Inclined Cosmic Ray Air Showers in IceCube

THE ICECUBE COLLABORATION

1 See special section in these proceedings

Abstract:
In this contribution we will consider the sensitivity of IceCube to inclined air showers produced by cosmic rays. Cosmic ray air shower analyses done with IceCube up to now only considered air showers arriving within a limited zenith angle range. IceTop analyses have included events up to about 40 degrees while coincident IceCube/IceTop analyses are limited to zenith angles smaller than 30 degrees. We study the possibility of extending the angular range to 60 degrees for both IceTop and coincident IceCube/IceTop. In the case of coincident IceCube/IceTop inclined events, the detector aperture is larger than that of IceTop at energies larger than 100 PeV due to the sensitivity to single muons at large distances from the shower axis. As part of this study, we have measured the average lateral distribution of muons at large distances to the shower axis.

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1 Motivation

It is well known that the muon content of an air shower, together with a measure of its electromagnetic component, can be used to estimate the energy and mass of its primary [1]. The IceCube collaboration has taken advantage of this in order to study the spectrum and mass-composition of cosmic rays between 1 PeV and 1000 PeV [2]. The main issue with the use of the muon content as an estimate of primary mass is the possible systematic differences between simulated and real air showers, arising from the lack of knowledge of high energy hadronic interactions, as shown by the Pierre Auger Observatory [3]. The angular dependence of the cosmic ray spectrum can be used as a cross-check of any such systematic difference [4]. For this reason, we want to extend as much as possible the angular range of the cosmic ray air showers studied in IceCube.

Another reason to extend the detector field of view is to search for hints of a possible galactic/extra-galactic transition above 100 PeV. According to Giacinti et al. [5], the flux of heavy cosmic rays with galactic origin, with energies around $1 \times 10^{17}$ eV, should show a large-scale anisotropy of a few percent. One can argue that the light cosmic rays that dominate the flux are predominantly of extra-galactic origin and for this reason no anisotropy has been measured between $1 \times 10^{17}$ and $1 \times 10^{18}$ eV. This leaves open the question of whether the heavy component displays some degree of anisotropy. The very first step in order to study the large-scale anisotropy of the heavy component is to increase the detector field of view.

Finally, the study of inclined air showers can lead to a direct determination of the muon content of air showers on an event-by-event basis. Of particular interest are the events where IceTop can be directly measured the muons far from the shower axis, enabling the study of new observables sensitive to primary composition, such as the Muon Production Depth distribution (MPD), as is done by the Auger collaboration [6]. In order to study this class of events, we require a detailed knowledge of the sensitivity of the detector and of the lateral distribution of muons in real air showers. The study of the lateral trigger probability as well as the muon lateral distribution function, using the IceTop detector, is presented in section 3. Using this knowledge, we can estimate the efficiency for detecting inclined air showers under various conditions. This will be shown in section 4.

We can distinguish two types of inclined air showers reaching IceCube, as shown in Fig. 1: the IceTop-contained showers, whose symmetry axis passes through the IceTop array, thereby completely missing the in-ice detector, and the IceCube-contained showers, whose symmetry axis passes through the in-ice component of IceCube. In this contribution we will be especially interested in IceCube-contained events.

Figure 1: The two kinds of inclined air showers detected by IceCube. Compare with the field of view studied so far in IceCube represented by the inverted cone.
2 IceCube as a Cosmic Ray Detector

The IceCube detector is composed of two major components. It can measure air showers on the surface with IceTop, high energy muon bundles with the in-ice detector, and both components in coincidence provided that its axis goes through the in-ice detector.

In its final configuration, the in-ice detector consists of 86 strings of 60 Digital Optical Modules (DOMs) each, extending from 1.5 km to 2.5 km under the ice. Each DOM contains a 10 inch photomultiplier tube (PMT) and electronics for signal processing and readout. The strings are separated by about 125 m. IceTop is an air shower array consisting of 81 stations, located above the in-ice detector, covering an area of one square kilometer. Each station consists of two ice Cherenkov tanks separated by ten meters.

Each IceTop tank contains two DOMs operating with different PMT gains for increased dynamic range, registering signals ranging from 0.2 to 1000 Vertical Equivalent Muons (VEM). A discriminator trigger occurs when the voltage in one of the DOMs in a tank has passed the discriminator threshold. A Hard Local Coincidence (HLC) occurs when there are discriminator triggers in two neighboring tanks within a time window of ±1 µs. If there is a discriminator trigger but not an HLC, the result is a Soft Local Coincidence hit (SLC). The SLC hits have a significant contribution from single muons while the HLC hits are a measure of the electromagnetic component of the air shower. The total charge collected at the PMT’s anode constitutes the tank’s signal. The primary cosmic ray properties are reconstructed by fitting the measured charges with a Lateral Distribution Function (LDF) and the signal times with a function describing the shape of the shower front. The primary energy is given by the shower size, defined as the signal at 125 m from the shower axis $S_{125}$. For a more detailed description of IceTop, refer to [7].

The cosmic ray energy spectrum has been measured with IceTop in the energy range between 1.58 PeV and 1.26 TeV by studying air showers arriving within 46° and 37° [8] from the vertical, which we called IceTop-contained events. The zenith angle restriction is especially important when requiring that the air showers are contained within IceTop and in-ice detectors [2], in which case the zenith angle is always less than 30°. The muon bundle multiplicity spectrum in IceCube-contained events has been studied as well and it is sensitive to the primary mass composition [10]. However, in this later case, no attention was paid to whether the air shower was detected by IceTop or not and therefore no combined reconstruction was attempted.

For this contribution, we have analyzed data taken by the IceTop array from June 1, 2010 to May 13, 2011 when IceTop consisted of 73 stations. The effective livetime of the detector during this time interval is 327 days.

3 The Lateral Distribution Function

An example of the average LDF for air showers, with fixed $S_{125}$ and zenith angle, can be seen in Fig. 2. At large distances, there are two distinct populations. One population is the continuation of the main distribution at smaller distances, where the electromagnetic component of the shower dominates. The other population, with signals around 1 VEM, is made up mostly of tanks hit by one or more muons. These two populations are clearly seen in Fig. 3, where we show the histograms of collected charge for all tanks at selected fixed distances to the shower axis.

The first population corresponds to the tanks detecting no muons. We approximate this distribution by a power-law multiplied by a function that describes the trigger probability. The trigger probability can be described by a sigmoidal function of the logarithm of the charge, centered at 0.25 VEM and with a width of 0.14. This approximation works well at large distances from the shower axis.

The second population, with a peak around 1 VEM, can be described by the contributions of tanks detecting an integer number of muons, determined by detailed simulations of the detector response. These contributions are weighted according to a Poisson distribution with a given mean number of muons $\langle N_\mu \rangle$. The resulting distribution is smeared and shifted to account for a very small contribution from electrons, positrons, and $\gamma$-rays. These parameters are left free in the fitting procedure.

We can fit the charge distribution at a sufficiently large distance from the shower axis using the distributions just described. The result is the number of tanks hit by at least one muon. This, together with the total number of tanks located at that distance provide an estimate of the probability to be hit by one or more muons, which leads to the mean number of muons $\langle N_\mu \rangle$:

$$p_{\mu \ hit} = 1 - e^{-\langle N_\mu \rangle}.$$  

In order to ensure that the distance from the shower axis is sufficiently large, this procedure is applied only to the charge distributions of tanks located at distances larger than a value that can depend on $S_{125}$ and zenith angle. This minimum distance is defined such that, given any tank with signal at this distance, there is less than 10% chance probability that it is an HLC. This can easily be determined at all $S_{125}$ and zenith angle values by looking at the corresponding distribution of tanks, such as the one displayed in Fig. 4. From these distributions, we can also estimate the probability that any tank at a given distance to the shower axis will record a hit, also called the Lateral Trigger Probability (LTP).

The resulting muon lateral distributions, corresponding to air showers arriving within 31° from the vertical, and
selected $S_{125}$ bins, are shown in Fig. 5. Each LDF can be described by the following function:

$$N_{\mu}(r) = A S_{125}^\beta r^{-0.75} \left(1 + \frac{r}{320\text{m}}\right)^{-\gamma},$$

where we decided to fix the first exponent of $r$ to -0.75, and the equivalent to the Moliere radius to 320 meters, as measured by Greisen [11], and fit the rest of the parameters.

4 Detection Efficiency for Inclined Air Showers

In order to estimate the efficiency for the detection of inclined IceCube-contained showers, we implemented a simple Monte Carlo algorithm. The first step of the algorithm is to generate a random geometry (position and direction) that intersects the in-ice detector. The next step is to choose either a primary energy or a value for $S_{125}$. The primary energy determines the mean value for $S_{125}$, using a relation known for angles up to 37° [9] extrapolated up to 60°. Given the geometry and $S_{125}$, we then use the lateral trigger probability, determined as described in the previous section, to generate many realizations of sets of tanks with signal. We can finally impose various conditions for detection and calculate the fraction of detected events. The precise condition to be used in the future will depend on the required reconstruction quality and is not determined at this time.

One can require that there be a certain number of SLCs or HLCs. As an example, the resulting detection efficiency as a function of zenith angle, for different $S_{125}$ values, can been seen in Fig. 6. We show two different conditions, one requiring 10 SLCs and another requiring 3 HLCs. It becomes apparent that, at large zenith angles, the events consist mostly of SLC hits. This is because the local trigger probability is more evenly distributed over the array.

The most striking feature is the increase in efficiency that occurs at zenith angles larger than 45°. To understand this, we need to remember that the lines in Fig. 6 correspond to air showers with fixed $S_{125}$. The feature is a reflection of the fact that, as the air shower zenith angle increases, it has to traverse a larger amount of atmosphere and the muon component gives a larger relative contribution at ground, thereby decreasing the steepness of the LDF. That is: for a given $S_{125}$, the trigger probability at large distances to the shower axis increases with zenith angle. To make the point clearer, we show the LTP corresponding to events with an $S_{125}$ around 3.6 VEM in Fig. 7, where we can see how the tail of the LTP is steeper at small zenith angles.

The resulting effective area, as a function of zenith angle, is displayed in Fig. 8. In this figure, the thick solid line represents the surface area of IceTop projected at that zenith angle. The effective area for showers arriving at an angle of 60° with the vertical, with an energy of 112.9 PeV, is comparable to the effective area of IceTop.

The result of integrating the effective area over the azimuth and zenith range is the aperture. This is displayed in Fig. 9 as a function of the primary energy. Here it becomes apparent that, with a requirement of 10 IceTop SLCs in coincidence with the in-ice event, the aperture for IceCube-contained events is comparable to that of the

Figure 3: Vertical slices of the 2-d histogram in Fig. 2. Each histogram corresponds to a vertical line in Fig. 2. They correspond to the radii at which the probability that a given tank with signal is part of an HLC is 0.1, 0.2, 0.3, and 0.5. At 297 m, the model described does not fit the distribution.

Figure 4: The radial distribution of all tanks (black), tanks with HLC (dark gray), tanks with SLC (light gray), and tanks with no hits (dotted) for events with $S_{125}$ between 4 and 5 VEM and zenith angle between 30° and 33°. Note that SLC hits dominate at large distances.

Figure 5: Reconstructed average lateral distribution of muons for air showers arriving at zeniths angles of 31° with the vertical and selected $S_{125}$ values. The small markers correspond to points below the radial cut and not used in the fitting procedure.
current IceTop analysis at energies of the order of 25 PeV and more than doubles it at energies larger than 200 PeV. At 80 PeV it becomes larger than the aperture of IceTop for the same angular range. Therefore, the addition of IceCube-contained events should triple the statistics above 200 PeV when compared to the current analysis.

5 Outlook

By studying IceTop-contained air showers arriving with zenith angles up to 60°, IceTop can double the statistics over the entire energy range. We have also shown that the aperture of IceCube for the detection IceCube-contained cosmic ray air showers is more than double that of IceTop alone. The study of these events opens the possibility of studying the Muon Production Depth distribution function, which we intend to explore in the near future. The muon lateral distribution function presented here will enable us to determine the muon content of air showers on an event-by-event basis.

References

[2] IceCube coll., paper #861, this proceedings.
[9] IceCube coll., paper #246, this proceedings.