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Multi-flavour neutrino searches from the Milky Way Galaxy

The IceCube Collaboration

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High-energy neutrinos are expected to be produced in the Milky Way by cosmic ray interactions at sites of acceleration or during their propagation. Neutrinos provide distinctive information on hadronic interactions and can be pointed back to production origins, unraveling unique properties of the Galaxy. We present an analysis on the search for the diffuse neutrino flux along the Galactic Plane by using data collected at the largest operating neutrino telescope in the world - the IceCube Neutrino Observatory. More than 10 years of data since the completion of the detector are used in this analysis. We utilize three event selections including through-going tracks, showers and starting-tracks to reach full-sky coverage and to be sensitive to all three neutrino flavours.

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1. Introduction

Situated at the geographic South Pole, the IceCube Neutrino Observatory stands as a cubic-kilometer neutrino detector, at a depth ranging from 1450 m to 2450 m [1]. IceCube provided evidence for the existence of various neutrino sources, including the flaring blazar TXS 0506+056 and the active galaxy NGC 1068 [2–4]. The identification of these sources relied on the analysis of data derived from charged-current muon-neutrino interactions, whose signature in the detector is a track-like event. Both TXS 0506+056 and NGC 1068 are located in the Northern Sky, in an optimal region for the search of point sources employing through-going tracks [5] from the Northern Hemisphere. However, the presence of a large atmospheric muon background greatly diminishes the discovery potential for sources within the Southern Sky. To address the challenge of enhancing sensitivity in the Southern Sky, two event selections have been introduced: cascade-like events and starting tracks, described in [6–9] and [10].

The study of neutrinos offers invaluable insights into both astrophysical phenomena and the fundamental realm of particle physics. Beyond hypothetical sources within our own Galaxy, the interaction of cosmic rays during their acceleration and propagation through the interstellar medium can generate high-energy neutrinos. Consequently, the Galactic plane has long been postulated as a possible source of neutrino emissions.

Recently, this postulated emission from the Milky Way has been observed at a 4.5σ level of significance by using cascade-like events collected by IceCube [11]. While this observation identifies the Galactic plane as a source of neutrinos, the utilization of cascade-like events alone complicates further interpretation of the signal. Both starting tracks and the through-going tracks from the Northern Hemisphere are characterized by higher resolution. For this reason, a combination of these three datasets can lead to a better interpretation of the emission description from the galactic plane.

In this work, we present a combined dataset that merges the different event selections, including through-going tracks from Northern Hemisphere, cascades, and starting tracks, to achieve comprehensive sky coverage and sensitivity to all three neutrino flavors. By exploiting the unique characteristics of each event selection, we aim to enhance our ability to identify and study astrophysical neutrino sources.

Here, we provide a description of the dataset, discuss its characterization in terms of effective area and angular resolution in section 2, and present the sensitivity of the combined dataset compared to individual event selections in section 3. Furthermore, in section 4 we explore the dataset's potential for Galactic Plane searches, where neutrinos produced from cosmic-ray interactions in the Galactic medium are expected to be present. The combined dataset offers improved sensitivity in probing the Galactic Plane emission, providing new opportunities for understanding the astrophysical processes involved.

2. Dataset Description

In this work, different event selections are combined to achieve full sky coverage and sensitivity to all three neutrino flavors. The event selections include through-going tracks from Northern

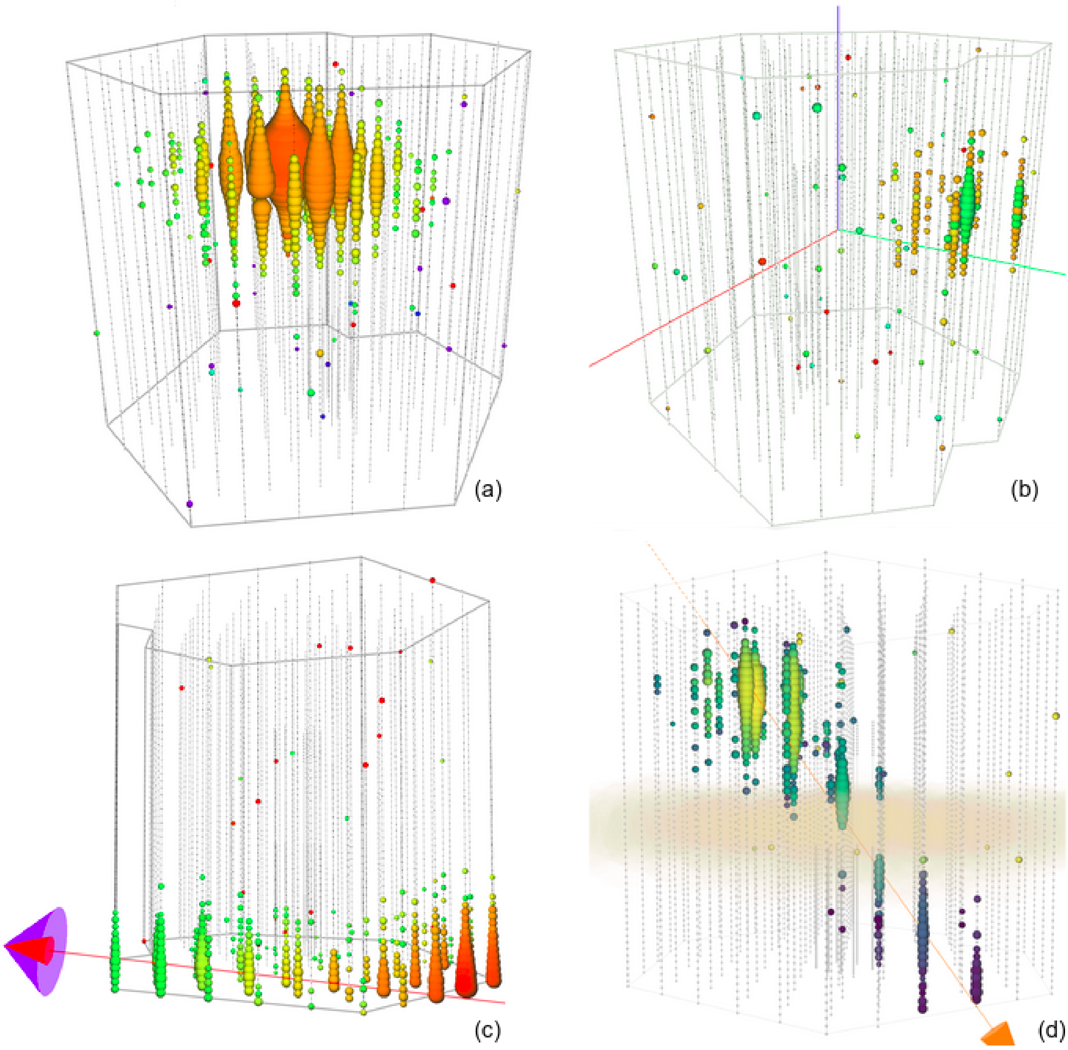


Figure 1: Simulated event topologies considered in this joint analysis: (a) contained cascades, (b) partially contained cascades, (c) through-going tracks, (d) starting tracks. Color, from red to blue, shows the photons arrival time at the optical module, while the arrow shows the reconstructed arrival direction of the event.

Hemisphere, cascades, and starting tracks. A visualization of the characteristic events included in this analysis is shown in Fig. 1, which are:

1. Contained (fig. 1a) and partially contained (fig. 1b) cascades-like events. Cascades are produced from neutral-current interactions of all neutrino flavors and charge current interactions of flavors other than muon neutrinos. These events have a lower angular resolution compared to track-like events but can be easily distinguished from the dominant background of downward-going muons from atmospheric interactions in the Southern Sky.

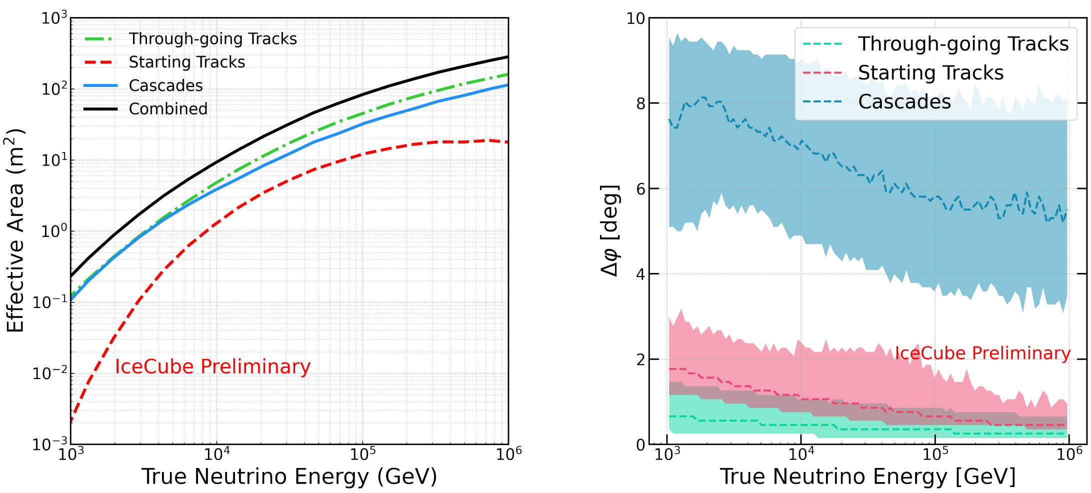
2. Through-going muon tracks (Fig. 1c) from Northern Emisphere. These events are induced by charged current muon neutrino events where the interaction vertex can be outside the detector volume. Allowing neutrinos to interact outside the instrumented volume achieves a large

effective area. However, the analysis needs to be limited to the Northern Hemisphere where the Earth efficiently filters atmospheric muons.

3. Starting muon tracks (Fig. 1c) are events induced by charged-current muonic neutrino interactions where the interaction vertex is contained in the detector. By identifying neutrino events that start in the detector, the atmospheric muon component is reduced while retaining a high rate of starting neutrino events.

Each of these event selections is differentiated not only by event topology but also by directional and energy reconstruction. To ensure independence among the different datasets and simplify their combination, an analysis of the overlapping events between them was performed using simulations. Our goal is to maximize the sensitivity of the combined dataset by establishing a rule for assigning overlapping events to a single dataset.

The overlap between cascades and tracks is minimal. The events belonging to the overlap exhibit a topology resembling cascades. As a consequence, the reconstruction of cascades offers a better angular and energy resolution compared to other selections. Therefore overlapping events are considered in the cascade event selection and removed by the other selections.



(a) **(b)**

Figure 2: (2a) Effective Area of the Combined Dataset (black solid line) compared to Through-going Tracks (green dashed-dotted line) [5], Cascades (solid blue line) [10], and Starting Events (red dashed line) [6]. (2b) Comparison between the angular resolution of the Through-going Tracks (blue), Cascades (green), and Starting Events (red).

On the other hand, the overlap between through-going muons from the Northern Hemisphere and starting tracks is more significant, with approximately 50 % of starting tracks being contained in the through-going dataset. The overlapping events are all up-going events with the interaction vertex contained within the detector. In this case, the reconstruction that maximizes sensitivity is that of starting tracks.

Fig. 2 shows the characterization of the combined dataset. The left panel presents the all-flavour effective area, averaged over the entire sky, of the combined dataset (solid black line) compared to through-going tracks (green dashed-dotted line), cascades (solid blue line), and starting events (red dashed line). The right panel illustrates the angular resolution of the different datasets considered. The combined dataset benefits from the large effective area of cascades/through-going tracks and the high angular resolution of starting/through-going tracks.

3. Sensitivity

The combined dataset can be used for the search of astrophysical neutrino sources. As previously shown, the dataset benefits from the advantages of the individual event selections. This implies that the dataset defined in this work is extremely promising for searches in both the Southern and Northern Sky.

Fig. 3 presents the per-flavor 90 % sensitivities of the combined dataset (black) compared to upgoing tracks (green), cascades (blue), and starting events (red). The figure also includes the 5σ discovery potential flux as a function of the sin of declination for a source spectrum proportional to E^{-2}. In the Northern Sky, through-going tracks have a dominant effect, while the contribution related to starting tracks and cascades is more relevant in the Southern Sky.

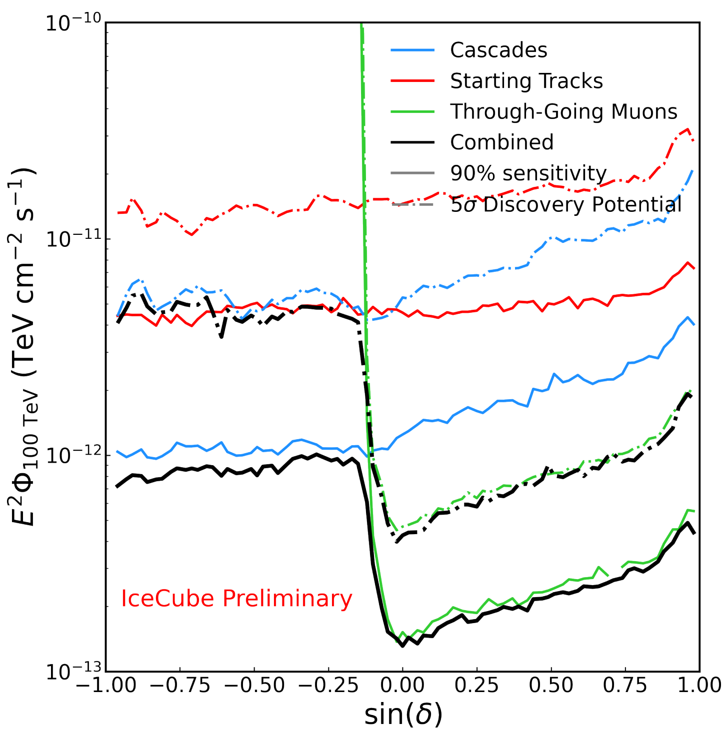


Figure 3: Per-flavor sensitivities of the combined dataset (black) compared to through-going tracks (green) [5], cascades (blue) [10], and starting events (red) [12]. See text for more details.

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4. Galactic Plane Searches

In cosmic-ray interactions with the Galactic medium, the production of neutral pions gives rise to high-energy gamma rays. Similarly, in the case of neutrinos, the production of neutrinos occurs through the decay of charged pions. By investigating the emission of neutrinos from the Galactic plane, we can gain insights into the properties of our Galaxy.

IceCube has detected neutrino emission from the Milky Way through the analysis of cascades applied to a 10-year dataset. By comparing diffuse emission models to a background-only hypothesis, a significant neutrino emission originating from the Galactic plane has been identified at a 4.5σ level of significance. The signal observed is consistent with diffuse emission of neutrinos from the Milky Way but could also arise from a population of unresolved point sources [11] therefore further investigations are needed.

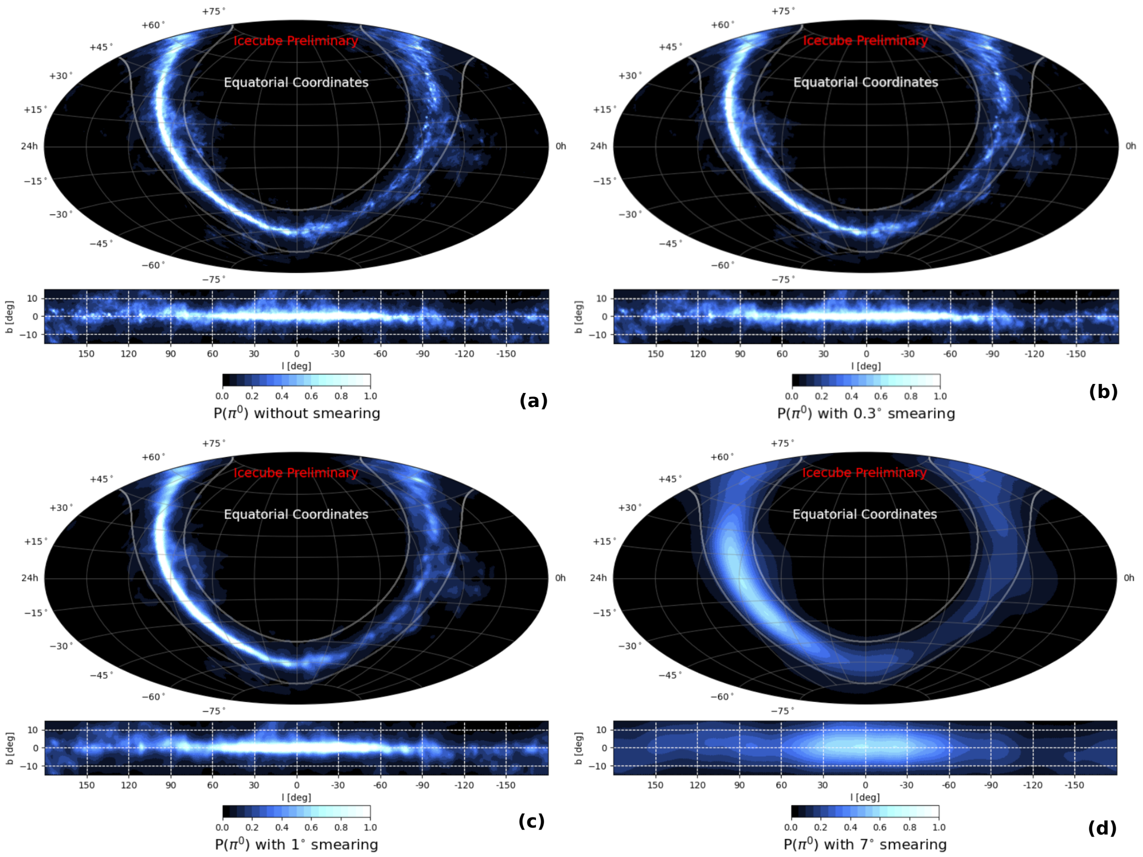

Figure 4: Fermi-π^0 model [13] of diffuse Galactic neutrino emission. The model is convolved with the IceCube detector acceptance, as shown in panel (a), and then smeared with Gaussian distributions representing the different dataset uncertainties. The applied smearing values are as follows: (b) 0.3° for upgoing-tracks, (c) 1.0° for starting tracks, and (d) 7.0° for cascades.

In this work, we explore the potential of the combined dataset for Galactic plane searches. The improved sensitivity and sky coverage of the combined dataset enable a more comprehensive investigation of neutrino emission from the Galactic plane. In this work a model based on *Fermi*-LAT observations [13] is tested. The model is reported in fig. 4 where the predicted neutrino flux from the plane is convolved with the IceCube detector acceptance, as illustrated in panel (a). To incorporate the uncertainties of the different datasets, Gaussian smearing is applied. It is important to note that the values used for smearing in panels (b), (c), and (d) (0.3° for through-going tracks, 1.0° for starting tracks, and 7.0° for cascades) are provided here as examples. In the actual analysis, a per-event uncertainty is utilized, which means that each event in the dataset has its own specific uncertainty rather than applying a single uncertainty value for the entire dataset.

The results show that the combined dataset provides a significant improvement in sensitivity compared to individual event selections, particularly in the Galactic plane region.

Dataset	**Sensitivity** $[10^{-11}\,\mathrm{TeV\,cm^{-2}\,s^{-1}}]$	**Discovery Potential** $[10^{-11}\,\mathrm{TeV\,cm^{-2}\,s^{-1}}]$
Starting Tracks	2.67	4.62
Cascades	0.60	2.46
Combined	0.49	1.71

Table 1: Sensitivity and discovery potential obtained through the combined dataset, to a model based on the *Fermi*-LAT observations [13]. The sensitivity and discovery potential are also reported for cascades [10] and starting tracks [6] for comparison. The combined dataset gives the best sensitivity.

The sensitivity derived for the model is presented in Table 1, compared to the published sensitivities obtained using starting tracks [6] and cascades [10]. Sensitivities in this work do not include the effects of systematic uncertainties. Due to their smaller effective area, starting tracks exhibit lower sensitivity compared to the other datasets. However, starting tracks offer a significant contribution in the southern sky. On the other hand, cascades have a larger effective area in the Southern sky, resulting in the highest sensitivity when considered individually. The combined dataset benefits from the contribution of all individual datasets, as can be observed in Table 1, resulting in the highest sensitivity overall.

5. Conclusion

In this work, we have presented a new analysis that combines through-going tracks, cascades, and starting tracks for comprehensive sky coverage and improved sensitivity to astrophysical neutrino sources. The dataset's characterization in terms of effective area and angular resolution demonstrates its advantages compared to individual event selections.

The combined dataset, as can be observed from the improved sensitivities, is extremely promising, and can provide the opportunity to probe potential neutrino sources with enhanced observation power.

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