Atmospheric muon and electron neutrino energy spectrum measured by first year of IceCube-86 detector

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Abstract. The flux of atmospheric neutrinos is the main background for searches for cosmic neutrinos. Precise measurement of its spectrum allows us to reduce uncertainty of any kind of signal analysis. A unified analysis of atmospheric neutrinos using data collected with the full IceCube detector between May 2011 and May 2012 is presented in which both muon and electron flavors are included in a single framework.

1. Introduction

Atmospheric neutrinos are produced through interactions of cosmic rays with nuclei in the Earth’s atmosphere. Atmospheric neutrinos with GeV energies are a high flux source for neutrino oscillation studies, while above energies of 100 TeV they constitute an important background in the search for astrophysical neutrinos. They also probe properties of the primary CR spectrum and of their hadronic interactions, such as the kaon to pion ratio. Muon and electron neutrinos from the decay of pions and kaons are referred to as ‘conventional’ atmospheric neutrinos, while neutrinos from the decay of mesons containing charmed quarks are a distinct component of atmospheric neutrinos called ‘prompt’ neutrinos.

The IceCube neutrino observatory, located at the South Pole, detects Cherenkov photons produced by charged particles propagating through the Antarctic ice [1]. When neutrinos interact in the ice, they produce two types of Cherenkov signatures, ‘tracks’ and ‘cascades’. Track-like events are produced by muons from the charged current (CC) interaction of muon neutrinos. Cascade-like events are produced by electromagnetic and/or hadronic showers of CC interactions of electron neutrinos as well as neutral current (NC) interactions of all neutrino flavors.

IceCube has measured the spectrum of conventional atmospheric muon and electron neutrinos in separate analyses [2][3][4]. Some uncertainty remains, especially in the electron neutrino flux, because the cascade sample is small, and it is dominated by muon neutrinos. In this paper we describe a unified approach to measure the muon and electron neutrino spectrum in a single analysis by combining the track and cascade samples. Due to the large amount of events and purity of flavor, it is possible to determine the muon neutrino flux with high precision based on the track sample. In this way, uncertainties in parameters common to both flavors (primary
spectrum, kaon/pion ratio, etc.) can be reduced in the analysis of the cascade sample [5]. The result from data taken in the first year of operation of the full IceCube detector is presented.

2. Event Selection
Track and cascade type samples for this analysis are selected from the first year of IceCube 86 full string data, which was obtained between May 2011 and May 2012. The track sample consists of 54966 up-going neutrino induced muons with a contamination from CR muons below 0.1% [5]. As cascade sample, this analysis uses 1078 events, which has been selected for the electron neutrino flux measurement in [4].

Figure 1 shows distributions of track and cascade events using data taken in the first year of operation of the full IceCube detector. The black points represent the measured neutrino flux. The colored curves are the expected atmospheric and astrophysical neutrino flux, simulated separately for each component using the same primary CR spectrum for the conventional and prompt atmospheric neutrinos.

3. Analysis Method
The conventional atmospheric neutrino spectrum is determined using a maximum log-likelihood fitting method. A baseline model of the conventional muon and neutrino spectrum is defined, then physics parameters are implemented to modify the baseline model spectrum during the fitting procedure. We choose the Honda2006+GaisserH3a knee model [7] as baseline.

To modify the baseline conventional atmospheric neutrino spectrum, we vary the following three spectral parameters. A normalization parameter scales up/down the conventional atmospheric neutrino spectrum. A second parameter shifts the spectrum index. The Kaon-to-pion ratio in extensive air showers also affects the shape of the atmospheric neutrino spectrum, which is parameterized using the analytic approximation in [8]. In addition to the physics parameters, detector related systematic uncertainties, optical efficiency of a Digital Optical Module (DOM) and optical properties of the surrounding ice are included in the fit as nuisance parameters with DOM efficiency as continuous (float) and three ice properties as discrete parameters. The best fit parameters are calculated maximizing the combined likelihood for the track and cascade samples. Detail formulations of modified model spectrum and loglikelihood function are described in [5].
Figure 2. Atmospheric neutrino flux determined in this analysis (thick lines and band) in comparison to model predictions (thin / dashed lines). Points with error bars reflect measurements by Super-K (circles) and former analysis of IceCube data (triangles).

4. Result

Figure 2 summarizes the results of the fit of the conventional electron and muon neutrino flux. The left panel shows the spectrum, while the right panels show the ratio between the best fit and the baseline model. The solid blue and red lines are the determined muon and electron neutrino spectrum from this analysis with the band denoting 90% of the statistical uncertainty obtained from the fit parameters and errors therein. The other lines represent the baseline HKKM7+H3a knee model flux [6] (blue or red thin lines), the original HKKM7 model flux [9] (blue or red dashed lines) and the latest HKKM14 model flux [10] (green dashed lines). Data points represent are measured flux from Super-K [11] (circles) and IceCube in the past [2][3][4] (triangles).

The determined muon neutrino spectrum (thick blue line) is consistent with the HKKM model spectrum (dashed lines) at low energy, then aligns well with the HKKM7+H3a knee model (thin blue line) at high energy. The determined electron neutrino spectrum (thick red line) has a lower best fit flux than any depicted model, yet the predicted fluxes are covered by the uncertainty band. Systematic uncertainties of this analysis are characterized by theoretical uncertainties and other detector systematics. Prompt and astrophysical flux are the main sources of theoretical uncertainties to the electron neutrino flux, which have been evaluated in [5]. Other detector systematics that have little effect on this analysis have not been included as nuisance parameter, will be added to the systematic estimation. The detail of which are under investigation.

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