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Search for ultrahigh-energy tau neutrinos with IceCube

R. Abbasi,28 Y. Abdou23 T. Abu-Zayyad,34 M. Ackermann,42 J. Adams,16 J. A. Aguilar,22 M. Ahlers,28 D. Altmann,1 K. Andeen,28 J. Auffenberg,38 X. Bai,31,32 M. Baker,28 S. W. Barwick,24 V. Baum,29 R. Bay,7 K. Beattie,8 J. J. Beatty,18,19 S. Bechet,13 J. K. Becker,10 K.-H. Becker,41 M. Bell,39 M. L. Benabderrahmane,42 S. BenZvi,28 J. Berdermann,42 P. Berghaus,35 D. Berley,17 E. Bernardini,42 D. Bertrand,13 D. Z. Besson,26 D. Bindig,41 M. Bisakov,1 E. Blaufuss,17 J. Blumenthal,4 D. J. Boersma,1 C. Bohm,39 D. Bose,14 S. Böser,11 O. Botner,40 L. Brayeur,14 A. M. Brown,16 S. Buitink,14 K. S. Caballero-Mora,39 M. Carson,23 M. Casier,14 D. Chirkin,28 B. Christy,17 F. Clevermann,20 S. Cohen,25 D. F. Cowen,39,38 A. H. Cruz Silva,42 M. V. D’Agostino,7 M. Danninger,35 J. Daughtheely,5 J. C. Davis,18 C. De Clercq,14 J. Blumenthal,1 D. J. Boersma,1 C. Bohm,35 D. Bose,14 S. Böser,11 O. Botner,40 L. Brayeur,14 A. M. Brown,16 S. Buitink,14 K. Andeen,28 J. Auffenberg,28 X. Bai,32,* M. Baker,28 S. W. Barwick,24 V. Baum,29 R. Bay,7 K. Beattie,8 J. J. Beatty,18,19 C. Spiering,42 M. Stamatikos,18, S. Kopper,41 D. J. Koskinen,39 M. Kowalski,11 M. Krasberg,28 G. Kroll,29 J. Kunnen,14 N. Kurahashi,28 T. Kuwabara,32 T. Schmidt,17 S. Schoeneberg,10 A. Schonwald,42 A. Schukraft,1 L. Schulte,11 A. Schultes,41 O. Schulz,31 M. Schunck,1 C. Pérez de los Heros,40 D. Pieloth,20 J. Posselt,41 P. B. Price,7 G. T. Przybylski,8 K. Rawlins,3 P. Redl,17 E. Resconi,31 T. Karg,41 A. Karle,28 J. Kiryluk,36 F. Kislat,42 S. R. Klein,8,7 J.-H. Köhne,20 G. Kohnen,30 H. Kolanoski,9 L. Köpke,29 K. Woschnagg,7 C. Xu,32 D. L. Xu,37 X. W. Xu,6 J. P. Yanez,42 G. Yodh,24 S. Yoshida,15 P. Zarzhitsky,37 and M. Zoll35 (IceCube Collaboration)

1III. Physikalisches Institut, RWTH Aachen University, D-52056 Aachen, Germany
2School of Chemistry & Physics, University of Adelaide, Adelaide SA, 5005 Australia
3Department of Physics and Astronomy, University of Alaska Anchorage, 3211 Providence Dr., Anchorage, Alaska 99508, USA
4CTSPS, Clark-Atlanta University, Atlanta, Georgia 30314, USA
5School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA
6Department of Physics, Southern University, Baton Rouge, Louisiana 70813, USA
7Department of Physics, University of California, Berkeley, California 94720, USA
8Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
9Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany
10Fakultät für Physik & Astronomie, Ruhr-Universität Bochum, D-44780 Bochum, Germany
11Physikalisches Institut, Universität Bonn, Nussallee 12, D-53115 Bonn, Germany
12Department of Physics, University of the West Indies, Cave Hill Campus, Bridgetown BB11000, Barbados
13Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium
14Vrije Universiteit Brussel, Dienst ELEM, B-1050 Brussels, Belgium
15Department of Physics, Chiba University, Chiba 263-8522, Japan
16Department of Physics and Astronomy, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
17Department of Physics, University of Maryland, College Park, Maryland 20742, USA

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Neutrinos are expected to arrive at Earth with a flavor ratio in proportion to the well-measured branching ratios, and are many astrophysical point sources of neutrinos, but each one is too weak to be distinguished individually from background, then a suitable detection strategy is to perform a cumulative search for “diffuse” flux of UHE neutrinos over the full available solid angle.

I. INTRODUCTION

Proposed astrophysical sources of observed ultrahigh-energy (UHE) cosmic rays are expected to also produce ultrahigh-energy neutrinos, mainly via charged pion decay following interactions on ambient matter and radiation [1,2]. Candidate neutrino sources include active galactic nuclei, gamma-ray bursts and microquasars [3–5]. Neutrinos are expected to arrive at Earth with a flavor ratio of $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$ in the standard neutrino oscillation scenario [6]. Other neutrino production and propagation models predict different flux ratios at Earth [7–9]. If there

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of multiple $\nu_\tau$ events. As shown below, the chief sources of possible background events are unlikely to mimic these signatures. Also, at these energies, there is negligible intrinsic $\nu_\tau$ background in the conventional atmospheric neutrino flux $^{[14]}$. The prompt $\nu_\tau$ flux from charm hadron decays in cosmic-ray-induced air showers is also expected to be small $^{[15–17]}$. The majority of the signal $\nu_\tau$ is expected to come from the vicinity of the horizon since there is insufficient material for interactions in the downward-going direction and $\nu_\tau$ passing through the Earth emerge $^{[18]}$ at energies too low to create a UHE signature.

The $\nu_\tau$ event topology depends on how much of the event is contained in the detector, the $\nu_\tau$ energy, and the composition of the $\tau$ decay products. In this work, only nonmuonic $\tau$ decays were considered. A partially contained UHE $\nu_\tau$ having only the decay vertex of $\tau$ in the instrumented volume is denoted a “lollipop,” while one having only the production vertex of the $\tau$ in the instrumented volume is denoted an “inverted lollipop.” A fully contained UHE $\nu_\tau$ having both production and decay vertices well-separated in the instrumented volume is denoted a “double bang” $^{[19]}$. Figure 1 shows a simulated double-bang event in the 22-string configuration of the IceCube detector (IC22) which had an instrumented volume of roughly 0.25 km$^3$.

Applying criteria to identify lollipop, inverted lollipop and double-bang signatures produced by $\nu_\tau$ interactions, we derived limits on the diffuse UHE neutrino flux. We assumed a flux ratio of $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$ for this analysis. We used 282.4 live-days of data collected in 2007–2008 by IC22. We describe the IC22 detector in Sec. II and the experimental and simulated data samples in Sec. III. We present our analysis in Sec. IV and the results in Sec. V. We discuss systematic errors in Sec. VI and our conclusions in Sec. VII.

II. THE ICECUBE 22-STRING DETECTOR

The 22-string configuration of IC22 was deployed in early 2007, began taking physics-quality data in May of that year and ended at the transition to IceCube’s 40-string configuration in April 2008. Each string consists of 60 digital optical modules (DOMs) buried deep in the icecap at the South Pole, with regular 17 m vertical spacing from 1450 to 2450 m below the surface, for a total of 1320 DOMs. The strings are situated on a regular grid with 125 m horizontal interstring spacing, covering the area shown in Fig. 2. Each DOM houses a photomultiplier tube (PMT) to detect the Cherenkov light, electronics for pulse digitization and other functions and remotely-controllable calibration light sources. To reduce the impact of PMT signals due to random noise, only detected signals with minimum 0.25 single photoelectron (p.e.) PMT pulse height were digitized by two types of waveform digitizers in situ: the analog transient waveform digitizer (ATWD).
and a fast analog to digital converter (fADC). The time resolution of the ATWD (fADC) is about 3.33 ns (25 ns) with a readout time window of about 450 ns (6.4 $\mu$s). Thus, the ATWD is used to capture detailed waveform information on a short time scale while the fADC records less detailed information on a longer time scale. The ATWD also supports three channels with different gains ($\times 16$, $\times 2$, and $\times 0.25$) to extend its effective dynamic range.

To further remove random noise, the digitized signal in a DOM was required to be in close temporal coincidence with a signal in neighboring DOMs. The signals satisfying such a temporal condition in hardware are called local coincidence (LC) hits. LC hits were then checked to see whether or not they satisfied a software-based trigger condition. Groups of hits which satisfied a trigger condition were packaged into “events.” Higher-level “filter” algorithms were applied to each event, and those events passing one or more filter conditions were transmitted over satellite to the northern hemisphere for higher-level analysis. However, all the data satisfying the software trigger conditions were stored on tape and shipped to the northern hemisphere once a year. The software trigger and filter conditions applied to the data used in this analysis are described in the section below. For more detail on the design, construction and performance of IceCube in general, see Refs. [20–23] and references therein.

III. DATA

A. Experimental data

The DOM signals satisfying the LC condition were required by the online data acquisition system at the surface computing system in the IceCube Laboratory to satisfy a “simple majority trigger” condition under which eight or more DOMs reported signals in a 5 $\mu$s time window (“SMT8”). The IC22 trigger rate of 500 to 620 Hz followed the seasonal variation in the cosmic-ray muon flux. The data acquisition system grouped together DOM hits satisfying the trigger condition into an event using a broadened $\pm 10$ $\mu$s time window. Triggered events used in this analysis were accepted if they also satisfied the extremely high-energy (EHE) filter algorithm applied to the data online at the South Pole to reduce low-energy events consistent with background. The EHE filter required $\geq 80$ DOMs registering hits in the event.

We split off about 30% of the full IC22 data set (82.4 live-days, uniformly distributed in time across the data-taking period) to use in conjunction with simulated data in the design of our subsequent selection criteria. In keeping with our procedures for maintaining blindness in the analysis of data, and thereby reducing human bias in the analysis of the data, the final result is based on the application of these selection criteria, unaltered, to the remaining 70% of the data set (200 live-days).

B. Simulated data

We employed simulated data to develop criteria which enhanced a possible astrophysical neutrino signal while diminishing backgrounds from atmospheric neutrinos and cosmic-ray muons. Exclusive use of simulated data also permitted us to maintain blindness. For the neutrinos, the All Neutrino Interaction Simulation package [24] was used and each neutrino flavor was produced separately. The neutrinos were generated following an $E^{-1}$ energy spectrum to enhance event statistics at higher energy where this analysis is sensitive. The neutrinos were propagated through the Earth where the Earth shadow effect [25] of neutrinos and $\nu_\tau$ regeneration [26,27] were taken into account in our simulation.

The events were then run through the IceCube detector simulation. The muon (electron) neutrinos were generated over all zenith angles in the energy range between 10 (50) GeV to 10 EeV while tau neutrinos were generated between 1 TeV and 1 EeV.

Cosmic-ray muon backgrounds were simulated by generating air shower events using the CORSIKA package [28], then propagating the muons to and through the detector volume with the MCM package [29] and finally applying the detector simulation to the resulting set of particles.

For solitary air showers, a two-component model [30] was used. In this model, the entire mass spectrum of cosmic rays is approximated by only proton and iron components. Compared to Hörandel’s polygonato model [31], the two-component model agrees better with experimental data at higher energy (beyond 100 TeV) where this analysis is sensitive. The cosmic-ray primaries are sampled with an $E^{-2}$ spectrum. In this way, we were able to produce events more efficiently at the higher primary energies which contribute most strongly to the background at ultra-high energies. The cosmic-ray flux was then reweighted to match the expected spectrum.

The acceptance of IC22 admits the possibility of detecting muons from multiple quasimultaneous air-shower events, so we also simulated muons from two coincident air-shower events. (Higher multiplicities occur at a negligible rate in IC22 and were not simulated.) For coincident air showers, Hörandel’s polygonato model of cosmic rays was used. Solitary (coincident) atmospheric air showers were generated with energies between 10(0.6) TeV–100 EeV and zenith angles between 0–90°.

After event generation and detector simulation, the simulated data were processed in the same way as real data, i.e., with sequential applications of trigger and filter conditions, as described earlier.

IV. TAU NEUTRINO IDENTIFICATION

A. Selection criteria

Based on the characteristics of simulated data, we formulated several event selection criteria to exploit the UHE
signatures of a track plus one or two showers, in contrast to conventional pure tracklike or pure showerlike events. Two such criteria use the reconstructed total number of photoelectrons \( N_{\text{pe}} \) per DOM. The time associated with such a multiphoton deposit in each DOM is the time of the first reconstructed photoelectron it detected. Looking at the full event time window, \( N_{\text{pe}} \) for each DOM is plotted vs time and denoted \( N_{\text{DOM}pe}(t) \). Figure 3 shows \( N_{\text{DOM}pe}(t) \) for a simulated inverted lollipop (top) and a simulated muon event (bottom). Note that the times of the hits are with respect to the event trigger time which has an extended readout time window of \( \pm 10 \mu s \) in IC22. For this reason, all the hit times exhibit at least a \( 10 \mu s \) offset.

To exploit the power of \( N_{\text{DOM}pe}(t) \), we devised a parameter called “maximum current ratio” \( (\text{IR}_{\text{max}}) \), defined as the maximum of \( I_{\text{in}}/I_{\text{out}} \) where \( I_{\text{in(out)}} = \Delta Q_{\text{in(out)}}/\Delta T_{\text{in(out)}} \). Here, \( \Delta Q_{\text{in}} \) was the charge, measured in p.e., collected by the DOMs in a sliding time window of length \( \Delta T_{\text{in}} \). The time window was optimized in this analysis to be 1.2 \( \mu s \) long. The corresponding “out” variables were the charge and time measured outside the sliding time window (see Fig. 4). As shown in Fig. 5, \( \text{IR}_{\text{max}} \) is small for tracklike events and large for events containing showers, such as those produced by \( \nu_\tau \). Since the \( \text{IR}_{\text{max}} \) cut is related to energy, it will be applied to data as the last cut together with the other energy related cut explained at the end of this subsection.

**FIG. 3.** The quantity \( N_{\text{DOM}pe}(t) \) for a simulated inverted lollipop (top) and a simulated muon event (bottom), with primary particle energies of 25.4 PeV and 2.38 PeV, respectively. The peak of the top plot is at roughly 2500 photoelectrons.

**FIG. 4 (color online).** The maximum current ratio \( (\text{IR}_{\text{max}}) \) for an event is calculated by finding the maximum ratio of charge inside a sliding time window to the charge outside this window. This variable is expected to be larger for \( \nu_\tau \) events (as in the example shown here) than for background events due to atmospheric muons.

**FIG. 5 (color online).** The logarithm of the \( \text{IR}_{\text{max}} \) parameter for simulated signal (green histogram for lollipop and blue points for all \( \nu_\tau \) events) and background (red points for atmospheric muon) events and for data (gray histogram) passing the EHE filter. The distributions have been normalized to unit integrals to highlight the separation between signal and background. The \( \text{IR}_{\text{max}} \) distributions of inverted lollipop and double-bang events are also well-separated from the background.
Although \( \text{IR}_{\text{max}} \) is very effective at distinguishing most simple tracklike background events from signal events, highly energetic muons can stochastically deposit large amounts of energy along their track lengths via bremsstrahlung, pair production or photonuclear interactions, potentially mimicking \( \nu_{\tau} \) events. Figure 6 shows an example of simulated muon with such a bremsstrahlung whose \( \text{IR}_{\text{max}} \) value could be similar to that of a \( \nu_{\tau} \) event. Theoretically, \( \nu_{\tau} \) events are most likely to have a large \( N_{\text{DOM}}(t) \) at one or both of the temporal edges of the event. In practice, \( \nu_{\tau} \) events had a large \( N_{\text{DOM}}(t) \) in the earliest third due to the presence of highly scattered photons which extended the temporal edge of the event to much later times. We expect future analyses to be able to devise criteria which reduce the impact of these scattered photons.

The “local charge density” parameter \( \rho_q \), with units of p.e./ns, was introduced to remove events consistent with a large energy deposit away from either temporal edge. Partitioning each event into three equal time windows, we calculate the per-DOM ratios of charge to time in each window. These ratios are denoted \( \rho_q(I) \), \( \rho_q(II) \) and \( \rho_q(III) \) in the first, second and third time window, respectively. Events for which \( \rho_q(I) < 5 \) p.e./ns or \( \rho_q(III) < 5 \) p.e./ns are rejected as being inconsistent with arising from a \( \nu_{\tau} \) event, since \( \nu_{\tau} \) are expected to make a significant energy deposition at the beginning and/or end of its interaction in the instrumented volume. Events with small \( \rho_q(II) \) are consistent with arising from \( \nu_{\tau} \) and are not rejected. We expect future analyses to be able to devise criteria that reduce the impact of these scattered photons.

Figure 7 shows \( N_{\text{DOM}}(t) \) vs time and thus illustrates how \( \rho_q \) can distinguish \( \nu_{\tau} \) events from muon bremsstrahlung events. Figure 8 shows how well \( \rho_q \) separates signal from background.

Additional selection criteria were applied to further remove backgrounds. The flux of downward-going muons from cosmic-ray air shower events was reduced by implementing a “veto layer” in software, removing any events in which the average \( Z \) position of the first 4 hits (\( Z_{\text{init}} \)) was in the top 50 m of the detection volume. Downward-going muons were further removed using the approximate event velocity \( \bar{V}_Z \) (m/ns), constructed from the difference between the positions \( Z_{\text{cog}} \) and \( Z_{\text{init}} \), divided by the difference in their respective times, i.e., \( T_{\text{cog}} \) and \( T_{\text{init}} \), where \( Z_{\text{cog}} \) (\( T_{\text{cog}} \)) were the \( Z \) position (time) of the center of gravity of
by requiring a minimum IR_{max} was smallest eigenvalue to the sum of all three eigenvalues equal to zero. We therefore required that the ratio of while perfectly tracklike events will have one eigenvalue events will have three equal tensor of inertia eigenvalues, from hit DOMs of each event and keeping only those pulse amplitudes (instead of conventional mass) [32] calculating the eigenvalues of the tensor of inertia of center of the detector).

required the average depth position of all DOMs with whose muon tracks may go undetected, are removed by processes at or near the bottom of the detector, events passing the EHE filter. The distributions have been normalized to unit integrals to highlight the separation between signal and background. The \( \frac{N_{\text{eff}}}{N_{\text{det}}} \) q \( \text{values were based on an opti-}
\[2 \text{sr} \]
\[ \text{spectrum.}
\[ T \quad \frac{N_{\text{det}}}{T} = 330 \text{ m} \]}
\[ \text{as measured from the center of the detector.
\]

We also applied a generic topological selection by calculating the eigenvalues of the tensor of inertia of pulse amplitudes (instead of conventional mass) [32] from hit DOMs of each event and keeping only those events that tended towards sphericity. Perfectly spherical events will have three equal tensor of inertia eigenvalues, while perfectly tracklike events will have one eigenvalue equal to zero. We therefore required that the ratio of smallest eigenvalue to the sum of all three eigenvalues was >0.1.

Remain remaining lower-energy events were further reduced in number by requiring a minimum IR_{max} and \( N_{\text{pe}} \) for each event. We required IR_{max} ≥ 200 and \( \log_{10} N_{\text{pe}} \) ≥ 4.2, the values of which were based on an optimization which is described in the following section. Figure 9 shows the distributions of these two selection criteria for simulated signal, simulated background and 30% of the data, prior to the overall optimization of all the selection criteria.

The selection criteria described above are summarized in Table I.

B. Optimization of selection criteria

The final values for IR_{max} and \( N_{\text{pe}} \) were optimized by minimizing the model rejection factor (MRF) [33] before applying them to the full data set. We varied the values of IR_{max} and log_{10} \( N_{\text{pe}} \) as shown in Fig. 10, finding a shallow minimum at MRF ~ 0.89. At this MRF, the expected all-flavor signal and background were 3.52 and 0.81 events, respectively, using the Waxman-Bahcall (WB) upper bound for signal, translated to account for what would be detected following standard neutrino oscillations, of \( E_{\nu}^2 \Phi_{\nu} \ll 3.5 \times 10^{-8} \text{ GeV cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} \) [4] for the signal neutrino flux normalization with \( E^{-2} \) spectrum. Assuming standard neutrino oscillations, we expect one-third of this flux to be \( \nu_\tau \). The corresponding optimized values are IR_{max} ≥ 300 and log_{10} \( N_{\text{pe}} \) ≥ 4.0. However, in order to be conservative in the face of limited simulated event statistics, we chose instead to use IR_{max} ≥ 200 and log_{10} \( N_{\text{pe}} \) ≥ 4.2, resulting in an MRF = 0.92 and expected all-flavor signal and background event counts of 3.18 and 0.60, respectively.

C. Signal selection efficiency

The event rates for the selection criteria described in Sec. IVA were grouped into sets (EHE, S1–4) for reference purposes and are summarized in Table II for simulated signals. It is evident from Table II that this analysis, though designed to be sensitive primarily to UHE \( \nu_\tau \) signals, also had appreciable sensitivity to UHE \( \nu_e \) and \( \nu_\mu \) signals. The final limit described below will therefore be applicable to all neutrino flavors. Figures 11–14 show the distribution of event rates (Hz) for each cut parameter for simulated signal as well as background and a sample of IC22 data. All plots show data after application of the EHE filter (Fig. 11) and sets of selection criteria S1 (Fig. 12), S2 (Fig. 13), and S3 (Fig. 14).

The efficiency of the event selection criteria for accepting signal can be obtained from Fig. 15 (top). The bottom plot of that same figure shows the effective area \( A_{\text{eff}} \) for each neutrino flavor after application of the SMT8 trigger condition and the full suite of selection criteria. Using simulated signal, \( A_{\text{eff}} \) is defined by \( \Phi_{\nu} A_{\text{eff}} T = N_{\text{det}} \), where \( \Phi_{\nu} \) is the neutrino flux prior to any propagation or interaction effects in the Earth, \( T \) is a length of time, and \( N_{\text{det}} \) is the number of detected events. The \( A_{\text{eff}} \) is not used in the calculation of our limit on UHE neutrino production, but event rates for a particular theoretical model subject to the selection criteria in this analysis may be estimated via the product of the effective area and the model’s predicted flux. In the energy range pertinent to this analysis, signal events must be either downward-going or horizontal due to Earth absorption of upward-going neutrinos for \( E_{\nu} > \sim 100 \text{ TeV} \).
D. Background selection efficiency

The event rates for simulated background and 30% of the data sample are summarized in Table III. Figures 11–14 show the distribution of event rates for background. The efficiency of the event selection criteria for rejecting background can be obtained from Fig. 15 (top), where the simulated background and 30% of the data sample match well at each cut level.

![Graphs showing event rates for background and data](image)

**TABLE I.** Summary of the selection criteria used in this analysis.

| Selection criterion | Purpose |
|---------------------|---------|
| D. Background selection efficiency | The event rates for simulated background and 30% of the data sample are summarized in Table III. Figures 11–14 show the distribution of event rates for background. The efficiency of the event selection criteria for rejecting background can be obtained from Fig. 15 (top), where the simulated background and 30% of the data sample match well at each cut level. |
| **NDOM > 80** | Selects high-energy events which produce light in many DOMs. |
| **ρ_1(I), ρ_3(III) > 5 p.e./ns** | Selects events creating light at beginning and/or end of event. |
| **Z_{init} < 450 m** | Removes events with initial light depositions high in the detector. |
| **V_{z} < -0.1 m/ns** | Removes events consistent with downward trajectories. |
| **Z_{cog} > -330 m** | Selects well-contained events and removes cosmic-ray muons interacting near or below the bottom of the detector. |
| **ToI > 0.1** | Favors events with more spherical than tracklike topologies. |
| **IR_{max} ≥ 200** | Selects events with large instantaneous light depositions. |
| **log_{10}N_{pe} ≥ 4.2** | Selects high-energy events which produce a large amount of light. |
FIG. 10 (color online). We optimized the selection criteria for $\text{IR}_{\text{max}}$ and $\log_{10}N_{\text{pe}}$ using the MRF formalism. The plot shows how the MRF varies as a function of $\log_{10}N_{\text{pe}}$ for different values of $\text{IR}_{\text{max}}$. We chose values for these parameters near but not exactly at the minimum shown for reasons explained in the text.

Figure 16 shows the distributions of the true zenith angle (top) and primary neutrino energy (bottom) from the simulation for the events which passed all the selection criteria. As expected, most $\nu_{\tau}$ were from near the horizon, with the angular acceptance peaking at about 100° from vertical.

V. RESULTS

After unblinding the remaining 200 live-days of data and applying all the selection criteria, three events remained in the data sample. The predicted background from all simulated sources was $0.60 \pm 0.19$ events. The remaining data events are shown in Fig. 17.

From a detailed study of these events, we determined that one was consistent with light produced by an AMANDA optical module observed to emit light intermittently (Fig. 17, top). A second event was qualitatively consistent with background from a nearly horizontal muon interacting near the bottom of the detector (Fig. 17, middle). The third event had the characteristics of a neutrino-induced shower (Fig. 17, bottom), and was also in the final sample of an independent IC22 analysis which searched for showerlike signals [34]. However, we cannot rule out this event as being produced by a cosmic-ray muon accompanied by a stochastic high-energy bremsstrahlung energy-loss process. We have conservatively included all three events in the final sample in the derivation of the final result.

VI. SYSTEMATIC AND STATISTICAL ERRORS

The systematic and statistical errors in this analysis were obtained using signal and background simulations and are summarized in Table IV. In the following subsections, systematic errors on signal and background are explained followed by our result including both errors.

| Set No. | Selection Criteria | MC simulation | Signal $\nu(E^{-2})$ |
|---------|--------------------|---------------|---------------------|
|         |                    | $\text{LP} \times 10^{-9}$ [Hz] | $\text{ILP} \times 10^{-9}$ [Hz] | $\text{DB} \times 10^{-9}$ [Hz] | $\nu_{\tau} \times 10^{-8}$ [Hz] | $\nu_{\mu} \times 10^{-8}$ [Hz] | $\nu_{e} \times 10^{-8}$ [Hz] |
| EHE     | $\text{NDOM} > 80$ | $3.48 \pm 0.11$ | $3.54 \pm 0.09$ | $4.45 \pm 0.16$ | $50.5 \pm 0.5$ | $119 \pm 2.2$ | $39.9 \pm 0.7$ |
| S1      | $p_{x}(I), p_{y}(III) \geq 5 \text{ p.e./ns}$ | $3.42 \pm 0.11$ | $3.05 \pm 0.08$ | $4.30 \pm 0.16$ | $24.0 \pm 0.2$ | $29.3 \pm 0.8$ | $23.9 \pm 0.6$ |
| S2      | $Z_{\text{init}} < 450 \text{ m}, V_{p} > -0.1 \text{ m/ns}$ | $2.55 \pm 0.11$ | $2.91 \pm 0.08$ | $3.95 \pm 0.16$ | $22.6 \pm 0.3$ | $24.9 \pm 0.8$ | $22.9 \pm 0.5$ |
| S3      | $Z_{\text{cog}} > -330 \text{ m}, \text{Tol} < 0.1$ | $2.32 \pm 0.10$ | $2.29 \pm 0.08$ | $3.02 \pm 0.14$ | $15.7 \pm 0.3$ | $11.8 \pm 0.6$ | $17.5 \pm 0.5$ |
| S4      | $\text{IR}_{\text{max}} \geq 200, \log_{10}N_{\text{pe}} \geq 4.2$ | $1.72 \pm 0.08$ | $1.72 \pm 0.06$ | $2.07 \pm 0.11$ | $5.63 \pm 0.08$ | $3.70 \pm 0.15$ | $9.08 \pm 0.2$ |
A. Systematic errors for signal

The systematic error due to our lack of precise knowledge of the DOM sensitivity to photons was obtained by simulating the effect of setting it to 90% and 110% of its nominal value resulting in $\pm 7\%$ error. The systematic error in the event rates reflecting uncertainties on the optical properties of the ice was obtained by simulating events using different ice models. The ice models were created from data generated using in situ light sources. The baseline ice model [35] for this analysis used optical properties of the ice measured at AMANDA depths and extrapolated to IceCube depths, while an alternative ice model [36] obtained them with a direct fit to the full range of IceCube light source data. Comparing the predictions of the two ice models resulted in a $+29.4\%$ error.

The systematic uncertainty in the neutrino cross section came from two sources. One was from theoretical uncertainty in the parton distribution function evaluation and structure function and the other was from errors in the experimental measurement of the parton distribution function by HERA [37]. From these two sources, we estimated
the systematic error in the neutrino cross section as ±6.4%. Very high-energy events could saturate PMTs by exceeding the PMT’s dynamic range. This could result in an incorrect estimation of the original neutrino energy. Since the observable quantity most closely related to the energy is \( N_{\text{pe}} \), the systematic error associated with the PMT saturation was obtained by observing the impact of changing the \( N_{\text{pe}} \) cut from 90% to 110% of its original value. This error was found to be [-5.7%, +5.0%].

### B. Systematic errors for background

The systematic errors due to uncertainties in DOM sensitivity, ice properties and DOM saturation behavior were obtained in the same manner as for the signals, as described in Sec. VI A. They were estimated as [−4.7%, +7.9%], [−62%, +85%] and [−28.9%, +5.3%], respectively.

### TABLE III. Predicted background event rates with statistical error after application of each set of selection criteria.

For conventional neutrinos (labeled “conv” in the table), the Bartol model [14] was used. For prompt neutrinos, the Martin’s Golec-Biernat-Wusthoff (GBW) model [17] was used for \( \nu_e \) and the Sarcevic standard model [16] was used for \( \nu_\mu \) and \( \nu_\tau \).

| Set No. | \( \nu_\mu^{\text{conv}} \times 10^{-8} \) [Hz] | \( \nu_e^{\text{conv}} \times 10^{-8} \) [Hz] | \( \nu_\mu^{\text{prompt}} \times 10^{-10} \) [Hz] | \( \nu_e^{\text{prompt}} \times 10^{-8} \) [Hz] | \( \nu_\mu^{\text{prompt}} \times 10^{-8} \) [Hz] | \( \nu_e^{\text{prompt}} \times 10^{-8} \) [Hz] | Background \( \mu \) \( \times 10^{-6} \) [Hz] | Data 30% sample \( \times 10^{-6} \) [Hz] |
|---------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|-----------------------------|-----------------------------|
| EHE     | 184 ± 14.0                      | 6.88 ± 0.26                     | 33.4 ± 0.4                      | 23.6 ± 0.50                     | 9.95 ± 0.13                     | 830000                          | 1.37 × 10^6 ± 438             |
| S1      | 8.21 ± 1.80                     | 0.96 ± 0.06                     | 9.74 ± 0.17                     | 2.19 ± 0.12                     | 3.46 ± 0.05                     | 303                             | 246 ± 5.9                    |
| S2      | 8.11 ± 1.80                     | 0.96 ± 0.06                     | 9.62 ± 0.17                     | 2.05 ± 0.12                     | 3.42 ± 0.05                     | 41.2                            | 53.3 ± 2.7                   |
| S3      | 4.16 ± 0.66                     | 0.70 ± 0.06                     | 7.12 ± 0.14                     | 1.26 ± 0.09                     | 2.55 ± 0.04                     | 14.4                            | 20.8 ± 1.7                   |
| S4      | 0.24 ± 0.06                     | 0.04 ± 0.003                    | 0.91 ± 0.03                     | 0.15 ± 0.02                     | 0.43 ± 0.01                     | 0.026 ± 0.01                    | 0                           |
In addition, there are systematic errors which applied only to the background. The muon event rate is known to change as a function of the atmospheric temperature above the South Pole plateau. Since our muon simulation assumed a rate pegged to that seen in October, the seasonal variation was taken into account as a systematic error and was estimated as $[-24\%, +18\%]$ when compared with IC22 data at EHE filter level. The systematic error due to cosmic-ray composition was also obtained by switching constants and slopes between proton and iron in the two-component model data. At S3, just before the final cut, to have enough statistics, we obtained $-24\%$ by this method.

There are alternative models for the prompt neutrino flux. For this analysis, the base models used for the prompt neutrino flux are Sarcevic standard flux model for $\nu_\mu$ and $\nu_e$ [16] and Martin’s Golec-Biernat-Wusthoff model for $\nu_\tau$ [17]. As an alternative, we have also considered the Sarcevic minimum and maximum flux models [16], from which we estimate a $[-59\%, +30\%]$ systematic error on the prompt neutrino flux.

C. Result including statistical and systematic errors

Since it was computationally feasible to generate a large amount of simulated signal, the statistical error on the simulated signal is small ($\pm 2.3\%$). By contrast, the considerably larger statistical error on the simulated background ($\pm 32\%$) reflects the aggregate effect of the high rejection efficiency of our selection criteria and the limitations imposed by finite computational resources. In summary, the expected signal and background events for 200 live-days with IC22 are $3.18 \pm 0.07$(stat)$^{+2.99}_{-3.08}$(syst) and
TABLE IV. Summary of the systematic and statistical errors for signal and background events from the simulated data.

| Source                | Signal          | Background       |
|-----------------------|-----------------|------------------|
| DOM sensitivity       | −4.7%, +7.9%    | −4.7%, +7.9%     |
| Ice properties        | −0%, +29%       | −62%, +85%       |
| ϱ cross section       | −6.4%, +6.4%    | ⋮                |
| PMT saturation         | −5.7%, +5.0%    | −29%, +5.3%      |
| Cosmic-ray flux       | ⋮               | −0%, +16%        |
| Cosmic-ray composition| ⋮               | −24%, +0%        |
| Seasonal variation    | ⋮               | −24%, +18%       |
| Prompt ϱ flux model   | ⋮               | −59%, +30%       |
| Total Systematic error| −7.9%, +31%     | −97%, +94%       |
| Total Statistical error| ±2.3%            | ±32%             |

0.60 ± 0.19(stat) ±0.56 (syst), respectively. When we unblinded 200 live-days of data, we observed 3 events which were deemed compatible with background. With a predicted background of 0.60 ± 0.19(stat) ±0.56 (syst) events, the probabilities of observing one, two or three events due solely to fluctuations in the background are 30%, 13% and 5%, respectively.

We combined the systematic errors in quadrature with the statistical errors and applied a profile log-likelihood method [38] to obtain the confidence interval [39].

The 90% C.L. upper limit on signal for 200 live-days was obtained as μ<sub>30</sub> = 7.7 events. The 90% C.L. upper limit on astrophysical all-flavor neutrino flux, Φ<sub>30</sub>(ν<sub>τ</sub>), was obtained using the following relation: Φ<sub>30</sub> = μ<sub>30</sub>/N<sub>WB</sub>, where Φ<sub>WB</sub> and N<sub>WB</sub> are the WB bound for all-flavor astrophysical neutrinos and the corresponding number of all-flavor astrophysical neutrinos for 200 live-days, respectively. The obtained 90% C.L. upper limit is E<sub>ν</sub><sup>2</sup>Φ<sub>30</sub>(ν<sub>τ</sub>) < 16.3 × 10<sup>-8</sup> GeV cm<sup>-2</sup> sr<sup>-1</sup> s<sup>-1</sup> for the 3 observed events from the 200 live-days of IC22 data.

This limit applies to the primary neutrino energy range of 340 TeV < E<sub>ν</sub> < 200 PeV, covering the middle 90% of the accepted simulated signal. Figure 18 shows this limit together with several theoretical model predictions. The upper limit on the tau neutrino flux is one-third that of the all-flavor astrophysical neutrino flux if one assumes a flavor ratio of ν<sub>μ</sub>:ν<sub>τ</sub>:ν<sub>τ</sub> = 1:1:1 at Earth.

VII. CONCLUSIONS AND OUTLOOK

A set of selection criteria designed for UHE ν<sub>τ</sub> detection were applied to IceCube data. These criteria also had appreciable efficiency for UHE ν<sub>μ</sub> and ν<sub>τ</sub> detection. We applied these criteria to 200 live-days of data from IceCube’s 22-string configuration and observed 3 events in the final sample. We therefore set a 90% C.L. upper limit on the astrophysical UHE all-flavor neutrino flux of E<sub>ν</sub><sup>2</sup>Φ<sub>30</sub>(ν<sub>τ</sub>) < 16.3 × 10<sup>-8</sup> GeV cm<sup>-2</sup> sr<sup>-1</sup> s<sup>-1</sup>. The analysis improves on the previous limit set by AMANDA [34,40,41] with comparable integrated exposure. Future IceCube searches specialized for ν<sub>τ</sub> will be more sensitive due to the increased instrumented volume relative to IC22. The large volume will also warrant the application of sophisticated ν<sub>τ</sub> reconstructions, further improving the sensitivity of these searches.

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