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Atmospheric muon and electron neutrino energy spectra from IceCube

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A framework for a unified analysis of high-energy atmospheric neutrinos with the full IceCube is presented in which both muon and electron flavors are included in a single analysis. Combining the IceCube measurements at high energy with measurements from smaller detectors at lower energy will, in the future, determine the atmospheric neutrino flux from <100 MeV to >100 TeV. Precise knowledge of the spectrum will lead to reduced uncertainty for any kind of signal analysis.
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1. Introduction

Atmospheric neutrinos produced through interactions of cosmic rays with nuclei in the Earth's atmosphere constitute an important background in the search for astrophysical neutrinos. They also probe properties of the primary spectrum and of hadronic interactions, such as the kaon to pion ratio. Muon and electron neutrinos from decay of pions and kaons are referred to as "conventional" atmospheric neutrinos. Most conventional atmospheric neutrinos are muon neutrinos from two-body decays of pions and kaons. Conventional atmospheric electron neutrinos are primarily from subsequent muon decay at low energies (< 1 TeV), while three-body decays of charged and neutral kaons give the main contribution to electron neutrinos at higher energy above 1 TeV. The spectrum of conventional neutrinos becomes asymptotically one power of energy steeper than the primary spectrum at high energy. Prompt neutrinos from the decay of mesons containing charmed quarks are a distinct component of the atmospheric neutrino flux. Because of the short lifetime of charmed hadrons, prompt neutrinos have a spectrum similar to the primary cosmic-ray spectrum. Fluxes of prompt electron neutrinos and prompt muon neutrinos are nearly identical to each other, and they become the dominant source at sufficiently high energy, $\geq$100 TeV for electron neutrino, and $\geq$1 PeV for muon neutrino.

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 hadronic showers from the CC interactions of electron neutrinos, or hadronic showers from neutral current (NC) interactions from any kind of neutrino flavors.

IceCube has measured the spectrum of atmospheric muon neutrinos [2] and electron neutrinos [3] in separate analyses. Some uncertainty remains, especially in the electron neutrino flux, because the cascade sample is small, and it contains multiple components. In this paper we describe a unified approach to measure the muon and electron 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 from the track sample. In this way, uncertainties in parameters common to both flavors (primary spectrum, kaon/pion ratio, etc.) can be reduced in the cascade analysis. In this paper, the event selection criteria for both track and cascade samples are introduced. The feasibility of the unified analysis has been tested by applying the event selection to simulated data. The statistical sensitivity from one year of IC86 full data sample and additional systematic effects are estimated and discussed.

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. Event selection criteria for both samples are established by using simulation and 10% sample of the data. The remaining 90% of data is blinded to avoid experimenter's bias at this stage.

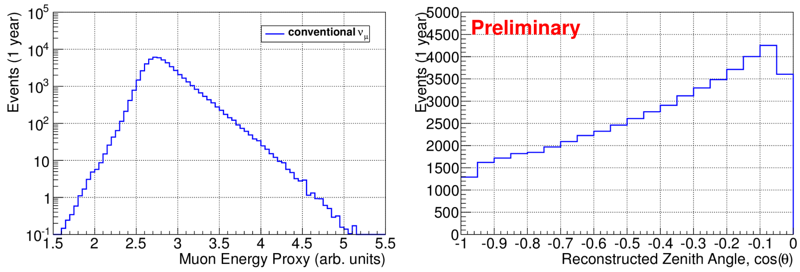


Figure 1: Event distribution of track sample from a simulation of the conventional muon neutrino flux, for reconstructed muon energy (left) and reconstructed zenith angle (right).

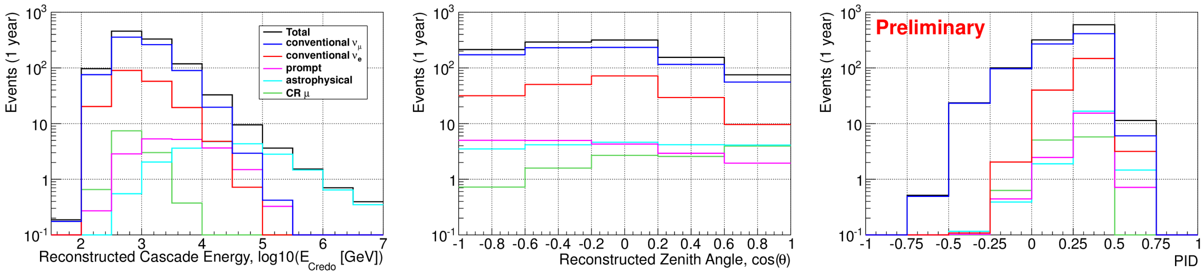


Figure 2: Event distribution of cascade sample for reconstructed energy (left) reconstructed zenith angle (center), and particle identification (right). Simulation of conventional muon neutrinos (blue), electron neutrinos (red), the sum of muon and electron prompt neutrinos (magenta), astrophysical neutrinos (cyan), cosmic ray muon background (green), and total flux (black) are shown.

IceCube has a $\sim$2.2kHz typical trigger rate of events with more than eight sensors recorded in a 5μsec time window, and each triggering sensor is required to have local coincidence with a nearby sensor within $\pm 1\mu$sec. Most of the triggers are from cosmic ray muons produced in air showers, and are the background for this analysis. To eliminate this background, simulation data sets are generated for both signal and background, then different cuts are applied to select the two types of signals. Signals of muon and electron neutrinos are simulated with our own module which is based on the ANIS package [4]. The background of atmospheric muons is simulated with CORSIKA [5].

Track Sample: Muons from CC interactions of muon neutrinos are detected as track events in IceCube. However at trigger level most of the track events are from background cosmic ray muons, and are detected as down-going tracks. After the track reconstruction, down-going events are rejected, yet many background events remain due to a misreconstruction of the zenith angle. Further quality cuts are applied to select a pure sample of neutrino induced muons [6]. From first year of IceCube 86, 5526 remained after all cuts are applied to a 10% sample of the data. The remaining background contamination is at the 1% level.

Cascade Sample: Cascade type events are created by electromagnetic and hadronic showers. Since it is not possible at present to distinguish between hadron and electromagnetic showers, the cascade sample includes muon neutrino events from NC interaction, and electron neutrino events from both CC and NC interaction. Charged current interactions of muon neutrinos that start inside the detector can sometimes be classified as cascades if most of the energy goes into the initial hadronic cascade vertex. This analysis uses cascade samples which had been selected for the electron neutrino measurement [3], in which the selection has been optimized by a Boosted Decision Tree (BDT). In total 86 events remained with 10% sample of the data. The breakdown of the cascade signal is 69% events from conventional muon neutrino flux (60% CC, 40% NC), 17% from conventional electron neutrino flux (92% CC, 8% NC), 11% from cosmic ray muon background, and the remaining 3% from prompt and astrophysical neutrinos.

Event Distribution: Figure 1 and 2 are simulated event distributions of track and cascade events corresponding to the first year of the IceCube 86 string. The colored curves are baseline distributions of expected neutrino flux, simulated separately for each component using the same primary spectrum with separate spectrum models of conventional, prompt and astrophysical neutrinos, as explained in the next section. Distributions are binned into reconstructed muon/cascade energy and zenith angle, for this analysis. We see in the cascade sample that each component has a different characteristic distribution, and these can be distinguished in the fit. The cascade sample analysis also uses additionally the particle identification (PID) number, ranging from -1 (track like events) to +1 (cascade like events), determined from the BDT score, to distinguish CC muon neutrino event from cascades. Additionally, the expected primary neutrino energy distributions of conventional muon neutrinos in the track sample, and conventional muon and electron neutrinos in the cascade sample are shown in Figure 3.

3. Analysis Method

The conventional atmospheric neutrino spectrum is determined with a maximum log-likelihood fitting method. A baseline model of conventional muon and neutrino spectrum is defined, then physics parameters are implemented to modify the baseline model during fitting procedure.

3.1 Model Spectrum

For the conventional atmospheric neutrino spectrum, the Honda2006+GaisseH3a Knee model is chosen. The low energy flux from Honda et al.[7] valid to 10 TeV is extrapolated to higher energy. Then the cosmic ray knee effect [8] is implemented by folding the neutrino yield per primary cosmic ray with the assumed primary spectrum and composition. Other components of the neutrino flux, prompt and astrophysical neutrinos, are included as the background of cascade sample. For the prompt flux, the Enberg model [9] is assumed with the cosmic-ray knee effect. For astrophysical neutrino flux, $10^{-8} \cdot E^{-2}[\mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{str}^{-1}]$ per flavor spectrum is assumed, which is consistent with the recent IceCube result $0.95 \times 10^{-8} \cdot E^{-2}[\mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{str}^{-1}]$ [10]. Figure 4 is the summary of the baseline spectrum.

3.2 Fit Parameters

The following physics parameters are allowed to vary and modify the baseline model assumptions of this analysis

Normalization, C_{ν_μ}**,** C_{ν_e}: Normalization parameters C_{ν_μ} and C_{ν_e} scale up/down conventional atmospheric neutrino spectrum, implemented for muon neutrino and electron neutrino. In addition, another normalization parameter, C_{CR}, is implemented for the cosmic-ray muon background in the

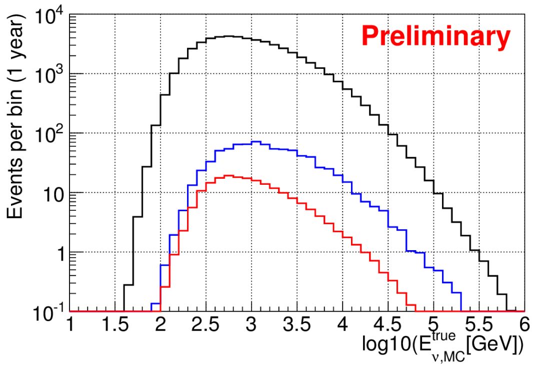


Figure 3: Primary neutrino energy distribution of muon neutrino in track sample (black), muon neutrino in cascade sample (blue), electron neutrino in cascade sample (red) from simulation after event selection.

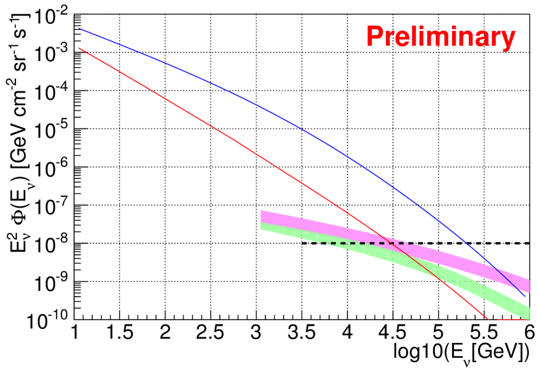


Figure 4: Honda2006+GaisseH3a Knee model of conventional muon neutrino (blue) and electron neutrino (red), prompt neutrinos from Enberg (magenta) and BERSS (light green), astrophysical neutrino (black dashed).

cascade sample.

Spectrum Index, $\Delta\gamma$: This parameter shifts the spectral index of the conventional atmospheric neutrinos. The same value is used for muon neutrino and electron neutrinos to reflect the common uncertainty in the primary cosmic-ray spectrum.

Kaon to Pion ratio, $R_{K/\pi}$: The kaon/pion ratio in extensive air showers affects the shape of the atmospheric neutrino spectrum. To implement this parameter, we use the following analytic approximation [11] for the sum of muon neutrinos and anti-neutrinos,

$$\begin{aligned} \phi_{\nu_\mu}(E_\nu) &= \phi_{\pi\to\nu_\mu} + \phi_{K\to\nu_\mu} \\ &= \phi_N(E_\nu) \times \left\{ \frac{Z_{N\pi}A_{\pi\nu}}{1+B_{\pi\nu}\cos\theta^* E_\nu/\varepsilon_\pi} + \frac{Z_{NK}A_{K\nu}}{1+B_{K\nu}\cos\theta^* E_\nu/\varepsilon_K} \right\} \end{aligned} \tag{3.1}$$

where the $A_{\pi,K\nu}$ and $B_{\pi,K\nu}$ are decay kinematic factors, described as combination of branching ratio, mass ratio and attenuation length of pion and kaon. $\cos\theta^*$ is the zenith angle where the neutrinos are produced, the critical energies are $\varepsilon_\pi = 115$ GeV and $\varepsilon_K = 850$ GeV. Z-factors ($Z_{N\pi}$ and Z_{NK}) are spectral-weighted moments of the inclusive cross section for a nucleon to produce secondary pions and kaons. At low energy the flux of conventional $\nu_e + \bar{\nu}_e$ is mostly dominated by the decay of muons from pions, however at high energy ($E_{\nu_e} > 100$ GeV) it is dominated by kaon contributions which is expressed as sum of the contributions from charged K, K-long and K-short [13],

$$\begin{aligned} \phi_{\nu_e}(E_\nu) &= \phi_{K\to\nu_e} + \phi_{K_L\to\nu_e} + \phi_{K_s\to\nu_e} \\ &= \phi_N(E_\nu) \times \left\{ \frac{Z_{NK}A_{Ke3\nu}}{1+B_{Ke3\nu}\cos\theta^* E_\nu/\varepsilon_K} \right. \\ &\quad \left. + \frac{Z_{NK_L}A_{K_Le3\nu}}{1+B_{Ke3\nu}\cos\theta^* E_\nu/\varepsilon_{K_L}} + \frac{Z_{NK_s}A_{K_se3\nu}}{1+B_{Ke3\nu}\cos\theta^* E_\nu/\varepsilon_{K_s}} \right\} \end{aligned} \tag{3.2}$$

where the parameters contain the branching ratios, attenuation lengths and Z-factors of K_{e3} decay. Critical energies of neutral kaons are $\varepsilon_{K_L} = 210$ GeV and $\varepsilon_{K_s} = 120,000$ GeV.

In the analysis, contributions of charged pion and charged kaon are modified by changing the ratio of Z-factors, $R_{K/\pi} = Z_{NK}/Z_{N\pi}$. The nominal value of K/pi ratio is taken to be $R_{K/\pi} = \frac{Z_{NK}}{Z_{N\pi}} = \frac{0.0118}{0.079} = 0.149 \pm 0.060$ which is based on laboratory measurements below 100 GeV center of mass energy[11]. The 40% uncertainty corresponds to that in the current cosmic ray interaction models [12]. In the fitting procedure, $R_{K/\pi}$ is floated with a constraint to keep the sum $Z_{N\pi} + Z_{NK}$ constant at its nominal value 0.0908. Change of expected neutrino flux from K/pi ratio is introduced as a weighting factor as $W_{K/\pi} = \frac{\Phi_\nu(R_{K/\pi})}{\Phi^0_\nu(R_{K/\pi}=1)}$

DOM Efficiency: In addition to the physics parameters, detector related systematic uncertainties are taken as a nuisance parameter. Currently one of the important detector systematics, optical efficiency of a Digital Optical Module (DOM) is implemented. Five different simulation data sets with different DOM efficiencies, ranging from -10% to +10%, are calculated. Final event rates in each bin are parameterized with these efficiencies. Another possible systematic uncertainty, optical properties of the surrounding ice, has not been taken into account, which will be included.

Fitted Model: With the physics parameters $C_{\nu_{\mu,e}}, \Delta\gamma, R_{K/\pi}$, the predicted neutrino flux is described as $\Phi_{\nu_{\mu,e}} = C_{\nu_{\mu,e}} \left(\frac{E_\nu}{E_\nu^{med}}\right)^{\Delta\gamma} W_{K/\pi}(R_{K/\pi}) \Phi^{h3a}_{\nu_{\mu,e}}$ where E_ν^{med} is the median energy of the analyzed event sample.

4. Loglikelihood Fitting

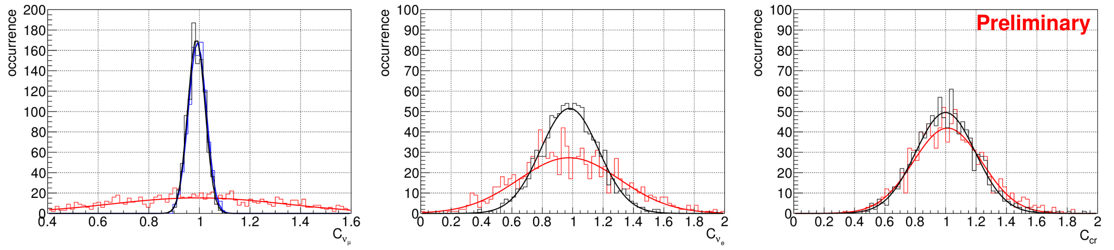
The likelihood $\mathscr{L}$ is calculated as the sum of the likelihood of the track sample and the cascade sample, with nuisance parameters constrained by an additional Gaussian term. Then the best fit parameters are obtained by minimizing the negative loglikelihood as

$$\begin{aligned} -2ln\mathscr{L} = & \; 2\sum_i \sum_j \left[\mu^{track}_{i,j} - n^{track}_{i,j} \ln \mu^{track}_{i,j} + \ln n^{track}_{i,j}!\right] \\ & +2\sum_i \sum_j \sum_k \left[\mu^{cascade}_{i,j,k} - n^{cascade}_{i,j,k} \ln \mu^{cascade}_{i,j,k} + \ln n^{cascade}_{i,j,k}!\right] \\ & + \frac{(DOM_{eff} - DOM^0_{eff})^2}{\sigma^2_{DOM_{eff}}} \end{aligned} \tag{4.1}$$

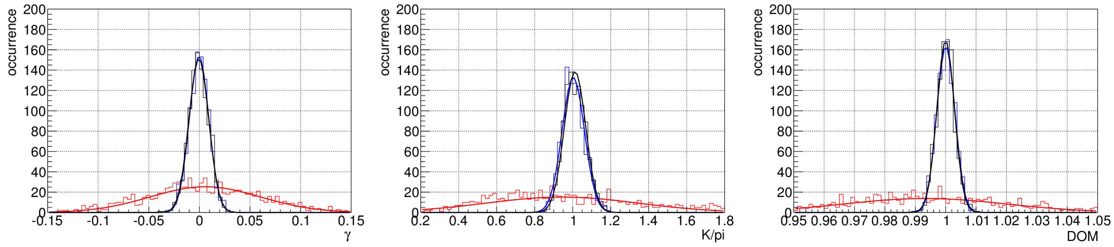
where $n_{i,j(k)}$ is the number of measured events, $\mu_{i,j(k)}$ is predicted events, at energy (i), zenith angle (j), and PID (k) bin. The first and second terms are respectively the loglikelihood of the track sample and the cascade sample. Predicted events are from conventional muon neutrino for the track sample, while all relevant components contribute to the cascade sample. In the last term from the nuisance parameter, DOM^0_{eff} is a central value, while $\sigma^2_{DOM_{eff}}$ is the prior uncertainty $\pm 10\%$.

5. Statistical Sensitivity

Statistical sensitivity to each fitted parameter is checked by analyzing artificial test data. Test data is generated from a simulation data set which corresponds to 100% full sample statistics of IC86 one year. Poisson random fluctuations are added to the test data in each bin. Then, maximum loglikelihood fitting is applied. In total, 1000 test data sets are generated. Then the distributions of determined fit parameters are evaluated. Figure 5 shows the histograms of fitted parameters from



(a) C_{ν_μ} (b) C_{ν_e} (c) C_{CR}



(d) $\Delta\gamma$ (e) $R_{K/\pi}$ (f) DOM Efficiency

Figure 5: Histogram of fitted parameters from 1000 trial of test data analysis from track + cascade sample (black), track sample only (blue), and cascade sample only (red).

1000 sets of trial test data. The black histograms are from the track + cascade combined analysis, while blue is from track sample only analysis, red is from cascade sample only analysis. Parameters C_{ν_e} and C_{cr} do not apply in the track sample only analysis. One sigma statistical uncertainties of each parameter are listed in the Table 1, for each case of track + cascade combined analysis, track only, and cascade only analysis. Since the track sample has many more events than the cascade sample, most of the parameters determined by the combined analysis are fixed by the track sample (e.g. C_{ν_μ}, $\Delta\gamma$ and $R_{K/pi}$). Since parameters are correlated each other, this reduces uncertainties of other parameters, that have previously been determined for the cascade only fit (e.g. C_{ν_e}).

6. Systematic Effect

Simultaneously, systematic uncertainties are checked by using simulated test data. Since in this analysis, fluxes of prompt and astrophysical neutrinos are fixed at baseline, we examine how different assumptions for those fluxes could change the results. Recently a new prompt flux called BERSS model [14] has been published, which has a lower flux than the Enberg flux previously used. A test analysis is applied by replacing the fitted model flux with BERSS, while test data is kept produced at Enberg flux. We got $+6\%$ higher C_{ν_e}, however no significant changes are confirmed in other parameters. The effect from astrophysical flux is also examined in the same way. The value in [10] has $\sim \pm 30\%$ uncertainty, so in extreme case twice of flux is assumed in fitted model flux. Then we got 3% lower C_{ν_e}, however no significant changes are seen in other parameters. Additional systematic uncertainties will be evaluated. The neutrino to antineutrino ratio is an uncertainty [12] and also an interest of this analysis, since it also affects the shape of atmospheric neutrino spectrum.

Table 1: Statistic and Systematic error of best fit. One sigma statistical uncertainties expected from test data analysis (Fig. 5) as well as systematic uncertainties are listed.

Fit Parameter	C_{ν_μ}	C_{ν_e}	C_{CR}	$\Delta\gamma$	$R_{K/\pi}$
			statistical		
Combined	±3%	±19%	±20%	±0.01	±6%
Track	±4%	-	-	±0.01	±6%
Cascade	±35%	±33%	±23%	±0.05	±40%
			systematic		
BERSS prompt model	-	+6%	-	-	-
2 × astrophysical	-	−3%	-	-	-

7. Summary

Conventional atmospheric muon and electron neutrinos will be measured from a combined data sample of track and cascade type events detected by IceCube. An event selection and analysis method has been established. Statistical sensitivity from first year of IceCube 86 string data is performed by test data produced by simulation, which is ±3% for conventional muon neutrino normalization, ±19% for conventional electron neutrino normalization, and ±0.01 for spectrum index. Statistical uncertainty in electron neutrino normalization will be reduced 43% by combining the track sample and the cascade sample. The statistical sensitivity of the kaon to pion ratio is ±6%, sensitive enough to compare with other experimental results [15]. Systematic effects are confirmed in electron neutrino flux, which have prompt and astrophysical neutrino flux model dependencies. Further investigation of model dependent effects will be done by assuming different neutrino fluxes.

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