Title
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Journal
The Astrophysical Journal, 967(1)

ISSN
0004-637X

Authors
Abbasi, R

Ackermann, M

Adams, J

et al.

Publication Date
2024-05-01

DOI
10.3847/1538-4357/ad3730

The Astrophysical Journal, 967:48 (9pp), 2024 May 20 https://doi.org/10.3847/1538-4357/ad3730

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All-sky Search for Transient Astrophysical Neutrino Emission with 10 Years of IceCube Cascade Events

R. Abbasi[1], M. Ackermann[2], J. Adams[3], S. K. Agarwalla[4,65], J. A. Aguilar[5], M. Ahlers[6], J. M. Alameddine[7], N. M. Amin[8], K. Andeen[9], G. Anton[10], C. Argüelles[11], Y. Ashida[12], S. Athanasiadou[2], L. Ausborm[13], S. N. Axani[8], X. Bai[14], A. Balagopal V.[4], M. Baricevic[4], S. W. Barwick[15], V. Basu[4], R. Bay[16], J. J. Beatty[17,18], J. Becker Tjus[19,66], J. Beise[20], C. Bellenghi[21], C. Benning[13], S. BenZvi[22], D. Berley[23], E. Bernardini[24], D. Z. Besson[25], E. Blaufuss[23], S. Blot[2], F. Bontempo[26], J. Y. Book[11], C. Boscolo Meneguolo[24], S. Böser[27], O. Botner[20], J. Böttcher[13], J. Braun[4], B. Brinson[28], J. Brostean-Kaiser[2], L. Brusa[13], R. T. Burley[29], R. S. Busse[30], D. Butterfield[4], M. A. Campana[31], K. Carloni[11], E. G. Carnie-Bronca[29], S. Chattopadhyay[4,65], N. Chau[5], C. Chen[28], Z. Chen[32], D. Chirkin[4], S. Choi[33], B. A. Clark[23], A. Coleman[20], G. H. Collin[34], A. Connolly[17,18], J. M. Conrad[34], P. Coppin[35], P. Correa[35], D. F. Cowen[36,37], P. Dave[28], C. De Clercq[35], J. J. DeLaunay[38], D. Delgado[11], S. Deng[13], K. Deoskar[39], A. Desai[4], P. Desiati[4], K. D. de Vries[35], G. de Wasseige[40], T. DeYoung[41], A. Diaz[34], J. C. Díaz-Vélez[4], M. Dittmer[30], A. Domi[10], H. Dujmovic[4], M. A. DuVernois[4], T. Ehrhardt[27], A. Eimer[10], P. Eller[21], E. Ellinger[42], S. El Mentawi[13], D. Elsässer[7], R. Engel[26,43], H. Erpenbeck[4], J. Evans[23], P. A. Evenson[8], K. L. Fan[23], K. Fang[4], K. Farrag[44], A. R. Fazely[45], A. Fedynitch[46], N. Feigl[47], S. Fiedlschuster[10], C. Finley[39], L. Fischer[2], D. Fox[36], A. Franckowiak[19], P. Fürst[13], J. Gallagher[48], E. Ganster[13], A. Garcia[11], L. Gerhardt[49], A. Ghadimi[38], C. Glaser[20], T. Glauch[21], T. Glüsenkamp[10,20], J. G. Gonzalez[8], D. Grant[41], S. J. Gray[23], O. Gries[13], S. Griffin[4], S. Griswold[22], K. M. Groth[6], C. Günther[13], P. Gutjahr[7], C. Ha[50], C. Haack[10], A. Hallgren[20], R. Halliday[41], L. Halve[13], F. Halzen[4], H. Hamdaoui[32], M. Ha Minh[21], M. Handt[13], K. Hanson[4], J. Hardin[34], A. A. Harnisch[41], P. Hatch[51], A. Haungs[26], J. Häußler[13], K. Helbing[42], J. Hellrung[19], J. Hermannsgabner[13], L. Heuermann[13], N. Heyer[20], S. Hickford[42], A. Hidvegi[39], C. Hill[44], G. C. Hill[29], K. D. Hoffman[23], S. Hori[4], K. Hoshina[4,67], W. Hou[26], T. Huber[26], K. Hultqvist[39], M. Hünnefeld[7], R. Hussain[4], K. Hymon[7], S. In[33], A. Ishihara[44], M. Jacquart[4], O. Janik[13], M. Jansson[39], G. S. Japaridze[52], M. Jeong[12], M. Jin[11], B. J. P. Jones[53], N. Kamp[11], D. Kang[26], W. Kang[33], X. Kang[31], A. Kappes[30], D. Kappesser[27], L. Kardum[7], T. Karg[2], M. Karl[21], A. Karle[4], A. Katil[54], U. Katz[10], M. Kauer[4], J. L. Kelley[4], A. Khatee Zathul[4], A. Kheirandish[55,56], J. Kiryluk[32], S. R. Klein[16,49], A. Kochocki[41], R. Koirala[8], H. Kolanoski[47], T. Kontrimas[21], L. Köpke[27], C. Kopper[10], D. J. Koskinen[6], P. Koundal[26], M. Kovacevich[31], M. Kowalski[2,47], T. Kozynets[6], J. Krishnamoorthi[4,65], K. Kruiswijk[40], E. Krupczak[41], A. Kumar[2], E. Kun[19], N. Kurahashi[31], N. Lad[2], C. Lagunas Gualda[2], M. Lamoureux[40], M. J. Larson[23], S. Latseva[13], F. Lauber[42], J. P. Lazar[4,11], J. W. Lee[33], K. Leonard DeHolton[37], A. Leszczyńska[8], M. Lincetto[19], Y. Liu[36,37], M. Liubarska[54], E. Lohfink[27], C. Love[31], C. J. Lozano Mariscal[30], L. Lu[4], F. Lucarelli[57], W. Luszczak[17,18], Y. Lyu[16,49], J. Madsen[4], E. Magnus[35], K. B. M. Mahn[41], Y. Makino[4], E. Manao[21], S. Mancina[4,24], W. Marie Sainte[4], I. C. Mariş[5], S. Marka[58], Z. Marka[58], M. Marsee[38], I. Martinez-Soler[11], R. Maruyama[59], F. Mayhew[41], T. McElroy[54], F. McNally[60], J. V. Mead[6], K. Meagher[4], S. Mechbal[2], A. Medina[18], M. Meier[44], Y. Merckx[35], L. Merten[19], J. Micallef[41], J. Mitchell[45], T. Montaruli[57], R. W. Moore[54], Y. Morii[44], R. Morse[4], M. Moulai[4], T. Mukherjee[26], R. Naab[2], R. Nagai[44], M. Nakos[4], U. Naumann[42], J. Necker[2], A. Negi[53], M. Neumann[30], H. Niederhausen[41], M. U. Nisa[41], A. Noell[13], A. Novikov[8], S. C. Nowicki[41], A. Obertacke Pollmann[44], V. O'Dell[4], B. Oeyen[61], A. Olivas[23], R. Orsoe[21], J. Osborn[4], E. O'Sullivan[20], H. Pandya[8], N. Park[51], G. K. Parker[53], E. N. Paudel[8], L. Paul[14], C. Pérez de los Heros[20], J. Peterson[4], S. Philippen[13], A. Pizzuto[4], M. Plum[14], A. Pontén[20], Y. Popovych[27], M. Prado Rodriguez[4], B. Pries[41], R. Procter-Murphy[23], G. T. Przybylski[49], C. Raab[40], J. Rack-Helleis[27], K. Rawlins[62], Z. Rechav[4], A. Rehman[8], P. Reichherzer[19], E. Resconi[21], S. Reusch[2], W. Rhode[7], B. Riedel[4], A. Rifaie[13], E. J. Roberts[29], S. Robertson[16,49], S. Rodan[33], G. Roellinghoff[33], M. Rongen[10], A. Rosted[44], C. Rott[12,33], T. Ruhe[7], L. Ruohan[21], D. Ryckbosch[61], I. Safa[4,11], J. Saffer[43], D. Salazar-Gallegos[41], P. Sampathkumar[26], S. E. Sanchez Herrera[41], A. Sandrock[42], M. Santander[38], S. Sarkar[54], S. Sarkar[63], J. Savelberg[13], P. Savina[4], M. Schaufel[13], H. Schieler[26], S. Schindler[10], L. Schlickmann[13], B. Schlüter[30], F. Schlüter[5], N. Schmeisser[42], T. Schmidt[23], J. Schneider[10], F. G. Schröder[8,26], L. Schumacher[10], S. Sclafani[23], D. Seckel[8], M. Seikh[25], S. Seunarine[64], R. Shah[31], S. Shefali[43], N. Shimizu[44], M. Silva[4], B. Skrzypek[11], B. Smithers[53], R. Snihur[4], J. Soedingrekso[7], A. Søgaard[6], D. Soldin[43], P. Soldin[13], G. Sommani[19], C. Spannfellner[21], G. M. Spiczak[64], C. Spiering[2], M. Stamatikos[18], T. Stanev[8], T. Stezelberger[49], T. Stürwald[42], T. Stuttard[6], G. W. Sullivan[23], I. Taboada[28], S. Ter-Antonyan[45], M. Thiesmeyer[13], W. G. Thompson[11], J. Thwaites[4], S. Tilav[8], K. Tollefson[41], C. Tönnis[33], S. Toscano[5], D. Tosi[4], A. Trettin[2], C. F. Tung[28], R. Turcotte[26], J. P. Twagirayezu[41], M. A. Unland Elorrieta[30], A. K. Upadhyay[4,65], K. Upshaw[45], A. Vaidyanathan[9], N. Valtonen-Mattila[20], J. Vandenbroucke[4], N. van Eijndhoven[35], D. Vannerom[34], J. van Santen[2], J. Vara[30], J. Veitch-Michaelis[4], M. Venugopal[26], M. Vereecken[40], S. Verpoest[8], D. Veske[58], A. Vijai[23], C. Walck[39], Y. Wang[36,37], C. Weaver[41], P. Weigel[34], A. Weindl[26], J. Weldert[37], A. Y. Wen[11], C. Wendt[4], J. Werthebach[7], M. Weyrauch[26], N. Whitehorn[41], C. H. Wiebusch[13], D. R. Williams[38], L. Witthaus[7], A. Wolf[13], M. Wolf[21], G. Wrede[10], X. W. Xu[45], J. P. Yanez[54], E. Yildizci[4], S. Yoshida[44], R. Young[25], S. Yu[41], T. Yuan[4], Z. Zhang[32], P. Zhelnin[11], P. Zilberman[4], and

M. Zimmerman[4]
IceCube Collaboration

[1] Department of Physics, Loyola University Chicago, Chicago, IL 60660, USA
[2] Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, D-15738 Zeuthen, Germany
[3] Dept. of Physics and Astronomy, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
[4] Dept. of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin—Madison, Madison, WI 53706, USA
[5] Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium
[6] Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark
[7] Dept. of Physics, TU Dortmund University, D-44221 Dortmund, Germany
[8] Bartol Research Institute and Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
[9] Department of Physics, Marquette University, Milwaukee, WI 53201, USA
[10] Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany
[11] Department of Physics and Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA 02138, USA
[12] Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA
[13] III. Physikalisches Institut, RWTH Aachen University, D-52056 Aachen, Germany
[14] Physics Department, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA
[15] Dept. of Physics and Astronomy, University of California, Irvine, CA 92697, USA
[16] Dept. of Physics, University of California, Berkeley, CA 94720, USA
[17] Dept. of Astronomy, Ohio State University, Columbus, OH 43210, USA
[18] Dept. of Physics and Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH 43210, USA
[19] Fakultät für Physik & Astronomie, Ruhr-Universität Bochum, D-44780 Bochum, Germany
[20] Dept. of Physics and Astronomy, Uppsala University, Box 516, SE-75120 Uppsala, Sweden
[21] Physik-department, Technische Universität München, D-85748 Garching, Germany
[22] Dept. of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA
[23] Dept. of Physics, University of Maryland, College Park, MD 20742, USA
[24] Dipartimento di Fisica e Astronomia Galileo Galilei, Università Degli Studi di Padova, I-35122 Padova PD, Italy
[25] Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA
[26] Karlsruhe Institute of Technology, Institute for Astroparticle Physics, D-76021 Karlsruhe, Germany
[27] Institute of Physics, University of Mainz, Staudinger Weg 7, D-55099 Mainz, Germany
[28] School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA 30332, USA
[29] Department of Physics, University of Adelaide, Adelaide, 5005, Australia
[30] Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, D-48149 Münster, Germany
[31] Dept. of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104, USA
[32] Dept. of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA
[33] Dept. of Physics, Sungkyunkwan University, Suwon 16419, Republic of Korea
[34] Dept. of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[35] Vrije Universiteit Brussel (VUB), Dienst ELEM, B-1050 Brussels, Belgium
[36] Dept. of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
[37] Dept. of Physics, Pennsylvania State University, University Park, PA 16802, USA
[38] Dept. of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA
[39] Oskar Klein Centre and Dept. of Physics, Stockholm University, SE-10691 Stockholm, Sweden
[40] Centre for Cosmology, Particle Physics and Phenomenology—CP3, Université catholique de Louvain, Louvain-la-Neuve, Belgium
[41] Dept. of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA
[42] Dept. of Physics, University of Wuppertal, D-42119 Wuppertal, Germany
[43] Karlsruhe Institute of Technology, Institute of Experimental Particle Physics, D-76021 Karlsruhe, Germany
[44] Dept. of Physics and The International Center for Hadron Astrophysics, Chiba University, Chiba 263-8522, Japan
[45] Dept. of Physics, Southern University, Baton Rouge, LA 70813, USA
[46] Institute of Physics, Academia Sinica, Taipei, 11529, Taiwan
[47] Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany
[48] Dept. of Astronomy, University of Wisconsin—Madison, Madison, WI 53706, USA
[49] Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[50] Dept. of Physics, Chung-Ang University, Seoul 06974, Republic of Korea
[51] Dept. of Physics, Engineering Physics, and Astronomy, Queen's University, Kingston, ON K7L 3N6, Canada
[52] CTSPS, Clark-Atlanta University, Atlanta, GA 30314, USA
[53] Dept. of Physics, University of Texas at Arlington, 502 Yates Street, Science Hall Rm 108, Box 19059, Arlington, TX 76019, USA
[54] Dept. of Physics, University of Alberta, Edmonton, Alberta, T6G 2E1, Canada
[55] Department of Physics & Astronomy, University of Nevada, Las Vegas, NV 89154, USA
[56] Nevada Center for Astrophysics, University of Nevada, Las Vegas, NV 89154, USA
[57] Département de physique nucléaire et corpusculaire, Université de Genève, CH-1211 Genève, Switzerland
[58] Columbia Astrophysics and Nevis Laboratories, Columbia University, New York, NY 10027, USA
[59] Dept. of Physics, Yale University, New Haven, CT 06520, USA

[60] Department of Physics, Mercer University, Macon, GA 31207-0001, USA
[61] Dept. of Physics and Astronomy, University of Gent, B-9000 Gent, Belgium
[62] Dept. of Physics and Astronomy, University of Alaska Anchorage, 3211 Providence Drive, Anchorage, AK 99508, USA
[63] Dept. of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, UK
[64] Dept. of Physics, University of Wisconsin, River Falls, WI 54022, USA
Received 2023 December 8; revised 2024 March 8; accepted 2024 March 22; published 2024 May 16

Abstract

Neutrino flares in the sky are searched for in data collected by IceCube between 2011 and 2021 May. This data set contains cascade-like events originating from charged-current electron neutrino and tau neutrino interactions and all-flavor neutral-current interactions. IceCube's previous all-sky searches for neutrino flares used data sets consisting of track-like events originating from charged-current muon neutrino interactions. The cascade data set is statistically independent of the track data sets, and while inferior in angular resolution, the low-background nature makes it competitive and complementary to previous searches. No statistically significant flare of neutrino emission was observed in an all-sky scan. Upper limits are calculated on neutrino flares of varying duration from 1 hr to 100 days. Furthermore, constraints on the contribution of these flares to the diffuse astrophysical neutrino flux are presented, showing that multiple unresolved transient sources may contribute to the diffuse astrophysical neutrino flux.

Unified Astronomy Thesaurus concepts: Neutrino astronomy (1100); High energy astrophysics (739); Transient sources (1851)

1. Introduction

The astrophysical processes responsible for producing, accelerating, and propagating high-energy cosmic rays have not been resolved. High-energy neutrinos can provide insights into the origins of cosmic rays. In 2013, IceCube reported observations of the diffuse astrophysical neutrino flux (Aartsen et al. 2013a). However, the majority of the diffuse astrophysical neutrino flux still has unresolved origins. Since then, IceCube has observed evidence of time-dependent and steady-state neutrino emission from astrophysical objects. In 2017, IceCube detected a 290 TeV neutrino (IceCube-170922A) in spatial coincidence with the blazar TXS 0506+056; IceCube-170922A was also temporally coincident with enhanced multiwavelength activity in the blazar (Aartsen et al. 2018a). The statistical significance of this spatial and temporal coincidence was reported at 3σ. An archival search of 9.5 yr of IceCube data found further evidence at a statistical significance of 3.5σ for a neutrino flare that occurred between 2014 September and 2015 March that was not coincident with gamma-ray emission (Aartsen et al. 2018b). Since then, further searches (Allakhverdyan et al. 2023; Albert et al. 2024) have hinted at the possible connection of neutrino flares and blazars. IceCube observed evidence for continuous neutrino emission from the Seyfert galaxy NGC 1068 with a significance of 4.2σ (Abbasi et al. 2022). Recently, IceCube has also observed steady diffuse neutrino emission from the Milky Way at a significance of 4.5σ (Abbasi et al. 2023). In the past decade, time-domain multimessenger astronomy has observed multiple breakthroughs that serve potential insight into which sources are capable of contributing to the diffuse astrophysical neutrino flux. Not all astrophysical transient events are expected to produce a neutrino flux; however, hadronic astrophysical transient events are primary candidates for contributing to the diffuse neutrino flux (Murase & Bartos 2019). In order to remain model-independent, this analysis excludes multimessenger information and solely uses 10 yr of IceCube's cascade data to perform a time-dependent search for neutrino flares across the entire sky.

The IceCube Neutrino Observatory is located at the geographic South Pole and occupies a cubic kilometer of ice instrumented with 5160 digital optical modules (DOMs). The DOMs are situated on 86 readout and support cables that have been frozen into the Antarctic glacier at depths between 1450 and 2450 m (Abbasi et al. 2009; Aartsen et al. 2017). The primary in-ice DOMs array is composed of 78 readout and support cables; the DOMs have a vertical spacing of 17 m and a horizontal spacing of 125 m. This design allows IceCube to detect the Cherenkov radiation from charged particles that are created by neutrinos with energies from 100 GeV to 10 PeV interacting with the Antarctic ice. The remaining eight cables were used to create a higher-density subvolume of IceCube in order to detect neutrinos down to 10 GeV (Abbasi et al. 2012). Since 2011, IceCube has been fully operational and taking data with >99% uptime (Aartsen et al. 2017).

2. Search for Neutrino Flares

2.1. Cascade Events: A New Avenue to Search for Flares

IceCube detects electron neutrinos (ν_e), muon neutrinos (ν_μ), and tau neutrinos (ν_τ), as well as their antiparticles. At Earth, we expect a flavor ratio ($\nu_e : \nu_\mu : \nu_\tau$) of approximately 1:1:1 due to neutrino oscillations occurring over astronomical distances (Learned & Pakvasa 1995). Depending on the interaction type, a neutrino will primarily produce two event topologies: cascades and tracks (Aartsen et al. 2014). Cascade events are produced by all-flavor neutral-current interactions, as well as charged-current ν_e and ν_τ interactions, which can produce hadronic and electromagnetic showers (Aartsen et al. 2014). Due to the spatial extent of the showers and the scattering length of light within the Antarctic ice, which is shorter

[65] also at Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India
[66] also at Department of Space, Earth and Environment, Chalmers University of Technology, 412 96 Gothenburg, Sweden
[67] also at Earthquake Research Institute, University of Tokyo, Bunkyo, Tokyo 113-0032, Japan

compared to the DOM spacing, cascade events appear nearly symmetric and have reconstructed angular resolutions of $\sim 5°$–$15°$ depending on the energy of the neutrino (Aartsen et al. 2013b; Abbasi et al. 2023). Conversely, tracks are produced when ν_μ interact with the ice through the charged-current channel and produce a muon that can travel for several kilometers while emitting Cherenkov light. At high energies, tracks have reconstructed angular resolutions $\lesssim 1°$ (IceCube Collaboration 2021).

However, a major disadvantage of the track data set is the much higher background rates compared to the cascade data set. Atmospheric muons are detected at a $\mathcal{O}(10^9)$ higher rate than signal neutrinos at the trigger level, and most of the atmospheric neutrinos that reach the IceCube detector are muon neutrinos. Thus, atmospheric backgrounds overwhelmingly produce track events. By using cascade events, the background contamination of the data set is greatly reduced (Abbasi et al. 2023). This has a large effect on sensitivities in the Southern Sky, where IceCube does not have the Earth to shield the detector from atmospheric muons. Because the atmospheric background fluxes are expected to be a softer spectrum of $E^{-3.7}$ compared to the neutrino spectrum from astrophysical flares at E^{-2} to E^{-3}, the reduction in background effectively lowers the energy threshold of the cascade analysis relative to the track analysis.

Figure 1 compares the 90% confidence level (C.L.) sensitivity fluxes of neutrino flares as detected in a track data set and the cascade data set. While track events have better sensitivity in the northern sky, the sensitivity deteriorates rapidly in the southern sky, as Earth shielding of atmospheric muons disappears. The cascade data set remains flat in sensitivity flux, since atmospheric muons are not the main background in this data set. Even in the northern sky, the sensitivity fluxes remain relatively close when a soft emission of $E^{-2.7}$ flare is assumed, and they will become the most sensitive at even softer spectra.

A region of particular interest to neutrino flare searches is the Galactic center. The Galactic center region hosts a supermassive black hole (SMBH) at the position of Sgr A*, which is the nearest object capable of strong flare activity. SMBHs can be sources of flare-like emission of cosmic rays and their secondaries, i.e., neutrinos and gamma-rays. By using cascade events, we lower the sensitivity flux to such flares by more than an order of magnitude for the emission duration and spectral index assumed in Figure 1. Astrophysical sources of PeV-scale cosmic-ray production, dubbed PeVatrons, are hypothesized along the Galactic plane, with most of the population in the southern sky (Cao et al. 2021; Cristofari 2021; Bustamante 2023; Cardillo & Giuliani 2023). Thus, the enhancement in neutrino flare sensitivities in the southern sky opens a new phase space in Galactic neutrino flare searches. Some models on neutrino emission from from PeVatrons, such as Galactic gamma-ray binaries (Bykov et al. 2021), show fluxes in the TeV range and beyond that are compatible with IceCube's sensitivity ranges.

A previous IceCube search for a neutrino flares yielded no statistically significant observation (Abbasi et al. 2021a). This analysis also scanned the entire sky for the most statistically significant neutrino flares in the northern and southern skies, and it did not utilize external triggers, such as alerts from gamma-ray telescopes. Such an "untriggered" search can detect astrophysical phenomena that solely produce neutrinos or

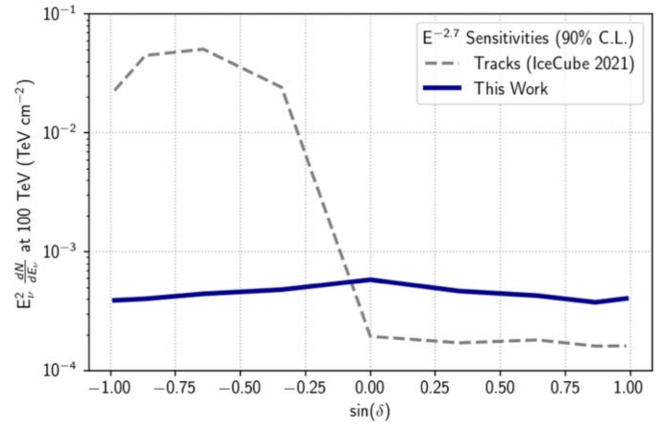

Figure 1. The 90% C.L. sensitivity flux to an $E^{-2.7}$ neutrino flare emission with a duration of 10 days at various declinations. Using IceCube's track data set (IceCube Collaboration 2021), the sensitivity deteriorates rapidly in the southern sky as the Earth shielding of atmospheric muons disappears, while cascade data set remains flat. Even in the northern sky, the sensitivity fluxes remain relatively close because of the soft emission of the $E^{-2.7}$ flare that is assumed here. This is due to the low background nature of the cascade data set, which effectively lowers the energy threshold of the analysis as described in the main text.

produce neutrinos and other astrophysical messengers at times offset from the detection of optical, X-ray, or gamma-ray flares. In IceCube, when searching for neutrino flares that have durations of $\mathcal{O}(10^2)$ days or less, this method becomes more sensitive than time-integrated searches (Braun et al. 2010). IceCube's previous untriggered analyses only used track events due to their high event rate and small angular uncertainties. The analysis of cascade events provides a new opportunity to use a statistically independent data set to observe the transient sky. This is the first such all-sky search utilizing a cascade data set.

2.2. Cascade Data Set

The cascade data set contains 59,592 cascade-like events detected with IceCube's complete 86-string configuration from 2011 May 13 to 2021 May 27 with energies between 500 GeV and 5.35 PeV. The angular resolution of the data set is energy-dependent. At 1 TeV, the median angular resolution is $>15°$; at 100 TeV, the median angular resolution is $\lesssim 10°$ and improves to $\sim 5°$ at PeV energies. The data set was designed to search for time-integrated all-sky and Galactic diffuse emission (Abbasi et al. 2023), and it uses novel event-reconstruction and event-selection techniques with neural networks and boosted decision trees (Abbasi et al. 2021b). Approximately 87% of the cascade events are estimated to be atmospheric neutrinos, 7% are astrophysical neutrinos, and the remainder are atmospheric muons (Abbasi et al. 2023). The atmospheric neutrino spectrum is comparatively softer than that of astrophysical neutrinos (Aartsen et al. 2015). Thus, at energies between 10 TeV and 100 TeV, atmospheric neutrinos become the subdominant component of the cascade data set (Abbasi et al. 2023).

2.3. Analysis Methods

We use 10 yr of cascade events to search for the most statistically significant spatial and temporal clustering of events in IceCube's northern ($\delta > -5°$) and southern ($\delta < -5°$) sky, which were predefined in a blind analysis. The north/south split was chosen to be consistent with previous IceCube analyses using track events. The points within 10° of the celestial poles are excluded due to their low statistics and limited background estimation. The clustering search uses a maximum likelihood method to identify time-dependent neutrino emission from point sources, similar to IceCube's previous analyses (Braun et al. 2010; Abbasi et al. 2021a). The likelihood,

$$\mathcal{L} = \prod_{i}^{N} (\frac{n_s}{N} S_i + (1 - \frac{n_s}{N}) B_i), \quad (1)$$

runs over every ith event in the data set that includes N events. Here, S_i and B_i are probability density functions (PDFs) that are products of individual spatial, energy, and temporal PDFs. To search for neutrino emission, the sky is partitioned into 12,288 pixels of equal solid angle using HEALPix[68] (Gorski et al. 2005). The spatial PDF accounts for the angular distance between the center of each pixel and the reconstructed arrival direction of each cascade event. Due to the rotation of the Earth, the angular distribution of background events is assumed to be uniform in R.A. We also assume a Gaussian PDF to test for temporal clustering between given cascade events and treat IceCube's background event rate as uniform in time while also accounting for detector livetime. IceCube's previous searches have been performed with both a Gaussian and a "box-shaped" temporal PDF that follows a Heaviside step function. Here, we use the Gaussian PDF, since it is less computationally intensive. The energy PDFs account for the astrophysical spectra and the energy distribution of the cascade events as a function of decl. We assume that, for the signal hypothesis, the neutrino flux follows an unbroken power law, $E^{-\gamma}$, where γ is the spectral index.

In this analysis, we define the null hypothesis such that there is no spatial and temporal neutrino clustering for a given area of the sky. The alternative hypothesis fits for the following four parameters at every pixel: number of signal events (n_s), which is constrained to be $n_s \geqslant 0$, signal spectral index (γ), allowed to fit within the range $1.0 \leqslant \gamma \leqslant 4.0$, mean time of the flare (T_0 [Modified Julian Date (MJD)]), allowed to fit to any time during the livetime of the data set, and half-width flare duration (σ_t [days]), constrained to $\sigma_t \geqslant 10^{-11}$ and maximally to half of the duration of the livetime of the data set, in order to search for neutrinos that are spatially and temporally clustered. The alternative hypothesis indicates an excess of signal-like events that surpass the expected background. To test the null and alternate hypotheses, we use the likelihood ratio test, as described in Wilks (1938), to construct a test statistic (TS):

$$\mathrm{TS} = -2 \log \left[\frac{T_{\max} - T_{\min}}{\sigma_t} \times \frac{\mathcal{L}(n_s = 0)}{\mathcal{L}(n_s, \gamma, T_0, \sigma_t)} \right]. \quad (2)$$

In Equation (2), $T_{\max}$ and $T_{\min}$ refer to the livetime bounds of the cascade data set. The TS includes a marginalization term for the flare duration in addition to the likelihood ratio; this prevents a bias that arises from overfitting for σ_t with shorter durations. IceCube's previous untriggered flare searches have searched for flares by imposing a signal-over-background (S/B) threshold to reduce the computational complexity of the analysis. The S/B threshold is used to seed potential flares with events that have a high probability of being a signal, based off their reconstructed direction and energy. Thus, S/B only accounts for the spatial and energy PDFs of a given event. Previous all-sky track analyses had data sets with high data rates; these analyses used thresholds of $S/B > 1000$ to efficiently search for flares. Since the cascade data set has an order of magnitude fewer events than IceCube's track data set, we relax this threshold to $S/B > 1$.

To calculate the TS, the events' arrival directions are uniformly randomized in R.A.; the time of the event is also randomized. A TS is then calculated for each pixel in the all-sky search. This process is repeated $\mathcal{O}(10^4)$–$\mathcal{O}(10^5)$ times in order to obtain an ensemble of TS that follows the null hypothesis of no spatial or temporal clustering. Each TS in the ensemble represents a different realization of background data. To minimize the computational expense of building an ensemble of TS for each pixel, and to account for the decl. dependence of the data, we build an ensemble of TS in 81 decl. bins and one R.A. bin. The decl. bins range from [−80°, 80°] and are evenly spaced in 2° increments. The TS for the data, $\mathrm{TS}_{\mathrm{data}}$, is then calculated for every pixel and compared to the corresponding ensemble of TS in order to calculate a local p-value (p_{local}), which is the probability of getting a $\mathrm{TS} \geqslant \mathrm{TS}_{\mathrm{data}}$ from a random background realization of our data. We report two local p-values, p_{local}, for the data that correspond to the most statistically significant pixels in the northern and the southern sky, respectively. Since we test many pixels on the sky, the two local p-values, p_{local}, for the northern and southern skies are corrected for statistical trials to report global p-values (p_{global}). We construct p_{global} by considering $\mathcal{O}(10^2)$ randomized sky scans that correspond to different realizations of background data, and then taking the most statistically significant pixels in the northern and southern sky from each sky scan in order to obtain respective distributions of the most statistically significant p_{local}. Finally, the two values of p_{global} are reported as the trial-corrected significances.

3. Results and Implications

No significant spatial and temporal clustering of astrophysical neutrinos was observed in this analysis.

In the northern sky, the most significant point is located at $(\alpha, \delta) = (322.^{\circ}03, -4.^{\circ}78)$ with a corresponding $p_{\mathrm{local}} = 2.45 \times 10^{-3}$ and a pre-trial significance of 2.81σ. The most significant point in the southern sky is located at $(\alpha, \delta) = (320.^{\circ}63, -5.^{\circ}98)$ with a respective $p_{\mathrm{local}} = 2.12 \times 10^{-3}$ and a pre-trial significance of 2.86σ. The "hottest" spots are separated by <2° in decl. and are located in the same extended "warm" spot. This is due in part to the angular resolution of the cascade events. Since cascade events are correlated with different pixels, the statistical fluctuations near the hottest spot have similar p_{local}. After correcting trials, we report the final p-values of $p_{\mathrm{global}} = 0.71$ in the northern sky, and $p_{\mathrm{global}} = 0.51$ in the southern sky. The results of this all-sky search for transient astrophysical neutrino emission are consistent with the background-only hypothesis.

3.1. Diffuse Flux Constraints

The sensitivity and discovery potential fluences at the hottest spot, along with two benchmark declinations of ±60o, are shown as a function of σ_t in Figure 2—left. IceCube has previously measured a time-integrated diffuse astrophysical neutrino flux with cascade events (Aartsen et al. 2020). This plot assumes the flare emission has a power law of $E^{-2.53}$ taken

[68] https://healpix.jpl.nasa.gov/

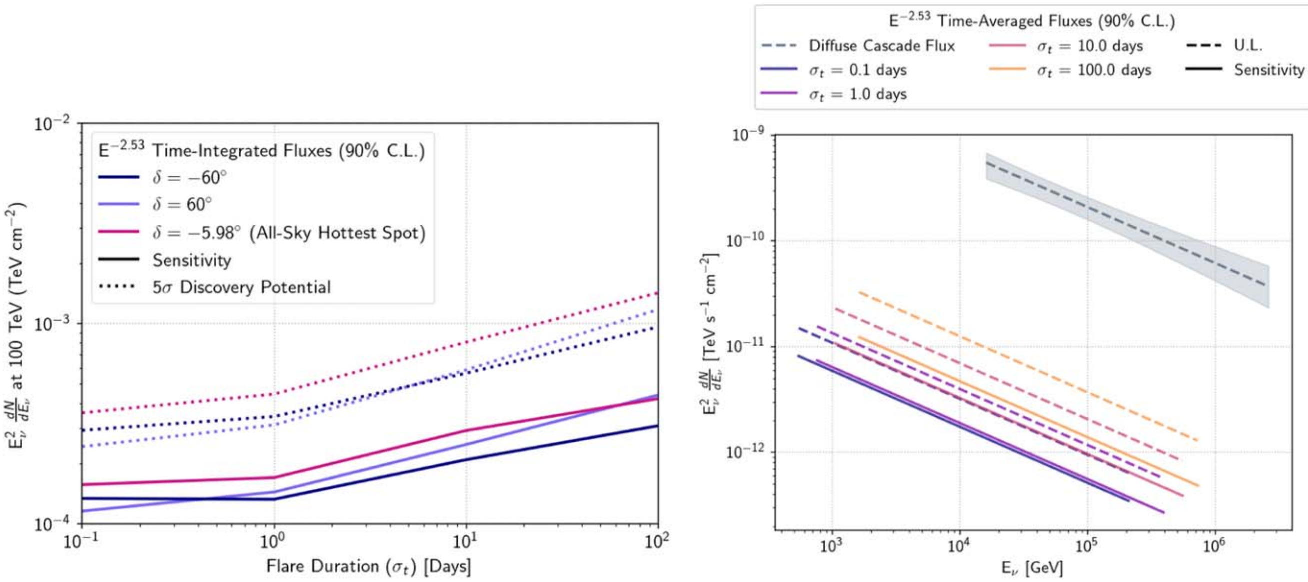

Figure 2. Left: Fluences of neutrino flares at the 90% sensitivity and 5σ discovery potential of this analysis, assuming flare durations between 0.1 and 100 days. An energy spectrum of $E^{-2.53}$ is assumed in these flares, to match that of the measured diffuse neutrino emission in cascades (Aartsen et al. 2020). Simulated flares are placed at the decl. of the hottest spot found, and also at a benchmark decl. of ±60o. Right: Comparison of the time-averaged upper limit and sensitivity fluxes, at the decl. of the hottest spot, to the previously measured steady-state diffuse neutrino flux (Aartsen et al. 2020). As the flare duration increases, the maximum possible contribution to the diffuse cascade flux increases. For each possible flare duration shown, hundreds or thousands of independent neutrino flares are needed to equal the entire diffuse astrophysical flux. At the longest flare duration (100 days), at least 100 neutrino flares are needed to account for the observed diffuse flux.

from the best-fit spectral index of the measured diffuse cascade flux.

As no significant flare was observed, we calculated the 90% upper limits (U.L.) on neutrino fluxes (Figure 2—right) for the all-sky hottest spot, and we discuss implications for the observed diffuse astrophysical flux. Assuming a power law of $E^{-2.53}$ taken from the measured diffuse cascade flux, we calculate the time-averaged fluxes at the sensitivity of this analysis and the resulting U.L. from data, each at the 90% C.L., at the location of the most significant point. The energy range used for each flux corresponds to the energy range of the neutrino events contributing to 90% of the flux. Fluxes are converted to time-averaged fluxes by distributing them over the entire livetime of the data set in order to compare to the measured diffuse cascade flux. As the flare duration increases, the maximum possible contribution from a single neutrino flare to the diffuse astrophysical neutrino flux increases. However, at least 100 neutrino flares of $\sigma_t = 100$ days are needed to account for the diffuse astrophysical flux.

4. Conclusions

In the all-sky search for transient neutrino emission, no significant spatial and temporal clustering was observed. We provide upper limits on the time-averaged neutrino flux at the 90% confidence level for various assumed flare durations, as shown in Figure 2—left. These all-sky upper limits show that, depending on the flare duration, hundreds or thousands of individual neutrino flares are needed in order to comprise the diffuse astrophysical neutrino flux. These all-sky upper limits are not dependent on a specified class of astrophysical transient objects; thus, multiple unresolved transient objects may contribute to the diffuse neutrino flux.

Cascades provide upper limits that can help constrain future searches for transient neutrino emission. Cascade data sets are considered to be independent of IceCube's track data sets, and future searches for transient neutrino emission could combine tracks and cascades. In addition, the next generation of IceCube, IceCube-Gen2, will have the capability to conduct a more sensitive search for transient neutrino emission across the entire sky (Aartsen et al. 2021). This will provide us with the opportunity to observe the origin of high-energy astrophysical neutrinos and further motivate time-domain multimessenger astronomy.

Acknowledgments

The IceCube collaboration acknowledges the significant contributions to this manuscript from Michael Kovacevich. USA—U.S. National Science Foundation–Office of Polar Programs, U.S. National Science Foundation–Physics Division, U.S. National Science Foundation–EPSCoR, U.S. National Science Foundation–Office of Advanced Cyberinfrastructure, Wisconsin Alumni Research Foundation, Center for High Throughput Computing (CHTC) at the University of Wisconsin–Madison, Open Science Grid (OSG), Partnership to Advance Throughput Computing (PATh), Advanced Cyberinfrastructure Coordination Ecosystem: Services & Support (ACCESS), Frontera computing project at the Texas Advanced Computing Center, U.S. Department of Energy–National Energy Research Scientific Computing Center, Particle Astrophysics Research Computing Center at the University of Maryland, Institute for Cyber-Enabled Research at Michigan State University, Astroparticle Physics Computational Facility at Marquette University, NVIDIA Corporation, and Google Cloud Platform; Belgium—Funds for Scientific Research (FRS-FNRS and FWO), FWO Odysseus and Big Science programmes, and Belgian Federal Science Policy Office (Belspo); Germany—Bundesministerium für Bildung und Forschung (BMBF), Deutsche Forschungsgemeinschaft (DFG), Helmholtz Alliance for Astroparticle Physics (HAP), Initiative and Networking Fund of the Helmholtz Association, Deutsches Elektronen Synchrotron (DESY), and High Performance Computing cluster of the RWTH Aachen; Sweden—

Swedish Research Council, Swedish Polar Research Secretariat, Swedish National Infrastructure for Computing (SNIC), and Knut and Alice Wallenberg Foundation; European Union—EGI Advanced Computing for Research; Australia—Australian Research Council; Canada—Natural Sciences and Engineering Research Council of Canada, Calcul Québec, Compute Ontario, Canada Foundation for Innovation, WestGrid, and Digital Research Alliance of Canada; Denmark—Villum Fonden, Carlsberg Foundation, and European Commission; New Zealand—Marsden Fund; Japan—Japan Society for Promotion of Science (JSPS) and Institute for Global Prominent Research (IGPR) of Chiba University; Korea—National Research Foundation of Korea (NRF); Switzerland—Swiss National Science Foundation (SNSF).

ORCID iDs

R. Abbasi https://orcid.org/0000-0001-6141-4205
M. Ackermann https://orcid.org/0000-0001-8952-588X
S. K. Agarwalla https://orcid.org/0000-0002-9714-8866
J. A. Aguilar https://orcid.org/0000-0003-2252-9514
M. Ahlers https://orcid.org/0000-0003-0709-5631
J. M. Alameddine https://orcid.org/0000-0002-9534-9189
K. Andeen https://orcid.org/0000-0001-9394-0007
G. Anton https://orcid.org/0000-0003-2039-4724
C. Argüelles https://orcid.org/0000-0003-4186-4182
Y. Ashida https://orcid.org/0000-0003-4136-2086
S. N. Axani https://orcid.org/0000-0001-8866-3826
X. Bai https://orcid.org/0000-0002-1827-9121
A. Balagopal V. https://orcid.org/0000-0001-5367-8876
S. W. Barwick https://orcid.org/0000-0003-2050-6714
V. Basu https://orcid.org/0000-0002-9528-2009
J. J. Beatty https://orcid.org/0000-0003-0481-4952
J. Becker Tjus https://orcid.org/0000-0002-1748-7367
J. Beise https://orcid.org/0000-0002-7448-4189
C. Bellenghi https://orcid.org/0000-0001-8525-7515
S. BenZvi https://orcid.org/0000-0001-5537-4710
E. Bernardini https://orcid.org/0000-0003-3108-1141
E. Blaufuss https://orcid.org/0000-0001-5450-1757
S. Blot https://orcid.org/0000-0003-1089-3001
J. Y. Book https://orcid.org/0000-0001-6687-5959
C. Boscolo Meneguolo https://orcid.org/0000-0001-8325-4329
S. Böser https://orcid.org/0000-0002-5918-4890
O. Botner https://orcid.org/0000-0001-8588-7306
J. Böttcher https://orcid.org/0000-0002-3387-4236
B. Brinson https://orcid.org/0000-0001-9128-1159
M. A. Campana https://orcid.org/0000-0003-4162-5739
C. Chen https://orcid.org/0000-0002-8139-4106
Z. Chen https://orcid.org/0000-0002-2813-7688
D. Chirkin https://orcid.org/0000-0003-4911-1345
B. A. Clark https://orcid.org/0000-0003-4089-2245
A. Coleman https://orcid.org/0000-0003-1510-1712
J. M. Conrad https://orcid.org/0000-0002-6393-0438
P. Coppin https://orcid.org/0000-0001-6869-1280
P. Correa https://orcid.org/0000-0002-1158-6735
D. F. Cowen https://orcid.org/0000-0003-4738-0787
P. Dave https://orcid.org/0000-0002-3879-5115
C. De Clercq https://orcid.org/0000-0001-5266-7059
J. J. DeLaunay https://orcid.org/0000-0001-5229-1995
D. Delgado https://orcid.org/0000-0002-4306-8828
A. Desai https://orcid.org/0000-0001-7405-9994
P. Desiati https://orcid.org/0000-0001-9768-1858
K. D. de Vries https://orcid.org/0000-0002-9842-4068
G. de Wasseige https://orcid.org/0000-0002-1010-5100
T. DeYoung https://orcid.org/0000-0003-4873-3783
A. Diaz https://orcid.org/0000-0001-7206-8336
J. C. Díaz-Vélez https://orcid.org/0000-0002-0087-0693
H. Dujmovic https://orcid.org/0000-0003-1891-0718
M. A. DuVernois https://orcid.org/0000-0002-2987-9691
P. Eller https://orcid.org/0000-0001-6354-5209
D. Elsässer https://orcid.org/0000-0001-6796-3205
H. Erpenbeck https://orcid.org/0000-0001-6319-2108
P. A. Evenson https://orcid.org/0000-0001-7929-810X
K. L. Fan https://orcid.org/0000-0002-8246-4751
A. R. Fazely https://orcid.org/0000-0002-6907-8020
A. Fedynitch https://orcid.org/0000-0003-2837-3477
C. Finley https://orcid.org/0000-0003-3350-390X
L. Fischer https://orcid.org/0000-0002-7645-8048
D. Fox https://orcid.org/0000-0002-3714-672X
A. Franckowiak https://orcid.org/0000-0002-5605-2219
P. Fürst https://orcid.org/0000-0002-7951-8042
E. Ganster https://orcid.org/0000-0003-4393-6944
A. Garcia https://orcid.org/0000-0002-8186-2459
A. Ghadimi https://orcid.org/0000-0002-6350-6485
T. Glauch https://orcid.org/0000-0003-1804-4055
T. Glüsenkamp https://orcid.org/0000-0002-2268-9297
S. J. Gray https://orcid.org/0000-0003-2907-8306
S. Griffin https://orcid.org/0000-0002-0779-9623
S. Griswold https://orcid.org/0000-0002-7321-7513
K. M. Groth https://orcid.org/0000-0002-1581-9049
P. Gutjahr https://orcid.org/0000-0001-7980-7285
C. Haack https://orcid.org/0000-0003-3932-2448
A. Hallgren https://orcid.org/0000-0001-7751-4489
L. Halve https://orcid.org/0000-0003-2237-6714
F. Halzen https://orcid.org/0000-0001-6224-2417
H. Hamdaoui https://orcid.org/0000-0001-5709-2100
A. Haungs https://orcid.org/0000-0002-9638-7574
K. Helbing https://orcid.org/0000-0003-2072-4172
J. Hellrung https://orcid.org/0009-0006-7300-8961
N. Heyer https://orcid.org/0000-0001-9036-8623
C. Hill https://orcid.org/0000-0003-0647-9174
W. Hou https://orcid.org/0000-0003-3422-7185
T. Huber https://orcid.org/0000-0002-6515-1673
K. Hultqvist https://orcid.org/0000-0003-0602-9472
M. Hünnefeld https://orcid.org/0000-0002-2827-6522
G. S. Japaridze https://orcid.org/0000-0002-7000-5291
M. Jeong https://orcid.org/0000-0003-2420-6639
M. Jin https://orcid.org/0000-0003-0487-5595
B. J. P. Jones https://orcid.org/0000-0003-3400-8986
D. Kang https://orcid.org/0000-0002-5149-9767
W. Kang https://orcid.org/0000-0003-3980-3778
A. Kappes https://orcid.org/0000-0003-1315-3711
T. Karg https://orcid.org/0000-0003-3251-2126
M. Karl https://orcid.org/0000-0003-2475-8951
A. Karle https://orcid.org/0000-0001-9889-5161
U. Katz https://orcid.org/0000-0002-7063-4418
M. Kauer https://orcid.org/0000-0003-1830-9076
J. L. Kelley https://orcid.org/0000-0002-0846-4542
A. Khatee Zathul https://orcid.org/0000-0002-8735-8579
A. Kheirandish https://orcid.org/0000-0001-7074-0539
J. Kiryluk https://orcid.org/0000-0003-0264-3133
S. R. Klein https://orcid.org/0000-0003-2841-6553
A. Kochocki https://orcid.org/0000-0003-3782-0128
R. Koirala https://orcid.org/0000-0002-7735-7169

H. Kolanoski https://orcid.org/0000-0003-0435-2524
T. Kontrimas https://orcid.org/0000-0001-8585-0933
C. Kopper https://orcid.org/0000-0001-6288-7637
D. J. Koskinen https://orcid.org/0000-0002-0514-5917
P. Koundal https://orcid.org/0000-0002-5917-5230
M. Kovacevich https://orcid.org/0000-0002-5019-5745
M. Kowalski https://orcid.org/0000-0001-8594-8666
J. Krishnamoorthi https://orcid.org/0009-0006-1352-2248
K. Kruiswijk https://orcid.org/0009-0002-9261-0537
A. Kumar https://orcid.org/0000-0002-8367-8401
N. Kurahashi https://orcid.org/0000-0003-1047-8094
N. Lad https://orcid.org/0000-0001-9302-5140
C. Lagunas Gualda https://orcid.org/0000-0002-9040-7191
M. Lamoureux https://orcid.org/0000-0002-8860-5826
M. J. Larson https://orcid.org/0000-0002-6996-1155
F. Lauber https://orcid.org/0000-0001-5648-5930
J. P. Lazar https://orcid.org/0000-0003-0928-5025
J. W. Lee https://orcid.org/0000-0001-5681-4941
K. Leonard DeHolton https://orcid.org/0000-0002-8795-0601
A. Leszczyńska https://orcid.org/0000-0003-0935-6313
M. Lincetto https://orcid.org/0000-0002-1460-3369
L. Lu https://orcid.org/0000-0003-3175-7770
F. Lucarelli https://orcid.org/0000-0002-9558-8788
W. Luszczak https://orcid.org/0000-0003-3085-0674
Y. Lyu https://orcid.org/0000-0002-2333-4383
J. Madsen https://orcid.org/0000-0003-2415-9959
E. Manao https://orcid.org/0009-0002-6197-8574
S. Mancina https://orcid.org/0009-0003-9879-3896
I. C. Mariş https://orcid.org/0000-0002-5771-1124
R. Maruyama https://orcid.org/0000-0003-2794-512X
F. Mayhew https://orcid.org/0000-0001-7609-403X
F. McNally https://orcid.org/0000-0002-0785-2244
K. Meagher https://orcid.org/0000-0003-3967-1533
M. Meier https://orcid.org/0000-0002-9483-9450
L. Merten https://orcid.org/0000-0003-1332-9895
T. Montaruli https://orcid.org/0000-0001-5014-2152
R. W. Moore https://orcid.org/0000-0003-4160-4700
M. Moulai https://orcid.org/0000-0001-7909-5812
T. Mukherjee https://orcid.org/0000-0002-0962-4878
R. Naab https://orcid.org/0000-0003-2512-466X
R. Nagai https://orcid.org/0000-0001-7503-2777
J. Necker https://orcid.org/0000-0003-0280-7484
H. Niederhausen https://orcid.org/0000-0002-9566-4904
M. U. Nisa https://orcid.org/0000-0002-6859-3944
A. Obertacke Pollmann https://orcid.org/0000-0002-2492-043X
V. O'Dell https://orcid.org/0000-0003-0903-543X
B. Oeyen https://orcid.org/0000-0003-2940-3164
E. O'Sullivan https://orcid.org/0000-0003-1882-8802
H. Pandya https://orcid.org/0000-0002-6138-4808
N. Park https://orcid.org/0000-0002-4282-736X
E. N. Paudel https://orcid.org/0000-0001-9276-7994
L. Paul https://orcid.org/0000-0003-4007-2829
C. Pérez de los Heros https://orcid.org/0000-0002-2084-5866
S. Philippen https://orcid.org/0000-0002-0276-0092
A. Pizzuto https://orcid.org/0000-0002-8466-8168
M. Plum https://orcid.org/0000-0001-8691-242X
B. Pries https://orcid.org/0000-0003-4811-9863
C. Raab https://orcid.org/0000-0001-9921-2668
A. Rehman https://orcid.org/0000-0001-7616-5790
E. Resconi https://orcid.org/0000-0003-0705-2770
W. Rhode https://orcid.org/0000-0003-2636-5000
B. Riedel https://orcid.org/0000-0002-9524-8943
M. Rongen https://orcid.org/0000-0002-7057-1007
C. Rott https://orcid.org/0000-0002-6958-6033
T. Ruhe https://orcid.org/0000-0002-4080-9563
D. Ryckbosch https://orcid.org/0000-0002-8759-7553
I. Safa https://orcid.org/0000-0001-8737-6825
D. Salazar-Gallegos https://orcid.org/0000-0002-9312-9684
A. Sandrock https://orcid.org/0000-0002-6779-1172
M. Santander https://orcid.org/0000-0001-7297-8217
S. Sarkar https://orcid.org/0000-0002-1206-4330
S. Sarkar https://orcid.org/0000-0002-3542-858X
H. Schieler https://orcid.org/0000-0002-2637-4778
S. Schindler https://orcid.org/0000-0001-5507-8890
L. Schlickmann https://orcid.org/0000-0002-9746-6872
F. Schlüter https://orcid.org/0000-0002-5545-4363
J. Schneider https://orcid.org/0000-0001-7752-5700
F. G. Schröder https://orcid.org/0000-0001-8495-7210
L. Schumacher https://orcid.org/0000-0001-8945-6722
S. Sclafani https://orcid.org/0000-0001-9446-1219
M. Seikh https://orcid.org/0000-0002-4464-7354
S. Seunarine https://orcid.org/0000-0003-3272-6896
M. Silva https://orcid.org/0000-0001-6940-8184
B. Skrzypek https://orcid.org/0000-0002-0910-1057
B. Smithers https://orcid.org/0000-0003-1273-985X
D. Soldin https://orcid.org/0000-0003-3005-7879
P. Soldin https://orcid.org/0000-0003-1761-2495
G. Sommani https://orcid.org/0000-0002-0094-826X
G. M. Spiczak https://orcid.org/0000-0002-0030-0519
C. Spiering https://orcid.org/0000-0001-7372-0074
T. Stezelberger https://orcid.org/0000-0003-2676-9574
T. Stuttard https://orcid.org/0000-0001-7944-279X
G. W. Sullivan https://orcid.org/0000-0002-2585-2352
I. Taboada https://orcid.org/0000-0003-3509-3457
S. Ter-Antonyan https://orcid.org/0000-0002-5788-1369
W. G. Thompson https://orcid.org/0000-0003-2988-7998
J. Thwaites https://orcid.org/0000-0001-9179-3760
K. Tollefson https://orcid.org/0000-0001-9725-1479
S. Toscano https://orcid.org/0000-0002-1860-2240
C. F. Tung https://orcid.org/0000-0001-6920-7841
M. A. Unland Elorrieta https://orcid.org/0000-0002-6124-3255
A. K. Upadhyay https://orcid.org/0000-0003-1957-2626
N. Valtonen-Mattila https://orcid.org/0000-0002-1830-098X
J. Vandenbroucke https://orcid.org/0000-0002-9867-6548
N. van Eijndhoven https://orcid.org/0000-0001-5558-3328
J. van Santen https://orcid.org/0000-0002-2412-9728
S. Verpoest https://orcid.org/0000-0002-3031-3206
C. Weaver https://orcid.org/0000-0003-2385-2559
C. Wendt https://orcid.org/0000-0001-8076-8877
N. Whitehorn https://orcid.org/0000-0002-3157-0407
C. H. Wiebusch https://orcid.org/0000-0002-6418-3008
M. Wolf https://orcid.org/0000-0001-9991-3923
S. Yoshida https://orcid.org/0000-0003-2480-5105
T. Yuan https://orcid.org/0000-0002-7041-5872

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