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A measurement of the diffuse astrophysical muon neutrino flux using multiple years of IceCube data

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The IceCube Collaboration has observed a high-energy astrophysical neutrino flux using neutrino candidates with interaction vertices contained within the instrumented volume. A complementary measurement can be done with charged current muon neutrinos where the interaction vertex can be outside the instrumented volume. Due to the large muon range the effective area is significantly larger but the field of view is limited to the Northern Hemisphere. IceCube data from 2009 through 2012 have been analyzed by a likelihood approach with reconstructed muon energy and zenith angle as observables. While the majority of these events are atmospheric neutrinos, the highest energy events are incompatible with that interpretation. Assuming the astrophysical muon neutrino flux to be isotropic the data is well described by an unbroken power law with a normalization of $\left(0.66^{+0.40}_{-0.30}\right) \cdot 10^{-18}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ at 100 TeV neutrino energy and a spectral index of $\gamma = 1.91 \pm 0.20$. A purely atmospheric origin of the observed events can be rejected with a significance of 4.3σ. The found spectrum is harder compared to other IceCube measurements of astrophysical neutrinos which are dominantly based on neutrino-induced cascades. These measurements are sensitive to lower neutrino energies. Investigations about the nature of the observed differences are ongoing.

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1. Introduction

More than a hundred years after their discovery, the origin of high-energy cosmic rays is still unknown. The dominant fraction of cosmic rays are protons or heavier nuclei. High-energy neutrinos may provide unique information about the nature of sources and acceleration mechanisms of cosmic rays. High-energy neutrinos may be produced in hadronic interactions of cosmic-rays with surrounding matter at the acceleration sites. These neutrinos would reach Earth unaffected by magnetic fields and interactions with the interstellar medium and thus reveal the location of sources. Generic models of the neutrino spectrum [1, 2, 3], based on the acceleration of cosmic rays in strong shock waves predict a power law spectrum with a spectral index $\gamma \approx 2$.

The IceCube Neutrino Observatory is located at the South Pole. The detector instruments a volume of one cubic-kilometer of antarctic ice in a depth between 1450 m and 2450 m with optical sensors [4]. These photosensors measure Cherenkov light caused by charged particles originating from neutrinos interacting in the detector's vicinity. Neutrino events measured with IceCube can be broadly classified in two basic signatures: tracks and cascades. Long-lived muons from muon-neutrino interactions produce elongated track-like light patterns. Cascade-like spherical patterns are produced by neutral-current (NC) interactions of neutrinos of all flavors, and electrons produced in charged-current (CC) interactions of electron neutrinos[1].

The discovery of astrophysical neutrinos was based on a sample of neutrino events with interaction vertices well-contained within the instrumented volume [6]. Although these events provide a clear signature for an astrophysical neutrino flux, event statistics and directional pointing are only moderate because the effective volume is reduced by requiring containment and the fact that the sample is dominated by cascade-like events. In this analysis a complementary approach is used selecting high-energy muons induced by muon neutrino interactions that can occur outside the instrumented volume. However, this implies using the Earth as shielding to reject the dominant background of atmospheric muons and therefore constrain the field of view to the Northern Hemisphere. Evidence for a flux of astrophysical muon neutrinos has already been shown by previous IceCube analyses. The first hint at the level of 1.8σ was found with one year of IceCube data taken with the partial detector in the 59-string configuration [7]. A second analysis using two years of data from IceCube in its 79- and 86-string configuration excludes the only atmospheric origin of the observed flux with a probability of 3.7σ [8]. We present a combined re-analysis of the two datasets here that is based on a significantly larger sample of neutrino-induced tracks than the earlier analyses. The larger data sample statistics are dominated by conventional atmospheric neutrinos which improve the constrains on the atmospheric flux model uncertainties. With the combination of these datasets a unified approach for a measurement of the astrophysical muon neutrino flux has been prepared. In the next step the same approach will be used to analyze a total of six years of IceCube data recorded between 2009 and 2015.

The main background for such a measurement are atmospheric neutrinos produced in cosmic-ray interactions with the Earth's atmosphere. Conventional atmospheric neutrinos are produced in the decay of pions and kaons. The expected energy spectrum is about one power in energy softer than the primary cosmic ray spectrum due to the competition between decay and interaction of the

[1]CC tau neutrino interactions can produce either signature depending on the decay mode of the tau as well as a "double bang"-signature [5].

mesons. The conventional atmospheric neutrinos flux follows roughly a power law with a spectral index of about -3.7. Additionally, the interplay between decay and interaction of the mesons leads to a characteristic zenith angle distribution. The flux of conventional atmospheric neutrinos from near the horizon is enhanced because the air shower development occurs higher in the atmosphere and interactions become less likely.

In contrast to conventional ones, "prompt" atmospheric neutrinos are produced in the decay of mesons containing heavy quarks. Though this flux has not been observed to date, several predictions exist [9, 10, 11]. Due to the short lifetime of these heavy mesons the prompt atmospheric neutrino flux will follow the primary cosmic ray spectrum up to very high energies. The expected spectral power law index is about -2.7 and the flux is almost isotropic.

A flux of astrophysical muon neutrinos can be identified by an excess of high-energy events ($\gtrsim 100\,\mathrm{TeV}$) over the expectations from atmospheric neutrinos of more than about $100\,\mathrm{TeV}$. Since high-energy neutrinos can be absorbed in the Earth an isotropic neutrino flux at the Earth's surface is shifted towards the horizon. Due to the harder energy spectrum the absorption effect is stronger for an astrophysical flux than for the prompt and conventional atmospheric neutrino flux. Hence, the distribution of arrival directions of neutrinos at the IceCube detector depends on the energy spectrum of the flux. Therefore, the correlation between both quantities contains additional information to distinguish between the different components.

2. Analysis

2.1 Search Strategy

A neutrino sample with a negligible contribution of atmospheric muons is required to measure the flux of astrophysical muon neutrinos based on the distribution of the reconstructed muon energy and zenith angle.

The IceCube detector is triggered by atmospheric muons produced in cosmic-ray air showers at a rate of about 2.5 kHz. The signature of these events are downgoing tracks entering the detector from the outside. In order to reject these events we require reconstructed zenith angles to be larger than 85° which corresponds to more than 12 km of overburden. As a result the remaining background are either mis-reconstructed events or muons produced in interactions of atmospheric neutrinos. The reconstruction of muon arrival directions is done by fitting the hypothesis of a relativistic particle emitting Cherenkov light to the detection times of observed photons which takes into account the propagation effects of photons in the ice. A boosted decision tree trained on parameters that estimate the quality of the directional reconstruction is used to identify and reject mis-reconstructed events. Additionally, cascade-like events are rejected based on the topology of the hit pattern that is different for track-like events. The resulting sample of about 70,000 muon neutrino events per year has a very high purity with a contamination of atmospheric muons below 0.1 %. For all events in the neutrino sample the muon energy at the detector is reconstructed using the truncated mean energy loss reconstruction algorithm described in [12].

The expected zenith angle and muon energy distributions for the conventional, prompt and astrophysical components are computed from Monte Carlo simulations of neutrinos traversing Earth and interacting in the vicinity of the IceCube detector. A generalized weighting scheme is used to transform a simulated flux of neutrinos to a physical flux. For the astrophysical muon neutrino flux a generic power law model $\Phi(E_\nu) = \Phi_0 (E_\nu / 100\,\mathrm{TeV})^{-\gamma}$ is used. Here, the parameters of interest are the flux normalization Φ_0 and the spectral index γ. The conventional atmospheric neutrino prediction is based on the HKKMS07 calculation [13]. The uncertainty on the flux prediction increases with energy to about 25 % at 1 TeV. It was primarily designed for energies up to 10 TeV and has been extrapolated to higher energies according to [7] including the effect of the cosmic-ray knee. As a prediction for the prompt atmospheric neutrino flux we use the ERS model [11] which is based on pQCD calculations.[2]

2.2 Likelihood Method

In order to compare the experimental data with the expectations which are a function of signal $\vec{\theta}$ and nuisance $\vec{\xi}$ parameters (description below) a binned Poisson likelihood fit is used. Therefore, the experimental and simulated data are binned in reconstructed muon energy and zenith angle. Then, for each bin the measured number of events is compared to the expected number by a Poisson likelihood [3]

$$\mathscr{L}_{\mathrm{bin}} = \frac{\mu^n(\vec{\theta}, \vec{\xi})}{n!} \times e^{-\mu(\vec{\theta}, \vec{\xi})}, \tag{2.1}$$

where n is the number of measured events in that bin and $\mu = \mu_{\mathrm{conv.}} + \mu_{\mathrm{prompt}} + \mu_{\mathrm{astro.}}$ is the expected number of events as a function of the physics and nuisance parameters. In this analysis, the physics parameters are the astrophysical normalization and spectral index. Additionally, nuisance parameters are introduced to take into account systematic uncertainties which can be divided in two categories: neutrino detection uncertainties and atmospheric flux uncertainties. The former include the optical efficiency of the detector, the neutrino nucleon cross section, the muon energy loss cross section and the optical properties of the antarctic ice. The latter include the flux normalizations, the spectral shape and composition of the cosmic-ray spectrum in the "knee" region, the spectral index of the primary cosmic ray spectrum and the relative production yield of pions and kaons in the atmosphere. The implementation of nuisance parameters in the likelihood function is done similar to [7], with an important improvement for discrete [4] nuisance parameters. The effect of former discrete parameters on per-bin expectations has been parameterized and it is possible to choose realizations in between discrete points.

The global likelihood is then simply the product of all per-bin-likelihoods $\mathscr{L} = \prod_{\mathrm{bins}} \mathscr{L}_{\mathrm{bin}}$. The significances and parameter uncertainties are derived using the profile likelihood and assuming Wilks' theorem [16]. The assumption that the test-statistic is χ^2-distributed and Wilks' theorem is applicable was tested on pseudo experiments.

Since IceCube's Monte Carlo simulations improve in quality from year to year, nuisance parameters do not only absorb the systematic effects they are based on but can also absorb differences in the simulated datasets. Thus, for a combined likelihood fit of all years it is necessary to align

[2] An improved version of the flux prediction [14] will be used in the future which predicts approximately a flux that is half the flux of the ERS calculation.

[3] An extended version of the Poisson likelihood which takes into account finite statistics of the Monte Carlo simulations is used [15].

[4] A discrete nuisance parameter is a parameter where the fit can only choose between a predefined set of models, e.g. cosmic-ray composition model A or B.

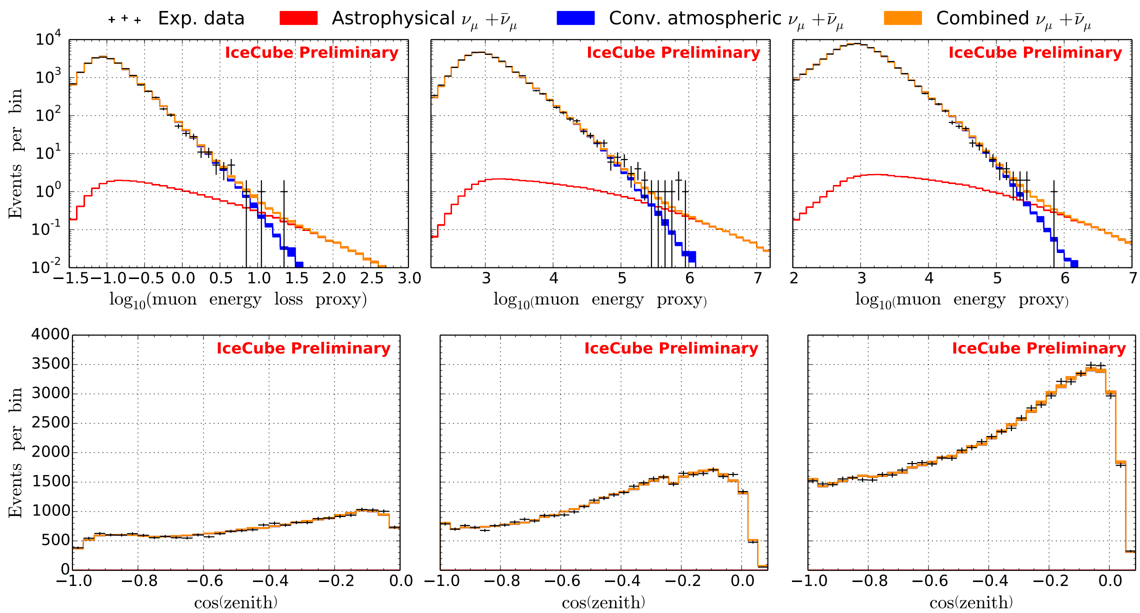

Figure 1: 1d-projections of the fit observables weighted by the best-fit spectrum for each year (left: 59-string, center: 79-string, right: 86-string). The reconstructed muon energy proxy is shown in the top row and the reconstructed zenith angle distribution in the bottom row. Note that [7] used the reconstructed muon energy loss as an observable which is correlated with the muon energy used in the later years. Only statistical errors are shown.

all nuisance parameters to a common baseline ξ_i. This means, that for each year the nuisance parameters are fit individually to adjust them to a common baseline. Then, in the combined fit these baseline values are scaled by a global parameter to give the combined fit the freedom to change the nuisance parameters.

3. Results

The best-fit astrophysical flux is given by

$$\Phi(E_\nu) = \left(0.66^{+0.40}_{-0.30}\right) \cdot 10^{-18}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\,(E_\nu/100\,\mathrm{TeV})^{-(1.91\pm0.20)} \tag{3.1}$$

in the energy range between 170 TeV and 3.8 PeV.[5] The quoted errors include both statistical and systematic uncertainties via the profile likelihood using the χ^2-approximation. The projections in reconstructed zenith angle and muon energy for each year are shown in Figure 1. The excess of events above atmospheric backgrounds becomes visible at high energies (Fig. 1, top center). No contribution from prompt atmospheric neutrinos is preferred for the best fit spectrum.

The significance for rejecting a flux of only atmospheric neutrinos is 4.3σ which is calculated with the profile likelihood assuming Wilks' theorem.

Figure 2 shows the two-dimensional profile likelihood for all combinations of astrophysical normalization, spectral index and prompt normalization. The likelihood ratios of the first column

[5] The energy range has been estimated by the central neutrino energy range which contributes 90% to the total squared significance. Note that this definition is different from [8, 17].

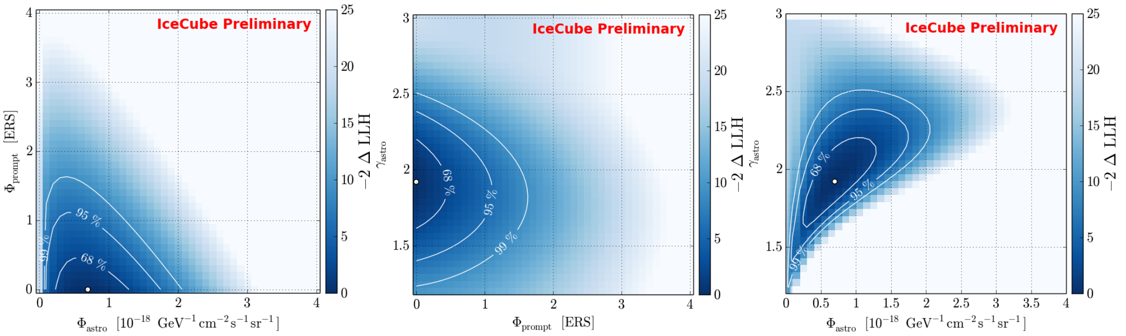

Figure 2: Two dimensional profile likelihood scans of the physics parameters Φ_{astro}, γ_{astro} and the prompt normalization Φ_{prompt} in units of the model in [11]. Additionally, contours at 68%, 90% and 95% CL assuming Wilks' theorem are shown.

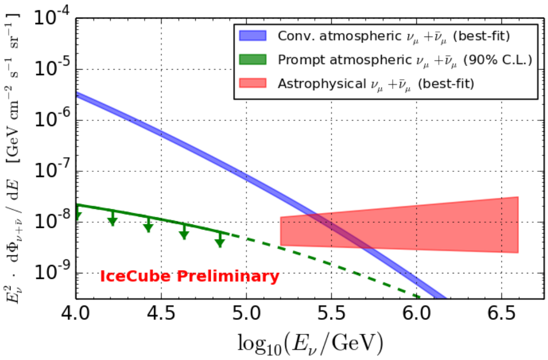

Figure 3: Best-fit muon neutrino spectra for the unbroken power-law model. The line widths (blue, red) represent the one sigma error on the measured spectrum where the green line represents the upper limit at 90% CL for the prompt model [11]. Note that systematic studies about the robustness of the prompt limit are still ongoing. The horizontal width of the red band denotes the energy range of neutrino energies which contribute 90% to the total squared significance.

in the left plot show that even a large prompt flux cannot explain the excess of high-energy neutrinos measured in the three years. The physics parameters are mainly correlated with each other (Figure 2, right) and only a small correlation with the normalization of prompt neutrinos is visible (Figure 2, left and center). The large statistics of conventional atmospheric neutrinos at lower energies strongly constrain the flux uncertainties in the region where the astrophysical component begins to contribute. Therefore, the nuisance parameters for the atmospheric flux uncertainties are strongly constrained and are only weakly correlated with the astrophysical flux parameters. The correlation between astrophysical normalization and spectral index is expected due to the interplay between both quantities. A larger normalization has a similar effect on the reconstructed muon energy spectrum as a softer spectral index. The most likely neutrino energy of the highest energy event assuming the overall best-fit neutrino flux is about 1.4 PeV. Figure 3 shows the best-fit moun neutrino spectrum. For prompt atmospheric neutrinos the 90%C.L. upper limit is shown. The vertical width of the bands corresponds to the flux uncertainties at the 1σ-level. Note that the results do not take into account the flux of muons originating from tau decays which themselves are

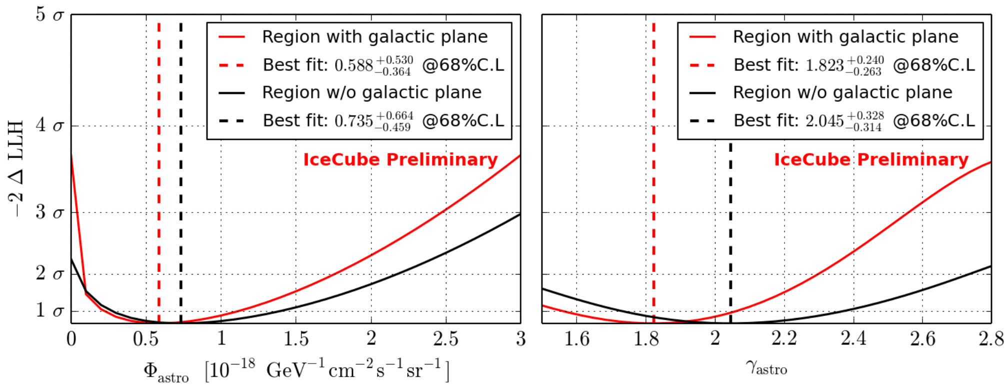

Figure 4: One dimensional profile likelihood scans the astrophysical normalization (left) and spectral index (right) using two different right ascension regions, one containing the Northern Hemisphere part of the Galactic plane (red) and one not (black).

produced by tau neutrino interactions. However, this only affects the astrophysical normalization by about $5-10\%$ [7].

In order to test if the measured muon neutrino flux is dominated by a Galactic flux the full sample (limited to the Northern Hemisphere) is split into two parts based on the reconstructed right ascension of the events: the first part contains the region where the Galactic plane intersects the Northern Hemisphere ($0^\circ \leq \alpha < 109^\circ$ and $275^\circ \leq \alpha < 360^\circ$), the second part contains the region where the Galactic plane lies in the Southern Hemisphere ($109^\circ \leq \alpha < 275^\circ$). Because the IceCube detector is located at the South Pole, it rotates daily with the Earth and therefore the systematics for both parts are identical. The likelihood fit has been applied to both parts, resulting in the one-dimensional profile likelihoods shown in Figure 4. Comparing the likelihood profiles, the results of both parts are statistically consistent. Hence, no statistically significant evidence for a Galactic component is found.

Modifying the astrophysical model from a unbroken power law to a power law with an exponential cut-off does not yield a significantly better fit result.

4. Conclusion

Re-analyzing the IceCube data measured between 2009 and 2012 with a significantly larger event sample than in previous analyses [7, 8] yield an excess of events at energies above 100 TeV. The atmospheric-only hypothesis can be rejected at 4.3σ [6]. Compared to [8] the significance increase is mainly due to the inclusion of the experimental data from [7]. The increased statistics of conventional atmospheric neutrinos and therefore better constrained systematic uncertainties additionally increase the significance. The measured astrophysical muon neutrino flux yields a normalization of $\left(0.66^{+0.40}_{-0.30}\right) \cdot 10^{-18}\,\mathrm{GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}}$ at 100 TeV neutrino energy and a hard spectral index of $\gamma = 1.91 \pm 0.20$. So far, no evidence for a cut-off at high energies is found. Additionally, there is no significant evidence for a Galactic component in the measured astrophysical muon neutrino flux.

[6] assuming Wilks' theorem

Comparing the measured spectral index to the measurement of other IceCube analyses [6, 8, 17] the index seems to be somewhat harder. However, due to the large uncertainties the results presented in [6] and [8] are statistically compatible. Investigations about the origin of the moderate tension with the spectral index measured in [17] are ongoing. It could be caused by a statistical fluctuation as well as an underlying more complex spectral shape of the astrophysical neutrino flux. Additionally, systematic studies are still ongoing. Extending this analysis by IceCube data recorded between 2012 and 2015 may show which scenario is more likely.

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