Physics Letters B 757 (2016) 251–256

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Low energy IceCube data and a possible Dark Matter related excess

M. Chianese [a,b,*], G. Miele [a,b], S. Morisi [a,b], E. Vitagliano [b,c]

[a] INFN, Sezione di Napoli, Complesso Univ. Monte S. Angelo, I-80126 Napoli, Italy
[b] Dipartimento di Fisica Ettore Pancini, Università di Napoli Federico II, Complesso Univ. Monte S. Angelo, I-80126 Napoli, Italy
[c] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany

A R T I C L E I N F O

Article history:
Received 16 February 2016
Received in revised form 21 March 2016
Accepted 30 March 2016
Available online 4 April 2016
Editor: S. Dodelson

Keywords:
IceCube
Neutrino telescopes
Neutrino physics
Dark Matter

A B S T R A C T

In this Letter we focus our attention on the IceCube events in the energy range between 60 and 100 TeV, which show an order 2-sigma excess with respect to a power-law with spectral index 2. We analyze the possible origin of such an excess by comparing the distribution of the arrival directions of IceCube events with the angular distributions of simply distributed astrophysical galactic/extragalactic sources, as well as with the expected flux coming from DM interactions (decay and annihilation) for different DM profiles. The statistical analysis performed seems to disfavor the correlation with the galactic plane, whereas rules out the DM annihilation scenario only in case of small clumpiness effect. The small statistics till now collected does not allow to scrutinize the cases of astrophysical isotropic distribution and DM decay scenarios. For this reason we perform a forecast analysis in order to stress the role of future Neutrino Telescopes.

1. Introduction

The observation of astrophysical neutrinos made by the IceCube experiment (IC) [1] has been an important step in the field of Neutrino Astronomy, whose impact on both Particle- and Astro-Physics has still to be unveiled. Recently [2] the IC Collaboration has delivered in a preliminary work the results of four years data. In Fig. 1 (upper panel) we report the so-called *excess* in the number of events as a function of the neutrino energy, which is the number of events detected in IC once one has subtracted the background (atmospheric conventional and prompt neutrinos plus muons [2]), and an astrophysical component characterized by a $E_\nu^{-\gamma}$ power-law, with $\gamma = 2$ being considered as benchmark prediction [1–3]. The plot seems to suggest the presence of an excess of events in the energy range 60–100 TeV that has some tension, order 2σ, with the simple E_ν^{-2} contribution. As can be seen from Ref. [2], such an excess partially disappears if one considers a steeper astrophysical component with power-law $E_\nu^{-2.58}$, even though such an exponent for a neutrino flux can be hardly explained.

In general, the cosmic ray spectrum is characterized by a power-law [4], which is usually understood in terms of acceleration from shock fronts, the so-called Fermi mechanism [4,5]. An astrophysical neutrino flux is expected to be produced during the hadronic matter acceleration and interaction with radiation ($p\gamma$) or with gas (pp). Thus its dependence on energy should be, at the source, mostly related to the differential spectrum of charged cosmic rays and to the pions production efficiency. If needed, one should take into account propagation effects so that, for example, the galactic cosmic ray spectrum at the Earth becomes $\propto E^{-(\gamma+\delta)}$ ($\gamma + \delta \approx 2.7$) up to the *ankle* at $1 \sim 10$ PeV [6]. The quantity δ depends on galactic magnetic fields and is evaluated through cosmic rays secondary to primary ratio measurements [4,7]. On the other hand, galactic astrophysical neutrinos, which are not affected by magnetic fields, have a flux $\propto E_\nu^{-\gamma}$, with $\gamma \approx 2$.

Even considering extragalactic sources to be significant (a reasonable hypothesis given the high galactic latitudes of some events) it is not easy to justify a steep flux [8]. Models with $p\gamma$ interactions produce peaked spectra [9], so one could have a steep flux depending on the position of the peak. However, in this case one expects a peak in the spectra in the region of several PeV like for Active Galactic Nuclei [10]. Another kind of $p\gamma$ source, Gamma Ray Burst, provides a flux with an upper limit (given by searches for correlation with observed GRB) more than one order of magnitude below the observed flux [11]. Moreover, hard and smooth spectra are expected in pp scenarios [12], like for extragalactic Supernova Remnants [13]. More generally, theoretical models of

* Corresponding author at: Dipartimento di Fisica Ettore Pancini, Università di Napoli Federico II, Complesso Univ. Monte S. Angelo, I-80126 Napoli, Italy.
E-mail address: chianese@na.infn.it (M. Chianese).

http://dx.doi.org/10.1016/j.physletb.2016.03.084

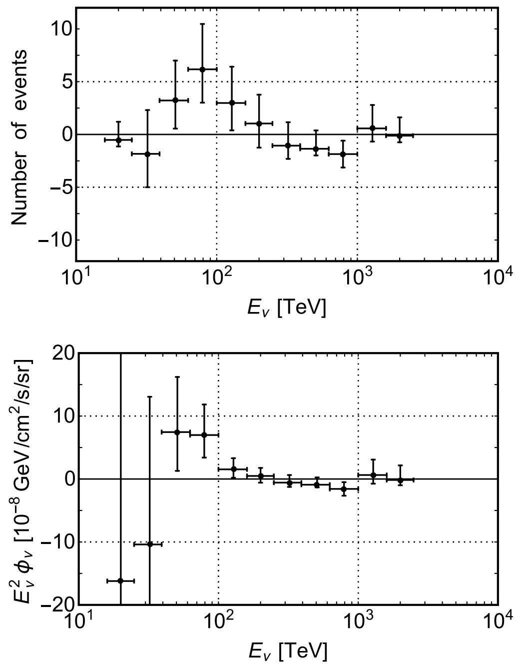

Fig. 1. The upper panel shows the excess in the number of IceCube neutrino events with respect to the sum of the background (atmospheric neutrinos and muons) and an astrophysical component described by a E_ν^{-2} power-law, as function of the neutrino energy. In the lower panel, we report the same excess in the whole neutrino flux (summed on all flavors) once that the average effective area of the particular energy bin and 1347 days of data taking have been taken into account.

acceleration mechanism for hadronic matter produce a flux that should be at most as soft as $E_\nu^{-2.2}$ [14].[1]

Independently of the detailed theoretical model, we have, most importantly, observational constraints coming from multimessenger approaches like [16], which combine IC data with Fermi γ-ray measurements, and give strong bounds to a hadronuclear origin (while leave room for hidden $p\gamma$ sources [17]). In fact, a spectrum as soft as the one obtained fitting IC data implies, when assuming sources transparent to radiation with respect to two-photon annihilation, an expected γ-ray flux bigger than the measured one [16,17]. The previous considerations support the assumption of an astrophysical E_ν^{-2} power-law used to obtain the excess reported in Fig. 1.

Starting from the excess in the number of events one can obtain the corresponding quantity for the whole neutrino flux (summed on all flavors) once the *effective area* of the detector is taken into account [1]. In Fig. 1 (lower panel) we report such a flux as a function of the neutrino energy. As already discussed in Ref. [18], we assume for simplicity the equality between the deposited and neutrino energy due to low statistics at our disposal. At the energy scale $\mathcal{O}(100)$ TeV, this is not strictly true for neutral current interactions [19]. When a significant statistics is collected, the average ratio between the two energies, which is of the order of $(97\%\sigma^{\rm CC} + 23\%\sigma^{\rm NC})/(\sigma^{\rm CC} + \sigma^{\rm NC}) \sim 75\%$, could be applied.

In this Letter we assume that the above excess, mainly concentrated in the energy range 60–100 TeV, has a genuine physical origin. Under this ansatz, it is worth pursuing, for this energy bin, a study in order to unveil the nature of such an excess. We perform our analysis assuming as *null hypothesis* one of the following alternatives for the source of the IC data:

i) astrophysical, which can be investigated by studying, in first approximation, the correlation with the galactic plane or with an isotropic distribution for galactic or extragalactic astrophysical sources, respectively;
ii) induced by Dark Matter via decay or annihilation, hence related to the first or second power of the particular Dark Matter (DM) density profile adopted.

Moreover, even though the small number of events already detected does not allow to exclude all DM scenarios, one can perform a forecast analysis in order to determine the required statistics.

In order to compare the IC observations with possible DM predictions we consider both decaying and stable Dark Matter cases. In the first case, 60–100 TeV neutrinos detected at IceCube would be originated directly from the decay of the DM particles, while for a stable DM particle neutrinos are only produced *via* annihilation. In both cases the resulting neutrino flux would be composed by both a galactic and an extragalactic DM component. Different approaches proposed in literature [18,20–34] have studied the possible presence of DM hints in the PeV range, namely for the most energetic IC events. Here we take an alternative point of view, assuming that PeV events have bottom-up origin and considering for lower energy data a possible top-down origin due to DM particles with mass scale $\mathcal{O}(100)$ TeV. Independently of the mass scale and of the DM couplings, neutrinos originated from DM would have an angular distribution that is more peaked around the Galactic Center where a higher DM density is expected. This is true in particular when assuming an annihilating DM, because of the squared enhancement factor. Of course, this effect is dependent on the assumed DM galactic halo profiles; for example, one could take the Navarro–Frenk–White profile (NFW) [35] or different distributions like the Isothermal profile (Isoth.), which implies a more isotropic flux.

2. The analysis

In order to infer about the physical origin of the excess we compare the angular distribution of the observed events in the energy bin 60–100 TeV (in the following we discuss the procedure to take into account the presence of the background and of the experimental errors) with the angular distributions of astrophysical galactic sources (galactic plane) and extragalactic ones (isotropic distribution), as well as with the expected flux coming from DM interactions (decay and annihilation). In this approach the astrophysical E^{-2} power-law contribution is regarded just as an additional term to the background events counting for atmospheric neutrinos and muons. For this reason hereafter we denote as *background* the sum of atmospheric neutrinos, muons and neutrinos coming from the astrophysical E^{-2} power-law. Moreover, due to the small number of events collected till now in the energy bin under study, in this analysis we take the simplicity assumption to consider just one additional component to neutrino background at a time (alternative scenarios i) or ii) of previous section) to explain the excess. This allows us to be more predictive even though more involved scenarios can be proposed where the excess in neutrino flux can be explained in terms of several components of different origin. Other analyses have already been presented in literature with different assumptions [29,36]. In particular, in Ref. [29] it has been studied the possibility that the whole neutrino spectrum has a DM origin, while Ref. [36] analyzed only the high energy neutrino spectrum ($E_\nu > 150$ TeV) considering also mixed components to the neutrino flux. Differently from previous analyses [29,36], we also take into account the angular efficiency of the IC detector for all neutrino flavors [44]. In Fig. 2 it is reported the normalized IC effective area, averaged in the energy range considered (60–100 TeV), as function of $\sin\delta$, where δ is the declination

[1] This is true when considering the minimal unbroken power law scenario; considering different values for δ [15] or including a break in the neutrino spectrum can lead to a steep flux, which is however constrained by data (see below).