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H.E.S.S. realtime follow-ups of IceCube high-energy neutrino alerts

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The evidence for multi-messenger photon and neutrino emission from the blazar TXS 0506+056 has demonstrated the importance of realtime follow-up of neutrino events by various ground- and space-based facilities. The effort of H.E.S.S. and other experiments in coordinating observations to obtain quasi-simultaneous multiwavelength flux and spectrum measurements has been critical in measuring the chance coincidence with the high-energy neutrino event IC-170922A and constraining theoretical models. For about a decade, the H.E.S.S. transient program has included a search for gamma-ray emission associated with high-energy neutrino alerts, looking for gamma-ray activity from known sources and newly detected emitters consistent with the neutrino location. In this contribution, we present an overview of follow-up activities for realtime neutrino alerts with H.E.S.S. in 2021 and 2022. Our analysis includes both public IceCube neutrino alerts and alerts exchanged as part of a joint H.E.S.S.–IceCube program. We focus on interesting coincidences observed with gamma-ray sources, particularly highlighting the significant detection of PKS 0625-35, an AGN previously detected by H.E.S.S., and three IceCube neutrinos.

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1. Introduction

The IceCube Neutrino Observatory in Antarctica discovered an astrophysical flux of high-energy neutrinos in 2013 [1], prompting a search for their sources. Despite the strong evidence of TeV neutrino emissions from the active galaxy NGC 1068 [2], the majority of the sources remain unidentified due to the limited angular resolution of neutrino detectors, the background noise from atmospheric neutrinos, and the low signal statistics (~10/year). To overcome these challenges, a multi-messenger approach combining observations in different wavelengths and astrophysical messengers is employed. Very-high-energy (VHE, $E > 100\,\mathrm{GeV}$) gamma rays are particularly promising in identifying neutrino sources, as they are produced alongside neutrinos through cosmic-ray interactions. Unlike neutrinos, gamma rays can be absorbed or scattered during their journey through the source region and extragalactic space. However, their detection or non-detection consistent with high-energy neutrinos provides valuable information about the distances and environments of the sources. Notably, the identification of the flaring gamma-ray blazar TXS 0506+056 coincident with a single, highly energetic neutrino in 2017 demonstrated the effectiveness of the multi-messenger approach [3]. In this contribution, the follow-up strategy of the H.E.S.S. imaging atmospheric Cherenkov Telescope (IACT) array to real-time neutrino alerts is presented, along with a summary of results from November 2021 to the end of 2022. Our analysis includes both public IceCube neutrino alerts and alerts exchanged as part of a joint H.E.S.S.-IceCube program.

2. H.E.S.S. neutrino follow-up program

H.E.S.S. is an array consisting of one 28 m and four 12 m IACTs, located in the Khomas Highland of Namibia, at an elevation of 1800 m above sea level, with a field-of-view (FoV) of 5° in diameter [4]. The H.E.S.S. observatory has been engaged in a neutrino Target of Opportunity (ToO) program since 2012, aimed at investigating potential correlations between neutrino and VHE gamma-ray emission. Initially triggered by real-time alerts from the ANTARES neutrino telescope, H.E.S.S. later joined the IceCube Realtime Alert Stream [5] and IceCube's Gamma-ray Follow-Up (GFU) program [6]. H.E.S.S. dedicates approximately 20 hours of observation time per year to deep investigations of intriguing neutrino events, with the goal of detecting VHE gamma-ray emissions. In case of detection, longer and deeper follow-up observations are triggered to perform source characterization [7].

This contribution presents the follow-up of six neutrino alerts received through IceCube's singlet alert stream and the GFU program, with singlet alerts comprising high-energy single events of likely astrophysical origin, categorized into *gold* and *bronze* alerts based on their signalness[1] probability [8]. Events with an average signalness value above 50% are flagged and distributed as *gold* alerts, while those with an average signalness value between 30% and 50% are categorized as *bronze* alerts. These events are broadcast by IceCube in realtime with a typical latency of ~30 s, and have a localization uncertainty of $\sim 1°$, matching a typical IACT field of view of $3.5 - 5°$. The GFU alerts, emitted when clusters of neutrino events around a priori defined list of sources surpass predefined significance thresholds, are accessible to H.E.S.S. through a Memorandum of

[1]Probability that this is an astrophysical signal relative to backgrounds, assuming the best-fit diffuse muon neutrino astrophysical power-law flux $E^{2.19}$

Understanding (MoU), allowing for fully automated follow-up observations via a VOEvent-based alert stream [9]. Without prior identification of promising source candidates (e.g., using the *Fermi*-LAT and IACT catalogs), the searches typically encompass the entire region of interest (ROI) defined by the uncertainty in neutrino localization. If the external conditions permit, such as receiving the alert during a dark night when the source is visible and the weather is favorable, an automatic re-pointing procedure is initiated by the telescopes, enabling immediate observation of the alert. Otherwise, observations usually occur within the next few days, once these conditions are met. As a result, the response time varies for each individual alert, with the fastest recorded at less than 70 seconds.

The H.E.S.S. data presented in this contribution were analyzed using the method described in [10] with estimated gamma-hadron separation and event selection cuts. The background was determined using the standard "reflected background" technique [11]. The results were validated by a cross-check analysis which uses an independent event calibration and reconstruction [12]. The flux upper limit calculation is performed using the Rolke method and assuming a power-law spectrum with a photon index of 2.0 [13]. The minimum energy is chosen as the energy where the effective area reaches 10% of its maximum value, while the maximum energy is determined by the last energy bin used in the spectrum, where the number of background events is $N_{\mathrm{OFF}} \geq 10$..

3. Multiwavelength observations

For follow-up observations triggered by the GFU stream or the identification of potential counterparts in single alerts, we conducted multiwavelength analyses using data from the *Fermi*-Large Area Telescope (LAT), the X-Ray Telescope on the Neil Gehrels Swift Observatory (*Swift*-XRT), and the Automatic Telescope for Optical Monitoring (ATOM). Our analysis of *Fermi*-LAT data involved a binned likelihood analysis using `Fermipy` (v.1.2.0) [14]. We utilized the `P8R3_SOURCE` event class and corresponding instrument response functions[2], selecting events in the energy range of 100 MeV to 300 GeV within 15° of the neutrino position and applying a zenith angle cut of 90°. The `PowerLaw` model[3] was used for the gamma-ray spectrum, with Galactic and isotropic templates for the background[4], and all catalog sources within 25° of the neutrino position were included [15]. Each analysis covered a two-day time-scale, spanning a day before and after the arrival time of the neutrino events, in order to be sensitive to the detection of fast, bright transients, even down to durations of a few hours. No significant emission from the neutrino events was observed in the *Fermi*-LAT data during the two-day time-scale that included the H.E.S.S. observations, resulting in the computation of 95% C.L. upper limits assuming an E^{-2} spectrum for the differential energy flux between 100 MeV and 300 GeV.

We conducted X-ray analysis using data from *Swift*-XRT [16]. The analysis was performed using version 6.29 of the HEASOFT software [17], with data collected around the time of the neutrino ToO observations. The data utilized and the results of the analysis integrated in the 0.3-10 keV energy range are presented in Table 1.

[2] https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_LAT_IRFs/IRF_overview.html

[3] https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/source_models.html

[4] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

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Neutrino ToO	Source	Obs. IDS	Photon Index	Energy Flux (unabs.) $\times 10^{-12}$ erg cm^{-2} s^{-1}	Galactic Column Density $\times 10^{20}$ cm^{-2}
GFU PKS 0625-35	PKS 0625-35	00039136003-00039136004	$2.19^{0.19}_{-0.18}$	$10.7^{+1.27}_{-1.00}$	7.9
IC-211125A	4FGL J0258.1+2030	00041549003	$1.60^{0.70}_{-0.50}$	$1.80^{0.80}_{-0.50}$	24.0
GFU PKS 0829+046	PKS 0829+046	00038144014	$1.87^{0.33}_{-0.30}$	$2.30^{0.40}_{-0.30}$	2.70
GFU 1ES 0229+200	1ES 0229+200	00031249115	$1.83^{0.18}_{-0.17}$	$17.96^{0.16}_{-0.15}$	12

Table 1: *Swift*-XRT data analysis parameters. The unabsorbed energy flux is obtained by integrating over the full energy range 0.3-10 keV, correcting for the Galactic column density value [19].

Optical data in the B, V, R, and I bands (440 nm, 550 nm, 640 nm, and 790 nm, respectively) were obtained using the 75 cm ATOM telescope located at the H.E.S.S. site in Namibia [18]. The ATOM data analyzed in this study corresponds to observation times that coincide with the H.E.S.S. ToO observations. Energy fluxes for candidate sources were derived for four neutrino follow-ups.

4. Results

4.1 GFU PKS 0625-35

On April 16, 2022, IceCube detected a neutrino flare originating from the blazar PKS 0625-35. The detection pre-trial significance was 3.56σ, with a false alarm rate of 0.003 per year. The three neutrinos were detected within an energy range of 63 TeV to 302 TeV. Given that the source had been previously observed by H.E.S.S. [20], a ToO observation was initiated on the night of April 19th, 2022 centered on the coordinates of the previous detection: RA: 6h26m58s, Dec: -35d29m50s. The observations lasted for three nights, resulting in approximately three hours of data. The source was detected in both H.E.S.S. chain analyses, with a significance of 3.5σ. The data was fitted with a power-law function, yielding a spectral index of 2.45 ± 0.42 in the energy range 0.35 to 6.58 TeV. The resulting spectral point is illustrated in Figure 1, alongside the H.E.S.S. flux points from the source's previous observation in 2018. During the same ToO, the source was also observed in optical and X-ray wavelengths. By comparing the flux distribution in April 2022 with archival data[5] and the H.E.S.S. data from 2018, it becomes evident that there was no variation in the shape of the spectral energy distribution (SED), implying no association with the neutrino flare.

4.2 IC-211125A

On November 25, 2021, IceCube reported the detection of a *bronze* track-like event with a 39% probability of having an astrophysical origin and a false alarm rate of 1.973 events per year due to atmospheric backgrounds [21]. Two sources in the ROI were identified as potential counterparts to the neutrino event: the bright optical transient AT2021afpi, which was detected by MASTER [22] and classified as a classical nova [23], and the AGN *Fermi*-LAT source 4FGL J0258.1+2030. During the first night of observations on November 29th, 2021 H.E.S.S. pointed at the position of the Nova source with a 0.5° "wobble" offset[6]. In the following four nights, a manual pointing pattern without wobble offsets was defined to cover both sources. However, due to bad weather conditions and resulting unstable trigger rates, only ~ 5 hours of observations were analyzed. Upper limits

[5] https://tools.ssdc.asi.it/SED/

[6] In wobble observation mode the source direction has an offset in declination with respect to the camera center.

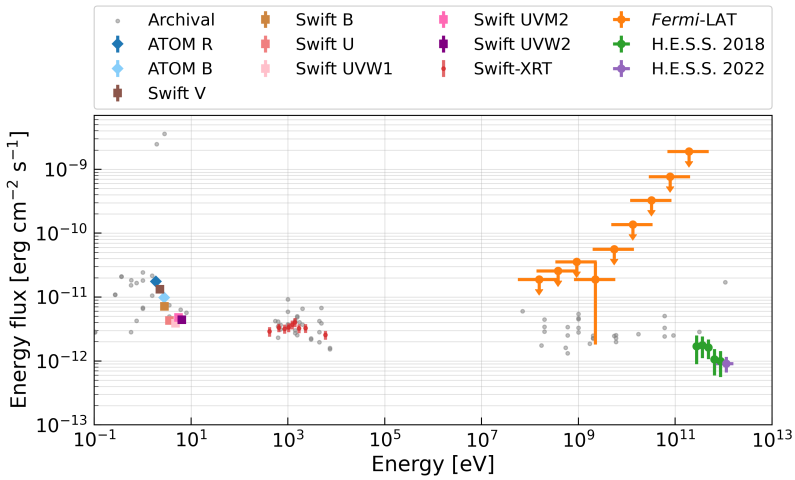
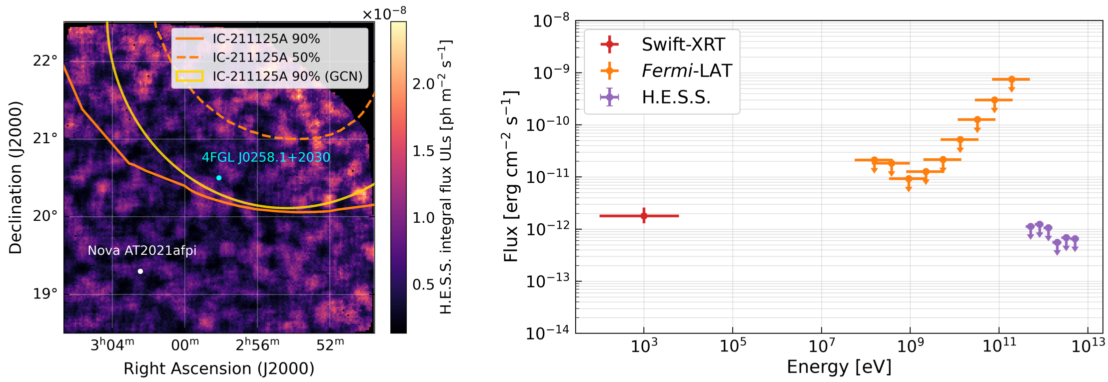


Figure 1: SED of the blazar PKS 0625-35 using data from H.E.S.S., *Fermi*-LAT, *Swift*-XRT, and ATOM. Archival data is displayed in gray.



(a) IC-211125A UL map

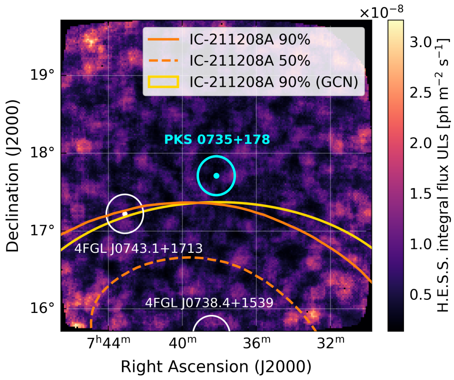
(b) IC-211125A SED

Figure 2: **(a)**: IC-211125A integral upper limits map of H.E.S.S. observations at 95% C.L. **(b)**: SED of the candidate source 4FGL J0258.1+2030 with *Fermi*-LAT upper limits and *Swift*-XRT data.

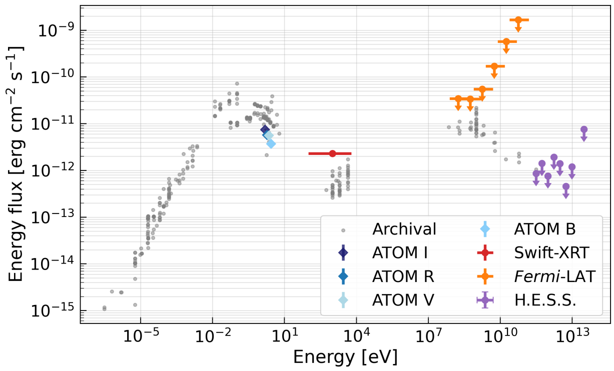
were then computed in the energy range between 0.42 and 100 TeV centered on the AGN position, as shown in Figure 2a. The yellow circle represents the first 90% error on the neutrino position, while the updated contours provided by IceCube are depicted as orange circles. The updated contours are calculated offline based on more sophisticated reconstruction algorithms. Notably, the Nova source lies outside the 90% IceCube contours. The minimum energy at the Nova position is 0.46 TeV. Additionally, both *Fermi*-LAT and *Swift*-XRT conducted observations during the neutrino alert, and a SED was generated on the 4FGL J0258.1+2030 source position (see Figure 2b).

4.3 IC-211208A

On December 8, 2021, IceCube reported the detection of a track-like neutrino event classified as a *bronze* alert with a 50.2% probability of being astrophysical in origin [24]. Three potential AGN gamma-ray counterparts were identified: 4FGL J0738.4+1539, 4FGL J0743.1+1713, and PKS 0735+178 (redshift $z = 0.45$). Multiwavelength observations revealed that the gamma-ray blazar



(a) IC-211208A



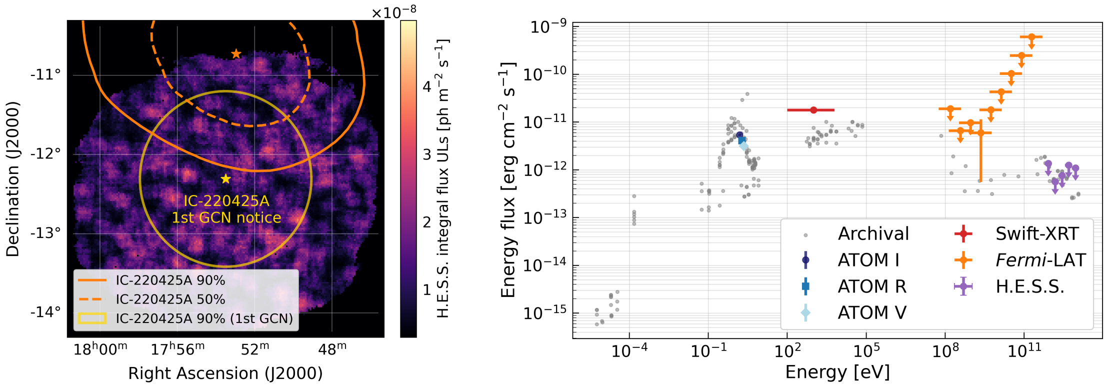
(b) GFU PKS 0829+046

Figure 3: (**a**): IC-211208A integral upper limits map of H.E.S.S. observations at 95% C.L. (**b**): SED of the PKS 0829+046 using data from H.E.S.S., *Fermi*-LAT, *Swift*-XRT, and ATOM. Archival data are displayed in gray.

PKS 0735+178 was in flaring state in the radio, optical, X-ray, and GeV gamma-ray band [25]. As depicted in Figure 3a, PKS 0735+178 was located just outside the 90% error region of the neutrino event, ∼2.0° away from the best-fit position. H.E.S.S. observed the direction of PKS 0735+178 for a total of 16 hours from December 8 to 15, 2021, at an average zenith angle of 42.2° above 0.1 TeV energy. 3.8 hours of data were selected based on strict criteria for weather conditions and instrumental status. Observations were performed in wobble mode at an offset from the center of the camera of 0.5° [4]. A circular ROI of 0.1° centered on the position of PKS 0735+178 was defined, and two regions of 0.25° radius around the nearby sources 4FGL J0738.4+1539 and 4FGL J0743.1+1713 were excluded from the background estimation. No significant gamma-ray excess above the expected background was detected from the direction of PKS 0735+178. Therefore, integral flux upper limits at 95% C.L. in the energy range between 0.4 TeV and 100 TeV in the full field of view (FoV) were calculated (see Figure 3a). A complete SED of this source during IC-211208A alert is given in [25].

4.4 GFU PKS 0829+046

PKS 0829+046 is a BL Lac type object located at RA: 08h 31m 48.88s, Dec: +04° 29' 39.09". The neutrino flare occurred on December 22nd, 2021, lasting ∼7.9 days. It had a pre-trial significance just above the trigger threshold (3.03σ) and a false alert rate of 0.055/year. The flare consisted of 8 events, with the most energetic event having an energy of 2 TeV. Observations by H.E.S.S. were conducted for two nights starting on December 30th, 2021, resulting in ∼4.7 hours of data. In contrast to the other analyses, the *loose cuts* configuration [10] has been employed in this particular case. However, the source was not detected at VHE, and an upper limit on the integral flux was computed above an energy threshold of 224 GeV. Similarly, the *Fermi*-LAT telescope did not detect the source. Nevertheless, during the IceCube alert, the source was detected in the optical band by ATOM and in the X-ray band by *Swift*-XRT. The flux and upper limit data points are presented in Figure 3b. Comparisons with archival data reveal no significant variation in the SED associated with the neutrino flare.



(a) IC-220425A **(b)** GFU 1ES0229+200

Figure 4: **(a)**: IC-220425A integral upper limits map between 0.37 TeV and 100 TeV at a 95% C.L. **(b)**: SED of the HBL GFU 1ES0229+200 using data from H.E.S.S., *Fermi*-LAT, *Swift*-XRT, and ATOM. Archival data is displayed in gray.

4.5 IC-220425A

The *gold* alert IC-20220425A was observed on April 25, 2022 and reported with a signalness of 17% [26]. The H.E.S.S. observation was triggered automatically within less than 70 seconds from the neutrino detection, resulting in 75 minutes observations under moonlight conditions. Due to lack of detection, 95% C.L. integral upper limits were calculated between 0.37 TeV and 100 TeV and using ad-hoc simulations of the instrument response to take into account moonlight condition [27]. As depicted in Figure 4a, the updated neutrino position was refined offline, causing the H.E.S.S. observation to fall outside the 90% neutrino error region. The *Fermi*-LAT analysis revealed no evidence of potential high-energy gamma-ray counterparts.

4.6 GFU 1ES0229+200

1ES0229+200 is a high-frequency peaked BL Lac (HBL) located at RA: 02h 32m 49s, Dec: +20d 17m 1s [28]. On August 25th, 2022, IceCube detected a short neutrino flare from this source, lasting 1.2 days. The flare had a pre-trial significance of 3.09σ and a false alert rate of 0.050/year. Only 4 neutrino events were detected, with the most energetic event having an energy of 1.3 TeV. Observations by H.E.S.S. were carried out over five nights starting on August 27th, 2022, resulting in approximately 13.5 hours of data. However, the observations were affected by unstable weather conditions and only ~8 hours are passing quality criteria. During the neutrino alert, the source was observed in the optical band by ATOM, in the X-ray band by *Swift*-XRT, and in the high-energy gamma-ray band by *Fermi*-LAT. The flux and upper limit data points are presented in Figure 4b. Comparisons with archival data reveal no significant variation in the spectral distribution associated with the neutrino flare.

5. Conclusions

We presented the follow-up strategy of H.E.S.S. to real-time neutrino alerts and summarized the search for gamma-ray emission from November 2021 to the end of 2022. While no significant gamma-ray excess was detected in the specific events studied, except for the blazar PKS 0625-35, the program contributed valuable insights into the search for neutrino sources and demonstrated the importance of multi-messenger observations in understanding high-energy astrophysical phenomena.

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