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 paper 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.

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].

Unfolding

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

$\mathbf{g} = \mathbf{A} \cdot \mathbf{f}$

• Here $\mathbf{g}$ is the histogram of the measured variables, $\mathbf{f}$ describes the energy and $\mathbf{A}$ 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 Tikhonov regularization with the 2nd derivative.

• 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

• In total more than 63 000 events were detected. The spectrum of the reconstructed muon energy is shown in figure 3 and covers 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 1: The IceCube detector located at the geographic South Pole including the low energy extension DeepCore and the air shower array IceTop.

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.

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].

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] and recently published IceCube results [6].

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