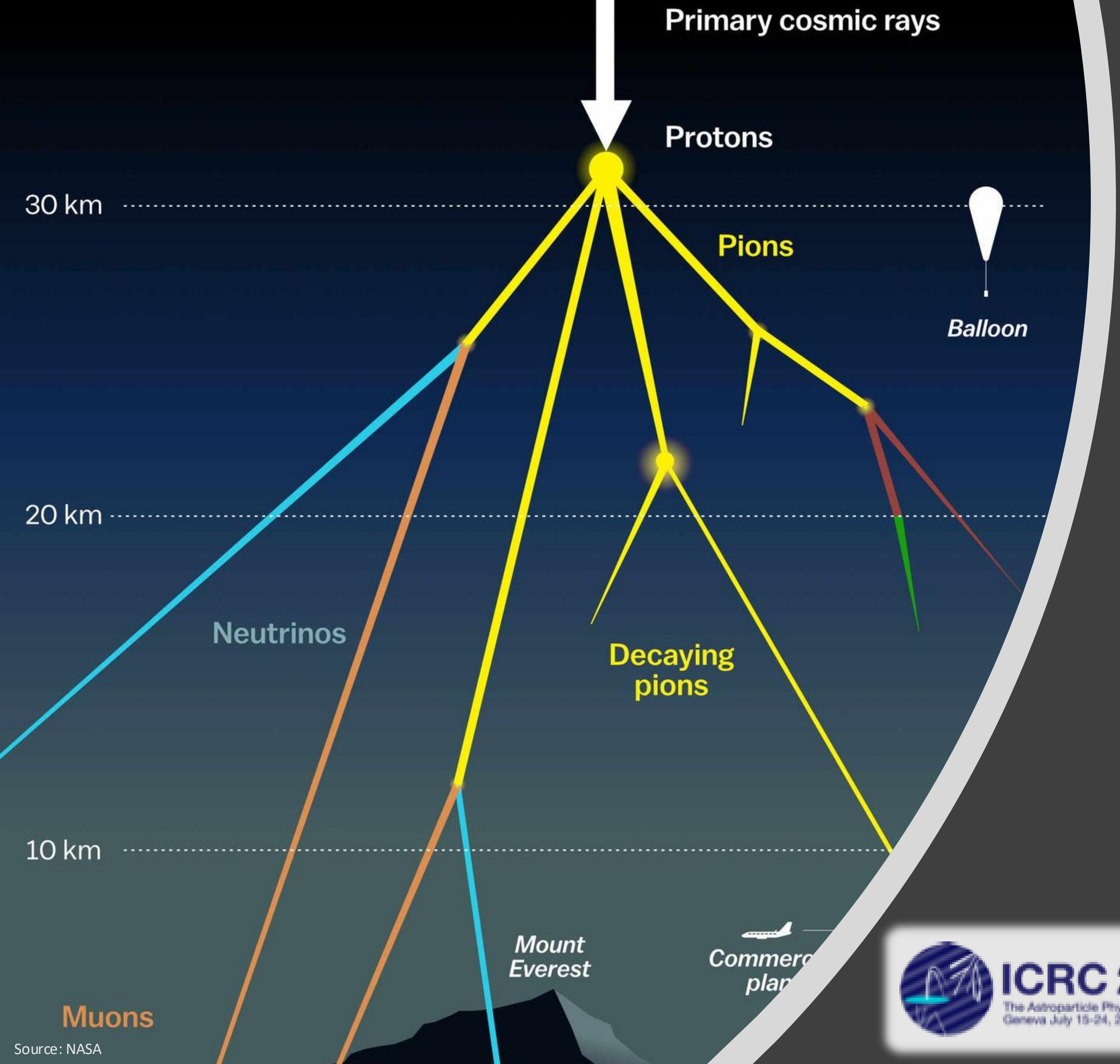


Source: NASA

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

Lucas Witthaus and Pascal Gutjahr
for the IceCube Collaboration

July 17, 2025

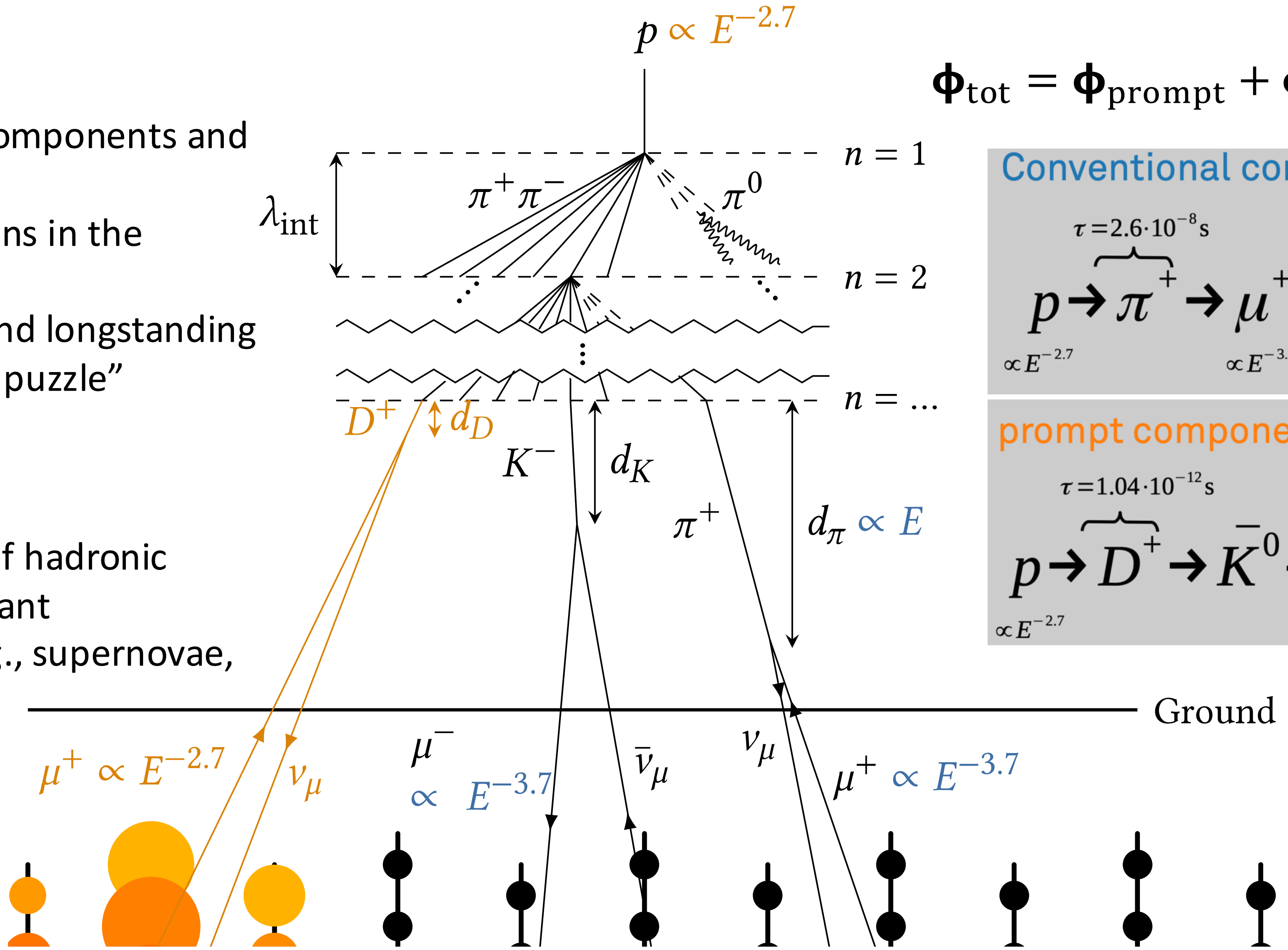
Introduction

Motivation
- Characterize muon flux components and depth intensity
- Probe hadronic interactions in the atmosphere
- Constrain uncertainties and longstanding questions like the “muon puzzle”

Long term
- Enhance understanding of hadronic processes relevant in distant astrophysical sources (e.g., supernovae, AGNs, …)

Conventional Muon: Parent is pion or kaon

$$\Phi_{\text{tot}} = \Phi_{\text{prompt}} + \Phi_{\text{conventional}}$$



Conventional component:

$$\underset{\propto E^{-2.7}}{p} \rightarrow \overbrace{\pi^+}^{\tau=2.6\cdot 10^{-8}\,\text{s}} \rightarrow \underset{\propto E^{-3.7}}{\mu^+} + \nu_\mu$$

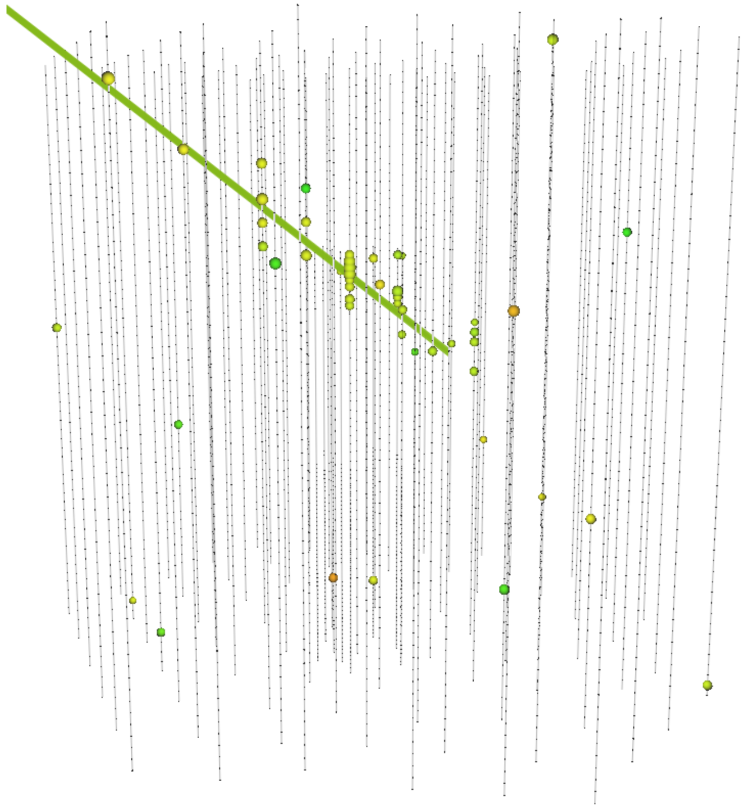
prompt component:

$$\underset{\propto E^{-2.7}}{p} \rightarrow \overbrace{D^+}^{\tau=1.04\cdot 10^{-12}\,\text{s}} \rightarrow \bar{K}^0 + \underset{\propto E^{-2.7}}{\mu^+} + \nu_\mu$$

Credit: Ludwig Neste

Stopping and Leading Muons

- Stopping muons:
  - Stop (decay) inside the in-ice array
  - Stopping point + direction → propagated length
  - Proxy to muon energy at the surface
  - Low-energy muons



- Leading muons:
  - Most energetic muon in the bundle
  - High energies above 10 TeV
  - Focus on muons carrying > 40% of the entire bundle

Insert muon bundle picture

Technical Basics

Unfolding and Machine Learning

Unfolding in a nutshell

measured proxy

detector response

background

$$g(y) = \int_{E_0}^{E_1} A(E_\mu, y) f(E_\mu)\,\mathrm{d}E_\mu + b(y)$$

true energy distribution

1. Discretized form: $\underbrace{\vec{g} = A\vec{f}}_{\text{folding}} \leftrightarrow \underbrace{\vec{f} = A^{-1}\vec{g}}_{\text{unfolding}}$

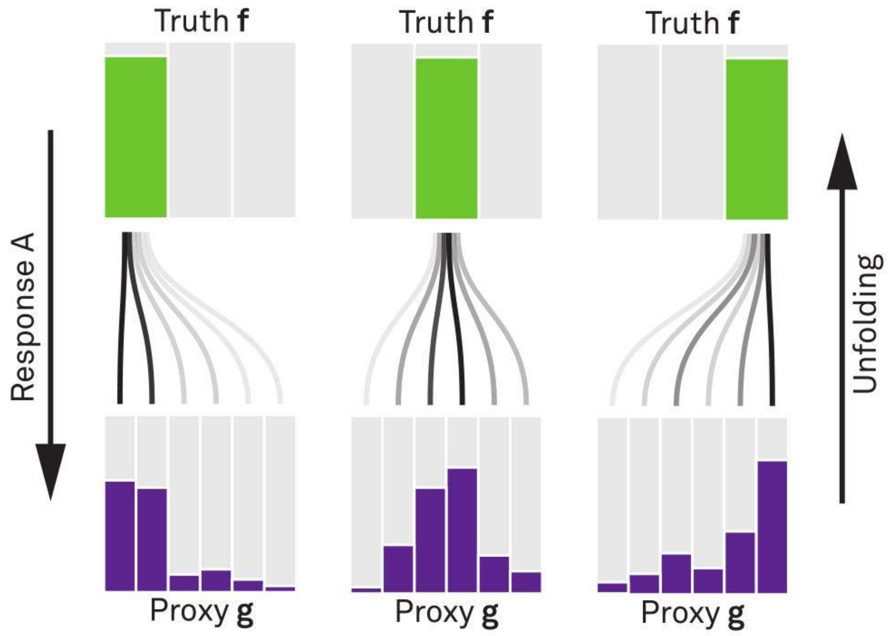
2. Maximum likelihod method:

$$\mathcal{L}(\vec{g}|\vec{f}) = \prod_{j=1}^{M} \frac{\lambda_j^{g_j}}{g_j!} \exp(-\lambda_j)$$

$$= \prod_{j=1}^{M} \frac{(A\vec{f})_j^{g_j}}{g_j!} \exp(-(A\vec{f})_j)$$

3. Thikonov regularization:

$$t(\vec{f}) = -\frac{1}{2}(C\vec{f})^T(\tau 1)^{-1}(C\vec{f})$$

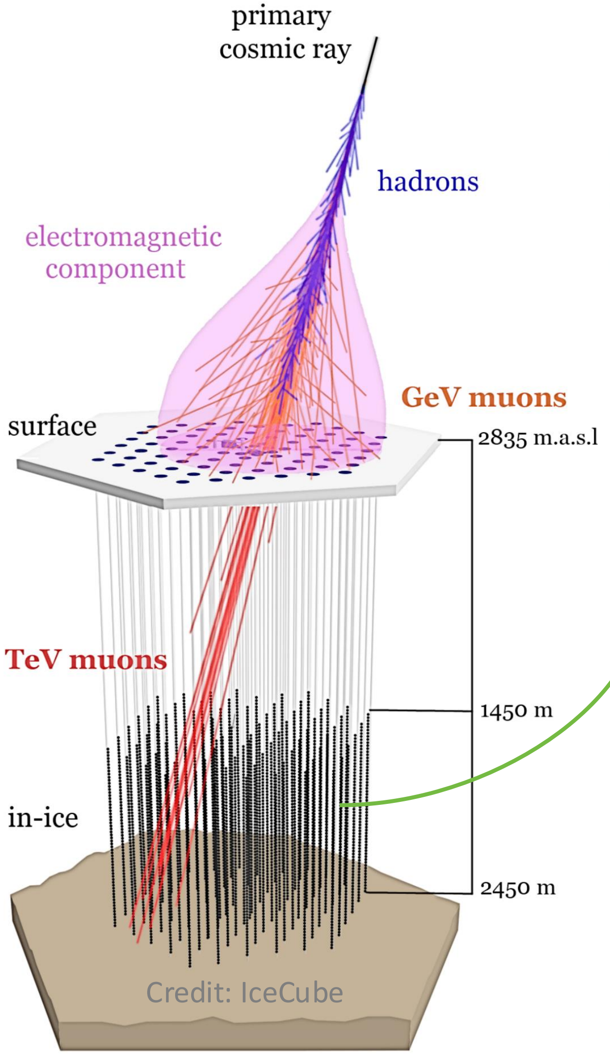


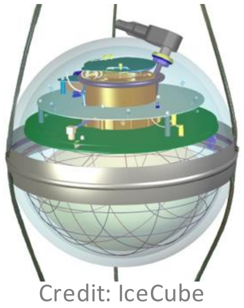
Credit: T. Hoinka

4. Maximize $\log(\mathcal{L}(\vec{g}|\vec{f})) + t(\vec{f})$ with respect to $\vec{f}$ using Markov Chain Monte Carlo (MCMC) or Minuit

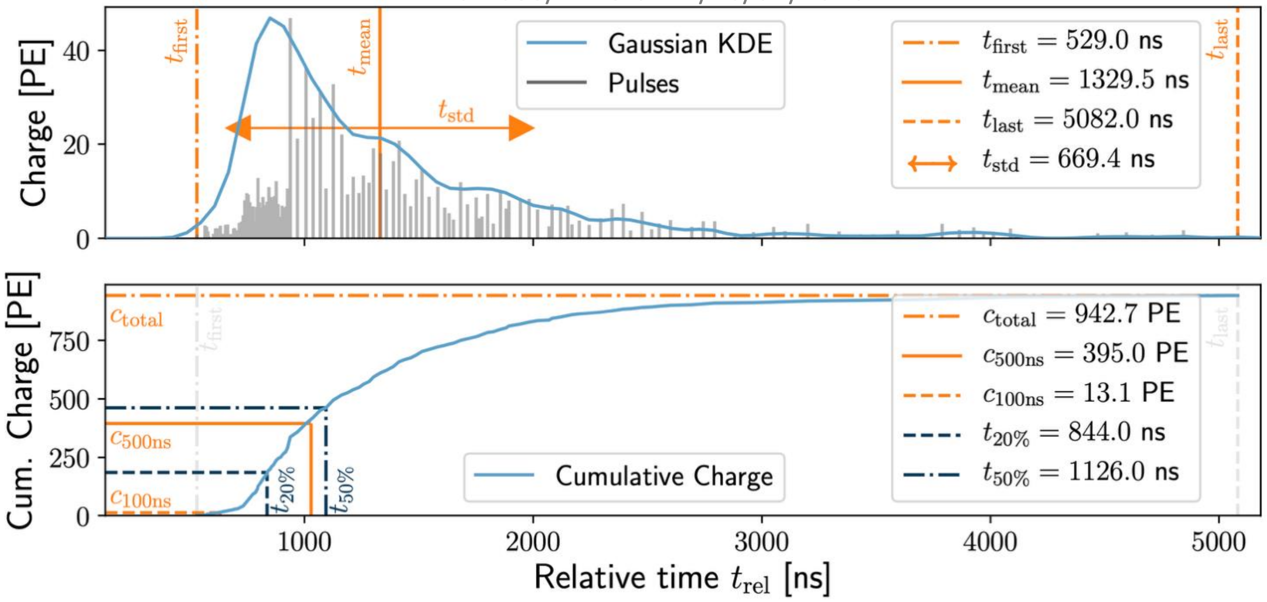
GitHub **funfolding** by M. Börner

Machine Learning Reconstructions





10.1088/1748-0221/16/07/P07041



Convolutional Neural Network

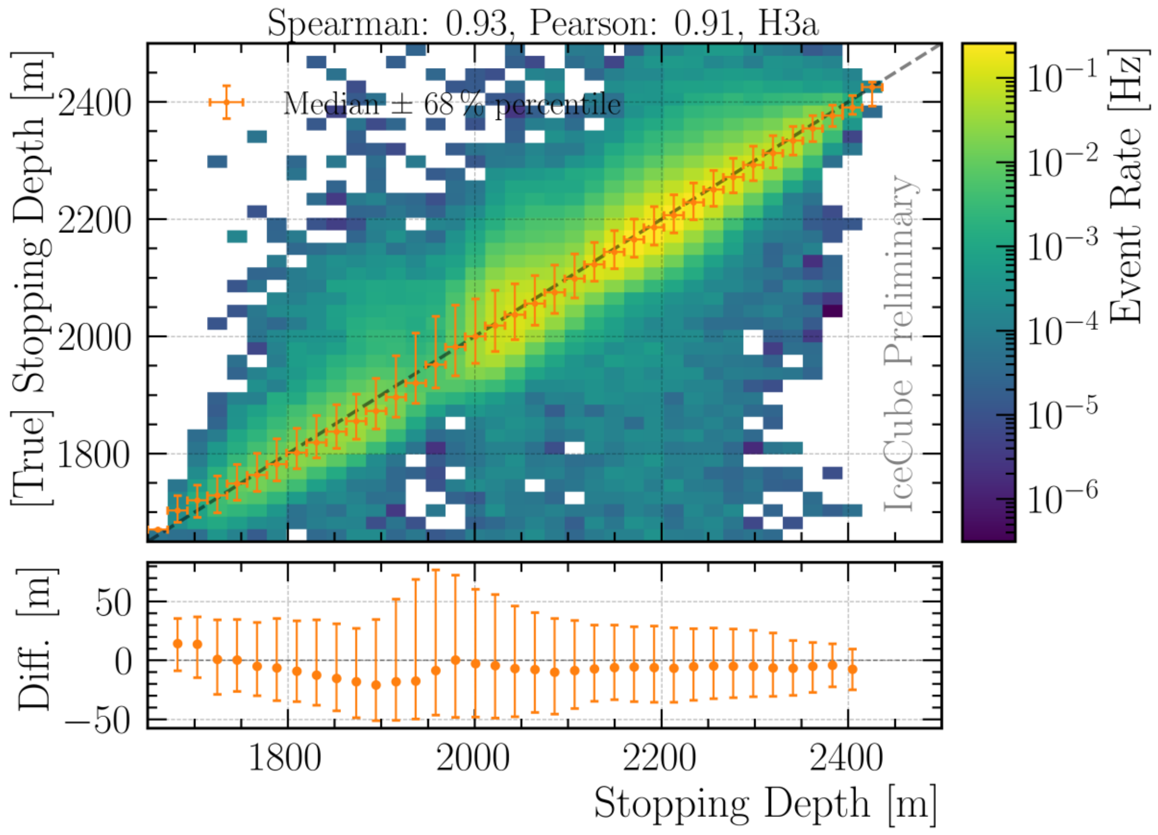
Inputs
- c_{total}: Total charge
  - Sum of charge
- t_{first}: Relative time of first pulse
  - Relative to total time offset
- t_{std}: Standard deviation of first pulse
  - Charge weighted standard deviation of pulse times

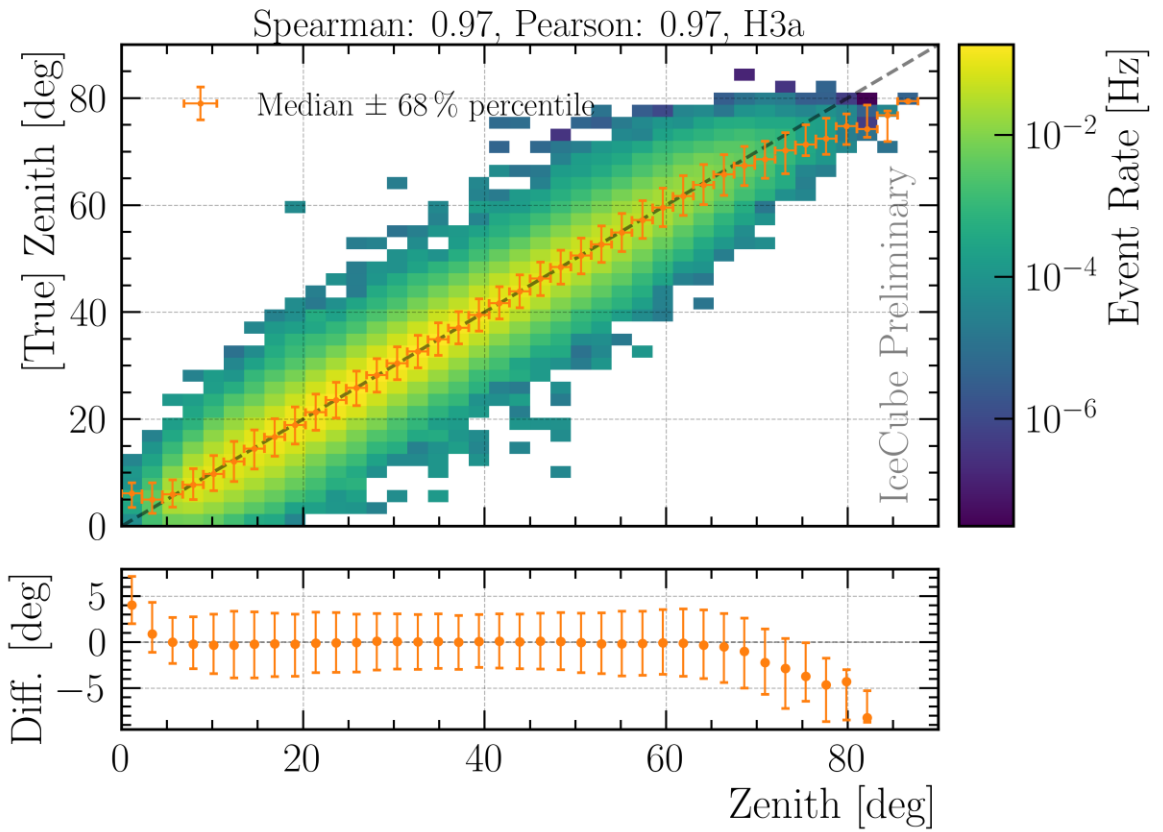
Outputs
- Direction
- Stopping point
- Entry point
- Energy at entry/surface
- …

Depth Intensity Unfolding

Reconstructions: Stopping Muons

- ➢ Good reconstruction of stopping depth and zenith angle
- ➢ Calculate propagation length → proxy variable for unfolding



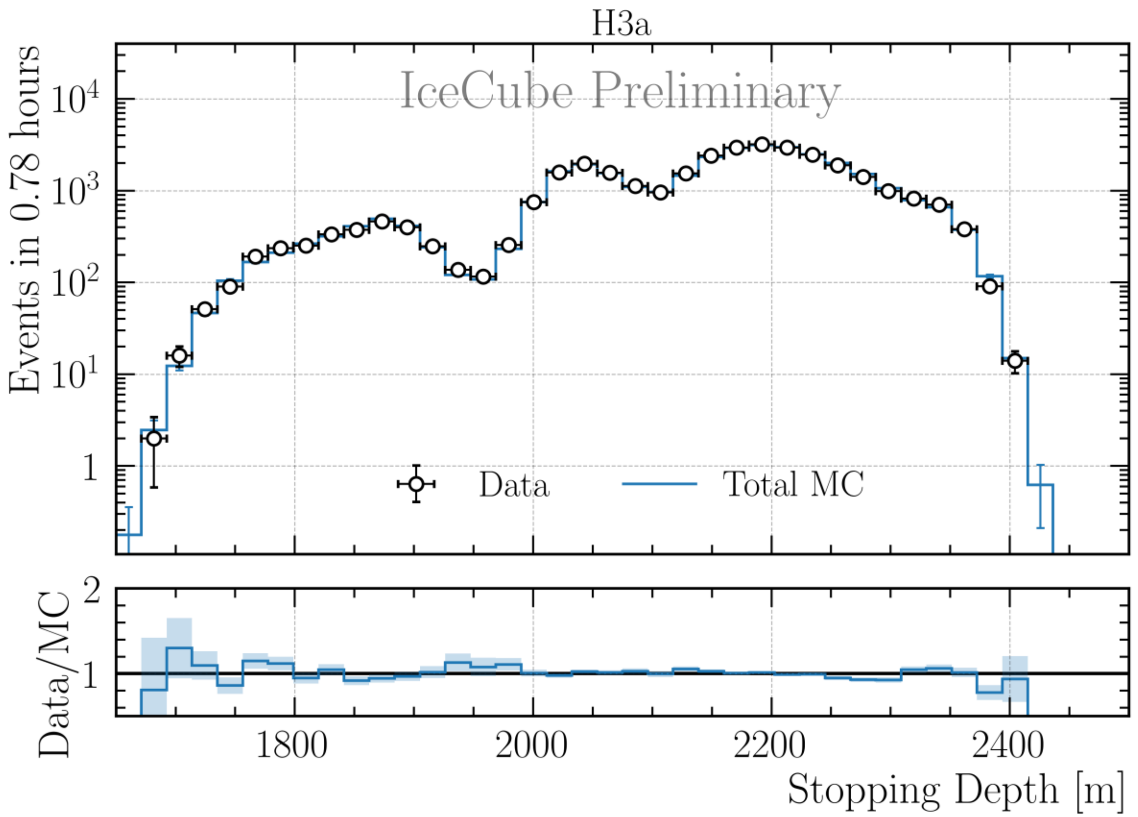


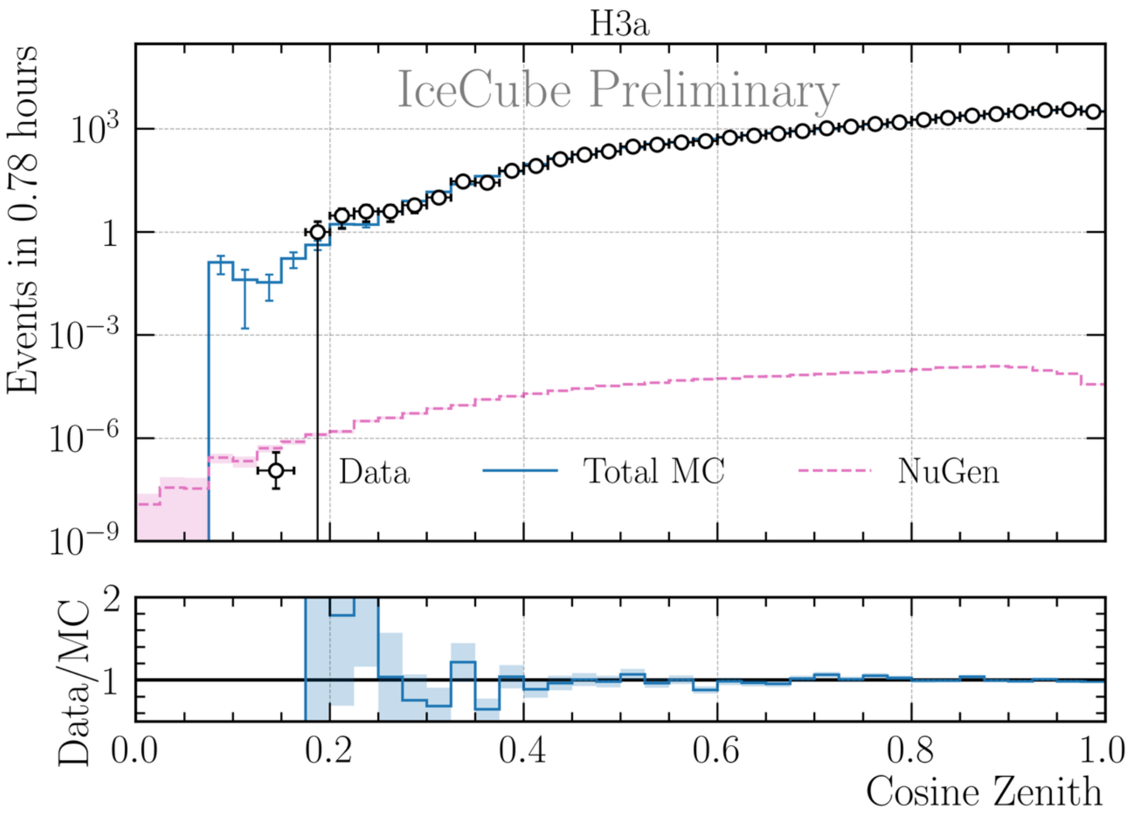
Data—MC: Stopping Muons

- Good data—MC agreement
- Global offset → upscale MC by 10%

Neutrino weighting:
SPL: n = 1.8, γ = 2.52

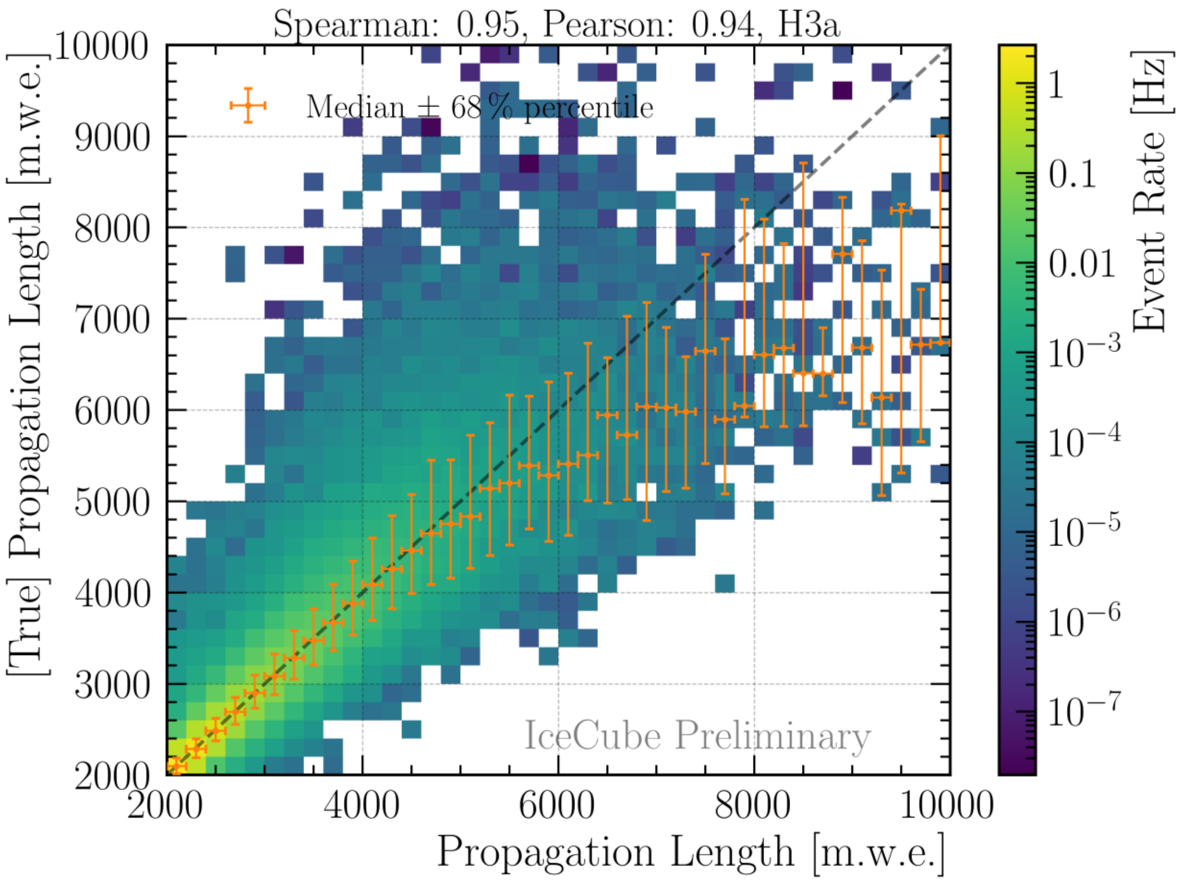
IceCube Collaboration PoS ICRC2023 1064



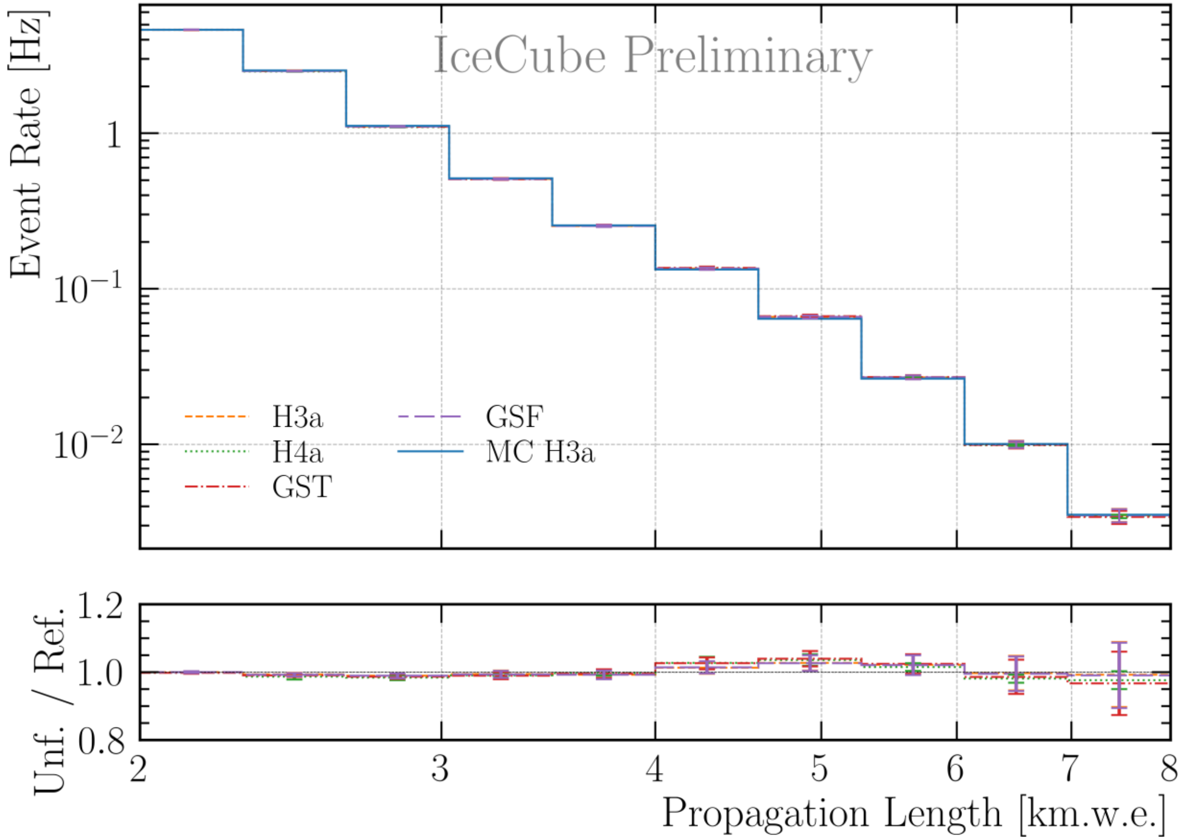


Correlation and Robustness Test: Stopping Muons

- Strong correlation between proxy and target



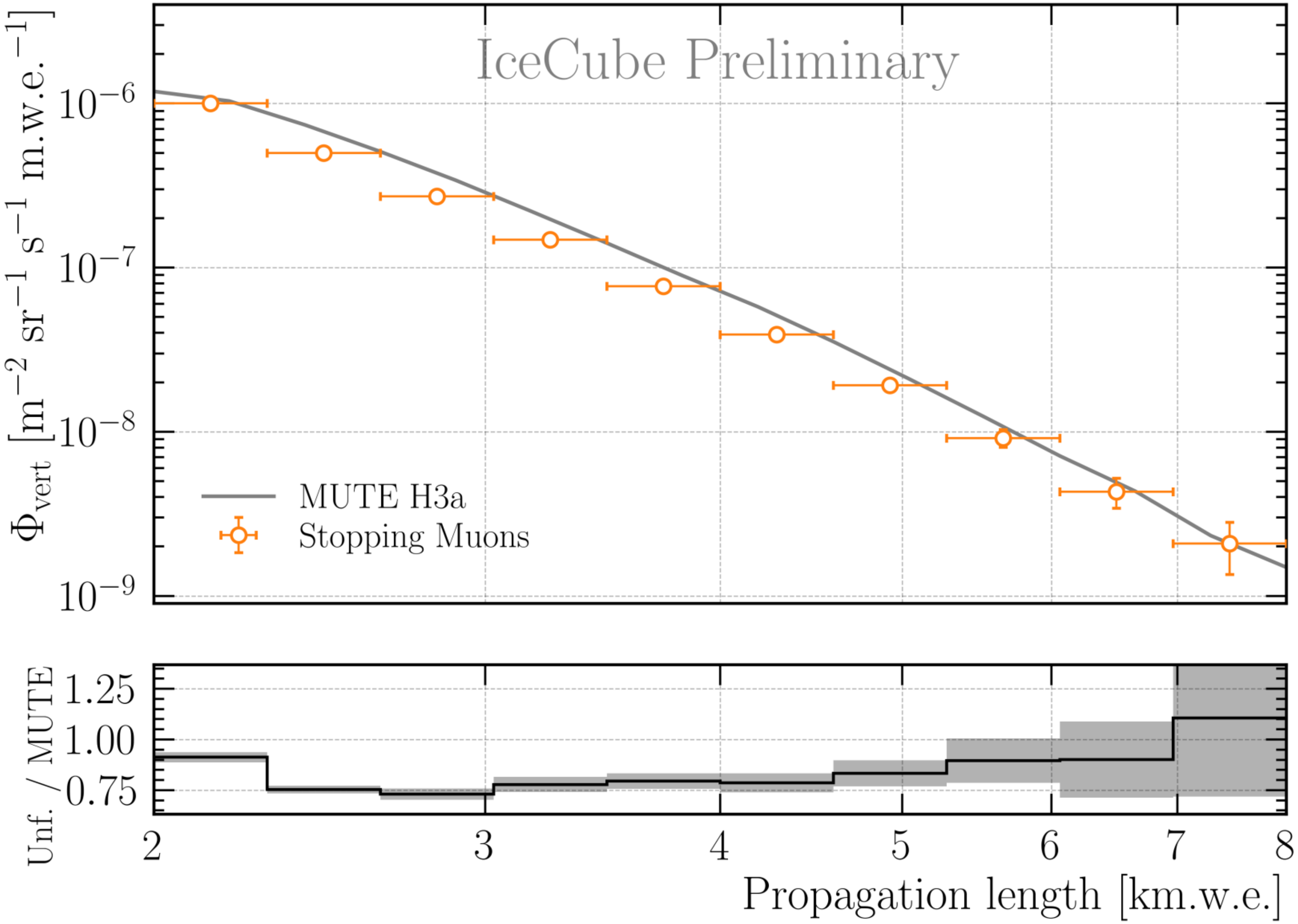
- Build unfolding matrix on H3a, H4a, GST & GSF
- Unfold H3a as test set
- Results are within uncertainties → robust



Depth Intensity Unfolding

- 47 min IceCube data
- 32943 events

- Comparison to MUTE[1]
- Up to 25 % below prediction at 2.5 – 5.5 km.w.e.
- Mismodelling in energy losses?

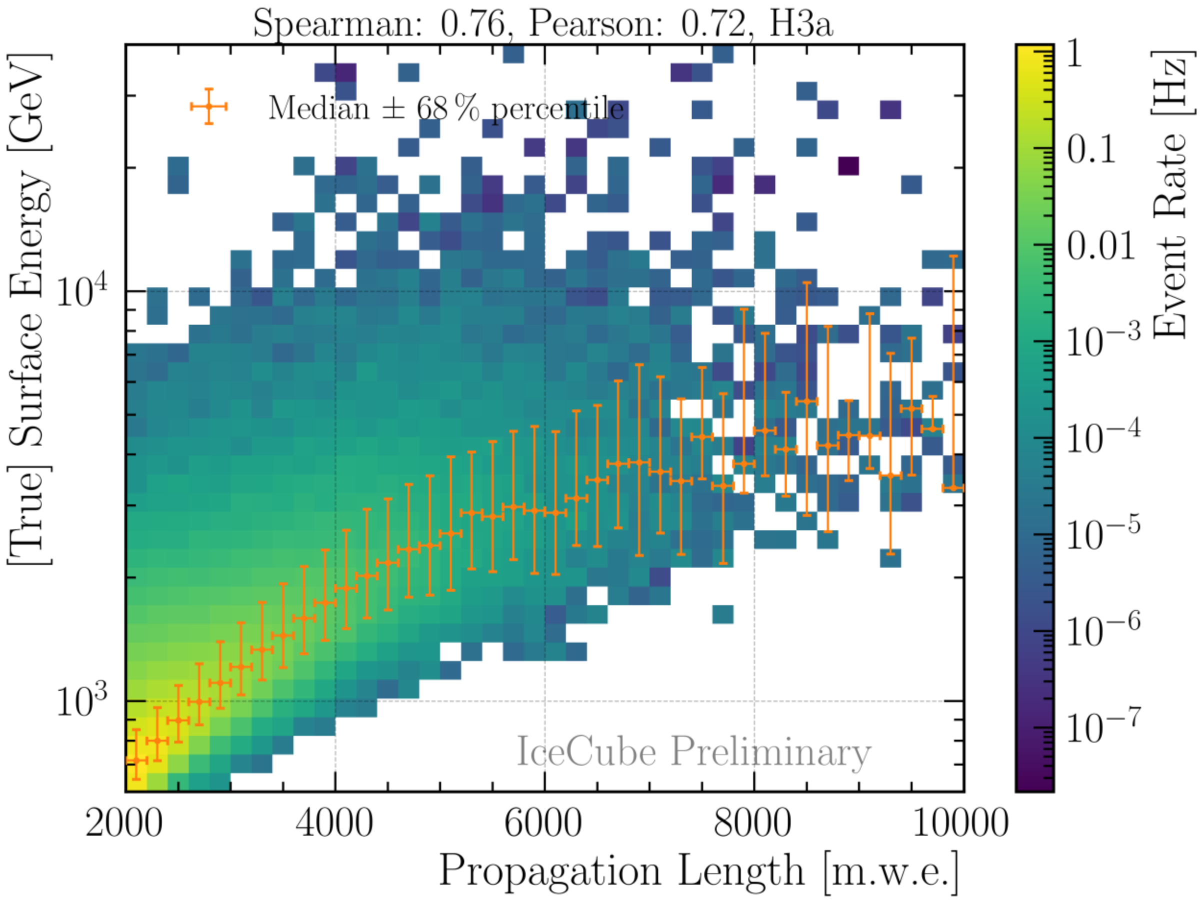


[1]W. Woodley et al. Phys. Rev. D 110 no. 6, (2024) 063006

Muon Flux Unfolding

Correlation and Robustness Test: Stopping Muons

- Correlation between proxy and target



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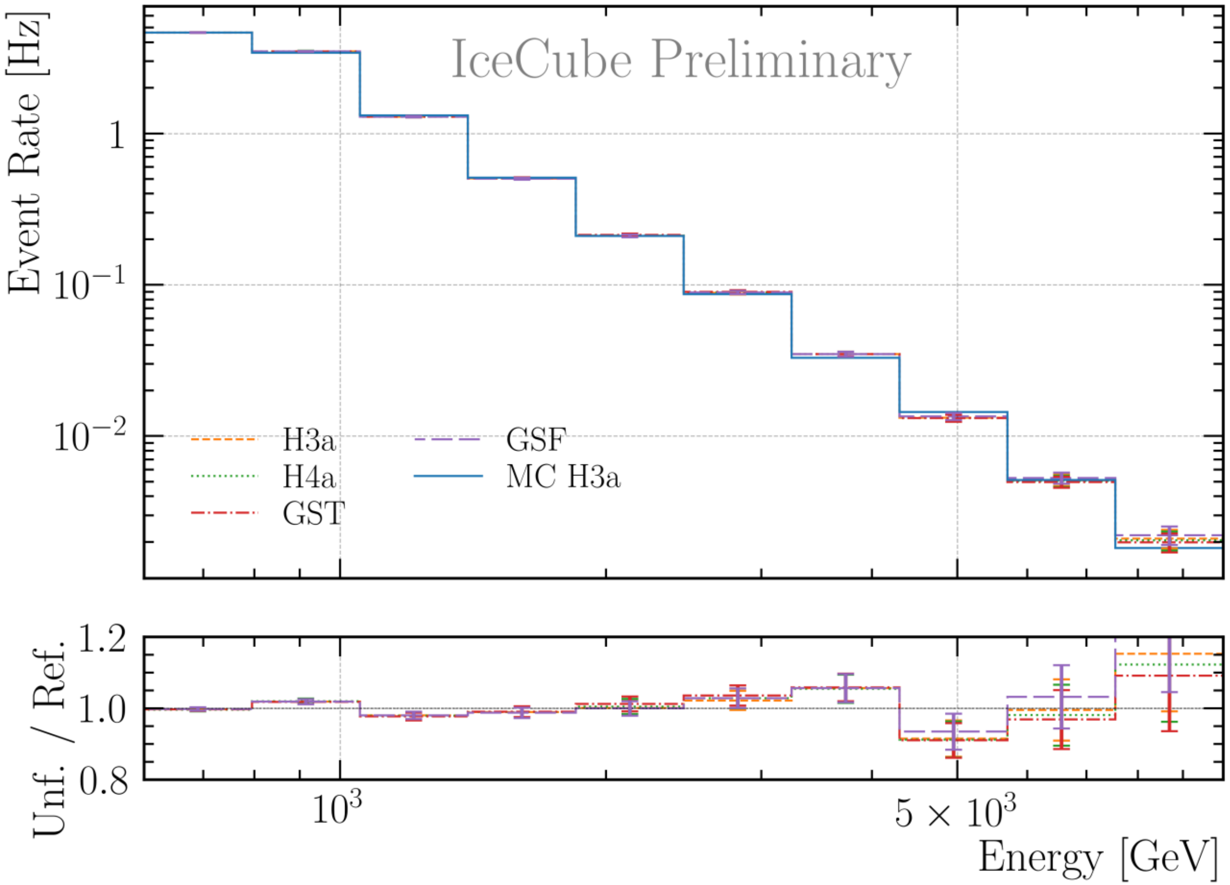
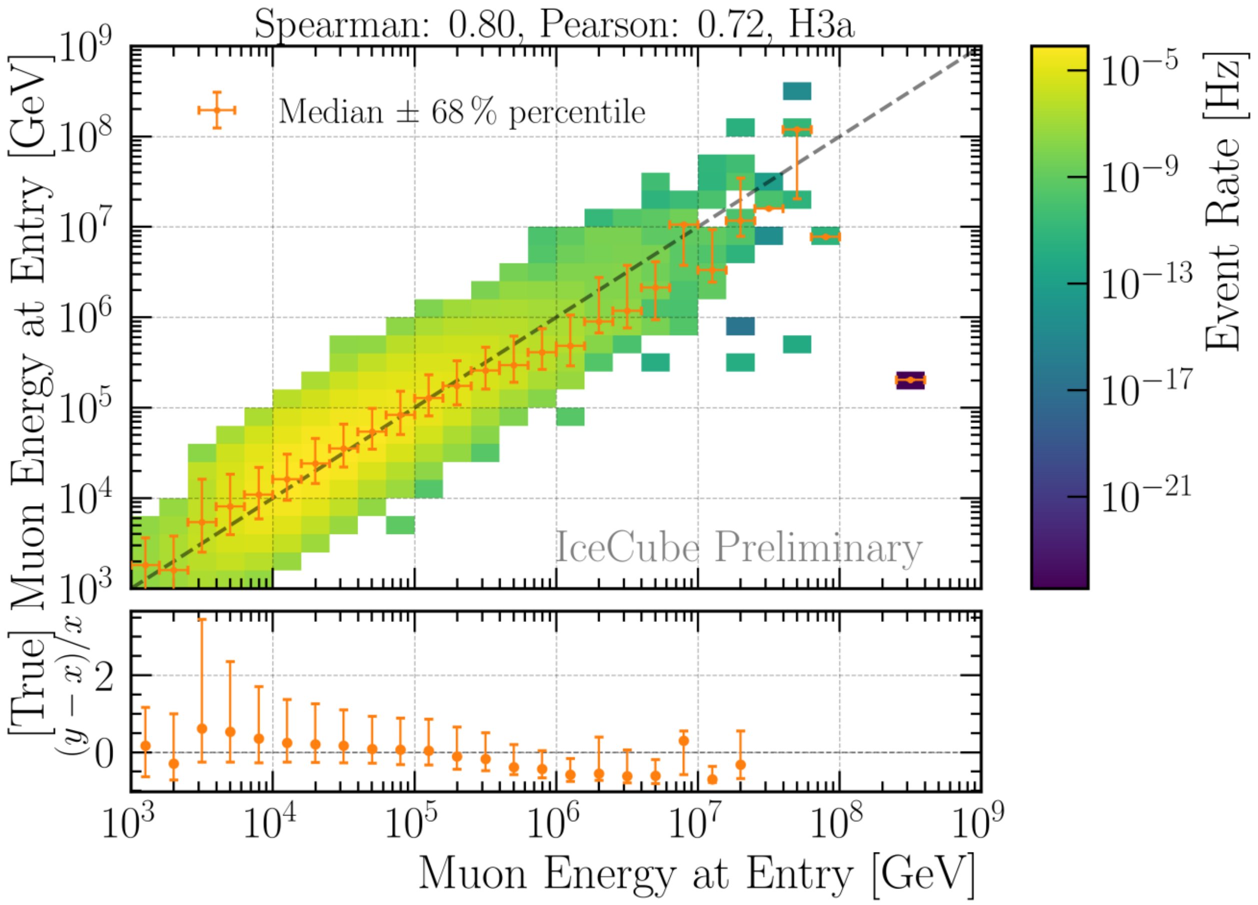
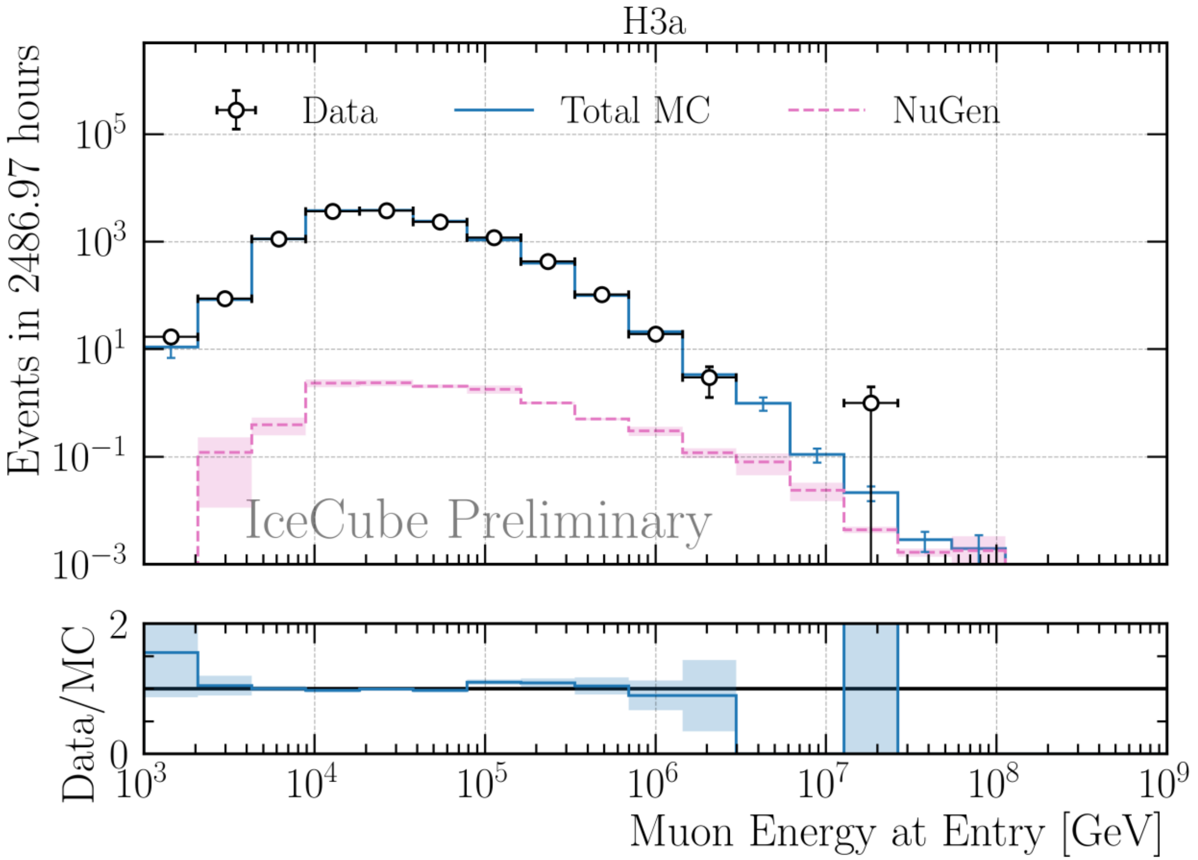


Reconstruction and Data—MC: Leading Muons

- ➢ Good reconstruction of leading muon energy → proxy

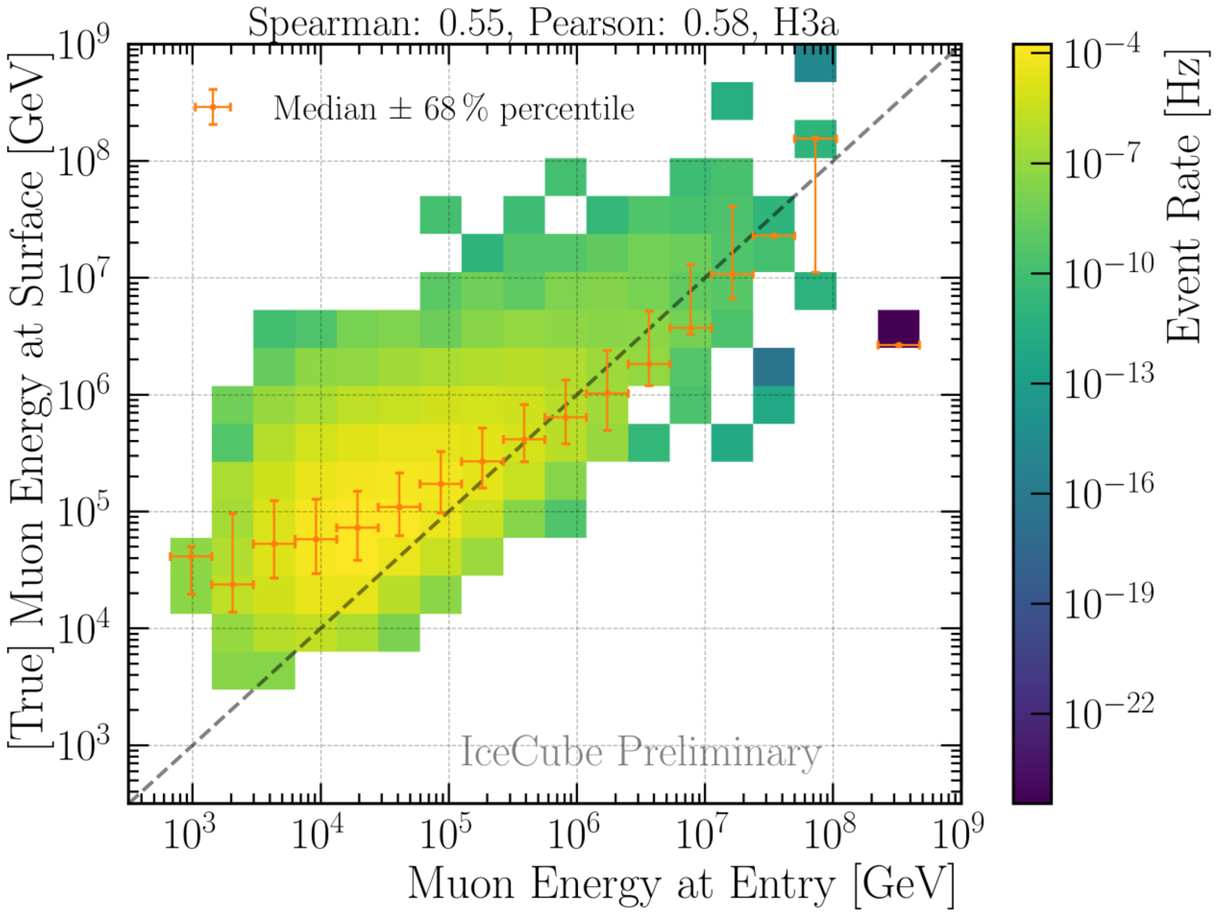


- ➢ Good data—MC agreement
- ➢ Global offset → upscale MC by 12%

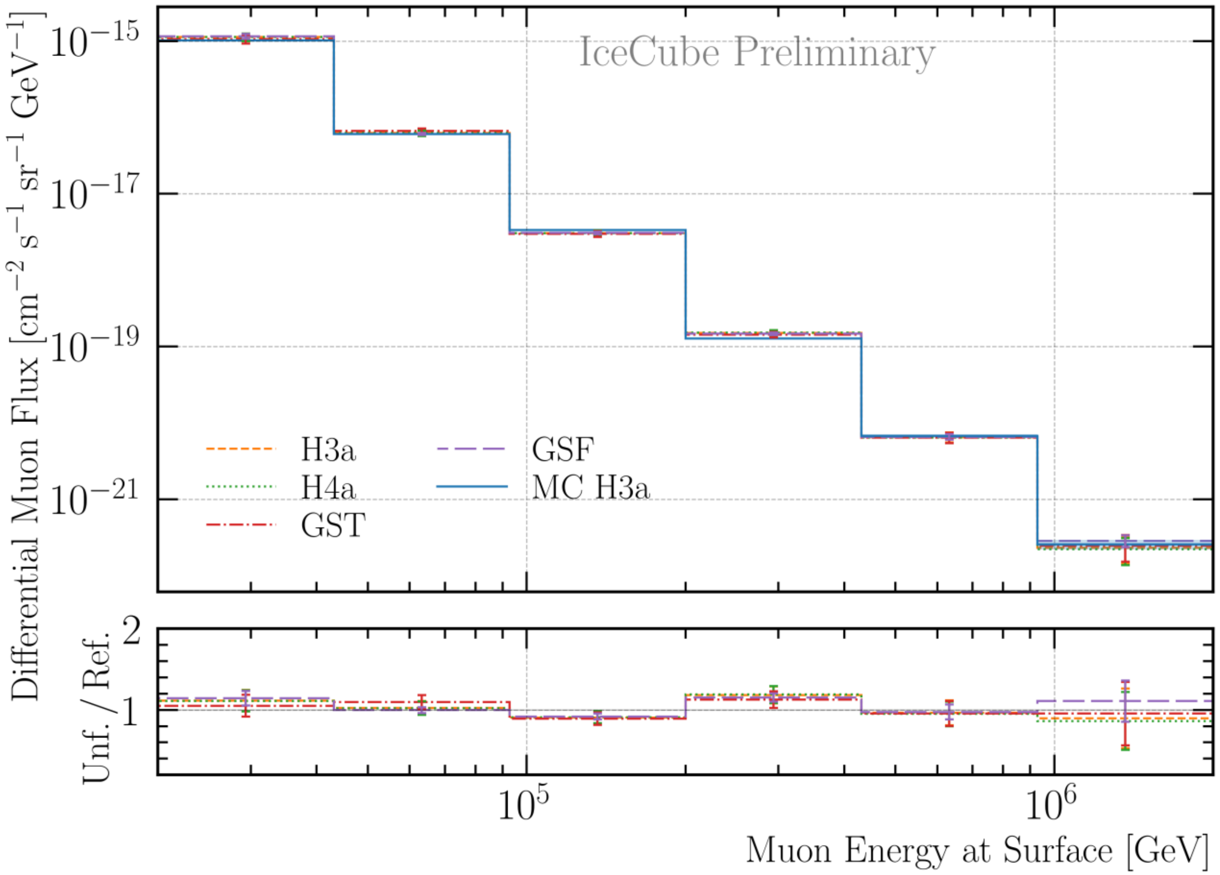


Correlation and Robustness Test: Leading Muons

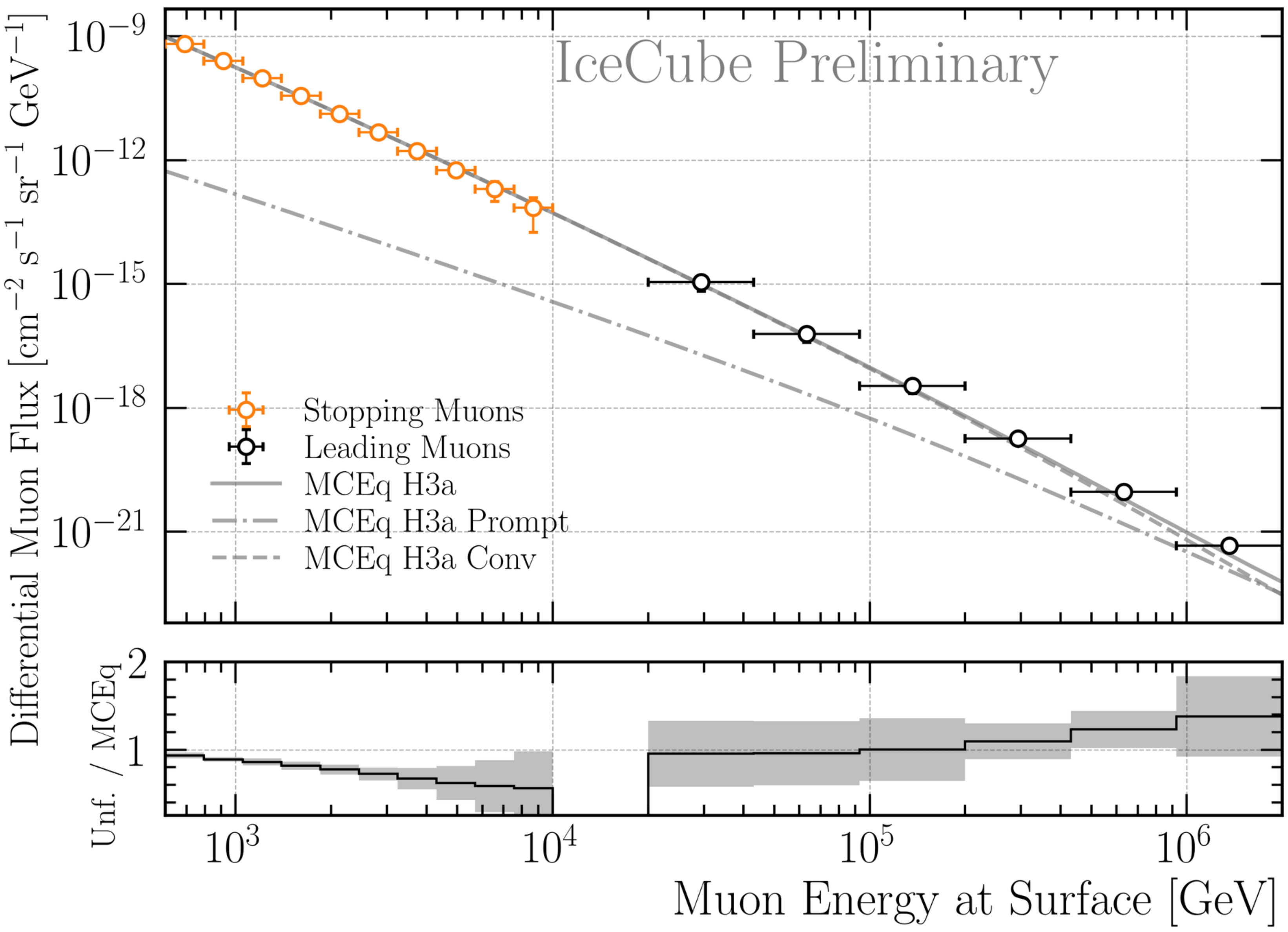
- Correlation between proxy and target



- Build unfolding matrix on H3a, H4a, GST & GSF
- Unfold H3a as test set
- Results are within uncertainties → robust



Muon Flux Unfolding



Stopping muons

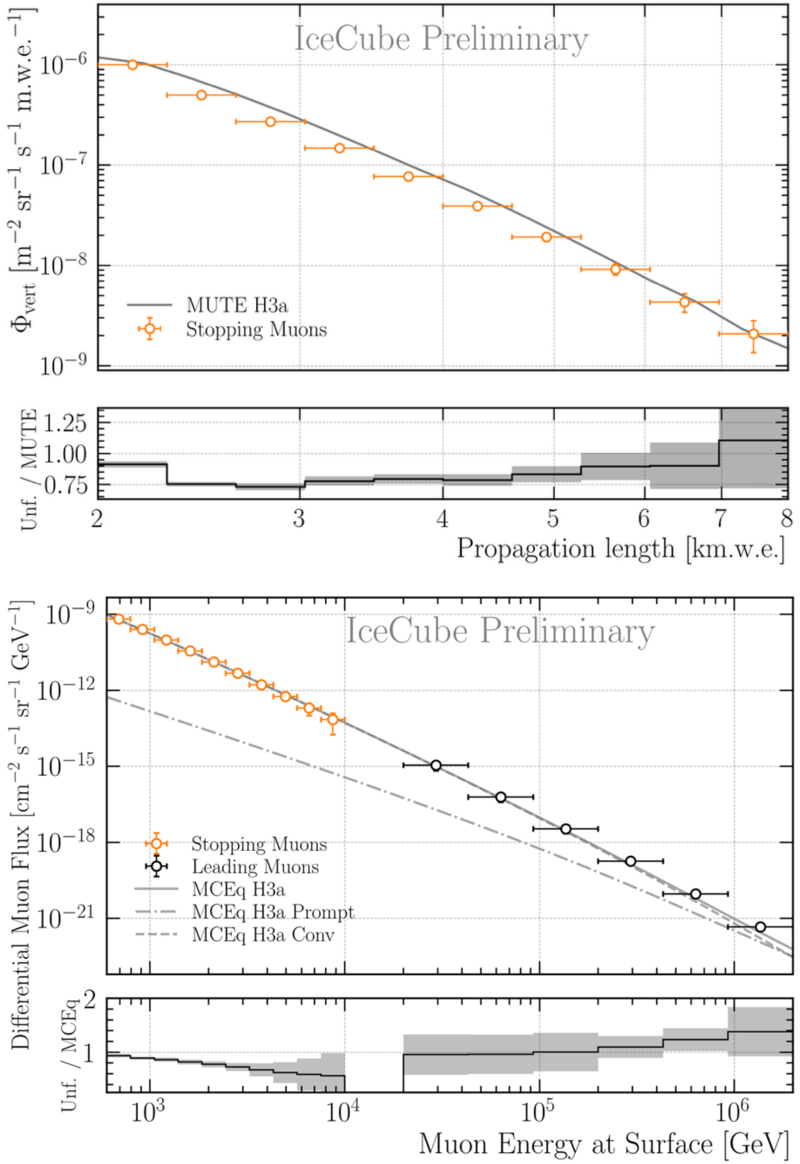
- 47 min IceCube data
- 32943 events
- Below MCEq prediction

Leading muons

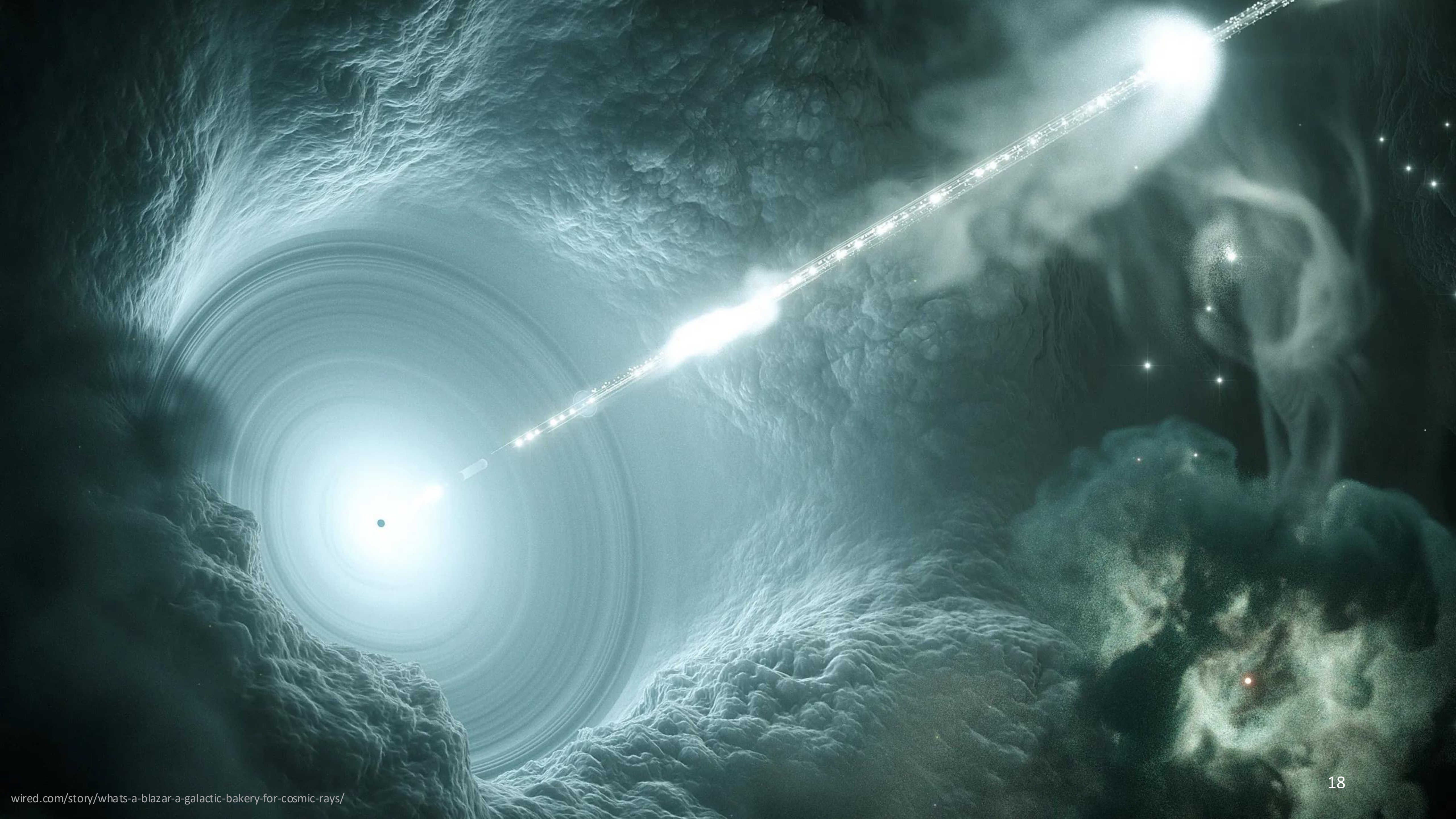
- 2487 h IceCube data
- 12754 events
- Agrees with MCEq

Conclusion & Outlook

- DNN-based reconstructions performed
  - Stopping muon selection
  - Leading muon selection
  - Good Data—MC agreement
- Depth intensity unfolded using 47 min of IceCube data
  - Undershoots MUTE prediction up to 5.5 km.w.e.
- Muon flux at surface unfolded using stopping muons and 2487 h of leading muon IceCube data
  - Flux undershoots up to 10 TeV (MCEq prediction) – stopping muons
  - Flux agrees from 20 TeV to 2 PeV with MCEq – leading muons
    - Slope increases towards higher energies
    - Prompt and conventional flux contributes similar the flux at ~2 PeV

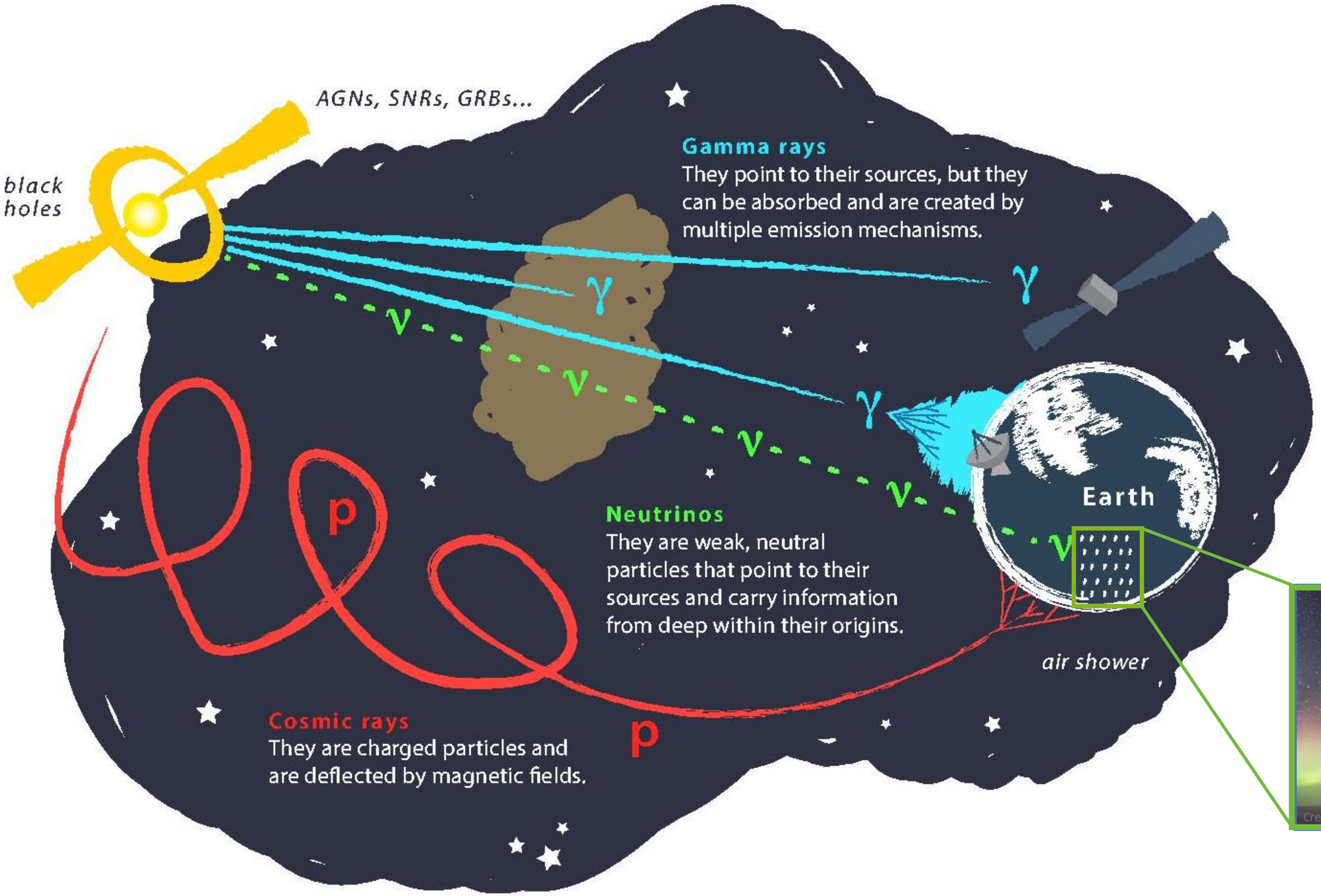


Thank you for your attention!



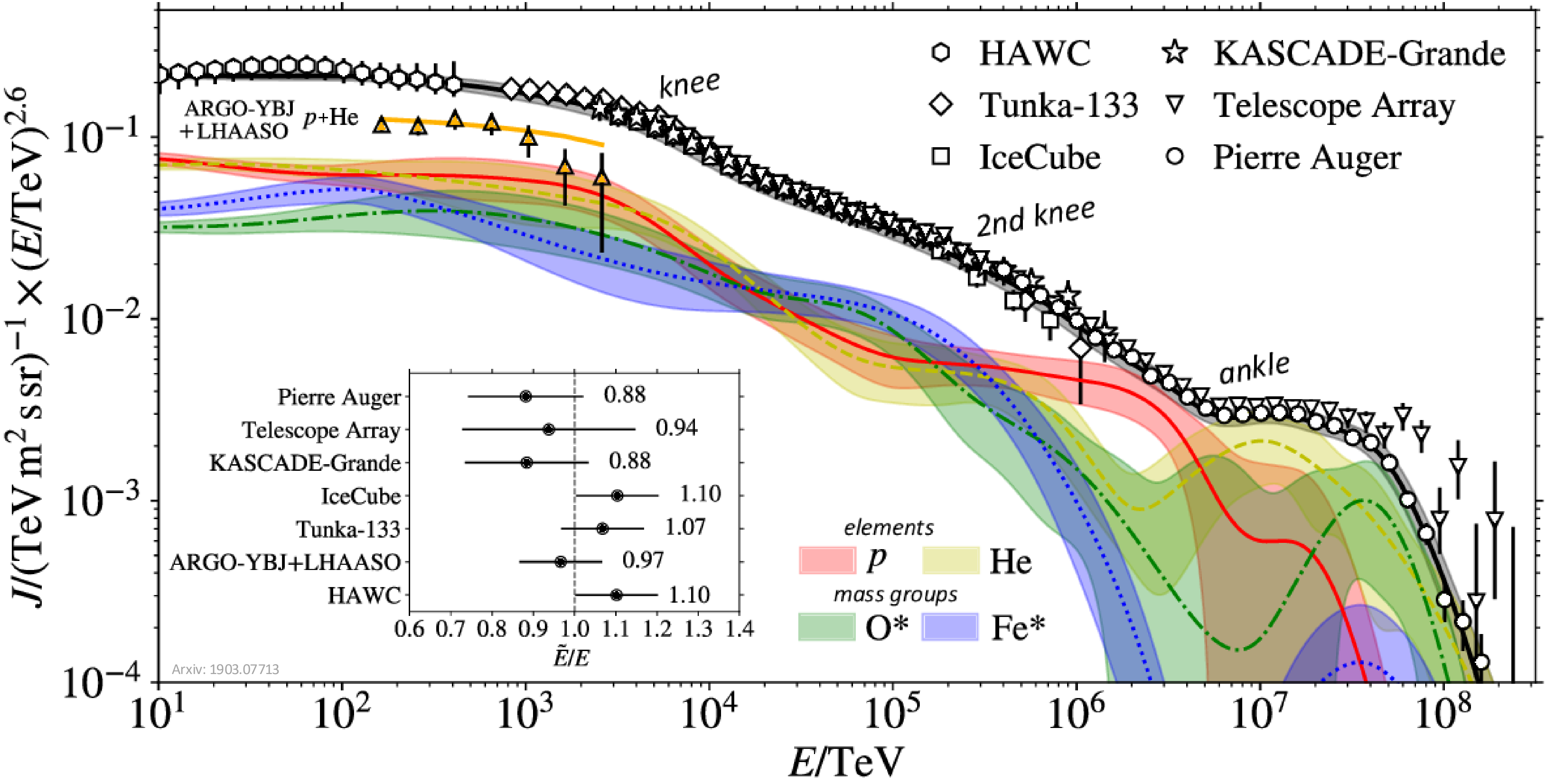
wired.com/story/whats-a-blazar-a-galactic-bakery-for-cosmic-rays/

Astroparticle physics

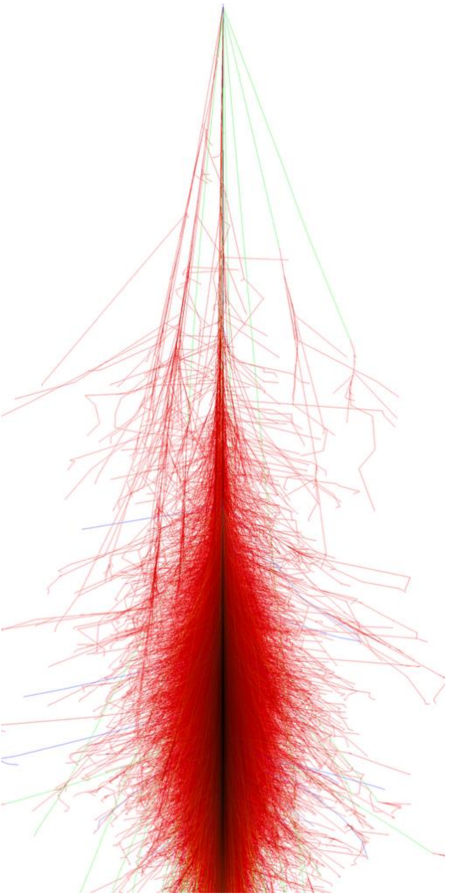


Source: gallery.icecube.wisc.edu

Cosmic ray flux

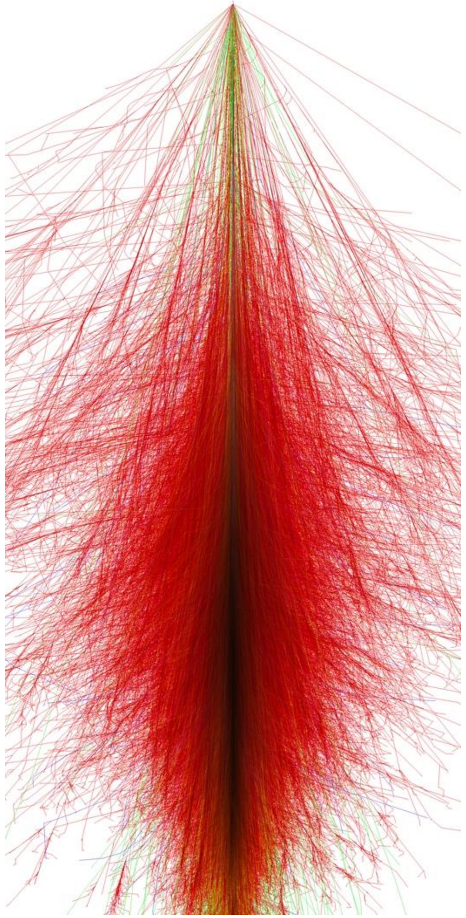


Air shower – 10 TeV

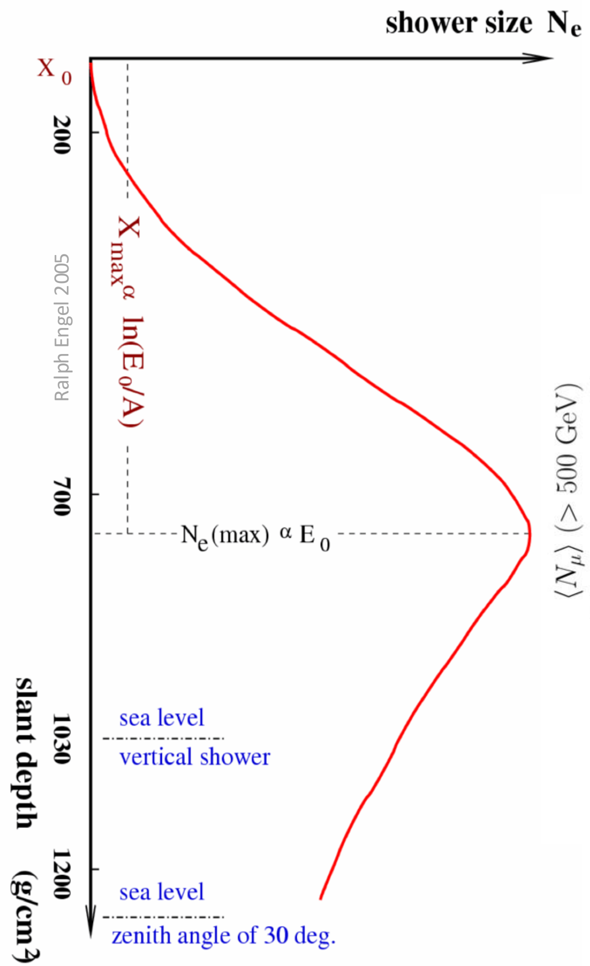


Proton

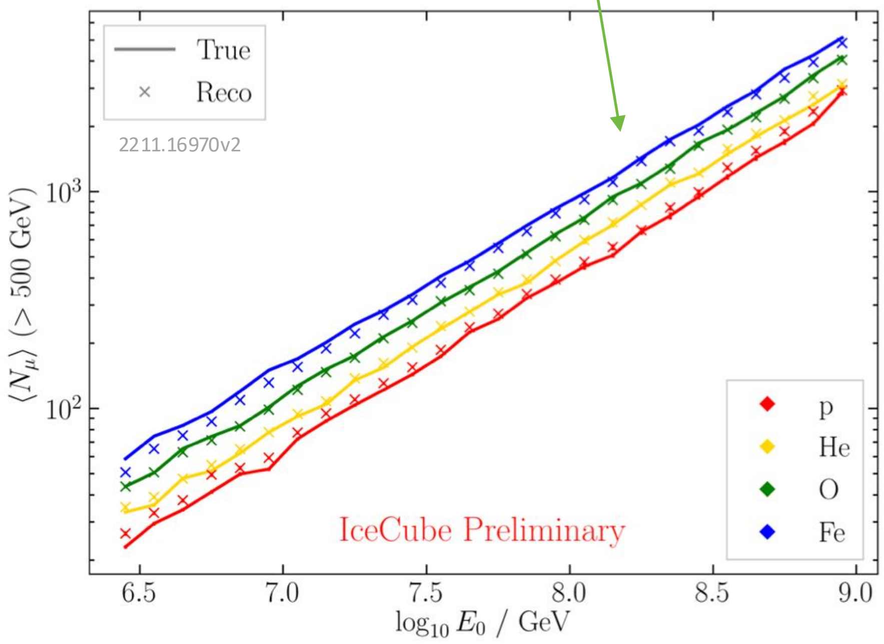
zeuthen.desy.de



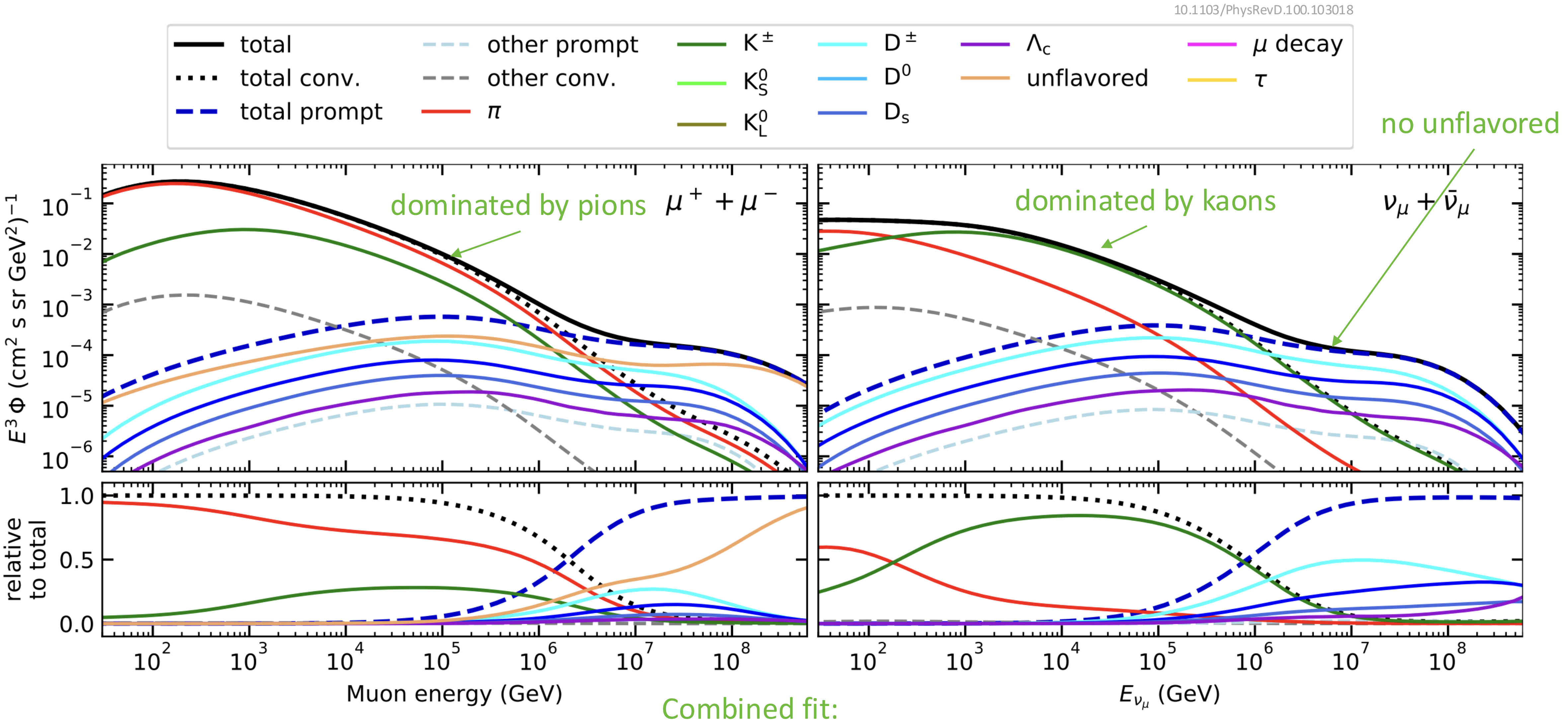
Iron



"muon bundles"



Prompt atmospheric muons and neutrinos



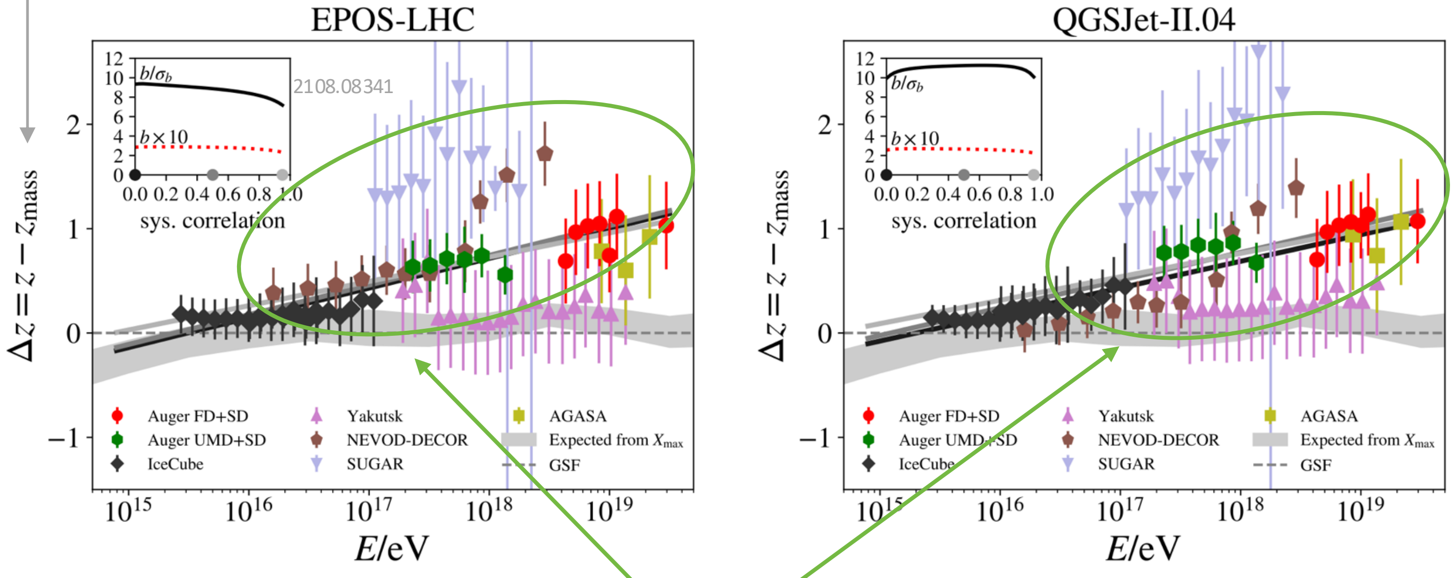
Combined fit:
- handle on pion/kaon ratio
- handle on charmed mesons

Muon puzzle and model uncertainties

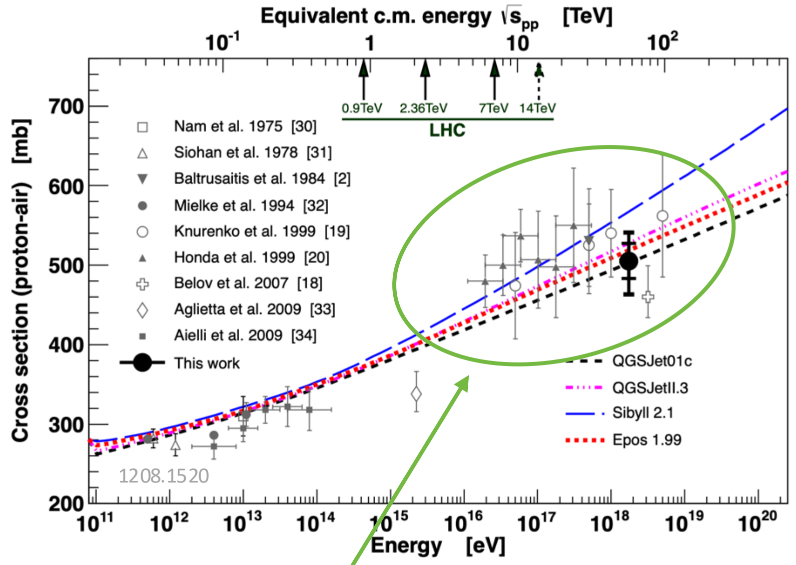
"muon number"

Expected z
("muon number")

$$z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_p}{\ln\langle N_\mu \rangle_{\mathrm{Fe}} - \ln\langle N_\mu \rangle_p}$$

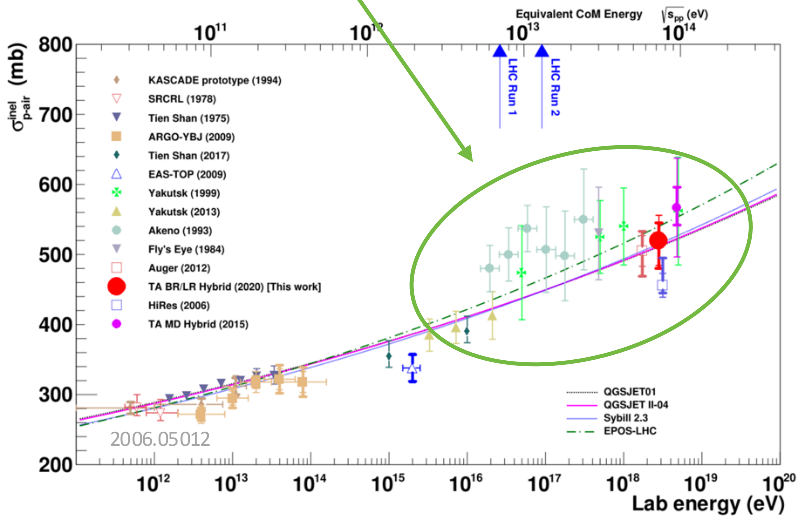


- More muons measured than simulated for E > 40 PeV ~ cms 8 TeV



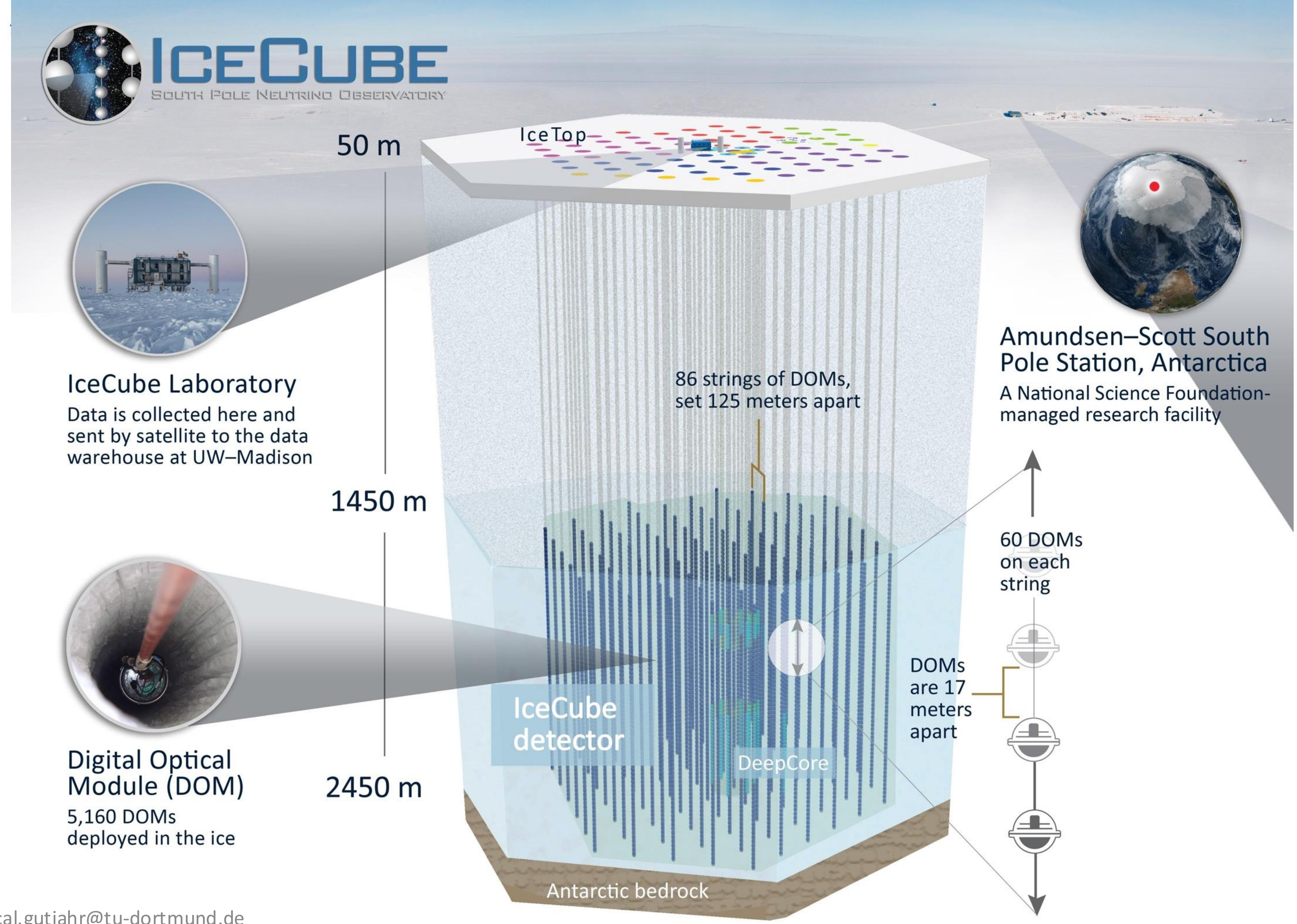
2012

- Uncertainties at E > 10 PeV



2020

pascal.gutjahr@tu-dortmund.de

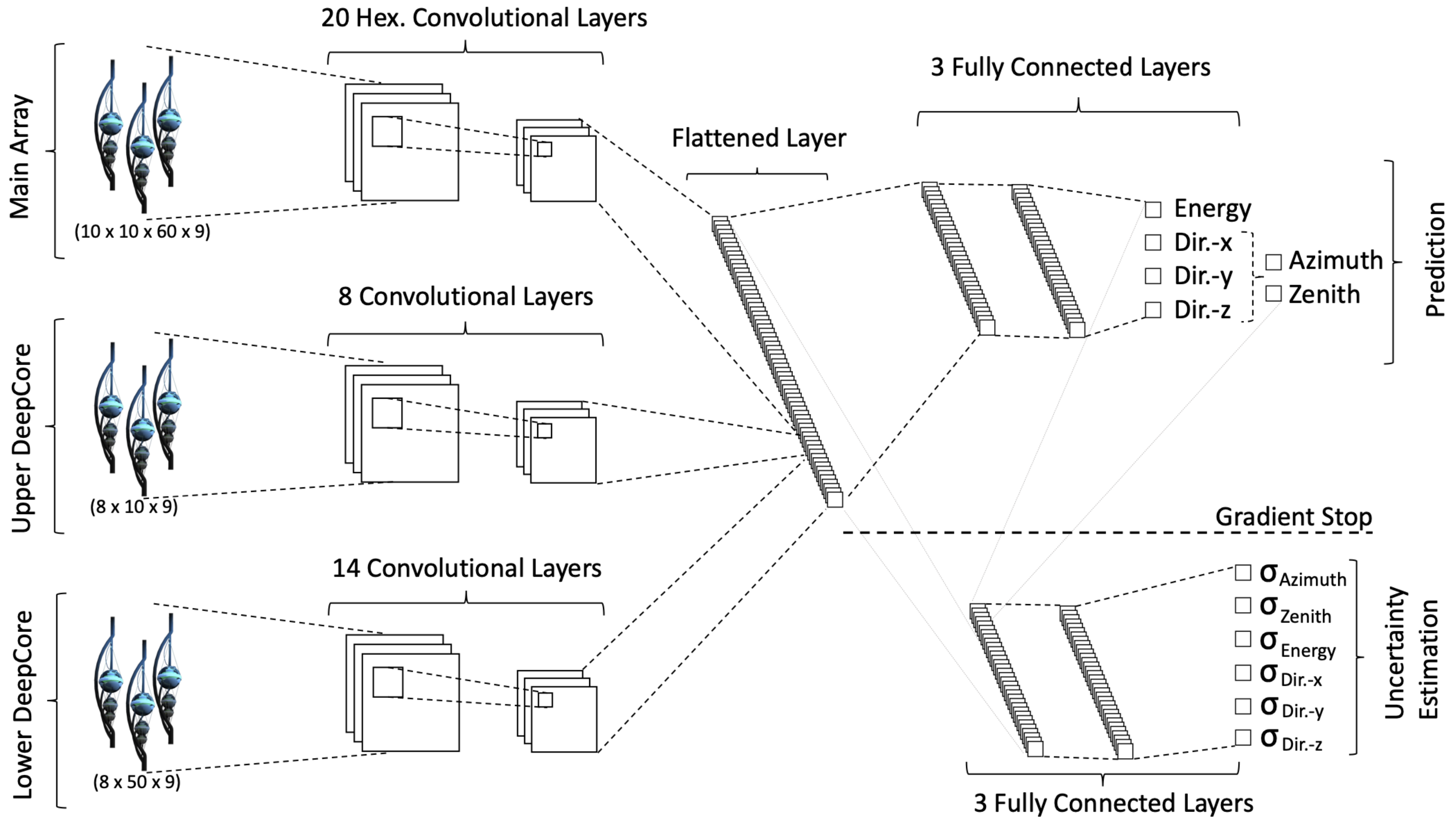


Credit: IceCube

Convolutional Neural Network (CNN)

Machine learning approach:

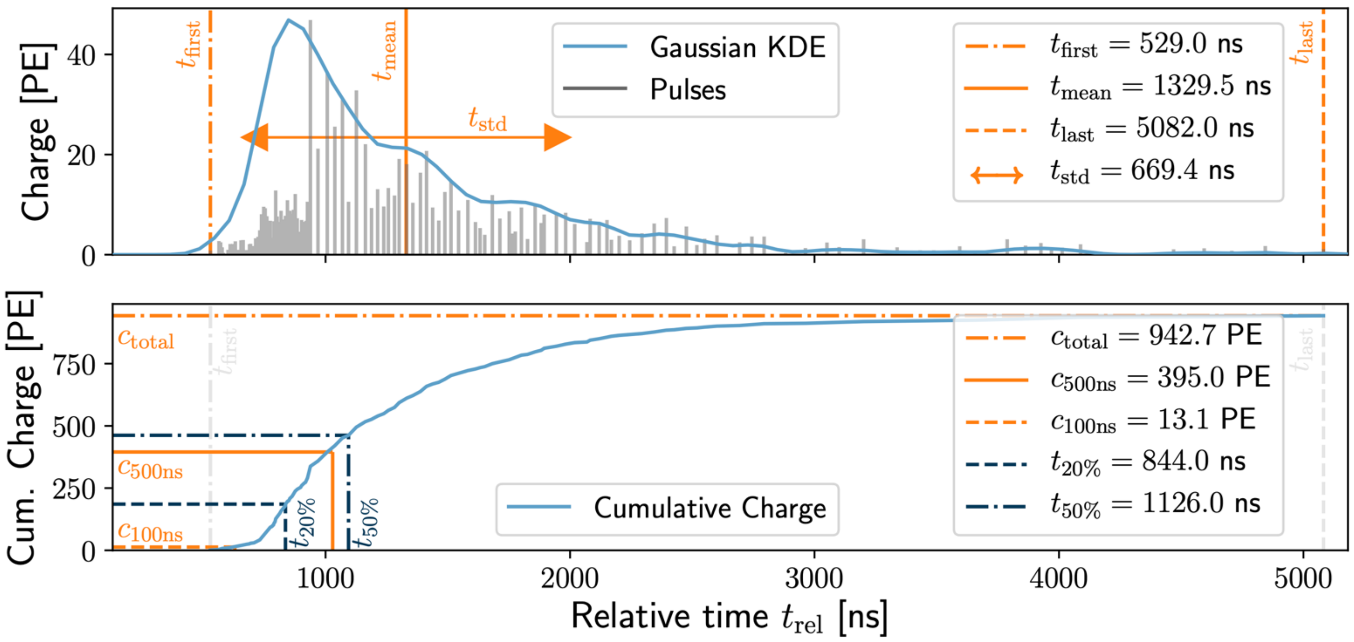
- fast
- identifying spatial patterns
- better event reconstruction and classification



2101.11589

Input data per DOM

10.1088/1748-0221/16/07/P07041



3 inputs

- c_{total}: Total charge
  - Sum of charge
- t_{first}: Relative time of first pulse
  - Relative to total time offset, calculated as the charge weighted mean time of all pulses
- t_{std}: Standard deviation of first pulse
  - Charge weighted standard deviation of pulse times relative to total time offset

9 inputs

- t_{last}: Relative time of last pulse
  - Relative to total time offset, calculated as the charge weighted mean time of all pulses
- $t_{20\%}$: Relative time of 20% charge
  - Relative to total time offset, calculated as the charge weighted mean time of all pulses
- $t_{50\%}$: Relative time of 50% charge
  - Relative to total time offset, calculated as the charge weighted mean time of all pulses
- t_{mean}: Mean time
  - Charge weighted mean time of all pulses relative to total time offset
- c_{500ns}: Charge at 500ns
  - Sum of charge after 500ns
- c_{100ns}: Charge at 100ns
  - Sum of charge after 100ns

Input pulses

- SplitInIceDSTPulses
- SplitInIceDSTPulsesTWCleaning6000ns
- (DNN framework performs an internal cleaning)

Training datasets

- 20904
- 21962
- 22020
- 22187

Reconstructed properties

Energy

- entry_energy: Leading muon energy at the detector entry
- bundle_energy_at_entry: Muon bundle energy at the detector entry
- muon_energy_first_mctree: Leading muon energy at surface
- bundle_energy_in_mctree: Muon bundle energy at surface

Network 1

Network 0: Muon bundle energy at surface (fast pre-cut)

Track geometry

- Length: Propagation length of muon in the ice
- LengthInDetector: Propagation length of muon in the detector
- center_pos_x: Closest x position of muon to center of the detector
- center_pos_y: Closest y position of muon to center of the detector
- center_pos_z: Closest z position of muon to center of the detector
- center_pos_t: Time of closest approach to the center of the detector
- entry_pos_x: x position of muon at the detector entry
- entry_pos_y: y position of muon at the detector entry
- entry_pos_z: z position of muon at the detector entry
- entry_pos_t: Time of muon at the detector entry

Network 2

Direction

- zenith: Zenith angle of muon
- azimuth: Azimuth angle of muon

Network 3

Level5: quality cuts

containment cuts	>	<
length in detector	1000 m	2000 m
entry pos x, y	-750 m	750 m
entry pos z	-500 m	750 m
center pos x, y	-550 m	550 m
center pos z	-650 m	650 m

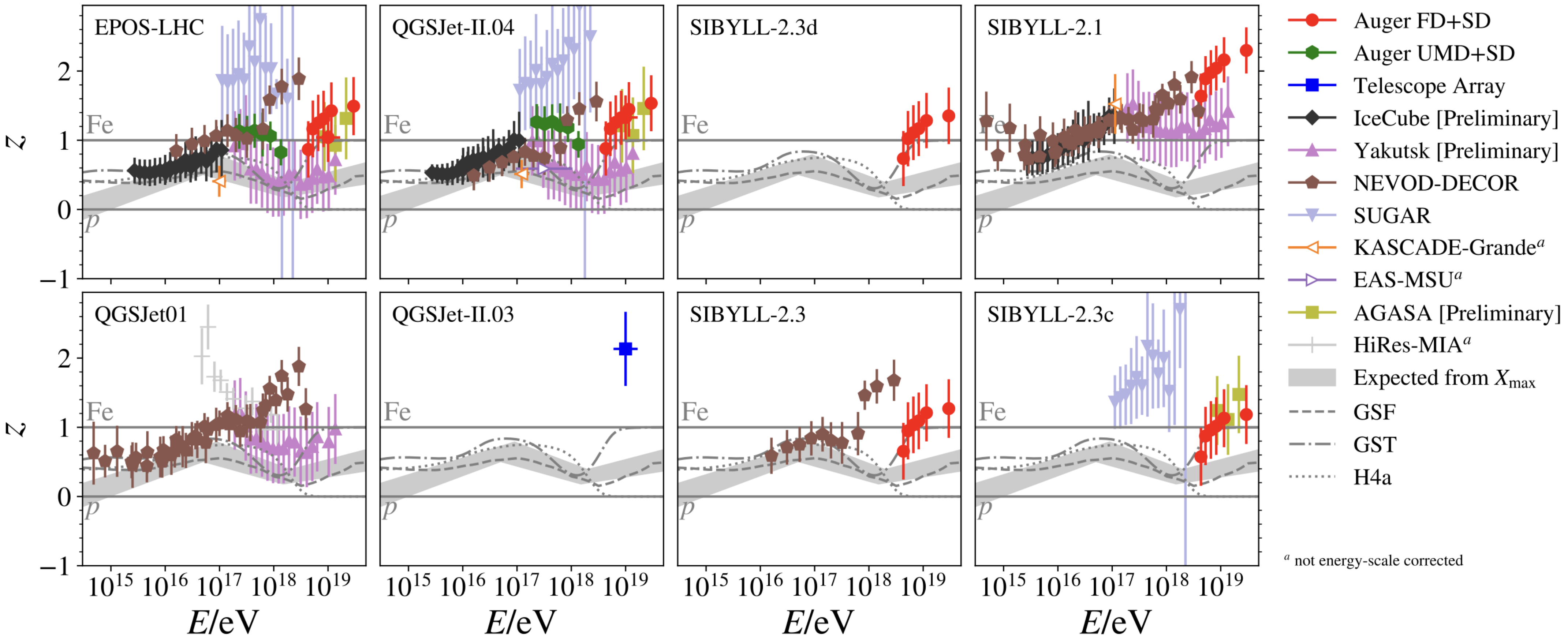
neutrino cuts	>	<
cos(zenith)	0.2	
length	5000 m	15000 m

uncertainty cuts	<
bundle energy at entry	0.9 log10(GeV)
bundle energy at surface	2.0 log10(GeV)
zenith	0.1 rad
azimuth	0.2 rad
entry pos x , y, z	42 m
center pos x, y, z	50 m
entry pos time	200 ns
center pos time	600 ns
length in detector	160 m
length	2000 m

"muon number"

The Muon Puzzle

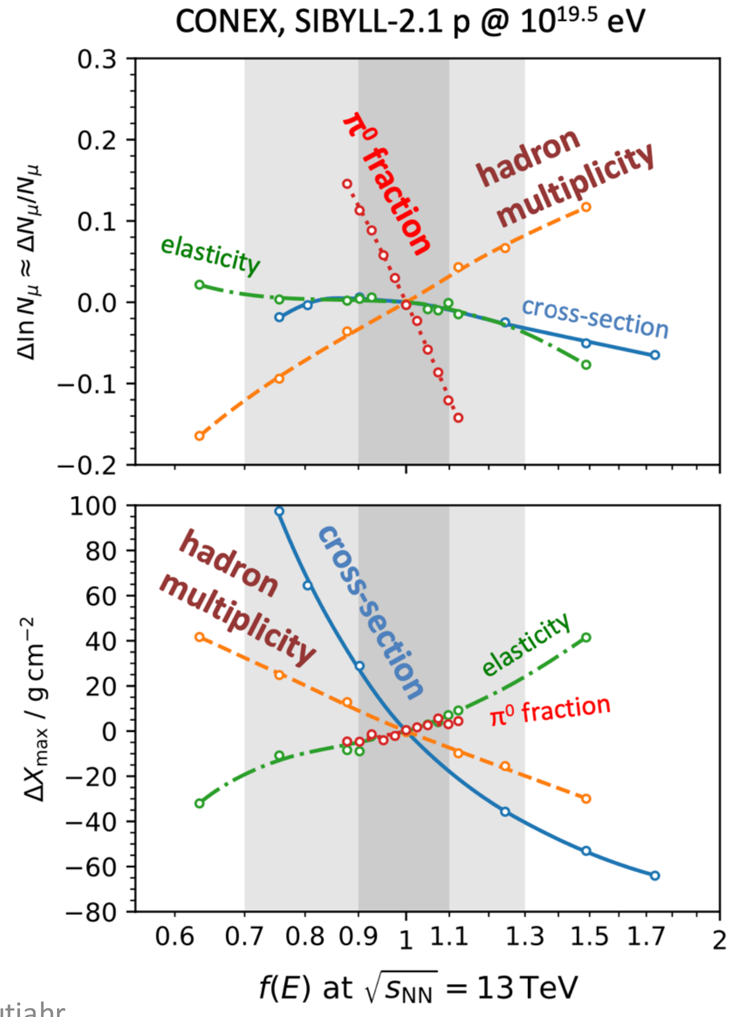
$$z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_p}{\ln\langle N_\mu \rangle_{\mathrm{Fe}} - \ln\langle N_\mu \rangle_p}$$



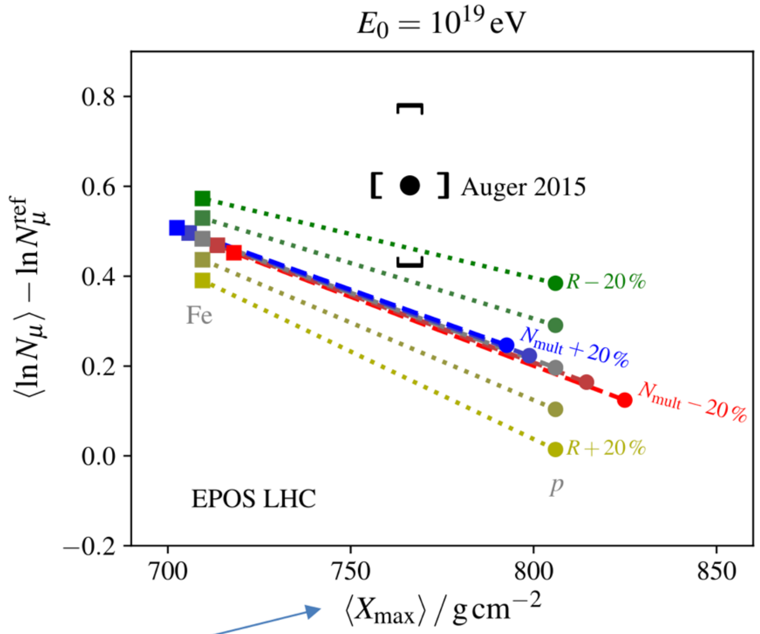
Arxiv: 2108.08341

Possible Solutions

R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026



S. Baur, HD, M. Perlin, T. Pierog, R. Ulrich, K. Werner, arXiv:1902.09265



$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

- Only changes to R can solve muon puzzle
- Small changes have large effect, R needs to be known to about 5 %

Slide taken from Hans Dembinski