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Low-latency neutrino follow-up combining diverse IceCube selections

The IceCube Collaboration

(a complete list of authors can be found at the end of the proceedings)

E-mail: chraab@icecube.wisc.edu, sahori@icecube.wisc.edu, ssclafani@icecube.wisc.edu, jthwaites@icecube.wisc.edu

Neutrino observations are a crucial component of multi-messenger astronomy, but are currently limited by effective area and high atmospheric background. However, while other telescopes with limited field of view must be pointed in order to capture observations, IceCube's full-sky field of view and high uptime make it an excellent instrument for realtime follow-up of astrophysical transient sources. IceCube searches for neutrino transients using an unbinned maximum likelihood method with parameters for the source's emission time period, extension, and energy spectrum. This Fast Response Analysis can provide analysis results within tens of minutes of an astrophysical transient. Besides the follow-up of astrophysical transients manually selected as candidates, it also routinely scans areas of the sky compatible with gravitational wave alerts from LIGO/Virgo/KAGRA and IceCube event singlets which have a high probability of originating from an astrophysical source. Currently the analysis uses TeV muon neutrino candidate events whose track signature is especially suited for a precise angular reconstruction, selected and reconstructed at the South Pole and transmitted with low-latency over a satellite connection. Recently, IceCube and the neutrino astronomy community are evolving to use event samples constructed with different selections. These efforts include the follow-up of gravitational wave events with GeV neutrinos detected by IceCube-DeepCore and the observation of the Galactic plane with cascade events produced by all neutrino flavors. With plans to make IceCube-DeepCore GeV neutrino candidates and cascade events available on a day-scale latency, they can also be used in Fast Response Analyses. Moreso, multiple event samples can be combined in a Fast Response Analysis that is sensitive to a broader energy range of a neutrino transient spectrum and ensures the inclusion of all neutrino flavors. We present the analysis method and technical aspects of such an extension of the existing framework. This includes a proposed new pipeline allowing the inclusion of the more computationally-intensive reconstruction methods used by the aforementioned event selections. The extension is validated using example analyses implemented in this framework.

Corresponding authors: Christoph Raab[1*], Sam Hori[2], Steve Sclafani[3], Jessie Thwaites[2]

[1] *CP3, Université catholique de Louvain*

[2] *Dept. of Physics and WIPAC, University of Wisconsin-Madison*

[3] *University of Maryland*

[*] Presenter

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1. Motivation

Many astrophysical transients, such as gamma ray bursts, supernovae, AGN flares and novae are expected to produce high-energy neutrinos via hadronic processes. The understanding of these sources would be greatly enhanced by observing such multi-messenger signals. IceCube is a cubic kilometer neutrino telescope installed at the South Pole and prominently positioned to contribute to these observations thanks to its high uptime and full-sky field of view. A small number of individual neutrino point sources associated with known counterparts has been found in archival analyses [1, 2]. After an astrophysical transient candidate, providing neutrino source detections with low latency to other telescopes would permit rapid follow-up observations especially for those with a narrower field of view. In this way, a low-latency neutrino source search contributes to the characterization of the transient in question.

2. Current usage and implementation

IceCube instruments a cubic kilometer of glacial ice at the South Pole with an array of 5,160 photo-multipliers. They detect Cherenkov light induced by charged particles exceeding the speed of light in the ice. For the charged-current interactions of ν_μ in this volume, the Cherenkov light traces the path of the outgoing muon in a so-called *track* event signature. This is particularly suited for event reconstruction methods to infer the neutrino arrival direction. The majority of neutrino interactions meanwhile produce charged particles which lose their energy within a smaller area. This spherical signature, called a *cascade*, also allows directional reconstruction, albeit with limited precision.

While the majority of IceCube data processing happens in the northern hemisphere, during IceCube data-taking, a sub-set of events are selected and reconstructed at the South Pole [3, 4]. This event selection, called the Gamma-ray Follow-up (GFU) dataset, consists of high energy tracks, transmitted to the North with high priority over a low-latency, low-bandwidth satellite link [3] and used in several online analyses including the gamma-ray follow-up program [5]. GFU events have a good angular resolution ($\lesssim 1°$ radius) and are reconstructed with low latency. These events are received in the northern hemisphere after roughly 60 s and can be quickly queried from a database according to the desired follow-up time window. Together with archival data of past seasons to represent the background and Monte Carlo simulation to represent the signal, these are used in low-latency likelihood analyses. Internal reports with detector status quantities and analysis results are automatically generated as part of the same pipeline.

The current implementation of this Fast Response Analysis (FRA) is used to search for neutrino emission from a variety of transients, including gravitational wave events [6] and electromagnetically-detected transients [7]. The FRA is also used to search for additional track events surrounding all public IceCube alert events, which would be indicative of a neutrino flare from a source [8]. One such follow-up of an IceCube alert was the case of IceCube-Cascade 240714A (ATel 16708). The FRA identified two track-like events spatially coincident with one another and the cascade alert event skymap (shown in figure 1). This represents a pre-trials p-value of 0.007 in the analysis. The public telegram sent by IceCube saw follow-ups from multiple observatories, including Fermi-LAT (GCN 36892) and Einstein Probe (EP, GCN 36894). Fermi-LAT saw no excess gamma-ray emis-

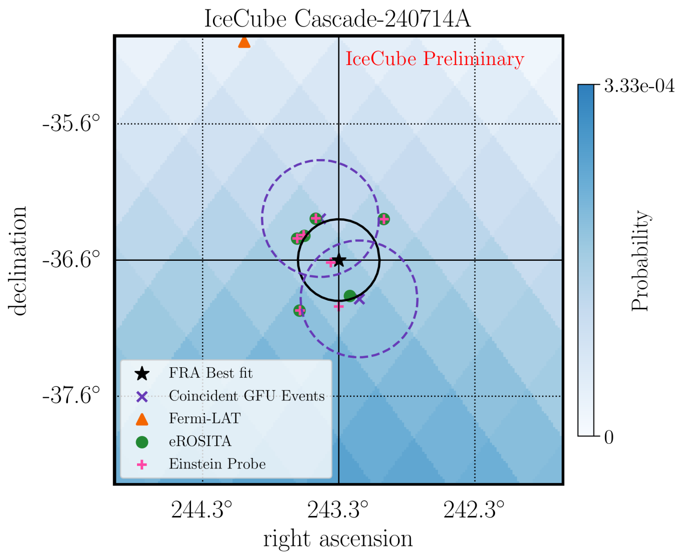


Figure 1: Skymap zoomed around the FRA best-fit for the ±1 day search for IceCube-Cascade 240714A. The two coincident GFU events are shown (purple) with the FRA best-fit provided in real-time (star). In real-time, an error around the best-fit was also provided with a radius of 0.3° (shown as a black circle). The nearest Fermi-LAT source (top of plot) is shown in an orange triangle. Einstein Probe followed up our ATel in real-time, and reported sources they detected (labeled Einstein Probe) and associated eROSITA catalog sources.

sion consistent with the best-fit position. EP identified 7 sources, including two within the 0.3° error circle of the analysis best-fit, one of which was previously uncatalogued. The EP sources were followed up by the Thai Robotic Telescope network, which found no uncatalogued sources consistent with the EP sources, and no apparent brightening for cataloged sources in the R-band (GCN 36902). This example illustrates the interest of the community in these short timescale analyses performed in the FRA, in order to rapidly detect and observe potential multimessenger sources.

3. Reduced-latency data stream method

The GFU track events provide good spatial resolution, but rejecting the background of atmospheric muons induced by cosmic rays requires a higher energy threshold in the southern sky. Transient neutrino source searches are expanding to use more diverse event selections. This includes for example cascade events [9], whose event signature is distinct from atmospheric muons, allowing for a more even sky coverage of all neutrino transient candidates. The DNN Cascades selection in particular was the sample used in the observation of a 4.5σ excess from the Galactic plane [10]. IceCube further possesses a denser in-fill array called DeepCore, allowing it to extend to sub-TeV energies, which is well-motivated by the predicted emission of GeV neutrinos from e.g. GRBs [11]. Available event selections are e.g. the reconstructed GRECO[1] tracks and cascades [9]. The ELOWEN[2] selection contains the faintest events triggering DeepCore [12], but currently can

[1] GeV Reconstructed Events with Containment for Oscillation
[2] Extremely LOW ENergy

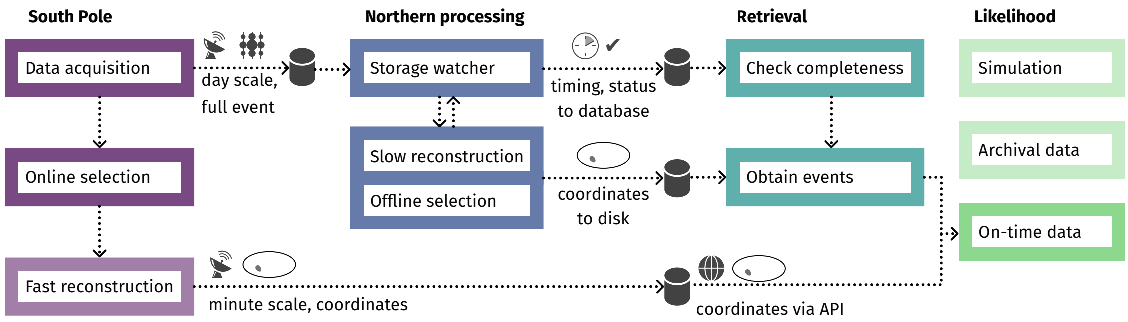


Figure 3: Flow chart of reduced latency data stream methods. The upper path corresponds to the day-scale latency method proposed in section 3 for DNN Cascades and GRECO, while the lower path describes the one currently used by GFU.

only rely on timing information to identify astrophysical activity. The goal of the current work is to allow a low-latency application of these event selections to transient searches.

Some of these new event selections use more computationally intensive reconstruction methods, which unlike GFU's can not be run at the South Pole in tandem with data acquisition. We propose an approach, illustrated by the diagram in fig. 3, to nevertheless make these accessible with day-scale latency, allowing for a range of follow-up analyses analogous to the archival ones.

Event data is transmitted from the South Pole over a high-bandwidth partial-uptime satellite link [3] and arrives in the North typically within $\approx$ 16 hours (half of events) to $\approx$ 1.5 days ($>$ 99%), divided into $O(1000)$ files per calendar day. Each file is bundled with metadata indicated the period of data covered therein. As it is forwarded to event selection and reconstruction, this metadata is stored in a tracking database. Upon completion, the processing success is stored in the same database and the reconstructed events in a separate repository, indexed by calendar day for convenient retrieval of on-time events.

The DNN Cascade selection uses a series of neural networks (NNs) and boosted decision trees (BDTs) to quickly identify cascade-like events in IceCube and reject incoming atmospheric muons. The selection is trained on data and simulation using summarized information based on the event light deposition. This differs from the previous strategy of using high-level information. Due to the speed of the NNs and the removal of high-level reconstruction, the selection can be applied at an earlier stage of the data selection pipeline. The result is a dataset that improves the efficiency when compared to previous selections. Between 2011 and 2021, 6% of its events are atmospheric muons, and 87% atmospheric neutrinos. The remaining 7% of events are attributed to astrophysical neutri-

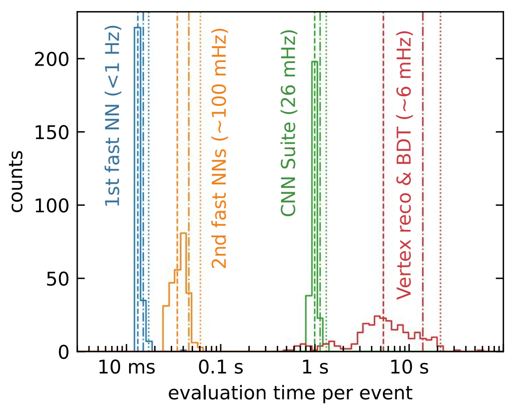


Figure 2: CPU time required per event for stages of the DNN Cascades selection leading up to the reconstruction. As the rate decreases, more computationally intensive methods can be used.

nos [10].

These events have an angular resolution that is $\sim 10^\circ$ at energies above 10 TeV, compared to GFU reaching sub-degree resolution. Despite the larger uncertainty, the purity of the dataset and the improved sensitivity in the southern hemisphere make realtime or near-realtime followup with this selection particularly interesting. The final reconstruction takes 2–3 minutes to complete for most events.

IceCube can send compressed event data records to the North with low latency at a limited rate. This can eventually be used in a scheme that runs the first stage of the DNN Cascades selection at the South Pole, reducing the data rate to 6 mHz, shown in fig. 2. Event data at this rate can then be transmitted to the North, and after applying the final reconstruction and selection with minimum latency these events would also available for analysis within tens of minutes.

Both the day-scale and minute-scale processing methods can be applied to GRECO, introduced previously, which currently also is reconstructed in the North with dedicated methods to accommodate for the low light yield in these events. These take an average of 2 minutes to complete, although some may take up to an hour, emphasizing the importance of asynchronous processing.

4. Data quality monitoring

IceCube data-taking proceeds in periods called *runs* which have a typical duration of 8 hours. The condition of the detector during one run and resulting data quality are verified manually afterwards, with help of an array of monitored quantities and knowledge of past problems. This allows to define the set of runs usable for a self-consistent archival data set. For FRA however, a heuristic is required that can assure data quality with a reasonable degree of confidence with lower latency. This has already been implemented to accommodate the GFU event selection [4]. This heuristic's starting point are the rates of intermediate event selection stages, measured in time intervals of typically 600 seconds. With this rate as X and the exponentially weighted averages $\langle X \rangle$ and $\langle X^2 \rangle$, a Z-score is calculated for the deviation of $X - \langle X \rangle$ relative to the standard deviation.

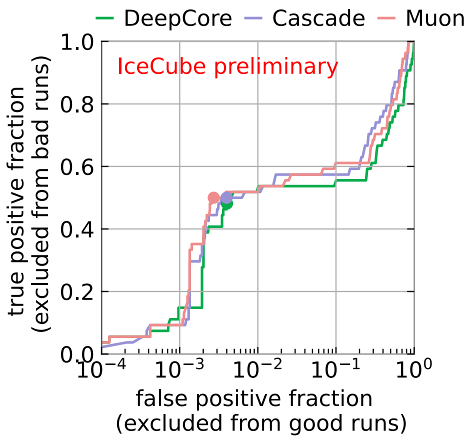
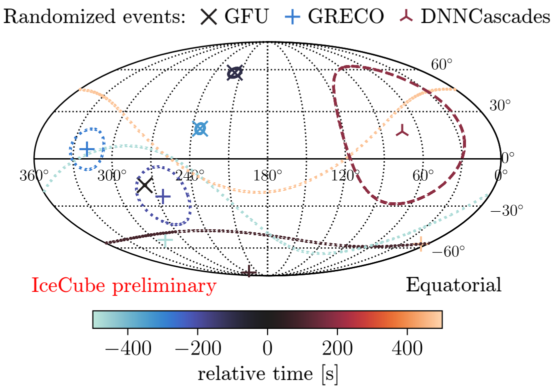


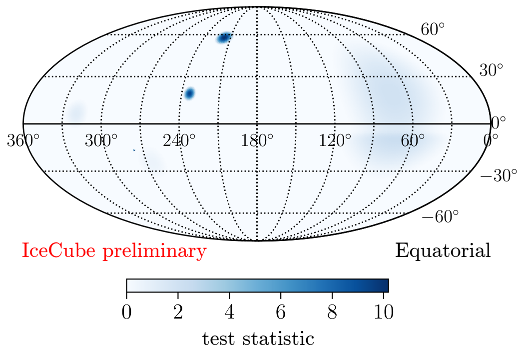
Figure 4: ROC curves comparing possible thresholds to be set on the three instability scores. The x-axis is a "false positive" rejection rate during good runs, while the y-axis is the "true positive" rejection during bad runs. The threshold of 10 is indicated by filled circles on the respective curves.

Summing this Z-score for several rates as well as the ratio between them results in the final instability score, which can be compared to a threshold. We present here instability scores that are analogously derived for a cascade selection like DNN Cascades, and a DeepCore-focused selection like GRECO or ELOWEN. These might eventually prove to take complementary roles to the original, ensuring the quality of the specific event selections.

In the new definitions, the Z-scores are also weighted proportionally to $\sqrt{\Delta t}$ in accordance with the expected variance. This suppresses the statistical fluctuations present for the GFU instability score during shorter-than-typical bins. Figure 4 shows that both new scores remain sensitive to



(a) Sky map of randomized events within a 1000-second interval including one DNN Cascades event.



(b) Corresponding test statistic map in a point source analysis combining the three event selections.

Figure 5

conditions flagged by the run monitoring, and a common threshold or multi-variate cut can be optimized for a particular analysis.

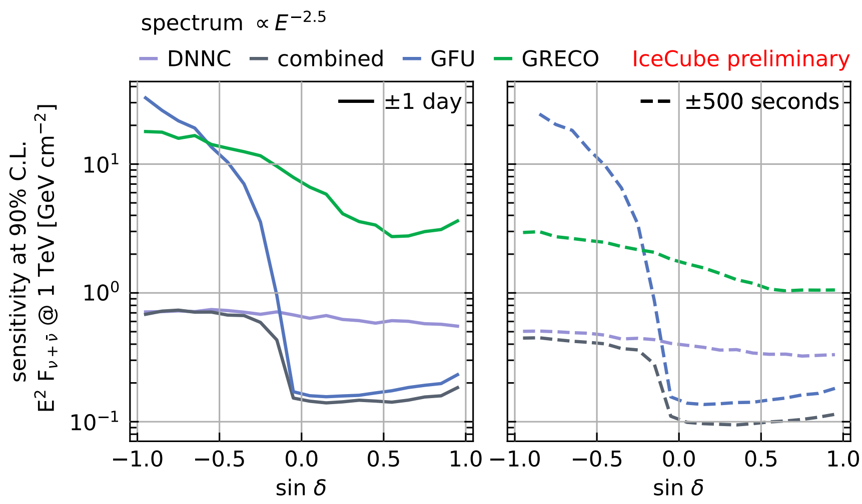
5. Examples and performance

As an example we show the combination of three event selections in a point source search, using the previously implemented unbinned likelihood method [13]. Instead of fitting the source hypothesis with each selection independently, they are able to share its parameters: position, time window, spectral index and flux normalization. Each event selection's acceptance to this signal determines the expected number of detected events.

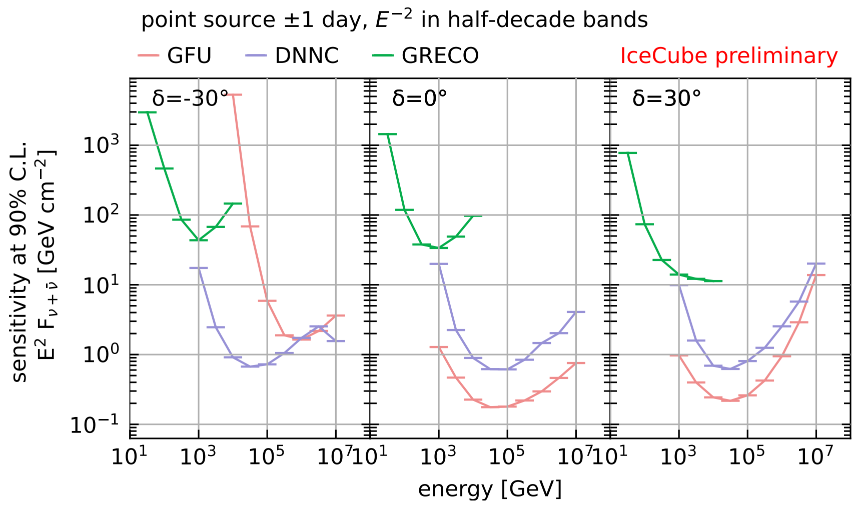
The selections comprise the GFU high-energy tracks (already used in the current implementation), the reconstructed DeepCore tracks and cascades of GRECO, and the high-energy cascades in DNN Cascades. The use of these selections for neutrino follow-up mirrors the original FRA [7] as well as archival analyses of gravitational wave events [9]. We include events that appear in multiple event selections: 1.8% of GFU events are also in GRECO and 0.03% also in DNN Cascades, and the latter selections have an overlap of 0.2%.

A sky map of a simulated background-only observation in a 1000 s window follow-up is shown in fig. 5a. Scanning the full sky, these then correspond to the test statistic map in fig. 5b, which the FRA can combine with the probability sky map of a neutrino or gravitational wave event [7] for a joint search and possible improved localization.

Sensitivities are calculated at 90% C.L. for a search in commonly used time windows of ±500 s or ±1 day. The comparison in fig. 6a shows that addition of other event selections to GFU helps regain sensitivity in the southern hemisphere lost to the latter's muon background. The number of background events within a typical point spread function meanwhile affects the sensitivity more for follow-ups in longer time windows. We also show differential sensitivities versus neutrino energy, which show the complementarity of event selections in fig. 6b.



(a) Time-integrated sensitivity towards a power-law $\nu + \bar{\nu}$ flux, per-flavor at 1 TeV. Shown are follow-ups in time windows of ±1 d (solid lines) and ±500 s (dashed lines). Each is performed individually with one of three event selections: GRECO (green), GFU (blue), DNN Cascades (purple) or their multi-FRA combination (gray).



(b) Differential sensitivity in energy for an E^{-2} per-flavor $\nu + \bar{\nu}$ flux in half-decade energy bands, assuming a time window of ±1 day. Each is performed individually with one of three event selections: GRECO (green), GFU (red), DNN Cascades (purple).

Figure 6

6. Conclusions and outlook

Building on a powerful framework and program (see section 2), the presented work shows a first step towards more comprehensive neutrino follow-ups which cover a larger fraction of the neutrino transient hypothesis space (see section 5). This involves a more even coverage of the sky, as well as sensitivity to GeV neutrino emission, shown in fig. 6. The implementation supports arbitrary event selections. In the future, the latency will be further decreased by implementation of the minute-scale approach described in section 3. Remaining points to resolve include the removal of events appearing in multiple event selections, although this is a rare exception.

Already now, the multi-selection FRA can accommodate spectral parameters, although so far it has only been used with single power-law spectra. Incorporating multiple independent spectral components promises to make fuller use of the broadened energy range. At extremely low energies, events are no longer reconstructed the same way and require a different formulation to the corresponding likelihood term, which remains for future work.

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Full Author List: IceCube Collaboration

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Khatee Zathul[39], A. Kheirandish[33,34], H. Kimku[53], J. Kiryluk[55], C. Klein[25], S. R. Klein[6,7], Y. Kobayashi[15], A. Kochocki[23], R. Koirala[43], H. Kolanoski[8], T. Kontrimas[26], L. Köpke[40], C. Kopper[25], D. J. Koskinen[21], P. Koundal[43], M. Kowalski[8,63], T. Kozynets[21], N. Krieger[9], J. Krishnamoorthi[39,a], T. Krishnan[13], K. Kruiswijk[36], E. Krupczak[23], A. Kumar[63], E. Kun[9], N. Kurahashi[48], N. Lad[63], C. Lagunas Gualda[26], L. Lallement Arnaud[10], M. Lamoureux[36], M. J. Larson[18], F. Lauber[62], J. P. Lazar[36], K. Leonard DeHolton[60], A. Leszczyńska[43], J. Liao[4], C. Lin[43], Y. T. Liu[60], M. Liubarska[24], C. Love[48], L. Lu[39], F. Lucarelli[27], W. Luszczak[19,20], Y. Lyu[6,7], J. Madsen[39], E. Magnus[11], K. B. M. Mahn[23], Y. Makino[39], E. Manao[26], S. Mancina[47,e], A. Mand[39], I. C. Mariş[10], S. Marka[45], Z. Marka[45], L. Marten[1], I. Martinez-Soler[13], R. Maruyama[44], J. Mauro[36], F. Mayhew[23], F. McNally[37], J. V. Mead[21], K. Meagher[39], S. Mechbal[63], A. Medina[20], M. Meier[15], Y. Merckx[11], L. Merten[9], J. Mitchell[5], L. Molchany[49], T. Montaruli[27], R. W. Moore[24], Y. Morii[15], A. Mosbrugger[25], M. Moulai[39], D. Mousadi[63], E. Moyaux[36], T. Mukherjee[30], R. Naab[63], M. Nakos[39], U. Naumann[62], J. Necker[63], L. Neste[54], M. Neumann[42], H. Niederhausen[23], M. U. Nisa[23], K. Noda[15], A. Noell[1], A. Novikov[43], A. Obertacke Pollmann[15], V. O'Dell[39], A. Olivas[18], R. Orsoe[26], J. Osborn[39], E. O'Sullivan[61], V. Palusova[40], H. Pandya[43], A. Parenti[10], N. Park[32], V. Parrish[23], E. N. Paudel[58], L. Paul[49], C. Pérez de los Heros[61], T. Pernice[63], J. Peterson[39], M. Plum[49], A. Pontén[61], V. Poojyam[58], Y. Popovych[40], M. Prado Rodriguez[39], B. Pries[23], R. Procter-Murphy[18], G. T. Przybylski[7], L. Pyras[52], C. Raab[36], J. Rack-Helleis[40], N. Rad[63], M. Ravn[61], K. Rawlins[3], Z. Rechav[39], A. Rehman[43], I. Reistroffer[49], E. Resconi[26], S. Reusch[63], C. D. Rho[56], W. Rhode[22], L. Ricca[36], B. Riedel[39], A. Rifaie[62], E. J. Roberts[2], S. Robertson[6,7], M. Rongen[25], A. Rosted[15], C. Rott[52], T. Ruhe[22], L. Ruohan[26], D. Ryckbosch[28], J. Saffer[31], D. Salazar-Gallegos[23], P. Sampathkumar[30], A. Sandrock[62], G. Sanger-Johnson[23], M. Santander[58], S. Sarkar[46], J. Savelberg[1], M. Scarnera[36], P. Schaile[26], M. Schaufel[1], H. Schieler[30], S. Schindler[25], L. Schlickmann[40], B. Schlüter[42], F. Schlüter[10], N. Schmeisser[62], T. Schmidt[18], F. G. Schröder[30,43], L. Schumacher[25], S. Schwirn[1], S. Sclafani[18], D. Seckel[43], L. Seen[39], M. Seikh[35], S. Seunarine[50], P. A. Sevle Myhr[36], R. Shah[48], S. Shefali[31], N. Shimizu[15], B. Skrzypek[6], R. Snihur[39], J. Soedingrekso[22], A. Søgaard[21], D. Soldin[52], P. Soldin[1], G. Sommani[9], C. Spannfellner[26], G. M. Spiczak[50], C. Spiering[63], J. Stachurska[28], M. Stamatikos[20], T. Stanev[43], T. Stezelberger[7], T. Stürwald[62], T. Stuttard[21], G. W. Sullivan[18], I. Taboada[4], S. Ter-Antonyan[5], A. Terliuk[26], A. Thakuri[49], M. Thiesmeyer[39], W. G. Thompson[13], J. Thwaites[39], S. Tilav[43], K. Tollefson[23], S. Toscano[10], D. Tosi[39], A. Trettin[63], A. K. Upadhyay[39,a], K. Upshaw[5], A. Vaidyanathan[41], N. Valtonen-Mattila[9,61], J. Valverde[41], J. Vandenbroucke[39], T. van Eeden[63], N. van Eijndhoven[11], L. van Rootselaar[22], J. van Santen[63], F. J. Vara Carbonell[42], F. Varsi[31], M. Venugopal[30], M. Vereecken[36], S. Vergara Carrasco[17], S. Verpoest[43], D. Veske[45], A. Vijai[18], J. Villarreal[14], C. Walck[54], A. Wang[4], E. Warrick[58], C. Weaver[23], P. Weigel[14], A. Weindl[30], J. Weldert[40], A. Y. Wen[13], C. Wendt[39], J. Werthebach[22], M. Weyrauch[30], N. Whitehorn[23], C. H. Wiebusch[1], D. R. Williams[58], L. Witthaus[22], M. Wolf[26], G. Wrede[25], X. W. Xu[5], J. P. Yañez[24], Y. Yao[39], E. Yildizci[39], S. Yoshida[15], R. Young[35], F. Yu[13], S. Yu[52], T. Yuan[39], A. Zegarelli[9], S. Zhang[23], Z. Zhang[55], P. Zhelnin[13], P. Zilberman[39]

[1] III. Physikalisches Institut, RWTH Aachen University, D-52056 Aachen, Germany
[2] Department of Physics, University of Adelaide, Adelaide, 5005, Australia
[3] Dept. of Physics and Astronomy, University of Alaska Anchorage, 3211 Providence Dr., Anchorage, AK 99508, USA
[4] School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA 30332, USA
[5] Dept. of Physics, Southern University, Baton Rouge, LA 70813, USA
[6] Dept. of Physics, University of California, Berkeley, CA 94720, USA
[7] Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[8] Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany
[9] Fakultät für Physik & Astronomie, Ruhr-Universität Bochum, D-44780 Bochum, Germany
[10] Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium

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[11] Vrije Universiteit Brussel (VUB), Dienst ELEM, B-1050 Brussels, Belgium
[12] Dept. of Physics, Simon Fraser University, Burnaby, BC V5A 1S6, Canada
[13] Department of Physics and Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA 02138, USA
[14] Dept. of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[15] Dept. of Physics and The International Center for Hadron Astrophysics, Chiba University, Chiba 263-8522, Japan
[16] Department of Physics, Loyola University Chicago, Chicago, IL 60660, USA
[17] Dept. of Physics and Astronomy, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
[18] Dept. of Physics, University of Maryland, College Park, MD 20742, USA
[19] Dept. of Astronomy, Ohio State University, Columbus, OH 43210, USA
[20] Dept. of Physics and Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH 43210, USA
[21] Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark
[22] Dept. of Physics, TU Dortmund University, D-44221 Dortmund, Germany
[23] Dept. of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA
[24] Dept. of Physics, University of Alberta, Edmonton, Alberta, T6G 2E1, Canada
[25] Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany
[26] Physik-department, Technische Universität München, D-85748 Garching, Germany
[27] Département de physique nucléaire et corpusculaire, Université de Genève, CH-1211 Genève, Switzerland
[28] Dept. of Physics and Astronomy, University of Gent, B-9000 Gent, Belgium
[29] Dept. of Physics and Astronomy, University of California, Irvine, CA 92697, USA
[30] Karlsruhe Institute of Technology, Institute for Astroparticle Physics, D-76021 Karlsruhe, Germany
[31] Karlsruhe Institute of Technology, Institute of Experimental Particle Physics, D-76021 Karlsruhe, Germany
[32] Dept. of Physics, Engineering Physics, and Astronomy, Queen's University, Kingston, ON K7L 3N6, Canada
[33] Department of Physics & Astronomy, University of Nevada, Las Vegas, NV 89154, USA
[34] Nevada Center for Astrophysics, University of Nevada, Las Vegas, NV 89154, USA
[35] Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA
[36] Centre for Cosmology, Particle Physics and Phenomenology - CP3, Université catholique de Louvain, Louvain-la-Neuve, Belgium
[37] Department of Physics, Mercer University, Macon, GA 31207-0001, USA
[38] Dept. of Astronomy, University of Wisconsin—Madison, Madison, WI 53706, USA
[39] Dept. of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin—Madison, Madison, WI 53706, USA
[40] Institute of Physics, University of Mainz, Staudinger Weg 7, D-55099 Mainz, Germany
[41] Department of Physics, Marquette University, Milwaukee, WI 53201, USA
[42] Institut für Kernphysik, Universität Münster, D-48149 Münster, Germany
[43] Bartol Research Institute and Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
[44] Dept. of Physics, Yale University, New Haven, CT 06520, USA
[45] Columbia Astrophysics and Nevis Laboratories, Columbia University, New York, NY 10027, USA
[46] Dept. of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom
[47] Dipartimento di Fisica e Astronomia Galileo Galilei, Università Degli Studi di Padova, I-35122 Padova PD, Italy
[48] Dept. of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104, USA
[49] Physics Department, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA
[50] Dept. of Physics, University of Wisconsin, River Falls, WI 54022, USA
[51] Dept. of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA
[52] Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA
[53] Dept. of Physics, Chung-Ang University, Seoul 06974, Republic of Korea
[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, Republic of 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, SE-75120 Uppsala, Sweden
[62] Dept. of Physics, University of Wuppertal, D-42119 Wuppertal, Germany
[63] Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, D-15738 Zeuthen, Germany
[a] also at Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India
[b] also at Department of Space, Earth and Environment, Chalmers University of Technology, 412 96 Gothenburg, Sweden
[c] also at INFN Padova, I-35131 Padova, Italy
[d] also at Earthquake Research Institute, University of Tokyo, Bunkyo, Tokyo 113-0032, Japan
[e] now at INFN Padova, I-35131 Padova, Italy

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