Study of High p_T Muons in IceCube

THE ICECUBE COLLABORATION[1]
[1] *See special section in these proceedings*

Abstract: Muons with a high transverse momentum (p_T) are produced in cosmic ray air showers mostly via semileptonic decay of heavy quarks and the decay of high p_T kaons and pions in jets. These high p_T muons have a large lateral separation from the shower core and accompanying muon bundle. IceCube, a kilometer-scale neutrino telescope consisting of an array of photodetectors buried in the ice of the South Pole and a surface air shower array, 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 do the same for the high p_T muon. This makes it possible to measure the cosmic ray muon lateral separation distribution at distances greater than 200 meters. The preliminary results from analysis of data from 25% of the full IceCube detector will be presented.

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1 Introduction

IceCube, a kilometer-scale neutrino telescope, is well suited for measuring the lateral separation of muons in cosmic ray air showers. Completed in December 2010, it consists 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 $\sim$1.5° and locate the shower core with an accuracy of $\sim$10 m [1]. The in-ice DOMs (here referred to as IceCube) are buried in the ice 1450 m under IceTop on kilometer-long strings of 60 DOMs with an intra-DOM spacing of 17 m. IceCube can reconstruct high quality tracks of high energy muons with $< 1^\circ$ accuracy. IceTop and IceCube can be used together to select cosmic ray events with a muon with a minimum lateral separation of $\sim$200 m. The measurement of the lateral separation distribution of muons in air showers provides a valuable check on air shower simulation models and can be used as an independent method for determining the cosmic ray composition [2].

The most common source of muons with a large lateral separation is muons with a high transverse momentum (p_T) primarialy from charm and bottom mesons and jets of high p_T partons [2]. The transverse separation is given by:

$$d_T = \frac{p_T h c}{E_\mu} \qquad (1)$$

where E_μ is the energy of the high p_T muon, 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. Using a separation of 200 m (75 meters more than the string separation) 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 8 GeV/c for a 1 TeV muon. Rough calculations predict on the order of tens of high p_T muon events in the studied data sample [2].

The combined acceptance for cosmic ray air showers that pass through both IceTop and IceCube is 0.3 km^{2}sr for the full 86-string IceCube array [3]. 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 trigger both IceTop-26 and IceCube-22 is 0.09 km^{2}sr. In 2007 the discriminator threshold settings for IceTop were changed partway through the year to sub-optimal values, so this analysis discards the data taken during this period leaving 114 days of livetime. A search has been conducted in this data for cosmic ray events with a muon with a large lateral separation.

The underground muon detector MACRO has previously measured the separation between muons in air showers for shower energies ranging roughly from 10^4 GeV to 10^6 GeV [4]. MACRO measured muon pair separations out to a distance of about 65 meters. They verified the linear relationship between p_T and separation shown in Eq. 1 (with a

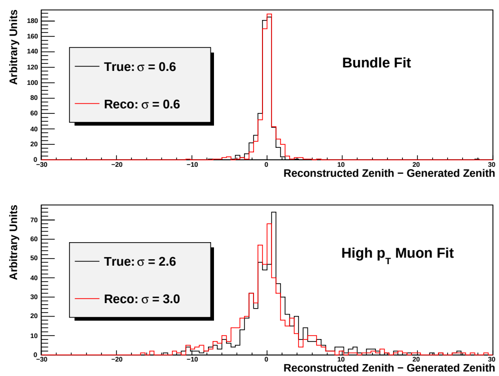

Figure 1: Zenith angle resolution of the high p_T reconstruction algorithm. The sigma are the results of Gaussian fits to the distributions.

small offset due to multiple scattering of the muons) out to momenta up to 1.2 GeV/c.

2 Reconstruction Methods

High p_T muons 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 high p_T double-track events the hit DOMs (i.e. DOMs that detect at least one photon) are attributed to either the muon bundle or high p_T muon based on their timing and position. The muon bundle is reconstructed first by the IceTop surface array. This reconstruction serves as a seed for a likelihood-based reconstruction using the IceCube DOMs. Only IceCube DOMs within 90 m of the seed track are used for bundle reconstruction. The high p_T muon hits are selected relative to the reconstructed bundle track. The high p_T muon arrives at the same time but laterally separated from the bundle, so its hits will have a negative time residual relative to the bundle reconstruction. Additionally, high p_T muon hits are required to be at least 90 m from the reconstructed muon bundle track. The high p_T muon hit track is reconstructed using a likelihood reconstruction with a downgoing hypothesis.

Figure 1 shows the performance of this procedure after reconstruction quality selection criteria have been applied. 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 splitting algorithm (red, dashed lines) for the muon bundle (top) and high p_T muon (bottom). Roughly 50% of the events fail to reconstruct because there are not enough DOMs in one of the groups.

These reconstruction algorithms achieve a zenith angle (space angle) resolution of 0.6° (1.3°) for the muon bundle and 2.6° (8.2°) for a high p_T muon separated by 200 m. The resolution is worse for the high p_T muon because fewer DOMs are hit. 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 hit fewer DOMs. The average number of DOMs hit by the high p_T muon is 15, compared to 90 for the muon bundle. Additionally, because high p_T muons have fewer hit DOMs, a DOM hit 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 (it can also degrade the bundle resolution, but to a lesser extent). These factors degrade the resolution of the high p_T track direction and timing. The spatial resolution of the high p_T muon track (as measured by the difference between the reconstructed track and the true track at the point of closest approach to the detector) is 40 m in x, y, and z.

3 Signal and Background Separation

Since high p_T muons occur in only a fraction of simulated showers, a toy model based on CORSIKA [5] 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.

Cosmic ray air showers that do not generate a high p_T muon (called 'single muon bundles') are a background to this search. Since they generate only one track in the array, these events are mostly eliminated by requiring there be two well-reconstructed tracks in the IceCube detector.

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 μs event window, producing two separated tracks. These so-called double-coincident events are another 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 (within 15° of each other) and occur within ±600 ns can eliminate most of these events. However, an irreducible background remains from double-coincident events that happen to come from roughly the same direction and time. The rate of double-coincident events can be estimated by looking at the off-time rate of events (i.e. events with tracks that occur more than 600 ns apart) in the data that pass all other selection criteria.

A number of selection criteria are applied to separate events with high p_T muons. The events are required to trigger at least 6 DOMs in IceTop and at least 8 DOMs in IceCube. The events are also required to have high quality two-track reconstructions. This includes requiring that the tracks have at least one hit DOM with a time residual of less than 15 ns (a 'direct hit') and that tracks pass within the detector fiducial volume. Further reduction of single muon bundles is done based on the differences in event topologies and timing. For instance, single muon bundles 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 muon bundles, and showers with an inserted 8 and 16 GeV/c p_T, 1 TeV muon (separation of 200 m and 400 m from the shower core, assuming an average interaction height of 25 km). Well-reconstructed events have a lower likelihood value on this plot. For large separations, this variable separates single muon bundles from showers which contain a high p_T muon. This analysis retains events with a likelihood greater than 7.5. Next we require that the high p_T muon track be a robust track in the detector with at least 6 direct hits. Finally, the remaining background single muon bundle events are removed by requiring the perpendicular separation between tracks to be at least 160 m. The number of events passing each type of selection criteria for data and simulated background and signal are shown in Table 1.

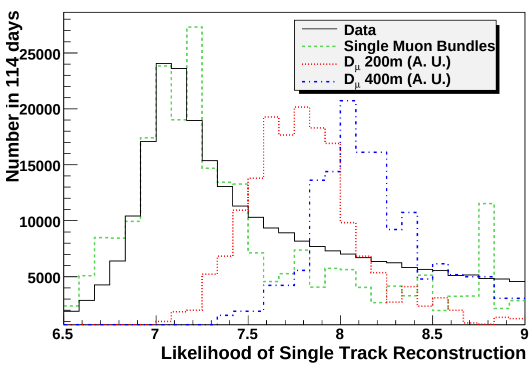

Figure 2: Negative log of the reduced likelihood for the single track reconstruction

4 Results

After applying all selection criteria 53 events remain in 114 days of data. No events remain in the simulated background. One event that passes all the selection criteria is shown in Fig. 3. The reconstructed high p_T muon and bundle track have a perpendicular separation of 207 m at the center of the detector. The two tracks arrive within 470 ns and 3.3° of each other.

4.1 Purity of Final Sample

Simulation of single muon bundle background events is too computationally intensive to accumulate large statistics. Although no simulated single muon bundle event passed all the selection criteria, the possibility exists that some single muon bundle background events could survive in the final data sample. In order to estimate the purity of

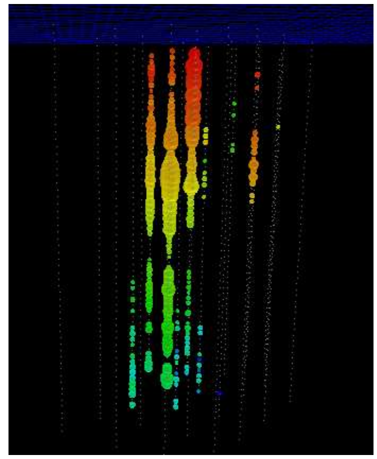

Figure 3: Candidate shower with a high p_T muon. The cosmic ray bundle is on the left and the high p_T muon is on the right.

the final sample a study has been conducted of simulated events which pass the reconstruction quality and double-coincident selection criteria (without applying the criteria designed to remove single track events). At this cut level, the only events left in the single muon bundle background are events which are incorrectly split into two tracks by the splitting algorithm. Two previously unused variables were developed that focused on studying how well the bundle fit described the high p_T muon hits and vice versa.

The first variable is the standard deviation of the time residual relative to the reconstructed bundle track (σ_{bundle}). Only hits belonging to the high p_T muon reconstructed track (time residual $<$ 100 ns and distance from the bundle $>$ 90 m) were used to calculate σ_{bundle}. In the single muon bundle background σ_{bundle} is small because the bundle reconstruction is equally good at describing both sets of hits. Conversely, events with high p_T muons have a laterally separated track that is causally disconnected from the bundle track. This leads to larger values of σ_{bundle}.

The second variable is the mean of the time residuals relative to the reconstructed high p_T muon track. Only hits within 90 m of the bundle track are used for this calculation. This variable uses the fact that the parallel but laterally separated high p_T muon track have a negative time residual relative to the bundle track. Single muon bundles incorrectly split into two groups tends to have time residuals that are closer to zero because both groups are causally consistent with the bundle hypothesis.

These two variables are shown in Fig. 4. The background single muon bundles and high p_T muon simulation are at a relaxed cut level with only reconstruction quality and double-coincidence selection criteria applied, while the data points are after all selection criteria have been applied. The dashed grey line is a fit to the mean of the background single muon bundle points. To estimate the purity of the data sample, this line has been moved upwards until every simulated single muon bundle event is below it. Thirty-one

Cut	Data	Simulation	Simulated Signal (%)
IceTop and IceCube Trigger	1.35 x 10^7	1.47 x 10^7	100%
Bundle and High p_T Reconstructions Successful	4.59 x 10^5	3.04 x 10^5	49%
Double-Coincidence Cuts	1.16 x 10^5	1.35 x 10^5	25%
Reconstruction Quality Cuts	2.57 x 10^4	1.64 x 10^4	13%
Single Track Cuts	53	0	8%

Table 1: Number of events in 114 days for data and simulated background. The percentage passing rates for simulated high p_T muons with a lateral separation of 200 m (8 GeV/c) are shown as well.

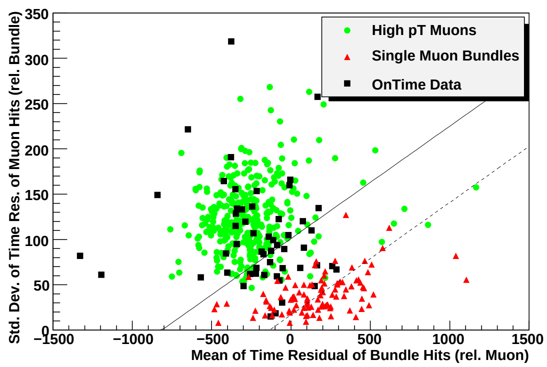

Figure 4: Standard deviation versus mean of time residuals. Note that the selection criteria have been relaxed for the simulated events.

of the fifty-three data events lie above the line, giving a preliminary estimation for the purity of the final event sample of at least 58%.

4.2 Estimation of Double-Coincident Rates

As mentioned in Section 3, an irreducible background remains from double-coincident cosmic rays. The number of these events in the on-time window (±600 ns) can be estimated by counting the number of events with tracks that occur with a time difference greater than 600 ns after applying all other selection criteria. In the final data sample, eight events were found in this off-time window. To be conservative, two events with a time difference greater than 20,000 ns are discarded. The remaining six events were spread over a time range of 2260 ns, giving an expectation that 3 of the 53 events in the ±600 ns on-time window are due to double-coincident cosmic rays.

4.3 Lateral Distribution of Muons

Figure 5 shows the preliminary perpendicular separation between the bundle and high p_T muon reconstructions at the center of the detector. The black solid lines are the 53 data events that passed all selection criteria. Preliminary estimations indicate that this sample is 58% pure. The dashed red lines are the data events that passed all selection criteria, but had time differences greater than ±600 ns. These events have been scaled down to the rate of 3 events in the on-time window.

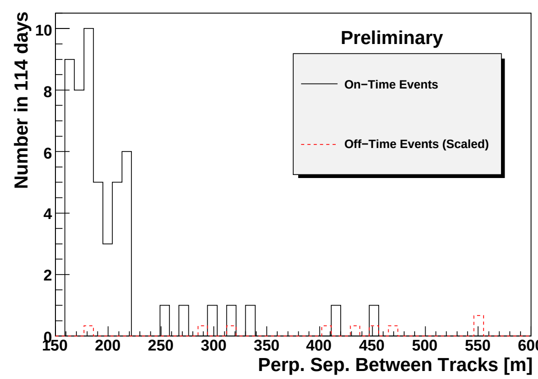

Figure 5: Preliminary perpendicular separation between bundle and high p_T muon reconstructions at the center of the detector.

5 Conclusions

A search for cosmic ray events with laterally separated muons has been conducted in 114 days with 25% of the full IceCube detector. The fraction of single muon bundle events remaining in the final sample has been conservatively estimated to be 42% and the number of background double-coincident events has been shown to be very small. Further searches with IceCube data with larger instrumented volume will have important implications for cosmic ray composition and air shower simulation.

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