technische universität dortmund

IceCube Neutrino Observatory

SFB1491

SFB 876 Providing Information by Resource-Constrained Data Analysis

Seasonal Variations of the Atmospheric Neutrino Flux measured in IceCube

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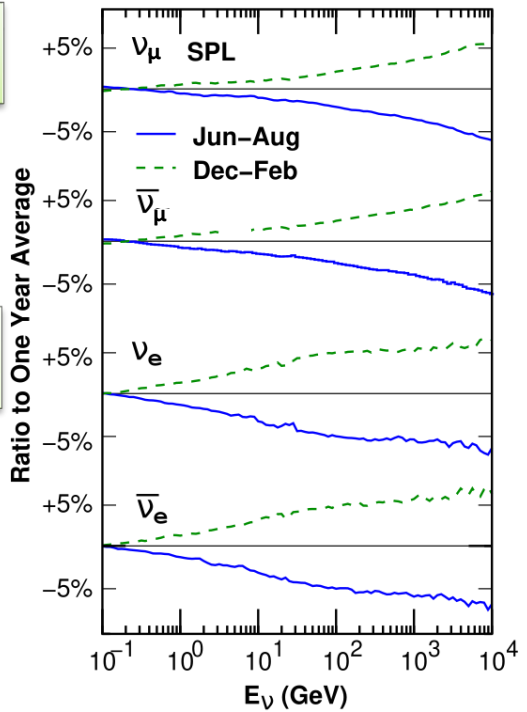
International Workshop on Neutrino Telescopes
Venice, October 26, 2023

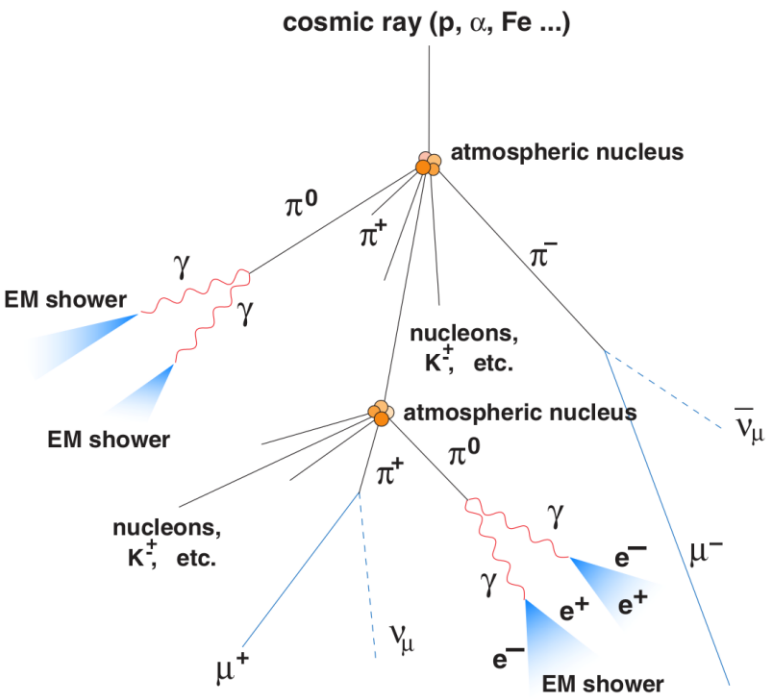
Overview

- Seasonal dependence of atmospheric muon neutrino flux
- Impact on spectral shape calculated by Honda et al. for $90° < \theta < 120°$
- Measurement with 11.5 years of IceCube data with spectrum unfolding technique
- Determination of seasonal energy spectra
- Comparison of variation strength to MCEq

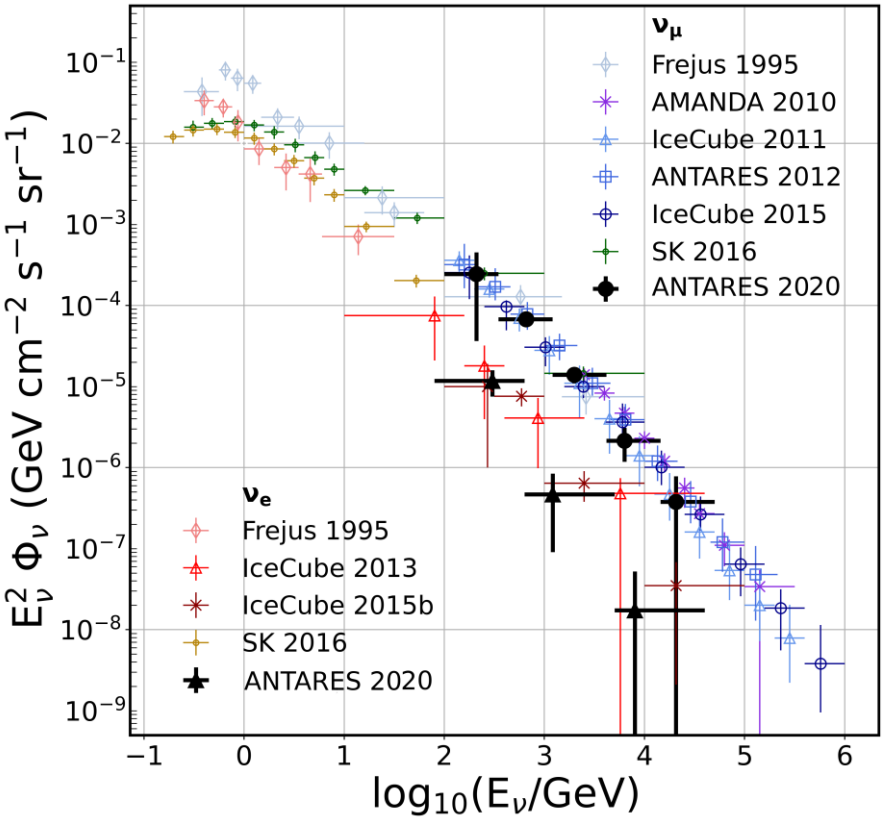


Honda et al., *JPS Conf.Proc.* 12 (2016)

Atmospheric Neutrinos



Wagner, PhD Thesis (2006)

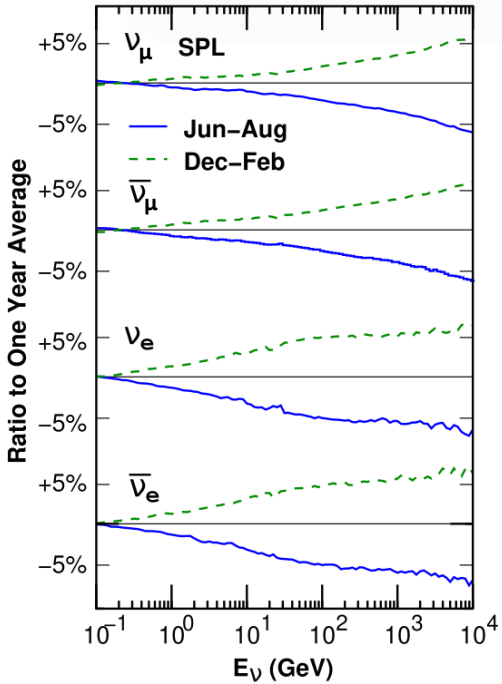


Antares Collab., Physics Letters B, Vol. 816 (2021)

Seasonal Variations of the Neutrino Flux

$$\Phi_\nu(E_\nu, \Theta, X) = \Phi_N(E_\nu) \cdot \int_0^{X_{\text{ground}}} \left(\frac{A_{\pi\to\nu}(X)}{1 + B_{\pi\to\nu}(X) \cdot \frac{E_\nu \cos(\Theta^\star)}{\epsilon_\pi(T(X))}} + \frac{A_{K\to\nu}(X)}{1 + B_{K\to\nu}(X) \cdot \frac{E_\nu \cos(\Theta^\star)}{\epsilon_K(T(X))}} \right) \mathrm{d}X$$

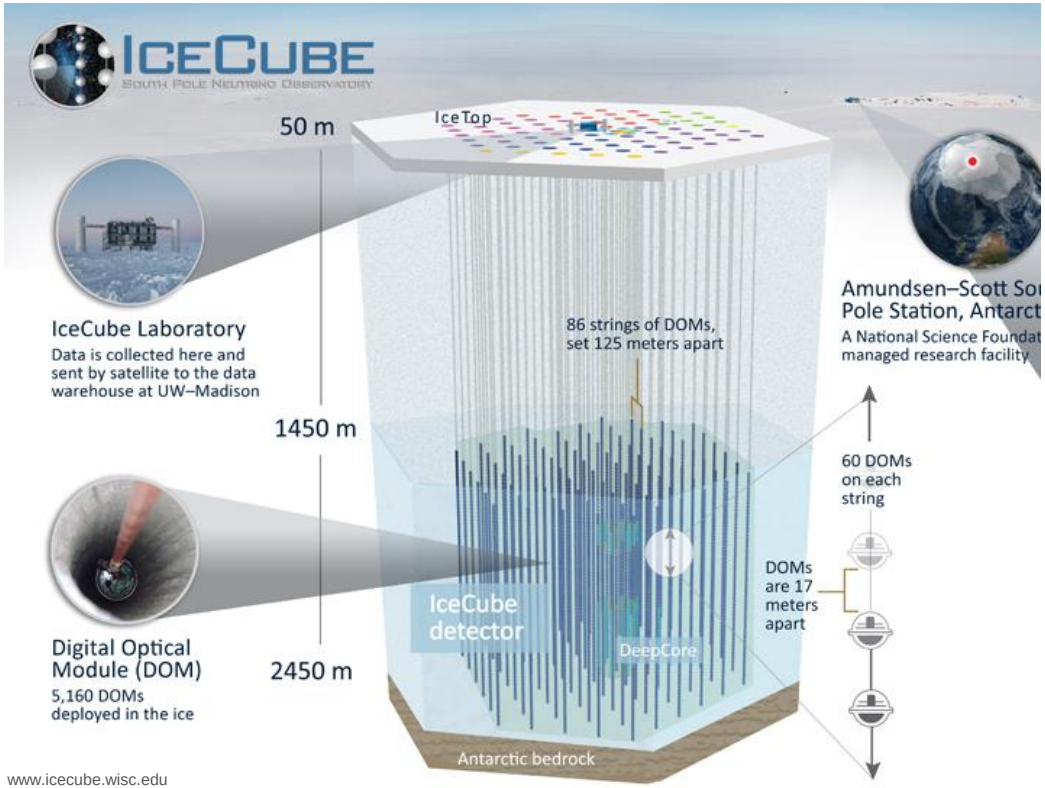
$$\varepsilon_i = T(X) \cdot \frac{R}{Mg} \frac{c \cdot m_i}{\tau_i}$$



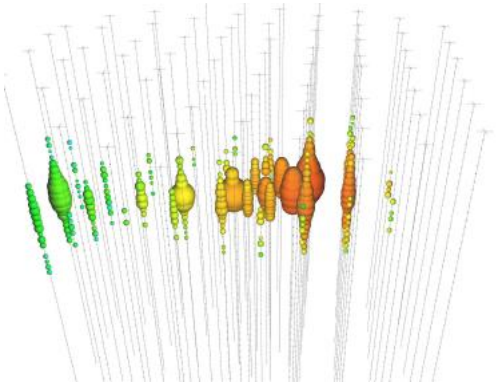
Honda et al., *JPS Conf.Proc.* 12 (2016)

- Neutrino production in stratosphere is governed by two processes: decay vs re-interaction of parent meson
- Flux impacted by temperature modulation throughout the year
- Effect increases with energy as re-interactions dominate

The IceCube Neutrino Observatory



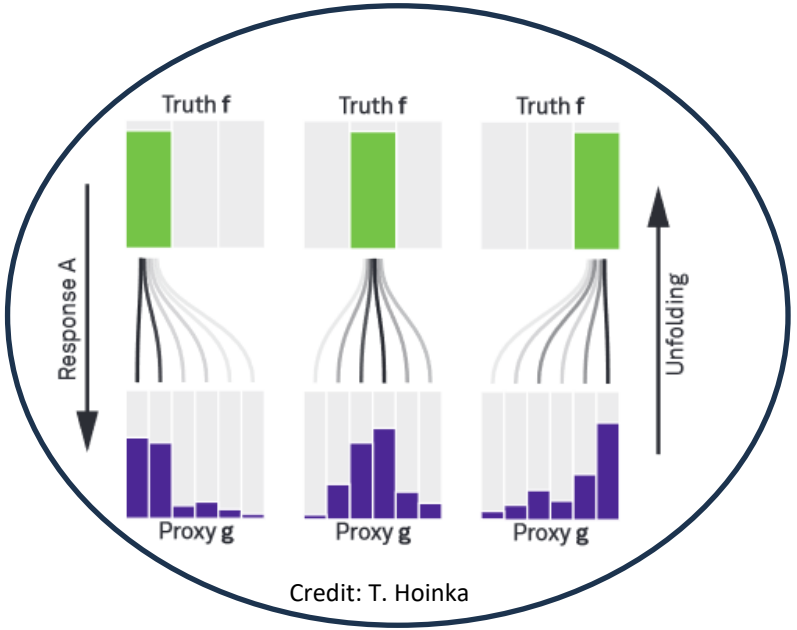
- Instrumented volume of 1km³
- Excellent laboratory for atmospheric neutrino studies
- Detection of muon track via Cherenkov light



$$\nu_\mu + N \rightarrow \mu + X$$

Determining the Neutrino Energy – an inverse Problem

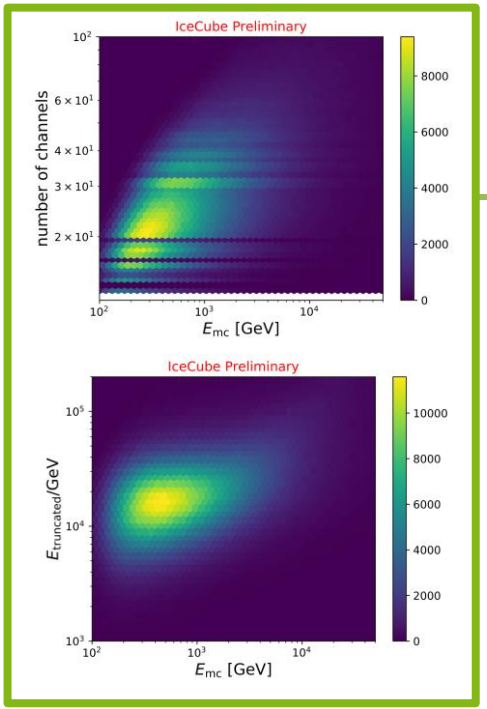
- E_ν needs to be inferred from muon track
- Position of interaction vertex is unknown
- μ production → statistical processes
- Energy losses along track in ice
- Limited detector acceptance

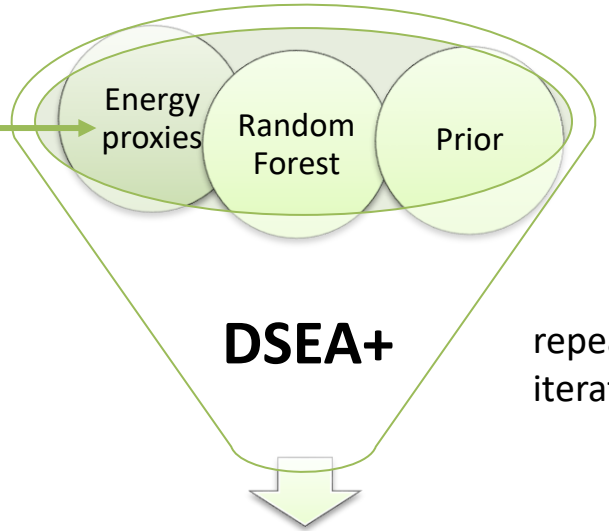


folding equation $\vec{g}(y) = \mathbf{A}(E_\nu, y)\vec{f}(E_\nu)$

measured truth

Dortmund Spectrum Estimation Algorithm [DSEA+]





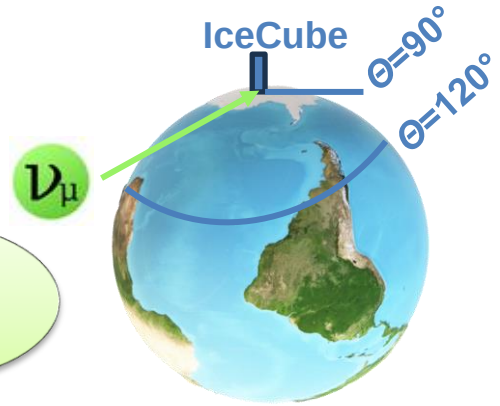
repeat for k iterations

$$\widehat{f}_i^{(k)} = \frac{1}{N} \sum_{n=1}^{N_{events}} c_M(i|x_n) \;\; \forall \; 1 \leq i \leq I$$

Regularization

- Energy bins treated as independent categories
- Accumulation of discrete pdf for every event

Event Selection & Analysis Scheme



Input MC + Optimized DSEA+ + Data

Weighting: atmospheric (MCEq) + astrophysical spectrum

- SIBYLL2.3c
- H3a composition
- NRLMSIS-00 atmospheric model (yearly average)

Unfolded Spectrum

Upgoing ν_μ track sample

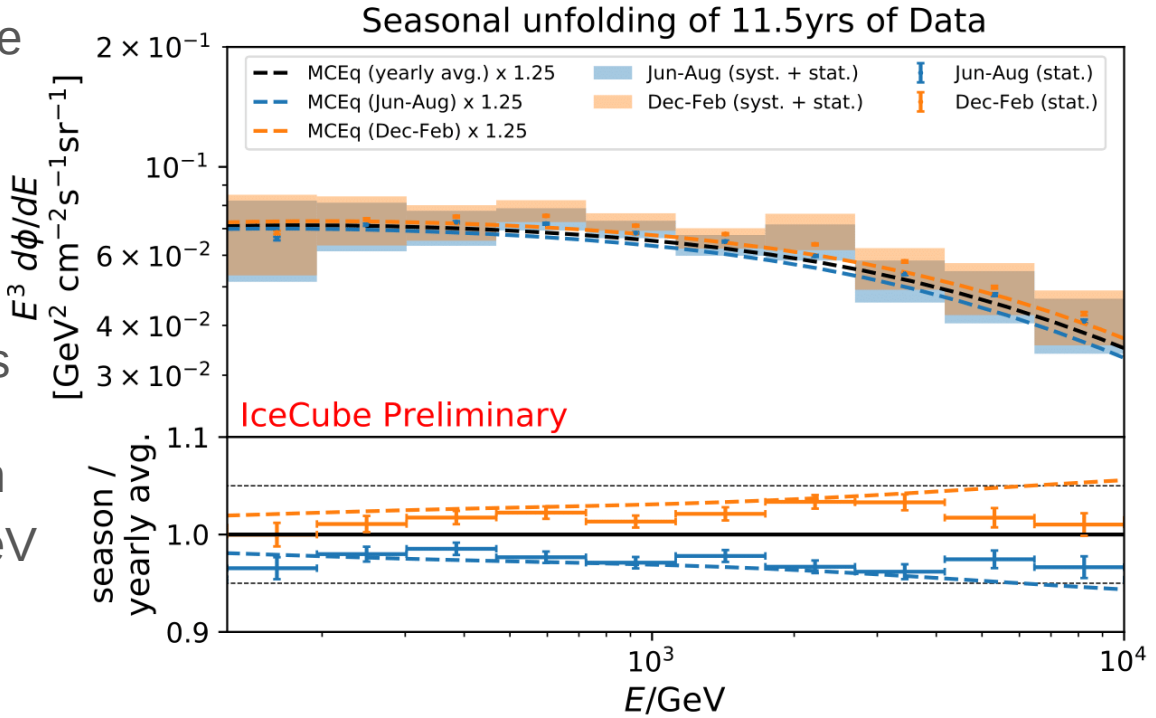
- 523736 events (May 2011- December 2022)
- Purity: > 99.7%

Aartsen *et al., ApJ* **833**

- Statistical error determined via bootstrapping
- $\sigma_{\text{sys}} = \sqrt{\sigma^2_{\text{DOM}} + \sigma^2_{\text{abs}} + \sigma^2_{\text{scat}} + \sigma^2_{\text{holeice}} + \sigma^2_{\text{flux}}}$

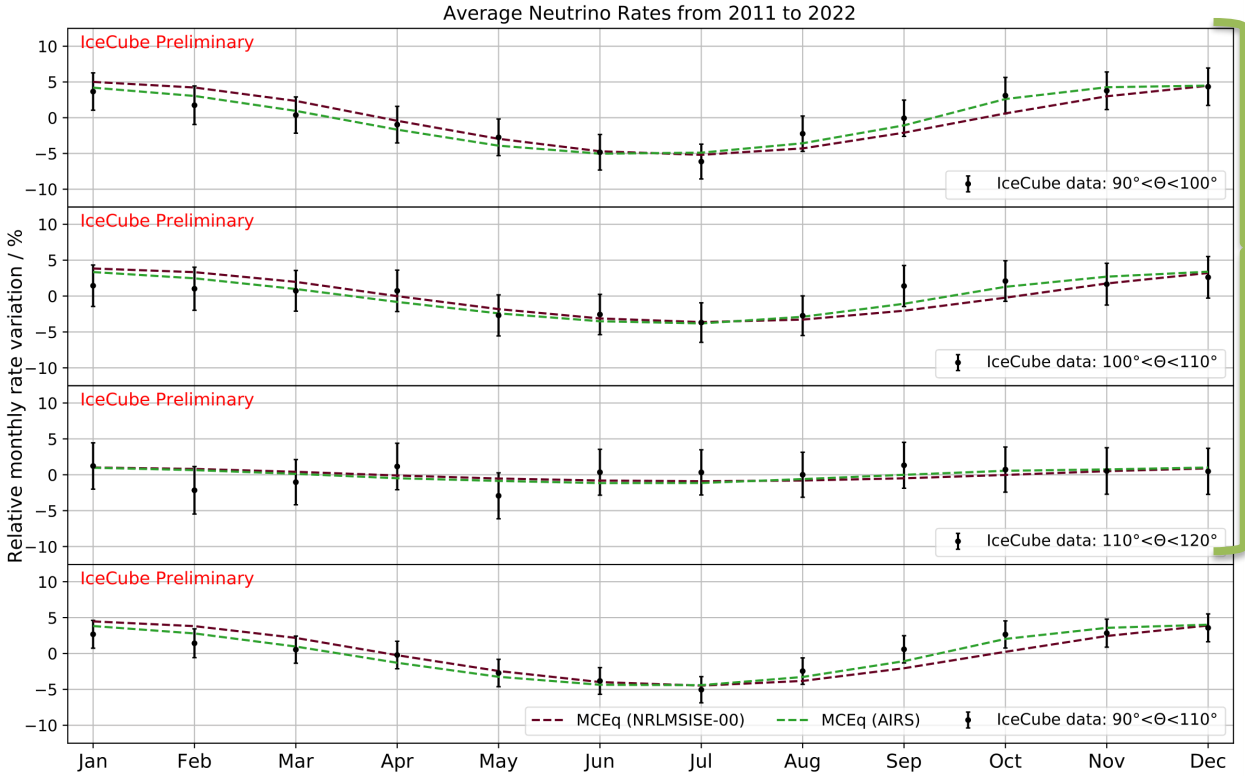
Unfolded Spectrum for 90°< θ <120°

- Systematic uncertainties are independent of the season
- Ratio depends only on statistical uncertainties
- Variation strength increases with neutrino energy in agreement with expectation
- Decrease of variation > 4TeV despite MCEq expectation



Follow-up investigation of zenith region

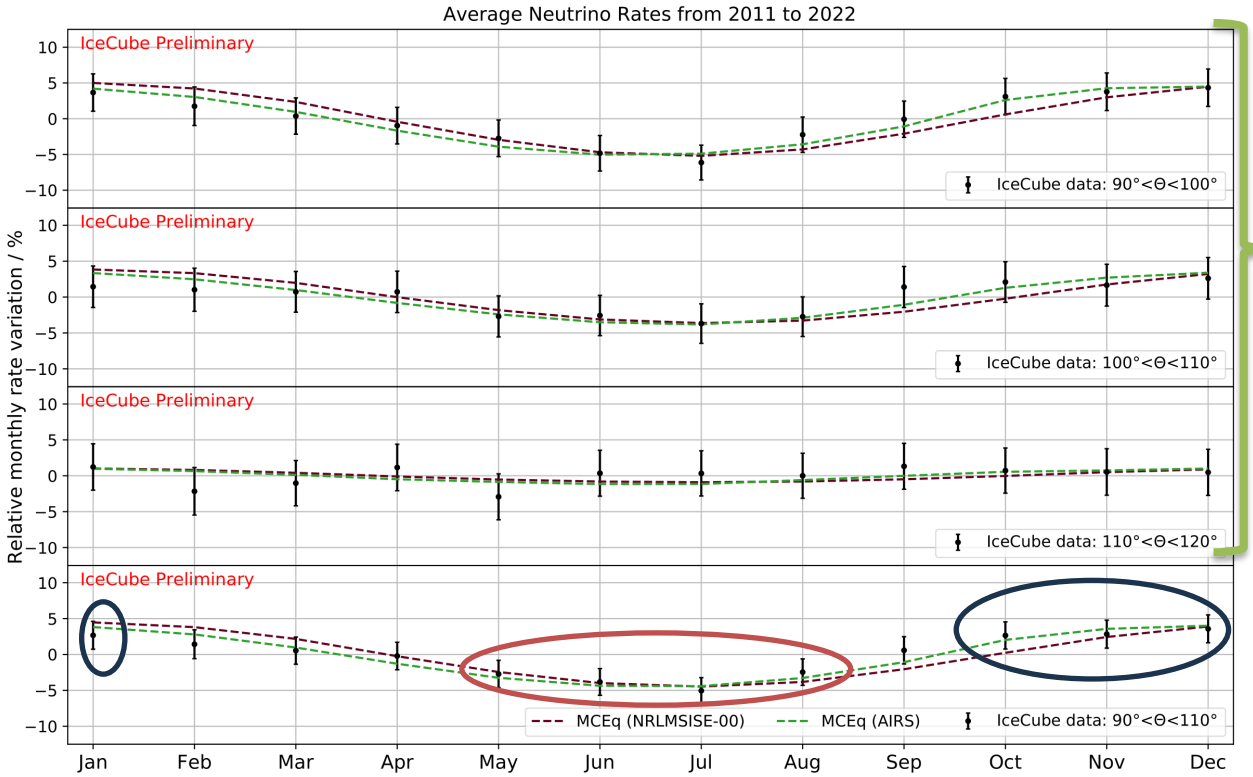
Predicted Variations & Measured Rate



- Rate compared to MCEq predictions
- NRLMSISE-00: atmospheric model
- AIRS: instrument on Aqua satellite – daily data from 2012-2017 as atm. input
- No variations between 110° - 120° → excluded

Asymmetric rate variation

Predicted Variations & Measured Rate



- Rate compared to MCEq predictions
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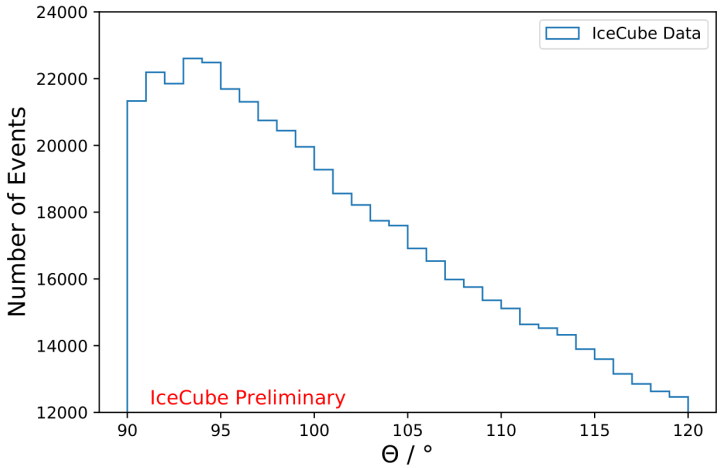
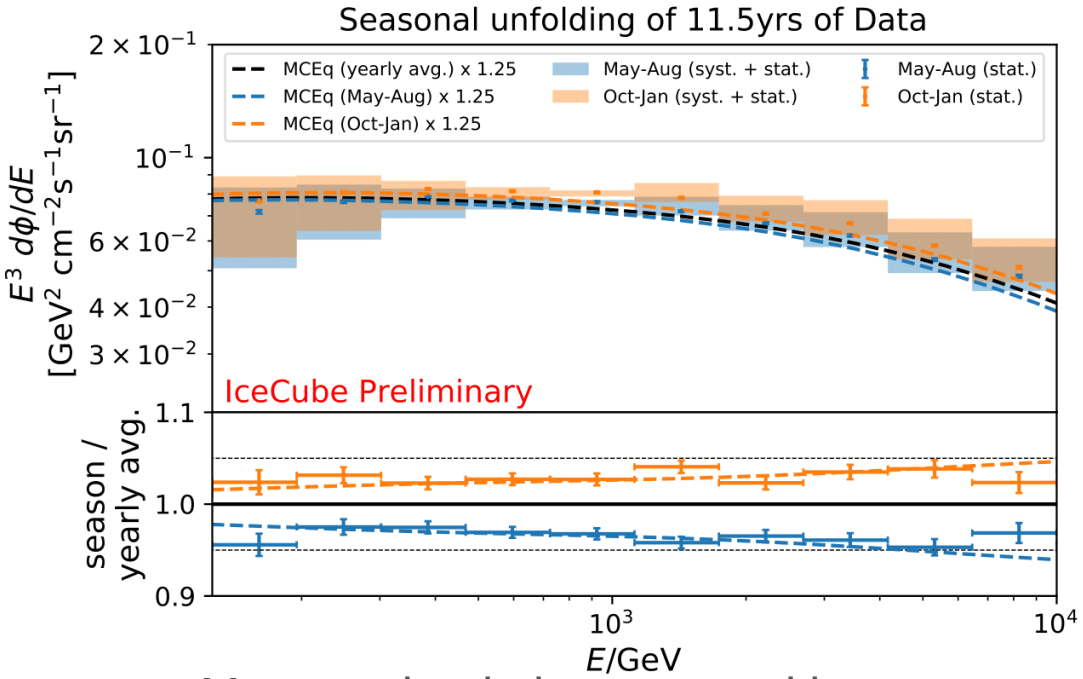
Asymmetric rate variation

Unfolded Spectrum for 90°< θ <110°

- Seasons re-defined by months with similar rates
- Ensures comparable statistics despite ~ 26% loss of events





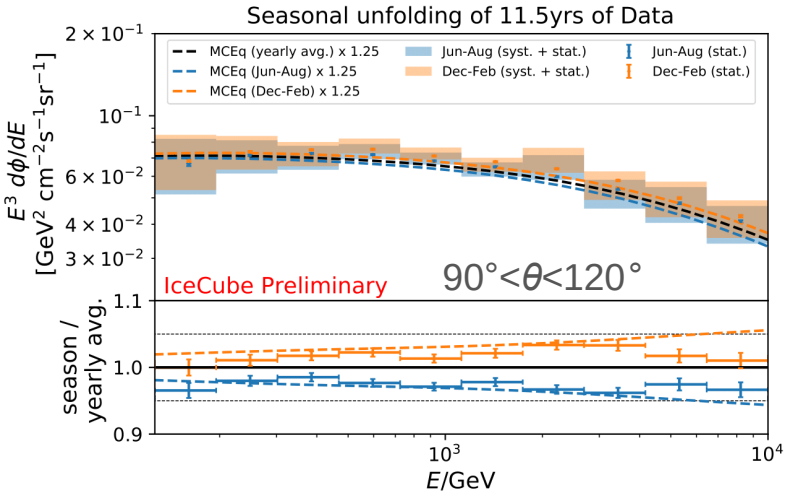
- Measured ratio increases with energy, as expected
- decrease in variation strength > 7 TeV

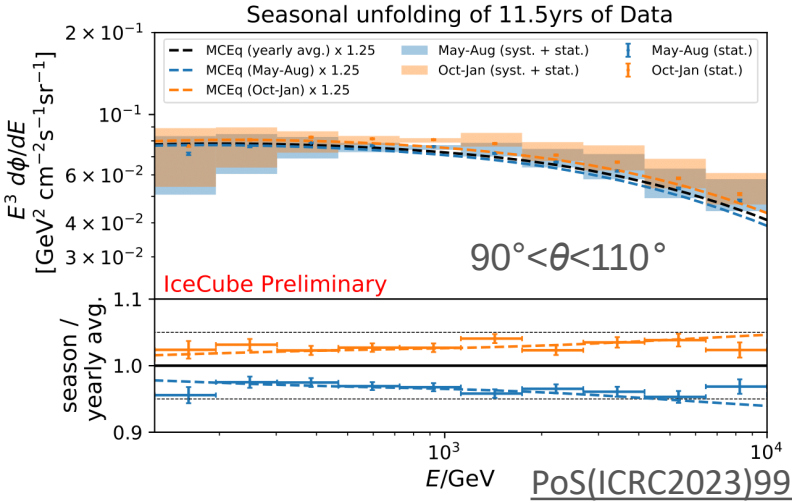
Summary

First measurement of seasonal variations in muon neutrino spectrum from 125 GeV to 10 TeV

- Energy spectrum estimation via unfolding technique for two zenith ranges
- Systematic uncertainties negligible in ratio of seasonal to annual average flux
- Variation strength measurement feasible at percent level

Variation strength increases, as expected, except for last energy bin





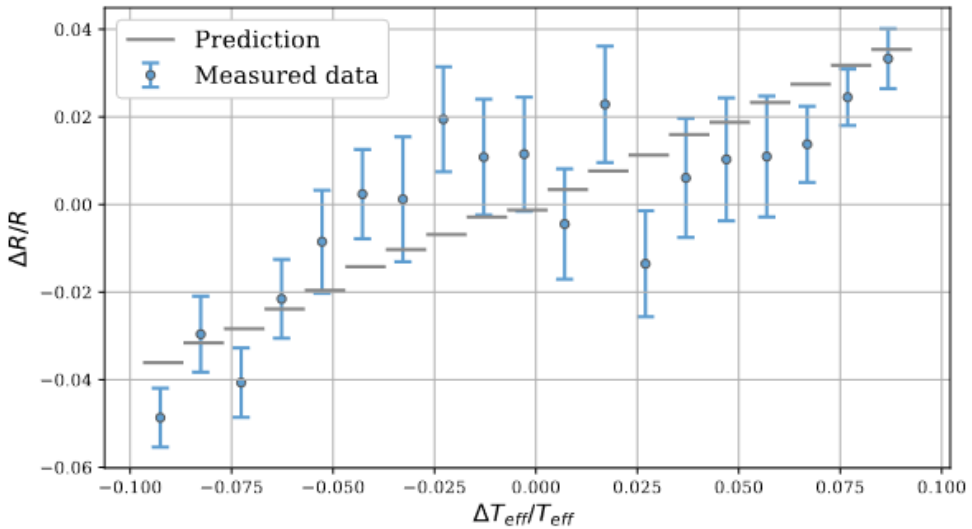
PoS(ICRC2023)993

BACKUP

Seasonal Variations in IceCube

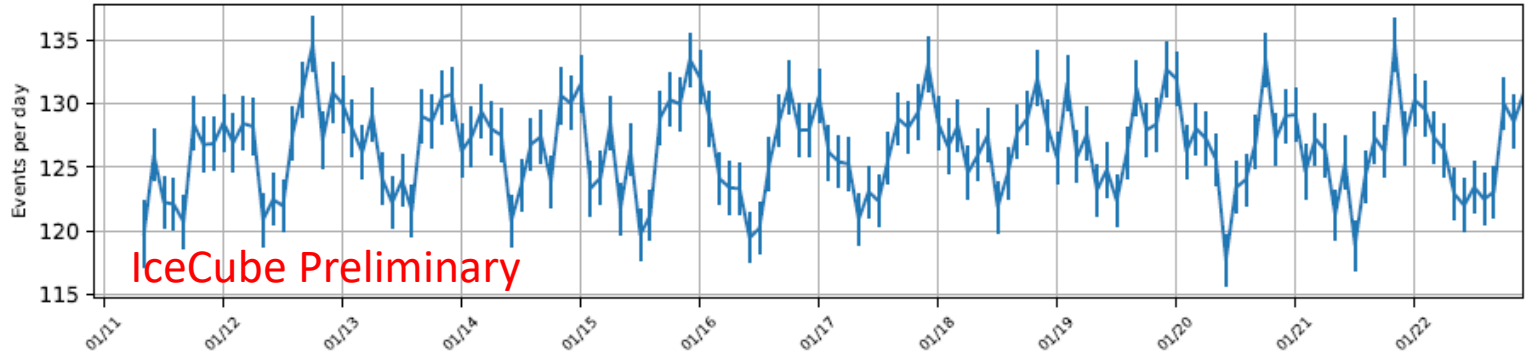
- Measure correlation between neutrino rate and atmospheric temperature

$$\frac{R(t)-\bar{R}}{\bar{R}} = \alpha \frac{T_{\text{eff}}(t)-\bar{T}_{\text{eff}}}{\bar{T}_{\text{eff}}} \qquad T_{\text{eff}}(t) = \frac{\int d\Omega\, T_{\text{eff}}(\theta,\varphi,t) \cdot \int dX R_X(\theta,\varphi,X,T)}{\int d\Omega \int dX R_X(\theta,\varphi,X,T)}$$

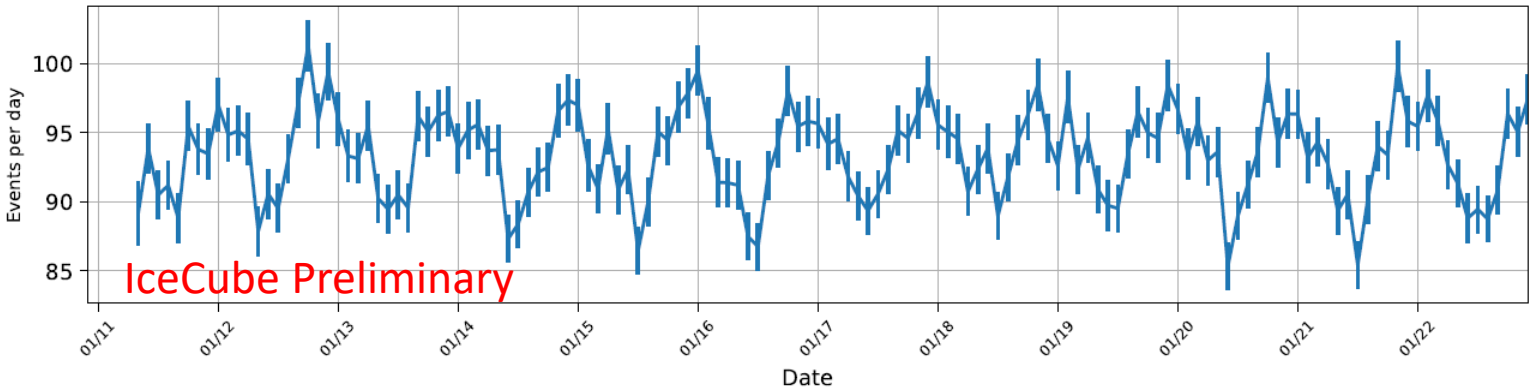


Abbasi et al., EPJC 83

Seasonal Variations

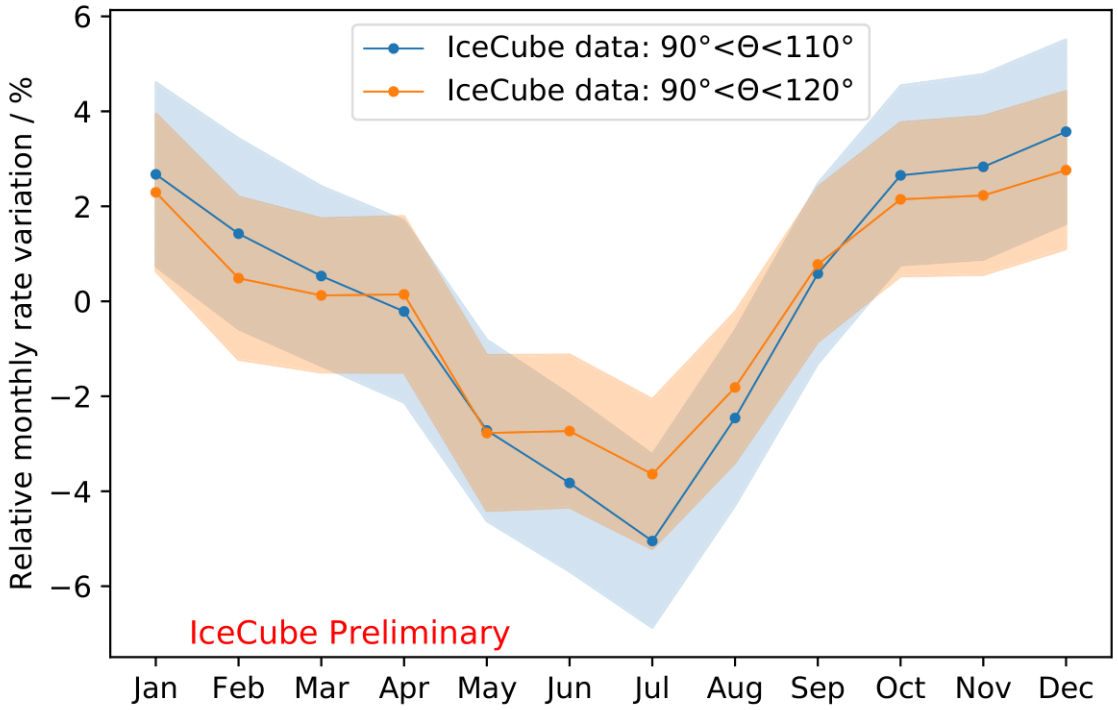


90°-120°



90°-110°

Comparison of Zenith Bands



Systematic Uncertainties

Investigate Parameter impact on unfolding

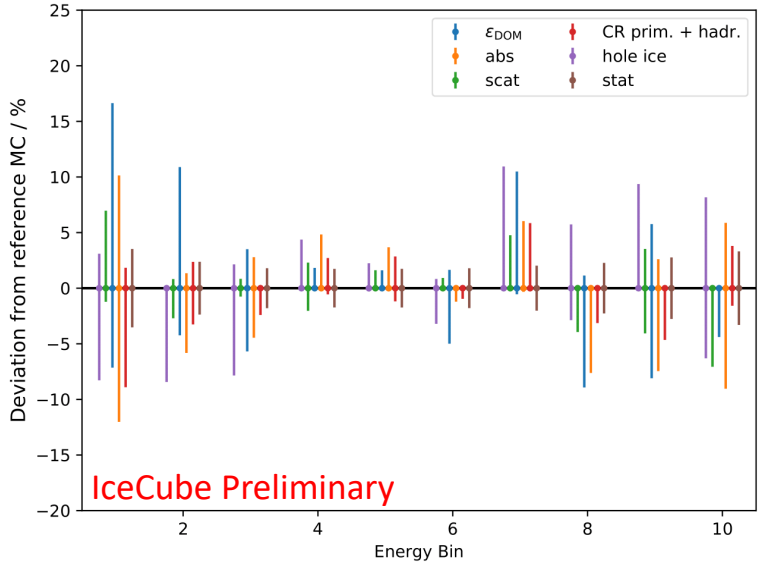
$$\sigma_{\text{sys}} = \sqrt{\sigma^2_{\text{DOM}} + \sigma^2_{\text{abs}} + \sigma^2_{\text{scat}} + \sigma^2_{\text{holeice}} + \sigma^2_{\text{flux}}}$$

Unfolding of pseudo-data with varied parameter & evaluation to reference MC

systematics are independent on sample size

- DOM efficiency $\pm$10%
- Ice model
  - absorption $\pm$ 5%
  - scattering $\pm$ 5%
  - Hole ice parameter $\pm$ 1%
- CR composition
  hadr. interaction model

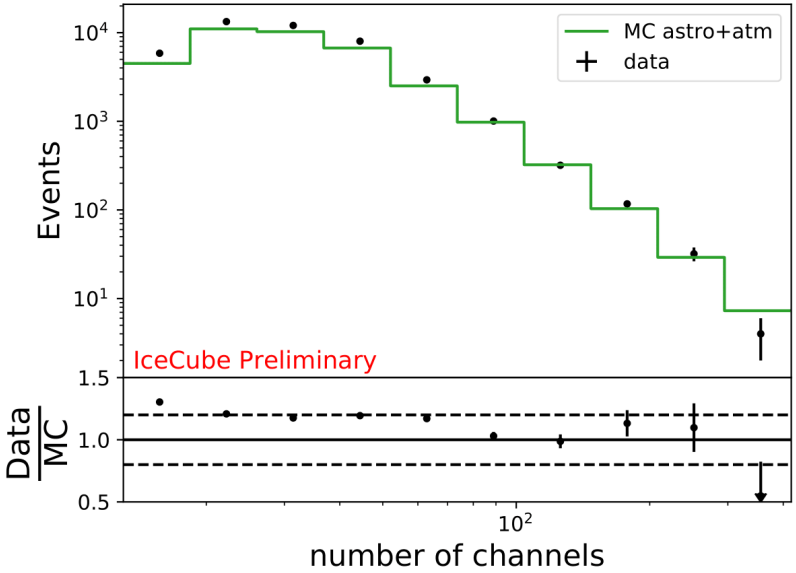
Fedynitch et al., Phys. Rev. D 86 (2012)

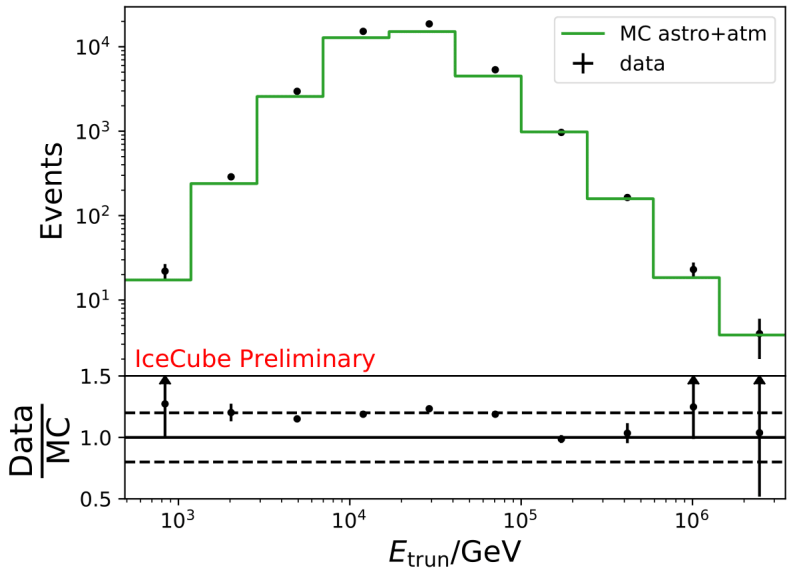


Data-to-MC Agreement

Weights: MCEq (SIBYLL 2.3c / H3a / NRLMSISE-00)

+ astrophysical: $1.44 \cdot 10^{-18}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1} \cdot E^{-2.37}$ @ 100TeV





Agreement in shape, but offset: ~20% → atmospheric normalization