Seasonal Variation of Atmospheric Neutrinos in IceCube

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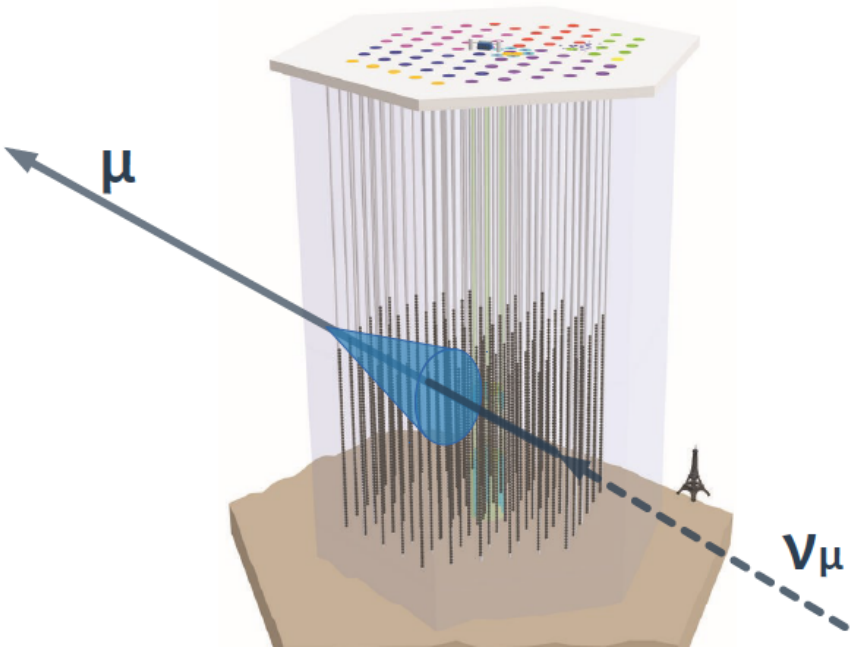
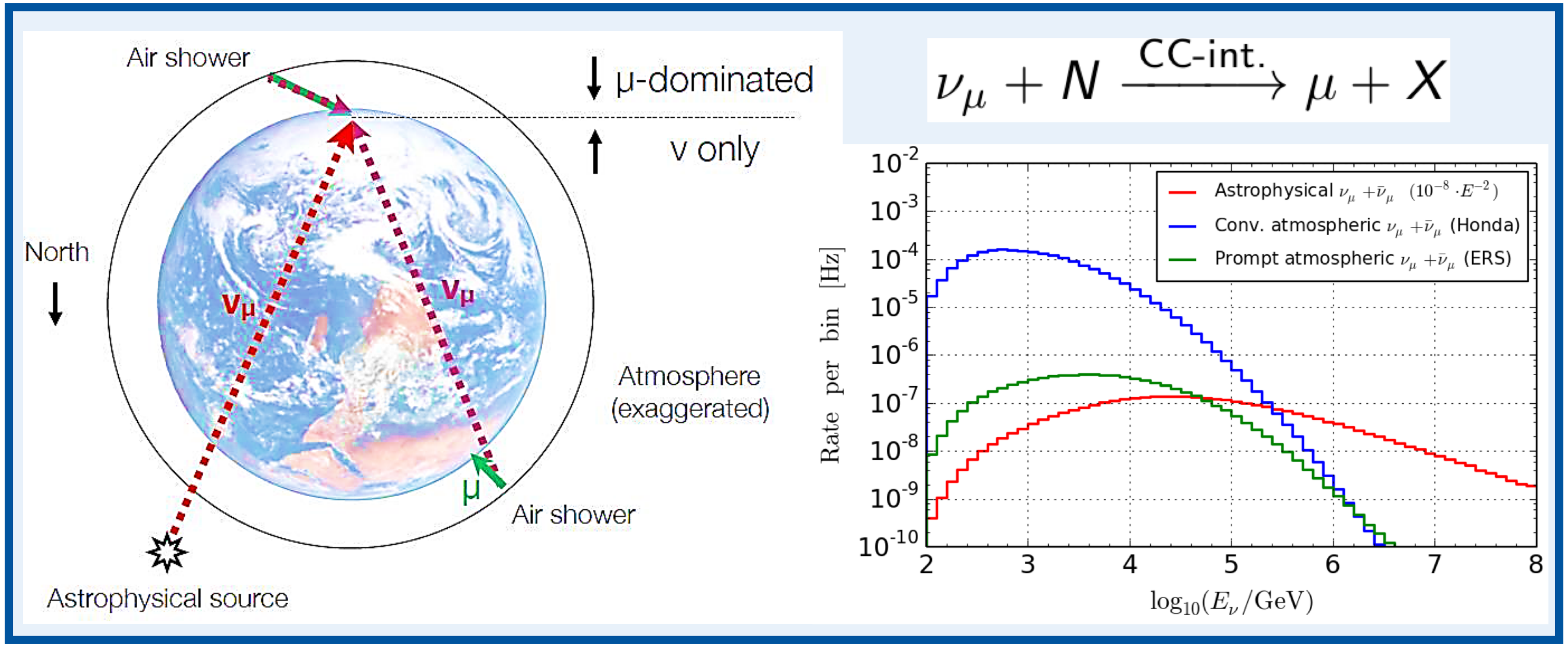
SOUTH POLE NEUTRINO OBSERVATORY

Measurement of atmospheric muon neutrinos in IceCube



Up-going muon tracks induced by ν_μ below the horizon



E_ν >100 GeV with a median energy ~ 1TeV 10^5 per year 99.7% purity

Production of atmospheric muon neutrinos in air showers

analytic approximation by Gaisser

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

Production yield $$P(X, E, \Theta, T) = \Phi_N(E) \left(\overbrace{\frac{A_\pi(X)}{1 + B_\pi(X) \frac{E \cos\Theta^*(\Theta,X)}{\boxed{\epsilon_\pi(T)}}}}^{\text{Pions}} + \overbrace{\frac{A_K(X)}{1 + B_K(X) \frac{E \cos\Theta^*(\Theta,X)}{\boxed{\epsilon_K(T)}}}}^{\text{Kaons}} \right)$$

$$\Phi_N(E) = \Phi_0 \cdot E_\nu^{-(\gamma+1)}$$

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

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

critical energy $$\boxed{\epsilon_{\pi,K}(T) = \frac{R\,T(X,\Theta)}{M\,g} \cdot \frac{m_{\pi,K}\,c}{\tau_{\pi,K}}}$$

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

$\Rightarrow \gamma,\ Z_{N\to\pi,K},\ \Lambda_{N,\pi,K}$ are free parameters for the fit

Effective Temperature and correlation coefficient

- Linear correlation between neutrino rate and temperature

$$\frac{\Delta R_\nu}{\overline{R_\nu}} = \alpha \frac{\Delta T_{\mathrm{eff}}}{\overline{T_{\mathrm{eff}}}}$$

- **Effective temperature**

Atmospheric temperature

$$T_{\mathrm{eff}}(\theta) = \frac{\iint A_{\mathrm{eff}}(E,\theta) P(E,\theta,T,X) T(\theta,X)\, dE\, dX}{\iint A_{\mathrm{eff}}(E,\theta) P(E,\theta,T,X)\, dE\, dX}$$

Effective area:
Detector response

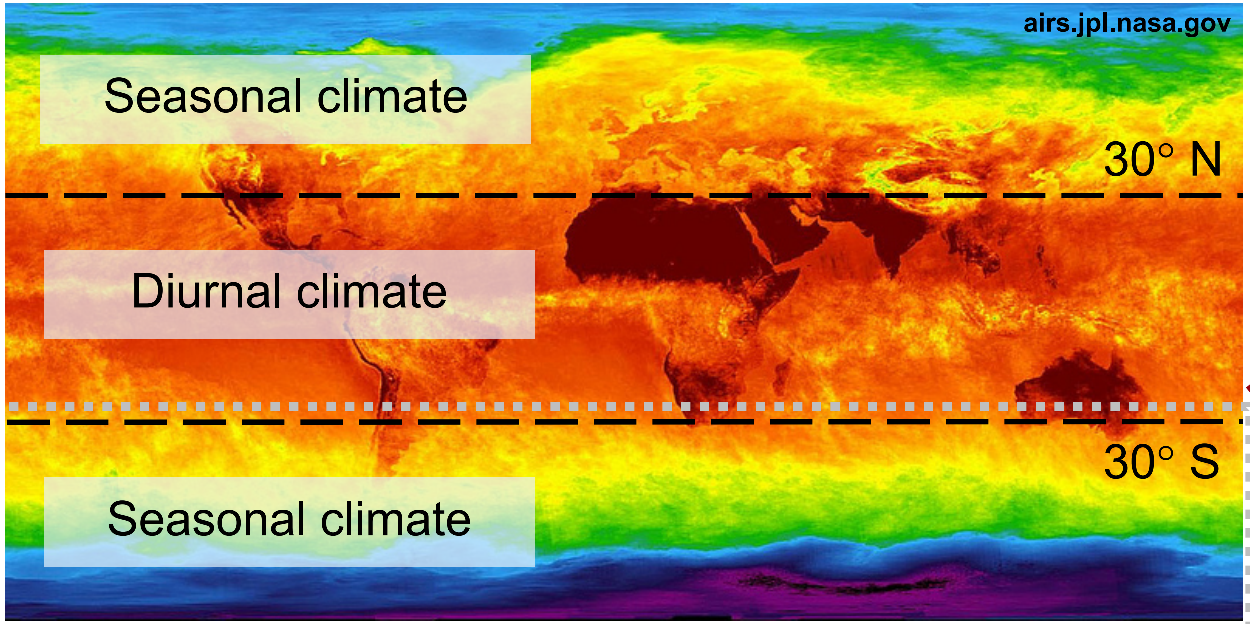
Production yield:
K/π decay ↔ re-interaction

- **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

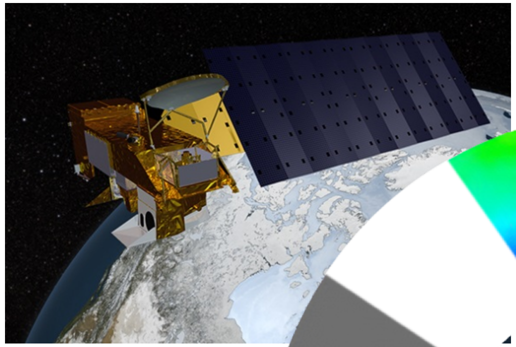
Decreasing ν rate



Resulting observation zone:
90° $< \theta_{\mathbf{IceCube}} <$ **120°**

ν

Temperatures



AIRS
Atmospheric Infrared Sounder

ICECUBE

Diffuse sample

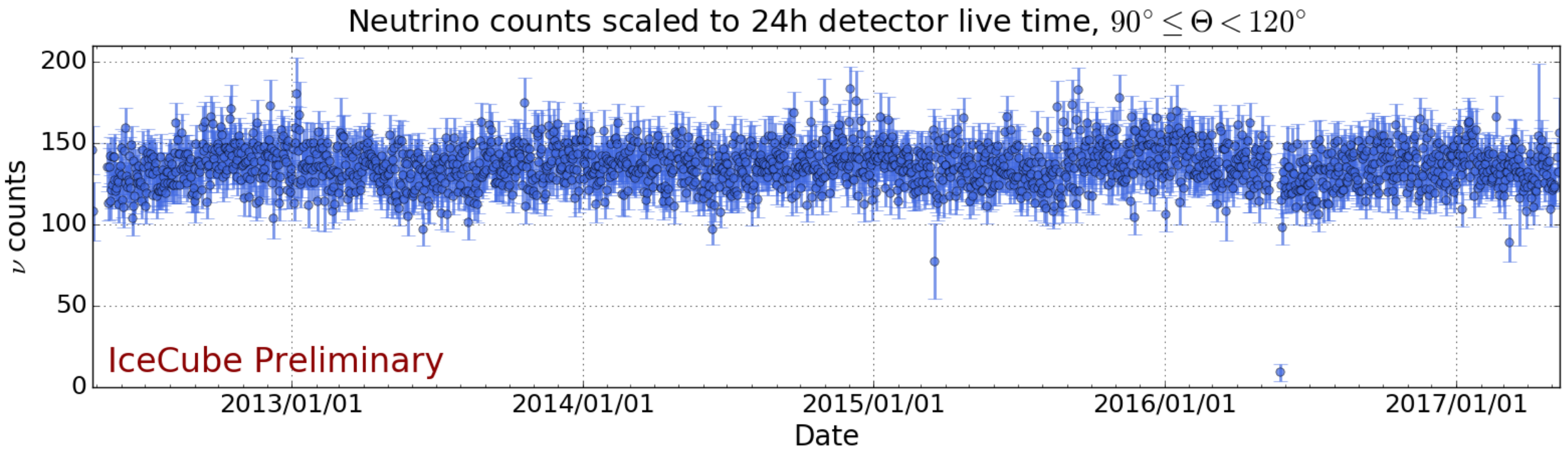
May 2012 – May 2017

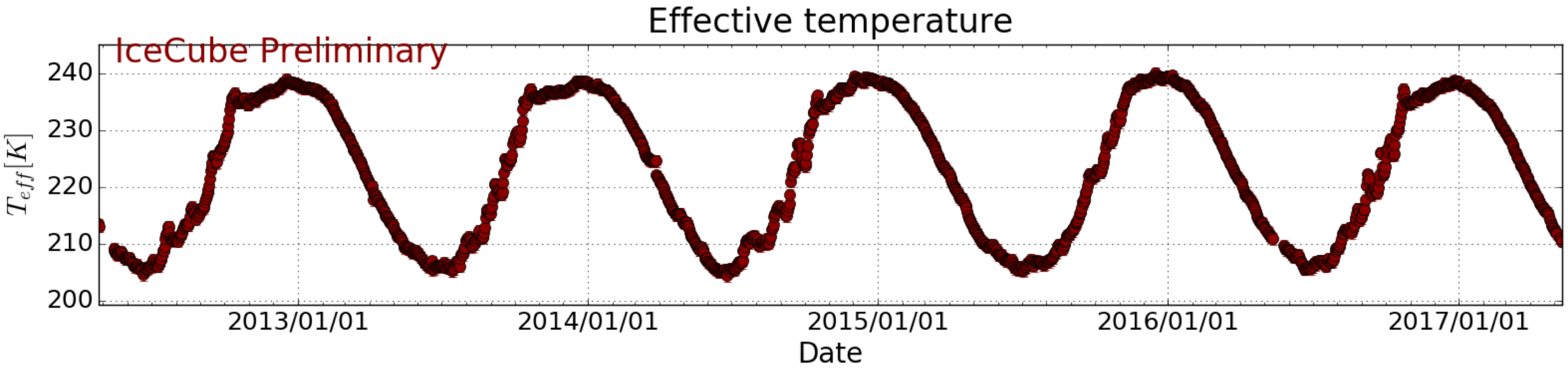
see talk by Jöran Stettner
PoS 1017

Atmospheric **I**nfrared **S**ounder 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**

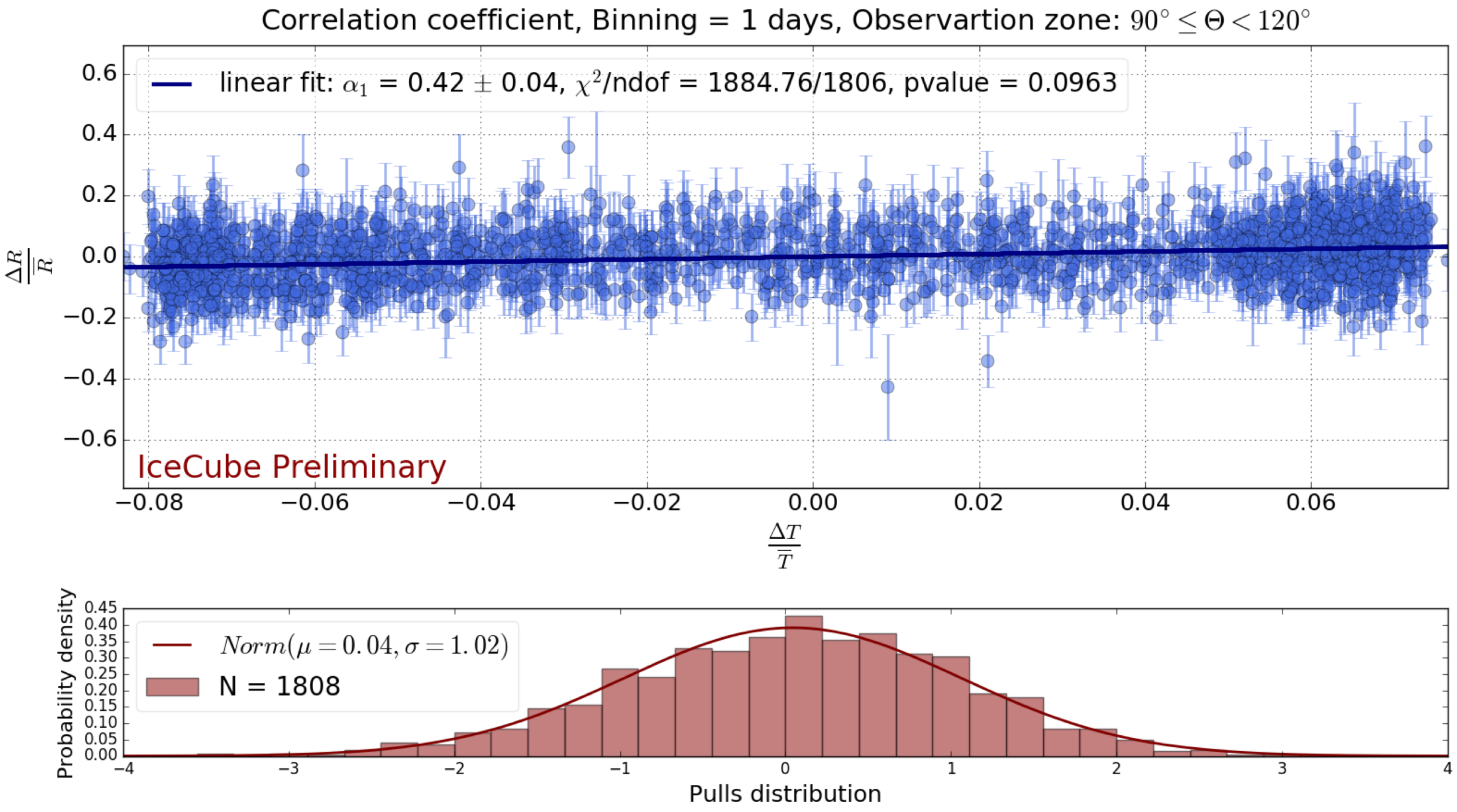
Seasonal variation of the neutrino rate and the effective temperature





Linear fit result

Correlation coefficient: $\frac{\Delta R_\nu}{\overline{R_\nu}} = \alpha \frac{\Delta T_{eff}}{\overline{T_{eff}}}$ $\Delta R = R_i - \overline{R}$ $\Delta T = T_i - \overline{T}$

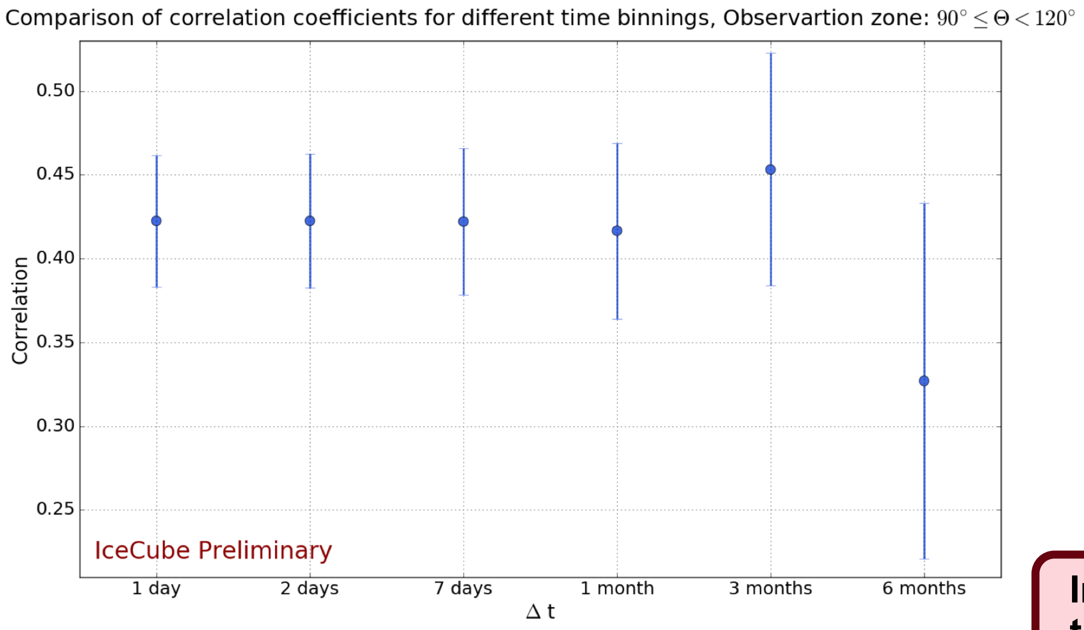


α = 0.42 ± 0.04

Note:
11 σ significance with respect to non-correlation hypothesis

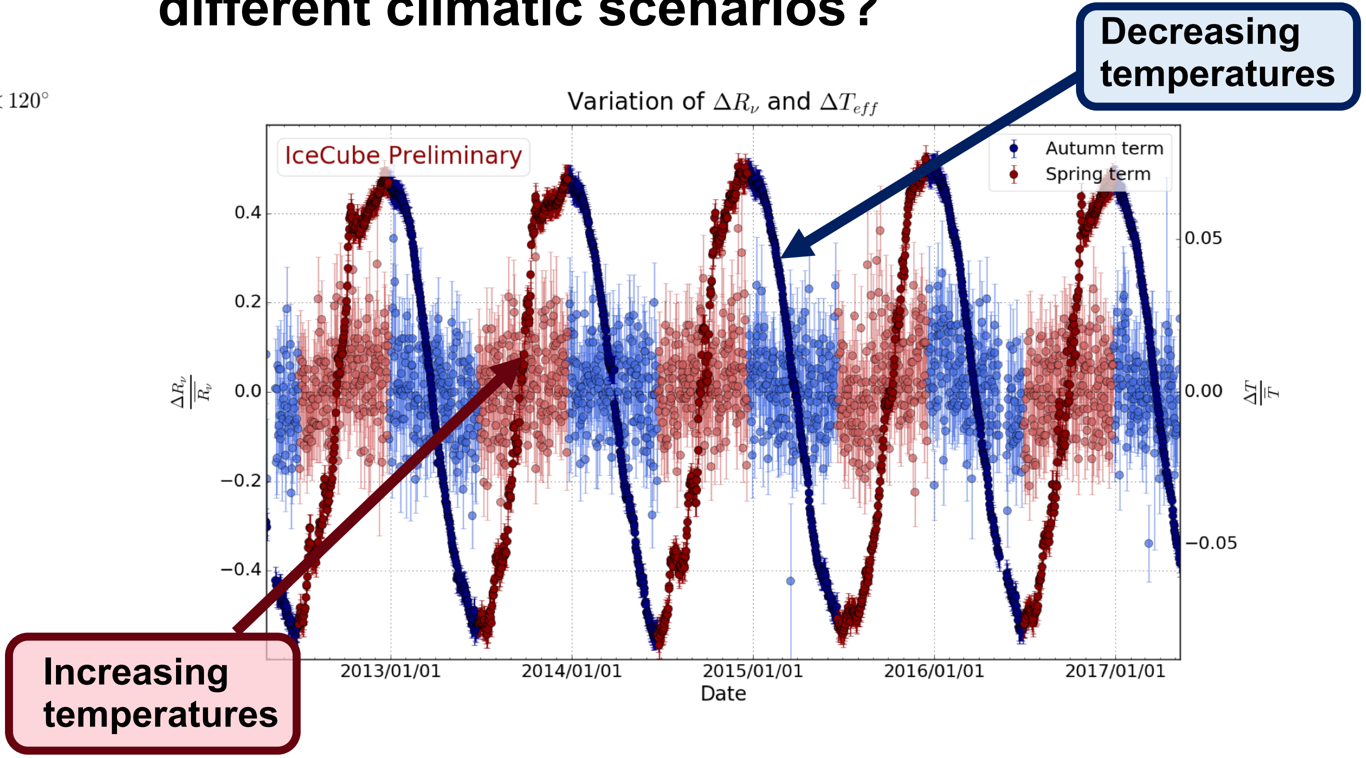
Stability tests

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?



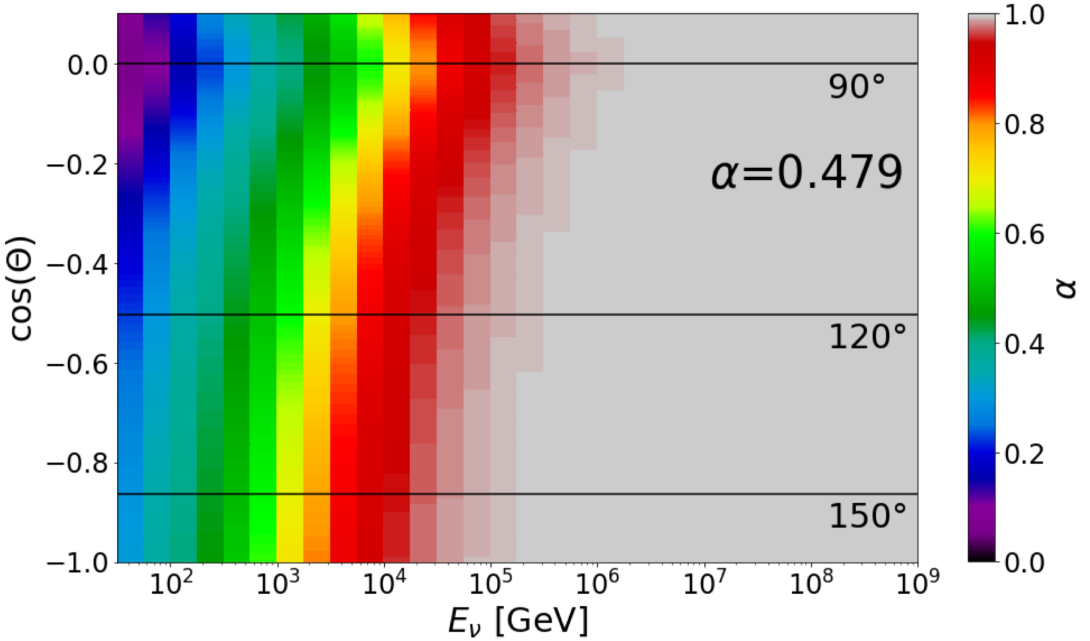
α^+ **= 0.40** ± **0.06** and α^- **= 0.45** ± **0.06** are compatible with each other and both are compatible with α **= 0.42** within **1**σ

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 Λ as in Sibyll 2.3
  II. Z-factors as in [1] and constant Λ as in Sibyll 2.1
  III. Z-factors as in [2] and constant Λ as in Sibyll 2.1
- Results:

Model	(I)	(II)	(III)
α	0.479	0.496	0.484



[1] T. Sanuki, M. Honda, T. Kajita, K. Kasahara, and S. Midorikawa,Phys. Rev.D75(2007) 043005
[2] T. K. Gaisser,Cosmic rays and particle physics. Cambridge University Press, 1990

Conclusion and outlook

Experimental approach

- First evident observation of correlation of R_ν and T_{eff} is α **= 0.42 ± 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: $\alpha = \alpha(\theta_i, \mathrm{lon}_i, T_i)$

  → Elimination of resolution losses
- Update with new IceCube data

Theoretical expectation

- α **= 0.49 ± 0.03**
- MCEq-based calculation of the expectation is currently being performed
- Test of hadronic interaction models with MCEq-based approach

➢ Together with muon seasonal variations measure K/π ratio