Universität Münster

IceCube Gen2

Towards Deep Learning-Based Event Reconstruction and Selection for Point-Source Searches with the IceCube-Gen2 Optical Array

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With funding from the:

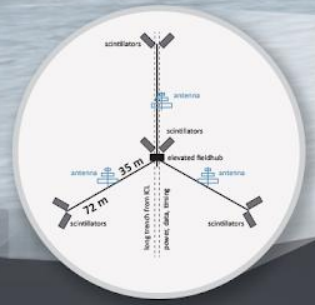
NSF

Federal Ministry of Research, Technology and Space

[Credit: IceCube-Gen2 Collaboration]

IceCube Gen2 | Detectors

Surface • Radio • Optical



Cosmic Ray Surface Array

An air shower array that sits on top of the optical array

One surface station installed above each optical string

IceCube Laboratory

50 m

1370 m

2780 m

IceCube-Gen2: 120 new strings of optical modules

IceCube: 86 strings of optical modules

DeepCore

Antarctic bedrock

IceCube-Gen2 Optical Module

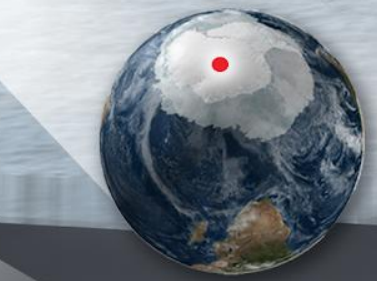
4x the sensitivity of IceCube's modules

9,600 new optical modules in total to be deployed in the ice

80 modules on each string, spaced 17 meters apart

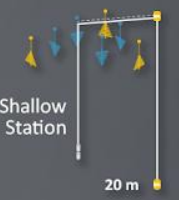
IceCube (1 km)

IceCube-Gen2 (3 km)



Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility



Below-Ice Radio Array

361 detector stations spread over an area of 500 km²

Neural Networks for IceCube-Gen2 Point-Source Searches

The new detector poses challenges for conventional event-processing and reconstruction methods

- Heterogeneous detector: Gen1 + Gen2 + Upgrade OMs
- Exploit segmented OM information
- Scale to Gen2's increased data rate

} NNs are a natural solution

Generate dedicated IceCube-Gen2 simulations:
- Using Gen2-DC16 OMs
- IceCube included
- Upgrade omitted
- Optical array only

Work on NN-based algorithms:
- Event processing
- Event reconstruction
- Event classification

Evaluate physics performance:
- Using Toise*
- Define 5-dimensional response tensor:

$$D_{f,E_\nu,\cos(\theta_\nu),E_{\mathrm{rec}},\Delta\Psi}$$

Gen2-DC16 OM

*[J. van Santen et al., 2022 JINST 17 T08009]

Neural Network Algorithms (through-going μ)

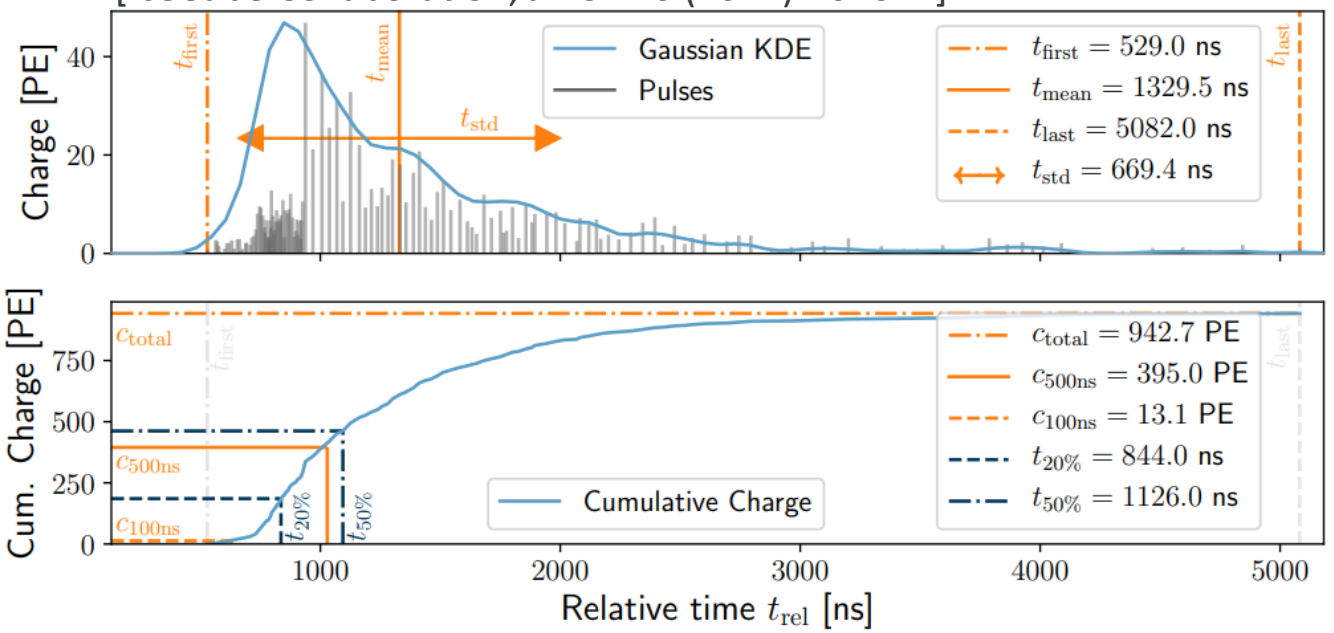
Methodology

- Implementation using a custom branch of **GraphNeT** [Søgaard et al. 2023, JOSS 8, 4971]

- **Noise cleaning**:
  - **GNN-based below 50k total pulses (rej. > 99 %) [IceCube-Gen2 Coll., PoS(ICRC2025) 1201]**
  - Classical SRT above 50k total pulses (rej. ≈ 70 %)

- **Neural network inputs:**
  - Pulse summary statistics per OM
  - OM position
  - Charge-weighted average orientation
  - Saturation and OM-type flags

[IceCube Collaboration, JINST 16 (2021) P07041]

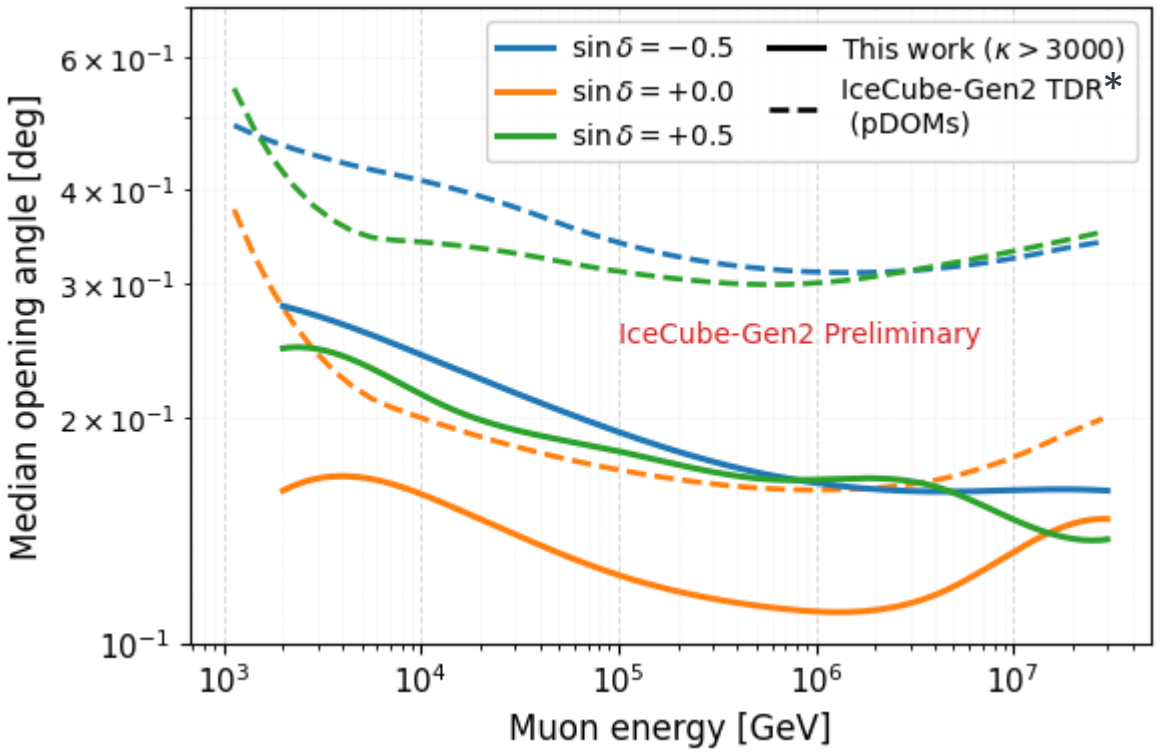


- Using an adaptation of the winning IceCube Kaggle solution [H. Bukhari et al., Eur. Phys. J. C 84 (2024) 646]

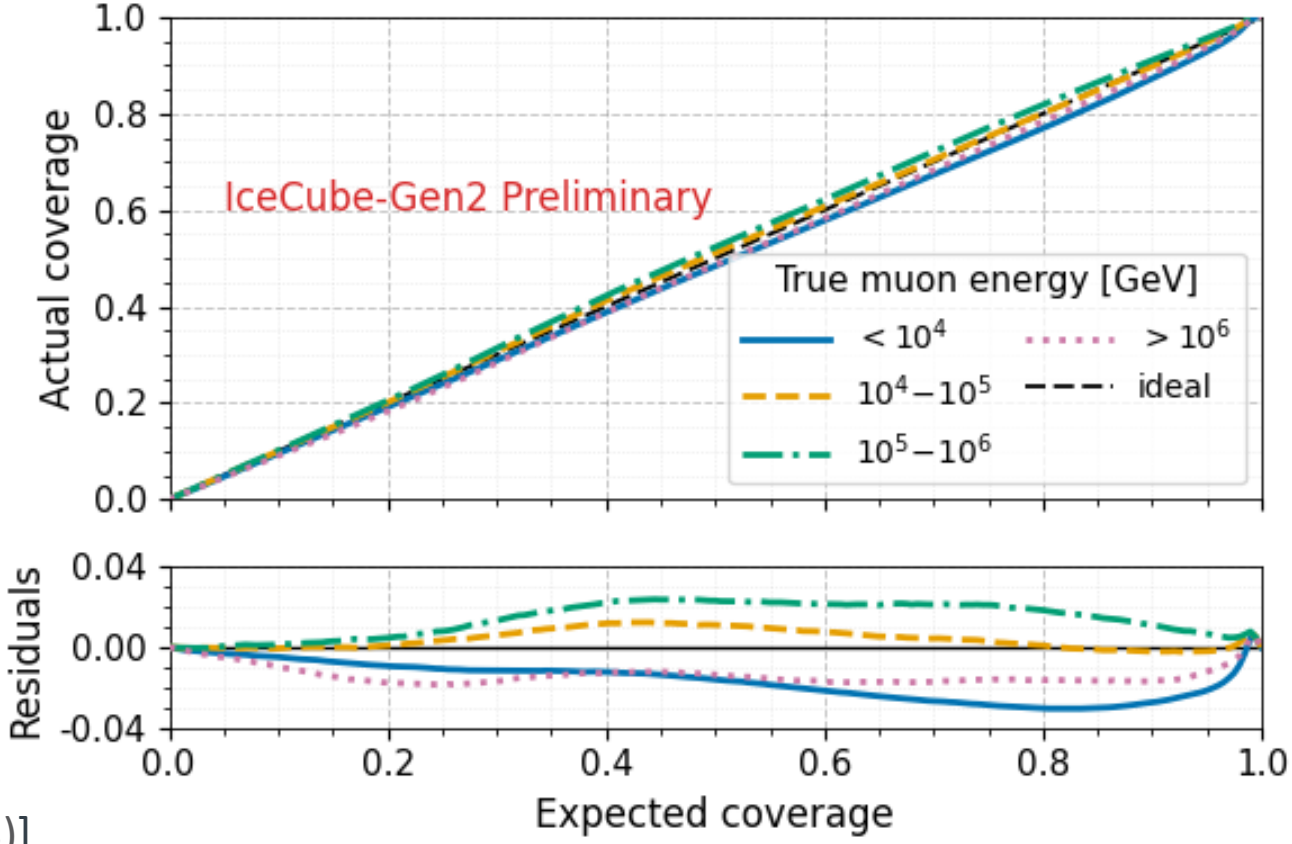
Direction Reconstruction: Normalizing-Flows

- Predict the full posterior PDF on the sphere

- Recently demonstrated state-of-the-art performance for IceCube direction reconstruction [IceCube Collaboration, arXiv:2604.19846 (2026)]



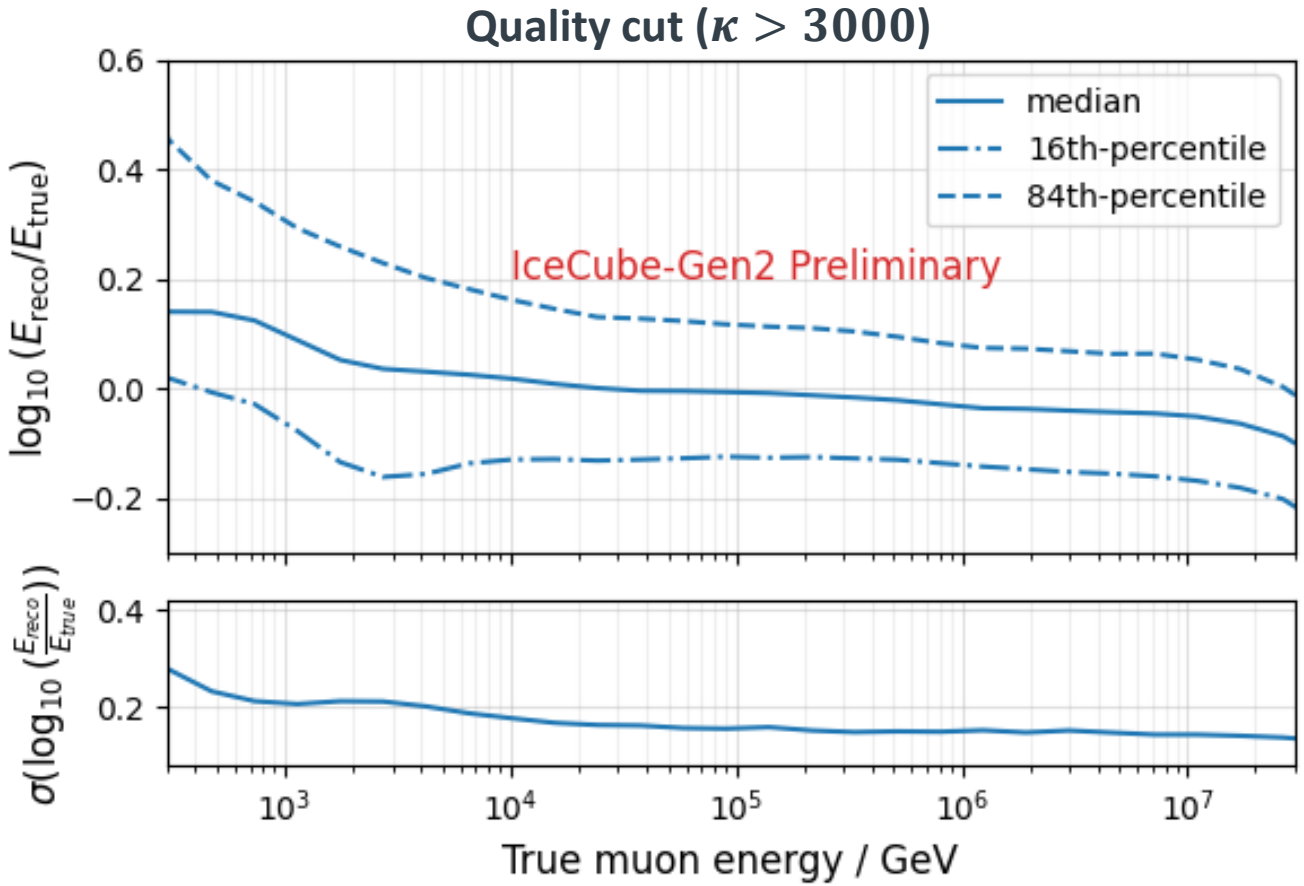
Quality cut ($\kappa > 3000$)



*[IceCube-Gen2 Coll., *Technical Design Report, Parts I & II* (2023)]

Through-Going Muon Energy Reconstruction

- Direct reconstruction of **muon energy at detector entry** with a NN
- Above TeV, **muon energy** can be reconstructed **from stochastic losses**



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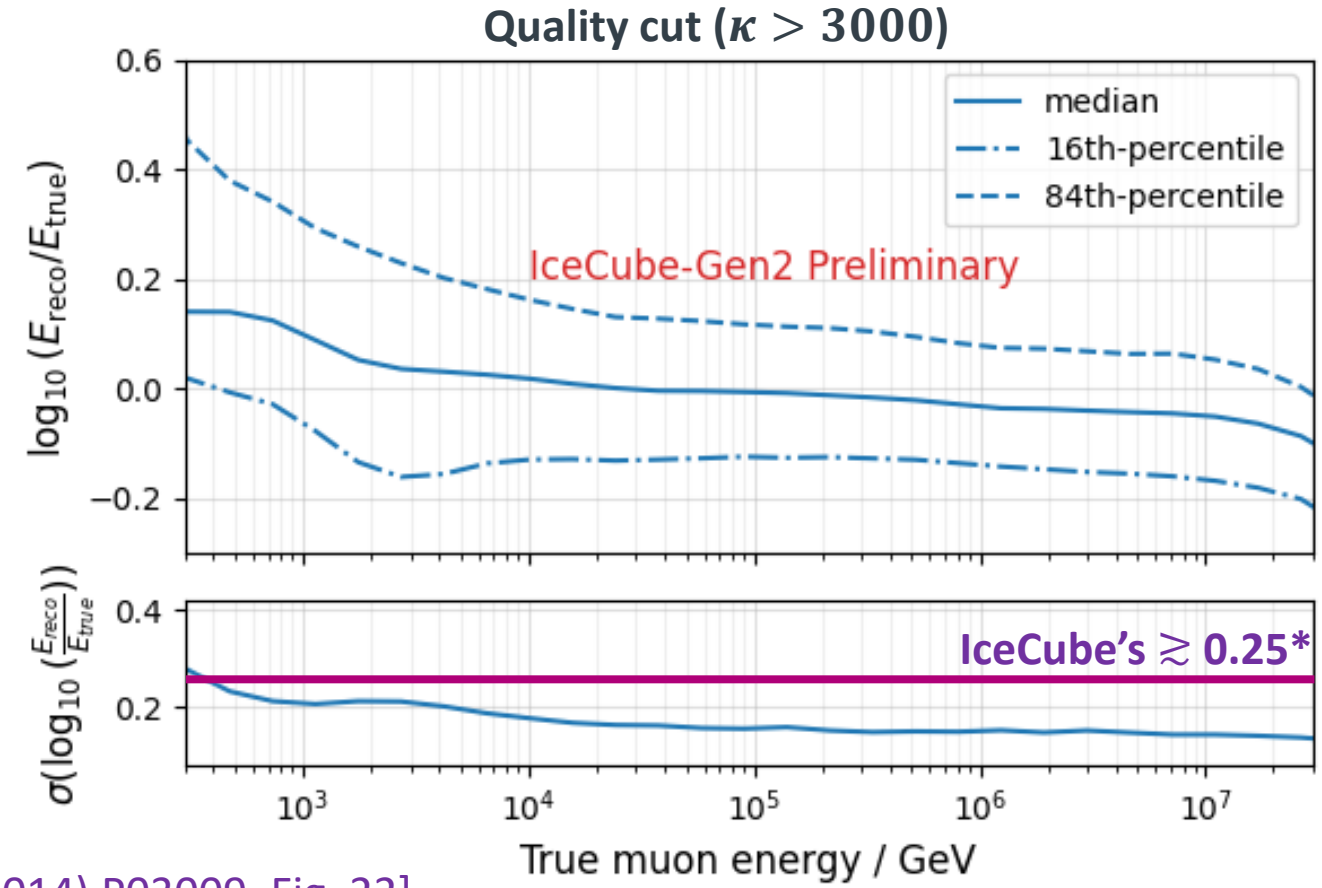
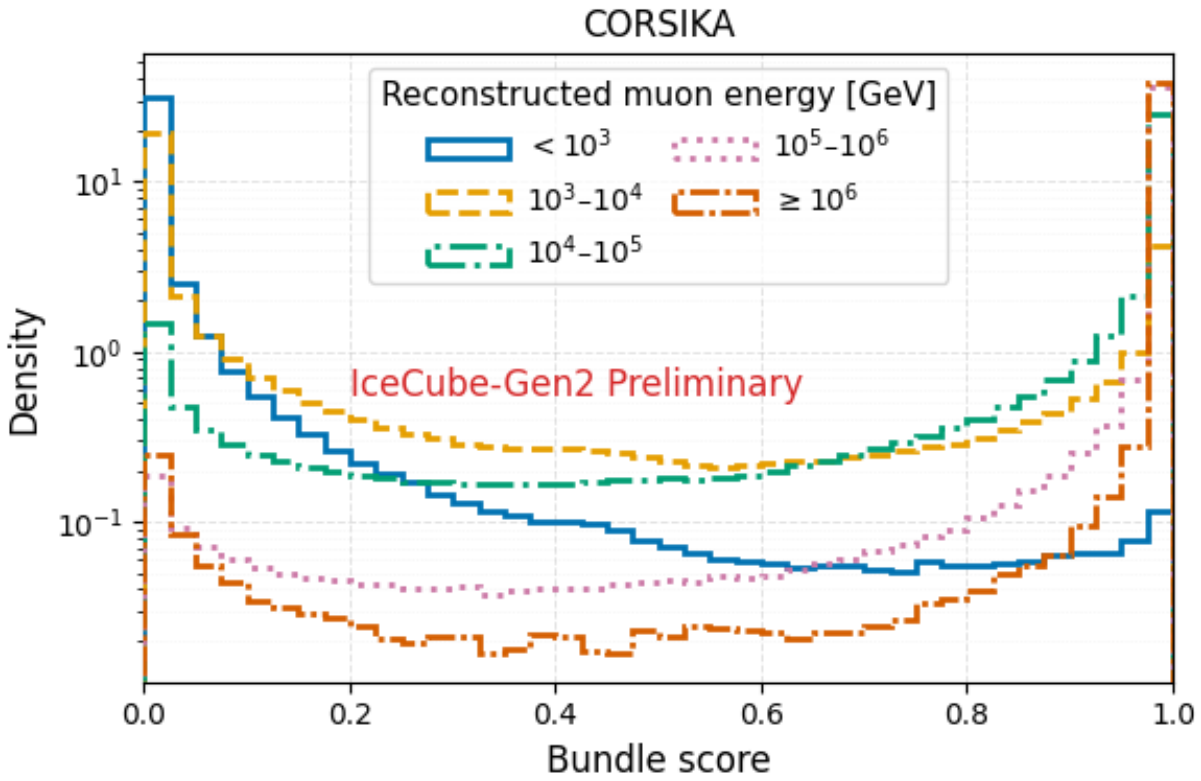
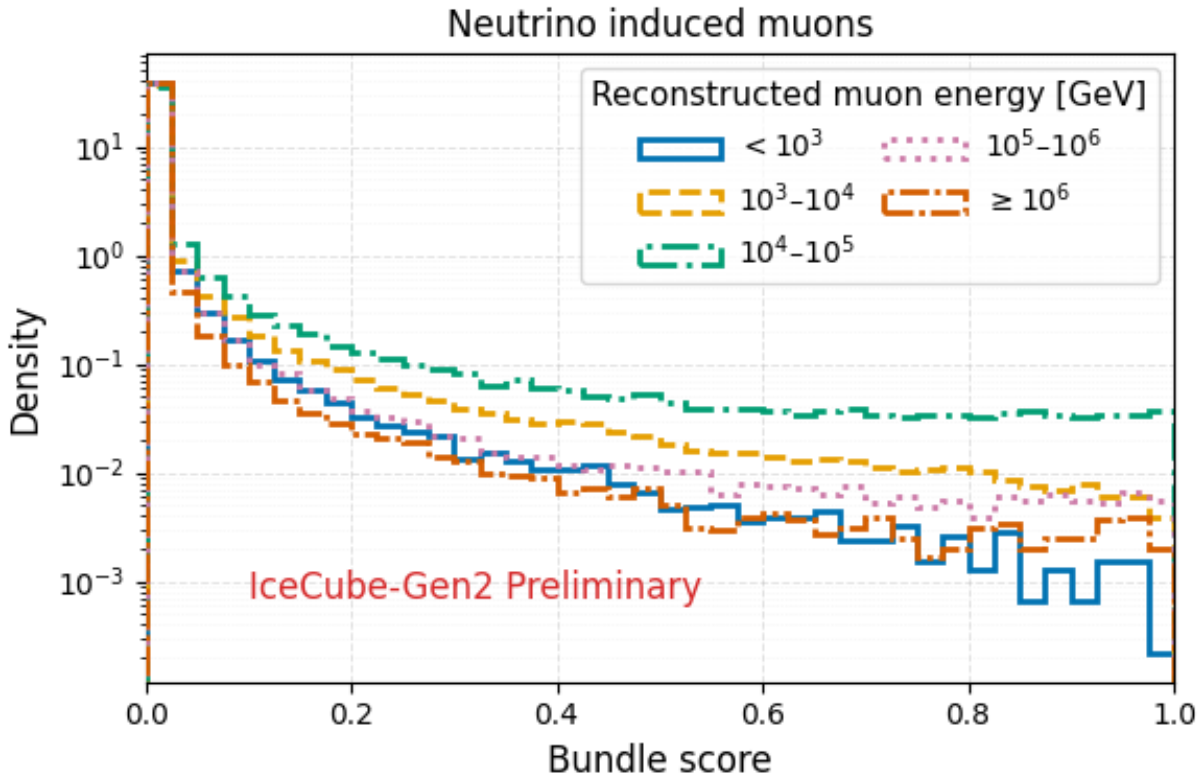


*[IceCube Collaboration, JINST 9 (2014) P03009, Fig. 22]

Muon Bundle vs. Single Muon Classification I

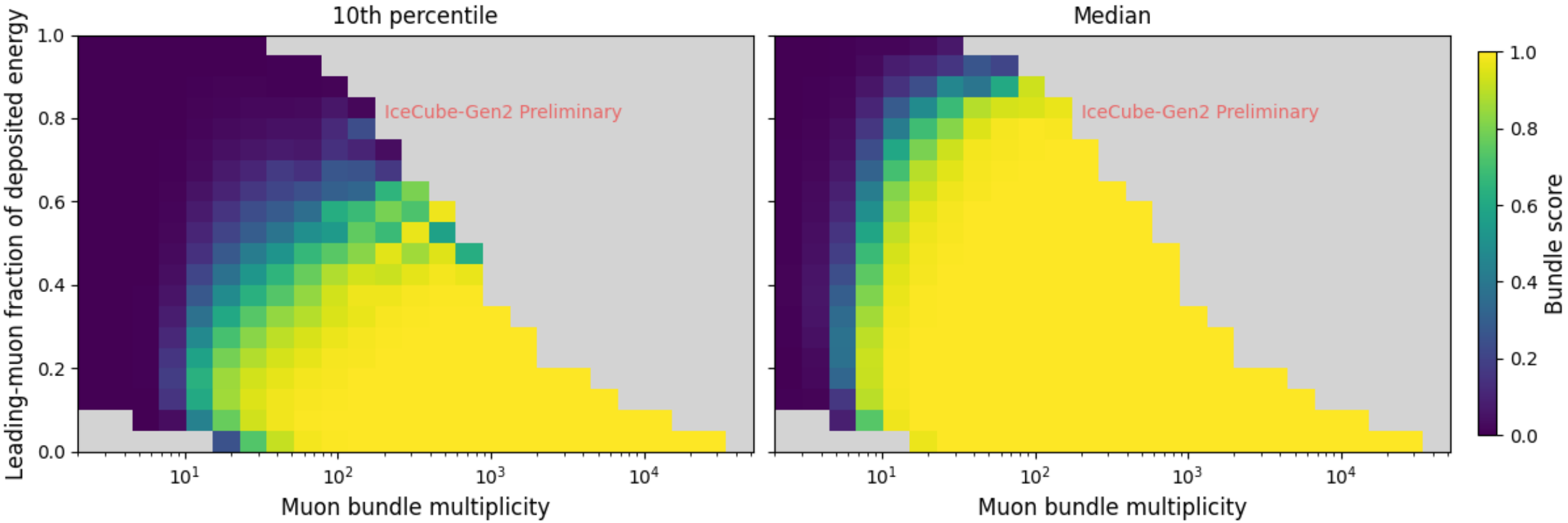
- **Atmospheric muons are the main background in the southern sky** for IceCube-Gen2
- Muon-bundle topology differs from that of single muons: lateral spread & energy-loss pattern
- Neural network trained to distinguish muon bundles (CORSIKA) from single muons (CORSIKA & neutrino-induced)





Muon Bundle vs. Single Muon Classification II

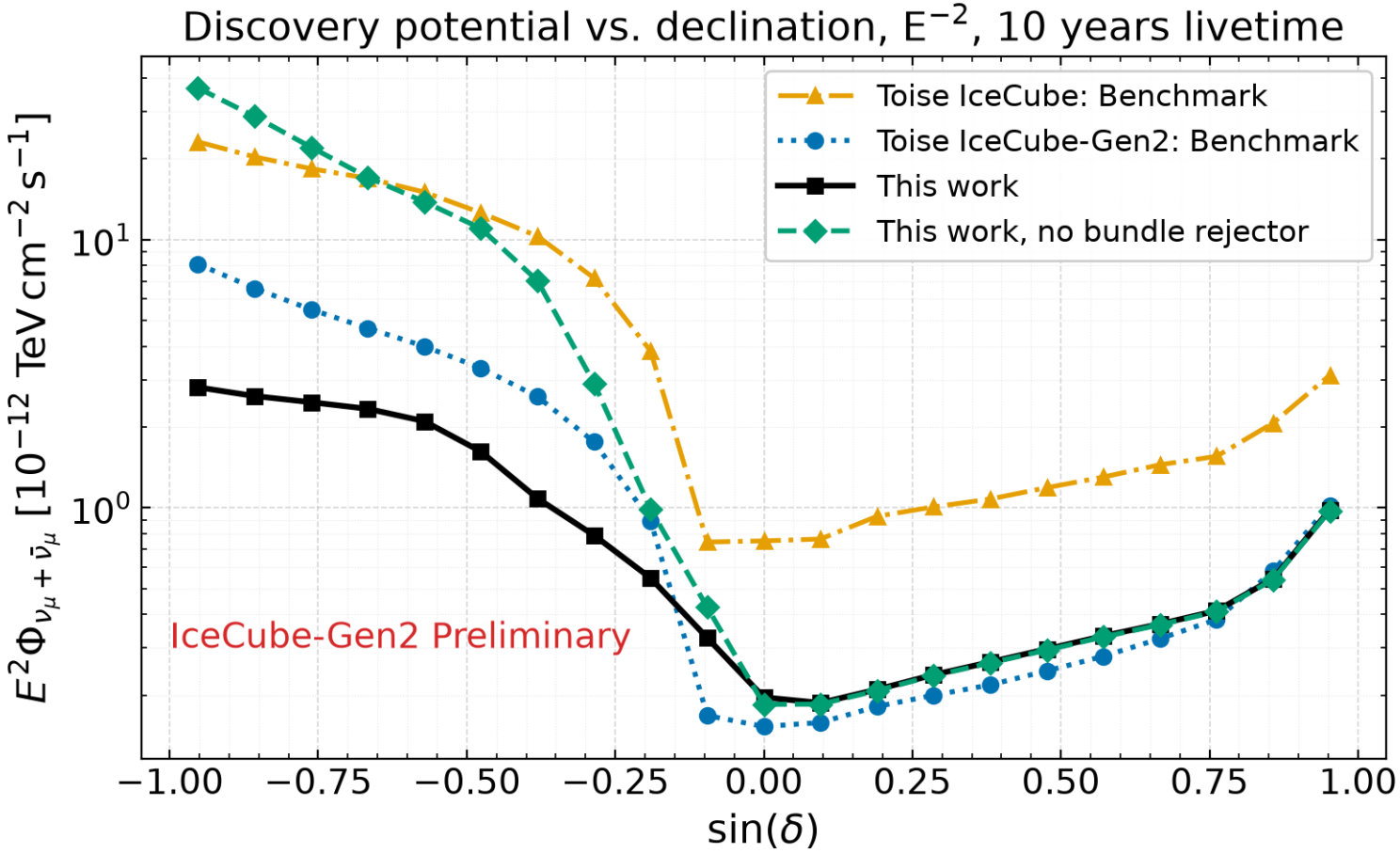
Bundle score correlates with physically expected bundle topology



Point-Source Performance

5σ Discovery Potential vs. sin(δ)

- **Benchmark**: TDR-based Toise parametrization*
  - **Optical array, through-going tracks, no surface veto**
- Atmospheric muon background:
  - This work: CORSIKA-derived
  - Benchmarks: single-muon approximation for bundles
- South sky ($\sin(\delta) < 0$):
  - **Large improvement from bundle rejection**
  - Additional sensitivity gains expected from starting events + surface veto
- North sky ($\sin(\delta) > 0$):
  - NN-based event-level MC parametrization is **broadly consistent with the Gen2 benchmark estimate**



*[J. van Santen et al., 2022 JINST 17 T08009];
[IceCube-Gen2 Coll., *TDR, Parts I & II* (2023)]

Summary and Outlook

Summary:

- NN-based reconstruction and classification methods developed for the IceCube-Gen2 optical array
- Detector-performance parametrizations derived directly from event-level, up-to-date IceCube-Gen2 simulations
- Point-source performance for through-going tracks broadly consistent with previous parametrized Gen2 expectations in the northern sky, with substantial gains in the southern sky from NN-based muon-bundle rejection

Outlook:

- Extend the analysis to starting events
- Further improve NN reconstruction and classification performance

With funding from the:

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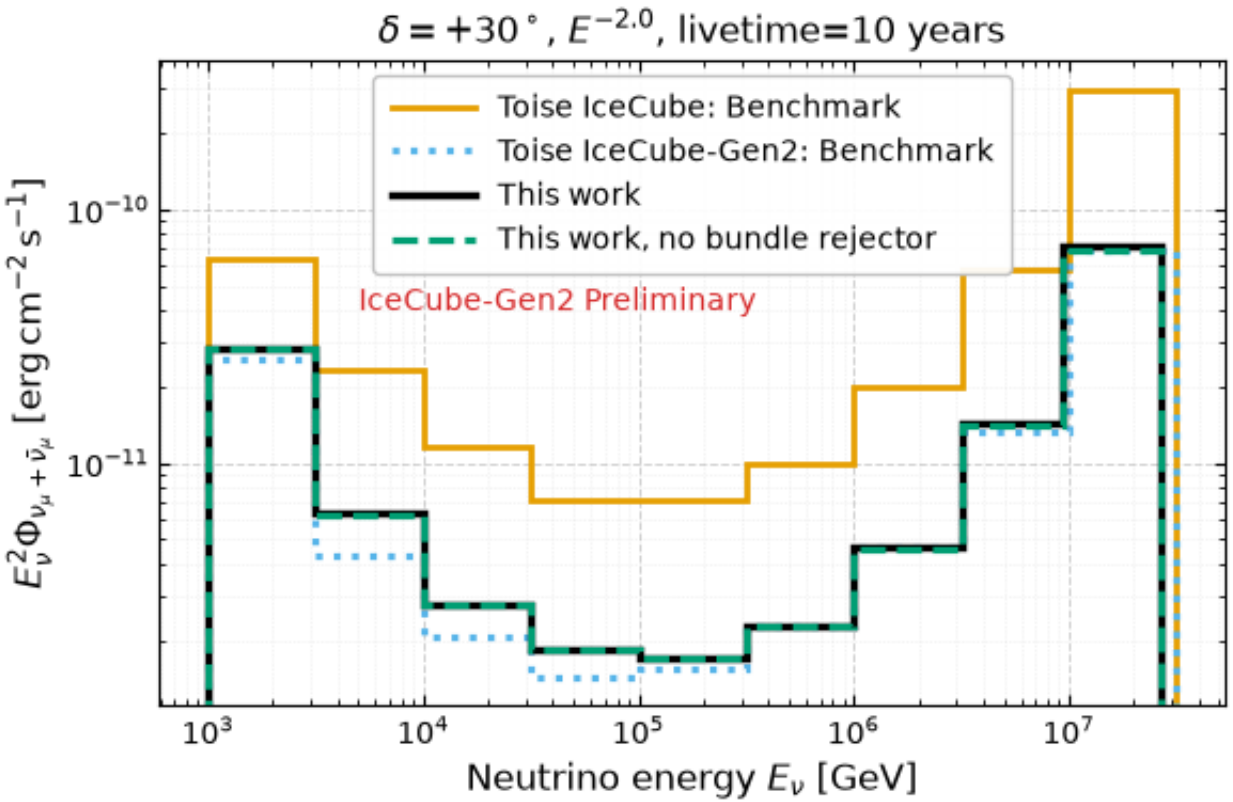
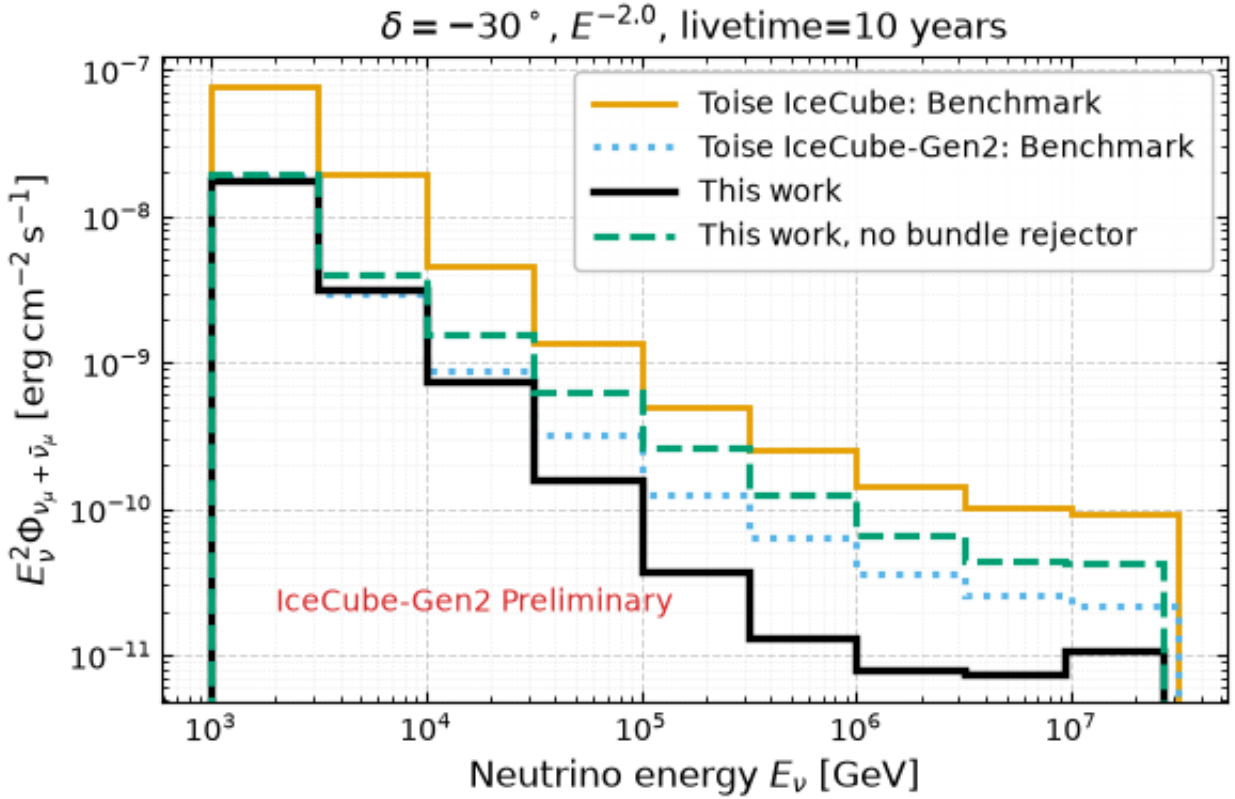
Backup

Differential 5σ Discovery Potential

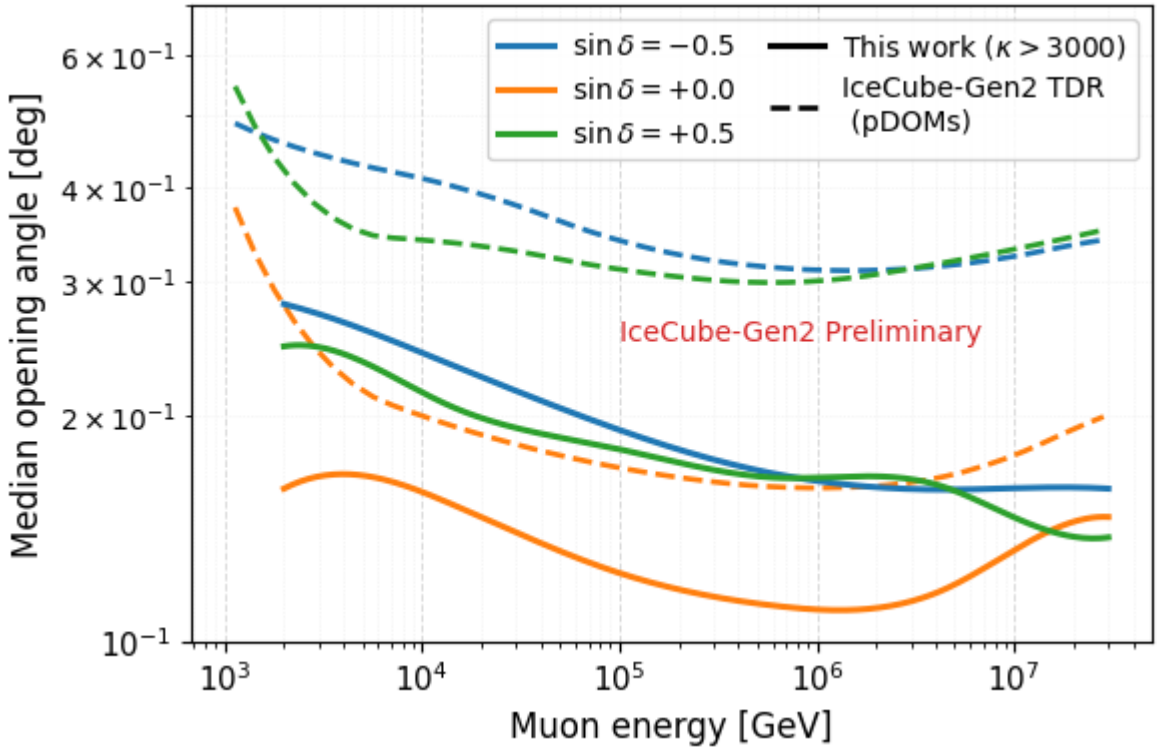


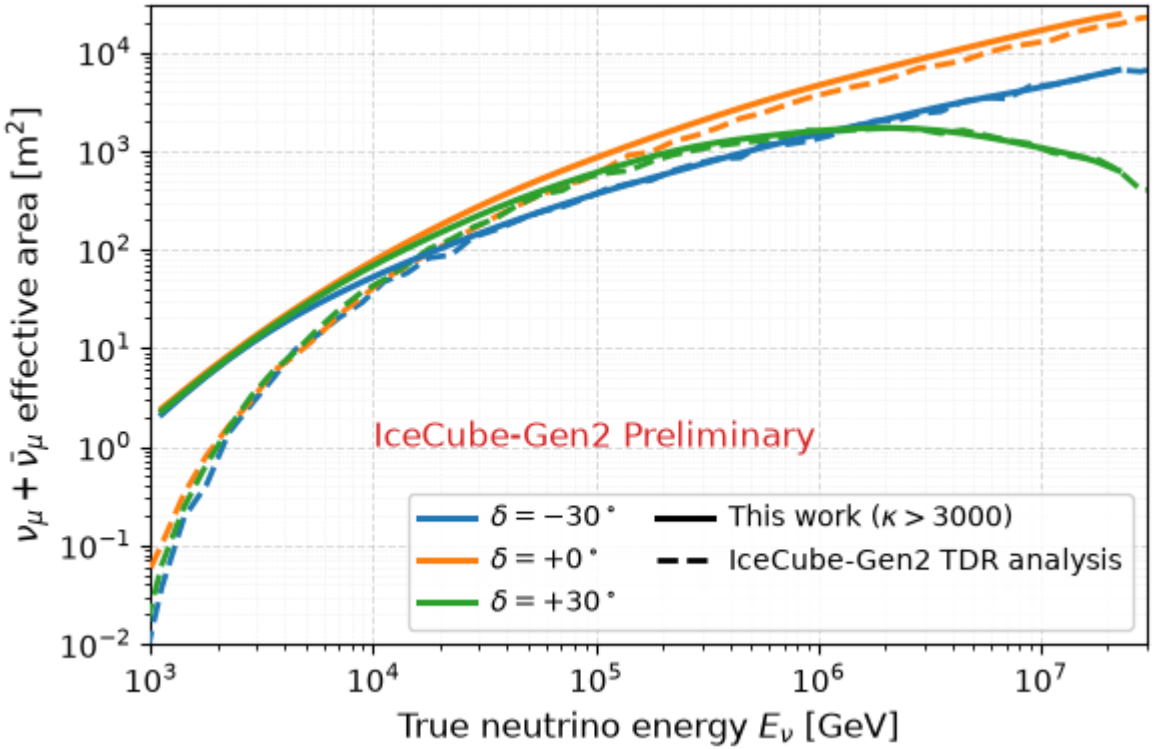


Direction Reconstruction: Resolution for Through-Going Tracks

- NN-based Gen2-DC16 reconstruction achieves better angular resolution than the IceCube pDOM + conventional reconstruction performance shown in the IceCube-Gen2 TDR*

- The $\kappa > 3000$ quality cut does not result in a severe loss in effective area





*[IceCube-Gen2 Coll., *Technical Design Report, Parts I & II* (2023)]

IceCube-Gen2 Noise Cleaning: GNN Performance