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Study of High p_T Muons in Air Showers with IceCube

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Abstract: With it's 1 km^2 area, IceCube and the associated IceTop surface detector array are large enough to study high p_T muon production in air showers. The muon p_T will be determined from the muon energy and it's distance from the core. A few thousand high p_T muons are expected to be observable each year in the full array. The flux of high p_T muons may be computed using perturbative QCD calculations; the cross-section is sensitive to the composition of the incident particles.

Introduction

The number of muons produced in cosmic-ray air showers is sensitive to the nuclear composition of the incident particles. Previous studies of the cosmic-ray composition have used relatively low ($\approx$ 1 GeV) or high ($\approx$ 1 TeV) energy muons. These studies relied on muon counting. Relating the muon count to the composition requires a model for the hadronic interactions; most of the muons come from π/K decay; the bulk of the mesons are produced at low transverse momentum (p_T) with respect to the direction of the incident particle. The production of these low p_T particles cannot be described in perturbative QCD (pQCD), so phenomenological models must be used.

In contrast, the production of particles with $p_T >\sim$ 2 GeV/c is calculable in pQCD. We label these tracks high p_T particles, and consider their production in cosmic-ray air showers. High p_T muons come from the decay of charm and bottom quarks, and from π/K produced in jets. Both of these processes can be described by pQCD, allowing for calculations of the energy and p_T spectra for different incident nuclei. The predictions depend sensitively on the composition of the incident nuclei - neglecting shadowing, a nucleus with energy E and atomic number A has the same parton distribution as A nucleons, each with energy E/A. Nuclei with $A=1$ and $A=10$ have very different parton energy spectra.

High p_T muons in Air Showers

Previous studies of high-energy muons associated with air showers have involved relatively small detectors. AMANDA has measured muon bundles near the shower core, but did not study the muon lateral distribution [1]. MACRO measured the muon decoherence function for separations up to 65 m [2]. The most likely pair separation was 4m; only 1% of the pairs have a separation greater than 20 m. MACRO simulated air showers and studied the pair separation as a function of the p_T of the mesons that produced the muons. The MACRO analysis established a clear linear relationship between muon separation and p_T; the mean p_T rose roughly linearly with separation, from 400 MeV/c at zero separation up to 1.2 GeV/c at 50 meter separation.

IceCube will observe both high-energy muons and the associated surface air showers that accompany them. For muons with energy E_μ above 1 TeV, the muon energy is proportional to the specific energy loss (dE/dx) that is measured by the deep detectors; the muon energy resolution is about 30% in $\log_{10}(E_\mu)$ [3, 4].

The muon energy and distance from the shower core can be used to find the p_T of a muon [6]:

$$d = \frac{hp_T}{E_\mu}. \quad (1)$$

Here, h is the height of the primary cosmic-ray interaction in the atmosphere. h follows an exponential distribution and depends somewhat on the cosmic-ray composition. A full analysis would include these effects. Here, we take $h = 30$ km.

Secondary interactions (of particles produced by the first interaction) are expected be only a small contribution to the high-energy flux, contributing at most 15% of the muons [7]. For muons far from the core, multiple scattering is expected to be a small contribution d.

Here, we consider showers where the core is inside the 1 km^2 area of IceTop, and muons following the core trajectory are inside the IceCube physical volume. This corresponds to about 0.3 km^2 sr total acceptance.

IceCube will detect air showers above an energy threshold of about 300 TeV; for vertical showers, the minimum muon energy is about 500 GeV. The rate for triggered IceTop-InIce coincidences for the 9-string IceCube array is about 0.2 Hz [8], or about 6 million events/year. The full 80-strings + stations should produce a rate more than an order of magnitude higher.

For vertical showers with energies above 1 PeV, the core location is found with a resolution of about 13 meters, and the shower direction is measured to about 2 degrees [9]. This allows the core position to be extrapolated to 1500 m in depth with an accuracy of about 55 meters, corresponding to a p_T uncertainty of 1.6 GeV/c for a 1 TeV muon.

Most of these air showers are accompanied by a muon bundle. A high p_T analysis will select events with a muon (or bundle) near the core, and another muon at a large distance from it. The near-core muon(s) can be used to refine the core position, avoiding the extrapolation error. The muon positions at a given depth can be determined within a 10-20 meters, allowing for better p_T resolution. Figure 1 shows an example of an IceCube 22-string event that contains an air shower that struck IceTop stations, plus muon bundle. Although the bulk of the bundle follows the shower direction, as projected from IceTop, there is a well-separated light source, consistent with a high p_T muon, about 400 meters from the bulk of the muon bundle. This secondary track hits 12 DOMs on a single string.

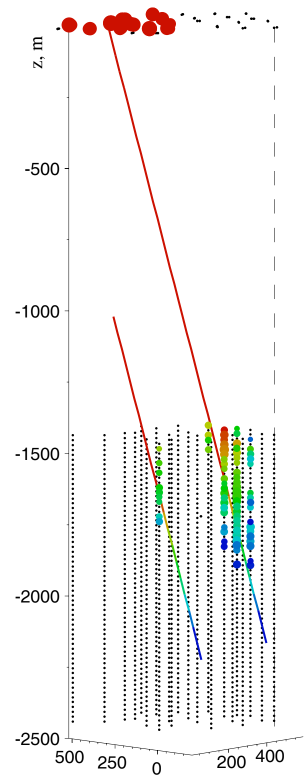

Figure 1: An IceTop air shower accompanied by a muon bundle including an apparent well-separated track. The air shower hits 11 surface stations (top of diagram). A total of 96 IceCube DOMs are hit; 84 DOMs on four strings near the extrapolated air shower direction, plus 12 DOMs on another string, about 400 m from the projection.

For this analysis, the key performance issue is two-track resolution. This remains to be determined. However, the 125 m string spacing and the comparable (depth-dependent) light absorption length set the scale for two-track resolution. Two muons 100 meters apart in IceCube will largely deposit light in different strings; for a DOM near one muon, the first light from the farther muon will arrive about 500 nsec after the first light from the nearby muon. If the second muon (or muon bundle) is bright enough to illuminate a DOM 100 meters away, this late light will be temporally separate from that from the nearby muon. A minimum ionizing muon is not bright enough to be visible 100 meters away, but muon bundles may be. Here, we estimate that IceCube can reconstruct muon pairs that are separated by 100 meters; smaller separations may be possible with optimized tracking.

For a muon with energy of 1 TeV, 100 meters separation corresponds to a p_T of 3 GeV/c. For a fixed separation, the minimum p_T rises linearly with muon energy, reaching $p_T > 150$ GeV/c for a 50 TeV muon. The highest energy muons are likely to come from high energy showers; the additional light will improve position reconstruction, and may allow for reconstruction at smaller separation distances. Still, there are unlikely to be useful events at higher energy/p_T.

Rates

High p_T muons come from two sources: prompt muons from charm/bottom decays, and non-prompt muons from decays of high p_T pions and kaons. The charm rates have been discussed previously [6, 5], about 600,000 muons per year with energy above 1 TeV are expected in the 0.3 km^2 acceptance. Only 1-2% of these muons will have $p_T > 3$ GeV/c. Still, this is a useful signal.

Bottom quark production in air showers has received much less attention. Although $b\overline{b}$ production in air showers is only about 3% of $c\overline{c}$ [10], the higher quark mass changes the kinematics, increasing the importance of $b\overline{b}$ production at high p_T. At LHC energies, about 10% of the muons from $b\overline{b}$ should satisfy the $p_T > 3$ GeV/c cut, and, at high enough p_T, they should be the dominant prompt contribution [11].

Although they are far more numerous than prompt muons, non-prompt muons have a much softer p_T spectrum. Non-prompt production may be estimated by using the measured p_T spectrum from π produced in high-energy collisions. The PHENIX collaboration has parameterized their π^0 spectrum at mid-rapidity with a power law: $dN/dp_T \approx 1/(1 + p_T/p_0)^n$, where $p_0 = 1.219$ GeV/c, and $n = 9.99$ [12]; about 1 in 200,000 π^0 has $p_T > 3$ GeV/c. This data is at mid-rapidity, while most muons seen in air showers come from far forward production. LHC will provide good data on forward particle production at the relevant energies. Here, we neglect this difference and ignore the minor differences between π^0 and $\pi^\pm \rightarrow \mu^\pm$ and $K^\pm \rightarrow \mu^\pm$ spectra. With the acceptance discussed above, IceCube expects to see more than 100 million muons/year associated with air showers, including at least 500 of them with $p_T > 3$ GeV/c.

Overall, based on the standard cosmic-ray models, we expect $\approx 1,000 - 3,000$ muons with $p_T > 3$ GeV/c year.

Muon spectral analysis & Composition Analysis

The 'cocktail' of charm, bottom and non-prompt muons is not so different from that studied at RHIC [13][14]; the prompt fraction is also not too different. There, the muon p_T spectrum is fitted to a mixture of prompt and non-prompt sources. In air showers, the accelerator beam is unknown; it constitutes the initial object of study.

The rate of high p_T muons is sensitive to the cosmic-ray composition. High p_T particles are produced in parton-parton collisions, and, as Fig. 2 shows, the parton densities of a 10^{17} eV proton and of a 10^{17} eV $A = 10$ nucleus are quite different. In contrast to the usual presentation, these are normalized to the parton energies, although the per-nucleon energies are different for the two cases. The nuclear distribution cuts off at an energy of $10^{17}/A$ eV, limiting the maximum parton-parton center of mass energy, and thereby constraining the possible muon kinematics. Because of this, the yield of high-energy, high p_T particles is much higher for protons than for heavier nuclei.

Most of the muons seen by IceCube are produced in the forward region, where a high$-x$ parton from the incident nucleus interacts with a low$-x$ parton from a nitrogen or oxygen atom in the atmosphere. The maximum muon energy is the incident parton energy $E_p = x_p E_c$ where x_p is the parton energy fraction and E_c is the cosmic-ray energy.

In the far-forward limit, the incident parton energy $x_{inc} = E_p/E_{incident} \approx E_\mu/E_{shower}$. So, these muons are quite dependent on the high$-x$ partons that are sensitive to nuclear composition.

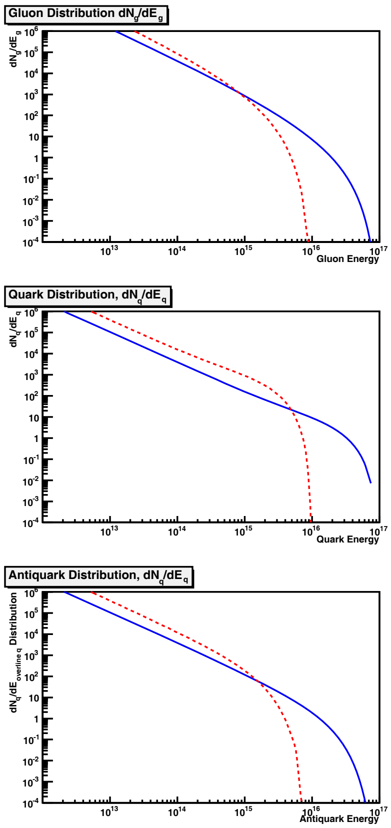

Figure 2: Quark (top), gluon (middle) and antiquark (bottom) densities $(dN_{parton}/dE_{parton})$ for a proton (solid line) and an $A = 10$ nucleus (dashed lines). The curves are based on the MRST99 parton distributions [15] evaluated at $Q^2 = 1000$ GeV^2. Nuclear shadowing is neglected.

Conclusions

IceCube is the first detector large enough to study high p_T muon production in cosmic-ray air showers. A 100 meter minimum muon-shower core separation would allow the study of muons with $p_T > 3$ GeV/c; a few thousand of these muons are expected each year.

By measuring the energy and core separation of muons associated with air showers, the muon p_T can be inferred. The cross-sections for high-p_T muon production can be related to perturbative QCD calculations of cosmic-ray interactions. The rate of high p_T muon production is very sensitive to the cosmic-ray composition; pQCD based composition measurements offer an alternative to existing cosmic-ray composition studies.

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