Seasonal Variation of Atmospheric Neutrinos in IceCube

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Measurement of atmospheric muon neutrinos in IceCube

Up-going muon tracks induced by $\nu_\mu$ below the horizon

$$E_\nu > 100 \text{ GeV} \quad \text{with a median energy } \sim 1 \text{ TeV} \quad 10^5 \text{ per year} \quad 99.7\% \text{ purity}$$
Production of atmospheric muon neutrinos in air showers

Flux

\[ \Phi_\nu = \int_0^{X_{\text{ground}}} P(X, E, \Theta, T) \, dX \]

Production yield

\[ P(X, E, \Theta, T) = \Phi_N(E) \left( \frac{A_\pi(X)}{1 + B_\pi(X)} \frac{E \cos \Theta^* (\Theta, X)}{\epsilon_\pi(T)} + \frac{A_K(X)}{1 + B_K(X)} \frac{E \cos \Theta^* (\Theta, X)}{\epsilon_K(T)} \right) \]

\[ \Phi_N(E) = \Phi_0 \cdot E^{-\gamma} \]

\[ A_{\pi, K}(X) = BR_{\pi, K \rightarrow \nu} \cdot \frac{Z_{N \rightarrow \pi, K}(1 - r_{\pi, K})}{\lambda_N(\gamma + 1)} e^{-\frac{X}{\Lambda_N}} \]

\[ B_{\pi, K}(X) = \frac{\gamma + 2}{\gamma + 1} \cdot \frac{1}{1 - r_{\pi, K}} \cdot \frac{\Lambda_{\pi, K} - \Lambda_N}{\Lambda_{\pi, K} \Lambda_N} \cdot \frac{X e^{-\frac{X}{\Lambda_N}}}{e^{-\frac{X}{\Lambda_{\pi, K}}} - e^{-\frac{X}{\Lambda_N}}} \]

Critical energy

\[ \epsilon_{\pi, K}(T) = \frac{R T(X, \Theta)}{M g} \cdot \frac{m_{\pi, K} c}{\tau_{\pi, K}} \]

\[ r_{\pi, K} = \frac{m_{\mu}^2}{m_{\pi, K}^2} \]

\[ \Rightarrow \gamma, Z_{N \rightarrow \pi, K}, \Lambda_{N, \pi, K} \text{ are free parameters for the fit} \]
Effective Temperature and correlation coefficient

- Linear correlation between neutrino rate and temperature

\[ \frac{\Delta R_v}{R_v} = \alpha \frac{\Delta T_{\text{eff}}}{T_{\text{eff}}} \]

- Effective temperature

\[ T_{\text{eff}}(\theta) = \frac{\int \int A_{\text{eff}}(E, \theta) P(E, \theta, T, X) T(\theta, X) \, dE \, dX}{\int \int A_{\text{eff}}(E, \theta) P(E, \theta, T, X) \, dE \, dX} \]

- Effective area: Detector response

- Production yield: $K/\pi$ decay $\leftrightarrow$ re-interaction

- Correlation coefficient

\[ \alpha(E, \Theta) = \frac{\int T \cdot \frac{dP(X, E, \Theta, T(X, \Theta))}{dT} \cdot dX}{\int P(X, E, \Theta, T(X, \Theta)) \cdot dX} \]
Data sets

Seasonal climate
Seasonal climate
Diurnal climate

Resulting observation zone: $90^\circ < \theta_{\text{IceCube}} < 120^\circ$

Diffuse sample
May 2012 – May 2017
see talk by Jöran Stettner
PoS 1017

Atmospheric Infrared Sounder instrument aboard NASA’s Aqua satellite

1 The IceCube Collaboration, Observation and characterization of a cosmic muon neutrino flux from the northern hemisphere using six years of IceCube data
Seasonal variation of the neutrino rate and the effective temperature

Neutrino counts scaled to 24h detector live time, $90^\circ \leq \Theta < 120^\circ$

Effective temperature
Linear fit result

Correlation coefficient:

\[
\frac{\Delta R_v}{R_v} = \alpha \frac{\Delta T_{\text{eff}}}{T_{\text{eff}}} \quad \Delta R = R_i - \bar{R} \quad \Delta T = T_i - \bar{T}
\]

Correlation coefficient, Binning = 1 days, Observation zone: \(90^\circ \leq \Theta < 120^\circ\)

\[\alpha = 0.42 \pm 0.04\]

Note:
11 \(\sigma\) significance with respect to non-correlation hypothesis
Stability tests

How stable is the fit result with respect to larger observation intervals?

The fit result is stable for time bins up to one month.

How stable is the fit result with respect to different climatic scenarios?

$\alpha^+ = 0.40 \pm 0.06$ and $\alpha^- = 0.45 \pm 0.06$ are compatible with each other and both are compatible with $\alpha = 0.42$ within 1σ.
Theoretical expectation

Semi-analytical approximation based on the Gaisser formula

- Recap: Correlation coefficient \( \alpha(E, \Theta) = \frac{\int T \cdot \frac{dP(X,E,\Theta,T(X,\Theta))}{dT} \cdot dX}{\int P(X,E,\Theta,T(X,\Theta)) \cdot dX} \)

- Tested models:
  
  I. Constant Z-factors and energy-dependent \( \Lambda \) as in Sibyll 2.3
  
  II. Z-factors as in ¹ and constant \( \Lambda \) as in Sibyll 2.1
  
  III. Z-factors as in ² and constant \( \Lambda \) as in Sibyll 2.1

- Results:

<table>
<thead>
<tr>
<th>Model</th>
<th>(I)</th>
<th>(II)</th>
<th>(III)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>0.479</td>
<td>0.496</td>
<td>0.484</td>
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</tbody>
</table>


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Conclusion and outlook

Experimental approach

- First evident observation of correlation of $R_{v}$ and $T_{\text{eff}}$ is $\alpha = 0.42 \pm 0.04$
- The fit result is stable with respect to larger observation intervals
- No significant hint at a seasonal dependence of correlation
- Zenith dependence: $\alpha = \alpha (\theta)$
- Unbinned likelihood-fit: $\alpha = \alpha (\theta_i, \text{lon}_i, T_i)$
  $\rightarrow$ Elimination of resolution losses
- Update with new IceCube data

Theoretical expectation

- $\alpha = 0.49 \pm 0.03$
- MCEq-based calculation of the expectation is currently being performed
- Test of hadronic interaction models with MCEq-based approach
  $\triangleright$ Together with muon seasonal variations measure $K/\pi$ ratio