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Abstract

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Leptoquark effects on ν_τ propagation in the Earth

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Abstract The detection of a ν_τ flux in a neutrino telescope would provide a way to measure the cosmic flux without the background of the atmospheric ν_μ's. Given that effects of new physics could alter the flux arriving at the detector, in this work we consider, as a particular scenario, the effects of leptoquarks on the propagation in the Earth of tau neutrinos. We calculate their contribution to the neutrino–nucleon interaction and their effect on the transport. We show the resulting ν_τ flux and compare it with the ν_μ flux after through the planet. Finally, we obtain the 90 % C.L. region (Sensitivity Region) where neutrino telescopes will be sensible to the leptoquark effects.

1 Introduction

The Standard Model (SM) for the interactions of elementary particles has been successfully tested at the level of quantum corrections. In particular, high precision and collider experiments have tested the model and have placed the border line for new physics effects at energies of the order of 1 TeV [1]. On the other hand, new physics (NP) effects in the neutrino sector have recently received an important amount of experimental information coming from flavor oscillation [2]. This fact is the first evidence of neutrino masses different from zero, and hence, of physics beyond the SM. Similarly, the neutrino sector, and in particular neutrino–nucleon interactions, could be the place where new physics (NP) may become manifest again.

Certain types of NP can already be present at the TeV scale and participate in neutrino–nucleon interactions yielding effects that could become apparent in neutrino telescopes. These machines are able to explore the high energy neutrino–nucleon collision reaching center-of-mass energies orders of magnitude above those of man made accelerators. In spite of having large uncertainties on the beam composition and fluxes, cosmic ray experiments present a unique opportunity to look for new physics in the neutrino sector at scales far beyond the TeV for which energetic cosmic and atmospheric neutrinos interact with the nucleons of the Earth. In particular, the physics associated to the third family is less known and their properties poorly measured, which turn this into a possible scenario where NP could become manifest.

Several models of astrophysical phenomena predict the generation of fluxes of electron and muon neutrinos. These appear from the disintegration of mesons (pions and kaons) which are produced by the interactions of accelerated particles with the astrophysical ambient matter and radiation (see e.g. [3–6]). Given the flavor mixing oscillations and the large distance between the production place and the detection on Earth, equal fluxes of the three flavors are expected: ν_e, ν_μ, and ν_τ.[1]

One way for disentangling a diffuse flux of astrophysical neutrinos of ultra-high energies from the atmospheric background is by studying the behavior of the flux as a function of the energy. On the other hand, since the ν_τ component does not belong to the atmospheric flux, it would be possible to detect the cosmic flux by identifying tau neutrinos. Thus, in the search for ultra-high energy cosmological neutrinos the cleanly identification of high energy tau neutrinos would be a convincing evidence. This is possible since tau neutrinos are not produced in standard cosmic ray atmospheric interactions which create electron and muon neutrinos. Furthermore, neither the effect of oscillations over atmospheric distances or the effect of prompt neutrinos originated in the decay of charmed particles in the atmosphere would produce extremely small atmospheric tau neutrino flux.

In these conditions, is important to understand different mechanisms which could modify the ν_τ propagation in the Earth. As was pointed in Ref. [8], high energy ν_τ flux attenuation in the Earth differs from ν_μ flux attenuation due to the

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[1] Deviations from a 1:1:1 ratio of neutrino flavors could arise if the dominant neutrino sources are strongly magnetized (see e.g. Ref. [7]).

fact that a τ produced in charged-current (CC) interactions with nucleons decays before it loses energy. For each ν_τ lost in CC interactions, another ν_τ appears after a τ decay, albeit at a lower energy.

The calculation of the propagation of ν_τ of cosmic origin in the Earth depends on our knowledge of the high energy neutrino cross section which is indeed limited and it could be significatively affected at center-of-mass energies beyond the TeV by the onset of new physics beyond the SM. In particular, the existence of families of quarks and leptons suggest a possible link between them [9]. Many theories, such as composite models, technicolor, and grand unified theories, predict the existence of new particles called leptoquarks, which mediate quark–lepton transitions [10, 11]. It is important to note that simultaneous trilinear coupling of the leptoquark to a purely hadronic channel is excluded in order to avoid a too fast baryon decay [12]. Current bounds on leptoquarks coming from pair production in colliders impose $m_{\rm LQ} > 660$ GeV for the first family [13], $m_{\rm LQ} > 600$ GeV for the second family [14], and $m_{\rm LQ} > 250$ GeV for the third family [15]. The low bound for the mass of the third family of leptoquarks implies the possibility that an appreciable effect in the tau neutrino propagation could be generated, and hence, affect the search of cosmic neutrinos through ν_τ detection. It is important to notice that the current limits on the masses of the third family of scalar leptoquarks were placed directly based on their contribution to the radiative corrections to the Z-physics. These bounds can be found in Table II of Ref. [16] for different kinds of leptoquarks. On the other hand, and in order to keep the analysis as simple as possible, we shall consider here only flavor diagonal contributions, although mixing between leptoquark generations could also take place.

In this work, we study the effects arising from leptoquarks on the ν_τ-propagation. We shall consider the simple case of a $SU(2)$-singlet scalar leptoquark $\mathcal{S}$ coupled to the third family, which interacts with quarks and leptons through the lagrangian

$$\mathcal{L}_{\rm LQ} = \left(g_L \bar{Q}_L^c i\tau_2 L_L + g_R \bar{t}_R^c \tau_R\right)\mathcal{S}, \tag{1}$$

where $Q = (t, b)^t$ and $L = (\nu_\tau, \tau)^t$ are the quarks and leptons $SU(2)$ left-handed doublets, t_R and τ_R are the right-handed singlets, and g_L and g_R the corresponding coupling constants.

In Fig. 1, we show the ν_τ–N processes. In addition to the SM contribution for charged and neutral currents, we show the leptoquark relevant diagram, for which the corresponding cross section for charged and neutral currents are given by [17, 18]:

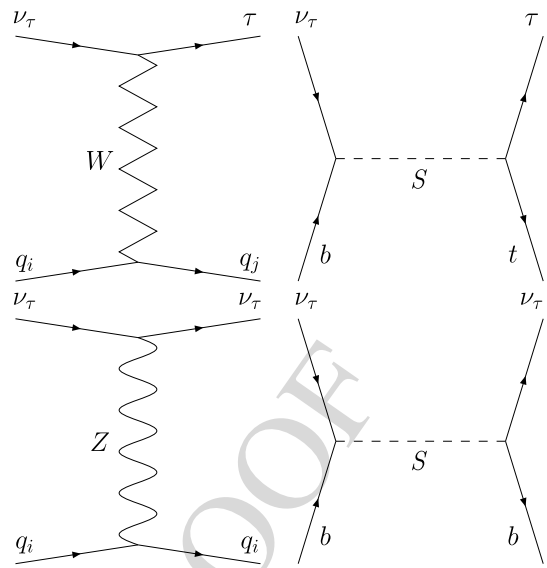

Fig. 1 Diagrams contributing to the weak and leptoquark ν_τ-nucleon cross section

$$\frac{d\sigma_{\rm LQ}^{\rm CC}}{dx\,dy} = \frac{g_L^2}{32\pi}\left(g_L^2 + g_R^2\right)\frac{\hat{s}}{(\hat{s} - m_{\rm LQ}^2)^2 + (\Gamma m_{\rm LQ})^2} \times s(x, m_{\rm LQ}), \tag{2}$$

$$\frac{d\sigma_{\rm LQ}^{\rm NC}}{dx\,dy} = \frac{g_L^4}{32\pi}\frac{\hat{s}}{(\hat{s} - m_{\rm LQ}^2)^2 + (\Gamma m_{\rm LQ})^2} s(x, m_{\rm LQ})$$

where $\hat{s} = xS$, $S = 2M_{\rm proton}E_\nu$ and the leptoquark width is

$$\Gamma = (m_{\rm LQ}/16\pi)\left[\left(g_L^2 + g_R^2\right)\left(1 - \frac{m_t^2}{m_{\rm LQ}^2}\right)^2 + g_L^2\right]. \tag{3}$$

On the other hand, the corresponding SM cross section reads for charged currents,

$$\frac{d\sigma^{\rm CC}}{dx\,dy} = \frac{G_{\rm F}^2 s}{\pi}\left(\frac{M_W^2}{(Q^2 + M_W^2)}\right)^2 x\left[Q^{\rm CC} + (1-y)^2\bar{Q}^{\rm CC}\right], \tag{4}$$

and for the neutral currents,

$$\frac{d\sigma^{\rm NC}}{dx\,dy} = \frac{G_{\rm F}^2 s}{\pi}\left(\frac{M_Z^2}{Q^2 + M_Z^2}\right)^2 \times \sum_{i=U,D} x\left[g_L^{i2}\left(Q^i + (1-y)^2\bar{Q}^i\right) + g_R^{i2}\left(\bar{Q}^i + (1-y)^2 Q^i\right)\right], \tag{5}$$

where the quark combinations $\bar{Q}^{\rm CC}$, $Q^{\rm CC}$, $\bar{Q}^i$ and Q^i for an isoscalar target are given in [19, 20] and $g_L^U = 1/2 - 2x_W/3$, $g_L^D = -1/2 + x_W/3$, $g_R^U = -2x_W/3$, $g_R^D = x_W/3$, $c_W = \cos\theta_W$, $x_W = \sin^2\theta_W$.

In Fig. 2, we show for completeness the diagrams for the τ–N collision. This process is not considered because it is negligible in comparison with τ-decay and those initiated by ν_τ. In particular, the leptoquark contribution is so weak because it is proportional to the t-quark distribution inside the nucleon.

In Fig. 3, we show the behavior of the total cross section ($\sigma^{\mathrm{T}}(E) = \sigma^{\mathrm{CC}}(E) + \sigma^{\mathrm{NC}}(E) + \sigma^{\mathrm{CC}}_{\mathrm{LQ}}(E) + \sigma^{\mathrm{NC}}_{\mathrm{LQ}}(E)$) with the neutrino energy for different values of m_{LQ} and the couplings $g_L = g_R = 1$. We can appreciate a disagreement with the SM predictions, due to the leptoquark contribution for values of E_ν where the leptoquark can be on shell.

On the other hand, for kinematic reasons there are no contributions of leptoquarks to the τ-decay since the final quark b or t is more massive than the τ lepton.

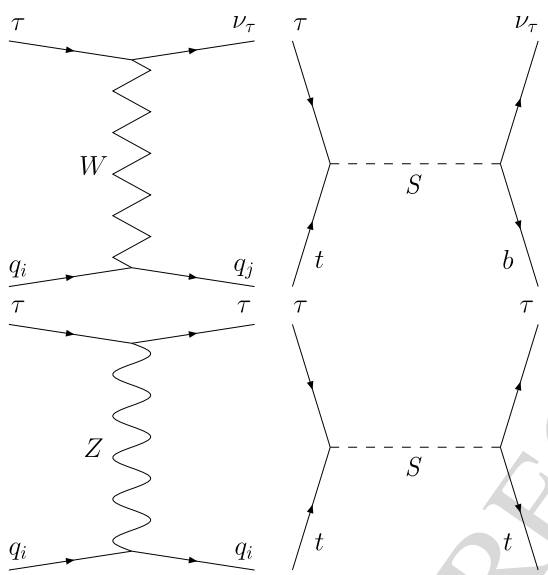

Fig. 2 Diagrams contributing to the weak and leptoquark τ-nucleon cross section

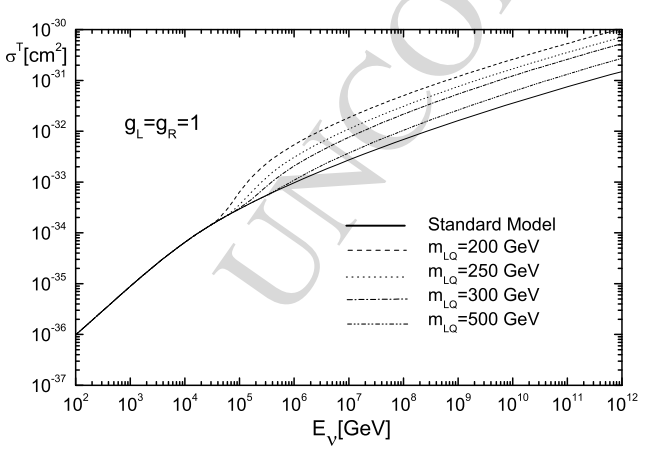

Fig. 3 Total cross section for the SM and for different values of the leptoquark mass m_{LQ} and for $g_L = g_R = 1$

2 The surviving neutrino flux

The surviving flux of neutrinos of energy E, with inclination θ with respect to nadir direction, $\Phi(E,\theta)$, is the solution of the complete transport equation [21–23]:

$$\begin{aligned}
\frac{\partial \Phi_{\nu_\tau}}{\partial \chi} &= -\sigma^{\mathrm{T}}_{\nu}(E)\Phi_{\nu_\tau}(E,\chi) \\
&\quad + \sigma^{\mathrm{T}}_{\nu_\tau}(E)\int_0^1 \frac{dy}{(1-y)}\Phi_{\nu_\tau}(E_y,\chi)K^{\mathrm{NC}}_{\nu_\tau}(E,y) \\
&\quad + \sigma^{\mathrm{T}}_{\tau}(E)\int_0^1 \frac{dy}{(1-y)}\Phi_{\tau}(E_y,\chi)K^{\mathrm{CC}}_{\tau}(E,y) \\
&\quad + \Sigma_\tau(E)\int_0^1 \frac{dy}{1-y}\Phi_{\tau}(E_y,\chi)K^{\mathrm{dec}}(1-y), \\
\frac{\partial \Phi_{\tau}}{\partial \chi} &= -\sigma^{\mathrm{T}}_{\tau}(E)\Phi_{\tau}(E,\chi) \\
&\quad - \Sigma_\tau(E)\Phi_\tau(E,\chi) + \frac{d}{dE}\big(\gamma(E)\Phi_\tau(E,\chi)\big) \\
&\quad + \sigma^{\mathrm{T}}_{\tau}(E)\int_0^1 \frac{dy}{(1-y)}\Phi_{\tau}(E_y,\chi)K^{\mathrm{NC}}_{\tau}(E,y) \\
&\quad + \sigma^{\mathrm{T}}_{\nu_\tau}(E)\int_0^1 \frac{dy}{(1-y)}\Phi_{\nu\tau}(E_y,\chi)K^{\mathrm{CC}}_{\nu_\tau}(E,y)
\end{aligned} \tag{6}$$

where $\chi(Z) = \int_0^Z N_A \rho(z)\,dz$ for the penetration distance Z in the Earth. The functions involved in the above equations are

$$\begin{aligned}
\Sigma_\tau &= \frac{1}{(E/m)\rho_n c\tau_\tau}, \\
K^{\mathrm{NC}}_{\nu_\tau}(E,y) &= \frac{1}{\sigma^{\mathrm{T}}_{\nu}(E)}\frac{d\sigma^{\mathrm{NC}}_{\nu}(E_y,y)}{dy}, \\
K^{\mathrm{CC}}_{\tau}(E,y) &= \frac{1}{\sigma^{\mathrm{T}}_{\tau}(E)}\frac{d\sigma^{\mathrm{CC}}_{\tau}(E_y,y)}{dy}, \\
K^{\mathrm{dec}}(E,y) &= (1-y)\frac{dn(1-y)}{dy}
\end{aligned} \tag{7}$$

where $dn/dy = \sum_i B_i(g^i_0 + Pg^i_1)$. The polarization of the decaying τ^- is P, which for τ^- production initiated by neutrino interactions $V-A$ is $P=-1$. The constants B_i are the branching fraction into decay channel i. The functions g^i_0, g^i_1, and the details of the calculation can be found in [24]. The functions

$$\begin{aligned}
K^{\mathrm{NC}}_{\tau}(E,y) &= \frac{1}{\sigma^{\mathrm{T}}_{\tau}(E)}\frac{d\sigma^{\mathrm{NC}}_{\tau}(E_y,y)}{dy}, \\
K^{\mathrm{CC}}_{\nu}(E,y) &= \frac{1}{\sigma^{\mathrm{T}}_{\nu}(E)}\frac{d\sigma^{\mathrm{CC}}_{\nu}(E_y,y)}{dy}
\end{aligned} \tag{8}$$

and the function for the losses of electromagnetic energy $\gamma(E) = \alpha + \beta E$ will not be taken into account because, in

the energy range studied ($<10^8$ GeV), they are negligible [22]. The negative term in Eq. (6) corresponds to absorption effects and the positive one to regeneration. Here, $0 < \chi < X(\theta)$ where $X(\theta) = \chi(2R_E \cos\theta) = \int_0^{2R_E \cos\theta} N_A \rho(z)\, dz$ is the number of nucleons per unit area in the neutrino path through the Earth, N_A is the Avogadro number, R_E is the radius of the Earth, θ is the nadir angle taken from the down-going normal to the neutrino telescope and the Earth density $\rho(r)$ is given by the Preliminary Reference Earth Model [25].

For $E_\nu < 10^8$ GeV, both the $\tau^\pm$ energy loss and the τ-nucleon interactions can be neglected in front of the τ-decay. Thus, we obtain a simplified system of transport equations:

$$\begin{aligned}\frac{\partial \Phi_{\nu_\tau}}{\partial \chi} &= -\sigma_\nu^{\mathrm{T}}(E)\Phi_{\nu_\tau}(E,\chi) \\ &\quad + \Sigma_\tau(E)\int_0^1 \frac{dy}{1-y}\Phi_\tau(E_y,\chi)K^{\mathrm{dec}}(1-y), \\ \frac{\partial \Phi_\tau}{\partial \chi} &= -\Sigma_\tau(E)\Phi_\tau(E,\chi) \\ &\quad + \sigma_{\nu_\tau}^{\mathrm{T}}(E)\int_0^1 \frac{dy}{(1-y)}\Phi_{\nu\tau}(E_y,\chi)K_{\nu_\tau}^{\mathrm{CC}}(E,y).\end{aligned} \tag{9}$$

To solve the system, we deal first with the propagation equation for the τ-lepton considering the term dependent on the ν_τ-flux as an inhomogeneity:

$$\frac{\partial \Phi_\tau}{\partial \chi} + \Sigma_\tau(E)\Phi_\tau = \mathcal{G}(E,\chi), \tag{10}$$

where

$$\mathcal{G}(E,\chi) = \sigma_{\nu_\tau}^{T}(E)\int_0^1 \frac{dy}{(1-y)}\Phi_{\nu_\tau}(E_y,\chi)K_{\nu_\tau}^{\mathrm{CC}}(E,y). \tag{11}$$

It is a first order differential equation with a trivial solution. If we replace the solution in the transport equation for the ν_τ, we obtain

$$\begin{aligned}&\frac{\partial \ln \Phi_{\nu_\tau}(E,\chi)}{\partial \chi} \\ &\quad = -\sigma_{\nu_\tau}^{\mathrm{T}}(E) \\ &\qquad + \sigma_{\nu_\tau}^{\mathrm{T}}(E)\int_0^1 \frac{dy}{(1-y)}\frac{\Phi_{\nu_\tau}(E_y,\chi)}{\Phi_{\nu_\tau}(E,\chi)}K_{\nu_\tau}^{\mathrm{NC}}(E,y) \\ &\qquad + \int_0^1\int_0^1\int_0^1 dy\,dy'\,d\eta\,\frac{\chi}{(1-y)(1-y')} \\ &\qquad \times \Sigma_\tau^{\mathrm{T}}(E)K_\tau^{\mathrm{dec}}(E,y)\sigma_{\nu_\tau}^{\mathrm{T}}(E_y)K_{\nu_\tau}^{\mathrm{CC}}(E_y,y') \\ &\qquad \times e^{-(1-\eta)\Sigma_\tau^{\mathrm{T}}(E_y)\chi}\frac{\Phi_{\nu_\tau}(E_{yy'},\eta\chi)}{\Phi_{\nu_\tau}(E,\chi)}.\end{aligned} \tag{12}$$

In order to find a solution for this equation, we make the following approximation [26]: we replace the fluxes ratio inside the integrals of the second member by the ratios of fluxes that solve the homogeneous equation (i.e., only considering absorption effects),

$$\frac{\Phi_{\nu_\tau}(E_y,\chi)}{\Phi_{\nu_\tau}(E,\chi)} \to \frac{\Phi_{\nu_\tau}^0(E_y)}{\Phi_{\nu_\tau}^0(E)}e^{-(\sigma_{\nu_\tau}^{\mathrm{T}}(E_y)-\sigma_{\nu_\tau}^{\mathrm{T}}(E))\chi} \tag{13}$$

and

$$\frac{\Phi_{\nu_\tau}(E_{yy'},\eta\chi)}{\Phi_{\nu_\tau}(E,\chi)} \to \frac{\Phi_{\nu_\tau}^0(E_{yy'})}{\Phi_{\nu_\tau}^0(E)}e^{-(\sigma_{\nu_\tau}^{T}(E_{yy'})-\sigma_{\nu_\tau}^{T}(E))\chi}, \tag{14}$$

where $\Phi_0(E)$ is the ν_τ initial flux at the Earth surface which is of cosmic origin. As we explain below, we will use different behaviors with the energy for the initial flow. Thus, integrating the transport equation we have

$$\Phi_{\nu_\tau}(E,\theta) = \Phi_{\nu_\tau}^0(E)e^{-\sigma_{\nu_\tau}^{\mathrm{eff}}(E,X(\theta))X(\theta)}, \tag{15}$$

where

$$\begin{aligned}&\sigma_{\nu_\tau}^{\mathrm{eff}}\big(E,X(\theta)\big) \\ &\quad = \sigma_{\nu_\tau}^{\mathrm{T}}(E) \\ &\qquad - \sigma_{\nu_\tau}^{\mathrm{T}}(E)\int_0^1 dy\,\xi(E,y)K_{\nu_\tau}^{\mathrm{NC}}(E,y)\left(\frac{1-e^{-\Delta(E_y,E)}}{X\Delta(E_y,E)}\right) \\ &\qquad - \int_0^1\int_0^1 dy\,dy'\,\xi\big(E_y,y'\big)\xi(E,y) \\ &\qquad \times \frac{\sigma_{\nu_\tau}^{\mathrm{T}}(E_y)K_{\nu_\tau}^{\mathrm{CC}}(E_y,y')}{X\Omega(E_y,E_{yy'})}\Sigma_\tau(E)K_\tau^{\mathrm{dec}}(E,y) \\ &\qquad \times \left\{\frac{1-e^{-\Delta(E_{yy'},E)}}{\Delta(E_{yy'},E)} - \frac{1-e^{-\Omega(E_y,E)}}{\Omega(E_y,E)}\right\}\end{aligned} \tag{16}$$

where

$$\begin{aligned}\xi(E,y) &= \frac{\Phi_\nu^0(E_y)}{(1-y)\Phi_\nu^0(E)}, \\ \xi\big(E_y,y'\big) &= \frac{\Phi_\nu^0(E_{yy'})}{(1-y')\Phi_\nu^0(E_y)}, \\ \Delta(E_1,E_2) &= \sigma_{\nu_\tau}^{\mathrm{T}}(E_1) - \sigma_{\nu_\tau}^{\mathrm{T}}(E_2), \\ \Omega(E_1,E_2) &= \Sigma_\tau(E_1) - \sigma_{\nu_\tau}^{\mathrm{T}}(E_2).\end{aligned} \tag{17}$$

It is important to mention that the solution of the transport equation, Eq. (15) is the first, but quite accurate, approximation of the iterative method described in Ref. [27].

The selection of up-going ν_τ's reduces the great majority of background events from muon bremsstrahlung and tracks arising from muons produced in cosmic ray showers. The

muon bremsstrahlung generates showers inside or near the detector and constitutes a background for the shower generated by the neutrino–nucleon collision. Moreover, as explained above, for ν_τ's there is no atmospheric flux competing with the cosmic flux. We here consider the cases of incident, energy dependent, neutrino flux of cosmic origin, and rather than using specific flux models, we consider power law fluxes $\sim E_\nu^{-n}$ for $n = 1, 2$:

$$\Phi^0_{\nu_\tau}(E_{\nu_\tau}) = \frac{\mathcal{N}_1}{E_{\nu_\tau}(1 + E_{\nu_\tau}/E_0)^2},$$
$$\Phi^0_{\nu_\tau}(E_{\nu_\tau}) = \frac{\mathcal{N}_2}{E^2_{\nu_\tau}}, \tag{18}$$

which originated by a different production mechanisms, and where $E_0 = 10^8$ GeV.

In order to show the effects caused by leptoquarks on the ν_τ propagation, we present in Figs. 4 and 5 the ratio

$$R(E,\theta) = \frac{\Phi_\nu(E,\theta)}{\Phi^0_\nu(E)} \tag{19}$$

as a function of the neutrino energy for two different angles, and in Figs. 6 and 7 as a function of the angle θ for two different energies. We present our results in a form that allows to disentangle the different contributions. With a solid line, we indicate the ratio R for the tau neutrino with the contribution of leptoquarks of different mass, the line labeled (a) for $m_{LQ} = 200$ GeV, (b) for $m_{LQ} = 300$ GeV and (c) for $m_{LQ} = 400$ GeV. The dashed line represents the corresponding ratio for the standard ν_τ propagation without leptoquark effects and finally, for comparison, a dotted line is used to show the ratio corresponding to ν_μ's. The quantity $R(E,\theta)$ is independent of the constants $\mathcal{N}_1$ and $\mathcal{N}_2$.

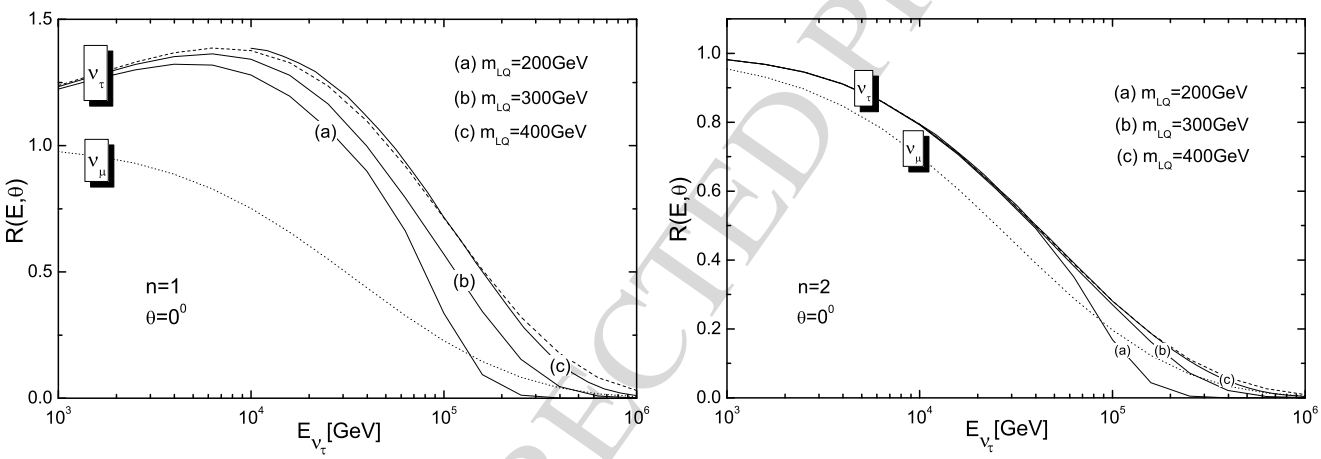

Fig. 4 The ratio $R(E,\theta)$ as a function of the energy for the nadir angle $\theta = 0°$ and two different behaviors with the energy of the initial flux

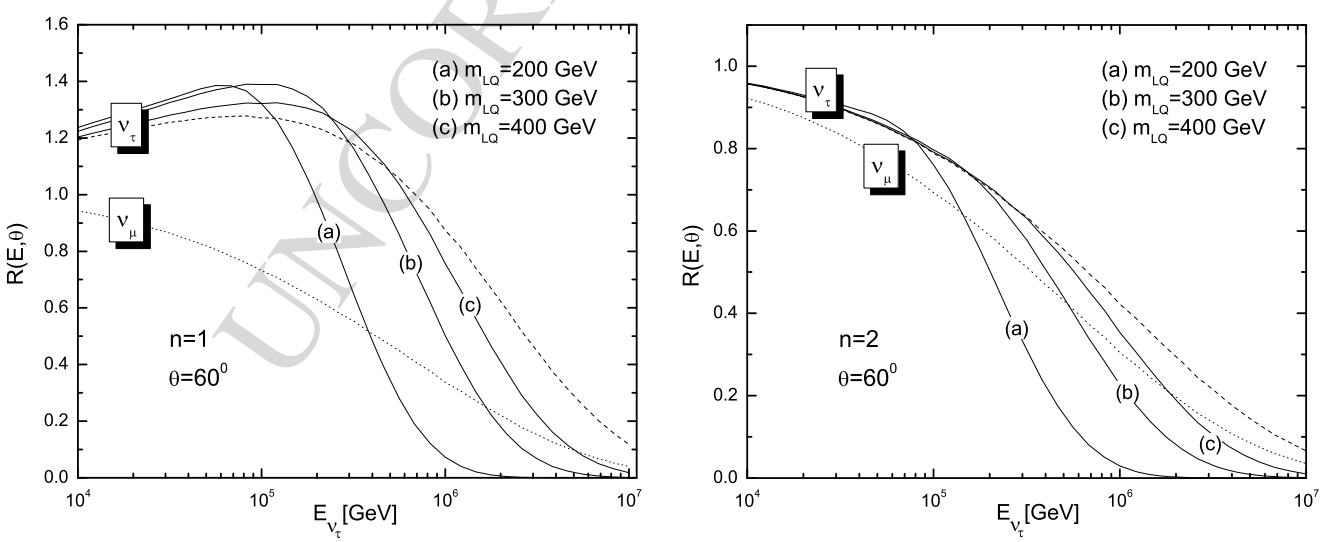

Fig. 5 As Fig. 4 but for $\theta = 60°$

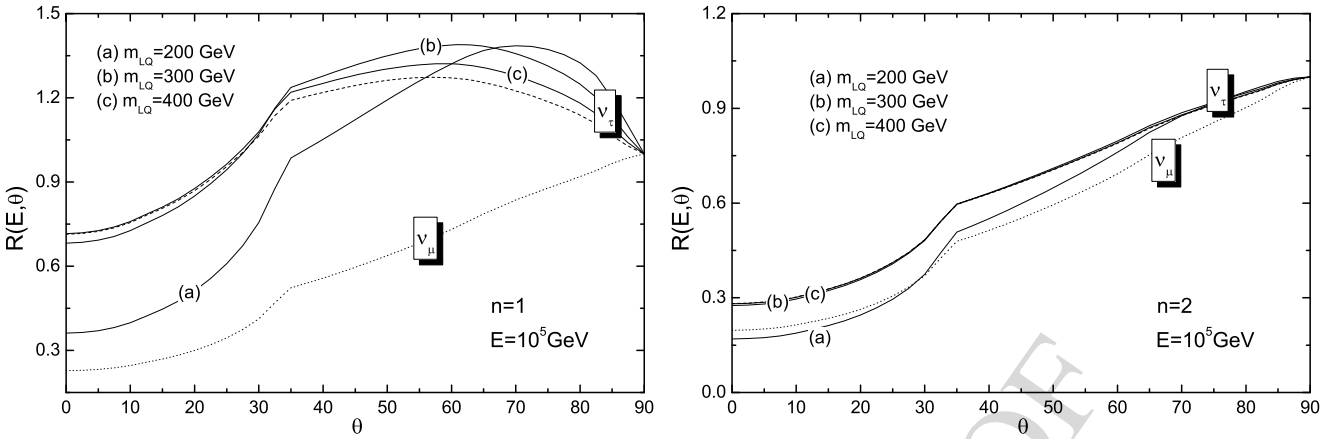

Fig. 6 The ratio $R(E,\theta)$ as a function of the nadir angle θ for the energy $E_\nu = 10^5$ GeV and two different behavior for the initial flux with the energy

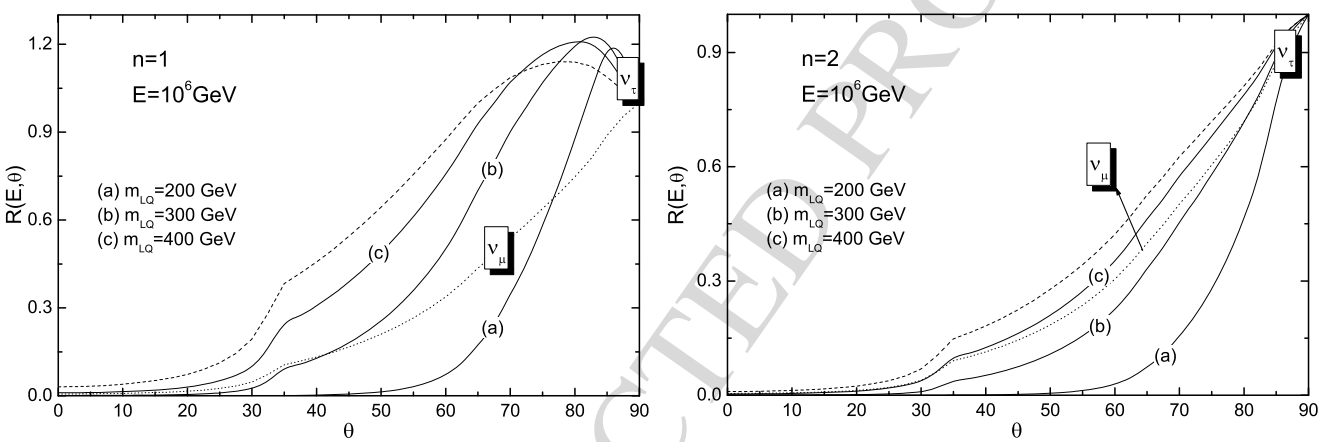

Fig. 7 As Fig. 6 but for the energy $E_\nu = 10^6$ GeV

In Fig. 8, we show the behavior with the energy for Earth skimming neutrinos which graze the Earth just below the horizon. These neutrinos have high probability of interacting with the crust and producing τ-leptons. If these τ-leptons are produced close enough to the surface, they can emerge and create an extensive air shower detectable by surface detector as those of the Auger observatory. Thus, it is essential to estimate of the emerging τ flux and as it can be affected by physics beyond the SM as in the case of leptoquarks. In this case of Earth skimming neutrinos, the regeneration effect is notable and reinforced by the leptoquark contribution for E^{-1} power law spectrum. For E^{-2}, the absorption effects are clearly dominant, as can be seen in Figs. 6 and 7, or, most specifically, in Fig. 8. Finally, and in order to estimate the sensitivity of neutrino telescopes to leptoquarks, we use the number of events as observable and define the statistical sensitivity as

$$\mathbf{S} = \sqrt{\frac{(N - N^{\mathrm{SM}})^2}{N}}. \tag{20}$$

This amount is basically a comparison between the observed number of events and the Standard Model prediction for events distributed according to a Poisson distribution. The expected number of events at a neutrino telescope like IceCube, in the energy interval ΔE and in the angular interval $\Delta\theta$, can be estimated as

$$N = n_{\mathrm{T}} T \int_{\Delta\theta} \int_{\Delta E} d\Omega\, dE_\nu\, \sigma^{\mathrm{CC}}(E) \Phi_{\nu_\tau}(E,\theta), \tag{21}$$

where n_{T} is the number of target nucleons in the effective detection volume, T is the running time that we take to be 15 yr, and $\sigma^{\mathrm{CC}}(E)$ is the charged-current neutrino–nucleon cross section. We take the detection volume for the events equal to the instrumented volume for IceCube, which is roughly 1 km^3 and corresponds to $n_{\mathrm{T}} \simeq 6 \times 10^{38}$. The function $\Phi_{\nu_\tau}(E,\theta)$ in Eq. (21) is the surviving flux (Eq. (15)).

In Eq. (20), we consider the total events in the energy range (10^6–10^7 GeV), which is sufficiently high to have appreciable leptoquark effects (see Fig. 3) and yet not so high to have enough neutrino flux. We perform this anal-

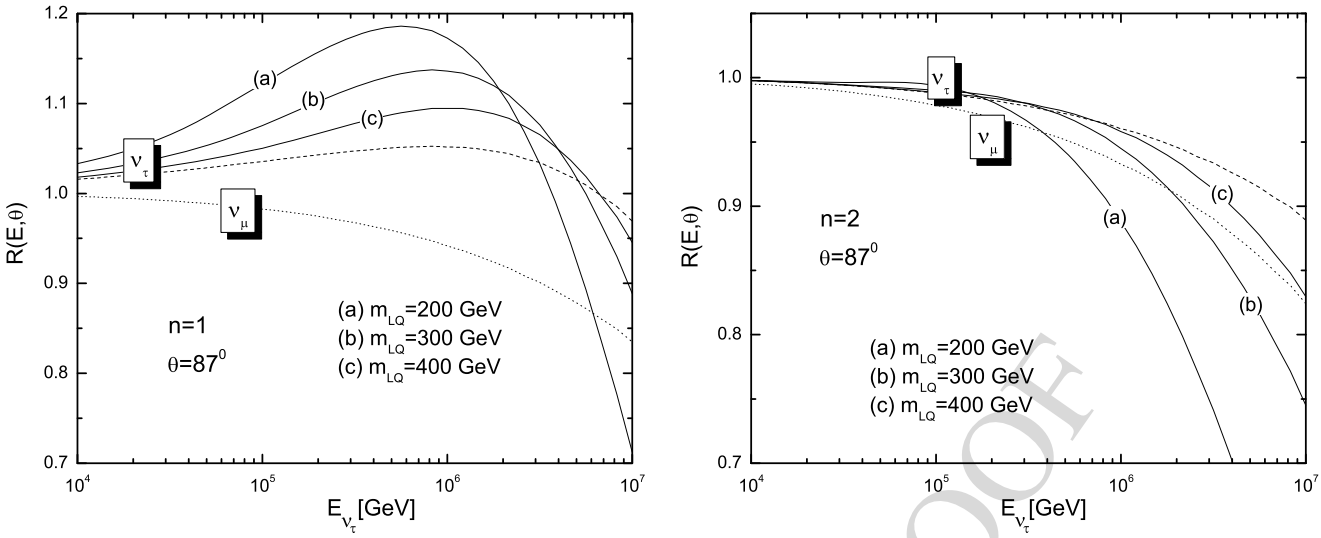

Fig. 8 $R(E,\theta)$ as a function of the ν_τ energy for Earth skimming neutrinos

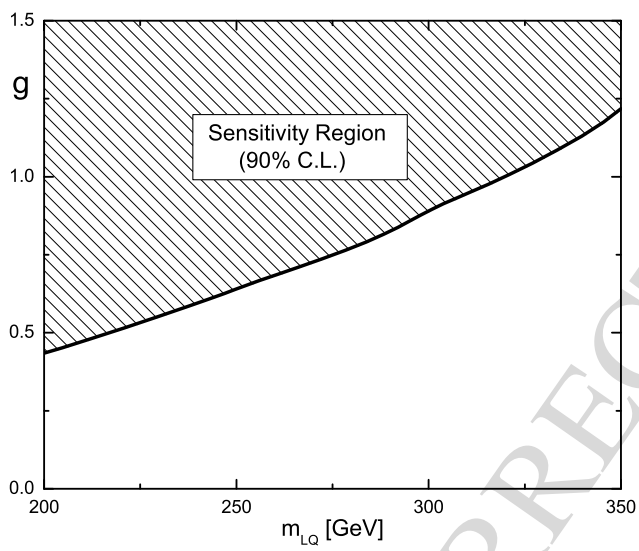

Fig. 9 90 % C.L. Sensitivity region in the (g, m_{LQ}) plane

ysis taking into account the neutrinos arriving to the telescope in the intermediate angular region $30° < \theta < 60°$. We consider both E^{-1} and E^{-2} power law spectra with the adequate constants to meet the preliminary IceCube upper limit $E^{-2}\Phi(E) = 1.4 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} in the energy range of interest [28]. We take into account the combined statistical of two neutrino telescopes working together: IceCube and the planed neutrino telescope in the north hemisphere, KM3NeT [29]. Moreover, we consider the effect of both ν_τ and $\bar{\nu}_\tau$. The results for both power law spectra are similar in the considered regions and then we only present the results for E^{-2} taking $\mathcal{N}_2 = 1.25 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}. In Fig. 9, we show our results as a 90 % C.L. sensitivity region in the (m_{LQ}, g) plane. This sensitivity region represents the possible bounds that could be obtained with neutrino telescopes, although lower than the obtained indirectly by Z-physics [16], they represent an independent complementary way to bound the physics of the third generation of leptoquark.

3 Conclusions

In the present work, we have studied the leptoquark contribution to the neutrino–nucleon cross section and the effect on the surviving tau-neutrino flux in a neutrino telescope like IceCube. We found a considerable disagreement with the SM prediction for the neutrino observable defined above, particularly for low values of m_{LQ}. For high values of m_{LQ}, this disagreement tends to disappear. Finally, we observe an enhanced regeneration effect due to leptoquark contribution for Earth skimming neutrinos and E^{-1} initial power law spectrum. We included a study on the sensitivity for the considered new physics showing the region where the effects would be appreciable to a 90 % C.L. (Fig. 9).

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References

1. J. Beringer et al. (Particle Data Group), Phys. Rev. D **86**, 010001 (2012)
2. M.C. Gonzalez-Garcia, M. Maltoni, Phys. Lett. B **663**, 405 (2008)
3. K. Mannheim, Astropart. Phys. **3**, 295 (1995)
4. J. Becker et al., Astropart. Phys. **23**, 355 (2005)
5. E. Waxman, J.N. Bahcall, Phys. Rev. Lett. **78**, 2292 (1997)
6. S. Razzaque, P. Meszaros, Phys. Rev. D **68**, 083001 (2003)

7. P. Lipari, M. Lusignoli, D. Meloni, Phys. Rev. D **75**, 123005 (2007)
8. F. Halzen, D. Saltzberg, Phys. Rev. Lett. **81**, 4305 (1998). arXiv:hep-ph/9804354
9. W. Buchmuller, R. Ruckl, Wyler, Phys. Lett. B **191**, 442 (1987) [Erratum: Phys. Lett. B **448**, 320]
10. H. Georgi, S.L. Glashow, Phys. Rev. Lett. **32**, 438 (1974)
11. J.C. Pati, A. Salam, Phys. Rev. D **10**, 275 (1974)
12. A.Y. Smirnov, F. Vissani, Phys. Lett. B **380**, 317 (1996)
13. J. Stupack III (ATLAS Collaboration), EPJ Web Conf. **28**, 12012 (2012)
14. G. Aad et al. (ATLAS Collaboration), Eur. Phys. J. C **72**, 2151 (2012)
15. V.M. Abazov et al. (D0 Collaboration), Phys. Lett. B **693**, 95 (2010)
16. J.K. Mizukoshi, O.J.P. Eboli, M.C. Gonzalez-Garcia, Nucl. Phys. B **443**, 20 (1995)
17. L.A. Anchordoqui, C.A. Garcia Canal, H. Goldberg, D. Gomez Dumm, F. Halzen, Phys. Rev. D **74**, 125021 (2006)
18. I. Romero, O.A. Sampayo, J. High Energy Phys. **05**, 111 (2009)
19. M.M. Reynoso, O.A. Sampayo, Phys. Rev. D **76**, 033003 (2007)
20. R. Gandhi, C. Quigg, M.H. Reno, I. Sarcevic, Astropart. Phys. **5**, 81 (1996)
21. A. Nicolaidis, A. Taramopoulus, Phys. Lett. B **386**, 211 (1996)
22. S.I. Dutta, M.H. Reno, I. Sarcevic, Phys. Rev. D **62**, 123001 (2000)
23. O. Blanch Bigas, O. Deligny, K. Payet, V. Van Elewyck, Nucl. Phys. B, Proc. Suppl. **196**, 418–421 (2009)
24. T.K. Gaisser, *Cosmic Rays and Particle Physics* (Cambridge University Press, Cambridge, 1990)
25. A.M. Dziewonski, D.L. Anderson, Phys. Earth Planet. Inter. **25**, 297 (1981)
26. P. Jain, S. Kar, D.W. McKay, S. Panda, J.P. Ralston, Phys. Rev. D **66**, 065018 (2002)
27. V.A. Naumov, L. Perrone, Astropart. Phys. **10**, 239 (1999)
28. A. Kappes et al. (IceCube Collaboration), J. Phys. Conf. Ser. **409**, 012014 (2013)
29. M. Spurio et al. (Km3Net Collaboration), Nucl. Instrum. Methods A **692**, 53–57 (2012)