Are there correlations in the HAWC and IceCube high energy skymaps outside the Galactic plane?

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(Received 16 February 2024; accepted 2 June 2024; published 8 July 2024)

We use publicly available data to perform a search for correlations of high energy neutrino candidate events detected by IceCube and high-energy photons seen by the HAWC Collaboration. Our search is focused on unveiling such correlations outside of the Galactic plane. This search is sensitive to correlations in the neutrino candidate and photon skymaps which would arise from a population of unidentified point sources. We find no evidence for such a correlation, but suggest strategies for improvements with new datasets.

DOI: 10.1103/PhysRevD.110.023009

I. INTRODUCTION

A variety of observatories are currently extending our understanding of astrophysics at high energy. The IceCube Neutrino Observatory has identified thousands of astrophysical neutrino candidate events, each of which could be a first glimpse of a future identification of a neutrino point source [1]. To identify such sources, searches have been performed for spatial and/or temporal clustering of events, in addition to multi-messenger approaches which attempt to correlate high-energy gamma rays with neutrino events [2–5]. Latter studies have been motivated by the fact that neutrinos and photons both point back to their astrophysical sources, as they are not bent by galactic magnetic fields. Moreover, weak processes which can produce high-energy neutrinos (such as the decays of highly boosted charged pions) are often related to electromagnetic processes which can produce high-energy gamma rays (such as the decays of highly boosted neutral pions) [6], implying that a source of high-energy neutrinos may also be bright in high-energy gamma rays. In this work, we determine if a correlation can be found between unidentified neutrino point sources and unidentified gamma-ray sources, using publicly available data from IceCube and HAWC. Although attenuation due to pair-production against extragalactic background light (EBL) and the cosmic microwave background (CMB) implies that the sources of higher energy gamma-rays observed by HAWC are likely galactic, lower energy photons observed by HAWC could certainly originate with extragalactic sources [7,8]. As a result, our search is sensitive to both extragalactic and Galactic unidentified point source populations that are outside of the Galactic plane.

We focus on a sample of 139 neutrino candidate events with energies ≥ PeV which lie outside of the Galactic plane and within the HAWC footprint, identified by IceCube during the time period of May 13, 2011 to July 08, 2018. The publicly available data released by IceCube includes neutrino candidate events in the range $(\sim 10^3, 10^7)$ GeV, observed between 2008 and 2018. This sample was released as a result of the analysis of the blazar TXS 0506 + 056 with the intention to perform multimessenger searches similar to the one presented here. We restrict our analysis to the last 7 years, after detector completion, and to energies above 1 PeV. The subtraction of the Galactic plane ($|b| < 20°$) results in the 139 events considered in this analysis. Using the publicly available HAWC point source search sky map employed in the creation of the HAWC catalog [9], we compare the combined test statistic for point sources in these regions with the distribution of combined test statistics for a sample of similarly chosen random regions. We find that the combined point source test statistic for the regions which contain high energy neutrino candidates lies well within the 68% containment region, indicating no significant correlation between high-energy neutrino candidates detected by IceCube and gamma rays detected by HAWC.

The plan of this paper is as follows. We begin by discussing the motivation for this work. We then describe the methodology and results of the analysis. Finally, we conclude.

II. MOTIVATION

There are good reasons to suspect that sources of high-energy neutrinos may also be sources of high-energy gamma rays. Examples of sources which have been found to emit both high-energy neutrinos and gamma-rays include the blazar TXS $0506 + 056$ [10,11] and the Seyfert galaxy NGC 1068 [12].

As a general rule, processes which can produce neutrinos are often related to processes which can produce photons. As an example, neutrinos can be produced by particle physics processes which produce highly boosted charged pions ($\pi^{\pm}$), which decay via $\pi^{\pm} \to \mu^{\pm}\nu$. But since isospin is an approximate symmetry, processes that produce charged pions are typically accompanied by processes producing neutral pions (π^0), which decay to photons via $\pi^0 \to \gamma\gamma$.

More generally, though, any hard processes which produce high-energy neutrinos are necessarily accompanied by processes in which weak gauge bosons ($W^{\pm}, Z$) are emitted from the neutrino via bremsstrahlung. These weak gauge bosons will decay with an $\mathcal{O}(1)$ branching fraction to hadrons, with hadronic decays also producing photons. These weak bremsstrahlung processes are suppressed by factors of the weak coupling constant, but because photons are much easier to detect than neutrinos, the photon production processes may be competitive with the high-energy neutrino production process that they accompany [2]. We thus see that, even if high energy neutrinos are produced by beyond-the-Standard-Model (BSM) physics, such as dark matter annihilation, we should generally expect an associated photon signal.

We have described a few processes in which both photons and neutrinos are produced, with related spectra. However, photons and neutrinos may be produced through multiple processes that are not directly related to each other. As one example, dark matter particles may annihilate into multiple Standard Model final states. The subsequent decays of these Standard Model particles produce photons and neutrinos, along with other stable particles. The relationship between the photon energy spectrum and the neutrino energy spectrum would then depend in detail not only on the dark matter mass, but also on the branching fractions to the various final states. As another example, a source of high-energy neutrinos may also produce other cosmic rays, such as high-energy electrons or positrons, which can produce gamma rays through inverse Compton scattering off background photons.

Moreover, even the rough energy scale of the gamma rays at production, in comparison to the neutrino energy scale, depends on the production mechanism. For example, if photons and neutrinos are produced by the decays of neutral and charged pions, respectively, then their energy scales will tend to be comparable. On the other hand, if a process such as dark matter annihilation produces neutrinos, then the photons produced as a result of electroweak bremsstrahlung will be suppressed by in energy by up to an order of magnitude [2].

Furthermore, the photon spectrum will generally be reprocessed by interactions, both at the source and along the line of sight to the detector. For example, the high-energy photons can generate electromagnetic cascades by scattering off intervening background light (including starlight, CMB photons, etc.) to produce e^+e^- pairs, which in turn produce gamma-rays by inverse Compton scattering off background light. As such, the photon spectrum may be degraded in energy in comparison to that of the neutrinos. But how much reprocessing occurs will also depend on distance from the source to the Earth, as well as the details of the environment of the source.

We thus see that, given a specific model for the processes which produce neutrinos and photons at the source, one can obtain a prediction for the gamma ray spectrum, which can be searched for in data. But if one is agnostic about the production mechanism, one more generally sees the possibility that objects which emit high-energy neutrinos are also sources of gamma rays, as well as other cosmic rays. But as neutrinos and gamma rays are the messengers which will both point back to the source, there may be a correlation between the photon and neutrino skymaps. It is this possibility which we will study.

Previous studies have searched for correlations between a neutrino flux and a gamma ray flux when one or both of these messengers are produced by identified point sources [13,14]. However, there are likely many neutrino point sources which have remained hidden. Due to the inherent difficulty of detecting neutrinos, the number of neutrinos detected from each of these sources is small. We only consider the most energetic neutrino candidate events, which carry a higher probability of being neutrinos of astrophysical origin, and utilize events that are reconstructed as track-like, the signature of muon neutrinos, for good pointing accuracy. For our analysis we consider these muon neutrino candidates from the Southern hemisphere, observed as "down-going" events by IceCube, with reconstructed energy $E \geq$ PeV. Assuming each high-energy neutrino candidate is a potential source, we determine if there is a statistical excess of high energy gamma rays observed by HAWC [15] from these regions, compared to a similar sample of random sky regions. This analysis could allow us to detect a correlation between neutrinos and gamma rays which, though insignificant in any single sky region, could be statistically significant when summed over all such regions. A similar search for correlations between the unresolved gamma-ray background and neutrino events was considered in the context of Fermi-LAT gamma-ray data in the 1–25 GeV range [4]. Our analysis will be sensitive to correlations at higher energies. Although there are reasons to expect that high energy astrophysical neutrinos are accompanied by much lower energy photons (see [16,17]), it is important, for the reasons discussed above, to test the possibility that higher energy photons from these sources also arrive at Earth.

III. METHODOLOGY AND RESULTS

We consider all IceCube events (IC86) with tracklike signatures and reconstructed energy $E \geq$ PeV, observed

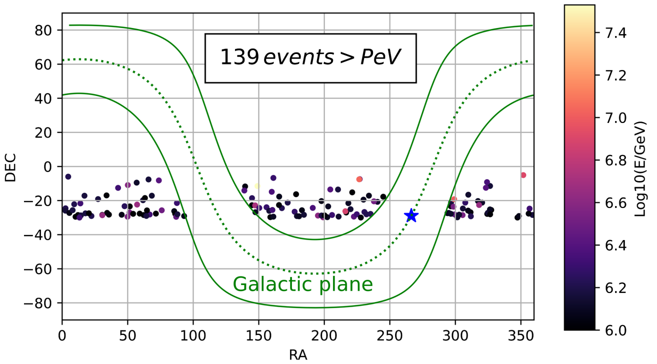

FIG. 1. Events above PeV, recorded between May 13, 2011 and July 08, 2018, the first seven years after IceCube detector completion. In green, we show the Galactic plane (green dotted line) as well as the $|b| = 20°$ band (green solid lines). The blue star represents the Galactic Center. The color of the dots indicates the reconstructed neutrino energy of the neutrino candidate events.

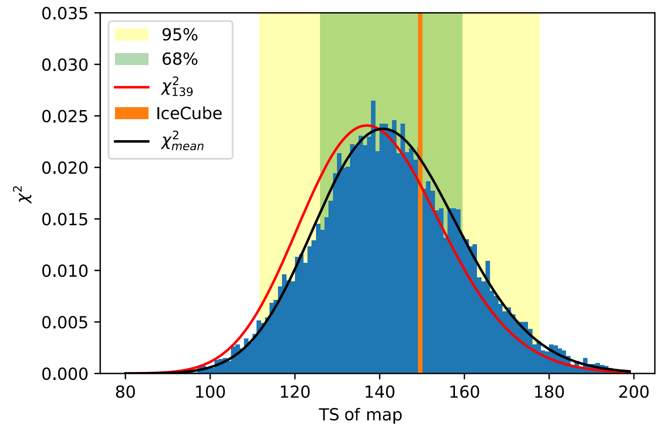

FIG. 2. Distribution of the test statistic for 10^4 random maps (blue) and the result for the 139 sky locations containing PeV neutrino candidates (orange line). A χ^2-distribution with 139 degrees of freedom (red curve) and the best-fit χ^2-distribution for 143 degrees of freedom (black curve) are also shown for comparison. Green and yellow shaded regions represent the 95 and 68% containment bands for the best fit distribution.

during the period May 13, 2011 to July 08, 2018, when the full IceCube array was operational [18]. All of these neutrino candidates are incident on the Earth in the Southern Hemisphere, because for such large energies, neutrino candidates (including atmospheric neutrinos and atmospheric muons) incident in the Northern Hemisphere would interact before reaching IceCube. We only consider neutrino candidates that arrive from regions of the sky that are within the HAWC footprint, which encompasses declinations from 70° to −30° [15]. In addition, we mask the Galactic plane ($|b| < 20°$), where a large number of gamma ray sources are present. We are left with 139 sky locations from which neutrino candidates with reconstructed energy $E \geq$ PeV have been detected by IceCube. Figure 1 shows the neutrino candidate events, each considered as a potential source, represented by dots, where the color indicates the reconstructed neutrino energy. The green dotted line shows the location of the Galactic plane, with the masked band ($|b| < 20°$) outlined in solid green. The blue star shows the location of the Galactic Center.

We use the publicly available data from the HAWC 3HWC point source catalog to obtain the signal significance for point source detection in each pixel, using data from 1523 days of operation [9]. The signal significance is the square of a test statistic given by $TS = 2\ln(\mathcal{L}_{s+b}/\mathcal{L}_b)$, where $\mathcal{L}_b$ is the likelihood of the HAWC data given the HAWC background model,[1] and $\mathcal{L}_{s+b}$ is the likelihood of the best fit model of background plus a point source with energy spectrum $\propto E^{-2.5}$, with the normalization as a free parameter.[2] Since the test statistic in each pixel is χ^2-distributed with 1 degree of freedom [9], the sum of the test statistic in 139 pixels should be χ^2-distributed with 139 degrees of freedom. To demonstrate this, we draw 10^4 sets of 139 random sky locations between declinations 0 and −30° (excluding the Galactic plane) and histogram the summed test statistics. In Fig. 2, we show the histogram of summed test statistics for the random sky regions (blue) and the result for the 139 sky locations containing PeV neutrino candidates (orange line). For comparison, we also plot a χ^2-distribution with 139 degrees of freedom (red curve), and the χ^2-distribution which is a best fit to the histogram (black curve). The best fit χ^2-distribution is for 143 degrees of freedom, similar to our expectations for the behavior of the test statistic.[3] The green and yellow bands are the 68% and 95% containment bands of the best fit χ^2-distribution. We see that the test statistic obtained from the sky locations containing the IceCube neutrino candidates fits well inside the 68% containment band, indicating that there is no statistical preference for point sources within these regions.

Note that the HAWC angular resolution varies between 0.1°–1.0°, and its pointing uncertainty may be as large as 0.3° in this region of the sky [9]. For the IC neutrino sample we use, in the energy range we consider, the median neutrino pointing uncertainty is ∼0.2° [1]. Our method amounts to a search for excess gamma ray emission from

[1]For a point source search, the HAWC Collaboration estimates background (dominated by misidentified hadronic cosmic rays) using the "direct integration" method detailed in Ref. [19]. The background rate in any region of sky is found by convolving an isotropic but time-dependent background rate with an acceptance factor which depends on the orientation with respect to the detector. Both of these factors are derived from HAWC data.

[2]The signal significance is reported with a negative sign if the best fit signal model has a negative signal normalization.

[3]It is not surprising that there is a slight deviation between the distribution of the summed test statistic and the expected distribution under the background-only hypothesis, since there may be point sources in this region (that is, between declinations of 0° and −30°, excluding the Galactic plane).

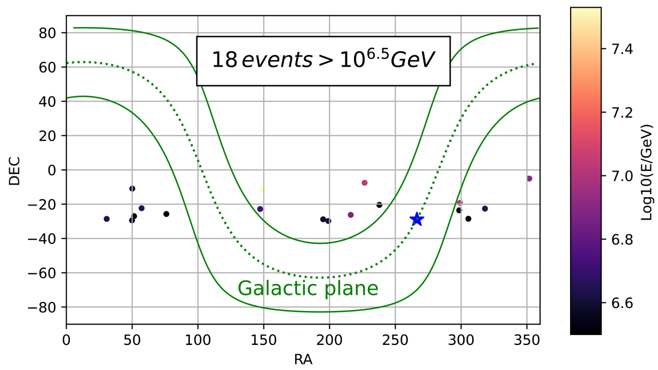

FIG. 3. Similar to Fig. 1, but for events with $E > 3.2$ PeV.

the reconstructed directions of high-energy IC neutrino candidate events. This method would not be sensitive to correlations between the neutrino and gamma ray fluxes if the reconstructed neutrino direction is sufficiently far from the actual source. Since the pointing uncertainties are comparable, a small but non-negligible fraction of $\nu - /\gamma-$sources would evade this search in this manner.

The solid angle encompassed by 139 sky regions of size 0.3° is small compared to the solid angle of the total sky region from which they are drawn. However, if the neutrino threshold were to be lowered significantly, one would obtain so many neutrinos that the regions of sky (of 0.3° radius) covering these neutrino candidates would be an $\mathcal{O}(1)$ fraction of the intersection of the HAWC and IceCube footprints, largely negating the validity of this type of analysis. One might ask, however, if there is a correlation between gamma rays seen by HAWC and the highest energy neutrino candidates seen by IceCube. We investigate this possibility by performing a similar analysis using only the 18 neutrino candidate events detected by IceCube with $E > 3.2$ PeV, which are also within the HAWC footprint but outside the mask of the Galactic plane. We present the corresponding skymap in Fig. 3, and the distribution of summed test statistics in Fig. 4. We again find no significant statistical preference for gamma-ray point sources in this combined region.

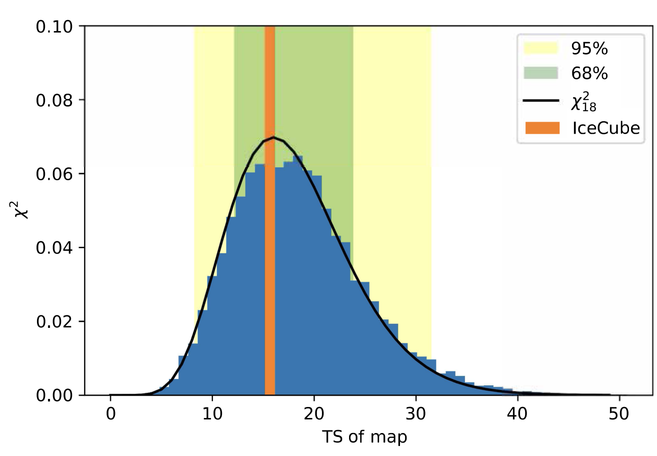

FIG. 4. Similar to Fig. 2, but restricted to neutrino candidates with reconstructed energy $E > 3.2$ PeV.

IV. CONCLUSION

We have investigated the possibility of a correlation between high energy neutrino candidate events ($E \geq 1$ PeV) observed by IceCube and the high energy photons observed by HAWC. We have used data from the publicly available 3HWC point source catalog and the publicly available IceCube data to compare the summed test statistic for gamma ray point sources in the regions of sky containing IceCube PeV neutrino candidates to the summed test statistic for the same number of random sky regions. We find that the test statistic for regions of sky containing high energy neutrino candidates lies well within the 68% containment region of the background distribution, indicating no statically significant correlation.

A correlation between high energy neutrinos and high energy photons could arise if there were a population of unidentified point sources that produce(d) both neutrinos and photons. It would be interesting to investigate this possibility further with future data and with dedicated analyses. We have used a publicly available HAWC point source search tool. However, HAWC's footprint largely covers the Northern Hemisphere, and only a fraction of its footprint covers the region of the Southern Hemisphere from which PeV + neutrinos could be seen at IceCube. As more extensive neutrino and high energy gamma-ray datasets become available, it would be useful to apply this technique to datasets with greater overlap.

While this analysis did not find any correlation between gamma-ray sources and high-energy neutrino candidate events, the study presented here has several limitations that a comprehensive analysis, conducted by the experimental collaborations, could overcome, potentially leading to significant sensitivity improvements. We do not use neutrino candidate reconstructed energy information other than for the definition of the applied energy thresholds. The reconstructed energy information combined with the declination angle can be used to assign a probability of a neutrino being of astrophysical origin. This information can be included as an event weighting for enhanced sensitivity. Further, the reconstruction uncertainty on the neutrino direction is not taken into account, while a weighting with the likelihood of individual neutrino points of origin would result in further sensitivity improvements. The publicly available HAWC analysis tool assumes that gamma-ray point sources have a power-law energy spectrum with a slope of −2.5. For a given model of high energy neutrino production (for example, from dark matter annihilation), one could also predict the expected gamma ray spectrum. Including spectral information in a dedicated analysis could potentially provide greater sensitivity to correlations between high energy photons and neutrinos.

Not all sources of both gamma-rays and neutrinos are amenable to the search we have conducted. In particular, we have searched for spatial correlations between high energy neutrino candidates (>PeV) seen by IceCube and lower energy photons seen by HAWC. Depending on the production mechanisms for these messengers, the distance to the source, and the environment between the source and Earth, even a source of both gamma rays and neutrinos may not produce detectable event rates within the available energy windows for these messengers. The limited publicly available data thus limits the information one could obtain about the nature of the sources to which a search of this type is sensitive, beyond the important fact of their existence. When more data are publicly available, a future study involving spectral information from broader data sets would allow constraints on (or detections of) specific classes of sources and messenger production mechanisms.

ACKNOWLEDGMENTS

We are grateful to Melissa Diamond for useful discussions. J. K. is grateful to the University of Utah for its hospitality. J. K. is supported in part by DOE Grant No. DE-SC0010504. P. S. is supported in part by NSF Grant No. PHY-2014075. C. R. acknowledges support from NSF Grant No. PHY-2309967 and from the National Research Foundation of Korea (NRF) for the Basic Science Research Program No. NRF-2020R1A2C3008356. N. T. thanks the University of Utah for its support.

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