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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

^a*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*

^b*Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS, Institut Polytechnique de Paris, Palaiseau, France*

^c*Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy, Padova, Italy*

^d*Max-Planck-Institut für Physik, München, München, Germany*

^e*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*

^f*ETH Zurich, Institute for Particle Physics and Astrophysics, Otto-Stern-Weg 5, 8093 Zürich, Switzerland*

^g*Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama, USA*

^h*Department of Physics and Electrical Engineering, Linnaeus University, Växjö, Sweden*

ⁱ*Deutsches Elektronen-Synchrotron (DESY), Zeuthen, Germany*

E-mail: fabian.schussler@cea.fr

*Speaker

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.

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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)¹ 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.

¹<https://gcn.nasa.gov/>

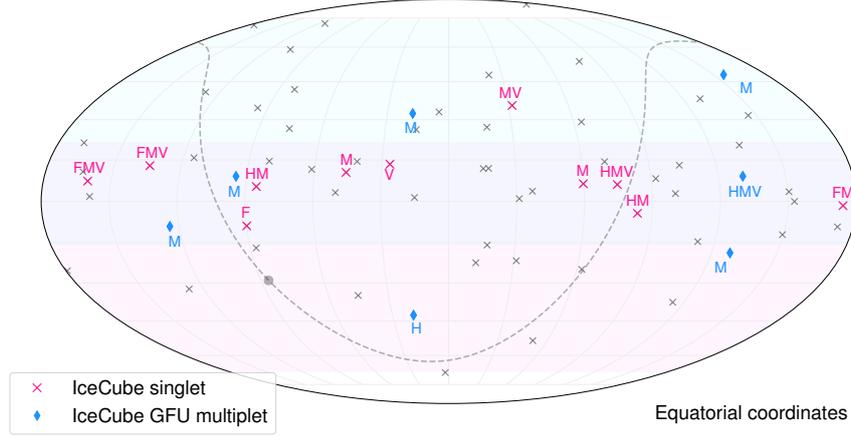


Figure 1: Sky map in equatorial coordinates showing IceCube alert positions observed by IACTs between October 2017 and January 2021 (in color, according to the alert type), and those not followed-up during the same period shown in gray. Letters indicate which IACTs participated in the observations (F - 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 $\Gamma = 2.85 \pm 0.47(\text{stat}) \pm 0.20(\text{sys})$ for the spectral index and a differential flux at 1 TeV of $\phi(1 \text{ TeV}) = (1.89 \pm 0.58(\text{stat}) \pm 0.39(\text{sys})) \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ [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 4σ . 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 $\Gamma = 2.73 \pm 0.27(\text{stat}) \pm 0.20(\text{sys})$ for the spectral index and $\phi(1 \text{ TeV}) = (5.83 \pm 3.2(\text{stat}) \pm 0.4(\text{sys})) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ 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.

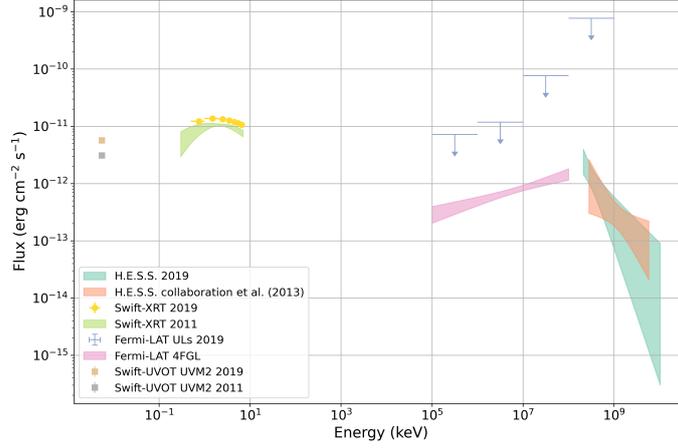


Figure 2: 1ES 1312-423 MWL SED showing archival data and observations obtained during the period following the GFU neutrino alert and contemporaneous to H.E.S.S. ToO observations.

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° ($+1.28^\circ$, -1.12° , 90% PSF containment) and Dec: 6.05° ($+0.95^\circ$ -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

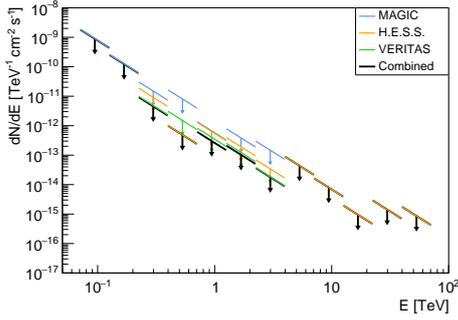


Figure 3: Combined differential flux upper limits on the VHE gamma-ray flux (black arrows) obtained from observations of IceCube-201114A by multiple IACTs (colored arrows).

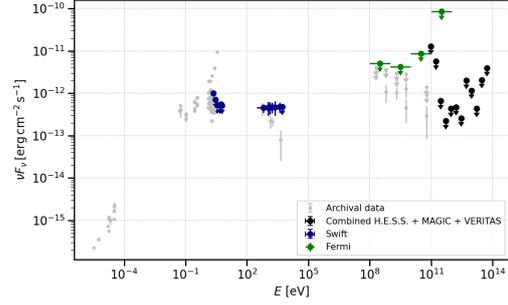


Figure 4: Multi-wavelength spectral energy distribution for NVSS J065844+063711 (4FGL J0658.6+0636) within the localisation uncertainty of IceCube-201114A.

observed spectrum modeled by a power law $dN/dE = KE^{-\Gamma}$ with index $\Gamma = 2.5$. The individual as well the combined upper limits at the position 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 (~ 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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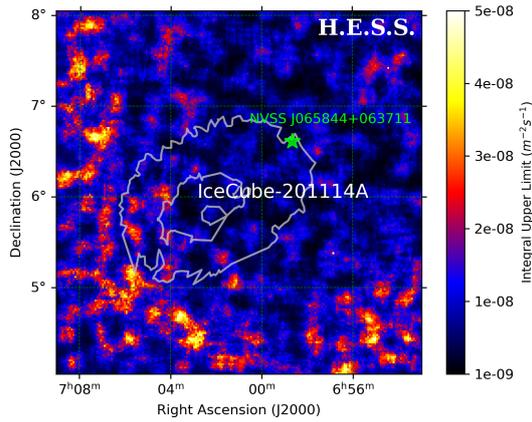


Figure 5: Integral upper limits on the VHE gamma-ray flux above 307 GeV derived from the H.E.S.S. observations of IceCube-201114A. The observations were centered around the location of NVSS J065844+063711, indicated by the green star. The grey lines denote the 50% (90%) contours of the localization of the event by IceCube.

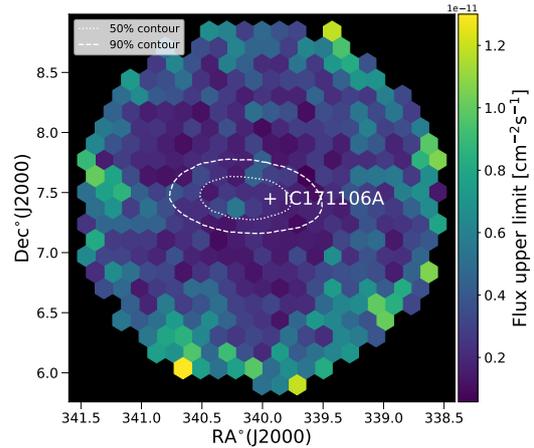


Figure 6: Map of integral upper limits of the VHE gamma-ray flux derived from the VERITAS observations of IceCube-171106A above an energy threshold of 350 GeV. The dashed lines denote the 50% (90%) contours of the localization of the event by IceCube.

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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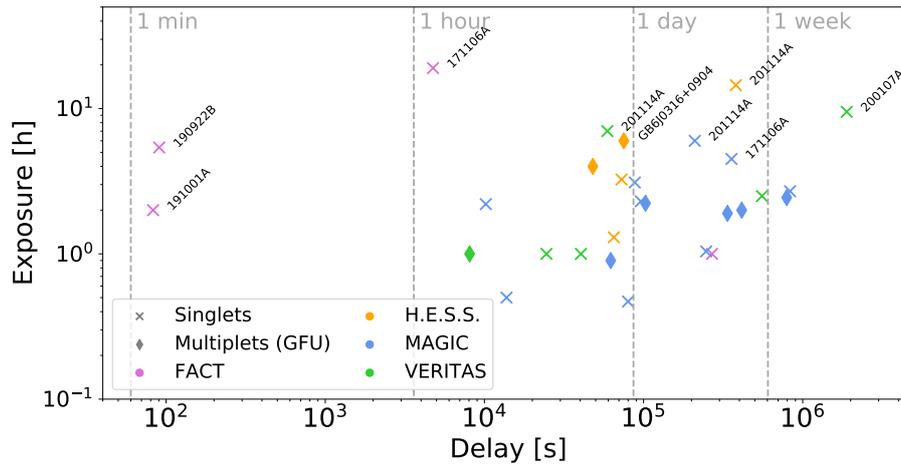


Figure 7: Delay vs exposure times for IACT follow-up of neutrino alerts from October 2017 until December 2020. The delay is calculated from the neutrino event arrival time (single events) or flare threshold crossing time (multiplets) up to the start of the IACT observation. Highlighted are observations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

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Full Author List: FACT Collaboration

J. Abhir¹, D. Baack², M. Balbo³, A. Biland¹, K. Brand⁴, T. Bretz¹ ^a, J. Buss², D. Dorner^{1,4}, L. Eisenberger⁴, D. Elsaesser², P. Günther⁴, D. Hildebrand¹, K. Mannheim⁴, M. Noethe², A. Paravac⁴, W. Rhode², B. Schleicher^{1,4}, V. Sliusar³, S. Hasan¹, R. Walter³

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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Full Author List: H.E.S.S. Collaboration

F. Aharonian^{1,2,3}, F. Ait Benkhali⁴, A. Alkan⁵, J. Aschersleben⁶, H. Ashkar⁷, M. Backes^{8,9}, A. Baktash¹⁰, V. Barbosa Martins¹¹, A. Barnacka¹², J. Barnard¹³, R. Batzofin¹⁴, Y. Becherini^{15,16}, G. Beck¹⁷, D. Berge^{11,18}, K. Bernlöhr², B. Bi¹⁹, M. Böttcher⁹, C. Boisson²⁰, J. Bolmont²¹, M. de Bony de Lavergne⁵, J. Borowska¹⁸, M. Bouyahiaoui², F. Bradascio⁵, M. Breuhaus², R. Brose¹, A. Brown²², F. Brun⁵, B. Bruno²³, T. Bulik²⁴, C. Burger-Scheidlin¹, T. Bylund⁵, F. Cangemi²¹, S. Caroff²⁵, S. Casanova²⁶, R. Cecil¹⁰, J. Celic²³, M. Cerruti¹⁵, P. Chambery²⁷, T. Chand⁹, S. Chandra⁹, A. Chen¹⁷, J. Chibueze⁹, O. Chibueze⁹, T. Collins²⁸, G. Cotter²², P. Cristofari²⁰, J. Damascene Mbarubucye¹¹, I.D. Davids⁸, J. Davies²², L. de Jonge⁹, J. Devin²⁹, A. Djannati-Atai¹⁵, A. Dmytriiev⁹, V. Doroshenko¹⁹, L. Dreyer⁹, L. Du Plessis⁹, K. Egberts¹⁴, S. Einecke²⁸, J.-P. Ernenwein³⁰, S. Fegan⁷, K. Feijen¹⁵, G. Fichet de Clairfontaine²⁰, G. Fontaine⁷, F. Lott⁸, M. Fülling¹¹, S. Funk²³, S. Gabici¹⁵, Y.A. Gallant²⁹, S. Ghafourizadeh⁴, G. Giavitto¹¹, L. Giunti^{15,5}, D. Glawion²³, J.F. Glicenstein⁵, J. Glombitza²³, P. Goswami¹⁵, G. Grolleron²¹, M.-H. Grondin²⁷, L. Haerer², S. Hattingh⁹, M. Haupt¹¹, G. Hermann², J.A. Hinton², W. Hofmann², T. L. Holch¹¹, M. Holler³¹, D. Horns¹⁰, Zhiqiu Huang², A. Jaitly¹¹, M. Jamroz¹², F. Jankowsky⁴, A. Jardin-Blicq²⁷, V. Joshi²³, I. Jung-Richardt²³, E. Kasai⁸, K. Katarzyński³², H. Katjajita⁸, D. Khangulyan³³, R. Khatoon⁹, B. Khélifi¹⁵, S. Klepser¹¹, W. Kluźniak³⁴, Nu. Komin¹⁷, R. Konno¹¹, K. Kosack⁵, D. Kostunin¹¹, A. Kundu⁹, G. Lamanna²⁵, R.G. Lang²³, S. Le Stum³⁰, V. Lefranc⁵, F. Leit²³, A. Lemièrè¹⁵, M. Lemoine-Goumard²⁷, J.-P. Lenain²¹, F. Leuschner¹⁹, A. Luashvili²⁰, I. Lypova⁴, J. Mackey¹, D. Malyshev¹⁹, D. Malyshev²³, V. Marandon⁵, A. Marcowith²⁹, P. Marinou²⁸, G. Marti-Devesa³¹, R. Marx⁴, G. Maurin²⁵, A. Mehta¹¹, P.J. Meintjes¹³, M. Meyer¹⁰, A. Mitchell³⁴, R. Moderski³⁴, L. Mohrmann², A. Montanari⁴, C. Moore³⁵, E. Moulin⁵, T. Murach¹¹, K. Nakashima²³, M. de Naurois⁷, H. Ndiyalala^{8,9}, J. Niemiec²⁶, A. Priyana Noel¹², P. O'Brien³⁵, S. Ohm¹¹, L. Olivera-Nieto², E. de Ona Wilhelmi¹¹, M. Ostrowski¹², E. Oukacha¹⁵, S. Panny³¹, M. Panter², R.D. Parsons¹⁸, U. Pensec²¹, G. Peron¹⁵, S. Pita¹⁵, V. Poireau²⁵, D.A. Prokhorov³⁶, H. Prokoph¹¹, G. Pühlhofer¹⁹, M. Punch¹⁵, A. Quirrenbach⁴, M. Regear¹⁵, P. Reichherzer⁵, A. Reimer³¹, O. Reimer³¹, I. Reis⁵, Q. Remy², H. Ren², M. Renaud²⁹, B. Reville², F. Rieger², G. Roellinghoff²³, E. Rol³⁶, G. Rowell²⁸, B. Rudak³⁴, H. Rueda Ricarte⁵, E. Ruiz-Velasco², K. Sabri²⁹, V. Sahakian³, S. Sailer², H. Salzmann¹⁹, D.A. Sanchez²⁵, A. Santangelo¹⁹, M. Sasaki²³, J. Schäfer²³, F. Schüssler⁵, H.M. Schutte⁹, M. Senniappan¹⁶, J.N.S. Shapopi⁸, S. Shilunga⁸, K. Shiningayamwe⁸, H. Sol²⁰, H. Spackman²², A. Specovius²³, S. Spencer²³, L. Stawarz¹², R. Steenkamp⁸, C. Stegmann^{14,11}, S. Steinmassl², C. Steppa¹⁴, K. Streil²³, I. Sushch⁹, H. Suzuki³⁷, T. Takahashi³⁸, T. Tanaka³⁷, T. Tavernier⁵, A.M. Taylor¹¹, R. Terrier¹⁵, A. Thakur²⁸, J. H.E. Thiersen⁹, C. Thorpe-Morgan¹⁹, M. Tluczykont¹⁰, M. Tsirou¹¹, N. Tsuji³⁹, R. Tuffs², Y. Uchiyama³³, M. Ullmo⁵, T. Unbehaun²³, P. van der Merwe⁹, C. van Eldik²³, B. van Soelen¹³, G. Vasileiadis²⁹, M. Vecchi⁶, J. Veh²³, C. Venter⁹, J. Vink³⁶, H.J. Volk², N. Vogel²³, T. Wach²³, S.J. Wagner⁴, F. Werner², R. White², A. Wiercholska²⁶, Yu Wun Wong²³, H. Yassin⁹, M. Zacharias^{4,9}, D. Zargaryan¹, A.A. Zdziarski³⁴, A. Zech²⁰, S.J. Zhu¹¹, A. Zmija²³, S. Zouari¹⁵ and N. Żywucka⁹.

¹Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland²Max-Planck-Institut für Kernphysik, P.O. Box 103980, D 69029 Heidelberg, Germany³Yerevan State University, 1 Alek Manukyan St, Yerevan 0025, Armenia⁴Landessternwarte, Universität Heidelberg, Königstuhl, D 69117 Heidelberg, Germany⁵IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France⁶Kapteyn Astronomical Institute, University of Groningen, Landleven 12, 9747 AD Groningen, The Netherlands⁷Laboratoire Leprince-Ringuet, École Polytechnique, CNRS, Institut Polytechnique de Paris, F-91128 Palaiseau, France⁸University of Namibia, Department of Physics, Private Bag 13301, Windhoek 10005, Namibia⁹Centre for Space Research, North-West University, Potchefstroom 2520, South Africa¹⁰Universität Hamburg, Institut für Experimentalphysik, Luruper Chaussee 149, D 22761 Hamburg, Germany¹¹DESY, D-15738 Zeuthen, Germany¹²Obserwatorium Astronomiczne, Uniwersytet Jagielloński, ul. Orla 171, 30-244 Kraków, Poland¹³Department of Physics, University of the Free State, PO Box 339, Bloemfontein 9300, South Africa¹⁴Institut für Physik und Astronomie, Universität Potsdam, Karl-Liebknecht-Strasse 24/25, D 14476 Potsdam, Germany¹⁵Université de Paris, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France¹⁶Department of Physics and Electrical Engineering, Linnaeus University, 351 95 Växjö, Sweden¹⁷School of Physics, University of the Witwatersrand, 1 Jan Smuts Avenue, Braamfontein, Johannesburg, 2050 South Africa¹⁸Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, D 12489 Berlin, Germany¹⁹Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, D 72076 Tübingen, Germany²⁰Laboratoire Univers et Théories, Observatoire de Paris, Université PSL, CNRS, Université de Paris, 92190 Meudon, France²¹Sorbonne Université, Université Paris Diderot, Sorbonne Paris Cité, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies, LPNHE, 4 Place Jussieu, F-75252 Paris, France²²University of Oxford, Department of Physics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK²³Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen Centre for Astroparticle Physics, Nikolaus-Fiebiger-Str. 2, D 91058 Erlangen, Germany²⁴Astronomical Observatory, The University of Warsaw, Al. Ujazdowskie 4, 00-478 Warsaw, Poland²⁵Université Savoie Mont Blanc, CNRS, Laboratoire d'Annecy de Physique des Particules - IN2P3, 74000 Annecy, France²⁶Instytut Fizyki Jądrowej PAN, ul. Radzikowskiego 152, 31-342 Kraków, Poland²⁷Université Bordeaux, CNRS, LP2I Bordeaux, UMR 5797, F-33170 Gradignan, France²⁸School of Physical Sciences, University of Adelaide, Adelaide 5005, Australia²⁹Laboratoire Univers et Particules de Montpellier, Université Montpellier, CNRS/IN2P3, CC 72, Place Eugène Bataillon, F-34095

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 Author List: IceCube Collaboration

R. Abbasi¹⁷, M. Ackermann⁶³, J. Adams¹⁸, S. K. Agarwalla^{40, 64}, J. A. Aguilar¹², M. Ahlers²², J.M. Alameddine²³, N. M. Amin⁴⁴, K. Andeen⁴², G. Anton²⁶, C. Argüelles¹⁴, Y. Ashida⁵³, S. Athanasiadou⁶³, S. N. Axani⁴⁴, X. Bai⁵⁰, A. Balagopal V.⁴⁰, M. Baricevic⁴⁰, S. W. Barwick³⁰, V. Basu⁴⁰, R. Bay⁸, J. J. Beatty^{20, 21}, J. Becker Tjus^{11, 65}, J. Beise⁶¹, C. Bellenghi²⁷, C. Benning¹, S. BenZvi⁵², D. Berley¹⁹, E. Bernardini⁴⁸, D. Z. Besson³⁶, E. Blaufuss¹⁹, S. Blot⁶³, F. Bontempo³¹, J. Y. Book¹⁴, C. Boscolo Meneguolo⁴⁸, S. Böser⁴¹, O. Botner⁶¹, J. Böttcher¹, E. Bourbeau²², J. Braun⁴⁰, B. Brinson⁶, J. Brostean-Kaiser⁶³, R. T. Burley², R. S. Busse⁴³, D. Butterfield⁴⁰, M. A. Campana⁴⁹, K. Carloni¹⁴, E. G. Carnie-Bronca², S. Chattopadhyay^{40, 64}, N. Chau¹², C. Chen⁶, Z. Chen⁵⁵, D. Chirkin⁴⁰, S. Choi⁵⁶, B. A. Clark¹⁹, L. Classen⁴³, A. Coleman⁶¹, G. H. Collin¹⁵, A. Connolly^{20, 21}, J. M. Conrad¹⁵, P. Coppin¹³, P. Correa¹³, D. F. Cowen^{59, 60}, P. Dave⁶, C. De Clercq¹³, J. J. DeLaunay⁵⁸, D. Delgado¹⁴, S. Deng¹, K. Deoskar⁵⁴, A. Desai⁴⁰, P. Desati⁴⁰, K. D. de Vries¹³, G. de Wasseige³⁷, T. DeYoung²⁴, A. Diaz¹⁵, J. C. Díaz-Vélez⁴⁰, M. Dittmer⁴³, A. Domi²⁶, H. Dujmovic⁴⁰, M. A. DuVernois⁴⁰, T. Ehrhardt⁴¹, P. Eller²⁷, E. Ellinger⁶², S. El Mentawi¹, D. Elsässer²³, R. Engel^{31, 32}, H. Erpenbeck⁴⁰, J. Evans¹⁹, P. A. Evenson⁴⁴, K. L. Fan¹⁹, K. Fang⁴⁰, K. Farrag¹⁶, A. R. Farrag⁷, A. Fedynitch⁵⁷, N. Feigl¹⁰, S. Fiedlschuster²⁶, C. Finley⁵⁴, L. Fischer⁶⁷, D. Fox⁵⁹, A. Frankowiak¹¹, A. Fritz⁴¹, P. Fürst¹, J. Gallagher³⁹, E. Ganster¹, A. Garcia¹⁴, L. Gerhardt⁹, A. Ghadimi⁵⁸, C. Glaser⁶¹, T. Glauch²⁷, T. Glusenkamp^{26, 61}, N. Goehke³², J. G. Gonzalez⁴⁴, S. Goswami⁵⁸, D. Grant²⁴, S. J. Gray¹⁹, O. Gries¹, S. Griffin⁴⁰, S. Griswold⁵², K. M. Groth²², C. Günther¹, P. Gutjahr²³, C. Haack²⁶, A. Hallgren⁶¹, R. Halliday²⁴, L. Halve¹, F. Halzen⁴⁰, H. Hamdaoui⁵⁵, M. Ha Minh²⁷, K. Hanson⁴⁰, J. Hardin¹⁵, A. A. Harnisch²⁴, P. Hatch³³, A. Haungs³¹, K. Helbing⁶², J. Hellrung¹¹, F. Henningsen²⁷, L. Heuermann¹, N. Heyer⁶¹, S. Hickford⁶², A. Hidvegi⁵⁴, C. Hill¹⁶, G. C. Hill², K. D. Hoffman¹⁹, S. Hori⁴⁰, K. Hoshina^{40, 66}, W. Hou³¹, T. Huber³¹, K. Hultqvist²³, M. Hünnefeld²³, R. Hussain⁴⁰, K. Hymon²³, S. In⁵⁶, A. Ishihara¹⁶, M. Jacquart⁴⁰, O. Janik¹, M. Jansson⁵⁴, G. S. Japaridze⁵, M. Jeong⁵⁶, M. Jin¹⁴, B. J. P. Jones⁴, D. Kang³¹, W. Kang⁵⁶, X. Kang⁴⁹, A. Kappes⁴³, D. Kappesser⁴¹, L. Kardum²³, T. Karg⁶³, M. Karle²⁷, A. Karle⁴⁰, U. Katz²⁶, M. Kauer⁴⁰, J. L. Kelley⁴⁰, A. Khatee Zathul⁴⁰, A. Kheirandish^{34, 35}, J. Kiryluk⁵⁵, S. R. Klein^{8, 9}, A. Kochocki²⁴, R. Koirala⁴⁴, H. Kolanoski¹⁰, T. Kontrimas²⁷, L. Köpke⁴¹, C. Kopper²⁶, D. J. Koskinen²², P. Koundal³¹, M. Kovacevich⁴⁹, M. Kowalski^{10, 63}, T. Kozynets²², J. Krishnamoorthi^{40, 64}, K. Kruijswijk³⁷, E. Krupczak²⁴, A. Kumar⁶³, E. Kun¹¹, N. Kurahashi⁴⁹, N. Lad⁶³, C. Lagunas Gualda⁶³, M. Lamoureux³⁷, M. J. Larson¹⁹, S. Latseva¹, F. Lauber⁶², J. P. Lazar^{14, 40}, J. W. Lee⁵⁶, K. Leonard DeHolton⁶⁰, A. Leszczyńska⁴⁴, M. Lincetto¹¹, Q. R. Liu⁴⁰, M. Liubarska²⁵, E. Lohfink⁴¹, C. Love⁴⁹, C. J. Lozano Mariscal⁴³, L. Lu⁴⁰, F. Lucarelli²⁸, W. Luszczyk^{20, 21}, Y. Lyu^{8, 9}, J. Madsen⁴⁰, K. B. M. Mahn²⁴, Y. Makino⁴⁰, E. Manao²⁷, S. Mancina^{40, 48}, W. Marie Sainte⁴⁰, I. C. Mariş¹², S. Marka⁴⁶, Z. Marka⁴⁶, M. Marsee⁵⁸, I. Martinez-Soler¹⁴, R. Maruyama⁴⁵, F. Mayhew²⁴, T. McElroy²⁵, F. McNally³⁸, J. V. Mead²², K. Meagher⁴⁰, S. Mechbal⁶³, A. Medina²¹, M. Meier¹⁶, Y. Merckx¹³, L. Merten¹¹, J. Micallef²⁴, J. Mitchell⁷, T. Montaruli²⁸, R. W. Moore²⁵, Y. Morii¹⁶, R. Morse⁴⁰, M. Moulai⁴⁰, T. Mukherjee³¹, R. Naab⁶³, R. Nagai¹⁶, M. Nakos⁴⁰, U. Naumann⁶², J. Necker⁶³, A. Negi⁴, M. Neumann⁴³, H. Niederhausen²⁴, M. U. Nisa²⁴, A. Noell¹, A. Novikov⁴⁴, S. C. Nowicki²⁴, A. Obertacke Pollmann¹⁶, V. O'Dell⁴⁰, M. Oehler³¹, B. Oeyen²⁹, A. Olivas¹⁹, R. Ørsøe²⁷, J. Osborn⁴⁰, E. O'Sullivan⁶¹, H. Pandya⁴⁴, N. Park³³, G. K. Parker⁴, E. N. Paudel⁴⁴, L. Paul^{42, 50}, C. Pérez de los Heros⁶¹, J. Peterson⁴⁰, S. Philippen¹, A. Pizzuto⁴⁰, M. Plum⁵⁰, A. Pontén⁶¹, Y. Popovych⁴¹, M. Prado Rodriguez⁴⁰, B. Pries²⁴, R. Procter-Murphy¹⁹, G. T. Przybylski⁹, C. Raab³⁷, J. Rack-Helleis⁴¹, K. Rawlins³, Z. Rechac⁴⁰, A. Rehman⁴⁴, P. Reichherzer¹¹, G. Renzi¹², E. Resconi²⁷, S. Reusch⁶³, W. Rhode²³, B. Riedel⁴⁰, A. Rifaie¹, E. J. Roberts², S. Robertson^{8, 9}, S. Rodan⁵⁶, G. Roellinghoff⁵⁶, M. Rongen²⁶, C. Rott^{53, 56}, T. Ruhe²³, L. Ruohan²⁷, D. Ryckbosch²⁹, I. Safa^{14, 40}, J. Saffer³², D. Salazar-Gallegos²⁴, P. Sampathkumar³¹, S. E. Sanchez Herrera²⁴, A. Sandrock⁶², M. Santander⁵⁸, S. Sarkar²⁵, S. Sarkar⁴⁷, J. Savelberg¹, P. Savina⁴⁰, M. Schaufel¹, H. Schieler³¹, S. Schindler²⁶, L. Schlickmann¹, B. Schlüter⁴³, F. Schlüter¹², N. Schmeisser⁶², T. Schmidt¹⁹, J. Schneider²⁶, F. G. Schröder^{31, 44}, L. Schumacher²⁶, G. Schwefer¹, S. Sclafani¹⁹, D. Seckel⁴⁴, M. Seikh³⁶, S. Seunarine⁵¹, R. Shah⁴⁹, A. Sharma⁶¹, S. Shefali³², N. Shimizu¹⁶, M. Silva⁴⁰, B. Skrzypek¹⁴, B. Smithers⁴, R. Snihur⁴⁰, J. Soedingrekso²³, A. Sogaard²², D. Soldin³², P. Soldin¹, G. Sommani¹¹, C. Spannfellner²⁷, G. M. Spiczak⁵¹, C. Spiering⁶³, M. Stamatikos²¹, T. Stanev⁴⁴, T. Stetzelberger⁹, T. Stürwald⁶², T. Stuttard²², G. W. Sullivan¹⁹, I. Taboada⁶, S. Ter-Antonyan⁷, M. Thiesmeyer¹, W. G. Thompson¹⁴, J. Thwaites⁴⁰, S. Tilav⁴⁴, K. Tollefson²⁴, C. Tönnes⁵⁶, S. Toscano¹², D. Tosi⁴⁰, A. Trettin⁶³, C. F. Tung⁶, R. Turcotte³¹, J. P. Twagirayezu²⁴, B. Ty⁴⁰, M. A. Unland Elorrieta⁴³, A. K. Upadhyay^{40, 64}, K. Uphaw⁷, N. Valtonen-Mattila⁶¹, J. Vandenbroucke⁴⁰, N. van Eijndhoven¹³, D. Vannerom¹⁵, J. van Santen⁶³, J. Vara⁴³, J. Veitch-Michaelis⁴⁰, M. Venugopal³¹, M. Vereecken³⁷, S. Verpoest⁴⁴, D. Veske⁴⁶, A. Vijai¹⁹, C. Walck⁵⁴, C. Weaver²⁴, P. Weigel¹⁵, A. Weindl³¹, J. Weldert⁶⁰, C. Wendt⁴⁰, J. Werthebach²³, M. Weyrauch³¹, N. Whitehorn²⁴, C. H. Wiebusch¹, N. Willey²⁴, D. R. Williams⁵⁸, L. Witthaus²³, A. Wolf¹, M. Wolf²⁷, G. Wrede²⁶, X. W. Xu⁷, J. P. Yanez²⁵, E. Yildizci⁴⁰, S. Yoshida¹⁶, R. Young³⁶, F. Yu¹⁴, S. Yu²⁴, T. Yuan⁴⁰, Z. Zhang⁵⁵, P. Zhelnin¹⁴, M. Zimmerman⁴⁰

¹ III. Physikalisches Institut, RWTH Aachen University, D-52056 Aachen, Germany² Department of Physics, University of Adelaide, Adelaide, 5005, Australia³ Dept. of Physics and Astronomy, University of Alaska Anchorage, 3211 Providence Dr., Anchorage, AK 99508, USA⁴ Dept. of Physics, University of Texas at Arlington, 502 Yates St., Science Hall Rm 108, Box 19059, Arlington, TX 76019, USA⁵ CTSPS, Clark-Atlanta University, Atlanta, GA 30314, USA⁶ School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA 30332, USA⁷ Dept. of Physics, Southern University, Baton Rouge, LA 70813, USA⁸ Dept. of Physics, University of California, Berkeley, CA 94720, USA⁹ Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA¹⁰ Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany¹¹ Fakultät für Physik & Astronomie, Ruhr-Universität Bochum, D-44780 Bochum, Germany¹² Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium

- ¹³ Vrije Universiteit Brussel (VUB), Dienst ELEM, B-1050 Brussels, Belgium
- ¹⁴ Department of Physics and Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA 02138, USA
- ¹⁵ Dept. of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
- ¹⁶ Dept. of Physics and The International Center for Hadron Astrophysics, Chiba University, Chiba 263-8522, Japan
- ¹⁷ Department of Physics, Loyola University Chicago, Chicago, IL 60660, USA
- ¹⁸ Dept. of Physics and Astronomy, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
- ¹⁹ Dept. of Physics, University of Maryland, College Park, MD 20742, USA
- ²⁰ Dept. of Astronomy, Ohio State University, Columbus, OH 43210, USA
- ²¹ Dept. of Physics and Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH 43210, USA
- ²² Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark
- ²³ Dept. of Physics, TU Dortmund University, D-44221 Dortmund, Germany
- ²⁴ Dept. of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA
- ²⁵ Dept. of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2E1
- ²⁶ Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany
- ²⁷ Technical University of Munich, TUM School of Natural Sciences, Department of Physics, D-85748 Garching bei München, Germany
- ²⁸ Département de physique nucléaire et corpusculaire, Université de Genève, CH-1211 Genève, Switzerland
- ²⁹ Dept. of Physics and Astronomy, University of Gent, B-9000 Gent, Belgium
- ³⁰ Dept. of Physics and Astronomy, University of California, Irvine, CA 92697, USA
- ³¹ Karlsruhe Institute of Technology, Institute for Astroparticle Physics, D-76021 Karlsruhe, Germany
- ³² Karlsruhe Institute of Technology, Institute of Experimental Particle Physics, D-76021 Karlsruhe, Germany
- ³³ Dept. of Physics, Engineering Physics, and Astronomy, Queen's University, Kingston, ON K7L 3N6, Canada
- ³⁴ Department of Physics & Astronomy, University of Nevada, Las Vegas, NV, 89154, USA
- ³⁵ Nevada Center for Astrophysics, University of Nevada, Las Vegas, NV 89154, USA
- ³⁶ Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA
- ³⁷ Centre for Cosmology, Particle Physics and Phenomenology - CP3, Université catholique de Louvain, Louvain-la-Neuve, Belgium
- ³⁸ Department of Physics, Mercer University, Macon, GA 31207-0001, USA
- ³⁹ Dept. of Astronomy, University of Wisconsin–Madison, Madison, WI 53706, USA
- ⁴⁰ Dept. of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin–Madison, Madison, WI 53706, USA
- ⁴¹ Institute of Physics, University of Mainz, Staudinger Weg 7, D-55099 Mainz, Germany
- ⁴² Department of Physics, Marquette University, Milwaukee, WI, 53201, USA
- ⁴³ Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, D-48149 Münster, Germany
- ⁴⁴ Bartol Research Institute and Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
- ⁴⁵ Dept. of Physics, Yale University, New Haven, CT 06520, USA
- ⁴⁶ Columbia Astrophysics and Nevis Laboratories, Columbia University, New York, NY 10027, USA
- ⁴⁷ Dept. of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom
- ⁴⁸ Dipartimento di Fisica e Astronomia Galileo Galilei, Università Degli Studi di Padova, 35122 Padova PD, Italy
- ⁴⁹ Dept. of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104, USA
- ⁵⁰ Physics Department, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA
- ⁵¹ Dept. of Physics, University of Wisconsin, River Falls, WI 54022, USA
- ⁵² Dept. of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA
- ⁵³ Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA
- ⁵⁴ Oskar Klein Centre and Dept. of Physics, Stockholm University, SE-10691 Stockholm, Sweden
- ⁵⁵ Dept. of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA
- ⁵⁶ Dept. of Physics, Sungkyunkwan University, Suwon 16419, Korea
- ⁵⁷ Institute of Physics, Academia Sinica, Taipei, 11529, Taiwan
- ⁵⁸ Dept. of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA
- ⁵⁹ Dept. of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
- ⁶⁰ Dept. of Physics, Pennsylvania State University, University Park, PA 16802, USA
- ⁶¹ Dept. of Physics and Astronomy, Uppsala University, Box 516, S-75120 Uppsala, Sweden
- ⁶² Dept. of Physics, University of Wuppertal, D-42119 Wuppertal, Germany
- ⁶³ Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany
- ⁶⁴ Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India
- ⁶⁵ Department of Space, Earth and Environment, Chalmers University of Technology, 412 96 Gothenburg, Sweden
- ⁶⁶ Earthquake Research Institute, University of Tokyo, Bunkyo, Tokyo 113-0032, Japan

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Full Authors List: MAGIC Collaboration

H. Abe¹, S. Abe¹, J. Abhir², V. A. Acciari³, I. Agudo⁴, T. Aniello⁵, S. Ansoldi^{6,46}, L. A. Antonelli⁵, A. Arbet Engels⁷, C. Arcaro⁸, M. Artero⁹, K. Asano¹, D. Baack¹⁰, A. Babic¹¹, A. Baquero¹², U. Barros de Almeida¹³, J. A. Barrio¹², I. Batkovic⁸, J. Baxter¹, J. Becerra González³, W. Bednarek¹⁴, E. Bernardini⁸, M. Bernardos⁴, J. Bernete¹⁵, A. Berti⁷, J. Besenrieder⁷, C. Bigongiari⁵, A. Biland², O. Blanch⁹, G. Bonnoli⁵, Ž. Bošnjak¹¹, I. Burelli⁶, G. Busetto⁸, A. Campoy-Ordaz¹⁶, A. Carosi⁵, R. Carosi¹⁷, M. Carretero-Castrillo¹⁸, A. J. Castro-Tirado⁴, G. Ceribella⁷, Y. Chai⁷, A. Chilingarian¹⁹, A. Cifuentes¹⁵, S. Cikota¹¹, E. Colombo³, J. L. Contreras¹², J. Cortina¹⁵, S. Covino⁵, G. D'Amico²⁰, V. D'Elia⁵, P. Da Vela^{17,47}, F. Dazzi⁵, A. De Angelis⁸, B. De Lotto⁶, A. Del Popolo²¹, M. Delfino^{9,48}, J. Delgado^{9,48}, C. Delgado Mendez¹⁵, D. Depaoli²², F. Di Pierro²², L. Di Venere²³, D. Dominis Prester²⁴, A. Donini⁵, D. Dorner²⁵, M. Doro⁸, D. Elsaesser¹⁰, G. Emery²⁶, J. Escudero⁴, L. Fariña⁹, A. Fattorini¹⁰, L. Foffano⁵, L. Font¹⁶, S. Fröse¹⁰, S. Fukami², Y. Fukazawa²⁷, R. J. García López³, M. Garczarczyk²⁸, S. Gasparyan²⁹, M. Gaug¹⁶, J. G. Giesbrecht Paiva¹³, N. Giglietto²³, F. Giordano²³, P. Gliwny¹⁴, N. Godinovic³⁰, R. Grau⁹, D. Green⁷, J. G. Green⁷, D. Hadasch¹, A. Hahn⁷, T. Hassan¹⁵, L. Heckmann^{7,49}, J. Herrera³, D. Hrupec³¹, M. Hütten¹, R. Imazawa²⁷, T. Inada¹, R. Iotov²⁵, K. Ishio¹⁴, I. Jiménez Martínez¹⁵, J. Jormanainen³², D. Kerszberg⁹, G. W. Kluge^{20,50}, Y. Kobayashi¹, P. M. Kouch³², H. Kubo¹, J. Kushida³³, M. Lázine Lezáun¹², A. Lamastra⁵, D. Lelas³⁰, F. Leone⁵, E. Lindfors³², L. Linhof¹⁰, S. Lombardi⁵, F. Longo^{6,51}, R. López-Coto⁴, M. López-Moya¹², A. López-Oramas³, S. Loporchio²³, A. Lorini³⁴, E. Lyard²⁶, B. Machado de Oliveira Fraga¹³, P. Majumdar³⁵, M. Makariev³⁶, G. Maneva³⁶, N. Mang¹⁰, M. Manganaro²⁴, S. Mangano¹⁵, K. Mannheim²⁵, M. Mariotti⁸, M. Martínez⁹, M. Martínez-Chicharro¹⁵, A. Mas-Aguilar¹², D. Mazin^{1,52}, S. Menchiari³⁴, S. Mender¹⁰, S. Mićanović²⁴, D. Miceli⁸, T. Miener¹², J. M. Miranda³⁴, R. Mirzoyan⁷, M. Molero González³, E. Molina³, H. A. Mondal³⁵, A. Moralejo⁹, D. Morcuende¹², T. Nakamori³⁷, C. Nanci⁵, L. Nava⁵, V. Neustroev³⁸, L. Nickel¹⁰, M. Nieves Rosillo³, C. Nigro⁹, L. Nikolic³⁴, K. Nilsson³², K. Nishijima³³, T. Njoh Ekoume³, K. Noda³⁹, S. Nozaki⁷, Y. Ohtani¹, T. Oka⁴⁰, A. Okumura⁴¹, J. Otero-Santos³, S. Paiano⁵, M. Palatiello⁶, D. Paneque⁷, R. Paoletti³⁴, J. M. Paredes¹⁸, L. Pavletić²⁴, D. Pavlović²⁴, M. Persic^{6,53}, M. Pihet⁸, G. Pirola⁷, F. Podobnik³⁴, P. G. Prada Moroni¹⁷, E. Prandini⁸, G. Principe⁶, C. Priyadarshi⁹, W. Rhode¹⁰, M. Ribó¹⁸, J. Rico⁹, C. Righi⁵, N. Sahakyan²⁹, T. Saito¹, S. Sakurai¹, K. Satalecka³², F. G. Saturni⁵, B. Schleicher²⁵, K. Schmidt¹⁰, F. Schmuckermaier⁷, J. L. Schubert¹⁰, T. Schweizer⁷, A. Sciacaluga⁵, J. Sitarek¹⁴, V. Sliusar²⁶, D. Sobczynska¹⁴, A. Spolon⁸, A. Stamerra⁵, J. Strišković³¹, D. Strom⁷, M. Strzys¹, Y. Suda²⁷, T. Suric⁴², S. Suutarinen³², H. Tajima⁴¹, M. Takahashi⁴¹, R. Takeishi¹, F. Tavecchio⁵, P. Temnikov³⁶, K. Terauchi⁴⁰, T. Terzić²⁴, M. Teshima^{7,54}, L. Tosti⁴³, S. Truzzi³⁴, A. Tutone⁵, S. Ubach¹⁶, J. van Scherpenberg⁷, M. Vazquez Acosta³, S. Ventura³⁴, V. Verguilov³⁶, I. Viale⁸, C. F. Vigorito²², V. Vitale⁴⁴, I. Vovk¹, R. Walter²⁶, M. Will⁷, C. Wunderlich³⁴, T. Yamamoto⁴⁵, ¹ Japanese MAGIC Group: Institute for Cosmic Ray Research (ICRR), The University of Tokyo, Kashiwa, 277-8582 Chiba, Japan

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 IPARCOS 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, 739-8526 Hiroshima, Japan

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

²⁹ Armenian MAGIC Group: ICRANet-Armenia, 0019 Yerevan, Armenia

- 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, Kyoto University, 606-8502 Kyoto, 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, 464-6801 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

Full Author List: VERITAS Collaboration

A. Acharyya¹, C. B. Adams², A. Archer³, P. Bangale⁴, J. T. Bartkoske⁵, P. Batista⁶, W. Benbow⁷, J. L. Christiansen⁸, A. J. Chromey⁷, A. Duerr⁵, M. Errando⁹, Q. Feng⁷, G. M. Foote⁴, L. Fortson¹⁰, A. Furniss^{11,12}, W. Hanlon⁷, O. Hervet¹², C. E. Hinrichs^{7,13}, J. Hoang¹², J. Holder⁴, Z. Hughes⁹, T. B. Humensky^{14,15}, W. Jin¹, M. N. Johnson¹², M. Kertzman³, M. Kherlakian⁶, D. Kieda⁵, T. K. Kleiner⁶, N. Korzoun⁴, S. Kumar¹⁴, M. J. Lang¹⁶, M. Lundy¹⁷, G. Maier⁶, C. E. McGrath¹⁸, M. J. Millard¹⁹, C. L. Mooney⁴, P. Moriarty¹⁶, R. Mukherjee²⁰, S. O'Brien^{17,21}, R. A. Ong²², N. Park²³, C. Poggemann⁸, M. Pohl^{24,6}, E. Poeschel⁶, J. Quinn¹⁸, P. L. Rabinowitz⁹, K. Ragan¹⁷, P. T. Reynolds²⁵, D. Ribeiro¹⁰, E. Roache⁷, J. L. Ryan²², I. Sadeh⁶, L. Saha⁷, M. Santander¹, G. H. Sembroski²⁶, R. Shang²⁰, M. Splettstoesser¹², A. K. Talluri¹⁰, J. V. Tucci²⁷, V. V. Vassiliev²², A. Weinstein²⁸, D. A. Williams¹², S. L. Wong¹⁷, and J. Woo²⁹

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 94307, 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

²¹ Arthur 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