Detecting the brightest HAWC sources with IceCube in the upcoming years

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We complete a detailed study of the gamma-ray sources eHWC J1907 + 063 and eHWC J2019 + 368. These are two out of only three sources detected by HAWC above 100 TeV. We also consider the source 2HWC J1857 + 027, which is coincident with the location of an IceCube neutrino excess. For these sources, we show the prediction for neutrinos at the IceCube detector. Moreover, we present a calculation of the statistical significance, considering 10 and 20 years of running time, and we comment on the current results reported by the collaboration. While some leptonic models have currently been produced to describe this emission, we note that for the two brightest HAWC sources, IceCube observations are needed to conclusively differentiate between leptonic and hadronic models. We found that a detection at 3σ or more should be within reach of the next decade for the sources eHWC J1907 + 063 and eHWC J2019 + 368. However, a 3σ detection of the 2HWC J1857 + 027 source will depend on the specific value of the flux, the extension of the source, and the cutoff energy.

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I. INTRODUCTION

Neutrinos are particles that rarely interact with matter and are unaffected by magnetic fields. Therefore, they can travel undeflected through cosmological distances, providing important information on some of the most energetic and distant phenomena of the Universe. They can shed light on the origin of cosmic-ray (CR) and the gamma-ray emission. Through their detection, it is, indeed, possible to discriminate between leptonic and hadronic particle acceleration scenarios. In the leptonic scenario, gamma rays are produced through processes like bremsstrahlung, synchrotron radiation, and inverse Compton scattering. In the hadronic scenario, instead, gamma rays are produced from the decay of neutral pions. In the latter case, from the decay of charged pions, neutrinos are also produced. For this reason, neutrino telescopes can unambiguously probe the hadronic particle acceleration scenario. The identification of the origin of the gamma-ray emission, specifically if it is leptonic or hadronic, is one of the most important goals in gamma-ray astronomy [1].

The IceCube detector has reported 102 neutrino events of astrophysical origin, of which 60 events with deposited energy $E_{dep} > 60$ TeV [2], considering 7.5 years of running time. The current event distribution is consistent with isotropy. For this reason, it is often interpreted in terms of extragalactic sources; see, e.g., Ref. [3].

Several studies have been carried out previously about the possible detection of galactic sources in the northern hemisphere at IceCube, in particular considering sources detected by the Milagro Collaboration, such as MGRO J1908 + 063 and MGRO J2019 + 368; see, e.g., [4–8].

In a previous study, Ref. [7], the authors revisited the prospects for observing the Milagro sources in light of the low-energy cutoff reported by the Milagro Collaboration [9,10]. Subsequently, in Ref. [8], it was concluded that for MGRO J1908 + 06 an evidence at 3σ could be obtained in about ten years assuming the values of the spectral index and the cutoff energy that are in good agreement with the best fit reported in [11]. The answer depends on the neutrino energy threshold considered in the specific analysis. In general, however, in about 15 years of IceCube data, the sources MGRO J1908 + 06 and MGRO J2019 + 37 should be detectable.

The HAWC observatory has reported new data on galactic sources in recent years; see, e.g., [12–14]. In the 2HWC catalog [12], 39 gamma-ray sources were identified, with an optimal sensitivity at about 7 TeV energy. The fit was done using a power-law spectrum, without an energy cutoff and considering two hypotheses for the sources: a point-source case and an extended emission within a uniform disk of fixed radius. An error of about 50% on the flux normalization was reported and an error of 0.1° on the tested radius. Recently, all HAWC sources present in the 2HWC catalog have been considered, excluding those for which the flux can fully be ascribed to a pulsar wind nebula (PWN),[1] and analyzed in comparison with the IceCube data [16]. Different analyses have been considered for the HAWC sources: sources in the northern hemisphere,

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[1]Note that recently the IceCube Collaboration also presented a search for neutrinos coming from PWN [15].

TABLE I. Declination, extension of the source in degrees, normalization of the flux ϕ_0 in units of 10^{-13} $\mathrm{TeV^{-1}\,cm^{-2}\,s^{-1}}$, spectral index α_γ, and β parameter, see Eq. (1), for two of the most luminous sources in the eHWC catalog, eHWC J1907 + 063 and eHWC J2019 + 368.

Source	Dec(°)	σ_{ext}(°)	ϕ_0	α_γ	β
eHWC J1907 + 063	6.32 ± 0.09	0.67 ± 0.03	0.95 ± 0.05	2.46 ± 0.03	0.11 ± 0.02
eHWC J2019 + 368	36.78 ± 0.04	0.30 ± 0.02	0.45 ± 0.03	2.08 ± 0.06	0.26 ± 0.05

the Cygnus region, and in particular the 2HWC J1908 + 063 and 2HWC J1857 + 027 region [16], reporting a p value of about 2% from the 2HWC J1857 + 027 region.

Subsequently, in the eHWC catalog of Ref. [14], nine sources were observed above 56 TeV, all of which were likely galactic in origin. Among these sources, the eHWC J1825 − 134 source, located in the southern sky, was detected with a hard spectrum that extended up to multi-TeV energies; thus, it represented a possible PeVatron source. Moreover, this is the brightest source detected by HAWC in the multi-TeV domain. For this reason, it was analyzed in detail in Ref. [17], specifically considering predictions for the KM3NeT detector and the possibility of discovering the source at the Baikal-GVD experiment and at the IceCube detector.

The sources eHWC J1907 + 063 and eHWC J2019 + 368 were identified with the eHWC catalog as well [14], as two of the three gamma-ray sources, together with the eHWC J1825 − 134 source, emit above 100 TeV. Six other sources were identified above 56 TeV. The source 2HWC J1857 + 027 does not belong to this list. Note, however, that IceCube reported a p value of about 2% from this source [16]. Moreover, for six of the sources that emit above 56 TeV, the integrated fluxes are reported in the eHWC catalog, assuming an E^{-2} and an $E^{-2.7}$ spectrum. Some of the sources detected by HAWC, that are in the eHWC catalog, were previously also detected by Milagro.

In this paper, we show the prospects to detect the gamma-ray sources eHWC J1907 + 063, eHWC J2019 + 368 (2HWC J2019 + 367), and 2HWC J1857 + 027 at the IceCube detector, considering 10 and 20 years of running time. The paper is organized as follows In Sec. II, we describe the data reported on these sources, eHWC J1907 + 063, eHWC J2019 + 368 (2HWC J2019 + 367), and 2HWC J1857 + 027 by the HAWC Collaboration, while in Sec. III, the calculation of the neutrino events from the sources and the atmospheric background is considered. In Sec. IV, we present our results on the p-value analysis and Sec. V contains our conclusions.

II. HAWC SOURCES

The new information from gamma-ray experiments turns out to be important for a better parametrization of the flux of the gamma-ray sources. The uncertainties in the normalization, and spectrum and extension of the sources can result in important variations in the prediction of the neutrino fluxes. In this context, using updated data is important to make more reliable predictions and more correct interpretations of the IceCube results.

Within the eHWC catalog [14,18], it was found that a better fit to the gamma-ray spectrum of two of the brightest sources is given by a log parabola, instead of a power law,

$$\frac{dN_\gamma}{dE_\gamma} = \phi_0 \left(\frac{E_\gamma}{10\ \mathrm{TeV}}\right)^{-\alpha_\gamma - \beta \ln(E/10\ \mathrm{TeV})}, \qquad (1)$$

with α_γ the spectral index and ϕ_0 the flux normalization; see values in Table I for the sources eHWC J1907 + 063 and eHWC J2019 + 368. The source eHWC J1825 − 134 was, instead, studied in detail in [17] in connection to the KM3NeT detector.

The explicit values of the systematic errors on the normalization of the flux vary with energy and are reported in [14]. They are of the order of the one reported for the Crab nebula [18], i.e., of the order of about 15%. To simplify our analysis, we did not consider them in the following.

The emission reported in the 2HWC catalog, instead, is given for point sources and for a bin radius and it is parametrized as

$$\frac{dN_\gamma}{dE_\gamma} = \phi_0 \left(\frac{E_\gamma}{7\ \mathrm{TeV}}\right)^{-\alpha_\gamma}, \qquad (2)$$

where no cutoff is reported. We report in Table II the parameters for the sources 2HWC J1908 + 063, 2HWC J2019 + 367, and 2HWC J1857 + 027 for the case of extended emission. For the values of the parameters in the case of point-source hypothesis, we refer to Ref. [12]. In the left panels of Figs. 1–3 are reported the spectra given in the eHWC and 2HWC catalog.

The 2HWC J1908 + 063 source has been studied in the recent source analysis search done by the IceCube Collaboration that has reported a p value of about 1% from this source; see Ref. [19]. This source, initially dubbed MGRO J1908 + 06, was first detected by the Milagro experiment [10,20,21] and subsequently by the ARGO-YBJ experiment [22]. It was then detected by HESS [11] and VERITAS [23]. It was then detected by HAWC [24] in 2015. As it was noted in Ref. [8], even if the Fermi-LAT observes a pulsar within the extension of the source [25], the large size of the source maybe consistent with a supernova remnant, which is the more accredited source

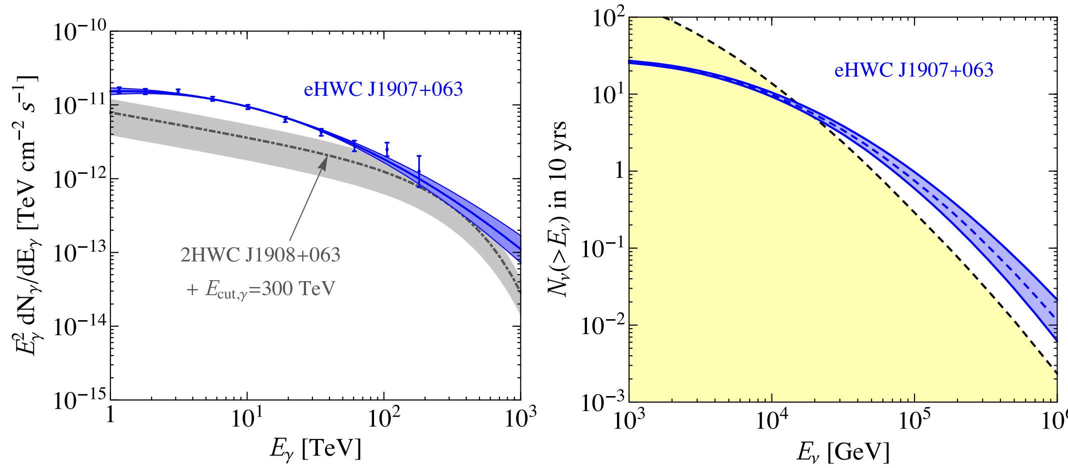

FIG. 1. Left panel: gamma-ray flux for eHWC J1907 + 063 as reported by the eHWC catalog, where the blue band encodes the statistical error in the β parameter. The gray dot-dashed line is the best fit reported by the 2HWC catalog. The shaded gray band encodes the 50% systematic error in the normalization of the fluxes, while the statistical error is not reported. Note that to the best fit given by the 2HWC catalog we have added a cutoff at 300 TeV energy. Right panel: events rate expected at the IceCube detector for the gamma-ray eHWC J1907 + 063 source in 10 years of running time. The shaded yellow band denotes the atmospheric background.

of the highest energy cosmic rays in the Galaxy [26]; see also Refs. [27,28].[2] While studying this source, we will consider only the latest parametrization as reported in the eHWC catalog [14].

The 2HWC J2019 + 367 source belongs to the Cygnus region, that is a complex region of about 5° where five 2HWC sources can be found, of which one is most probably associated with the Cygnus Cocoon field [12]. This source has been detected in the 2HWC catalog within a radius of 0.7°. The emission from this region is compatible with the one detected previously by the Milagro experiments as coming from MGRO J2019 + 37; see Refs. [9,20,21]. VERITAS [29] resolved the emission into two sources, VER J2016 + 371 and the brighter VER J2019 + 368. The first emission can be associated with the supernova remnant CTB 87 or a blazar, while the second can be associated with two pulsars and a star-forming region; see Ref. [12] for a detailed description about the different emission components.

The Cygnus region is a star-forming region and a more complex picture for the 2HWC J2019 + 367 source might be present, since the physics behind the production might be more complex; see, e.g., [28] about the production of neutrinos in association with supernova remnants and molecular clouds and Ref. [30] for an analysis of the Cygnus region, where it was shown that a detection from the whole Cygnus region is probable with IceCube.

Considering the complexity of the Cygnus region, we decided to consider for this source the extended emission at a radius of 0.7°, as reported in the 2HWC catalog, as well as the parametrization for eHWC J2019 + 368 reported in the eHWC catalog [14], for which an extension of 0.3° was reported. We will always work under the assumption that the γ-ray production from this region is hadronic and thus the neutrino flux will be calculated using the standard formalism highlighted in Sec. III.

The source 2HWC J1857 + 027 has been classified in the 2HWC catalog and studied in connection with the IceCube data in Ref. [16]. In this analysis, an excess of neutrinos was found from the 2HWC J1857 + 027 region, resulting in a p value of about 2%. Concerning gamma-ray subsequent studies carried out by the HAWC Collaboration, namely, the eHWC catalog, this source failed to pass the threshold to belong to the sources with high-energy emission, explicitly above 56 TeV. Note, instead, that the eHWC J1850 + 001 source belongs to the eHWC catalog, but this source is at a declination of $(0.14 \pm 0.12)°$. This means that the emission from the 2HWC J1857 + 027 source above 56 TeV is fainter than the emission from the sources present in the eHWC catalog. Nevertheless, we considered this source since an excess in neutrinos is present. For this reason, we compared the integrated flux above 56 TeV from this source with the ones reported for the others eHWC sources. Fixing α_γ to the best-fit value and considering a systematic error of +50% in the normalization, we find the integrated flux to be about 8.32×10^{-15} cm^{-2} s^{-1} for $E_{\mathrm{cut},\gamma} = 100$ TeV, while considering the normalization best fit, we find 5.55×10^{-15} cm^{-2} s^{-1}. Considering $E_{\mathrm{cut},\gamma} =$ 300 TeV, instead, we find integrated fluxes of about 1.5×10^{-14} cm^{-2} s^{-1} and 10^{-14} cm^{-2} s^{-1}, respectively. On the other hand, the fainter source of the eHWC catalog has an integrated flux of about $(0.9 \pm 0.2) \times 10^{-14}$ ph cm^{-2} s^{-1}. We will show how the systematic error on the normalization of the source 2HWC J1857 + 027 has an impact on

[2]Note that the Fermi Large Area Telescope has detected gamma-ray spectra of the supernova remnants IC 443 and W44 that are compatible with a pion-decay feature [27].

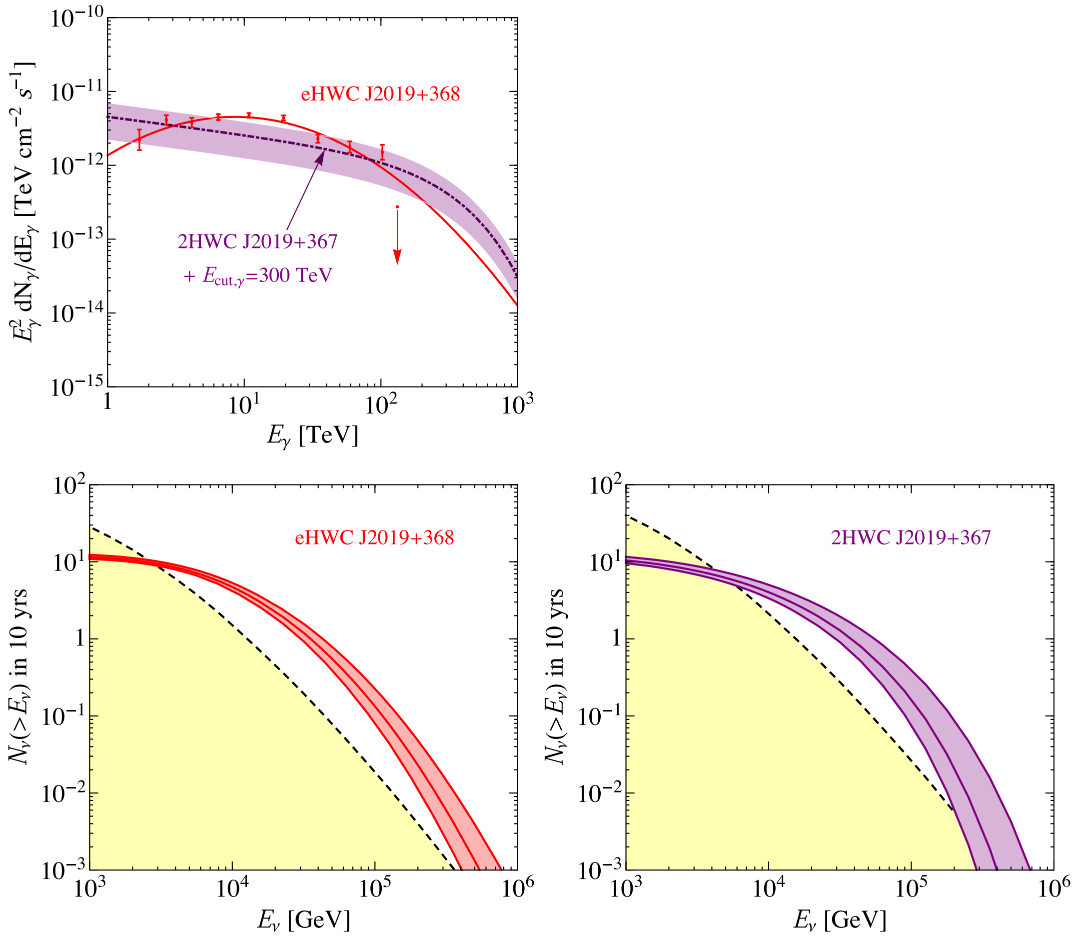

FIG. 2. Upper panel: same as Fig. 1 but for the eHWC J2019 + 368 source. The red line is the best-fit spectrum reported in the eHWC catalog. The purple dot-dashed line is the best fit reported by the 2HWC catalog. The shaded purple band encodes the 50% systematic error in the normalization of the fluxes, while the statistical error is not reported. Lower panel: events rate expected at the IceCube detector for the gamma-ray parametrization reported for the eHWC J2019 + 368 and 2HWC J2019 + 367 source in 10 years of running time. The red band encodes the statistical error in the β parameter, while the purple band the variation in the cutoff energy parameter $E_{\mathrm{cut},\gamma} = 100$, 150, and 300 TeV. The shaded yellow band denotes the atmospheric background.

statistical significance. Moreover, as exemplification, we will consider as cutoff energy 50, 100, and 300 TeV. In the left panel of Fig. 3, we reported the resulted spectrum and, as comparison, we also showed the spectrum for the most luminous source of the eHWC catalog, eHWC J1825 − 134, that has a power law with exponential cutoff fit.

III. NEUTRINO EVENT RATE

In this work, we will consider the possible detection of the eHWC J1907 + 063, eHWC J2019 + 368 (2HWC J2019 + 367), and 2HWC J1857 + 027 sources at the IceCube detector through tracks events originated by muon neutrino charged current interactions. The main assumption in this study is that the emission is hadronic. Recent works, see Refs. [31,32], have indicated that the emission from eHWC J1907 + 063 and eHWC J2019 + 368 is well fitted by a leptonic origin. Note, however, that the gamma-ray emission from the PWN can be of leptonic [33] or hadronic origin [34–36]. These two different scenarios can be probed by neutrino telescopes, since neutrinos serve as the optimal method for differentiating hadronic and leptonic sources. For this reason, we study the potential of using upcoming IceCube observations to confirm, or rule out, hadronic models for each source.

For the effective area of the IceCube detector, we use the one reported in Ref. [37], where different bands in the zenith angle θ_z were considered: $-1.00 \leq \cos\theta_z \leq -0.75$, $-0.75 \leq \cos\theta_z \leq -0.50$, $-0.50 \leq \cos\theta_z \leq -0.25$, and $-0.25 \leq \cos\theta_z \leq 0.08$.

The number of events at IceCube can be described by the following expression:

$$N_{\mathrm{ev}} = \epsilon_\theta t \int_{E_\nu^{\mathrm{th}}} dE_\nu \frac{dN_\nu(E_\nu)}{dE_\nu} \times A_\nu^{\mathrm{eff}}(E_\nu, \cos\theta_Z), \quad (3)$$

where a sum over neutrino and antineutrino contributions is implicit. The parameter $\epsilon_\theta = 0.72$ is a reduction factor

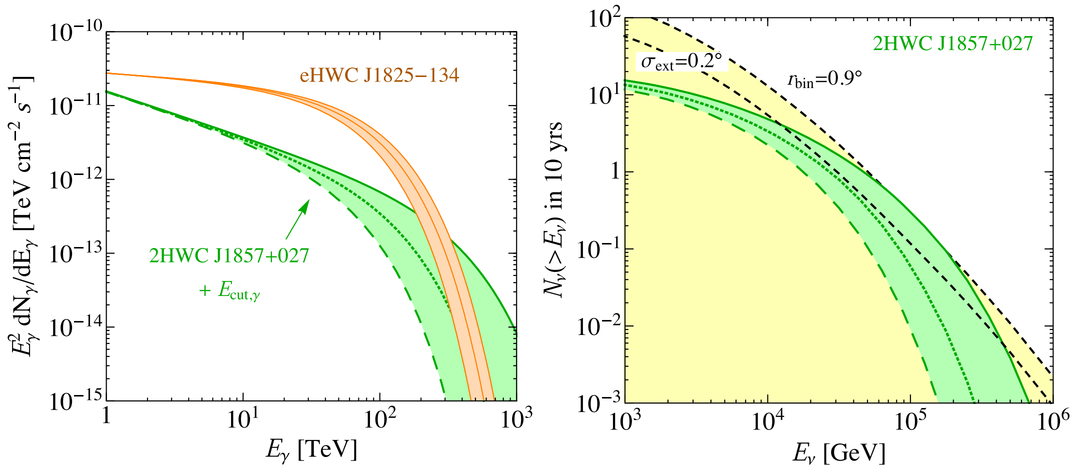

FIG. 3. Left panel: best-fit spectrum for the 2HWC J1857 + 027 source. The green dashed, dotted, and solid lines represent different values for $E_{\mathrm{cut},\gamma} = 50$, 100, and 300 TeV, respectively. As a comparison, we also report the spectrum for the eHWC J1825 − 134 source, the most luminous source in the eHWC catalog, with orange lines, where the band encodes the statistical error in the parameter $E_{\mathrm{cut},\gamma}$; see text for more details. Right panel: events rate expected at the IceCube detector for the gamma-ray 2HWC J1857 + 027 source in 10 years of running time. The shaded yellow band denotes the atmospheric background.

present because only a fraction of the signal can be detected if the source morphology is assumed to be a Gaussian of standard deviation σ_{ext}. For the IceCube detector, we considered $\sigma_{\mathrm{res}} \sim 0.4°$ [38]. The number of neutrino events $\frac{dN_\nu(E_\nu)}{dE_\nu}$ was calculated considering the expressions given in Ref. [39]. For the calculation of the atmospheric muon neutrinos, we followed Ref. [7], using the values reported in Refs. [40–42].

We estimate the neutrino flux from the eHWC sources as described in Eq. (3). The results are reported in the right panel of Fig. 1 for the eHWC J1907 + 063 source. We fixed the normalization and the size of the source to its best-fit values. The spectral index α_γ was also fixed to the best-fit values, while β varied within the statistical errors. The results are reported in the lower panels of Fig. 2 for the eHWC J2019 + 368 (2HWC J2019 + 367) source. For the eHWC parametrization, we considered the spectral index α_γ fixed to its best-fit value, as well as the normalization and the size of the source, while the parameter β varied within the statistical errors. Considering the 2HWC parametrization, as exemplification, we fixed the normalization, as well as α_γ, to the best-fit reported in the 2HWC catalog. We then considered an energy cutoff of 100, 150 and 300 TeV and an extension equal to the circular bin reported in the 2HWC catalog ($r_{\mathrm{bin}} = 0.7°$). Finally, in the right panel of Fig. 3, we reported the results for the 2HWC J1857 + 027 source. In this case, we considered the best-fit normalization and the best-fit value for α_γ reported in the 2HWC catalog. Moreover, since the information on the specific morphology of the region is currently not public, we decided to also consider the case in which the emission is Gaussian with $\sigma_{\mathrm{ext}} = 0.2°$ and with the same flux as the one given in the 2HWC catalog.

TABLE II. Declination, tested radius in degrees, normalization of the flux ϕ_0 in units of 10^{-15} TeV^{-1} cm^{-2} s^{-1}, and spectral index α_γ; see Eq. (2). Besides the sources 2HWC J1908 + 063 and 2HWC J2019 + 367, we have also considered the source 2HWC J1857 + 027, for which an excess in neutrinos has been reported; see text for more details.

Source	Dec(°)	r_{bin}(°)	ϕ_0	α_γ
2HWC J1908 + 063	6.39	0.8	85.1 ± 4.2	-2.33 ± 0.03
2HWC J2019 + 367	36.80	0.7	58.2 ± 4.6	-2.24 ± 0.04
2HWC J1857 + 027	2.80	0.9	97.3 ± 4.4	$-2.61 \pm 0, 04$

IV. STATISTICAL SIGNIFICANCE

The eHWC J1907 + 063 was detected by HAWC with a higher flux in respect to previous data from Atmospheric Cherenkov Telescopes experiments, like HESS. The normalization by HAWC is more compatible with the Milagro best fit [9]. This could be due to the different fields of view of the different experiments. Note that in this respect the LHAASO [43] experiment, which is already running and taking data, might give important complementary information on the high-energy tail of this source. Indeed, the experiment will be able to give information of sources in the PeV domain. Also future experiments, like the planned CTA, that have a sensitivity from 20 GeV up to beyond 300 TeV [44], could provide important information in this respect.

We estimated the statistical significance as reported in Ref. [45] and as described in Refs. [7,8]. We report in Fig. 4 the results for the p value as a function of the energy threshold for 10 and 20 years of running time of the IceCube detector. We find for the eHWC J1907 + 063

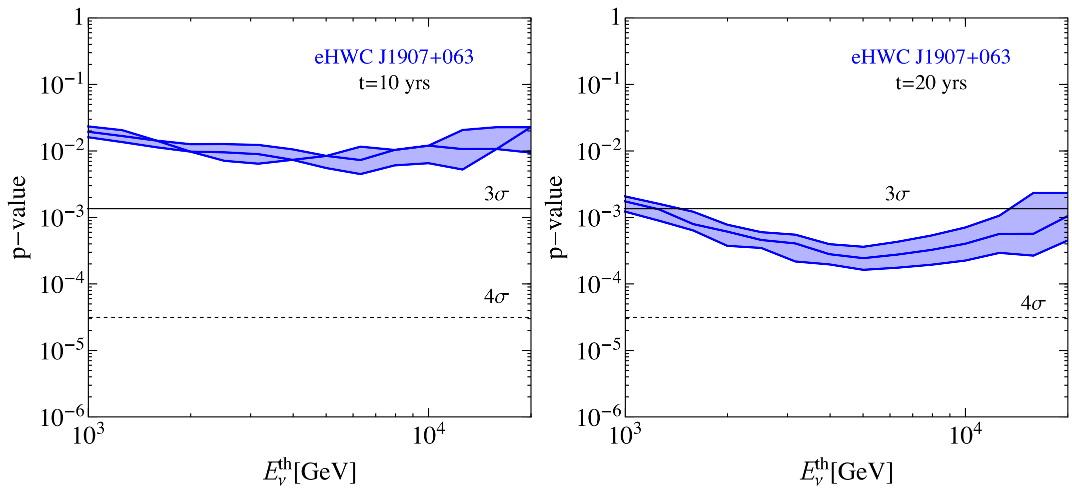

FIG. 4. Left panel: statistical significance expected at the IceCube detector for the eHWC J1907 + 063 source after 10 years running time. Right panel: same as the left panel but for 20 years of running time.

source a p value of about 1% in 10 years, almost independently of the energy threshold used in the analysis, while in 20 years a 3σ is reached for an energy threshold of about 1 TeV. The IceCube detector currently reported a p value of about 1% from this source [19]. Note that the IceCube point source analysis uses an unbinned likelihood method that takes into account the energy distribution of the events with their individual angular uncertainties. This source, previously identified as MGRO J1908 + 06, was considered as one of the most promising sources to be detected by IceCube, because neutrinos from this source can reach the detector without significant absorption in the Earth [4–8].

We report in Fig. 5 the results for the p value as a function of the energy threshold for 10 and 20 years of running time of the IceCube detector for the eHWC J2019 + 368 parametrization and extension, while in Fig. 6 the result for the 2HWC J2019 + 367 region. As can be seen from the figures, considering the eHWC J2019 + 368 parametrization and extension, a detection with a p value of about 1% could reach in 10 years (3σ for an energy threshold of about 10 TeV), while it could reach about 3σ or more (4σ for an energy threshold of about 10 TeV) in 20 years of running time. In case about 50% of the emission is leptonic, the 3σ will not be reached in 20 years of running time. Considering, instead, the 2HWC J2019 + 367 parametrization and extension, almost 3σ could be reached in 10 years for an energy threshold of 10 TeV in neutrinos, while almost 4σ could be reached in 20 years, if the cutoff energy is of about 300 TeV. Note that, even if the detection of neutrinos from the 2HWC J2019 + 367 region might be difficult, the discrimination between the search in a smaller region—the eHWC

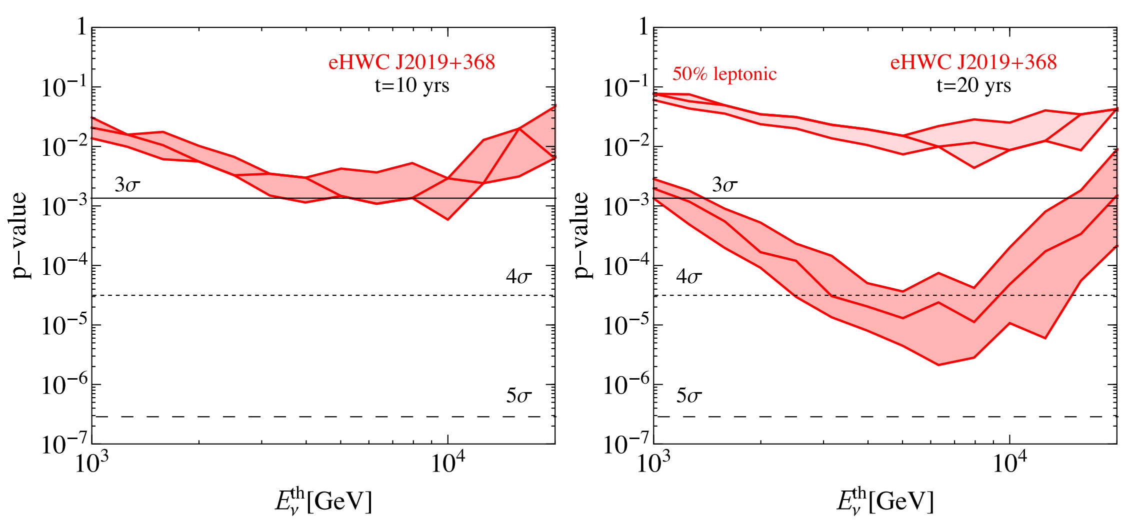

FIG. 5. Left panel: statistical significance expected at the IceCube detector for the eHWC J2019 + 368 source after 10 years of running time. Right panel: same as the left panel but for 20 years of running time.

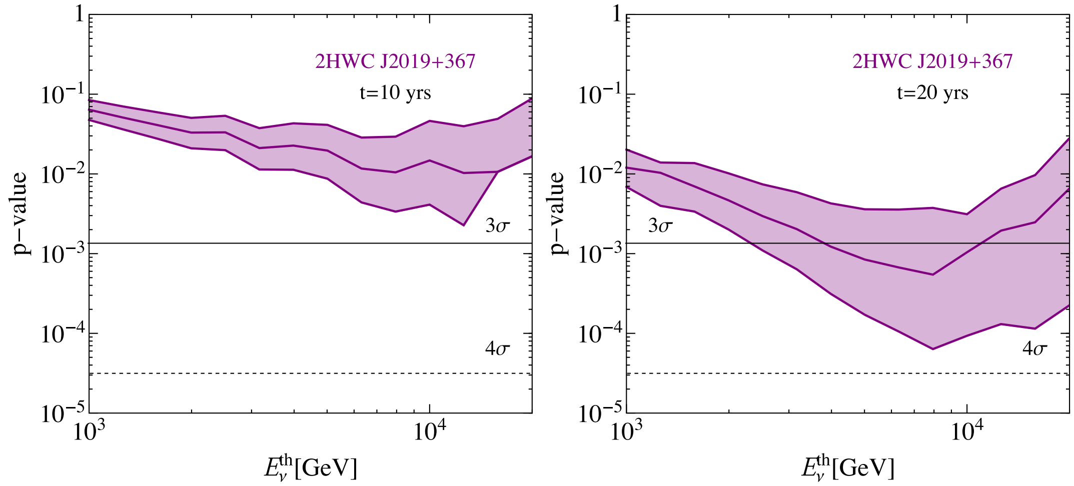

FIG. 6. Left panel: statistical significance expected at the IceCube detector for the 2HWC J2019 + 367 source after 10 years of running time. Right panel: same as the left panel but for 20 years of running time.

J2019 + 368 parametrization and extension—or from the full 2HWC J2019 + 367 region could be important also to discriminate between different production mechanism, i.e., if, e.g., the neutrinos are produced by the single source or by a more complex picture of supernova remnant and molecular clouds. Note that in a previous analysis [8] it was found that we expect to obtain about 3σ discovery in roughly 15 years at IceCube, considering the spectrum reported by VERITAS. This is consistent with what was reported for the eHWC J2019 + 368 parametrization and extension.

Finally, we report in Fig. 7 the results for the p value as a function of the energy threshold for 10 years of running time of the IceCube detector for the 2HWC J1857 + 027 source, while in Fig. 8 the dependence on the running time is shown explicitly. In this case, we also considered the systematic error in the normalization of the flux and a cutoff energy of 50, 100, 300 TeV, having, however, in mind that the latter value is in tension with the fact that the source has not been reported in the eHWC catalog. Moreover, in the 2HWC catalog, a specific circular bin was considered for the search, giving however no explicit information on the morphology of the source. For this reason, we considered the circular bin reported in the 2HWC catalog, 0.9°, as well as a Gaussian morphology with an extension of 0.2°. The IceCube detector recently reported a p value of about 2% from this region. Within our statistical method, we found that this could be possible only considering the systematic error on the normalization of the flux. Moreover, a better agreement is found considering a Gaussian morphology with an extension of about 0.2° for the source and an energy cutoff greater than 100 TeV. Since this source has not been detected in the eHWC catalog, this represents a puzzling result that needs additional data to clarify the situation. This conclusion indicates that we are entering the era of precision physics both on multi-TeV gamma-ray and on

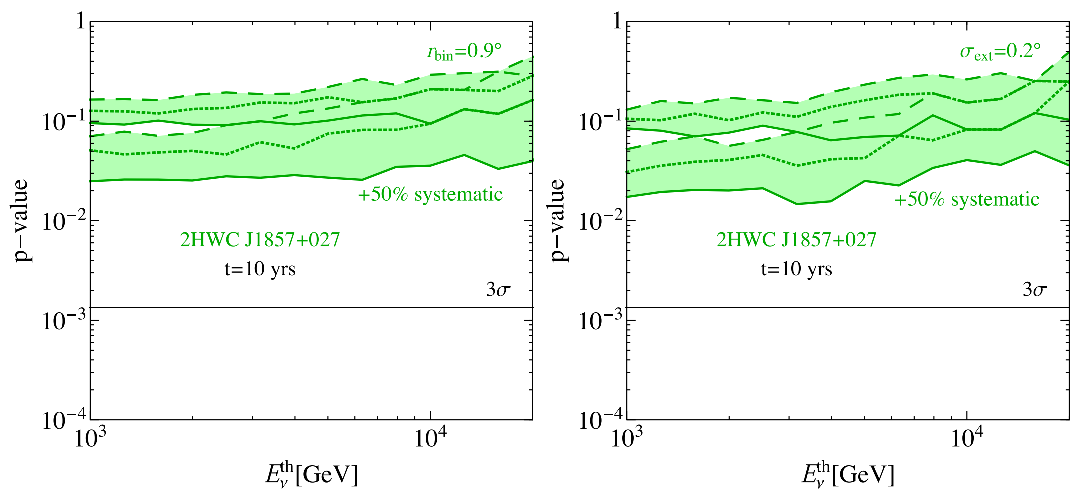

FIG. 7. Left panel: statistical significance expected at the IceCube detector for the 2HWC J1857 + 027 source after 10 years of running time. Right panel: same as the left panel but for a Gaussian morphology with $\sigma_{ext} = 0.2°$.

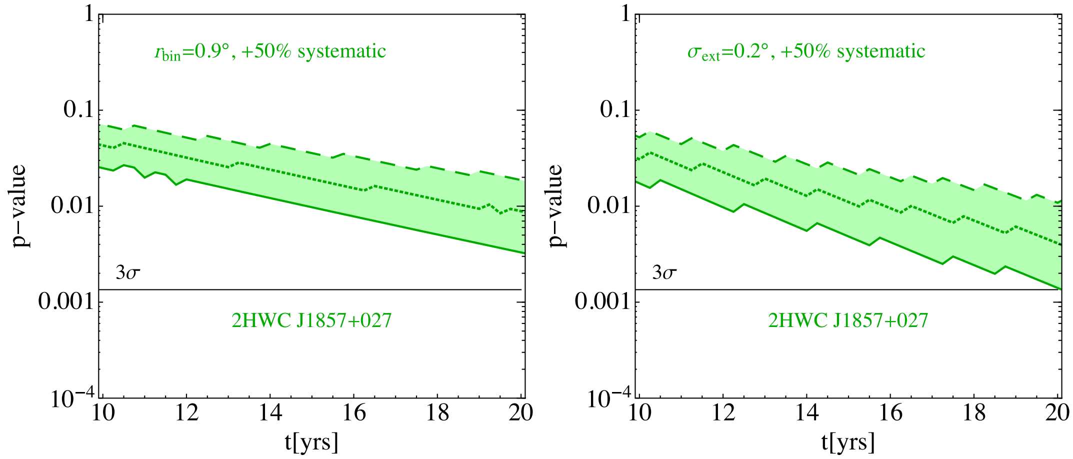

FIG. 8. Dependence of the statistical significance expected at the IceCube detector for the 2HWC J1857 + 027 source on the running time.

high-energy neutrino astronomy. For this reason, a synergy between these two types of experiments, gamma-ray astronomy and neutrinos, will be important to shed light on the origin of galactic cosmic rays and on the characteristics of the source.

V. CONCLUSIONS

Using updated information on the spectrum provided by the HAWC Collaboration, we calculated the number of events expected at the IceCube detectors for the two brightest sources eHWC J1907 + 063 and eHWC J2019 + 368. For the latter, we considered also how things change considering the extended region 2HWC J2019 + 367. Since an excess in neutrinos is present from 2HWC J1857 + 027, we also studied the neutrino emission from this source.

Moreover, we calculated the statistical significance for these sources at the IceCube detector considering 10 and 20 years of running time. We found that the significance can exceed 3σ in the next decade, independently of the statistical errors, for the sources eHWC J1907 + 063 and eHWC J2019 + 368. Considering the 2HWC J2019 + 367 region, instead, a detection at about 3σ or more is expected in 20 years of running time, for a neutrino energy threshold of about 10 TeV. For the source 2HWC J1857 + 027, we explicitly showed the dependence on the systematic error of the normalization on the cutoff energy and extension of the source for the p value. Assuming a Gaussian morphology, a high value of the normalization (within the +50% error), an extension of 0.2° or smaller, and a cutoff energy of 100 TeV or higher, we find a p value of a few percent in 10 years. Future gamma-ray and neutrino data are needed to verify the gamma-ray emission above 56 TeV for this source and the excess in neutrino data.

Respect to previous works we used updated information on the spectra from the eHWC and 2HWC catalog and we also added the source 2HWC J1857 + 027 to the analysis, showing explicitly the dependence on the systematic error of normalization, the energy cutoff, and the extension of the source.

The possibility of detecting these sources with the future KM3NeT detector depends on the visibility of these sources at KM3NeT, that is in general below or close to 50%. Considering a latitude of 36° 16’ N for the KM3NeT detector and the expression of the visibility as reported in Ref. [46], we found that $\epsilon_v = 0.47, 0.31, 0.49$ for eHWC J1907 + 063, eHWC J2019 + 368, 2HWC J1857 + 027, respectively. Note also that the visibility can increase considering tracks that are 6 or 10 degrees above the horizon, thus increasing the sensitivity to these sources; see [47,48]. The most promising sources to be detected at KM3NeT are eHWC J1907 + 063 and 2HWC J1857 + 027. For the source in the Cygnus region, its position is not optimal for a detector in the northern hemisphere. Similar considerations hold true for the Baikal-GVD detector [49], for which we considered a latitude of 51°N and the visibilities that we found are $\epsilon_v = 0.46$, 0.13, and 0.48.

We want here to comment on the possibility of detecting these sources with IceCube Gen2 [50,51]. IceCube Gen2 is planned to have an effective area of about 5 times bigger than the current IceCube detector; see Ref. [51]. Thus, even one year of running of this bigger detector could improve the sensitivity to these sources dramatically.

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