

Unfolding the Atmospheric Muon Flux with IceCube

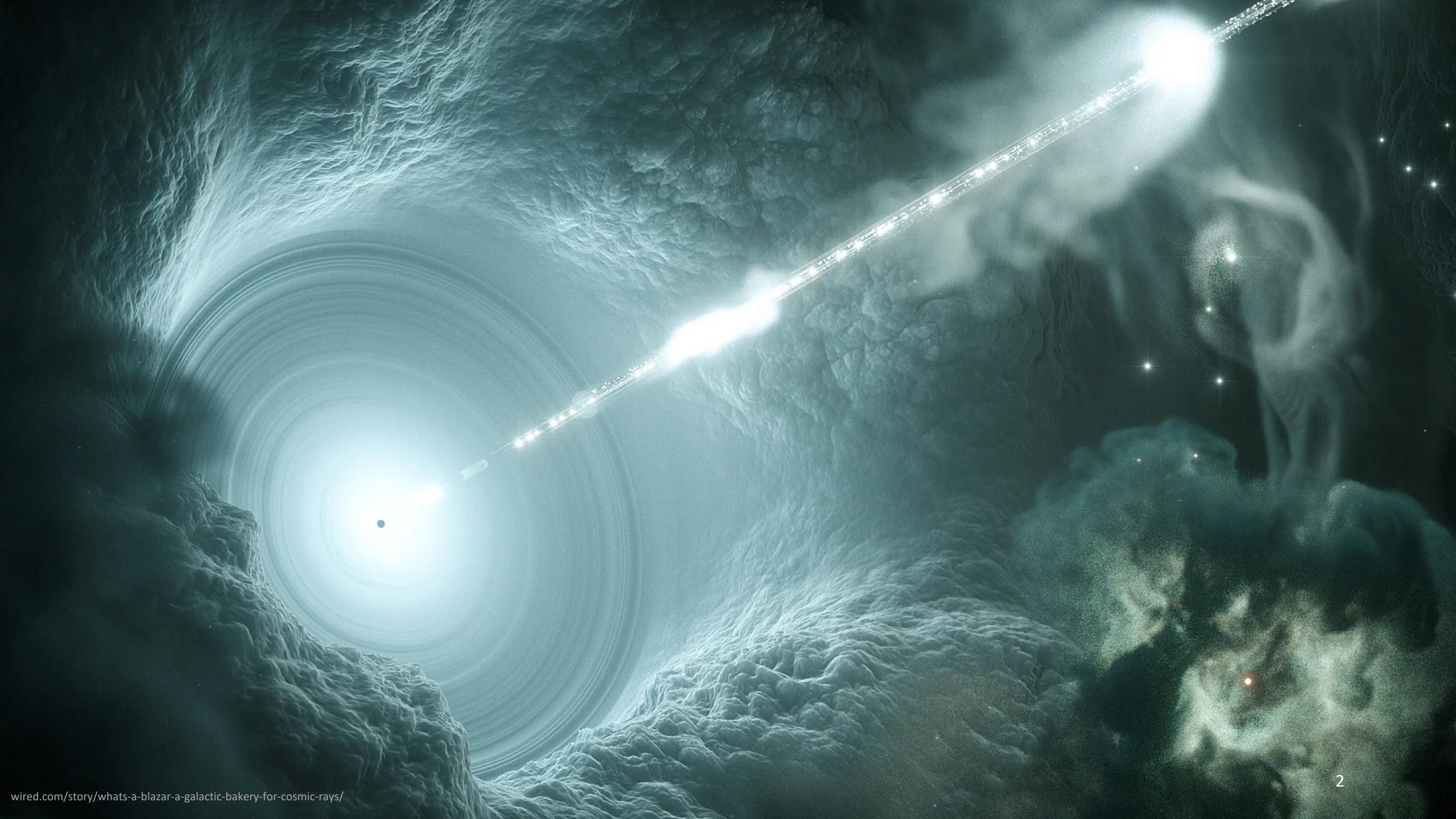
Pascal Gutjahr
for the IceCube Collaboration

Cosmic Ray physics with high-energy atmospheric muons

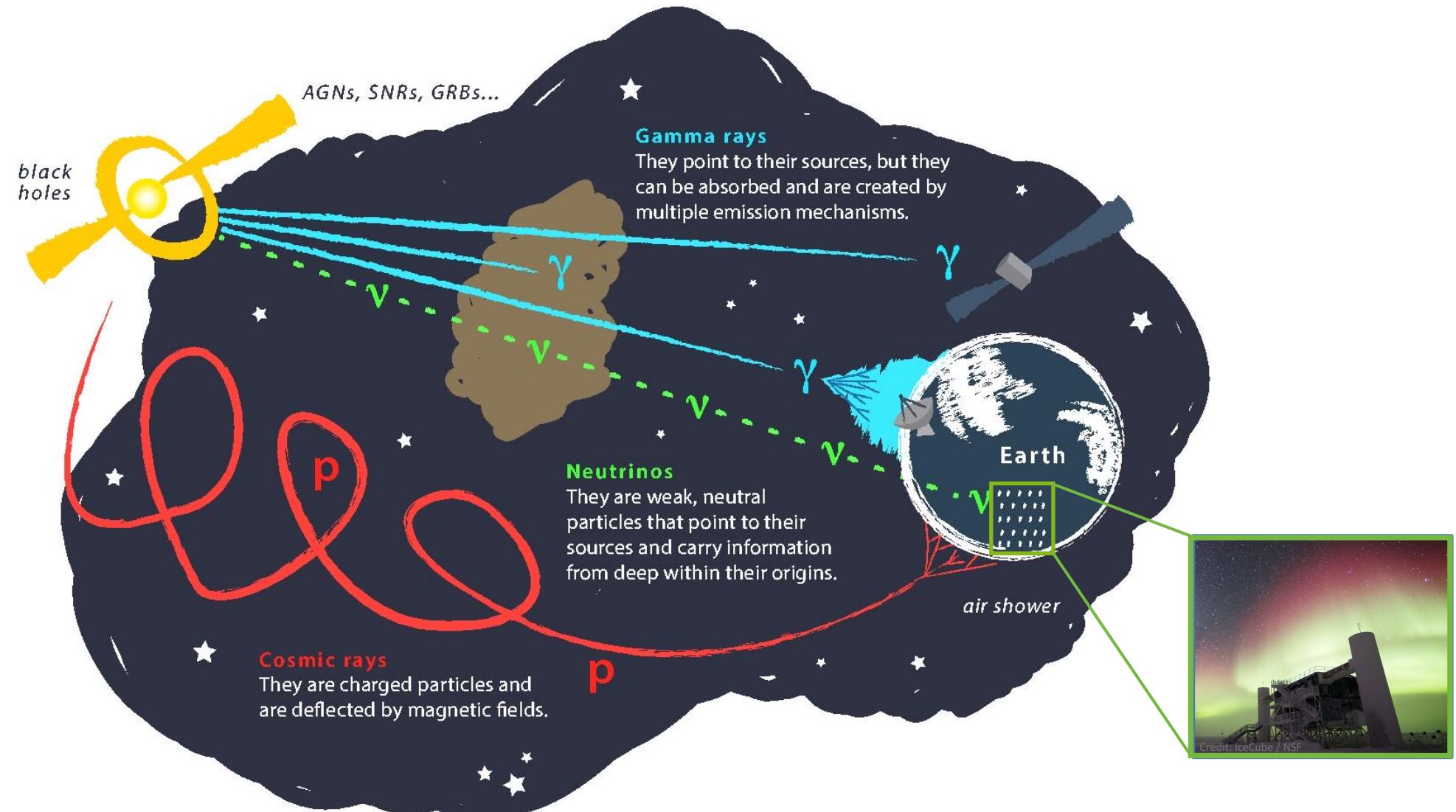


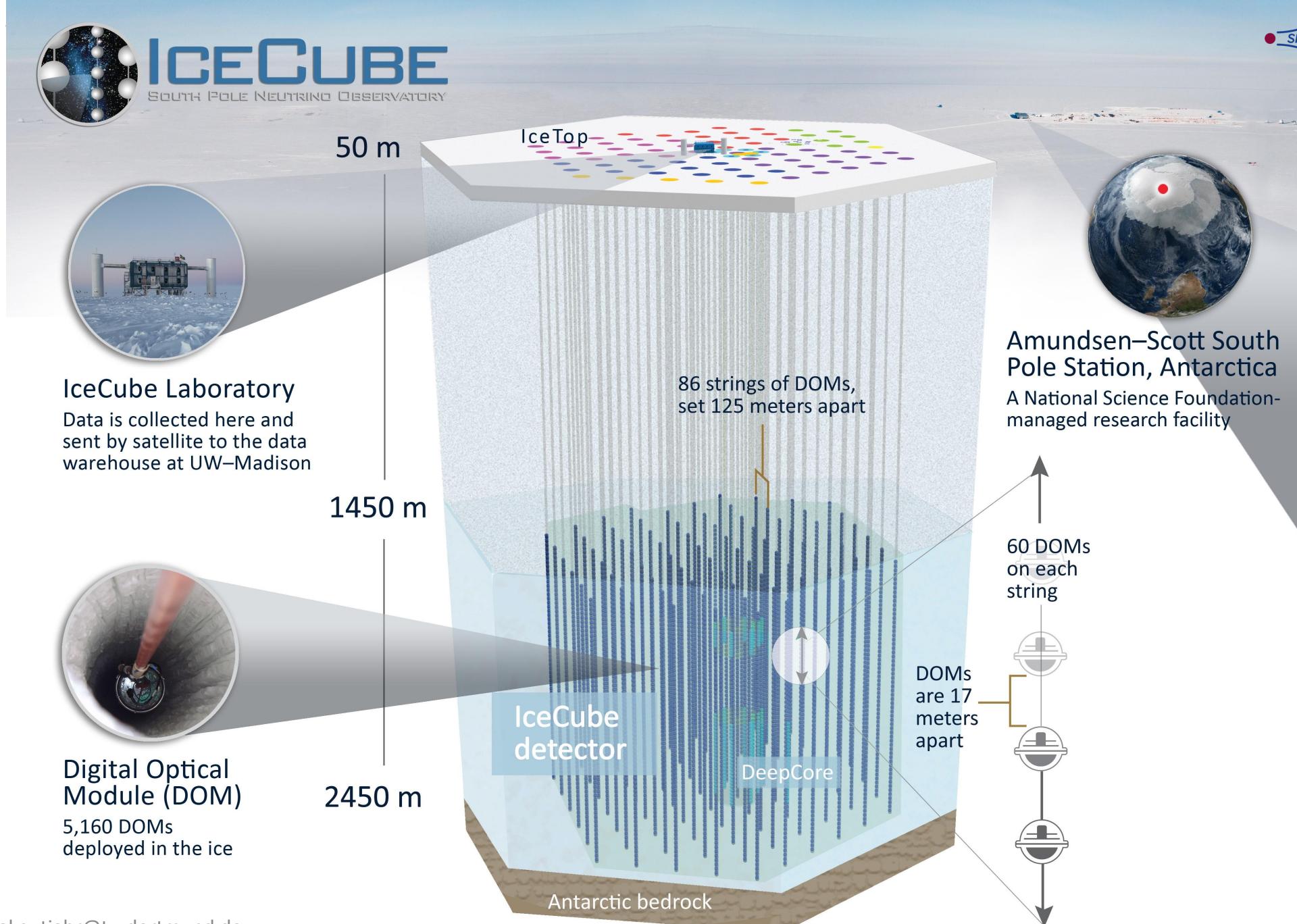
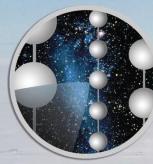
LPC Caen

September 17-19, 2025



Astroparticle physics





Introduction

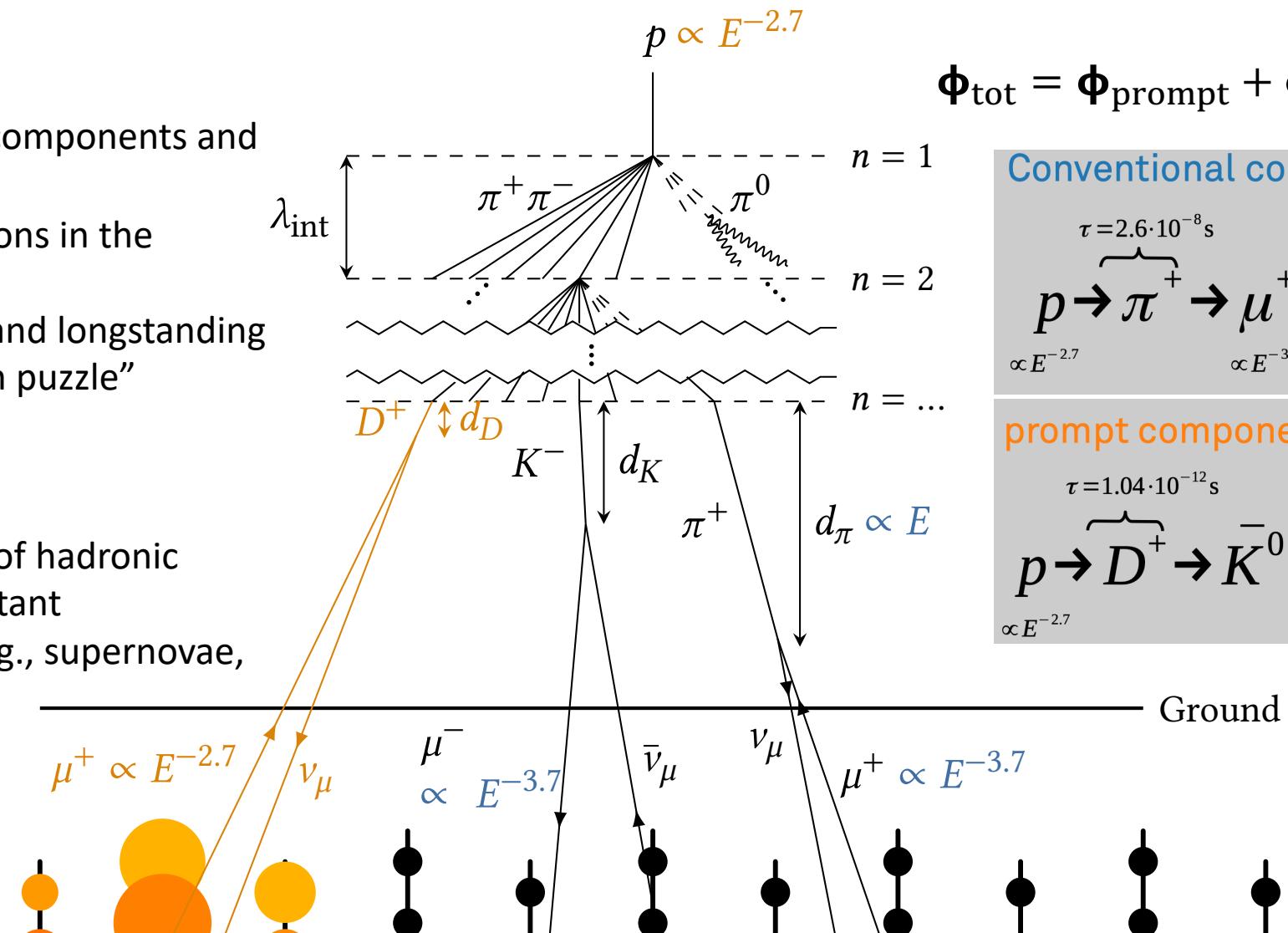
Motivation

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

Long term

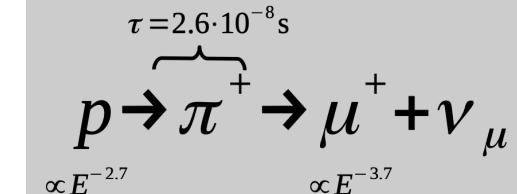
- Enhance understanding of hadronic processes relevant in distant astrophysical sources (e.g., supernovae, AGNs, ...)

Conventional Muon:
Parent is pion or kaon

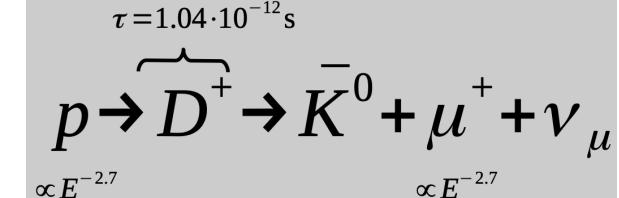


$$\Phi_{\text{tot}} = \Phi_{\text{prompt}} + \Phi_{\text{conventional}}$$

Conventional component:

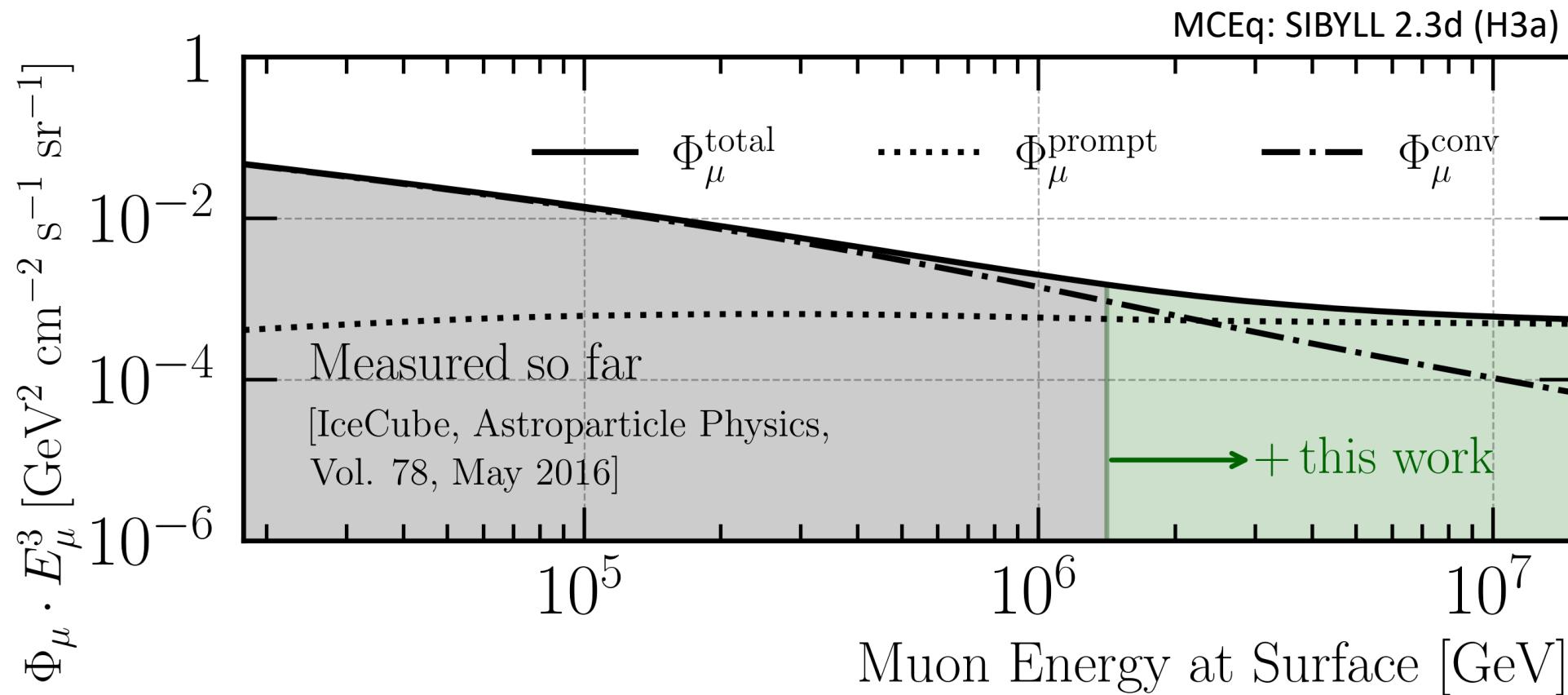


prompt component:

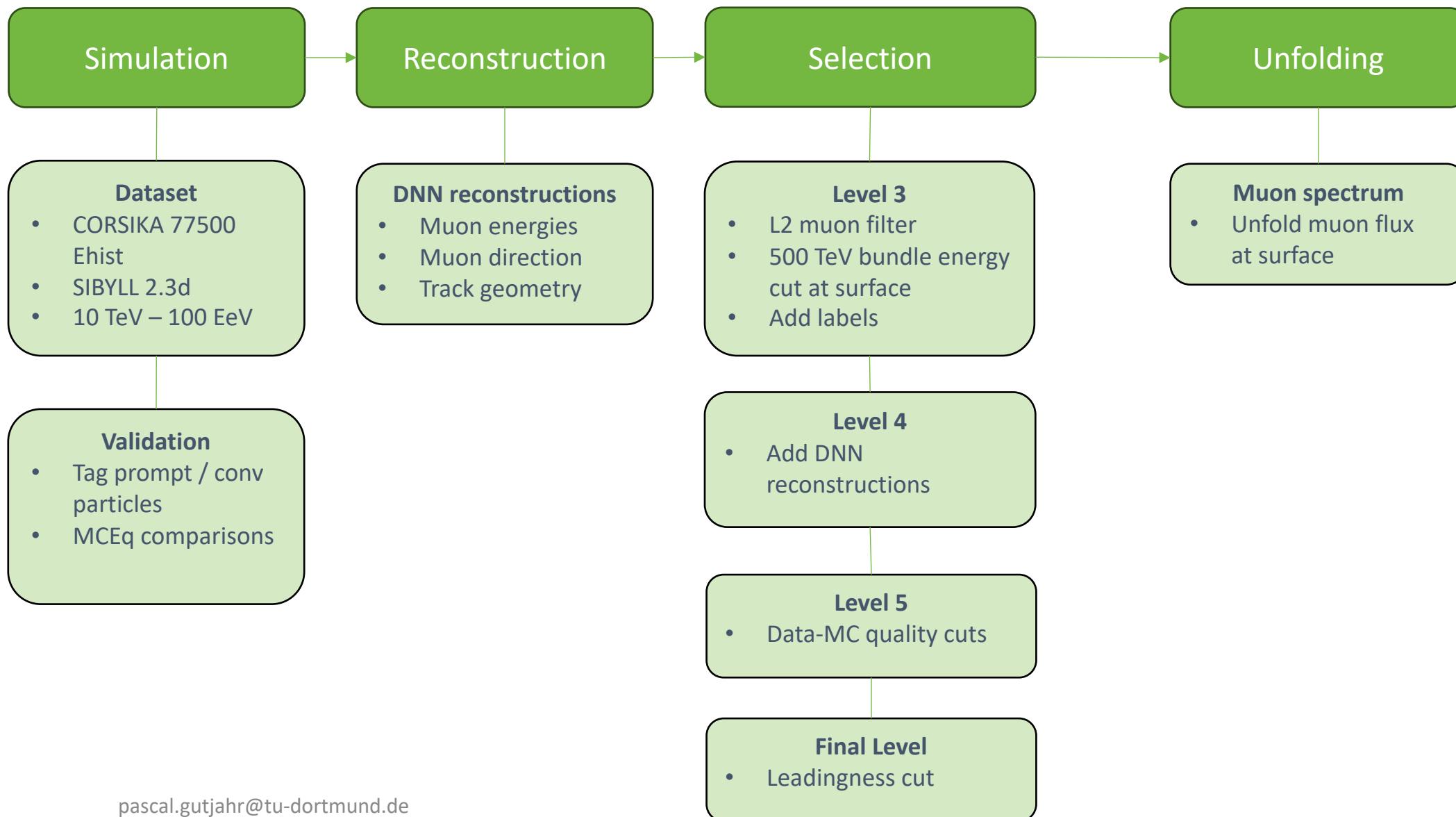


Credit: Ludwig Neste

Goal: Measure Muon Flux at Surface



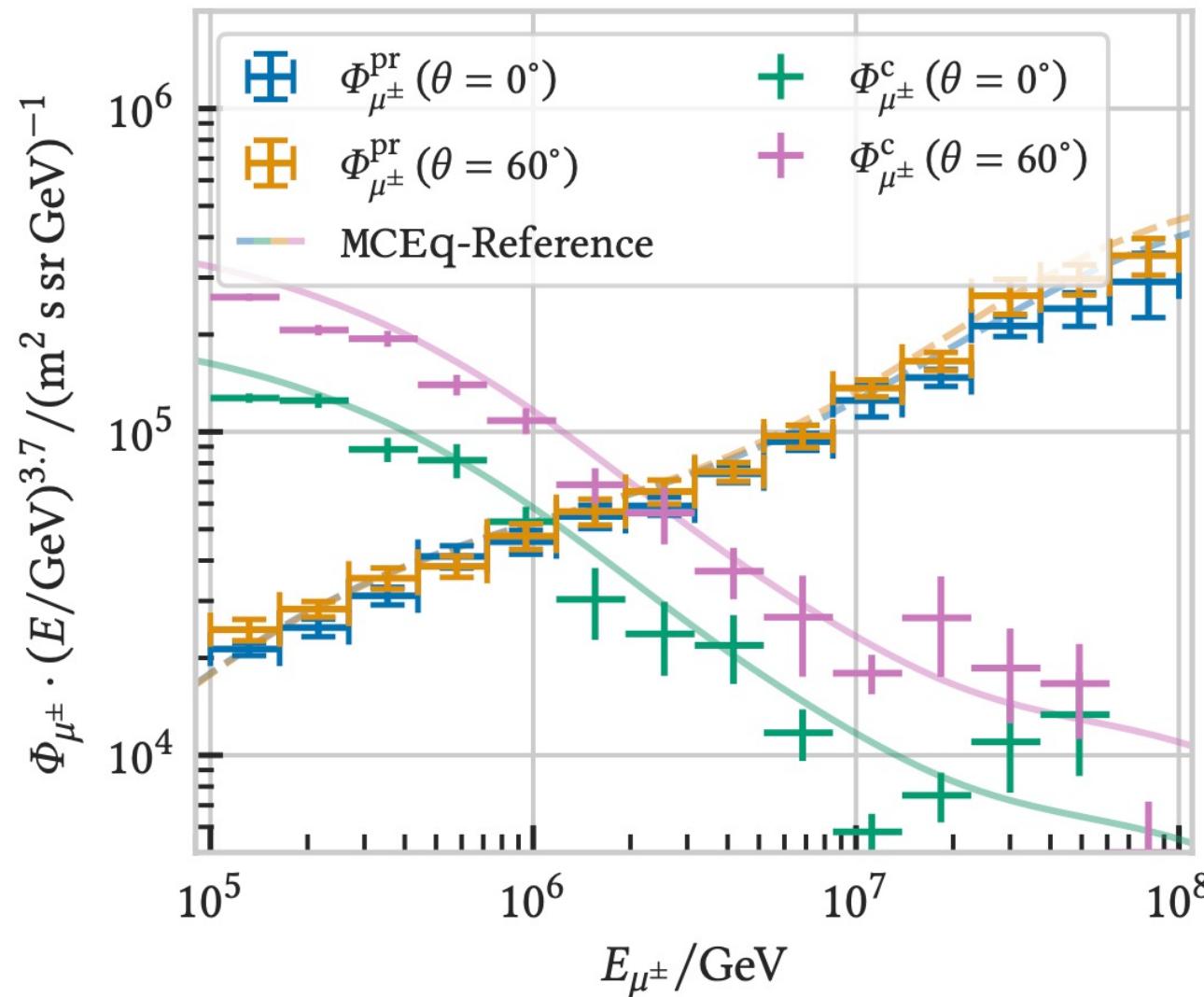
Overview



New CORSIKA simulation

with extended history option for information about the parent particles

CORSIKA 7 vs. MCEq

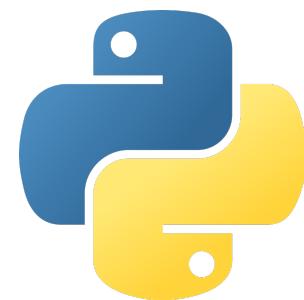


MCEq: tool to numerically solve the cascade equations that describes the evolution of particle densities as they propagate through a gaseous, dense medium
<https://github.com/mceq-project/MCEq>

➤ Good agreement for inclusive flux

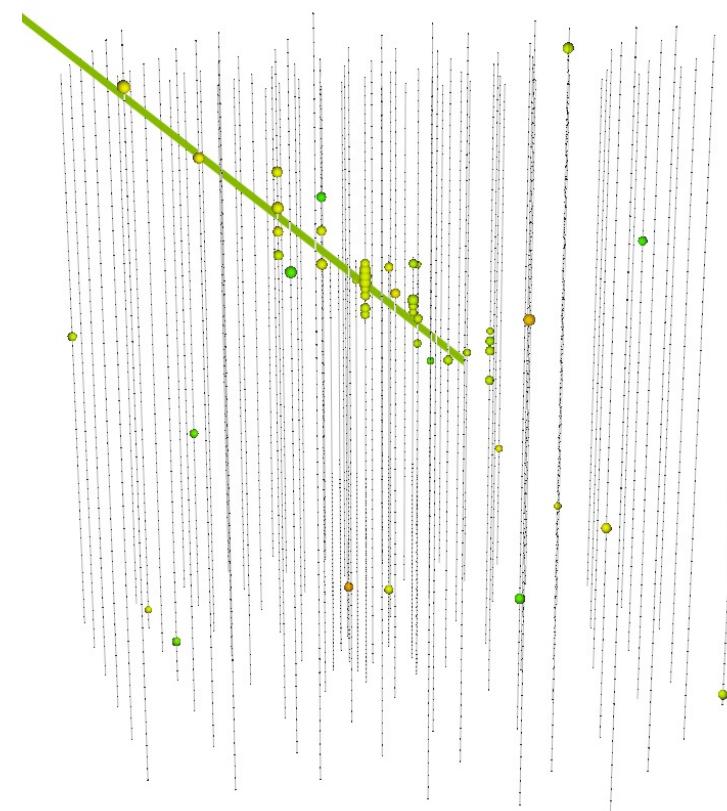
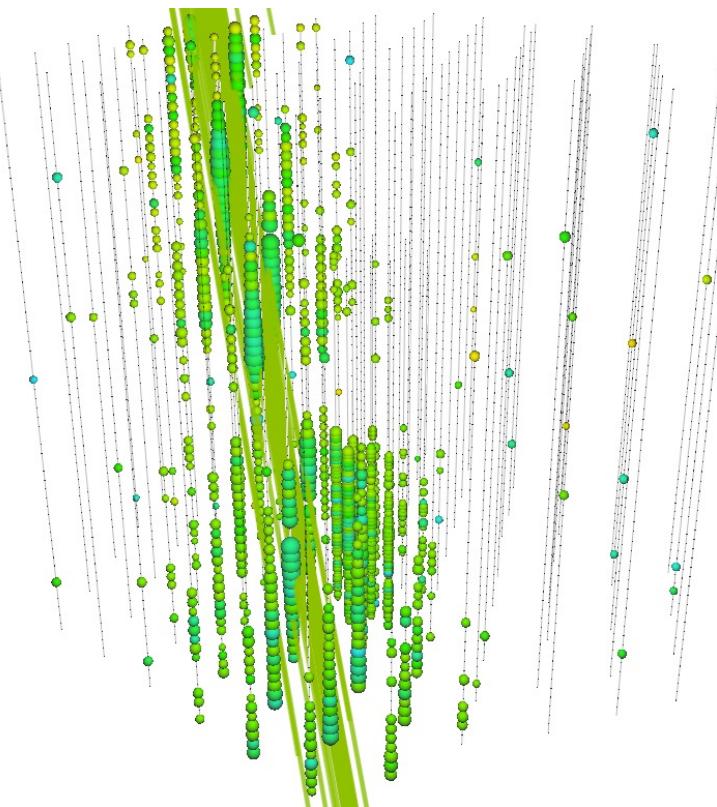
Python package developed – PANAMA

- Execute CORSIKA 7 (multi core)
- Read DAT files → pandas DataFrames
- Parse EHIST option
- Calculate primary weightings



Stopping and Leading Muons

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



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

Reconstruction

Machine Learning (CNN)

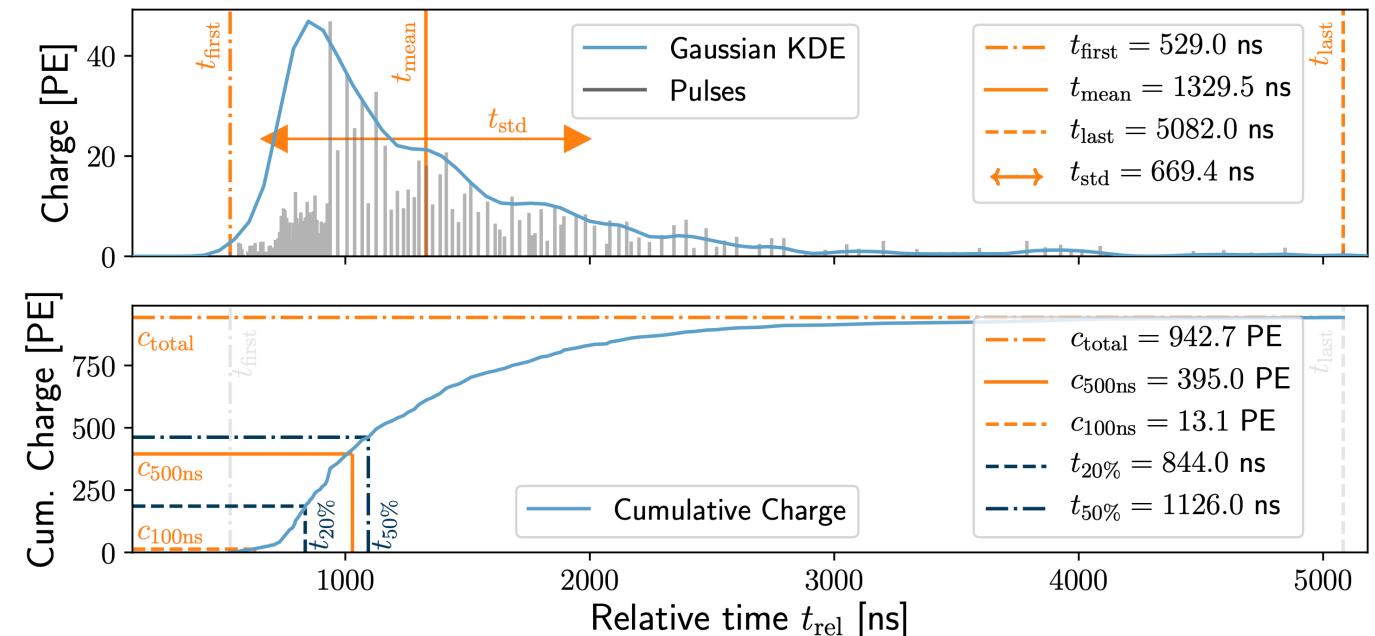
Input data per DOM

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

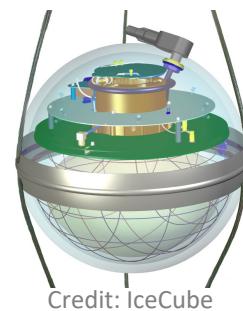


Input pulse cleaning

- 6000 ns

Training data

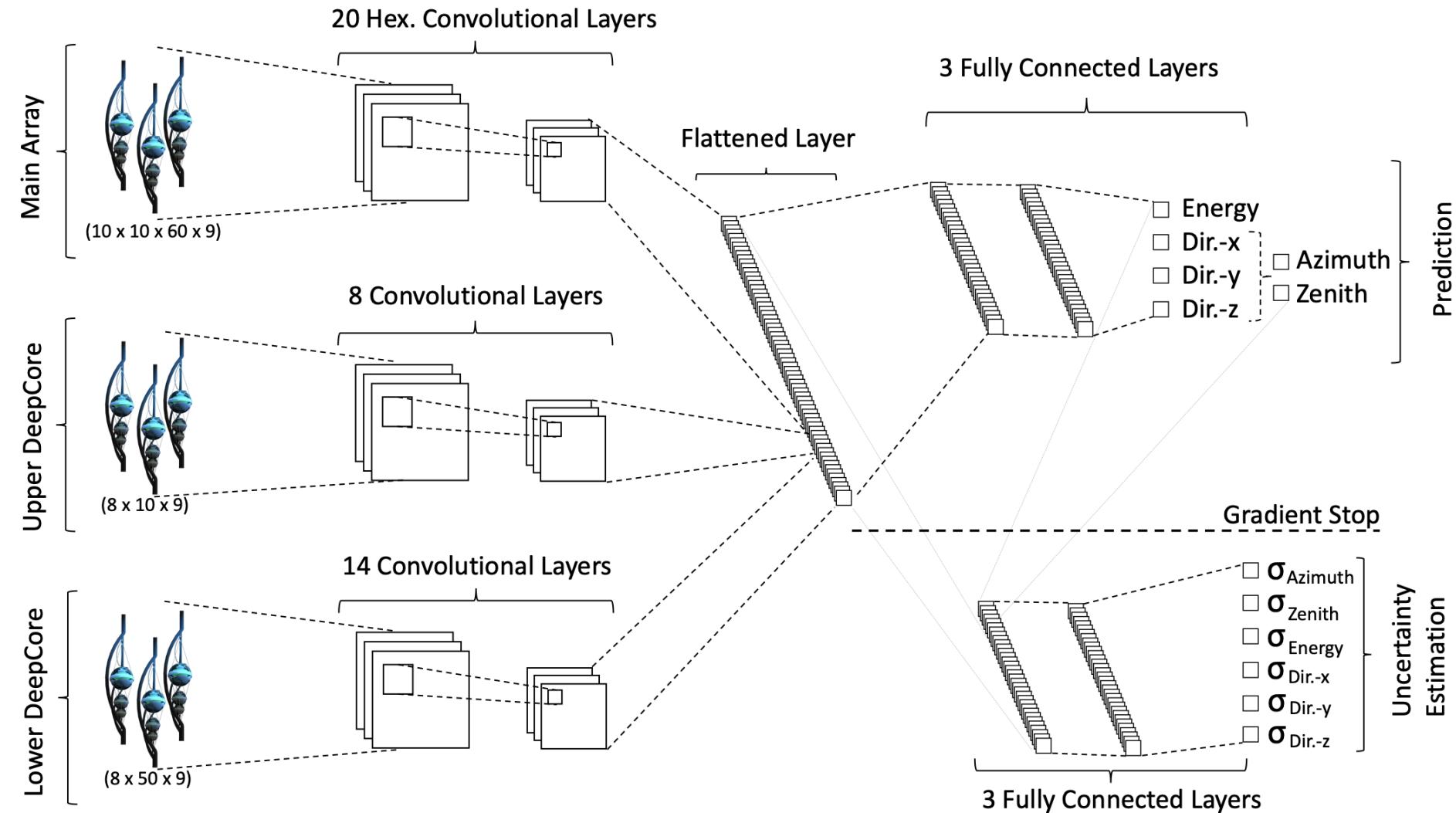
- Different simulations for robustness



Convolutional Neural Network (CNN)

Machine learning approach:

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



Reconstructed properties

Energy

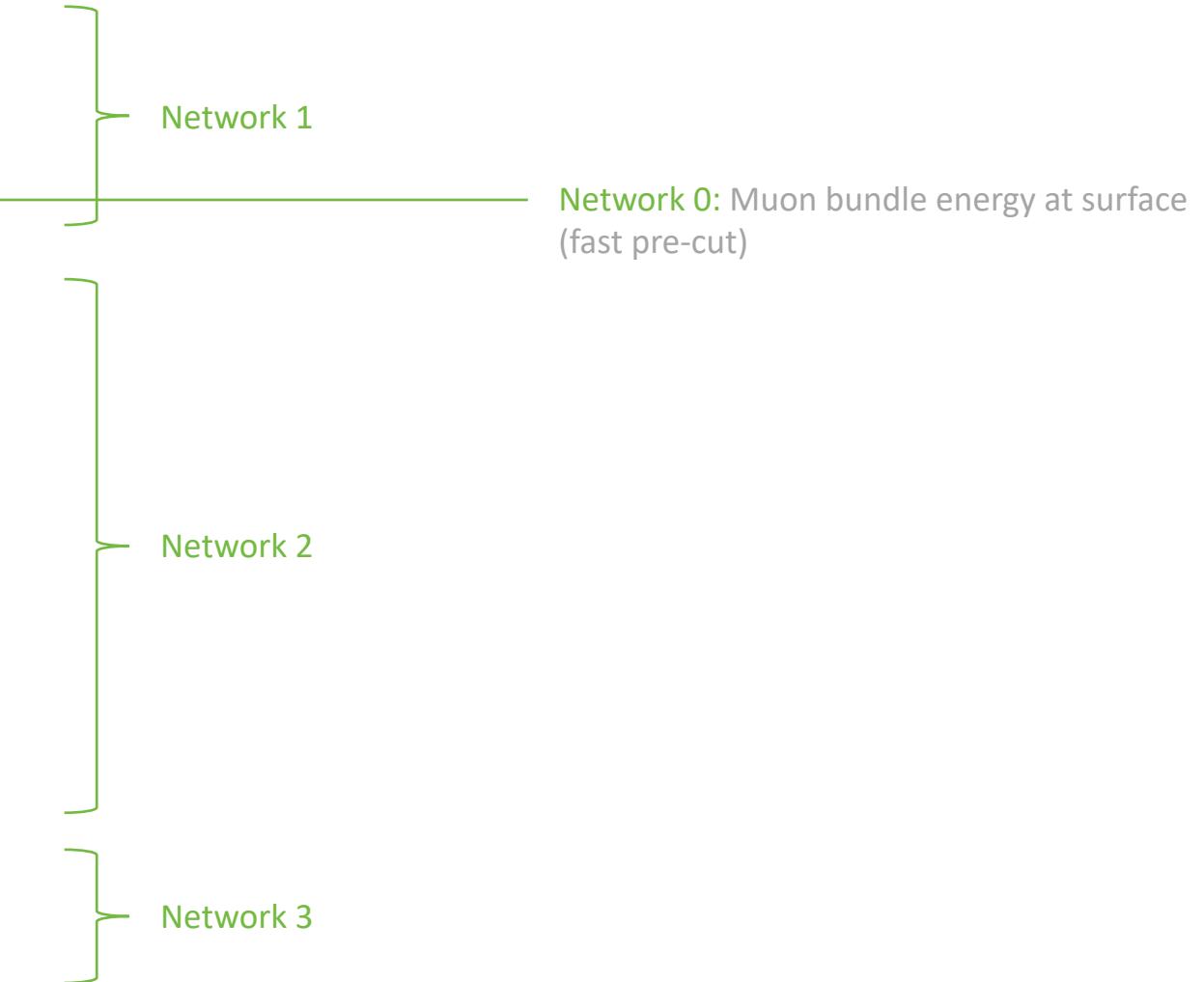
- `entry_energy`: Leading muon energy at the detector entry
- `bundle_energy_at_entry`: Muon bundle energy at the detector entry
- `muon_energy_first_mctree`: Leading muon energy at surface
- `bundle_energy_in_mctree`: Muon bundle energy at surface

Track geometry

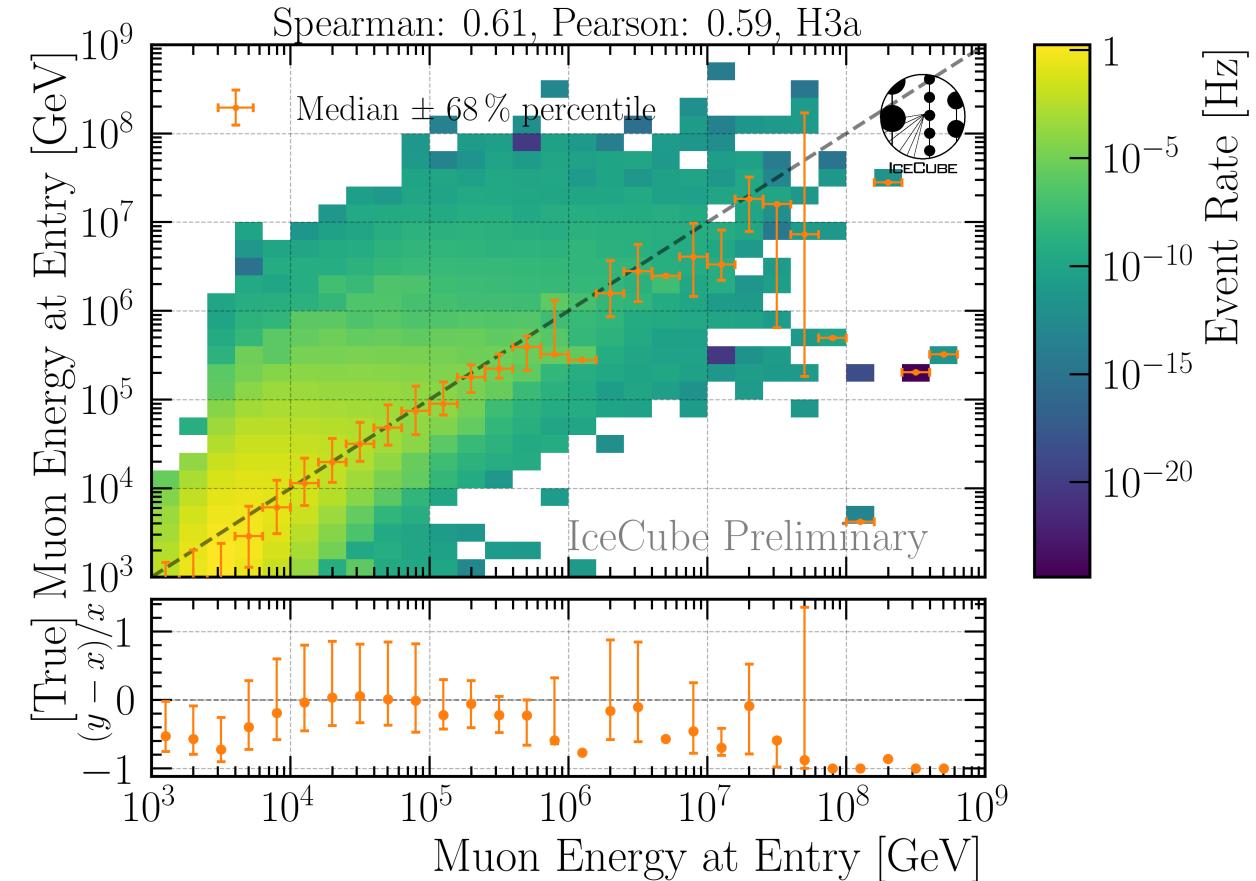
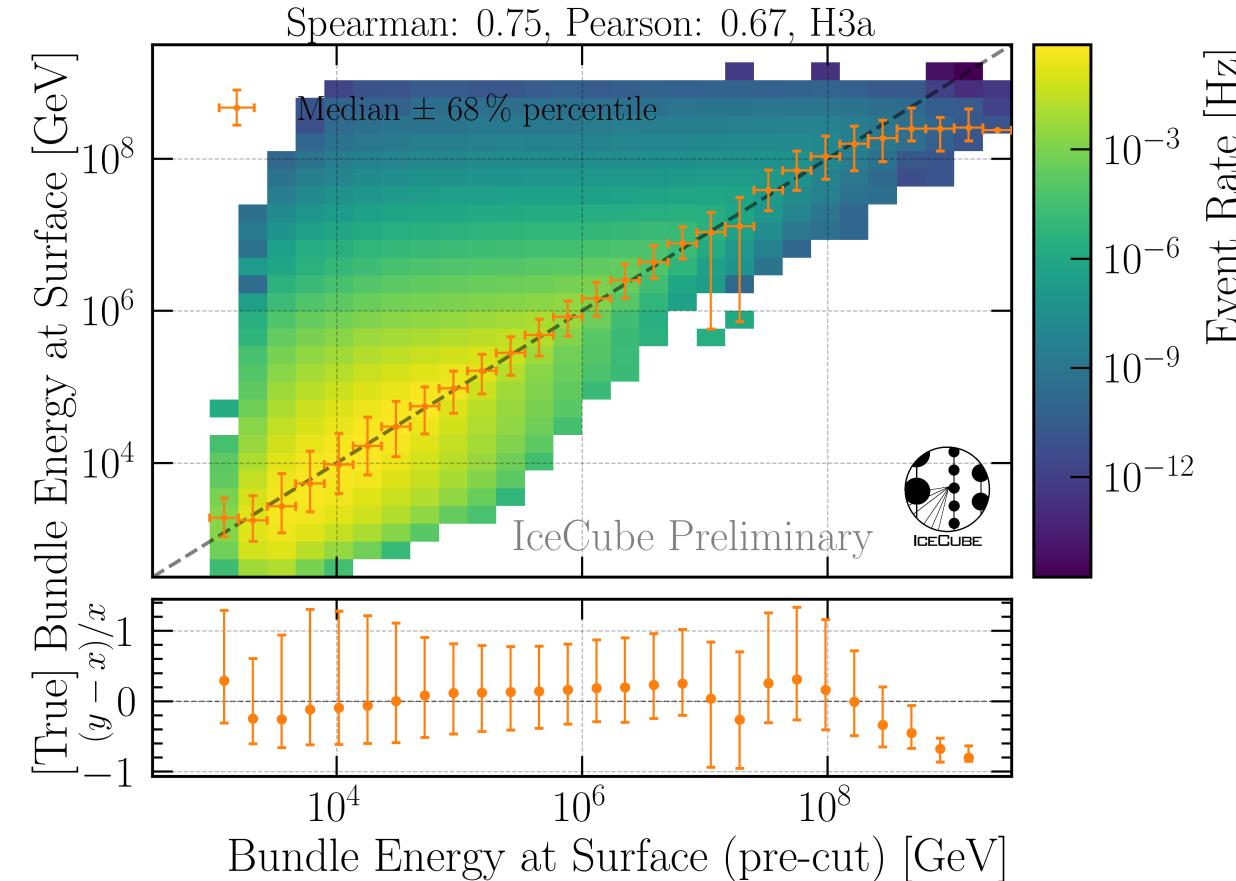
- `Length`: Propagation length of muon in the ice
- `LengthInDetector`: Propagation length of muon in the detector
- `center_pos_x`: Closest x position of muon to center of the detector
- `center_pos_y`: Closest y position of muon to center of the detector
- `center_pos_z`: Closest z position of muon 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



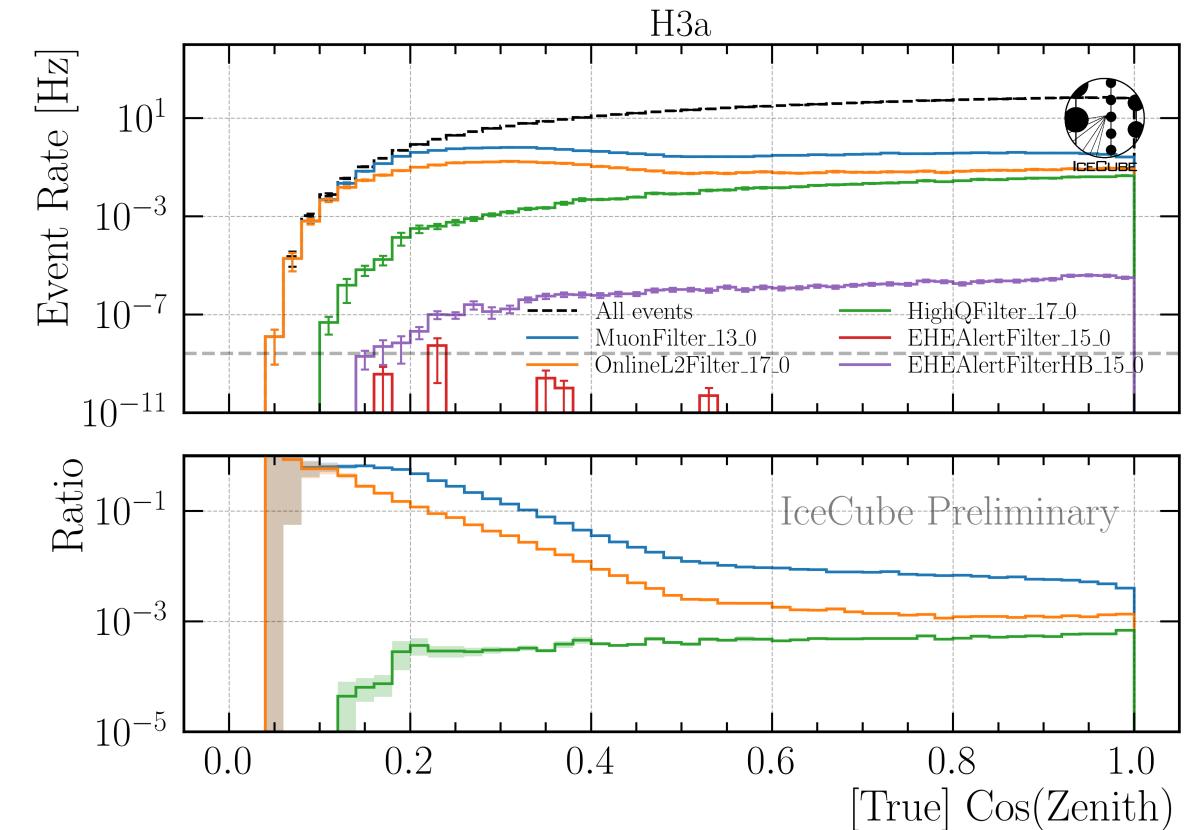
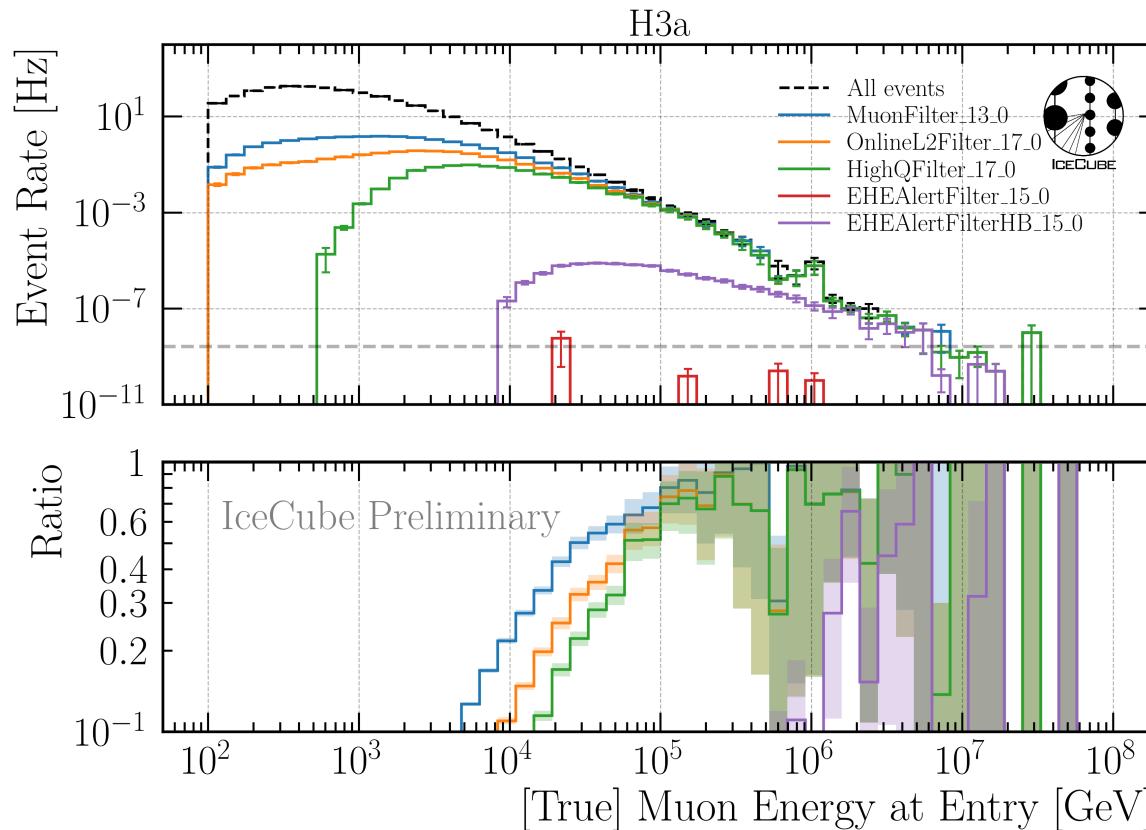
Energy Reconstructions



- Sufficient energy reconstructions
- Tight 68 % intervals, with outliers

Selection

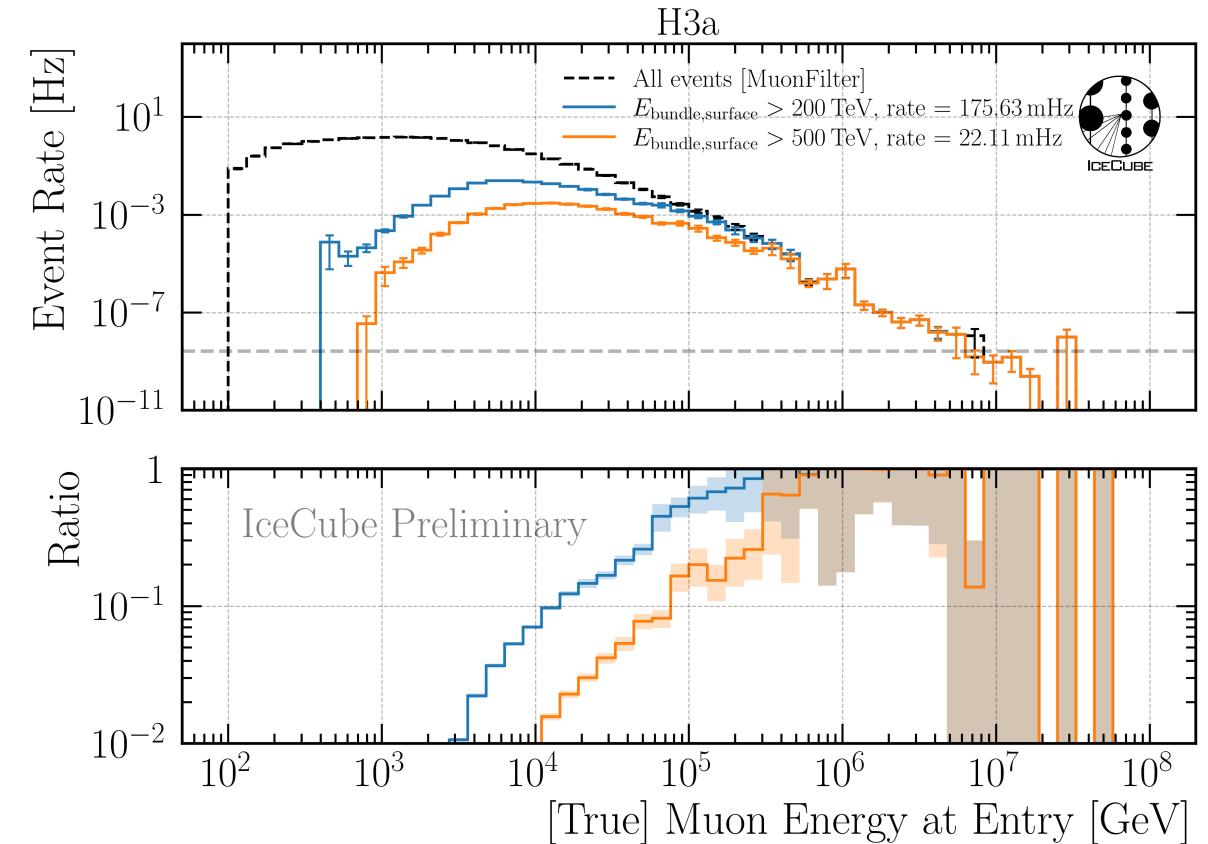
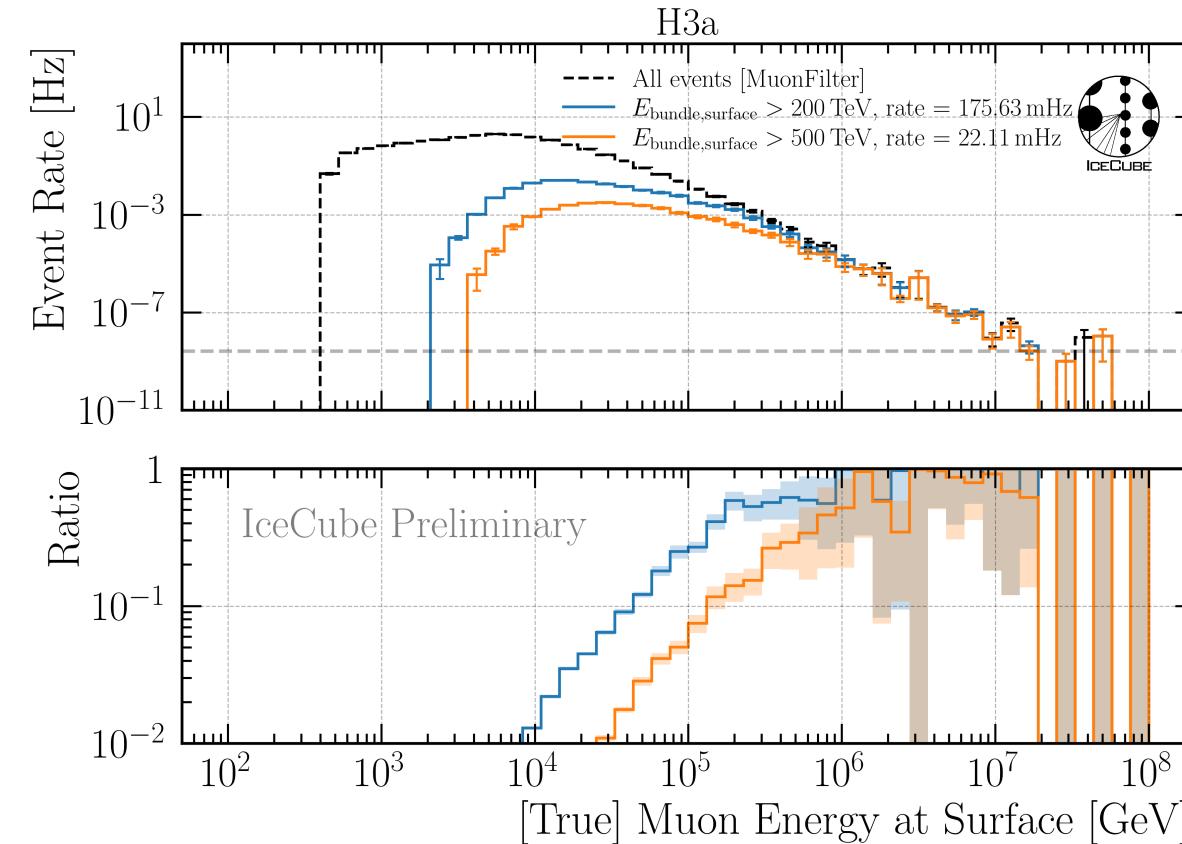
Level 3: Muon Filter



Muon filter: zenith-dependent charge and quality cut

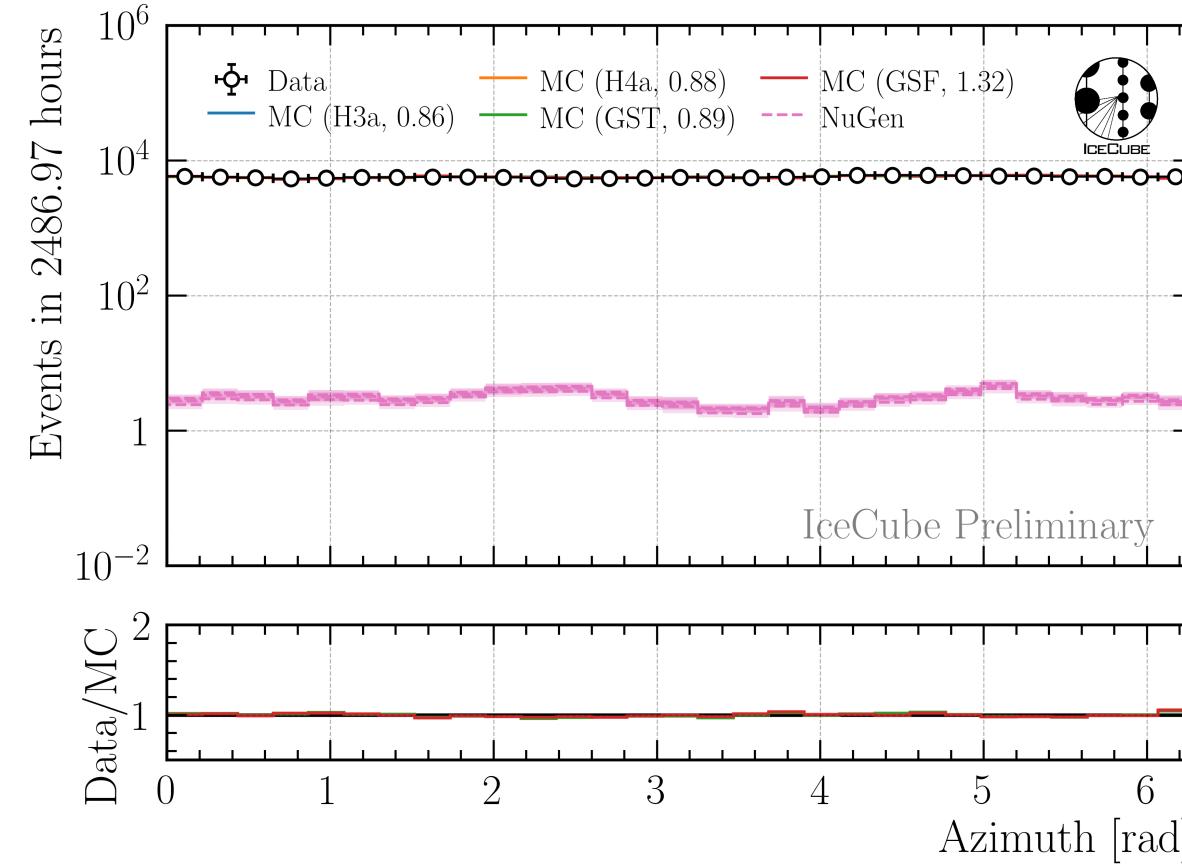
➤ Choose muon filter to select as many high-energy muons as possible

Level 4: Energy Cut



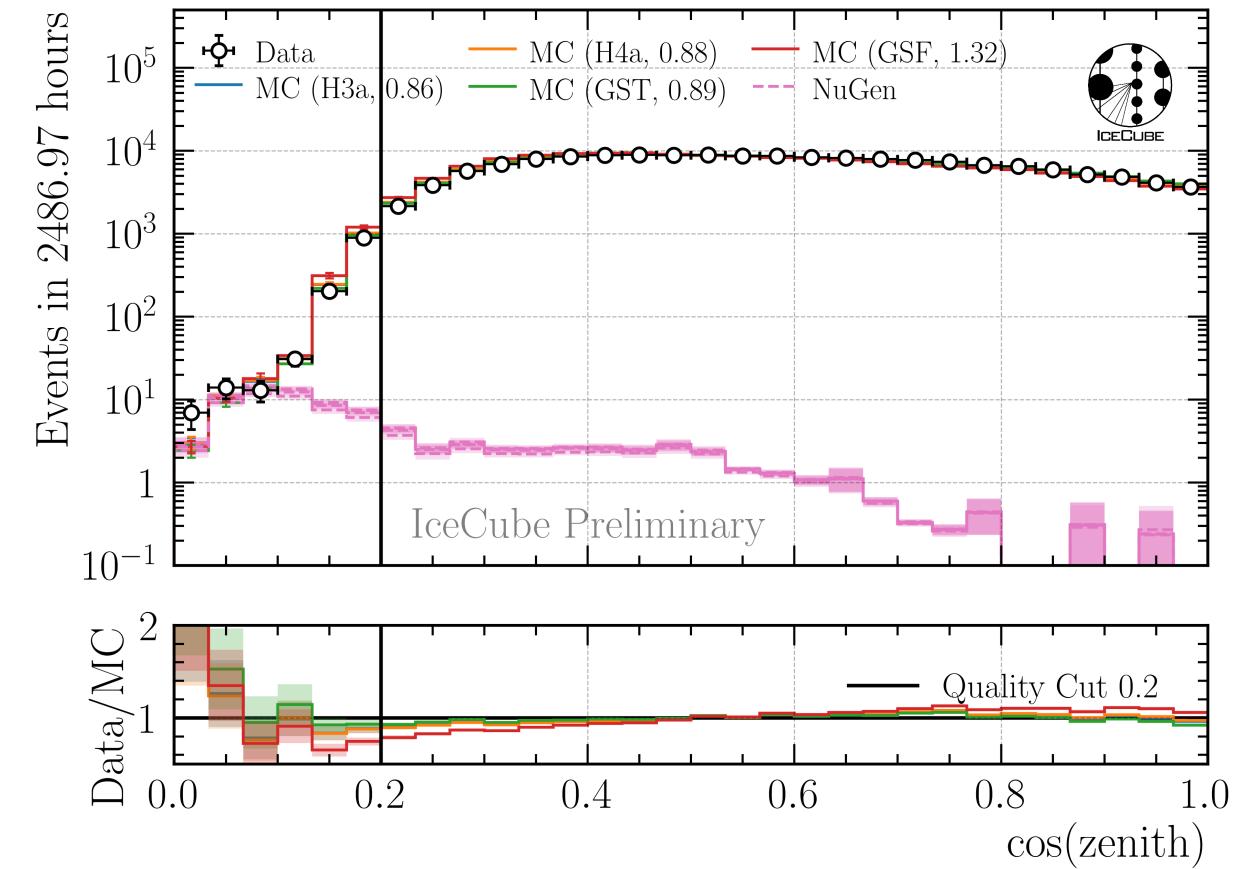
- 6 billion events expected in 10 years → computationally not feasible
- focus on high-energetic events
- Remove low-energy muons: bundle energy at surface > 500 TeV

Level 5: Data/MC Quality Cuts



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

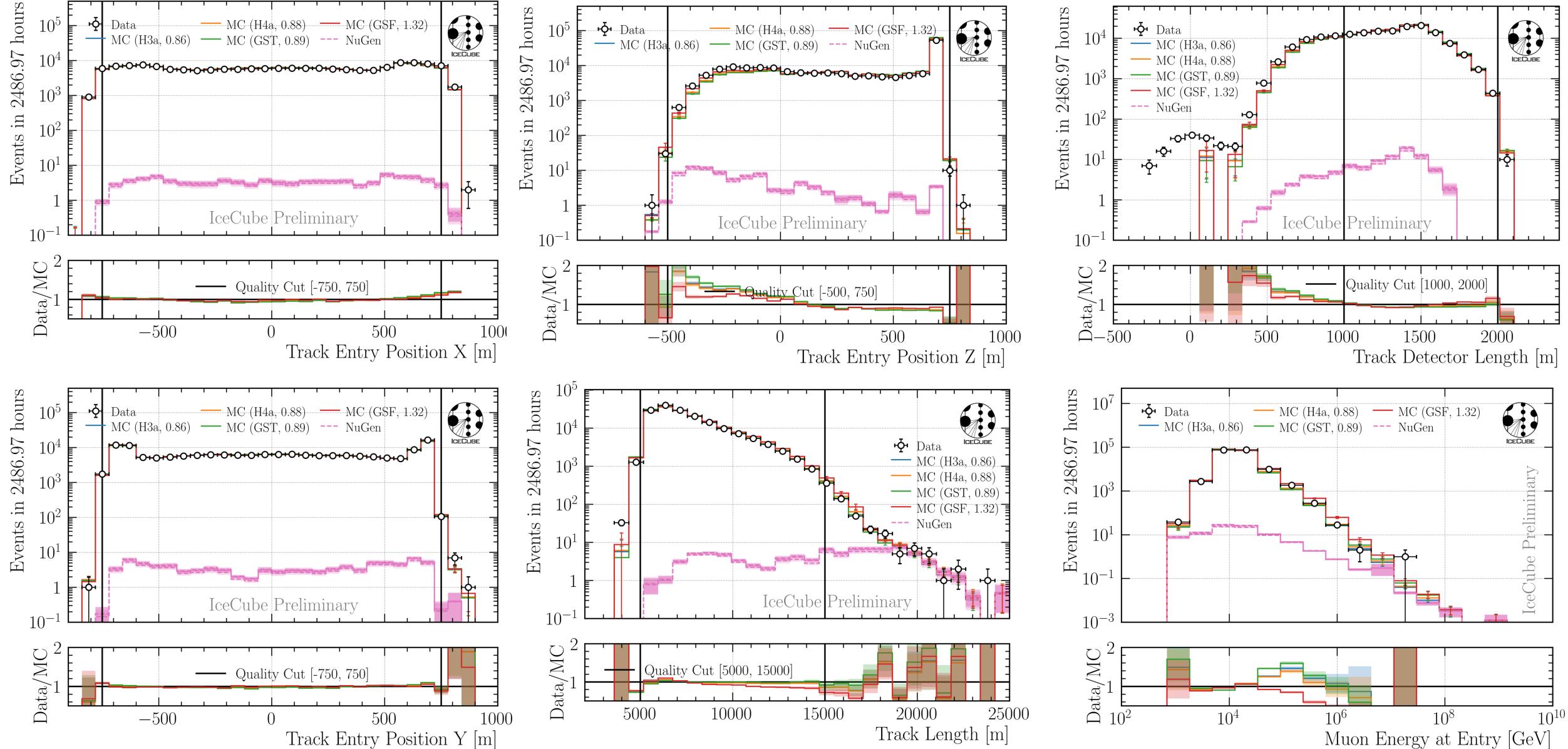
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- Good directional reconstruction
- Cut: $\cos(\text{zenith}) > 0.2$

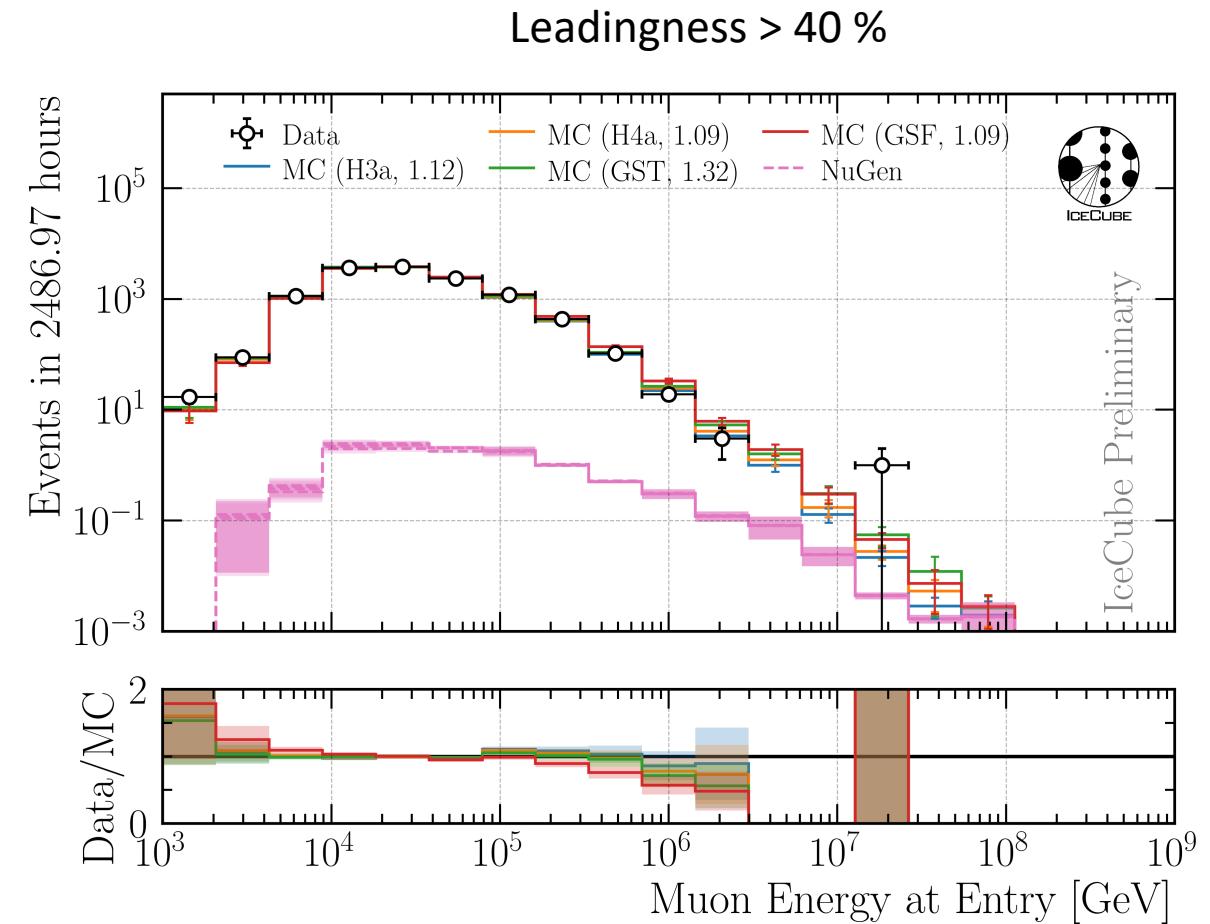
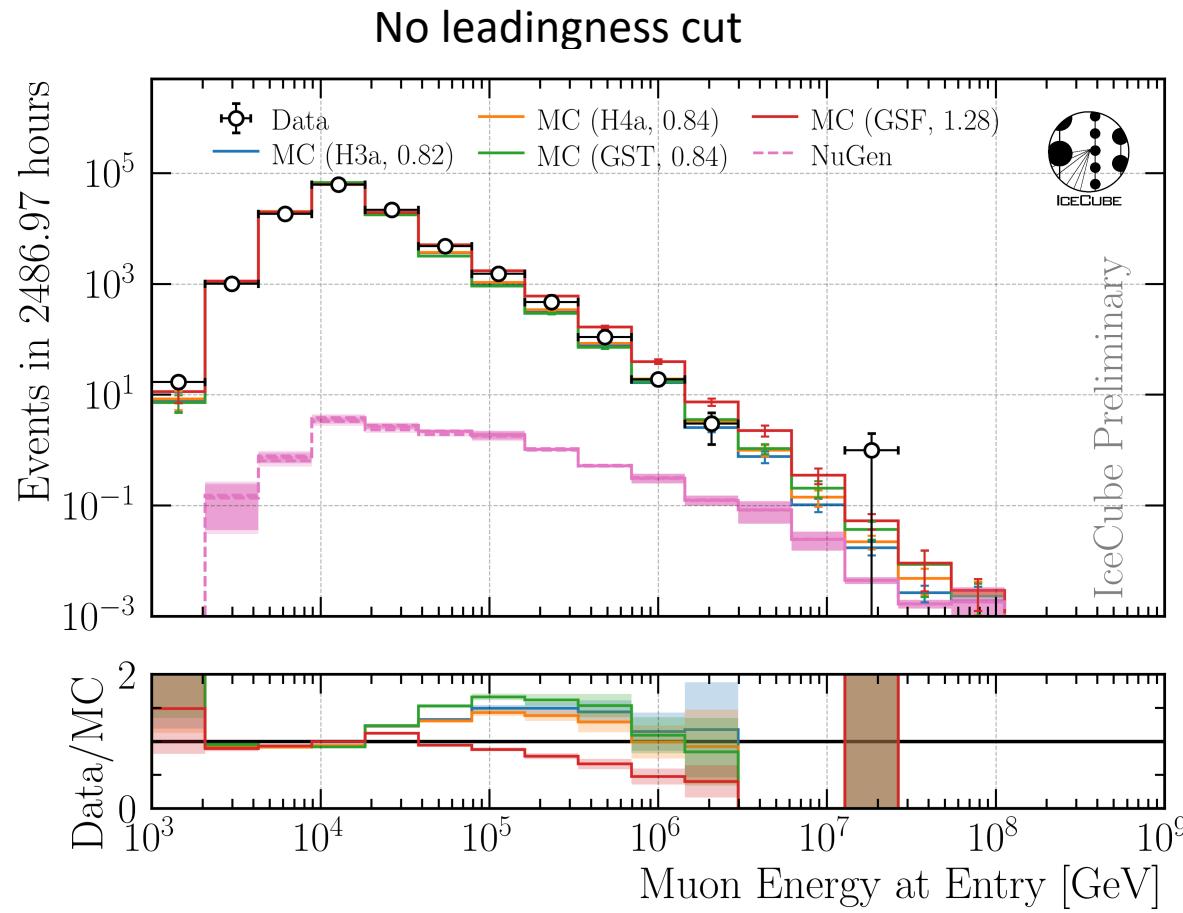
- Remove outliers
- Depth—dependent slope (no analysis relevance)
- CR—model impact on energy reconstruction
- 23 quality cuts in total

Level 5: Data/MC Quality Cuts



Final Level: Leadingness > 40 %

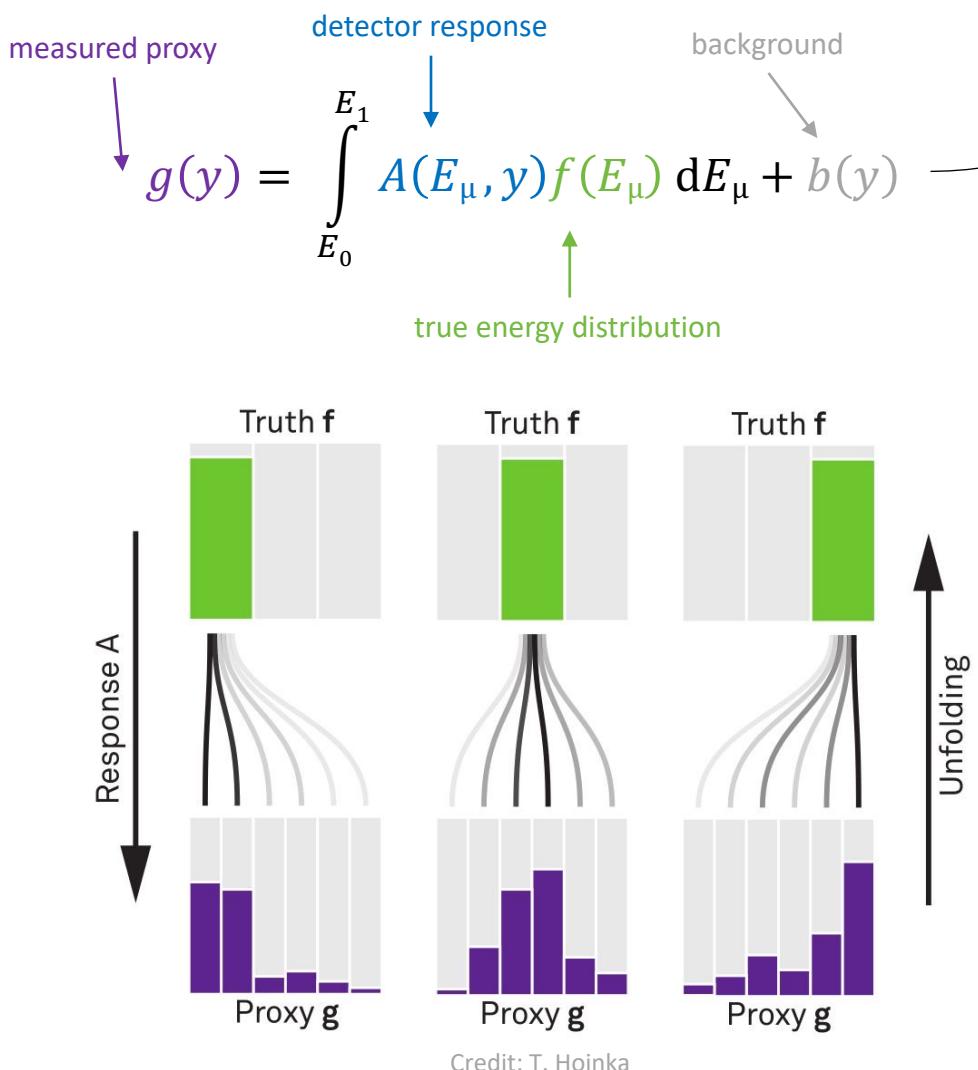
$$L = \frac{\text{Leading Energy at Entry}}{\text{Bundle Energy at Entry}}$$



➤ Improve Data/MC by leadingness cut

Unfolding

Unfolding in a nutshell



folding

unfolding

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

2. Maximum likelihood method:

3. Tikhonov regularization:

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

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

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



funfolding
by M. Börner

Muon Flux Unfolding

- ❑ Effective area
- ❑ Systematics
- ❑ Proxy that correlates with target
- ❑ Regularization
 - Unfolding

Event Rate to Flux → Effective Area

- Unfolding estimates an event rate
- Transfer event rate to flux

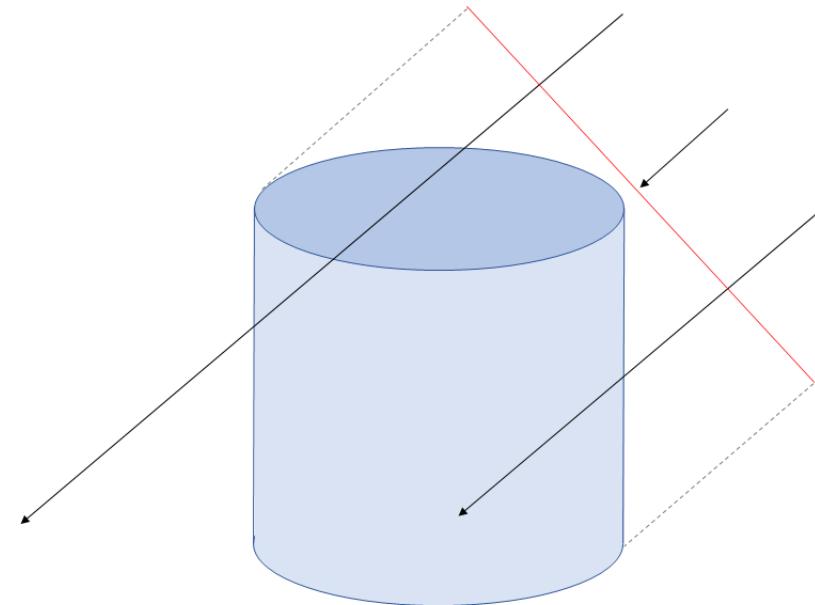
$$\Phi_i = \frac{N_i}{T \cdot \Delta L_i \cdot \Omega_i \cdot A_{\text{eff},i}}$$

- with solid angle

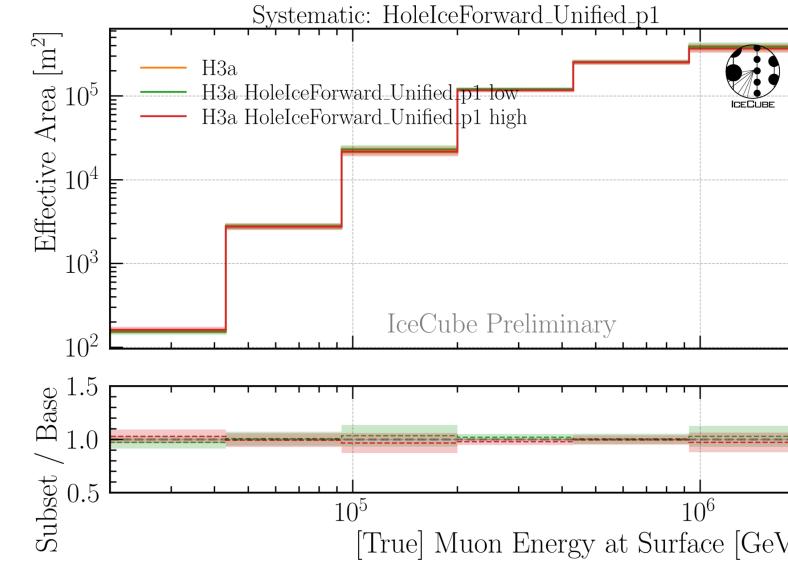
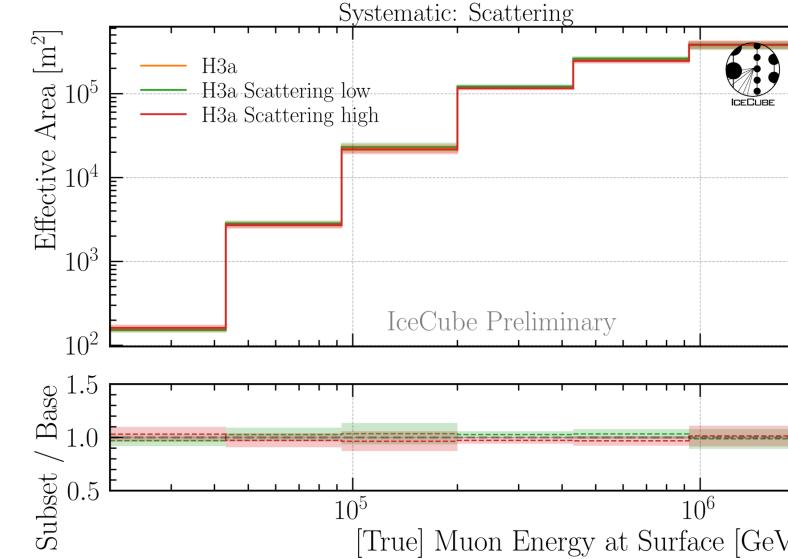
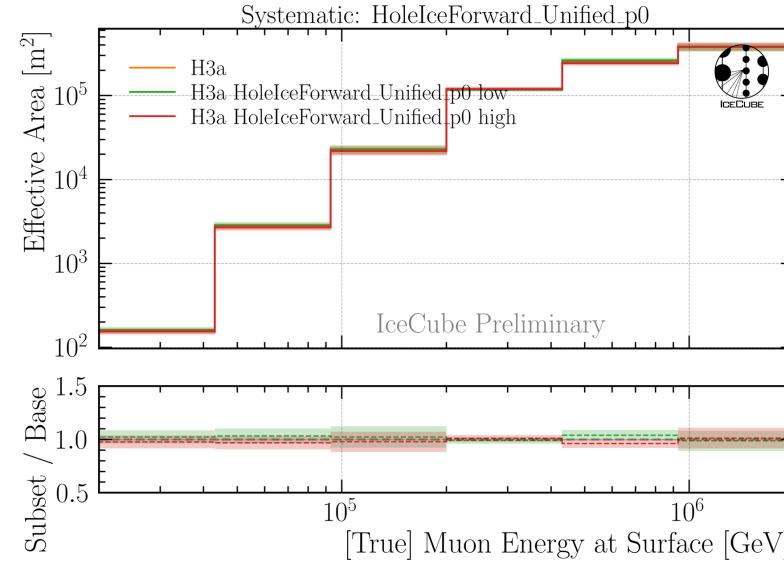
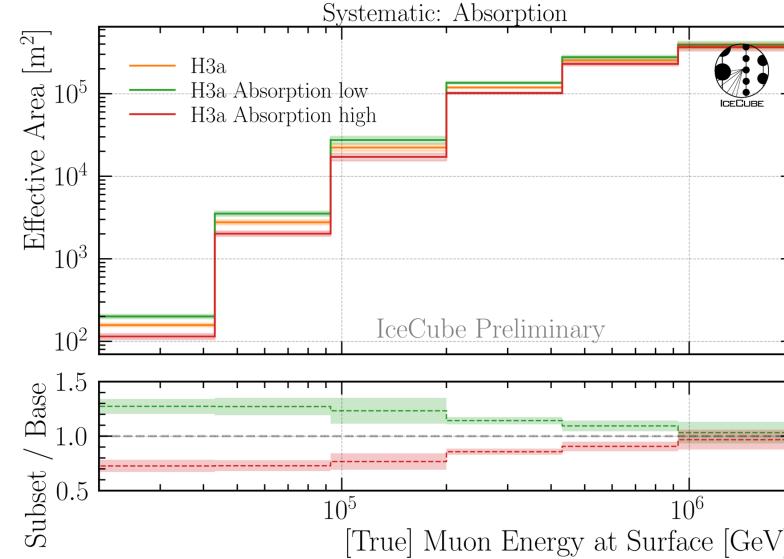
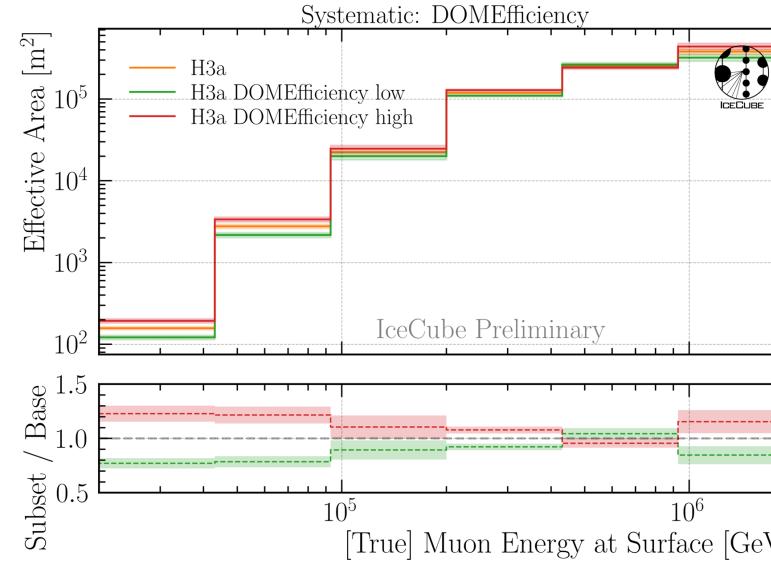
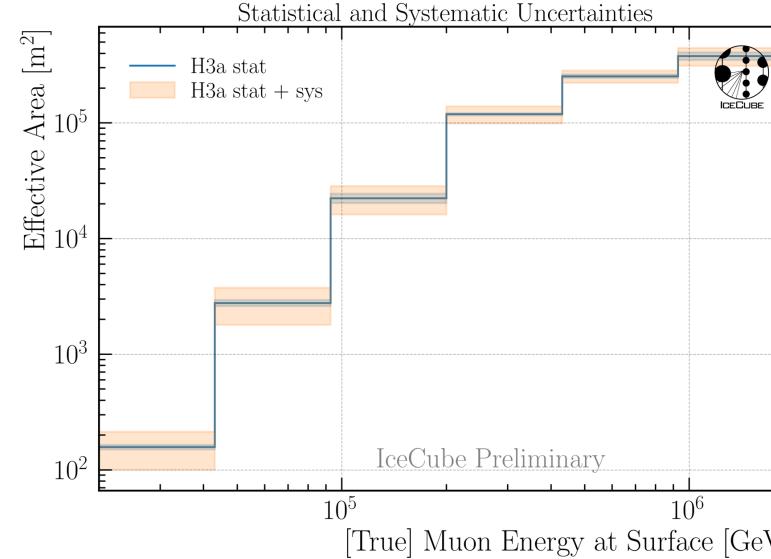
$$\Omega_i = 2\pi \cdot (\cos \Theta_{\min,i} - \cos \Theta_{\max,i})$$

- and effective area

$$A_{\text{eff}} = A_{\text{sim}} \frac{N_{\text{sel}}}{N_{\text{gen}}}$$



Ice & Detector Systematics



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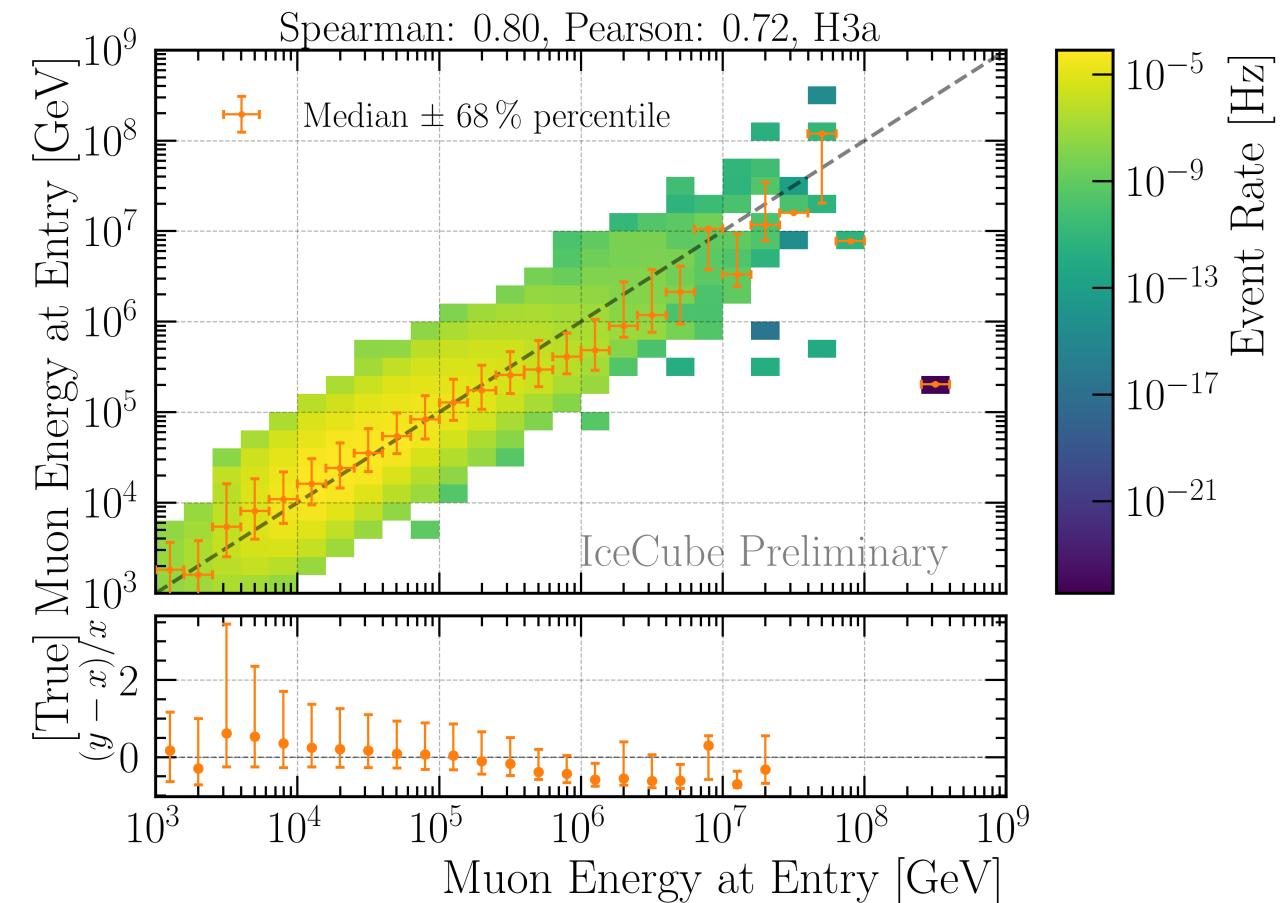
- Baseline: entire set
- Subset: above/below center

$$\sigma_{\text{sys},i} = \max(A_{\text{low}} - \sigma, A_{\text{high}} + \sigma) - A_{\text{base}}$$

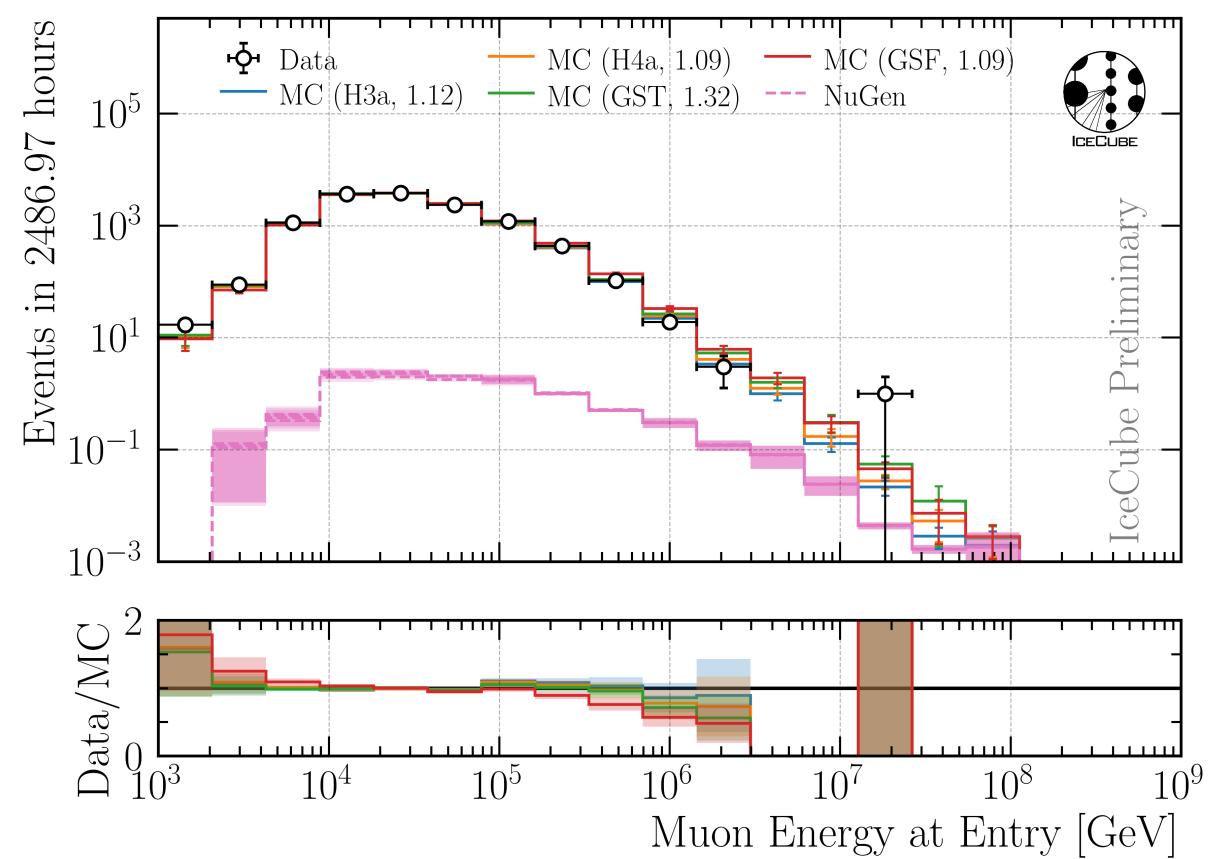
$$\sigma_{\text{tot}} = \sqrt{\sigma_{\text{stat}}^2 + \sum_i \sigma_i^2}, i: \text{scat, abs, DOME, holeice p0, p1}$$

Reconstruction and Data—MC: Leading Muons

- Good reconstruction of leading muon energy → proxy

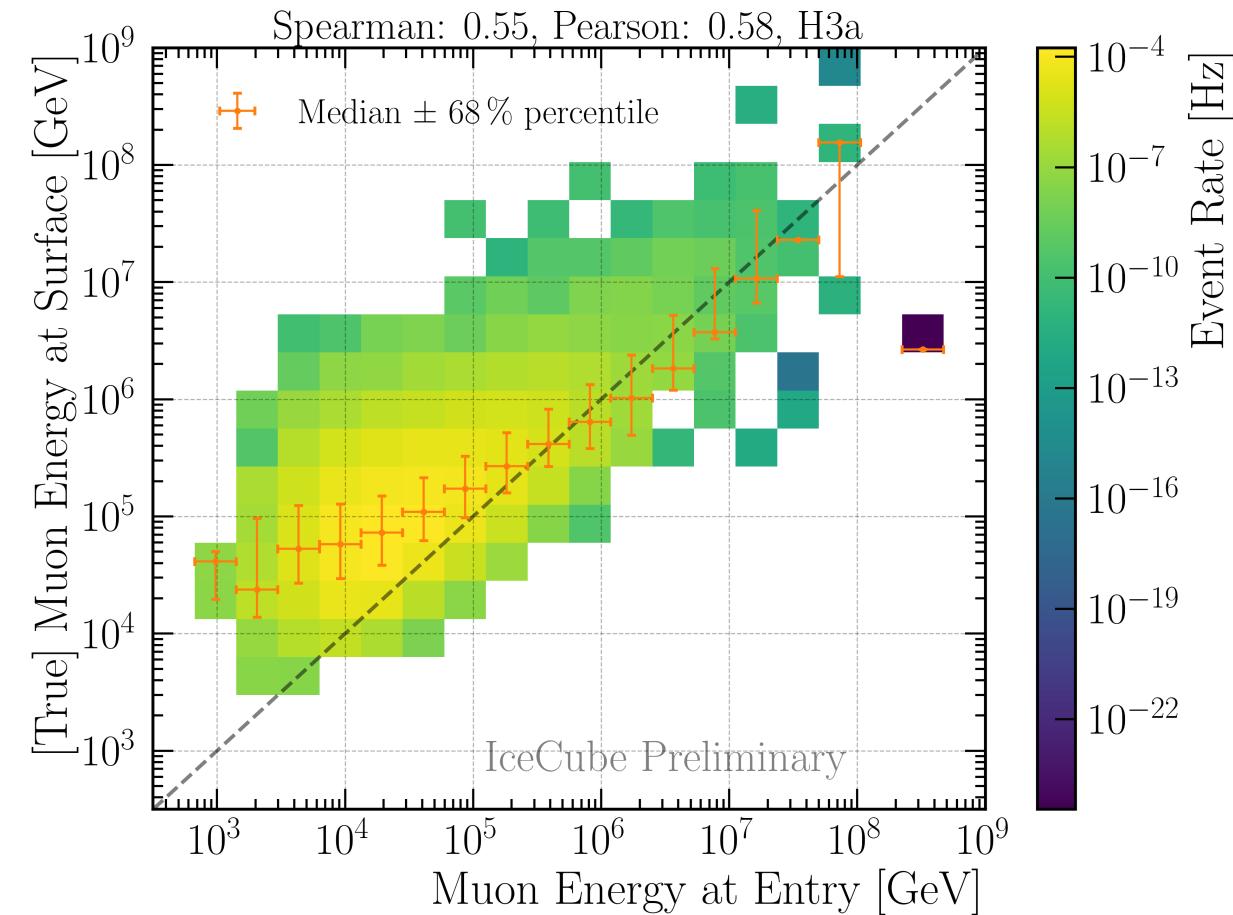


- Good data—MC agreement
- Global offset → upscale MC by 12%

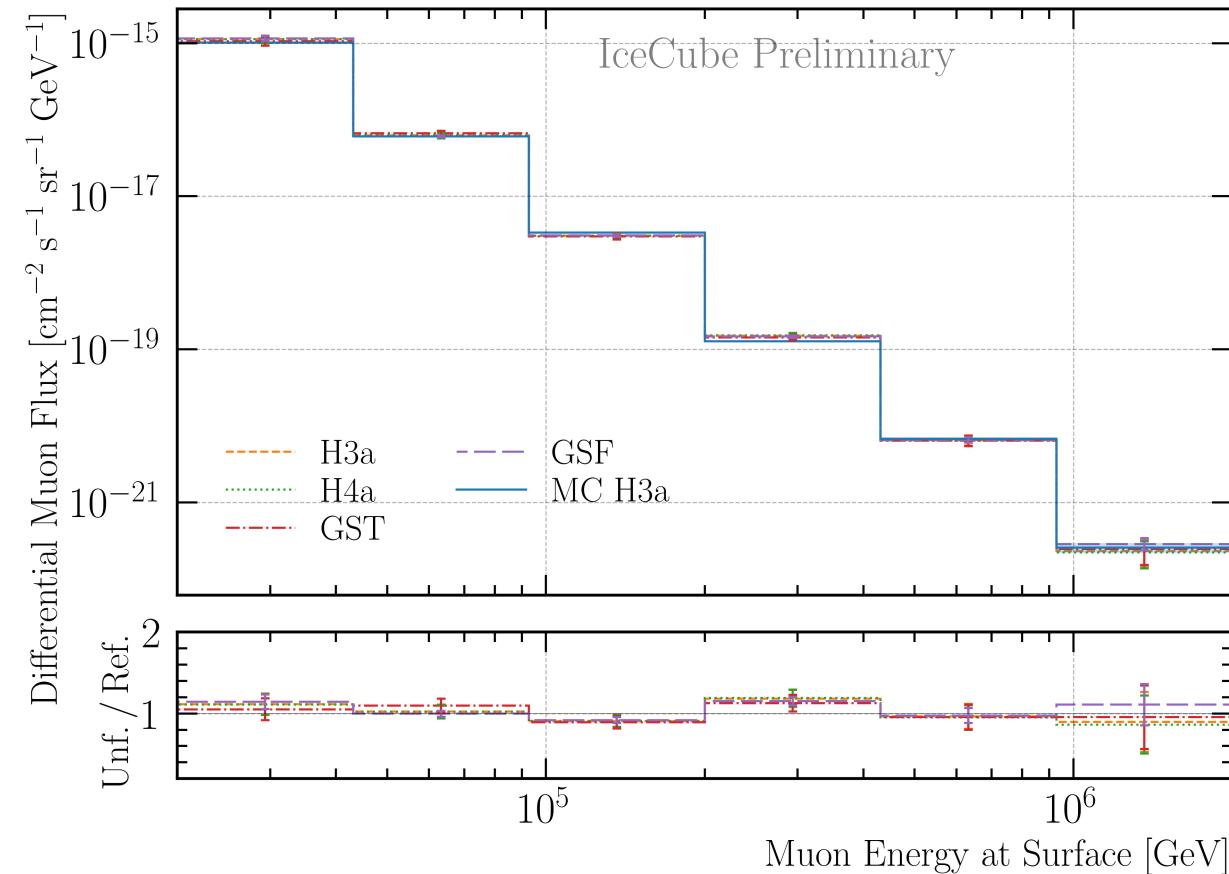


Correlation and Robustness Test: Leading Muons

- Correlation between proxy and target



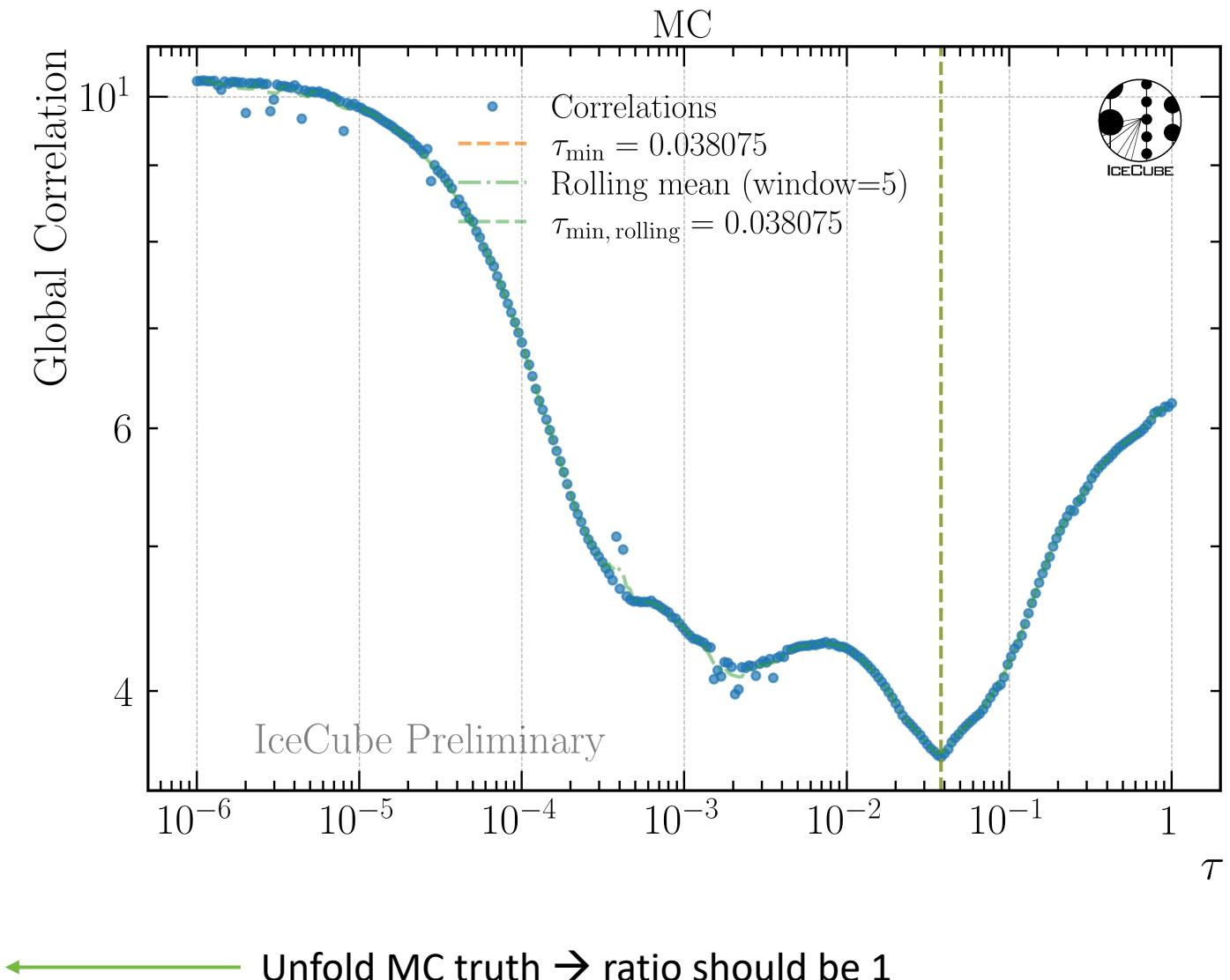
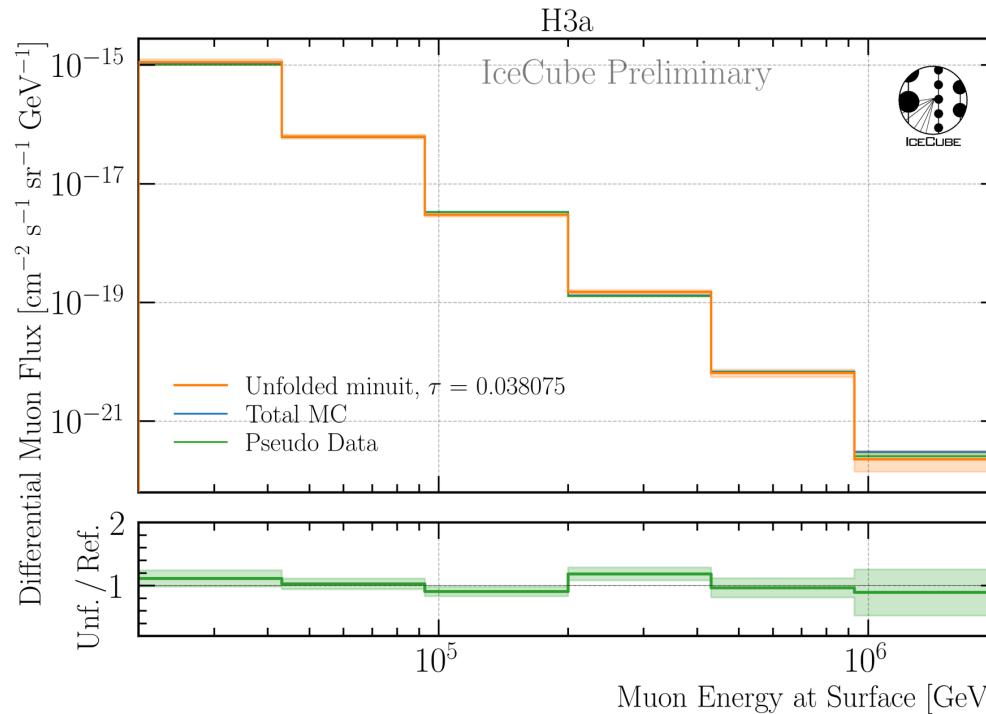
- Build unfolding matrix on H3a, H4a, GST & GSF
- Unfold H3a as test set
- Results are within uncertainties → robust



Determine Regularization

- Find regularization τ with minimal bin-to-bin correlation
- LLH minimization (unfolding) provides full covariance matrix V

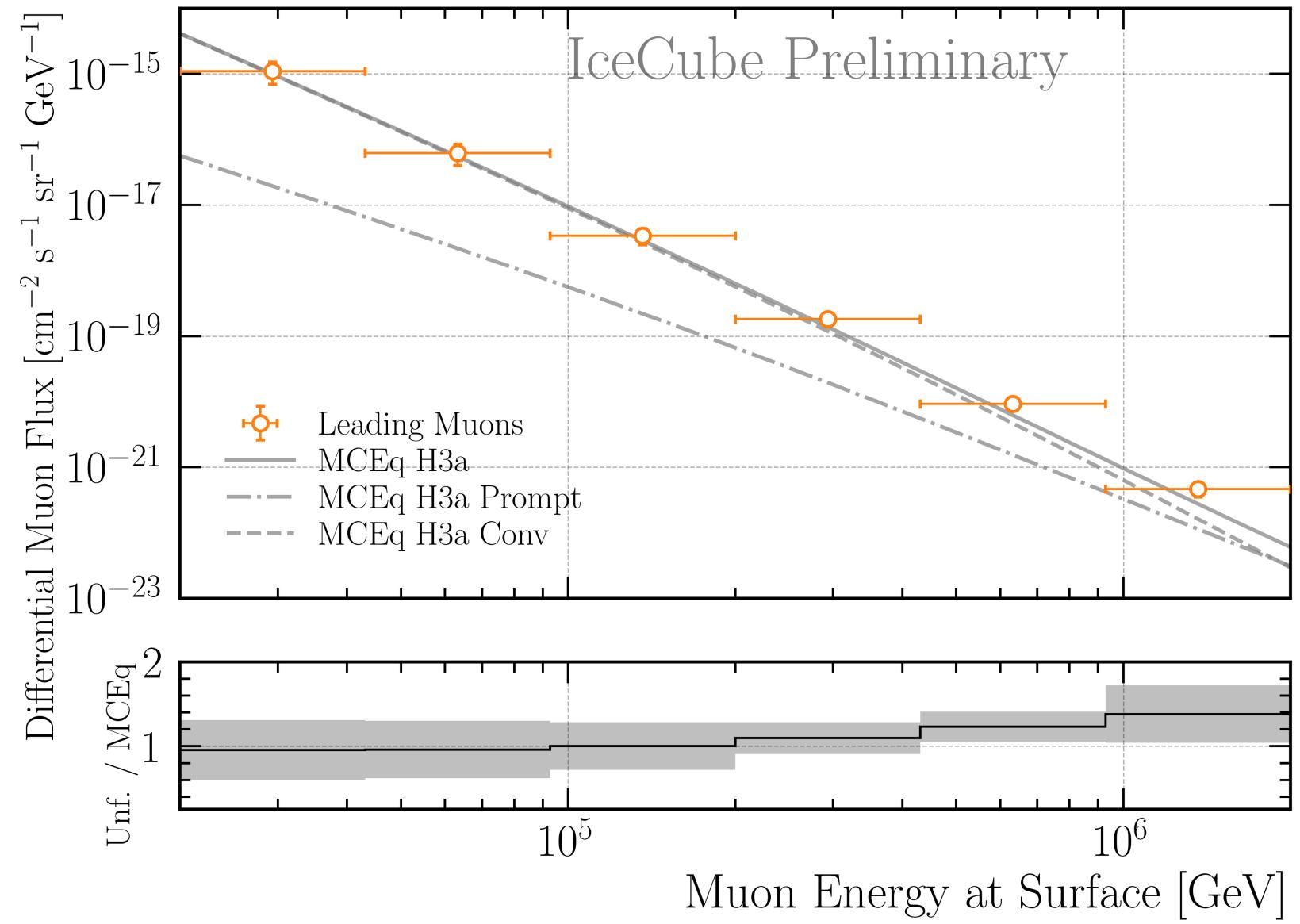
➤ Minimize global correlation $\rho = \sum_{i > i} V_{ij}$



Muon Flux Unfolding

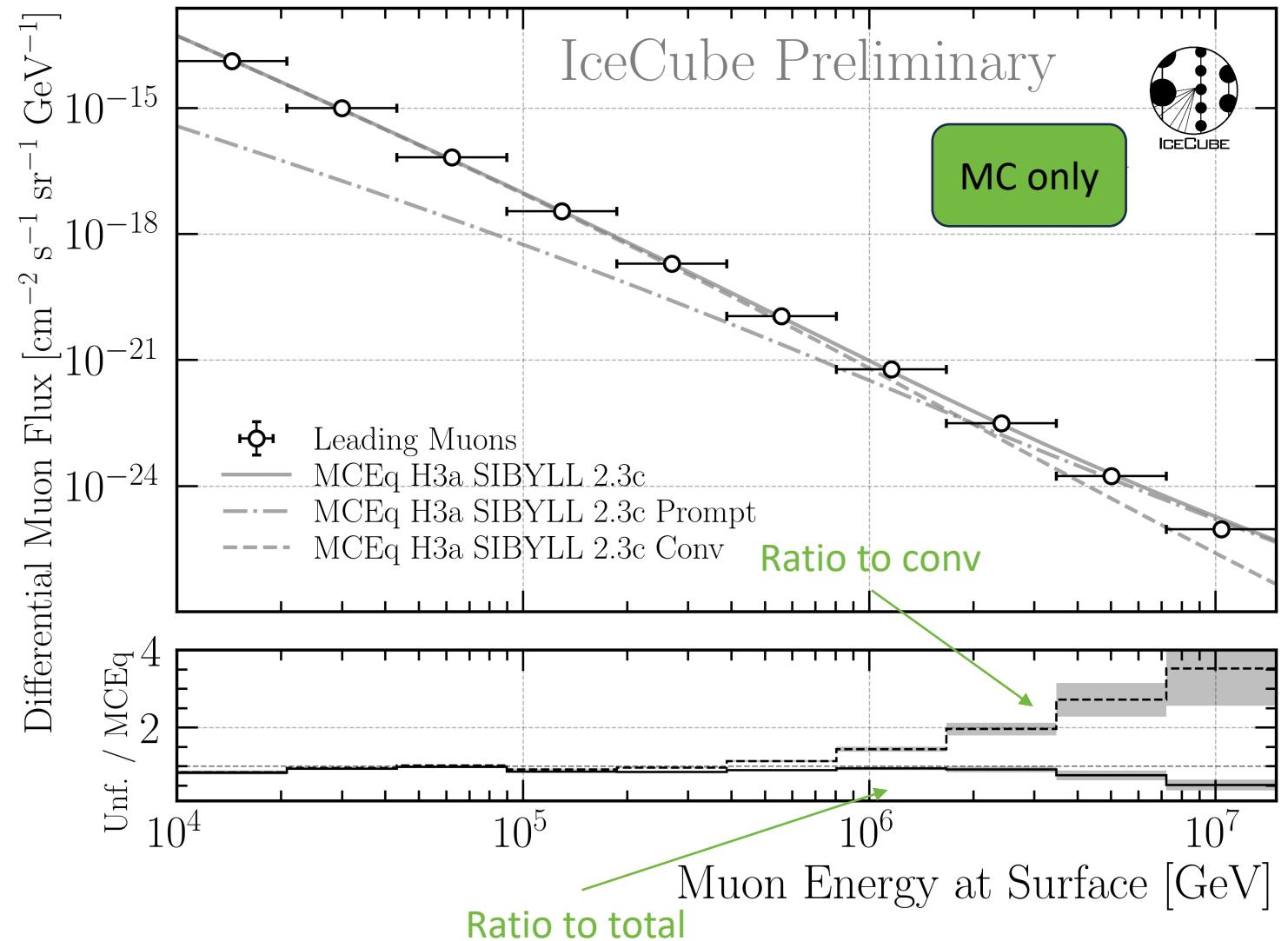
Leading muons

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



Future: 12 Years of IceCube Data Unfolding

- Finalize analysis
 - Proper systematic uncertainty estimation
- Unfold 12 years of data
- Extend energy range to >10 PeV
- Characterize the atmospheric muon flux
 - Determine prompt component



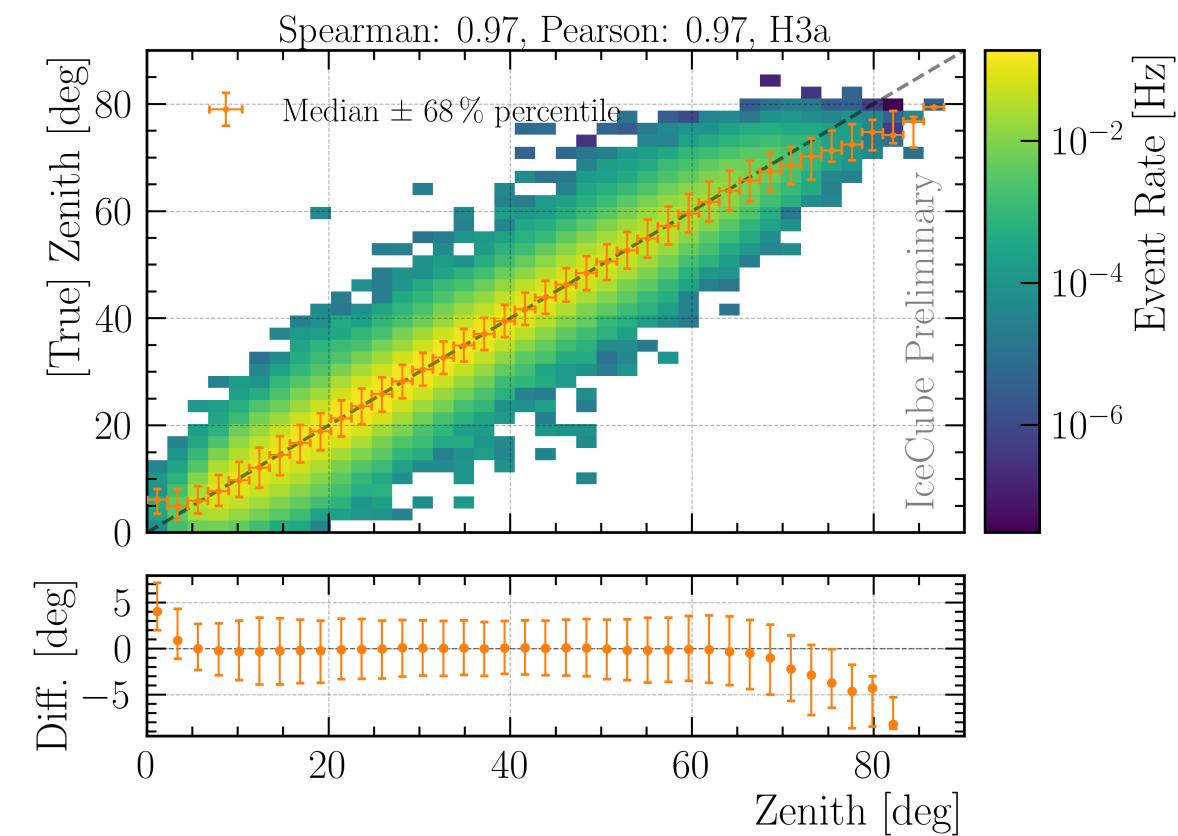
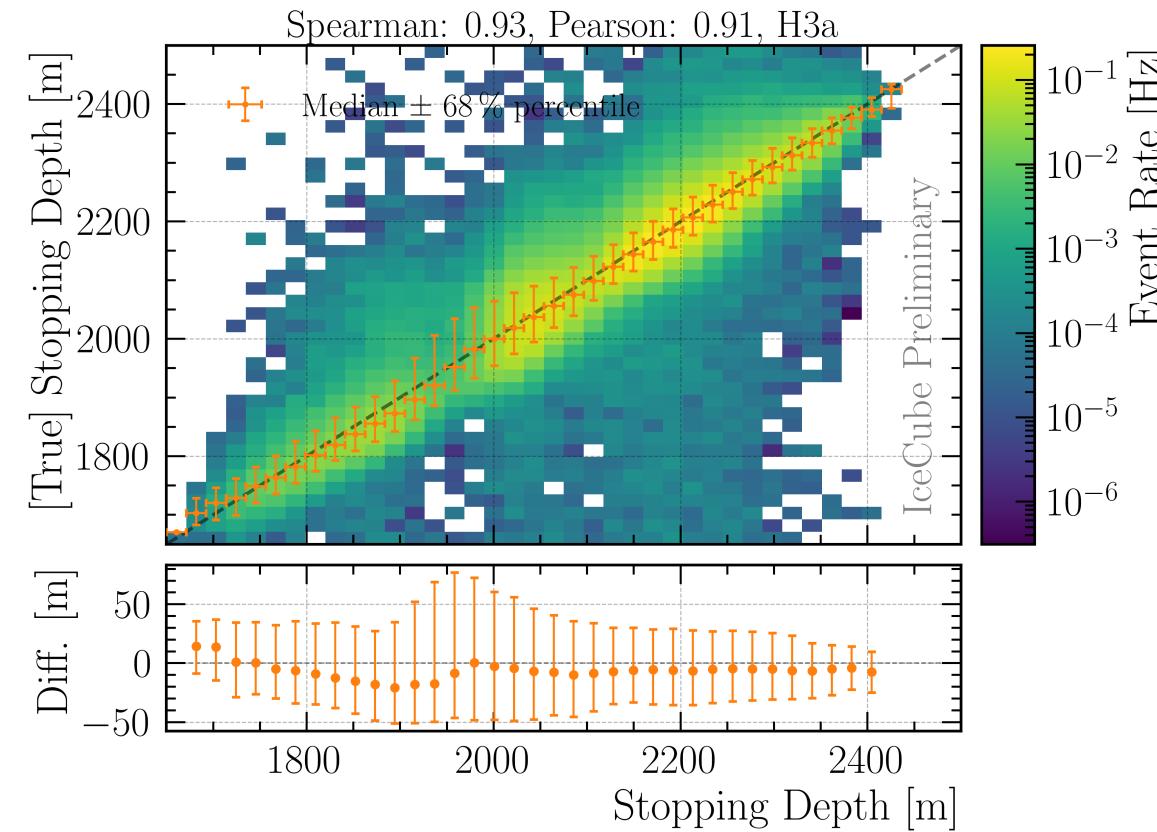
Depth Intensity Unfolding

Utilizing stopping muons

by Lucas Witthaus

Reconstructions: Stopping Muons

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

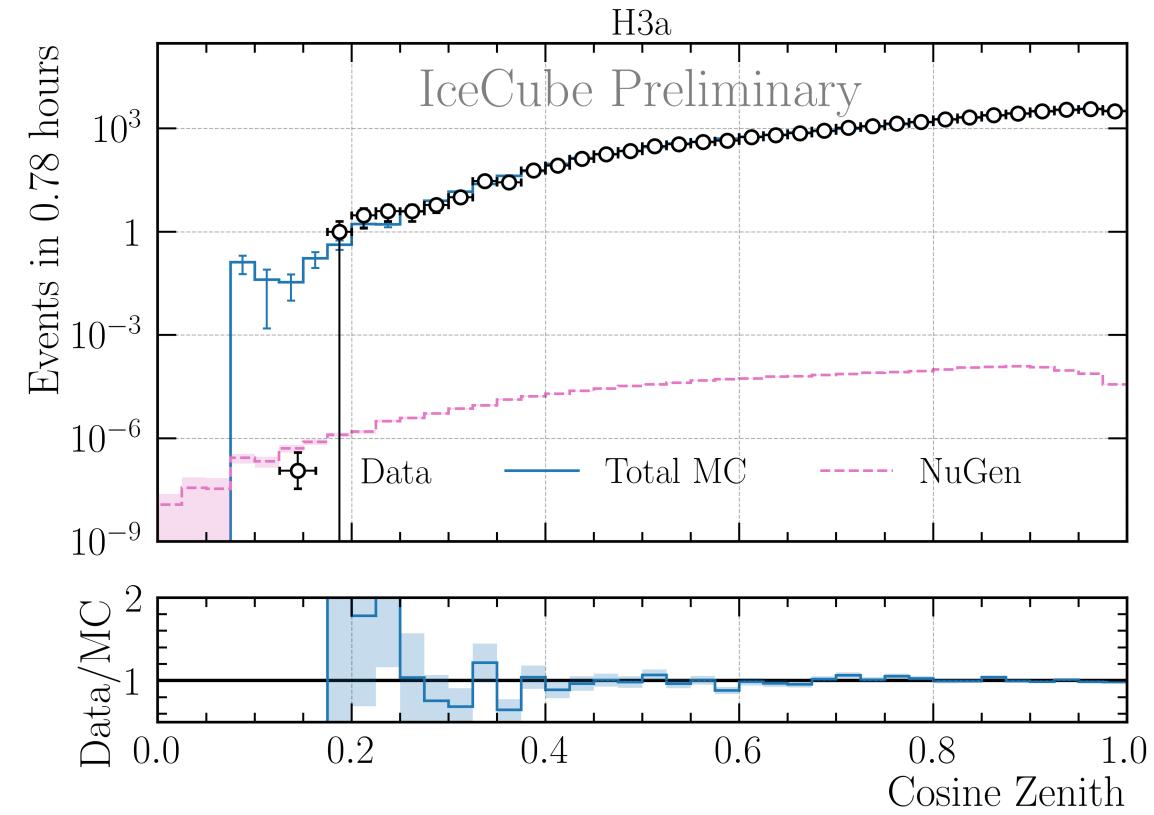
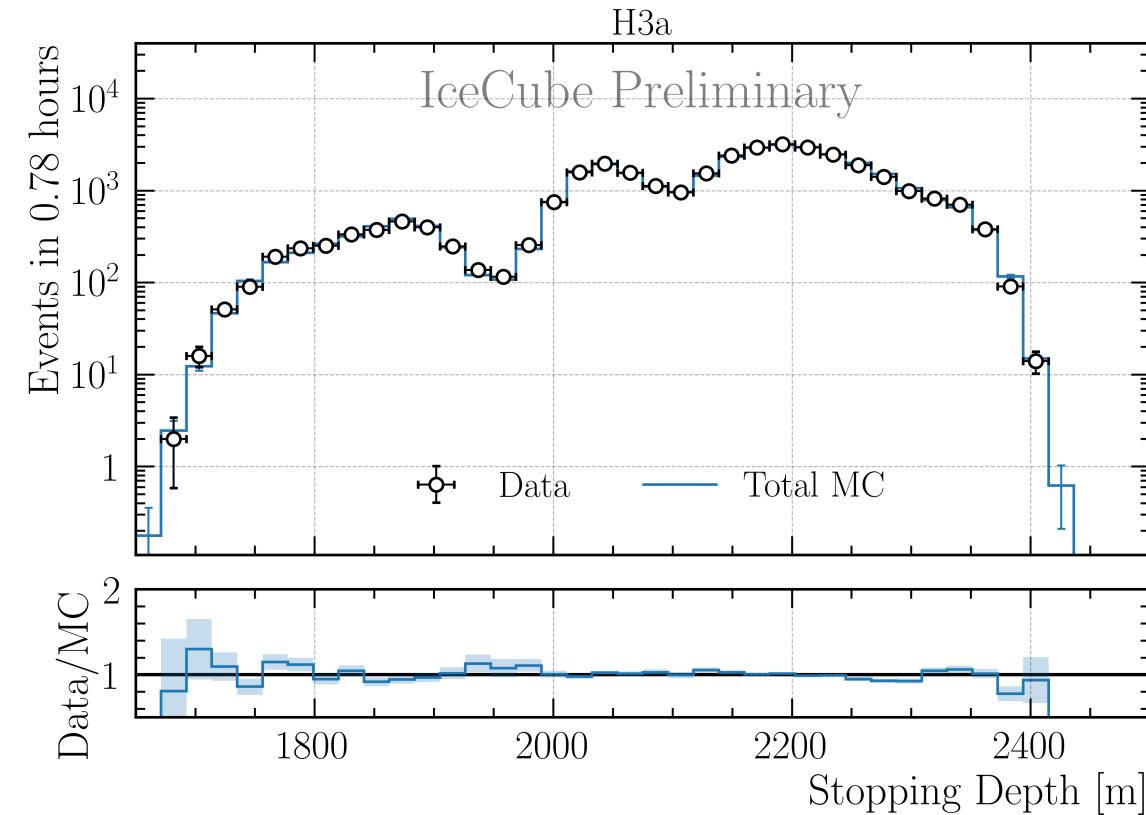


Data—MC: Stopping Muons

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

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

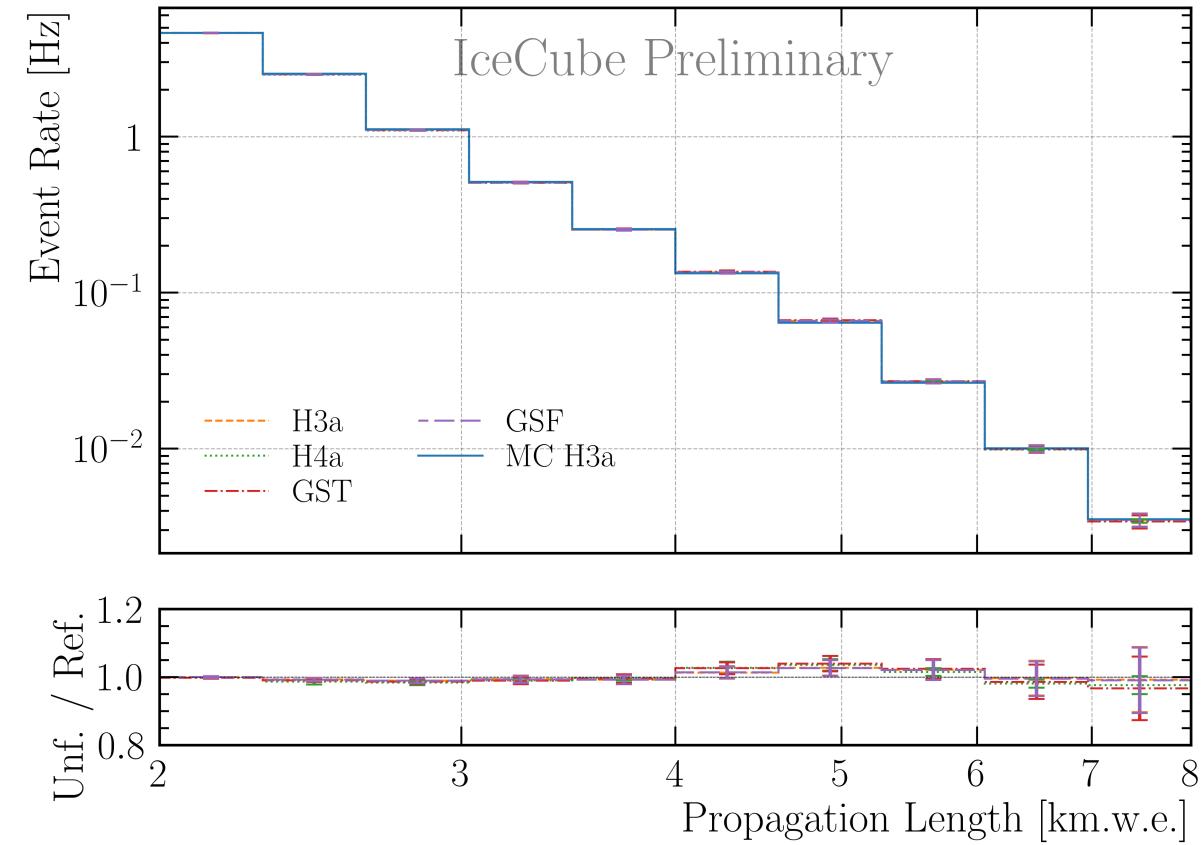
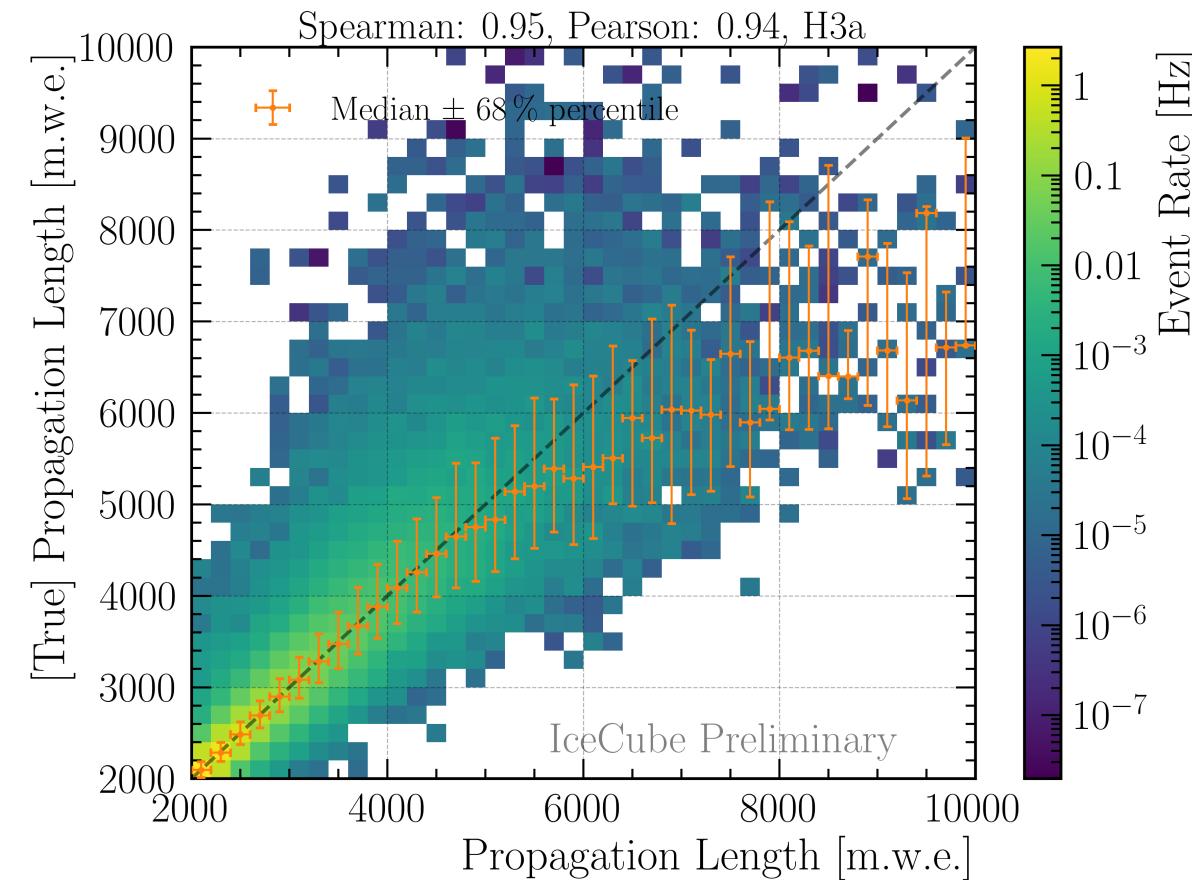
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Correlation and Robustness Test: Stopping Muons

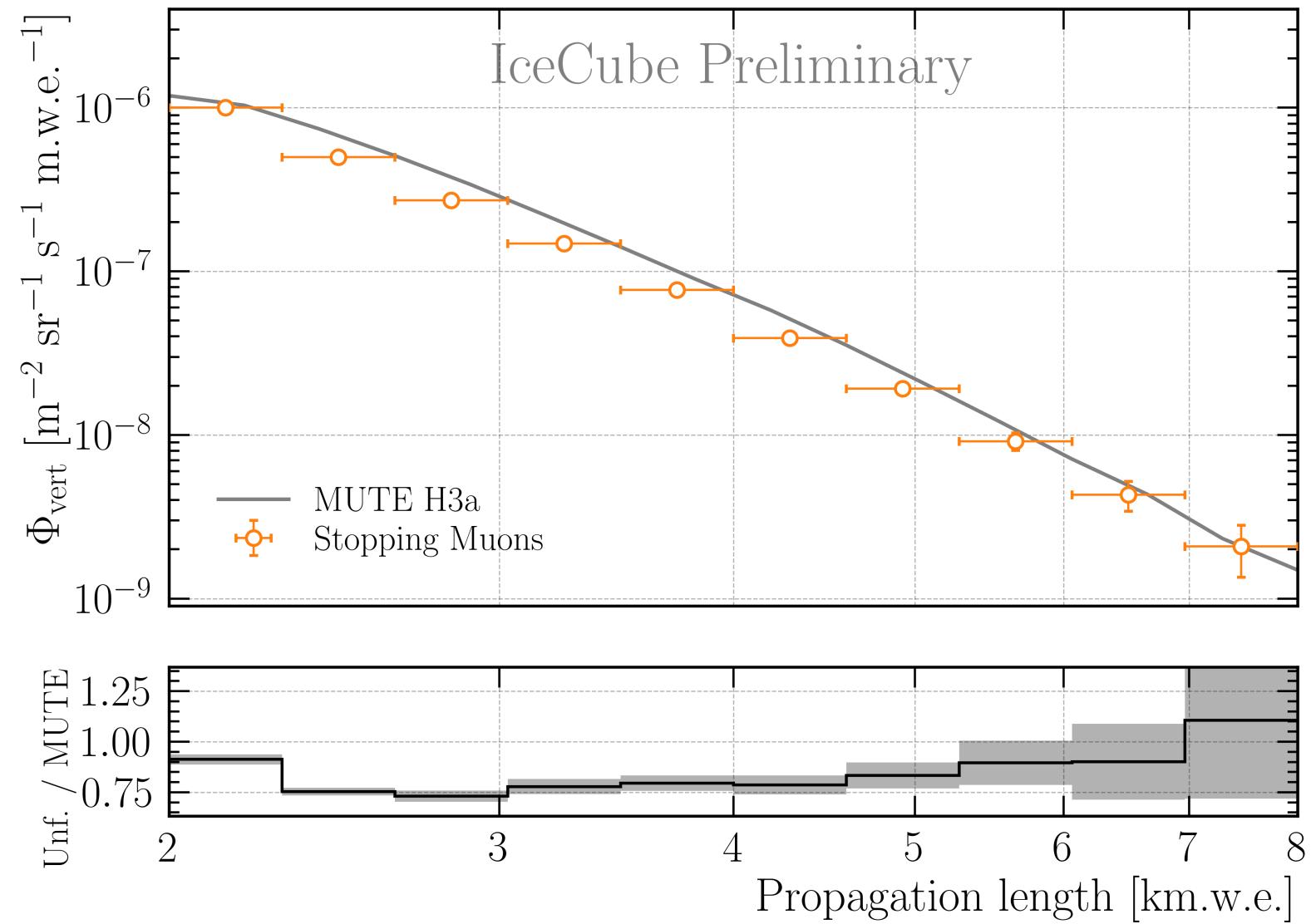
➤ Strong correlation between proxy and target

- 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

Stopping and Leading muons

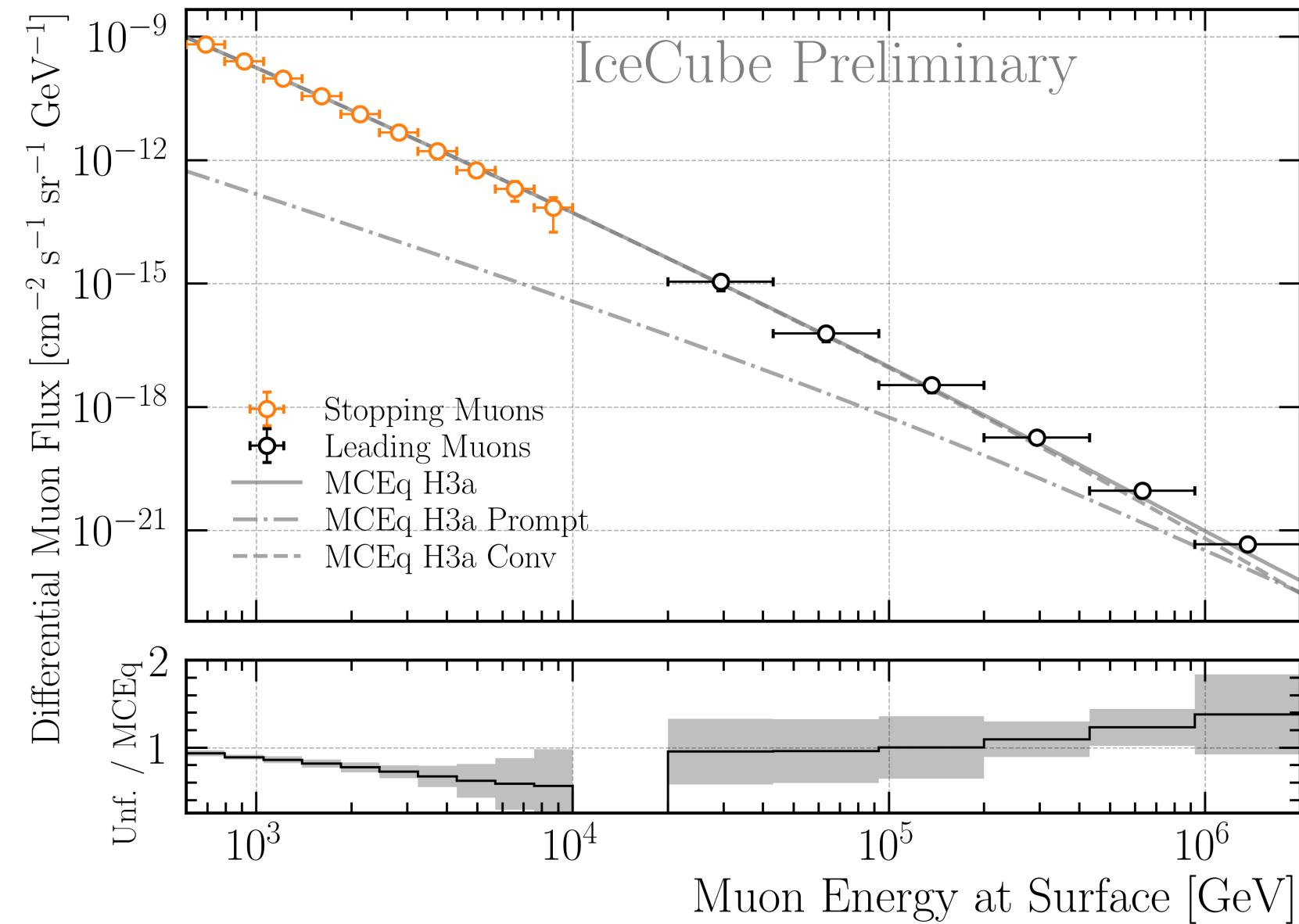
Muon Flux Unfolding

Leading muons

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

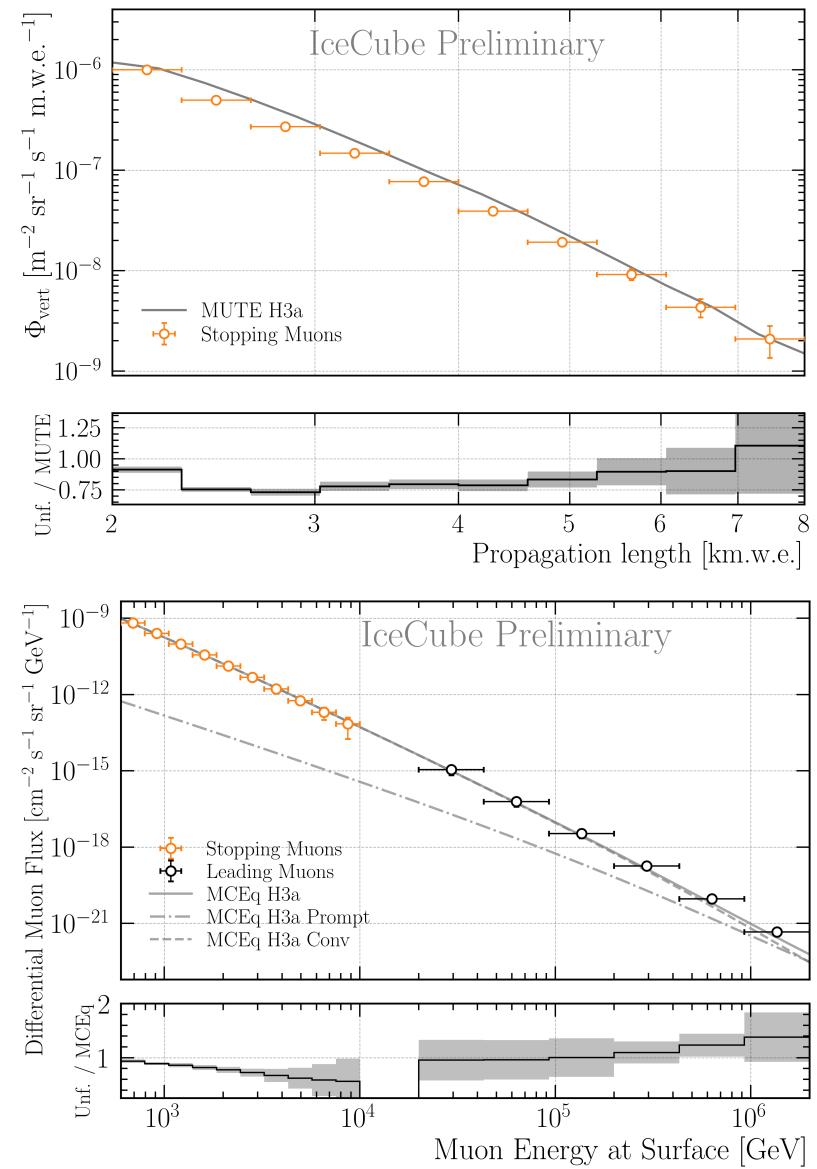
Stopping muons

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



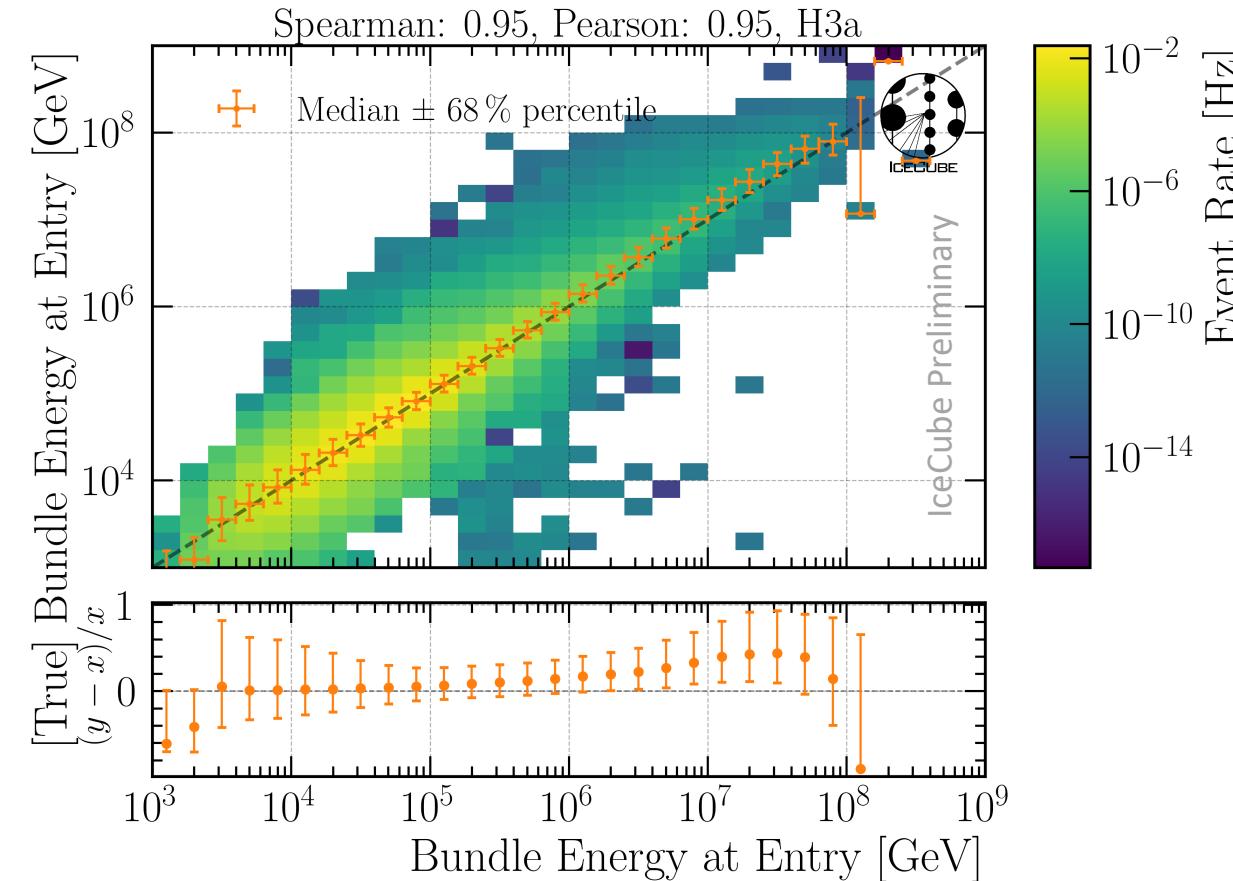
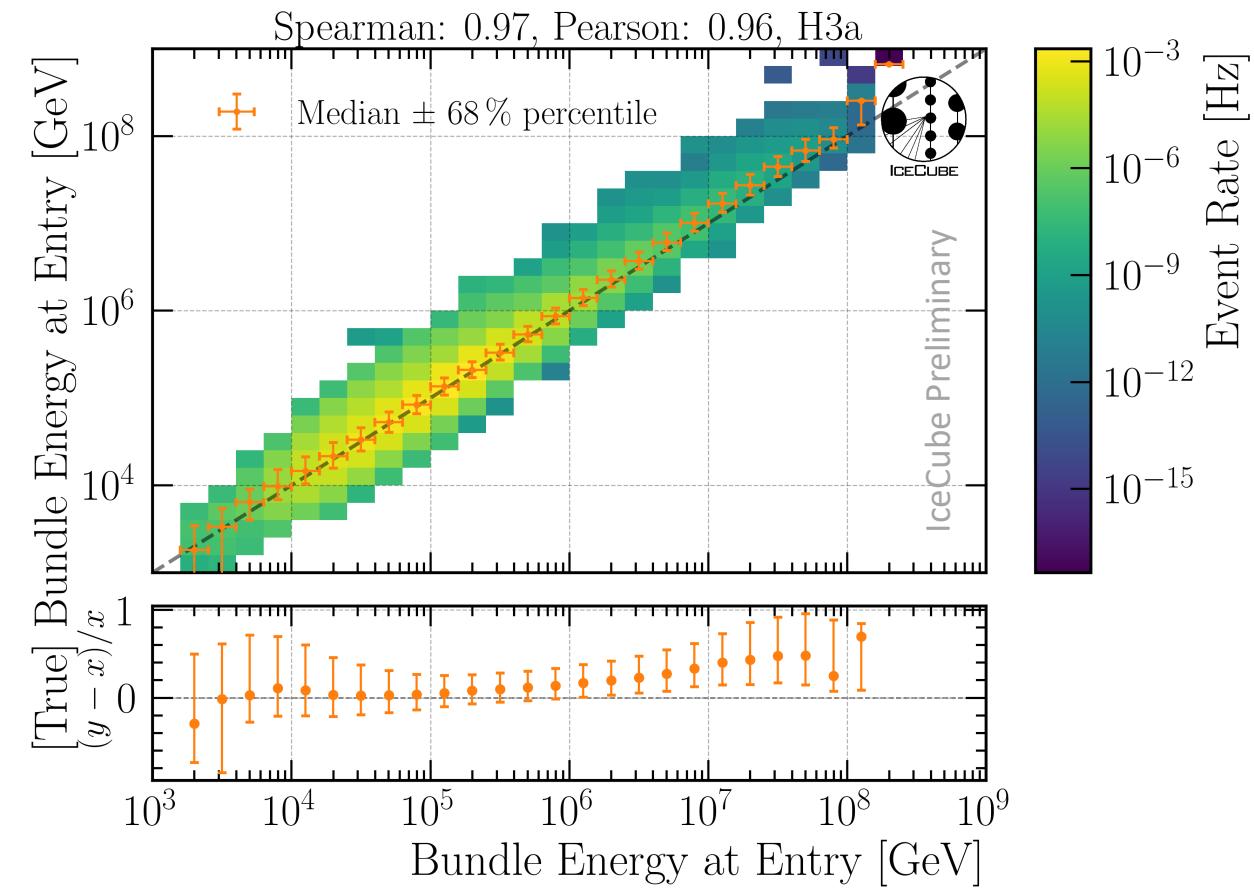
Conclusion & Outlook

- 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 to the flux at \sim 2 PeV
- Finalize both analyses → unfold with more data
 - Extend energy range up to \sim 10 PeV



Backup

Bundle Energy Reconstruction

Level 4**Level 5**

Muon Filter

MuonFilter The I3MuonFilter_13 selects events based on reconstructed track quality and charge brightness, using criteria that depend on the reconstructed zenith angle. It requires three inputs: a cleaned pulse series map, a reconstructed track, and the log-likelihood fit parameters associated with the track. From the pulse series map, the number of hit DOMs N_{ch} and the total charge Q_{tot} , defined as the sum of the pulse charges over all DOMs, is determined. Then, the logarithmic charge $\ell = \log_{10}(Q_{\text{tot}})$ is calculated. The cosine of the reconstructed zenith angle is computed as $\cos(\theta)$, and the per-DOM log-likelihood value is retrieved from the fit parameters.

Events are classified into three angular zones based on the value of $\cos(\theta)$:

- Zone 1: $-1.0 < \cos \theta \leq 0.2$
- Zone 2: $0.2 < \cos \theta \leq 0.5$
- Zone 3: $0.5 < \cos \theta \leq 1.0$

Each zone applies a different selection criterion:

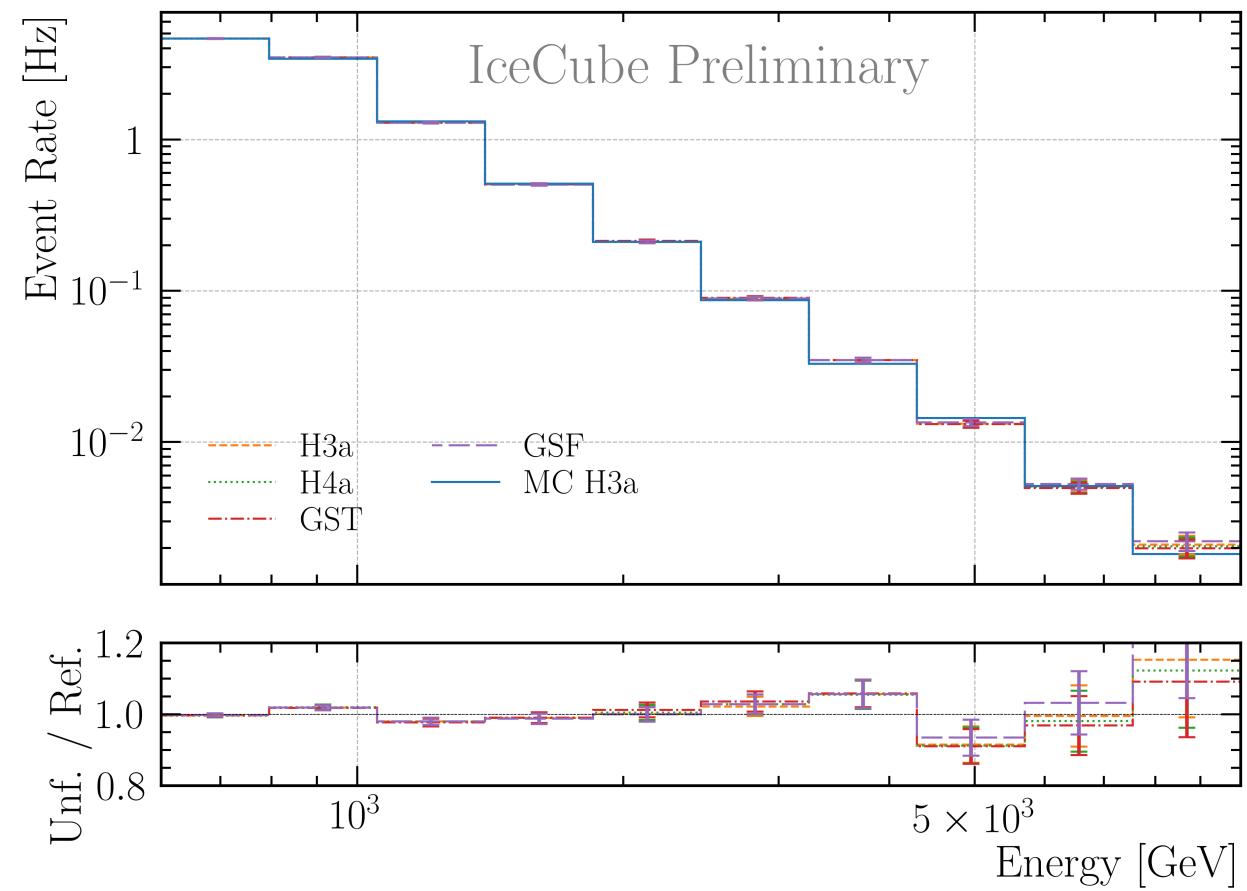
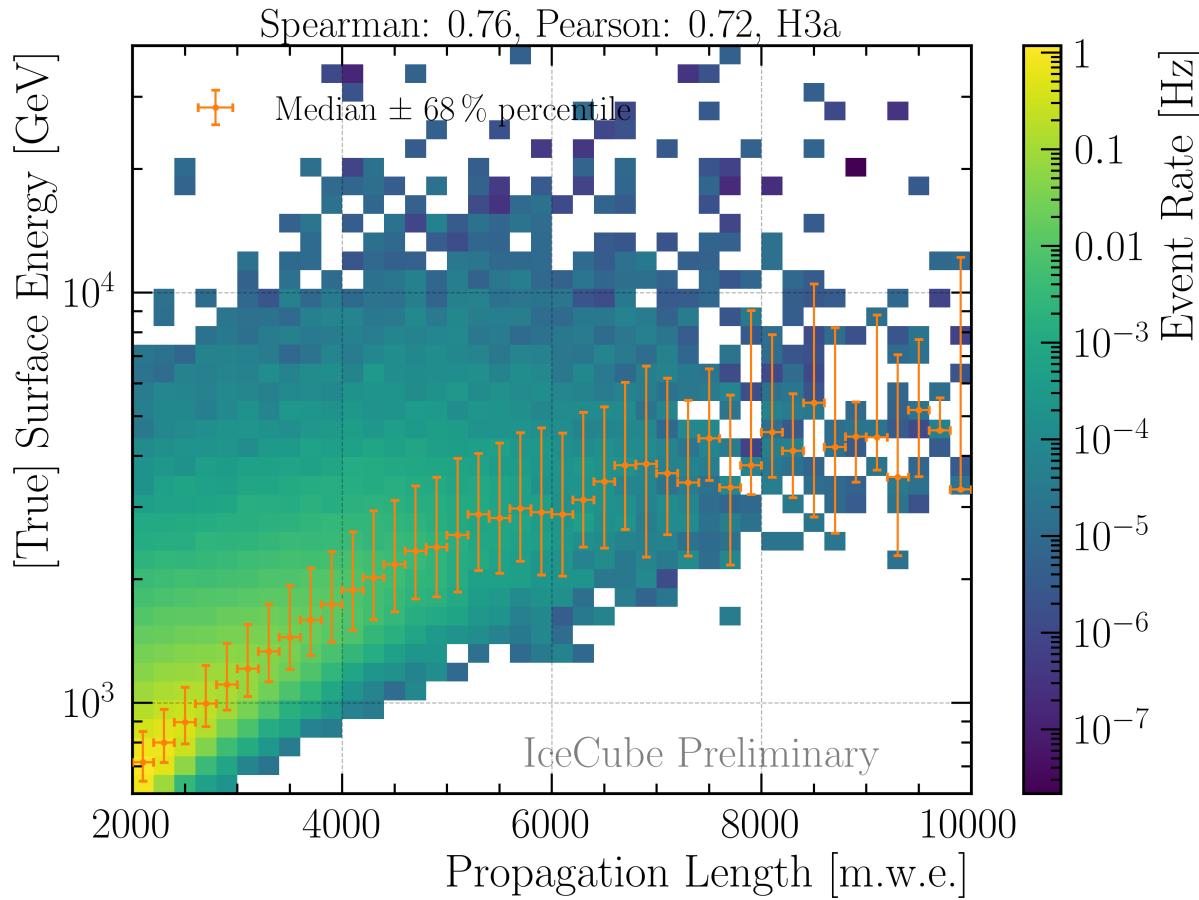
- Zone 1: the filter computes a scaled log-likelihood value $\tilde{\lambda} = \text{rlogl} \cdot \frac{N_{\text{ch}} - 5}{N_{\text{ch}} - 3}$, and accepts the event if $\tilde{\lambda} \leq 8.7$.
- Zone 2: the filter applies a brightness-based cut and accepts the event if $\ell > 3.9 \cdot \cos \theta + 0.65$.
- Zone 3: a similar brightness cut is used with a shallower slope $\ell > 0.6 \cdot \cos \theta + 2.3$.

The event is accepted if it passes the selection criteria for any of the three zones. This design ensures that events are selected based on fit quality in the near-horizontal region and on brightness in the vertical direction, balancing background suppression with high signal efficiency across the full zenith range.

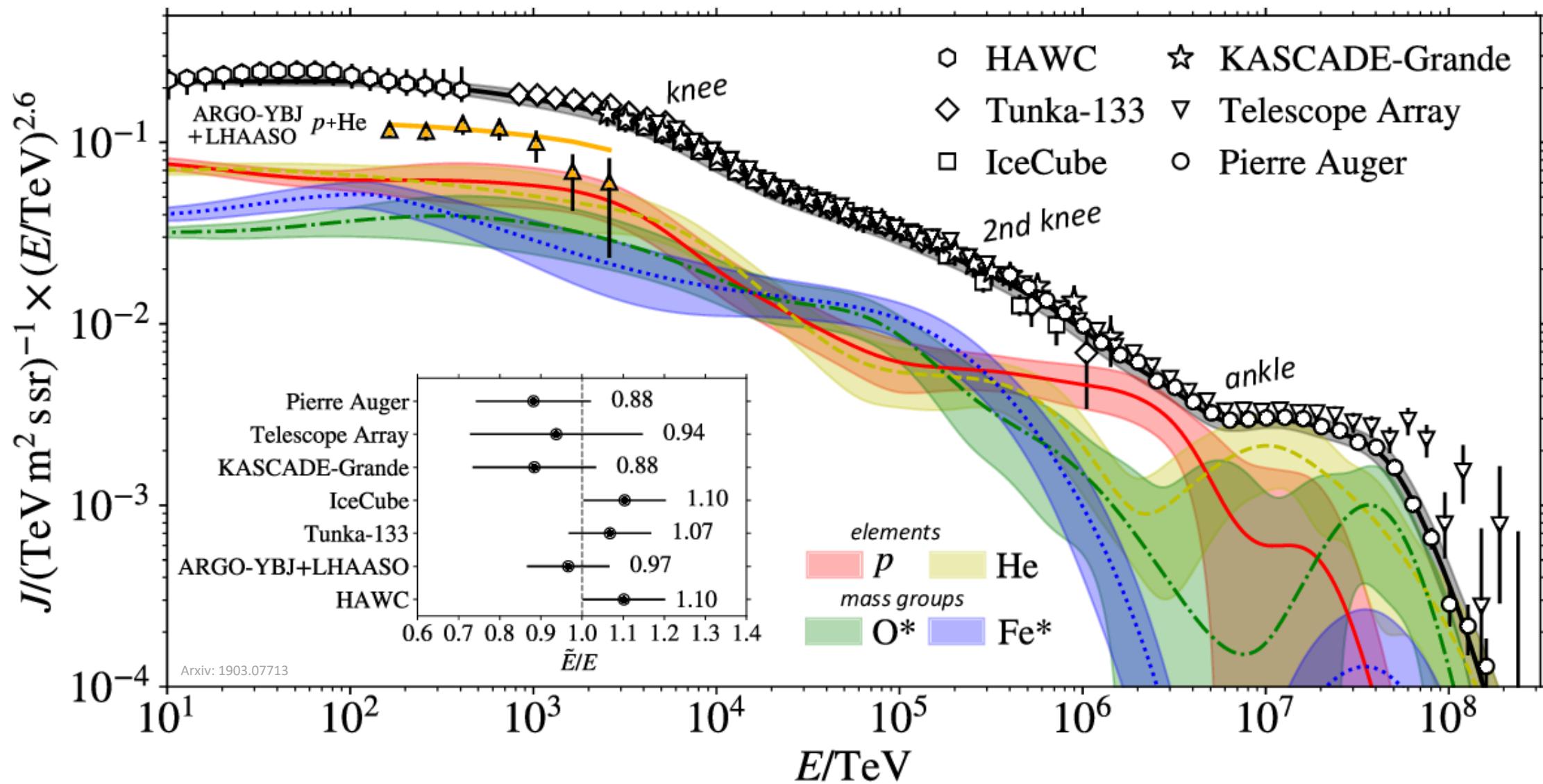
Correlation and Robustness Test: Stopping Muons

- Correlation between proxy and target

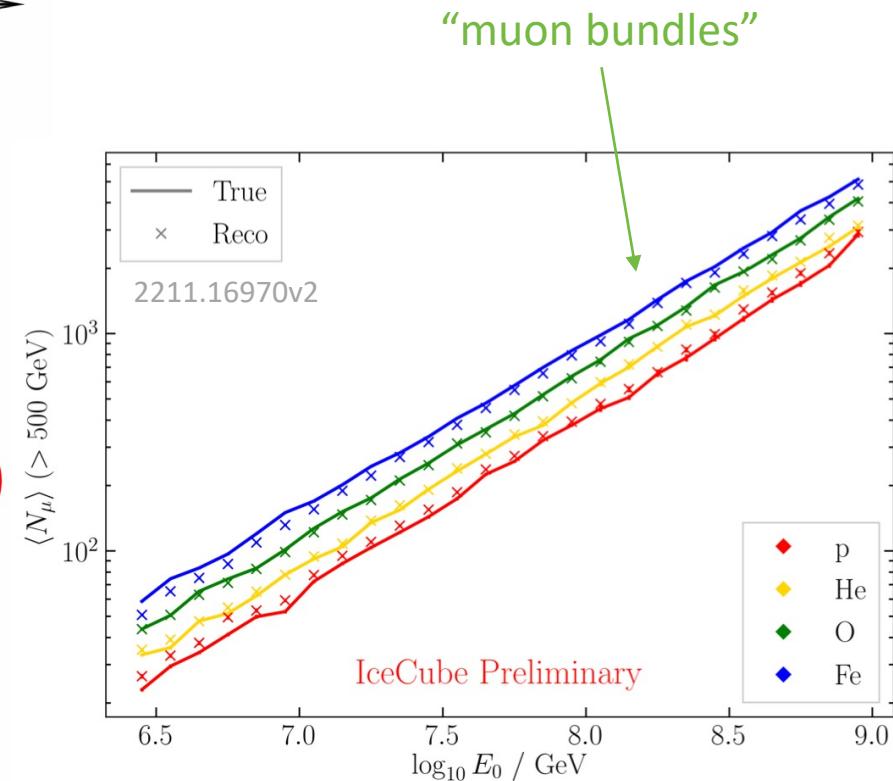
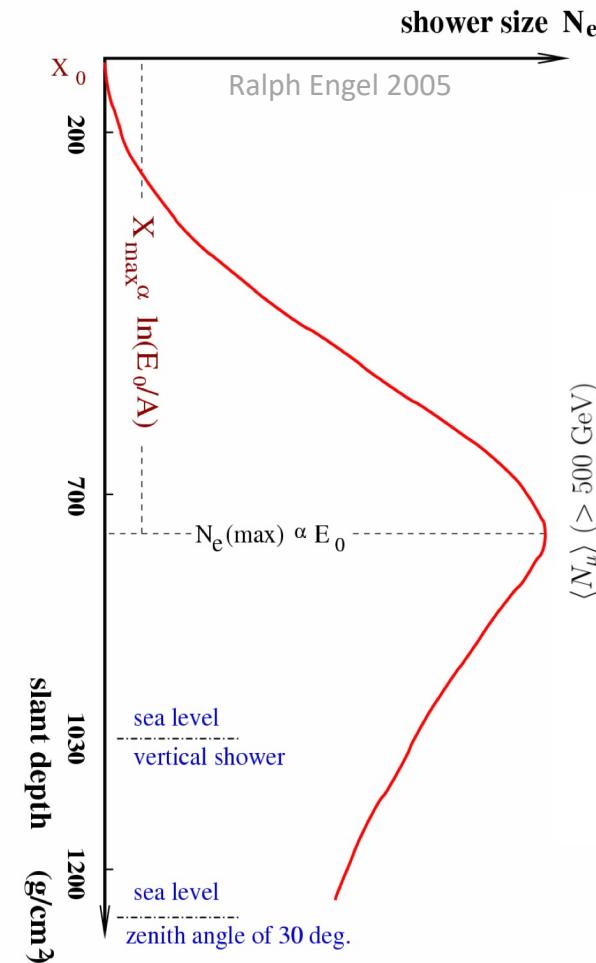
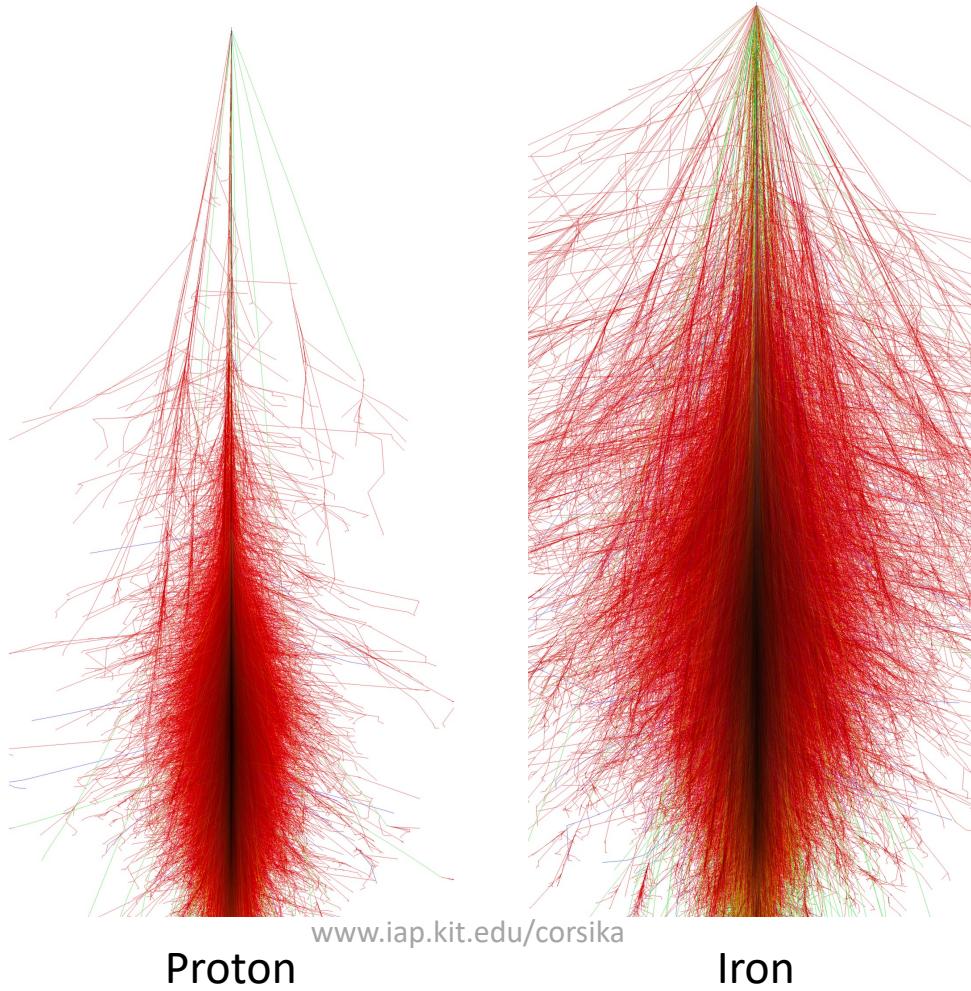
- Build unfolding matrix on H3a, H4a, GST & GSF
- Unfold H3a as test set
- Results are within uncertainties → robust



Cosmic ray flux

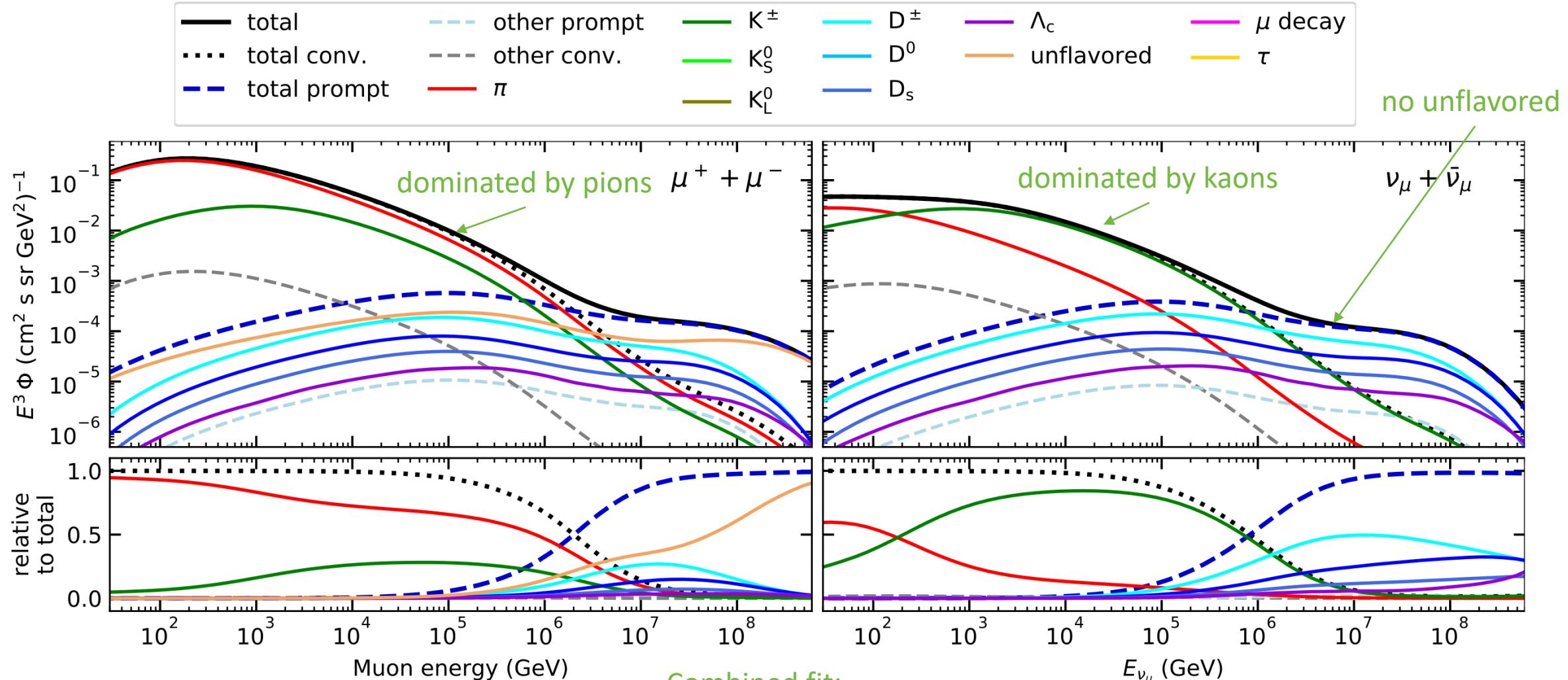


Air shower – 10 TeV



Prompt atmospheric muons and neutrinos

10.1103/PhysRevD.100.103018



Combined fit:

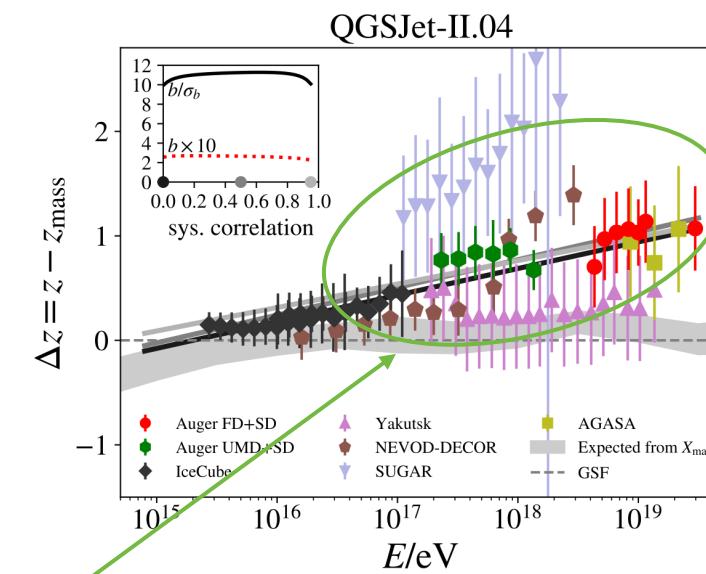
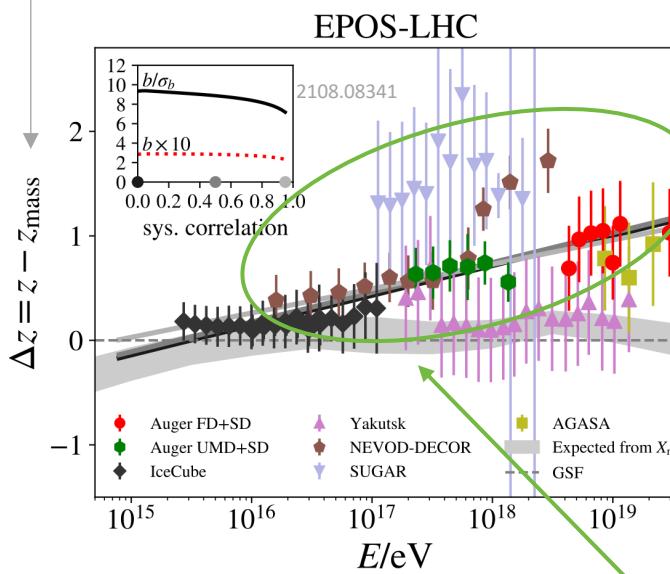
- handle on pion/kaon ratio
- handle on charmed mesons

Muon puzzle and model uncertainties

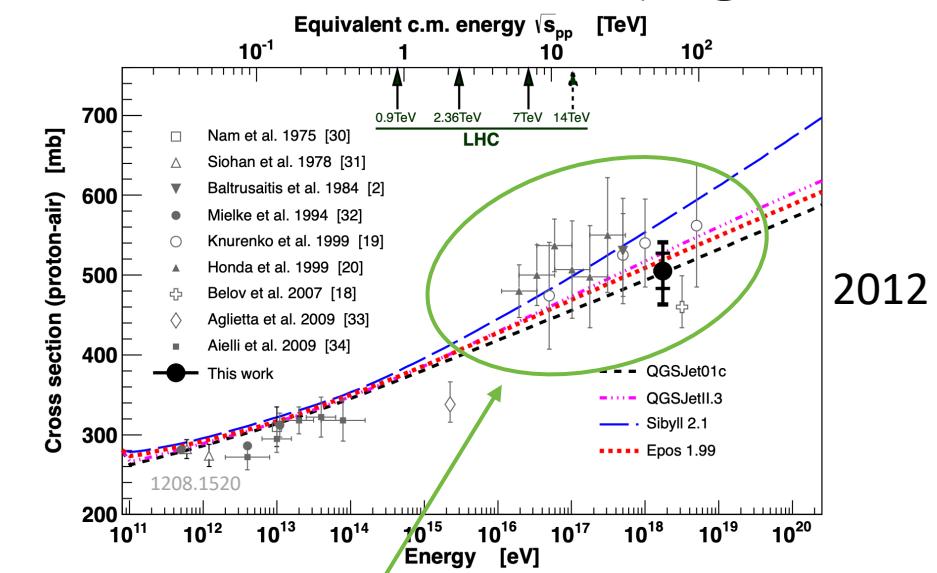
"muon number"

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

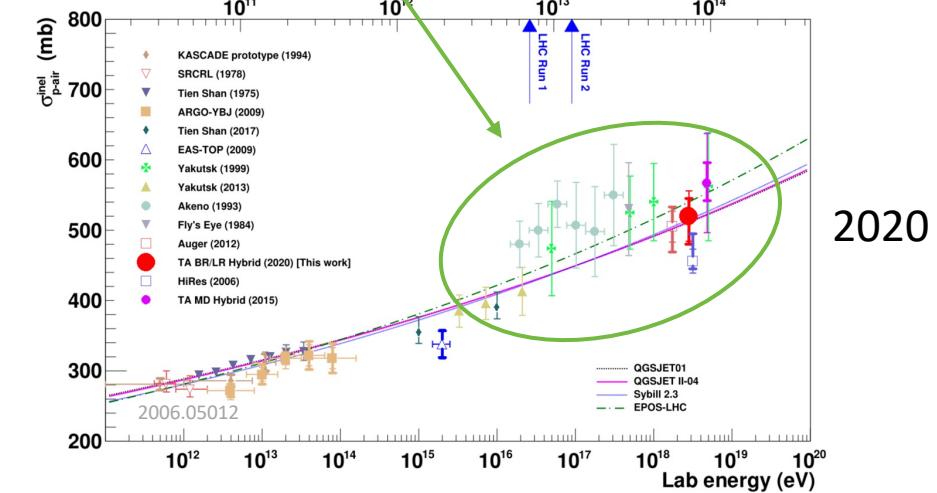
Expected z
("muon number")



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

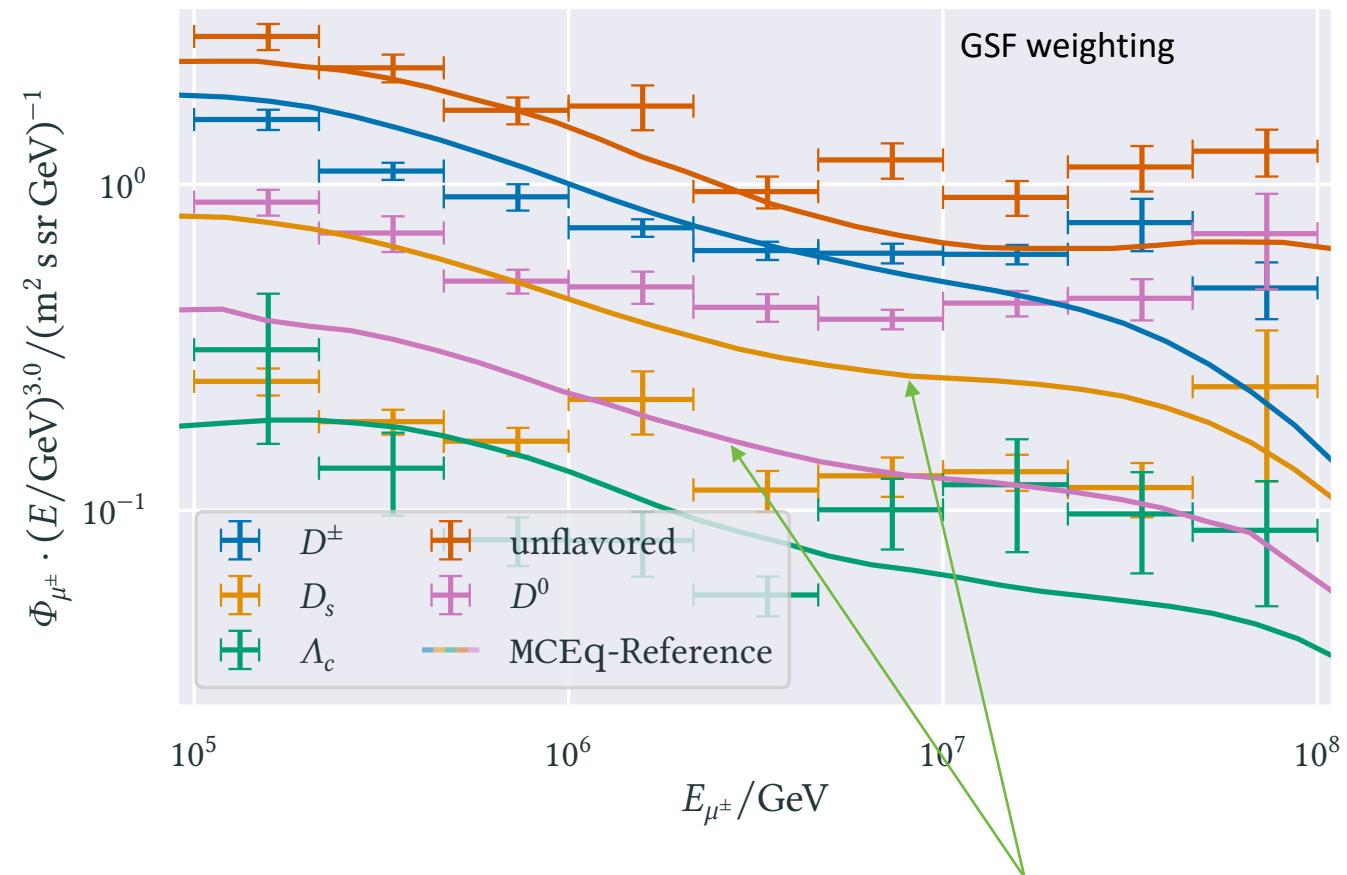
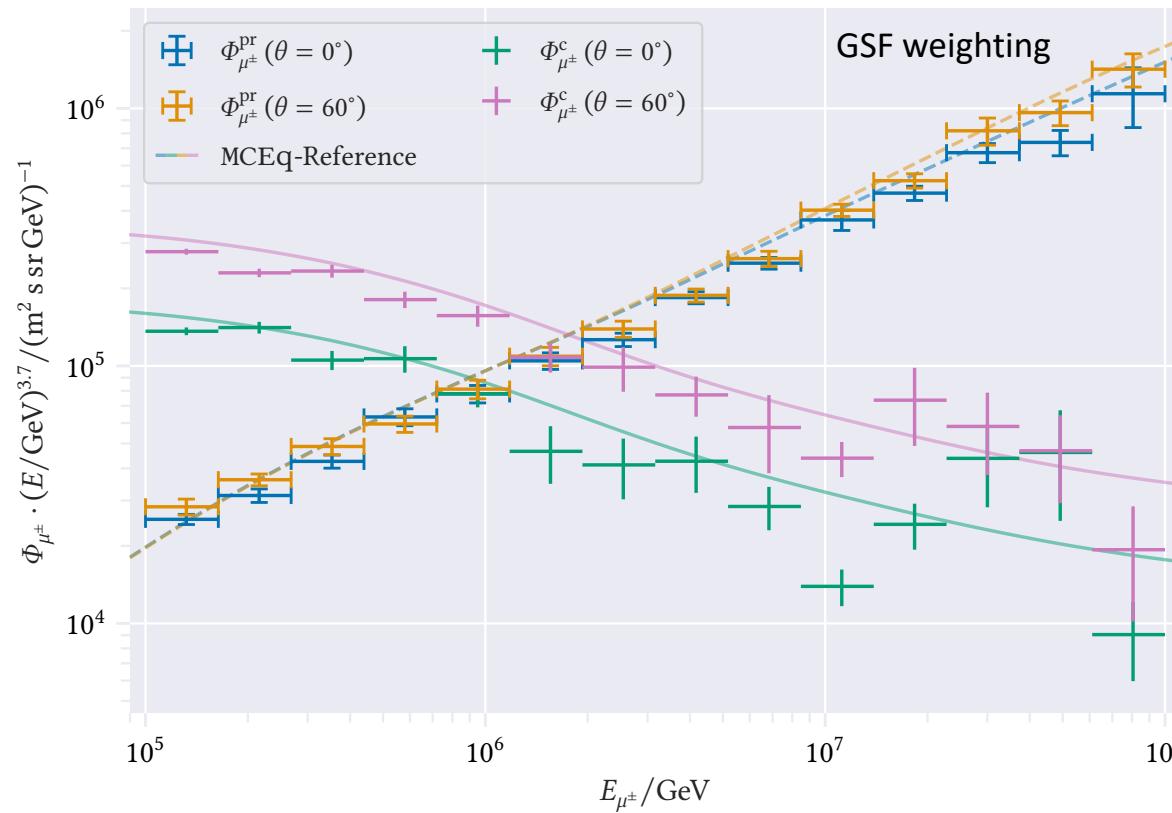


➤ Uncertainties at $E > 10 \text{ PeV}$



CORSIKA 7 tagging and MCEq comparison

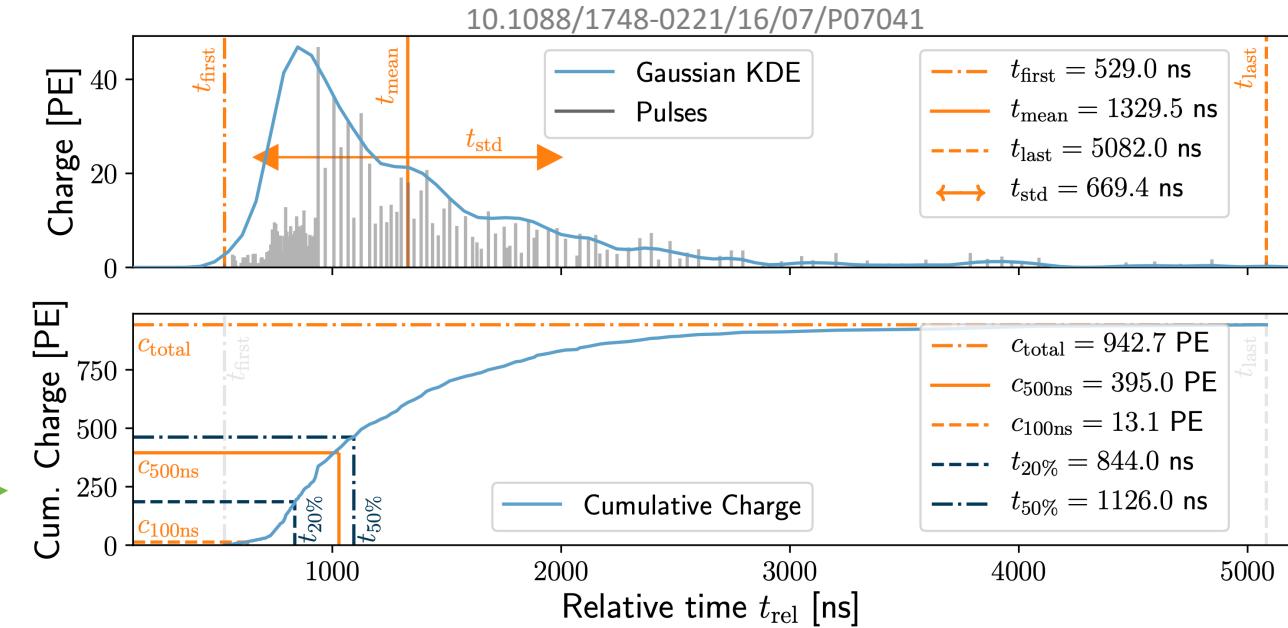
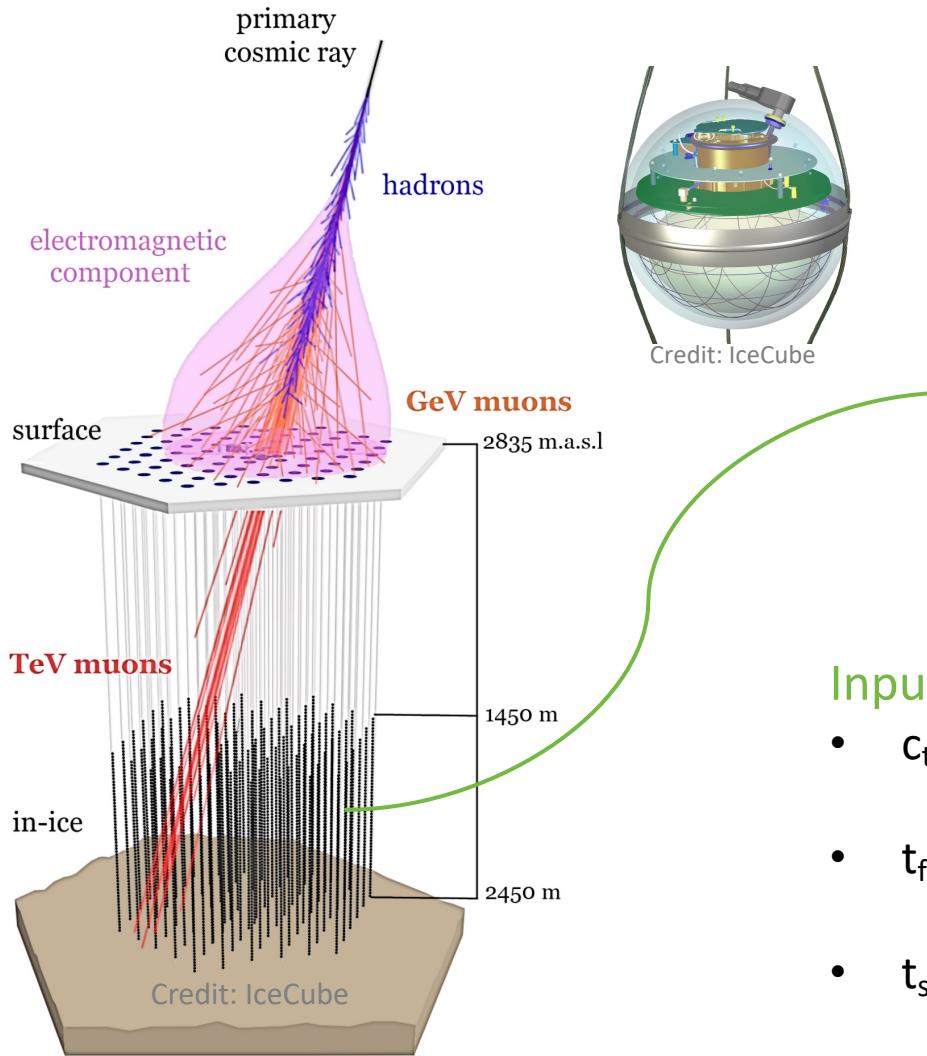
MCEq: tool to numerically solve the cascade equations that describes the evolution of particle densities as they propagate through a gaseous, dense medium
<https://github.com/mceq-project/MCEq>



- Good agreement in total prompt and conv muon flux

mention panama

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
- ...

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

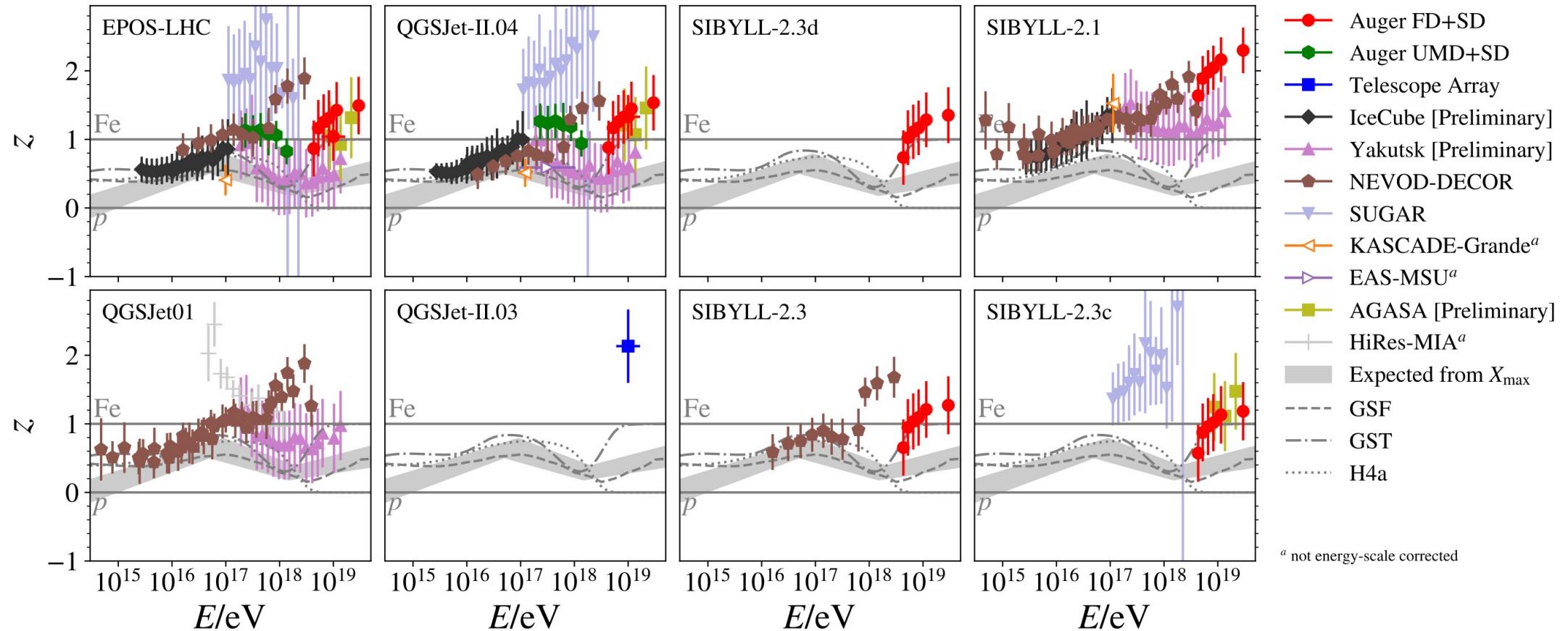
neutrino cuts	>	<
$\cos(\text{zenith})$	0.2	
length	5000 m	15000 m

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"

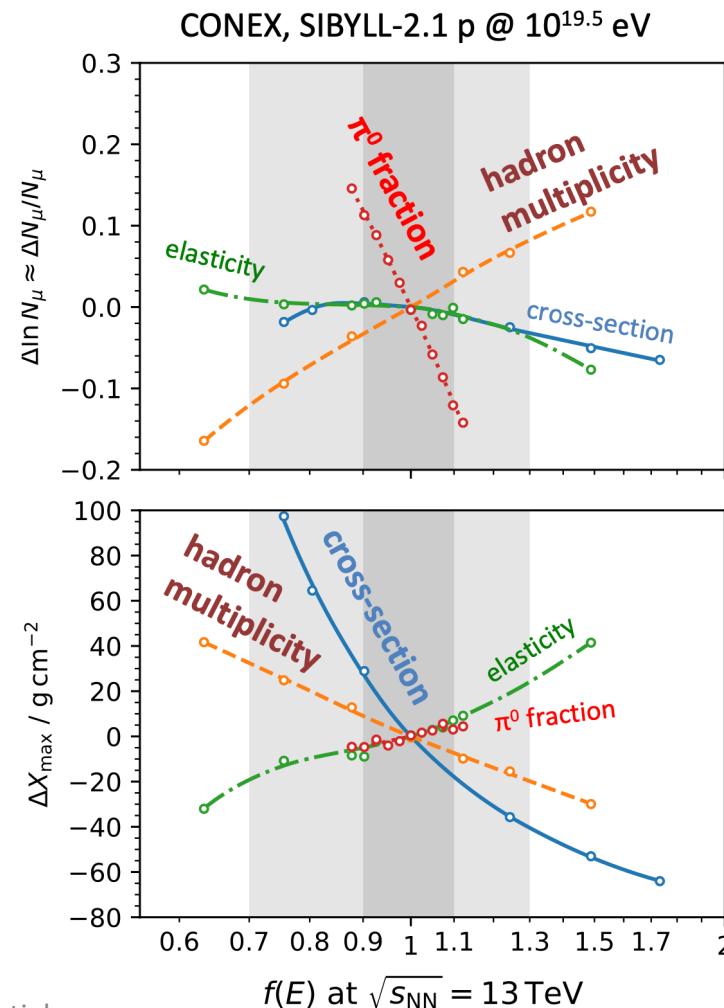
$$z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_p}{\ln\langle N_\mu \rangle_{\text{Fe}} - \ln\langle N_\mu \rangle_p}$$



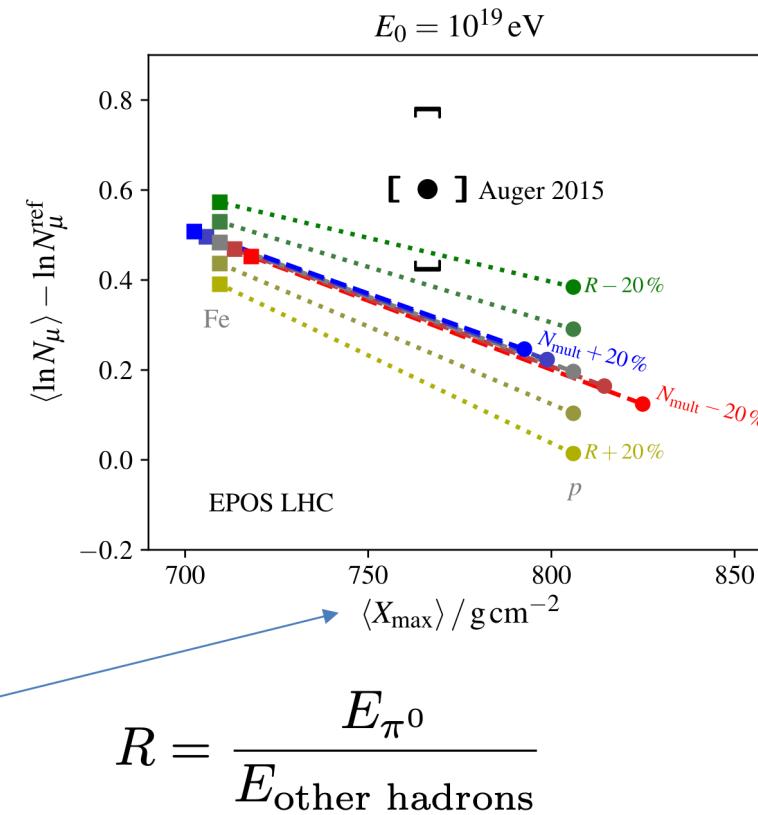
Arxiv: 2108.08341

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



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

MCEq vs CORSIKA

