Cosmic ray physics with TeV muons in large volume detectors

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2016 J. Phys.: Conf. Ser. 675 032032

(http://iopscience.iop.org/1742-6596/675/3/032032)

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 131.169.5.251
This content was downloaded on 21/02/2016 at 22:04

Please note that terms and conditions apply.
Cosmic ray physics with TeV muons in large volume detectors

Patrick Berghaus for the IceCube Collaboration

National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoye highway 31, Moscow, 115409, Russia
E-mail: berghaus@icecube.wisc.edu

Abstract. Large volume detectors such as IceCube, designed for the detection of astrophysical neutrinos register cosmic ray-induced atmospheric muon bundles at a rate of several thousand events per second. Due to the large amount of surrounding material, the effective energy threshold for muons reaching the detector typically lies at approximately one TeV. Through careful evaluation of event profiles it is possible to address cosmic ray and particle physics issues in an unprecedented energy region. Results from the analysis of one year of IceCube data are presented and their implications discussed.

1. Introduction

For underground detectors placed within mountains or below earth or sea level, the amount of material between the surface and the instrumented volume is of the order of several thousand tons per square meter. The only charged particles produced in cosmic ray air showers remaining at detector depth are muons, and even for these the energy threshold lies in the TeV region.

Large-volume underground detectors have for a long time been used for cosmic ray physics. The most common and simplest measurement is the zenith angle distribution of atmospheric muons. Although the exact functional form depends on the geometry of the surrounding material, the distance that particles have to traverse before reaching the detector usually increases towards the horizon as a function of the zenith angle $\theta_{zen}$. The muon energy spectrum can be derived by relating threshold energy to the varying distance between surface and detector. Measurements during the early 1990s, summarized in [1], often showed significant excesses over model predictions, a situation that was rectified in 1998 by the LVD collaboration [2], who demonstrated that the muon flux was in fact consistent with air shower simulations based on a primary nucleon flux following a simple power law of the form $E^{-2.78 \pm 0.05}$.

The IceCube array, designed primarily for the detection of astrophysical neutrinos, is the first particle detector with an instrumented volume of the order of a cubic kilometer [3]. The consequent increases in effective area and observable track length represent a significant qualitative advance for the study of cosmic ray physics. In recognition of this fact, the underground detector was complemented with the surface array IceTop, whose primary stated purpose is to measure the electromagnetic component of air showers in coincidence with high-energy muon bundles traversing the main detector volume [4].

1 http://icecube.wisc.edu
Upcoming projects such as the pair of deep-sea neutrino detectors collectively referred to as KM3Net [7] currently have no provision for a surface array, and cosmic ray studies will have to rely exclusively on the large underground volume. One analysis opportunity, pioneered by the IceCube collaboration, is the measurement of cosmic ray anisotropies using the enormous statistics provided by atmospheric muon events registered at a rate of approximately 3,000 s\(^{-1}\) [8]. Another, less directly connected to cosmic ray physics but with important implications for the study of nuclear interactions, is the measurement of showers containing individual muons with high transversal momentum [9].

That this is by far not the limit of possibilities can be seen from figure 1. The energy spectrum of cosmic ray primary particles responsible for air shower events in IceCube covers over six orders of magnitude, starting at about 10 TeV and reaching up to more than 10 EeV. Within this region lie several regions sparsely covered by existing detectors, and features of major interest, such as the knee and the ankle, which are not yet fully understood. The following is a brief description of techniques for the exploitation of atmospheric muon data in cosmic ray studies, taking advantage of sophisticated analysis methods developed for use in the latest generation of high-energy neutrino detectors.

2. IceCube Results

2.1. Event Types

Atmospheric muon events at high energies can be roughly divided into two basic types, illustrated in figure 2. In one case, the shower contains at least one unusually energetic muon, produced by a hadron decay at the early stage of shower development. In the other, a very energetic primary produces a bundle of very high multiplicity but with a rather modest median energy of a few hundred GeV at detector depth. As the integrated energy deposition in either case can be very similar, and the coarse instrumentation of the detector does not permit the resolution of individual muon tracks, any distinction between the two types must be based on the differential energy loss profile.

In practice, the simplest classification method relies on the identification of very strong individual energy losses, the majority of which are caused by bremsstrahlung [11]. While the selection efficiency for high-energy muon events is limited by the comparatively low probability of such an interaction taking place within the detector volume, the method is quite robust and has the added advantage that the reconstructed energy of the particle shower can be used as an estimator for the muon energy.

A clean sample of high-multiplicity bundles can be obtained by inverting the selection criteria, keeping only tracks without exceptional energy losses. This does not strictly exclude the presence
of high-energy muons, but assures that their contribution to the overall energy deposition is not unusually high. The two categories are illustrated in figure 3 in terms of the leading muon energy fraction. A full description of selection and analysis procedures can be found in [10].

2.2. Muon Bundles

The multiplicity of muon bundles $N_\mu$ can be approximated by the simple proportionality $N_\mu \propto E_{\text{prim}}^\alpha \cdot A^{1-\alpha}$, where $E_{\text{prim}}$ is the energy of the primary nucleus and $A$ its atomic mass. From an experimental perspective, the number of muons is proportional to the energy deposition in the detector, provided an event sample is selected that excludes exceptional catastrophic energy losses.

While energy and mass of incident cosmic rays cannot be measured simultaneously based solely on the muon bundle multiplicity in the deep detector, it is possible to derive a qualitative description of the behavior of the average mass in dependence of primary energy by adding external information from air shower arrays as illustrated in figure 4. The experimental measurement is in this case presented under two assumptions about the primary composition,

![Figure 2. Example for atmospheric muon events in IceCube experimental data. Top: Event display. The size of the spheres is proportional to the number of photo-electron registered by an optical module, their color indicates the arrival time of the first photon (red: early, blue: late). Bottom: Reconstructed differential energy deposition along track. The x-axis indicates the distance to the surface, measured along the track. The dip near x=2800 m is an artifact caused by the presence of a horizontal ice layer with very high dust concentration. Left: High energy muon, identified by the large stochastic loss near x=2400 m. Right: High-multiplicity bundle with smooth energy deposition.](image-url)
reflecting the extreme cases of pure proton and iron fluxes. The position of the all-particle measurement relative to the two hypotheses corresponds approximately, but not rigorously, to the average logarithmic mass of cosmic rays at a given energy.

In the interesting and poorly explored region beyond $10^{17}$ eV, the measurement indicates a uniformly heavy primary composition, consistent with data from KASCADE-Grande [12] and preliminary findings by IceCube using events registered in coincidence between surface and deep detector arrays [13].

2.3. High-Energy Muons

The analysis of high-energy muons provides an opportunity for the study of cosmic rays as well as particle physics, particularly the forward production of heavy quarks in nuclear collision. Recent theoretical calculations for the atmospheric lepton flux component from charm decays contain large uncertainties [17, 18] and in the case of muons the situation is further complicated by rare electromagnetic decays of light vector mesons [19], not present in neutrino fluxes.

The first limit for the contribution of prompt decays of short-lived hadrons to the atmospheric lepton flux was set by the LVD collaboration [20]. An analysis using data taken with the BUST detector at Baksan showed an indication for a strong excess at high energies whose underlying cause is not fully understood [21], and which has so far not been corroborated independently. A measurement of the prompt flux based on atmospheric neutrinos is difficult due the presence of a poorly constrained background from astrophysical sources [22].
The muon energy spectrum derived from IceCube data is shown in figure 5. Since the ratio between lepton and parent nucleon energy is generally about one order of magnitude, the measurement covers the region of the knee, where most current primary flux models predict a sharp cutoff in the all-nucleon spectrum. The fact that the measured spectrum is consistent with an unbroken power law can be interpreted as an indication for the presence of a flux component from prompt meson decays whose spectrum is not attenuated by re-interactions with atmospheric nuclei and therefore harder than that originating in decays of pions and kaons.

It would in principle be possible to separately constrain cosmic ray nucleon flux and magnitude of the prompt component by adding information about the angular distribution of high energy muon events. However, careful examination of experimental data reveals the presence of an unexplained systematic effect, most likely related to the exclusively downward orientation of optical modules in IceCube and the very short scattering length for photons in the refrozen ice of the drill holes [10].

3. Outlook
The current results demonstrate that atmospheric muon measurements in large volume detectors are a valuable tool for cosmic ray physics. Using the constantly accruing amount of experimental data in IceCube, it will soon be possible to repeat the muon bundle multiplicity measurement with statistics increased by one order of magnitude. Physics issues that can be addressed are the nature of the recently identified structure of the cosmic ray flux beyond the knee [14], the composition of cosmic rays around the ankle with potential implications for the interpretation of the cutoff at EHE energies [23], and investigation of the apparent excess in the number of muons for air showers at energies around 10^{19} eV as reported by the Pierre Auger collaboration [24].

Water-based detectors currently under construction do not have the disadvantages inherent to the IceCube array and its potential future extensions. Specifically, optical modules contain multiple photomultiplier tubes and are designed for uniform directional acceptance. The very long scattering length of photons in water as compared to the complex and varying optical properties of the Antarctic ice will reduce systematic uncertainties and make track reconstruction simpler and more reliable. An accurate simultaneous measurement of both atmospheric prompt leptons and cosmic ray nucleon flux around the knee should be within reach of one or both of the Mediterranean water detectors. Its validity can be further supported by demonstrating consistency with a simple angular distribution measurement, and by comparing results from the two individual arrays against each other.
References

[1] Sinegovsky S I et al. 2010 \textit{Int. J. Mod. Phys.} A 25 3733 (arXiv:0906.3791 [astro-ph.HE])
[2] Aglietta M et al. (LVD Collaboration) 1998 \textit{Phys. Rev.} D 58 092005 (arXiv:hep-ex/9806001)
[3] Karle A (IceCube Collaboration) arXiv:1401.4496 [astro-ph.HE]
[4] Abbasi R et al. (IceCube Collaboration) 2013 \textit{Nucl. Instrum. Meth.} A 700 188 (arXiv:1207.6326 [astro-ph.IM])
[5] URL: https://web.ikp.kit.edu/corsika/
[6] Gaisser T K, Staniey T and Tilav S 2013 \textit{Front. Phys. China} 8 748 (arXiv:1303.3565 [astro-ph.HE])
[7] Margiotta A (KM3NeT Collaboration) 2014 \textit{JINST} 9 C04020 (arXiv:1408.1132 [astro-ph.IM])
[8] Abbasi R et al. (IceCube Collaboration) 2012 \textit{Astrophys. J.} 746 33 (arXiv:1109.1017 [hep-ex])
[9] Abbasi R et al. (IceCube Collaboration) 2013 \textit{Phys. Rev. D} 87 012005 (arXiv:1208.2979 [astro-ph.HE])
[10] Aartsen M G et al. (IceCube Collaboration) arXiv:1506.07981 [astro-ph.HE]
[11] Koehne J H et al. 2013 \textit{Comput. Phys. Commun.} 184 2070
[12] Apel W D et al. 2013 \textit{Astropart. Phys.} 47 54 (arXiv:1306.6283 [astro-ph.HE])
[13] The IceCube Collaboration, T. Feusels, ICRC 2015, PoS 334
[14] Aartsen M G et al. (IceCube Collaboration) 2013 \textit{Phys. Rev. D} 88(4) 042004 (arXiv:1307.3795 [astro-ph.HE])
[15] Aab A et al. (Pierre Auger Collaboration) arXiv:1307.5059 [astro-ph.HE]
[16] Abu-Zayyad T et al. (Telescope Array and Pierre Auger Collaborations) arXiv:1310.0647 [astro-ph.HE]
[17] Garzelli M V, Moch S and Sigl G arXiv:1507.01570 [hep-ph]
[18] Bhattacharya A et al. 2015 \textit{JHEP} 1506 110 (arXiv:1502.01076 [hep-ph])
[19] Fedynitch A et al. arXiv:1503.00544 [hep-ph]
[20] Aglietta M et al. (LVD Collaboration) 1999 \textit{Phys. Rev. D} 60 112001 arXiv:hep-ex/9906021)
[21] Bogdanov A G et al. 2012 \textit{Astropart. Phys.} 36 224 (arXiv:0911.1692 [astro-ph.HE])
[22] Aartsen M G et al. (IceCube Collaboration) 2015 \textit{Astrophys. J.} 809(1) 98 arXiv:1507.03991 [astro-ph.HE]
[23] Watson A A, 2014 \textit{Rept. Prog. Phys.} 77 036901 (arXiv:1310.0325 [astro-ph.HE])
[24] Aab A et al. (Pierre Auger Collaboration) 2015 \textit{Phys. Rev. D} 91(3) 032003
2015 \textit{Phys. Rev. D} 91(5) 059901 (arXiv:1408.1421 [astro-ph.HE])