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

The IceCube Collaboration - http://icecube.wisc.edu

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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 ± 8% annual modulation. The correlation between the muon rate and the upper atmospheric temperature is related to the relative contribution of π and K to secondary cosmic rays. 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 ± 0.04 at cosmic ray median energy of about 20 TeV.

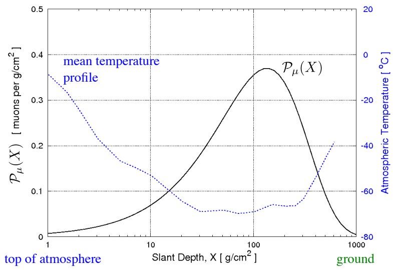
Muon Intensity

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]. If $\phi_N(E_\mu)$ is the primary spectrum of nucleons (N) evaluated at the energy of the muon, the differential flux of muons with energies larger than 100 GeV can be described with good approximation as [2]

$$\phi_\mu(E_\mu,\theta) = \int_0^\infty \mathcal{P}_\mu(E_\mu,\theta,X)\,dX$$

muon production spectrum $\mathcal{P}_\mu(E_\mu,\theta,X)$ gives the muon energy spectrum as a function of atmospheric depth X(g/cm²). It is the probability distribution for meson decay to muons integrated over the parent meson spectrum [2]

$$\phi_\mu(E_\mu,\theta) = \phi_N(E_\mu) \times \left(\frac{1}{1 + B_{\pi\mu}\, cos\theta^\star\, E_\mu/\epsilon_\pi} + \frac{A_{K\mu}/A_{\pi\mu}}{1 + B_{K\mu}\, cos\theta^\star\, E_\mu/\epsilon_K} \right) \quad \gamma \approx 1.7$$



$$A_{K\,\mu}/A_{\pi\,\mu} = \left(\frac{BR_{K\,\mu}}{BR_{\pi\,\mu}}\right)\left(\frac{Z_{K\,\mu}}{Z_{\pi,\mu}}\right)\left(\frac{Z_{N\,K}}{Z_{N\,\pi}}\right)$$

kaon/pion ratio $R(K/\pi) = \frac{Z_{N\,K}}{Z_{N\,\pi}}$

$$\epsilon_{\pi,K} = \frac{kT}{Mg}\,\frac{m_{\pi,K}\,c^2}{c\,\tau_{\pi,K}}$$

$$Z_{N\,\pi,K} = \frac{1}{\sigma_{N-air}}\int_0^1 x^\gamma\,\frac{d\sigma_{N\,\pi,K}(x)}{dx}$$

spectrum weighted moment of the cross section for a nucleon N to produce a secondary π or K from a target nucleus in the atmosphere

$BR_{\pi,K\,\mu}$ branching ratio for π, K → μ + X decay

$Z_{\pi,K\,\mu}$

spectrum weighted moment of the decay distribution for π, K → μ + X decay

critical energy regulates competition between meson interaction and decay

$\epsilon_{\pi,K}$ depends on atmospheric density, i.e. on its temperature at a given depth X(g/cm²)

$\epsilon_\pi = 111\,GeV \qquad \epsilon_K = 823\,GeV$ critical energies at mean temperature $T_0 = 211\,K$

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

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

$$\alpha_T^{th} = \frac{\int d\Omega\,\alpha_\mu(\theta)\,\frac{dN_\mu}{d\Omega}}{\int d\Omega\,\frac{dN_\mu}{d\Omega}}$$

temperature coefficient [1,3,4,5,6,7,8]

$$\frac{\Delta I_\mu}{I_\mu} = \alpha_T^{th}\,\frac{\Delta T_{eff}}{T_{eff}}$$

relative variations in muon intensity proportional to relative changes in effective temperature

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

experimental determination of temperature correlation

$$T_{eff}(\theta) = \frac{\int dE_\mu\int dX\,T(X)\,\mathcal{P}_\mu(E_\mu,\theta,X)\,A_{eff}(E_\mu,\theta)}{\int dE_\mu\int dX\,\mathcal{P}_\mu(E_\mu,\theta,X)\,A_{eff}(E_\mu,\theta)}$$

$$T_{eff} = \frac{\int d\Omega\,T_{eff}(\theta)\,\frac{dN_\mu}{d\Omega}}{\int d\Omega\,\frac{dN_\mu}{d\Omega}}$$

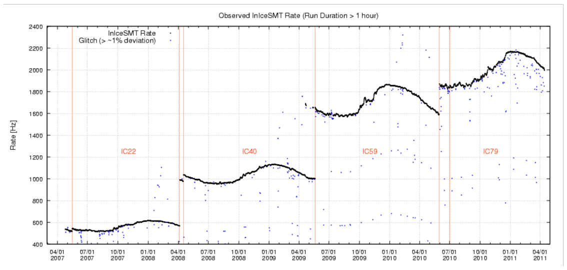
effective temperature [1,3,4,5,6,7,8]

$A_{eff}(E_\mu,\theta)$ muon effective area: detection response function vs muon energy and zenith angle

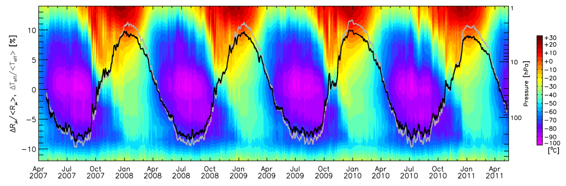
$\frac{dN_\mu}{d\Omega}$ muon angular distribution

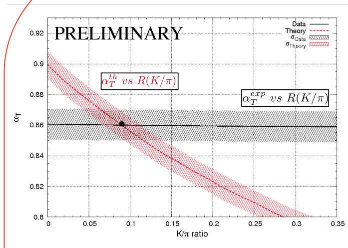
$T(X)$ temperature data by NASA AIRS on board the Aqua satellite. Daily atmospheric temperatures at 20 pressure levels from 1 to 600 hPa from level 3 Daily Gridded Product by NASA Goddard Earth Sciences [9]

observed event rate in IceCube from 2007 to 2011 [10]



relative **event rate** variations and **effective temperature** profiles from 2007 to 2011



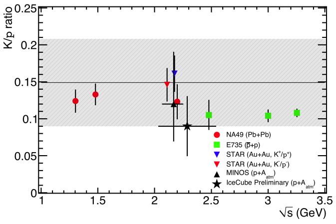


$$\alpha_T^{exp} = 0.860 \quad \pm 0.002(stat.) \quad \pm 0.010(syst.)$$

α_T^{exp} weakly depends on $R(K/\pi)$ because the effective temperature is relatively insensitive to K/π ratio.

α_T^{th} primarily depends on critical energy and on $R(K/\pi)$.

Matching theory with observation provides an indirect determination of $R(K/\pi)$.



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

$$R^{exp}(K/\pi) = 0.09 \pm 0.04$$

systematic uncertainties:

- effective temperature weakly dependent on spectral index & proton attenuation length
- α_T^{th} changes by < 1% if spectral index and proton attenuation length changes by 10%
- α_T^{exp} affected by experimental uncertainties on detector response, coincidence of uncorrelated events & second order effects

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