A multiwavelength view of BL Lacs neutrino candidates

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ABSTRACT

The discovery of high-energy astrophysical neutrinos by IceCube kicked off a new line of research to identify the electromagnetic counterparts producing these neutrinos. Among the extragalactic sources, active galactic nuclei (AGN), and in particular Blazars, are promising candidate neutrino emitters. Their structure, with a relativistic jet pointing to the Earth, offers a natural accelerator of particles and for this reason a perfect birthplace of high energy neutrinos. A good characterisation of the spectral energy distribution (SED) of these sources can improve the understanding of the physical composition of the source and the emission processes involved. Starting from our previous works in which we assumed a correlation between the $\gamma$-ray and the neutrino flux of the BL Lacs of the 2FHL catalogue (detected by Fermi above 50GeV), we select those BL Lac in spatial correlation with the IceCube events. We obtain a sample of 7 sources and we start an observational campaign to have a better characterisation of the synchrotron peak. During the analysis of the data a new source has been added because of its position inside the angular uncertainty of a muon track event detected by IceCube. This source, namely TXS0506+056, was in a high-state during the neutrino event and we will consider it as benchmark to check the proprieties of the other sources of the sample during the related neutrino detection.

We obtain a better characterisation of the SED for the sources of our sample. A prospective extreme Blazar, a very peculiar low synchrotron peak (LSP) source with a large separation of the two peaks and a twin of TXS0506+056 come up. We also provide the $\gamma$-ray light curve to check the trend of the sources around the neutrino detection but no clears patterns are in common among the sources.

Key words: astroparticle physics — neutrinos — BL Lac objects: general — radiation mechanisms: non-thermal — $\gamma$–rays: galaxies

1 INTRODUCTION

The recent detection of gravitational waves together with the discovery, few years ago, of an extraterrestrial component of high-energy neutrinos, inaugurate the era of multimessenger astrophysics. In particular, the IceCube detection of a still unresolved high-energy (above $\sim 60$ TeV to 2.8 PeV) neutrino diffuse emission (Aartsen et al. 2013, Aartsen et al. 2016) reveals the presence of astrophysical sources hosting hadrons at energy up to 100 PeV, possibly connected with the still mysterious sources of ultra-high energy cosmic rays.

Despite the low number of detected events ($\sim 60$ since 2010), their distribution on the sky clearly excludes a purely galactic population of sources, leaving the possibility of a combination of galactic and extragalactic sources, as advocated by Palladino et al. (2016) and Palladino & Winter (2018).

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\textsuperscript{1} We will not distinguish from $\nu$ and $\bar{\nu}$.

The basic ingredient required to produce PeV neutrinos is a population of high-energy protons colliding against matter ($pp$) or radiation ($p\gamma$). Both kind of reactions produce charged pions, which quickly decay in electrons and neutrinos through the chain $\pi^\pm \rightarrow \mu^\pm + \nu_\mu \rightarrow e^\pm + \nu_e + 2\nu_\mu$. The neutrinos resulting from parent protons of energy $E_p$ are characterized by an energy $E_\nu \approx E_p/20$. The detection of $\sim$PeV neutrinos therefore implies the presence of cosmic rays with energy in the range $10^{16} - 10^{17}$ eV. In case of galactic sources, star forming galaxies (Tamborra et al. 2014, Loeb and Waxman 2006), low-power radio galaxies (Tavecchio et al. 2018), or galaxy clusters (Murase & Beacom 2013; Zandanel et al. 2014) the favorite channel is the interaction of protons with gas. On the other hand, for other extragalactic sources, such as relativistic jets and GRB (Mannheim et al. 1993, Waxman & Bahcall 1997; Tamborra et al. 2015), the jet density is expected...
to be too low and the most efficient interaction is expected to be the $p\gamma$.

Among AGN, blazars (Romero et al. 2017) are often considered potential neutrino emitters because their jets are thought to offer suitable conditions to accelerate the required high-energy protons (Murase et al. 2014; Dermer et al. 2014). Blazars belong to a subclass of AGN hosting a relativistic jet pointing at the Earth. The spectral energy distribution (SED) of this class is dominated by the relativistically beamed non-thermal emission of the jet with the characteristic "double hump" shape. The observed emission, predominantly originating in the jet, displays strong variations at all wavelength and, due to the intense emission in the $\gamma$-ray band, they are the most numerous extragalactic $\gamma$-ray sources (Ajello et al. 2015). The first bump of the SED, peaking between the IR and the soft X-ray band, is due to synchrotron emission of relativistic electrons inside the jet. For the second bump, peaking in the $\gamma$-ray band, there are two main scenarios: the leptonic one ascribes the origin of this bump to the inverse Compton emission of the same electrons that generate the first bump (e.g. Ghisellini et al. 1998), while the synchrotron emission of protons or photo-meson reactions are the main mechanisms in the hadronic scenario (Aharonian 2000, Mucke et al. 2004, Boettcher et al. 2013).

Depending on the luminosity and the presence of broad emission lines in the optical spectrum, blazars can be divided in two subclasses: Flat Spectrum Radio Quasars (FSRQs) and BL Lac objects. The main differences between the two groups likely stem from the different regime of the accretion flow in these sources, which regulates the presence of the broad line region (BLR). High-accretion rates and the concomitant presence of a BLR are the main features determining the strong luminosity in the $\gamma$-ray band. From this perspective FSRQ could be a good neutrinos emitter candidates (Kadler et al. 2016). However there are a couple of difficulties against the idea that FSRQ are the main contributors to the neutrino flux observed by IceCube. One of these is given by Murase & Waxman (2016). Their point is based on the fact that the non-detection of neutrino multiplets by IceCube can be used to constrain the power and the cosmic density of potential sources. A population of powerful and rare sources as FSRQ can be already excluded by current data. Another point concerns the properties of the reconstructed spectrum of the diffuse neutrino intensity. Indeed, current data suggest a relatively soft spectrum (spectral index around 2), while for FSRQ the predictions show a hard spectrum in the PeV energy range. This feature is quite robust, being the result of the spectral properties of the target radiation field (Murase et al. 2014).

Focusing on BL Lac objects, Padovani et al.(2016)(hereafter P16), showed a hint for a spatial correlation between the highly peaked BL Lac of the Second Catalog of Hard Fermi-LAT Sources (2FHL; Ajello, 2016) and a sample of IceCube events (both high-energy starting events, HESE, and tracks). Highly peaked BL Lac objects, or so called high synchrotron peak (HSP), are the subset of BL Lac for which the maximum of the synchrotron peak occurs above a frequency of $10^{12}$ Hz. These sources are also the most abundant blazars detected in the TeV band. For these sources, Tavecchio et al. (2014) suggested that efficient neutrino emission can occur due to the possible structure of the relativistic jet, previously suggested in Ghisellini Tavecchio & Chiaberge (2005). In this scenario protons inside the fast jet core can interact with photons produced in a slower external layer triggering the photo-meson reaction. A possible association of an HESE IceCube event with and HSP was suggested by Lucarelli et al. (2017). Inspired by these results, Righi et al. (2017) assumed a linear correlation between the neutrino flux $F_{\nu}$ and the $\gamma$-ray flux $F_{\gamma}$ of the BL Lac objects of the 2FHL and inferred the expected neutrino rate for each source. In this framework, the $\gamma$-ray emission is thought to be dominated by the inverse Compton emission from the relativistic electrons. The $\gamma$-ray emission associated to the neutrino production (through the $\pi^0 \rightarrow \gamma\gamma$ decay) is assumed to be subdominant and, after internal reprocessing, is expected to leave the source as a low-level flat component (e.g. Zeichet al. 2017, MAGIC paper).

A quite strong support to the idea that a fraction of the neutrino flux is associated to BL Lacs comes from the recent possible association between a muon track event with an exceptionally good reconstructed direction and the active BL Lac TXS 0506+056 (Kopper & Blaufuss 2017, Tanaka et al. 2017, Mirzoyan for the MAGIC Collaboration 2017).

To further investigate the hypothesis of BL Lacs as sources of neutrino events, we started a program aimed at obtaining a better multiwavelength characterization of the emission properties of these sources, and their modelling. First of all, we define a sample of 2FHL BL Lacs potentially associated to IceCube events. Then, we complemented very sparse existing MW data, with observations with the Neil Gehrels Swift Observatory (hereafter Swift) for three candidates of our sample, and with REM campaigns for two others sources. The final datasets allowed us to model the SED and to obtain the physical parameters of their jets, in order to compare theoretical expectation for neutrino flux from BL Lacs with the observed one. We describe our sample in Sect. 2. Data reduction and analysis is reported in Sect. 3 and in Sect 4 we describe and model the SED. Finally we discuss our results in Sect. 5.

Throughout the paper, the following cosmological parameters are assumed: $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, $\Omega_L = 0.7$. We use the notation $Q = Q_X 10^{27}$ in cgs units.

## 2 SELECTION OF THE BL LAC NEUTRINO CANDIDATES

Periodically, the IceCube Collaboration releases a list of detected tracks and HESE events. To create a sample of BL Lacs belonging to the 2FHL catalogue and investigate a spatial correlation with a neutrino event, we use the list of neutrino events reported in P16. For the HESE events, P16 used the list provided by the IceCube Collaboration in Aartsen et al. (2014), including the events recorded during the period 2010-2012. To reduce the background by atmospheric neutrino events they selected only the events with a reconstructed energy, $E_\nu \geq 60$ TeV. Moreover, to limit the number of counterparts, only the events with angular uncertainty $\leq 20^\circ$ have been used. For the tracks, P16 considered the list given in Aartsen et al. (2015). For these tracks they assumed an average angular uncertainty of 0.4°, except for the 2.6 PeV event, for which the median angular error is 0.27° as reported in Schoenen & Raedel (2015). Since a recent release of muon tracks events (from the northern emisphere) is given in Aartsen et al. (2016), we combine the HESE list by P16 with this more recent list of tracks. The position and the corresponding uncertainty of the neutrino events included in our sample are reported in the sky map shown in Fig.1 (HESE; orange circles; muon tracks: red circles), together with the 193 BL Lac of the 2FHL (blue crosses).

We selected all the BL Lacs whose positions lie within the (large) angular uncertainty of the HESE events. We list all the BL Lacs found to satisfy the above selection criteria in Table 1. For the track events, instead, we choose to consider significant any case in which there is a BL Lac at a distance less than 2.5° from the reconstructed centroid of the neutrino direction. Due to the large
BL Lac neutrino candidates

Table 1. List of all BL Lacs of the 2FHL catalogue in spatial correlation with a HESE neutrino event detected by IceCube and in the list of P16. As expected the majority are HSP, defined as BL Lacs with the synchrotron peak $\nu_S > 10^{15}$.

| ID | Source name | Class |
|----|-------------|-------|
| RXJ0950.2+4553 | ISP |
| Ton1015 | HSP |
| Tot0396 | HSP |
| I1H013+498 | HSP |
| Mkn421 | HSP |
| RXJ1022.7-0112 | HSP |
| PMNJ0953-0840 | HSP |
| NVSSJ02668-174858 | HSP |
| PKS2005-489 | HSP |
| PMNJ1936-4719 | HSP |
| RXJ171405.2-202747 | HSP |
| PG1553+113 | HSP |
| IES0505-546 | HSP |
| IRXJ094357.3-55320 | HSP |
| RBS0351 | HSP |
| PKS0229-581 | ISP |
| PKS0552-686 | HSP |
| PMNJ1921-1607 | HSP |
| I1H1914-194 | HSP |
| IRXJ199851.6-30111 | HSP |
| Tot0396 | HSP |
| MG1J090534+1358 | HSP |
| PMNJ0816-1311 | HSP |
| PMNJ0810-7530 | ISP |
| PKS1029-85 | HSP |
| RXJ1931.1+0937 | HSP |
| IRXJ194246.3+10333 | HSP |
| IRXJ13543.1-66400 | HSP |
| MS13121-4221 | HSP |
| IRXJ130737.8-42594 | HSP |
| IRXJ130421.2-43530 | HSP |
| TXS0626-240 | HSP |
| PMNJ0622-2605 | HSP |
| IES0414+009 | HSP |
| 87GB061258.1+570222 | LSP |
| GB061258.1+570222 | HSP |

Table 2. List of candidates neutrino sources studied in this work. For each source the equatorial (J2000) coordinates are reported (in degrees), the redshift, the $A_E$ extinction coefficient from Schlafly & Finkbeiner (2011) (re-calibration of the Schlegel, Finkbeiner & Davis (1998) infrared-based dust map) and the ID of neutrino detected by IceCube. The neutrino ID is taken from: $^a$Aartsen et al. 2014, $^b$Aartsen et al. 2015, $^c$Aartsen et al. 2018. Bold face characters identify the name of those sources for which we obtained dedicated Swift pointings.

| Source name | $\alpha$ (J2000) | $\delta$ (J2000) | $z$ | $A_E$ | $\nu$ | ID |
|-------------|------------------|------------------|-----|-------|-------|----|
| PMNJ0816-1311 | 124.113 | -13.197 | 0.045 | 0.296 | 27$^a$ |
| IRXS171405.2-202747 | 258.521 | -20.463 | 1.579 | 14$^a$ |
| 4C+41.11 | 65.983 | 41.834 | - | 2.665 | 13$^a$ |
| NVSSJ140450+655428 | 211.206 | 65.908 | 0.363 | 0.049 | 47$^a$ |
| MG1J0211114+1051 | 32.804 | 10.859 | 0.200 | 0.539 | 23$^b$ |
| TXS0506+056 | 77.358 | 5.693 | 0.336 | 0.392 | 25$^c$ |

well studied in literature (Raiteri et al. 2017). Therefore in the following we only focus our attention on the remaining poorly known 5 sources, whose properties are listed in Table 2. To these sources we also add TXS 0506+056, that satisfy our selection criterion but whose potentially associated neutrino event was not included in the lists considered above. This is the most plausible association observed so far and in our study we can use TXS 0506+056 as a benchmark case to discuss the other potential candidates. An important point to note is that not all selected sources are HSP, the BL Lac subclass favored by the P16 analysis. In fact, even TXS 0506+056, whose synchrotron component peaks in the optical band, is classified as an intermediate synchrotron peak ($\nu_S < 10^{15}$ Hz). Bold face is used for the sources for which we requested dedicated Swift observations. For MG1J0211114+1051 and TXS 0506+056 we also obtained optical and IR observations with the Rapid Eye Mount (REM) telescope. For the other sources we only used archival data. The source TXS 0506+056 will be discussed in detail in the next section.

3 DATA ANALYSIS

In the following, we describe the analysis performed on the Swift/XRT, Swift/UVOT, REM and Fermi/LAT data.

3.1 REM data

The Rapid Eye Mount telescope (REM) is a 60-cm robotic telescope located at the ESO La Silla Observatory. It includes an optical camera with the Sloan filters $g$, $r$, $i$, $z$ and a near-infrared camera equipped with J-H-K filters. In these bands we observed MG1 J0211114+1051 and TXS 0506+056. Data reduction was carried out following the standard procedures, with the subtraction of an averaged bias frame dividing by the normalised flat frame. The photometric calibration was achieved by using the 2MASS and APASS catalogues. In order to minimise any systematic effect, we performed differential photometry with respect to a selection of non-saturated reference stars. Table 3 shows the observation period of these sources and the magnitude obtained at different filters.
Figure 1. Sky map in galactic coordinates reporting the reconstructed direction of the neutrinos detected by IceCube. The dotted black line is the equatorial line, the orange circles corresponds to the angular uncertainty associated to 30 HESE events from P16 and the red dots indicates the direction of 29 muon tracks taken from Aartsen et al. 2016. The light blue dots show the position of the 2FHL BL Lacs objects. We also indicate the sources in our sample.

| Period                  | Filters | J       | H       | K        | g       | r       | i       |
|-------------------------|---------|---------|---------|----------|---------|---------|---------|
| MG1J021114+1051         |         |         |         |          |         |         |         |
| 01Oct2016/25Nov2016     |         | -       | -       | 17.088 ± 0.010 | 15.111 ± 0.025 | 14.578 ± 0.022 | 14.163 ± 0.032 |
| TXS 0506+056            |         |         |         |          |         |         |         |
| 30Sep2017               |         | 12.781 ± 0.056 | 11.945 ± 0.035 | 11.205 ± 0.100 | 15.013 ± 0.026 | 14.547 ± 0.020 | 14.174 ± 0.032 |
| 01Oct2017               |         | 12.632 ± 0.042 | 11.930 ± 0.051 | 11.061 ± 0.064 | 14.867 ± 0.022 | 14.361 ± 0.022 | 14.037 ± 0.033 |

Table 3. Observation period and filter used for the observation with REM telescope.

3.2 Swift/UVOT data

The satellite *Swift* includes a 30 cm diffraction-limited optical-UV telescope (UVOT) (Roming et al. 2005) equipped with six different filters that covered the 170 – 650nm wavelength range, in a 17 arcmin × 17 arcmin FoV. From the High Energy Astrophysics Science Archive Research Center (HEASARC)\(^2\) data base we download the UVOT images in which our target sources were observed. For all the sources the analysis was performed with the \( f\text{append}, u\text{votimsum}\) and \( u\text{votsource tasks}\(^3\). Due to the position of 1RXSJ171405.2-202747 full-stars field we perform a dedicated analysis. For the other sources we use a source region of 5 arcsec and the background was extracted from a source-free circular region with radius equal to 20 arcsec. The extracted magnitudes were corrected for Galactic extinction using the values of Schlegel et al. (1998), reported in the last column of Table 2 and applying the formulae by Pei 1992 for the UV filters, and eventually were con-

\(^2\) https://heasarc.gsfc.nasa.gov/docs/archive.html

\(^3\) https://heasarc.gsfc.nasa.gov/docs/software/lheasoft/
erted into fluxes following Poole et al. 2008. Table 5 reports the observed Vega magnitudes in the Swift/UVOT \( v, b, u, m1, m2 \), and \( w1 \) filters, together with statistical uncertainties. Systematic uncertainties are never greater than 0.03 mag and therefore dominated by statistical ones in the vast majority of cases.

### 3.3 Swift/XRT data

Swift/XRT (Burrows et al. 2005) data were analysed by using HEASOFT v6.20 software package. We analysed the spectra of the sources with XSPEC v12.9.1 (Dorman & Arnaud, 2001) in order to extract the flux in the 0.3 – 10 keV energy band and the photon index \( \Gamma \), using the \( \chi^2 \) minimization. For all sources an absorbed power-law model provides a good description of the spectrum. In all cases the fits are compatible with an absorption column, \( N_H \), fixed to the Galactic value. Table 4 shows the best fit parameters.

### 3.4 Fermi/LAT data

Fermi-LAT data analysis was performed using the Fermi Science Tools (v10r0p5) and PASS8 response Functions (P8R2_SOURCE_V6). Gamma-ray data were selected running \texttt{gtselect} for SOURCE events class, collected within 20° from the source under investigation; the chosen zenith angle cut was 90°. GTIs were prepared running \texttt{gtmktime} to select good quality data, collected during standard data taking mode. Livetime cubes were prepared taking into account the chosen zenith angle cut.

Gamma-ray light curves were produced in the energy range 0.3-100 GeV with a bin size of 4d and 16d for all sources. The flux reported for the chosen time-bins of the light curves is obtained with the standard unbinned likelihood analysis. The sources positions and spectral templates reported in the 3FGL Fermi catalogue.

Summing-up all Swift/XRT observations, an absorbed power-law model does not fit to the data (reduced \( \chi^2 \approx 2.2 \), see table 4). A log-parabolic (Tramacere et al. 2007) model fit to the data: Using the \texttt{eplogpar} function \( \left( F(E) = \frac{K}{E^\beta} \cdot \Gamma \left( \log \left( \frac{E}{E_P} \right) \right)^\alpha \right) \), the estimated parameters (for a confidence level of 90%) are: peak energy \( E_P = 1.83^{+0.32}_{-0.27} \), curvature term \( \beta = 0.86^{+0.36}_{-0.37} \), unabsorbed flux (in the 0.3-10 keV energy range) \( F = \left( (5.0^{+0.3}_{-0.2}) \times 10^{-12} \right) \) erg cm\(^{-2}\) s\(^{-1}\). The \( \chi^2 \) is 5.9 for 15 degree of freedom, the null hypothesis probability is 0.92.
we also peak frequency resemble a characteristic feature of the so-called detail), suggests a peak around 1 keV. Such a large synchrotron display a quite notable similarity and fulfill the criteria to be de-
ponent above 10^{15} h.

Table 5. Swift/UVOT observed magnitudes. Statistical uncertainties only are reported: systematic error is always lower than 0.03 mag. For TXS 0506+056 there are two states: h: high state of the source on 27/09/2017 (MJD: 58023.752), l: low state of the source on 25/07/2009 (MJD: 55037.512).

| Source               | $\gamma_{\text{min}}$ | $\gamma_b$ | $\gamma_{\text{max}}$ | $n_1$ | $n_2$ | B    | K    | R    | $\delta$ | $P_0$ |
|----------------------|------------------------|------------|------------------------|-------|-------|------|------|------|---------|-------|
| 1RXS J171405.2-202747| 100                    | $6 \times 10^5$ | $9 \times 10^5$       | 1.8   | 4.95  | 0.05 | $6 \times 10^3$ | 0.41 | 15     | 0.2    |
| 4C+41.11 TBD         | 500                    | $1.7 \times 10^5$ | $2 \times 10^5$       | 2.2   | 4.8   | 0.075 | $1.3 \times 10^4$ | 1    | 25     | 9.0    |
| NVSS J140540+655428  | 100                    | $2.3 \times 10^4$ | $5.8 \times 10^5$     | 1.8   | 4.35  | 0.3  | $10^3$ | 1    | 15     | 0.7    |
| PMN J0816-1311       | 100                    | $8.5 \times 10^4$ | $10^6$                | 2.0   | 4.2   | 0.1  | $10^4$ | 0.33 | 20     | 6.3    |
| MGI J021114+1051     | 10                     | $8 \times 10^5$ | $5.8 \times 10^5$     | 1.8   | 4.35  | 0.07 | $2.5 \times 10^2$ | 6    | 25     | 17     |
| TXS 0506+056 TBD     | 500                    | $1.7 \times 10^5$ | $2 \times 10^6$       | 2.2   | 4.8   | 0.075 | $1.3 \times 10^4$ | 1    | 25     | 9.0    |

Table 6. [1]: source; [2], [3] and [4]: minimum, break and maximum electron Lorentz factor. [5] and [6]: slope of the electron energy distribution below and above $\gamma_b$. [7]: magnetic field [G]. [8]: normalization of the electron distribution in units of cm^{-3}. [9]: radius of the emission zone in units of 10^{16} cm. [10]: Doppler factor. [11]: jet power carried in units of 10^{45} erg s^{-1}.

4 SPECTRAL ENERGY DISTRIBUTIONS

The Spectral Energy Distributions (SED) of the 6 sources, built by using historical data (green) and the data described above, are shown in Figs. 3-4.

The SED display a large variety of shapes. In particular, two sources (PMN J0816-1311 and NVSS J1404+65) clearly belong to the HSP population, with a peak frequency of the synchrotron component above 10^{15} Hz. MG1 J021114+1051 and TXS 0506+056 display a quite notable similarity and fulfill the criteria to be defined ISP. The SED of the remaining two sources have a less clear nature.

As discussed above, the analysis of the data of 1RXS J1714-20 is complicated by its position on the sky, close to the galactic plane. In particular, the confusion introduced by the complexity of the field makes difficult to understand the correct association of some of the data found in literature. For this reason we made a careful selection of the archival data. The concave X-ray spectrum from XRT, modelled with a log-parabolic fit (see section 3.5 for detail), suggests a peak around 1 keV. Such a large synchrotron peak frequency resemble a characteristic feature of the so-called extreme BL Lacs (e.g. Costamante et al. 2001, Bonnoli et al. 2015, Costamante et al. 2018). Besides a peak in the X-ray band, these peculiar sources display a quite hard gamma-ray continuum, often peaking in the TeV band. The optical band, instead, is dominated by the emission from the host galaxy. The data for 1RXS J1714-20 are consistent with both characteristics. The LAT data track a hard spectrum peaking above 100 GeV. The exceptional hardness of the spectrum is confirmed by the fact that this source belongs to the 2FHL (selection above 50 GeV) but it is absent in the 3FHL (selection above 10 GeV). Unfortunately, the description of the optical emission is poor. However, the UVOT upper limits together with the 2MASS datapoint are consistent with the emission from a typi-cal elliptical host galaxy of BL Lac objects (the dashed line reports the template for a giant elliptical by Silva et al. 2004).

The SED associated to 4C+41.11 is puzzling. The archival and the UVOT data locate the maximum of the synchrotron peak in the IR band. The hard XRT spectrum suggests that the X-ray continuum is associated to the second bump, likely peaking in the LAT energy band. The position of the synchrotron peak define 4C+41.11 as a LSP. However, the flat LAT spectrum (photon index $\approx 2$) is quite atypical for this class (Ackermann et al. 2015). As detailed below, this particular SED is quite difficult to be reproduced with standard emission models.

The case of TXS0506+056 has raised the attention of the whole high-energy astrophysics community (Kopper & Blaufuss 2017, Tanaka et al. 2017, Mirzoyan for the MAGIC Collaboration 2017). The facts that the source was in a high-state in the $\gamma$-ray band during the neutrino detection, that the event was a muon track event with a very good reconstructed direction (less than 1°) and the detection for the first time in the TeV band, make this event unique and particularly relevant. Paiano et al. (2018) showed the optical spectrum of the sources taken with the Gran Telescopio CANARIAS (GTC) with which, thanks to the emission lines of [OII],[OIII] and [NII], they attested a redshift of $z = 0.3365 \pm 0.0010$. Here we report both the high state, with data taken in the period 27/09/2017-01/10/2017, and the low state, data of 25/07/2009.

Together with the electromagnetic output, in Figs. 3-4 we also report the inferred level of the neutrino emission. In particular, the orange circles have been derived calculating the expected neutrino flux, $F_{\nu}$, required to have one neutrino detected during the seven year of operation of IceCube and assuming the energy estimated for that event. To this aim we use the declination-dependent effective area provided by Yacobi et al. (2014). The light blue triangle instead show the flux, $F_{\nu_{\text{HH}}}$ derived by using the model.
BL Lac neutrino candidates

Figure 2. $\gamma$-ray light curve of all 8 candidate sources. The bin is 16 days apart from PG1553+113 and TXS 0506+056 in which the bin is 4 days. The horizontal orange line represents the mean flux reported on the 3LAC catalogue. The data do not show flares in correspondence with the neutrino emission (red vertical line) however a discussion about the expected coincidence between a neutrino event and a $\gamma$-ray flare is in Section 5.

of Righi et al. (2017), which assumed that BL Lacs belonging to the 2FHL account for the entire observed neutrino diffuse emission and that for each source the neutrino flux is correlated to its $\gamma$-ray flux. In both cases the flux of the neutrino emission is close to $F_{\nu_{\text{2FHL}}} \sim 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, not far from level of the corresponding $\gamma$-ray flux. For all sources the neutrino flux $F_{\nu_{c}}$ is always above $F_{\nu_{\text{2FHL}}}$. This, besides the fact that the brightest BL Lac sources of 2FHL catalogue are absent from our sample (such as Mkn421 or Mkn 501), suggests an overestimation of the flux $F_{\nu_{\text{2FHL}}}$. This raises a question about the neutrino emission from Mkn-like sources (see Righi et al. in prep.). Note that in Righi et al. (2017) we considered only the northern hemisphere, for this reason, for the 1RXS J 1714-20, we present only $F_{\nu_{c}}$. The electromagnetic output of BL Lacs is traditionally reproduced with one-zone leptonic models (Ghisellini et al. 1998, Tavecchio et al. 2010, Dermer & Lott 2011, Weidinger et al. 2010), in which one assumes...
that the two-bump structure derives from the synchrotron and inverse Compton emission of relativistic leptons (electrons or pairs). In particular, for BL Lacs the lack of strong thermal components supports the synchrotron-self Compton scenario (e.g. Maraschi et al. 1994, Tavecchio et al. 1998), in which the target photons for the IC process are the synchrotron photons themselves. In Figs. 3-4 we report, as an illustration, the one-zone SSC models for all sources. We have reproduced the SEDs with the one-zone leptonic model fully described in Maraschi & Tavecchio (2003). Briefly, the emission is assumed to be produced by relativistic electrons following a smoothed broken power law energy distribution – parametrized by the normalization $K$, by the slopes $n_1$ and $n_2$ and by the minimum ($\gamma_{\text{min}}$) and maximum Lorentz factor ($\gamma_{\text{max}}$) – filling a spherical region of radius $R$ containing a tangled magnetic field of intensity $B$. The region is moving with bulk Lorentz factor $\Gamma$ at an angle $\theta_v$ with respect to the line of sight, resulting in a relativistic boosting of the emission parameterized by the relativistic Doppler factor $\delta = \left[ \Gamma \left( 1 - \beta \cos \theta_v \right) \right]^{-1}$. The electrons emit synchrotron and inverse Compton emission (calculated including the full Klein-Nishina cross section). For the latter component we assume in the following that the dominant target radiation field is the synchrotron one. The derived parameters are reported in Table 6, in which we also report the derived energy flux (of power) of the jet. The inferred parameters are typical for this class of sources when the SED are reproduced with leptonic models (e.g. Ghisellini et al. 2010).

Of course, the requirement to produce a sizeable neutrino emission, implies that at least a fraction of the electromagnetic output derives from the $\gamma$-rays and the pairs injected in the source after the decay of neutral and charged pions. To properly model these processes (in particular the associated electromagnetic cascades) one needs to fully implement all the processes as in e.g., Mannheim (1995) and Boettcher et al. (2013). However, the paucity of soft target photons provided by the synchrotron component alone, requires the existence of external sources, such as the photons from the accretion flow (Righi et al., in prep) or those envisioned in the spine-layer scenario (e.g. Tavecchio et al. 2014).

5 DISCUSSION

Following the idea that BL Lacs can be the emitters of high-energy neutrinos detected by IceCube, we started a observational campaign of a sample of sources. From a list of 30 HESE + 29 muon tracks events respectively from P16 and Aartsen et al. (2016), and the BL Lac of the 2FHL catalogue of Fermi, we built a sample of 8 candidate neutrino BL Lacs spatially correlating with the IceCube events. Two of these are very well-known high-energy emitting sources observed also in the TeV band (PG1553+113 and 1ES0414+009). For the other six sources we obtained observations with REM and Swift (optical, UV and X-ray band), to have a more accurate description of the synchrotron peak. Coupled with the archival data we built the spectral energy distribution and we reproduced it with a pure leptonic model to extract the main parameters of the jet. The sources show a variety of SED. As expected, the small sample of sources we selected is for the most part comprised by HSP, i.e. with the synchrotron peak at frequencies $\nu_S > 10^{12}$Hz, but in a sample of 8 sources 3 can be catalogued as LSP or ISP. Assuming to have detected only one neutrino in 7 years with IceCube, we calculate the expected muon neutrino flux ($F = N/A_{\gamma} \nu$, with $N = 1$, $t = 7y$ and $A_{\gamma}$ the muonic effective area at the specific declination and energy), obtaining for all sources a value around $F_\nu \sim 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. We also showed the expected muon neutrino flux obtained in the previous work (Righi et al. 2017) getting numbers in agreement with the previous calculation. It is important to remark that these numbers are affected by large statistical uncertainty assuming, for instance, a constant flux of the sources (even if the large scale variability is one of the main characteristic of this class) and that this class is the unique emitter of the IceCube events.

To investigate the possibility that the neutrino emission is associated to a particularly active state of the sources we have derived the light curves in the LAT band. While in the case of TXS 0506+056 the neutrino detection (Sep. 2017) coincides with a long lasting active state starting in April 2017 (see IceCube, Fermi and MAGIC Collaboration 2018), none of the other sources show such a significant increase of activity close to or in correspondence of the epoch of the neutrino detection. Small amplitude variability possibly correlated with the neutrino detection occurred in MG1.
J021114+1051, PMN J0816-1311 and in 1ES 0414+009. However the quality of the data prevent any conclusion. A dedicated analysis of the correlation between the LAT light curves and possible excesses recorded by IceCube around the position of these sources could be interesting. The low sensitivity of the neutrino detector with the strong variability of the sources make difficult the observation of a strong correlation between a $\gamma$-ray flare and the neutrino detection. For these reasons we do not expect an extremely high probability to detect a neutrino during a $\gamma$-ray flare.

From this sample it becomes clear that the brightest BL Lac source of the 2FHL catalogue, such as Mkn 421 and Mkn 501, do not appear to be clearly correlated with any neutrino event (however see Petropoulou et al. 2015). The lack of a events correlated with these sources, after 7 years of activity by IceCube, starts to question about the HSP as main neutrino emitters. In fact from Righi et al. (2017) these sources provide $\sim 50\%$ of the entire muon neutrino emission. In Righi et al. (2017b) we derived the expected significance of a possible detection by IceCube of Mkn 421 considering the background due to the atmospheric neutrinos. Even if the calculation is highly simplified, we obtain a significance of $3\sigma$ after 8 years. We should start to observe an excess of IceCube events from the direction of these two sources. The lack of this excess, together with the possible observation of a neutrino emission by TXS 0506+056 source (not a HSP), bring us to rethink about the photon component involved in the photo-meson reaction. In Tavecchio et al. (2014) and Tavecchio et al. (2015), the photons produced on the external and slow shield of the jets are engaged on the neutrino productions. This scenario is applied to the high energy BL Lacs, those sources in which there are indications of the presence of the spine-layer structure. In Righi et al. (in prep.) we propose an alternative photon target that favour LSP sources as neutrino emitters and at the same time disfavour the ISP and HSP objects.

A possible continuation of this paper could be a study of those BL Lac objects of the Third Catalog of Hard Fermi-LAT Sources (3FHL; Ajello 2017), which contains the sources detected in 7 years above 10 GeV by Fermi. This catalogue is composed of $\sim 50\%$ ISP and $\sim 50\%$ ISP+LSP. Table 7 shows the spatial correlation with the same sample of neutrino events and the BL Lacs of the 3FHL catalogue. A in-depth study of the SED and the light curve of these sources will be pursued. This work highlights an increasing importance of the multiwavelength research and in particular of the multimessanger one to inquire both the physical structure of the sources, and of the relativistic jets in particular; both on the nature of the high energy and very high energy astroparticles ($\nu$ and cosmic rays).

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