Unfolding of the Muon Neutrino Energy Spectrum with IceCube

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IceCube

- IceCube is a cubic-kilometer detector located at the geographic South Pole. In the deep ice (1.5 km to 2.5 km) below the surface, 86 strings are deployed.
- Each string contains 60 Digital Optical Modules (DOMs) with PMTs to measure Cherenkov radiation of high energy leptons propagating in the ice.
- IceCube is a multipurpose detector able to measure many different particles. In this poster we focus on muon neutrinos measured with IceCube in its 79 string configuration.
- Muon neutrinos can interact with matter via neutral current or charged current interactions. In a charged current interaction a high energy muon is produced. This muon propagates through the rock and the ice before it enters into the detector and can be measured.
- Because of this IceCube has a big effective volume for muon neutrinos. The pointing accuracy of muon neutrinos is high because of the track like structure. Since the track is just partly contained, energy reconstructions of muon neutrinos is more difficult.

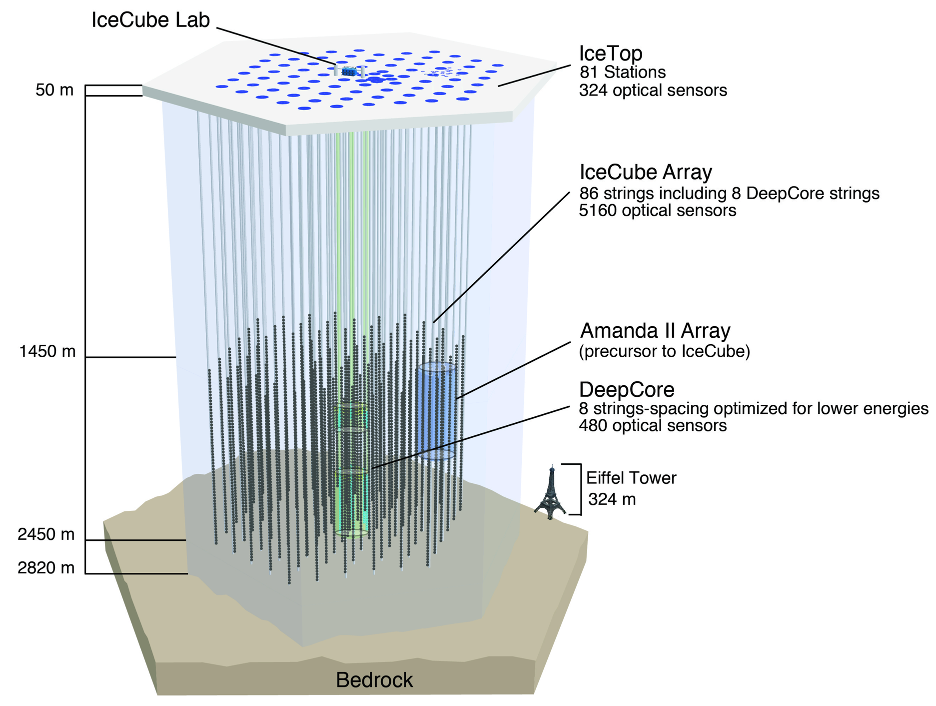


Figure 1: The IceCube detector located at the geographic South Pole including the low energy extentsion DeepCore and the air shower array IceTop.

Analysis

Separation

- The IceCube data is highly dominated by atmospheric muons. To remove them precuts are introduced to select up going track like events. Because of mis-reconstructions the background still remains dominant after these cuts.
- To remove background even further a Breiman Random Forest [1] is used. The observables used to train this random forest were obtained using a minimum redundancy maximum relevance feature selection [2].

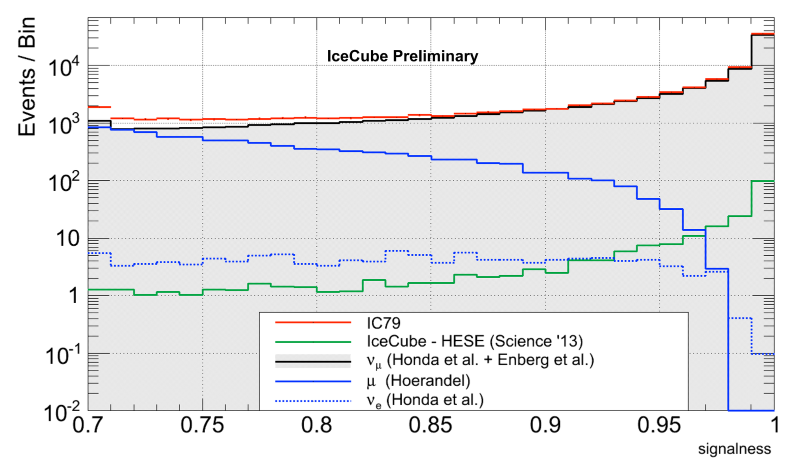


Figure 1: Distribution of the scoring of the Random Forest. Higher values indicate higher signal probability. The cut to distinguish between neutrinos and background was applied at 0.92.

- The obtained sample has a purity of (99.5 +/- 0.03)%. The error was obtained using a 150 fold bootstrap validation. The same validation also showed that the remaining background is at low energy.

Unfolding

- The determination of the energy spectrum is a so called 'inverse problem'. It can be written as a matrix equation of the form:

$$\vec{g} = \underline{\underline{A}}\,\vec{f}$$

- Here *g* is the histogram of the measured variables, *f* describes the energy and **A** is the response matrix.
- Since the problem is ill-posed a simple matrix inversion does not solve the problem. Instead a regularized likelihood fit is performed using Thikonov regularization with the 2nd derivative.

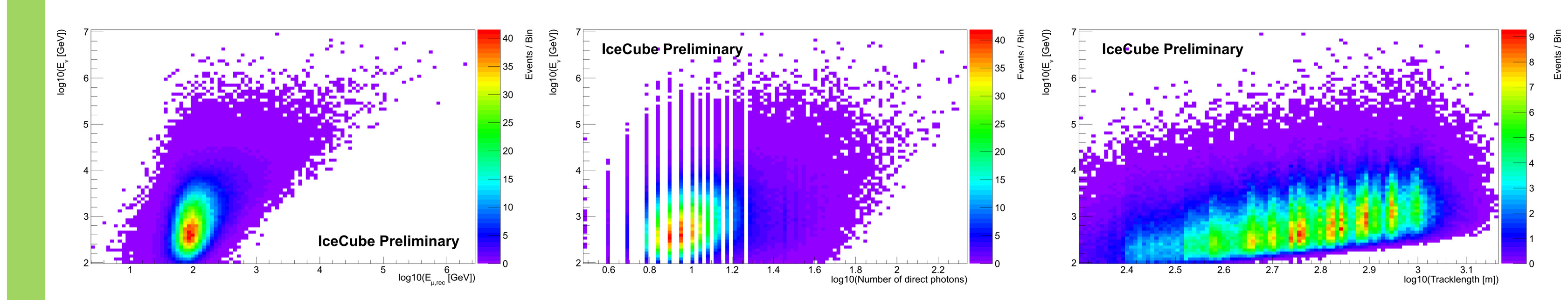


Figure 2: Correlation plots for the observables used in this unfolding. The used observables are: a) reconstructed muon energy, b) number of direct photons and c) track length in the detector.

- The unfolding was performed using the software TRUEE [3] which uses a 3D likelihood fit. Thus it is possible to use up to three observables for the process.

Results

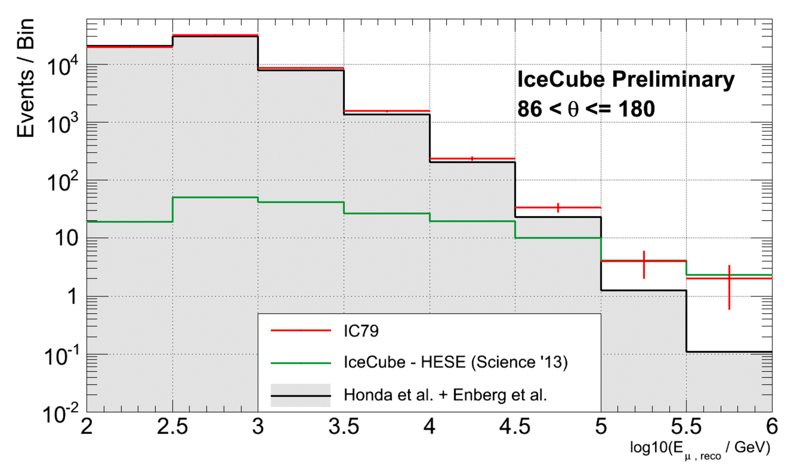
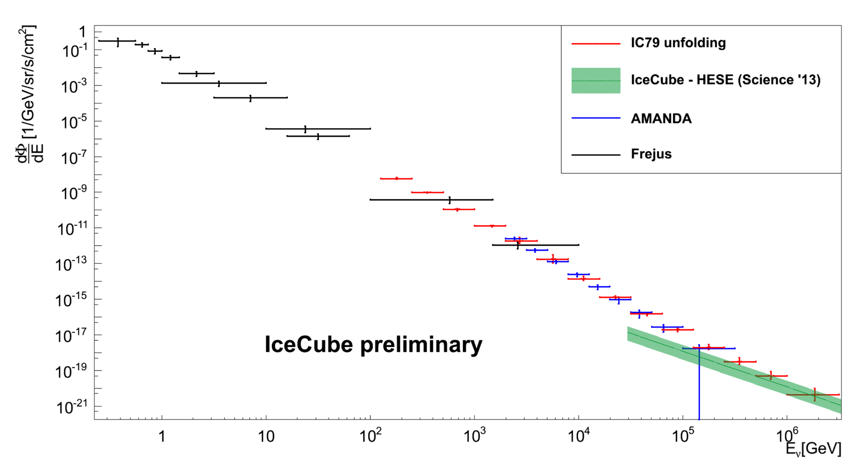


Figure 3: Spectrum of reconstructed muon energy compared to predictions for atmospheric neutrinos based on [4] and [5] as well as a signal as seen in [6].

- In total more than 63 000 events were detected. The spectrum of the reconstructed muon energy is shown in figure 3 and coveres more than 4 decades in energy.
- There is a clear excess in reconstructed muon energy which can be described well with the recent measurement published by IceCube [6].



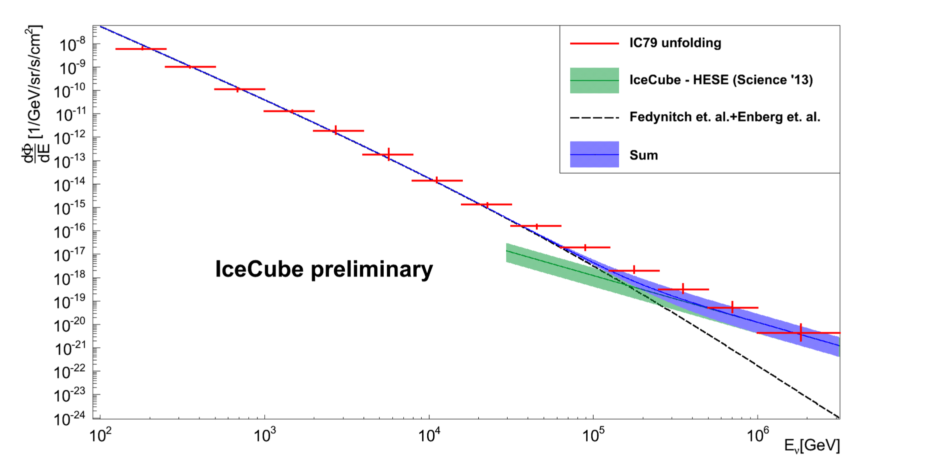


Figure 4a: Unfolding results compared to other measurements including AMANDA [7], and Frejus [8], and the recently published IceCube results [6].

Figure 4b: Unfolding results compared to atmospheric models calculated in [5][9] and recently published IceCube results [6].

- The unfolding covers an energy range of more than four decades and has an excess over the atmospheric prediction above 100 TeV.
- This excess can be explained by astrophysical neutrinos as seen in [6].
- In energy regions dominated by atmospheric neutrinos, good agreement with other measurements, as well as atmospheric predictions can be observed.

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