Seasonal Variations of the Unfolded Atmospheric Neutrino Spectrum with IceCube

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SFB 876 Providing Information by Resource-Constrained Data Analysis

ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

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Introduction

The atmospheric neutrino flux is imposed to seasonal variations caused by temperature changes in the Stratosphere at energies above 100 GeV [1-3]. Being currently the largest neutrino detector on Earth, the majority of neutrinos detected by IceCube is of atmospheric origin. The detector itself is installed in the ice at the geographic South Pole between depths of 1450m and 2450m. Reconstruction of the direction, energy and neutrino flavor relies on the optical detection of Cherenkov radiation [4].

This analysis aims to investigate the detection of seasonal variations of the atmospheric muon neutrino energy spectrum from 8 years of IceCube data using unfolding techniques.

Seasonal Variations

The flux of atmospheric neutrinos is produced by kaon and pion decays within cosmic ray air showers:

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

with the primary cosmic ray flux $\phi_N(E_\nu)$ of nucleon N at neutrino energy, decay branching ratios $A_{i\rightarrow\nu}$ and cross sections $B_{i\rightarrow\nu}$ [5]. The denominator defines whether the neutrino flux is dominated by kaon and pion decays of the production of secondary mesons. At critical energies $\varepsilon_\pi \approx 125$ GeV / $\varepsilon_K \approx 850$ GeV above $E_\nu \cos\theta^*$ at the zenith angle θ^* at neutrino production, the latter process is favored, and the neutrino spectrum steepens. The flux becomes proportional to the stratospheric temperature in the atmospheric isothermal approximation of the ideal gas law.

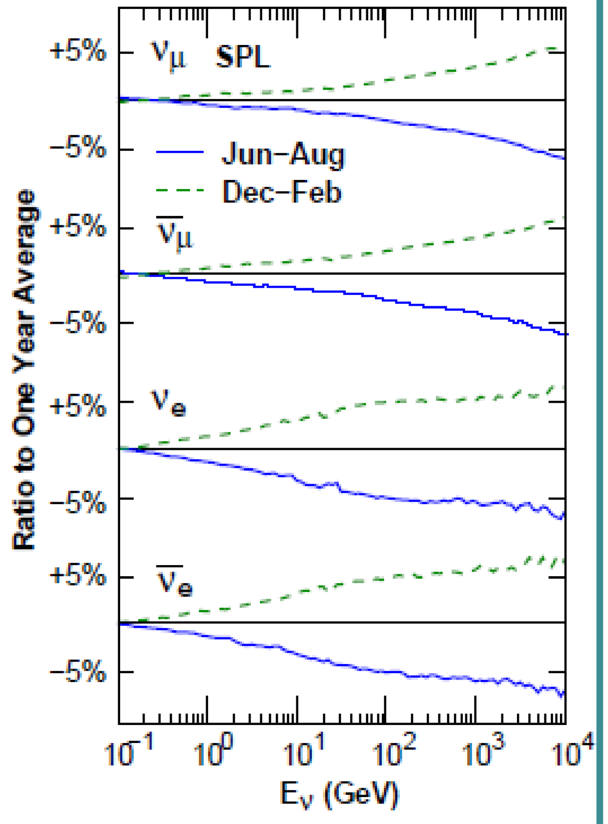

Fig. 1: Calculated neutrino flux at South Pole based on the NRLMSISE-00 model [17] of the Earth's atmosphere [6]. As expected, a distinct variations is observable above ε_i.

Spectrum Unfolding

The inverse problem [7,8]:

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

- Goal: Reconstruction of energy distribution $\vec{f}(E_\nu)$
- Indirect neutrino detection via induced muons
- Challenging reconstruction due to stochastic energy losses and limited detector resolution
- Smearing of energy reconstruction represented by response matrix A
- Estimation via detector variables y

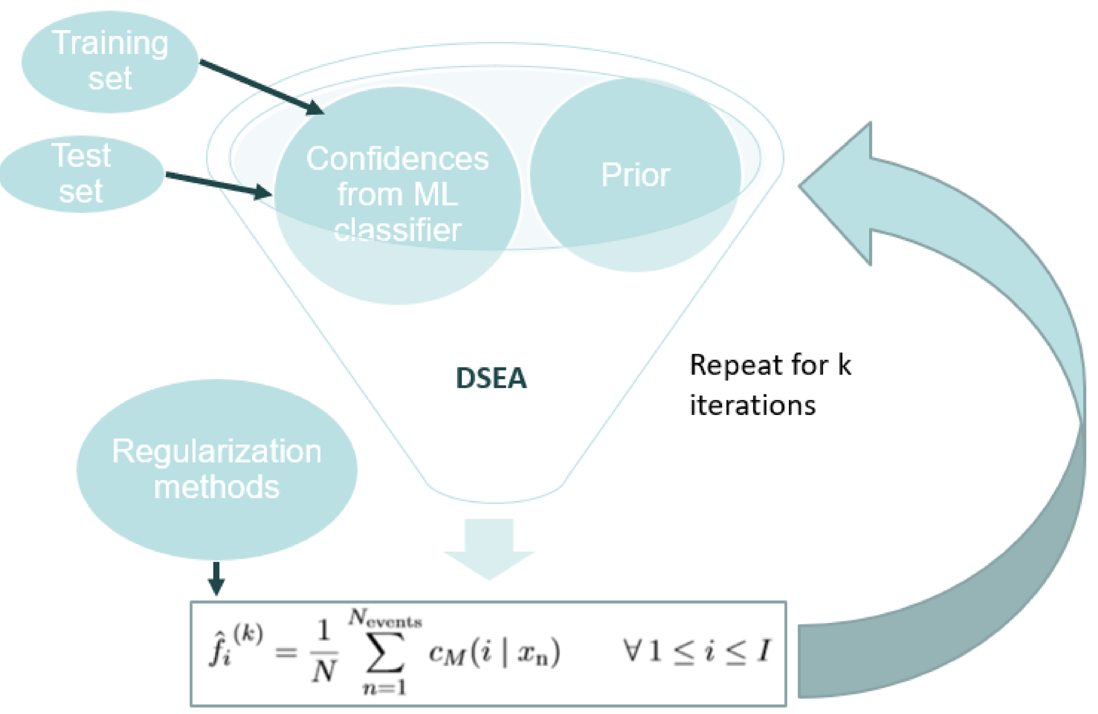

Fig. 2: Workflow of the iterative Dortmund Spectrum Estimation Algorithm (DSEA) [9,10]. The spectrum reconstruction is regarded as a classification task in supervised machine learning (ML). The selected ML algorithm is trained on Monte Carlo (MC) events, the number of events per energy bin i is predicted by accumulating the classifier's confidences c_M for each event x_N.

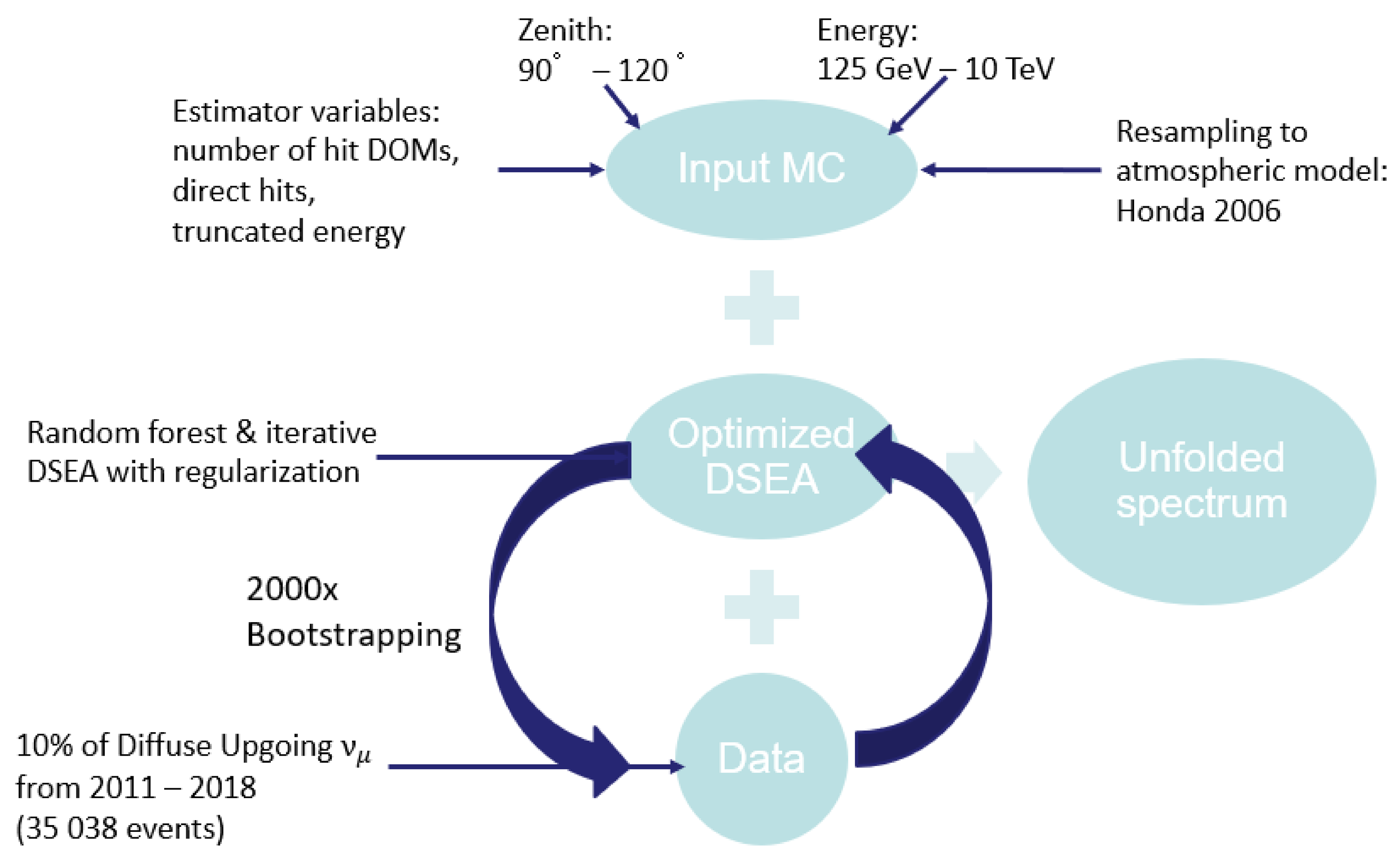

Fig. 3: Illustration of the unfolding procedure. DSEA's internal parameters are selected in a 10-fold cross-validation on the smallest Wasserstein Distance [11]. The input Monte Carlo simulation (MC) is sampled according to the atmospheric flux model Honda 2006 [12]. Definitions of the energy-dependent estimator variables are given in [13,14]. The data set is sampled via replacement and unfolded with iterative DSEA. The unfolded spectrum is determined by the average, the standard deviation accounts for the statistical fluctuations.

Systematic uncertainties imposed by the detector simulation and variable reconstruction are estimated by treating MC events with scaled parameters as pseudo-data. The uncertainty of the parameter variation is determined by the ratio to the reference result. The parameters are scaled by:

- DOM efficiency ε_{DOM} $\pm$ 10%
- Absorption and scattering coefficient in ice model [15] : - 7% / +10%
- Flux model Honda 2006 [12]

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

Since we aim to estimate the flux ratio between seasons, further systematic parameters, such as the primary cosmic ray composition, are negligible.

Results

The Diffuse Upgoing Event Sample [16] is divided into separate seasons and unfolded as illustrated in Fig. 3. In addition, the detection of seasonal variations of the atmospheric neutrino spectrum is investigated on MC simulations in Fig. 4.

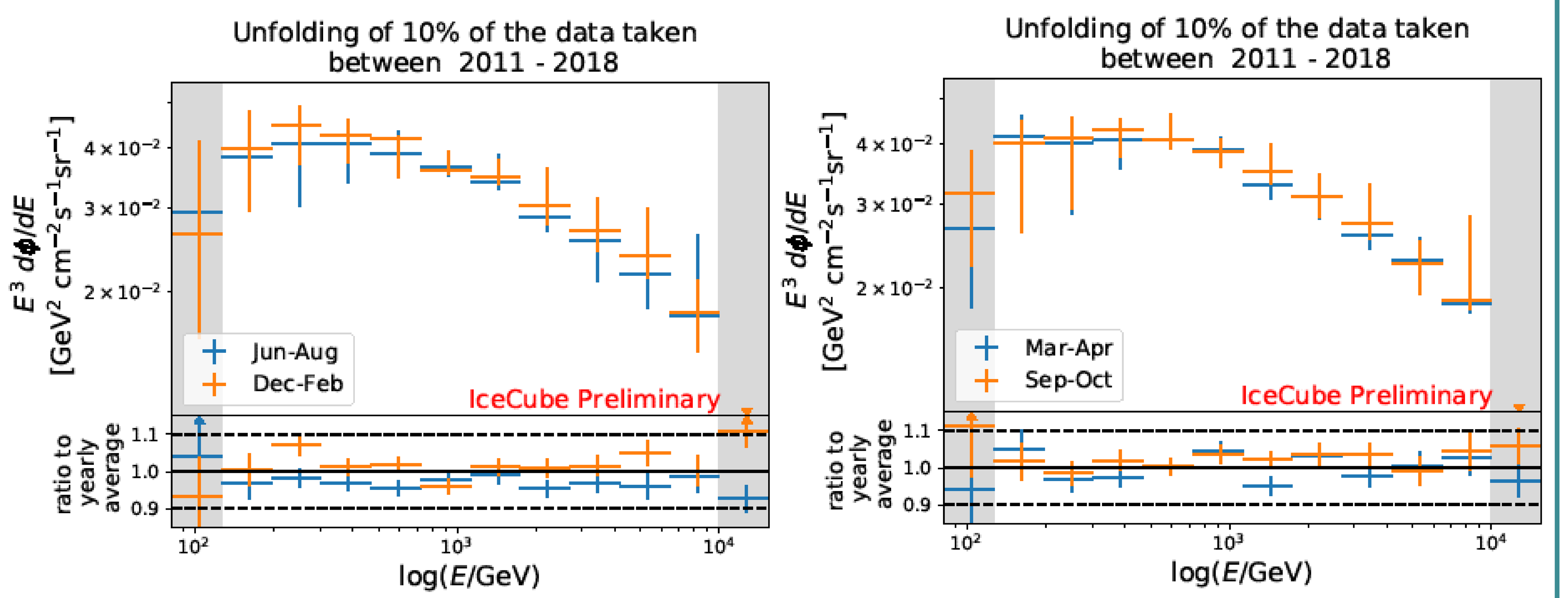

Fig. 4: Unfolded seasonal neutrino spectra including statistical and systematic uncertainties. The ratio to the unfolded energy spectrum averaged over all seasons is displayed below. Systematic uncertainties are negligible in this illustration since the uncertainties of all investigated parameters is supposed to remain constant for all seasons. Despite large statistical fluctuations because of the small size of the data sets, initial tendencies towards an increased flux for the Austral summer (Dec-Feb) is observable. As expected, the spectra for the spring and autumn season agree with the average flux.

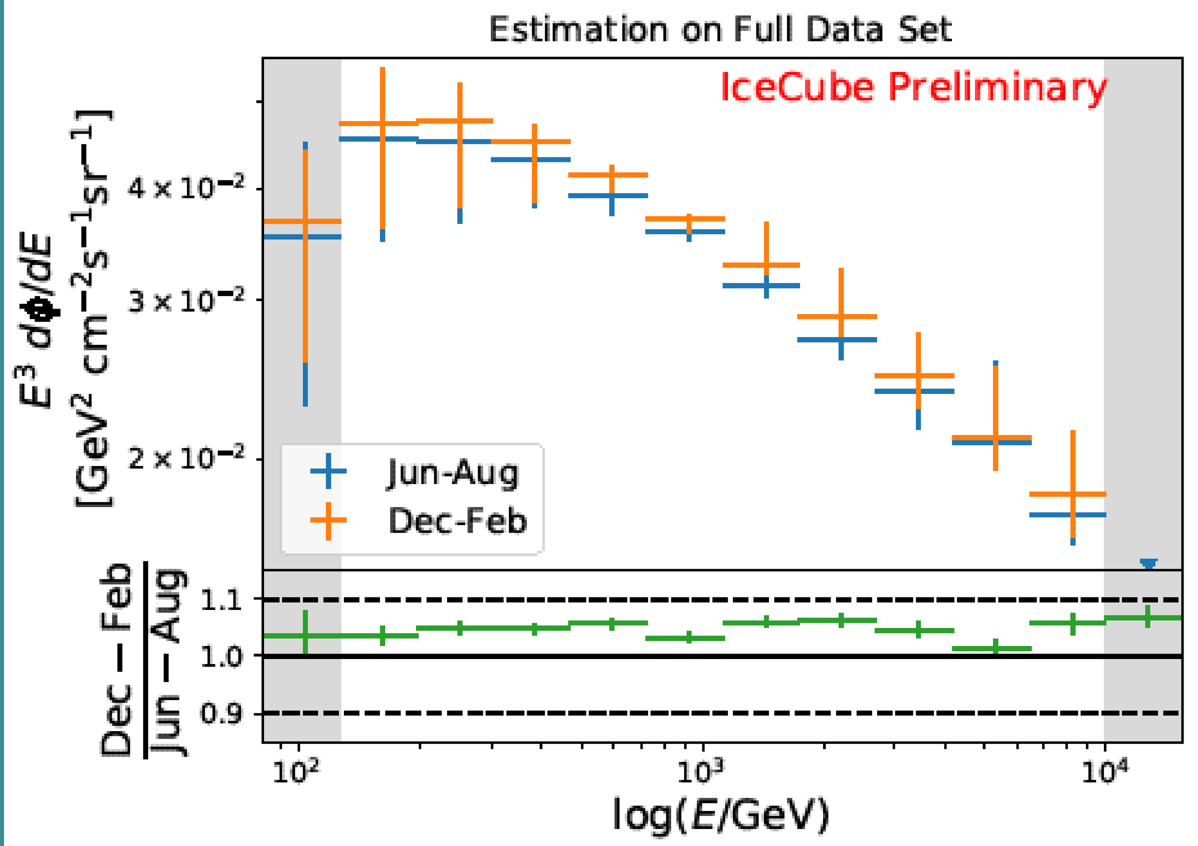

Fig. 5: Estimation of seasonal spectra using MC as pseudo-data. The number of events and the corresponding livetime is increased by a factor of 10. The simulation sets are reweighted according to the seasonal flux model provided by Ref. [6]. The unfolded spectra agree within the uncertainties. However, regarding the ratio of both seasons within statistical uncertainties, an increased flux is expected for the Austral summer (Dec-Feb). The statistical uncertainties decrease by the square root of ten compared to the test on 10% of the data taken between 2011 and 2018.

Conclusion and Outlook

The analysis, being independent of systematic uncertainties in the detector simulation and flux model assumptions, holds a great potential for detecting seasonal variations by the ratio of the atmospheric neutrino energy spectra with IceCube data. Further improvements of this analysis are in progress. The significance of the measured variations with respect to the annual mean will be determined on 10% of the data taken between 2011 to 2018 before expanding the data set to all events in the time frame. Using the full 9-year data sample will potentially allow measurements of the seasonal neutrino spectra with sufficient statistics for the first time.

References

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