Keine Elemente im grau hinterlegten Druckrand!

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The Atmospheric Muon Flux from Sub-TeV to PeV Energies with IceCube

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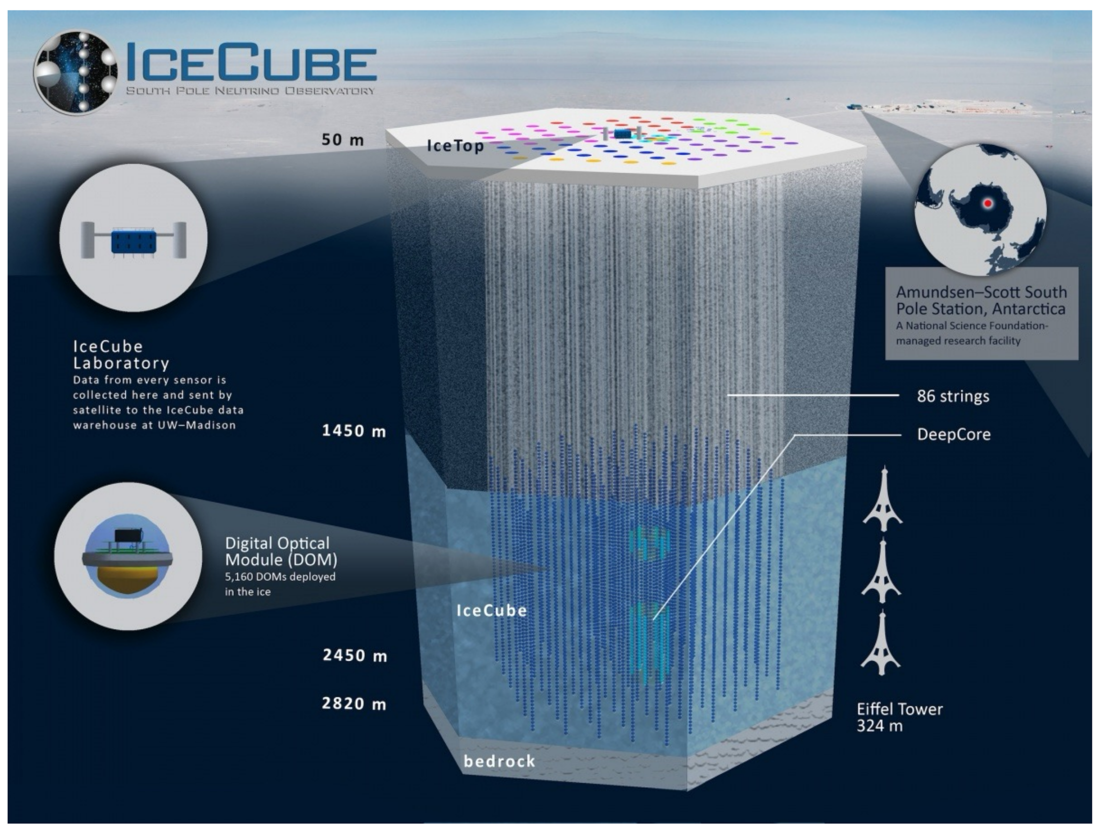
Introduction

Cosmic rays entering the Earth's atmosphere initiate extensive air showers, hadronic cascades that produce a broad spectrum of secondary particles. Muons reach deep underground detectors while carrying the imprint of the high-energy hadronic interactions that drive shower development. Across most of the spectrum these muons are conventional, originating from charged pion and kaon decays, while at the highest energies a prompt component from charmed and unflavoured hadron decays is expected to dominate.

Measuring this flux probes hadronic particle production in regions beyond the reach of collider experiments and constrains cosmic-ray composition, while the prompt component sets the irreducible background for astrophysical neutrino searches. In this work, we unfold the atmospheric muon energy spectrum from 600 GeV to PeV energies using IceCube data using stopping muons and leading muons that are sensitive to the low-energy and high-energy range, respectively.



Atmospheric Muon Flux

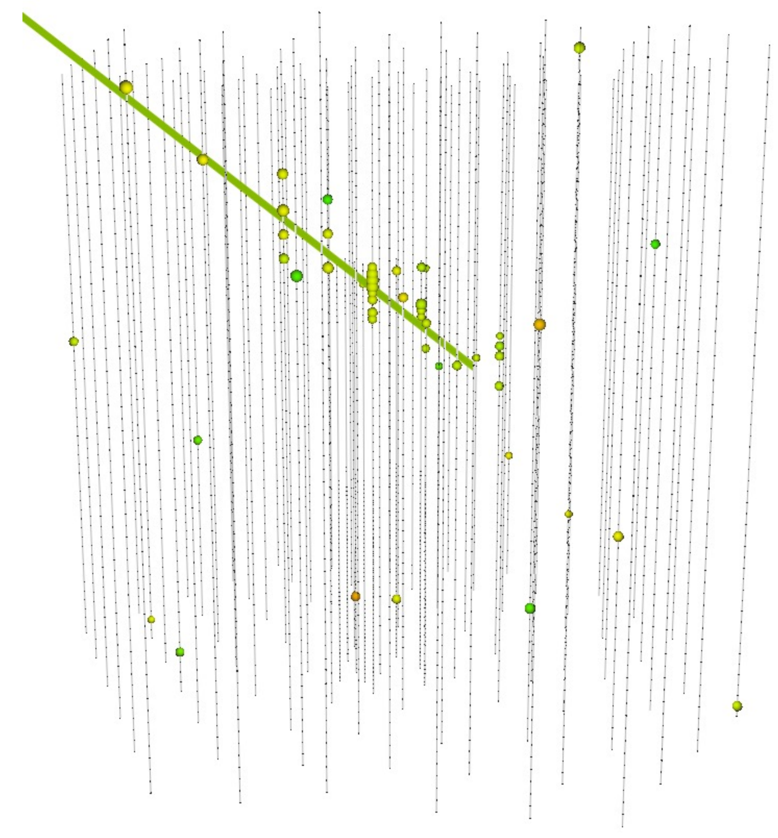
$$\Phi_{\mathrm{tot}} = \Phi_{\mathrm{conv}} + \Phi_{\mathrm{prompt}}$$

π, $K \propto E^{-3.7}$

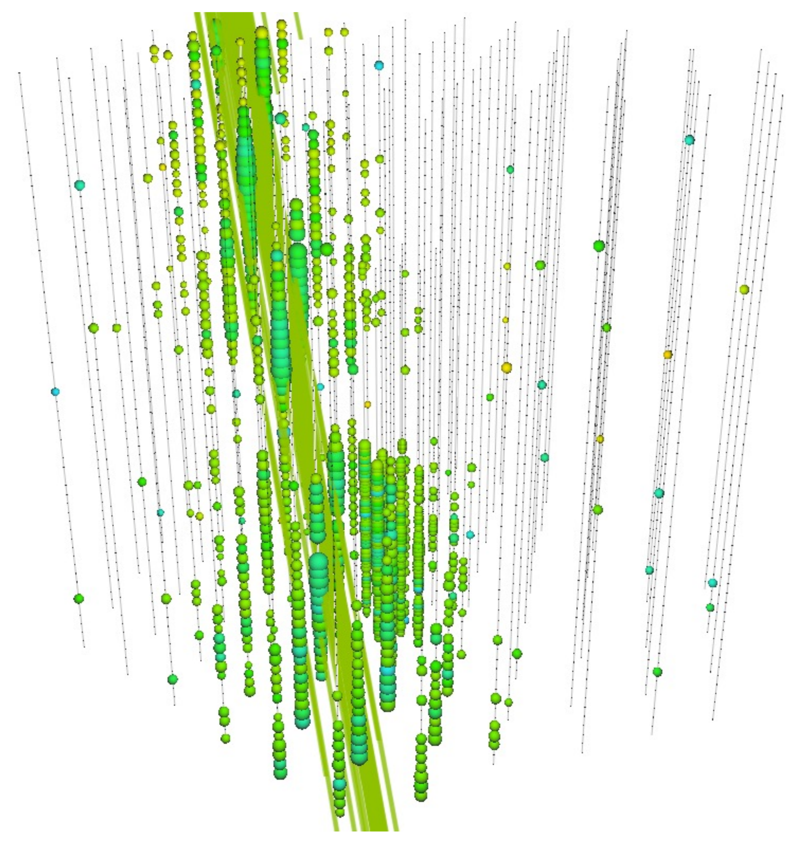
prompt $\propto E^{-2.7}$
(all other particles) [1]

Event Selections

- Convolutional neural networks used to select atmospheric muons
→ 2 classes
- Stopping muons: decay inside of the detector volume
- Sensitive to low-energy flux



- Leading muons: most energetic muon inside a muon bundle
- Sensitive to high-energy flux



Analyses

- Unfolding of the atmospheric muon flux

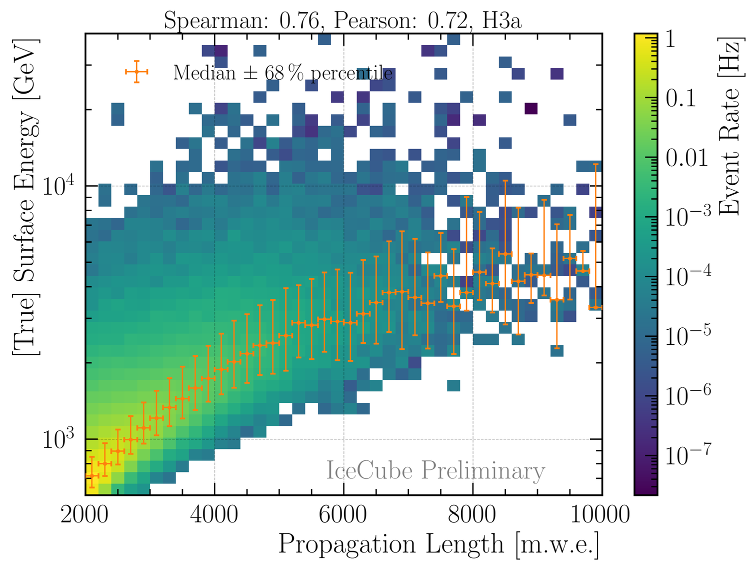
detector response | background

$$g(y) = \int A(x,y)\, f(x)\, \mathrm{d}x + b(y)$$

proxy | true muon flux

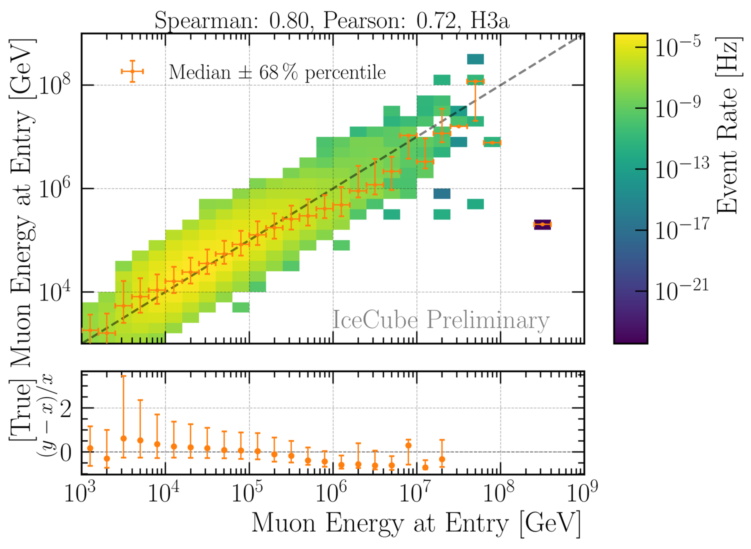
- 2 separate unfoldings: stopping and leading muons → machine learning based selections
- Background is neglected (<1%)
- Thikonov regularization determined by minimizing the bin-to-bin correlations
- Proxy variables:
  1. stopping muons: stopping depth + cosine zenith = propagation length

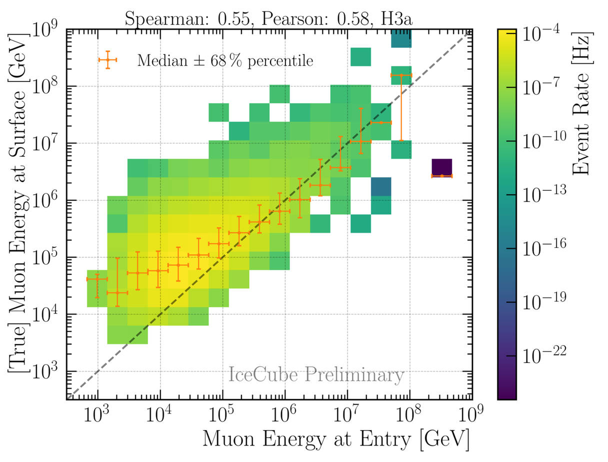
proxy – target correlation



  2. leading muons: leading muon energy at detector entry

reconstruction





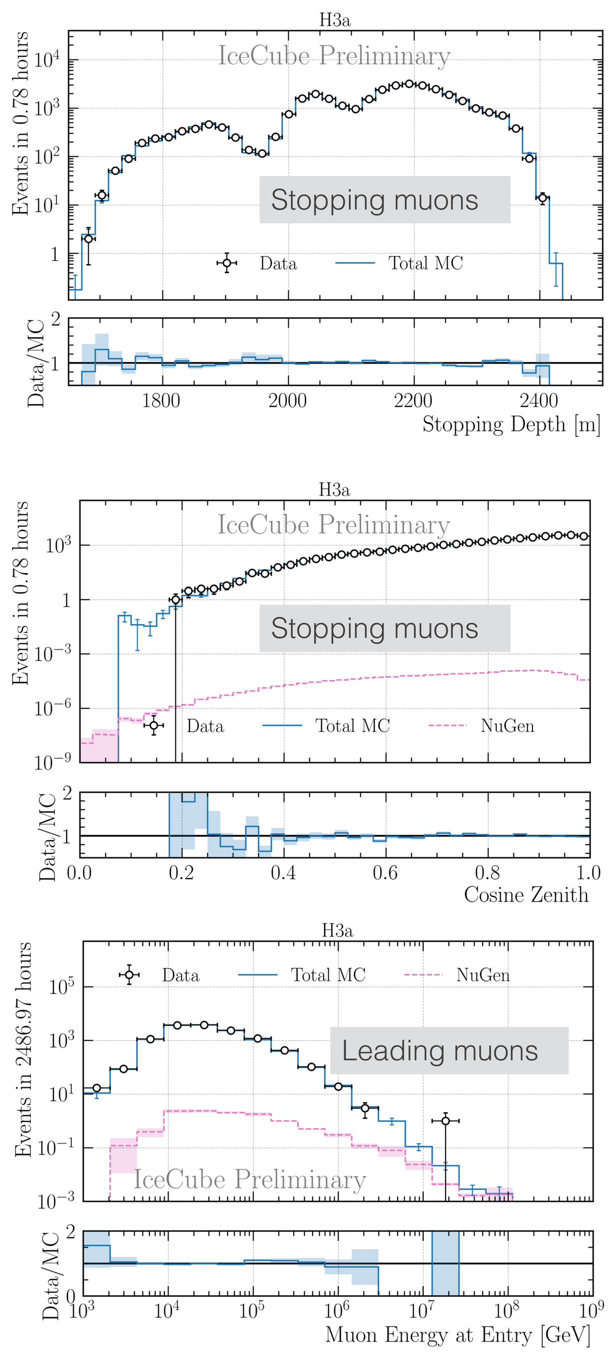
proxy – target correlation

[2]

Data—MC

Calculate propagation length
→ input for low-energy unfolding

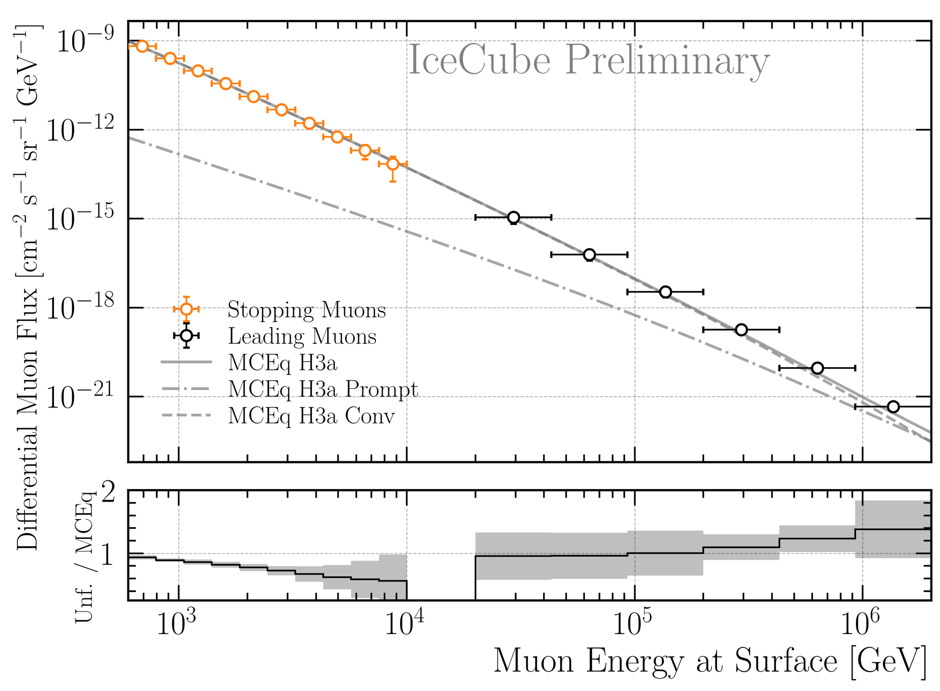
Reconstructed leading muon energy
→ input for high-energy unfolding



*MC is scaled up to match total event count: 10% (stopping), 12% (leading) [2]

Results

- Unfolded datasets of 47 min (stopping, 32943 events) and 2487 days (leading, 12754 events) of lifetime
- High-energy flux agrees with H3a
- Low-energy flux undershoots → fixed now



[2]

Current Status

- Both stopping and leading muon fluxes are unblinded → final post-unblinding checks
- Results are going to be presented at TeVPa in Japan → stay tuned!

References

[1] Neste, L., Gutjahr, P. et al. EPJC 85 (2025) 759
[2] IceCube Collaboration PoS ICRC (2025) 281

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