Study of very bright cosmic-ray induced muon bundle signatures measured by the IceCube detector

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***Abstract*. We present the study of cosmic-ray induced atmospheric muon signatures measured by the underground IceCube array, some of which coincide with signals in the IceTop surface detector array. In this study, cosmic-ray primary energies are associated with the total number of photoelectrons (NPEs) measured by the underground IceCube optical sensors with two methods. We found that multiple muons that produce $10^4 \sim 10^5$ NPEs in the IceCube detector in 2008 is corresponding to the cosmic-ray primary energies of $10^7 \sim 10^9$ GeV.**

This association allows us to study cosmic-ray physics using photon distributions observed by the underground detector that are characterized by the properties of muon bundles. It is observed that the detailed NPE space distributions in longitudinal and lateral directions from muon tracks display the ranging-out effect of low energy muons in each muon bundle. The distributions from 2008 high energy muon data samples taken with the IceCube detector are compared with two different Monte Carlo simulations. The first is an extreme case that assumes a single high energy muon in which nearly all of the energy loss is due to stochastic processes in the ice. The other uses the CORSIKA program with SYBILL and QGSJET-II high energy hadron interaction models, in which approximately half of the energy loss is due to ionization of low energy muons.

***Keywords*: IceCube, muon-bundle, high-energy**

I. INTRODUCTION

Bundles of muons produced in the forward region of cosmic-ray air showers appear as bright signals in Cherenkov detectors. The multiple-muon tracks with a small geometrical separation (called 'muon-bundles') resemble a muon with a higher energy. Understanding of the background muon bundles using a full air shower MC simulation in the high energy range above 10^7 GeV is limited because the calculation involves poorly characterized hadronic interactions and a knowledge on the primary cosmic ray composition at energies where there is no direct measurement available. The experimental measurement of atmospheric muons provides an independent probe of the hadronic interactions and the primary cosmic-ray compositions.

The IceCube neutrino observatory [1] provides a rare opportunity to access the primary cosmic-ray energies beyond accelerator physics. The IceCube detector located at the geographic South Pole consists of an array of photon detectors which contains a km^3 fiducial volume of clean glacier ice as a Cherenkov radiator. Half of the final IceCube detector (IC40) was deployed by the end of austral summer of 2008. The IC40 detector consists of 40 strings of cable assemblies with an intra-string spacing of 125 m. Each string has 60 optical sensors (DOMs) spacing at intervals of ∼17 m and stretching between depths of ∼1450 m and ∼2450 m in the glacial ice. DOMs are also frozen into tanks located on the surface near the top of each string. The ice-filled tanks constitute an air shower array called IceTop [2]. IceTop can act as an independent air-shower array to measure cosmic-ray spectra as well as trigger simultaneously with the underground detector. This provides a reliable method to study the atmospheric muon bundles.

The data taking with the IC40 detector configuration was performed from April, 2008 through March, 2009. The high energy muon-bundle (HEMu) sample consists of events which measure between 6.3×10^2 and 6.3×10^4 photo-electrons (PEs) in at least 50 underground DOMs. An IceTop coincidence (HECoinc) sample is a subset of the HEMu sample with the additional requirement that IceTop can successfully reconstruct the air shower event. Similarly, samples (called VHEMu and VHECoinc) with higher NPE threshold of 7.0×10^3 are studied. Definitions of samples are summarized in Table I.

Data studied in this paper is taken in the period of July to December 2008 with a livetime of 148.8 days. Event distributions of the samples are presented in Fig. 1.

TABLE I
DEFINITIONS OF SAMPLE CONDITIONS.

	threshold NPE value	IceTop coincidence required
HEMu	6.3×10^2	no
HECoinc	6.3×10^2	yes
VHEMu	7.0×10^3	no
VHECoinc	7.0×10^3	yes

II. COSMIC-RAY ENERGY AND UNDERGROUND BRIGHTNESS RELATION

Because the energy losses of muon-bundles are indicators of their energies and multiplicities, measurements of the total energy deposit of muons (E_{loss}) in the detection volume is important for understanding of the nature of muon-bundles. Here, we use the total number of photoelectrons recorded by the all underground DOMs (NPE) as an indicator of E_{loss}. The effective light deposit from

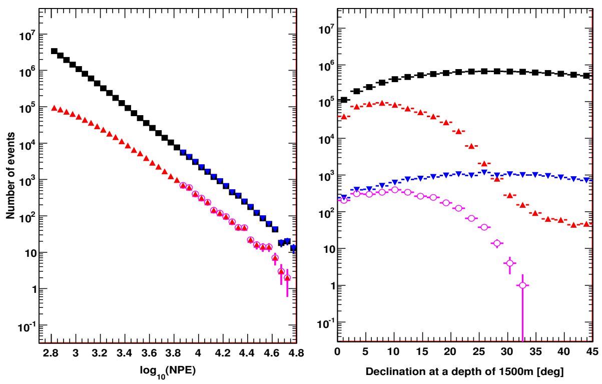


Fig. 1. Atmospheric muon event distributions from 2008 sample as a function of NPE (left) and reconstructed zenith angle θ (right). Filled square denotes HEMu and triangles are HECoinc. Inverse triangles and open circles are that of VHE samples as defined in table I. Coincidence samples show a high detection efficiency for vertical events and the efficiency drops with zenith angles. Event rates decreased by ≈ 2.5 orders of magnitude when NPE is increased by an order of magnitude.

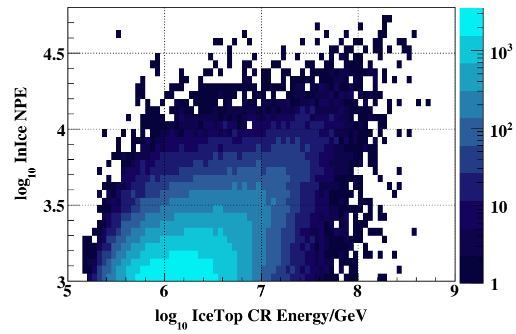


Fig. 2. Event distributions of HECoinc sample as a function of NPE and IceTop reconstructed primary cosmic-ray energies. A clear correlation is observed.

bundles can be parameterized with an effective track length l_0 as [3], [4],

$$\mathrm{NPE} \sim l_0(\eta N_\mu + \xi \Sigma E_\mu) \quad \propto \quad \mathrm{E}_{\mathrm{loss}}. \qquad (1)$$

Here, N_μ and ΣE_μ indicate multiplicities and energy sum of underground muons respectively. η and ξ are ionization and radiative energy loss coefficients assumed to be constant with energy. Primary cosmic-ray energies are related to the NPE with two methods. The first method is to directly relate the underground NPEs with IceTop cosmic-ray energy reconstruction results. The other is to construct an empirical model to characterize the event frequencies of underground NPEs from the experimentally measured cosmic-ray surface fluxes [5]. The former method has the advantage that both cosmic-ray energy and underground brightness are consistently measured quantities, while the directional acceptance is limited to near vertical. The latter method requires a model assumption in the underground bundle spectra shape but full angular acceptance is available.

A. *IceTop coincidence signals*

Figure 2 shows the measured underground NPE distribution as a function of cosmic-ray energies reconstructed by the IceTop air-shower array. The energy determination method by the IceTop array is described in [6]. A clear correlation exhibits that bright underground events are associated with the high energy cosmic-ray induced air showers and each NPE region roughly corresponds to different cosmic-ray energy regimes. For example, it shows that the cosmic-ray primary energy of $\sim 3.0 \times 10^7$ GeV are associated with 10^4 NPE underground events. As shown in Fig. 1, because of the IceTop coincidence condition, most of events in this sample is near vertical.

B. *The empirical model*

A high energy muon empirical model is constructed as in [7]. In the model construction, the amount of energy that goes to muon-bundle from cosmic-ray primaries is expressed in terms of energy weighed integral of the Elbert formula [8]. Because a major part of NPEs from muon tracks is expected to be due to the radiative processes in the very bright events, it is assumed in the model that the NPEs from the ionization is negligible compared to the stochastic energy losses, *i.e.* $N_\mu = 1$ in Eq. 1. We then fit experimental data with this model by varying ΣE_μ in Eq. 1 until it reproduces the experimentally observed NPE event rates. The total energy in the bundle ΣE_μ is carried by a single muon and the muon is simulated with [9]. The model is constructed based on the data sample taken in 2007. The present sample from 2008 under study separately confirms the agreement as shown in Fig. 3 above the NPE threshold of 7.0×10^3. Below the threshold value, the model assumption that nearly all energy losses are due to radiative processes is expected to fail. The relation between the true cosmic-ray energy and NPE is shown in Fig. 4. The relation shows reasonable agreement with the experimentally measured relation shown in Fig. 2 in the overlapped acceptance region. An extrapolation of the relation indicates that corresponding primary cosmic-ray energy is increased to 10^9 GeV for the muon bundle signals with 10^5 underground NPE.

III. Energy losses of muons in bundles

A. *Muon spectra in bundles*

Average muon spectra in a bundle for different total NPE range from CORSIKA MC simulation using SYBILL and QGSJET-II as high energy interaction models with iron primaries and corresponding single muon energy distribution from the empirical model are shown in Fig 5. The plot shows that the number of muons reaching the IceCube depth from CORSIKA simulations increase with their total NPE. While there is a large difference between the muon bundle spectra from the CORSIKA full air-shower simulations and the high energy single muon empirical model, both describe the NPE event rates with a reasonable agreement (Fig 3). There is no significant difference in muon spectra from

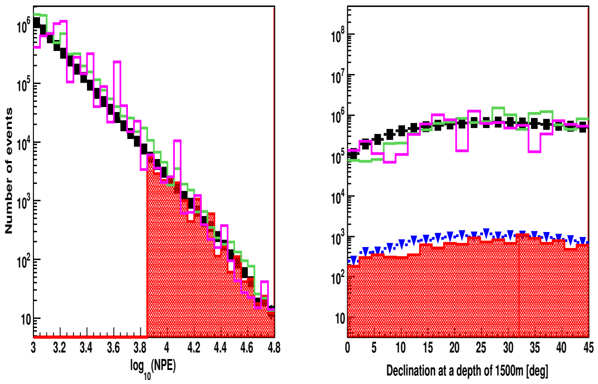


Fig. 3. Event distributions as a function of NPE (left) and reconstructed zenith angle θ (right). Squares and inverse triangles denote 2008 high energy event sample as in Fig. 1. Filled histograms are from the Monte Carlo simulation of the high energy muon empirical model as described in the text. Dark and light colored histograms are from CORSIKA MC simulation using SYBILL and QGSJET-II as high energy interaction models with iron primaries respectively. Event distributions from proton primaries highly underestimate the event rates. It can be seen that all of three MC simulation gives a reasonable agreement with experimental observation.

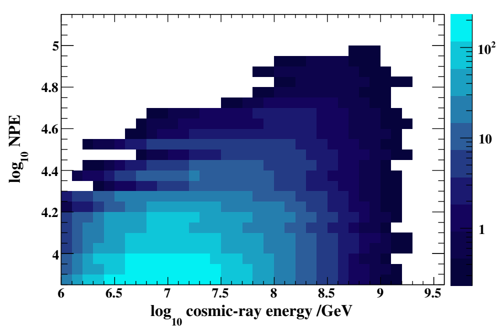


Fig. 4. The correlation between primary cosmic-ray energy to underground NPE from MC simulation with the high energy muon empirical model. A consistent relation obtained with IceTop/underground coincidence measurement is obtained.

SYBILL and QGSJET-II high energy interaction models with iron primary below 4.0×10^4 NPE, but they exhibits some difference for the brighter events which approximately corresponds to the primary cosmic ray energies above $\sim 10^8$ GeV.

The fact that the event rates as a function of the total NPE appear consistent among the three estimations with different muon bundle models indicates that the NPEs of an event insensitive to the energy spectra of muon bundles. It implies that to distinguish whether the observed photon emission is dominated by either the first or the second term in Eq. 1 is difficult with the total NPE. This indicates that the NPE measure is a systematically robust variable when used in analysis as in [7]. On the other hand, to evaluate muon bundle structure in each event, this variable is not sufficient. The nature of muon bundles, such as the muon spectra

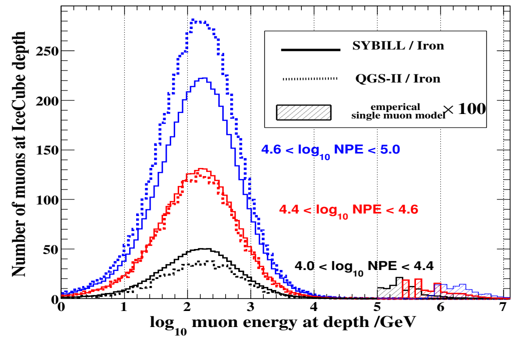
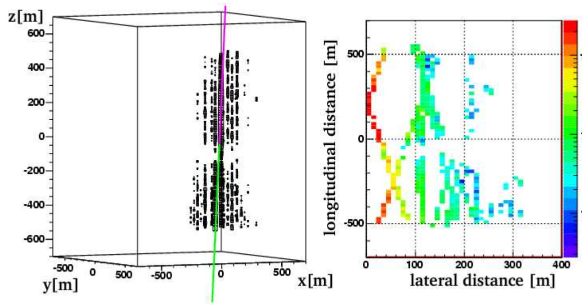


Fig. 5. Average muon MC-truth energy spectra in a bundle in different NPE range are shown for SYBILL, QGSJET-II with iron primaries and the empirical single muon model which is multiplied by 100 for a better visibility. Each of solid and dashed lines represents different NPE regions which approximately correspond to different cosmic-ray primary energies as shown in Fig. 4. In the brightest events, both CORSIKA high-energy models predicts more than 5,000 muons in a bundle reaching the underground detector. The muon in the single muon empirical model has energies between 100 TeV and 10 PeV.

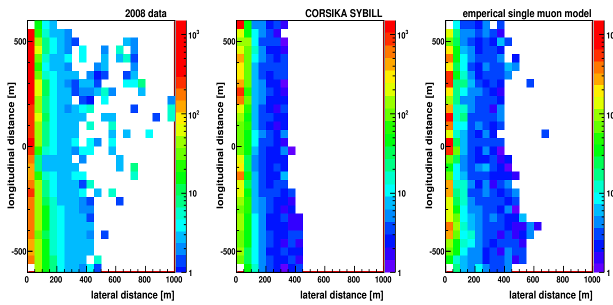
as in Fig. 5, is expected to appear in more detailed NPE distributions along the muon bundle tracks.

B. The lateral and longitudinal NPE distributions

The NPE distributions as functions of distances along and perpendicular to the track are shown in Fig. 6. In the plots, only vertically reconstructed events ($\theta \leq$ 15 degrees) are used. Vertical tracks are suitable for measurement of detailed longitudinal development of the energy losses because the DOM separation in the z direction is only 17 m compared to 125 m in x-y direction. The detected Cherenkov photon profile shows a good correlation with the depth dependence of the measured optical properties of glacier ice. Fig. 6a shows a typical 3-dimensional NPE distributions of an observed high energy muon-bundle track. The lower panels shows averaged NPE distributions in the 2D plane from vertical VHEMu events for 2008 data, SYBILL-iron and the empirical model. There are visible differences in the 2D light deposit distributions between data and models which give similar NPE. The detailed NPE distributions can be further examined as a function of longitudinal distances along tracks at various lateral distances as shown in the Fig. 7. Each solid line denotes different lateral distance with a 50 m interval and the distributions correspond to the slices along the longitudinal distances in the left panel of the Fig. 6b. It can be seen that the NPE observed by each DOM decreases rapidly with lateral distances. The closest longitudinal NPE distribution ($\leq$ 50 m) shows that at the upper IceCube detector $\sim$800 NPEs are observed in each DOM and gradually decreased to $\sim$300 NPEs at the bottom of detector. This is expected to be due to ranging-out of low energy muons in bundles as they travel through the detector. This clearly shows that the longitudinal NPE profiles close to the track is sensitive to the muon energy loss profile. The effect is less visible when photons



(a)



(b)

Fig. 6. The lateral and longitudinal NPE distributions from high energy muon-bundle events which produces very bright event signatures. (a) Left: A typical NPE space distributions of a bright event in 2008. The size of squares indicates log_{10} NPE. Solid line indicates the reconstructed direction. There is a loss of photons due to a dusty layer of ice positioning around z = -100 m. Right: The NPEs from each DOM are plotted as functions of distances perpendicular to and along the reconstructed track. Filled bins are the position where the DOMs exist in this lateral and longitudinal two dimensional space and z-axis indicates measured NPEs. When there is more than one DOMs in a bin, NPE averages are calculated. (b) An averaged lateral and longitudinal NPE distribution of vertical bright events. Left: Vertically reconstructed VHEMu sample. Middle: CORSIKA-SYBILL with iron primary. Right: the high energy single muon empirical model.

propagated more than 50 m from the track where the effects of ice properties begin to dominate. The effect of the ice layers with different scattering/absorption properties highly modifies the lateral NPE distributions in this case. The distributions of NPEs close to tracks are suitable to study muon-bundle properties and NPEs at distance reflects the nature of photon propagation through the ice.

IV. Outlook

The various parts of lateral and longitudinal profiles of the NPE distributions in 2-dimensional space are governed by the nature of muon bundles and optical properties of the ice in different way. Specifically, detailed study of the longitudinal NPE profiles at different lateral distances is important for a better understanding of both the muon-bundle and ice property modeling.

The contributions from ionization and radiative energy losses in the obtained lateral and longitudinal NPE distributions are not distinguishable so far. This is because longitudinal NPE profiles shown in Fig. 7 are obtained from multiple events and stochastic nature of energy losses are averaged out. However, a large

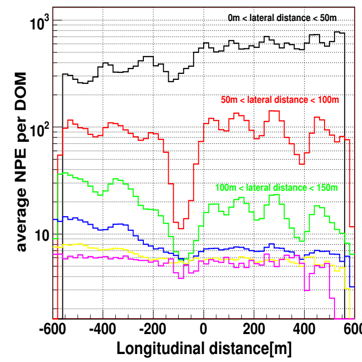


Fig. 7. Averaged longitudinal NPE distributions of the vertical VHEMu event sample. Each solid line denotes longitudinal NPE distributions at various lateral distances with an interval of 50 m. From the top line to the bottom, the intervals corresponding to each line are 0 m∼50 m, 50 m∼100 m, 100 m∼150 m, 150 m∼200 m, 200 m∼250 m and 250 m∼300 m respectively. A clear NPE developments in both longitudinal and lateral directions are visible.

difference between ionization and radiative energy losses is expected to appear in the event-by-event fluctuations of longitudinal/lateral NPE distributions. The sizes of fluctuations from stochastic energy losses are evaluated in [4] using the MMC program [10] and the fluctuations from ionization are expected to be $\propto \sqrt{N_\mu}$.

The deviations of NPE along track from an average NPE per DOM are contributed from variations of ice properties. Because the ice properties does not fluctuate an event-by-event basis, it is possible to distinguish the variation due to ice properties and the fluctuation due to stochastic energy losses. The variations in NPEs near the tracks where less affected from ice properties and also the event-by-event NPE fluctuation at given depth are expected to be sensitive parameters to the stochastic part of the muon bundle energy losses.

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