PROCEEDINGS OF SCIENCE

Summary of IceCube Tau Neutrino Searches and Flavor Composition Measurements of the Diffuse Astrophysical Neutrino Flux

The IceCube Collaboration

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

E-mail: neha.lad@desy.de, cowen@phys.psu.edu

We present a summary of the flavor composition measurements for the diffuse astrophysical neutrino flux using data from the IceCube Neutrino Observatory at the South Pole. IceCube has identified candidate astrophysical tau neutrinos through two different approaches. One approach used a dedicated particle identification algorithm for the classification and reconstruction of the 'Double Cascade' event topology, a signature of tau neutrino charged current interactions. This first approach is applied to the High Energy Starting Events (HESE) sample, an all-sky, all-flavor set of neutrino events with energy above 60 TeV encompassing 12 years of IceCube livetime. We show that the addition of more years of data and updated ice properties on the HESE sample delivers tighter constraints on the flavor composition of the astrophysical neutrino flux than previous IceCube analyses, in particular when it is fit in combination with high statistics samples of through-going tracks and cascades. A second approach uses a sensitive machine-learning-based selection technique that finds seven candidate events in 9.7 years of IceCube data. This approach excludes the zero astrophysical tau neutrino hypothesis at the highest statistical significance to date.

Corresponding authors: Neha Lad[1,2,*], D. F. Cowen[3,4]

[1] *Deutsches Elektronen-Synchrotron DESY: Zeuthen, Germany*

[2] *Institut für Physik, Humboldt-Universität zu Berlin: Berlin, Germany*

[3] *Dept. of Physics, Pennsylvania State University, University Park, PA, USA*

[4] *Dept. of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA, USA*

[*] Presenter

The 38th International Cosmic Ray Conference (ICRC2023)
26 July – 3 August, 2023
Nagoya, Japan

https://pos.sissa.it/

PoS(ICRC2023)1122

1. Introduction

The IceCube Neutrino Observatory [1], buried deep in the ice at the South Pole, has played a pivotal role in the study of the astrophysical diffuse neutrino flux by reporting evidence of diffuse astrophysical neutrinos [2]. However, this measurement alone does not give a complete picture of the astrophysical sources or the mechanisms by which they generate neutrinos. A study measuring the neutrino flavor content can thus enhance our understanding of various high-energy particle factories of the universe.

By employing an array of 5,160 digital optical modules (DOMs) buried in the ice, IceCube detects the flashes of light produced by neutrino interactions. These interactions can create different signatures in IceCube based on the type and flavor involved. Single cascades can be created by charged current (CC) electron neutrino (ν_e) and neutral current (NC) interactions of any flavor. Light depositions along a long track traversing the detector are created by muon neutrino (ν_μ) CC interactions and atmospheric muons. Tau neutrino (ν_τ) interactions can be distinguished from other neutrino interactions, provided their energies and interaction vertices are favorable. We focus here on ν_τ CC interactions [3] that have the “Double Pulse” and “Double Cascade” topologies, where a ν_τ interacts with nucleon to produce a tau lepton, which then travels some distance in ice ($\propto E_\tau$) and decays into an electron or multiple hadrons. This yields a topology with two causally-connected cascades that can give double-humped waveforms in one or more DOMs and/or characteristic photon arrival times across multiple DOMs and strings, respectively.

This proceeding summarizes two separate analyses that exploit these aforementioned ν_τ CC interaction topologies to search for ν_τ and do a flavor component measurement of diffuse astrophysical neutrinos. Later, we also discuss the sensitivities of combining different event selections of IceCube to obtain the best astrophysical flavor component measurement to date.

2. Search for ν_τ-induced Double Cascades

Within 3 years of its livetime, IceCube reported evidence of an astrophysical component of diffuse neutrino flux [2]. The event sample used for this discovery, the High Energy Starting Events (HESE), was updated over time with more years of data and updated detector and glacial ice treatment [4]. This updated sample was then used to detect, for the first time, two tau neutrino candidates [5] to perform a flavor composition measurement.

Here we use the same event selection and an updated reconstruction [6] method (compared to the one originally developed in [7] and further used in HESE-7.5 ν_τ search [5]), for 12 years of IceCube HESE data, to search for “Double Cascade” events. The reason for using this same selection is that it is an all-sky, all-flavor selection, which also uses a self-veto technique to reject atmospheric neutrinos from the sample, with all events having reconstructed deposited energy of $E \geq 60$ TeV, giving it high astrophysical purity. We use a likelihood-based reconstruction method that compares different source hypotheses (single cascade, double cascade, and track) and assigns a topology to each event that is present in the HESE sample. PDFs of various reconstructed variables are used for flavor tagging. Table 1 contains all the reconstructed variables of interest for each topology and their binning ranges and space. In the HESE-7.5 tau search, dedicated re-simulations of two observed ν_τ candidates were produced to estimate the error on the tau decay length and to estimate the probability of how compatible each event is with the background. PDFs obtained from these re-simulations were used to extend the likelihood used in [4] to improve the flavor composition measurement. For this analysis, the variables used to generate PDFs are as indicated in Table 1. A new variable, 'energy asymmetry', is included as it is a good estimator to separate single cascades from double cascades at lower reconstructed lengths. To measure flavor fractions, a

Topology	Variable	Bin range	Number of Bins	Bin Space
Single Cascades	Energy	60TeV - 10PeV	21	$\log_{10}$
	Zenith	-1 - 1	10	cosine
Tracks	Energy	60TeV - 10PeV	21	$\log_{10}$
	Zenith	-1 - 1	10	cosine
Double Cascades	Energy	60TeV - 10PeV	21	$\log_{10}$
	Length	1m - 1000m	20	$\log_{10}$
	Energy Asymmetry	-1 - 0.3	26	linear

Table 1: Reconstructed observables of each topology and their binning information. Reconstructed energy and zenith are the total deposited energy of and zenith of an event. Reconstructed length is the distance between vertices of two Cascades (in other words distance that tau lepton travels before it decays). Reconstructed Energy asymmetry is a measure of how the relative amount of deposited energy in each cascade is distributed and is defined as $E_A = \frac{E_1 - E_2}{E_1 + E_2}$, where E_1 and E_2 are reconstructed energies of first and second cascades.

forward-folding likelihood fit is performed where, in addition to astrophysical spectral parameters such as spectral index γ_{astro} and all flavor norm ϕ_{astro} (See Equation 1), individual flavor fractions f_α contributing to ϕ_{astro} are also fitted (where f_α is fraction of ν_α observed on earth). To account for atmospheric neutrino spectra, ϕ_{conv} (normalization of neutrino flux for the conventional component) and ϕ_{prompt} (normalization of neutrino flux for the prompt component) are also considered in the fit. Detector systematics are taken into account by using the SnowStorm method [8], where each systematic is varied for every event while generating the Monte-Carlo simulation, allowing us to be able to combine different analysis samples in one fit. The DOM efficiency for detecting photons, the bulk ice properties such as scattering, absorption, and anisotropy, and hole ice properties (forward acceptance of DOMs due to refreezing of glacial ice after deployment of optical modules) are used as nuisance parameters in the fit.

2.1 HESE-12 Flavor Fit

In this section, we discuss the Asimov sensitivity to constrain flavor contours using 12 years of IceCube HESE data. The astrophysical spectrum is modeled here as a single power-law with flavor ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$, following a measurement from a sample taken with 9.5 years of IceCube data [9],

$$\phi(E) = \phi_{\text{astro}} \left(\frac{E}{100\ \text{TeV}} \right)^{-\gamma_{\text{astro}}} 10^{-18}\ \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1} \quad (1)$$

with a total normalization of $\phi_{\text{astro}} = 4.32$ and spectral index $\gamma_{\text{astro}} = 2.37$.

PoS(ICRC2023)1122

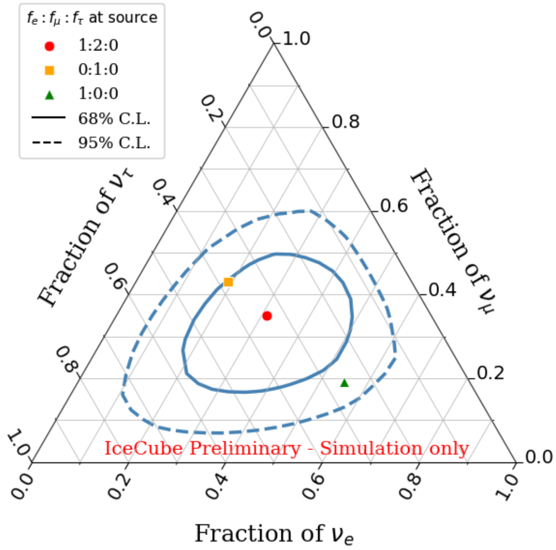

Figure 1: Asimov sensitivity of this analysis to measure flavor composition using 12 years of IceCube HESE data, for an astrophysical neutrino spectrum following the single unbroken power-law given in Equation 1, with a flavor composition of $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$.

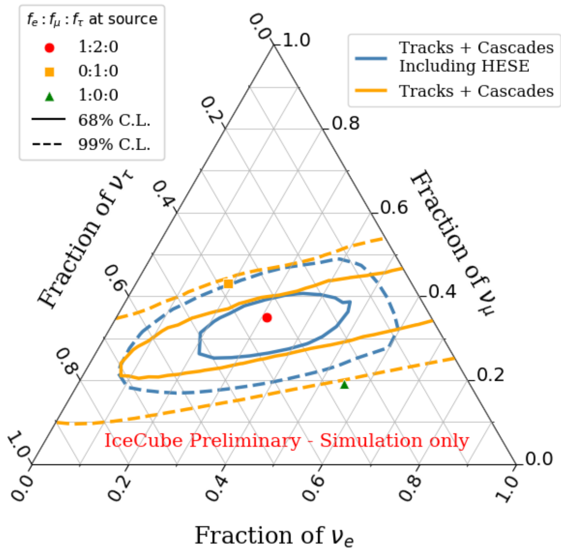

Figure 2: Asimov sensitivity of this analysis to measure flavor composition by combining 12 years of HESE sample with current GlobalFit sample [10], for an astrophysical neutrino spectrum following the single unbroken power-law given in Equation 1, with a flavor composition of $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$.

2.2 Towards a GlobalFit of flavor Measurement

The ultimate goal of this analysis is to measure the flavor content of diffuse astrophysical neutrinos using not just the HESE sample but doing so by combining it with other event samples. The HESE sample, as pure as it may be, does not contain enough events to tightly constrain the ν_μ and ν_e fractions. The idea of a GlobalFit is to combine samples that individually have their advantages and disadvantages in a combined fit to model all nuisance and signal parameters in a self-consistent way. In the current GlobalFit scheme of IceCube, it is shown that this cogent treatment of all parameters in a fit is not only possible but also gives the most precise measurement of the astrophysical neutrino spectrum (assuming single power law) made to date [10]. The addition of a ν_τ identifier is capable of excluding the neutron beam scenario ($\nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0$ at the source) with $>3\sigma$ confidence if the injected source mechanism is the Pion-Production scenario ($\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ at the source).

As can be seen from Fig.1 and Fig. 2, it is clear that the HESE-only fit is sensitive to constraining the ν_τ fraction very well but fails to do so for the ν_μ fraction. This is understandable as in the HESE sample, the number of distinguishable ν_μ events is low. This, in turn, can be provided by Tracks from GlobalFit.

3. Observation of Seven Astrophysical ν_τ Candidates

In a second approach, we used convolutional neural networks (CNNs) that had been trained on images derived from both simulated ν_τ events and simulated background events. These images, shown for one of the candidate events in the top row of Fig. 3, encapsulated the full waveform information from up to 180 DOMs on three neighboring strings centered on the string with the highest charge in the event. Based on simulations, a median detected neutrino energy of approximately 200 TeV is predicted for ν_τ events, which assume an astrophysical neutrino flux from Ref. [11]. These simulations indicate that the events exhibit energies ranging from roughly 20 TeV to 1 PeV. Combined with a few other selection criteria, the CNNs identified seven candidate ν_τ events. Considering backgrounds from astrophysical neutrinos, conventional atmospheric neutrinos, conventional atmospheric muons, and prompt atmospheric neutrinos, we obtain a total estimated background of roughly 0.5 events, depending on the assumed astrophysical neutrino flux. The dominant background contribution is from non-ν_τ astrophysical neutrinos, and we assumed the prompt muon flux was zero. In the context of these backgrounds, we are thus able to exclude the absence of astrophysical ν_τ at the 5σ level. We also measure the astrophysical ν_τ flux, finding that it is consistent with expectations based on previously published IceCube astrophysical neutrino flux measurements [11–14].

One of the seven candidate ν_τ events is shown in Fig. 3. While this event shows some evidence of DOM waveforms with the double pulse signature, studies where individual waveforms were smoothed showed that the CNN scores were sensitive to the overall event structure rather than local double-pulse waveforms of individual DOMs. Figure 4 shows the best-fit tau neutrino fluxes (black dots) for four IceCube-measured astrophysical fluxes (colored dots). The inner (outer) bars denote the frequentist 68% (90%) confidence intervals. The best-fit points from the respective IceCube analyses are each within the 68% confidence intervals of this analysis.

4. Conclusions and Outlook

A dedicated study to look for tau neutrinos is needed to do a flavor measurement of astrophysical neutrinos that reach Earth. The fraction of each flavor is related to the population of their sources and their neutrino production mechanisms. When a tau neutrino has a CC interaction in IceCube,

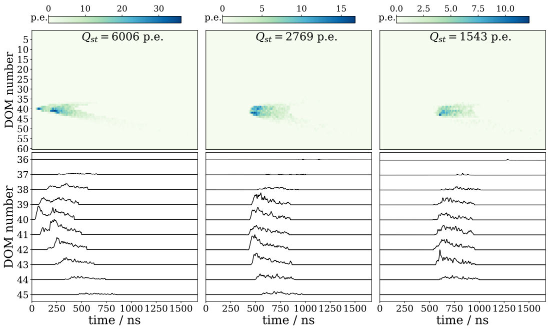

Figure 3: Candidate astrophysical ν_τ detected in Nov. 2019. Each column corresponds to a string in the selected event. The top row of figures shows the DOM number (proportional to depth) versus the time of the digitized PMT signal in 3 ns bins, with the color scale giving the signal amplitude in p.e. in each time bin. The total p.e. detected on each string, $Q_{\rm str.}$, is shown. The bottom row shows the digitized waveforms for a subset of the DOMs on each string. The amplitudes of the waveforms in each string are normalized to the peak amplitude in that string.

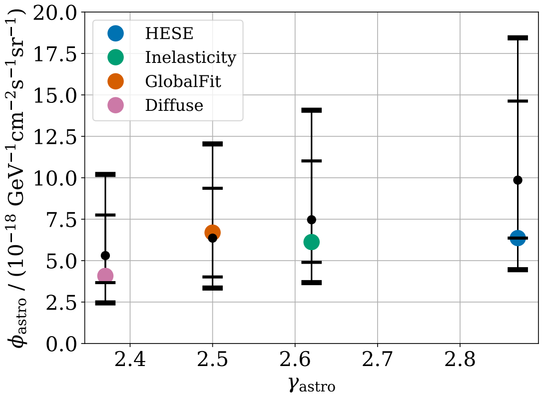

Figure 4: Measured $\nu_\tau^{\rm astro}$ flux normalizations (black dots) with 68% and 90% confidence intervals (black error bars), for each of $\phi^{\rm IC}_{\rm astro}$, denoted by colored circles and labeled as "HESE" [11], "Inelasticity" [12], "GlobalFit" [13] and "Diffuse" [14]. The spectral index $\gamma_{\rm astro}$ was not measured by this analysis. The fluxes shown have each been normalized to their all-flavor values under the assumption of a 1:1:1 flavor ratio at Earth.

a tau lepton is created, which upon traveling some distance, often decays to create another shower of particles, giving two causally connected light depositions, producing a double cascade and/or double pulse signature.

Here we described two methods in IceCube used to identify these ν_τ events, building on previous IceCube searches [15–17]. The first approach was used in the 7.5-year HESE sample [18] to find two double-cascade ν_τ candidates and performed a flavor composition measurement that yielded the first-ever non-zero ν_τ fraction measured at earth. In this proceeding, we discussed the IceCube sensitivity achieved by extending this sample to 12 years, together with a novel treatment of detector systematics in the fit, to deliver tighter constraints on the flavor measurement. We also showed that if this tau identifier is combined with other high statistics samples of cascades and tracks, the analysis becomes capable of rejecting the neutron beam neutrino production mechanism at greater than 3σ. The second approach using CNNs made the most highly-significant rejection to date of the null hypothesis of zero astrophysical tau neutrinos.

References

[1] **IceCube** Collaboration, M. G. Aartsen *et al.* *JINST* **12** no. 03, (2017) P03012.

[2] **IceCube** Collaboration, M. G. Aartsen *et al.* *Science* **342** no. 6161, (Nov, 2013) .

[3] **IceCube** Collaboration, D. F. Cowen *Journal of Physics: Conference Series* **60** no. 1, (Mar, 2007) 227.

[4] **IceCube** Collaboration, R. Abbasi *et al.* *Physical Review D* **104** no. 2, (Jul, 2021) .

[5] **IceCube** Collaboration, R. Abbasi *et al.* *The European Physical Journal C* **82** no. 11, (Nov, 2022) .

[6] **IceCube** Collaboration, T. Yuan *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **1054** (2023) 168440.

[7] M. Usner, *Search for Astrophysical Tau-Neutrinos in Six Years of High-Energy Starting Events in the IceCube Detector*. PhD thesis, Humboldt-Universität zu Berlin, Mathematisch-Naturwissenschaftliche Fakultät, 2018.

[8] **IceCube** Collaboration, M. G. Aartsen *et al.* *Journal of Cosmology and Astroparticle Physics* **2019** no. 10, (Oct, 2019) 048.

[9] **IceCube** Collaboration, R. Abbasi, M. Ackermann, J. Adams, *et al.* *Astrophysical Journal* **928** (Mar., 2022) .

[10] **IceCube** Collaboration, E. Ganster, R. Naab, and Z. Zhang *PoS* **ICRC2023** 1064.

[11] **IceCube** Collaboration, R. Abbasi *et al.* *Phys. Rev. D* **104** (2021) 022002.

[12] **IceCube** Collaboration, M. G. Aartsen *et al.* *Phys. Rev. D* **99** no. 3, (2019) 032004.

[13] **IceCube** Collaboration, M. G. Aartsen *et al.* *Astrophys. J.* **809** no. 1, (2015) 98.

[14] **IceCube** Collaboration, R. Abbasi *et al.* *Astrophys. J.* **928** no. 1, (2022) 50.

[15] **IceCube** Collaboration, R. Abbasi *et al.* *Phys. Rev. D* **86** (Jul, 2012) 022005.

[16] **IceCube** Collaboration, M. G. Aartsen *et al.* *Phys. Rev. D* **93** (Jan, 2016) 022001.

[17] **IceCube** Collaboration, M. Meier and J. Soedingrekso *PoS* **ICRC2019** (2020) 960.

[18] **IceCube** Collaboration, R. Abbasi *et al.* *Eur. Phys. J. C* **82** no. 11, (2022) 1031.

Full Author List: IceCube Collaboration

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

[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] Dept. of Physics, University of Texas at Arlington, 502 Yates St., Science Hall Rm 108, Box 19059, Arlington, TX 76019, USA
[5] CTSPS, Clark-Atlanta University, Atlanta, GA 30314, USA
[6] School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA 30332, USA
[7] Dept. of Physics, Southern University, Baton Rouge, LA 70813, USA
[8] Dept. of Physics, University of California, Berkeley, CA 94720, USA
[9] Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[10] Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany
[11] Fakultät für Physik & Astronomie, Ruhr-Universität Bochum, D-44780 Bochum, Germany
[12] Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium

PoS(ICRC2023)1122

[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

Acknowledgements

The authors gratefully acknowledge the support from the following agencies and institutions: USA – U.S. National Science Foundation-Office of Polar Programs, U.S. National Science Foundation-Physics Division, U.S. National Science Foundation-EPSCoR, Wisconsin Alumni Research Foundation, Center for High Throughput Computing (CHTC) at the University of Wisconsin–Madison, Open Science

Grid (OSG), 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, and Astroparticle physics computational facility at Marquette University; 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 Compute 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); United Kingdom – Department of Physics, University of Oxford.