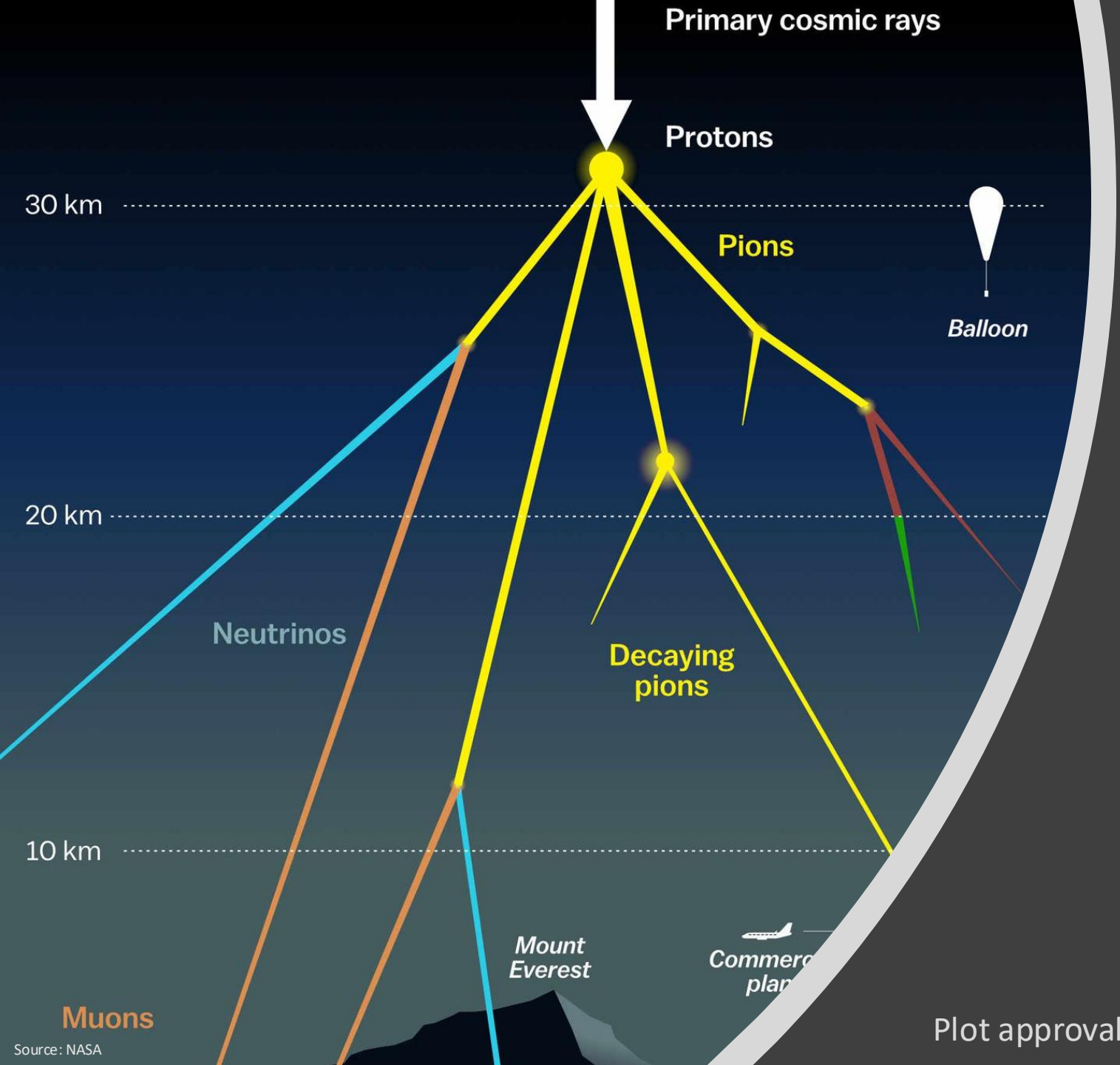

Unfolding the Atmospheric Muon Flux with IceCube: Investigating Stopping Muons and High-Energy Prompt Contributions

Pascal Gutjahr

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May 29, 2025

WG reviewer: Dennis Soldin
Coll. reviewer: Anatoli Fedynitch
Technical reviewer: Karolin Hymon
Wiki: prompt wiki
Last update: Uppsala May 14

Plot approval: wiki

Abstract

Atmospheric muons produced in cosmic-ray air showers are classified as conventional muons from pion and kaon decays and prompt muons from heavy hadron decays. Conventional muons dominate at lower energies, and the prompt component becomes more significant at PeV energies and above. Precisely measuring the atmospheric muon flux from a few GeV to several PeV is valuable for advancing our understanding of cosmic-ray interactions and testing hadronic interaction models. Low-energy muons that stop within the IceCube in-ice array provide valuable information about the energy spectrum of muons from a few 100 GeV up to 10 TeV.

Machine learning techniques are employed to enhance event reconstruction and selection to provide insights into the conventional and prompt components. This contribution presents the unfolding of the energy spectrum of stopping muons in IceCube as well as the unfolding of high-energy muons to probe the prompt component.

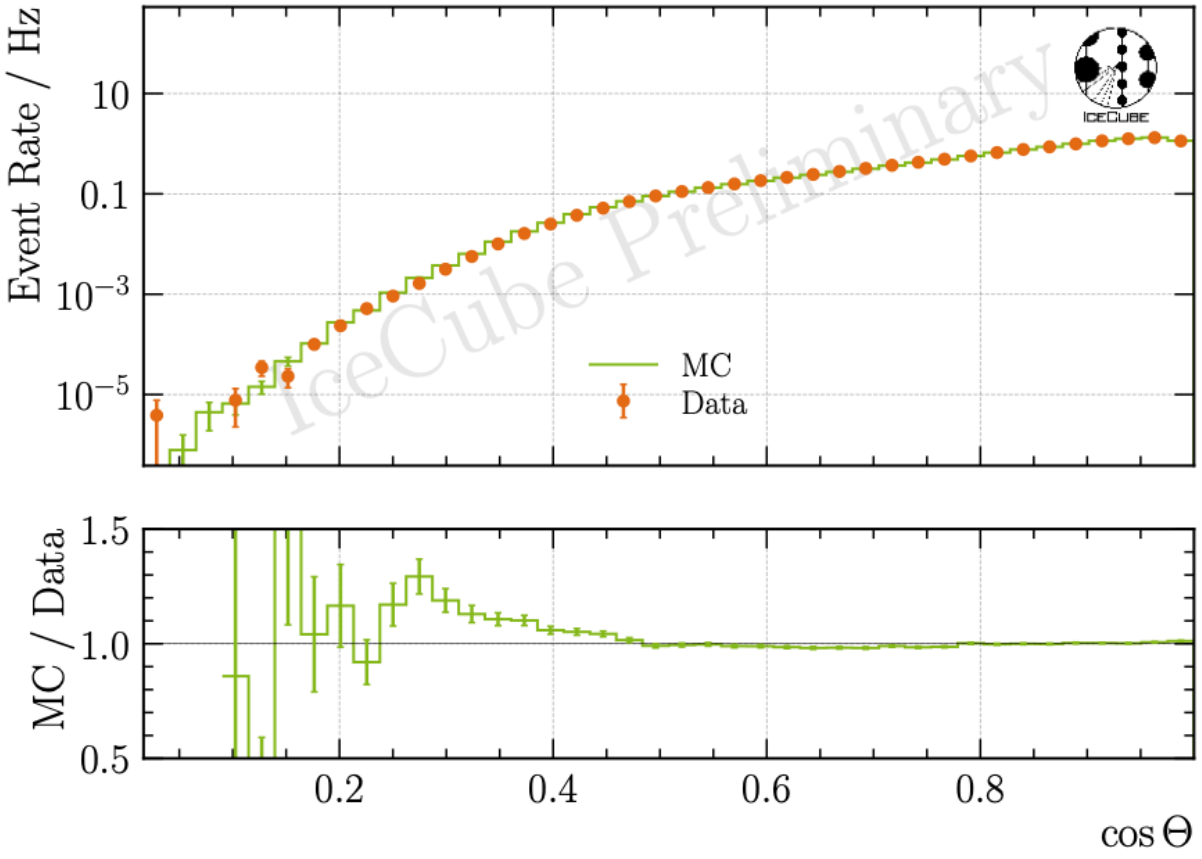
Presenter: Pascal Gutjahr

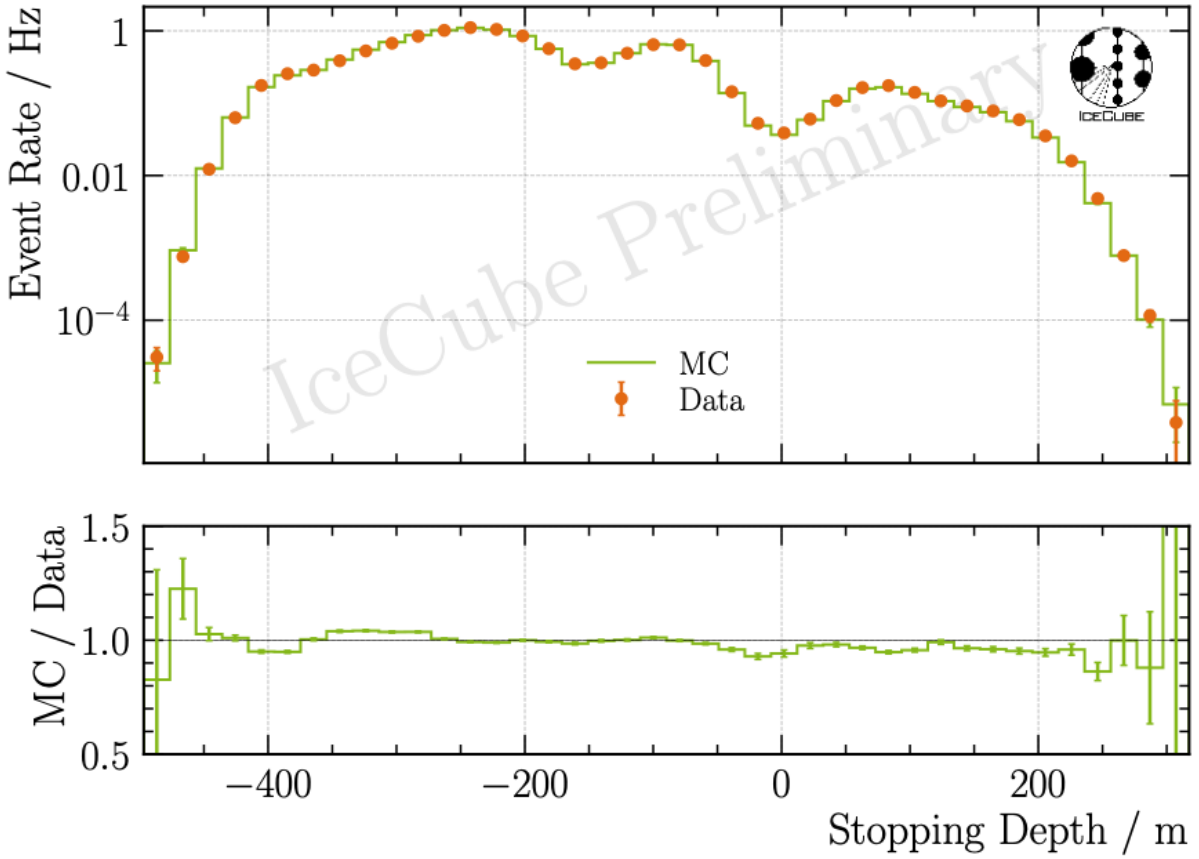
Authors: Lucas Witthaus and Pascal Gutjahr

Outline

1. Introduction / Motivation
    1. Hadronic Interaction Models / Muon Puzzle
    2. Prompt / Conventional
2. Event Selection
    1. Stopping Muons
    2. High Energy Muons
    3. Event Reconstruction (DNN based)
3. Unfolding
    1. Method + Regularization
    2. Acceptance Correction
    3. Systematics
4. Results
    1. Proxy Variable Correlations (Depth + Energy + Zenith)
    2. Data-MC (Depth + Energy + Zenith)
    3. Unfolded Propagation Length (MC + Burnsample)
    4. Unfolded Muon Flux at Surface (MC + Burnsample) – Stopping and High Energy
    5. Robustness Tests (vary spectral index)
5. Conclusion & Outlook

Data-MC: Stopping Muons

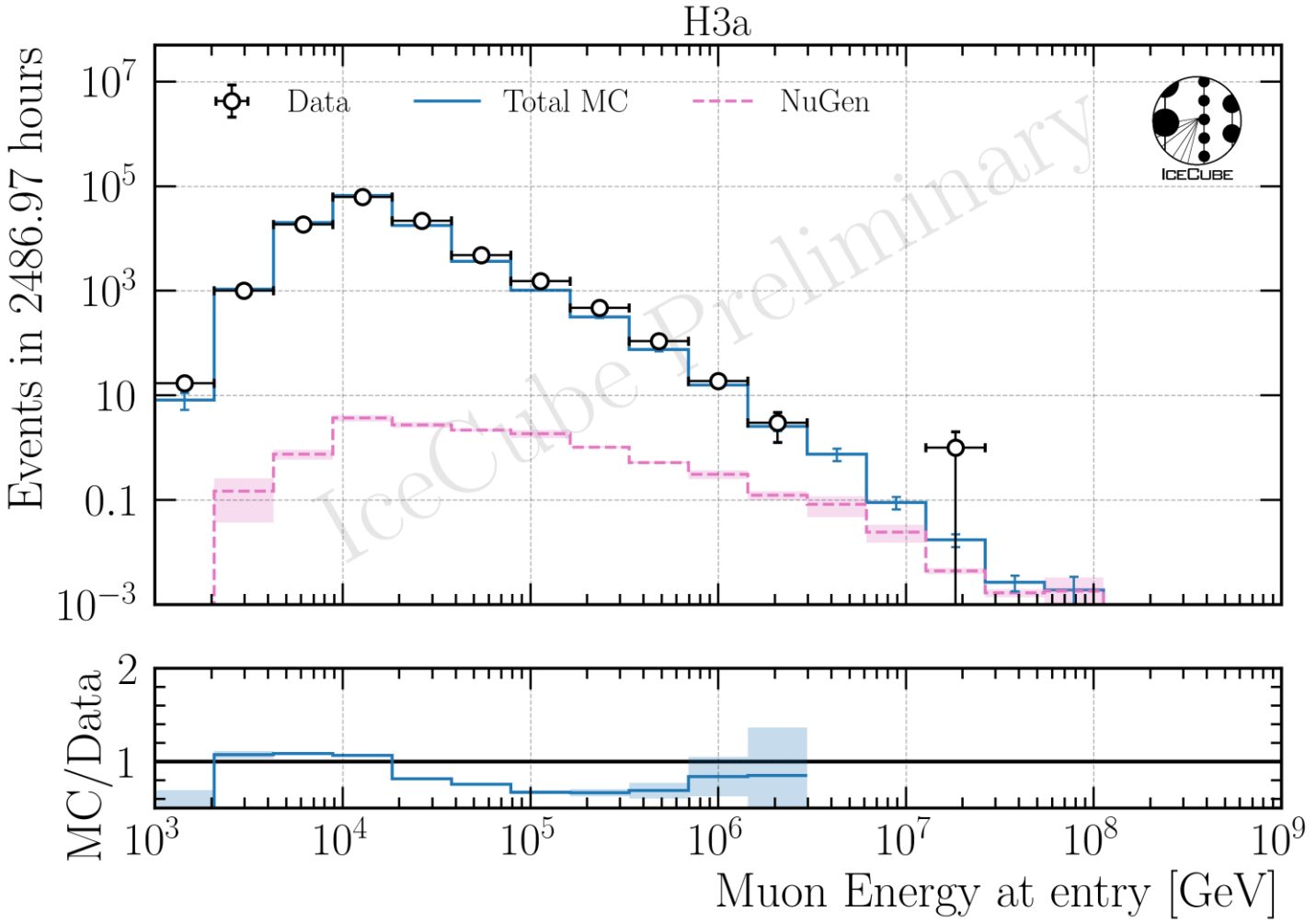




- build proxy variable for unfolding: propagation length

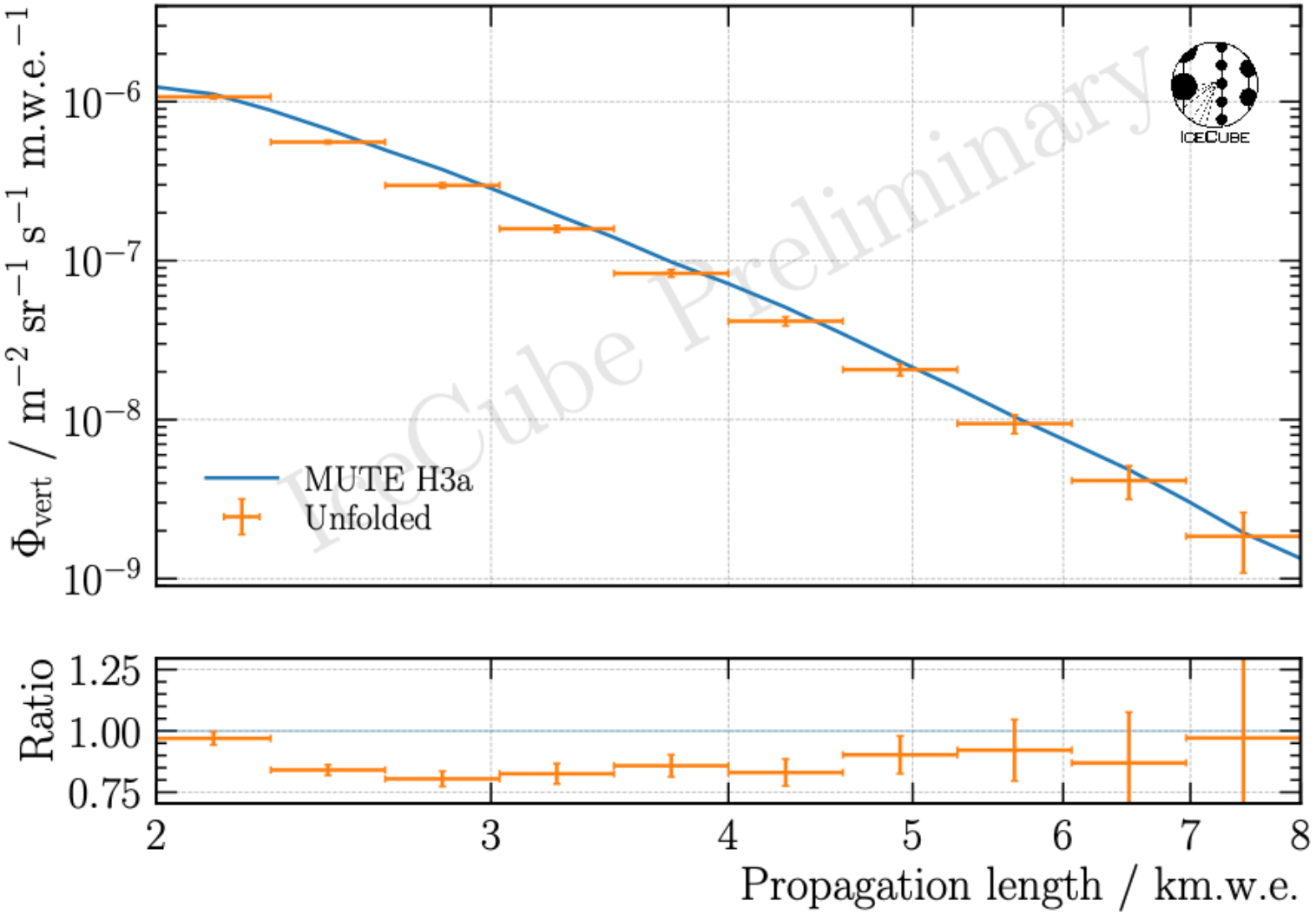
Data-MC: High Energy Muons

- proxy variable for unfolding



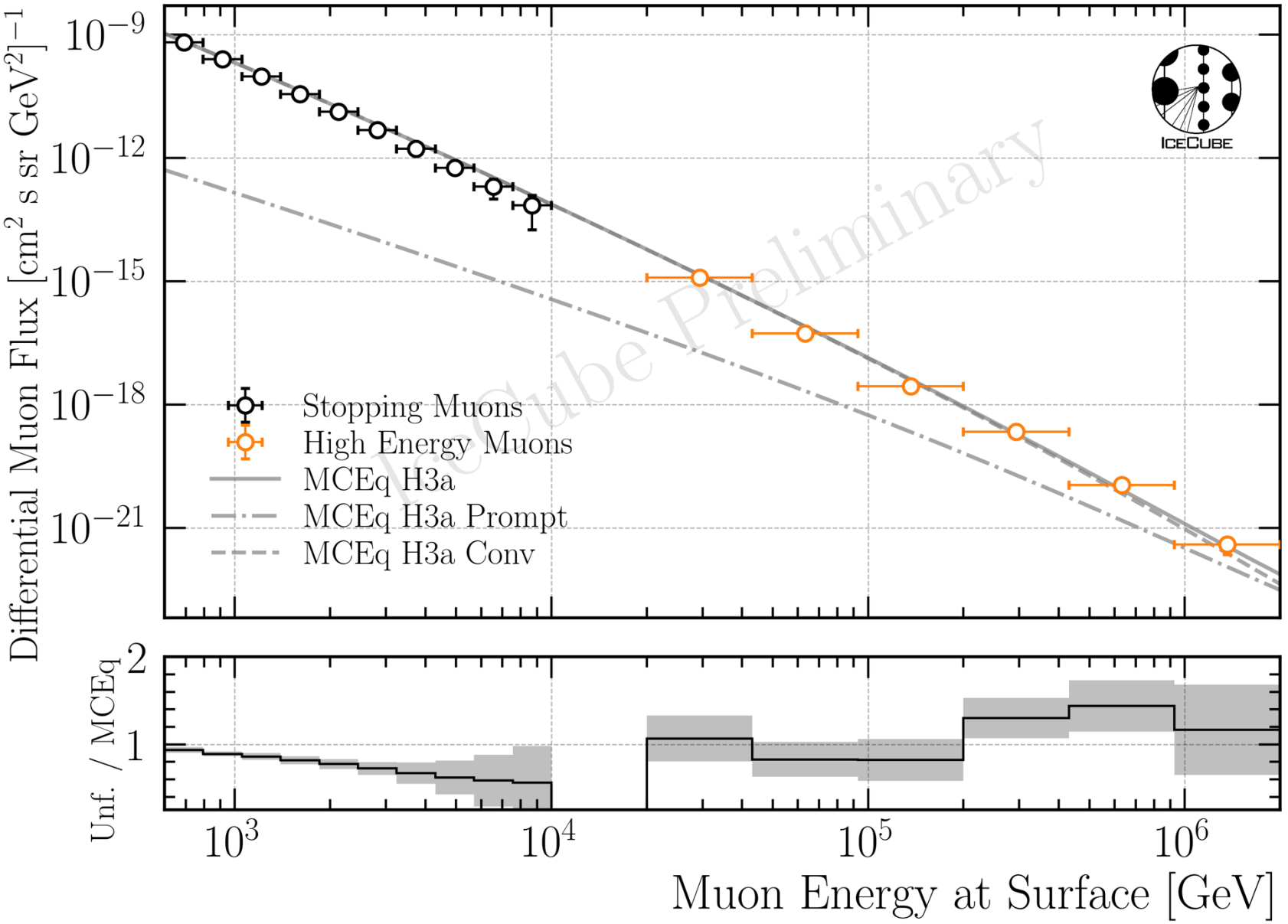
Unfolding Propagation Length

- Unfolding on burnsample



Unfolding Muon Flux

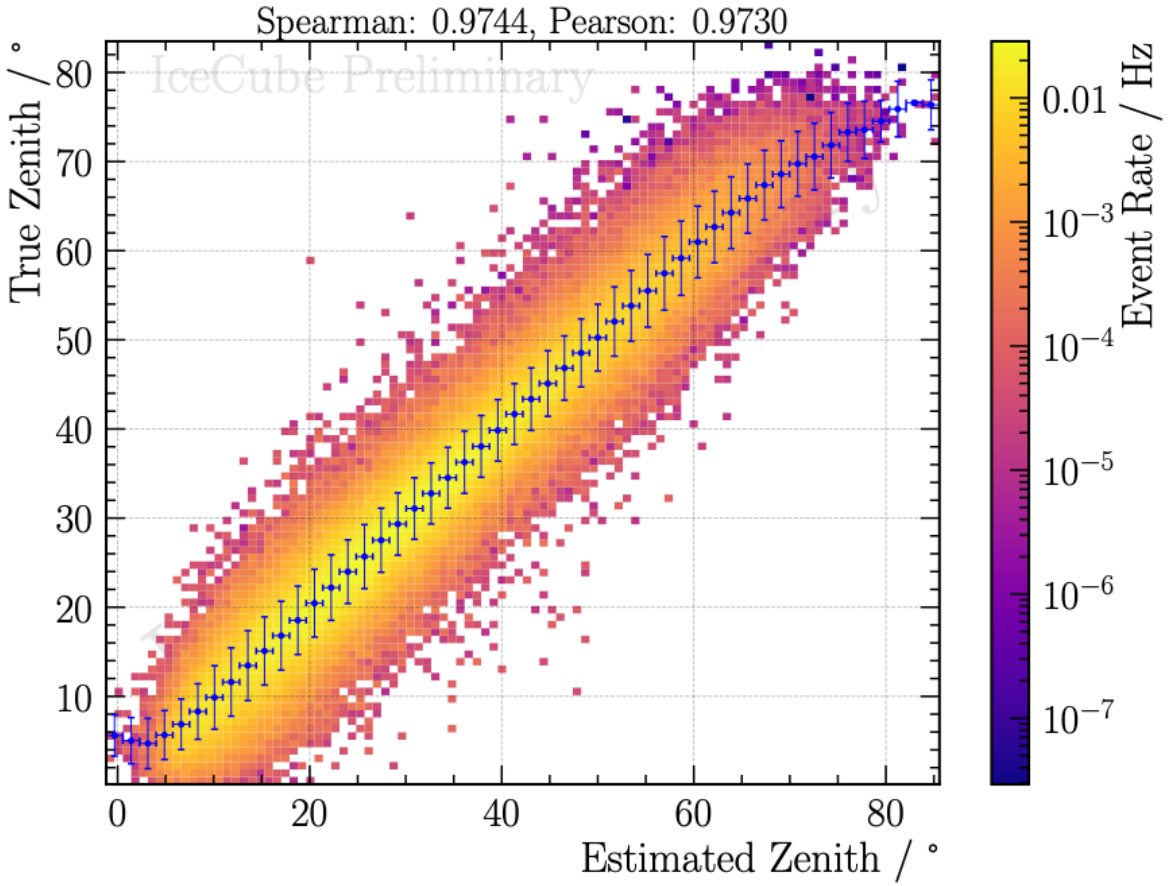
- Both stopping muons and high energy muons show burnsample unfolding

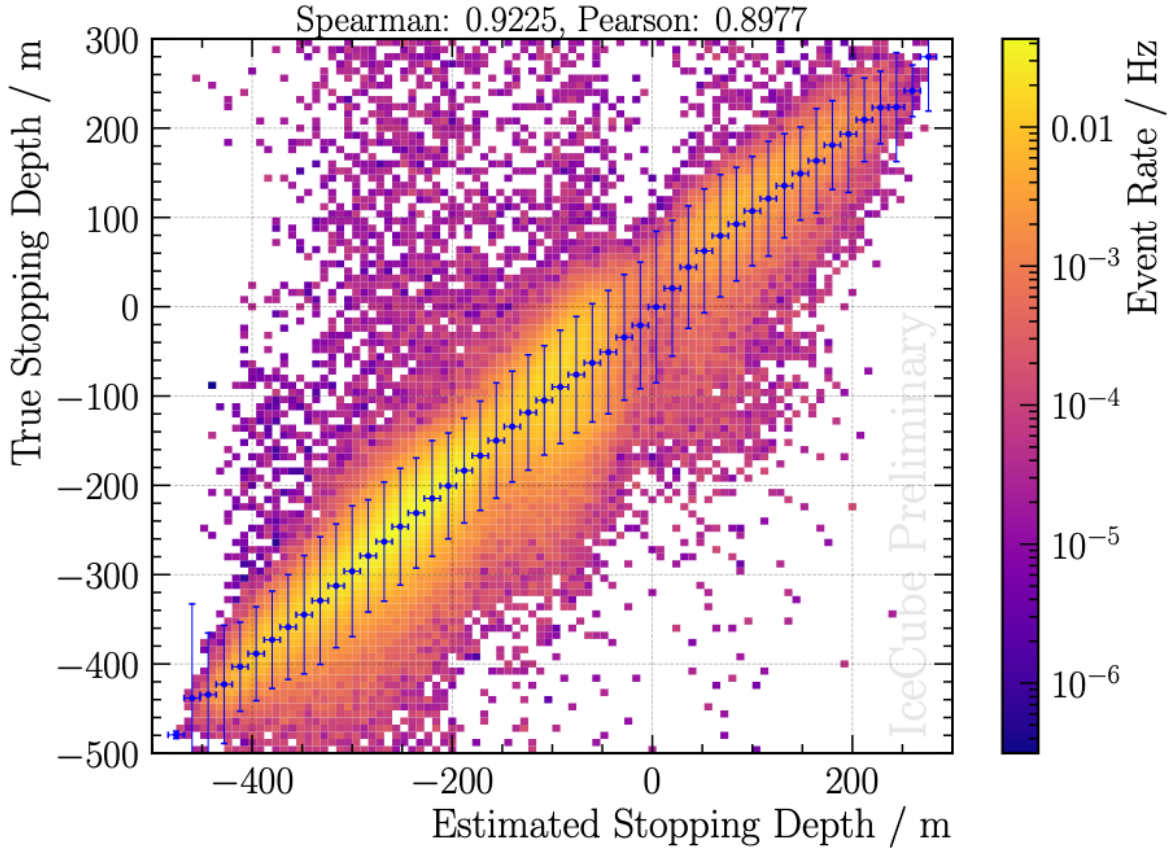


Thank you for your comments

Backup

Reconstructions: Stopping Muons

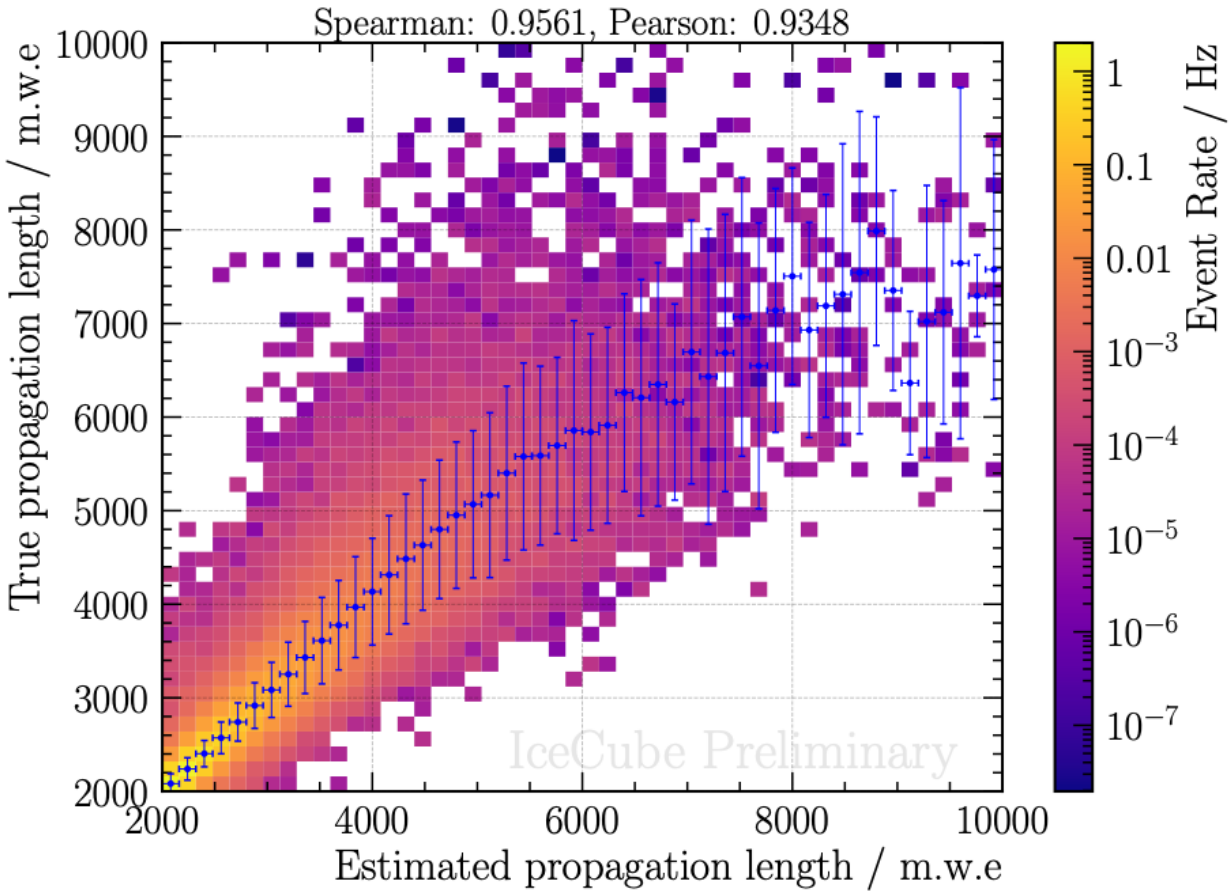




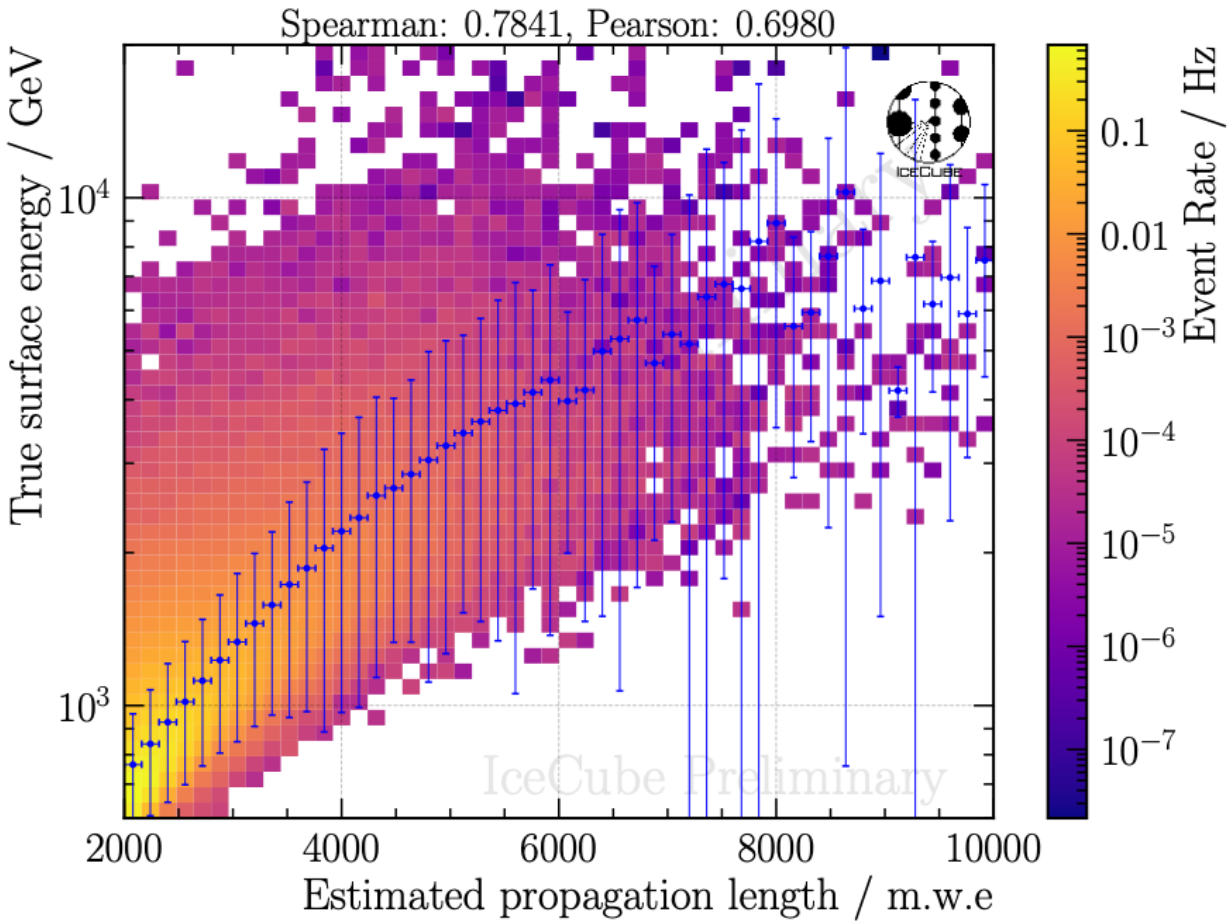
- DNN reconstruction of zenith angle and stopping depth
- Used to calculate the propagation length → proxy variable in unfolding

Proxy Variable: Stopping Muons

Propagation length



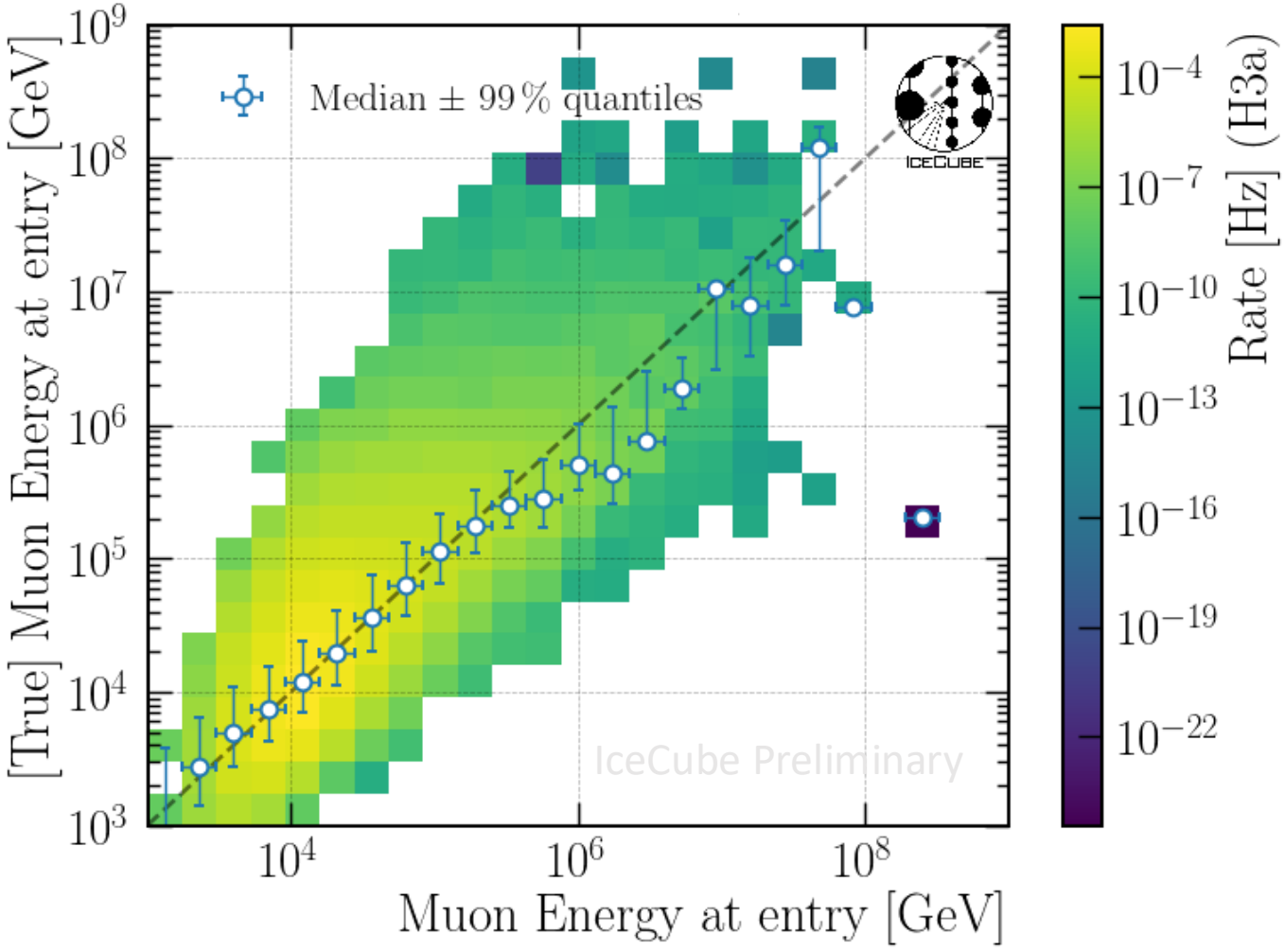
Muon energy at surface



- Correlation between proxy and target variable in unfolding

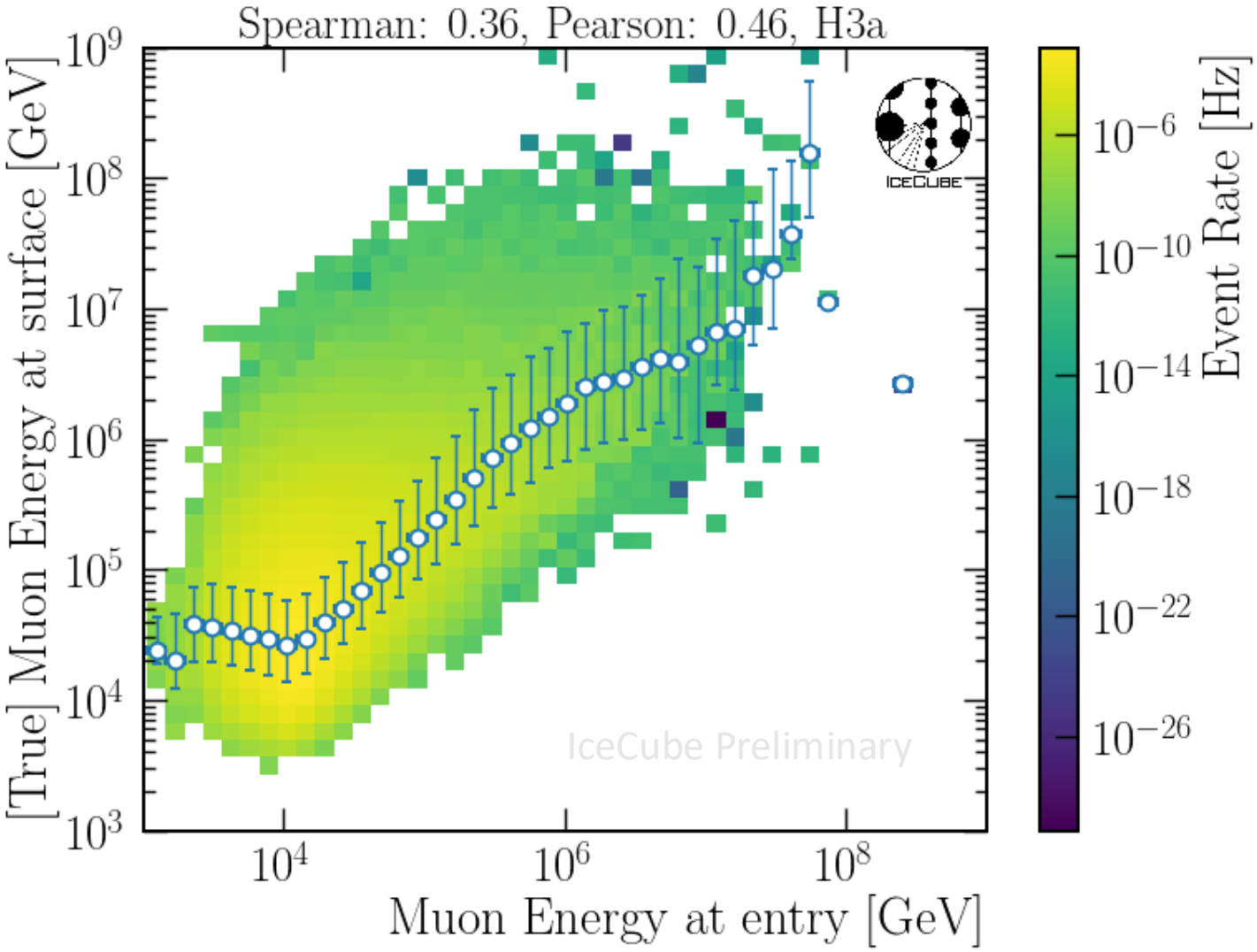
Reconstruction: High Energy Muons

- DNN reconstruction of leading muon energy at detector entry
- proxy variable in unfolding

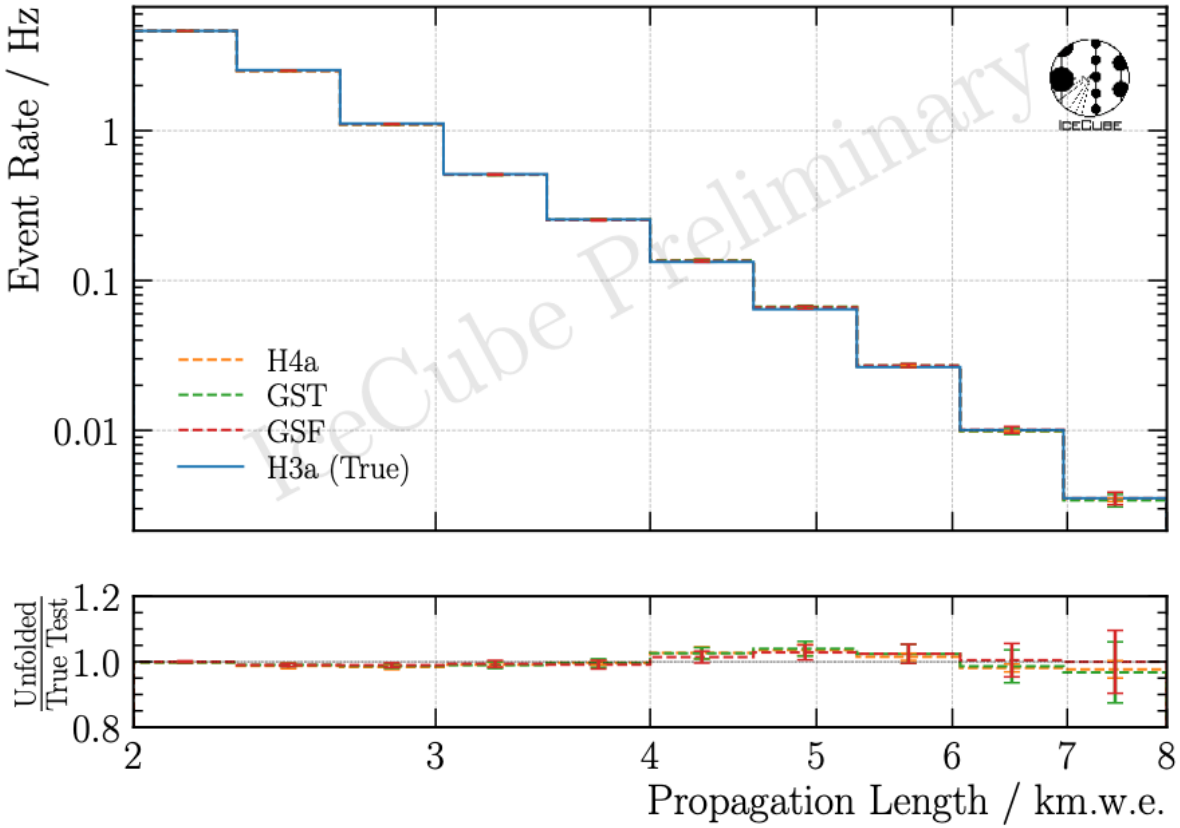


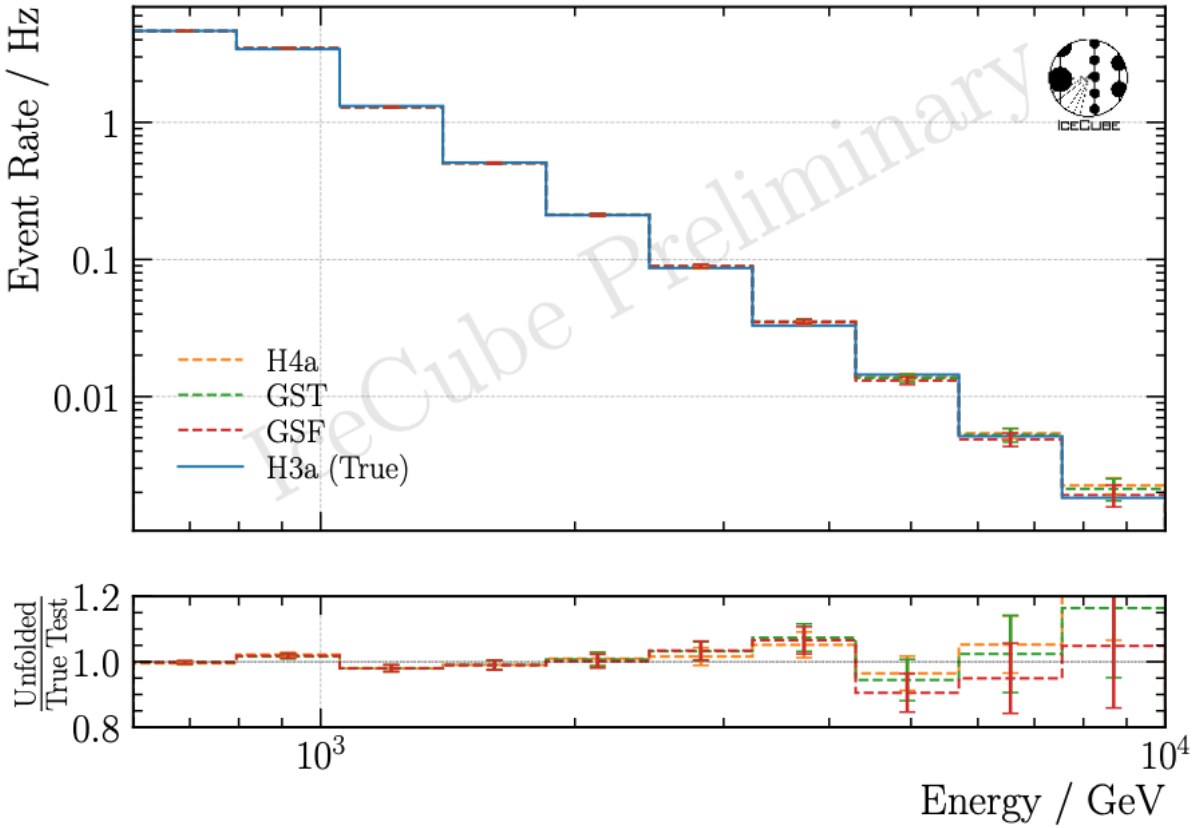
Proxy Variable: High Energy Muons

- Correlation between proxy and target variable in unfolding



Robustness Stopping Muons





Robustness High Energy Muons – Starting at 20 TeV