

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

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July XX, 2025

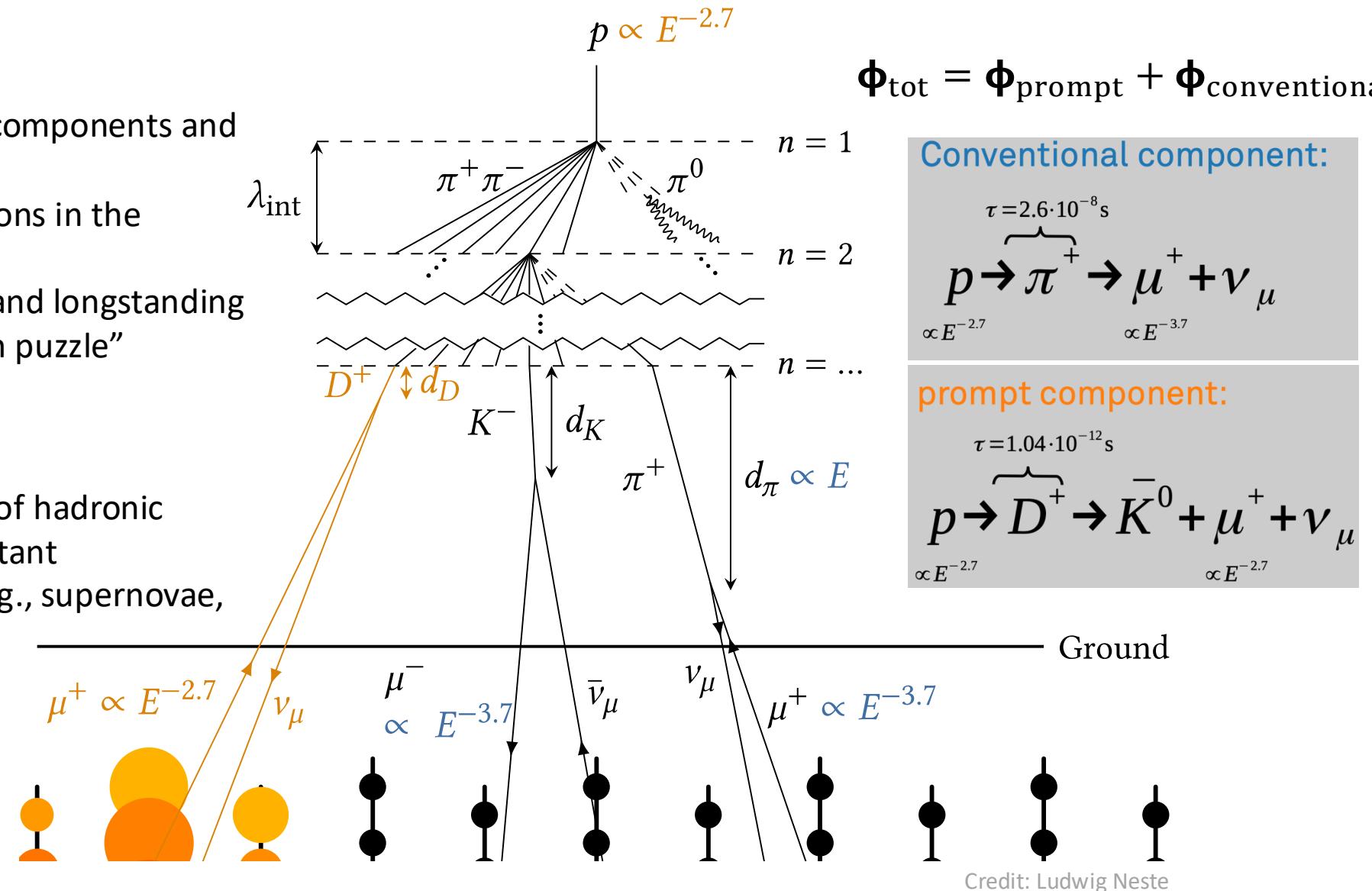
Introduction

Motivation

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

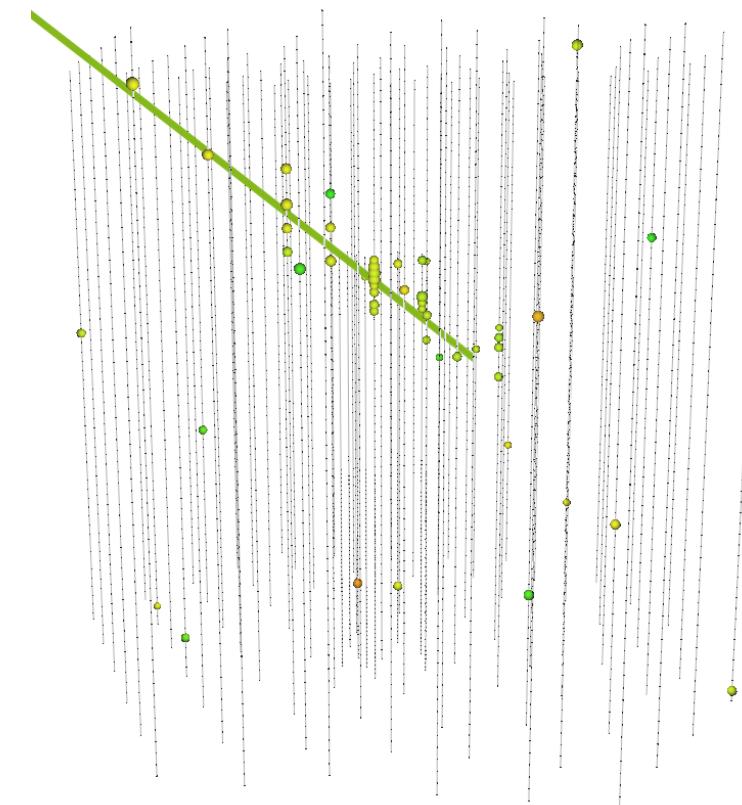
Long term

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



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

Unfolding in a nutshell

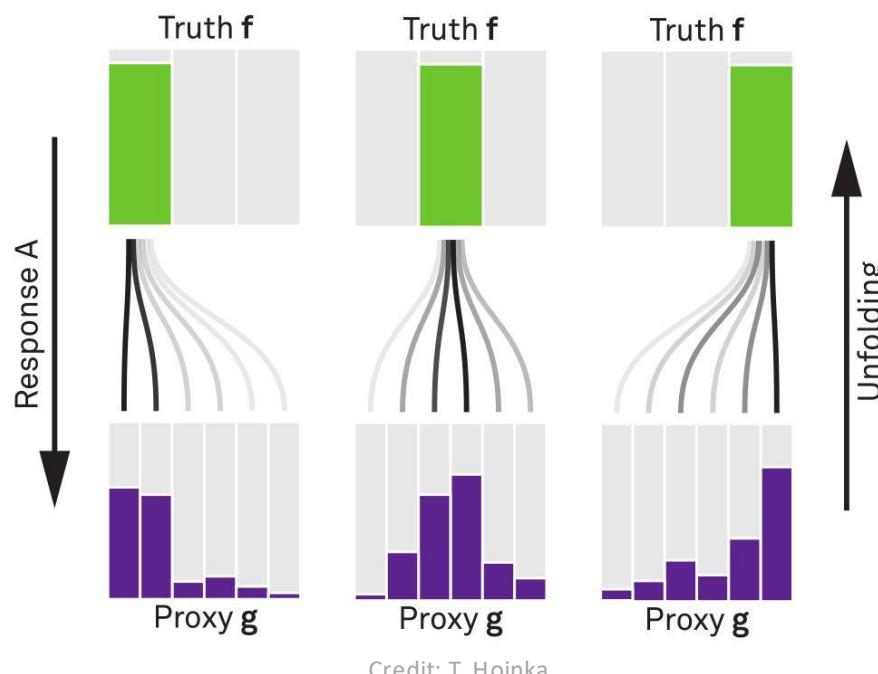
measured proxy

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

detector response

background

true energy distribution



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1. discretized form: $\vec{g} = A\vec{f} \leftrightarrow \vec{f} = A^{-1}\vec{g}$

2. maximum likelihood method:

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

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

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

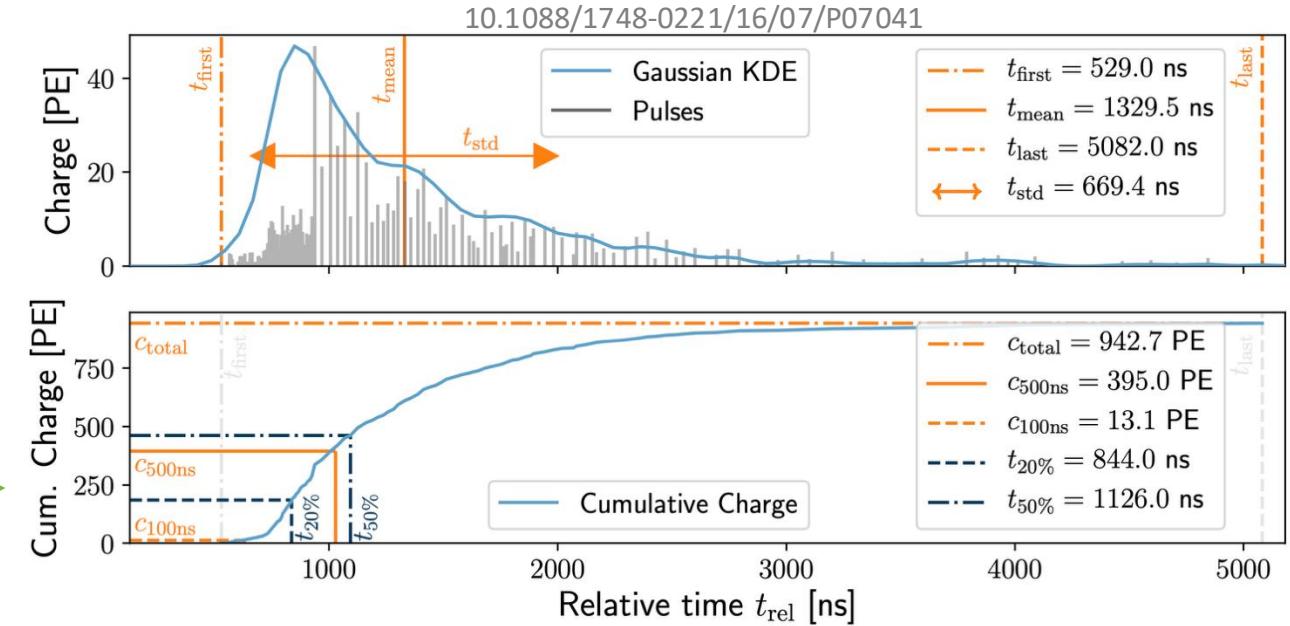
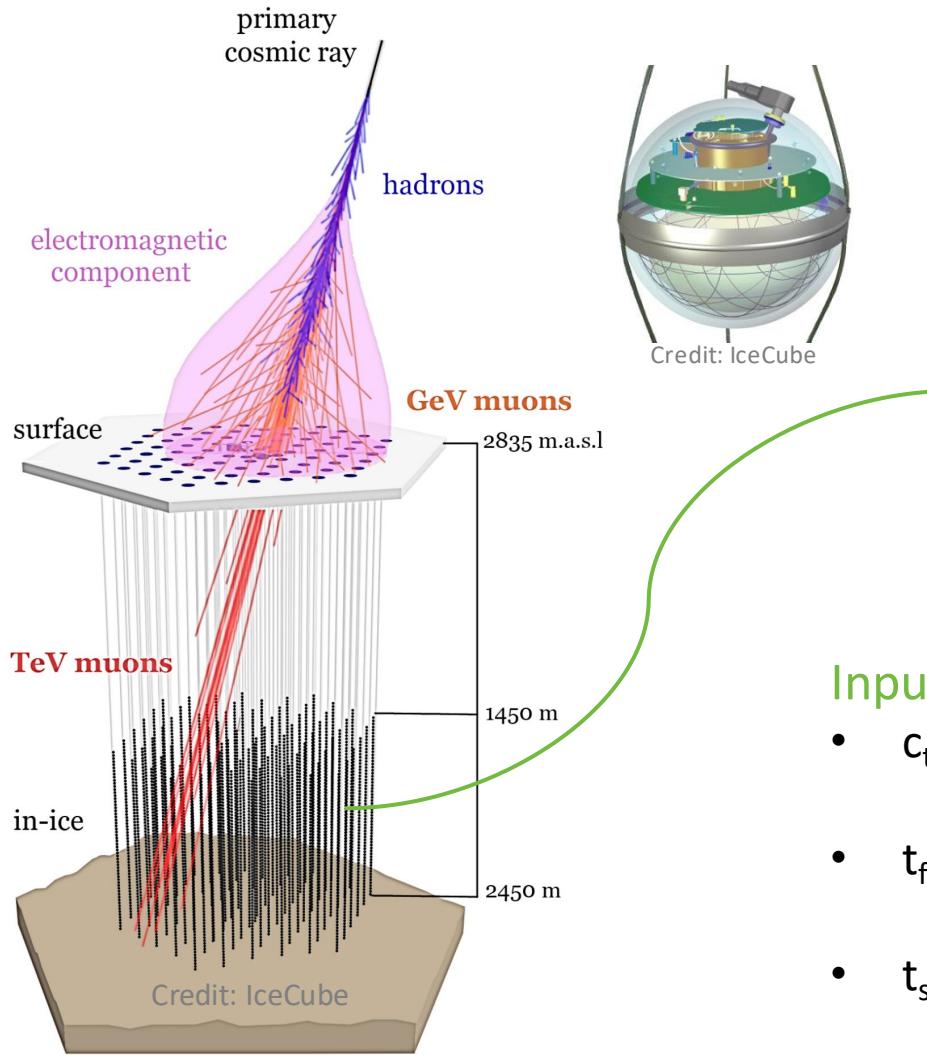
3. Tikhonov regularization:

$$t(\vec{f}) = -\frac{1}{2} (\vec{C}\vec{f})^T (\tau_1)^{-1} (\vec{C}\vec{f})$$



funfolding
by M. Börner

Machine Learning Reconstructions



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

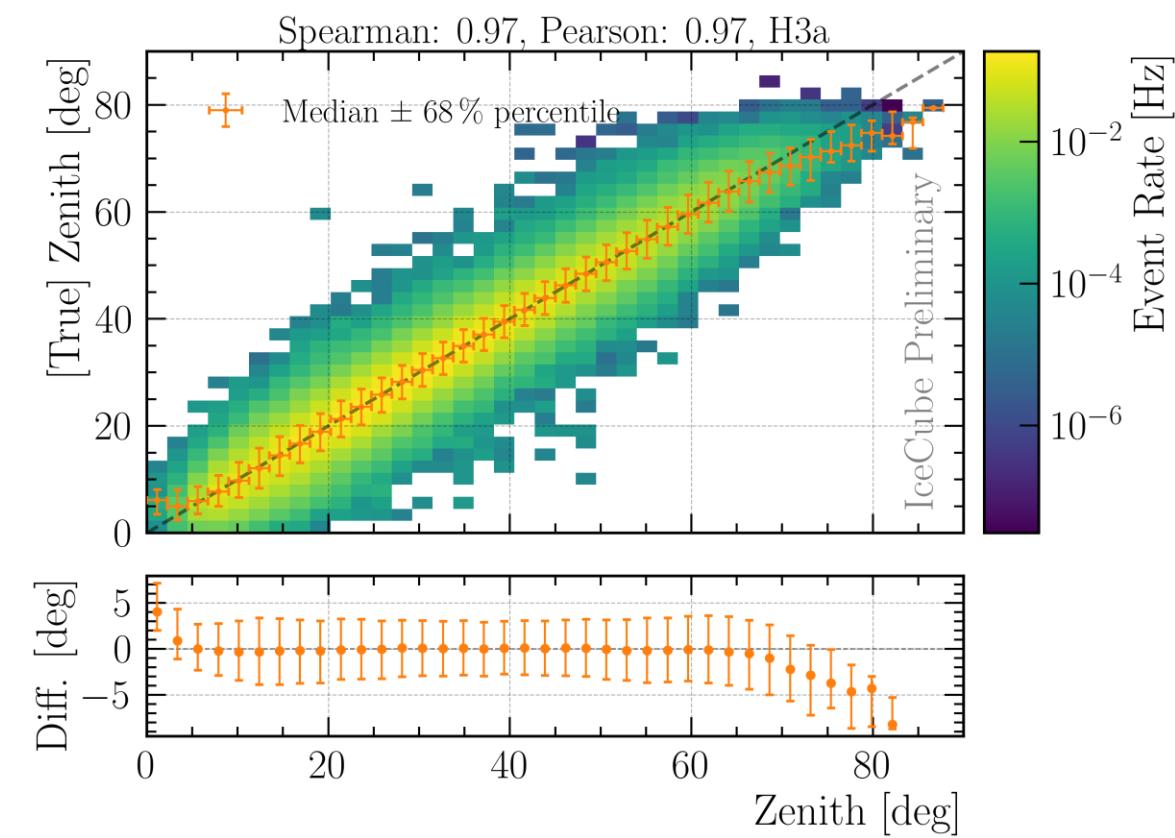
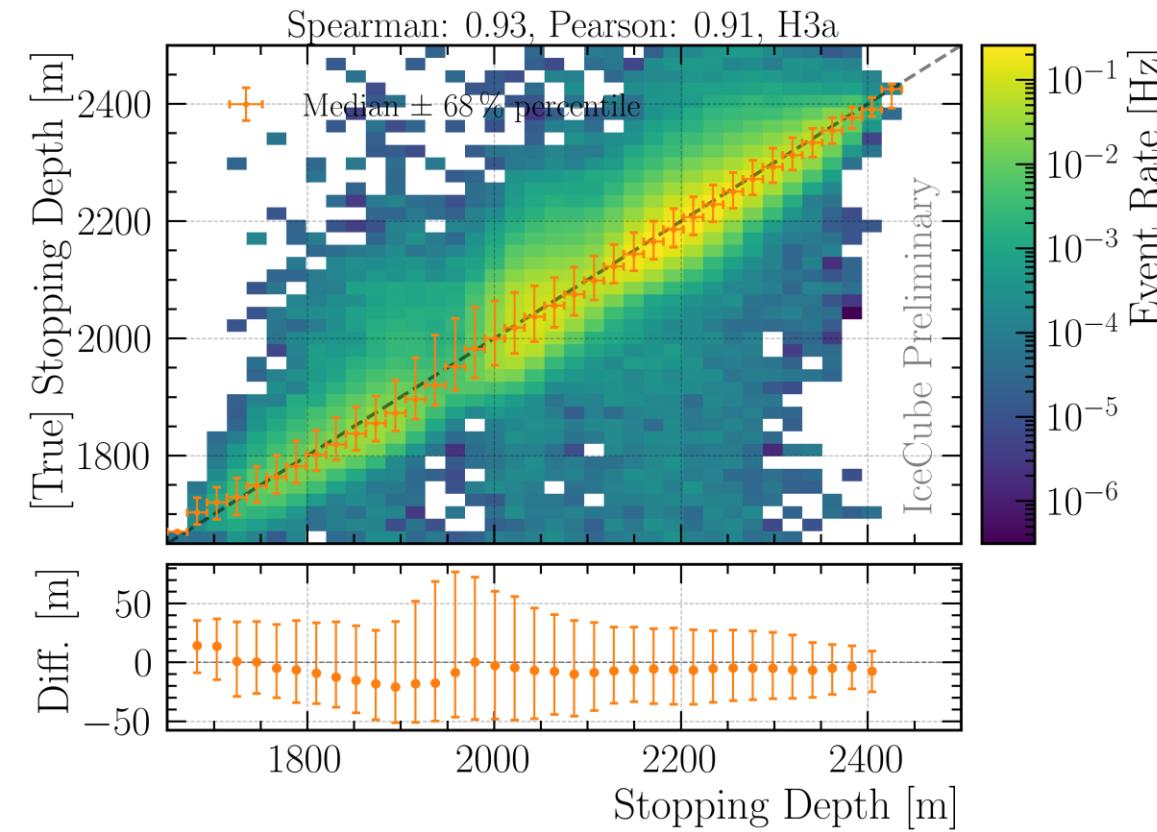
Outputs

- 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

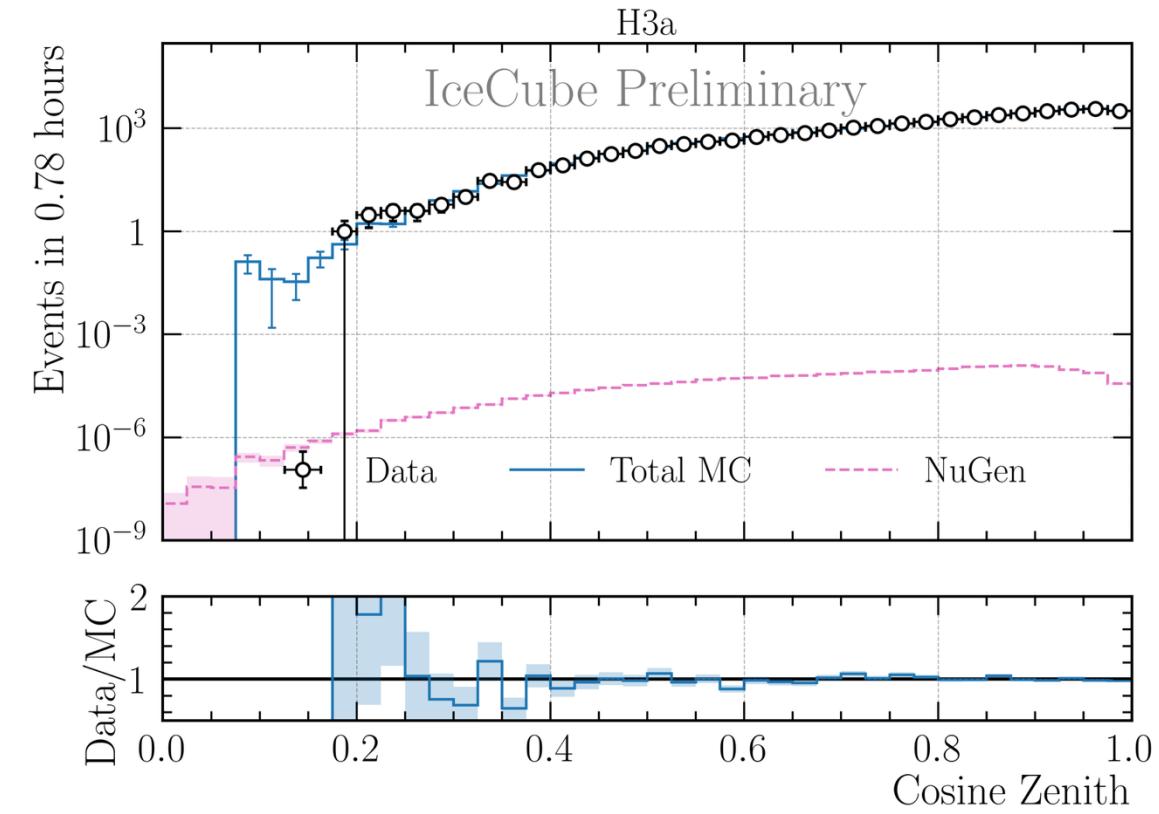
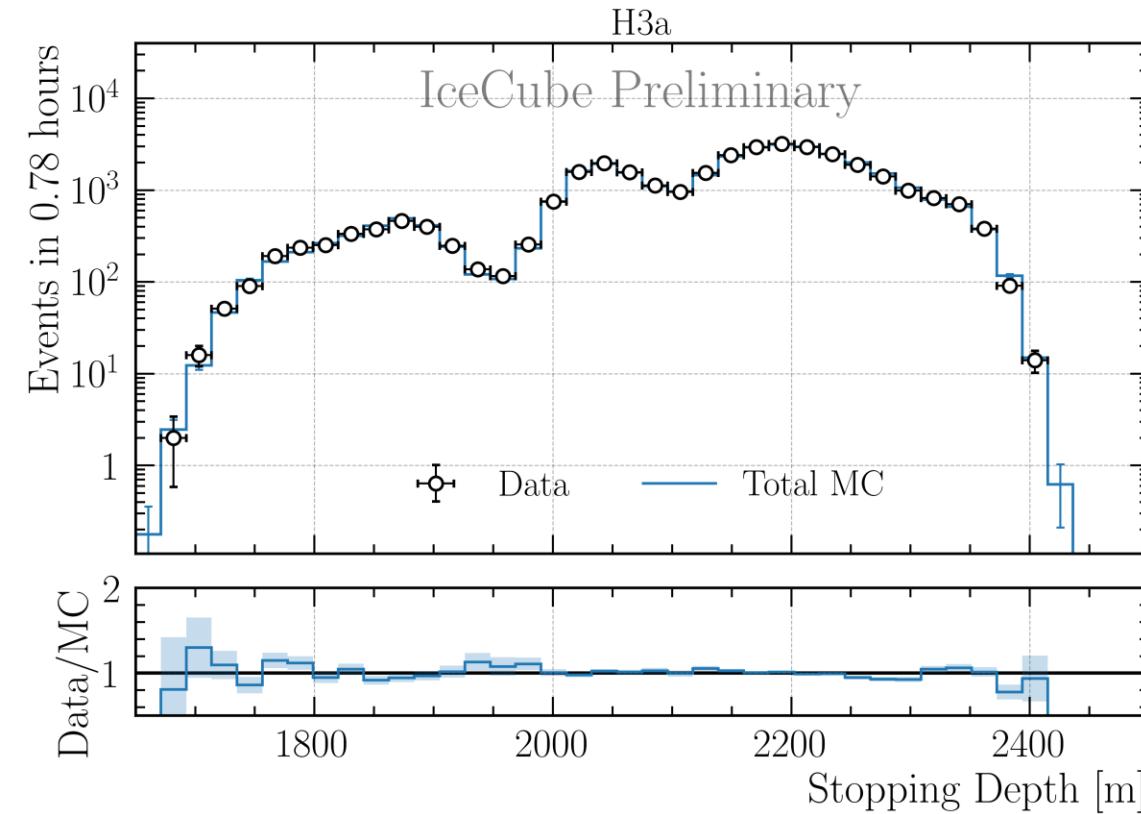


Data—MC: Stopping Muons

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

Neutrino weighting:
 $SPL: n = 1.8, \gamma = 2.52$

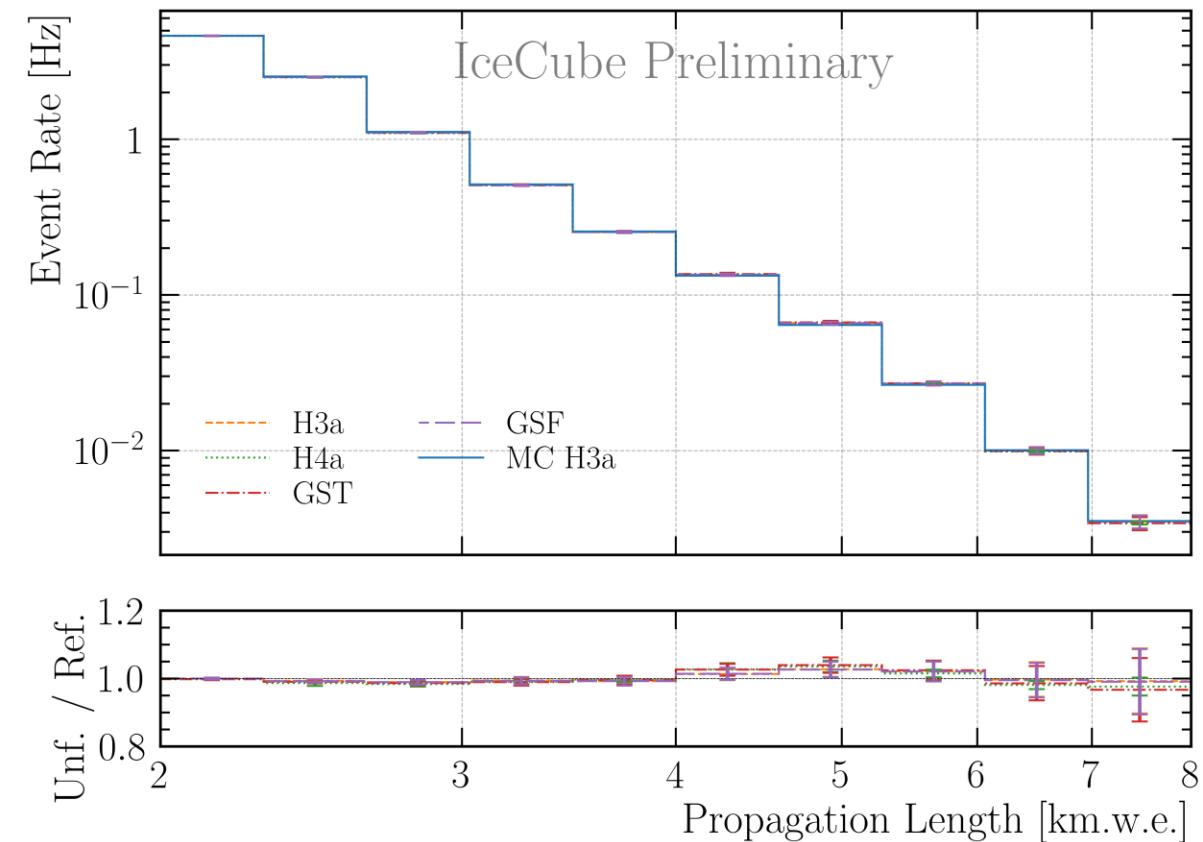
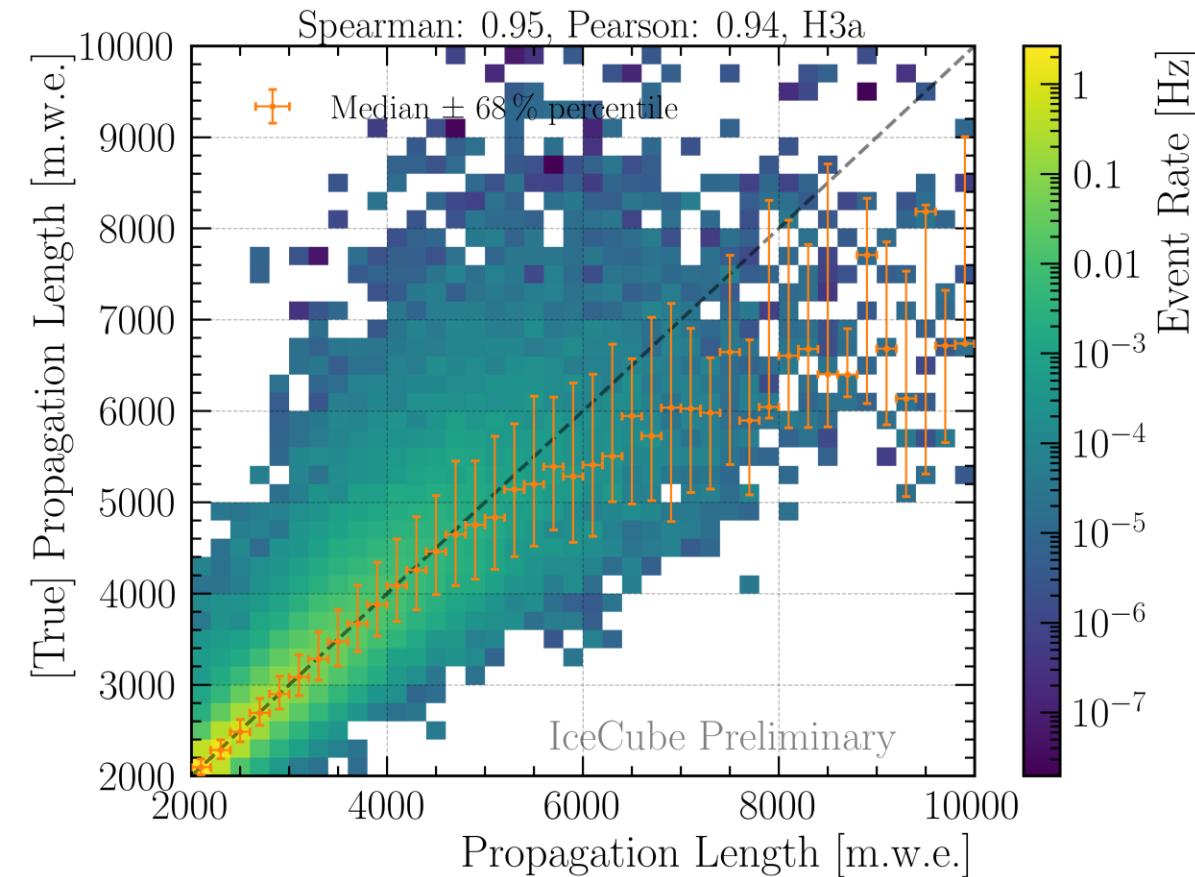
IceCube Collaboration PoS ICRC2023 1064



Correlation and Robustness Test: Stopping Muons

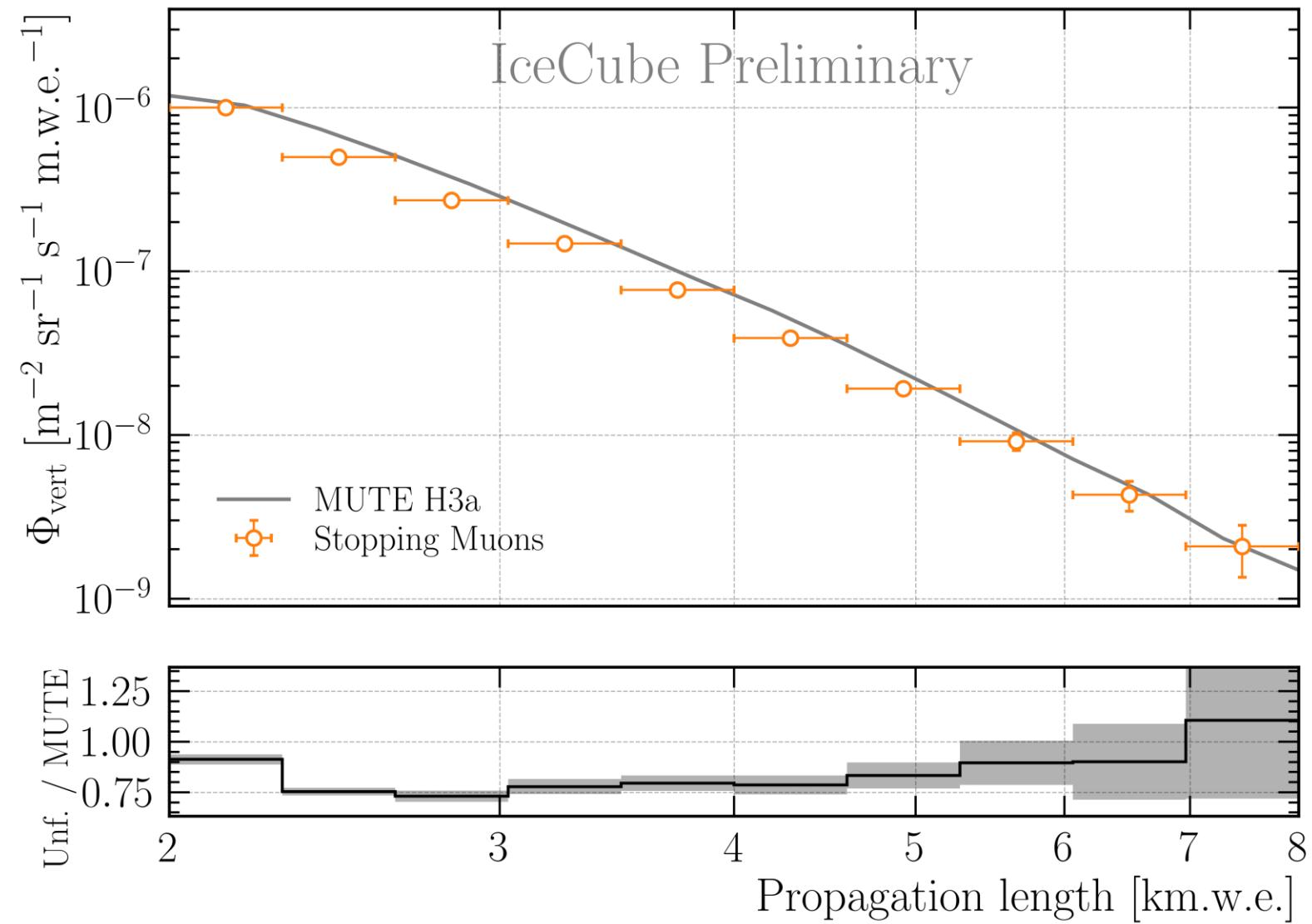
➤ Strong correlation between proxy and target

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



Depth Intensity Unfolding

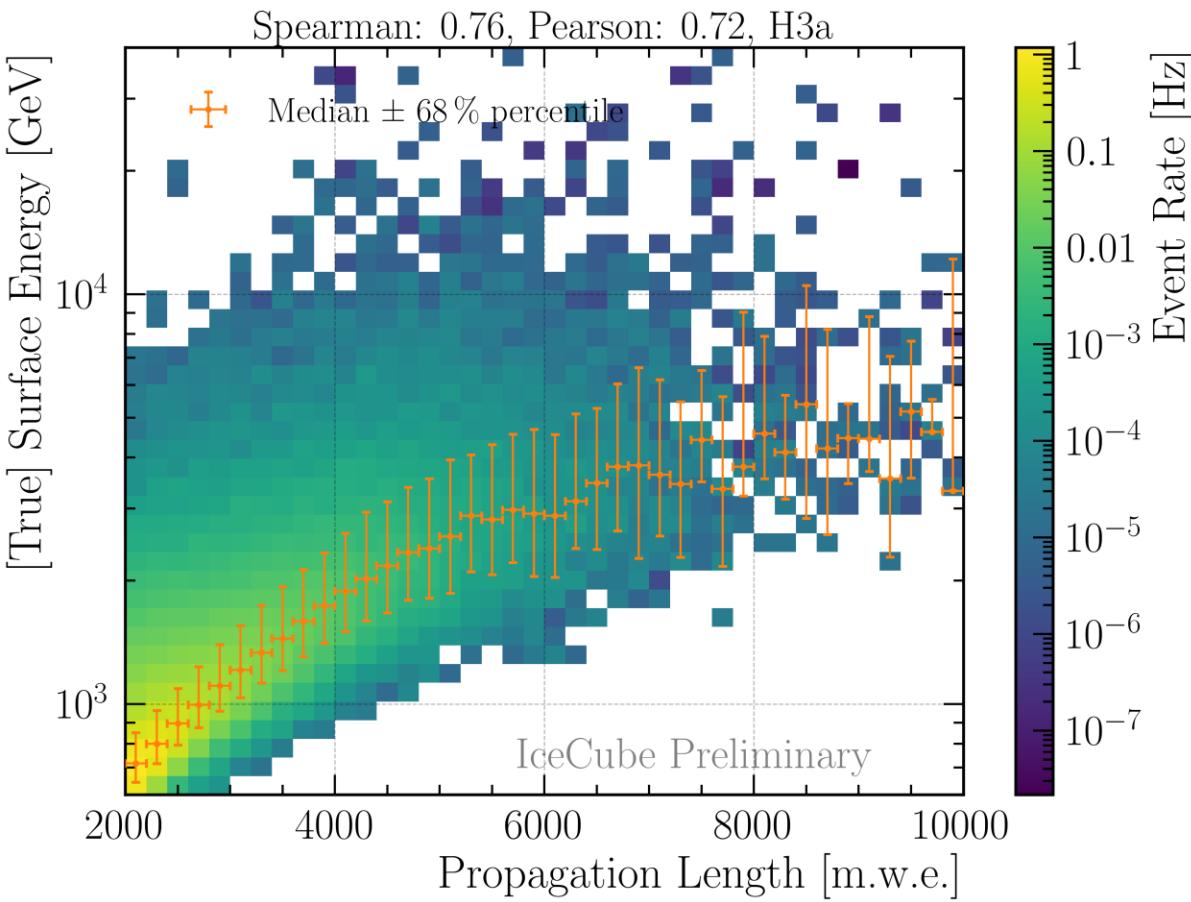
- 47 min IceCube data
- 32943 events
- Comparison to MUTE¹
- Up to 25 % below prediction at 2.5 – 5.5 km.w.e.
- Mismodelling in energy losses?



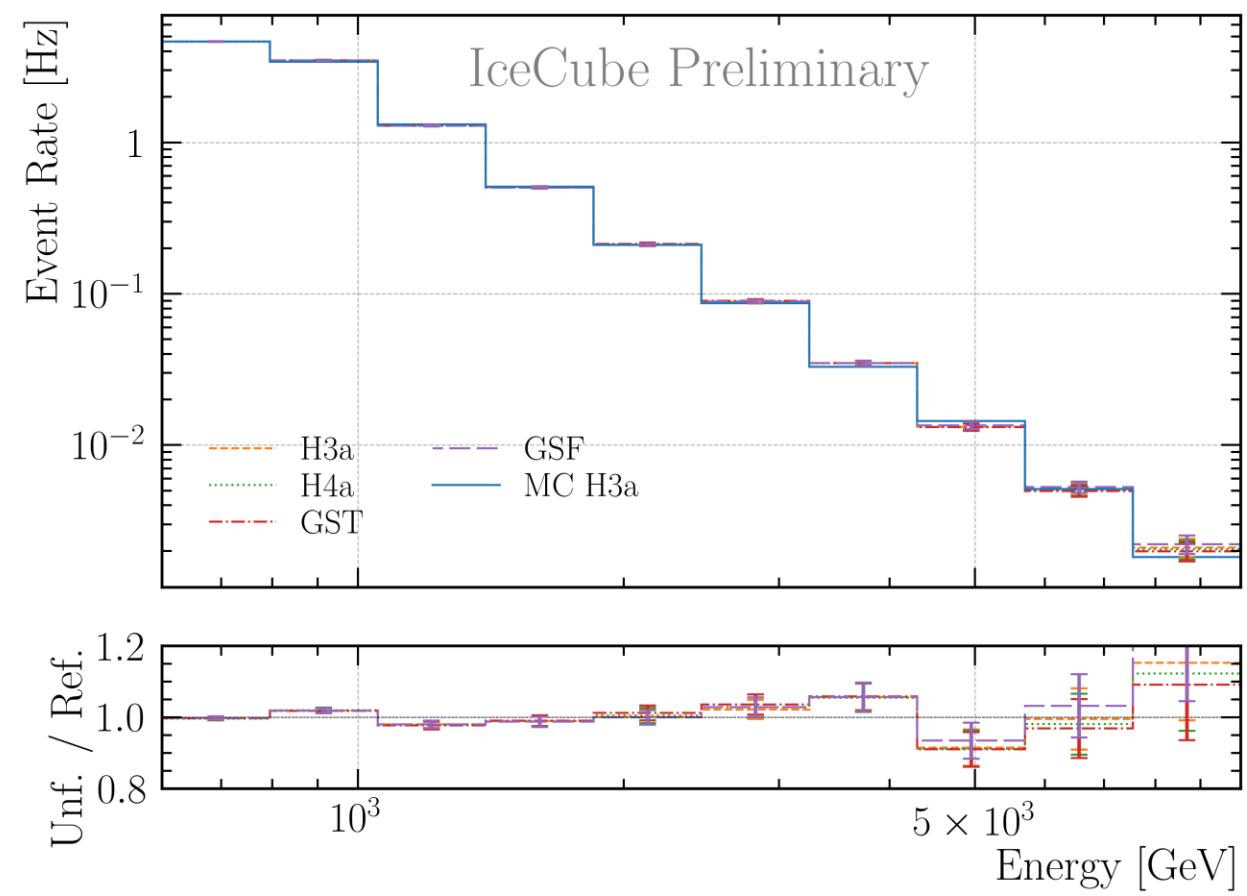
Muon Flux Unfolding

Correlation and Robustness Test: Stopping Muons

- Correlation between proxy and target

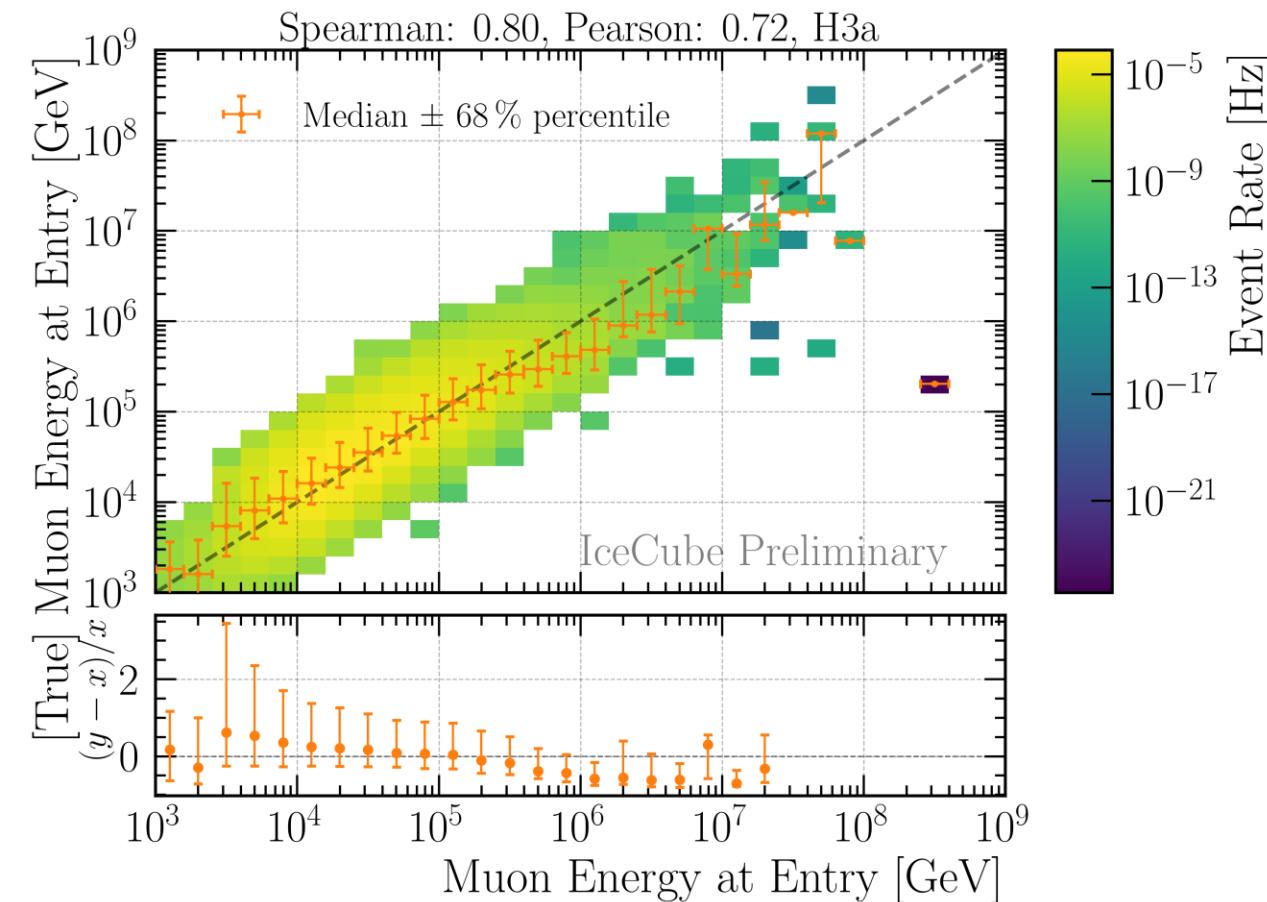


- Build unfolding matrix on H3a, H4a, GST & GSF
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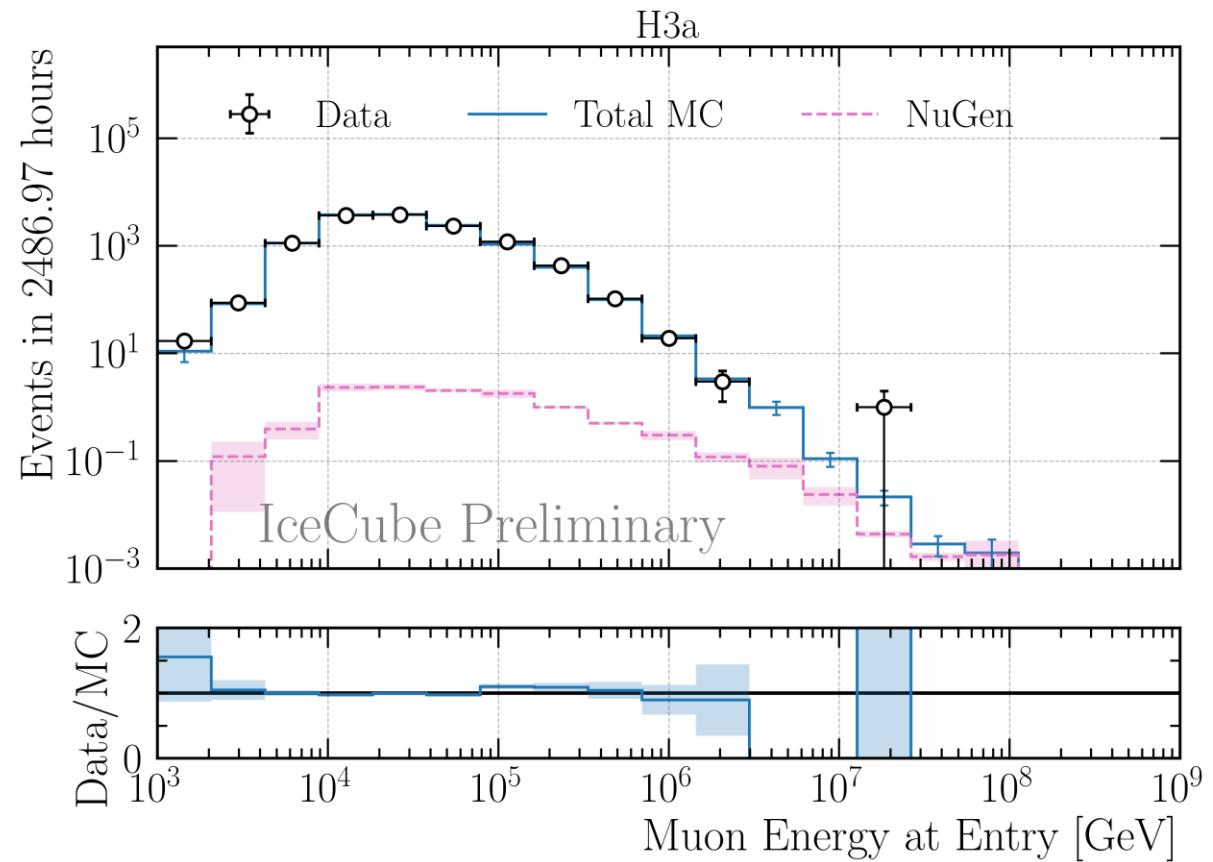


Reconstruction and Data—MC: Leading Muons

- Good reconstruction of leading muon energy → proxy

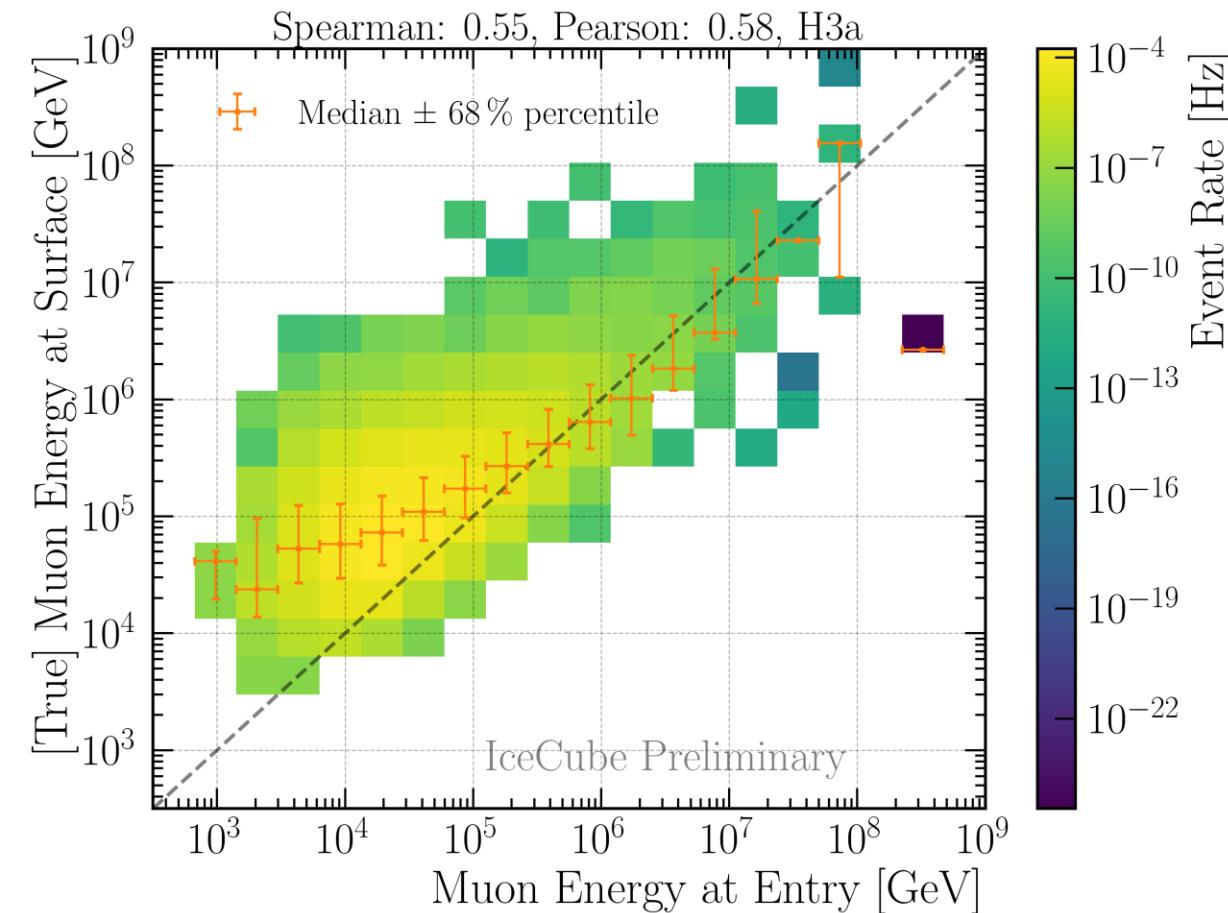


- Good data—MC agreement
- Global offset → upscale MC by 12%

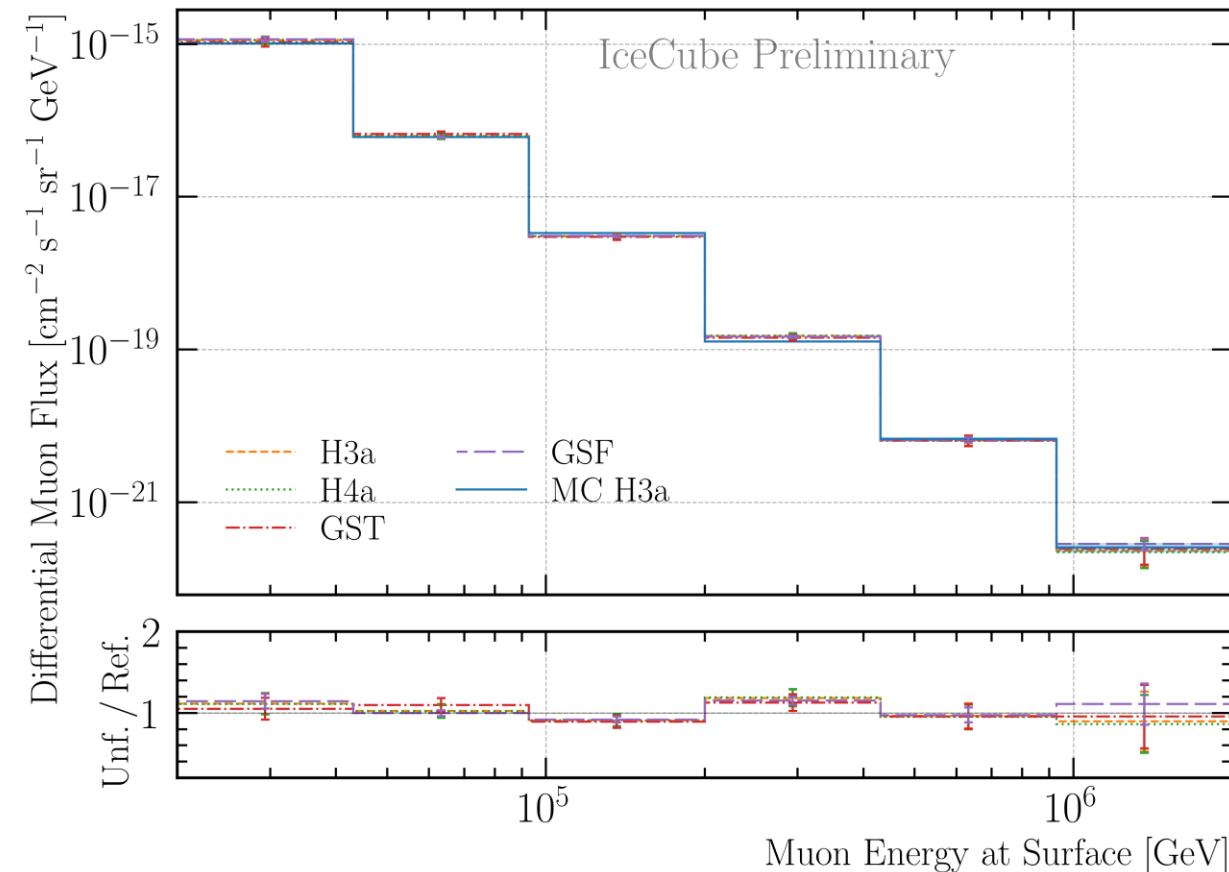


Correlation and Robustness Test: Leading Muons

- Correlation between proxy and target



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



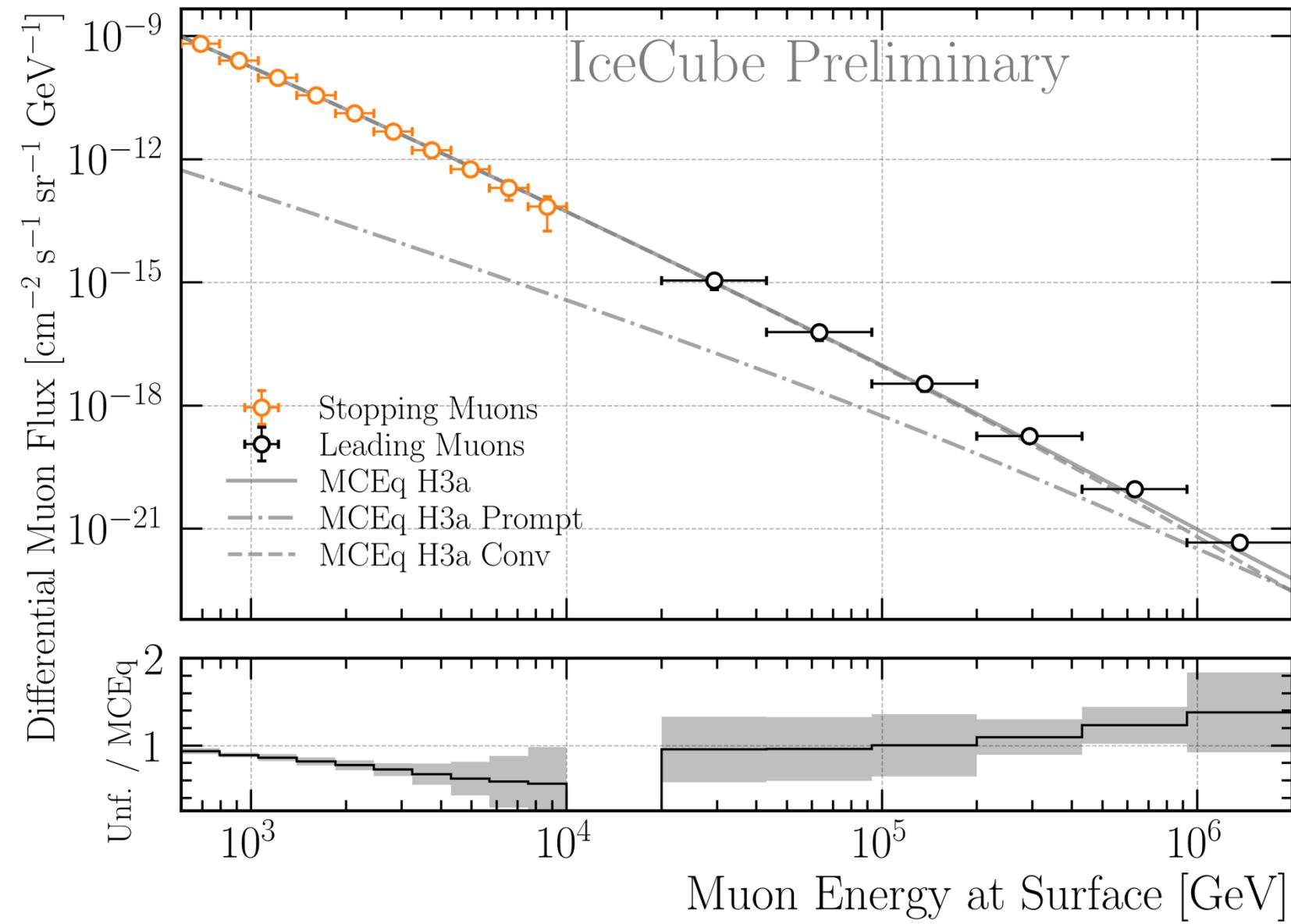
Muon Flux Unfolding

Stopping muons

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

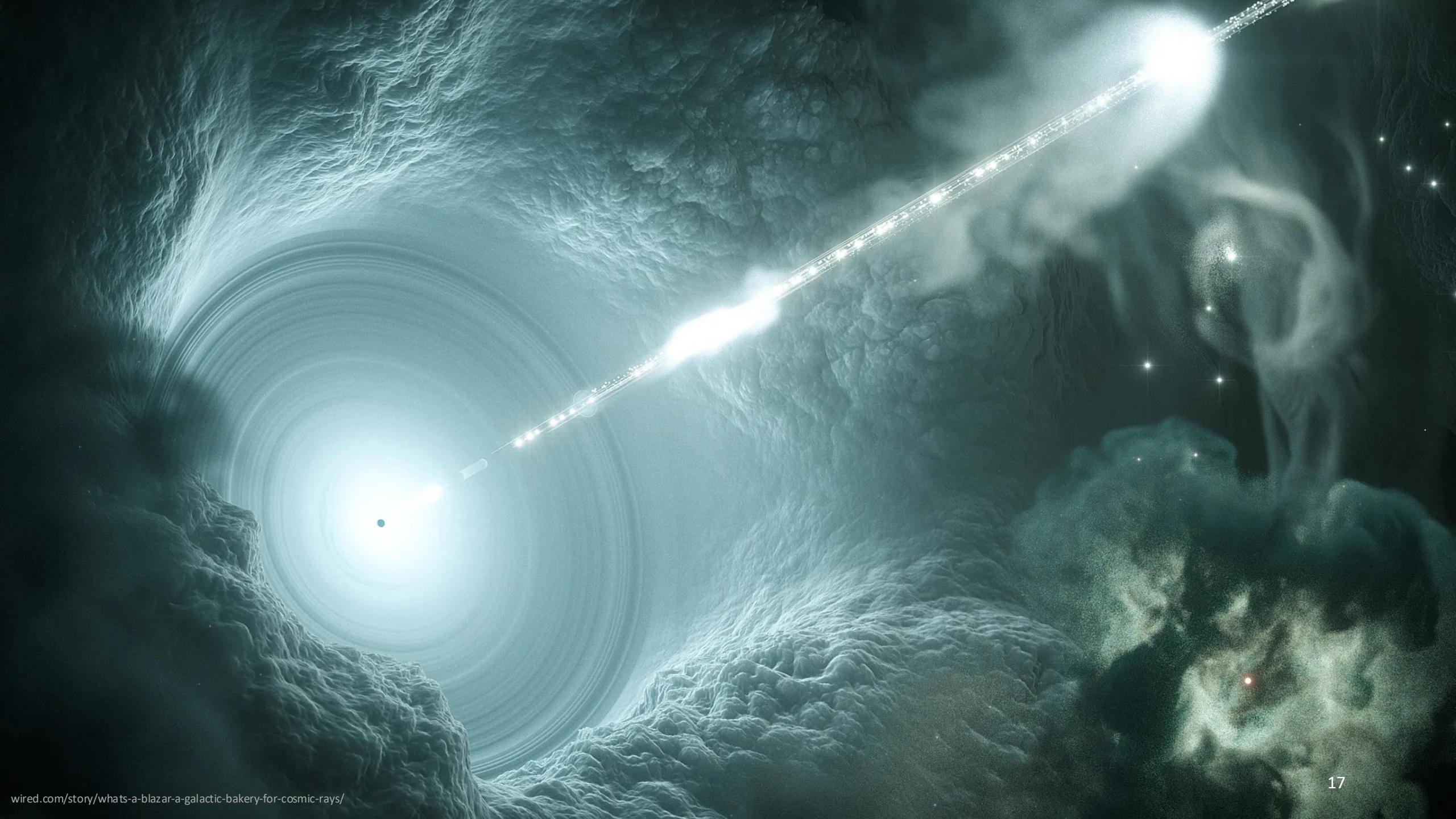
Leading muons

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

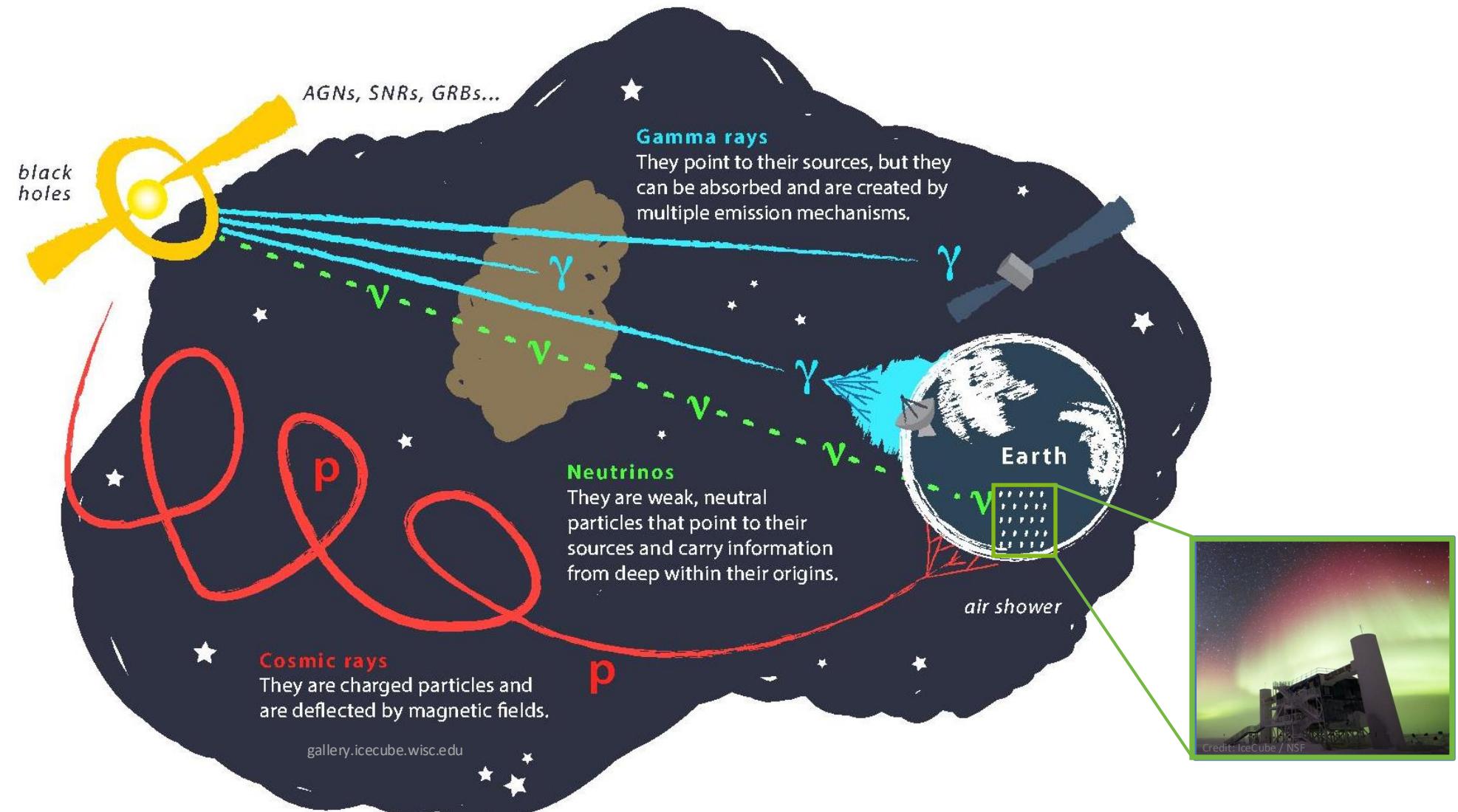


Conclusion & Outlook

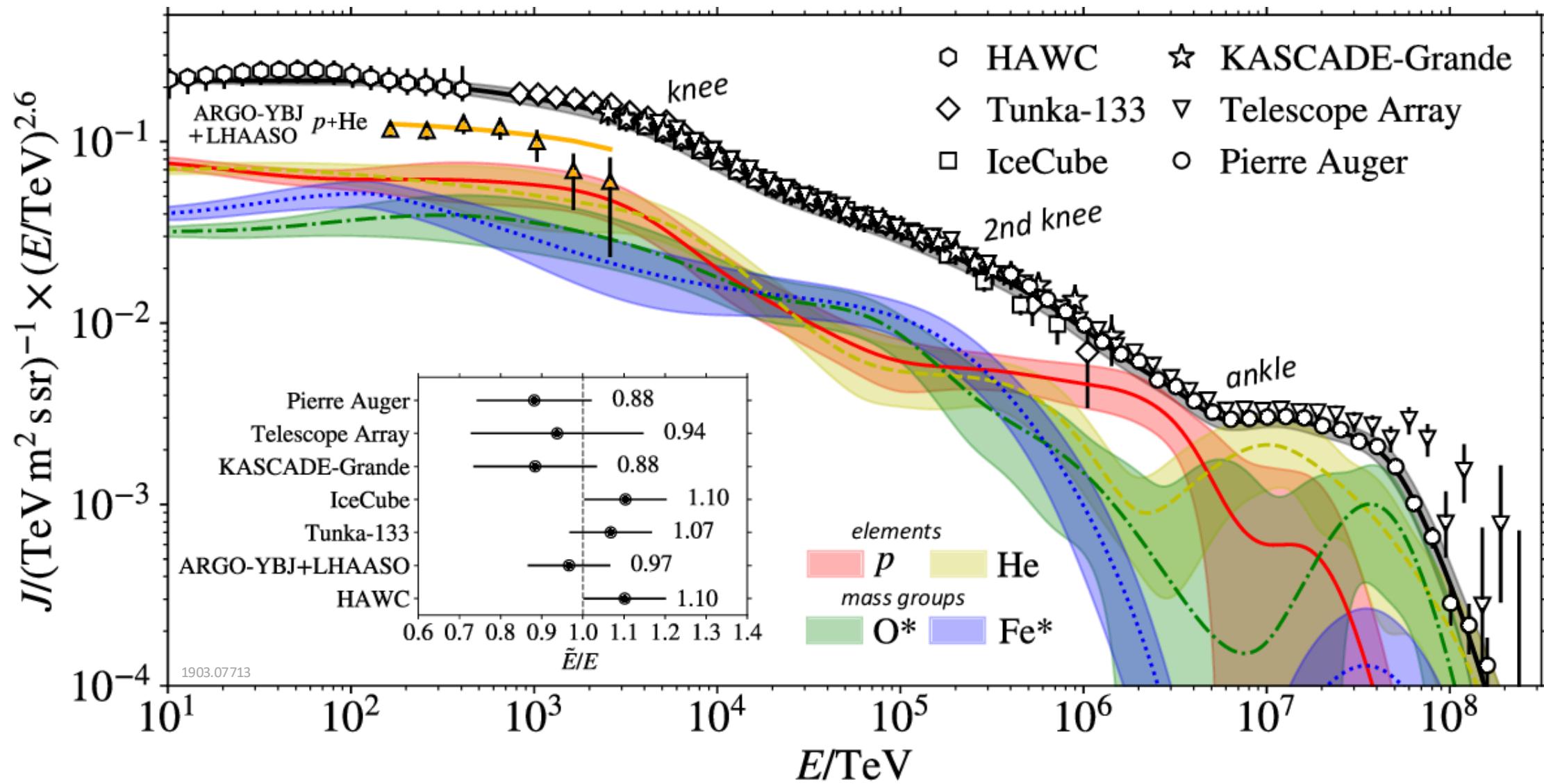
- DNN-based reconstructions have been performed
 - Stopping muon selection
 - Leading muon selection
 - Good Data—MC agreement
- Depth intensity unfolded using 47 min of IceCube data
 - Undershoots MUTE prediction up to 5.5 km.w.e.
- Muon flux at surface unfolded using stopping muons and 2487 h of leading 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 \sim 2 PeV



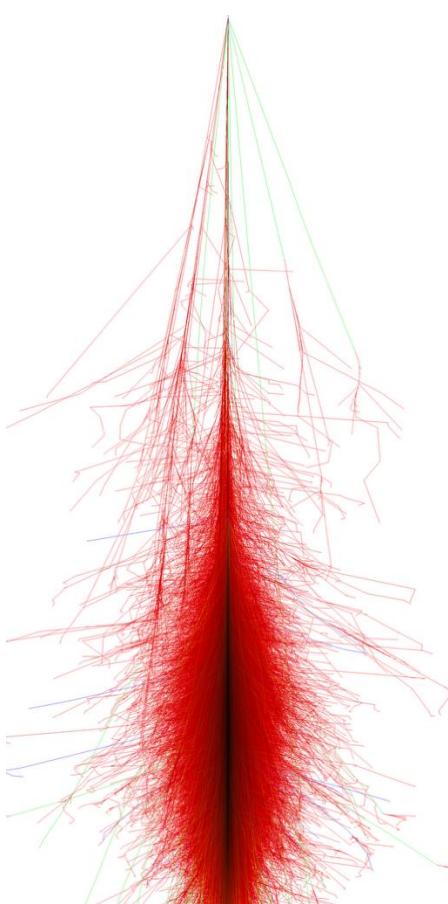
Astroparticle physics



Cosmic ray flux

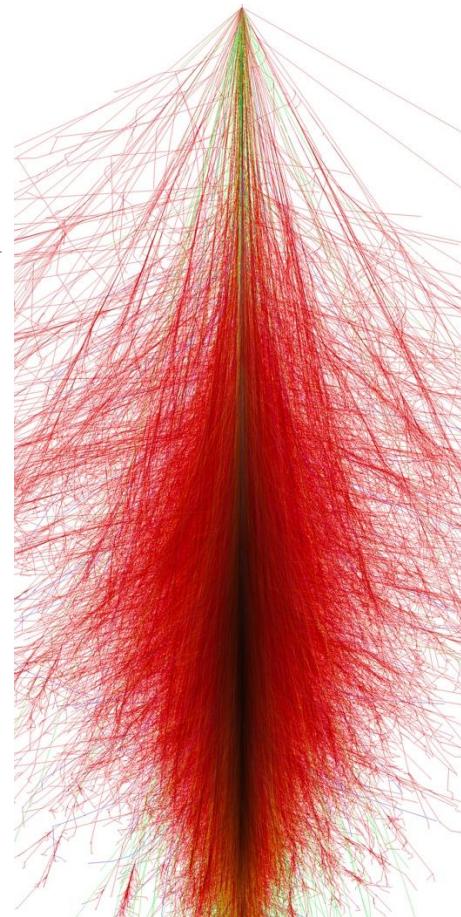


Air shower – 10 TeV

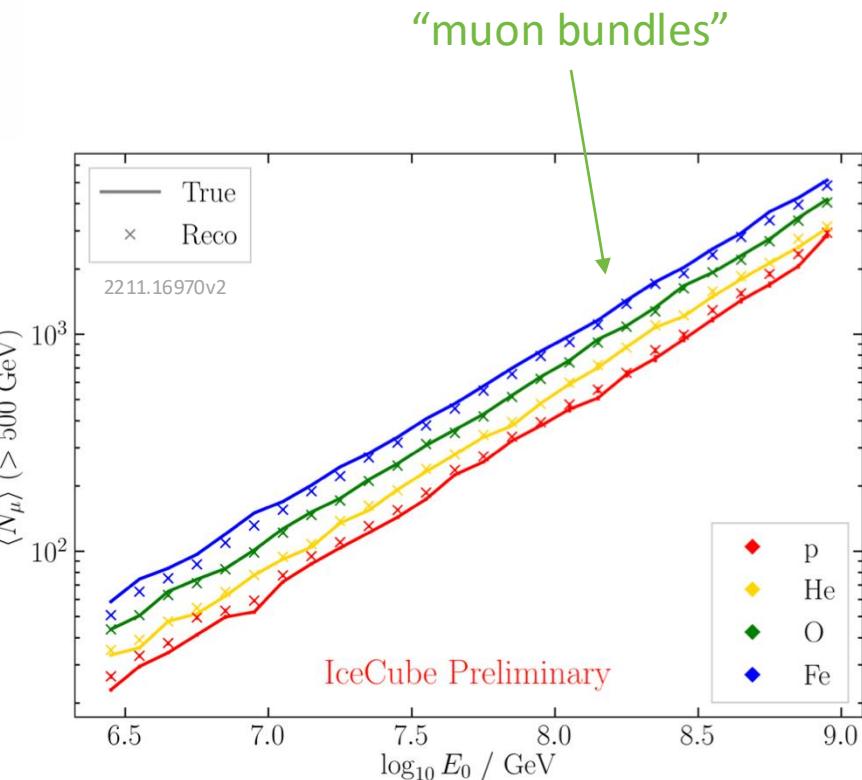
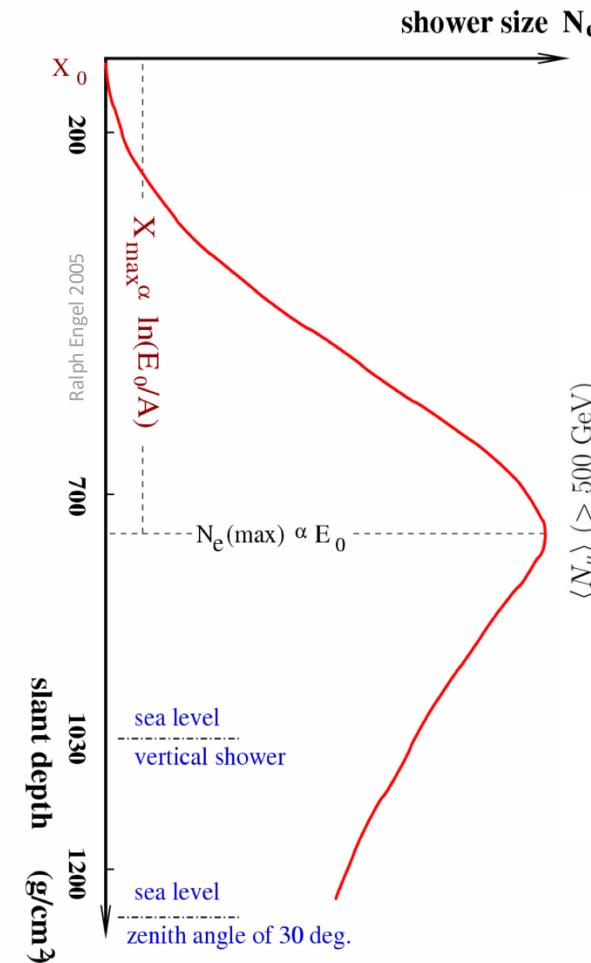


Proton

zeuthen.desy.de



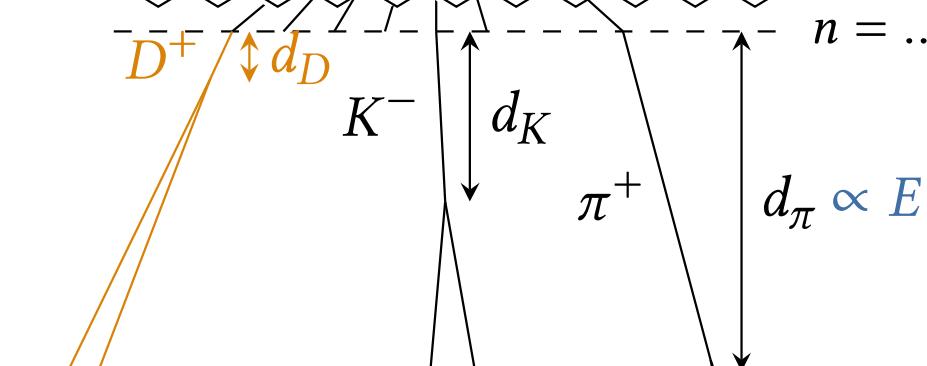
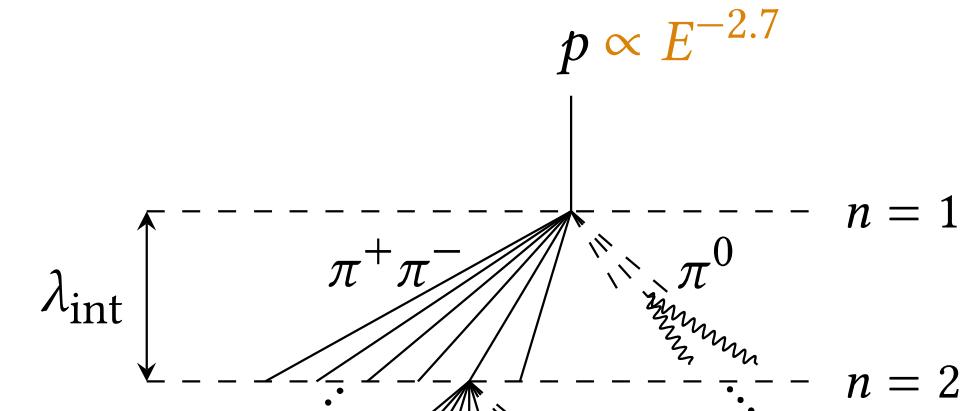
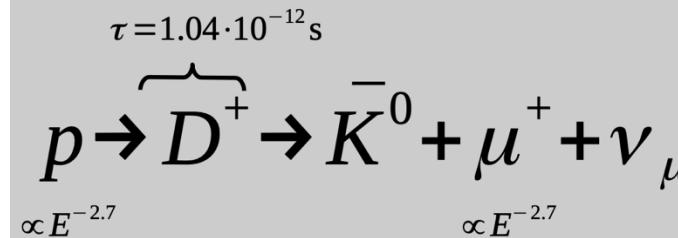
Iron



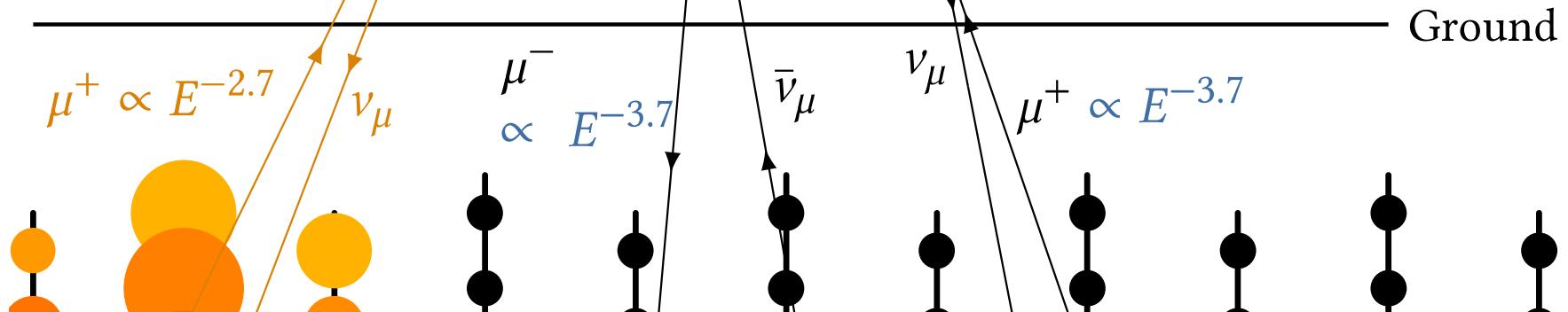
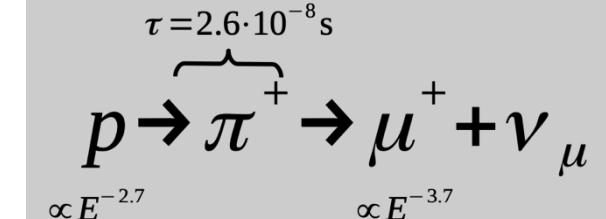
Muon flux

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

prompt component:

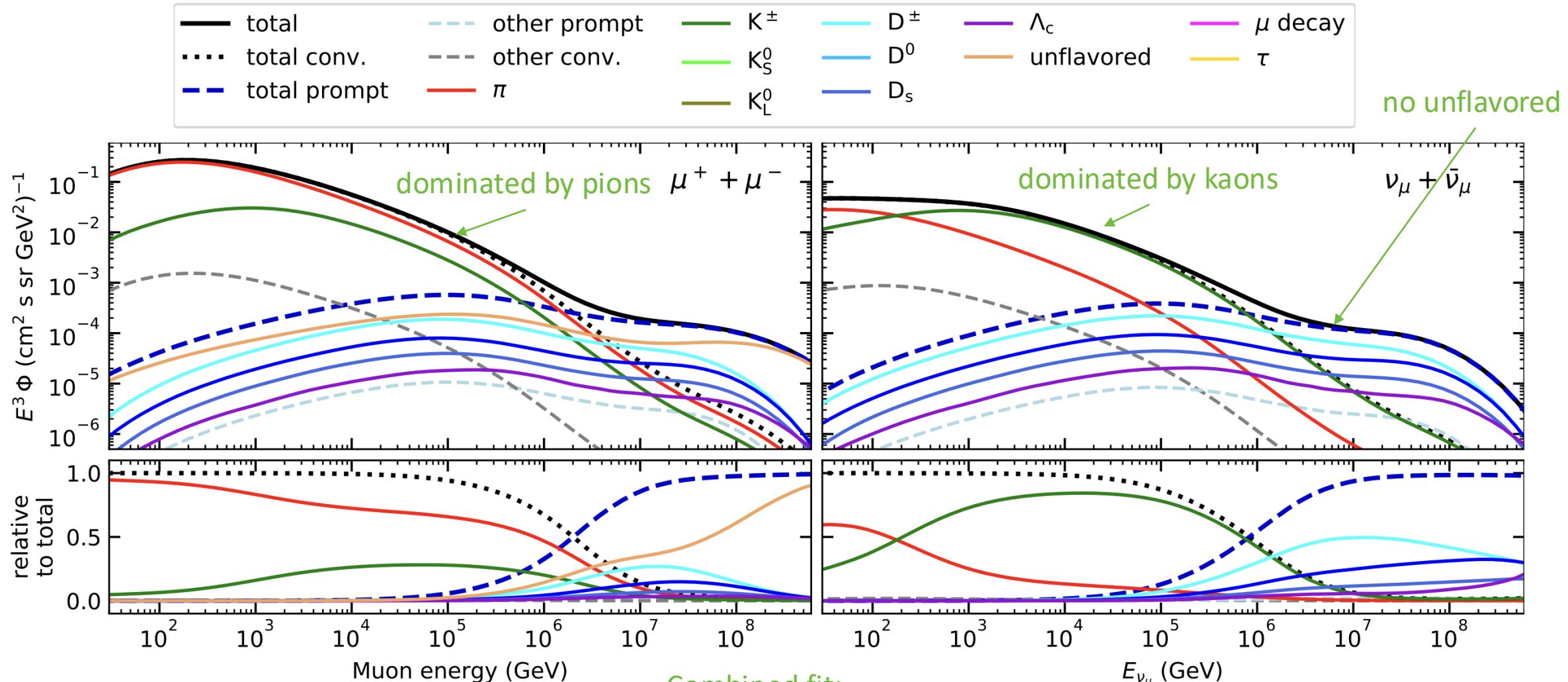


Conventional component:



Prompt atmospheric muons and neutrinos

10.1103/PhysRevD.100.103018



Combined fit:

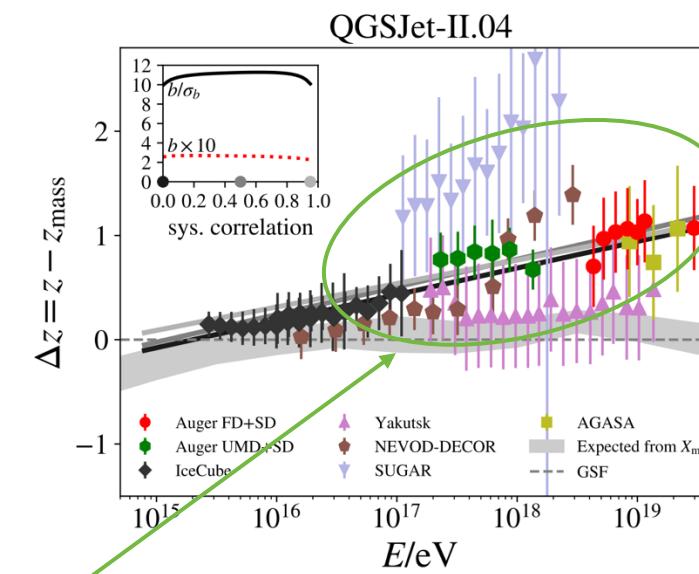
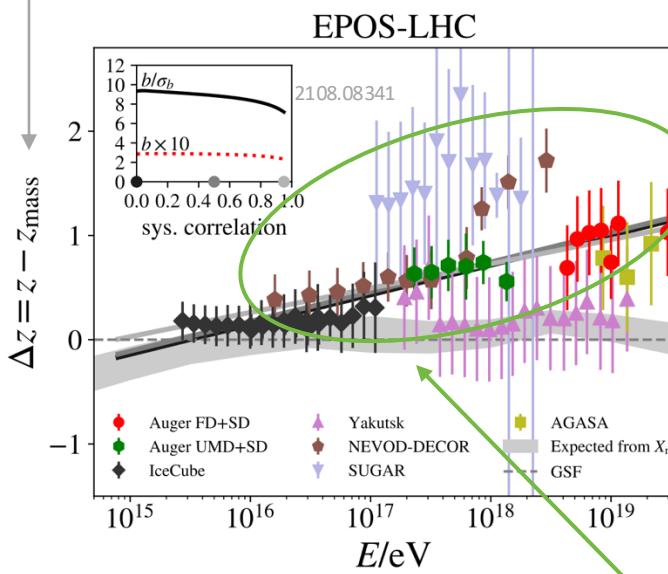
- handle on pion/kaon ratio
- handle on charmed mesons

Muon puzzle and model uncertainties

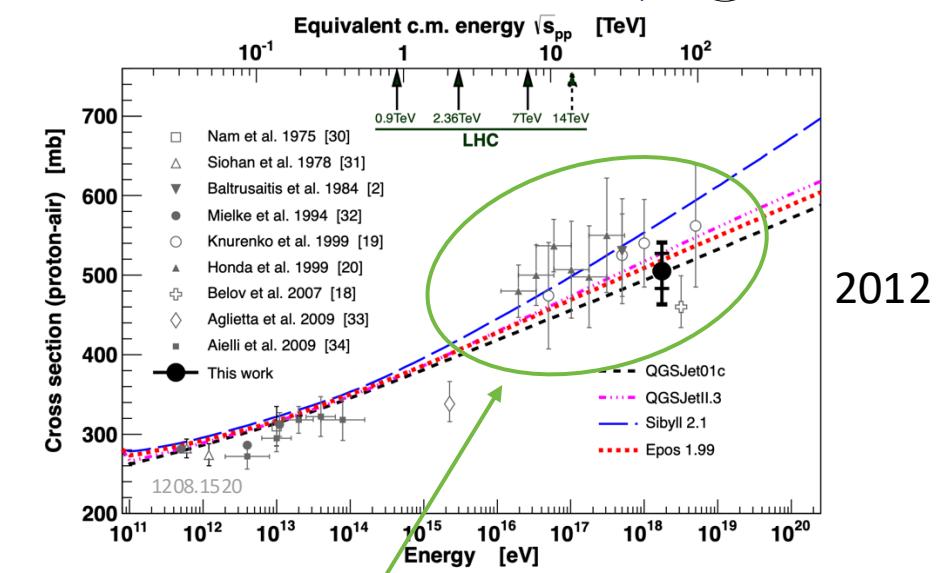
"muon number"

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

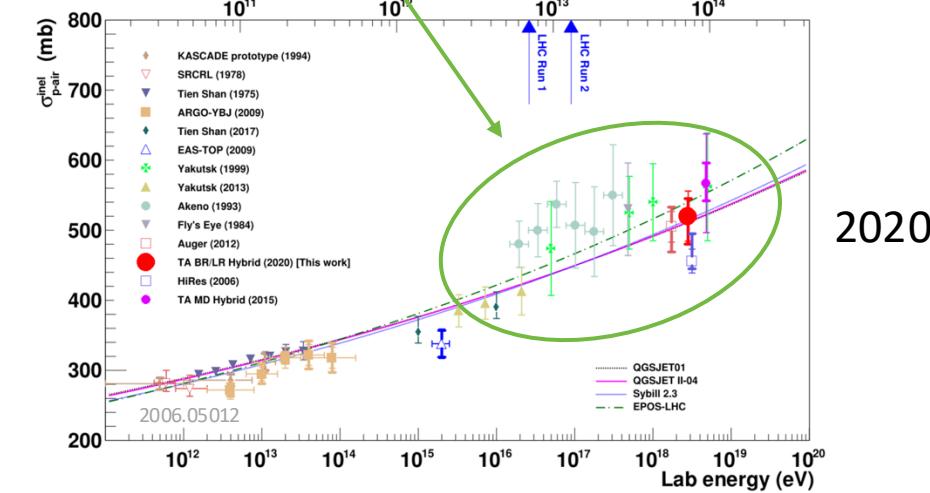
Expected z
("muon number")

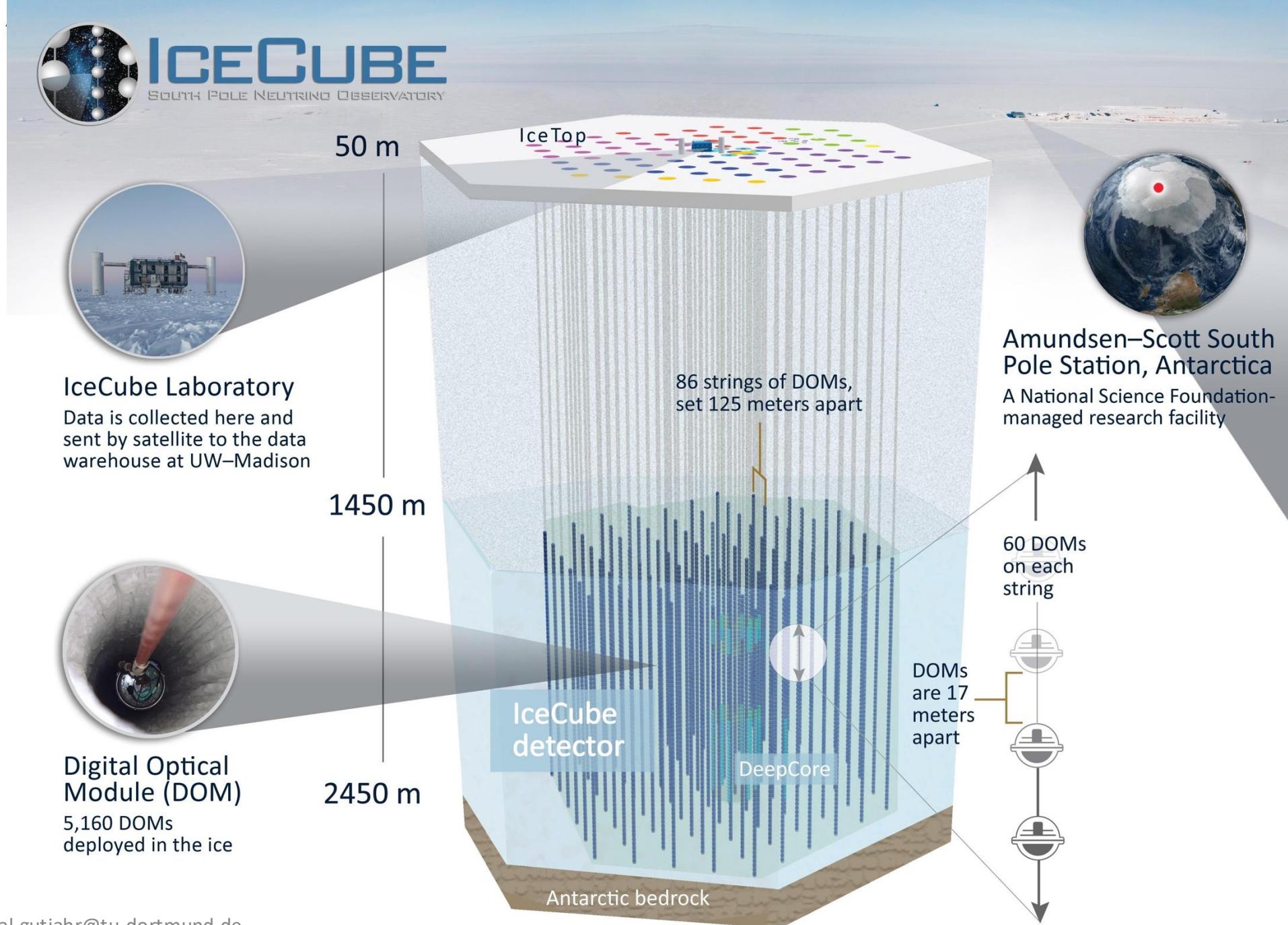
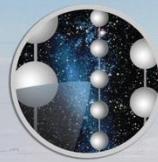


➤ More muons measured than simulated for $E > 40 \text{ PeV} \sim \text{ cms } 8 \text{ TeV}$



➤ Uncertainties at $E > 10 \text{ PeV}$

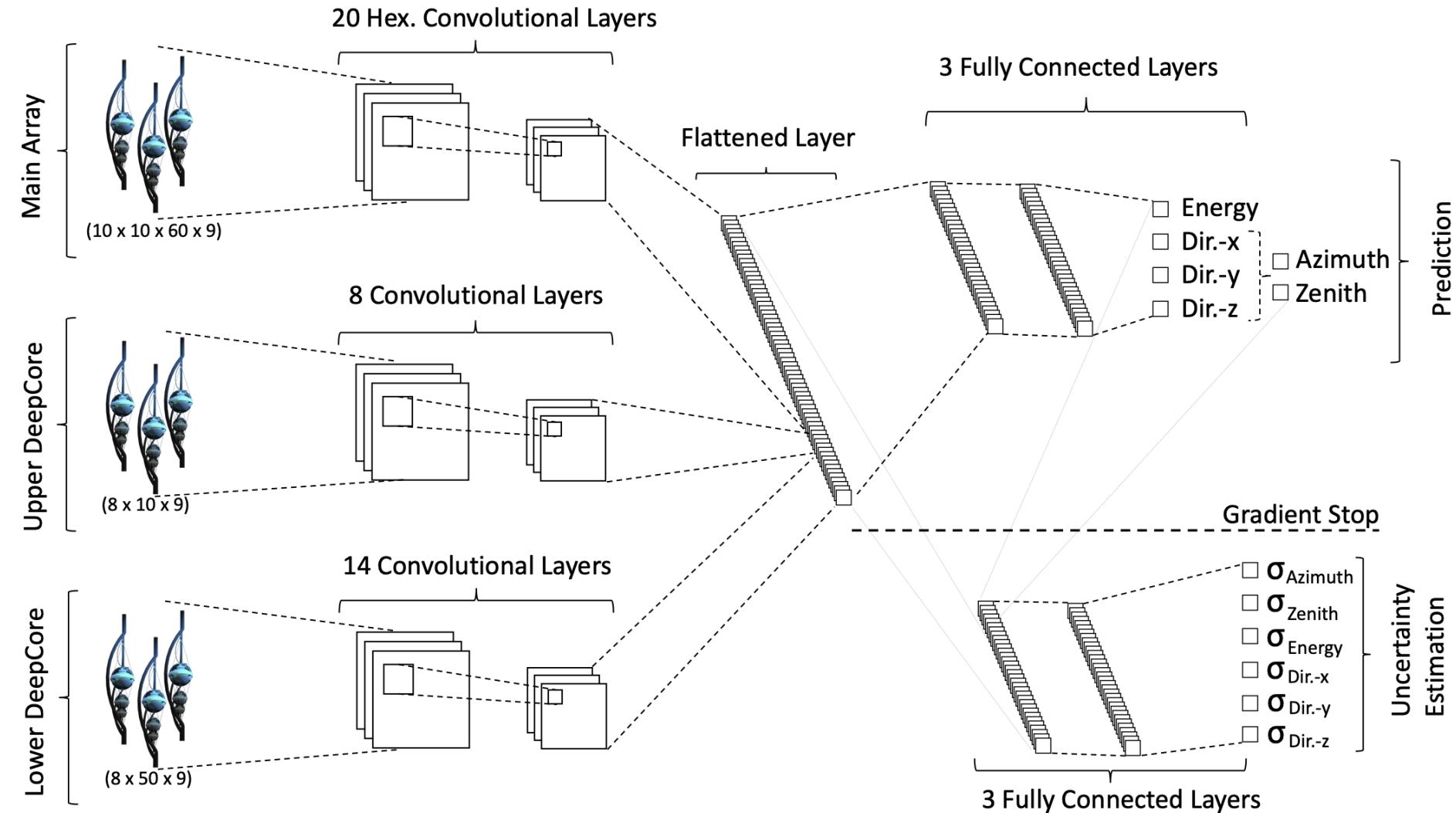




Convolutional Neural Network (CNN)

Machine learning approach:

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



Input data per DOM

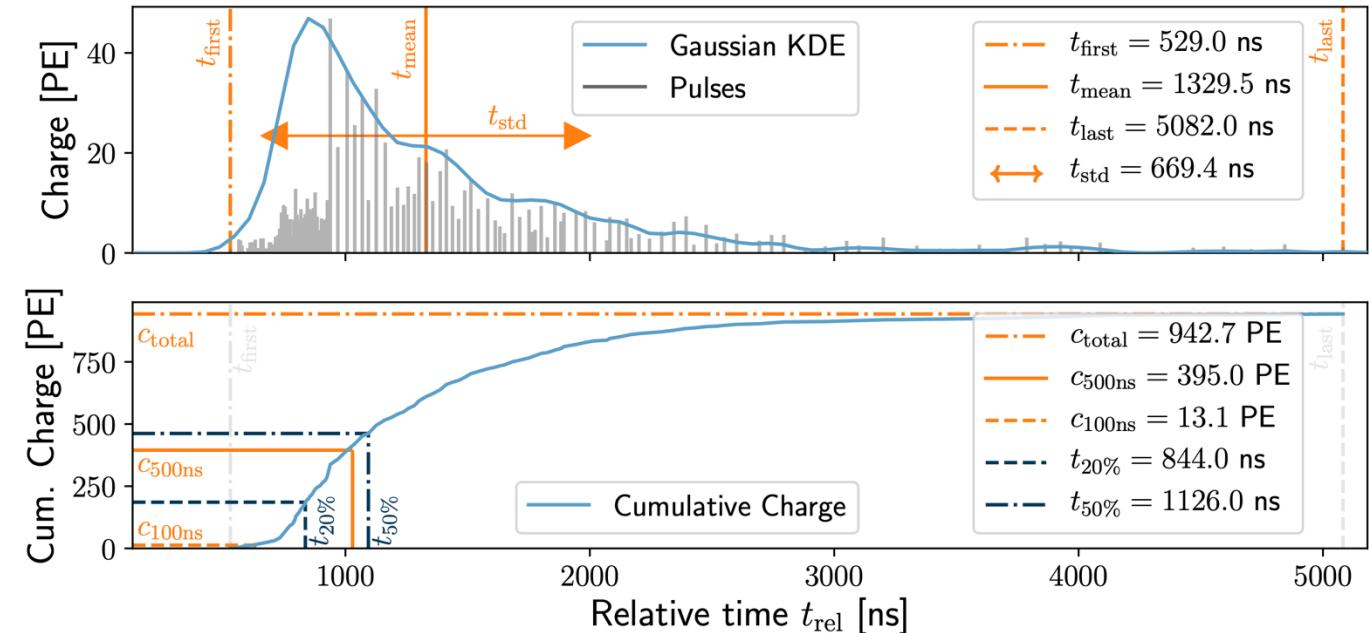
10.1088/1748-0221/16/07/P07041

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
- $c_{500\text{ns}}$: Charge at 500ns
 - Sum of charge after 500ns
- $c_{100\text{ns}}$: 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

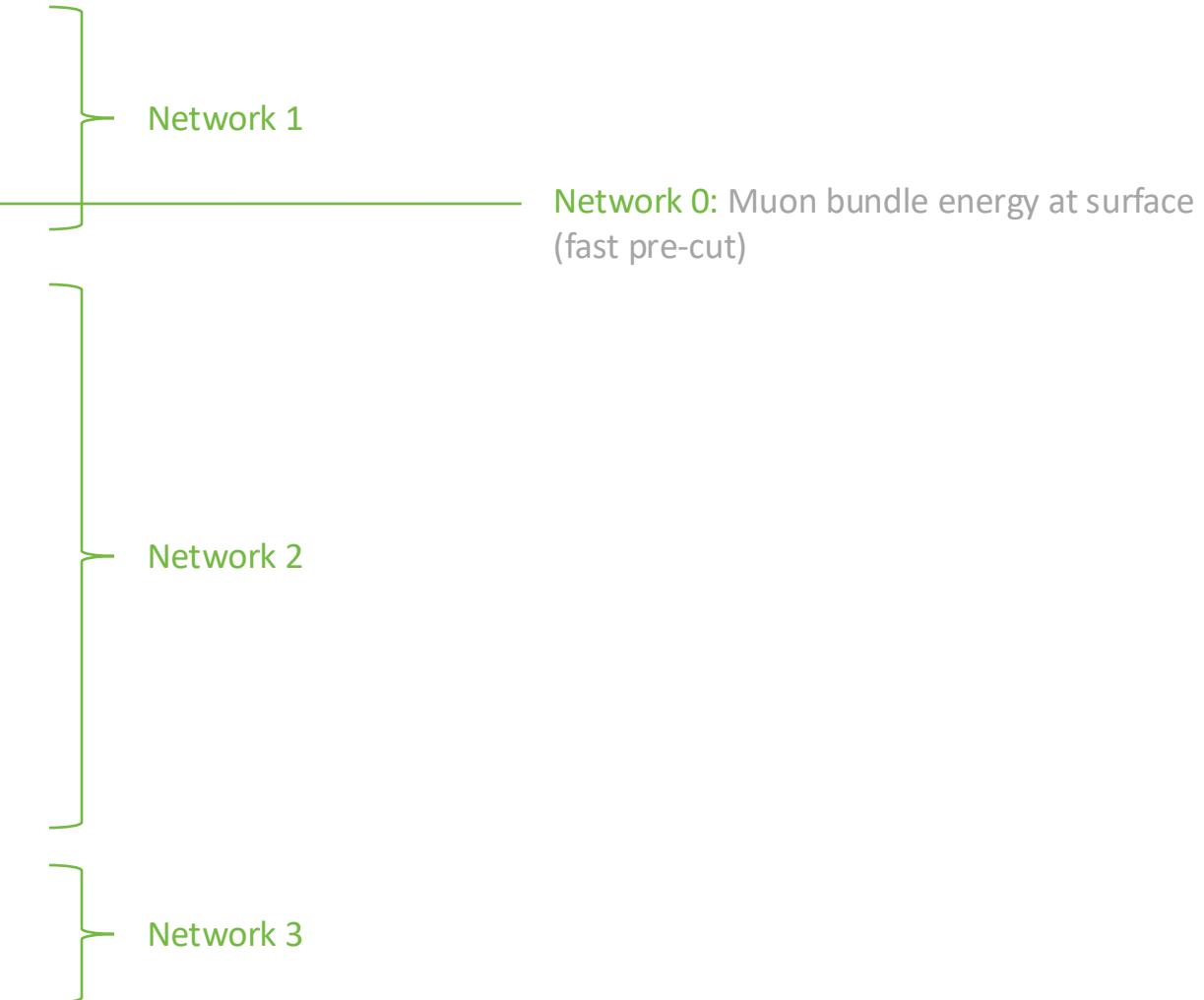
- `entry_energy`: Leading muon energy at the detector entry
- `bundle_energy_at_entry`: Muon bundle energy at the detector entry
- `muon_energy_first_mctree`: Leading muon energy at surface
- `bundle_energy_in_mctree`: Muon bundle energy at surface

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

Direction

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



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

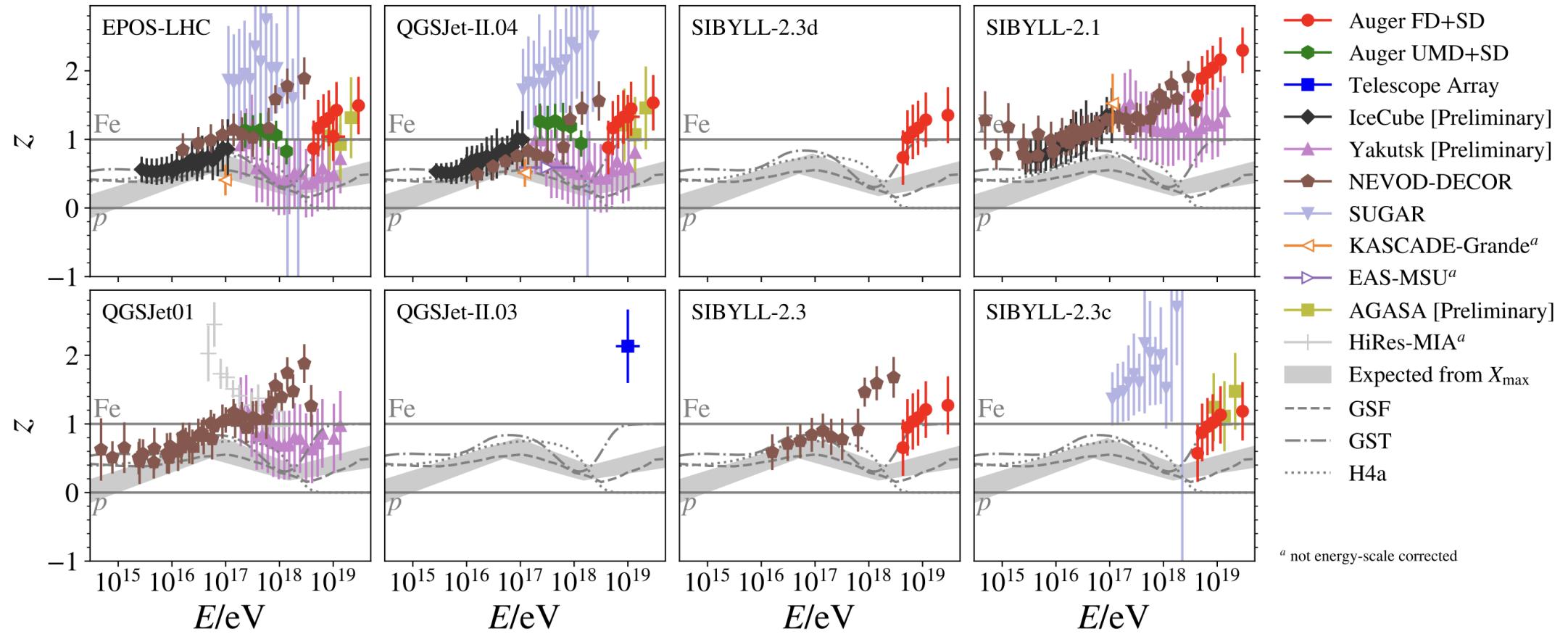
neutrino cuts	>	<
$\cos(\text{zenith})$	0.2	
length	5000 m	15000 m

uncertainty cuts	<
bundle energy at entry	$0.9 \log_{10}(\text{GeV})$
bundle energy at surface	$2.0 \log_{10}(\text{GeV})$
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

The Muon Puzzle

"muon number"

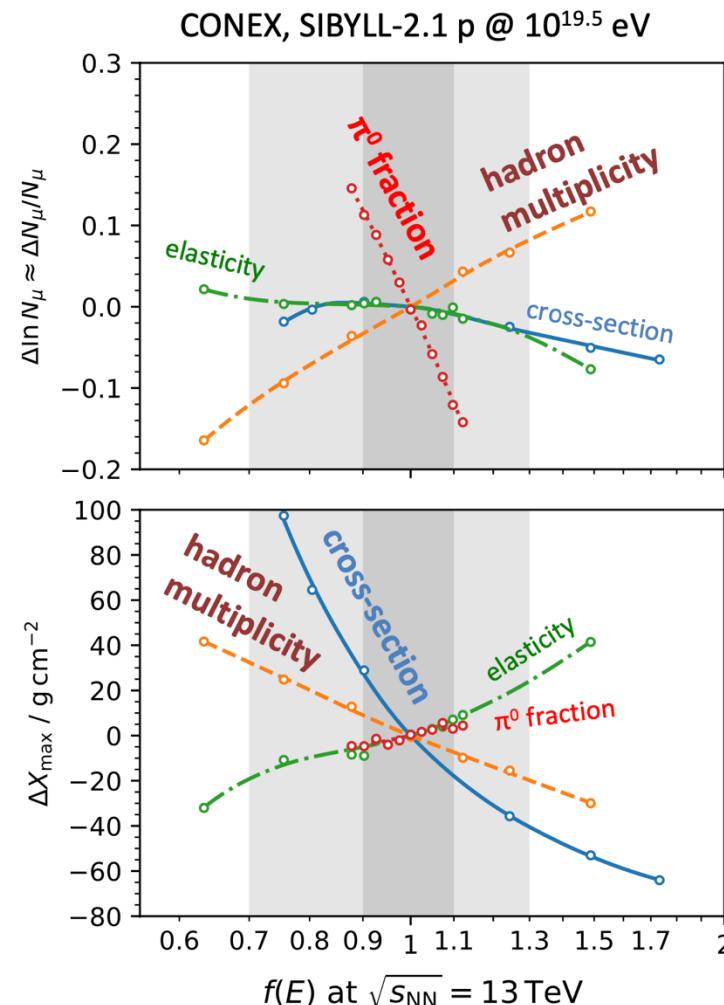
$$z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_p}{\ln\langle N_\mu \rangle_{\text{Fe}} - \ln\langle N_\mu \rangle_p}$$



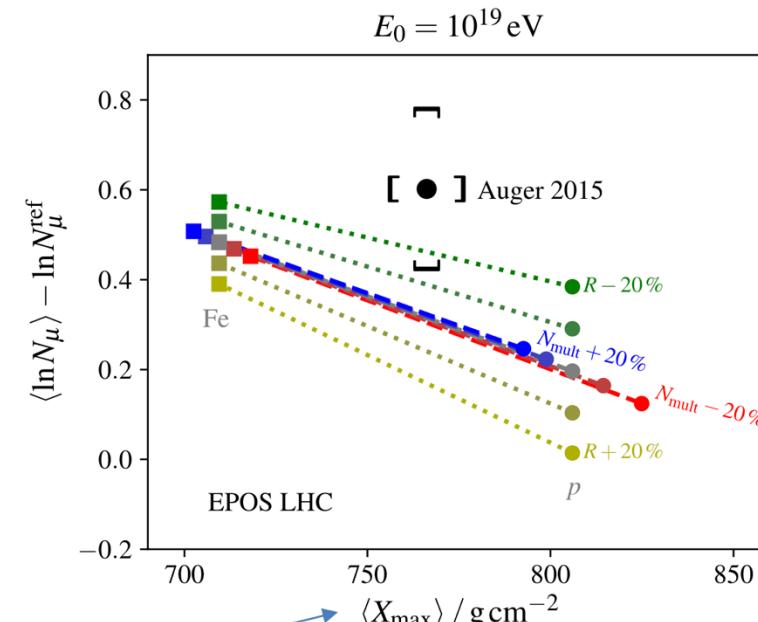
2108.08341

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 %