Carpet–2 search for gamma rays above 100 TeV in coincidence with HAWC and IceCube alerts[1)]

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Important multimessenger observations became possible thanks to alerts distributed by gravitational-wave, neutrino and conventional astronomical observatories to the worldwide community of observers. Up to now, in the electromagnetic channel, these alerts have been followed up at the energies up to ~ 100 TeV, above which the sensitivity of the highest-energy participating observatory, HAWC, fades, while higher energies have been accessible only for the neutrino and cosmic-ray channels. The purpose of the present paper is to push further this high-energy limit for the photon channel and to report the results of the first ever multimessenger alert follow-up in the 100 TeV to several PeV gamma-ray band.

This energy band is especially important for high-energy neutrino alerts because it is precisely the range where the estimated neutrino energies fall to. The origin of these astrophysical neutrinos remains uncertain. In the dominant part of the scenarios of the astrophysical production of high-energy neutrinos, they are born in $\pi^{\pm}$-meson decays, while the decays of π^0 mesons result in the accompanying gamma rays of similar energies. The $\sim(100\ldots1000)$ TeV photons efficiently produce $e^{\pm}$ pairs on the cosmic microwave background, so the mean free path of these photons does not exceed the size of the Milky Way. Therefore, photons of these energies can reach us only from Galactic sources.

IceCube issues public alerts corresponding to detections of individual muon-track events passing certain criteria since 2017. Most of the alert events have estimated energies between 100 TeV and 1 PeV. The criteria are chosen to maximize the probability that the event is of astrophysical origin. Still, many of them are background atmospheric events. Another window into sub-PeV astrophysics is provided by observations of gamma rays at slightly lower energies in the TeV range. In parallel with pointing observations by atmospheric Cherenkov telescopes, air-shower installations monitor the sky continuously. In particular, HAWC has recently started to issue various public alerts when a significant point-like signal is observed during one dayly passage of the "flare" direction through the HAWC field of view. These alerts are of particular interest because the energies are very close to the band we study here, and a discovery of a flaring Galactic source in this energy range would have important astrophysical consequences.

We report here on the results of 2.5 years of following up the HAWC and IceCube alerts with Carpet–2. The search is based on the set of photon candidate events which are selected as muon-poor air showers. The photon detection efficiency and the angular resolution were determined by the Monte-Carlo simulations. Here, we extend the analysis down to 100 TeV energies because the combined directional and temporal selection reduces efficiently the hadronic background, which otherwise is the main problem in the search for gamma rays with Carpet–2 below 300 TeV. Photon candidate events are selected by their reconstructed number of charged particles, $N_e > 10^{4.2251}(10^{4.6372})$ for $E > 100\,(300)$ TeV, and the number of muons in the 175 m^2 muon detector, n_μ. It was found optimal to consider only muonless events, $n_\mu = 0$, for these energies, though at higher energies the cut was determined in terms of the ratio n_μ/N_e. For $E > 100\,(300)$ TeV photon candidate samples, the number of events is 1021 (598) and the efficiency of the gamma-ray selection cuts is 0.995 (0.509). These can-

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didates were selected from 52791 air showers, recorded between April 8, 2018, and October 26, 2020 (675 live days), succesfully reconstructed and passing the quality cuts.

Carpet–2 dataset consists of events being observed with zenith angles up to 40°, but the efficiency decreases fastly for inclined showers. We select the alerts with declinations between +5° and +76° so that the maximal elevation corresponds to a zenith angle not exceeding 35°. In addition, we drop the events arrived at the days when our data were not recorded because of maintenance. In this way we arrive to the list of 9 HAWC alerts and 22 IceCube alerts.

Most of the alert directions, however, were outside the Carpet–2 field of view at the moment of the event, but they passed through the field of view during the day. We therefore determine time windows of 24 h and of 30 days, centered at the event moment, to search for coinciding gamma-ray candidates. The angular window was set to the 90 % CL angular resolution, which at these energies is about 6.15°. The expected number of candidate events was calculated by randomizing arrival times of photon candidates in the sample.

For each particular alert we determined the expected and observed numbers of the events, the estimated flux within the selected time window and the fluence. No significant excess of photon candidates was found, and we present 95 % CL upper limits on the flux and fluence. These limits vary strongly from one alert to another because of the strong dependence of the reconstruction efficiency for photons on the zenith angle. In all cases we are close to the "zero signal, zero background" regime which motivates us to use stacking to improve sensitivity, and stacked results for all HAWC alerts and all IceCube alerts are also obtained.

A weak, two-sigma excess, 8 events observed for 4.25 expected, is found at $E > 100$ TeV for stacked IceCube events, dominated by the 200911A alert. This excess is consistent with expected fluctuations, given multiple trials.

Directions of two IceCube events, 190331A and 191215A, were in the Carpet–2 field of view at the moment of neutrino arrivals, which allows us to estimate directly their fluence assuming a fast flare. We use the time window of 1000 s for these two alerts. For good viewing conditions, that is small zenith angles, the effective area of Carpet–2 in the configuration used for the photon search in the present analysis is of the same order as the effective area of IceCube for neutrinos of similar energies, see Fig. 1. Therefore, the fluence upper limits of order $\lesssim 1$ GeV/cm^2 start to constrain the origin of neutrinos in fast flares of Galactic sources. Assuming flares longer than a few hours, we obtain less constraining limits because the arrival direction of the alert event leaves the field of view of Carpet–2. All HAWC alerts happen outside of the Carpet–2 field of view because of the difference in geographical longuitudes of the two installations.

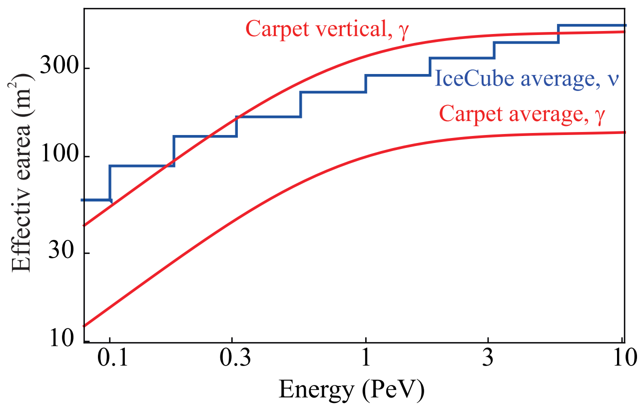

Fig. 1. (Color online) Comparison of effective areas of Carpet–2 (red continuous lines, photon detection, present analysis) and IceCube (blue step line, neutrino detection, muon tracks, average over the Northern hemisphere). For Carpet–2, the full line gives the average over the field of view while the dashed line corresponds to vertical events

The program of multimessenger observations with Carpet–2 continues. Besides HAWC and IceCube alerts, it includes also LIGO/VIRGO alerts and low-energy neutrino burst alerts from the Baksan Underground Scintillator Telescope. Soon, when Baikal-GVD high-energy neutrino alerts become available, they will join the list. At the same time, the upgrade of the installation to Carpet–3 is ongoing with an order of magnitude increase in the collection area and more than a twofold increase in the area of the muon detector. This will allow to reach the sensitivity in the sub-PeV gamma rays at the level of the corresponding neutrino sensitivity of IceCube not only for short flares, but also for long-term observations and for the diffuse flux.

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