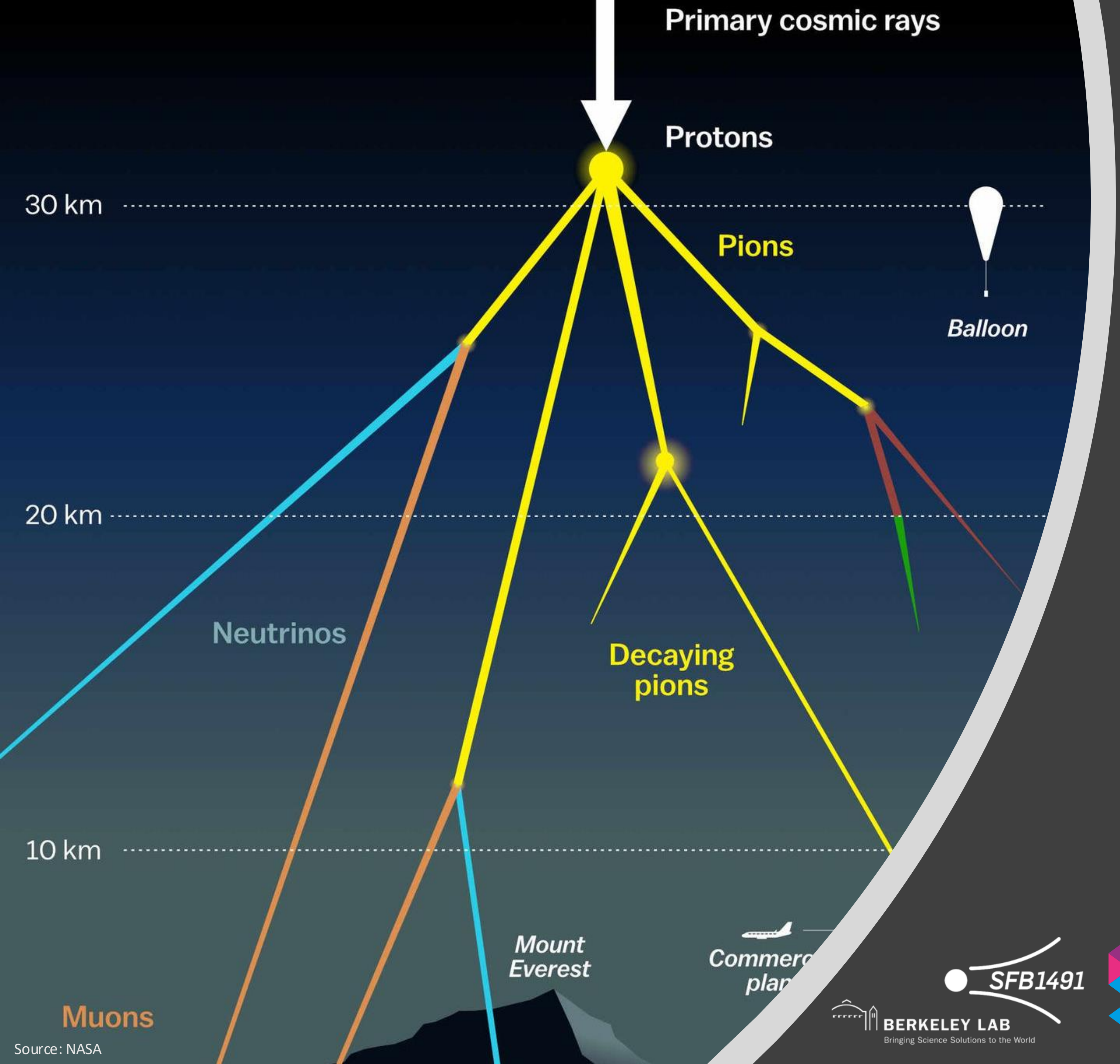


Unfolding the Atmospheric Muon Flux with IceCube

Pascal Gutjahr

wiki page

CR Call

October 28, 2025

Determine Regularization

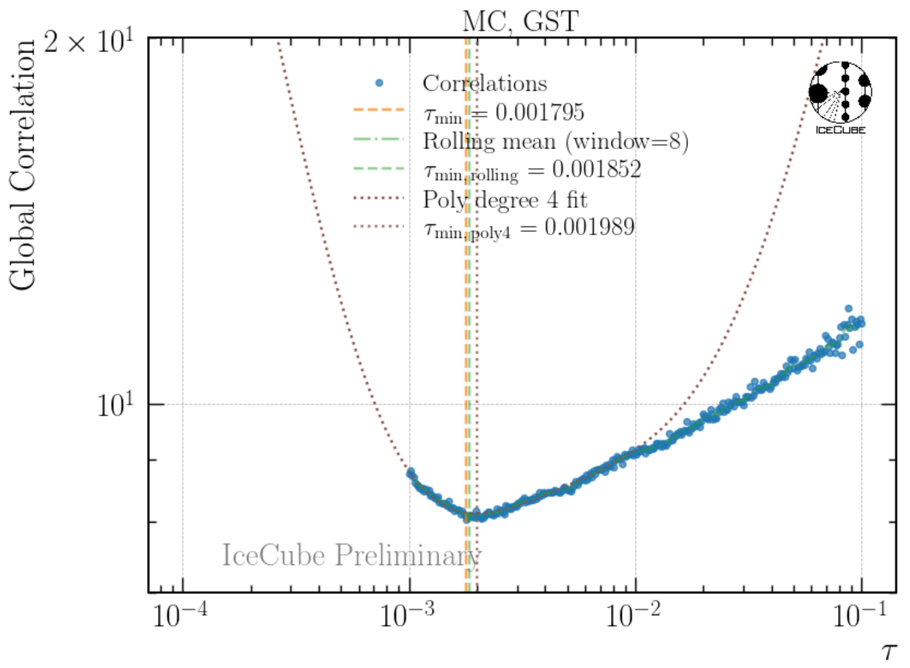
Regularization

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

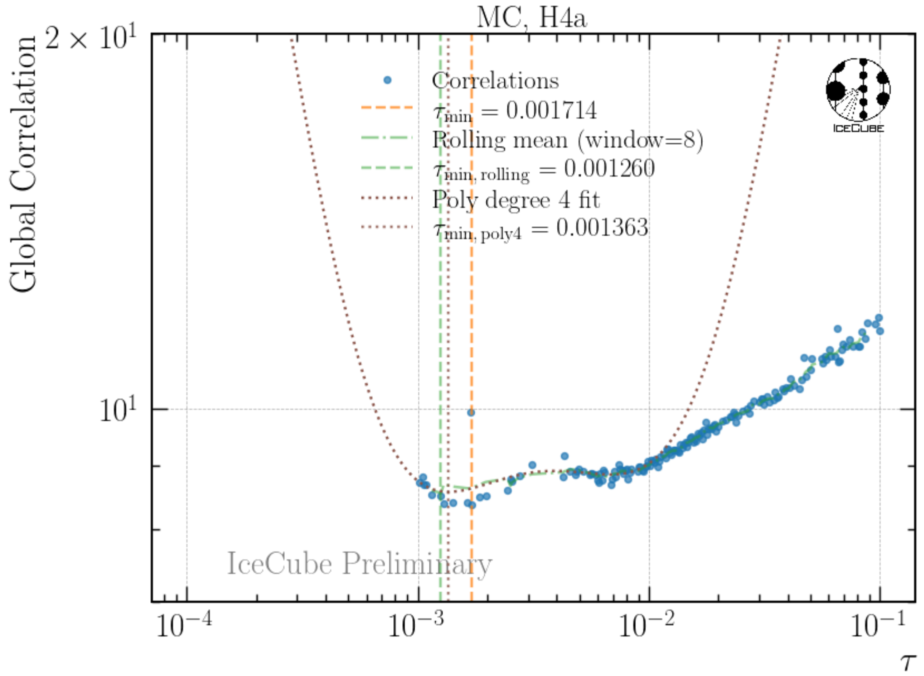
➢ Minimize global correlation $\rho = \sum_{i>j} V_{ij}$

➢ Fits are only accepted, when minuit minimization is valid
  ➢ Sometimes fits fail around the minimum

➢ Fit polynom from $10^{-3} - 10^{-2}$ to determine minimum



2 examples

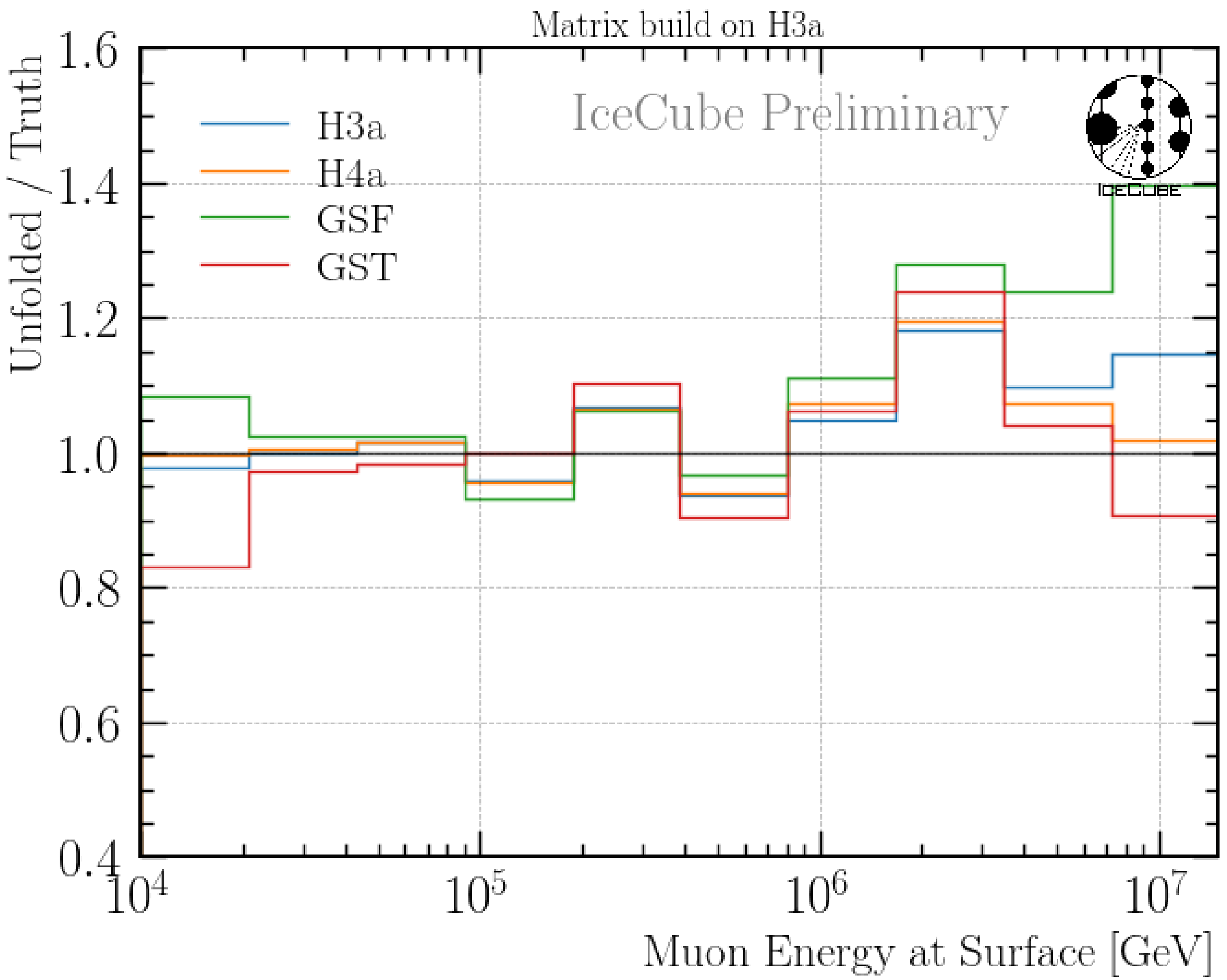


“Method Bias”

Uncertainties: “Unfolding Bias” (for H3a Matrix)

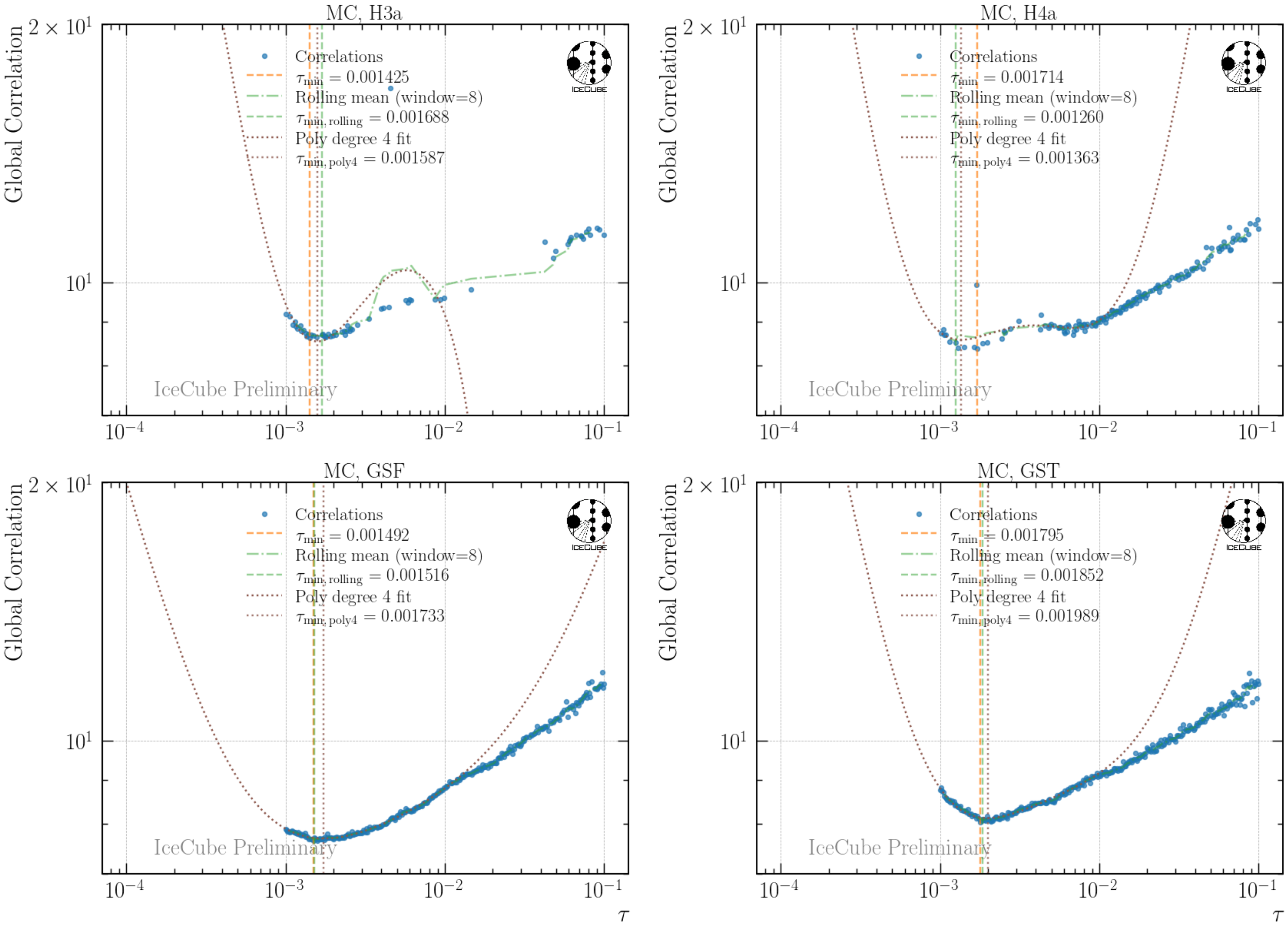
- Build unfolding matrix on H3a
- Unfold 4 MC weighted datasets for the 4 primary models
- Divide each unfolding by its true MC distribution

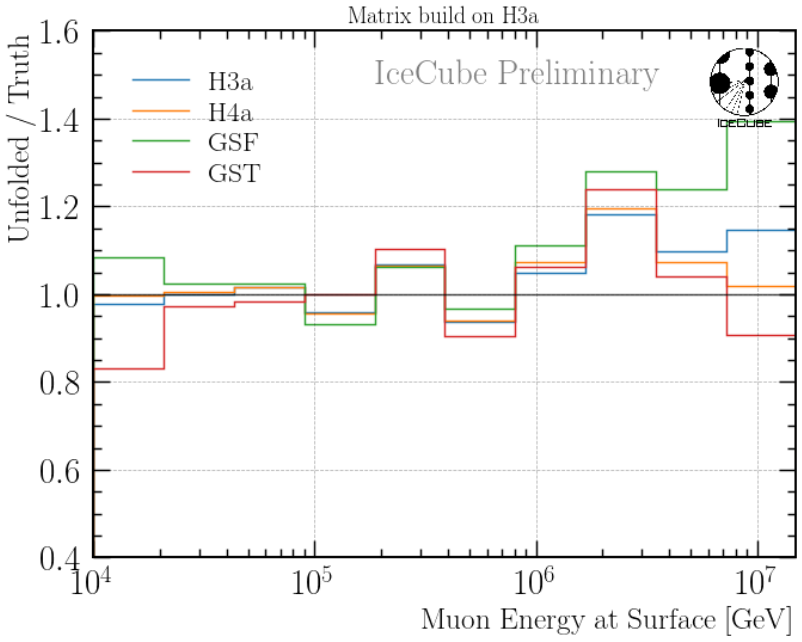
➢ Ratio of 1 expected
➢ Offset to 1 → bias



- Fit $\tau \in 10^{-3} - 10^{-2}$

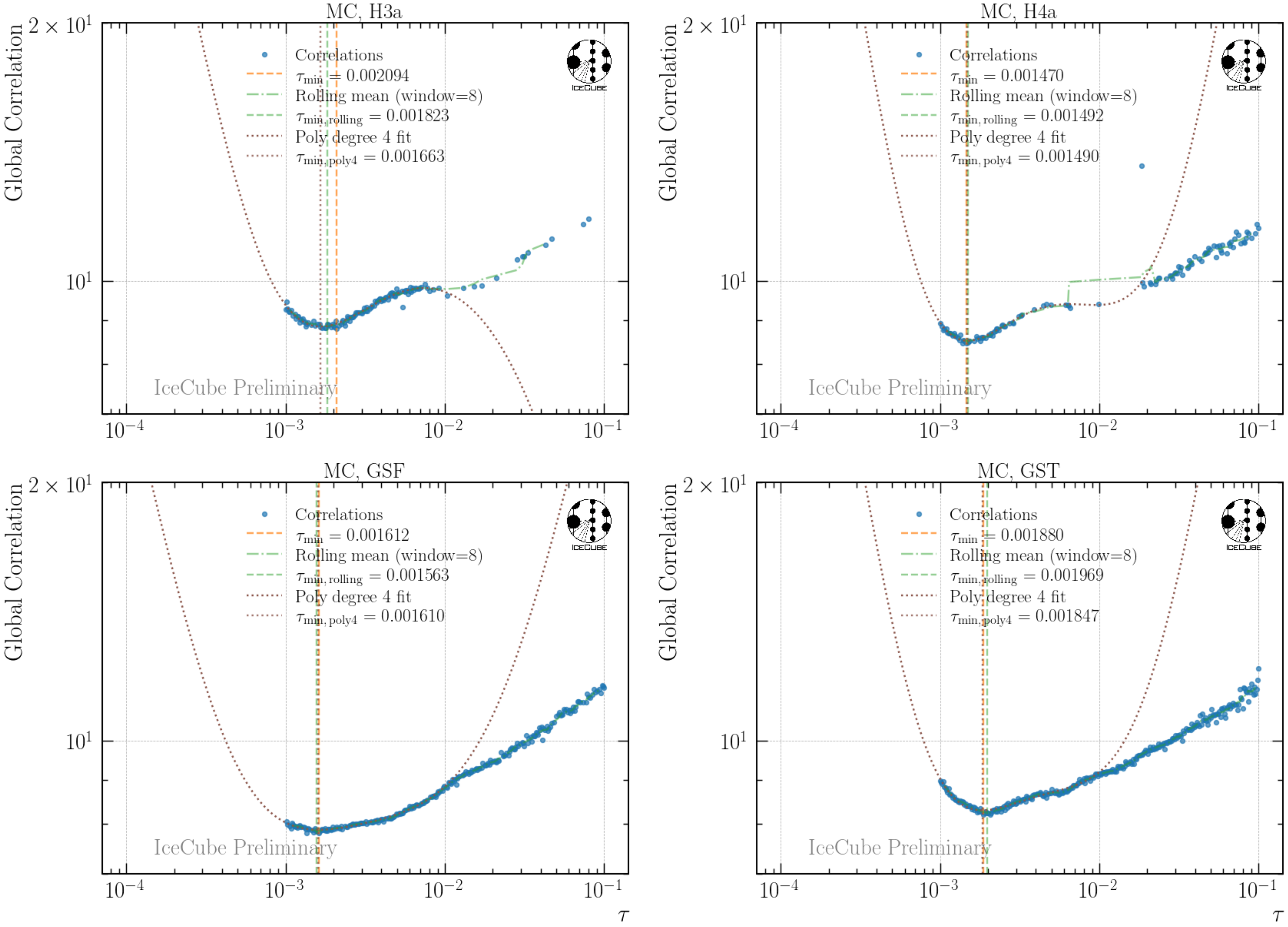
H3a Unfolding Bias

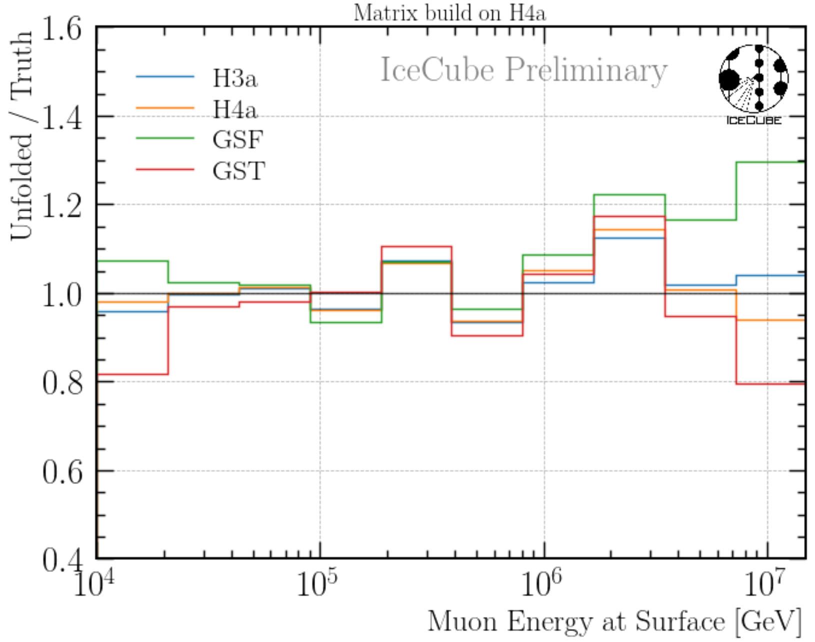




H4a Unfolding Bias

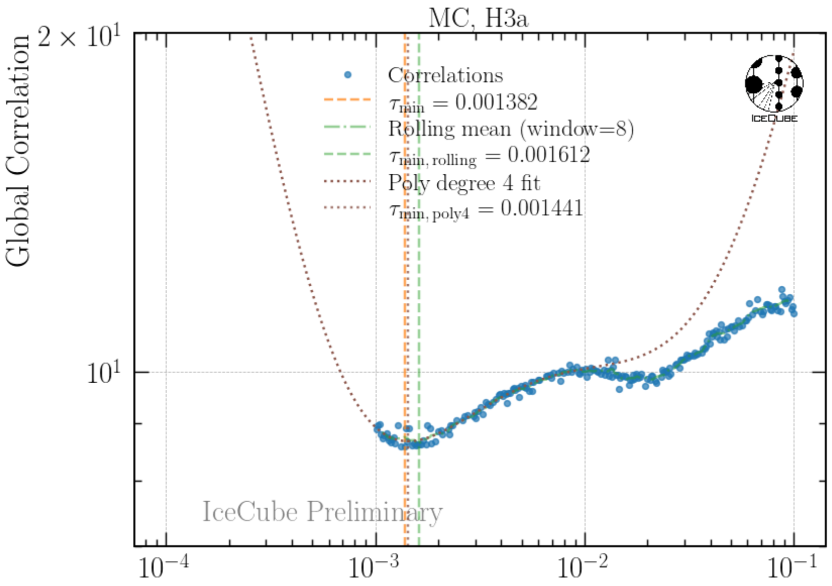
- Fit $\tau \in 10^{-3} - 10^{-2}$

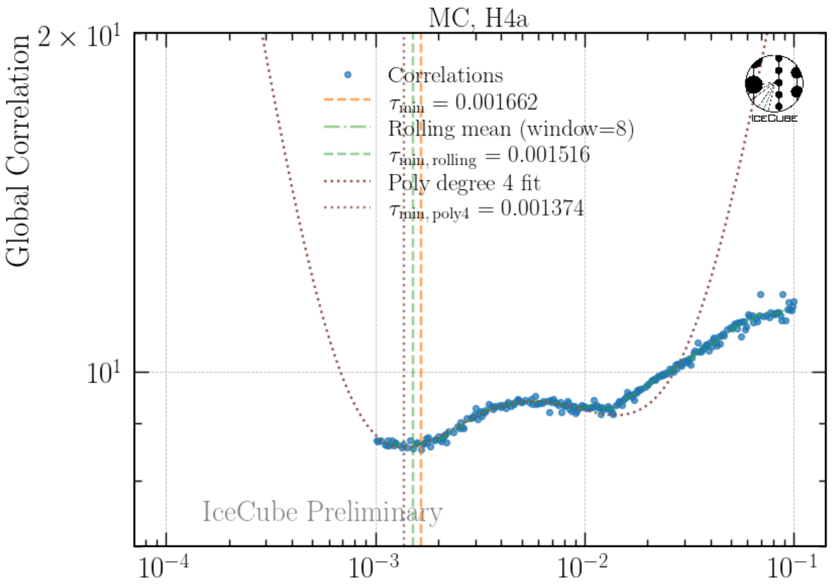


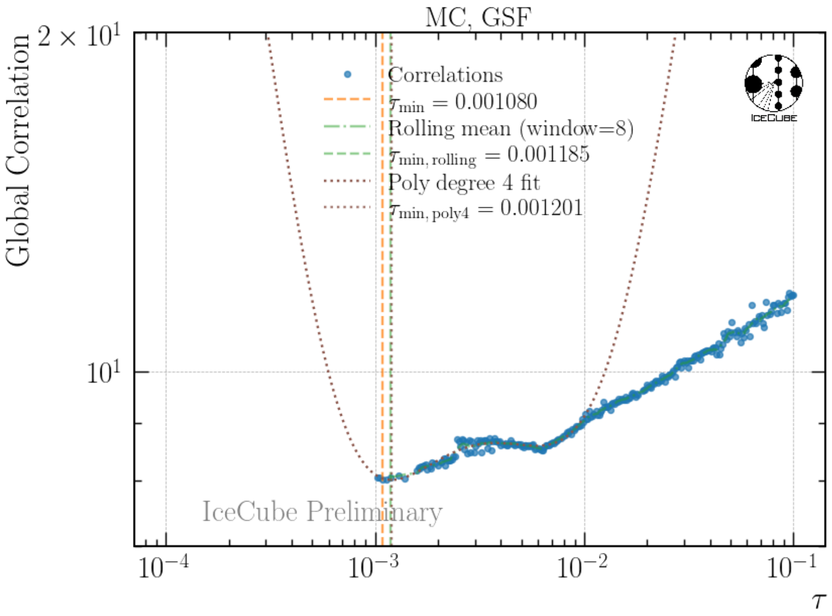


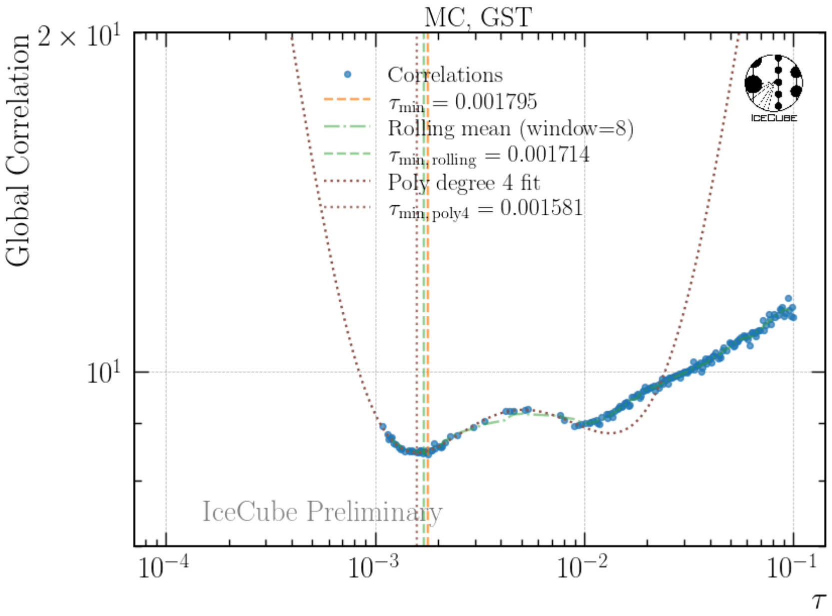
GST Unfolding Bias

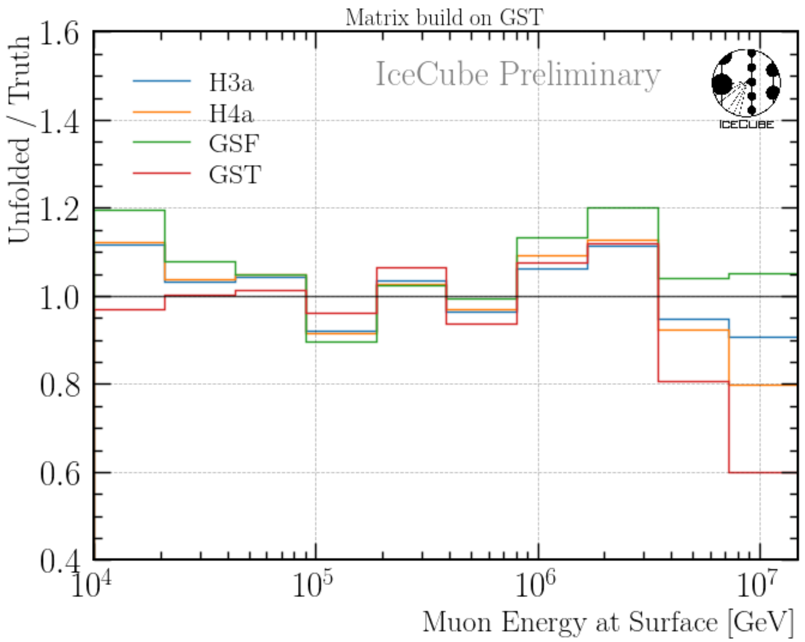
- Fit $\tau \in 10^{-3} - 10^{-2}$





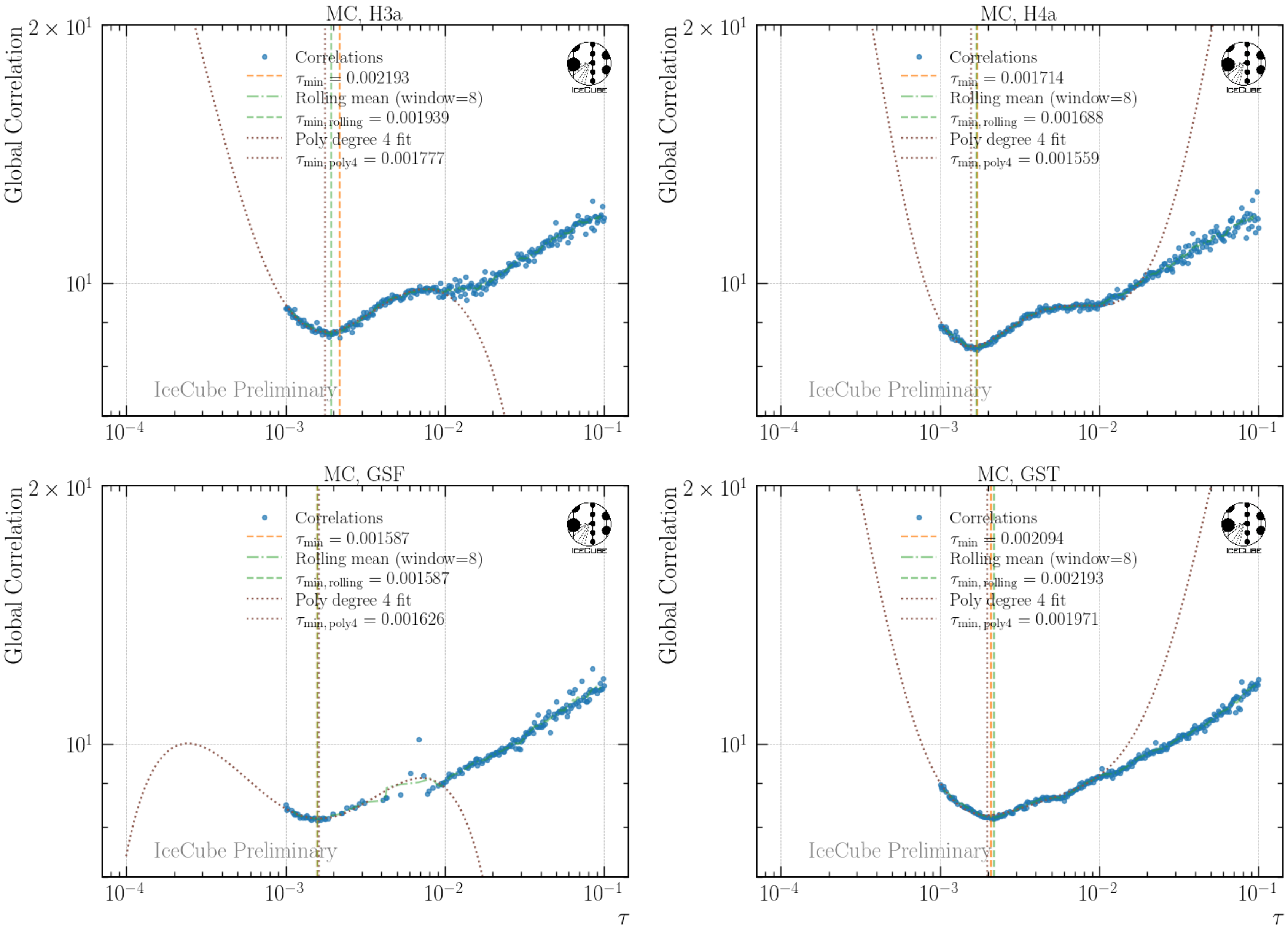


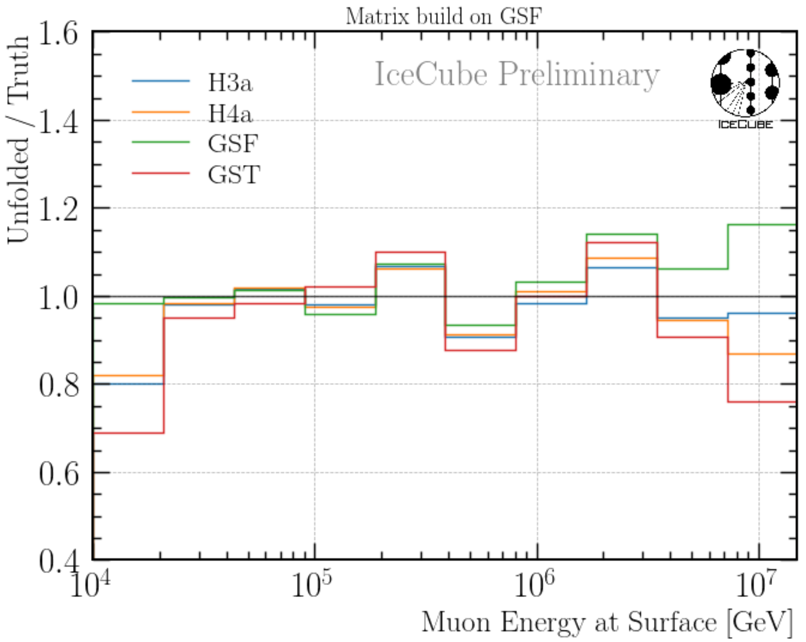




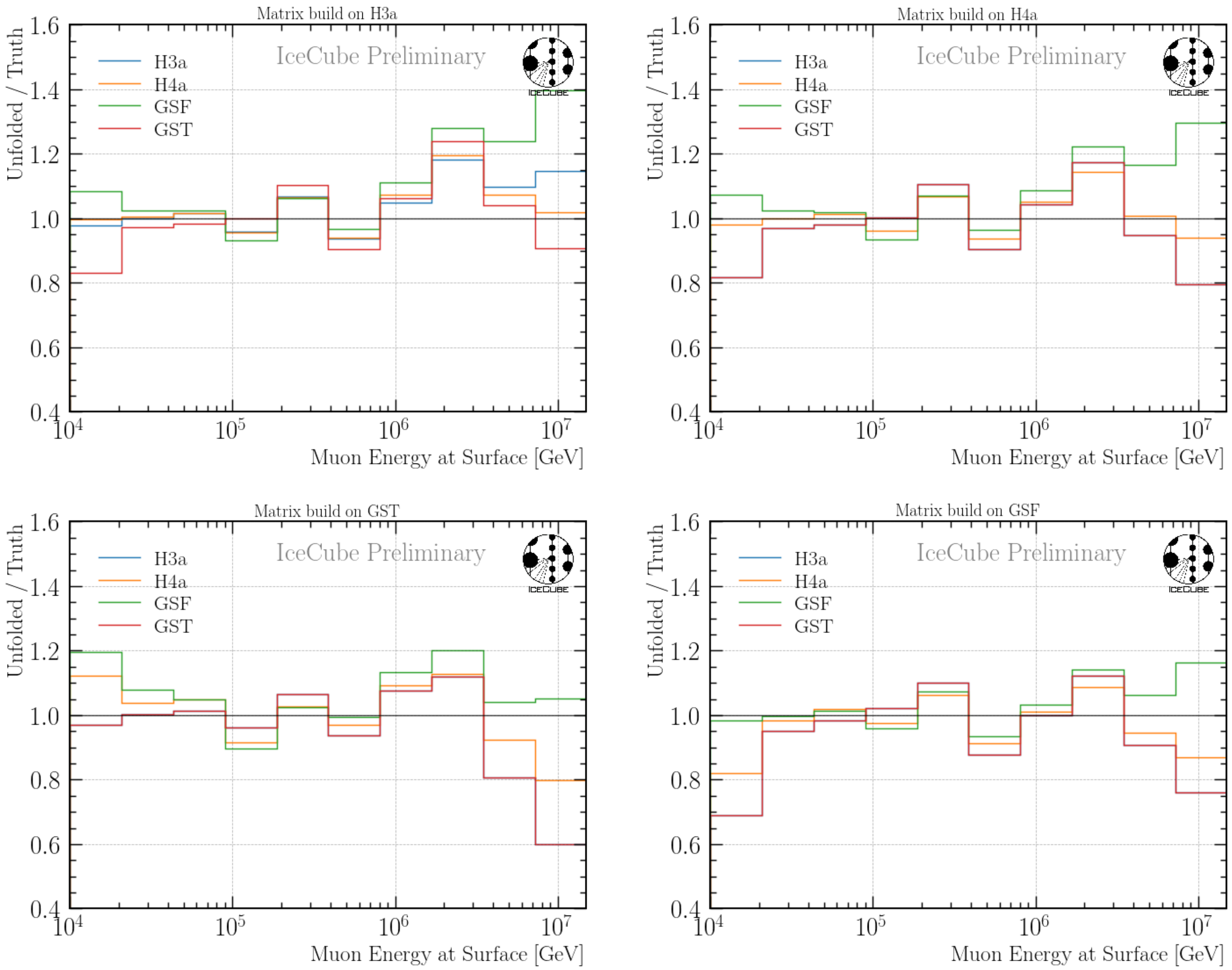
- Fit $\tau \in 10^{-3} - 10^{-2}$

GSF Unfolding Bias

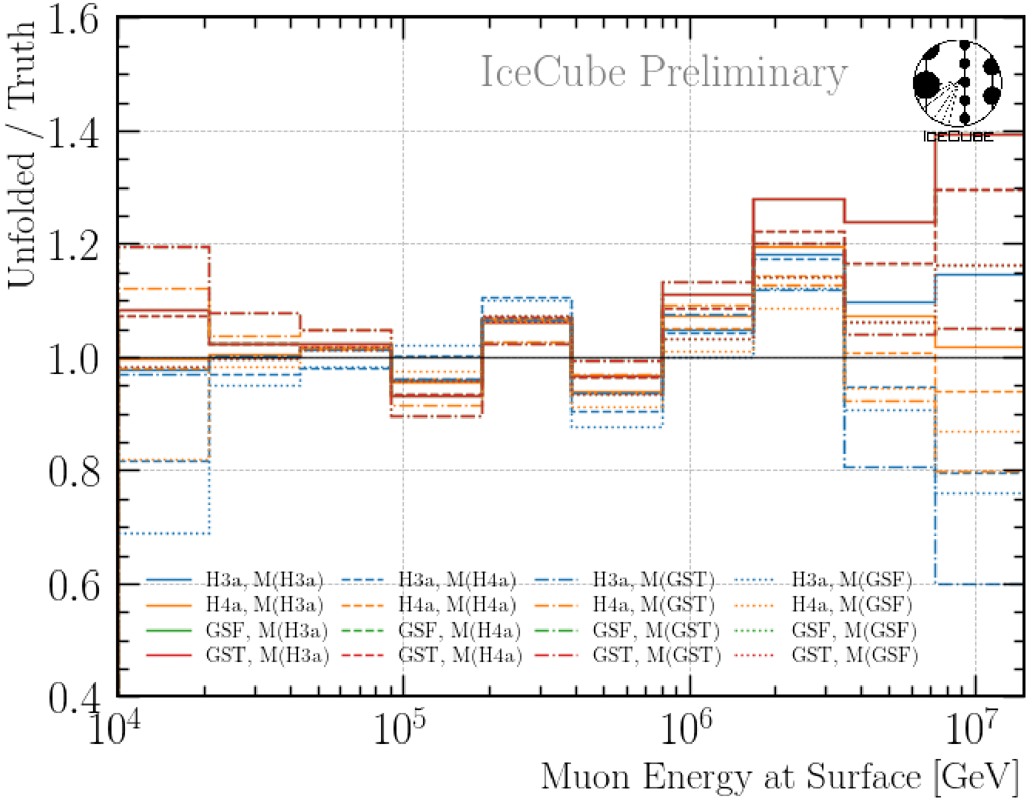




Unfolding Bias for All Models



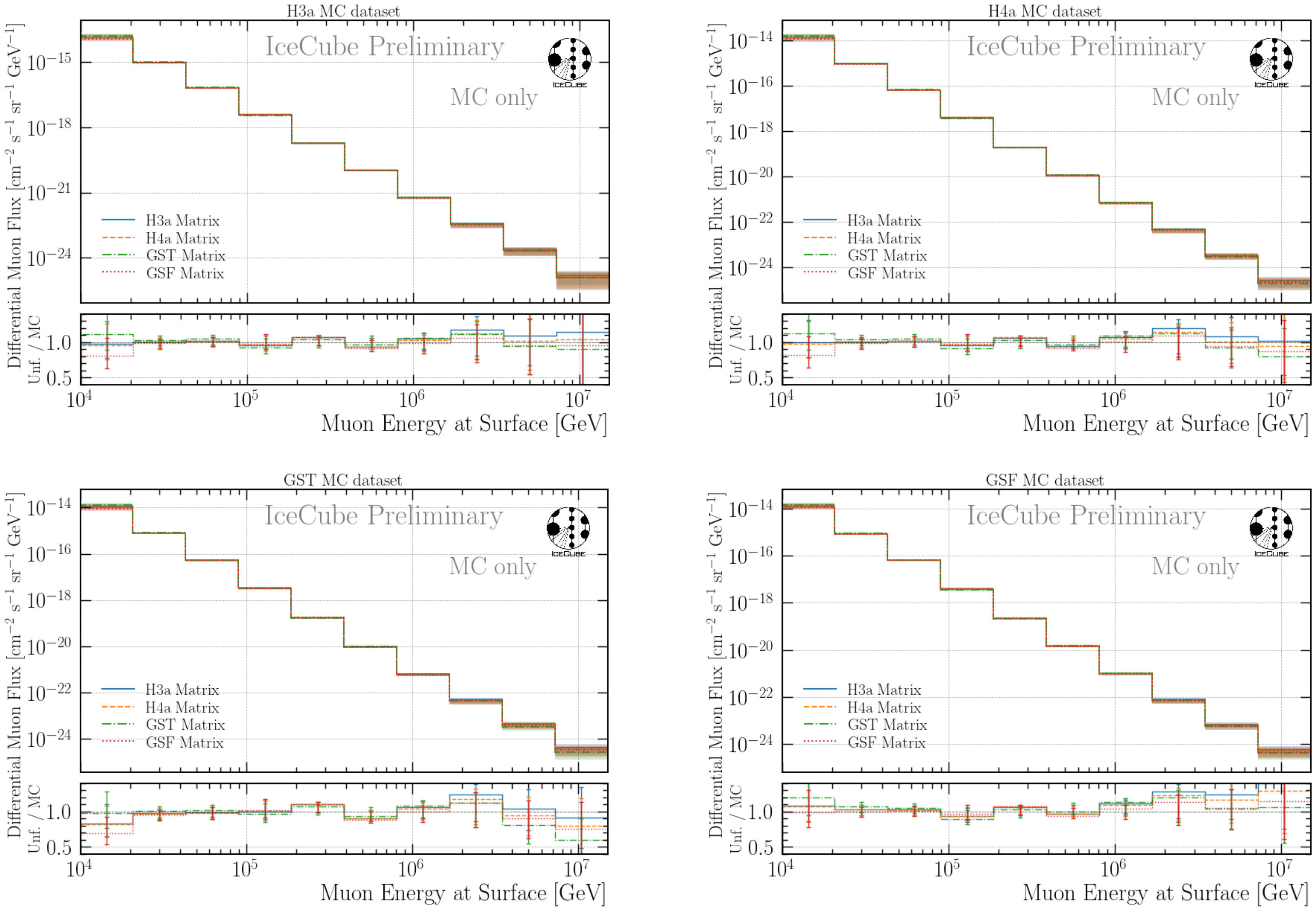
Summary



- Add these biases as an uncertainty to the unfolding result

Include Uncertainties

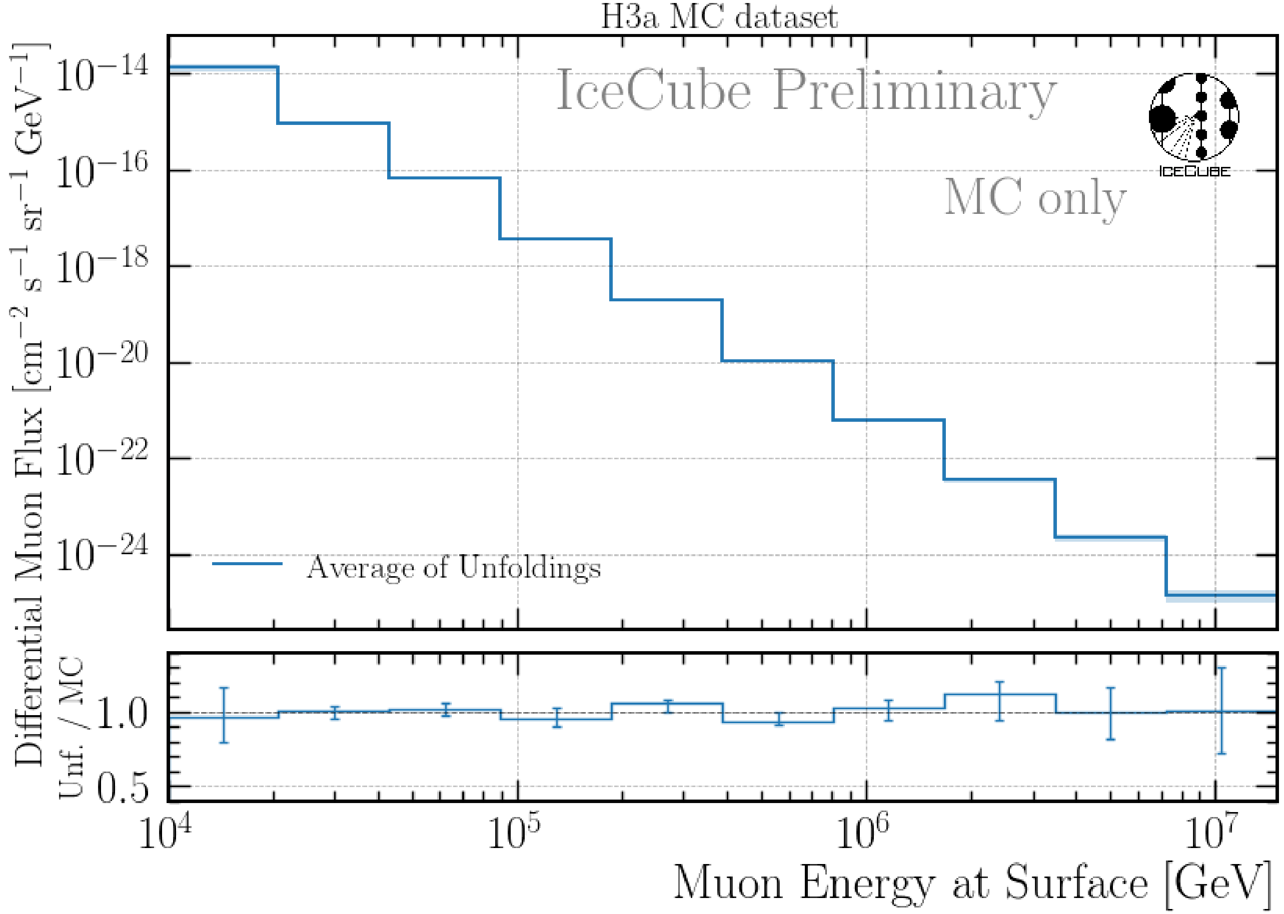
$$\sigma_{\mathrm{tot}} = \sqrt{\sigma^2_{\mathrm{minuit}} + \sigma^2_{\mathrm{unf-bias}} + \sigma^2_{\mathrm{A_{eff},stat}}}$$



- All 4 test dataset unfoldings agree within the uncertainties with the truth

Nominal / Best Fit → Average of 4 Unfoldings

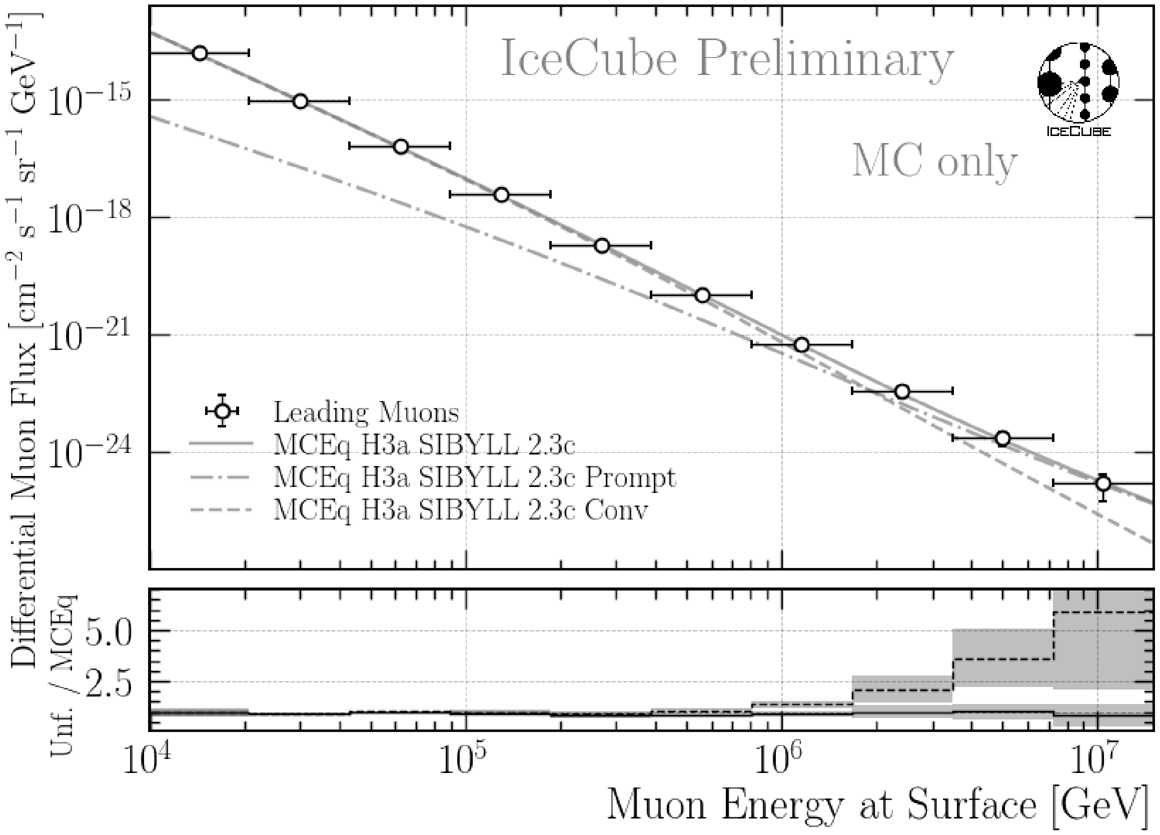
- Unfold H3a test dataset with all 4 primary models
- Build average
- $\sigma_{\text{tot}} = \sqrt{\sigma_{\text{unf}}^2 + \sigma_{\text{spread}}^2}$
- with
- $\sigma_{\text{unf}} = \frac{\sqrt{\sum \sigma^2}}{N}$
- $\sigma_{\text{spread}} = \text{std}(f_i)$



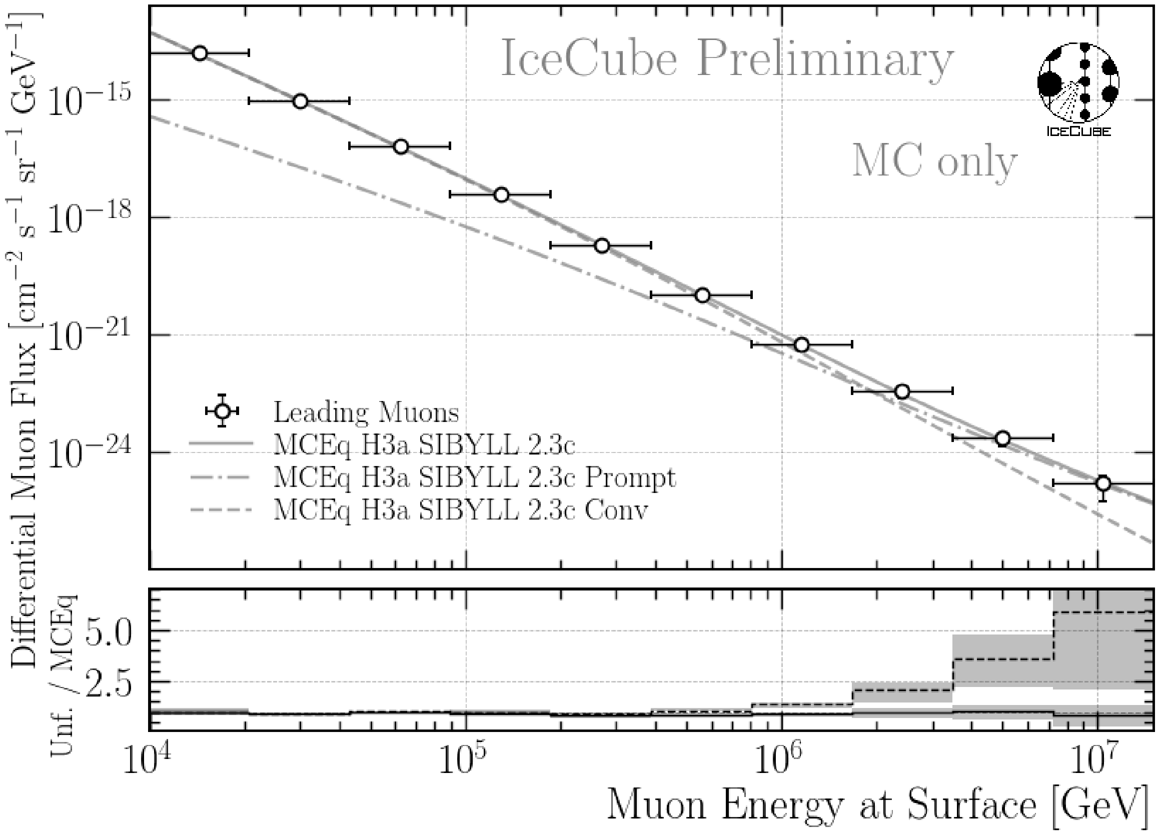
unfolding bias taken from H3a because H3a matrix was used here

12 Years Prediction

symmetric errors



asymmetric errors

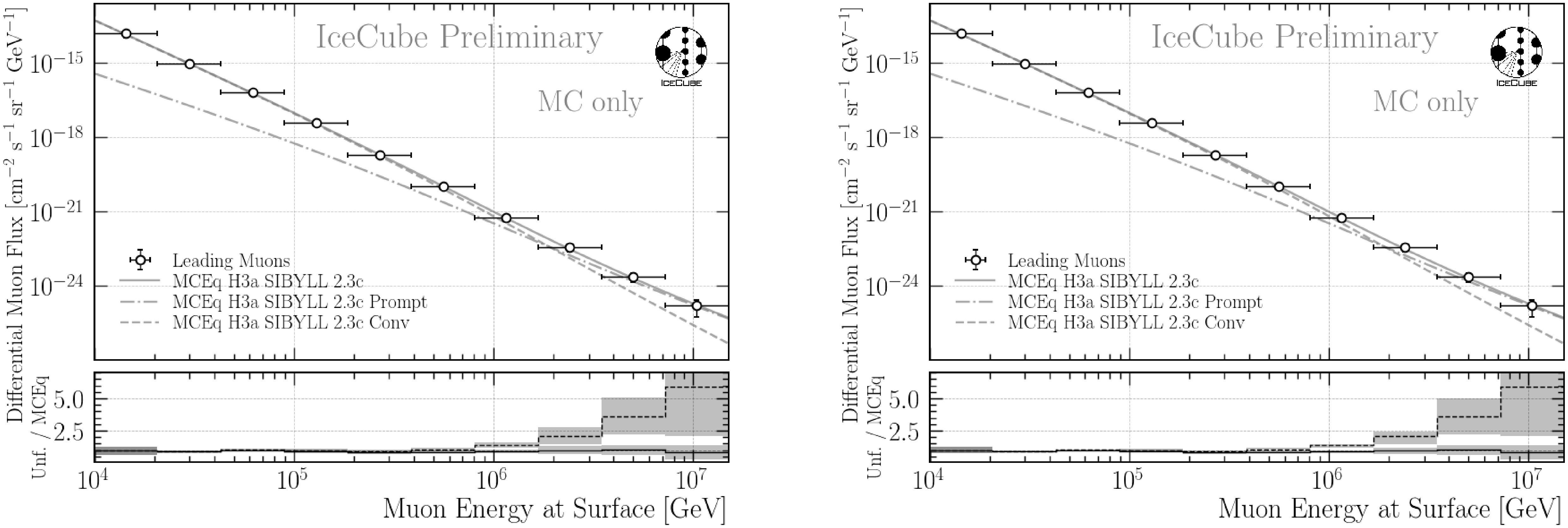


$$\sigma_{\mathrm{tot}} = \sqrt{\sigma^2_{\mathrm{minuit}} + \sigma^2_{\mathrm{unf-bias}} + \sigma^2_{A_{\mathrm{eff}},\mathrm{stat}}}$$

12 Years Prediction

symmetric errors

asymmetric errors

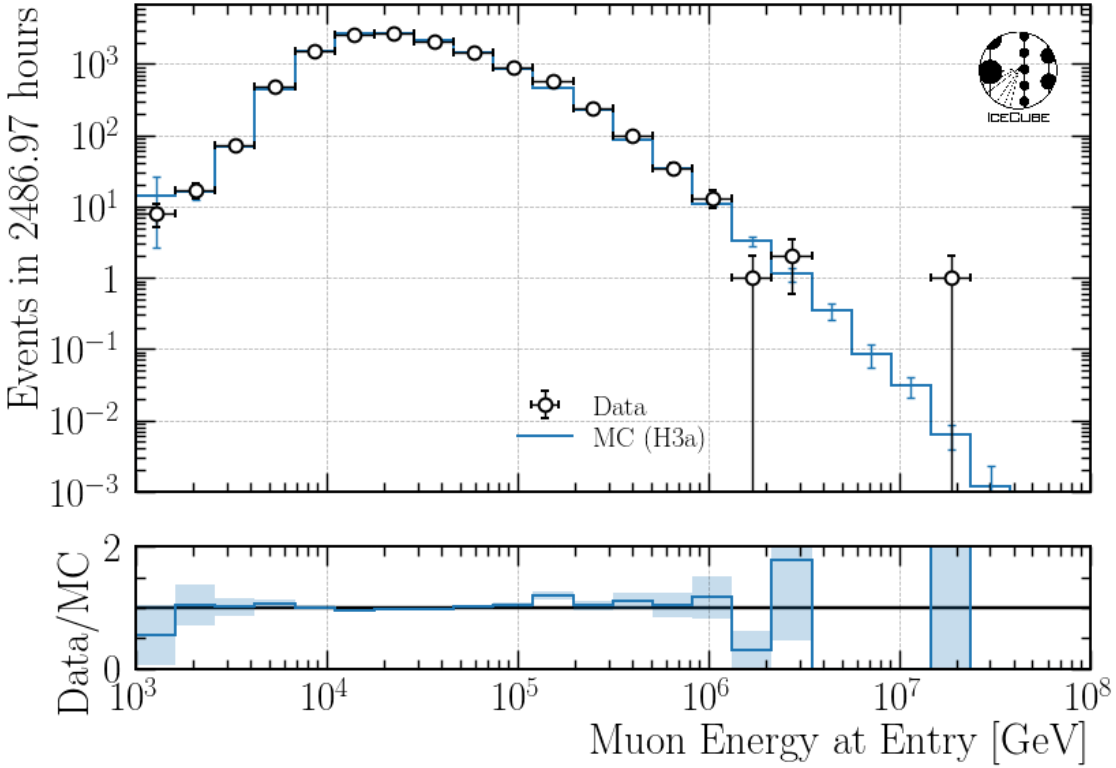


$$\sigma_{\mathrm{tot}} = \sqrt{\sigma^2_{\mathrm{minuit}} + \sigma^2_{\mathrm{unf-bias}} + \sigma^2_{A_{\mathrm{eff}},\mathrm{stat}}}$$

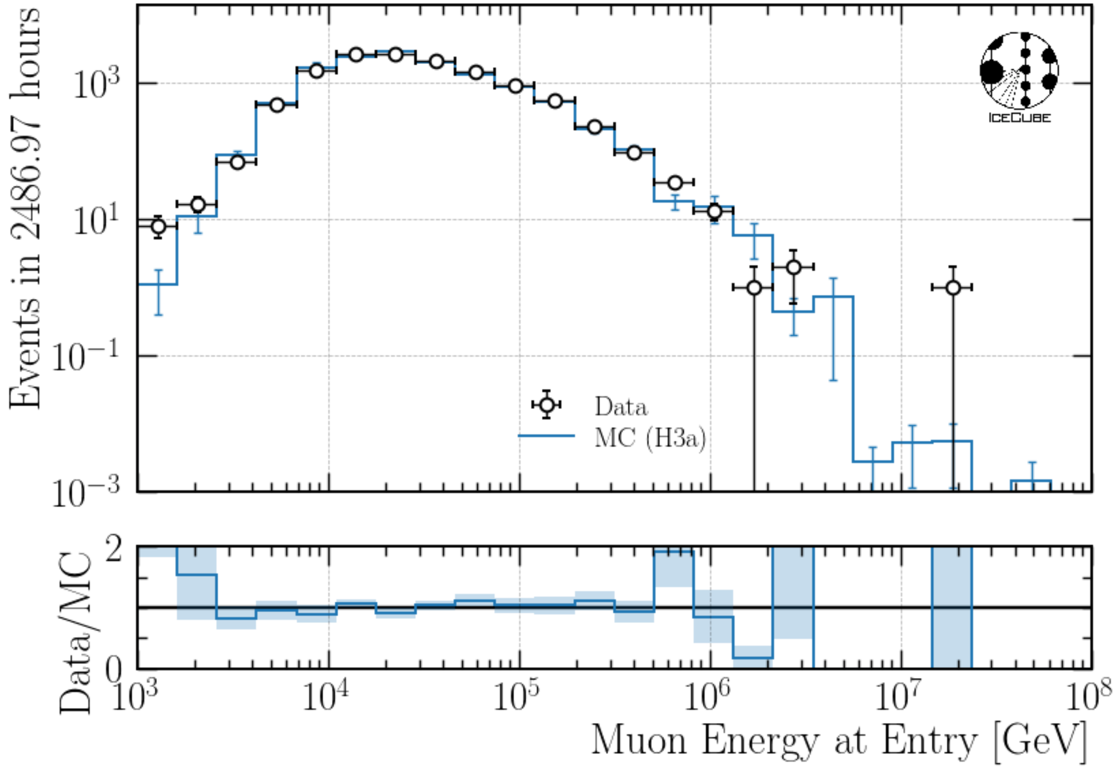
Data-MC Post Fit

Data-MC: Burnsample

Pre Fit



Post Fit



- include entire Snowstorm dataset
- re-weight to best fit systematics

Flux Characterization

```
[LikelihoodFitter] Using asymmetric uncertainties (2×N).
============================================================
LIKELIHOOD FIT SUMMARY
============================================================

Best-Fit Parameters:
  Prompt normalization:        1.051024 ± 0.301881
  Conventional normalization:  0.997005 ± 0.042235

χ² = 0.87   ndof = 8   χ²/ndof = 0.108
  Parameter correlation: -0.6246

------------------------------------------------------------
HYPOTHESIS TEST: H₀: prompt normalization = 0
------------------------------------------------------------
  Δχ² = 6.061
  p (one-sided, boundary-corrected) = 6.911184e-03
  significance ≈ 2.46σ
  → Reject H₀ at 95 % CL → evidence for prompt component.
============================================================
```

Unblinding Plan

Unblinding Proposal

Unblinding plans
- Unfold 12 years of data for IC86 from 2011 to 2022
- Determine regularization strength on data
- Perform unfolding on data
  - Build matrix on all 4 primary models
  - Fit prompt/conv normalization (significance) on all 4 unfoldings each
  - Build average of all 4 unfoldings → nominal values

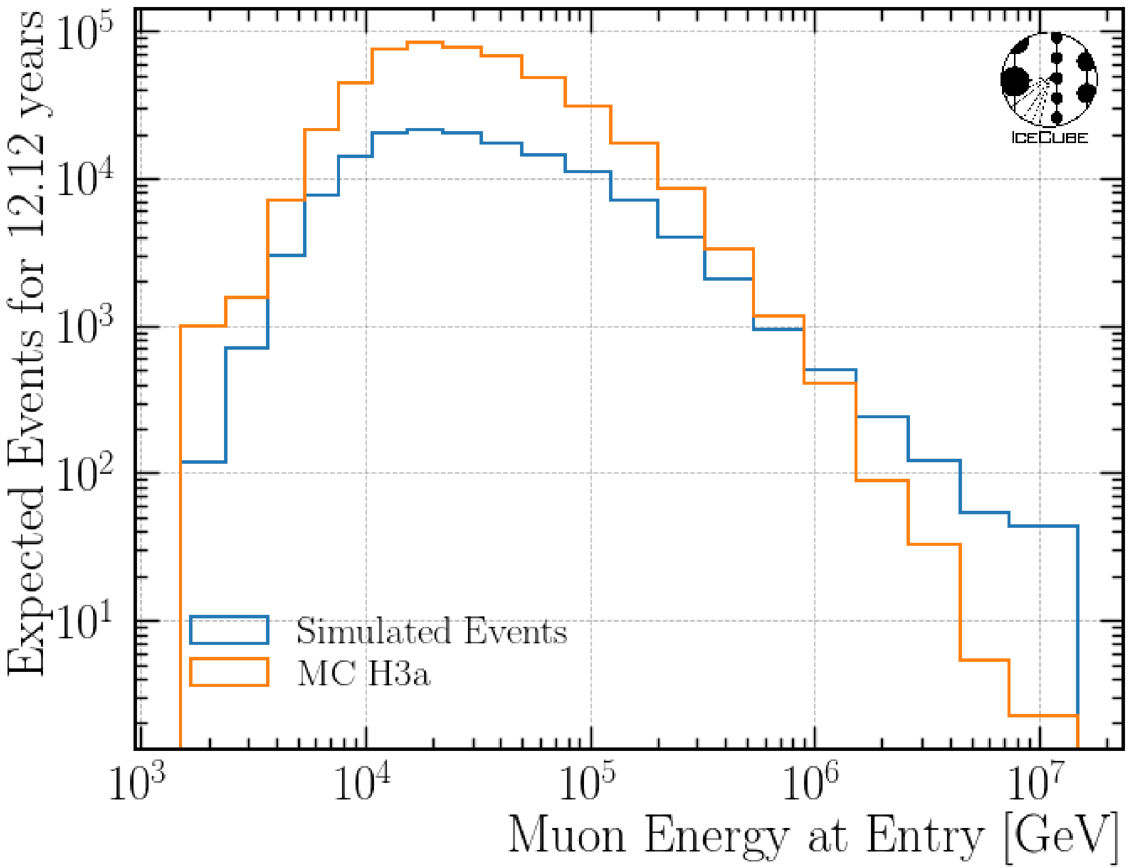
Post-unblinding checks
- Check the data-MC agreement for proxy variable (leading energy)
  - pre-fit (on the entire Snowstorm dataset)
  - post-fit (re-weight to fitted systematics)
- Divide total dataset in 3 subsets á 4 years to analyze systematic impacts over the years
- Divide dataset into 4 seasons

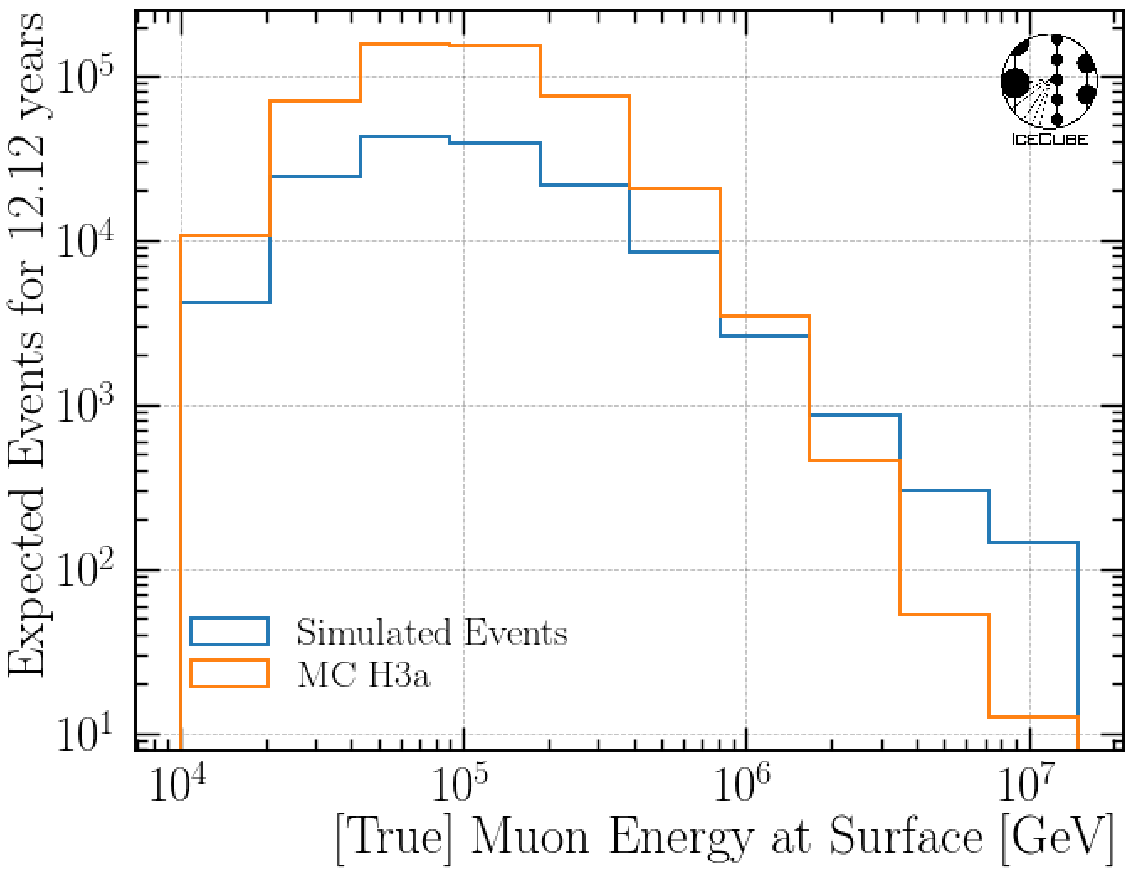
Paper Proposal
- Present status of forward folding in November
  - If results look promising → cross—checks can be done until end of January next year
    - ➢ Combined forward and unfolding paper: Discovery of prompt?
  - Elif, forward folding needs much more work
    - ➢ Unfolding paper: Measurement of muon flux

Thank you for your attention!

Backup

MC Statistics





Minuit output

	Name	Value	Hesse Error	Minos Error-	Minos Error+	Limit-	Limit+	Fixed
0	x0	0.2e3	0.4e3			2.77	2.77E+04	
1	x1	11.1e3	0.7e3			107	1.07E+06	
2	x2	68.3e3	1.8e3			696	6.96E+06	
3	x3	161.4e3	3.1e3			1.58E+03	1.58E+07	
4	x4	147.9e3	2.9e3			1.55E+03	1.55E+07	
5	x5	79.8e3	1.7e3			749	7.49E+06	
6	x6	19.7e3	0.7e3			208	2.08E+06	
7	x7	3.44e3	0.19e3			34.2	3.42E+05	
8	x8	490	60			4.47	4.47E+04	
9	x9	56	15			0.55	5.5E+03	
10	x10	15	7			0.13	1.3E+03	
11	x11	0	70			0.01	100	
12	x12	1.006	0.020			0.913	1.09	
13	x13	0.9994	0.0029			0.913	1.09	
14	x14	0.998	0.005			0.9	1.1	
15	x15	0.2	0.4			-0.1	0.5	
16	x16	-0.05	0.07			-0.1	0	

	x0	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13	x14	x15	x16
x0	1.74e+05	-0.21e6 (-0.725)	0.24e6 (0.321)	0.16e6 (0.126)	-0.35e6 (-0.287)	-0.08e6 (-0.116)	0.05e6 (0.158)	0.02e6 (0.196)	3.3e3 (0.136)	0.52e3 (0.084)	180 (0.061)	-130 (-0.033)	1.6651 (0.201)	-737.090e-3 (-0.615)	1.199859 (0.630)	-0.00 (-0.000)	0.0006
x1	-0.21e6 (-0.725)	4.71e+05	-0.3e6 (-0.252)	-0.4e6 (-0.168)	0.4e6 (0.214)	0 (0.034)	-0 (-0.083)	-0.01e6 (-0.099)	-2.7e3 (-0.068)	-0.42e3 (-0.040)	-140 (-0.029)	100 (0.016)	-3.7011 (-0.271)	416.026e-3 (0.211)	-1.320718 (-0.421)	0.00 (0.000)	-0.0008
x2	0.24e6 (0.321)	-0.3e6 (-0.252)	3.27e+06	-3.8e6 (-0.685)	0.9e6 (0.175)	-0.4e6 (-0.118)	0.1e6 (0.047)	0.04e6 (0.121)	10.9e3 (0.104)	1.88e3 (0.070)	670 (0.053)	-580 (-0.034)	-13.6553 (-0.379)	-2.720238 (-0.524)	1.698607 (0.206)	-0.01 (-0.000)	0.0011 (0.000)
x3	0.16e6 (0.126)	-0.4e6 (-0.168)	-3.8e6 (-0.685)	9.49e+06	-7e6 (-0.747)	1.4e6 (0.267)	0.1e6 (0.058)	-0.04e6 (-0.065)	-7.1e3 (-0.039)	-0.70e3 (-0.015)	-140 (-0.007)	510 (0.017)	30.4744 (0.497)	309.518e-3 (0.035)	2.800072 (0.199)	-0.00 (-0.000)	0.0003
x4	-0.35e6 (-0.287)	0.4e6 (0.214)	0.9e6 (0.175)	-7e6 (-0.747)	8.7e+06	-3.0e6 (-0.594)	0.1e6 (0.068)	0.05e6 (0.094)	-8.2e3 (-0.048)	-3.49e3 (-0.079)	-1.65e3 (-0.080)	1.02e3 (0.037)	-14.3596 (-0.244)	2.565423 (0.303)	-4.189896 (-0.311)	0.01 (0.000)	-0.0013 (-0.000)
x5	-0.08e6 (-0.116)	0 (0.034)	-0.4e6 (-0.118)	1.4e6 (0.267)	-3.0e6 (-0.594)	2.85e+06	-0.8e6 (-0.637)	-0.07e6 (-0.206)	15.7e3 (0.159)	5.10e3 (0.202)	2.26e3 (0.192)	-2.29e3 (-0.144)	-1.5699 (-0.047)	679.608e-3 (0.140)	-1.052575 (-0.136)	0.00 (0.000)	-0.0002
x6	0.05e6 (0.158)	-0 (-0.083)	0.1e6 (0.047)	0.1e6 (0.058)	0.1e6 (0.068)	-0.8e6 (-0.637)	4.91e+05	-0.03e6 (-0.209)	-18.3e3 (-0.447)	-3.61e3 (-0.345)	-1.36e3 (-0.278)	1.74e3 (0.265)	802.9e-3 (0.058)	-376.997e-3 (-0.187)	592.997e-3 (0.185)	-0.00	0.0001
x7	0.02e6 (0.196)	-0.01e6 (-0.099)	0.04e6 (0.121)	-0.04e6 (-0.065)	0.05e6 (0.094)	-0.07e6 (-0.206)	-0.03e6 (-0.209)	3.64e+04	2.8e3 (0.253)	-0.14e3 (-0.049)	-170 (-0.126)	20 (0.010)	285.8e-3 (0.075)	-108.224e-3 (-0.197)	217.212e-3 (0.249)	-0.00	0.0001
x8	3.3e3 (0.136)	-2.7e3 (-0.068)	10.9e3 (0.104)	-7.1e3 (-0.039)	-8.2e3 (-0.048)	15.7e3 (0.159)	-18.3e3 (-0.447)	2.8e3 (0.253)	3.41e+03	0.69e3 (0.788)	260 (0.638)	-320 (-0.580)	50.8e-3 (0.044)	-23.767e-3 (-0.142)	46.781e-3 (0.175)	-0.00	0.0000
x9	0.52e3 (0.084)	-0.42e3 (-0.040)	1.88e3 (0.070)	-0.70e3 (-0.015)	-3.49e3 (-0.079)	5.10e3 (0.202)	-3.61e3 (-0.345)	-0.14e3 (-0.049)	0.69e3 (0.788)	223	100 (0.936)	-100 (-0.727)	6.8e-3 (0.023)	-3.941e-3 (-0.092)	7.366e-3 (0.108)	-0.00	0.0000
x10	180 (0.061)	-140 (-0.029)	670 (0.053)	-140 (-0.007)	-1.65e3 (-0.080)	2.26e3 (0.192)	-1.36e3 (-0.278)	-170 (-0.126)	260 (0.638)	100 (0.936)	48.7	-50 (-0.711)	2.1e-3 (0.015)	-1.390e-3 (-0.069)	2.506e-3 (0.079)	-0.00	0.0000
x11	-130 (-0.033)	100 (0.016)	-580 (-0.034)	510 (0.017)	1.02e3 (0.037)	-2.29e3 (-0.144)	1.74e3 (0.265)	20 (0.010)	-320 (-0.580)	-100 (-0.727)	-50 (-0.711)	88.1	-2.0e-3 (-0.010)	920e-6 (0.034)	-2.090e-3 (-0.049)	0.00	-0.0000
x12	1.6651 (0.201)	-3.7011 (-0.271)	-13.6553 (-0.379)	30.4744 (0.497)	-14.3596 (-0.244)	-1.5699 (-0.047)	802.9e-3 (0.058)	285.8e-3 (0.075)	50.8e-3 (0.044)	6.8e-3 (0.023)	2.1e-3 (0.015)	-2.0e-3 (-0.010)	0.000397	5e-6 (0.091)	0.040e-3 (0.443)	-0	0
x13	-737.090e-3 (-0.615)	416.026e-3 (0.211)	-2.720238 (-0.524)	309.518e-3 (0.035)	2.565423 (0.303)	679.608e-3 (0.140)	-376.997e-3 (-0.187)	-108.224e-3 (-0.197)	-23.767e-3 (-0.142)	-3.941e-3 (-0.092)	-1.390e-3 (-0.069)	920e-6 (0.034)	5e-6 (0.091)	8.26e-06	-6e-6 (-0.437)	0e-6	-0e-6
x14	1.199859 (0.630)	-1.320718 (-0.421)	1.698607 (0.206)	2.800072 (0.199)	-4.189896 (-0.311)	-1.052575 (-0.136)	592.997e-3 (0.185)	217.212e-3 (0.249)	46.781e-3 (0.175)	7.366e-3 (0.108)	2.506e-3 (0.079)	-2.090e-3 (-0.049)	0.040e-3 (0.443)	-6e-6 (-0.437)	2.09e-05	-0	0
x15	-0.00 (-0.000)	0.00 (0.000)	-0.01 (-0.000)	-0.00 (-0.000)	0.01 (0.000)	0.00 (0.000)	-0.00	-0.00	-0.00	-0.00	-0.00	0.00	-0	0e-6	-0	0.0912	-0.0000
x16	0.0006	-0.0008	0.0011 (0.000)	0.0003	-0.0013 (-0.000)	-0.0002	0.0001	0.0001	0.0000	0.0000	0.0000	-0.0000	0	-0e-6	0	-0.0000	0.00253

Introduction

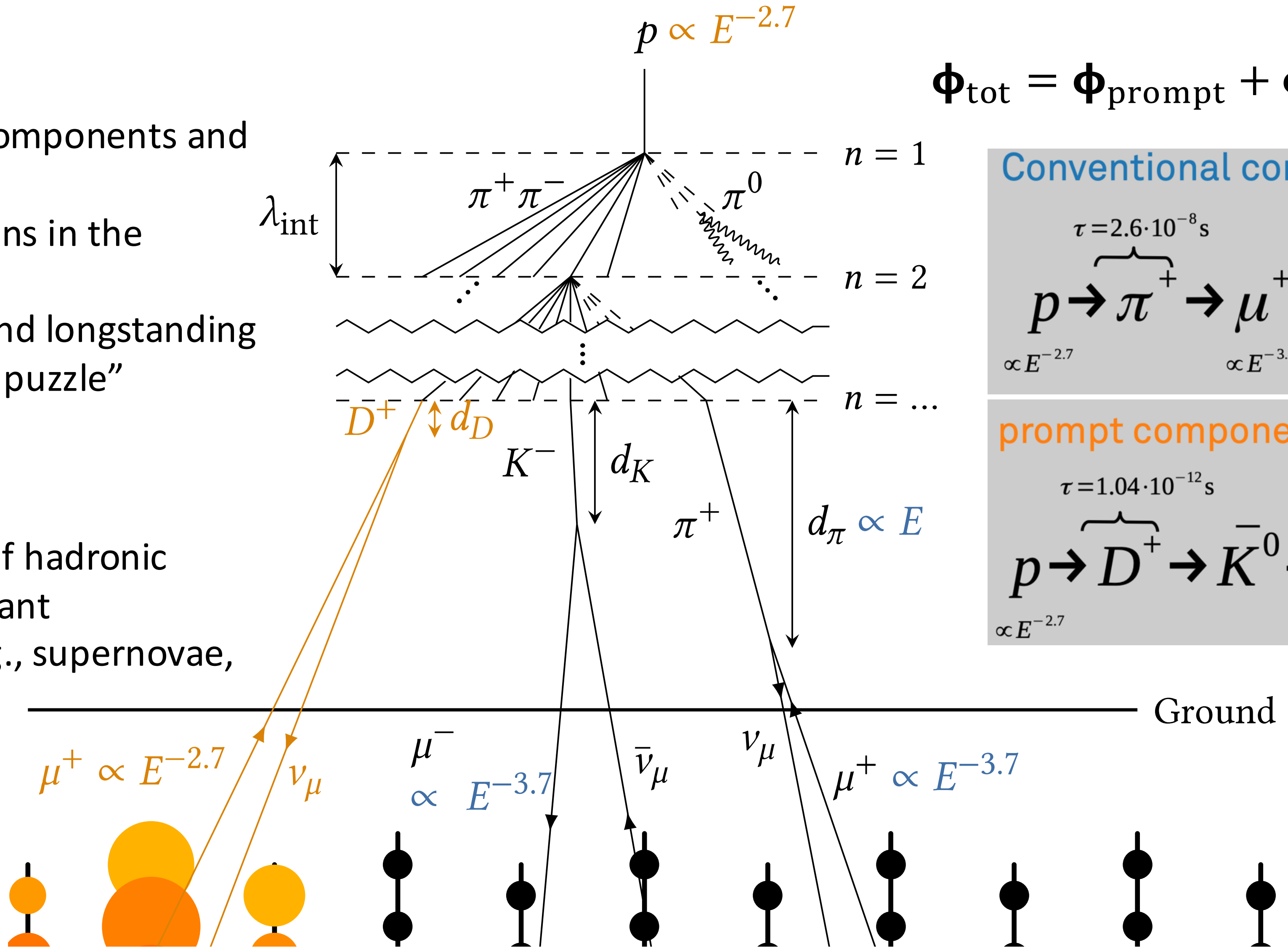
Motivation

- 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:

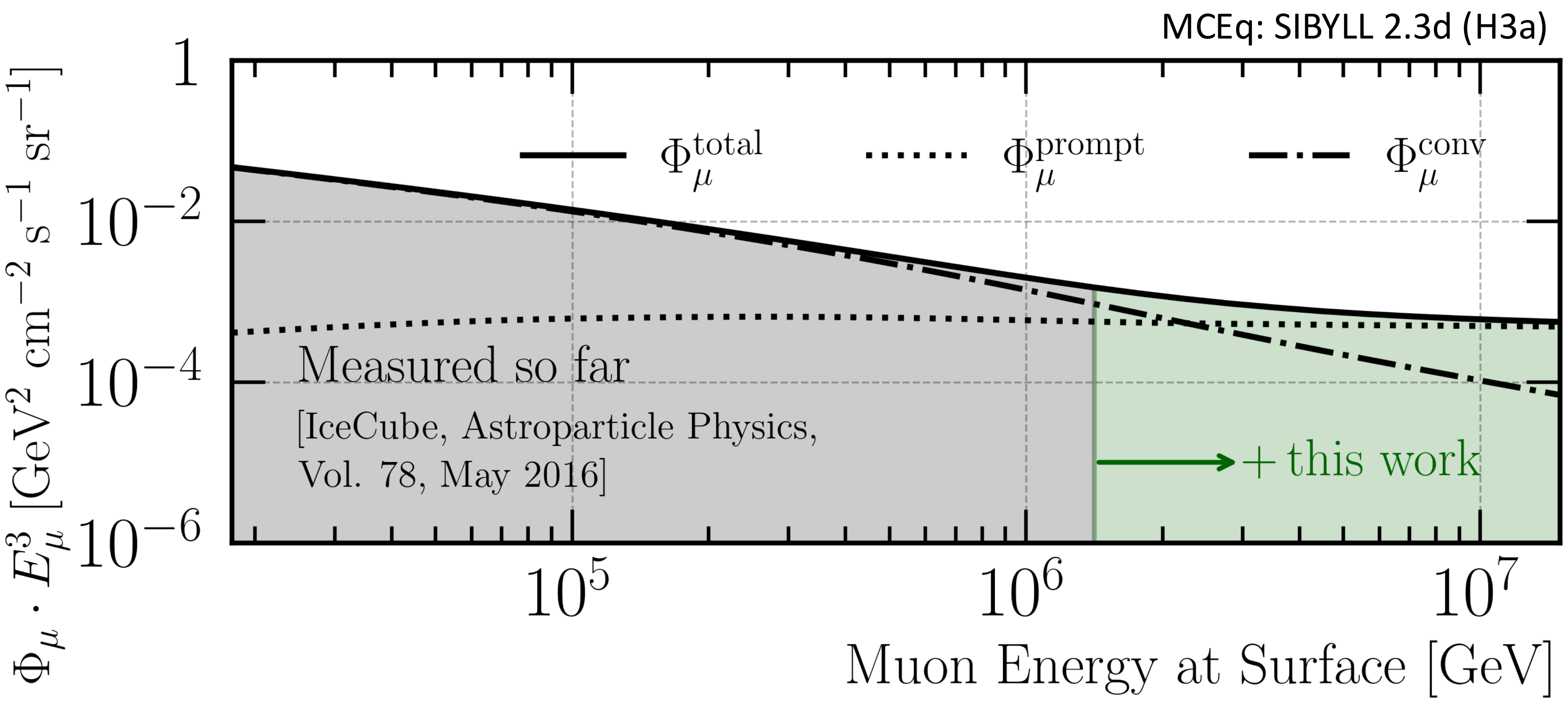
$$\underset{\propto E^{-2.7}}{p} \rightarrow \overbrace{\pi^+}^{\tau = 2.6 \cdot 10^{-8}\,\text{s}} \rightarrow \underset{\propto E^{-3.7}}{\mu^+} + \nu_\mu$$

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

Goal: Measure Muon Flux at Surface



Overview

Simulation

Dataset
- CORSIKA 77500 Ehist
- SIBYLL 2.3d
- 10 TeV – 100 EeV
- Snowstorm

Validation
- Tag prompt / conv particles
- MCEq comparisons

Reconstruction

DNN reconstructions
- Muon energies
- Muon direction
- Track geometry

Selection

Level 3
- L2 muon filter
- Add labels

Level 4
- 500 TeV bundle energy cut at surface
- Add DNN reconstructions

Level 5
- Data-MC quality cuts

Final Level
- Leadingness cut

Unfolding

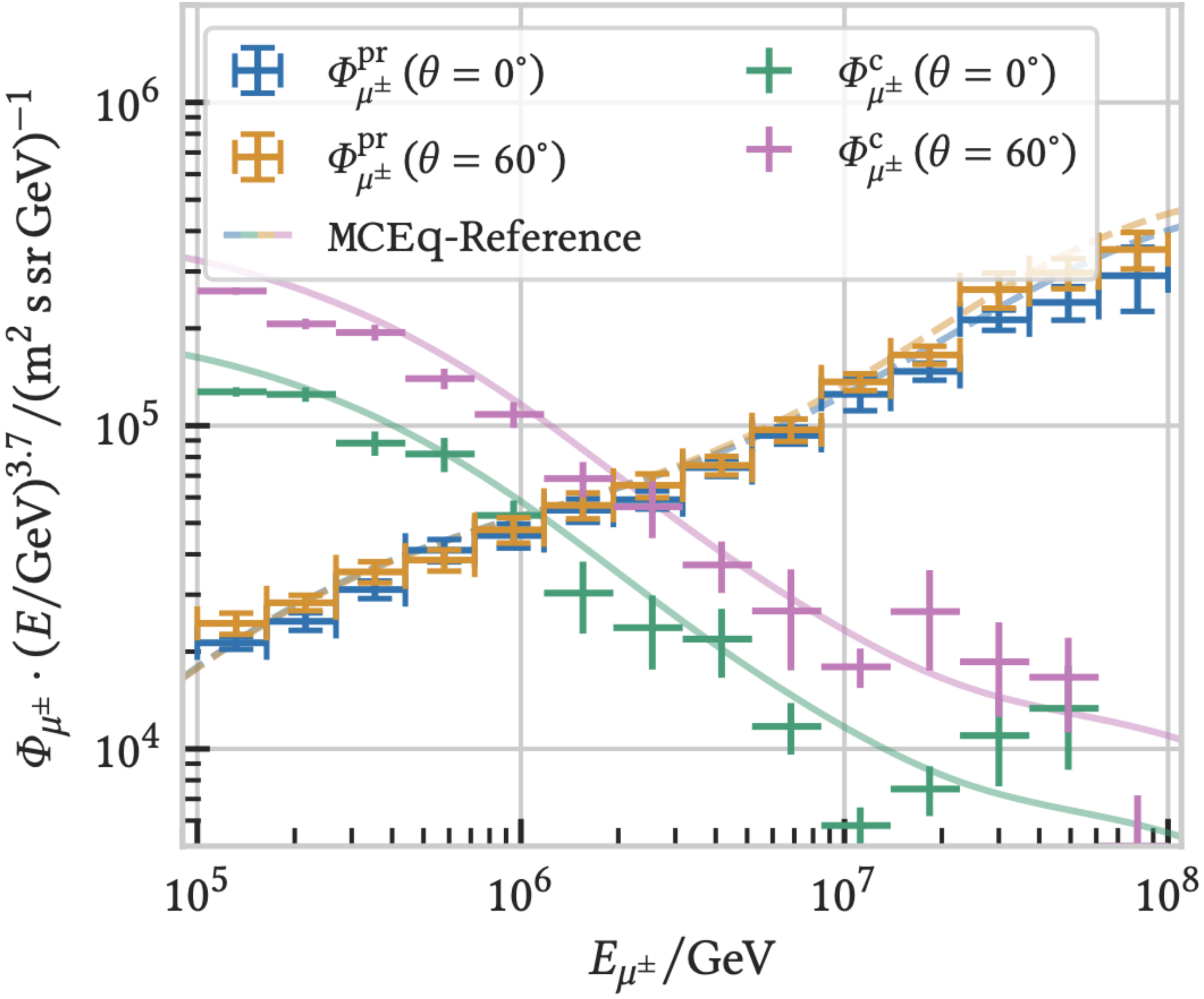
Muon spectrum
- Unfold muon flux at surface

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

https://github.com/The-Ludwig/PANAMA
Neste & Gutjahr et al., EPJ C, 85, 759 (2025)

Reconstruction

Machine Learning (CNN)

Input data per DOM

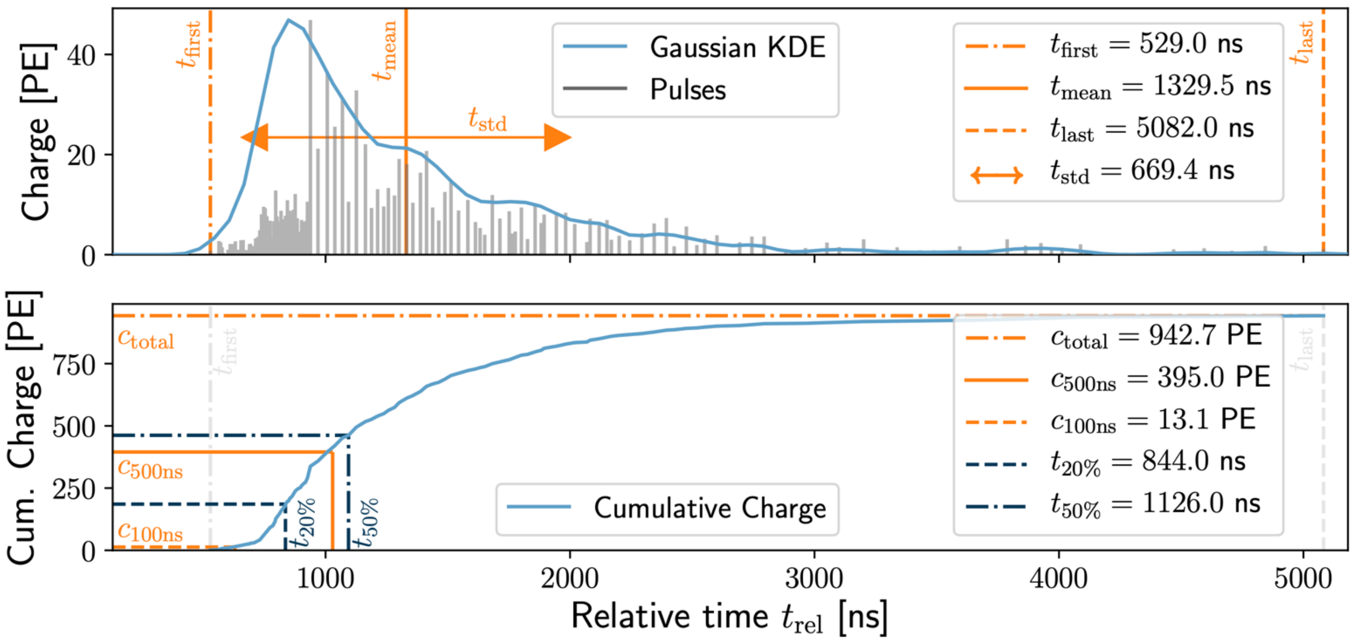
10.1088/1748-0221/16/07/P07041

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

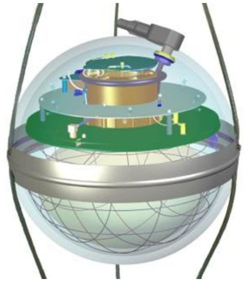


Input pulse cleaning

- 6000 ns

Training data

- Different simulations for robustness



Credit: IceCube

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

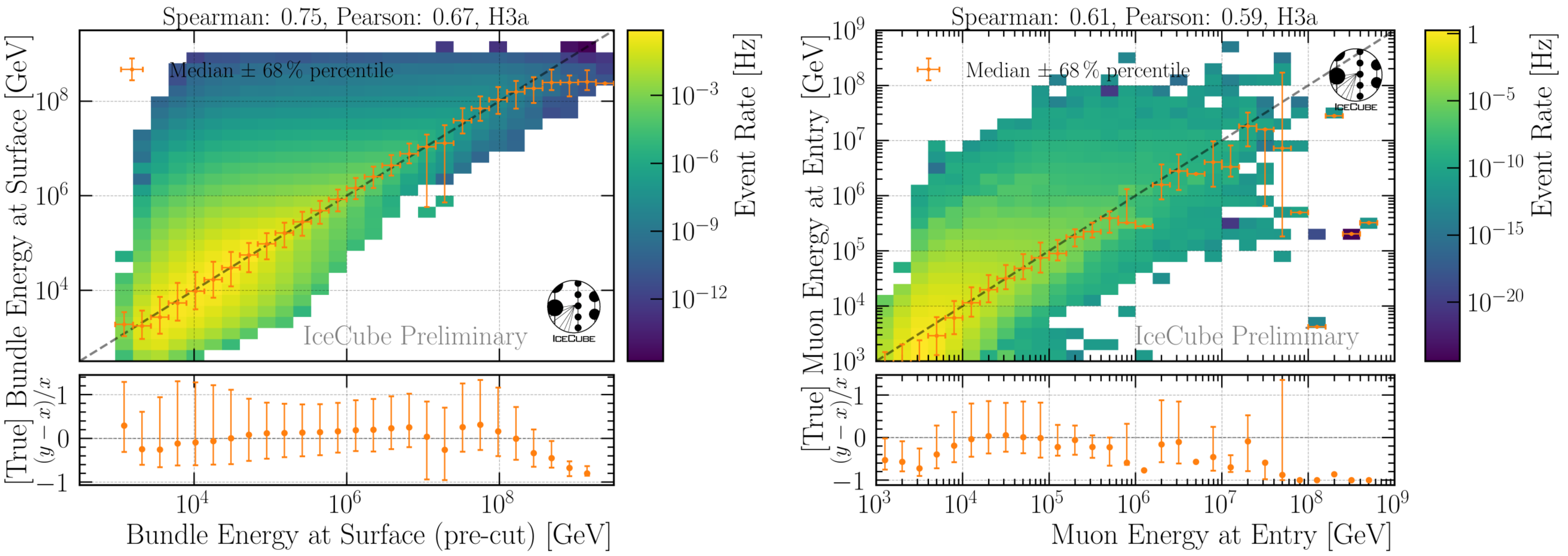
Network 2

Direction

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

Network 3

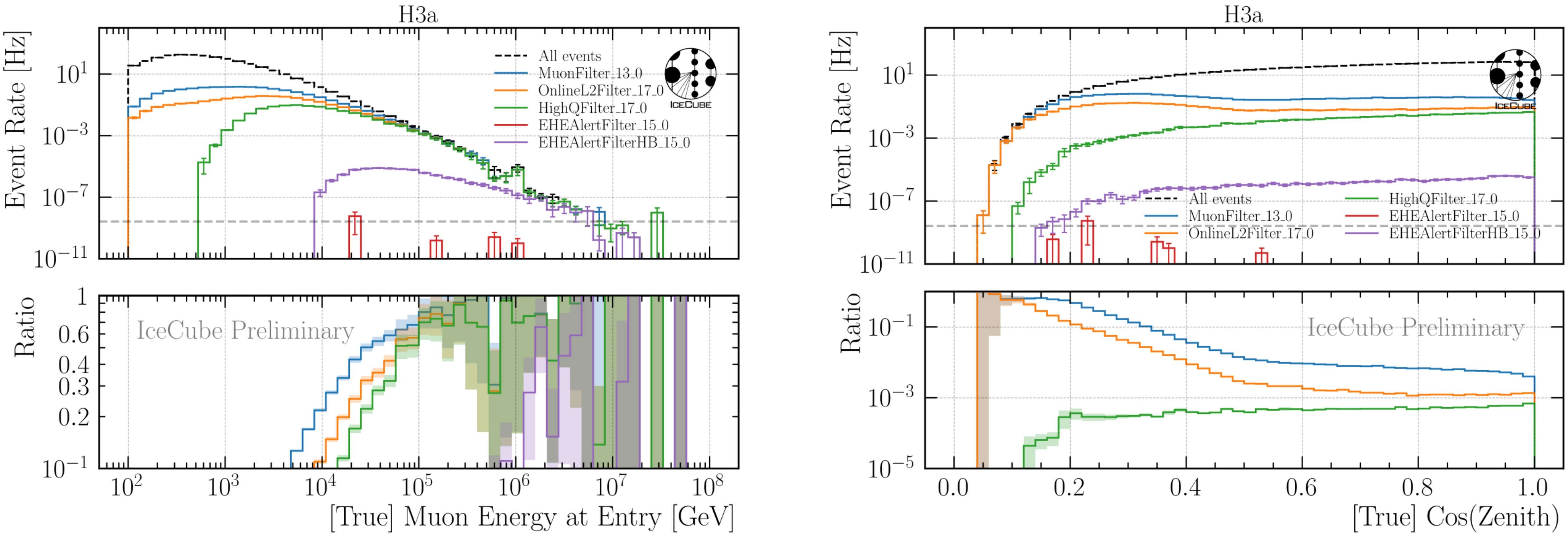
Energy Reconstructions



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

Selection

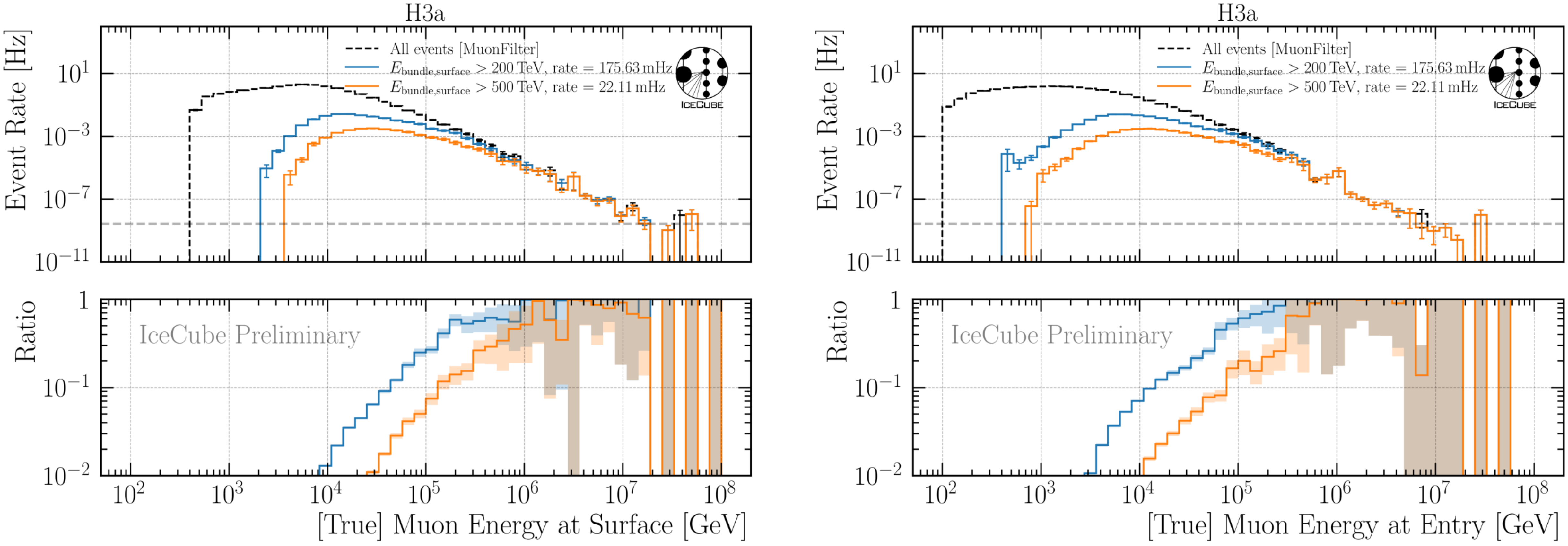
Level 3: Muon Filter



Muon filter: zenith-dependent charge and quality cut

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

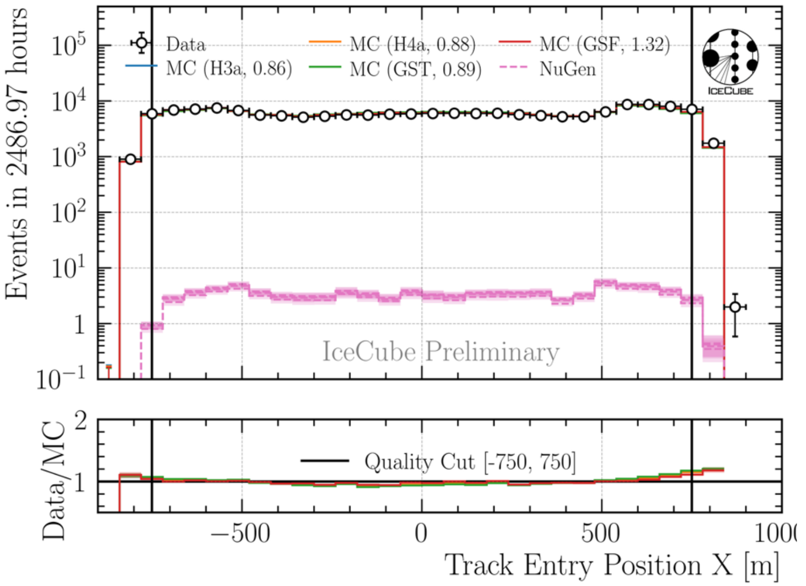
Level 4: Energy Cut

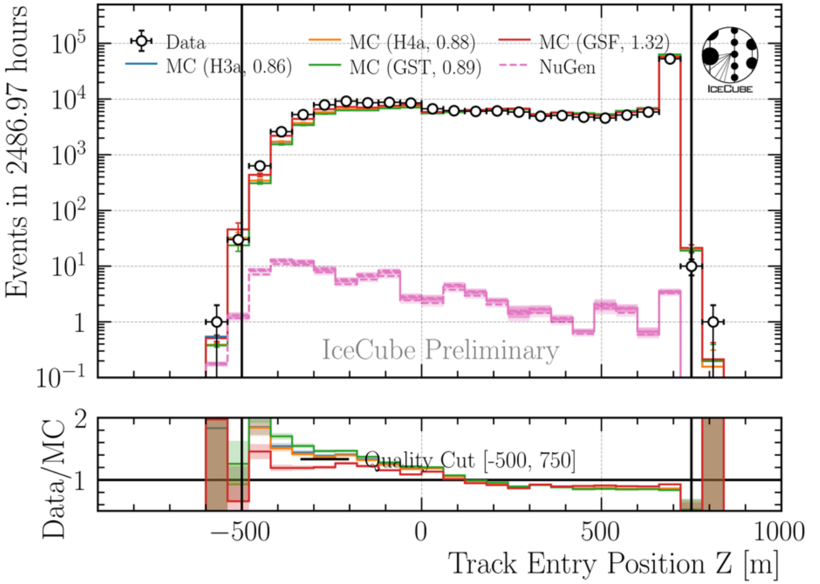


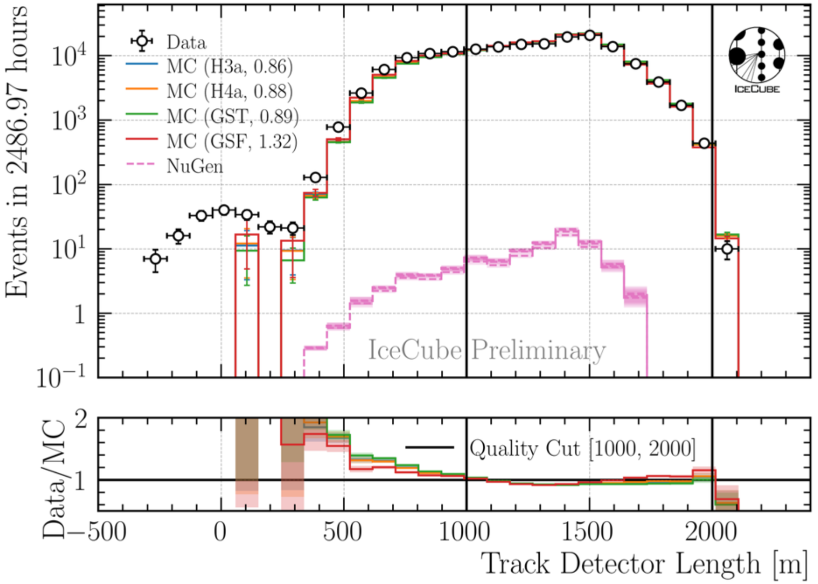
- 6 billion events expected in 10 years → computationally not feasible
- focus on high-energetic events
- Remove low-energy muons: bundle energy at surface > 500 TeV

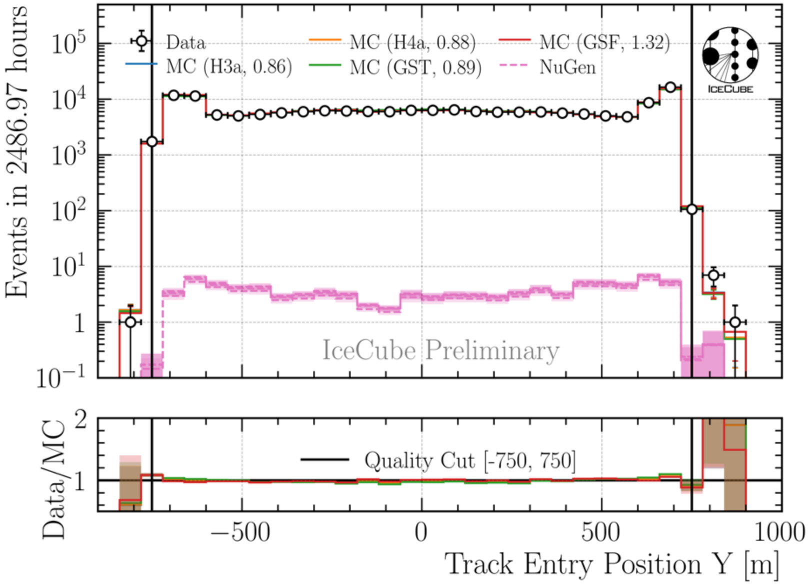
Level 5: Data/MC Quality Cuts

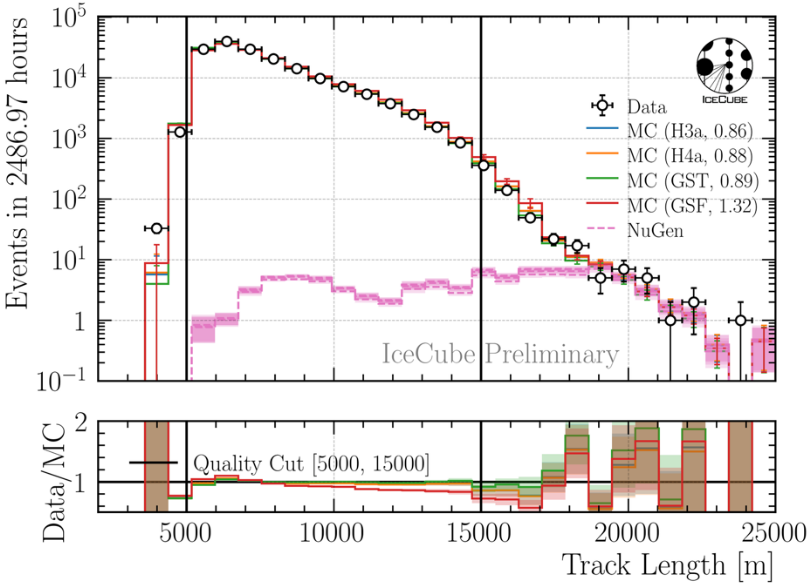
- Remove outliers
- Depth—dependent slope (no analysis relevance)
- CR—model impact on energy reconstruction
- 23 quality cuts in total

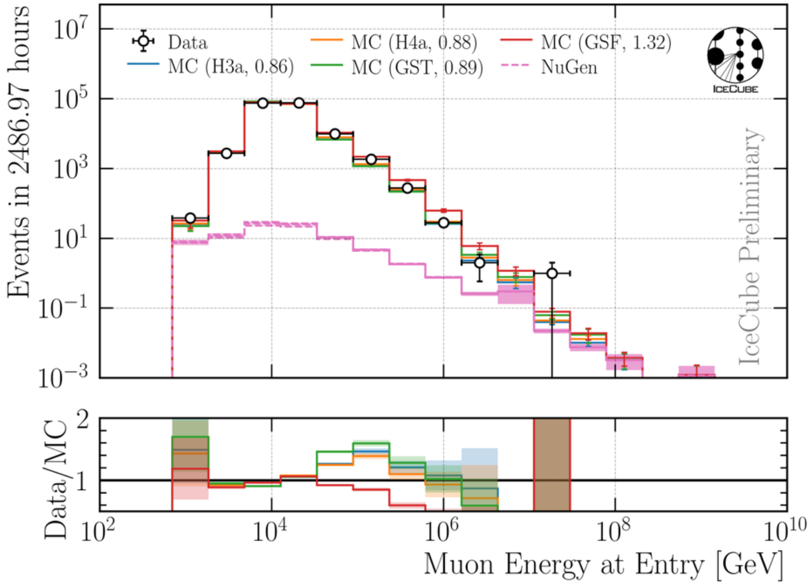








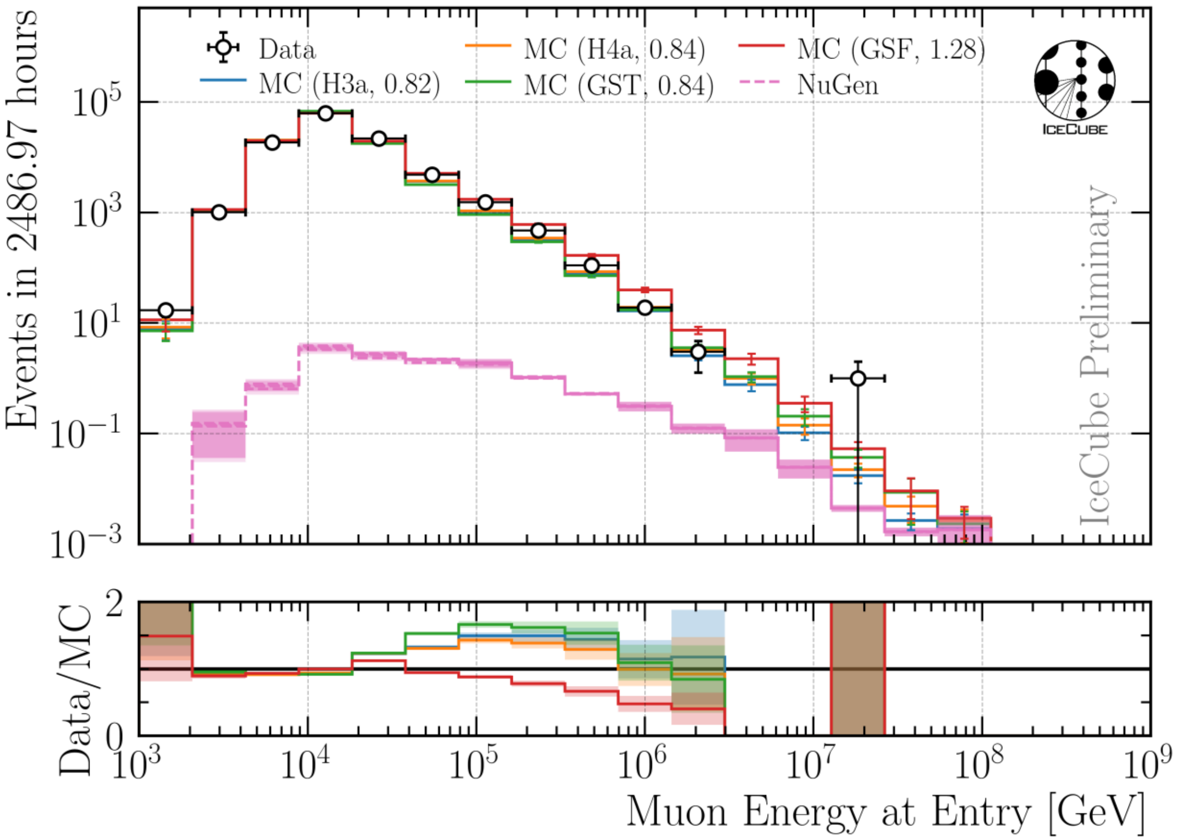




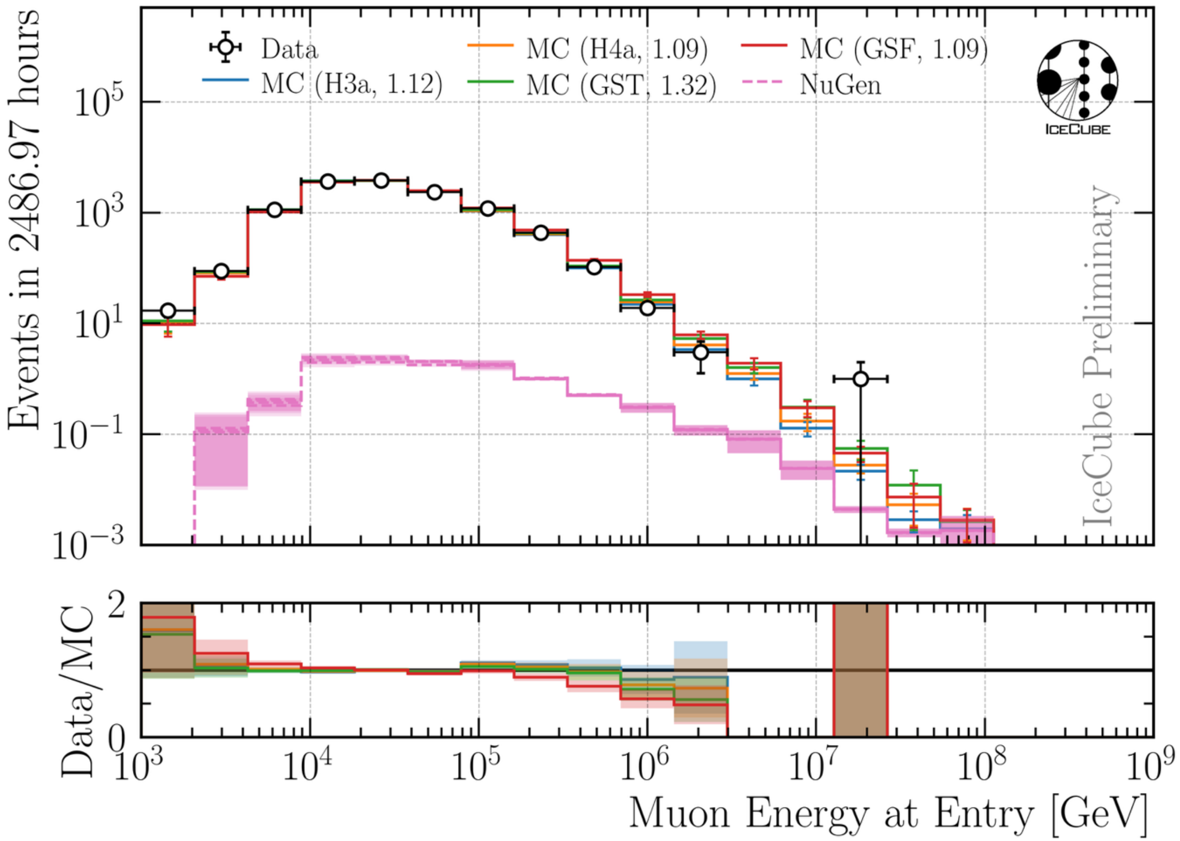
Final Level: Leadingness > 40 %

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

No leadingness cut



Leadingness > 40 %



➢ Improve Data/MC by leadingness cut

Unfolding

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: $\overbrace{\vec{g} = A\vec{f}}^{\text{folding}} \leftrightarrow \overbrace{\vec{f} = A^{-1}\vec{g}}^{\text{unfolding}}$

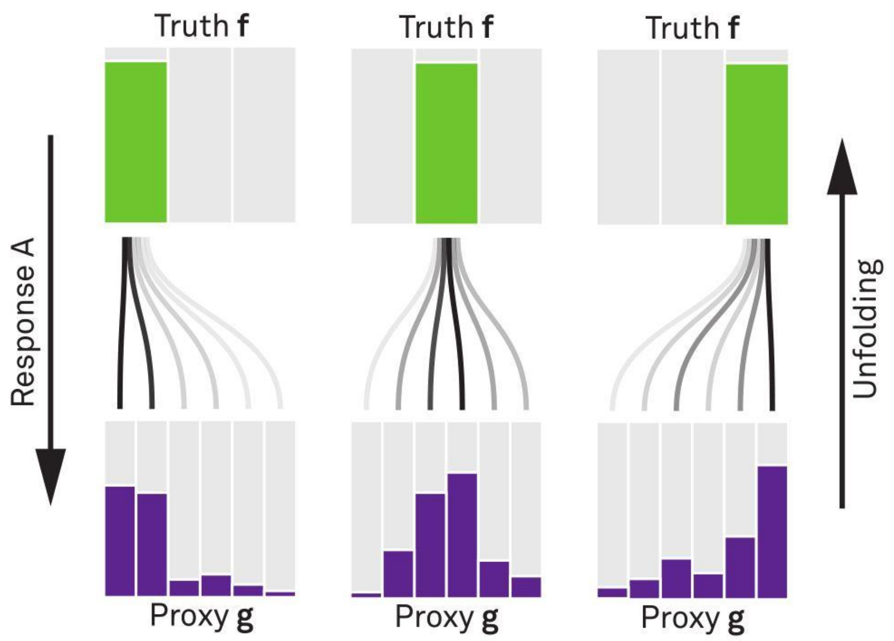
2. Maximum likelihod method:

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

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

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

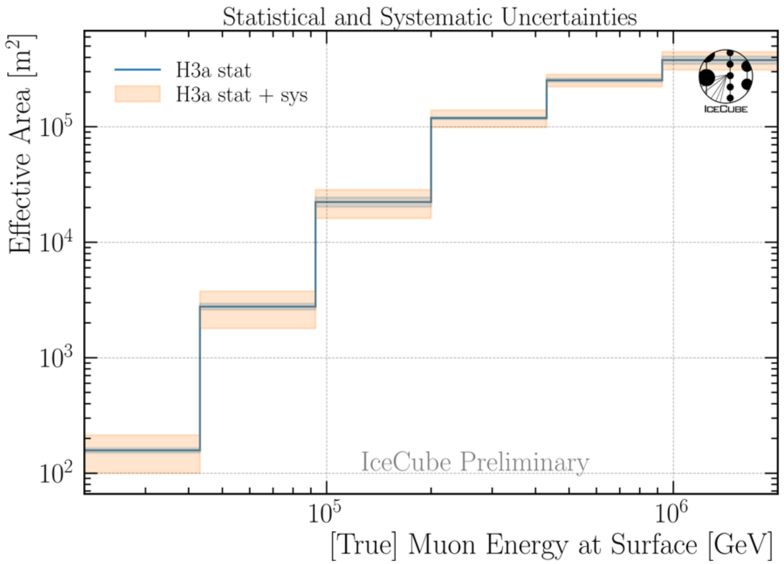
by M. Börner

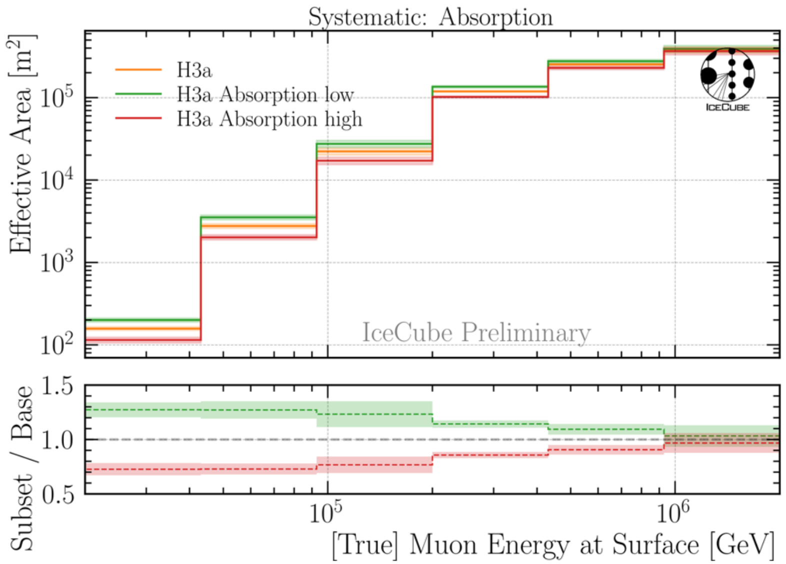
Muon Flux Unfolding

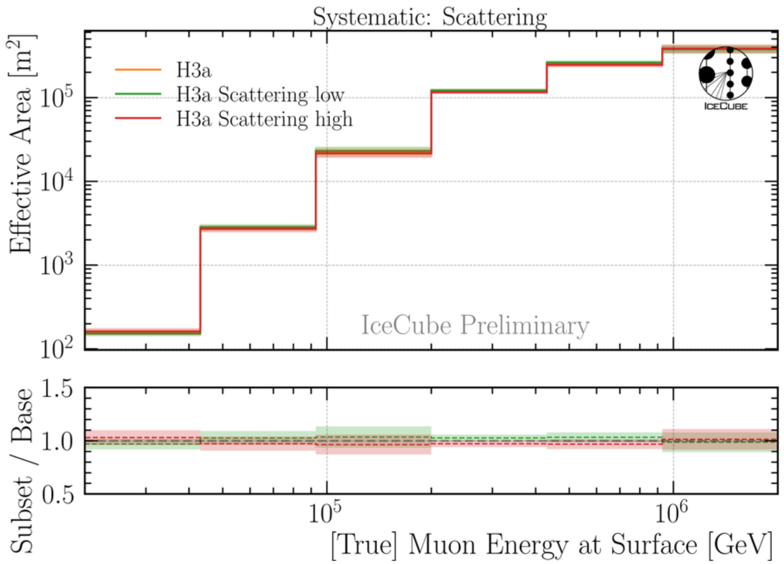
- ❑ Effective area
- ❑ Systematics
- ❑ Proxy that correlates with target
- ❑ Regularization
- ➢ Unfolding

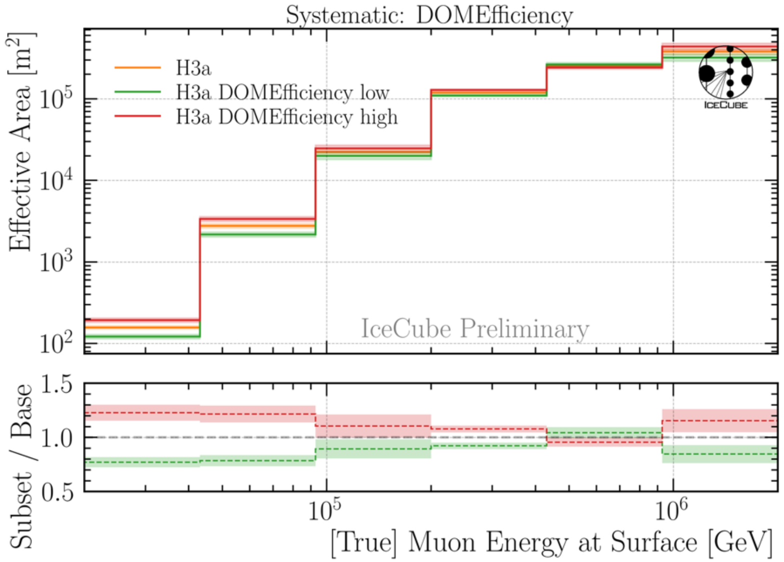
Ice & Detector Systematics

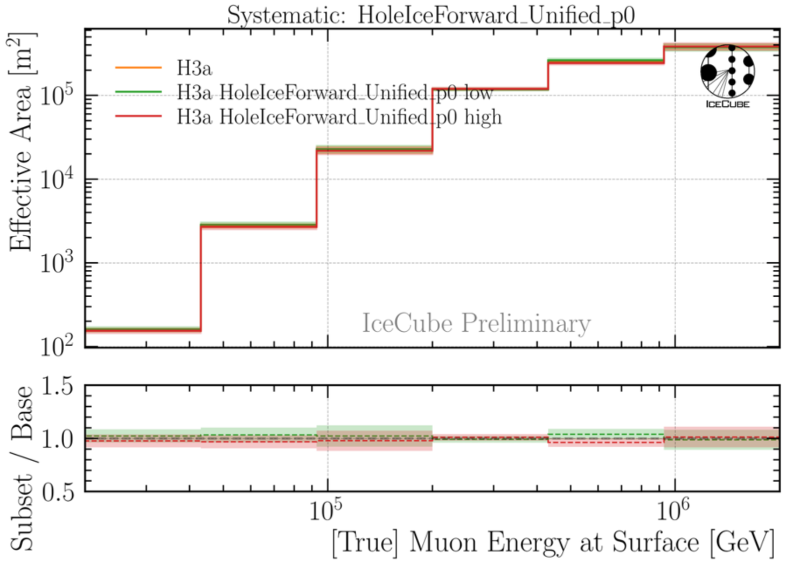
$$\sigma_{\mathrm{sys},i} = \max(A_{\mathrm{low}}, A_{\mathrm{high}}) - A_{\mathrm{base}}$$

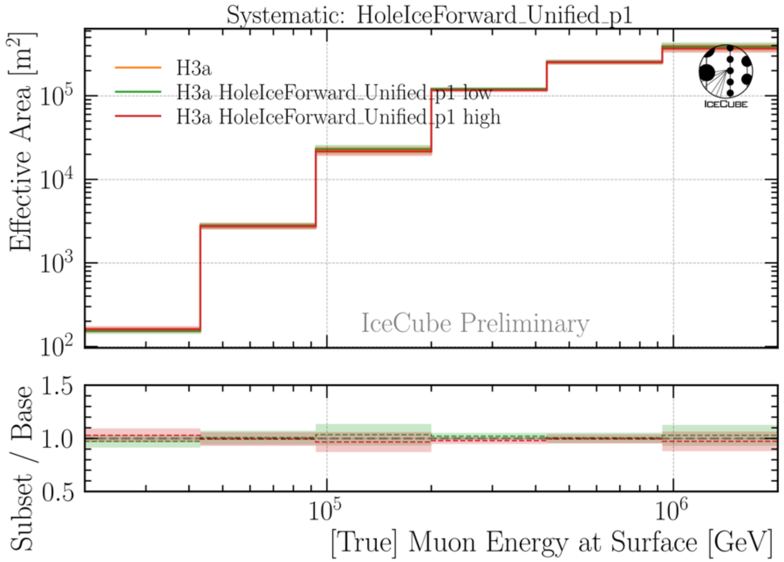










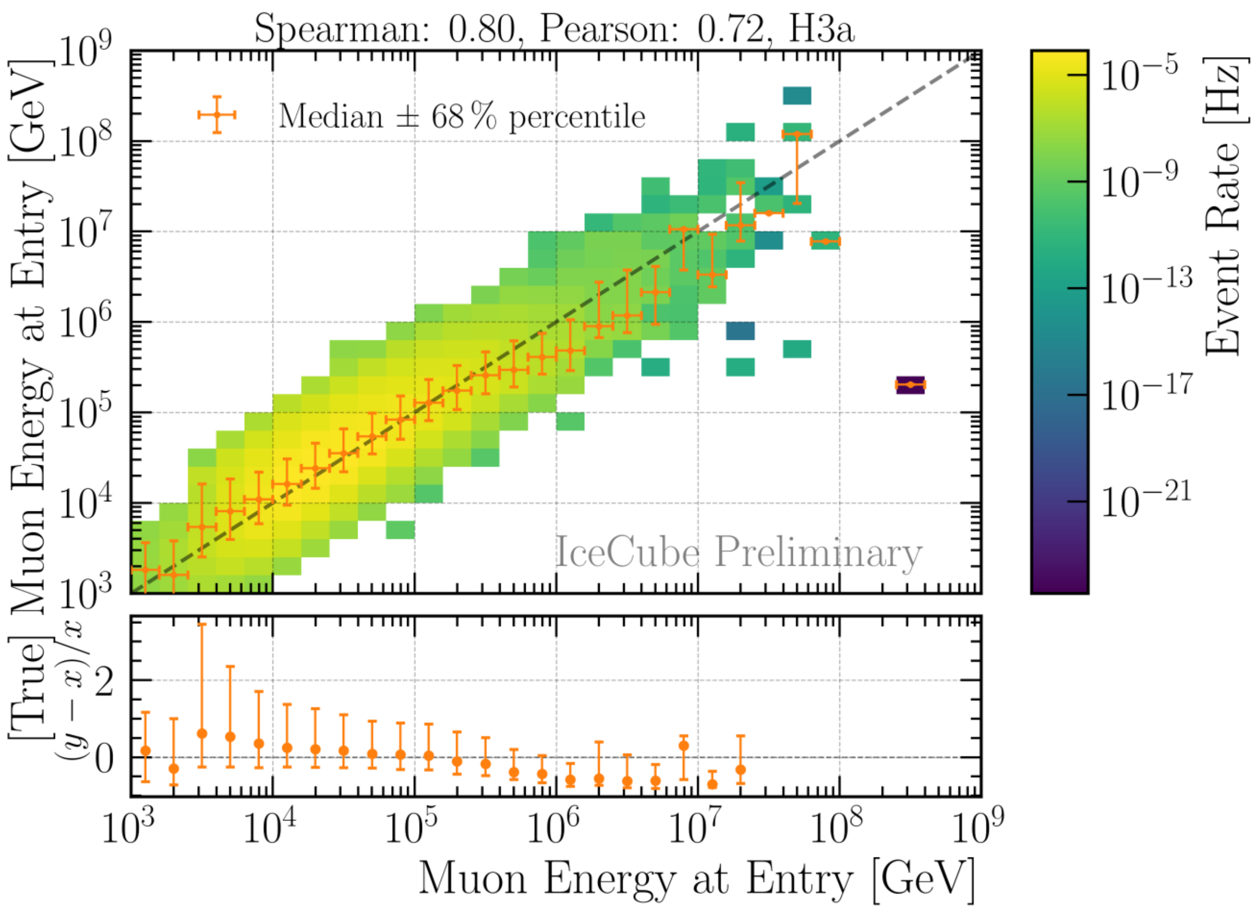


- Baseline: entire set
- Subset: above/below center

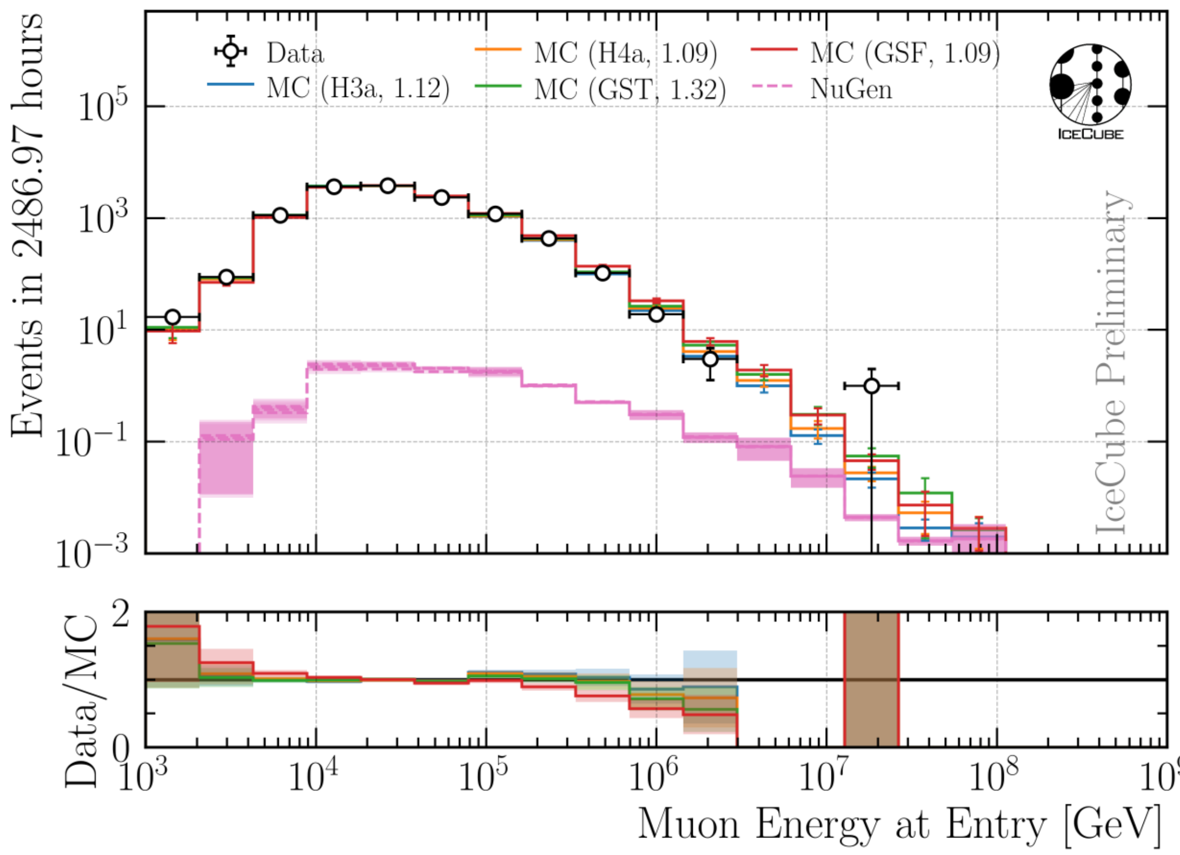
$$\sigma_{\mathrm{tot}} = \sqrt{\sigma_{\mathrm{stat}}^2 + \sum \sigma_i^2}\,, i: \mathrm{scat, abs, DOME, holeice\ p0, p1}$$

Reconstruction and Data—MC: Leading Muons

- Good reconstruction of leading muon energy → proxy

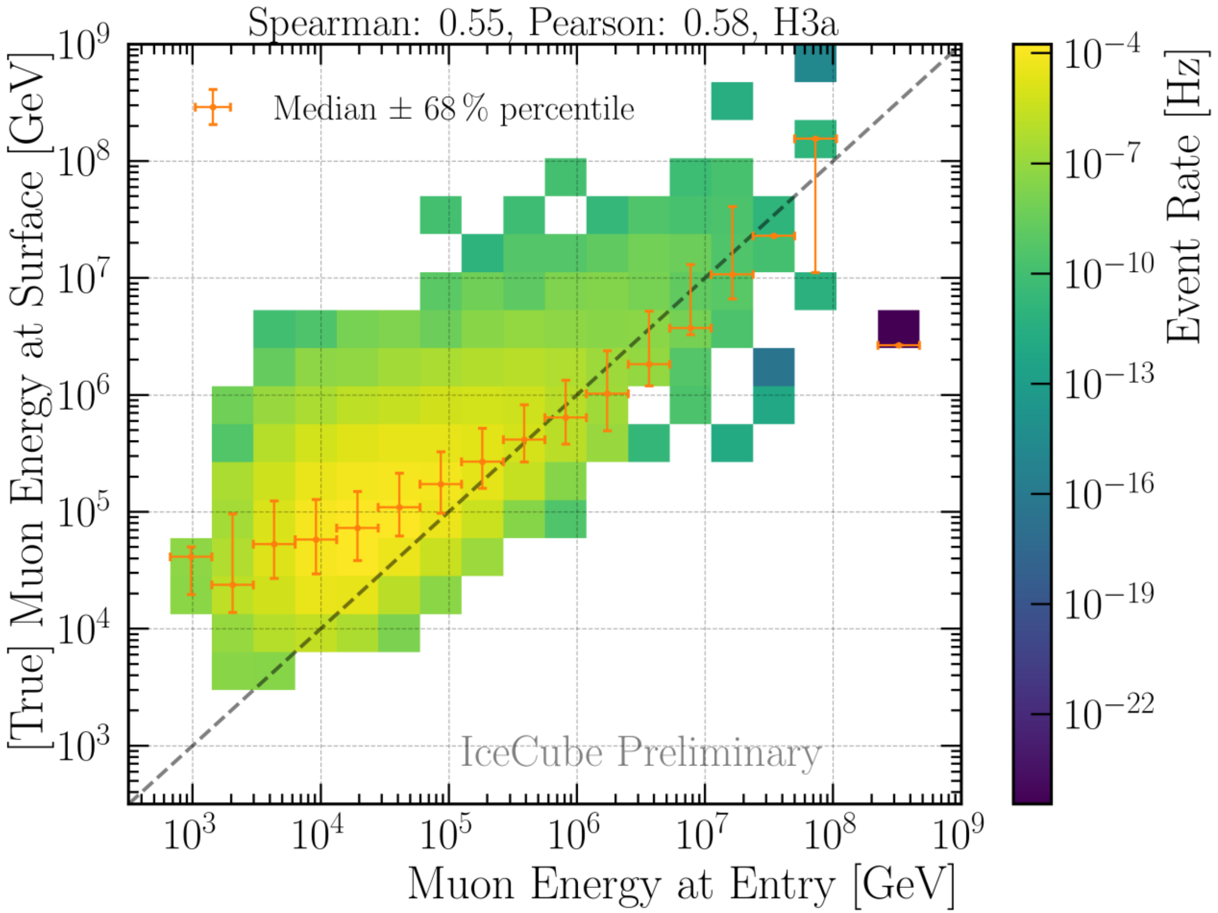


- Good data—MC agreement
- Global offset → upscale MC by 12%

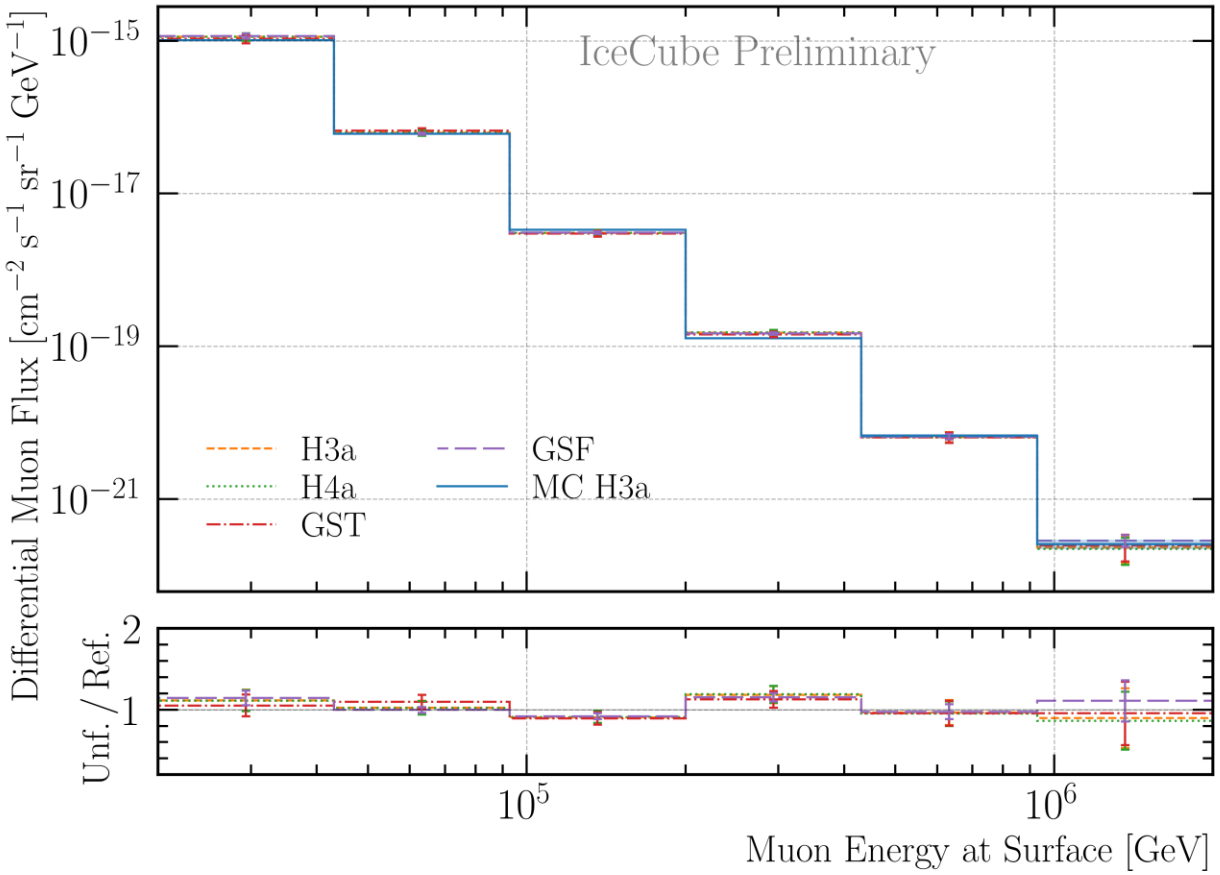


Correlation and Robustness Test: Leading Muons

- Correlation between proxy and target



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

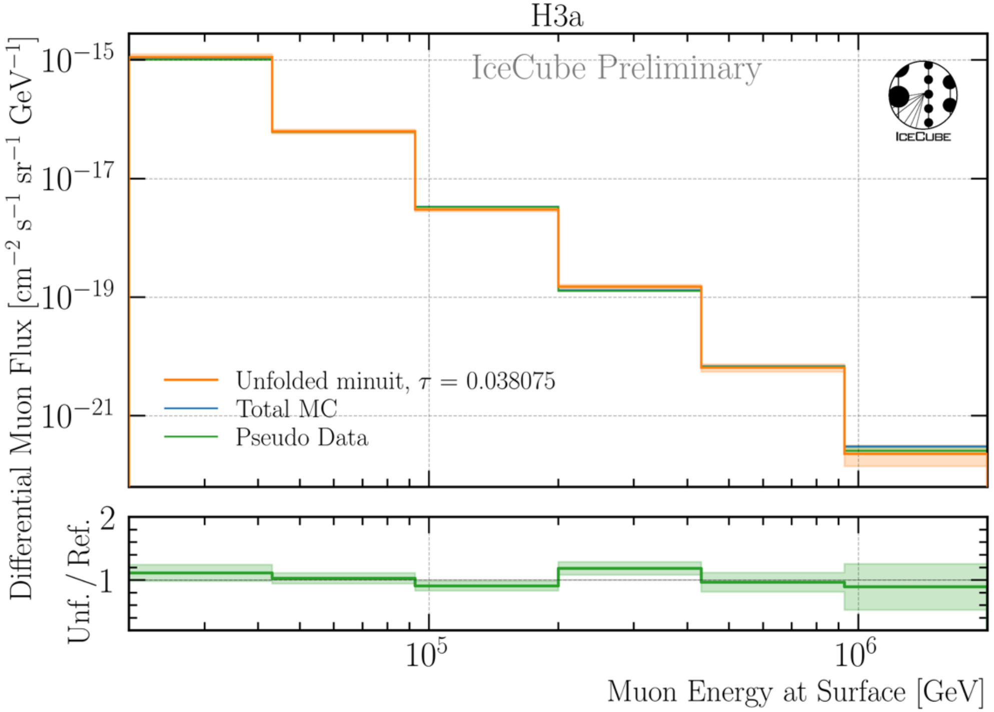


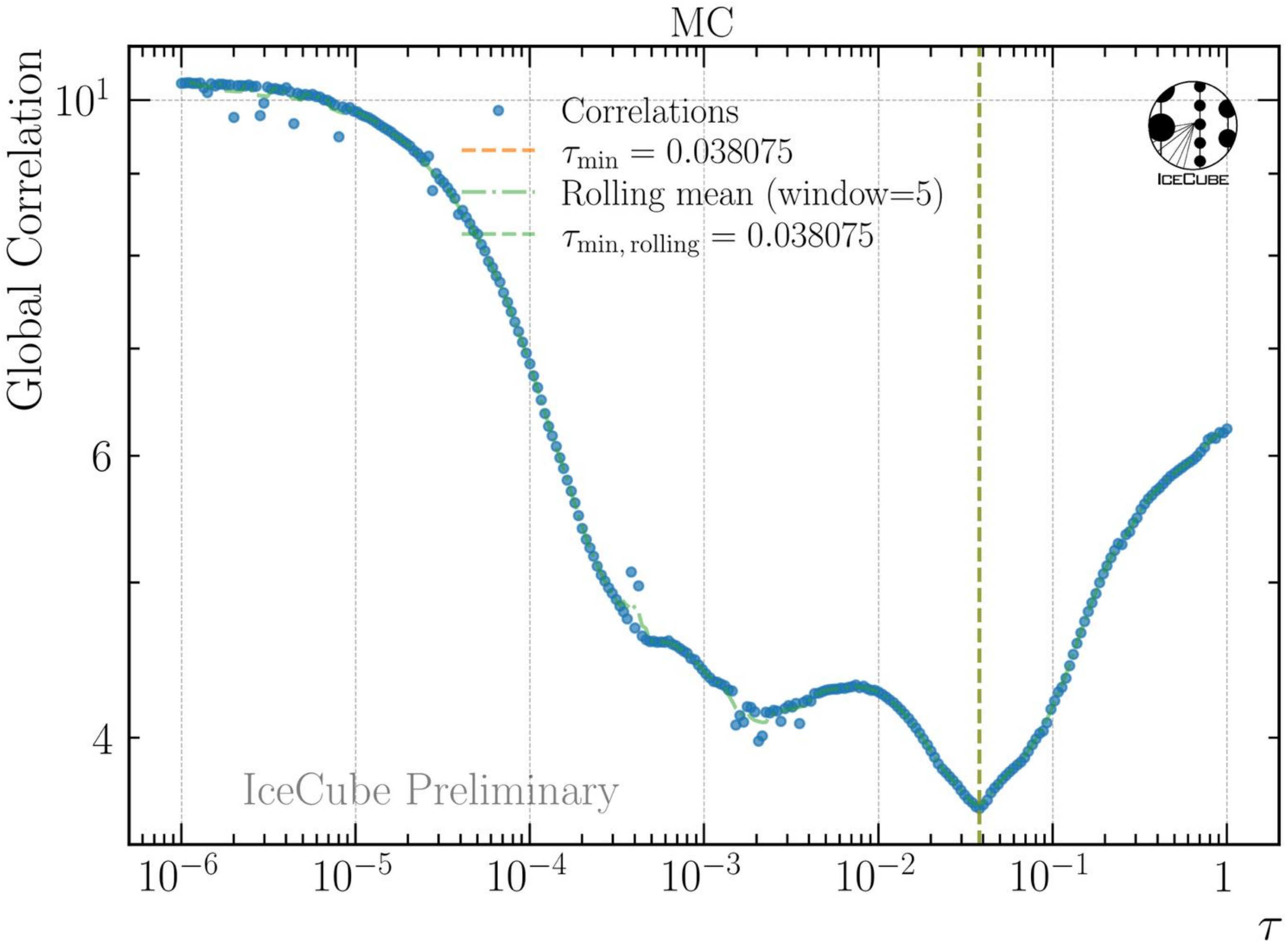
Burnsample

Determine Regularization

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

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





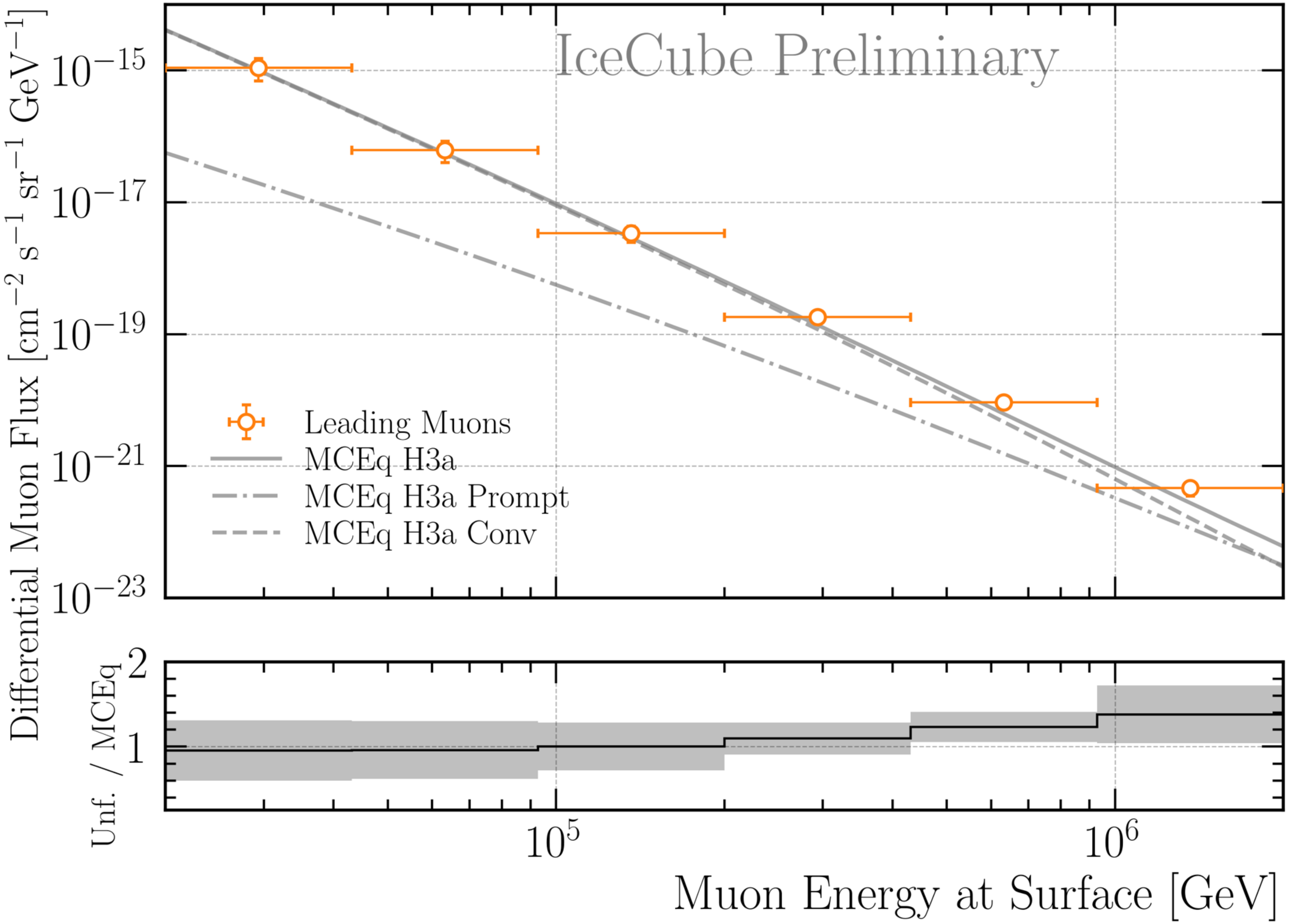
Unfold MC truth → ratio should be 1

Burnsample

Burnsample Unfolding

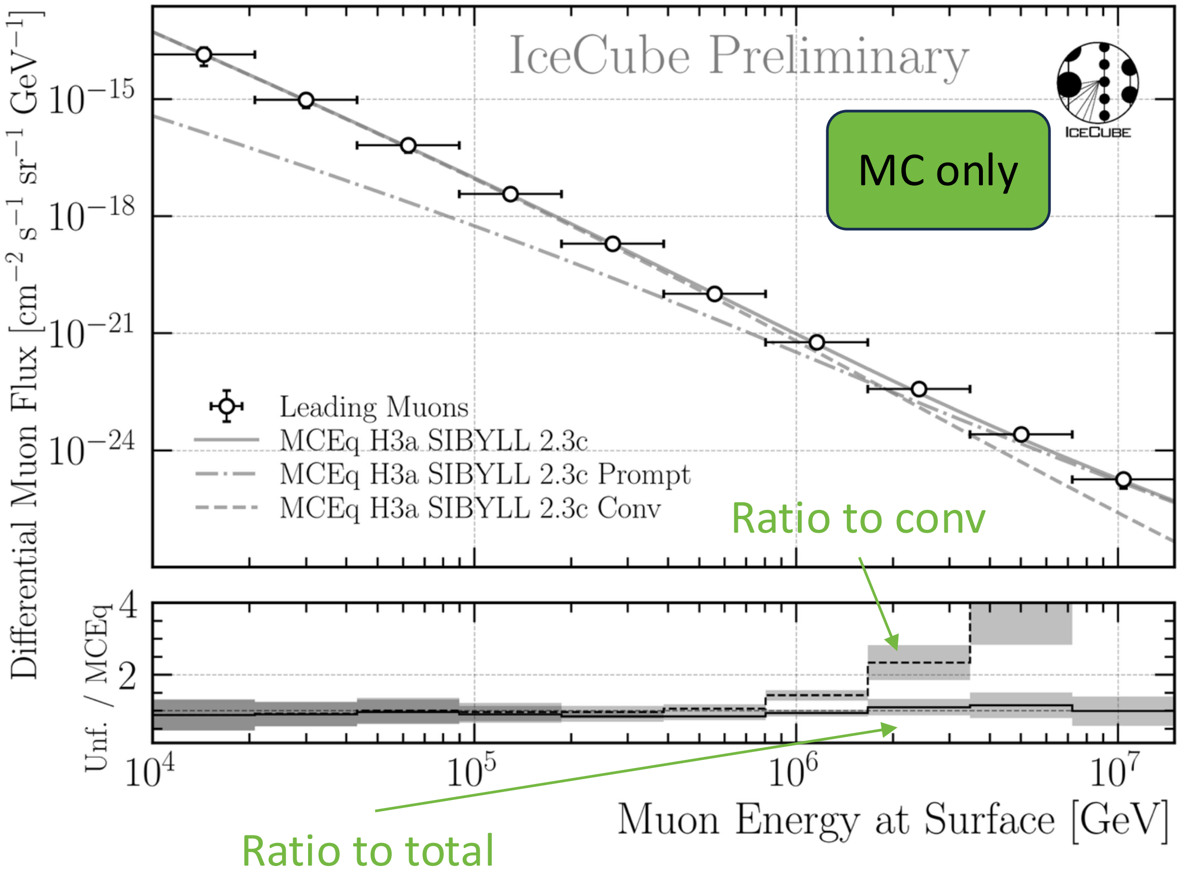
Leading muons

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

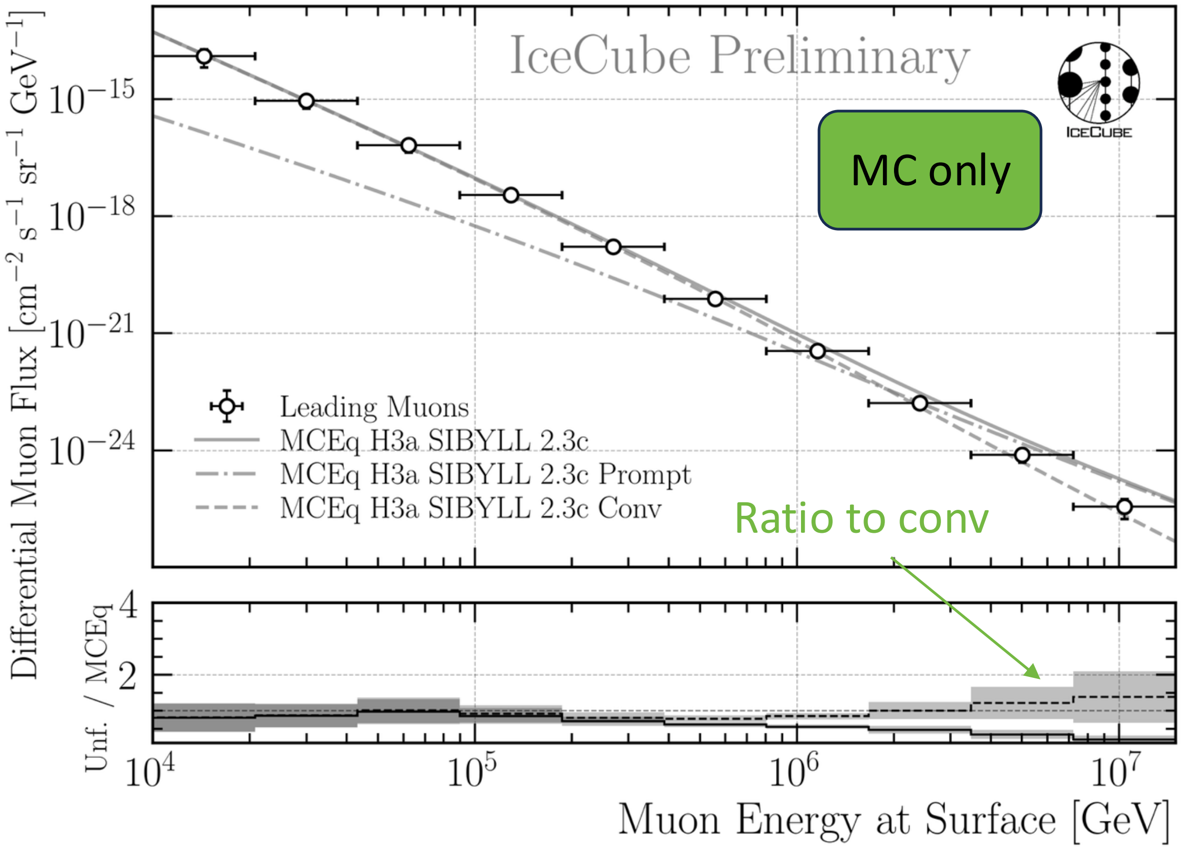


Prediction: 12 Years of IceCube Data Unfolding

Pseudo Sample has prompt



Pseudo Sample has NO prompt



➢ Unfolding is sensitive to the prompt component

*with systematic uncertainties from effective area

Event Rate to Flux → Effective Area

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

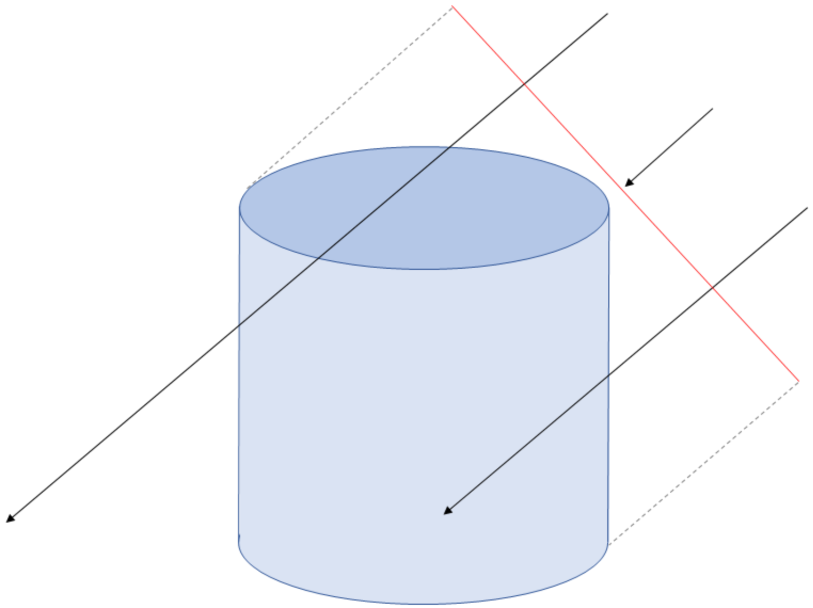
$$\Phi_i = \frac{N_i}{T \cdot \Delta L_i \cdot \Omega_i \cdot A_{\mathrm{eff},i}}$$

- with solid angle

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

- and effective area

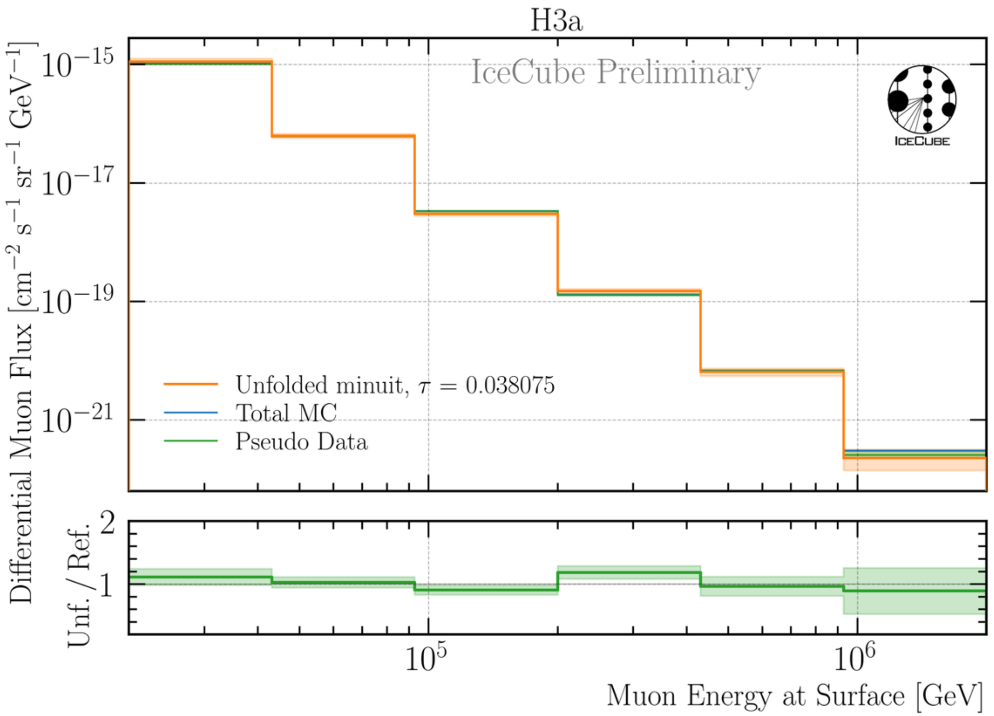
$$A_{\mathrm{eff}} = A_{\mathrm{sim}} \frac{N_{\mathrm{sel}}}{N_{\mathrm{gen}}}$$

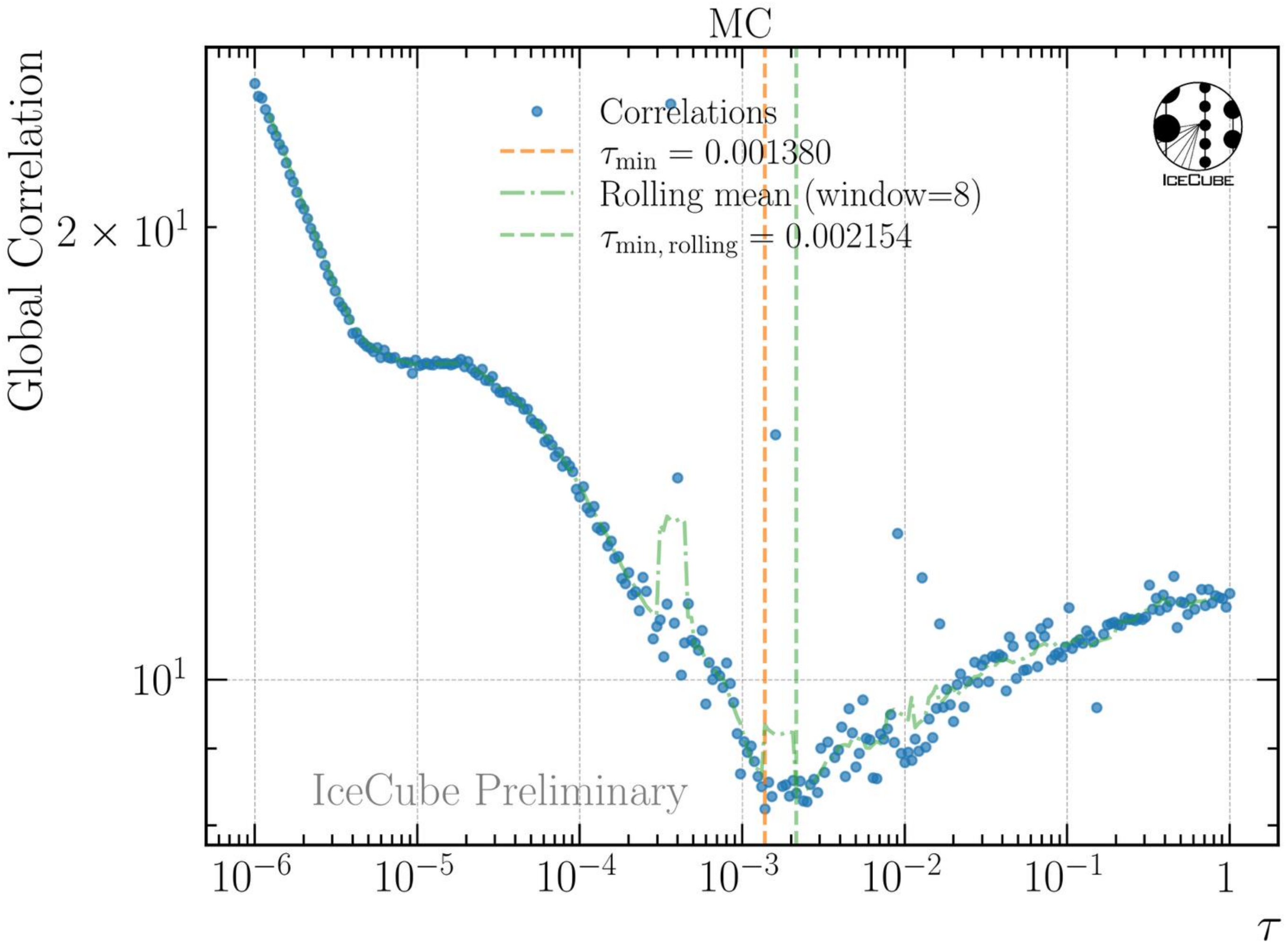


Determine Regularization

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

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





Unfold MC truth → ratio should be 1

Burnsample

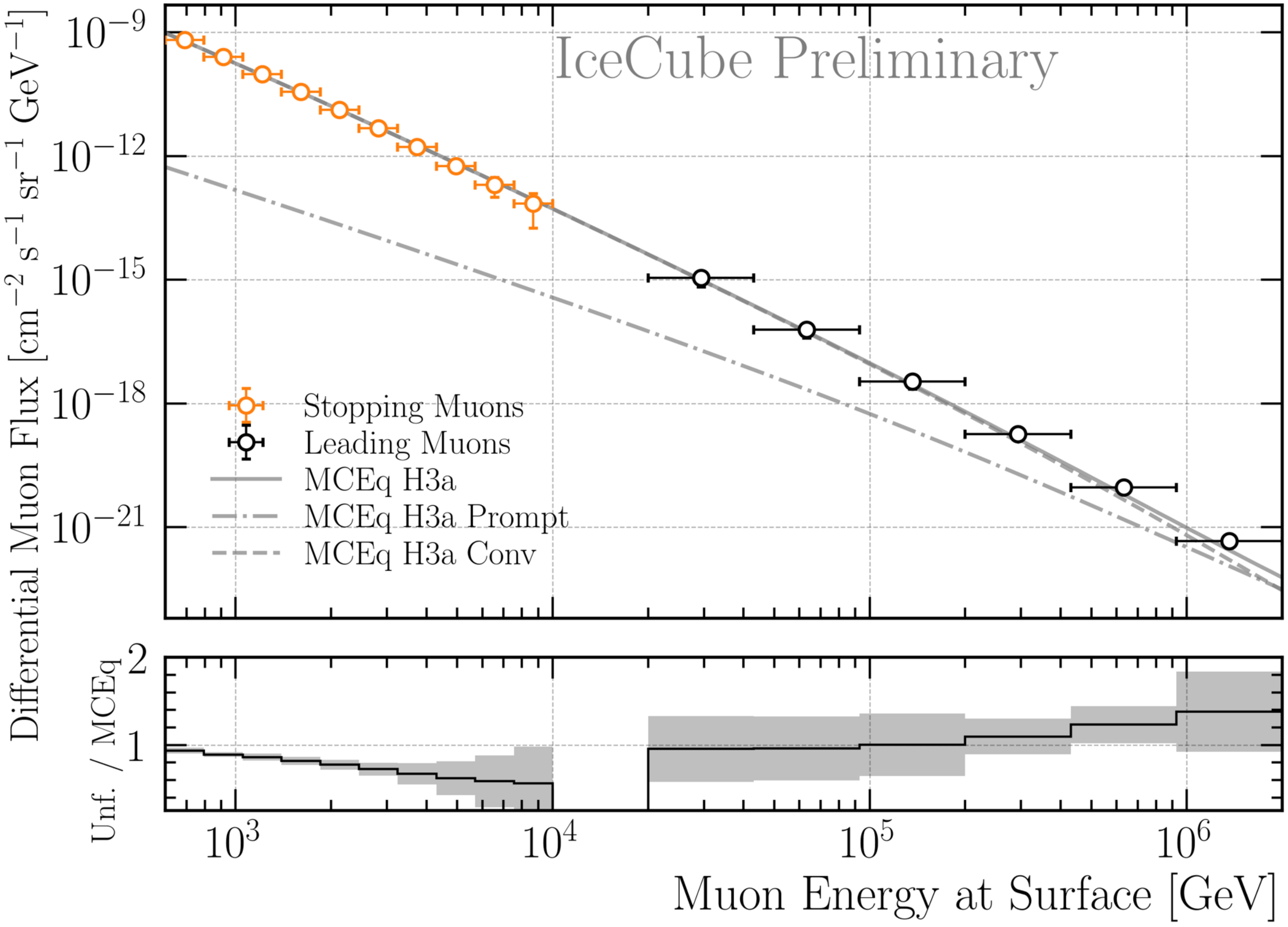
Muon Flux Unfolding

Leading muons

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

Stopping muons

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

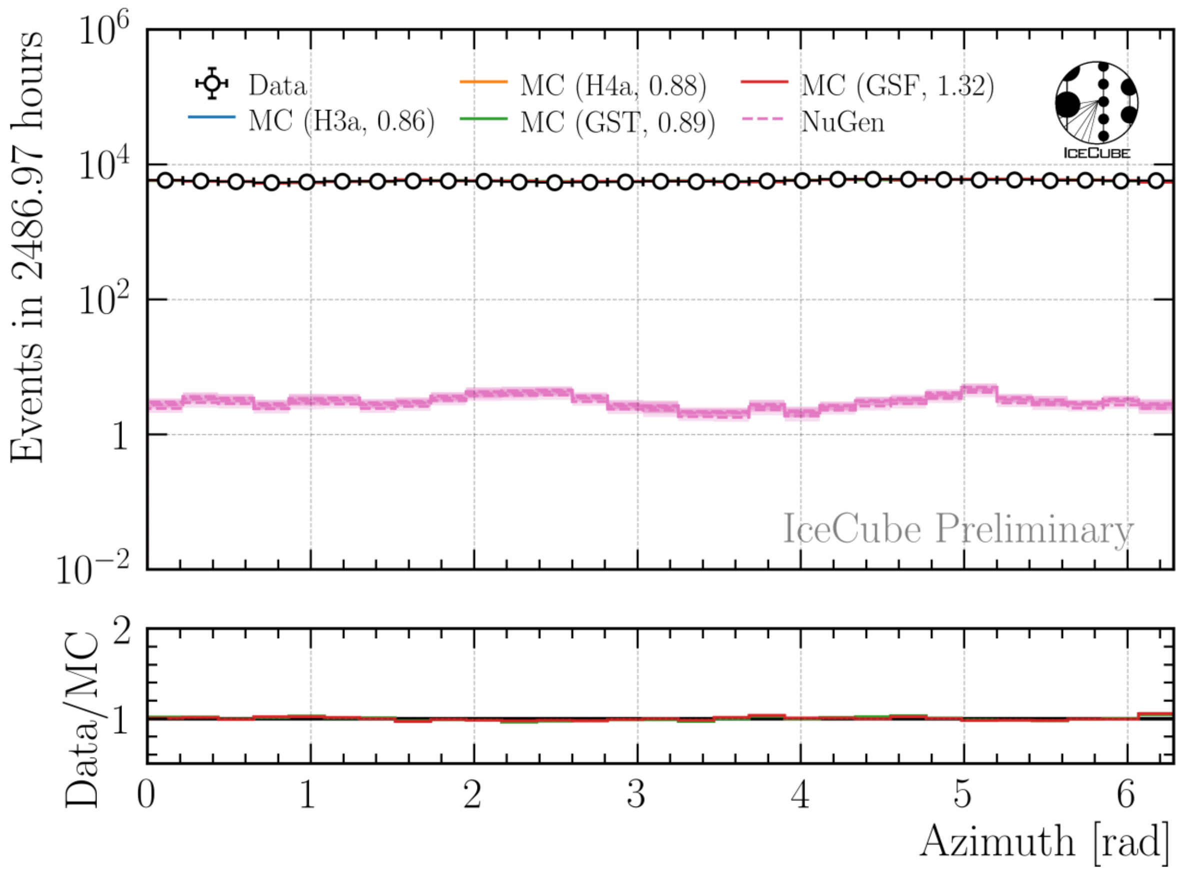


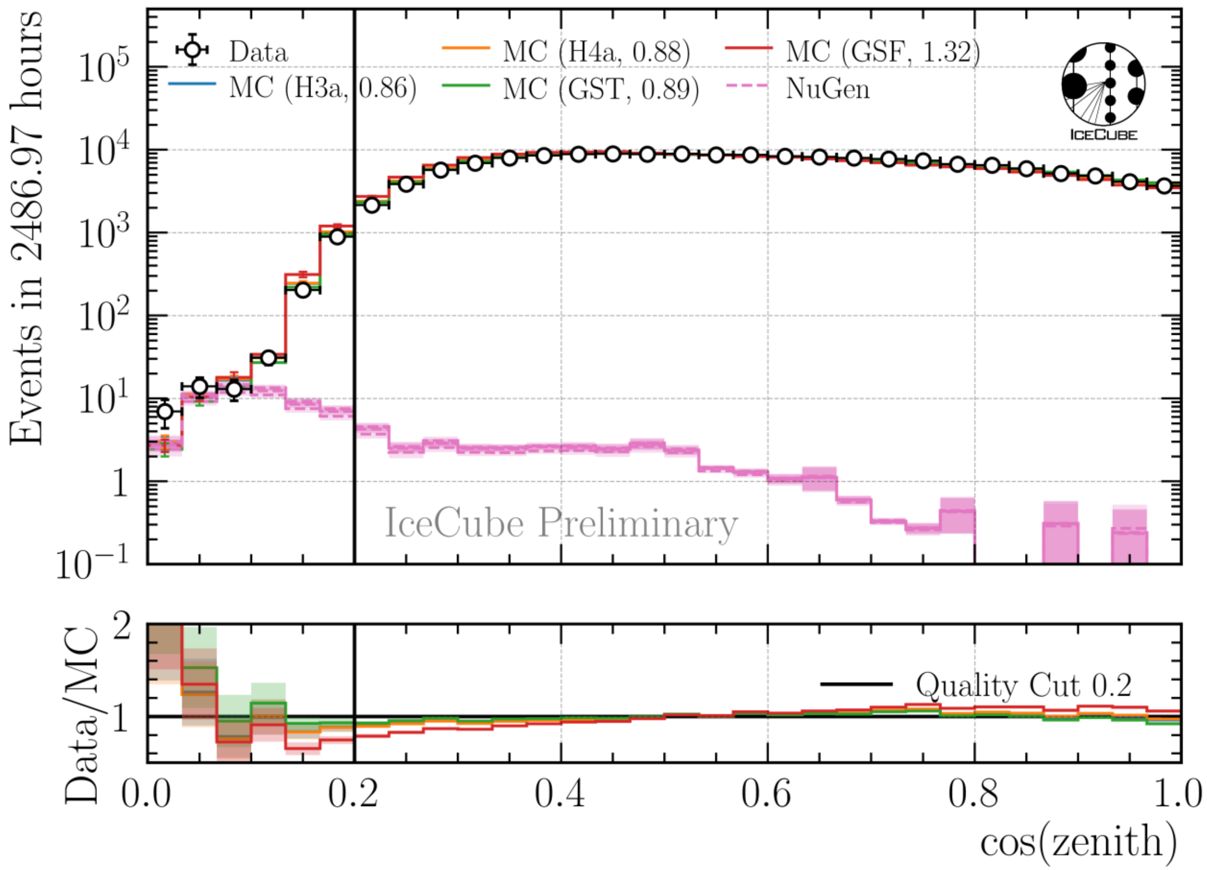
*Stopping muon analysis done by Lucas Witthaus

Level 5: Data/MC Quality Cuts

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

IceCube Collaboration PoS ICRC2023 1064

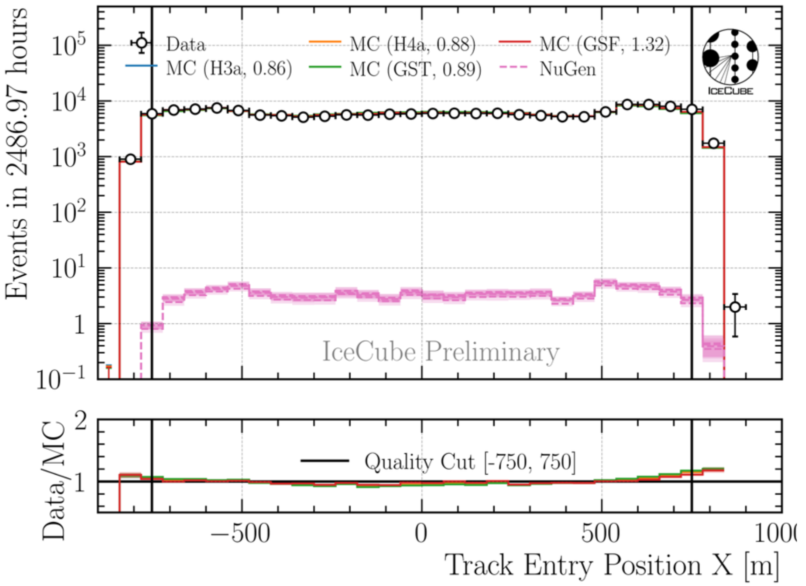


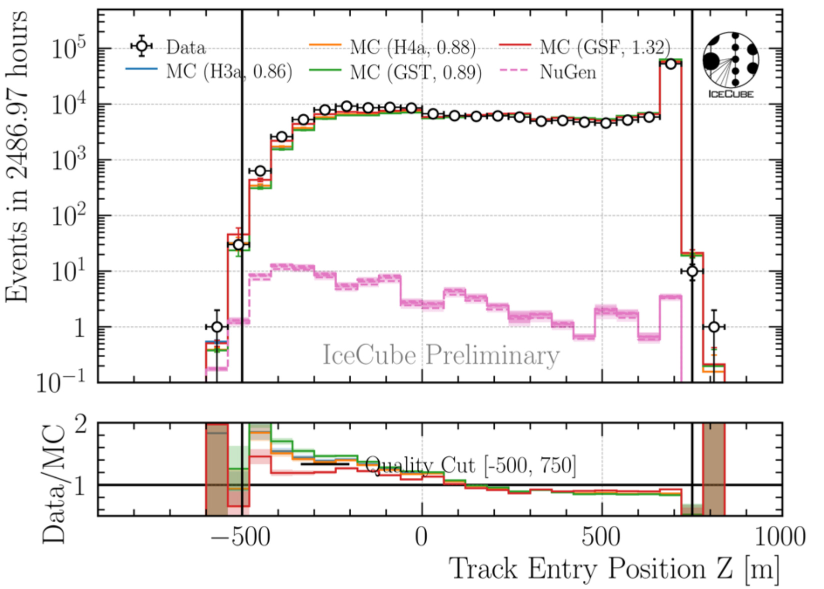


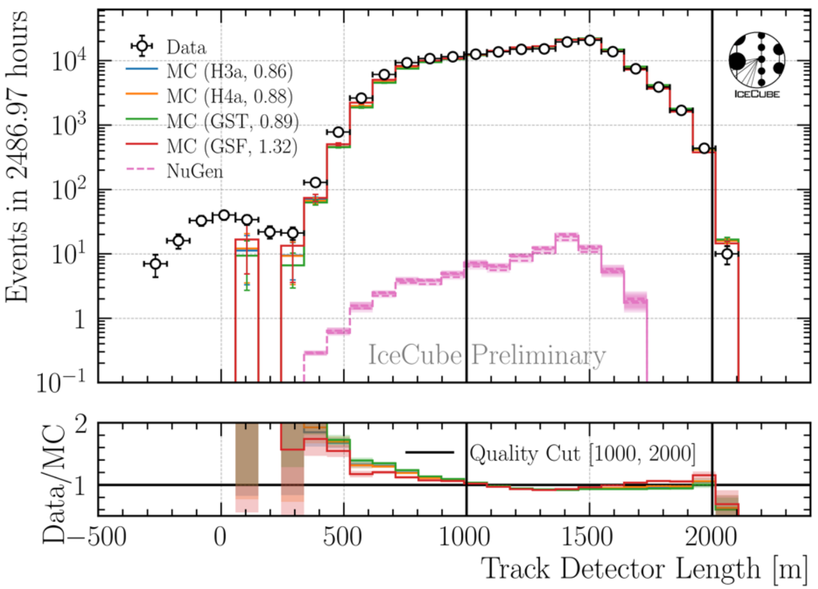
- Good directional reconstruction
- Cut: cos(zenith) > 0.2

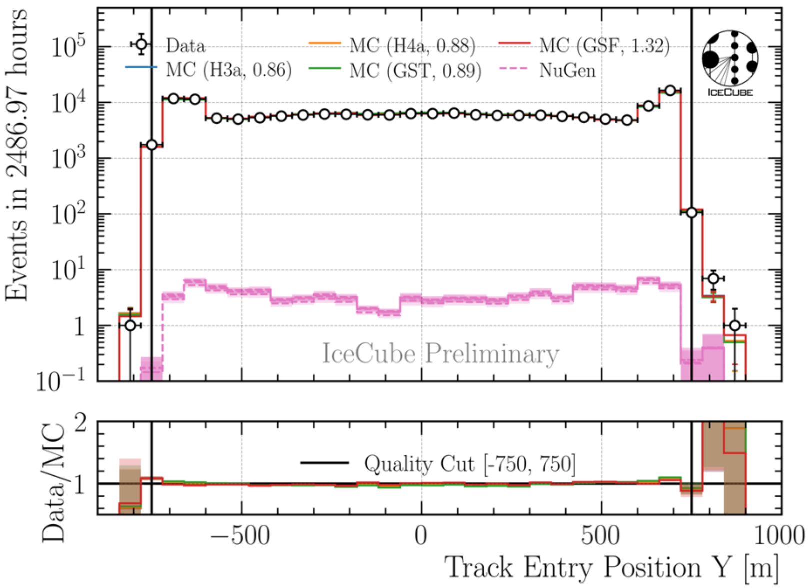
Level 5: Data/MC Quality Cuts

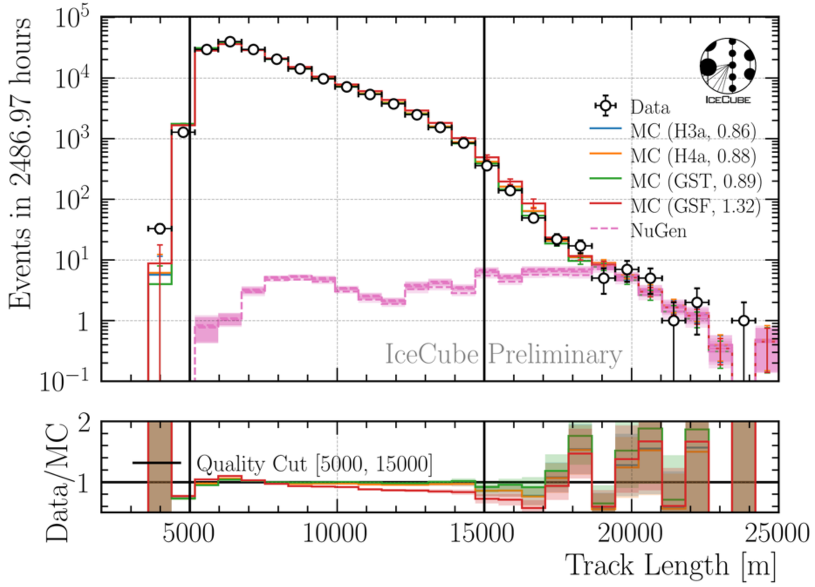
- Remove outliers
- Depth—dependent slope (no analysis relevance)
- CR—model impact on energy reconstruction
- 23 quality cuts in total

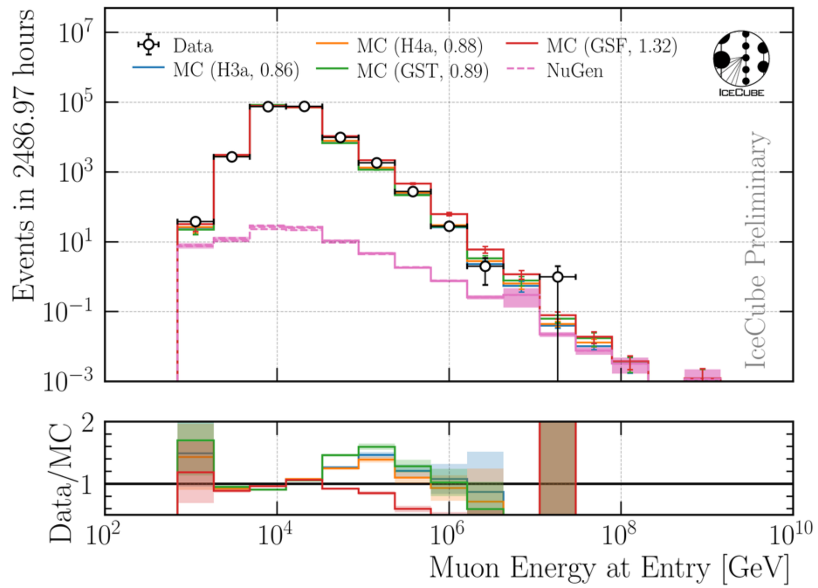






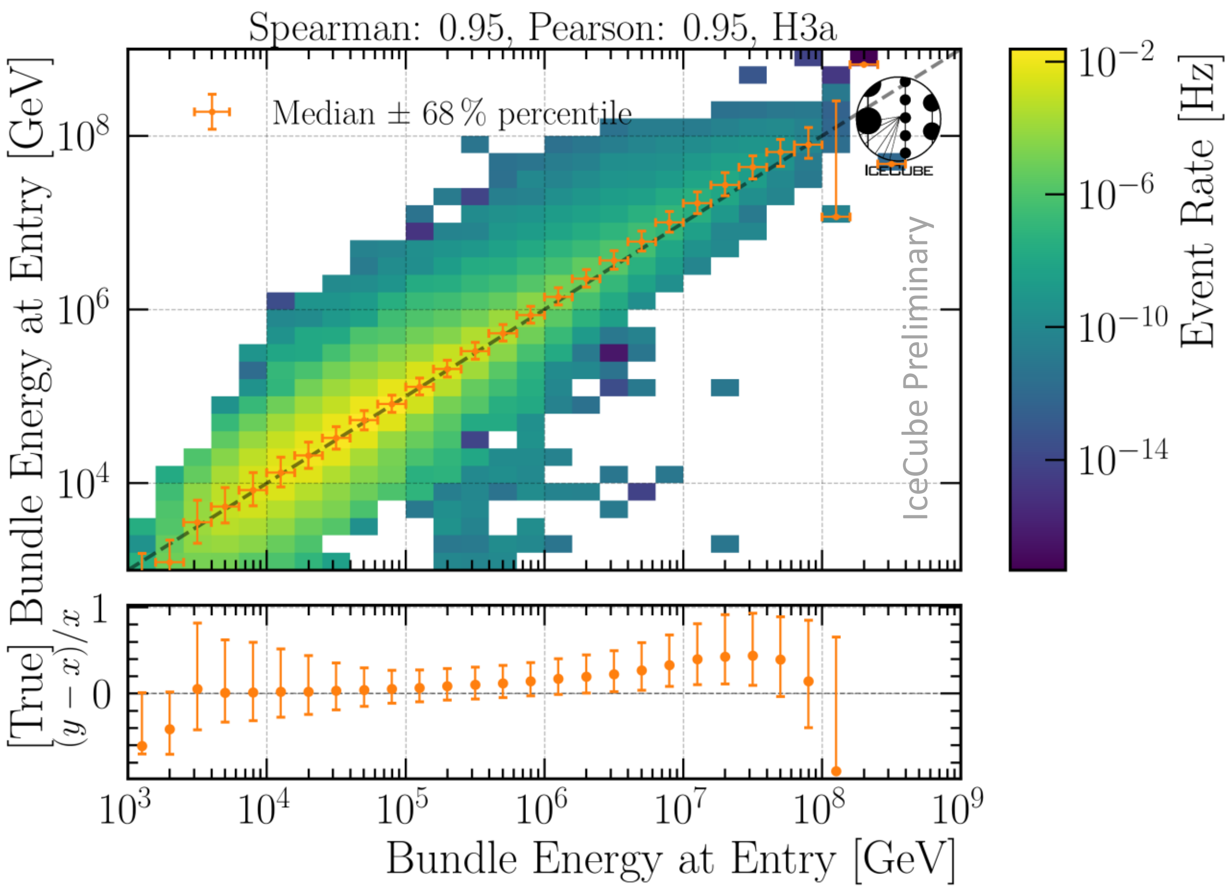




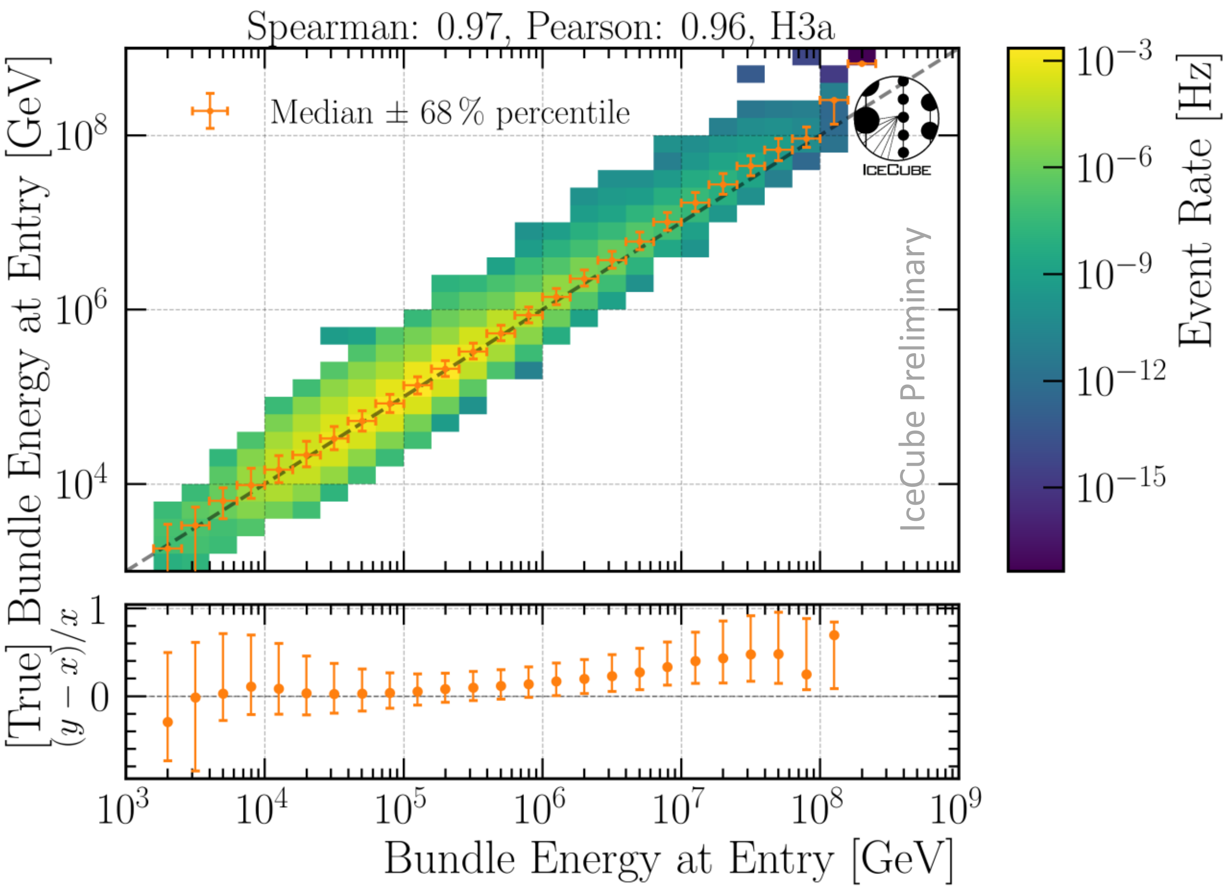


Bundle Energy Reconstruction

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 $\ell = \log_{10}(Q_{\mathrm{tot}})$ 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: $0.5 < \cos\theta \leq 1.0$

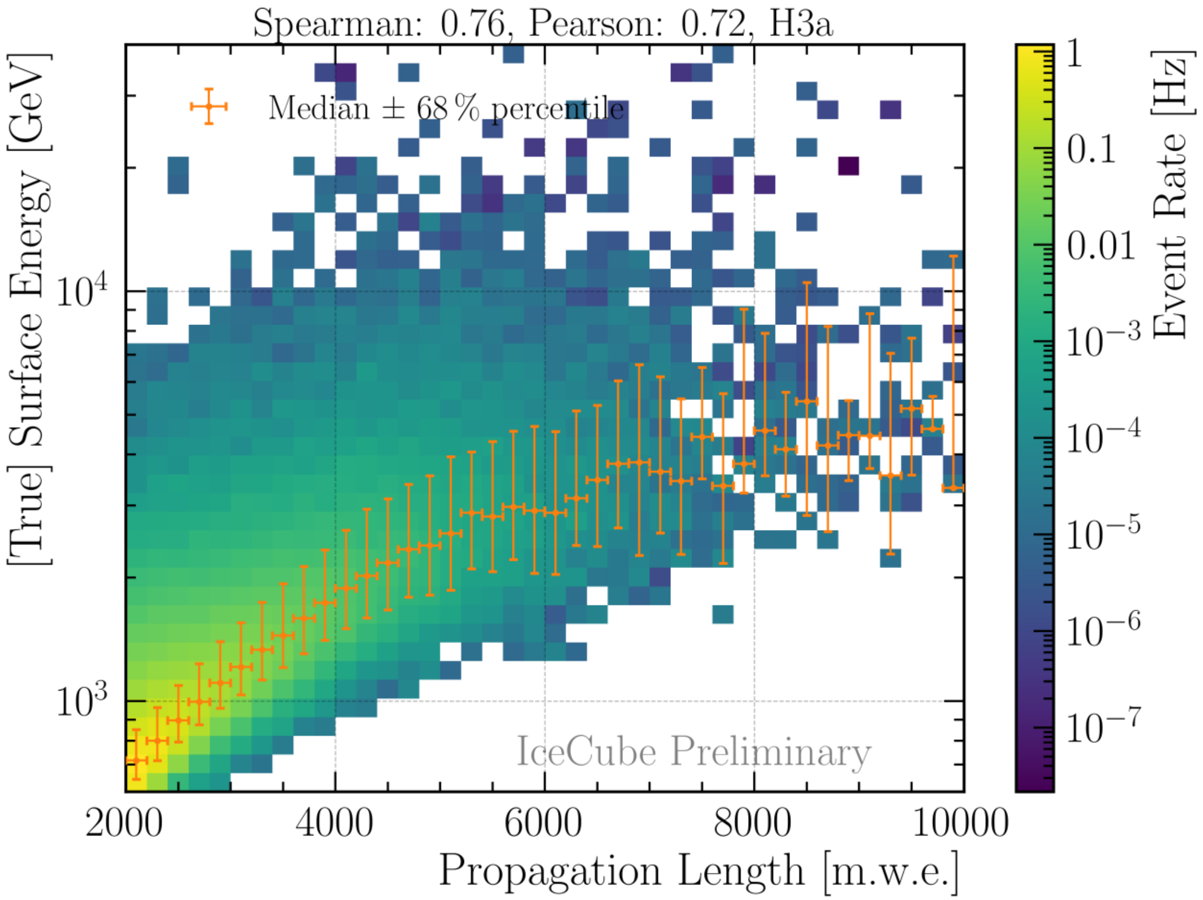
Each zone applies a different selection criterion:

- Zone 1: the filter computes a scaled log-likelihood value $\tilde{\lambda} = \mathrm{rlogl} \cdot \frac{N_{\mathrm{ch}}-5}{N_{\mathrm{ch}}-3}$, 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 $\ell > 0.6 \cdot \cos\theta + 2.3$.

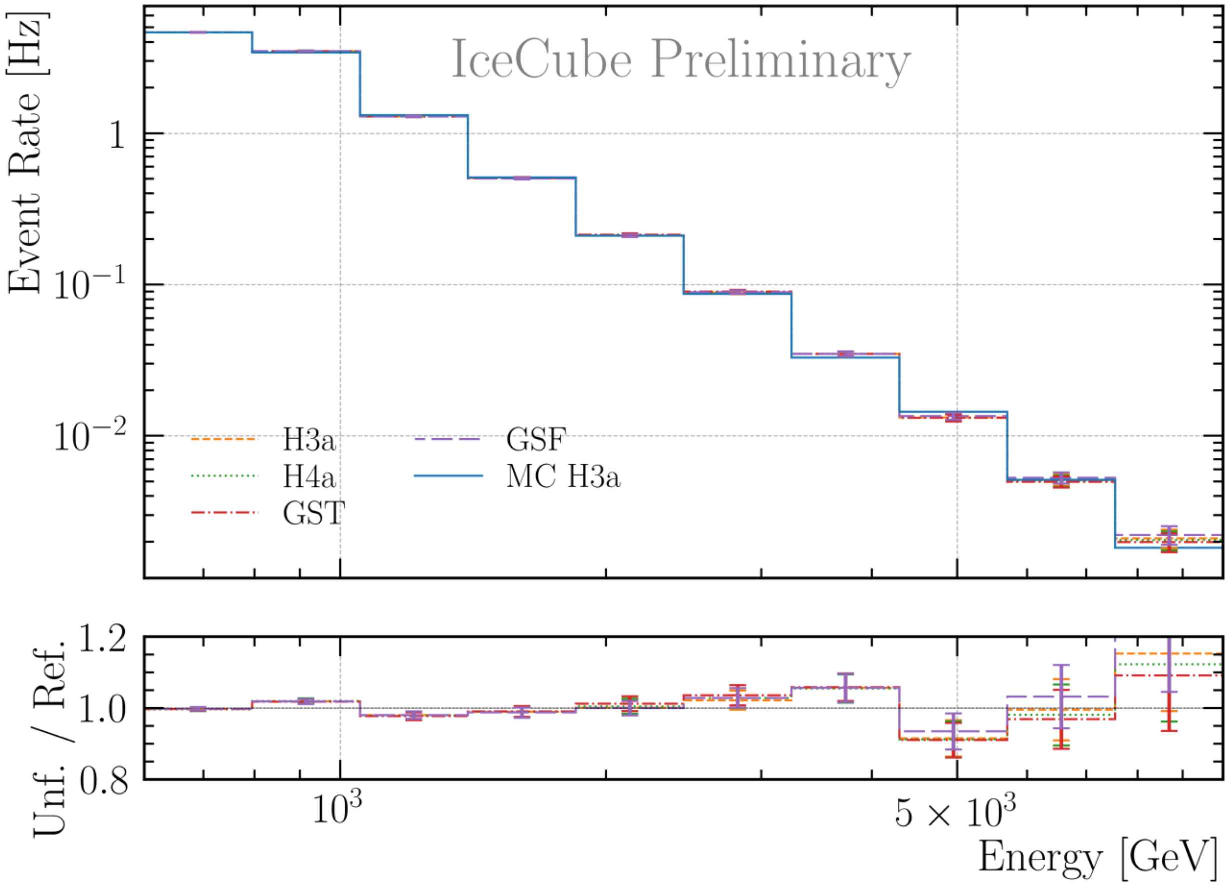
The event is accepted if it passes the selection criteria for any of the three zones. This design ensures that events are selected based on fit quality in the near-horizontal region and on brightness in the vertical direction, balancing background suppression with high signal efficiency across the full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

Correlation and Robustness Test: Stopping Muons

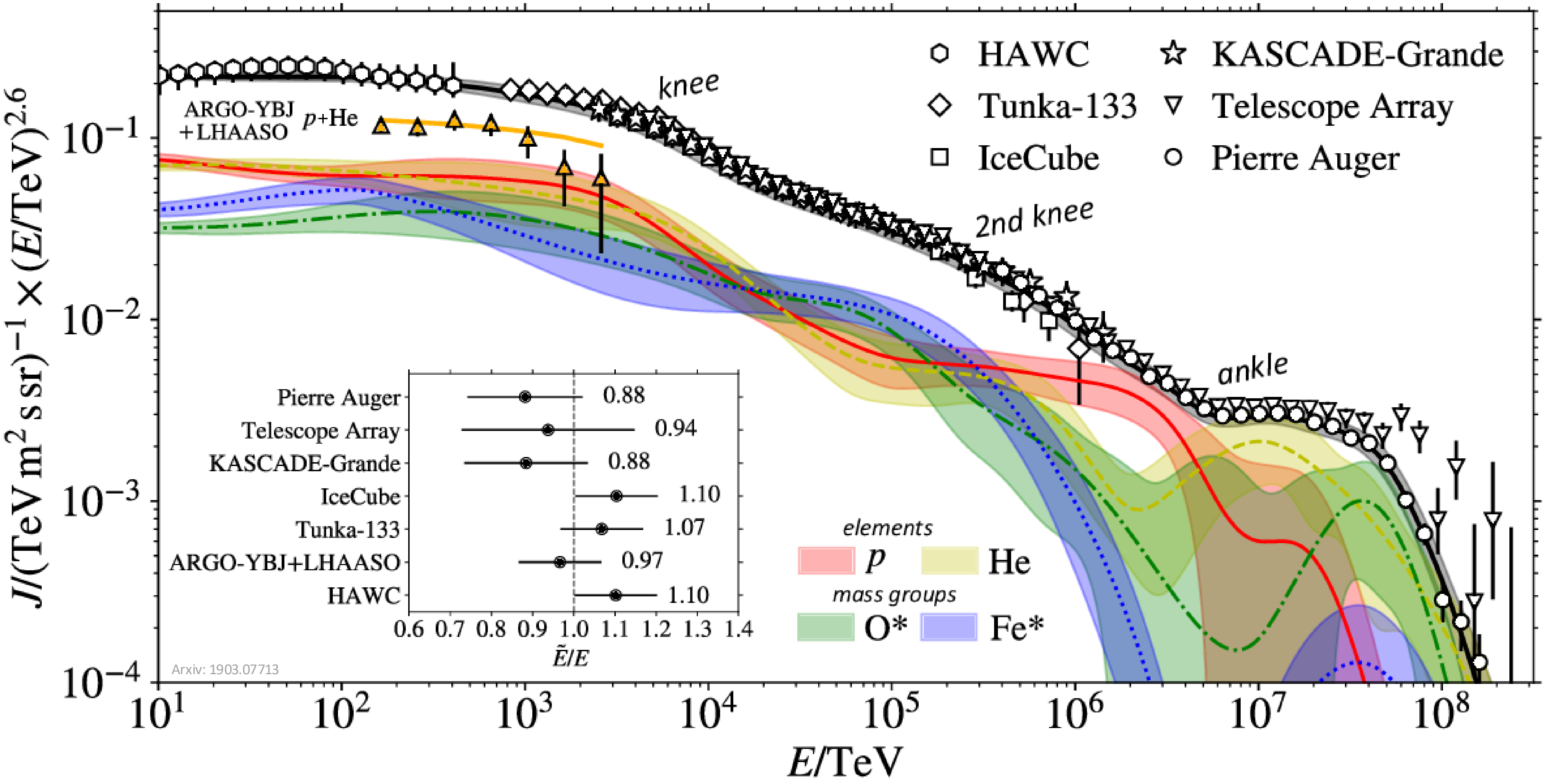
- Correlation between proxy and target



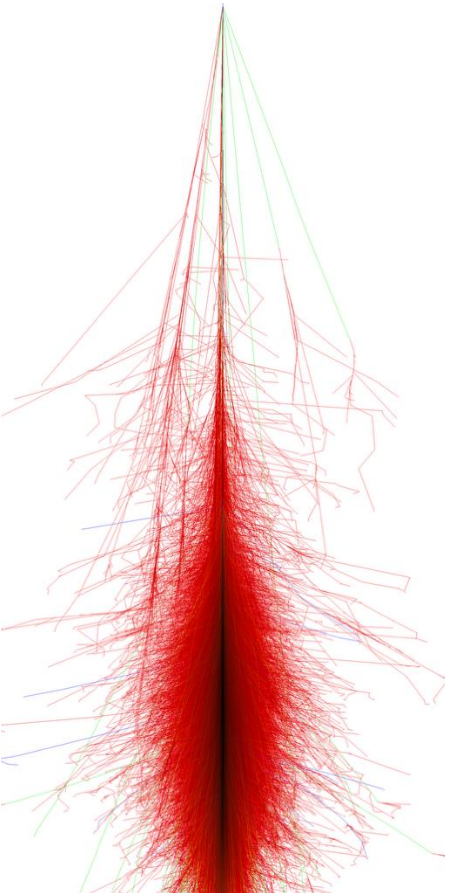
- Build unfolding matrix on H3a, H4a, GST & GSF
- Unfold H3a as test set
- Results are within uncertainties → robust



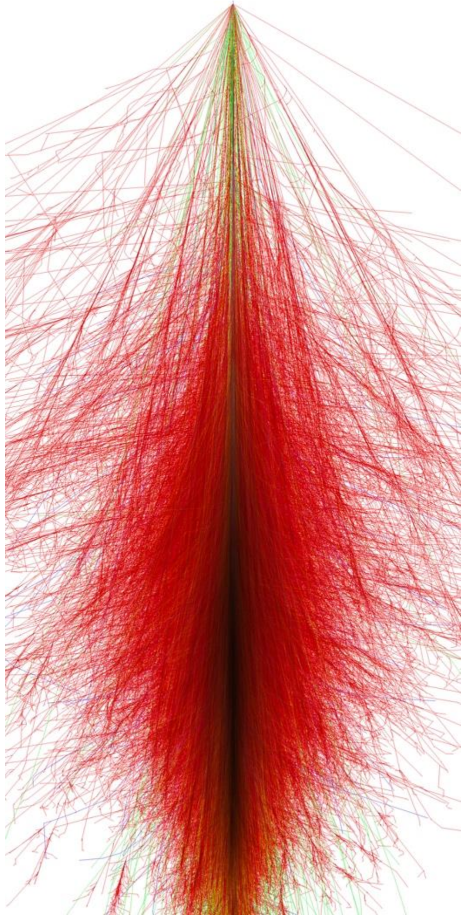
Cosmic ray flux



Air shower – 10 TeV

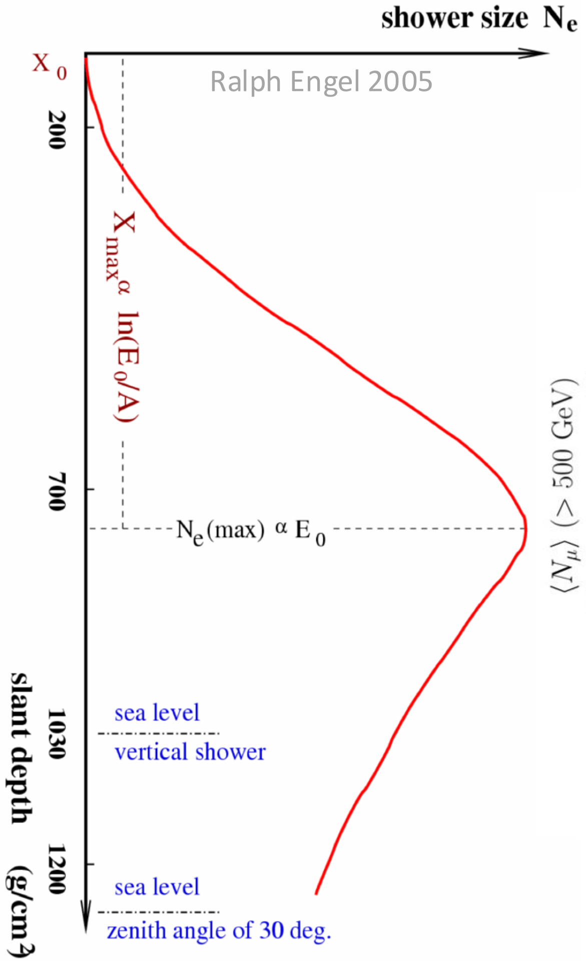


Proton

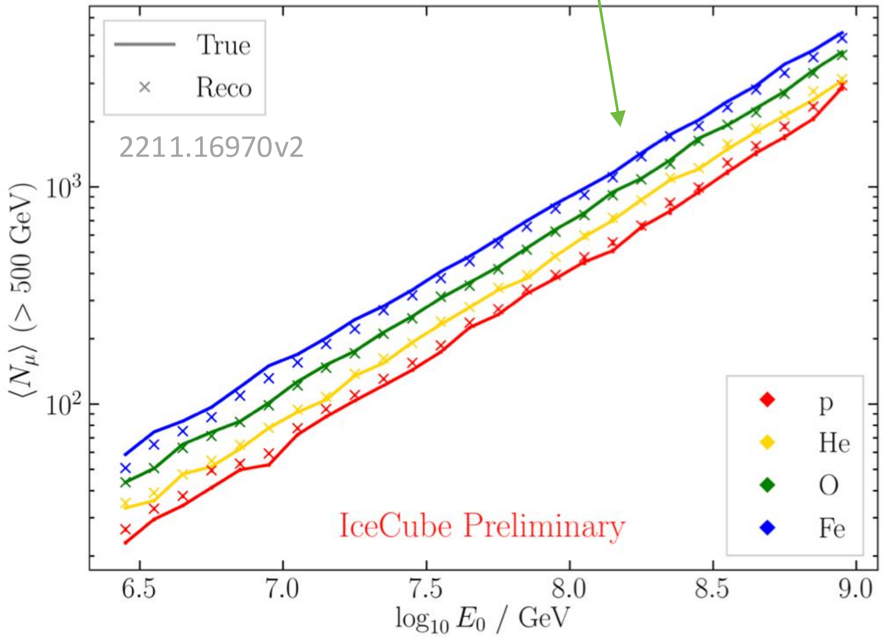


Iron

www.iap.kit.edu/corsika

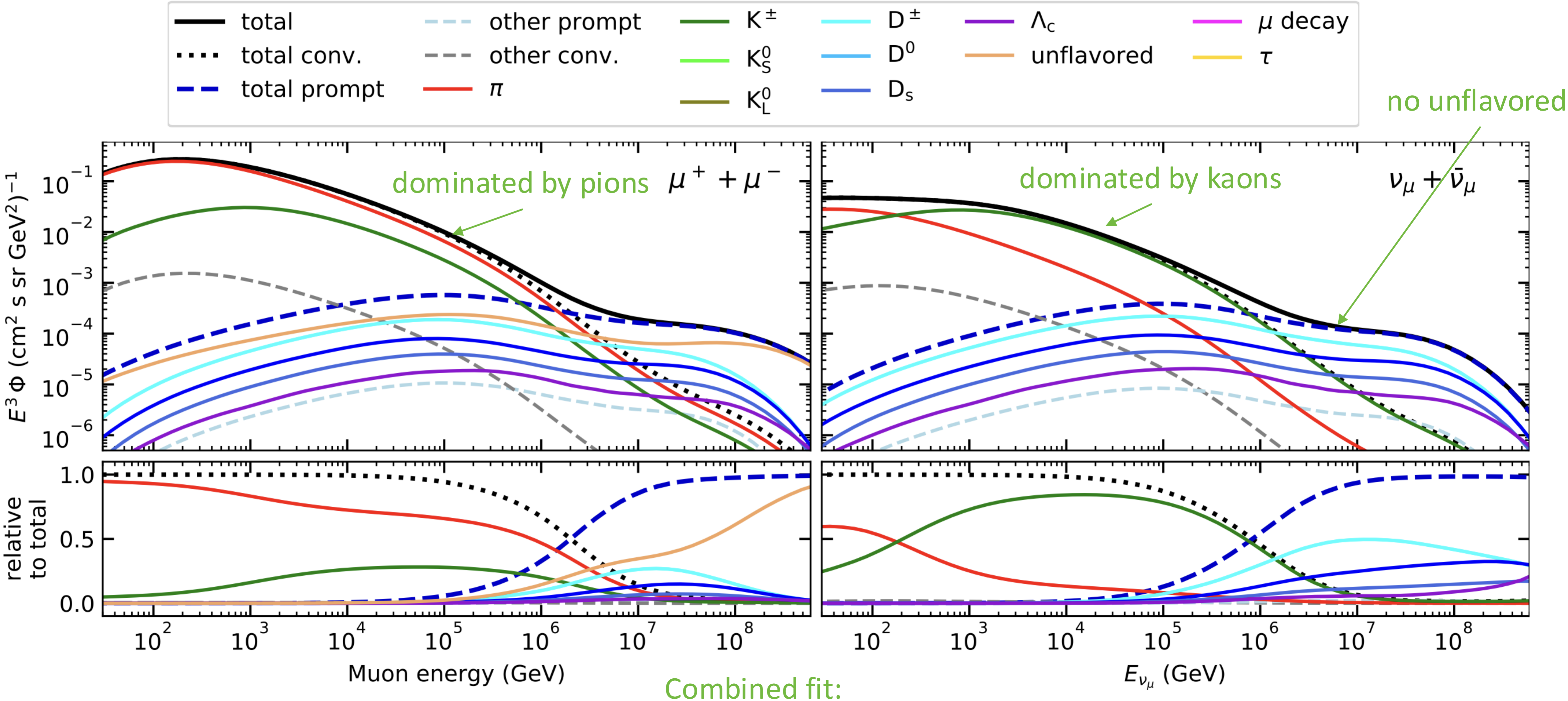


"muon bundles"



Prompt atmospheric muons and neutrinos

10.1103/PhysRevD.100.103018



Combined fit:

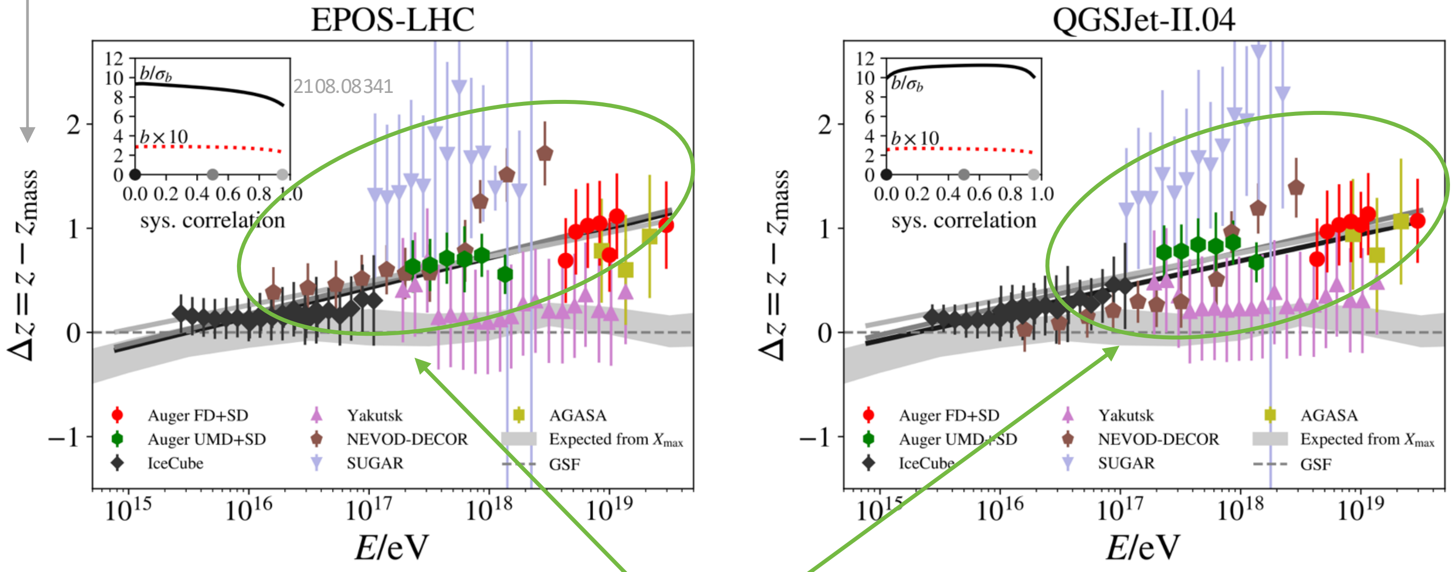
- handle on pion/kaon ratio
- handle on charmed mesons

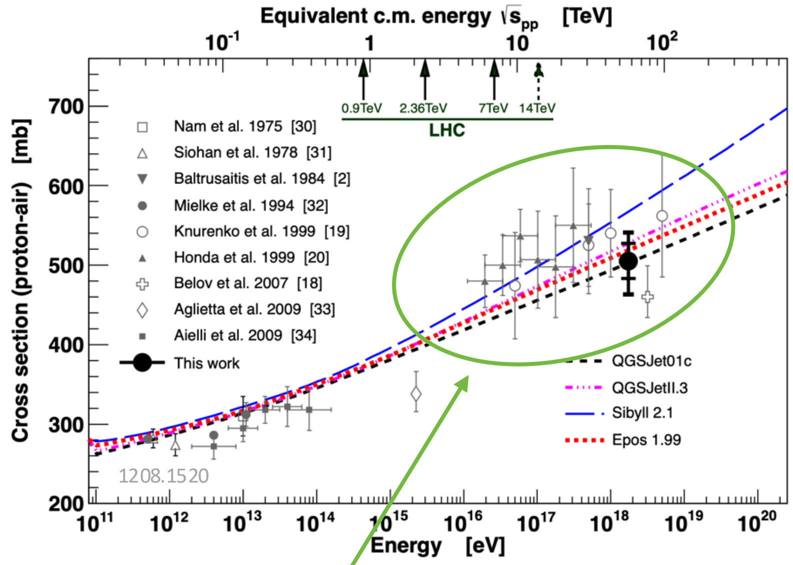
Muon puzzle and model uncertainties

"muon number"

Expected z
("muon number")

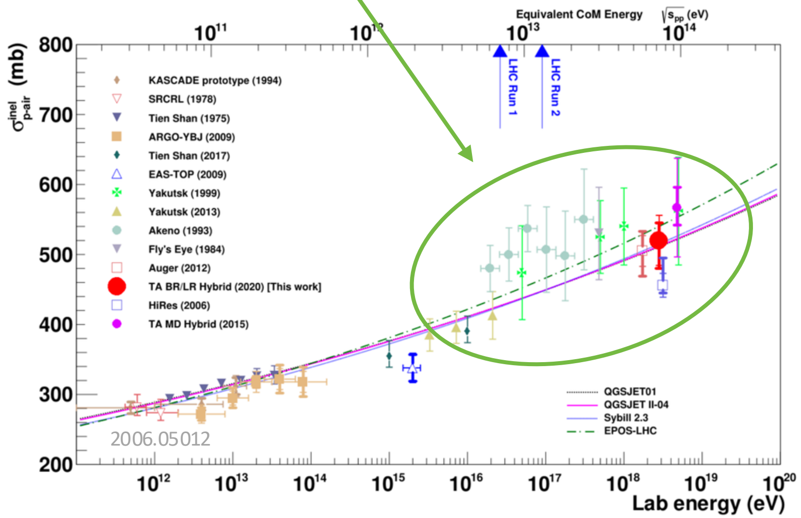
$$z = \frac{\ln\langle N_\mu\rangle - \ln\langle N_\mu\rangle_p}{\ln\langle N_\mu\rangle_{\mathrm{Fe}} - \ln\langle N_\mu\rangle_p}$$





2012

➢ Uncertainties at E > 10 PeV

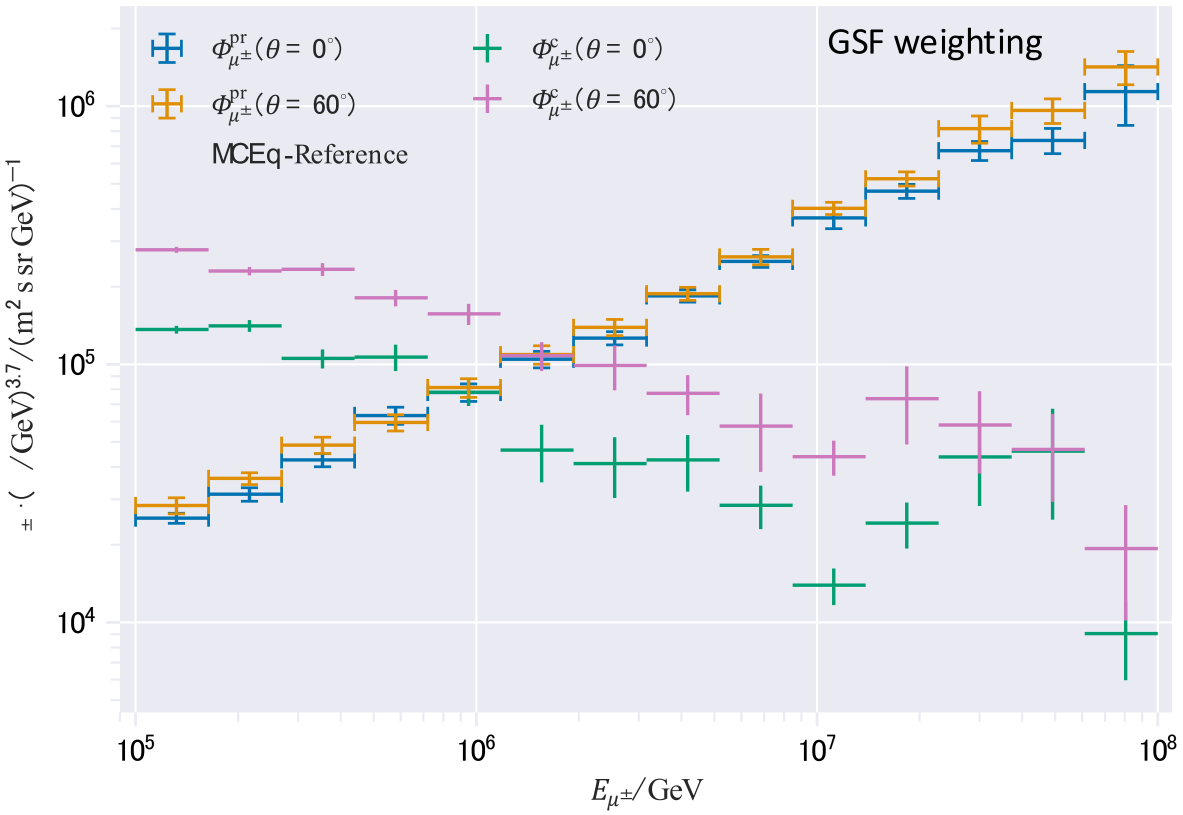


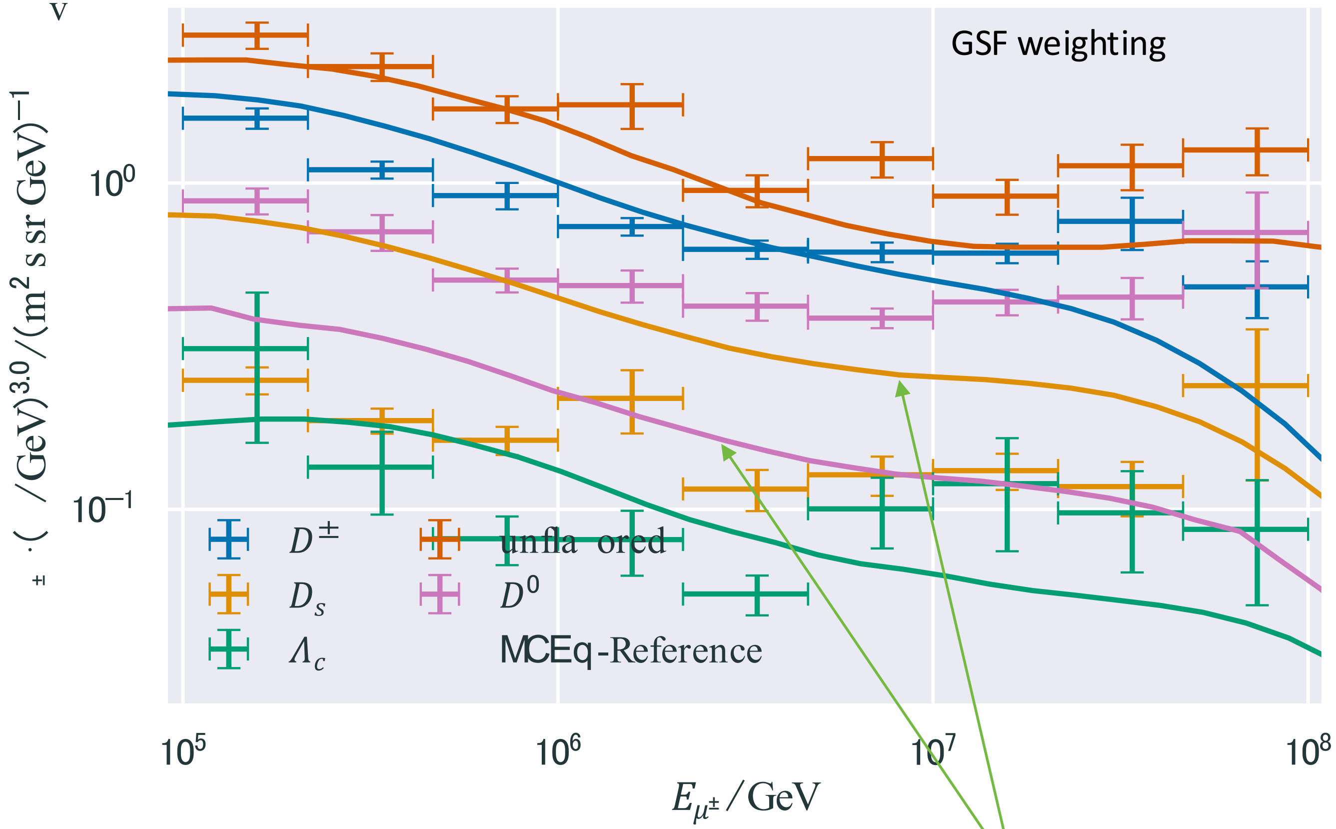
2020

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

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



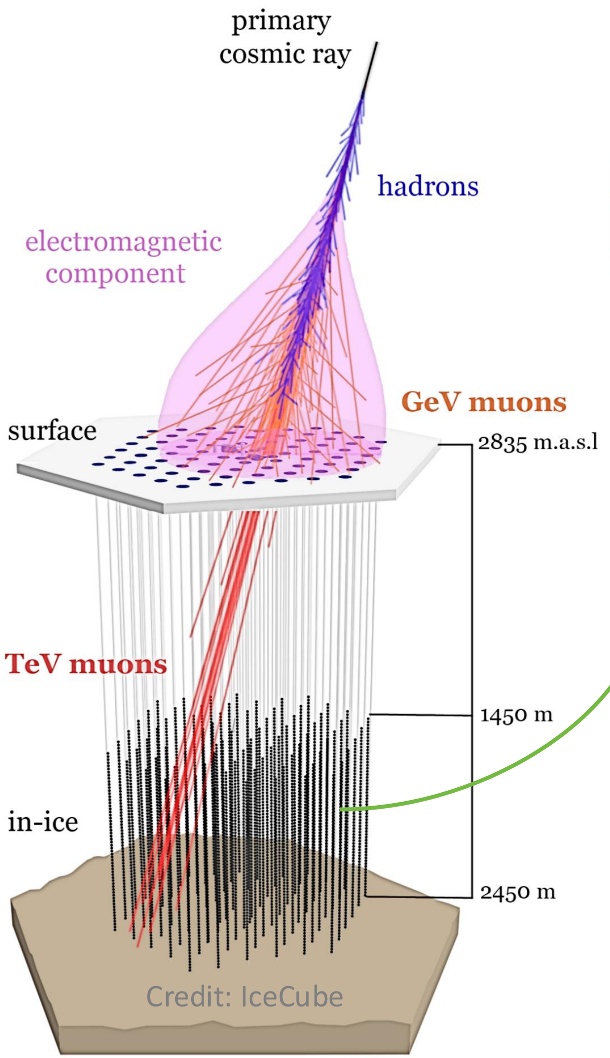


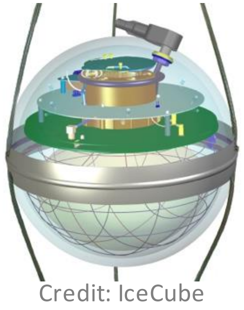
➢ Good agreement in total prompt and conv muon flux

➢ D^0 and D_s are swapped here but this is fixed in MCEq

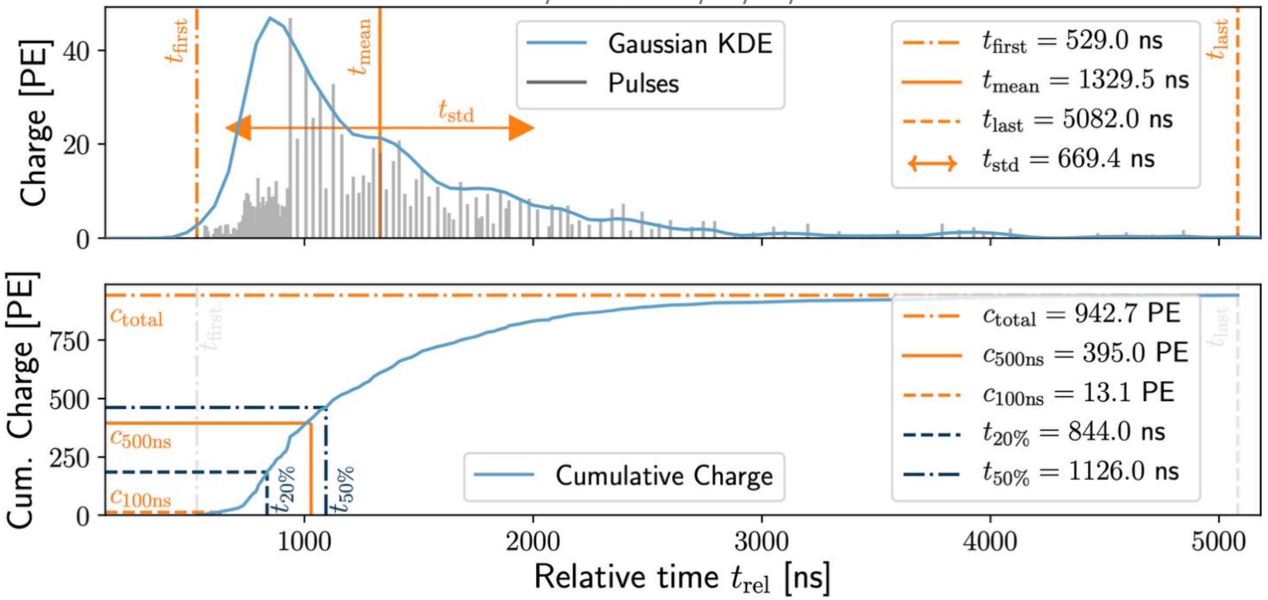
mention panama

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
- …

tu dortmund university   BERKELEY LAB   SFB1491   ICECUBE NEUTRINO OBSERVATORY

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

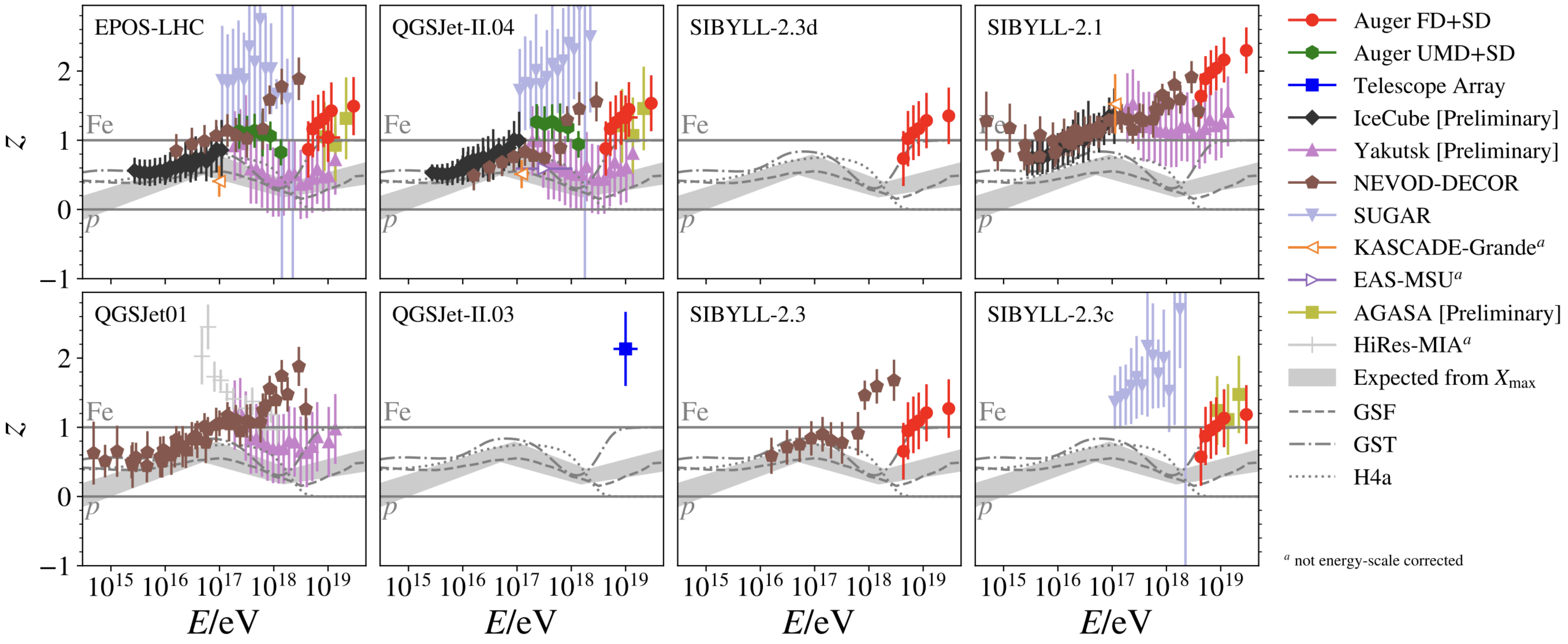
neutrino cuts	>	<
cos(zenith)	0.2	
length	5000 m	15000 m

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

The Muon Puzzle

"muon number"

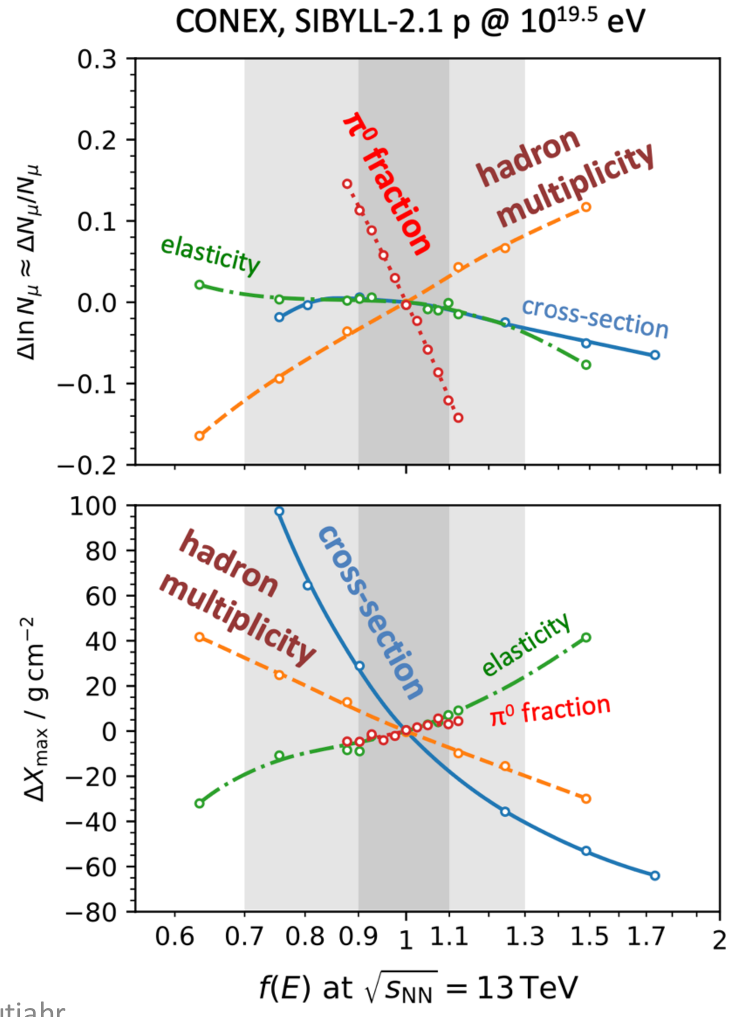
$$z = \frac{\ln\langle N_\mu\rangle - \ln\langle N_\mu\rangle_p}{\ln\langle N_\mu\rangle_{\mathrm{Fe}} - \ln\langle N_\mu\rangle_p}$$



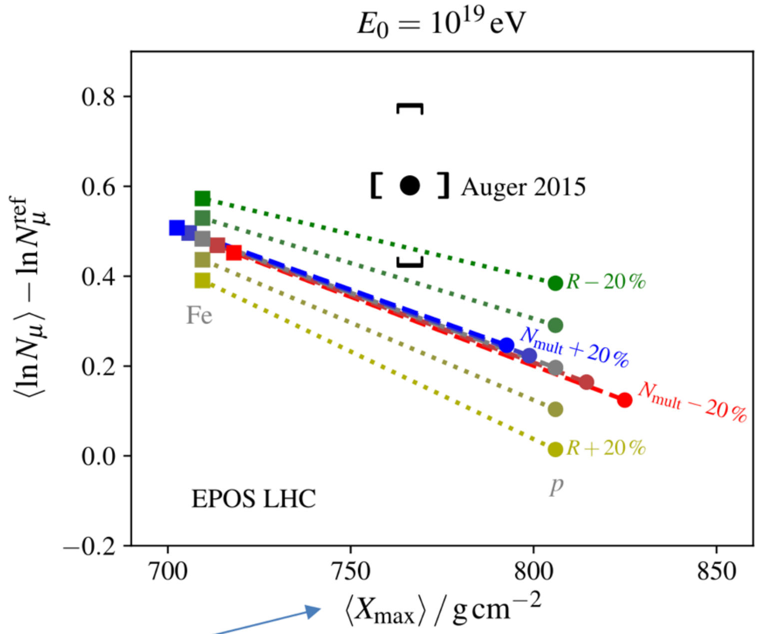
Arxiv: 2108.08341

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

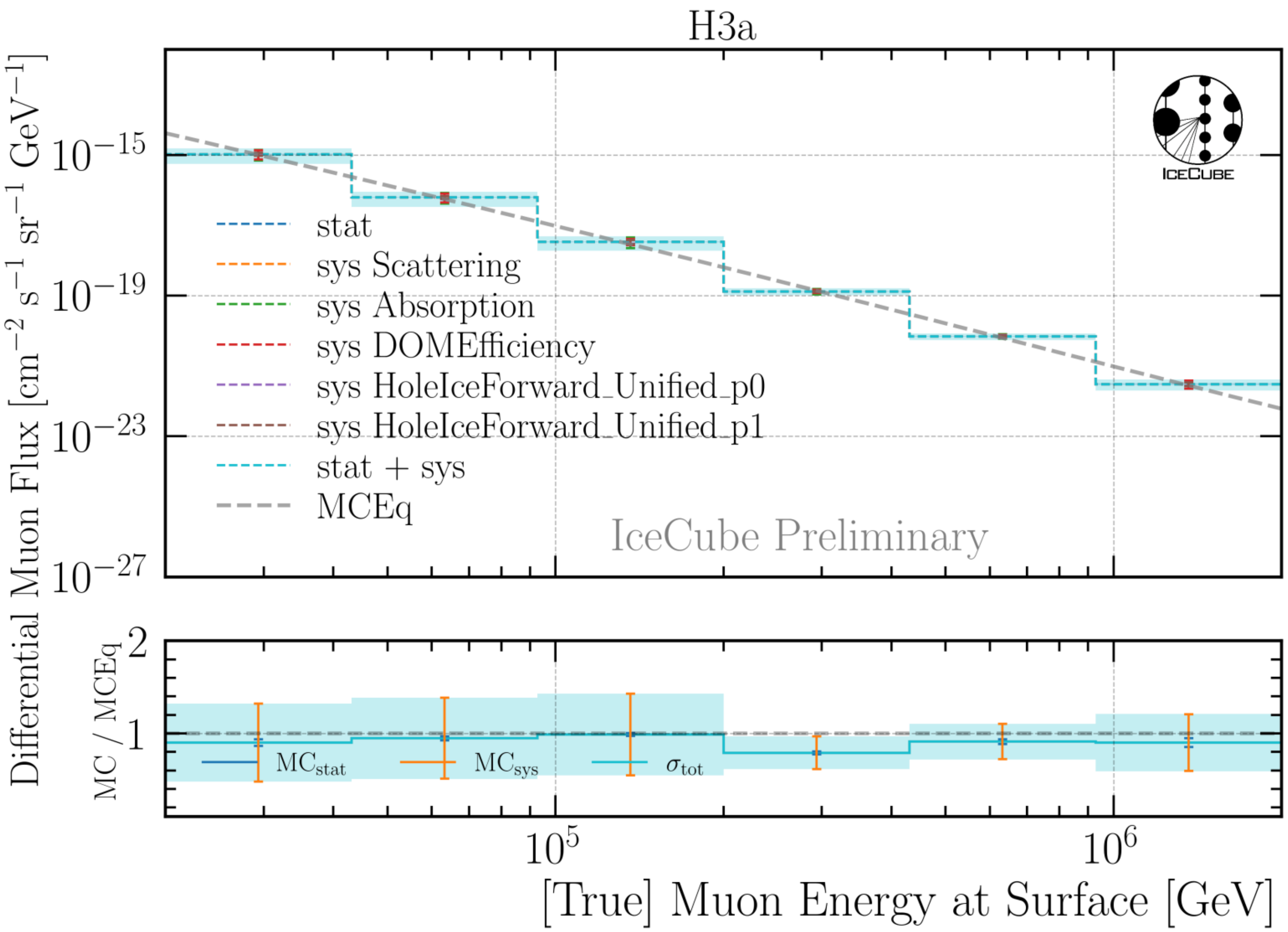


$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

- 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

MCEq vs CORSIKA



Overview

Simulation

Dataset
- CORSIKA 77500 Ehist
- SIBYLL 2.3d
- 10 TeV – 100 EeV

Validation
- Tag prompt / conv particles
- MCEq comparisons

Reconstruction

DNN reconstructions
- Muon energies
- Muon direction
- Track geometry

Selection

Level 3
- L2 muon filter
- Add labels

Level 4
- 500 TeV bundle energy cut at surface
- Add DNN reconstructions

Level 5
- Data-MC quality cuts

Final Level
- Leadingness cut

Unfolding

Muon spectrum
- Unfold muon flux at surface