Seasonal Variations of High Energy Cosmic Ray Muons Observed by the IceCube Observatory as a Probe of Kaon/Pion Ratio

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Abstract: The high statistics of cosmic ray induced muon events detected by the IceCube Observatory makes it possible to study the correlation of muon intensity with the stratospheric temperature over Antarctica with high precision. Using 150 billion events collected by IceCube experiment over 4 years, the muon rate was found to be highly correlated with daily variations of the stratospheric temperature and exhibits a $\pm$ 8% annual modulation. The correlation between the muon rate and the upper atmospheric temperature is related to the relative contribution of π and K in the extensive air showers. Therefore it is possible to estimate the K/π ratio from the seasonal variation of the muon rate, which was found to be 0.09 $\pm$ 0.04 at cosmic ray median energy of about 20 TeV.

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1 Introduction

When cosmic ray particles enter the Earth's atmosphere, they generate a hadronic cascade in which mesons are produced, primarily pions and kaons. These mesons can either interact again or decay into muons. The relative probability of decay or interaction depends on the local density of the atmosphere, which in turn depends on the temperature [1]. The differential flux of muons with energies larger than 100 GeV can be described with good approximation as [2]

$$\begin{aligned}\phi_\mu(E_\mu,\theta) \quad &= \phi_N(E_\mu) \times \left\{ \frac{A_{\pi\mu}}{1 + B_{\pi\mu}\cos\theta^\star\, E_\mu/\epsilon_\pi} \right. \\ &\left. + \frac{A_{K\mu}}{1 + B_{K\mu}\cos\theta^\star\, E_\mu/\epsilon_K} \right\}, \qquad (1)\end{aligned}$$

where $\phi_N(E_\mu)$ is the primary spectrum of nucleons (N) evaluated at the energy of the muon. The first term in Eq. 1 corresponds to muon production from leptonic and semileptonic decays of pions, while the second term is related to kaons. The constants $A_{\pi\mu}$ and $A_{K\mu}$ include the branching ratio for meson decay into muons, the spectrum weighted moments of the cross section for a nucleon to produce secondary mesons, and those of the meson decay distribution. The denominators in Eq. 1 reflects the competition between decay and interaction of secondary mesons in the atmosphere. When $E_{\pi,K} < \epsilon_{\pi,K}/\cos\theta^\star$, the meson decay is the dominant process, and muons are produced with the same spectral index as the parent cosmic rays. At high energy meson interaction dominates and the corresponding muon spectrum becomes one power steeper than the primary spectrum. The characteristic critical energies $\epsilon_{\pi,K}$ at a given atmospheric depth are inversely proportional to the atmosphere's density at that point, and therefore are affected by temperature variations. In an isothermal approximation of the atmosphere, the density is described by an exponential with a scale height of $h_\circ \approx 6.19$ km (over Antarctica). The numerical value applies to the lower stratosphere, where most of the muons are generated. In this approximation $\epsilon_{\pi,K}$ are proportional to the atmosphere's temperature in the perfect gas state limit. At a mean atmospheric temperature of $T_\circ = 211°$K the critical energies are $\epsilon_\pi = 111$ GeV and $\epsilon_K = 823$ GeV. The dependence of the critical energies on temperature is the main source of the seasonal variation in muon rate. This modulation was studied by underground experiments such as MACRO [3], LVD [4] and MINOS [5], and by AMANDA [6] and IceCube [7]. Here we update the analysis with four years of IceCube data with an emphasis on the systematic effects that can be studied with a very large amount of data.

2 Temperature Correlation

The relation between the variation of temperature and the variation of muon intensity at a particular energy and zenith angle can be expressed in terms of a theoretical correlation coefficient calculated from Eq. 1 as

$$\alpha_\mu(E_\mu,\theta) = \frac{T}{\phi_\mu(E_\mu,\theta)}\frac{\partial\phi_\mu(E_\mu,\theta)}{\partial T}, \qquad (2)$$

which depends explicitly on the characteristic critical energies $\epsilon_{\pi,K}$.

Measured rates depend on the convolution of the muon differential spectrum with the detector response, which depends on muon energy and zenith angle. To compare with measurements, it is therefore necessary to calculate a weighted correlation coefficient as

$$\alpha_T^{th}(\theta) = \frac{T\cdot\frac{\partial}{\partial T}\int dE_\mu\,\phi_\mu(E_\mu,\theta)\,A_{eff}(E_\mu,\theta)}{\int dE_\mu\,\phi_\mu(E_\mu,\theta)\,A_{eff}(E_\mu,\theta)}, \qquad (3)$$

where $A_{eff}(E_\mu,\theta)$ is the effective detector area obtained from simulation. Eq. 3 defines the correlation coefficient for a particular zenith angle θ. The total correlation coefficient is then obtained by averaging $\alpha_T^{th}(\theta)$ over θ with a weight given by the observed event angular distribution. With this definition the variation in muon intensity I_μ is given by

$$\frac{\Delta I_\mu}{I_\mu} = \alpha_T^{th}\,\frac{\Delta T_{eff}}{T_{eff}}, \qquad (4)$$

where T_{eff} is the effective atmospheric temperature as defined below. Since the rate R_μ of observed muons is proportional to the incident muon intensity I_μ, it is correlated with the effective temperature as well

$$\frac{\Delta R_\mu}{\langle R_\mu\rangle} = \alpha_T^{exp}\,\frac{\Delta T_{eff}}{\langle T_{eff}\rangle}, \qquad (5)$$

where α_T^{exp} is the experimentally determined correlation coefficient.

Since muon production occurs over an extended portion of the upper atmosphere and the temperature depends on altitude, it is necessary to define a parameter referred to as effective temperature, in order to quantify the relationship between variations in temperature and those in measured muon rate.

The pion and kaon terms in Eq. 1 are derived from the integral over the atmospheric slant depth X (in g/cm^2) of the muon production spectrum $P_\mu(E_\mu,\theta,X)$, which in turn is given by the probability distribution for meson decay to muons integrated over the parent meson spectrum [2].

The effective temperature as a function of muon energy and zenith angle is defined as the actual temperature profile weighted by the muon production spectrum

$$T_{eff}(E_\mu,\theta) = \frac{\int dX\,P_\mu(E_\mu,\theta,X)T(X)}{\int dX\,P_\mu(E_\mu,\theta,X)}, \qquad (6)$$

where $P_\mu(E_\mu,\theta,X)$ is the sum of muon production spectrum from pion and kaon contributions. The rationale for this definition is that the depth dependence of the muon production spectrum weights the temperature with the regions of the atmosphere where the meson decay to muons occurs. The critical energies that appear in the production spectrum are evaluated at the mean temperature, $T_\circ$, but the production profile does not depend strongly on temperature.

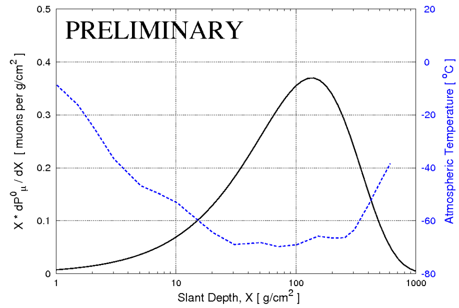

Figure 1: The differential weighting function used in the calculation of the T_{eff}, as a function of atmospheric depth X (continuous line), superimposed on the average atmospheric temperature profile (dashed line).

This formulation of the effective temperature differs from that in Grashorn et al. [8], where the low energy limit of the temperature derivative of muon production spectrum produces an unphysical discontinuity. The IceCube observatory is located at a depth of $>$1.3 km.w.e./cosθ so only muons with energies above about 400 GeV/cosθ can reach and trigger the detector. At these energies muon decay and energy loss in the atmosphere are negligible. This enables us to use analytic forms for muon production analogous to Eq. 1 without accounting for decay and energy loss and hence to obtain a physically correct result without any discontinuity.

To compare predictions with measurements it is necessary to determine the convolution with the detector response function

$$T_{eff}(\theta) = \frac{\int E_\mu\,\int dX\,P_\mu(E_\mu,\theta,X)\,A_{eff}(E_\mu,\theta)\,T(X)}{\int E_\mu\,\int dX\,P_\mu(E_\mu,\theta,X)\,A_{eff}(E_\mu,\theta)}, \qquad (7)$$

where the denominator, as in Eq. 3, is the total measured muon intensity. As for the correlation coefficient, the total effective temperature T_{eff} is the weighted average of Eq. 7 over the event zenith distribution. Fig. 1 shows the differential weighting function used in the calculation of the effective temperature along with the average atmospheric temperature profile over the seasons. It peaks at about 100 g/cm^2, which is where most of the muons are produced.

3 Muon and Temperature Data

In this analysis we used 150 billion muon events collected by the partially completed IceCube Observatory from March 2007 to April 2011 (see [9] for an overview on IceCube). These events are generated by cosmic rays with median energy of about 20 TeV.

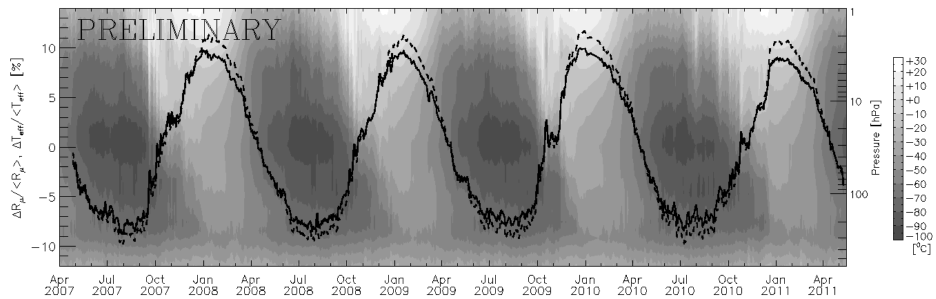

Figure 2: The daily atmospheric temperature profiles over Antarctica produced by NASA AIRS instrument on board the Aqua satellite [10] are shown from 2007 to 2011 (in grey shade code), along with the relative modulation in the measured muon event rate (continuous line) and the relative variation of the effective temperature (dashed line). Note that the statistical uncertainties in the data are between 0.02 Hz (in 2007) and 0.008 Hz (in 2011).

The muon rate increased substantially over these four years as new detectors were added during each construction season. As the instrumented volume increased, the probability that one data record included two or more separate cosmic-ray events increased from about 1% to about 4%. A correction to the daily recorded rate was therefore applied to obtain to correct rate of muon events, R_μ.

The atmospheric temperature profile data used in this analysis were collected by the NASA Atmospheric Infrared Sounder (AIRS) on board the Aqua satellite. Daily atmospheric temperatures at 20 different pressure levels from 1 to 600hPa above the South Pole were obtained from the AIRS Level 3 Daily Gridded Product available on NASA Goddard Earth Sciences, Data and Information Services Center (GES DISC) [10]. Using these data the daily effective temperature T_{eff} was calculated based on the zenith-weighted average of Eq. 7.

4 Results and Determination of K/π Ratio

Fig. 2 shows the measured $\frac{\Delta R_\mu}{\langle R_\mu \rangle}$ as a black continuous line along with $\frac{\Delta T_{eff}}{\langle T_{eff} \rangle}$ as a black dashed line. The figure also shows the actual atmospheric temperature profile as a function of pressure level (equivalent to atmospheric depth X). The statistical uncertainties in the measured muon rate are too small to show in the figure. Note that besides the large seasonal modulation, the daily muon rate is strongly correlated with short time temperature variations in the upper atmosphere.

Based on Eq. 5, the experimental temperature coefficient was determined from regression analysis and found to be $\alpha_T^{exp} = 0.860 \pm 0.002$ (stat.) $\pm$ 0.010 (syst.). The experimental systematic uncertainty on α_T^{exp} is dominated by the effective area $A_{eff}(E_\mu, \theta)$, which is used in the calculation of the effective temperature and of the theoretical correlation coefficient in Eq. 3. Most of the detected muons range out within the large instrumented volume of IceCube, and the energy profile of the effective area depends on the distribution of depths the muons reach within the array. The spread on this distribution, translates into an estimated uncertainty in the experimental correlation coefficient of 0.01.

Since the temperature correlation coefficient depends on the relative contribution of pions and kaons, it is possible to use the seasonal variations of the muon rate to determine the K/π ratio.

The effective temperature T_{eff} is relatively insensitive to variations in the cosmic ray spectral index, the proton attenuation length, the critical energies and K/π ratio because the dependence cancels to a large extent due to the normalization in Eq. 7.

The theoretical correlation coefficient α_T^{th}, on the other hand, depends primarily on the critical energies and on the K/π ratio. Changing the cosmic ray spectral index and proton attenuation length within a wide range, has an effect smaller than 1%. Therefore it is possible to use the parameters for attenuation lengths and spectrum weighted moments from Ref. [2], assuming a cosmic ray spectral index of -2.7. The critical energies evaluated at the average effective temperature of $T_\circ = 211°$K are used.

In particular, the kaon to pion ratio $R_{K/\pi} = \frac{Z_{NK}}{Z_{N\pi}}$ depends on the spectrum weighted moments Z_{NK} and $Z_{N\pi}$ of the cross section for a nucleon N to produce secondary kaons and pions, respectively, from a target nucleus in the atmosphere. The dependence on the spectrum weighted moments Z_{NK} and $Z_{N\pi}$ is implicit in the parameters $A_{\pi\mu}$ and $A_{K\mu}$ in Eqs. 1, 3, 7.

The nominal value of K/π ratio is taken to be [2]

$$R_{K/\pi} = \frac{0.0118}{0.079} = 0.149 \pm 0.060, \tag{8}$$

which is based on laboratory measurements below 100 GeV center of mass energy. The 40% uncertainty corresponds to that in the current cosmic ray interaction models [11].

By calculating the theoretical correlation coefficient α_T^{th} as a function of $R_{K/\pi}$ and comparing it with the experimental value, it is possible to measure the kaon to pion ratio for proton interaction with atmospheric nuclei (mainly nitrogen) at cosmic ray particle energy of 20 TeV.

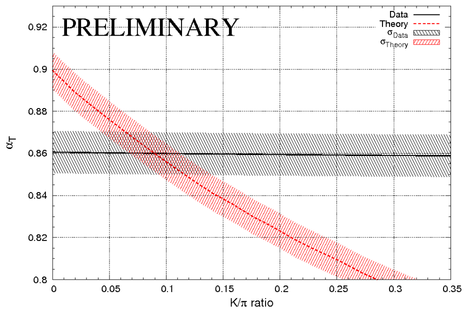

Figure 3: The preliminary α_T^{exp} determined by IceCube as a function of the K/π ratio (continuous line), with its error given by the band, and the predicted α_T^{th} (dashed line) with the corresponding error given by the band. The intersection region between the two bands is at $R_{K/\pi} = 0.09 \pm 0.04$.

Fig. 3 shows the experimental and theoretical values of α_T as a function of K/π ratio for the IceCube data. While, as mentioned above, α_T^{exp} is almost insensitive to $R_{K/\pi}$, the value of α_T^{th} has a strong dependence. Since the statistical uncertainties are very small, the band on α_T^{exp} is dominated by systematic uncertainties. The band on α_T^{th} reflects the theoretical uncertainties in the calculation of the correlation coefficient mentioned above, and conservatively estimated to be 1%. The crossover in Fig. 3 is at $R_{K/\pi} = 0.09 \pm 0.04$. Fig. 4 shows a comparison of the IceCube measurement with other observations.

5 Conclusions

Using 150 billion cosmic ray induced muon events collected in four years by IceCube, a strong correlation of the daily observed muon rate with the stratospheric temperature was observed, along with a $\pm 8\%$ annual modulation. The K/π ratio at 20 TeV cosmic ray energies was determined by comparing the observed temperature correlation coefficient with the theoretical one, and found to be $R_{K/\pi} = 0.09 \pm 0.04$.

The value obtained with IceCube implies that $Z_{NK} \sim 0.0071$, which is about 40% lower than its nominal value from Ref. [2]. In calculating the theoretical correlation coefficient the sum $Z_{NK} + Z_{N\pi}$ was kept constant to its nominal value 0.0908. One way to reconcile the measurement of $R_{K/\pi}$ with other results is by reducing the amount of associated production $pN \to nK^+$. Keeping the nominal value of $Z_{NK^-} = 0.0028$, while reducing Z_{pK^+} from its nominal value of 0.0090 to 0.0043 is also likely to give a better agreement with recent measurements of the ratio of the atmospheric muon charge ratio from MINOS [16] and OPERA [17].

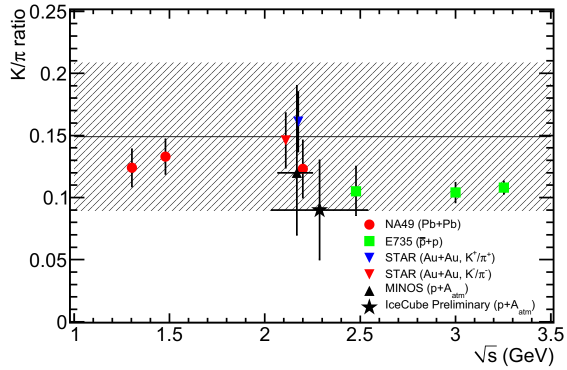

Figure 4: A compilation of selected measurements of K/π for various center of mass energies. Data points are from NA49 [12, 13], E735 [14], STAR [15] and MINOS [5]. The horizontal line and gray band represents the reference value K/π ratio 0.149 ± 0.060 [2, 11].

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References

[1] P.H. Barret, *et al.*, Rev. Mod. Phys., 1952, **24**(3), 133.
[2] T.K. Gaisser, 1990, Cosmic Rays and Particle Physics, ed. CUP
[3] M. Ambrosio, *et al.*, Astrop. Phys., 1997, **7**, 109.
[4] M. Selvi, Proc. of 31st ICRC, 2009, Łòdž, Poland.
[5] P. Adamson, *et al.*, Phys.Rev., 2010, **D81**,01200.
[6] A. Bouchta, Proc. of 26th ICRC, 1999, Salt Lake City, UT, U.S.A.
[7] S. Tilav, *et al.*, Proc. of 31st ICRC, 2009, Łòdž, Poland, arXiv:1001.0776.
[8] E.W. Grashorn, *et al.*, Astrop. Phys., 2010, **33**, 140.
[9] H. Kolanoski, IceCube summary talk, these proceedings.
[10] http://disc.sci.gsfc.nasa.gov/AIRS/data-holdings.
[11] G.D. Barr, *et al.*, Phys. Rev., 2006, **D74**, 094009.
[12] S.V. Afanasiev, *et al.*, Phys. Rev., 2004, **C66**, 054902.
[13] C. Alt, *et al.*, Eur. Phys. J. C, 2006, **45**, 343.
[14] T. Alexopoulos, *et al.*, Phys. Rev., 1993, **D48**, 984.
[15] C. Adler, *et al.*, Phys .Lett., 2004, **B595**, 143.
[16] P. Adamson, *et al.*, Phys. Rev., 2007, **D76**, 052003.
[17] N. Agafonova, *et al.*, 2010, arXiv:1003.1907.