

Study of High p_T Muons in IceCube

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Abstract. Muons with a high transverse momentum (p_T) are produced in cosmic ray air showers via semileptonic decay of heavy quarks and the decay of high p_T kaons and pions. These high p_T muons have a large lateral separation from the shower core muon bundle. IceCube is well suited for the detection of high p_T muons. The surface shower array can determine the energy, core location and direction of the cosmic ray air shower while the in-ice array can reconstruct the energy and direction of the high p_T muon. This makes it possible to measure the decoherence function (lateral separation spectrum) at distances greater than 150 meters. The muon p_T can be determined from the muon energy (measured by dE/dx) and the lateral separation. The high p_T muon spectrum may also be calculated in a perturbative QCD framework; this spectrum is sensitive to the cosmic-ray composition.

Keywords: high transverse momentum muons, cosmic ray composition, IceCube

I. INTRODUCTION

The composition of cosmic rays with energies above 10^6 GeV is not well known. At these energies, the flux of cosmic rays is so low that direct detection with balloon or satellite-borne experiments is no longer feasible and indirect measurement with larger ground arrays must be used. These arrays measure the electronic and hadronic components of a cosmic ray air shower, and must rely on phenomenological interaction models to relate observables like muon and electron density to primary composition. These interaction models are based on measurements made at accelerators that reach a maximum energy roughly equivalent to a 10^6 GeV proton cosmic ray [1]. Extrapolation to the energy of the detected cosmic rays leads to uncertainties in the composition of cosmic rays at high energies. An alternate method of determining the composition is to use muons with a high transverse momentum (p_T) [2].

At transverse momenta on the order of a few GeV/c, the muon p_T spectrum can be calculated using perturbative QCD (pQCD). Such calculations have been made for RHIC and the Tevatron, and the data is in quite good agreement with modern fixed order plus next-to-leading log (FONLL) calculations [3]. These experimental studies give us some confidence in pQCD calculations for air showers.

Most of the high-energy muons that are visible in IceCube are produced from collisions where a high-energy (large Bjorken- x) parton interacts with a low Bjorken- x parton in a nitrogen target. These collisions will produce heavy (charmed and bottom) quarks and also jets from high p_T partons; the jets will fragment into pions and kaons. Pions and kaons produce “conventional” muons that have a soft spectrum roughly proportional to $E^{-3.7}$ [4] and typically have a low p_T . In contrast, charm and bottom quarks are produced early in the shower. The resulting muons (“prompt” muons) have a harder spectrum, a higher p_T , and are the dominant source of atmospheric muons above 10^5 GeV [5].

If these particles are produced in the forward direction (where they will be seen by ground based detectors), they can carry a significant fraction of the energy of the incident nucleon. The muon energy and p_T can be related to the energy of the partons that make up the incident cosmic ray. For example, a 10^{16} eV proton has a maximum parton energy of 10^{16} eV, while the maximum parton energy for a 10^{16} eV iron nucleus (with $A=56$) is 1.8×10^{14} eV. These two cases have very different kinematic limits for high p_T , high-energy muon production, so measurements of high p_T muon spectra are sensitive to the cosmic-ray composition.

High p_T muons constitute a small fraction of the muons visible in IceCube; the typical muon p_T is of order a few hundred MeV/c. In this domain of “soft physics,” the coupling constants are very large, and pQCD calculations are no longer reliable. One is forced to rely on phenomenological models; different hadronic interaction models give rather different results on composition [6].

IceCube, a kilometer-scale neutrino telescope, is well suited for the detection of muons with p_T s above a few GeV/c [2]. When completed in 2011, it will consist of a 1 km^3 array of optical sensors (digital optical modules, or DOMs) buried deep in the ice of the South Pole and a 1 km^2 surface air shower array called IceTop. IceTop has an energy threshold of 300 TeV and can reconstruct the direction of showers with energies above 1 PeV within 1.5° and locate the shower core with an accuracy of 9 m [7]. The in-ice DOMs (here referred to as IceCube) are buried in the ice 1450 m under IceTop in kilometer-long strings of 60 DOMs with an intra-DOM spacing of 17 m. IceCube can reconstruct high energy muon tracks with sub-degree accuracy. The IceTop measurements can be used to extrapolate the interaction height of the

shower and IceCube can measure the energy, position and direction of the muons. These values, can be used to calculate the p_T :

$$p_T = \frac{dE_\mu}{hc} \quad (1)$$

where E_μ is the energy of the high p_T muon, d is its lateral separation and h is the interaction height of the shower, here taken as an average value of 25 km. The interaction height loosely depends on the composition and a full treatment of this is planned in the future. Taking 150 m, 25 meters more than the separation between strings of DOMs in IceCube, as a rough threshold for the two-track resolution distance of the high p_T muon from the shower core gives a minimum resolvable p_T of 6 GeV/c for a 1 TeV muon.

Multiple scattering and magnetic fields can deflect the muons as they travel to the IceCube detector, but this is only equivalent to a few hundred MeV worth of p_T and is not a strong effect in this analysis. The high p_T muon events are near-vertical which gives them a short slant depth. In order for muons to reach the IceCube detector they must have an energy of at about 500 GeV at the surface of the Earth. These higher energy muons are deflected less by multiple scattering and the Earth's magnetic field.

The combined acceptance for cosmic ray air showers which pass through both IceTop and IceCube is 0.3 km²sr for the full 80-string IceCube array [8]. By the end of the austral summer of 2006/2007, 22 IceCube strings and 26 IceTop tanks had been deployed. The combined acceptance for showers that pass through both IceTop-26 and IceCube-22 is 0.09 km²sr. While this acceptance is too small to expect enough events to generate a p_T spectrum, it offers an excellent opportunity to test reconstruction and background rejection techniques.

II. PREVIOUS MEASUREMENT OF HIGH p_T MUONS

MACRO, an underground muon detector, has previously measured the separation between muons in air showers with energies ranging roughly from 10⁴ GeV to 10⁶ GeV [9]. MACRO measured muon separations out to a distance of about 65 meters. The average separation between muons was on the order of 10 m, with 90% of the muons found with a separation of less than 20 m [9]. MACRO simulated air showers and studied the muon pair separations as a function of the p_T of their parent mesons. They verified the linear relationship between p_T and separation shown in Eq. 1 (with a small offset due to multiple scattering of the muons) out to momenta up to 1.2 GeV/c.

III. HIGH p_T RATE ESTIMATIONS

The decay of charm will produce roughly 10⁶ prompt muons/year with energies in excess of 1 TeV inside the 0.3 km²sr combined acceptance of the full IceCube array [10]. Different calculations agree well in overall rate in IceCube, but, at high (1 PeV) energies, differences in

TABLE I: Estimated number of events from charm above different p_T thresholds in 1 year with the 80-string IceCube array

| p_T [GeV/c] | Separation [m] | Number |
|---------------|----------------|------------|
| ≥ 6 | 150 | ~ 500 |
| ≥ 8 | 200 | ~ 200 |
| ≥ 16 | 400 | ~ 5 |

parton distribution functions lead to rates that differ by a factor of 3 [11].

We can roughly estimate the fraction of muons that are produced at high p_T using PYTHIA pp simulations conducted for the ALICE muon spectrometer at a center of mass energy of 14 TeV, which indicate that roughly 0.6% of these events will have a p_T of at least 6 GeV/c [12]. These simulations are done at a higher center of mass energy than the bulk of the IceCube events, and also were for muons produced at mid-rapidity (and, therefore, higher projectile x values and lower target x values than in IceCube). However, they should be adequate for rough estimates. These estimated rates of high p_T muons are further reduced by approximately a factor of 10 by requiring that the high p_T muon be produced in coincidence with a shower that triggers IceTop, leaving a rough expectation of ~ 500 events per year with a p_T greater than 6 GeV/c in the 80-string configuration of IceCube. The estimated number of events above a given p_T from the decay of charm is given in Table I neglecting the uncertainties mentioned above. At higher p_T , bottom production may also contribute significantly to muon production.

The rate of 1 TeV muons from conventional flux is expected to be about 10⁹ events/year in the full IceCube configuration. The vast majority of these muons will have a low p_T . Based on the p_T spectrum measured from pions produced in 200 GeV center of mass energy pp collisions by the PHENIX collaboration, the number of events expected with $p_T > 6$ GeV/c is estimated to be 1 in 6×10^6 [13]. Requiring a $p_T > 6$ GeV/c and an IceTop trigger leaves roughly 20 events/year in the full IceCube configuration from the conventional flux of muons.

IV. RECONSTRUCTION METHODS

High p_T muons will appear as a separate track coincident in time and parallel with the track from the central core of low p_T muons. Generally the bundle of low p_T muons leaves more light in the detector than the high p_T muon.

Current reconstruction algorithms in IceCube are designed to reconstruct single tracks. In order to reconstruct these double-track events the activated DOMs are split into groups using a k-means clustering algorithm [14]. The first group is the muon bundle and the second group is the high p_T muon. Each group is then reconstructed with a maximum likelihood method that takes into account the scattering of light in ice. After this initial reconstruction, the groups are resplit

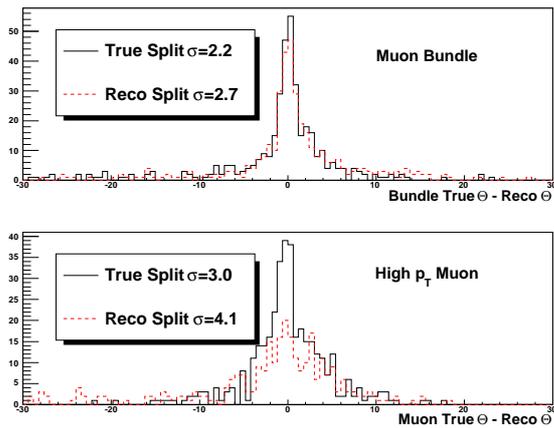


Fig. 1: Zenith angle resolution of the high p_T reconstruction algorithm. The sigma are the results of Gaussian fits to the distributions.

according to their time residual relative to the muon bundle reconstruction and re-fit. The first splitting forces the activated DOMs into two groups, which is not correct for the background events which don't have a high p_T muon and generate only a single shower in the array. Splitting the activated DOMs a second time according to their time residual allows for the possibility for all the activated DOMs to end up in a single group. Figure 1 shows the performance of this clustering algorithm. The zenith angle resolution for groups determined using the true simulation information (black, solid lines) is compared to the resolution for groups determined using the clustering algorithm (red, dashed lines) for the muon bundle (top) and high p_T muon (bottom). Roughly 20% of the events fail to reconstruct because there are not enough DOMs in one of the groups.

These reconstruction algorithms achieve a zenith angle resolution of 2.7° for the muon bundle and 4.1° for a high p_T muon separated by 400 m. The resolution is worse for the high p_T muon because fewer DOMs are activated. While high p_T muons with a greater separation are much easier to resolve with the two track algorithm, they also tend to be lower energy (see Eq. 1) and activate fewer DOMs. The average number of DOMs activated by the high p_T muon is 12, compared to 50 for the muon bundle. Additionally, because high p_T muons have less activated DOMs, a DOM activated by the muon bundle that is incorrectly placed in the high p_T group has a much larger effect on the reconstruction of the high p_T track. These factors lead to a poorer resolution in the high p_T track direction.

V. SIGNAL AND BACKGROUND SEPARATION

Many of the processes that can generate a high p_T muon are not properly modeled or included in CORSIKA [15] with the exception of the modified DPMJET model discussed in [16]. Also, since high p_T muons will occur in only a fraction of simulated showers making simulation very time intensive, a toy model

based on CORSIKA proton showers was used to model the signal. A single muon is inserted into an existing CORSIKA event containing a muon bundle from an air shower. This modified shower is then run through the standard IceCube propagation, detector simulation, and reconstruction routines. Simulations insert a muon with energy of 1 TeV separated 100, 150, 200, and 400 m from the shower core. This gave a clean sample ideal for the development of reconstruction routines optimized to identify simultaneous parallel tracks inside the detector.

Cosmic rays air showers that do not generate a high p_T muon are considered a background to this search. Since they generate only a single shower in the array, these events are mostly eliminated by requiring there be two well-reconstructed tracks in the IceCube detector. These single showers are well-reconstructed by a single track hypothesis, while the high p_T muon events are not. Figure 2 shows the negative log of the reduced likelihood of a single track reconstruction for single showers, and showers with an inserted 4, 8, and 16 GeV/c p_T , 1 TeV muon (separation of 100 m, 200 m, and 400 m from the shower core, assuming an average interaction height of 25 km). Well reconstructed events have a lower value on this plot. For large separations, this variable separates single showers from showers which contain a high p_T muon. When the separation between the high p_T muon and the shower core drops below the interstring distance (the blue, dot-dashed line in Figure 2), it is no longer possible to cleanly resolve the high p_T muon from the shower core and the event looks very similar to a single shower.

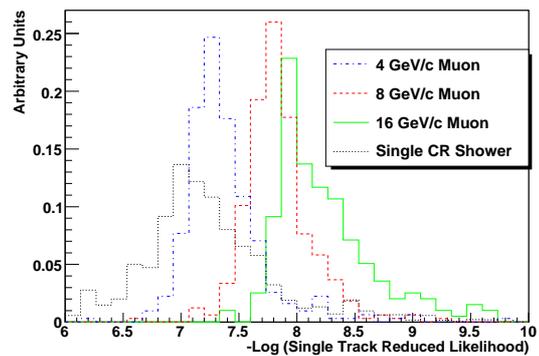


Fig. 2: Negative log of the reduced likelihood for the single track reconstruction

The IceCube 22-string configuration is large enough that the rate of simultaneous events from cosmic rays is significant. Muon bundles from two (or more) air showers can strike the array within the $10 \mu s$ event window, producing two separated tracks. These so-called double-coincident events are the dominant background for air showers with high p_T muons. Since these double-coincident events are uncorrelated in direction and time, requiring that both reconstructed tracks be parallel and occur within $1 \mu s$ can eliminate most of these events.

Due to misreconstructions some events will survive this selection, and criteria to eliminate these misreconstructed events are being developed. However, an irreducible background remains from double-coincident events that happen to come from roughly the same direction and time.

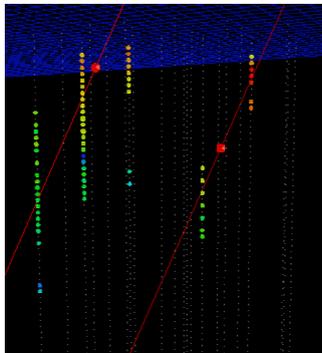


Fig. 3: Candidate shower with a high p_T muon. The colored circles show DOMs that are activated by light. The color and size of the circle corresponds to the time (red being earliest) and magnitude of the signal, respectively and the white dots indicate DOMs that are not activated in the event. The red lines show the reconstructed tracks.

After applying selection criteria to reduce the cosmic ray background, a 10% sample of the IceCube data was scanned by eye for high p_T muon candidates. Several events were found and Figure 3 shows a representative event. The two tracks occur within 600 ns of each other and the spaceangle between the two reconstructions is 5.6° .

VI. HORIZONTAL EVENTS

One possible method to avoid the backgrounds from single and double-coincident cosmic ray air showers is to search for events that come from the horizontal direction. At a zenith angle of 60° the slant depth through the ice is about 3 km. Only muons with energies in excess of several TeV will reach IceCube [17] and the event multiplicity is greatly reduced. Because the intra-DOM spacing is 17 m, compared to the intra-string spacing of 125 m relevant for vertical events, the two-track resolution should improve. A disadvantage to searching in the horizontal direction is the increase in the deflection from the magnetic field and multiple scattering with the slant depth, which could lead to a greater spread in the muon bundle and create event topologies which mimic a high p_T muon event. Nevertheless, the advantage of background suppression is strong. In addition to high p_T muons in cosmic rays, there are a number of other processes (such as the decay of the supersymmetric stau [18]) that can produce horizontal parallel tracks, making the horizon an interesting direction.

A search was conducted in 10% of the IceCube data from 2007 for these horizontal events using simple topological selection criteria. Events which reconstructed

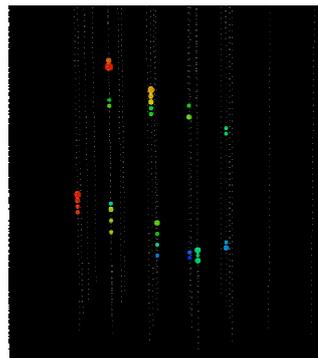


Fig. 4: Candidate double track near-horizontal event

within 30° of horizontal were selected and searched for a double track topology. Several interesting candidate events were found, one is shown in Figure 4. The two tracks occur within 1 ns of each other and the spaceangle between the two reconstructions is 33° .

VII. CONCLUSIONS

IceCube is large enough that the study of high p_T muons has become viable. Resolution of tracks separated by at least 150 meters from the shower core will allow identification of muons with p_T s of at least 6 GeV/c. A two-track reconstruction algorithm has been developed and selection criteria for identification of air showers with high p_T muons is under development. A search for horizontal double tracks is also under way. The rate of high p_T muon production is sensitive to the composition of the cosmic rays and offers an alternative to existing composition studies.

This work is made possible by support from the NSF and the DOE.

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