Muon bundle energy loss in deep underground detector

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***Abstract*. High energy air showers contain bundles of muons that can penetrate deep underground. Study of these high energy muons can reveal the cosmic ray primary composition and some features of the hadronic interactions. In an underground neutrino experiment like IceCube, high energy muons are also of interest because they are the dominant part of the neutrino background. We study muon bundle energy loss in deep ice by full Monte Carlo simulation to define its fluctuations and relation to the cosmic ray primary nuclei. An analytical formula of muon bundle mean energy loss is compared with the Monte Carlo result. We also use the simulation to set the background for muons with catastrophic energy loss much higher than those of normal muon bundles.**

***Keywords*: cosmic ray, muon bundle, energy loss.**

I. Introduction

When high energy cosmic ray particles interact in the atmosphere and develop extensive air showers (EAS), muons are produced through the decay of mesons, such as pions and kaons. IceCube is primarily a high energy neutrino telescope but it can also study high energy muon bundles which, together with the EAS size determined by the surface array IceTop [1], will contribute to studies of the cosmic ray composition and hadronic interactions.

A proton shower contains one muon above 500 GeV when the primary energy is about 100 TeV. Muons with that energy can reach the underground detector. At higher energies more high energy muons are produced in bundles. The muons above a several hundred GeV in the bundle are highly collimated and closer to each other in space [2], [3] than the distance between IceCube strings. This makes it very hard to count the number of individual muons in the bundle.

In this work we study the energy loss of muon bundles produced by proton and iron showers at different primary energies by carrying out a Monte Carlo simulation. An analytical formula of muon bundle mean energy loss is compared with the Monte Carlo result in Section II. We discuss the fluctuations in the energy loss and their association with cosmic ray primary particles in Section III. With the energy loss limits set by the simulation, we also discuss in Section IV the search for muons above 100 TeV.

We first calculated proton and iron showers with CORSIKA (version 6.735, with SIBYLL 2.1 as high energy hadronic interaction model). This version of CORSIKA does not include charm production. All the muons produced are from pion or kaon decay. Two hundred showers were generated for eight energy points from 1 PeV to 1 EeV for proton and iron primaries. The production was set for the South Pole location (2835 meters above sea level). The atmospheric parametrization for July 01, 1997 was chosen. All muons above 200 GeV in each shower were extracted from the shower ground particle file. Each of these muons was then propagated through the ice to the depth of 2450 meters using the Muon Monte Carlo (MMC) simulation package [4]. All processes in which a muon loses more than 10^{-3} of its energy are treated stochastically. Energy losses due to ionization, bremsstrahlung, photo-nuclear interaction, pair production and their continuous components were kept for each of the five-meter step size along the muon track.

II. High energy muons in air showers: Elbert formula and CORSIKA showers

The number of high energy muons in an EAS depends on the energy and mass of the primary cosmic ray particle. A well-known parametrization was given by Elbert [5] as follows:

$$\begin{aligned} &N_{\mu,B}(E_\mu > E_\mu(0)) \\ &= A\frac{0.0145TeV}{E_\mu(0)cos\theta}\left(\frac{E_0}{AE_\mu(0)}\right)^{p_1}\cdot\left(1-\frac{AE_\mu(0)}{E_0}\right)^{p_2} \\ &\simeq \frac{0.0145TeV}{cos\theta}\frac{E_0^{p_1}}{A^{p_1-1}}E_\mu(0)^{-p_1-1}\left(1-p_2\frac{A}{E_0}E_\mu(0)\right) \end{aligned} \quad (1)$$

in which A, E_0 and θ are the mass, total energy and zenith angle of the primary nucleus. $p_1 = 0.757$ and $p_2 = 5.25$. The approximation only keeps the first two terms in the Taylor's expansion on $(1-\frac{A}{E_0}E_\mu(0))^{p_2}$. It will be used later in this paper to derive the mean energy loss of muon bundles in matter.

Both Elbert parametrization and the approximation were compared with air shower Monte Carlo results for protons and irons from several hundred TeV up to 1 EeV. Two examples are shown in Fig. 1. Except in the threshold region (where the Elbert parametrization may not be valid) the agreement over the whole energy region is remarkable. This is shown by the two peaks at zero in the two plots at the bottom in Fig. 1. One can also see that CORSIKA with SIBYLL 2.1 has slightly higher yield at higher muon energies. The excess increases with the energy of the primary particle.

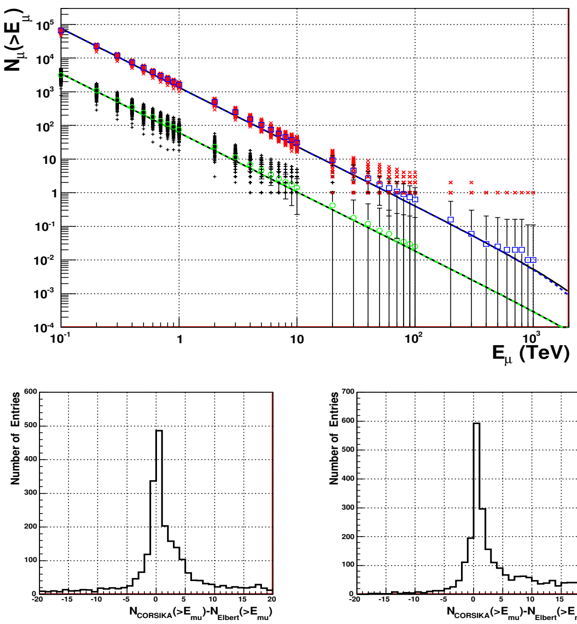

Fig. 1. Number of muons in the bundles as a function of the muon energy. Top entry: 50 PeV proton at 30 degree zenith (lower black +) and 1 EeV iron at zero degree zenith (higher red ×). The open squares and circles are the averages over all 200 showers at each energy points. The curves represent Elbert formula. Dashed lines are the approximation to the Elbert formula, which correspond to the last line in Eq. (1). Bottom entries: The difference between the number of muons (for $E_\mu \geq 100$ GeV and a increment step size of 100 GeV) in CORSIKA showers and that predicted by the Elbert formula. (left: 50 PeV proton, right: 1 EeV iron)

III. MUON BUNDLE ENERGY LOSS AND COMPOSITION SENSITIVITY

A. Muon bundle energy loss in ice

Since IceCube measures the energy loss instead of the number of muons in the bundle, we derive an analytical expression for the muon bundle mean energy loss to understand better the bundle energy loss. Starting from the approximation in Eq. (1) with muon energy loss

$$\frac{dE_\mu(X)}{dX} \approx -a - b \cdot E_\mu(X), \quad (2)$$

the energy loss of a muon bundle at the slant depth X is an integral over the energy loss of the muons in the bundle:

$$\frac{dE_{\mu,B}(X)}{dX} = \int_{E_\mu^{min}(X)}^{E_\mu^{max}(X)} \frac{dE_\mu(X)}{dX} \frac{dN_{\mu,B}(X)}{dE_\mu(X)} dE_\mu(X)$$
$$= -\int_{E_\mu^{min}(X)}^{E_\mu^{max}(X)} [a + b \cdot E_\mu(X)] \cdot \frac{dN_{\mu,B}(X)}{dE_\mu(X)} dE_\mu(X). \quad (3)$$

Here, $E_\mu^{min}(X)$ and $E_\mu^{max}(X)$ represent the possible minimum and maximum energy of muons in the bundle at slant depth X. They can be written as follow [6]:

$$\begin{aligned} E_\mu^{min}(X) &= max\{[(E_\mu(0) + \tfrac{a}{b})e^{-bX} - \tfrac{a}{b}]^{min}, 0\} \\ &= 0 \\ E_\mu^{max}(X) &= (E_\mu^{max}(0) + \tfrac{a}{b})e^{-bX} - \tfrac{a}{b} \\ &= (\tfrac{E_0}{A} + \tfrac{a}{b})e^{-bX} - \tfrac{a}{b}. \end{aligned} \quad (4)$$

The approximate mean energy loss of a muon bundle can be obtained by doing the integration [6]. The expression can be further simplified by assuming that the high energy corrections can be ignored:

$$\begin{aligned} \frac{dE_{\mu,B}(X)}{dX} &= \omega \cdot b \cdot (p_1+1)\tfrac{1}{V+1}[\tfrac{1}{p_1+1}(\tfrac{a}{b})^{-p_1} \\ &\cdot V^{-p_1-1} + \tfrac{1}{p_1}(\tfrac{a}{b})^{-p_1}V^{-p_1} - \tfrac{1}{p_1+1}(\tfrac{a}{b}) \\ &\cdot (\tfrac{E_0}{A})^{-p_1-1} - \tfrac{1}{p_1}(\tfrac{E_0}{A})^{-p_1}] \end{aligned} \quad (5)$$

in which $\omega = \frac{0.0145TeV}{cos\theta}\frac{E_0^{p_1}}{A^{p_1-1}}$ and $V = (e^{bX} - 1)$. For the ice at the South Pole, $a = 0.26\ GeV\ mwe^{-1}$ and $b = 3.60 \cdot 10^{-4}\ mwe^{-1}$ [4] in units of meter water equivalent mwe. X is the slant depth in mwe along the muon bundle track.

The comparison with the full Monte Carlo can be seen in Fig. 2. Despite the large fluctuations in the energy loss mainly due to bremsstrahlung the mean energy loss in the full Monte Carlo (the blue and green dots) can be well described by the analytic approximation of Eq. (5). It needs to be pointed out, however, that for low energy showers, or for the energy loss at larger slant depth, Eq. (5) can have larger offset from the mean Monte Carlo values. This is due to the fact that the Elbert formula (Eq. (1)) is not exact at high E_μ values or a and b can be different from the constant values being used here.

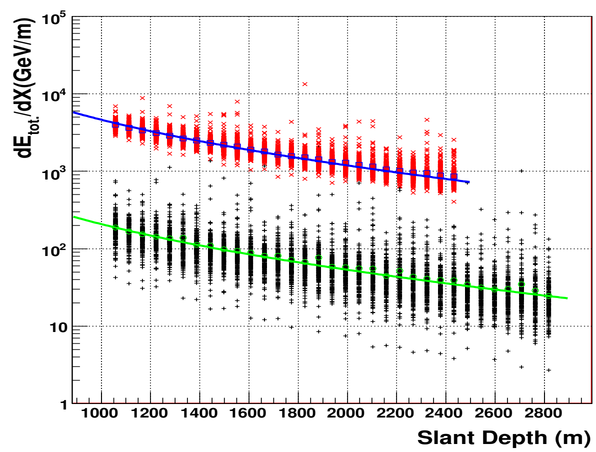

Fig. 2. Muon bundle energy loss as function as slant depth. Two examples are given in the figure: red × for vertical 1 EeV iron showers and the black + for 30 degree 50 PeV proton showers. Open squares and circles are the mean value of the Monte Carlo results for iron and proton showers. Eq. (5) is represented by the two curves.

B. Muon bundle energy loss and composition

To study the muon bundle energy loss and composition sensitivity, in the two component case of this work, we first define the composition resolving parameters $(A|Y)$ and $(B|Y)$ based on an observable Y as follows:

$$(A|Y) = \frac{\sum_{i=1} N_i^A/(N_i^A + N_i^B)}{\sum_{i=1} P_i^A} \quad (6)$$

$$(B|Y) = \frac{\sum_{i=1} N_i^B/(N_i^A + N_i^B)}{\sum_{i=1} P_i^B} \quad (7)$$

in which $P_i^A = 1.0$ (or $= 0.0$) when $N_i^A \neq 0.0$ (or $= 0.0$), and N_i^A and N_i^B represent the number of proton and iron events in the i^{th} bin on dN/dY distribution as shown in Fig. 3. $(A|Y)$ and $(B|Y)$ have values between 0 and 1. When the two distributions are well separated from each other, both $(A|Y)$ and $(B|Y)$ are equal to 1. When the two distributions are identical and fully overlapped, $(A|Y) = (B|Y) = 0.5$, which means the chance to assign a particle as proton or iron is 50%.

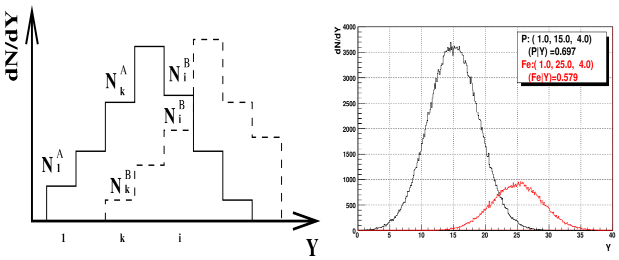

Fig. 3. Left: Definition of composition resolving parameters used in this work, $(A|Y)$ and $(B|Y)$: Two histograms represent the distribution of variable Y (e.g. muon bundle energy loss in deep ice detector) for two types of primary particles (say proton and iron). Right: Particles A and B are represented by two Gaussian shaped distributions with the amplitude, mean and σ in the parentheses. Particle A and B each has 320000 and 80000 samples in this test.

The value of the parameter also depends on the frequency of the detectable signals of different particles. This can be seen in Fig. 3 (right-hand panel), in which $(A|Y) = 0.697$ and $(B|Y) = 0.579$. This definition can be easily extended to cases in which each event has multiple observable variables.

IceCube is sensitive to the Cherenkov light emitted by high energy charged particles. Simulation shows the Cherenkov light yield of an in-ice event is nearly proportional to the particle total energy loss [7]. Since we are not doing the full experiment simulation, we use the total energy loss of muon bundles in small bins along the bundle track as a measure of the signal size. The distributions of muon bundle energy loss in five-meter steps at the slant depths between 1958 m and 2010 m in the ice are shown in Fig. 4. Proton energy loss distribution has a significant overlap with iron, much bigger than the overlap in the muon number distributions.

To improve the separation between the energy loss signals from different nuclei we excluded the large energy loss events caused mostly by bremsstrahlung. The effect from eliminating all energy loss events larger than 85% of the average (cut_1, red) and 500% (cut_2, blue) is shown in the bottom panel of Fig. 4.

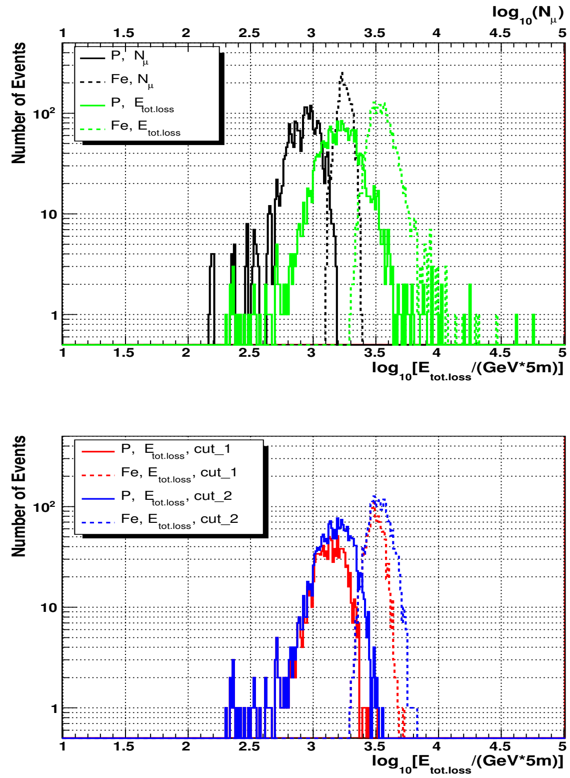

Fig. 4. Top: Histograms of the number of muons and the muon bundle total energy loss in five-meter steps at depths between 1958 m and 2010 m in ice. The example is for 600 PeV proton and iron showers at zenith angle of 30 degrees. Bottom: Histograms of the muon bundle total energy loss for the same Monte Carlo data sample after two cuts were applied. See more details in the text.

Fig. 5 summarizes how the composition resolving parameter varies at different slant depth after these two cuts in proton and iron showers. Several features can be seen in this figure, (1) the tighter cut (cut_1) gives a higher value of resolving parameter corresponding to less overlap between the two histograms shown at the bottom plot of Fig. 4, (2) when tighter cut is applied, the composition resolving power using the muon bundle energy loss can be close to that obtained by the number of muons in the bundle in the simulation, (3) using the same cut, the composition resolving power is slightly better at shallower depth. It would be very interesting to explore these features in real data analysis.

IV. SIGNATURE OF HIGH ENERGY PROMPT MUONS IN MUON BUNDLE EVENTS

Very high-energy muons in air showers are produced either in the decay of very short-lived particles, i.e. charm or from the first interaction whether the parent is conventional (pion or kaon) or charm. The crossing from conventional to prompt muon fluxes was estimated to happen between 40 TeV and 3 PeV [8]. Such muons may be used to study the composition of cosmic ray primaries, as well as heavy quark production in high energy p-N interactions. There are several ways to separate the prompt muons from the conventional ones in

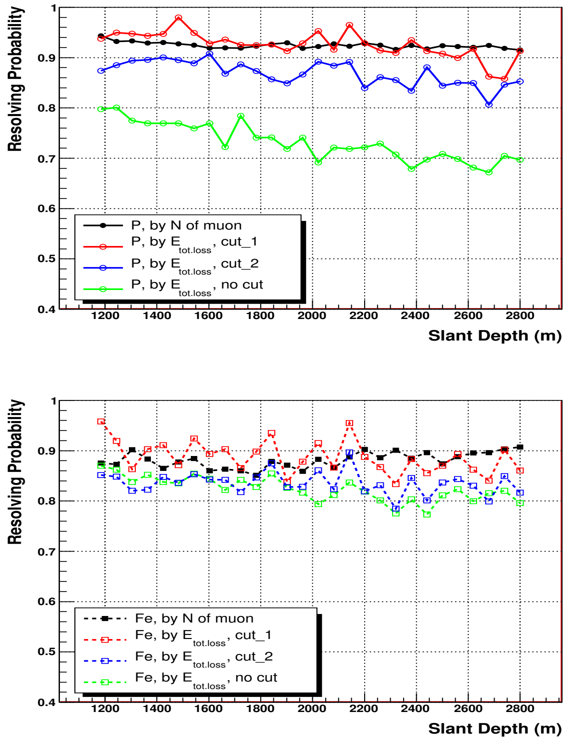

Fig. 5. The values of composition resolving parameters for proton and iron under different cuts at different slant depths. The calculation was done with 200 proton showers and 200 iron showers with 600 PeV primary energy at zenith angle of 30 degrees. The two cuts correspond to the cuts used in Fig. 4

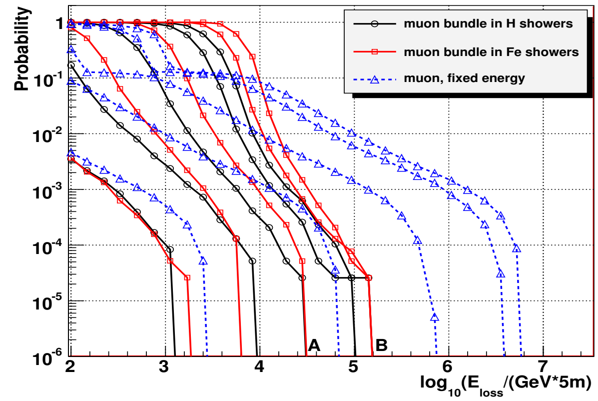

Fig. 6. The probability of the energy loss (in a five-meter step) of muon bundles in air showers (solid lines) and muons with fixed energy (dashed lines). Vertical proton and iron showers with primary energy of 500 TeV, 10 PeV, 100 PeV, 600 PeV and 1EeV are plotted together with vertical muons with fixed energy of 5 TeV, 100 TeV, 1 PeV, 6 PeV, and 10 PeV on the surface. The probability increases at larger energy loss as the energy of primary or single muon goes higher. The energy loss sample for the probability calculation is taken from the depth of 1450. m to the bottom of the in-ice array.

underground experiments, such as using the difference in their zenith angle distributions, the different depth dependence at a given depth and zenith angle [9]. Another technique that is explored here relies on recognizing catastrophic dE/dX signature from these leading muons as bursts of light on an otherwise smoother light deposition from a bundle of lower energy muons.

The probability of finding a certain amount of energy loss in five-meter steps from 1450 to 2450 meters under ice is shown in Fig. 6. The chance to have an energy loss of about 30 TeV (point A in Fig. 6) in a five-meter step is much higher for a muon with energy of 100 TeV than conventional muon bundles from showers below 100 PeV. If one sees a burst energy loss above 160 TeV, it is almost certain ($P > 1\times10^{-3}$ versus $P < 3\times10^{-5}$) that the event consists of a single muon with energy above 1 PeV rather than showers below 1 EeV (point B in Fig. 6).

Since the cosmic ray primary energy can be determined by the surface array in IceCube, this method can be explored further with IceTop and in-ice coincidence data.

V. Summary

In this work, we studied the muon bundle energy loss in ice and its association with cosmic ray primary composition. The analytic formula of the mean muon bundle energy loss given here has reasonably good agreement with the full Monte Carlo. It can be used in muon bundle event reconstruction in IceCube. The parameters (cosmic primary energy and mass) in the formula can be further explored in composition study using IceTop and in-ice coincidence data [10]. Using IceTop in-ice coincidence data, one can also look for signatures from very high energy muons from charm decay by recognizing large catastrophic dE/dX along the muon bundle track.

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