Constraints on neutrino-nucleon interactions at energies of 1 EeV with the IceCube Neutrino Observatory

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A search for extremely high energy cosmic neutrinos has been carried out with the IceCube Neutrino Observatory. The main signals in the search are neutrino-induced energetic charged leptons and their rate depends on the neutrino-nucleon cross section. The upper limit on the neutrino flux has implications for possible new physics beyond the standard model such as the extra space-time dimension scenarios which lead to a cross section much higher than the standard particle physics prediction. In this study we constrain the neutrino-nucleon cross section at energies beyond 10^9 GeV with the IceCube observation. The constraints are obtained as a function of the extraterrestrial neutrino flux in the relevant energy range, which accounts for the astrophysical uncertainty of neutrino production models.

I. INTRODUCTION

High energy cosmic neutrino observations provide a rare opportunity to explore the neutrino-nucleon (νN) interaction behavior beyond energies accessible by the present accelerators. These neutrinos interact during their propagation in the Earth and produce energetic muons and taus. These secondary leptons reach underground neutrino detectors and leave detectable signals. The detection rate is, therefore, sensitive to neutrino-nucleon interaction probability. The center-of-mass energy of the collision, $\sqrt{s}$, is well above ~ 10 TeV for cosmic neutrino energies on the order of 1 EeV ($= 10^9$ GeV). This is a representative energy range for the bulk of the GZK (Greisen-Zatsepin-Kuzmin) cosmogenic neutrinos, generated by the interactions between the highest energy cosmic ray nucleons and the cosmic microwave background photons [1].

The νN collision cross section can vary greatly if nonstandard particle physics beyond the standard model (SM) is considered in the high energy regime of $\sqrt{s} \gg$ TeV. The extra-dimension scenarios, for example, have predicted such effects [2,3]. In these scenarios, the virtual exchange of the Kaluza-Klein graviton [2] or microscopic black hole production [4] leads to a substantial increase of the neutrino-nucleon cross section by more than 2 orders of magnitude above the SM prediction. The effect would be sizable enough to affect the expected annual event rate [$O(0.1 - 1)$] of the GZK neutrinos in the $\sim$km^3 instrumentation volume of an underground neutrino telescope such as the IceCube observatory. Thereby, the search for extremely high energy (EHE) cosmic neutrinos leads to constraints on nonstandard particle physics [5].

The IceCube neutrino observatory has already begun EHE neutrino hunting with the partially deployed underground optical sensor array [6]. The 2007 partial IceCube detector realized a ~ 0.7 km^2 effective area for muons with 10^9 GeV and recently placed a limit on the flux of EHE neutrinos approximately an order of magnitude higher than the expected GZK cosmogenic neutrino intensities with 242 days of observation [7]. Since new particle physics may vary the cross section by more than an order of magnitude as we noted above, this result should already imply a meaningful bound on the νN cross section. In this paper, we study the constraint on the νN cross section ($\sigma_{\nu N}$) by the null detection of EHE neutrinos with the 2007 IceCube observation. A model-independent bound is derived by estimating the lepton intensity at the IceCube depth with the SM cross section scaled by a constant. The constraint is displayed in the form of the excluded region on the plane of the cosmic neutrino flux and $\sigma_{\nu N}$. It is equivalent to an upper bound on $\sigma_{\nu N}$ for a given flux of astrophysical EHE neutrinos. We also study the model-dependent constraint on the microscopic black hole creation by neutrino-nucleon collision predicted in the extra-dimension scenario [5]. We calculate the fluxes of leptons propagating in the Earth including the black hole cross section and the final states to estimate expected event rate in an equivalent IceCube 2007 measurement as a function of extraterrestrial neutrino intensity. The null detection of signal candidates leads to a constraint on this particular scenario.

There are several works on model-independent upper bounds of $\sigma_{\nu N}$ using the observational limit of EHE neutrino flux in the literature. References [3,4,8] derived the bound using the results of horizontal air shower search by AGASA [9] and Fly's Eye [10]. References [8,11] set the limit based upon the flux bound by the RICE experiment [12]. Our approach in the present study is different mainly in two respects. The previous works assumed the GZK cosmogenic neutrino bulk as the *guaranteed* beam and deduced the cross section limit using the GZK neutrino intensity. Here extraterrestrial neutrino intensity is considered a free parameter. This method is an application of the

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technique to derive the flux limit based upon the quasidifferential event rate [7,12,13], which is independent of specific neutrino flux models. It is valid when the cosmic neutrino flux and the cross section $\sigma_{\nu N}$ do not rapidly change over a decade of a given neutrino energy. As EHE cosmic ray composition and their origin are still quite uncertain, this approach provides more appropriate conservative limits on $\sigma_{\nu N}$. It also allows estimation of the minimum intensity of neutrino flux required to constrain the cross section. Another difference is that the previous works introduced the simplification that event rate solely depends on rates of electromagnetic or hadronic cascades directly initiated by neutrinos inside the effective volume of the detector. This is in fact a good approximation for the RICE experiment which is sensitive to radio emission from shower events. However, underground neutrino telescopes such as IceCube have larger effective areas for throughgoing muons and taus in EHE neutrino search [14–16]. This study of the model-independent limit includes calculation of not just intensities of neutrinos but also the secondary muon and tau fluxes reaching the detection volume for a given $\sigma_{\nu N}$ and includes their contributions in the overall event rate.

The paper is outlined as follows: First we discuss the model-independent constraint in Sec. II. The method to calculate the neutrino and the secondary lepton propagation from the Earth's surface to the IceCube detector depth is described. The fluxes for different strengths of $\sigma_{\nu N}$ are calculated and the resultant constraint is shown for both $\sigma_{\nu N}$ and the cosmic neutrino flux at neutrino energies of 1 and 10 EeV, respectively. Section III describes the constraint on the microscopic black hole production by neutrino-nucleon interaction as an example of the model-dependent bound on $\sigma_{\nu N}$. Fluxes of muons and taus from evaporation of black holes produced in the neutrino-nucleon collision in the Earth are calculated. Their contributions, as well as those from contained hadronic showers induced directly by the evaporation, would give an observable event rate in the IceCube 2007 measurement, and thereby put constraints on the black hole scenario. We summarize our conclusions in Sec. IV.

II. MODEL-INDEPENDENT CONSTRAINT ON THE NEUTRINO-NUCLEON CROSS SECTION

The flux limit obtained by the present IceCube observations allows us to place an upper bound on the neutrino-nucleon cross section in a model-independent manner; new physics cannot increase $\sigma_{\nu N}$ too much, otherwise EHE neutrinos would have produced observable events. As an underground neutrino telescope is sensitive to not just shower events induced from neutrinos, but also to through-going muons and taus generated by the neutrino-nucleon scattering, one must understand how much fluxes of these leptons reaching an underground detection volume is increased with $\sigma_{\nu N}$. In this section, we first discuss our

method to calculate intensities of neutrinos, muons, and taus at the underground depth of the IceCube observatory for a wide range of $\sigma_{\nu N}$ strength, followed by a description of how they would contribute to the event rate. Finally the constraint on both $\sigma_{\nu N}$ and cosmic neutrino flux is described together with the relevant discussions.

A. The method

Given a neutrino flux at the surface of the Earth, the neutrino and charged lepton fluxes at the IceCube depth are calculated by the coupled transportation equations [16]:

$$\frac{dJ_\nu}{dX} = -N_A \sigma_{\nu N,\text{CC+NC}} J_\nu + \frac{m_l}{c\rho\tau_l^d} \int dE_l \frac{1}{E_l} \frac{dn_l^d}{dE_\nu} J_l(E_l)$$

$$+ N_A \int dE_\nu' \frac{d\sigma_{\nu N,\text{NC}}}{dE_\nu} J_\nu(E_\nu')$$

$$+ N_A \int dE_l' \frac{d\sigma_{lN,\text{CC}}}{dE_\nu} J_l(E_l'), \tag{1}$$

$$\frac{dJ_l}{dX} = -N_A \sigma_{lN} J_l - \frac{m_l}{c\rho\tau_l^d E_l} J_l$$

$$+ N_A \int dE_\nu' \frac{d\sigma_{\nu N,\text{CC}}}{dE_l} J_\nu(E_\nu') + N_A \int dE_l' \frac{d\sigma_{lN}}{dE_l} J_l(E_l')$$

$$+ \frac{m_l}{c\rho\tau_l^d} \int dE_l' \frac{1}{E_l'} \frac{dn_l^d}{dE_l} J_l(E_l'), \tag{2}$$

where $J_l = dN_l/dE_l$ and $J_\nu = dN_\nu/dE_\nu$ are differential fluxes of charged leptons (muons and taus) and neutrinos, respectively. X is the column density, N_A is the Avogadro's number, ρ is the local density of the medium (rock/ice) in the propagation path, σ is the relevant interaction cross section, dn_l^d/dE is the energy distribution of the decay products which is derived from the decay rate per unit energy, c is the speed of light, and m_l and τ_l^d are the mass and the decay life time of the lepton l, respectively. CC(NC) denotes the charged (neutral) current interaction. In this study we scale $\sigma_{\nu N}$ to that of the SM prediction with the factor N_scale, i.e., $\sigma_{\nu N} \equiv N_\text{scale} \sigma_{\nu N}^\text{SM}$. It is an extremely intensive computational task to resolve the coupled questions above for every possible value of $\sigma_{\nu N}$. To avoid this difficulty, we introduce two assumptions to decouple the calculation of J_ν from the charged lepton transportation equation. The first is that distortion of the neutrino spectrum by the neutral current reaction is small and the other is that regeneration of neutrinos due to muon and tau decay and their weak interactions is negligible. These are very good approximations in the energy region above 10^8 GeV where even tau is unlikely to decay before reaching the IceCube instrumentation volume. Then the neutrino flux is simply given by the beam dumping factor as

$$J_\nu(E_\nu, X_\text{IC}) = J_\nu(E_\nu, 0) e^{-N_\text{scale} \sigma_{\nu N}^\text{SM,CC} X_\text{IC}}, \tag{3}$$

where X_{IC} is column density of the propagation path from the Earth's surface to the IceCube depth. The charged lepton fluxes, $J_{l=\mu,\tau}(E_l, X_{IC})$, are obtained as

$$J_{\mu,\tau}(E_{\mu,\tau}, X_{IC}) = N_A \int_0^{X_{IC}} dX \int dE'_{\mu,\tau} \frac{dN_{\mu,\tau}}{dE_{\mu,\tau}}(E'_{\mu,\tau} \to E_{\mu,\tau})$$
$$\times \int dE_\nu N_{scale} \frac{d\sigma_{\nu N}^{SM,CC}}{dE'_{\mu,\tau}}$$
$$\times J_\nu(E_\nu, 0) e^{-N_{scale}\sigma_{\nu N}^{SM,CC}X}. \qquad (4)$$

Here $dN_{\mu,\tau}/dE_{\mu,\tau}(E'_{\mu,\tau} \to E_{\mu,\tau})$ represents distributions of muons and taus with energy of $E_{\mu,\tau}$ at X_{IC} created by νN collisions at depth X with an energy $E'_{\mu,\tau}$. This is calculated in the transportation equation, Eq. (2), with a replacement of $J_\nu(E'_\nu)$ by Eq. (3).

Calculation of the neutrino and the charged lepton fluxes with this method is feasible for a wide range of N_{scale} without any intensive computation. A comparison of the calculated fluxes with those obtained without the introduced simplification for a limited range of N_{scale} indicates that the relative difference we found in the resultant $J_{\nu,\mu,\tau}(X_{IC})$ is within 40%. Since this analysis involves an *order* of magnitude of increase in $\sigma_{\nu N}$, the introduced approximations provide sufficient accuracy for the present study.

Figure 1 shows the calculated intensities of the secondary muons and taus for various N_{scale} factors. Here the primary neutrino spectrum is assumed to follow the GZK cosmogenic spectrum and flux calculated in Ref. [17] assuming an all-proton cosmic ray composition with a moderately strong source evolution, $(1 + z)^m$ with $m = 4$
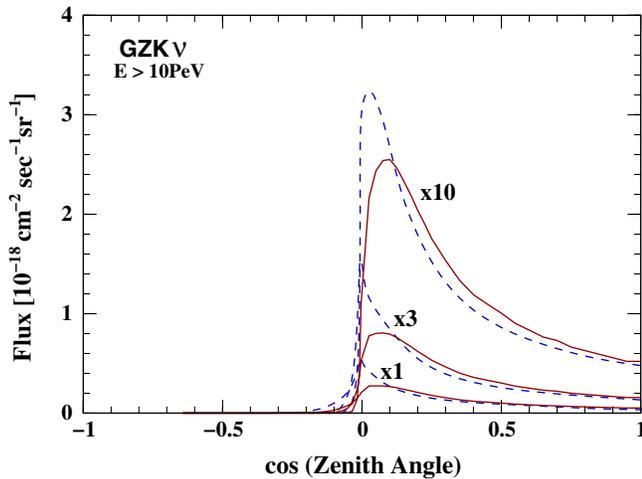

FIG. 1 (color online). Integral fluxes of the muon and taus above 10 PeV ($= 10^7$ GeV) at IceCube depth (~ 1450 m) for GZK cosmogenic neutrinos [17]. The solid lines represent muons while the dashed lines represent taus. Numbers on each of the curves are the multiplication factors (N_{scale}) that enhance the standard νN cross section [19] in the relevant calculations.

extending to $z = 4$. One can see that the intensity is nearly proportional to N_{scale} as expected since the interaction probability to generate muons and taus linearly depends on $\sigma_{\nu N}$. It should be pointed out, however, that the dependence starts to deviate from the complete linearity when the propagation distance is comparable to the mean free path of neutrinos, as one can find in the case of $N_{scale} = 10$ in the figure. This is because the neutrino beam dumping factor in Eq. (3) becomes significant under these circumstances.

The flux yield of leptons at the IceCube depth, Y_ν^l ($l = \nu$'s, μ, τ), originating from neutrinos with a given energy at the Earth's surface, E_ν^s, is given by Eq. (4) for muons and taus and by Eq. (3) for neutrinos, with an insertion of $J_\nu(E_\nu, 0) = \delta(E_\nu - E_\nu^s)$. Here E_ν^s denotes a given incoming neutrino energy at the Earth's surface. The resultant event rate per neutrino energy decade is then obtained by [7,12,13],

$$N_\nu(E_\nu^s) = \sum_{\nu=\nu_e,\nu_\mu,\nu_\tau} \frac{1}{3} \frac{dJ_{\nu_e+\nu_\mu+\nu_\tau}}{d\log E_\nu}(E_\nu^s) \int d\Omega \sum_{l=\nu_e,\nu_\mu,\nu_\tau,\mu,\tau}$$
$$\times \int dE_l A_l(E_l) Y_\nu^l(E_\nu^s, E_l, X_{IC}(\Omega), N_{scale}), \qquad (5)$$

where A_l is the effective area of the IceCube to detect the lepton l. In the equation above, the $l = \mu, \tau$ terms represent the through-going track events while the contribution of events directly induced by neutrinos inside the detection volume is represented by the terms $l = \nu_e, \nu_\mu, \nu_\tau$. The effective area for ν's, A_ν, is proportional to $\sigma_{\nu N}$ i.e., N_{scale} so the rate of contained shower events is linearly dependent on the neutrino-nucleon scattering probability. Note that the differential limit of the neutrino flux is given by Eq. (5) for $N_{scale} = 1$ with $N_\nu = \bar{\mu}_{90}$ which corresponds to the 90% confidence level average upper limit. It calculates an upper bound of the number of events observed with bin width of a decade of energy with the condition that energy dependence of neutrino flux multiplied by the effective area behaves as $\sim 1/E$ [4,12]. Limiting $\sigma_{\nu N}$ in the present analysis corresponds to an extraction of the relation between N_{scale} and the (unknown) cosmic neutrino flux $J_{\nu_e+\nu_\mu+\nu_\tau}$ yielding $N_\nu = \bar{\mu}_{90}$. The obtained constraints on $\sigma_{\nu N}$ is represented as a function of $J_{\nu_e+\nu_\mu+\nu_\tau}$ for a given energy of E_ν^s. It consequently accounts for astrophysical uncertainties on the cosmic neutrino flux.

In scenarios with extra dimensions and strong gravity, Kaluza-Klein gravitons can change only the neutral current (NC) cross section because gravitons are electrically neutral. Any scenarios belonging to this category can be investigated by scaling only $\sigma_{\nu N}^{NC}$ in the present analysis. The event rate calculation by Eq. (5) is then performed for $Y_\nu^l(N_{scale} = 1)$ with the effective area for ν's, A_ν, enhanced by $(\sigma_{\nu N}^{SM,CC} + N_{scale}\sigma_{\nu N}^{SM,NC})/(\sigma_{\nu N}^{SM,CC} + \sigma_{\nu N}^{SM,NC})$ since the rate of detectable events via the NC reaction by IceCube

is proportional to $\sigma_{\nu N}^{\rm NC}$. We also show the constraint in this case.

B. Results

In this analysis we use the IceCube observation results with 242 days data in 2007 to limit $\sigma_{\nu N}$ using Eq. (5). No detection of signal candidates in the measurement has led to an upper limit of the neutrino flux of 1.4×10^{-6} GeV cm^{-2} sec^{-1} sr^{-1} [7] in the energy range from 3×10^7 to 3×10^9 GeV. The effective area A_l is ~ 0.7 km^2 for μ, ~ 0.4 km^2 for τ, and 3×10^{-4} km^2 for ν's [7]. Constraints on $\sigma_{\nu N}$ are then derived with Eq. (5). The results for $E_\nu^s = 10^9$ and 10^{10} GeV are shown in Fig. 2. Enhancing the charged current cross section by more than a factor of 30 for $E_\nu = 1$ EeV (10^9 GeV) is disfavored if the astrophysical neutrino intensities are around $\sim 10^{-7}$ GeV cm^{-2} sec^{-1} sr^{-1}, near the upper bound of the GZK cosmogenic neutrino bulk. Note that neutrino-nucleon collision with $E_\nu = 1$ EeV corresponds to $\sqrt{s} \sim 40$ TeV and the present limit on $\sigma_{\nu N}$ would place a rather strong constraint on scenarios with extra dimensions and strong gravity, although more accurate estimation requires studies with a model-dependent approach which implements the cross section and the final-state particles from the collision predicted by a given particle physics model. Taking into account uncertainty on the astrophysical neutrino fluxes, any model that increases
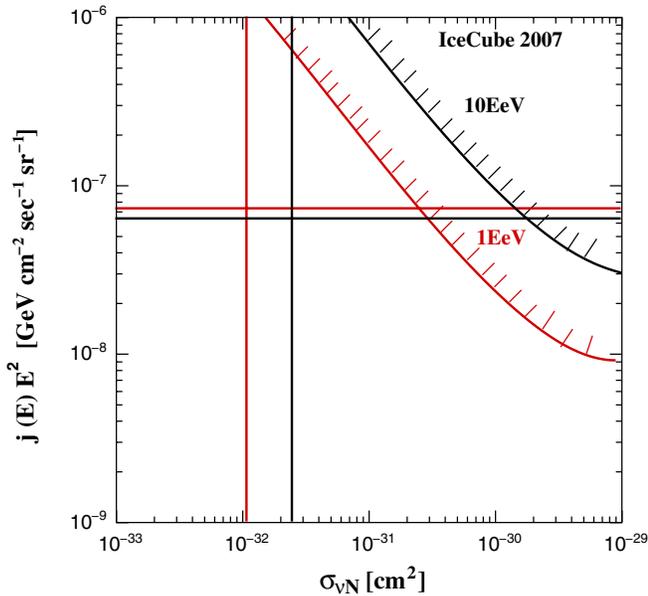

FIG. 3 (color online). Constraints on the all-flavor sum of cosmic neutrino flux and the neutral current νN cross section for the scenario that only the neutral current reaction is enhanced by a new physics beyond the standard model. The right upper region is excluded by the present analysis. The horizontal lines provide references of the expected GZK cosmogenic neutrino fluxes [20] and the vertical lines correspond to the SM cross section [19].
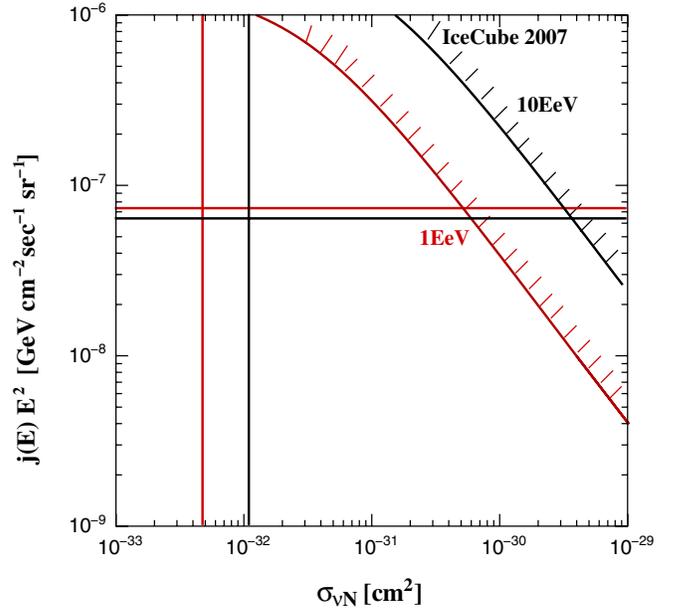

FIG. 2 (color online). Constraints on the all-flavor sum of cosmic neutrino flux and the charged current νN cross section based on the null detection of neutrino signals by the IceCube 2007 observation. The right upper region is excluded by the present analysis. The horizontal lines provide references of the expected GZK cosmogenic neutrino fluxes [20] and the vertical lines correspond to the SM cross section [19].

the neutrino-nucleon cross section to produce charged leptons by more than 2 orders of magnitude at $\sqrt{s} \sim 40$ TeV is disfavored by the IceCube observation. However, we should point out that the IceCube 2007 data could not constrain the charged current cross section if the intensity of cosmic neutrinos in the relevant energy region is fewer than $\sim 10^{-8}$ GeV cm^{-2} sec^{-1} sr^{-1}, within the lower range of prediction for the cosmogenic neutrino fluxes [18]. Absorption effects in the Earth becomes sizable in this case, resulting in less sensitivity to the cross section. This limitation will be improved for larger detection areas of the full IceCube detector.

Figure 3 shows the constraints when only the NC cross section is varied. Enhancement of $\sigma_{\nu N}^{\rm NC}$ by a factor beyond 100 at $\sqrt{s} \sim 40$ TeV is disfavored, but this strongly depends on the cosmic neutrino flux one assumes. Because the NC interaction does not absorb neutrinos during their propagation though the Earth, the cross section could be bounded even in the case when the neutrino flux is small, but the limit becomes rather weak; the allowed maximum enhancement factor is on the order of $\sim 10^3$.

III. CONSTRAINT ON THE MICROSCOPIC BLACK HOLE PRODUCTION

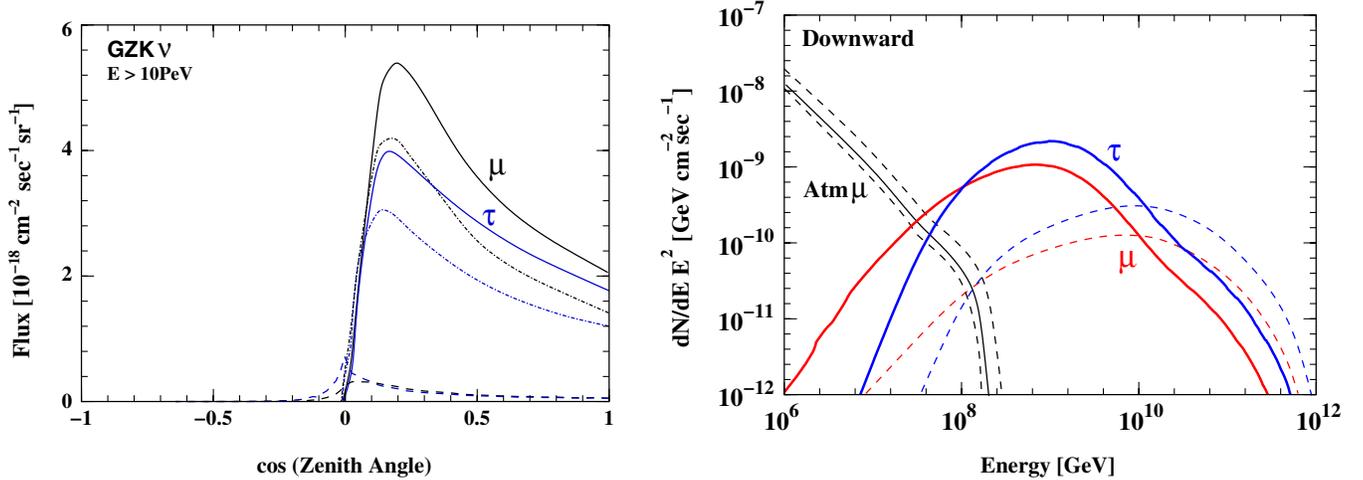A constraint on a specific physics model that enhances the neutrino-nucleon cross section is obtained by the same

FIG. 4 (color online). (Left) integral fluxes of the muon and taus above 10 PeV ($= 10^7$ GeV) at IceCube depth (~ 1450 m) of the GZK cosmogenic neutrinos [17] in case of the microscopic black hole creation scenario [5] for $(M_D, x_{\min}) = (1$ TeV, 1) (solid line), (1 TeV,3) (dotted-dashed line). The dashed line corresponds to the intensities obtained by the SM νN cross section [19]. (Right) energy spectra of the GZK ν induced muons and taus at IceCube depth with downgoing [i.e. cos(zenith) ≥ 0] geometry expected by the black hole model for $(M_D, x_{\min}) = (1$ TeV, 1). The spectra produced by the SM cross section are also shown as dashed lines for comparison. The curve labeled "Atm μ" represents the atmospheric muon intensity estimated by the IceCube observation with its uncertainty expressed by the two dashed lines [21].

procedure for the model-independent bound, except the transport equations, Eqs. (1) and (2), would have total and differential neutrino cross section provided by both SM and the new model. Here we study the model of black hole creation as a possible consequence of low-scale gravity that may occur if space-time has more than four dimensions. We use the predicted cross section of lack hole production via the neutrino-nucleon scattering described by Ref. [5], parametrized by the Planck scale M_D, the ratio of the minimal black hole mass to the Planck scale $x_{\min}$, and the space-time dimension $D = 4 + n$. In this paper $n = 6$ and $M_D = 1$ TeV are assumed as representative numbers. The resultant cross section may exceed SM interaction rates by 2 orders of magnitude or even greater. Therefore, the model-independent bound shown in the previous section indicated that the 2007 IceCube observation should be already sensitive to some of the parameter space in the black hole creation model.

The final states in the neutrino-nucleon scattering in this model are quite different from the SM case. Black holes evaporate and generate multiple particles of all kinds, like leptons, quarks, gluons, and bosons. These products are distributed according to the number of degrees of freedom. Consequently, the average number of muons and taus, $N_{\mu+\tau}$, are 1/30 of all particle average multiplicity $\bar{N}$, which is also determined by the specific model. As $\bar{N} \sim 10$ at neutrino energy of $E_\nu = 1$ EeV, multiple muon or tau production would very rarely occur. Then the *effective* differential cross section $d\sigma_{\nu N}/dE_{\mu,\tau}$ in the transport equations (1) and (2) in the black hole model is represented by

$$\frac{d\sigma_{\nu N}}{dE_{\mu,\tau}} = \frac{N_{\mu+\tau}(E_\nu)}{2}\sigma_{\nu N}(E_\nu)\frac{\bar{N}(E_\nu)}{2E_\nu} \qquad (6)$$

with $0 \leq E_{\mu,\tau} \leq 2E_\nu/\bar{N}$. We take $\bar{N}$ from Ref. [5] in the present calculation. In this specific scenario, a muon or a tau carries a small fraction $(1/\bar{N} \sim 0.1)$ of incoming neutrino energy E_ν in average, in contrast to the SM collision that takes away $1 - y \sim 0.8$ of neutrino energy by a generated charged lepton.

Solving the transport equations gives the intensities of secondary muons and taus, which are shown in Fig. 4. One can find in the zenith angle distribution (the left panel) that the intensities are increased by more than 2 orders of magnitude above the SM case. The large increase of $\sigma_{\nu N}$ enhances downgoing event rates while the upgoing muon and tau rates are more suppressed. The zenith angle distribution is consistent with the original work in Ref. [5]. It should also be noted that the energy spectra is substantially modified from those in the SM case (the right panel). The peak energy is around 1 EeV, an order of magnitude lower than the SM spectrum, reflecting the fact that a smaller fraction of neutrino energy is channeled into muons and taus via the black hole evaporation. The peak happens to match the most sensitive energy region in the IceCube EHE neutrino search [7].

Because $\sigma_{\nu N}$ is solely predicted by the specific model, the model-dependent constraints on νN interactions is represented in the plane of extraterrestrial neutrino flux and the number of events the IceCube 2007 run would have detected. Figure 5 shows the number of events as a function of the neutrino intensity at energy of 1 EeV, if the
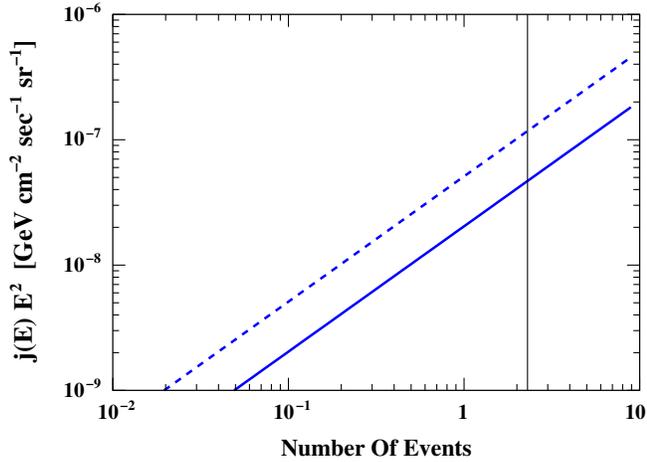
FIG. 5 (color online). Number of events as a function of extraterrestrial neutrino flux at 1 EeV for $(M_D, x_{\min}) = (1 \text{ TeV}, 1)$ (solid line), (1 TeV,3) (dashed line). The 90% C.L. line determined by the Poisson statistics is also shown as a vertical line for reference.

microscopic black hole evaporation occurs as in Ref. [5]. The Poisson statistics then determine the upper limit of neutrino flux that can be still consistent with the null observation by IceCube. It is indicated that the neutrino intensity of 10^{-7} GeV cm^{-2} sec^{-1} sr^{-1} is disfavored in this scenario. More parameter space of M_D and $x_{\min}$ will be further constrained by near future observation with IceCube whose detection volume is rapidly growing with an increase of the number of detectors in operation.

IV. CONCLUSIONS

The IceCube 2007 observation indicated that any scenario to enhance either the NC or both the NC and CC equivalent cross section by more than 100 at $\sqrt{s} \sim 40$ TeV is unlikely if the sum of the all three flavors of astrophysical neutrino fluxes are greater than $\sim 3 \times 10^{-8}$ GeV cm^{-2} sec^{-1} sr^{-1} in the EeV region. Many models of the GZK cosmogenic neutrinos exist to predict this flux range, thus the present constraints limit new particle physics beyond the SM, unless the extraterrestrial neutrino intensity is smaller than the expectation. The example of the model-dependent bound on $\sigma_{\nu N}$ has been also shown for the microscopic black hole evaporation scenario. A high cosmic neutrino intensity constrains the parameter space of the black hole creation. Future observation by the rapidly growing IceCube detectors will strongly limit particle physics models which predict an increase of neutrino-nucleon interaction probability.

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