Exploring the Cosmic Frontiers: IceCube's Update on Neutrinos and Cosmic Rays

Matthias Plum[1★] for the IceCube Collaboration,

1 South Dakota School of Mines & Technology, Rapid City, SD, USA

★ matthias.plum@icecube.wisc.edu

22nd International Symposium on Very High Energy Cosmic Ray Interactions (ISVHECRI 2024)
Puerto Vallarta, Mexico, 8-12 July 2024
doi:10.21468/SciPostPhysProc.?

Abstract

The IceCube Neutrino Observatory detects particles produced from cosmic rays and neutrinos to explore the high-energy universe. It consists of a deep in-ice Cherenkov detector, IceCube and is complemented by IceTop, a square-kilometer surface detector. IceTop studies a wide range of topics in cosmic-ray science. An overview of results from the joint analysis of IceCube and IceTop data will be presented, including recent results about galactic neutrino emission as well as the measurement of the high-energy cosmic ray mass composition, GeV muon density and a search for the prompt atmospheric neutrino flux with IceCube. An outlook on the planned extension IceCube-Gen2 will be given.

Received Date
Accepted Date
Published Date

Contents

---

1 Introduction

The IceCube Neutrino Observatory [1] is an astroparticle detector near the Amundsen-Scott South Pole Station, designed to detect high-energy neutrinos from astrophysical sources. Encompassing a cubic kilometer of Antarctic ice, IceCube uses thousands of digital optical modules to capture the faint Cherenkov light emitted from secondary charged particles when neutrinos interact with ice molecules, helping to explore some of the universe's most energetic phenomena related to cosmic rays. IceTop [2], a surface array composed of ice-Cherenkov detectors, complements the main in-ice detector by studying cosmic rays and providing a veto for cosmic-ray induced background events. The IceCube observatory plays a significant role in multimessenger astronomy, allowing scientists to investigate a broad set of fundamental questions in astrophysics and particle physics that we are highlighting in the following.

2 Galactic Plane Neutrinos

The IceCube Neutrino Observatory has recently achieved a significant milestone by detecting high-energy neutrinos emanating from the Galactic plane for the first time [3]. These neutrinos possess energies considerably higher than those generated by stellar fusion and are believed to result from interactions between cosmic rays and galactic material, which also produce gamma rays. Advanced statistical and machine learning reconstruction methods [4] have played a crucial role in improving the sensitivity and accuracy of these detections, allowing IceCube to effectively differentiate neutrino sources from atmospheric background noise. This breakthrough presents a novel view of the Milky Way, offering new avenues for understanding the universe beyond what traditional light-based observations can reveal. The long-term analysis has provided strong evidence for the Milky Way as a source of these high-energy neutrinos. The study utilized a decade's worth of data, involving 60,000 neutrino events, supporting the robustness of these findings at the 4.5σ level of significance. This dataset not only exemplifies the potential of machine learning in astrophysics but also sets the stage for future research aimed at pinpointing specific high-energy neutrino sources within the galaxy. This breakthrough sets a foundation for neutrino astronomy, offering a new lens for exploring

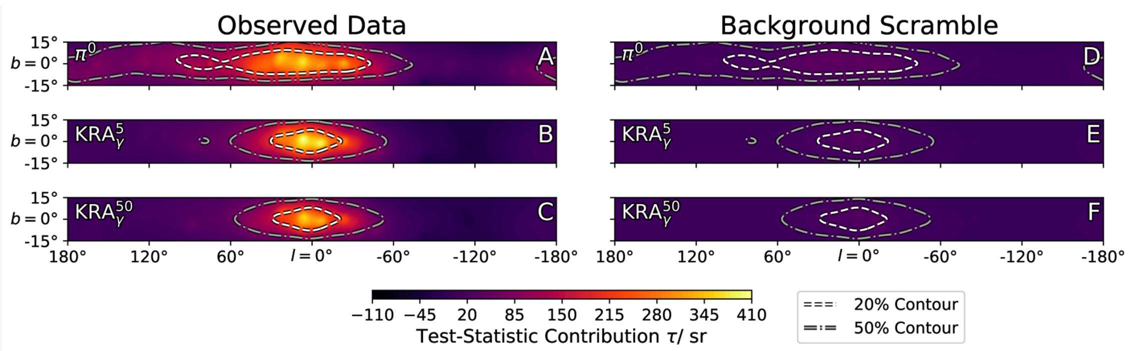

Figure 1: Galactic plane test-statistic contributions. The contribution to the test-statistic τ is shown in galactic coordinates (longitude and latitude indicated by l and b, respectively) for each of the three tested Galactic plane models, for details, see [3]. The overall test-statistic value was obtained by integration over the sky. The contribution for the observed data (A-C) is compared to the contribution for a single randomly selected mock experiment using scrambled data (D-F). Contours enclose 20% (white) and 50% (gray) of the predicted model flux. Figure adapted from [3].

cosmic phenomena beyond what is possible with traditional electromagnetic observations.

3 Cosmic Rays Analysis Results

3.1 Cosmic Rays Mass Composition

Hadronic interaction models are employed to simulate the interactions of cosmic rays as they enter the Earth's atmosphere, leading to the generation of air showers. These models are essential for predicting the observables of these air showers. By reconstructing composition-dependent observables from these simulations, the performance of various interaction models was tested against the coincident air-shower data taken from IceTop and IceCube. Coincident air-shower data represent simultaneous observations of the same event at the surface by IceTop and in the deep ice by IceCube. The mass composition results of 3 years of coincident data [5] are significantly influenced by the choice of hadronic interaction models used in their analysis. These models are integral in predicting how cosmic ray particles interact with the Earth's atmosphere, which is critical for interpreting the measurements of cosmic rays. The use of models such as Sibyll 2.1 [6], Sibyll 2.3 [7], QGSJet-II.04 [8], and EPOS-LHC [9] introduce uncertainties in the mass composition results due to their varied predictions of air-shower observables, as shown in Figure 2. These models are crucial for indirect composition measure-

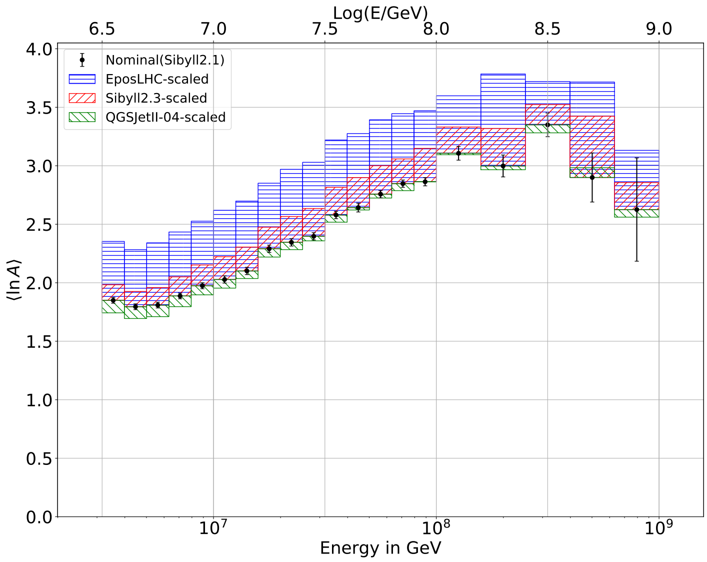

Figure 2: Hadronic interaction model uncertainty range on ⟨ln A⟩ relative to the nominal model Sibyll2.1 [6] for Sibyll2.3 [7] (red), QGSJetII-04 [8] (green), and Epos-LHC [9] (blue). Figure adapted from [5].

ments, yet their limitations emphasize a significant uncertainty in interpreting cosmic ray data. Current research continues to focus on refining these models to better align with experimental data and improve compositional determinations.

3.2 GeV Muon Density

The study on GeV muon density [10] using data from the IceTop array presents significant findings regarding the behavior of these particles in air showers. The research leverages three years of collected data from near-vertical air showers to measure the density of GeV muons at reference distances of 600 meters and 800 meters from the shower axis, for primary energies ranging from 1 PeV to 120 PeV. These measurements are taken at an atmospheric depth of approximately 690 g/cm^2, which provides insights into muon production at various energy levels. In order to compare the measured distributions to model predictions, the z—value is used, which is defined as

$$z = \frac{\log(\rho_\mu) - \log(\rho_{\mu,p})}{\log(\rho_{\mu,Fe}) - \log(\rho_{\mu,p})}. \tag{1}$$

The results from IceTop are compared with various theoretical models to assess their consis-

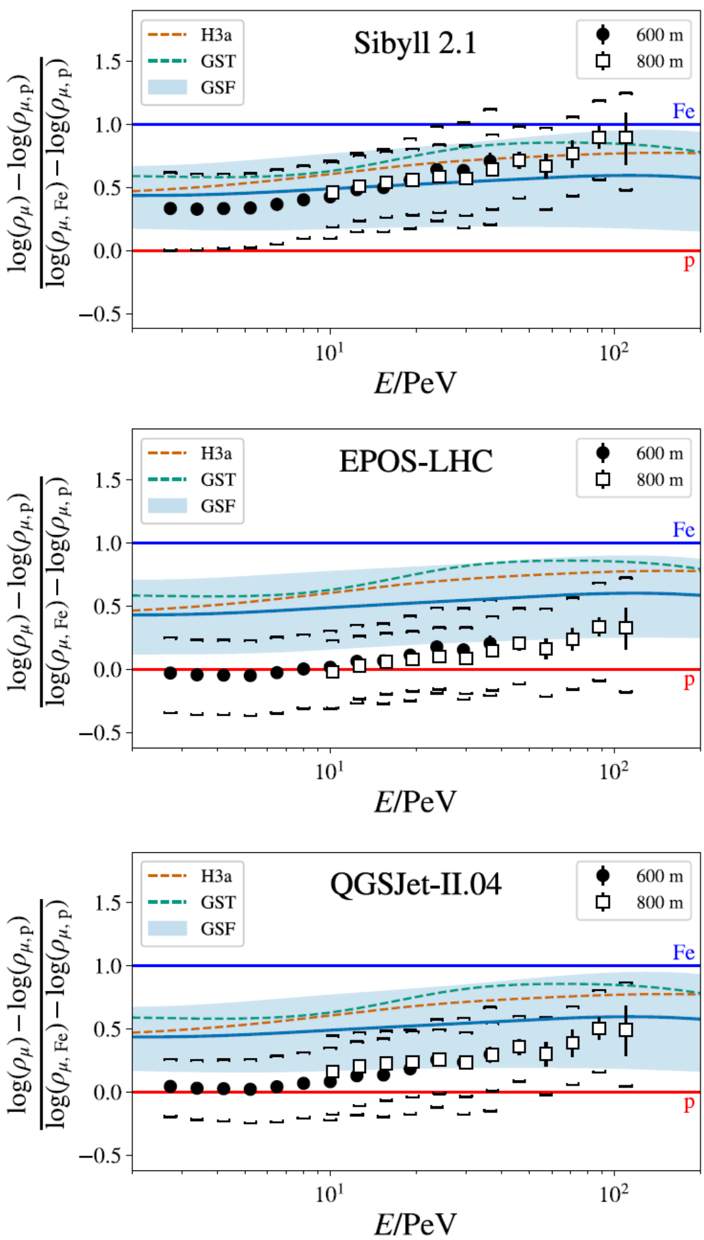

Figure 3: Muon densities in terms of the z-values defined in Equation 1, compared to predictions from the hadronic interaction models Sibyll 2.1, EPOS-LHC, and QGSJetII.04. Expectations from the cosmic ray flux models H3a [11], GST [12], and GSF [13] are also shown. Figure adapted from [10].

tency [10] and are shown in Figure 3. Measurements are generally in line with predictions from the Sibyll 2.1 model when considering any plausible cosmic ray flux scenario. However, when benchmarked against post-LHC hadronic interaction models such as QGSJet-II.04 and EPOS-LHC, the post-LHC models tend to predict higher muon densities than what is experimentally observed at the corresponding energy ranges. This discrepancy highlights potential areas for refinement in the modeling of air-shower processes above certain energy levels. The findings suggest an adjustment might be necessary for the post-LHC models to harmonize with observed data, which is critical because these models are fundamental in understanding cosmic ray physics and interactions. Across all measured energy levels, the post-LHC models predict denser muon production, which conforms better with experimental observations at higher energy ranges, but still reveals inconsistencies.

3.3 Prompt Atmospheric Neutrino Flux Search

The search for prompt atmospheric muons in the IceCube Neutrino Observatory focuses on identifying prompt atmospheric neutrinos [14]. Prompt atmospheric neutrinos are generated alongside high-energy cosmic rays through the decay of charm mesons in atmospheric air showers. This search is vital because understanding the behavior and yield of these neutrinos can significantly enhance the model of hadronic interactions in cosmic ray events and improve the precision of astrophysical neutrino measurements. Prompt atmospheric neutrinos differ from conventional atmospheric neutrinos as they arise from the immediate decay of charm mesons, which occur at different energy scales compared to decay paths in the more common processes involving pions and kaons. Their detection is crucial as they serve as a background to the diffuse astrophysical neutrino flux that IceCube measures. Detecting or placing limits on these neutrinos provides essential data that can refine our understanding of cosmic-ray interactions. One of the significant challenges in detecting prompt neutrinos is distinguishing them from the more dominant astrophysical neutrino flux, as shown in Figure 4. These detections are contingent on the assumptions made regarding the astrophysical flux, which can complicate interpreting the data and setting robust upper limits for prompt neutrino fluxes. To address this, new methods are proposed to calculate these limits, taking into account model dependencies to enhance the robustness of the results.

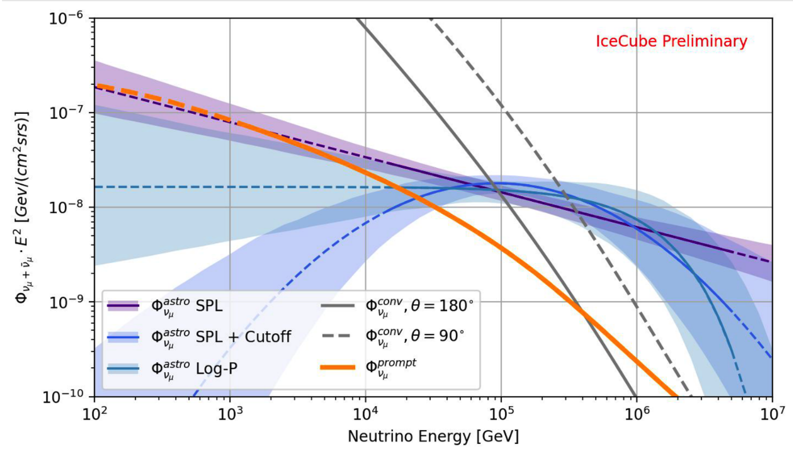

Figure 4: Plot comparing different astrophysical neutrino flux models (blue lines) to the prompt atmospheric neutrino flux (orange). Figure adapted from [14].

4 IceCube-Gen2

Looking forward, the planned extension of the observatory, IceCube-Gen2 [15], aims to significantly enhance detection capabilities. IceCube-Gen2 will expand the instrumented volume of the deep in-ice optical array by a factor of 8, improving sensitivity to a broader range of neutrino energies, and is expected to enable more precise determination of high-energy cosmic phenomena. The large in-ice detector will be complemented by a surface array designed to enhance cosmic-ray science and gamma-ray measurements by combining cosmic-ray detectors with scintillators and radio antennas, as shown in Figure 5. By filtering millions of muons, the surface array facilitates improved calibration of the optical and radio arrays and offers insights into hadronic interactions in air showers on the surface as well as in the deep in-ice detector. A small array of air Cherenkov IceAct telescopes will provide an additional

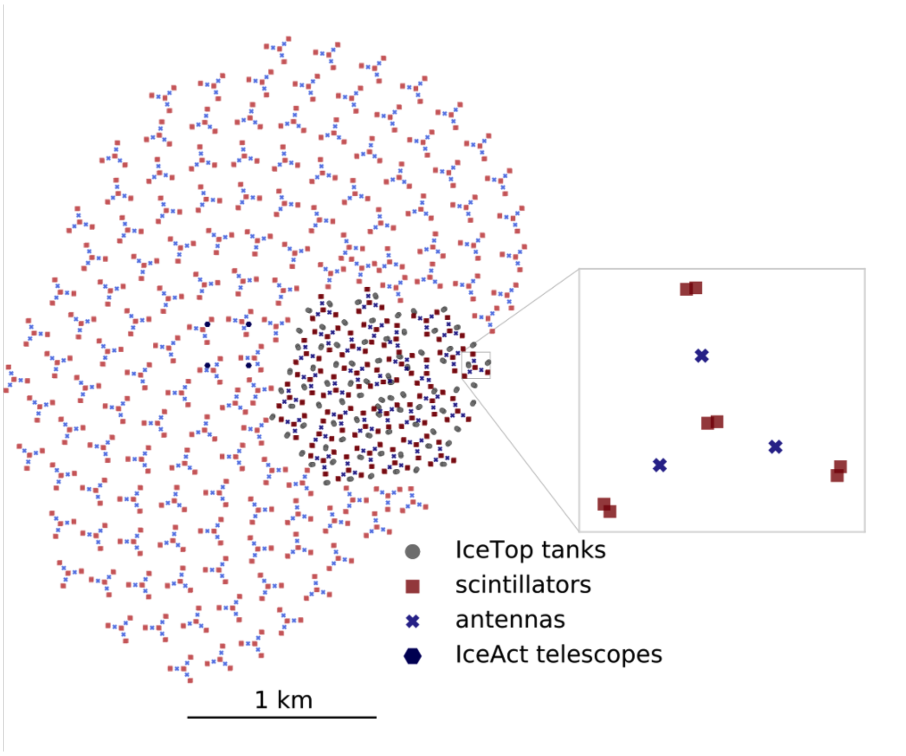

Figure 5: The surface array of IceCube-Gen2 consists of elevated scintillation panels (red squares) and elevated radio antennas (blue crosses) per station. Four IceAct stations (purple hexagons) will be deployed in the center of IceCube-Gen2. The existing IceTop tanks are indicated by gray circles. Figure adapted from [15].

independent measurement of air showers inside the atmosphere, which will further enhance the physics capabilities of the Gen2 detector. This next-generation facility is anticipated to uncover new neutrino sources and provide deeper insights into the mechanisms driving cosmic ray production, ultimately advancing our understanding of the most energetic and intriguing processes in the universe, and also enabling the further testing and refining of hadronic interaction models. With the successful implementation of IceCube-Gen2, the field of neutrino and cosmic ray astrophysics is poised to enter an exciting era of discovery and exploration.

5 Conclusion

The detection of high-energy neutrinos from the Galactic plane by the IceCube Neutrino Observatory marks a pivotal step forward in astrophysics, providing compelling evidence for the Milky Way as a significant source of astrophysical neutrinos and opening new avenues for exploring cosmic phenomena beyond traditional electromagnetic observations. The IceTop measurements provide crucial empirical data that can improve the fidelity of air shower models. While the Sibyll 2.1 model aligns well with IceTop's observations, adjustments to post-LHC models might be necessary to fully accommodate the empirical evidence across the studied energy ranges. Accurate measurement and detection of the prompt atmospheric neutrino flux will not only improve cosmic ray interaction models but also contribute to the general understanding of the high-energy universe. IceCube's exploration of prompt atmospheric neutrinos through various detection channels aims to separate this particular component from the total atmospheric background, which is a critical step toward more accurate astrophysical measurements in the future. This endeavor highlights the ongoing efforts to reduce uncertainties and advance neutrino astrophysics, paving the way for future discoveries in the field. The 8 times larger deep in-ice and surface array of the IceCube-Gen2 detector will play a crucial role in enhancing scientific capabilities by providing deeper insights into cosmic-ray interactions.

Acknowledgements

This contribution was funded by the U.S. National Science Foundation-EPSCoR (RII Track-2 FEC).

References

[1] M. G. Aartsen *et al.*, *The IceCube Neutrino Observatory: Instrumentation and Online Systems*, JINST **12**(03), P03012 (2017), doi:10.1088/1748-0221/12/03/P03012, 1612.05093.

[2] R. Abbasi *et al.*, *IceTop: The surface component of IceCube*, Nucl. Instrum. Meth. **A700**, 188 (2013), doi:10.1016/j.nima.2012.10.067, 1207.6326.

[3] R. Abbasi *et al.*, *Observation of high-energy neutrinos from the galactic plane*, Science **380**(6652), 1338 (2023), doi:10.1126/science.adc9818.

[4] M. Huennefeld *et al.*, *Combining Maximum-Likelihood with Deep Learning for Event Reconstruction in IceCube*, PoS **ICRC2021**, 1065 (2021), doi:10.22323/1.395.1065.

[5] M. G. Aartsen *et al.*, *Cosmic ray spectrum and composition from PeV to EeV using 3 years of data from IceTop and IceCube*, Phys. Rev. D **100**, 082002 (2019), doi:10.1103/PhysRevD.100.082002.

[6] E.-J. Ahn, R. Engel, T. K. Gaisser, P. Lipari and T. Stanev, *Cosmic ray interaction event generator SIBYLL 2.1*, Phys. Rev. D **80**, 094003 (2009), doi:10.1103/PhysRevD.80.094003, 0906.4113.

[7] F. Riehn, H. P. Dembinski, R. Engel, A. Fedynitch, T. K. Gaisser and T. Stanev, *The hadronic interaction model SIBYLL 2.3c and Feynman scaling*, PoS **ICRC2017**, 301 (2018), doi:10.22323/1.301.0301, 1709.07227.

[8] S. Ostapchenko, *Monte Carlo treatment of hadronic interactions in enhanced Pomeron scheme: QGSJET-II model*, Physical Review D **83**(1) (2011), doi:10.1103/physrevd.83.014018.

[9] T. Pierog, I. Karpenko, J. M. Katzy, E. Yatsenko and K. Werner, *EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider*, Physical Review C **92**(3) (2015), doi:10.1103/physrevc.92.034906.

[10] R. Abbasi *et al.*, *Density of GeV muons in air showers measured with IceTop*, Phys. Rev. D **106**, 032010 (2022), doi:10.1103/PhysRevD.106.032010.

[11] T. K. Gaisser, *Spectrum of cosmic-ray nucleons, kaon production, and the atmospheric muon charge ratio*, Astroparticle Physics **35**(12), 801 (2012), doi:https://doi.org/10.1016/j.astropartphys.2012.02.010.

[12] T. Stanev, T. K. Gaisser and S. Tilav, *High energy cosmic rays: sources and fluxes*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **742**, 42 (2014), doi:https://doi.org/10.1016/j.nima.2013.11.094.

[13] H. Dembinski, R. Engel, A. Fedynitch, T. Gaisser, F. Riehn and T. Stanev, *Data-driven model of the cosmic-ray flux and mass composition from 10 GeV to* 10^{11} *GeV* (2017), 1711.11432.

[14] J. Boettcher *et al.*, *Search for the Prompt Atmospheric Neutrino Flux in IceCube*, PoS **ICRC2023**, 1068 (2023), doi:10.22323/1.444.1068.

[15] IceCube-Gen2 Collaboration, *IceCube-Gen2 Technical Design Report* (2023).