Extreme blazars as counterparts of IceCube astrophysical neutrinos

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Accepted 2016 January 25. Received 2016 January 22; in original form 2015 December 18

ABSTRACT

We explore the correlation of γ-ray emitting blazars with IceCube neutrinos by using three very recently completed, and independently built, catalogues and the latest neutrino lists. We introduce a new observable, namely the number of neutrino events with at least one γ-ray counterpart, \( N_{\nu} \). In all three catalogues we consistently observe a positive fluctuation of \( N_{\nu} \) with respect to the mean random expectation at a significance level of \( 0.4 \pm 0.3 \) per cent. This applies only to extreme blazars, namely strong, very high energy γ-ray sources of the high energy peaked type, and implies a model-independent fraction of the current IceCube signal \( \sim 10^{-20} \) per cent. An investigation of the hybrid photon – neutrino spectral energy distributions of the most likely candidates reveals a set of \( \approx 5 \) such sources, which could be linked to the corresponding IceCube neutrinos. Other types of blazars, when testable, give null correlation results. Although we could not perform a similar correlation study for Galactic sources, we have also identified two (further) strong Galactic γ-ray sources as most probable counterparts of IceCube neutrinos through their hybrid spectral energy distributions. We have reasons to believe that our blazar results are not constrained by the γ-ray samples but by the neutrino statistics, which means that the detection of more astrophysical neutrinos could turn this first hint into a discovery.

Key words: neutrinos — radiation mechanisms: non-thermal — BL Lacertae objects: general — gamma-rays: galaxies — pulsars: general

1 INTRODUCTION

The IceCube South Pole Neutrino Observatory\textsuperscript{1} has recently reported the first observations of high-energy astrophysical neutrinos\textsuperscript{2} (Aartsen et al. 2013; IceCube Collaboration 2013, 2014). More recently, it has confirmed and strengthened these observations by publishing a sample of 54 starting events collected over about four years and with a deposited energy up to 2 PeV (IceCube Collaboration 2015a). These events are coming from the entire sky and consist of neutrinos of all flavours which interact inside the instrumented volume. The neutrino interaction vertex dominates the signature of these events, the majority of which are shower-like. The complementary sample of through-going charged current \( \nu_\mu \) from the northern sky has been also studied over a period of two (Aartsen et al. 2015) and four years (IceCube Collaboration 2015b) showing that the spectrum is inconsistent with the hypothesis of purely terrestrial origin at 3.7σ and 4.3σ level respectively. These track-like events confirm the general picture of a diffuse isotropic neutrino background although their energy spectrum \( E^{-\gamma} \) is harder (\( \gamma = 1.91 \pm 0.20 \)) with respect to the all sky one obtained from the starting events sample (\( \gamma = 2.58 \pm 0.25 \)), suggesting a mixed origin of the signal observed by IceCube.

Many diverse scenarios for the astrophysical counterparts of IceCube neutrinos have been put forward (see, e.g. Ahlers & Halzen 2015, for a comprehensive discussion) but none has so far been statistically supported by the observational data described above. One of the candidate neutrino-emitting astronomical classes of sources is that of

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\textsuperscript{2} In this paper neutrino means both neutrino and antineutrino.

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blazars. These are Active Galactic Nuclei (AGN) hosting a jet oriented at a small angle with respect to the line of sight with highly relativistic particles moving in a magnetic field and emitting non-thermal radiation (Urry & Padovani 1995). The two main blazar sub-classes, namely BL Lacertae objects (BL Lacs) and flat-spectrum radio quasars (FSRQ), differ mostly in their optical spectra, with the latter displaying strong, broad emission lines and the former instead being characterised by optical spectra showing at most weak emission lines, sometimes exhibiting absorption features, and in many cases being completely featureless. The general idea that blazars could be sources of high-energy neutrinos dates back to long before the detection of sub-PeV neutrinos and has since been explored in a number of studies (e.g., Mannheim 1995; Halzen & Zas 1997; Mücke et al. 2003; Kistler, Stanee, & Yitokel 2014; Murase, Inoue & Dermer 2014; Tavecchio & Ghisellini 2015, and papers from our group, as detailed below).

The spectral energy distributions (SEDs) of blazars are composed of two broad humps, a low-energy and a high-energy one. The peak of the low-energy hump ($\nu^{\text{peak}}_{\text{low}}$) can occur at widely different frequencies, ranging from about $\sim 10^{12.5}$ Hz ($\sim 0.01$ eV) to $\sim 10^{18.5}$ Hz ($\sim 13$ keV). The high-energy hump, which may extend up to $\sim 10$ TeV, has a peak energy that ranges between $\sim 10^{20}$ Hz ($\sim 0.4$ MeV) to $\sim 10^{26}$ Hz ($\sim 0.4$ TeV) (Giommi et al. 2012b; Arsioli et al. 2015). Based on the rest-frame value of $\nu^{\text{peak}}_{\text{BL}}$, BL Lacs can be further divided into Low energy peaked (LBL) sources ($\nu^{\text{peak}}_{\text{BL}} < 10^{14}$ Hz [< 0.4 eV]), Intermediate ($10^{14}$ Hz $< \nu^{\text{peak}}_{\text{BL}} < 10^{15}$ Hz [0.4 eV $< \nu^{\text{peak}}_{\text{BL}} < 4$ eV]) and High ($\nu^{\text{peak}}_{\text{BL}} > 10^{15}$ Hz [4 eV $> \nu^{\text{peak}}_{\text{BL}}$]) energy peaked (LBL and HBL) sources respectively (Padovani & Giommi 1995).

Padovani & Resconi (2014) (hereafter PR14), on the basis of a joint positional and energetic diagnostic using very high energy (VHE)3 lists and studying γ-ray SEyDs, have suggested a possible association between eight BL Lacs (all HBL) and seven neutrino events reported by the IceCube collaboration in 2014 (IceCube Collaboration 2014). Following up on this idea, Petropoulou et al. (2015) have modelled the SEDs of six of these BL Lacs using a one-zone lepto-hadronic model and mostly nearly simultaneous data. The SEDs of the sources, although different in shape and flux, were all well fitted by the model using reasonable parameter values. Moreover, the model-predicted neutrino flux and energy for these sources were of the same order of magnitude as those of the IceCube neutrinos. In two cases, i.e. MKN 421 and H 1914–194, a suggestively good agreement between the model predictions and the neutrino fluxes was found.

Very recently, Padovani et al. (2015) have calculated the cumulative neutrino emission from BL Lacs “calibrated” by fitting the spectral energy distributions of the sources studied by Petropoulou et al. (2015) and their (putative) neutrino spectra. Within the so-called blazar simplified view (Giommi et al. 2012a; Giommi, Padovani, & Polenta 2013; Padovani & Giommi 2015; Giommi & Padovani 2015) and by adding a hadronic component for neutrino production, BL Lacs as a class were shown to be able to explain the neutrino background seen by IceCube above $\sim 0.5$ PeV while only contributing on average $\sim 10$ per cent at lower energies. However, some room was left for individual BL Lacs to still make a contribution at the $\approx 20$ per cent level to the IceCube low-energy events.

The hypothesis put forward by PR14 and Petropoulou et al. (2015), if correct, should materialise in an IceCube detection but this has not happened yet. At present, in fact, IceCube has not identified any point sources and therefore its signal remains unresolved. The published upper limits on blazars start to be in the ballpark of the scenario described above (PR14) although they do not rule it yet out (IceCube Collaboration 2015c).

Together with the larger neutrino samples recently provided by the IceCube Collaboration, new and better catalogues of high energy sources are now available, which overcome some of the limitations pointed out in PR 14, like the lack of an all-sky flux-limited TeV catalogue. The purpose of this paper is to study in a more quantitative way the possible connection between the IceCube astrophysical neutrinos and γ-ray emitting blazars. To this aim, we have selected a priori 2FHL (The Fermi-LAT Collaboration 2015) and 2WHSP (Chang et al. 2015, in preparation) as the best VHE catalogues, as detailed below. The Fermi 3LAC catalogue (Ackermann et al. 2015) was also used because of its size and all-sky coverage, although it reaches γ-ray photons of lower energy. We note that the scanning strategy and the intervals over which the connection between neutrinos and γ-ray sources was studied have also been fixed before any test was carried out.

Section 2 describes the neutrino and γ-ray catalogues used in this paper, while Section 3 discusses our statistical analysis. Section 4 gives our results, while in Section 5 we investigate the γ-ray counterparts and their SEDs. Section 6 summarises our conclusions. Appendix A deals with the 2FHL Galactic sources.

2 THE CATALOGUES

2.1 Neutrino lists

This work is based on the IceCube high-energy starting events (HESE) published by IceCube Collaboration (2014) and IceCube Collaboration (2015a), which cover the first four years of data plus the $\nu_{\mu}$ selected from a large sample of high-energy through-going muons (see Aartsen et al. 2015, and the IceCube online link4 for the full list). Finally, we also included the very high energy (2.6 PeV deposited energy) event announced by the IceCollaboration in July 2015 (Schoenen & Raudel 2015).

Following PR14 we made the following two cuts to the HESE list: 1. neutrino energy $E_{\nu} \geq 60$ TeV, to reduce the residual atmospheric background contamination, which might still be produced by muons and atmospheric neutrinos and concentrates in the low-energy part of spectrum

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3 We adopt here the definitions used in Aharonian (2004) for γ-ray astronomy: “high energy” (HE) or GeV astronomy spans the 30 MeV to 30 GeV energy range while VHE or TeV astronomy refers to the 30 GeV to 30 TeV range.

4 https://icecube.wisc.edu/science/data/HE_NuMu_469
Table 1. Selected list of high-energy neutrinos detected by IceCube.

| IceCube ID | Dep. Energy TeV | $\nu_{\mu}$\(^a\) $10^{-11}$ erg/cm\(^2\)/s | RA (2000) | Dec (2000) | Median angular error deg | $b_\|$ deg |
|------------|-----------------|-----------------------------|-----------|-----------|-------------------------|-----------|
| 3          | 78.7            | 1.4 +3.3                   | 08 31 36  | −31 12 00 | ≤1.4                    | +5        |
| 4          | 165.7           | 0.8 +1.2                   | 11 18 00  | −51 12 00 | 7.1                     | +9        |
| 5          | 71.4 +9.0       | 1.3 +3.0                   | 07 22 24  | −00 24 00 | ≤1.2                    | +7        |
| 6          | 63.2 +8.8       | 2.1 +1.7                   | 10 05 12  | +33 36 00 | 16.5                    | +54       |
| 7          | 97.2 +12.4      | 1.2 +2.5                   | 00 20 00  | −29 24 00 | 8.1                     | −83       |
| 8          | 88.4 +10.7      | 1.2 +2.9                   | 10 21 12  | −08 54 00 | 16.7                    | +39       |
| 9          | 104 +13.0       | 0.9 +2.5                   | 19 44 24  | −52 48 00 | 9.8                     | −29       |
| 10         | 253 +22         | 1.2 +1.0                   | 04 31 36  | +40 18 00 | ≤1.2                    | −5        |
| 11         | 1041 +144       | 1.1 +0.9                   | 17 42 24  | −27 54 00 | 13.2                    | +1        |
| 12         | 209 +27         | 1.2 +2.5                   | 16 29 36  | +14 30 00 | 11.6                    | +38       |
| 13         | 71.5 +7.2       | 1.3 +3.0                   | 05 07 36  | −59 42 00 | 9.7                     | −36       |
| 14         | 1141 +143       | 1.1 +2.6                   | 02 33 12  | −67 12 00 | 10.7                    | −47       |
| 15         | 220 +24         | 0.7 +1.7                   | 19 34 48  | −22 06 00 | 12.1                    | −19       |
| 16         | 82.2 +8.4       | 1.5 +1.2                   | 13 54 48  | −13 12 00 | ≤1.9                    | +47       |
| 17         | 210 +26         | 1.1 +0.9                   | 09 33 36  | +22 42 00 | 11.8                    | +45       |
| 18         | 60.2 +5.6       | 1.8 +4.0                   | 08 06 48  | −12 36 00 | 6.6                     | +10       |
| 19         | 129 +12         | 0.8 +1.9                   | 06 52 48  | −82 42 00 | 8.0                     | −27       |
| 20         | 325 +36         | 1.4 +3.2                   | 19 30 00  | +07 48 00 | 13.5                    | −5        |
| 21         | 2004 +236       | 1.4 +3.3                   | 13 53 36  | −55 48 00 | 15.9                    | +6        |
| 22         | 201 ±16         | 1.2 +2.9                   | 06 13 12  | +14 00 00 | ≤1.2                    | −2        |
| 23         | 101 +13         | 0.9 +1.2                   | 07 04 48  | −17 54 00 | 14.2                    | −5        |
| 24         | 157 +43         | 0.8 +1.5                   | 09 35 36  | −48 30 00 | 11.7                    | +3        |
| 25         | 87.6 +10.9      | 1.4 +2.9                   | 04 24 24  | +03 18 00 | 11.1                    | −30       |
| 26         | 84.6 +7.9       | 1.4 +2.1                   | 22 26 48  | +00 00 00 | ≤1.2                    | −46       |
| 27         | 430 +57         | 0.9 +1.5                   | 14 36 00  | −86 18 00 | ≤1.2                    | −24       |
| 28         | 158 +17         | 0.8 +0.7                   | 10 02 00  | −22 24 00 | 7.6                     | +26       |
| 29         | 74.3 +8.3       | 1.6 +1.4                   | 13 57 36  | +67 24 00 | ≤1.2                    | +48       |
| 30         | 105 +14         | 0.9 +1.2                   | 14 12 24  | −31 12 00 | 8.1                     | +27       |
| 31         | 66.2 +10        | 2.2 +2.6                   | 05 54 24  | −54 00 00 | 6.5                     | +14       |
| 32         | 158 +16         | 0.8 +1.8                   | 16 51 12  | −54 00 00 | 7.8                     | −6        |
| 33         | 2600 ±300       |                             | 07 21 22  | +11 28 48 | 0.27                    | +12       |

\(^a\) Fluxes in units of $10^{-8}$ GeV cm\(^{-2}\) s\(^{-1}\) can be obtained by multiplying the numbers in this column by 0.614.

(see Fig. 2 in IceCube Collaboration 2014); 2. median angular error \(\leq 20^\circ\), to somewhat limit the number of possible counterparts. The final list includes 30 HESE and 21\(^5\) through-going $\nu_\mu$, for a total of 51 IceCube events. The former, together with the 2.6 PeV event, are listed in Tab. 1, which gives the deposited energy of the neutrino, the flux at the deposited energy in $\nu_\mu$ units, the coordinates, the median angular error in degrees, and the Galactic latitude. For the through-going $\nu_\mu$, for which we refer the reader to the online IceCube link, we assumed a median angular error of 0.4°, as prescribed by the IceCube collaboration, apart from the 2.6 PeV event, for which the median angular error is 0.27° (Schoenen & Raudel 2015).

Neutrino fluxes have been derived as in PR14 but using a live time of detection of 1,347 days (IceCube Collaboration 2015a). This means that the values for the sources studied in PR14 are now smaller by a factor 1,347/998 = 1.363. The derived fluxes are in the range 0.7 – 2.2 × 10\(^{-11}\) erg cm\(^{-2}\) s\(^{-1}\) (i.e., 0.4 – 1.3 × 10\(^{-8}\) GeV cm\(^{-2}\) s\(^{-1}\)) and errors are Poissonian for one event (Gehrels 1986).

2.2 γ-ray catalogues

2.2.1 Fermi 2FHL

The second catalogue of hard Fermi-Large Area Telescope (LAT) sources (2FHL: The Fermi-LAT Collaboration 2015) includes 360 sources and provides an all-sky view of VHE sources at $E \geq 50$ GeV. We remind the reader that 1FHL (Ackermann et al. 2013), the first Fermi-LAT catalogue of hard sources, had a 10 GeV threshold, i.e. still not on the VHE side. 2FHL, instead, bridges the gap between Fermi-LAT and ground based Cherenkov telescopes. Given its all-sky nature we can use 2FHL also to select a sample of Galactic sources. We then defined two subsamples: 1. the $|b_\|| \geq 10^\circ$ subsample, which contains 257 objects, of which a very large fraction (\(\sim 90\) per cent) are blazars\(^6\). The remaining sources are mostly still unclassified but very likely to be blazars; 2. the $|b_\|| < 10^\circ$ subsample, which contains 103 objects, of which a good fraction (\(\sim 41\) per cent) are still blazars. The remaining 59 per cent is composed of Galactic objects.

\(^5\) One of the $\nu_\mu$ events coincides with HESE ID 5 and was therefore discarded.

\(^6\) These and the following numbers reflect our own classification of many of the unclassified 2FHL sources, using also 2WHSP (see below), and are somewhat different from those given in the 2FHL paper.

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objects, that is supernova remnants (SNR) and pulsar wind nebulae (PWN) (~33 per cent), and unclassified sources (~26 per cent), very likely to be Galactic as their VHE Fermi spectrum is harder than that of extragalactic sources (The Fermi-LAT Collaboration 2015). The Galactic sources are discussed in Appendix A.

We further subdivided the $|b_{|b|}| \geq 10^4$ subsample into HBL ($v_{\text{peak}}^S > 10^{15}$ Hz) and non HBL. The former sample contains 149 sources, all BL Lacs, while the latter, which is made up of 108 objects, contains mostly blazars of the IBL and LBL type (~69 per cent, including some FSRQs (~9 per cent]], unclassified sources (~23 per cent), and radio galaxies (~8 per cent).

2.2.2 2WHSP

The 1WHSP catalogue (Arsioli et al. 2015) provided a large area ($|b_{|b|}| > 20^\circ$) catalogue of ~1,000 blazars and blazar candidates selected to have $v_{\text{peak}}^S > 10^{15}$ Hz and therefore expected to radiate strongly in the HE and VHE bands. 1WHSP sources were characterized by a “figure of merit” (FoM), which quantified their potential detectability in the TeV band by the current generation of Imaging Atmospheric Cherenkov telescopes. This was defined as the ratio between the synchrotron peak flux of a source and that of the faintest blazar in the 1WHSP sample already detected in the TeV band. 1WHSP sources are all BL Lacs, with a large fraction of those with high FoM being known TeV sources (e.g., 36 per cent of those with FoM > 1.2) and the remaining ones thought to be within reach of detection by current VHE instrumentation. Although technically not a γ-ray catalogue, 1WHSP represented at the time the best way to compensate for the lack of full sky coverage in the TeV band for blazars. Moreover, ~30 per cent of the sources already had a Fermi 1FGL, 2FGL or 3FGL γ-ray counterpart.

Chang et al. (2015, in preparation) have updated the 1WHSP catalogue and produced 2WHSP, which reaches down to $|b_{|b|}| \geq 10^4$ and drops one of the previously adopted selection criteria (the IR colour-colour cut) to increase completeness at low IR fluxes and better include some HBL sources dominated in the optical and IR bands by the light from the host giant elliptical galaxy. The 2WHSP catalogue includes ~1,700 sources and therefore provides a ~70 per cent increase in size as compared to 1WHSP. It reaches much lower VHE fluxes, and it is almost seven times larger than 2FHL.

The 2FHL and 2WHSP catalogues do not have the same composition in terms of blazar types. Of the 240 sources in the 2FHL catalogue that are identified with a counterpart at other frequencies and are located at $|b_{|b|}| \geq 10^4$ only ~71 per cent are also in 2WHSP. The remaining objects are all blazars with $v_{\text{peak}}^S < 10^{15}$ Hz, which therefore cannot be included in the 2WHSP sample by definition. On the other hand, ~93 per cent of the 2FHL HBL with $|b_{|b|}| \geq 10^4$ are also part of 2WHSP while ~70 per cent of the 2WHSP subsample with FoM ≥ 2 are 2FHL HBL sources. We note that 2WHSP has an advantage over 2FHL, as it not affected by extragalactic background light (EBL) absorption, since the FoM is defined at $v_{\text{peak}}^S$, while 2FHL is selected based on the flux at $E > 50$ GeV. A relatively high redshift source, for example is less likely to be in the 2FHL sample than in 2WHSP.

2.2.3 Fermi 3LAC

We also used the third catalogue of AGN detected above 100 MeV by the Fermi-LAT (3LAC: Ackermann et al. 2015), more specifically the “clean sample” of 1,444 sources at $|b_{|b|}| \geq 10^4$ and free of the analysis issues, which affect some of the 3LAC detections. Basically all objects (~98.8 per cent) are blazars. We do not expect a neutrino signal from this sample, however, at least as far as the full sample is concerned, based on the results of Gliskenkamp et al. (2015), who found no evidence of neutrino emission and a maximal contribution from Fermi 2LAC (Ackermann et al. 2011) blazars ~20 per cent. Moreover, Brown, Adams, & Chadwick (2015), using 70 months of Fermi-LAT observations, found no evidence of γ-ray emission associated with IceCube’s track-like neutrino events.

We further subdivided the 3LAC sample into an HBL ($v_{\text{peak}}^S > 10^{15}$ Hz), an FSRQ, and an “others” sample, which include 386, 415, and 645 sources respectively. The “others” sample is made up for the most part of BL Lacs and “unclassified AGN” of the IBL and LBL type (~97 per cent), with the remaining ~3 per cent including steep-spectrum radio quasars and radio galaxies.

3 THE STATISTICAL ANALYSIS

To study the possible connection between the IceCube neutrinos and the source catalogues, we have introduced the observable $N_{\nu}$ defined as the number of neutrino events with at least one γ-ray counterpart found within the individual median angular error. To evaluate this, we also took into account the case of IceCube neutrinos with $|b_{|b|}| < 10^4$ but which could still be associated with a $|b_{|b|}| > 10^4$ γ-ray source given their large error radii. We do not only consider the whole γ-ray catalogues but within a given catalogue we scan versus flux, $N_{\nu}(f_{\gamma})$ or, equivalently, versus FoM for 2WHSP, $N_{\nu}(\text{FoM})$. If only the strongest sources are associated to IceCube events such a scan will reveal a deviation from the randomised cases, we explored three different procedures: 1. randomisation of the γ-ray sample coordinates by drawing an equal number of positions homogeneously distributed over the sky, making sure that only random sources with $|b_{|b|}| < 10^4$ values in the same range as the original γ-ray catalogue are considered. This leaves untouched the IceCube positions, which are known to be not uniformly distributed, but might lose any large scale structure present in the γ-ray sample; 2. to at least partially obviate this, we have also randomised only the γ-ray sample right ascensions; 3. randomisation of the IceCube right ascensions, making sure that only random sources that can be associated with the γ-ray catalogue within the relevant error circles are considered (for example, a $|b_{|b|}| < 10^4$ IceCube random source can still be associated with a

7 These numbers sum up to 1,446 (and not 1,444) because two FSRQ happen to be HBL.

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squares), HBL (black circles), and non HBL (empty blue triangles). All cases refer to a randomisation of the γ-ray sample on right ascension. The numbers give the observed (above the points) and average random values (below the points) of $N_{\nu}$ for HBL. The two dashed lines denote the 2σ and 3σ values.

Figure 1. The chance probability of association of 2FHL with IceCube events for objects having $F(>50 \text{ GeV})$ larger than the value on the x axis for the whole high Galactic latitude sample (red squares), HBL (black circles), and non HBL (empty blue triangles). All cases refer to a randomisation of the γ-ray sample on right ascension. The numbers give the observed (above the points) and average random values (below the points) of $N_{\nu}$ for HBL. The two dashed lines denote the 2σ and 3σ values.

with a 2WHSP object provided it has a large enough error radius. This preserves any large scale structure present in the γ-ray sample plus the IceCube declinations. However, the requirement above does not conserve the total area sampled by the IceCube error circles, resulting in a biased test statistics. As a result, we used procedures 1 and 2, conservatively taking as our best estimate of the probability of random association the largest of the two probabilities. Since our three catalogues are somewhat overlapping, in particular at large fluxes and FoM (see Section 2.2.2), the number of bins per scan is < 10, and the points are not independent, we do not correct the probabilities for the "look elsewhere effect" (which would take into account the artificial p-value reduction due to the application of multiple tests). We have also fixed the catalogues studied at the beginning of this work as well as the bins in flux and FoM used for the scans.

4 RESULTS

4.1 Fermi 2FHL

Figure 1 shows the chance probability of association of 2FHL high Galactic latitude sources with IceCube events for objects having $F(>50 \text{ GeV})$ larger than the value on the x axis and a randomisation of the γ-ray sample on right ascension, which gives the most conservative result. Red squares indicate the whole high Galactic latitude sample, black circles denote HBL only, and blue triangles represent non HBL sources. The numbers give the observed (above the points) and average random value (below the points) of $N_{\nu}$ for HBL. Figure 1 shows the following:

- for the whole sample and for HBL the chance probability is strongly dependent on γ-ray flux, with an anti-correlation between probability and flux up to $F(>50 \text{ GeV}) \sim 1.8 \times 10^{-11} \text{ photon cm}^{-2} \text{ s}^{-1}$ with a p-value < 10^{-4} according to a Spearman test. We attribute the turnover in p-value at very large γ-ray fluxes to small number statistics;
- p-values ~ 1.8 per cent are reached for $F(>50 \text{ GeV}) \geq 1.8 \times 10^{-11} \text{ photon cm}^{-2} \text{ s}^{-1}$ for the whole sample;
- p-values ~ 0.4 per cent are reached for $F(>50 \text{ GeV}) \geq 1.8 \times 10^{-11} \text{ photon cm}^{-2} \text{ s}^{-1}$ for HBL;
- non HBL sources display no correlation between γ-ray flux and p-value, the latter being always $\geq 50$ per cent. This shows that the relatively low p-values reached by the whole sample are driven solely by HBL;
- at the flux at which p-value is minimum for HBL $N_{\nu}$ is 16, while the average value from the randomisation is 10.4, which means that only $\approx 6$ IceCube events have a "real" counterpart;
- for the same flux the number of HBL γ-ray sources with a neutrino counterpart is 27, while the whole "parent" γ-ray sample includes 92 sources.

At this level of p-value this result would be significant for astronomers but only at the level of "a hint" for physicists, who require a 5σ level to claim a "discovery". We follow physicists here and consider this a potentially very interesting result, worth of further investigations. Therefore, we can say that a hint of an association between the 2FHL high Galactic latitude HBL and IceCube events is present in the data.

4.2 2WHSP

Figure 2 shows the chance probability of association of 2WHSP sources with IceCube events for objects having FoM larger than the value on the x axis and a randomisation of the γ-ray sample on both coordinates, which gives the most conservative result. The numbers give the observed (above the points) and average random values (below the points) of $N_{\nu}$. The figure shows the following:

- the chance probability is dependent on FoM, with an anti-correlation between probability and flux up to FoM ~ 1 with a p-value < 10^{-4} according to a Spearman test;
- p-values ~ 0.7 per cent are reached for FoM $\geq 1$;
- at the flux at which p-value is minimum for HBL $N_{\nu}$ is 18, while the average value from the randomisation is 12.7, which means that only $\approx 5$ IceCube events have a "real" counterpart;
- for the same flux the number of γ-ray sources with a neutrino counterpart is 32, while the whole "parent" γ-ray sample includes 137 sources.

Therefore, a hint of an association between the 2WHSP sample and IceCube events is present in the data. Note that a FoM ~ 1 is roughly equivalent to $F(>50 \text{ GeV}) \sim 2.5 \times 10^{-11} \text{ photon cm}^{-2} \text{ s}^{-1}$ (de-absorbed). Taking into account
Figure 2. The chance probability of association of 2WHSP sources with IceCube events for objects having FoM larger than the value on the x axis for a randomisation of the γ-ray sample on both coordinates. The numbers give the observed (above the points) and average random values (below the points) of $N_\nu$. The dashed line denotes the 2σ value.

Figure 3. The chance probability of association of 3LAC “clean” sources with IceCube events for objects having $F(>100\text{MeV})$ larger than the value on the x axis. Filled red squares indicate the whole sample, randomised on both coordinates, black circles denote HBL, randomised on right ascension, blue triangles represent FSRQ, while empty red squares are for other sources, namely non-HBL and non-FSRQ; empty blue squares are for other sources, namely non-HBL and non-FSRQ. Only HBL are randomised on right ascension, while the other samples are randomised on both coordinates. The numbers give the observed (above the points) and average random values (below the points) of $N_\nu$ for HBL. The dashed line denotes the 2σ value.

4.3 Fermi 3LAC

Figure 3 shows the chance probability of association of 3LAC “clean” sources with IceCube events for objects having $F(>100\text{MeV})$ larger than the value on the x axis. Filled red squares indicate the whole sample, randomised on both coordinates, black circles denote HBL, randomised on right ascension, blue triangles represent FSRQ, while empty red squares are for other sources, namely non-HBL and non-FSRQ, both randomised on both coordinates. The numbers give the observed (above the points) and average random values (below the points) of $N_\nu$ for HBL. The dashed line denotes the 2σ value.

- the chance probability is strongly dependent on γ-ray flux, with an anti-correlation between probability and flux up to $F(>100\text{MeV}) \sim 6 \times 10^{-9}$ photon cm$^{-2}$ s$^{-1}$ with a p-value $< 7 \times 10^{-3}$ for all samples apart from the FSRQ one;
- the minimum p-value for the whole 3LAC sample and for “others” is $\sim 24$ per cent for $F(>100\text{MeV}) \sim 6 \times 10^{-9}$ photon cm$^{-2}$ s$^{-1}$;
- the minimum p-value for HBL is $\sim 1.3$ per cent for $F(>100\text{MeV}) \sim 6 \times 10^{-9}$ photon cm$^{-2}$ s$^{-1}$;
- the minimum p-value for FSRQ is $\sim 74$ per cent for $F(>100\text{MeV}) \sim 3 \times 10^{-8}$ photon cm$^{-2}$ s$^{-1}$;
- at the flux at which the p-value is minimum for HBL $N_\nu$ is 19, while the average value from the randomisation is 14.2, which means that only $\approx 5$ IceCube events have a “real” counterpart:
  - for the same flux the number of HBL γ-ray sources with a neutrino counterpart is 38, while the whole “parent” γ-ray sample includes 147 sources.

In summary, there is no evidence for an association between the 3LAC “clean” sample and IceCube events. As discussed in Section 2.2.3, this was to be expected for the full sample, as Glusenkamp et al. (2015) did not make any cut on γ-ray flux. However, there is a hint of an association between the 3LAC HBL and IceCube events. This is not the case for the 3LAC FSRQ.

5 ASTROPHYSICS OF POSSIBLE ICECUBE COUNTERPARTS

The deviations from random expectation of $N_\nu$ for the 2FHL HBL and the 2WHSP samples are $\sim 0.4$ per cent for $F(>50\text{GeV}) \gtrsim 1.8 \times 10^{-11}$ photon cm$^{-2}$ s$^{-1}$ and $\sim 0.7$ per cent for FoM $\gtrsim 1$ respectively. We therefore examined in detail the corresponding counterparts to IceCube events, which are all HBL by definition.

Table 2 lists the main properties of the 2FHL HBL and 2WHSP sources satisfying the requirements mentioned above by giving the IceCube ID, the 2WHSP name (which includes the coordinates), the 2FHL name, the common
name, the offset between the reconstructed position of the IceCube event and the blazar one, the redshift of the source (if available), the FoM, and the > 50 GeV flux from the 2FHL catalogue (if available). Given the very strong variability of blazars the flux values should be taken only as approximate. Nevertheless, on average a stronger neutrino source should also be a stronger γ-ray source, unless significant absorption is present.

The table contains 37 objects matched to 18 IceCube events. The overlap between the two samples, as expected, is quite large: 25 of the 27 2FHL objects are also 2WHSP sources, although three of them are below the FoM cut of 1, while 28 of the 32 2WHSP objects are also 2FHL sources, although five of them are below the γ-ray flux cut of $F(>50 \text{ GeV}) \geq 1.8 \times 10^{-11}$ photon cm$^{-2}$ s$^{-1}$. Two sources are matched to two different IceCube events: 2WHSP J091552.4+293324 (ID 9 and 26) and 2FHL J1027.0−1749 (ID 11 and 46).

The comments in Table 2 refer to the hybrid photon−neutrino SED of the sources. Namely, following PR14 we have first put together the γ-ray SEDs of all sources using

| ID  | 2WHSP name   | 2FHL name   | Common name  | offset (deg) | FoM | flux (E > 50 GeV) | Comments |
|-----|--------------|-------------|--------------|--------------|-----|-----------------|----------|
| 9   | J091037.0+332924 | J0910.4+3327 | Ton 1015     | 11.4         | 0.350 | 2.0 0.283       | positional match (PR14) |
| 27  | J035257.3−48053 | J0309.4−4849 | PKS 2005−489 | 5.6          | 0.071 | 10.0 0.970      | most probable match (PR14) |
| 11  | J235907.8−303740 | H 2356−309  |             | 4.7          | 0.165 | 2.0 0.69       | most probable match (PR14) |
| 11  | J095307.2−084018 | J0952.9−0841 | IRXS J095303.4−084003 | 7.0 | ... | 0.8 0.385 | positional match (PR14) |

Table 2. 2FHL HBL sources with $F(>50 \text{ GeV}) \geq 1.8 \times 10^{-11}$ photon cm$^{-2}$ s$^{-1}$ and 2WHSP sources with FoM $\geq 1.0$ in one median angular error radius around the positions of the IceCube events. The counterparts of the most probable matches are indicated in boldface.
the SED builder\textsuperscript{8} of the ASI Science Data Centre (ASDC) adding, if needed, VHE data taken from the literature. We have also included the flux per neutrino event at the specific energy. We then performed an “energetic” diagnostic by checking if a simple extrapolation succeeded in connecting the most energetic $\gamma$-rays to the IceCube neutrino in the hybrid SED, taking into account the rather large uncertainty in the flux of the latter. If this was the case we considered the source to be a “most probable” match. Otherwise, the object was considered a simple positional match. The idea behind this was to see how the neutrino and photon energetics compared and therefore have a much stronger discriminant than a simple cross-correlation.

We note that we do not include here the 3LAC counterparts for the simple reason that the few sources not overlapping with 2FHL or 2WHSP do not have, by definition, VHE $\gamma$-ray data and therefore the hybrid SED is not very informative.

As it turns out, the large majority of the sources in Table 2, that is all but six of those associated with the IceCube events discovered in the first three years of data, had already been considered by PR14. Based on the new data available and the revised neutrino fluxes (see Section 2.1), the classifications made by PR14 have been changed for six sources, as detailed in the Table.

The SEDs of sources associated with IceCube events having ID > 35 in Table 2, associated with the fourth year of IceCube data, were studied ex-novo. At least one, that is 1ES 0414+009, whose SED is shown in Fig. 4, is without doubt a most probable match, giving its rising SED and large de-absorbed TeV fluxes, while three more could be most probable matches.

The detailed SED study of the 2FHL and WHSP candidates suggests then that five IceCube events (9, 10, 17, 22, and 41) have most probable matches (with the respective counterparts highlighted in boldface), with a few more (11, 12, 14, 39, 40, and 46) having possible counterparts. SUMSS J102356−433600, however, the possible counterpart of ID 40, is an unlikely counterpart once one considers the Galactic source Vela Junior (see Appendix A and Fig. A1).

6 DISCUSSION

Consistently with PR14, HBL appear to be the only plausible blazar counterparts of at least some of the IceCube events. However, while in PR14 this statement could not be properly supported by a statistical analysis due to the lack of complete, all-sky, VHE catalogues, in this paper we have addressed this issue by introducing a new observable, $N_\nu$, and by making use of the very recently completed, and independently built, 2FHL, 3LAC, and 2WHSP catalogues. The former is defined as the number of neutrino events discovered in the first three years of data, had already been considered by PR14. Based on the new data available and the revised neutrino fluxes (see Section 2.1), the classifications made by PR14 have been changed for six sources, as detailed in the Table.

The detailed SED study of the 2FHL and WHSP catalogues; candidates suggests then that five IceCube events (9, 10, 17, 22, and 41) have most probable matches (with the respective counterparts highlighted in boldface), with a few more (11, 12, 14, 39, 40, and 46) having possible counterparts. SUMSS J102356−433600, however, the possible counterpart of ID 40, is an unlikely counterpart once one considers the Galactic source Vela Junior (see Appendix A and Fig. A1).

\textsuperscript{8} http://tools.asdc.asi.it/SED/
date a blazar needs to be: 1. a relatively strong source; 2. a VHE γ-ray source; 3. an HBL. This is relevant also to explain the lack of signal from Fermi blazars in IceCube Glüsenkamp et al. (2015), who, we note, did not make any cut on γ-ray flux, although they considered, apart from the whole 2LAC, also FSRQ, LBL, and IBL+HBL sub-samples.

We have in fact applied the same statistical tests not only to HBL, but also to FSRQ and IBL and LBL in general, with null results (see Fig. 1 and 3). This leaves HBL as the only possible extragalactic γ-ray detected IceCube counterparts. We note that, since PR14 used TeVCat, 1WHSP, and 1FHL, the sensitivity to FSRQ was only marginal (e.g. only ∼ 10 per cent of the sources in their Table 2 are FSRQ). This is not the case in this paper, since we also consider the 3LAC sample. None of the matches in Tab. 2 are track-like events. To probe this further, we have re-done the statistical analysis separately for the 29 track-like events, with null results. Namely, no counterparts were observed for the full 2FHL and 3LAC HBL samples, while three were detected in the full 2WHSP catalogue (all with FoM < 0.3). The corresponding curves in Fig. 1 to 3 would then be an horizontal line at 100% for the first two samples and a very similar line (with a small dip to ∼ 20% only for FoM < 0.3) for 2WHSP. The lack of track-like events in Tab. 2 persists even if we assume a median angular error of 1° for the νµ events. Only for an error of 2° one counterpart with FoM ≥ 2 appears in the 2WHSP catalogue, while ∼ 0.5 are expected, based on our simulations. This indicates that by using tracks only we are still not sensitive to the HBL neutrino signal, as also expected from the fact that tracks trace only about 1/6 of the astrophysical signal under the assumption of a flavour ratio νe : νµ : ντ = 1 : 1 : 1. We note that IceCube Collaboration et al. (2015) have looked for correlations between IceCube neutrinos and the highest-energy cosmic rays measured by the Pierre Auger Observatory and the Telescope Array. Even in their case the smallest of the p-values comes from the correlation between ultrahigh-energy cosmic rays with IceCube cascades (i.e. non track-like).

It is important to stress that we are not limited by the γ-ray samples but by the neutrino statistics. As illustrated, in fact, in Fig. 5, comparing the first half of the HES sample with the four year one, the p-value decreases steadily at relevant γ-ray fluxes for the 2FHL HBL time increases. Assuming there is indeed a signal, this gives us hope that the continuous accumulation of data from IceCube and future neutrino observatories (e.g. KM3NeT, IceCube-Gen2: Margiotta 2014; IceCube-Gen2 Collaboration 2014) can turn the hint we observed into a discovery.

7 CONCLUSIONS

We have investigated the correlation between γ-ray sources from the 2FHL, 2WHSP, and 3LAC samples with the latest list of IceCube neutrinos. This was done by first deriving the number of neutrino events with at least one γ-ray counterpart within the individual IceCube median angular error and then by estimating the related chance probability using an ensemble of 10⁷ – 10⁸ random maps. For the three catalogues the p-values reach 0.4 – 1.3 per cent for HBL and appears to be strongly dependent on γ-ray flux and FoM. Through careful examination of the hybrid γ-ray – neutrino SEDs of the sources giving the strongest signal (the “energetic” test of PR14) we have identified ≈ 5 HBL as the most probable IceCube counterparts. This number is in very good agreement with the value coming from our randomisations, highlighting once more the importance of the SED diagnostic in singling out the best candidates, and corresponds to a model-independent fraction of the current IceCube signal ∼ 10 – 20 per cent. Other types of blazars give null results, indicating that to be a neutrino source candidate a blazar needs to be a relatively strong VHE γ-ray source with ⁵⁰ GeV.) larger than 10⁻²⁰ Hz. The p-values obtained for the 2FHL HBL by comparing the first half of the HES sample with the four year one indicates that we are limited by the neutrino statistics. If a signal is indeed there, more data from IceCube and future neutrino observatories should turn our hint into a discovery.

As for Galactic sources, although we cannot perform a correlation study similar to that done for blazars due to the complications related to the randomisation in this case, we nevertheless studied their hybrid SEDs and found that two IceCube neutrinos have most probable Galactic 2FHL counterparts (with one more having a possible counterpart: see Appendix A).

ACKNOWLEDGMENTS

We thank Stefan Coenders for useful comments and the many teams, which have produced the data and catalogues used in this paper for making this work possi-
ble. ER is supported by a Heisenberg Professorship of the Deutsche Forschungsgemeinschaft (DFG RE 2262/4-1), BA by the Brazilian Scientific Program “Ciências sem Fronteiras” Cnpq, and YLC by a scholarship provided by the Government of the Republic of China (Taiwan). We acknowledge the use of data and software facilities from the ASDC, managed by the Italian Space Agency (ASI).

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Figure A1. γ-ray SEDs of two sources in the error circle of ID 40, namely: the Vela Junior SNR (black filled circles: The Fermi-LAT Collaboration 2015; Acero et al. 2015; Aharonian et al. 2007) and the HBL SUMSS J102356–433600 (open blue circles: Acero et al. 2015). The (red) open square represents the neutrino flux for the corresponding IceCube event; error bars as described in the caption of Fig. 4.

APPENDIX A: GALACTIC SOURCES

The case for Galactic sources is more complex: a randomisation of the γ-ray positions is, in fact, in this case meaningless because one loses the information on the concentration of sources at small bI (≤ 2°) values. And, as discussed in Sec. 3, the randomisation of the IceCube right ascensions would result in a biased test statistics. Nevertheless, based on the results of PR14, who had singled out two PWN as most probable counterparts to two IceCube neutrinos, we list in Table A1 the main properties of all Galactic 2FHL matches with |bI| ≤ 10°, defined as non blazar sources excluding the unclassified ones. The table gives the IceCube ID, the 2FHL name, the common name, the 2FHL coordinates, the offset between the reconstructed position of the IceCube event and the blazar one, the 2FHL > 50 GeV flux, and the class. Note that 3/5 events are also listed in Tab. 2.

We note that all sources in Table A1 associated with the IceCube events discovered in the first three years of data had been already considered by PR14. Based on the data
available now and the revised neutrino fluxes (see Section 2.1), we confirm the classification made by PR14 for all but one source: HESS J1800−240B was considered a positional match but we now believe it could be a most probable match. We note that none of the two PWN in Table 4 of PR14, namely HESS J1809−193 (connected to IceCube event 14) and MGRO J1980+06 (related to IceCube event 33) are in Table A1. This could be due to their relatively steep γ-ray spectra. Based on Figs. 6 and 7 of PR14 we still consider these two sources to be most probable matches.

The SEDs of the last seven 2FHL sources in Table A1, associated with the fourth year of IceCube data, were studied ex-novo. Of the first three, associated with ID 40, Vela Junior is without doubt a most probable match. Its SED is shown in Fig. A1, together with that of the HBL SUMSS J102356−433600. It turns out that the Galactic source is a better candidate. Of the last four 2FHL sources, all associated with ID 52, only the last one is a simple positional match, while none of the other three can be dismissed on the basis of the “energetic” diagnostic. Their SEDs are shown in Fig. A2. HESS J1614−518 might be more favoured simply because its SED does not drop at high energies like the other two sources for lack of data.

The detailed SED study of the 2FHL candidates suggests then that two IceCube events (40 and 52) have most probable Galactic 2FHL counterparts (with the respective counterparts highlighted in boldface), with one more (14) having a possible counterpart.

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### Table A1. 2FHL Galactic sources in one median angular error radius around the positions of the IceCube events. The counterparts of the most probable matches are indicated in boldface.

| ID   | 2FHL name       | Common name          | RA (2000) | Dec (2000) | offset deg | \( f (E > 50 \text{ GeV}) \) Class\(^a\) | Comments                  |
|------|-----------------|----------------------|-----------|------------|------------|-----------------------------------|---------------------------|
| 14   | J1745.7−2900    | SgrA*                | 17 45 42.4 | −29 00 37  | 1.3        | 1.070 Ext. Gal. positional match (PR14) |
|      |                 |                      |           |            |            |                                   |                           |
| 15   | J1801.7−2358    | HESS J1800−240B      | 18 01 47.0 | −23 58 39  | 5.9        | 0.569 SNR positional match         |
|      |                 |                      |           |            |            |                                   |                           |
| 16   | J1801.3−2326    | W28                  | 18 04 21.5 | −23 26 24  | 6.3        | 1.280 SNR positional match         |
|      |                 |                      |           |            |            |                                   |                           |
| 22   | J1805.6−2130    | W30                  | 18 05 38.4 | −21 36 36  | 8.2        | 2.680 Ext. Gal. positional match   |
|      |                 |                      |           |            |            |                                   |                           |
| 33   | J1911.0+0905    | W49B                 | 19 11 01.4 | +09 05 13  | 4.9        | 0.462 SNR positional match         |
|      |                 |                      |           |            |            |                                   |                           |
| 35   | J1303.4−6312    | HESS J1303−631       | 13 02 59.9 | −63 12 00  | 9.8        | 0.910 PWN positional match         |
|      |                 |                      |           |            |            |                                   |                           |
| 37   | J1355.1−6420    | HESS J1356−645       | 13 55 07.1 | −64 20 24  | 8.5        | 0.833 PWN positional match         |
|      |                 |                      |           |            |            |                                   |                           |
| 38   | J1443.2−6221    | RCW86                | 14 43 16.8 | −62 21 00  | 9.1        | 0.683 SNR positional match         |
|      |                 |                      |           |            |            |                                   |                           |
| 40   | J1419.3−6047    | HESS J1420−607       | 14 19 19.1 | −60 48 00  | 6.0        | 1.650 PWN positional match         |
|      |                 |                      |           |            |            |                                   |                           |
| 43   | J1514.0−5915    | HESS J1514−591       | 15 14 02.3 | −59 15 36  | 11.3       | 1.490 PWN positional match         |
|      |                 |                      |           |            |            |                                   |                           |
| 45   | J0835.3−4511    | Vela Pulsar          | 08 35 23.7 | −45 11 09  | 10.8       | 0.274 Radio Pulsar positional match |
|      |                 |                      |           |            |            |                                   |                           |
| 46   | J0852.4−631     | Vela Junior          | 08 52 48.0 | −46 31 12  | 7.5        | 5.030 SNR most probable match     |
|      |                 |                      |           |            |            |                                   |                           |
| 52   | J1615.3−514     | HESS J1614−518       | 16 15 19.2 | −51 46 48  | 5.8        | 2.340 Ext. Gal. positional match   |
|      |                 |                      |           |            |            |                                   |                           |
| 53   | J1616.2−5054    | HESS J1616−508       | 16 16 14.4 | −50 54 36  | 6.2        | 1.860 PWN most probable match?    |
|      |                 |                      |           |            |            |                                   |                           |
| 54   | J1633.5−4746    | HESS J1632−478       | 16 33 00.0 | −47 46 12  | 6.9        | 2.580 PWN most probable match?    |
|      |                 |                      |           |            |            |                                   |                           |
| 55   | J1649.6−4632    | HESS J1641−463       | 16 49 41.7 | −46 33 00  | 7.6        | 1.030 SNR positional match         |

\(^a\) SNR: supernova remnant; PWN: pulsar wind nebula; ext. Gal.: extended Galactic source.