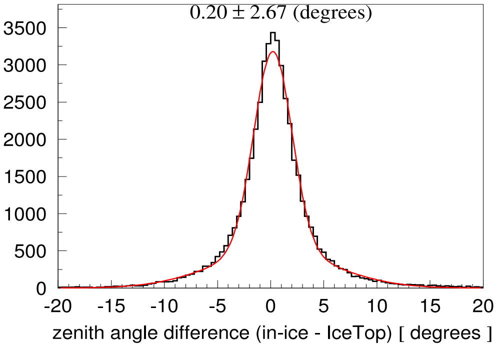

Figure 6. Distribution of the difference between directions determined by IceTop alone and by using the in-ice muon reconstruction algorithm.

Finally, Figs. 5 and 6 illustrate cross calibration of angular resolution between IceTop and the deep-ice array of IceCube. When the realistic curved shower front (dashed in 5) is used, the directions agree well (FWHM$\approx 5^o$). A sub-array analysis is in progress to determine the angular resolution of the IceTop reconstruction algorithm. This analysis uses the pairwise distribution of tanks to form one sub-array of all 16 “A” tanks and an second sub-array of all 16 “B” tanks at each station. Comparison of the separately determined “A” and “B” directions for each event give a measure of the resolution of IceTop alone. Deconvolving the distribution of Fig. 6 will then give a measure of the resolution of the in-ice reconstruction algorithm as applied to muon bundles.

[1] Achterberg A et al. (IceCube Collaboration) 2006 *Astropart. Phys.* **26** 155

[2] Ahrens J et al. 2004 *Astropart. Phys.* **21** 565

[3] Aglietta M et al. (EAS-TOP and MACRO Collaborations) 2004 *Astropart. Phys.* **20** 641; 1994 *Phys. Lett.*B **337** 376

[4] Hillas A M *”Cosmic Rays: Recent Progress and some Current Questions”* arXiv:astro-ph/0607109