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TESTING NEUTRINO INTERACTIONS WITH ICECUBE

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In this article we study the possibility to bound effects of new interactions between neutrinos and the nucleons of the Earth using a recently introduced angular observable, α. This observable, which is to be registered in km^3 neutrino telescopes such as IceCube, is only weakly dependent on the initial diffuse flux uncertainties. We investigate the capability of the observable to bound new interactions by fitting a set of values obtained for α using the Standard Model cross-section and statistical errors distributed according a Poisson distribution for the surviving neutrino flux.

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1. Introduction

The Standard Model for the interactions among elementary particles has been successfully tested at the level of its quantum corrections. In particular high precision and collider experiments have tested the model and have placed the border line with new physics effects at energies of the order of 1 TeV [1]. On the other hand, neutrino physics have recently received an important amount of experimental information coming from flavour oscillation. This fact is the first evidence of neutrino masses different from zero, and hence, of physics beyond the Standard Model. In this way, the neutrino sector and in particular neutrino–nucleon interactions, could be the place where new physics may become manifest again. The Standard Model of elementary particles and fundamental interactions (SM) has been successful to describe the world at short distances. However, the model leaves several questions unanswered, *i.e.*, it does not predict the fermions masses, it leaves several parameters free, the mass of the Higgs boson is not predicted, *etc.* In

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these conditions, it is believed that we should have some kind of physics beyond the SM, which is called New Physics (NP). The search of NP proceeds mainly through the comparison of data with the SM predictions. The experimental way to look for NP in a model independent fashion is to construct observables that can be affected by it, and then compare measurements with the mentioned SM expectation. Certain types of NP can already be present at the TeV scale and could participate in neutrino–nucleon interactions. Hence, these NP effects could possibly become apparent in neutrino telescopes. In this work we study the possible manifestation of NP effects on an observable recently proposed [2].

As very high energy cosmic rays are known to reach the Earth, it is likely that the same type of producing mechanisms for cosmic rays could act to produce neutrinos in astrophysical sources. The integrated flux over all such sources in the sky is then supposed to lead to a diffuse neutrino flux. Another source of neutrinos that contributes to this diffuse flux is given by the collisions of cosmic rays with the nucleons of the atmosphere. This last contribution is, in fact, the dominant one for energies lower than 10^5 GeV.

The mentioned diffuse neutrino flux is expected to be detected by IceCube, a neutrino telescope which is currently under construction in the Antarctic ice [3]. When finished, IceCube will present a cubic kilometer of instrumented volume with regularly placed strings of photomultipliers sensitive to the Cherenkov light produced by charged leptons resulting from charged-current (CC) νN interactions. One of the relevant characteristics of IceCube is that it is expected to achieve a good angular resolution, a fact that will be exploited in the present discussion.

The diffuse neutrinos flux can then be used to search for NP effects in νN interactions with the nucleons of the Earth as targets. In order to bound such effects, the different observables that have been studied, basically arise from comparing the upward-going flux that survives after passing through the Earth (which is strongly dependent on the neutrino–nucleon cross-section) with the Standard Model prediction [4–7].

In the traditional observation mode, energetic muons are originated by CC $\nu_\mu N$ interactions of the upward-going neutrinos, leading to a reduced atmospheric background of muons (the muons produced in the atmosphere are mainly downward-going). As simulations based on AMANDA data indicate, the muon direction will be reconstructed with a sub-degree accuracy, and its energy with an error possibly better than 30% in the logarithm of the energy. Still, as mentioned in Ref. [5, 8], it will be possible to separately assign the energy fractions corresponding to the muon track and the hadronic shower, allowing the determination of the inelasticity distribution and then of the neutrino energy. Hence, in the following we shall take the ν_μ-energy bin partition interval as $\Delta \log_{10} E = 0.5$.

2. The observable $\alpha(E)$

The angle α introduced in Ref. [2] is the observable that we shall use in this work making use of the above mentioned sub-degree accuracy expected in IceCube. By definition α is the angle that divides the Earth into two homo-event sectors. When neutrinos traverse the planet in their journey to the detector, they find different matter densities, and then, different number of nucleons to interact with. In this conditions, the number of neutrinos that finally arrive to detector depends on the arrival directions, indicated by the angle θ with respect to the nadir direction. If we consider only upward-going neutrinos of a given energy E, that is, the ones with arrival directions θ such that $0 < \theta < \pi/2$, there will always exist an angle $\alpha(E)$ such that the number of events for $0 < \theta < \alpha(E)$ equals that for $\alpha(E) < \theta < \pi/2$. Considering an isotropic diffuse neutrino flux that is decreasing with energy, (as *e.g.* [9]), the approximate surviving neutrino flux as (*e.g.* [10]),

$$\Phi(E,\theta) = \phi_0(E)e^{-\sigma_{\rm tot}(E)\tau(\theta)}\,, \tag{1}$$

where $\tau(\theta)$ is the number of nucleons per unit area in the neutrino path through the Earth,

$$\tau(\theta) = N_{\rm A} \int\limits_0^{2R_{\rm E}\cos\theta} \rho(z)dz\,. \tag{2}$$

$\phi_0(E)$ is the initial neutrino flux, $N_{\rm A}$ is the Avogadro number, $R_{\rm E}$ is the radius of the Earth, and θ is the nadir angle taken from the downward-going normal to the neutrino telescope.

The expected number of events at IceCube in the energy interval ΔE and in the angular interval $\Delta\theta$ can be estimated as

$$\mathcal{N} = n_{\rm T}T \int\limits_{\Delta\theta}\int\limits_{\Delta E} d\theta dE_\nu \sigma(E)\Phi(E,\theta)\,, \tag{3}$$

where $n_{\rm T}$ is the number of target nucleons in the effective detection volume, T is the running time, and $\sigma(E)$ is the neutrino–nucleon cross-section. We take as the detection volume for contained events the instrumented volume for IceCube, which is roughly 1 km^3 and corresponds to $n_{\rm T} \simeq 6\times10^{38}$. In this case, an accurate measurement of the inelasticity can be obtained.

The definition of α is essentially the equality between two number of events, thus, to a good approximation, for each energy bin all the previous factors cancel except the integrated fluxes at each side. In this way, α can be defined by the equation

$$\int_{0}^{\alpha_{\mathrm{SM}}(E)} d\theta \sin\theta e^{-\sigma^{\mathrm{SM}}(E)\tau(\theta)} = \int_{\alpha_{\mathrm{SM}}(E)}^{\pi/2} d\theta \sin\theta e^{-\sigma^{\mathrm{SM}}(E)\tau(\theta)}\,, \tag{4}$$

which is numerically solved to give the results shown in the shaded region of Fig. 1(A), where we have taken into account the uncertainties in the extrapolation of the SM cross-section and the Earth density. There we have considered the SM cross-section as it was calculated in Ref. [11], while for $\tau(\theta)$ we use Eq. (2) with the Earth density as given by the Preliminary Reference Earth Model [12]. The other curves in the mentioned figure correspond to different contributions of NP as we will show below in this section.

TABLE I

Sets of parameters for the new four-fermion contact interactions.

Set	η_{LL}	η_{LR}	Λ (TeV)
1	1	1	1
2	−1	−1	1
3	−1	−1	2
4	1	1	0.8
5	−1	−1	0.8

The main characteristics of $\alpha(E)$ have been reported recently in Ref. [2]. It is worth to notice that $\alpha(E)$ is weakly dependent on the initial flux but, at the same time it is strongly dependent on the neutrino–nucleon cross-section. Hence, the use of the observable $\alpha(E)$ reduces the effects of the experimental systematics and initial flux dependence. Since the functional form of $\alpha(E)$ sharply depends on the interaction cross-section neutrino–nucleon, if physics beyond the Standard Model operates at these high energies, it will become manifest directly onto the function $\alpha(E)$.

As it was done in Ref. [2], we consider general 4-fermion scenario which is characterised by an effective operator that includes also the SM fields involved in the neutrino–nucleon scattering with left-handed neutrinos. Admitting new interactions between quarks and leptons, the NP effects should become unveiled at a sufficiently high energy scale Λ. For energies below it, these interactions are suppressed by an inverse power of Λ and the dominant effects should come from the lowest dimensional interactions with 4-fermions [13], which can be described by the Lagrangian density

$$\mathcal{L} = \quad \mathcal{L}^{\mathrm{SM}} + \frac{g_N^2}{2\Lambda^2}\Big[\sum_{i=d,j=u}\big(\bar{l}\gamma_\mu P_{\mathrm{L}}\nu\bar{q}_j\gamma^\mu(\eta_{\mathrm{LL}}P_{\mathrm{L}} + \eta_{\mathrm{LR}}P_{\mathrm{R}})q_i\big)$$

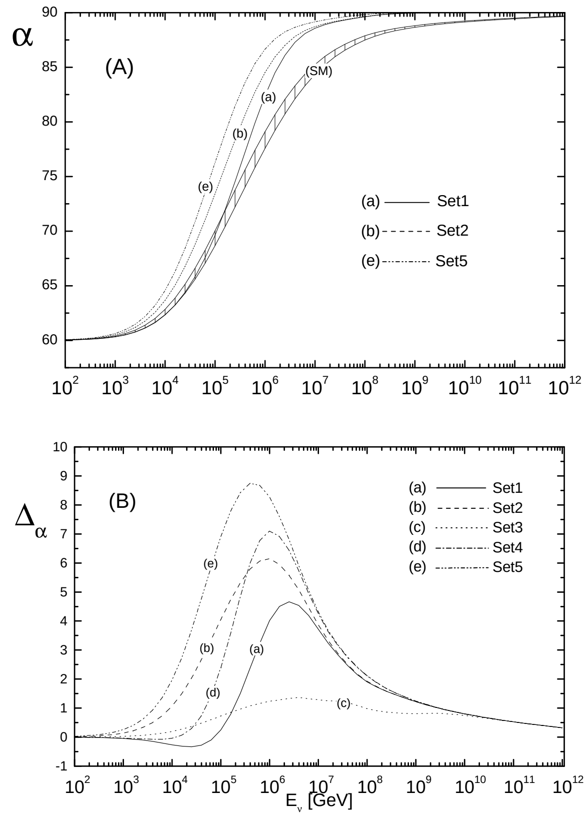

Fig. 1. (A) $\alpha(E)$ for the different sets of NP parameters and the Standard Model prediction including the uncertainties coming form different high energy extrapolations for the structure functions. (B) Differences between α for different sets of parameters and the Standard Model prediction ($\Delta_\alpha = \alpha_{\rm SM} - \alpha_{{\rm Set}_i}$). In both figures E is the energy of the neutrino and the different sets are defined in Table I.

$$+ \sum_{i=u,d} (\bar{\nu}\gamma_\mu P_{\rm L}\nu \bar{q}_i \gamma^\mu (\eta_{\rm LL} P_{\rm L} + \eta_{\rm LR} P_{\rm R}) q_i) \Big] , \qquad (5)$$

for left-handed neutrinos, where we take $g_N^2 = 4\pi$, and the coefficients $\eta_{\rm LL}$ and $\eta_{\rm LR}$ can take up the values -1, 0, and 1. Choosing different values of Λ, $\eta_{\rm LL}$, and $\eta_{\rm LR}$, we can test the α observable under different scenarios of new physics.

Using the effective operator we can calculate its contribution to the neutrino–nucleon inclusive cross-section: $\nu N \to \mu +$ anything. A detailed calculation of these effects can be founded in Ref. [2].

In order to illustrate the behaviour of the angle α with the new contributions coming from the Lagrangian in Eq. (5), we show in Fig. 1(A) the results for α for different coupling parameters and NP scales, which are summarised in Table I. In Fig. 1(B) we show the differences between the values of α for the different sets of parameters and the SM values as a function of the energy. It can be seen that the maximum sensitivity is reached in the intermediate energy range (10^5 GeV $< E < 10^7$ GeV).

In order to evaluate the impact of the observable α to bound new physics effects, we have estimated the corresponding uncertainties. Considering the number of events as distributed according to a Poisson distribution the uncertainty can be propagated onto the angle $\alpha(E)$. The number of events N as a function of α_{SM} is

$$N = 2\pi n_{\mathrm{T}} T \Delta E \sigma(E) \phi_0(E) \int\limits_0^{\alpha_{\mathrm{SM}}} d\theta \sin\theta e^{-\sigma_T(E)\tau(\theta)}\,, \tag{6}$$

where we have considered the effective volume for contained events so that an accurate and simultaneous determination of the muon energy and shower energy is possible. For IceCube, it corresponds to the instrumented volume, roughly 1 km^3, implying a number of target nucleons $n_{\mathrm{T}} \simeq 6 \times 10^{38}$. We have considered an integration time $T = 15$ yr which is the expected lifetime of the experiment.

To propagate the error on N to obtain the one on α, we note that

$$\delta N = \frac{dN}{d\alpha}\delta\alpha\,, \tag{7}$$

and dividing by N we obtain

$$\delta\alpha = \left[\int\limits_0^{\alpha_{\mathrm{SM}}(E)} d\theta \left(\frac{\sin\theta}{\sin\alpha_{\mathrm{SM}}(E)}\right) e^{\sigma_T(E)[\tau(\alpha_{\mathrm{SM}}(E))-\tau(\theta)]}\right] \left(\frac{\delta N}{N}\right)\,, \tag{8}$$

where for Poisson distributed events we have

$$\delta N = \sqrt{N}\,. \tag{9}$$

In order to evaluate the errors on $\alpha(E)$, it is necessary to consider a level of initial flux $\phi_0^{\nu_\mu}$. Here we have added together the cosmological diffuse flux and the atmospheric one. For the atmospheric flux, we have considered the one given in Ref. [14]. As for the cosmological diffuse flux, the usual benchmark is the so-called Waxman–Bahcall (WB) flux for each flavour, $E_{\nu_\mu}^2 \phi_{\mathrm{WB}}^{\nu_\mu} \simeq 2 \times 10^{-8}$ GeV cm^{-2}s^{-1}sr^{-1}, which is derived assuming that neutrinos come from transparent cosmic ray sources [9], and that there is an adequate transfer of energy to pions following *pp* collisions. However, one should keep in mind that if there are in fact hidden sources which are opaque to ultra-high energy cosmic rays, then the expected neutrino flux will be higher.

On the other hand, we have the experimental bounds set by AMANDA. A summary of these bounds can be found in Ref. [15, 16] and as a representative value we take $E^2_{\nu_\mu}\phi^{\nu_\mu}_{\rm AM} \simeq 2\times 10^{-7}$ GeV cm^{-2}s^{-1}sr^{-1}.

With the intention to estimate the number of events, we have considered an intermediate flux (INT) level slightly below the present experimental bound by AMANDA,

$$E^2_{\nu_\mu}\phi^{\nu_\mu}_{\rm INT} \simeq 10^{-7}{\rm GeV\ cm^{-2}s^{-1}sr^{-1}}\,. \tag{10}$$

The sum of this cosmological diffuse contribution and the atmospheric one is shown in Fig. 2, and it is the flux that we shall use to estimate the uncertainty on the angle α.

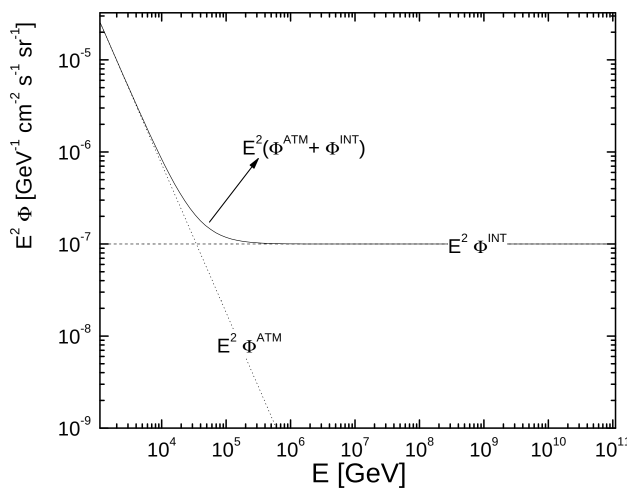

Fig. 2. The atmospheric diffuse flux ($\Phi^{\rm ATM}$), the cosmological diffuse flux ($\Phi^{\rm INT}$) and sum of both.

As we have mentioned above, the interval for maximum sensitivity for α is 10^5 GeV $< E < 10^7$ GeV. However, as for lower energies the atmospheric flux grows and then the errors fall, we have considered as an energy window for the fits the interval: 10^3 GeV $< E < 10^7$ GeV.

In Fig. 3 we show our results for the observable α and the corresponding errors within the mentioned energy window as it was discussed above.

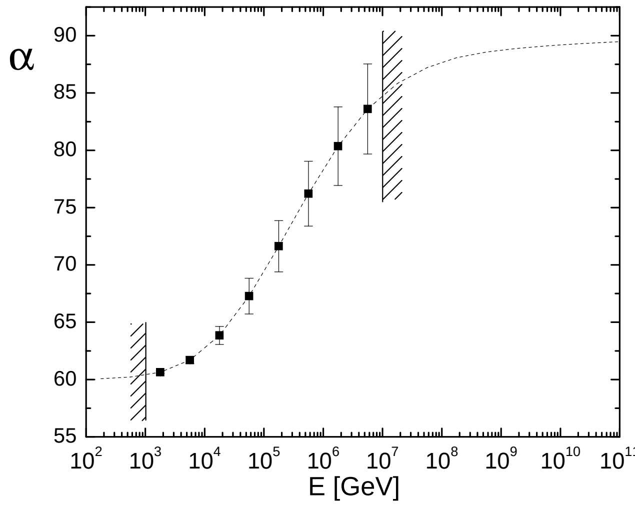

Fig. 3. Data for α that we will use in the fit. The curve correspond to the Standard Model prediction for α.

In order to estimate the capability of $\alpha(E)$ to bound NP effects, we have considered the values for α along with their error bars in Fig. 3 as if they had been obtained from experimental measurements for α. We proceed, then, to perform a χ^2-analysis taking as free parameters the NP scale (Λ) and the coefficient $\eta = \eta_{\rm LL} = \eta_{\rm LR}$.

We define the χ^2 function in the usual way,

$$\chi^2 = \sum_{i=1,8} \frac{(\alpha_{\rm SM}(E_i) - \alpha(E_i, \eta, 1/\Lambda))^2}{(\delta\alpha(E_i))^2} \,. \tag{11}$$

The function χ^2 is minimised to obtain the allowed 90% C.L. region in the (η, Λ) plane, which corresponds to the shaded region shown in Fig. 4. As it can be seen in this figure that for values of the coefficient ($\eta = \eta_{\rm LL} = \eta_{\rm LR}$) of the order of one ($|\eta| \approx 1$), it will be possible to obtain bounds on the NP scale of roughly $\Lambda \sim 1.5$ TeV. In this conditions, if the diffuse flux is of the order of the considered in this work, then the observable $\alpha(E)$ will be able to place bounds on Λ of the order of 1.5 TeV for NP effects taken into account in a general and effective fashion through the effective Lagrangian indicated in Eq. (5). However, it is possible that for a specific NP model we could possibly obtain even higher values of Λ, a matter which is left for future work.

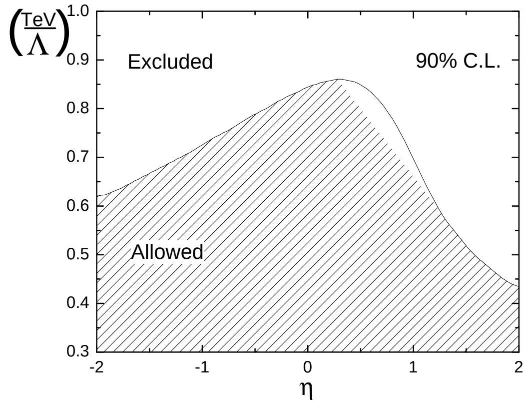

Fig. 4. Allowed region (90% C.L.) for the new physics scale Λ and coefficient η.

3. Conclusions

In the present work, we have studied the possibility to bound effects of new interactions between neutrinos and the nucleons of the Earth using the observable $\alpha(E)$. To do it, we have considered effective four-fermion interactions depending on the coupling parameter η and the NP energy scale Λ. In this context, we have fitted the theoretical expression for α as a function of the parameters η and $1/\Lambda$ taking as experimental data the SM values obtained for α along with the errors derived for a number of events distributed according to a Poisson distribution. The results are shown in Fig. 4 as a 90 % C.L. region. The use of this observable reduces the experimental systematics and the dependence with the initial neutrino flux. On the other hand the function $\alpha(E)$ is sharply dependent on the neutrino–nucleon cross-section, which makes it a useful observable to bound new physics. We remark that, in order to make the fit, we have used an energy interval where the differences between α and $\alpha_{\rm SM}$ is important and the contribution of the atmospheric flux reduces the experimental errors.

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