Joint searches by FACT, H.E.S.S., MAGIC and VERITAS for VHE gamma-ray emission associated with neutrinos detected by IceCube

Fabian Schüssler, a,∗ H. Ashkar, b E. Bernardini, c A. Berti, d F. Bradascio, a S. Buson, e D. Dorner, e,f W. Jin, g G. Kukec Mezek, h M. Santander, g K. Satalecka, i B. Schleicher, e,f M. Senniappan h and I. Viale c on behalf of the FACT, Fermi-LAT, H.E.S.S., IceCube, MAGIC and VERITAS collaborations

aIRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
bLaboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS, Institut Polytechnique de Paris, Palaiseau, France
cDipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Padova, Italy, Padova, Italy
dMax-Planck-Institut für Physik, München, München, Germany
eJulius-Maximilians-Universität Würzburg, Fakultät für Physik und Astronomie, Institut für Theoretische Physik und Astrophysik, Lehrstuhl für Astronomie, Emil-Fischer-Str. 31, D-97074 Würzburg, Germany
fETH Zurich, Institute for Particle Physics and Astrophysics, Otto-Stern-Weg 5, 8093 Zürich, Switzerland
gDepartment of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama, USA
hDepartment of Physics and Electrical Engineering, Linnaeus University, Växjö, Sweden
iDeutsches Elektronen-Synchrotron (DESY), Zeuthen, Germany

E-mail: fabian.schussler@cea.fr

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Joint IACT observations of neutrinos detected by IceCube

Fabian Schüssler

The sources of the astrophysical flux of high-energy neutrinos detected by IceCube are still largely unknown, but searches for temporal and spatial correlation between neutrinos and electromagnetic radiation are a promising approach in this endeavor. All major imaging atmospheric Cherenkov telescopes (IACTs) - FACT, H.E.S.S., MAGIC, and VERITAS - operate an active follow-up program of target-of-opportunity observations of neutrino alerts issued by IceCube. These programs use several complementary neutrino alert streams. A publicly distributed alert stream is formed by individual high-energy neutrino candidate events of potentially astrophysical origin, such as IceCube-170922A (which could be linked to the flaring blazar TXS 0506+056). A privately distributed alert stream is formed by clusters of neutrino events in time and space around either pre-selected gamma-ray sources or anywhere in the sky. Here, we present joint searches for multi-wavelength emission associated with a set of IceCube alerts, both private and public, received through mid-January 2021. We will give an overview of the programs of the participating IACTs. We will showcase the various follow-up and data analysis strategies employed in response to the different alert types and various possible counterpart scenarios. Finally, we will present results from a combined analysis of the VHE gamma-ray observations obtained across all involved instruments, as well as relevant multi-wavelength data.
1. Introduction

All currently operating imaging atmospheric Cherenkov telescopes (IACTs): FACT [1], H.E.S.S. [2], MAGIC [3] and VERITAS [4] operate observational programs in cooperation with IceCube. These target-of-opportunity (ToO) follow-up observations aim at identifying potential gamma-ray emission associated to the detected neutrino events. The programs can be broadly divided into two categories, depending on the type of IceCube neutrino alert that triggered the ToO observations. The first involves following up on individual high-energy (>60 TeV) neutrino events that are likely of astrophysical origin, referred to as "singlets." These singlets are openly broadcasted by IceCube through AMON [5] via the NASA’s General Coordinates Network (GCN) on two streams, “GOLD” and “BRONZE”, with an average astrophysical probability per event of 50% and 30%, respectively. IceCube has recently released a catalog of singlets of likely astrophysical origin up to December 2020 [6]. The second type involves conducting follow-up observations of known gamma-ray sources for which IceCube has detected a cluster of candidate neutrino events, typically with energies around ∼1 TeV, over a specific time period, known as "multiplets." These alerts are privately distributed by IceCube to individual IACTs under mutual agreements in the framework of the Gamma-ray Follow-Up (GFU) program [7].

Single-event alerts have a typical localization uncertainty of approximately 1°. This aligns well with the standard field of view (FOV) of imaging atmospheric Cherenkov telescopes (IACTs), which ranges from 3.5 to 5°. Often, potential neutrino source candidates can be found within the region of interest (ROI) defined by the uncertainty of the neutrino localization. These candidates may include previously identified objects such as active galactic nuclei (AGN) like TXS 0506+056 from the Fermi-LAT and IACT catalogs, or transient sources detected by other electromagnetic (EM) observatories. In such cases, observations are typically focused on these objects. However, in the absence of pre-identified promising candidates, the searches generally aim to cover the entire ROI indicated by the neutrino localization uncertainty.

On the other hand, the primary objective of the GFU multiplet alerts is to notify the IACTs of neutrino flares from the direction of known gamma-ray emitters. The duration of these flares is not predetermined and can span from seconds to 180 days. Since the associated source of the alert is already known and identified as a GeV and/or TeV emitter, the IACT observations aim to determine possible changes to the state of the source (e.g., quiescence vs. flaring or spectral changes). In its current configuration, a GFU multiplet alert is sent to the participating IACT if the statistical significance of the identified neutrino excess is greater than a predefined threshold, typically 3σ before accounting for statistical trials.

The directions of the alerts sent by IceCube as neutrino event “singlets” and GFU neutrino flares between October 2017 and January 2021 are illustrated on a skymap in Figure 1. In the covered time period, the IACTs observed 11 of the 62 single-event alerts sent by IceCube. In the framework of the GFU program, IceCube sent 27 neutrino flare alerts from 17 sources, of which seven, including one “all-sky alert”, were observed. Here, we do not attempt to report a comprehensive summary of these alerts and follow-up observations, but rather will present a few examples and highlights to illustrate the various programs.

1https://gcn.nasa.gov/
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Figure 1: Sky map in equatorial coordinates showing IceCube alert positions observed by IACTs between October 2017 and January 2021 (in color, according to the alert type), and those not followed-up during the same period shown in gray. Letters indicate which IACTs participated in the observations (F - FACT, H - H.E.S.S., M - MAGIC, V - VERITAS). Light cyan and magenta bands indicate regions of the sky potentially observable at a zenith distance below 45° from the Northern (FACT, MAGIC, VERITAS) and Southern (H.E.S.S.) IACTs, respectively. The visibility windows for instruments in both hemispheres overlap around the celestial equator, where the IceCube sensitivity to neutrinos in the ∼ 100 TeV-energy-range is maximal.

2. Follow-up of neutrino multiplets: 1ES 1312-423

The blazar known as 1ES 1312-423, located approximately 2 degrees away from the Centaurus A (CenA) radio galaxy, has a redshift of $z = 0.105 \pm 0.001$ [8]. Between April 2004 and July 2010, it has been observed by H.E.S.S. as part of the deep observation of Cen A, collecting a total exposure time of 150.6 h centered on CenA. This archival dataset revealed a power-law fit to the differential energy spectrum $\phi(E) = dN/dE$ of the VHE gamma-ray emission above 280 GeV. The best-fitting parameters obtained were $\Gamma = 2.85 \pm 0.47$ (stat) $\pm 0.20$ (sys) for the spectral index and a differential flux at 1 TeV of $\phi(1 \text{ TeV}) = (1.89 \pm 0.58$ (stat) $\pm 0.39$ (sys)) $\times 10^{-13}$ cm$^{-2}$ s$^{-1}$ TeV$^{-1}$ [9].

Due to its Southern location 1ES 1312-423 is only part of the H.E.S.S. GFU program. On March 12, 2019, IceCube reported the detection of a short neutrino flare lasting 6.24 h from this source. H.E.S.S. conducted observations of the source for a total of 2.6 h over two nights on March 12 and 13, 2019. 1ES 1312-423 was detected above 140 GeV with a significance of 4$\sigma$. This is the only detection of VHE gamma rays in any of the ToO campaigns conducted by the IACTs in the time period covered here. Again applying a power-law fit, the best-fit parameters $\Gamma = 2.73 \pm 0.27$ (stat) $\pm 0.20$ (sys) for the spectral index and $\phi(1 \text{ TeV}) = (5.83 \pm 3.2$ (stat) $\pm 0.4$ (sys)) $\times 10^{-12}$ cm$^{-2}$ s$^{-1}$ TeV$^{-1}$ for the differential flux at 1 TeV were obtained. A comparison of the spectral energy distribution (SED) with the archival dataset is shown in Figure 2, along with the results obtained from dedicated observations by Swift (UV + X-rays) and ATOM (optical). Although some variations are observed in the X-ray and UV domains, no clear change in the state of 1ES 1312-423 could be identified in this neutrino-triggered ToO.
3. Follow-up of neutrino singlets: IceCube-201114A + IceCube-171106A

IceCube reported the detection of a track-like neutrino event classified as a GOLD alert on November 14th, 2020. The event had an energy of 214 TeV and a probability to be of astrophysical origin of 0.56. Its false alert rate was determined to be 0.92 per year. The refined direction of the alert was determined to be RA: 105.25° (+1.28°, −1.12°, 90% PSF containment) and Dec: 6.05° (+0.95° −0.95°, 90% PSF containment). The position of the neutrino event is compatible with the blazar NVSS J065844+063711, also known as the Fermi source 4FGL J0658.6+0636 (RA: 104.64°, Dec: 6.60°). A map of the region is shown in Figure 5.

The event was observed by H.E.S.S., MAGIC, and VERITAS. H.E.S.S. collected 14.3 hours of data during an observation campaign conducted from November 18th to November 25th, 2020, and from December 10th, 2020, to December 11th, 2020. No significant emission was detected in the ROI, and integral upper limits on the VHE gamma-ray flux were derived at the position of NVSS J065844+063711 as \(5.37 \times 10^{-13} \text{ cm}^{-2} \text{s}^{-1}\) above 326 GeV. The MAGIC telescopes observed the direction of NVSS J065844+063711 on November 16th, 17th, and from November 19th to 25th, 2020. The 6h of data did not result in a detection. The integral flux upper limit was calculated above an energy threshold of 120 GeV to be \(8.39 \times 10^{-10} \text{ cm}^{-2} \text{s}^{-1}\). VERITAS conducted observations from November 15th to November 19th, 2020, collecting approximately 7 hours of quality-selected observation data. No detection was made at the location indicated by the IceCube neutrino event or elsewhere in the VERITAS field of view. The integral flux upper limit above an energy threshold of 200 GeV at the position of the blazar NVSS J065844+063711 was determined to be \(1.37 \times 10^{-12} \text{ cm}^{-2} \text{s}^{-1}\).

The profile maximum likelihood approach described in [10] is employed to generate combined flux upper limits across all IACTs. For this purpose, all collaborations utilized the same energy binning, dividing the VHE range between 71 GeV and 71 TeV into four bins per decade. We used the Rolke method [11] with a confidence level set to 95%, and including a 30% global systematic uncertainty in the efficiency of the applied cuts. Upper limits were calculated considering an
observed spectrum modeled by a power law $\frac{dN}{dE} = KE^{-\Gamma}$ with index $\Gamma = 2.5$. The individual as well the combined upper limits at the position of of the blazar NVSS J065844+063711 are shown in Figure 3.

Complementing the VHE gamma-ray observations, Swift-XRT observations were triggered on November 15th, 2020. They revealed a slight increase in the X-ray flux around the time of the neutrino emission compared to previous observations in May 2012. The X-ray flux level remained relatively consistent until December 11th, 2020. A full MWL SED is shown in Figure 4.

Single-event public IceCube alerts are characterized by relatively large localization errors ($\sim 0.5$ degree to a few degrees at 50% confidence level). As a consequence, the exact localization of the neutrino origin can not be pin-pointed to any point-source with high accuracy. Therefore, we derive sky maps containing the integral gamma-ray flux upper limits and covering the neutrino arrival localization uncertainty. Dedicated searches for a variety of possible source candidates in this region are thus possible. Examples for these upper limit maps are given in Figure 5 and Figure 6. The latter has been derived above an energy threshold of 350 GeV from about 2.5 hours of quality-selected observation data taken by VERITAS between November 13 to November 20, 2017. This ToO, that was also followed by MAGIC and FACT, was triggered following the detection of IceCube-171106A on November 6th, 2017, an event with an energy of 230 TeV and a signalness indicating the probability of the event to be of astrophysical origin of 75%.

### 4. Conclusions

Figure 7 shows the delay and exposure of the IACT observations of single-event alerts and GFU neutrino flares between October 2017 and January 2021. The delay is derived from the detection time of the neutrino event (for single events) or the threshold crossing time of the flare (for multiplets) up to the start of IACT observation.

From this overview, several general trends in the follow-up strategies can be inferred. Approximately 50% of the cases achieve a reaction within one day, while observations conducted more than one week after the trigger are rare. The total time allocated to the follow-up of public IceCube alerts is comparable across all collaborations, amounting to approximately 20 hours for the covered
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Figure 5: Integral upper limits on the VHE gamma-ray flux above 307 GeV derived from the H.E.S.S. observations of IceCube-201114A. The observations were centered around the location of NVSS J065844+063711, indicated by the green star. The grey lines denote the 50% (90%) contours of the localization of the event by IceCube.

Figure 6: Map of integral upper limits of the VHE gamma-ray flux derived from the VERITAS observations of IceCube-171106A above an energy threshold of 350 GeV. The dashed lines denote the 50% (90%) contours of the localization of the event by IceCube.

period. However, there are differences in the approaches taken. H.E.S.S., and VERITAS primarily focus on longer exposures for a few selected alerts, whereas MAGIC conducts a larger number of follow-ups with shorter average exposure. Similar trends are observed for GFU neutrino alerts.

The geographic distribution of the IACTs in terms of latitude has facilitated complete coverage of the entire sky, encompassing both the Northern and Southern hemispheres. Moreover, the observatories’ locations in longitude have expanded the field of regard of the combined network of IACTs, thereby increasing the likelihood of promptly conducting follow-up observations. This is particularly crucial in cases where observability from a single observatory site is restricted due to factors such as adverse weather conditions, the presence of the sun or moon, or technical issues. This aspect holds significant importance, as it enables the observation of VHE gamma rays associated with rare transient neutrino candidate events. It also allows for the exploration of other time-domain or multi-messenger triggers, as exemplified by follow-up observations of gravitational wave events (e.g., GW170817A) or gamma-ray bursts (e.g., VHE-detected GRBs and GRB 221009A). These examples underscore the value of conducting joint analyses, as presented here, to fully leverage the capabilities and strengths of the collective observatory network.

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Figure 7: Delay vs exposure times for IACT follow-up of neutrino alerts from October 2017 until December 2020. The delay is calculated from the neutrino event arrival time (single events) or flare threshold crossing time (multiplets) up to the start of the IACT observation. Highlighted are observations performed with a start delay less than 100s or with a total exposure longer than 4h. Marker color represents the IACT observing while the marker type represents the alert type.


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Full Author List: FACT Collaboration

J. Abhir 1, D. Baack 2, M. Balbo 3, A. Biland 1, K. Brand 4, T. Bretz 1 a, J. Buss 2, D. Dorner 1,4, L. Eisenberger 4, D. Elsaesser 2, P. Günther 4, D. Hildebrand 1, K. Mannheim 4, M. Noethe 2, A. Paravac 4, W. Rhode 2, B. Schleicher 1,4, V. Sliusar 3, S. Hasan 1, R. Walter 3

1 ETH Zurich, Institute for Particle Physics and Astrophysics, Otto-Stern-Weg 5, 8093 Zürich, Switzerland
2 TU Dortmund, Experimental Physics 5, Otto-Hahn-Str. 4a, 44227 Dortmund, Germany
3 University of Geneva, Department of Astronomy, Chemin d’Ecogia 16, 1290 Versoix, Switzerland
4 Julius-Maximilians-Universität Würzburg, Fakultät für Physik und Astronomie, Institut für Theoretische Physik und Astrophysik, Lehrstuhl für Astronomie, Emil-Fischer-Str. 31, D-97074 Würzburg, Germany
a also at RWTH Aachen University

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Fabian Schüssler

Montpellier Cedex 5, France

30Aix Marseille Université, CNRS/IN2P3, CPPM, Marseille, France

31Leopold-Franzens-Universität Innsbruck, Institut für Astro- und Teilchenphysik, A-6020 Innsbruck, Austria

32Institute of Astronomy, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziadzka 5, 87-100 Torun, Poland

33Department of Physics, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima-ku, Tokyo 171-8501, Japan

34Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716 Warsaw, Poland

35Department of Physics and Astronomy, The University of Leicester, University Road, Leicester, LE1 7RH, United Kingdom

36GRAPPA, Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands

37Department of Physics, Konan University, 8-9-1 Okamoto, Higashinada, Kobe, Hyogo 658-8501, Japan

38Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes for Advanced Study (UTIAS), The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa, Chiba, 277-8583, Japan

39RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

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Full Authors List: MAGIC Collaboration


2 ETH Zürich, CH-8093 Zürich, Switzerland

3 Instituto de Astrofísica de Canarias and Dpto. de Astrofísica, Universidad de La Laguna, E-38200, La Laguna, Tenerife, Spain

4 Instituto de Astrofísica de Andalucía-CSIC, Glorieta de la Astronomía s/n, 18008, Granada, Spain

5 National Institute for Astrophysics (INAF), I-00136 Rome, Italy

6 Università di Udine and INFN Trieste, I-33100 Udine, Italy

7 Max-Planck-Institut für Physik, D-80805 München, Germany

8 Università di Padova and INFN, I-35131 Padova, Italy

9 Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology (BIST), E-08193 Bellaterra (Barcelona), Spain

10 Technische Universität Dortmund, D-44221 Dortmund, Germany

11 Croatian MAGIC Group: University of Zagreb, Faculty of Electrical Engineering and Computing (FER), 10000 Zagreb, Croatia

12 IPARCS Institute and EMFTEL Department, Universidad Complutense de Madrid, E-28040 Madrid, Spain

13 Centro Brasileiro de Pesquisas Físicas (CBPF), 22290-180 URCA, Rio de Janeiro (RJ), Brazil

14 University of Lodz, Faculty of Physics and Applied Informatics, Department of Astrophysics, 90-236 Lodz, Poland

15 Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, E-28040 Madrid, Spain

16 Departament de Física, and CERES-IEEC, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain

17 Università di Pisa and INFN Pisa, I-56126 Pisa, Italy

18 Universitat de Barcelona, ICCUB, IEEC-UB, E-08028 Barcelona, Spain

19 Armenian MAGIC Group: A. Alikhanyan National Science Laboratory, 0036 Yerevan, Armenia

20 Department for Physics and Technology, University of Bergen, Norway

21 INFN MAGIC Group: INFN Sezione di Catania and Dipartimento di Fisica e Astronomia, University of Catania, I-95123 Catania, Italy

22 INFN MAGIC Group: INFN Sezione di Torino and Università degli Studi di Torino, I-10125 Torino, Italy

23 INFN MAGIC Group: INFN Sezione di Bari and Dipartimento Interateneo di Fisica dell’Università e del Politecnico di Bari, I-70125 Bari, Italy

24 Croatian MAGIC Group: University of Rijeka, Faculty of Physics, 51000 Rijeka, Croatia

25 Universität Würzburg, D-97074 Würzburg, Germany

26 University of Geneva, Chemin d’Ecogia 16, CH-1290 Versoix, Switzerland

27 Japanese MAGIC Group: Physics Program, Graduate School of Advanced Science and Engineering, Hiroshima University, 733-8526 Hiroshima, Japan

28 Deutsches Elektronen-Synchrotron (DESY), D-15738 Zeuthen, Germany

29 Armenian MAGIC Group: ICRA.Net-Yerevan, 0019 Yerevan, Armenia
Joint IACT observations of neutrinos detected by IceCube

Fabian Schüssler

30 Croatian MAGIC Group: University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture (FESB), 21000 Split, Croatia
31 Croatian MAGIC Group: Josip Juraj Strossmayer University of Osijek, Department of Physics, 31000 Osijek, Croatia
32 Finnish MAGIC Group: Finnish Centre for Astronomy with ESO, University of Turku, FI-20014 Turku, Finland
33 Japanese MAGIC Group: Department of Physics, Tokai University, Hiratsuka, 259-1292 Kanagawa, Japan
34 Università di Siena and INFN Pisa, I-53100 Siena, Italy
35 Saha Institute of Nuclear Physics, A CI of Homi Bhabha National Institute, Kolkata 700064, West Bengal, India
36 Inst. for Nucl. Research and Nucl. Energy, Bulgarian Academy of Sciences, BG-1784 Sofia, Bulgaria
37 Japanese MAGIC Group: Department of Physics, Yamagata University, Yamagata 990-8560, Japan
38 Finnish MAGIC Group: Space Physics and Astronomy Research Unit, University of Oulu, FI-90014 Oulu, Finland
39 Japanese MAGIC Group: Chiba University, ICEHAP, 263-8522 Chiba, Japan
40 Japanese MAGIC Group: Department of Physics, Kyushu University, 606-8502 Fukuoka, Japan
41 Japanese MAGIC Group: Institute for Space-Earth Environmental Research and Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, 464-8501 Nagoya, Japan
42 Croatian MAGIC Group: Ruđer Bošković Institute, 10000 Zagreb, Croatia
43 INFN MAGIC Group: INFN Sezione di Perugia, I-06123 Perugia, Italy
44 INFN MAGIC Group: INFN Roma Tor Vergata, I-00133 Roma, Italy
45 Japanese MAGIC Group: Department of Physics, Konan University, Kobe, Hyogo 658-8501, Japan
46 also at International Center for Relativistic Astrophysics (ICRA), Rome, Italy
47 now at Institute for Astro- and Particle Physics, University of Innsbruck, A-6020 Innsbruck, Austria
48 also at Port d’Informació Científica (PIC), E-08193 Bellaterra (Barcelona), Spain
49 also at Institute for Astro- and Particle Physics, University of Innsbruck, A-6020 Innsbruck, Austria
50 also at Department of Physics, University of Oslo, Norway
51 also at Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
52 Max-Planck-Institut für Physik, D-80805 München, Germany
53 also at INAF Padova
54 Japanese MAGIC Group: Institute for Cosmic Ray Research (ICRR), The University of Tokyo, Kashiwa, 277-8582 Chiba, Japan
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Fabian Schüssler

Full Author List: VERITAS Collaboration


1Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA
2Physics Department, Columbia University, New York, NY 10027, USA
3Department of Physics and Astronomy, DePauw University, Greencastle, IN 46135-0037, USA
4Department of Physics and Astronomy and the Bartol Research Institute, University of Delaware, Newark, DE 19716, USA
5Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA
6DESY, Platanenallee 6, 15738 Zeuthen, Germany
7Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138, USA
8Physics Department, California Polytechnic State University, San Luis Obispo, CA 93407, USA
9Department of Physics, Washington University, St. Louis, MO 63130, USA
10School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA
11Department of Physics, California State University - East Bay, Hayward, CA 94542, USA
12Santa Cruz Institute for Particle Physics and Department of Physics, University of California, Santa Cruz, CA 95064, USA
13Department of Physics and Astronomy, Dartmouth College, 6127 Wilder Laboratory, Hanover, NH 03755 USA
14Department of Physics, University of Maryland, College Park, MD, USA
15NASA GSFC, Greenbelt, MD 20771, USA
16School of Natural Sciences, University of Galway, University Road, Galway, H91 TK33, Ireland
17Physics Department, McGill University, Montreal, QC H3A 2T8, Canada
18School of Physics, University College Dublin, Belfield, Dublin 4, Ireland
19Department of Physics and Astronomy, University of Iowa, Van Allen Hall, Iowa City, IA 52242, USA
20Department of Physics and Astronomy, Barnard College, Columbia University, NY 10027, USA
21Arthur B. McDonald Canadian Astroparticle Physics Research Institute, 64 Bader Lane, Queen’s University, Kingston, ON Canada, K7L 3N6
22Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA
23Department of Physics, Engineering Physics and Astronomy, Queen’s University, Kingston, ON K7L 3N6, Canada
24Institute of Physics and Astronomy, University of Potsdam, 14476 Potsdam-Golm, Germany
25Department of Physical Sciences, Munster Technological University, Bishopstown, Cork, T12 P928, Ireland
26Department of Physics and Astronomy, Purdue University, West Lafayette, IN 47907, USA
27Department of Physics, Indiana University-Purdue University Indianapolis, Indianapolis, IN 46202, USA
28Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA
29Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA