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Measurement of High Energy Neutrino–Nucleon Cross Section and Astrophysical Neutrino Flux Anisotropy Study of Cascade Channel with IceCube

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We present a novel analysis method and performance studies to determine the neutrino-nucleon deep-inelastic scattering cross section at high energies. The analysis uses atmospheric and extraterrestrial neutrino-induced electromagnetic and hadronic showers (cascades) in the TeV-PeV energy range, and assumes that the extraterrestrial neutrino flux is isotropic. Signal samples are separated into two groups, "down-going" (from the Southern Hemisphere) and "up-going" (from the Northern Hemisphere). Since up-going events may interact and be absorbed by the Earth while down-going event rate remains unaffected, the ratio of down-going events and up-going events for certain energy range is correlated with the cross section value. At the energies in this study, the yields are sensitive to the neutrino-nucleon cross section and nucleon structure in a region of kinematic overlap with HERA and with the LHC. We present the method for the neutrino-nucleon cross section measurement in the TeV-PeV energy range using neutrino induced cascades with the complete IceCube detector. In addition, we will test the hypothesis of a North-South anisotropy in astrophysical neutrino flux, assuming the knowledge of the neutrino-nucleon cross section from the electroweak physics.

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Introduction IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole [1] between depths of 1450 m and 2450 m, completed in 2010. It detects all-sky neutrinos of all flavors. Reconstruction of the direction, energy and flavor of the neutrinos relies on the optical detection of Cherenkov radiation emitted by charged particles produced in the interactions of neutrinos in the surrounding ice or the nearby bedrock. IceCube is sensitive to neutrinos above 100 GeV [2], and the energy range of this study is TeV-PeV, which overlaps with the kinematic of HERA [3] and with the LHC [4]. Their actual measurement forms a valuable proof-of-concept towards measurement in the high energy regime, which will provide sensitivity to new physics with unique neutrino probes. Direct neutrino-nucleon cross section measurements done with fixed target experiments cease at neutrino energies 370 GeV. The energy sensitivity of IceCube makes it possible to make measurements beyond the fixed target experiments' energy limit. IceCube has recently made the first measurement of the muon-neutrino-nucleon cross section at neutrino energies above 6 TeV using ν_μ coming from the Northern Sky observed by the IceCube 79-string configuration in 2010 [5]. This analysis proposes a novel method [6] using neutrinos of all flavors from all-sky collected with the 2011-2015 IceCube 86-string configuration to measure the neutrino-nucleon cross section.

Event Selection Events observed in IceCube are classified by their topology. Cascade events are induced by ν_e, ν_τ charge current and neutral current interactions, or ν_μ neutral current interactions. The emitted light forms a shower-like pattern. Track-like events are through-going muons. The source of track-like events can be cosmic ray induced muons from the Southern Sky or muons induced by ν_μ charge current interactions. When ν_μ charge current interactions happen within the detector volume, it creates a hybrid event. A hybrid event is the combination of a hadronic shower and a track left by an out-going muon. At trigger level, the majority of events seen in the detector are cosmic muons. They are the background for this analysis. To better understand detected events and design filters for event classification, Monte Carlo simulations are generated. *MuonGun* software is used to directly generate muons in ice with the composition from [7]. *Neutrino-generator* is used to generate neutrino interactions. Conventional atmospheric neutrino flux is calculated with HKKMS06 [8] and prompt atmospheric neutrino flux is calculated with BERSS [9]. For atmospheric flux, the "self-veto" effect [10] is taken into consideration. Astrophysical neutrino flux modeled with is a single, unbroken power law with the preliminary fit result from the IceCube 4-Year Cascade analysis: normalization: $(1.5^{+0.23}_{-0.22}) \times 10^{-18}\ \mathrm{GeV^{-1} s^{-1} sr^{-1} cm^{-2}}$, spectrum index: -2.48±0.08 [11]. The signal for this analysis is contained cascade events. The energy resolution for such events can be as good as 15% of deposited energy [12]. Event selection for this analysis is the same as in Ref. [11]. The selection separates the sample into two parts: the high energy part (E_{reco} >60 TeV) and the low energy part (E_{reco} <=60 TeV). The high energy event selection uses a 2D straight cut to select cascade events with high purity, has high efficiency, and is nearly background free. Low energy event selection uses a Boosted Decision Tree to classify events into three categories: cascade sample, muon sample, and starting track sample. Only cascade sample is used in this analysis. The low energy sample which consists 4017 neutrino events has a much higher statistic compare to high energy sample (19 neutrino events), and the background rate is lower than 10%. This analysis aims to use data collected from May, 2011 to May, 2016, 1730 days of livetime in total. To keep the development of the analysis method unbiased, only Monte

Carlo simulation and 10% of the collected data are currently used in this analysis. This 10% of the experimental data consists of data equally spaced throughout the years and is called *burn sample*. Final sample consists of neutrinos of all flavors. The number of events from Southern Sky and Northern Sky in each reconstructed energy bin for data and Monte Carlo is shown in Table 1

Table 1: Number of events (burn sample livetime) in reconstructed energy bins for data & Monte Carlo (numbers in parentheses are statistical uncertainties).

Southern Sky						
$log_{10}(E_{reco}/GeV)$	ν_e	ν_μ	ν_τ	μ	MC_{sum}	Data
2.2-2.8	2.56(7)	5.6(5)	0.035(2)	3(1)	11(2)	9
2.8-3.4	17.8(1)	42(1)	0.95(1)	12(4)	73(4)	66
3.4-4.0	17.00(7)	31.8(8)	3.06(1)	6(2)	58(2)	52
4.0-4.6	6.02(1)	6.2(1)	2.484(9)	0.5(1)	15.2(2)	19
4.6-5.2	1.712(4)	0.59(2)	0.937(5)	0	3.24(2)	5
5.2-5.8	0.505(2)	0.082(3)	0.261(2)	0	0.848(4)	1
5.8-6.4	0.140(1)	0.027(2)	0.068(1)	0	0.236(2)	1
6.4-7.0	0.082(2)	0.003(1)	0.008(1)	0	0.093(2)	0
Northern Sky						
$log_{10}(E_{reco}/GeV)$	ν_e	ν_μ	ν_τ	μ	MC_{sum}	Data
2.2-2.8	10.8(1)	41(1)	0.342(5)	0	52(1)	51
2.8-3.4	48.2(2)	166(2)	3.77(2)	14(4)	231(4)	242
3.4-4.0	26.87(8)	71(1)	4.76(2)	8(3)	111(3)	93
4.0-4.6	6.15(1)	8.5(1)	2.17(1)	0.6(1)	17.4(2)	17
4.6-5.2	1.252(3)	0.58(2)	0.620(6)	0	2.45(2)	3
5.2-5.8	0.258(1)	0.050(2)	0.135(2)	0	0.443(3)	0
5.8-6.4	0.052(1)	0.013(1)	0.028(1)	0	0.093(1)	0
6.4-7.0	0.015(1)	0.002(1)	0.004(1)	0	0.021(1)	0

Analysis Method This analysis follows the theoretical approch from Ref. [6]. In IceCube, neutrinos from Northern Sky travel through the Earth to reach the detector. When traveling through the Earth, a fraction of the neutrinos are absorbed by the Earth. This fraction is a function of cross section [6]. The fraction can be obtained by calculating a ratio of down-going events (Southern Sky) and up-going events (Northern Sky), since neutrinos from Southern Sky are not affected by the Earth absorption effect. The desired relationship is between cross section and neutrino energy, as shown in Fig. 4. The number of down-going events and up-going events in reconstructed energy bins can be experimentally measured, and an unfolding method (discussed later) is applied to get the number of events in neutrino energy bins. The ratio in each neutrino energy bin is the number of down-going events divided by the number of up-going events. With Monte Carlo simulation, we can get the relationship between the Earth absorption effect (which is expressed by the ratio of down-going events and up-going events) and cross section. In this way, the cross section for a certain neutrino energy range can be measured. The relationship between the ratio of down-going events and up-going events and cross section can be obtained by using *neutrino-generator* Monte Carlo simulation. Neutrinos with different interacting cross sections (from $\sim 10^{-9}$ mb to $\sim 10^{-4}$ mb) are simulated and propagated towards the detector from all directions. The Earth model used in the simulation is PREM [13]. All neutrinos are forced to interact and are given a proper weight according to cross section. For each cross section bin, events inside are separated into two parts: $cos(Zenith_{reco}) < 0$ as up-going, and $cos(Zenith_{reco}) >= 0$ as down-going. The reconstructed zenith(θ) distribution is shown in Fig. 1 (Right). The ratio of the number of down-going events over the number of up-going events is plotted for each cross section bin (shown as Fig. 1 (Left)). Both atmospheric neutrino flux and astrophysical neutrino flux are taken into consideration when counting the number of events, since we can't distinguish these two types of neutrinos at lower energy. Due to the existence of *self-veto effect* [10] in atmospheric neutrinos, the detector accepts down-going atmospheric neutrinos at a much lower rate than up-going atmospheric neutrinos due to the accompanied muons in down-going events. Also, the event selection [11] applied shows differences in the down-going and up-going events acceptance rates. With all these factors, the ratio of down-going events and up-going events will contain not only the information of Earth absorption, but also detector acceptance effects. These acceptance effects are neutrino energy dependent and can be factorized. Therefore, it is necessary to apply a correction factor (as shown in Fig. 3 (Right)) once the ratio in neutrino energy bins is obtained. This way, we decouple the acceptance effect and the ratio reflects the Earth absorption effect only. Occasionally, a neutral current interaction happens in the Earth and produces a secondary neutrino that will reach the detector and interact again within. This secondary neutrino will have a lower energy and a smaller cross section for neutrino-to-matter interaction. This will result in more up-going neutrinos in the lower cross section bin. In general, this effect must be corrected with dedicated simulations, however, in this analysis, we ignored the effect because the statistical uncertainties from the observed events are much larger than this effect. The experimental data are separated into down-going events and

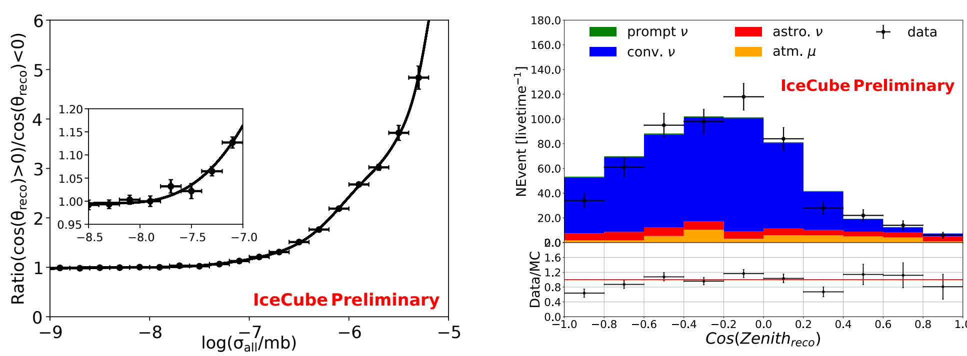

Figure 1: Left: cross section vs ratio of down-going and up-going events. Right: reconstructed zenith distribution for data and Monte Carlo.

up-going events as well. Reconstructed energy histograms are plotted for down-going events and up-going events separately (shown as Fig. 2 (Left column)). What we measure in the experiment is deposited energy, this is not equivalent to neutrino energy, due to out-going neutrinos in neutral current interactions and out-going μ carrying away energy in ν_μ charge current interactions. To get the ratio in neutrino energy bins, an unfolding procedure is needed. The unfolding method used here is the matrix method [14]. We define:

$$y_{i,dir} = \sum_j A_{ij,dir} x_{j,dir}, \quad A_{ij,dir} = \frac{N^{reco,true}_{ij,dir}}{N^{true}_{j,dir}}, \tag{1}$$

where $x_{j,dir}$ is the number of events in neutrino energy bin j for a certain direction (down-going/up-going according to reconstructed zenith), and $y_{i,dir}$ is the number of events in reconstructed energy bin i for a certain direction (down-going/up-going according to reconstructed zenith). $A_{ij,dir}$ are the elements of the resolution matrix, defined as the number of events in both neutrino energy bin j and in reconstructed energy bin i for a certain direction divided by the number of events in neutrino energy bin j for a certain direction. This matrix is calculated using Monte Carlo simulation. Resolution matrices are calculated for up-going and down-going events respectively. Once we have obtained these resolution matrices, the number of events in neutrino energy bins can be calculated using:

$$x_{j,dir}^{INVERT} = \sum_i (A^{-1})_{ji,dir}(y_{i,dir}^{data} - y_{i,dir}^{bgr}), \tag{2}$$

where $y_{i,dir}^{bgr}$ is the background expectation from IceCube's MuonGun simulation in reconstructed energy bin i for a certain direction, as shown in Fig. 2 (Left column). The uncertainty is defined as $\delta x_{j,dir}^{INVERT} = \sqrt{V_{jj,dir}}$, where

$$V_{jk,dir} = \sum_i (A^{-1})_{ji,dir}(\delta(y_{i,dir}^{data} - y_{i,dir}^{bgr})^2 (A^{-1})_{ki,dir}. \tag{3}$$

The reconstructed energy distributions for up-going and down-going events are shown in Fig. 2 (Left column). After unfolding, neutrino energy distributions for up-going and down-going events are shown in Fig. 2 (Right column). The ratio of down-going events and up-going events for each neutrino energy bin is calculated as $Ratio_j = \frac{x_{j,down}}{x_{j,up}}$. After applying the correction factor for acceptance effects (self-veto, efficiency), the result is shown in Fig. 3 (Left).

Cross Section Result Figure 3 shows the corresponding ratio for each neutrino energy bin, and Fig. 1 (Left) shows the corresponding cross section value for each ratio. With this information, we can evaluate the cross section in neutrino energy bins. Figure 4 (Left) shows the sensitivity of this measurement with 5 years' livetime predicted by Monte Carlo simulation. The dark red band and light red band cover 68% and 95% of confidence range respectively (systematic uncertainties are not included). Figure 4 (Right) shows the neutrino-nucleon cross section evaluated with 10% of 5 years of IceCube data (uncertainties are statistical only). The black dots in Fig. 4 represent the CSMS calculations [15]. Here we use the sum of charge current interaction and neutral current interaction cross sections averaged over neutrino and anti-neutrino.

Astrophysical Neutrino Flux Anisotropy Study The neutrino-nucleon cross section and the parton distribution functions at the kinematic range where this analysis is sensitive are well understood by the Standard Model and HERA data. In this section, we assume the knowledge of the cross section, and the ratio is sensitive to the (an)isotropy of astrophysical neutrino flux. The approach is to assume the known cross section and calculate the ratio of down-going events and up-going events (separated by reconstructed zenith angle) based on the isotropy model and the anisotropy model respectively. We then compare the ratio from experimental data with the ratios calculated from these two different flux models. For the isotropy model, we assume the neutrino

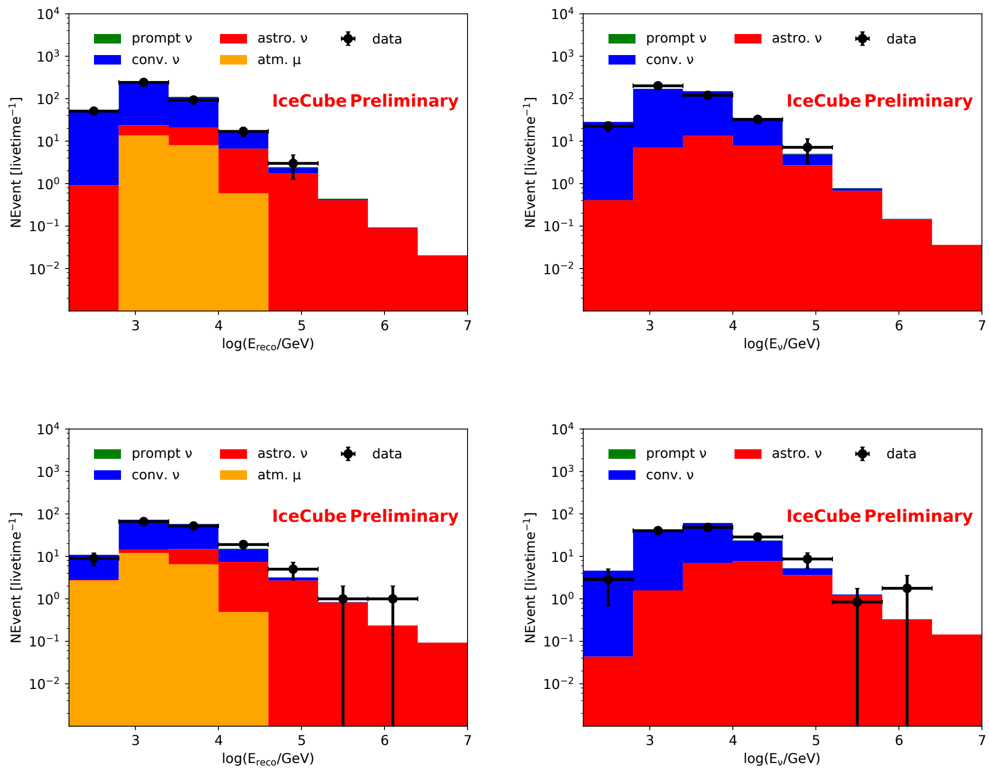

Figure 2: Top Left: reconstructed energy distribution for up-going events. Top Right: neutrino energy distribution for up-going events. Bottom Left: reconstructed energy distribution for down-going events. Bottom Right: neutrino energy distribution for down-going events.

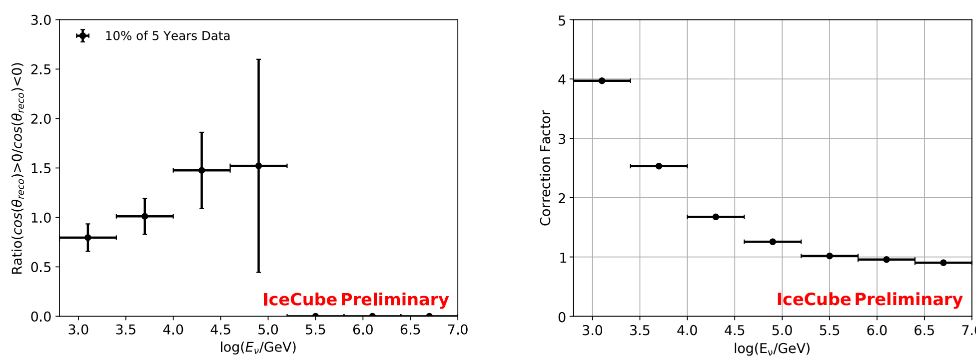

Figure 3: Left: neutrino energy vs ratio of down-going and up-going events for 10% of 5 years data. Uncertainties are statistical only. Right: neutrino energy vs correction factor.

flux is a single power law:

$$\Phi(E_\nu) = \Phi_1 (\frac{E_\nu}{E_0})^{-\gamma_1}. \tag{4}$$

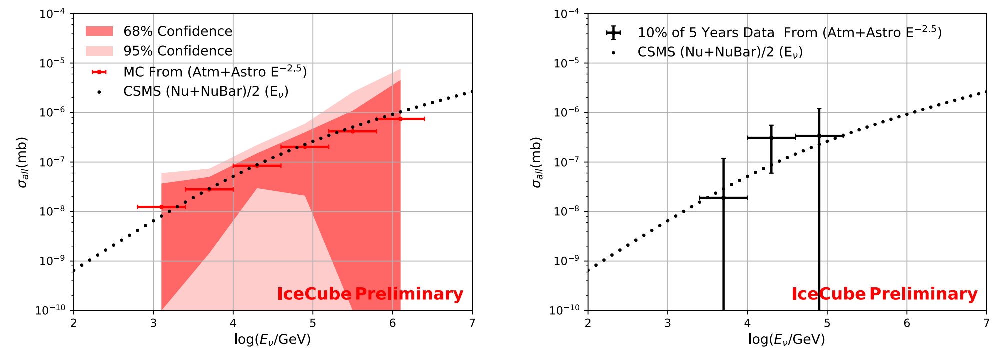

Figure 4: Left: measured neutrino energy vs cross section using Monte Carlo simulation and expected precision with 100% of 5 years of data. Right: measured neutrino energy vs cross section using 10% of 5 years experimental data. Uncertainties are statistical only.

For the anisotropy model, we assume the down-going flux is the same as for the isotropy model and the up-going neutrino flux is:

$$\Phi(E_\nu) = \Phi_1\left(\frac{\Phi_1}{\Phi_1+\Phi_2}\left(\frac{E_\nu}{E_0}\right)^{-\gamma_1} + \frac{\Phi_2}{\Phi_1+\Phi_2}\left(\frac{E_\nu}{E_0}\right)^{-\gamma_2}\right), \tag{5}$$

where $\Phi_1 = (1.5^{+0.23}_{-0.22}) \times 10^{-18}\ \mathrm{GeV^{-1}s^{-1}sr^{-1}cm^{-2}}$, $\gamma_1 = 2.48 \pm 0.08$ are the fit result from the IceCube 4-year cascade analysis [11], and $\Phi_2 = (1.01^{+0.26}_{-0.23}) \times 10^{-18}\ \mathrm{GeV^{-1}s^{-1}sr^{-1}cm^{-2}}$, $\gamma_2 = 2.19 \pm 0.10$ are the fit result from the IceCube 8-year ν_μ analysis [16]. Note that there are many possible anisotropy models, we have tested this one so far to demonstrate how this method works. Figure 5 (Right) shows the ratio of down-going events and up-going events as a function of the (logarithm of) neutrino energy. The bands around the curves are calculated from 68% contours from fit result of [11] and [16] as shown in Fig. 5 (Left). The uncertainty band covers all the ratio values calculated with all the combinations of normalization and index values on the contour. We can see that for the isotropy model the uncertainty band is very narrow, as expected, due to the cancellation of flux in the ratio. The difference in ratio between the two models starts to show at a relative high energy, since in the lower energy range the flux is dominated by atmospheric neutrino component. With 10% of 5 years' statistic, the data doesn't favor one model over another.

Summary We have developed a new analysis method [6] to measure the neutrino-nucleon cross section at high energy (TeV-PeV). This method uses the ratio of down-going events and up-going events to probe the effect of Earth absorption in order to get the measurement of cross section. Under the assumption of isotropy of astrophysical neutrino flux the effect of flux is canceled in the ratio, which makes the result of the cross section measurement independent of the flux model. This method has been applied on 10% of 5 years of IceCube data in the cascade channel, and the initial study shows consistency with CSMS [15] cross section calculation. When assuming the standard model cross section, this method can be used to explore the anisotropy of astrophysical neutrino flux. The ratio of down-going events and up-going events for burn sample data is compared with ratios calculated with CSMS calculations for anisotropy

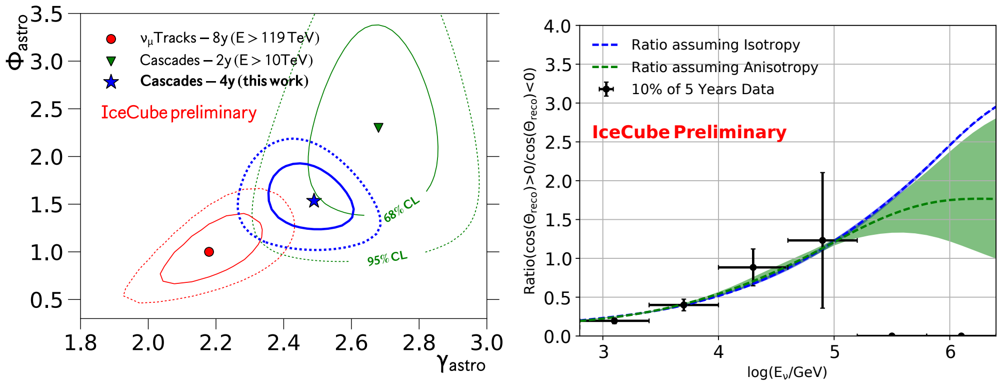

Figure 5: Left: uncertainty contours of IceCube analyses [11]. Right: ratio vs Neutrino Energy for 10% of 5 years' IceCube data.

model and isotropy model. The anisotropy hypothesis studied is single power law flux for Southern Sky and double power law flux for Northern Sky, while the isotropy hypothesis is single power for the whole sky. With 10% of 5 years' statistic, the two hypotheses are indistinguishable. Evaluation of systematic uncertainties is in progress.

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