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A multi-messenger study of the Fermi Bubbles: very high energy gamma rays and neutrinos

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The Fermi Bubbles have been imaged in sub-TeV gamma rays at Fermi-LAT, and, if their origin is hadronic, they might have been seen with low statistics in $\sim 0.1 - 1$ PeV neutrinos at IceCube. We discuss the detectability of these objects at the new High Altitude Water Cherenkov (HAWC) gamma ray detector. HAWC will view the North Bubble for $\sim 2 - 3$ hours a day, and will map its spectrum at 0.1–100 TeV. For the hard primary proton spectrum required to explain five events at IceCube, a high significance detection at HAWC will be achieved in less than 30 days. The combination of results at HAWC and IceCube will substantiate the hadronic model, or constrain its spectral parameters.

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Introduction. — Studying the sky at Very High Energies (VHE) of ~ 100 GeV and beyond is at the frontier of astrophysics today. Until very recently, Gamma Ray Astronomy has been the only avenue to probe the VHE sky, and has revealed the existence of powerful natural particle accelerators, whose physics is still largely unknown [1]. It is expected that collisions of accelerated hadrons with the ambient medium are at least partly responsible for VHE gamma ray emission from these sources. The same processes also produce neutrinos, and therefore a VHE neutrino counterpart of the gamma ray flux is expected. In 2013, the IceCube Neutrino Observatory reported the detection of astrophysical neutrinos in the 0.1–1 PeV energy range [2–4], which opened a new avenue of multi-messenger exploration of the VHE sky. The complementarity between gamma rays and neutrinos is strong, mainly because they both probe the sites of the cosmic-ray accelerators in the universe.

Since the neutrino data are still limited by low statistics, a multi-messenger study of a single, specific source is possible only for the closest and most powerful emitters in the sky, like the Galactic Center and the Fermi Bubbles (FB). The FB have recently emerged as an ideal candidate for multi-messenger astronomy. These large globular-shaped Galactic structures, extending up to ~ 9 kpc symmetrically out of the Galactic plane (see Fig. 1), were discovered [5] in the gamma-ray data of the *Fermi* Large Area Telescope (LAT), which has since mapped them in details at energies ~ 0.1 –400 GeV [6]. Complementary observations in radio [7] and X-ray [8] confirm multi-wavelength emission from the FB.

Both hadronic [9, 10] and leptonic [5, 11] mechanisms have been proposed for the origin of the FB gamma rays.

For hadronic models, it has been pointed out that a neutrino counterpart should exist [9, 12], and might be responsible for a fraction of IceCube astrophysical neutrinos [13]. In particular up to five of the IceCube astrophysical neutrinos of energy ~ 100 TeV–1 PeV, that are spatially strongly correlated with the bubble geometry (see Fig. 1) [32]), are consistent with the hadronic flux model that reproduces the *Fermi*-LAT gamma-ray data [14]. Therefore, the FB could be the first object to have been seen in both gamma rays and neutrinos. The two observations, however, probe different parts of the FB spectrum, and therefore their connection is only indirect.

An interesting development at the front of multi-messenger studies of the FB is expected very soon, with the advent of the High Altitude Water Cherenkov detector (HAWC), which has started operations in Mexico this year [15]. With a large field of view ($\sim 2\pi$ sr), excellent positional resolution ($\sim 0.1^\circ$ at $\gtrsim 5$ TeV), and strong sensitivity in the ~ 0.1 –100 TeV range, HAWC will observe the FB in great detail in a window of energy that partly overlaps with the regimes already probed by the *Fermi*-LAT and IceCube. It will bridge the energy gap between them, thus leading to a more complete mapping of the FB spectrum. The interplay of the *Fermi*-LAT, HAWC and IceCube data has the potential to disfavor or to fully establish the hadronic origin of the FB, and, in the latter event, constrain the spectrum of the primary proton/ion flux. Such interdisciplinary study will be a good test bed for the development of new analysis techniques that could then be applied to other, less luminous, VHE neutrino and gamma ray sources [16] when neutrino telescopes reach the phase of high statistics data taking.

The interplay between gamma ray and neutrino observations of the FB is the focus of this paper. Here we study HAWC’s ability to detect VHE gamma rays from the FB in the hadronic model, and present the first discussion of the potential of joint analyses of HAWC and IceCube data.

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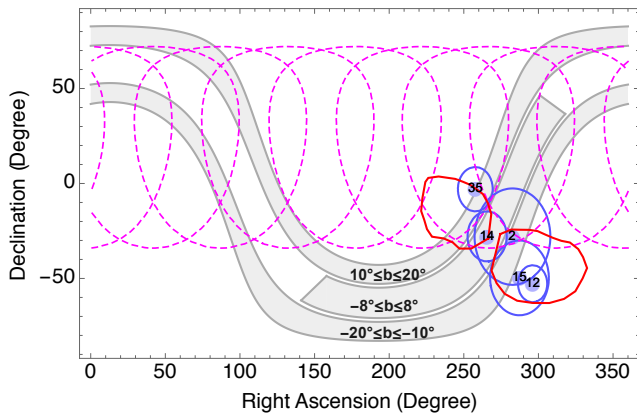


FIG. 1: Map of the Fermi Bubbles in equatorial coordinates (red solid contours). The blue dots show the IceCube events that are spatially strongly correlated with the FB with their sequence numbers [4] and their positional errors (blue ellipses, see text). Also shown are the contours of the HAWC’s field of view ($0.6 \leq \cos \theta \leq 1$), for which the effective area is published [17], at several times of the day (magenta dashed contours). The shaded curves represent the inner Galaxy region (corresponding to Galactic coordinates $-80^\circ \leq l \leq 80^\circ$, $-8^\circ \leq b \leq 8^\circ$) and the low intermediate latitude region ($0^\circ \leq l \leq 360^\circ$, $10^\circ \leq |b| \leq 20^\circ$), where *Fermi*-LAT has measured diffuse Galactic gamma-ray emission [18].

Observing the FB with HAWC and IceCube. — The FB are extended sources in the sky subtending a total solid angle $\Omega_{\text{FB}} \simeq 0.808$ sr [5]. Depending on its field of view, location and time of the day, a detector on Earth will be able to observe only a fraction, f_Ω , of this solid angle. Due to its privileged location near the South Pole, IceCube has $f_\Omega \simeq 1$ [12], meaning that it is equally sensitive to the FB at all times of the day. This is true for the High-Energy Starting Events (HESE) for which the νN interaction vertex is within the detector volume [3].

Instead, for HAWC f_Ω is time-dependent. HAWC is located in the Northern hemisphere, at longitude 97.3° W and latitude 19.0° N. Its field of view has a half-opening angle $\delta \simeq 60^\circ$, meaning that it will be able to observe objects at angular distance $\theta < \delta$ from its zenith ($\cos \theta > \cos \delta = 0.6$). Fig. 1 shows the FB in equatorial coordinates in comparison with the time-dependent region observed by HAWC. We see that the north bubble is observable entirely at least for 2-3 hours in a day, while instead only a small portion of the south bubble is accessible to HAWC.

For the purpose of obtaining event rates at HAWC, we have calculated the daily-averaged fraction of the solid angle [21], $\langle f_\Omega(\theta_1, \theta_2) \rangle$, that is subtended by the FB and falls in angular bins defined by the values $\cos \theta = 0.6, 0.7, 0.8, 0.9, 1$. These bins correspond to the intervals for which the HAWC effective area is reported [17]. For each bin, in order of increasing $\cos \theta$, we find $\langle f_\Omega(\theta_1, \theta_2) \rangle = 4.5 \times 10^{-2}, 3.5 \times 10^{-2}, 4.1 \times 10^{-2}, 1.0 \times 10^{-2}$. On average, only a few percent of Ω_{FB} falls within a certain zenith bin. This plays the role of an efficiency

factor in the calculation of the event rates.

We model the expected neutrino and gamma-ray fluxes in a simple hadronic model, with primary proton spectrum of the form $dN_p/dE \propto E^{-k} \exp(-E/E_0)$ and pp interactions with dilute gas in the FB, as described in details in ref. [12]. We focus on relatively hard spectra, with $k \simeq 2.2 - 2.3$ and $E_0 \sim 3 - 30$ PeV, that are required by the interpretation of the five neutrino data in fig. 1 as due to the FB [14]. In Fig. 2, the gamma ray and neutrino fluxes are shown for $k = 2.25$, $E_0 = 30$ PeV. Using a χ^2 test, we checked that these spectra are a good fit of the *Fermi*-LAT observation of both bubbles. In particular, $\chi^2/dof \approx 13/40$, including penalty for χ^2 when the fit violates the upper limits (last four energy bins of the *Fermi*-LAT data), which are treated as half-Gaussian. Of course, the *Fermi*-LAT data alone are also compatible with a lower-energy cutoff in the proton spectrum, and slightly favor $E_0 \sim \mathcal{O}(10)$ TeV [6]. These values would require a different explanation, other than the FB, for the neutrino data.

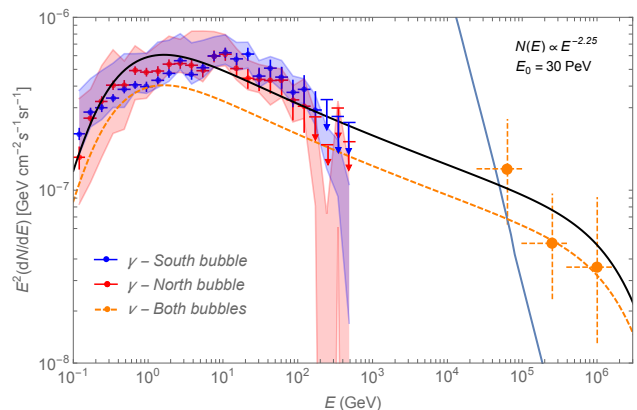


FIG. 2: The spectrum of the gamma-ray flux from the FB (crosses), as measured by *Fermi*-LAT [6]. The shaded areas indicate the systematic errors. The solid curve is the corresponding prediction of a hadronic model (parameters in the inset). The counterpart neutrino flux is shown too (dashed), and compared with the flux required by the IceCube data (the three dots at high energies, with error bars), in the assumption that FB are the sources of the five neutrino events that are strongly correlated with them spatially [14]. The neutrino errors assume Poisson statistics, following Pearson’s χ^2 intervals approach [22, 23]. The atmospheric neutrino background [24], averaged over $25^\circ - 95^\circ$ zenith angle, is shown for comparison (steep solid line).

Results: VHE gamma-ray and neutrino event rates. — As is typical of high energy cosmic-ray detectors, the response of HAWC and IceCube to a given flux Φ (of gamma rays and neutrinos, respectively) can be parameterized by an effective area, $A(E, \theta)$, which depends on the particle arrival direction and energy. In the assumption that the FB are uniformly bright in gamma rays (and hence in neutrinos in hadronic models) [5, 6, 12], Φ is zenith-independent. The number of events with primary particles in a certain zenith bin, $[\theta_1, \theta_2]$, and for an

exposure time T , is given by [12]

$$N = \int_0^T dt \int_{\substack{\Sigma(t) \\ \theta_1 \leq \theta \leq \theta_2}} d\Omega \int_{E_{th}}^{\infty} dE \Phi(E) A(E, \theta) \\ \simeq T \langle f_{\Omega}(\theta_1, \theta_2) \rangle \Omega_{FB} \int_{E_{th}}^{\infty} dE \Phi(E) \langle A(E) \rangle_{\theta}, \quad (1)$$

where the zenith-averaged effective area (for each bin) is used as an approximation. Here $\Sigma(t)$ indicates that the integral in the solid angle is done over the region of the bubbles for which the condition on the zenith angle is satisfied. An expression similar to eq. (1) also applies to the calculation of background rates in the two experiments, which is required to evaluate statistical significance of a signal from the FB.

For neutrino event rate calculation in IceCube, we adopt the same method as in [14], using the averaged effective area as in ref. [3] for each neutrino flavor. The main background here is due to the flux of atmospheric neutrinos [24], shown in Fig. 2. The FB and atmospheric neutrino flux models well-reproduce the 5 cascade events that are strongly-correlated with the FB spatially, over a 1000 day IceCube live time (see Fig. 3).

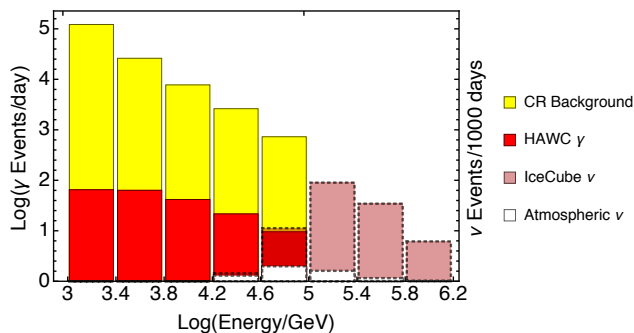


FIG. 3: *Solid histogram* - number of gamma ray events (in logarithmic scale) from the FB at HAWC, in bins of the gamma ray energy, for 1 day exposure (left vertical axis). The corresponding cosmic ray background is also shown. *Dashed histogram* - number of neutrino events (in linear scale) at IceCube, in bins of neutrino energy. Here the exposure is 10^3 days (right vertical axis), and the background is due to atmospheric neutrinos. The primary flux parameters are the same as in Fig. 2.

For the VHE gamma-ray event rate at HAWC, both for signal and background, we use the effective area in ref. [17]. The absorption of gamma rays due to electron-positron pair production with photons from starlight or cosmic microwave background is negligible in the HAWC energy range. The dominant background in HAWC is due to cosmic rays, mostly protons and helium nuclei, whose fluxes are $\sim 4 - 5$ orders of magnitude larger than the flux of the FB gamma rays. We use the hadron rejection efficiency for HAWC, which is 5×10^{-3} at energies above 10 TeV, from ref. [25]. Another background is

diffuse gamma-ray emissions, which have been well measured by *Fermi-LAT* [18]. To estimate the gamma-ray background in different sky regions, we adopt the spectra for the $^S S^Z 4^R 20^T 150^C 5$ model (extrapolated to the energies of interest here) in ref. [18] for the inner Galaxy region (see also ref. [19] for gamma-ray background in this region), high and low intermediate latitude region as shown in Fig. 1. The cosmic electron background is negligible.

Figure 3 shows the signal and background daily event rates in HAWC from the FB region. With several signal events per day, HAWC will rapidly accumulate a high statistics data sample. Although the signal from the FB is $\sim 2 - 3$ orders of magnitude smaller than the background, the high statistics will allow to establish a high significance, given by the number of Gaussian standard deviations with respect to background as $\sigma = \sqrt{\sum_i \sigma_i^2} = \sqrt{T} \sqrt{\sum_i S_i^2 / (S_i + B_i)}$. Here S_i and B_i are FB signal and background (total of cosmic-ray and diffuse gamma-ray fluxes) event rates, respectively, in each energy bin i . We find that, for the total of all energy and zenith bins, $\sigma > 3$ ($\sigma > 5$) already after 10 days (35 days) of running time. After a year of operation, a significance of at least 5σ will be reached in each zenith bin separately.

Discussion: HAWC-IceCube complementarity. — We have found that HAWC has an excellent potential to observe the FB with high significance within a relatively short time scale. Depending on the parameters, this signal could be consistent with the hypothesis that the bubbles might be the (hadronic) source of the IceCube neutrino events that spatially correlate with them. Let us outline below what can be learned from HAWC and IceCube, in combination and individually, on the FB.

Figure 4 elaborates on the multi-messenger connection between the IceCube and HAWC, showing the regions of the parameter space ($k = 2.15 - 2.30$ and $E_0 = 10^{4.5} - 10^{7.5}$ GeV) that correspond to a given signal at the two detectors (significance for the HAWC and number of events for IceCube). For each pair (E_0, k) , the flux normalization is determined by the low-energy *Fermi-LAT* data for the k and E_0 values, similar to the fit shown in Fig. 2. It can be seen that, while HAWC can probe the entire space with high statistical significance within a year or so of operation, IceCube is insensitive to a neutrino flux with a spectral cutoff in the primary proton energy $E_0 \lesssim 1$ PeV, as expected, considering the higher threshold of IceCube. Therefore, the different combinations of possible outcomes (detection or exclusion) at the two observatories will be informative of the spectral parameters.

IceCube has already observed 5 neutrino events that are correlated in position with the FB (see Fig. 1). With a few more years of operation, this hint could become a statistically significant observation of the FB. This observation would confirm the hadronic hypothesis for the bubbles, and indicate a primary proton population with a relatively hard spectrum, $k \simeq 2.15 - 2.25$, and high

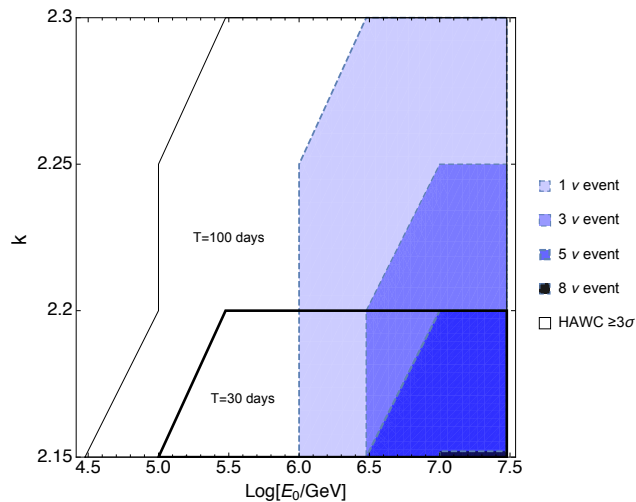


FIG. 4: Solid lines: contours in the space of the flux parameters, k and E_0 , corresponding to more than 3σ significance at HAWC (for two different running times, see legend). Dashed, shaded regions: isocontours of numbers of events at IceCube, for 1000 days running time. These numbers of events have been calculated at discrete points on a grid with step 0.5 (0.05) on the horizontal (vertical) axis.

energy cutoff, $E_0 \simeq 3 - 30$ PeV. It may provide the best information on the highest energy tail of the FB spectrum, $E \gtrsim 0.1$ PeV, which is beyond the sensitivity of *Fermi*-LAT and HAWC. Furthermore, IceCube will observe both bubbles, therefore testing the degree of symmetry between them, in a way that complements the lower energy information from *Fermi*-LAT. A negative result at IceCube will be compatible with either a hadronic scenario with sub-PeV cutoff, or a primary leptonic origin of the FB.

If IceCube observes the FB, and therefore the primary spectrum extends above PeV, a high statistics observation in gamma rays is expected at HAWC within about a year of operation. This telescope is mainly sensitive to the North Bubble and will produce a detailed intensity map of it, at energies higher than those probed so far by the *Fermi*-LAT. This map will test a number of features seen by *Fermi*-LAT, like the uniform projected intensity of the bubbles [5, 6]. Due to its lower energy threshold, HAWC could see a signal even for a negative result at IceCube. In particular, thanks to its good energy resolution, HAWC could reveal the presence of a spectral cutoff at the $\sim 0.1 - 100$ TeV energy window.

Outlook. — Looking at the longer term future, a larger overlap between the energy windows of the two experiments would be desirable, especially to fully exclude the hadronic model in the absence of a signal at IceCube,

accompanied by a clear detection at HAWC in the same energy range. This larger overlap could be achieved by lowering the energy threshold of the IceCube analysis. It has to be considered that atmospheric neutrino backgrounds at IceCube become quickly overwhelming when lowering the threshold, therefore the potential of such exercise is unclear at this time.

Besides a direct comparison of the IceCube and HAWC data, the indirect influence of one experiment over the other will be important as well. Indeed, each data set will lead to improved theoretical models of the FB, which in turn will result in more precise predictions for the next generation of experiments. In particular, the ratio of gamma ray and neutrino fluxes may be constrained and compared with predictions, to help discriminate between different versions of the hadronic model and possibly test neutrino and/or gamma ray propagation effects over galactic scales of distance. Similar multi-messenger studies for a point source or diffuse emission at the Galactic Center region can be done as well [26].

Eventually, the interdisciplinary research on the FB with neutrinos and gamma rays will include more participants. One of them will be KM3NeT, the multi-km³ neutrino detector currently planned in the Mediterranean sea [27]. It's current predecessor ANTARES has already searched for a signal from the FB direction, resulting in a flux upper limit [28]. Relative to IceCube, KM3NeT will have a larger effective area (~ 6 km³ instrumented volume) and may detect the FB in about one year of its operation [27]. Finally, IceCube itself might be able to probe the highest energy end ($\gtrsim 1$ PeV) of the FB gamma-ray spectrum using the IceTop surface detector array [29]. Prospects for PeV gamma-ray detection have also been considered for the upcoming ground-based detectors LHAASO (Large High Altitude Air Shower Observatory) [30] and HiSCORE (Hundred**i* Square-km Cosmic ORigin Explorer) [31].

We conclude that, by extending the gamma ray mapping of the FB to 100 TeV, HAWC will be an important complement to neutrino searches of these objects. With IceCube and other neutrino observatories, it will further advance the new field of multi-messenger astronomy at very high energy.

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