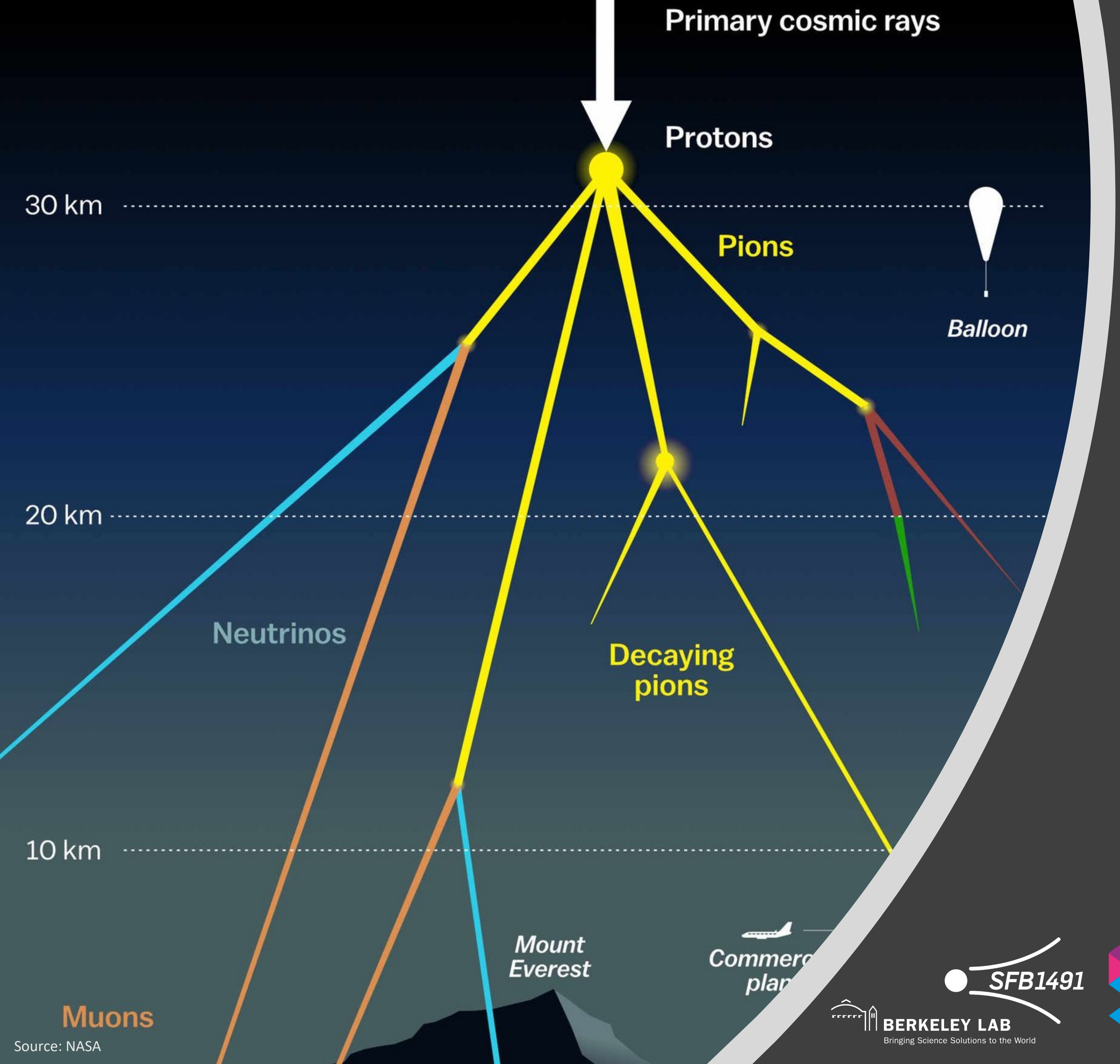


Unblinding Request:

Unfolding the Atmospheric Muon Flux with IceCube

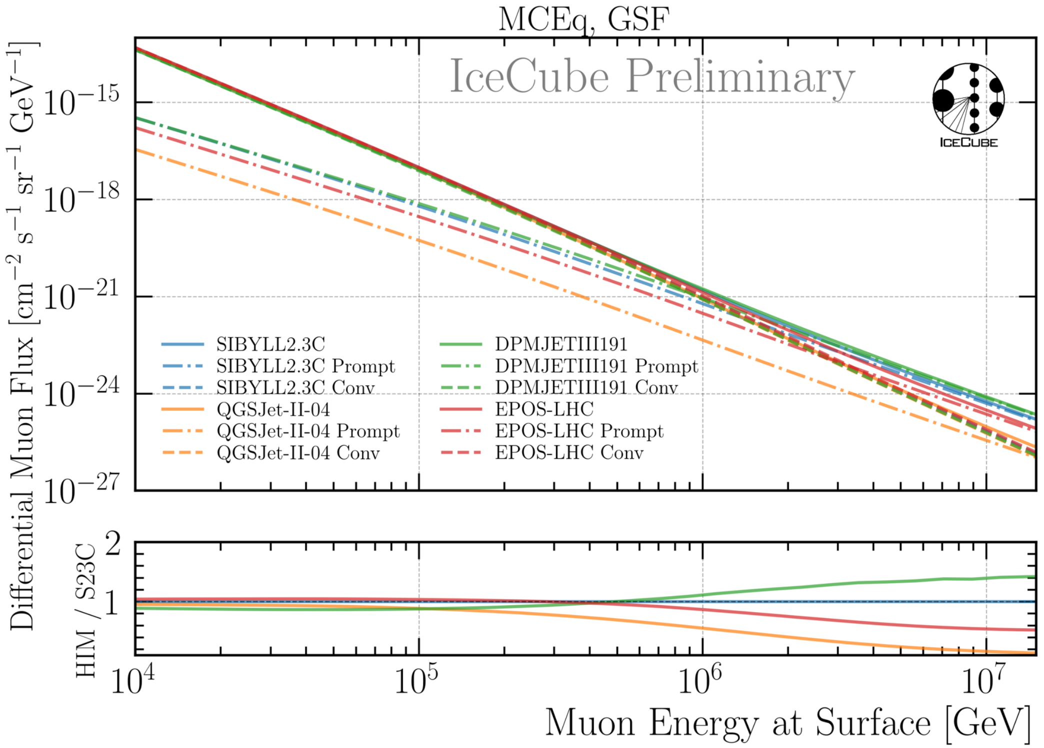
Pascal Gutjahr

WG: Dennis
Coll.: Anatoli
Tech: Karolin
wiki page

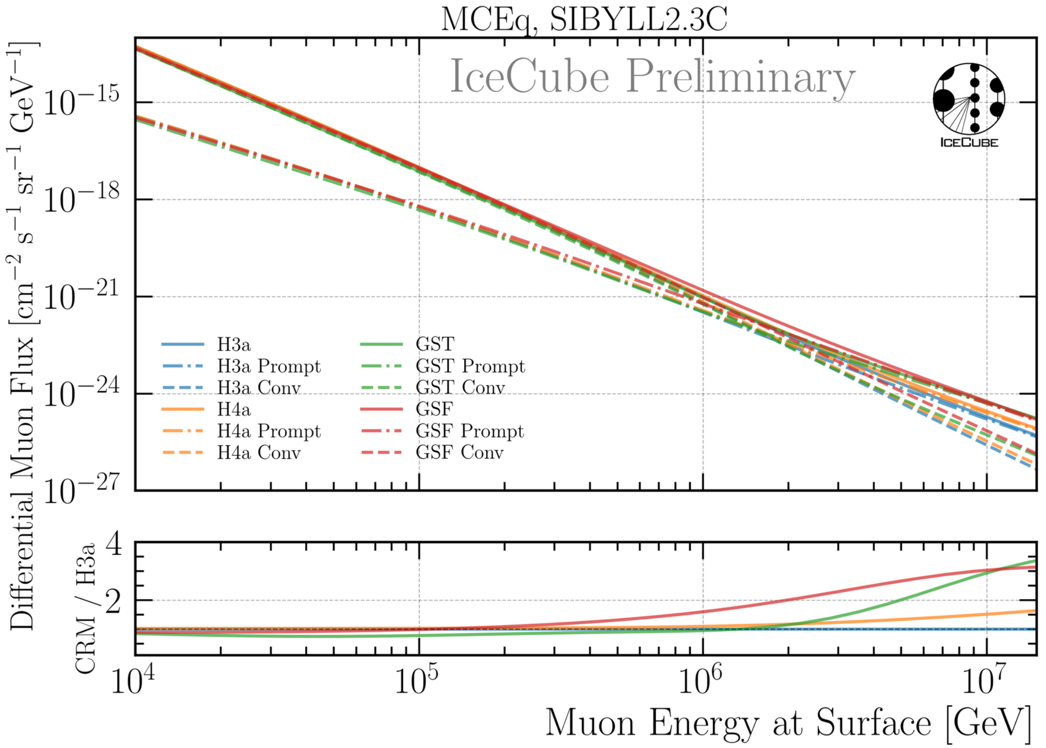
tu dortmund university
IceCube Neutrino Observatory
SFB1491
Berkeley Lab Bringing Science Solutions to the World
LAMARR Institute for Machine Learning and Artificial Intelligence
NSF

Analysis Call
December 04, 2025

Impact of Hadronic Interaction Models?



+50%



+250%

- Only SIBYLL and DPMJET include charm
- Constant offset < 100 TeV → irrelevant for unfolding
- Up to 50% difference at highest energies
- Difference between primary models about 250%
- Unfolding recovers this spectral index change within uncertainties

Combine CORSIKA Sets

22774—8 (my dataset)

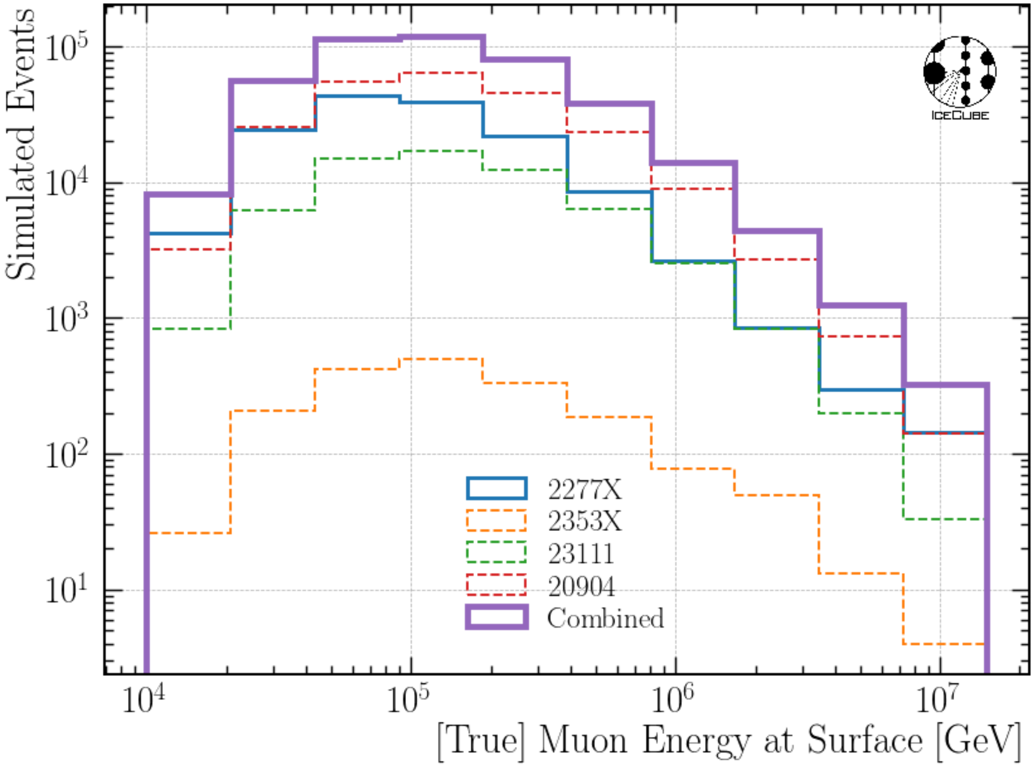
23530—1 (additional high energetic events)

23111 (Lucas dataset)

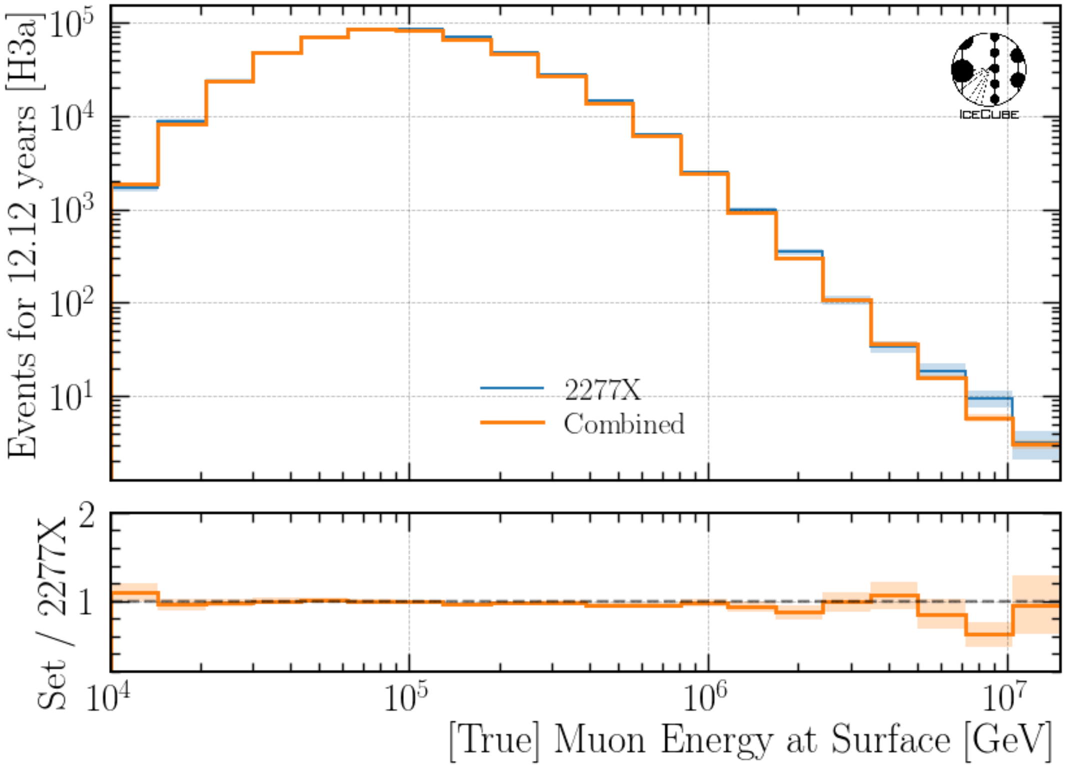
20904 (Standard CORSIKA)

Combine Several CORSIKA Datasets

simulated

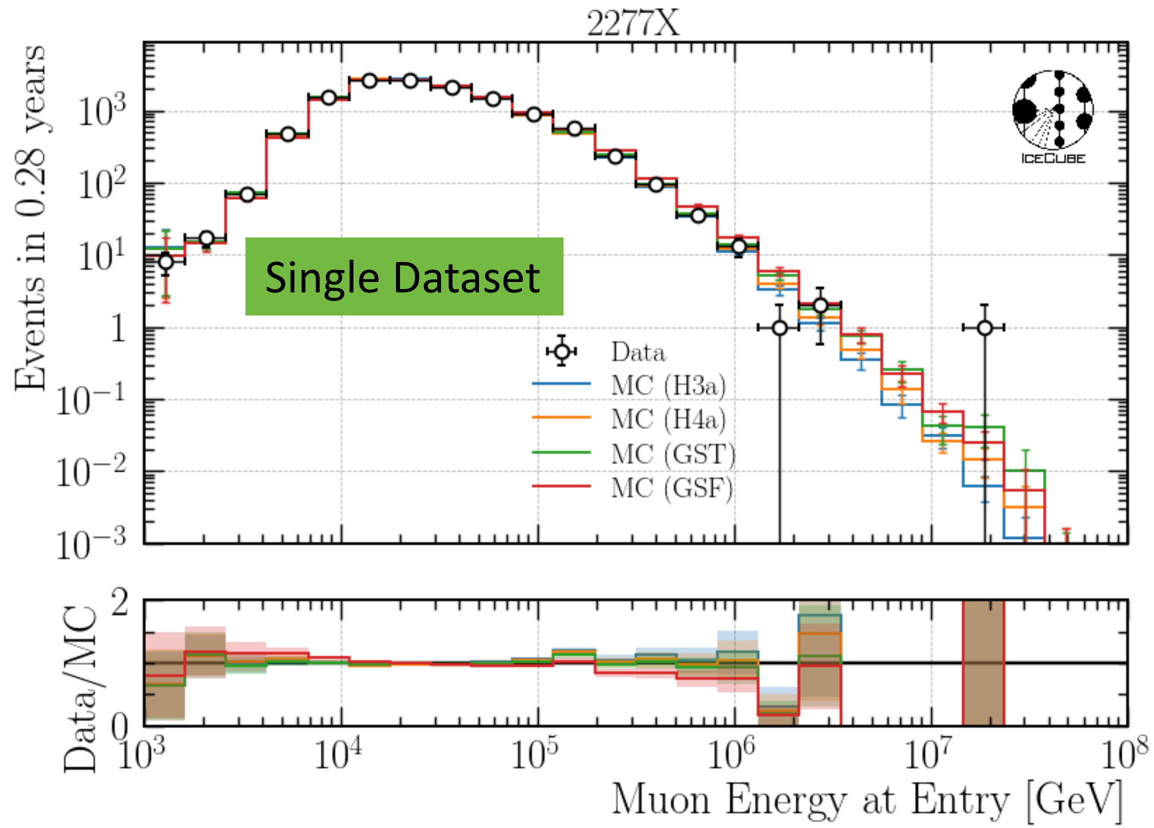


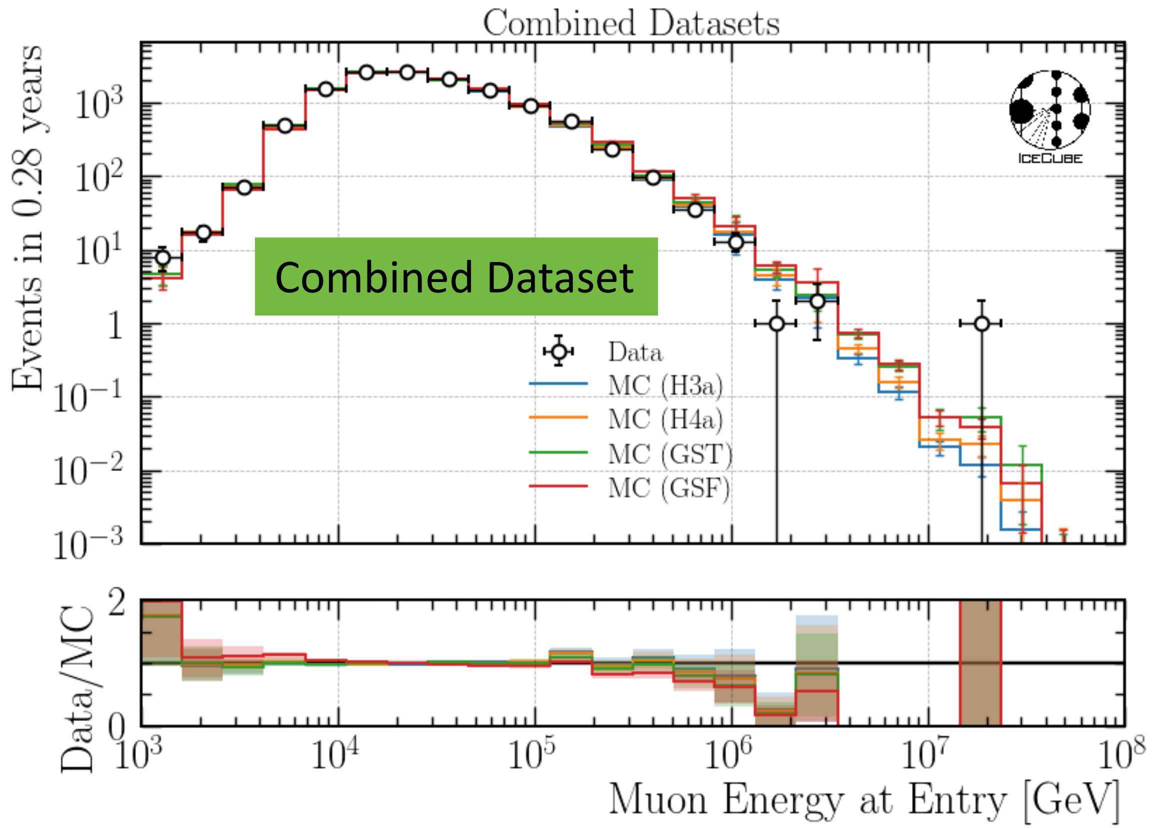
weighted



- Before: Only 2277X
- After: All sets → better statistics
- Weighting works

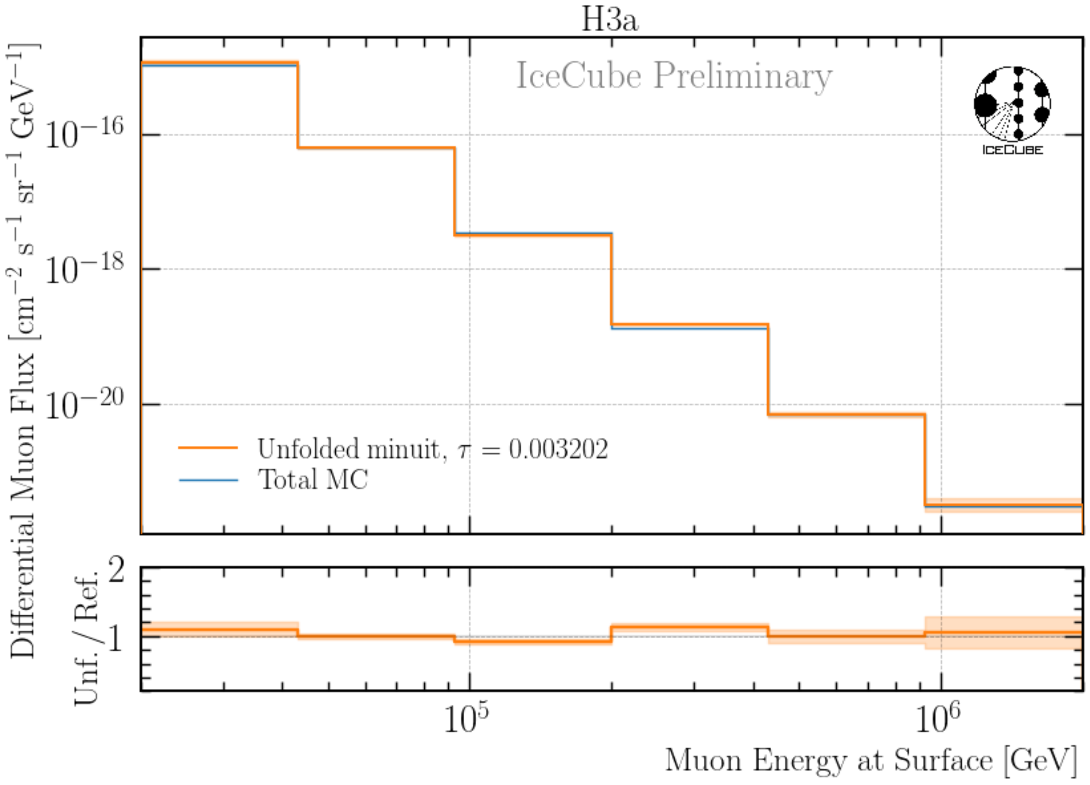
Check Data-MC on Burnsample



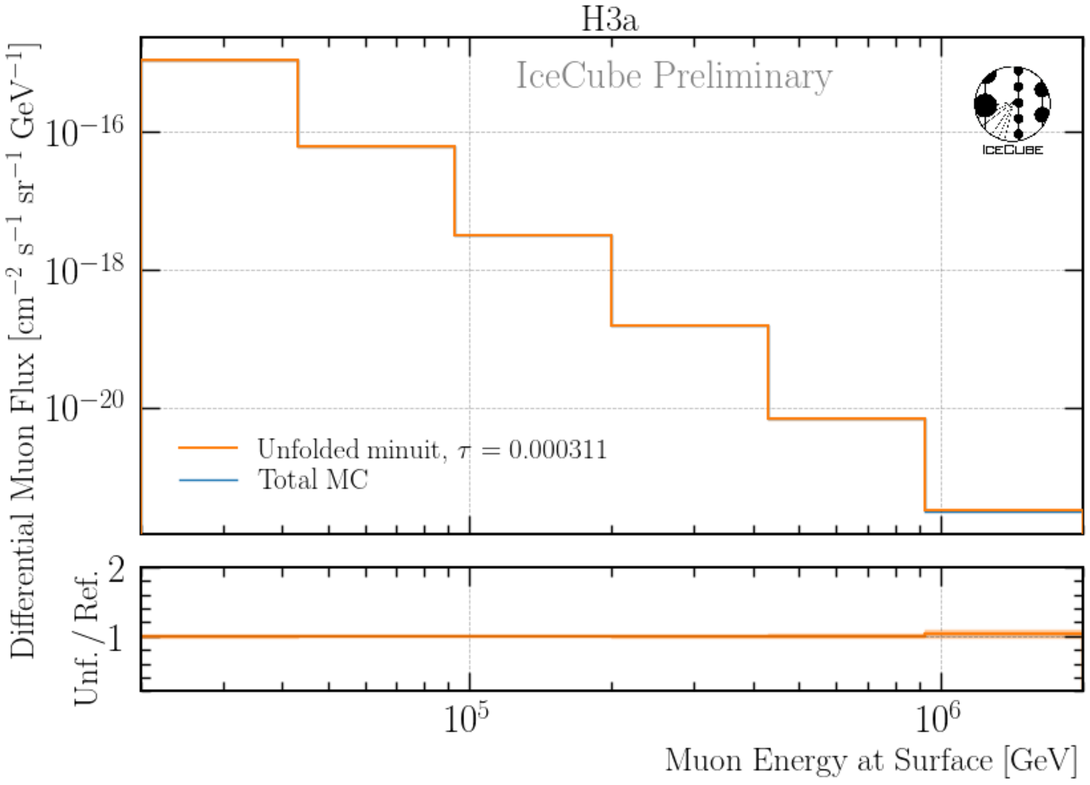


- Same agreement between 2277X and combined datasets

Compare Burnsample Unfolding Bias



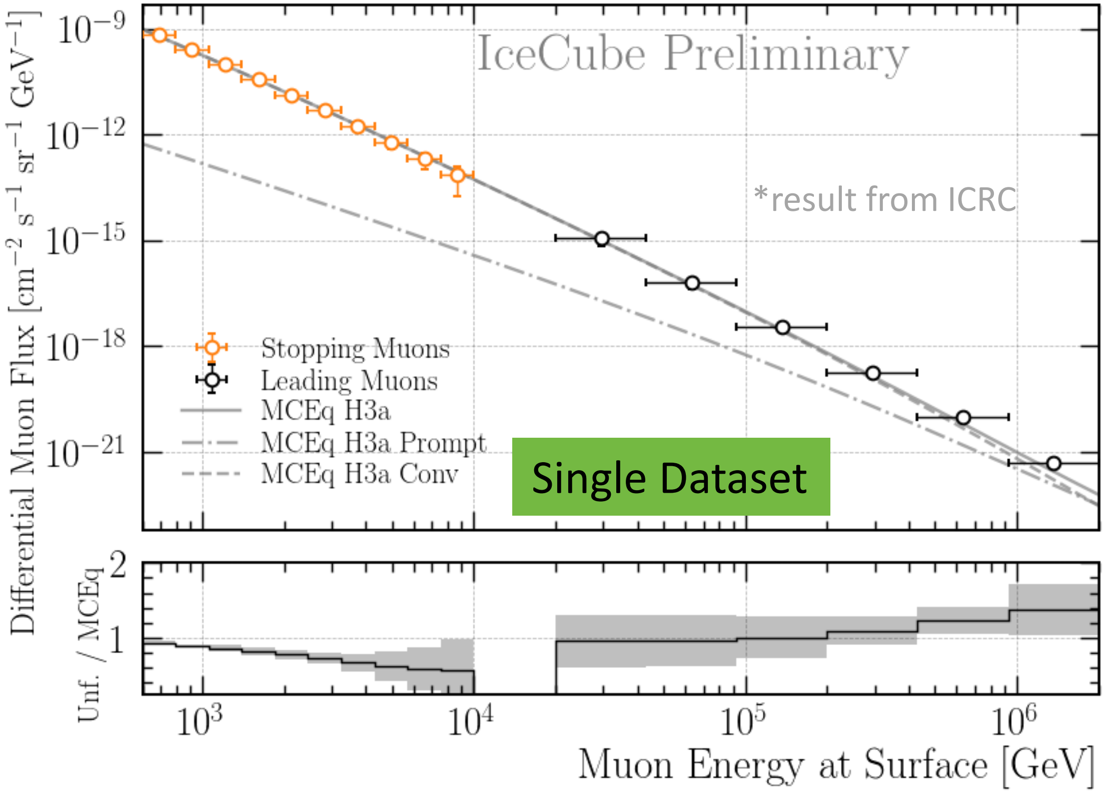
Single Dataset

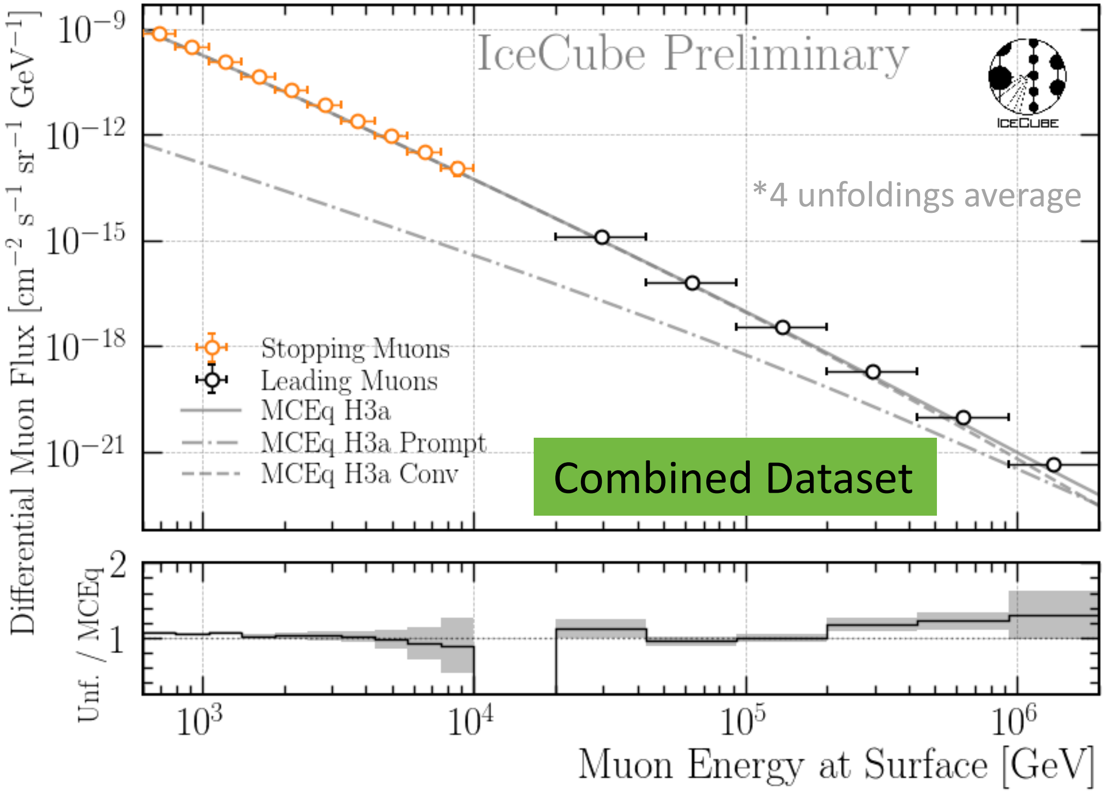


Combined Dataset

Compare Burnsample Unfolding

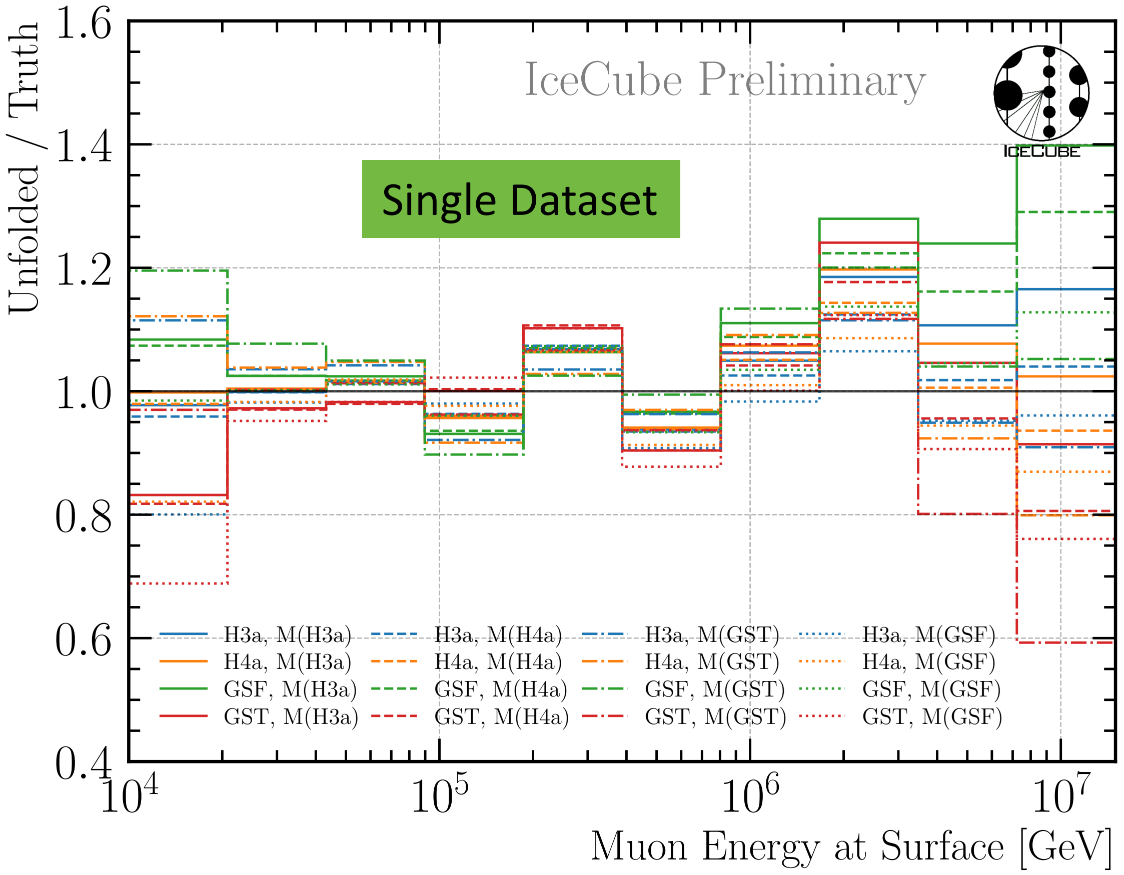
Stopping muon unfolding has improved since ICRC
→ Unblinding request soon

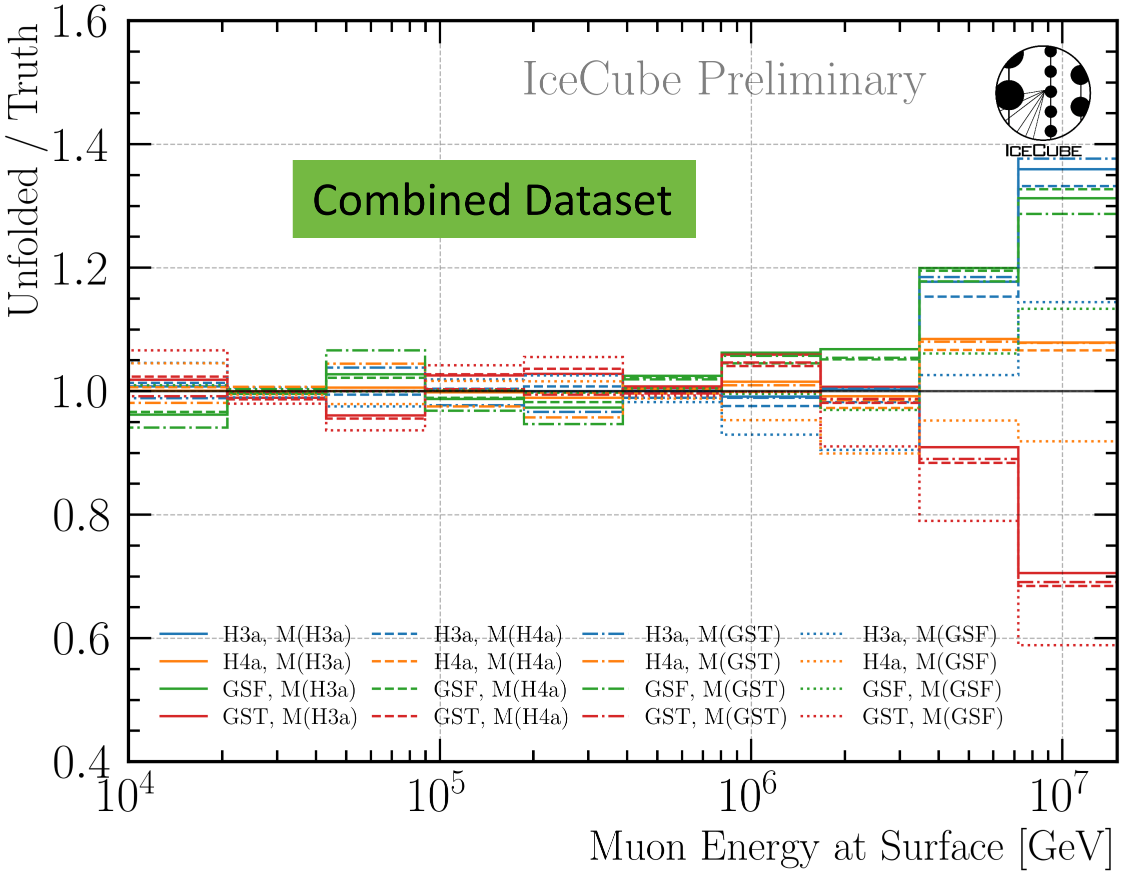




- Same result for 2277X unfolding and combined unfolding

Compare “Unfolding Bias”





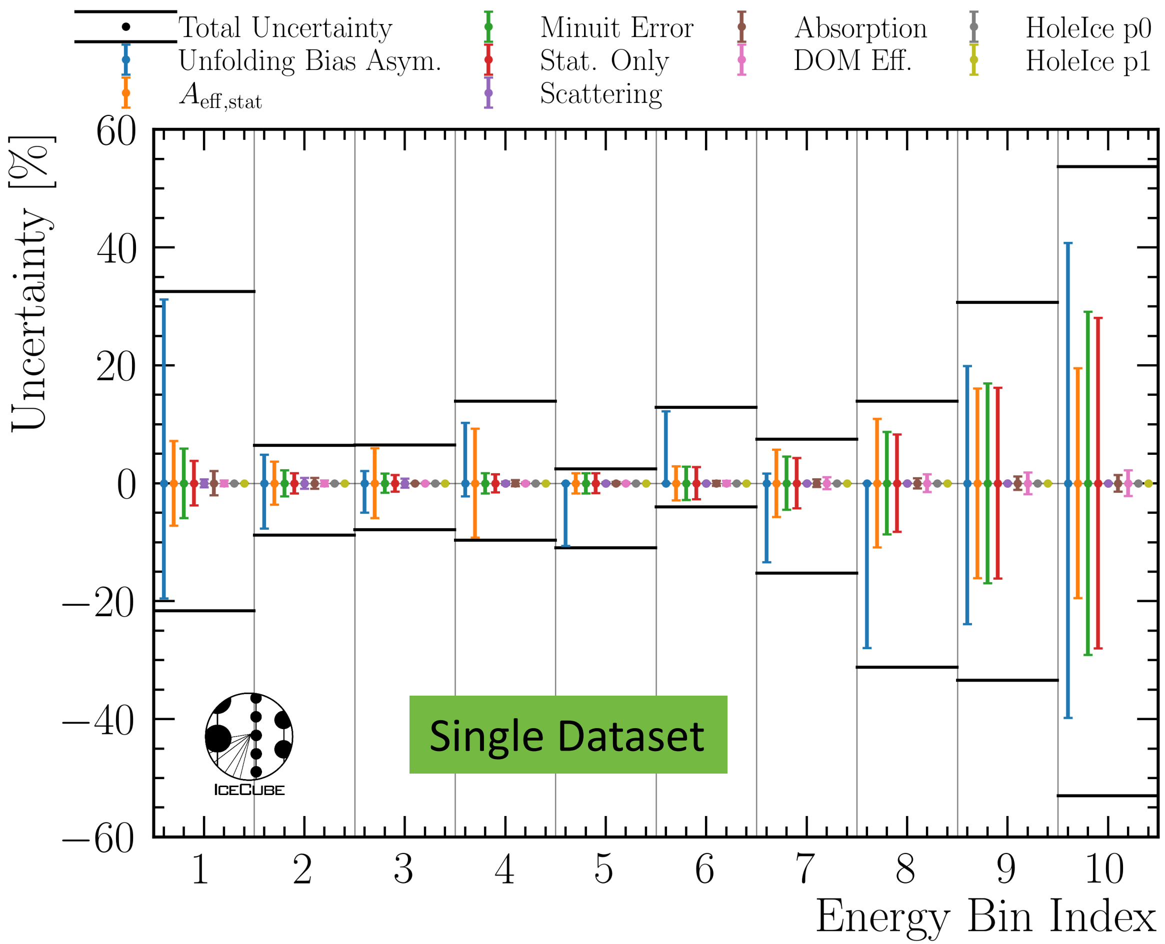
- Combining datasets improves injection recovery

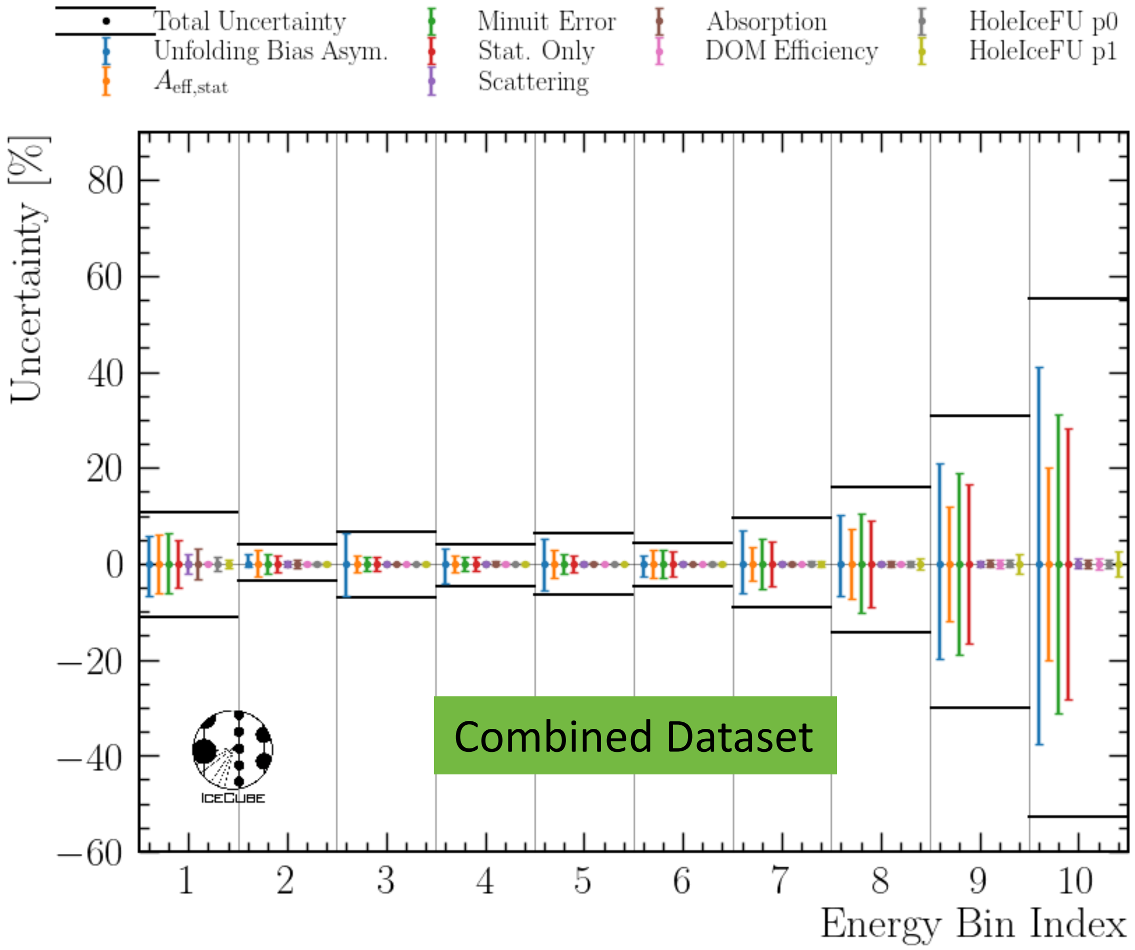
Summary

- HIM impact: smaller than primary model impact
  - Specific simulations take too many resources → not feasible
- Combine multiple CORSIKA datasets
  - Better statistics
  - Same data—MC agreement
  - Better injection recovery
  - Burnsample unfolding compatible with ICRC result
  - ➢ Use combined datasets for unfolding
- Post unblinding: include stopping muon result in normalization fit to pinpoint conventional component
  - Stopping muons unblinding request will start in December?!

Backup

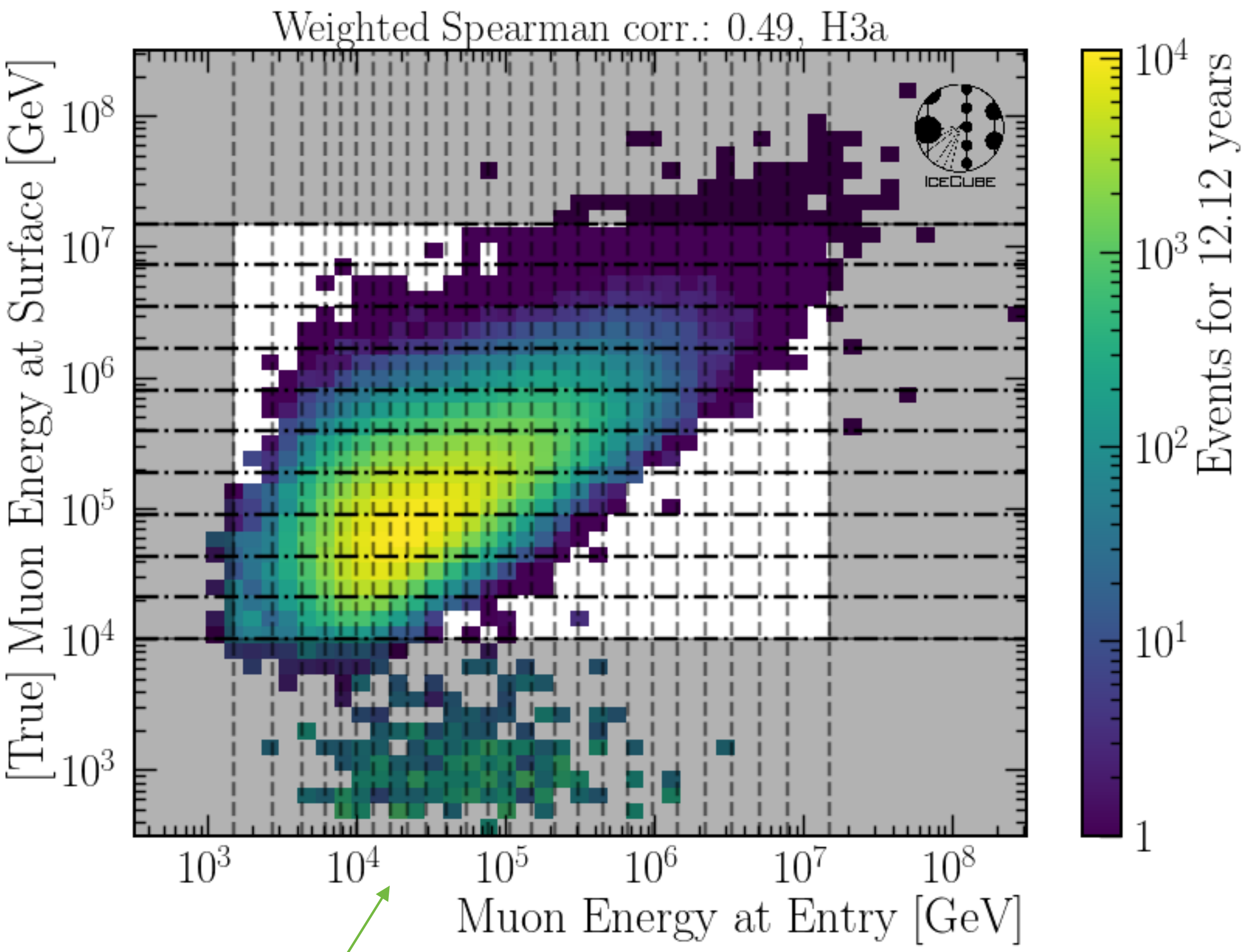
Comparison Uncertainties per Bin





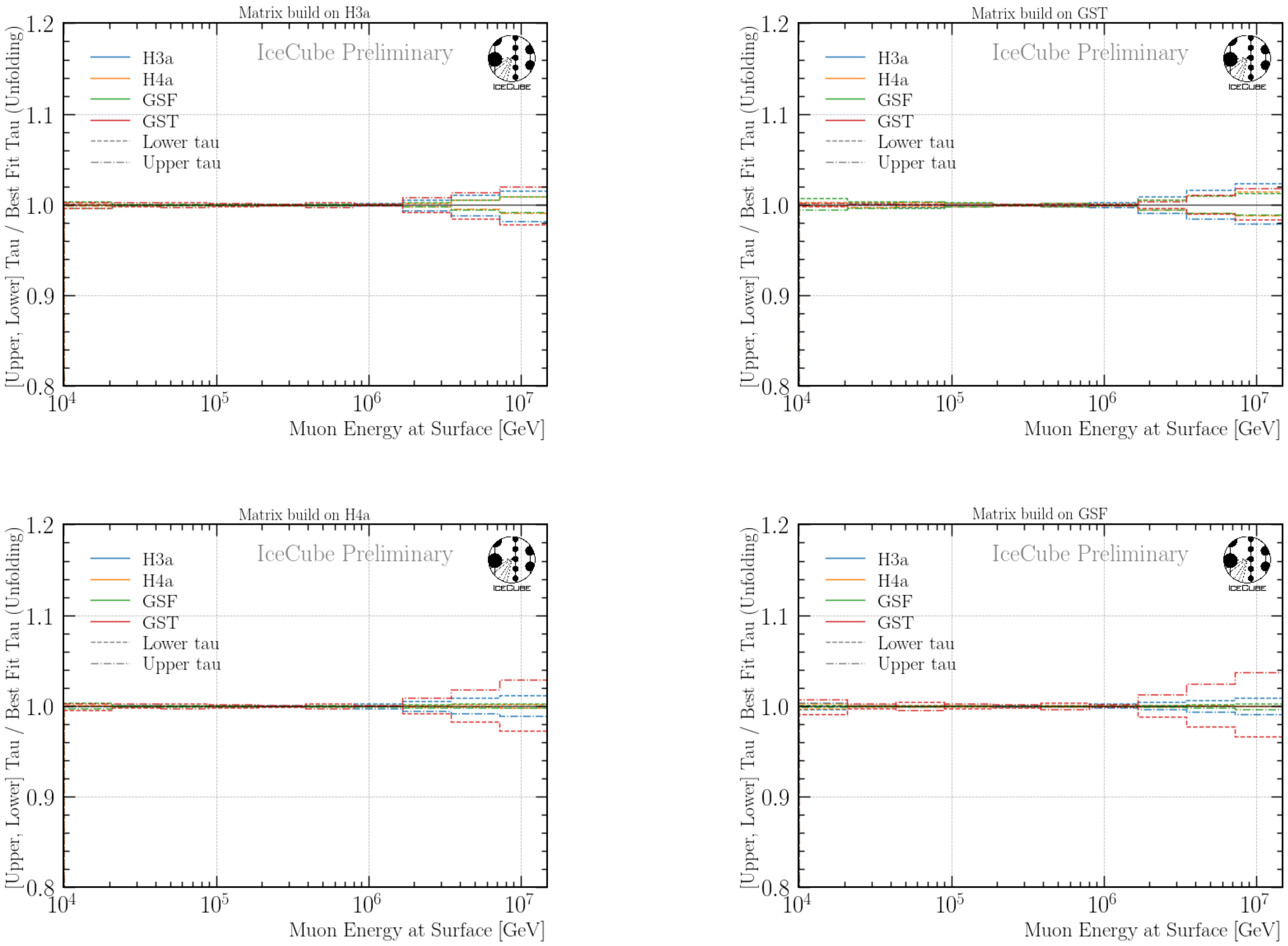
Target – Pseudo Correlation

- shaded area indicates analysis binning



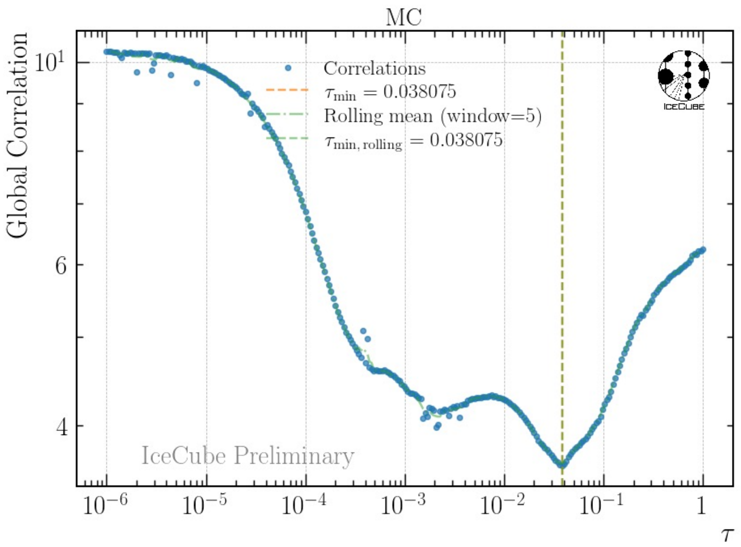
coincident primary events, as expected below 10 TeV

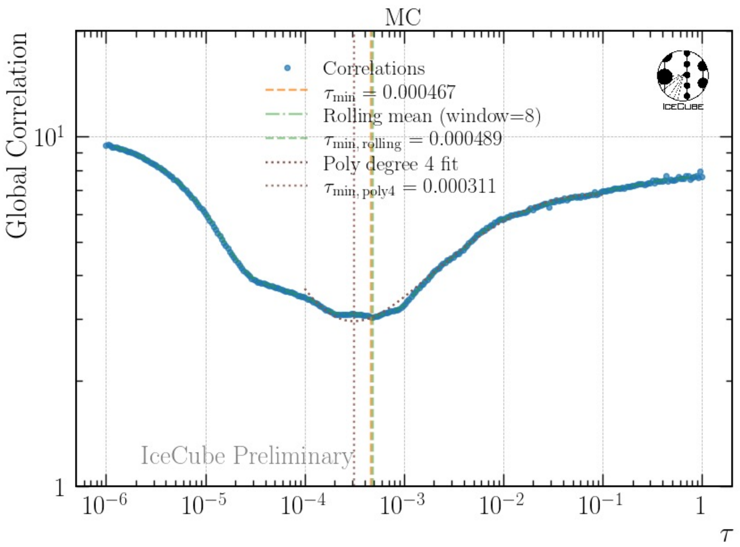
Regularization Impact



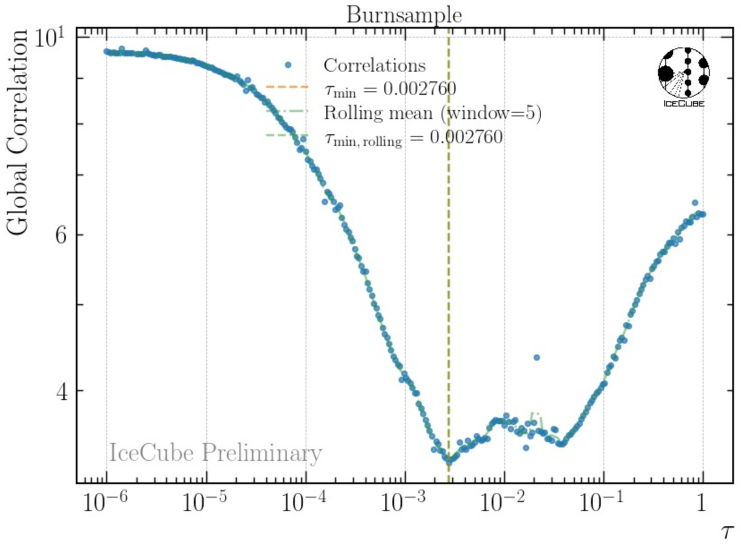
- regularization impact below 5%

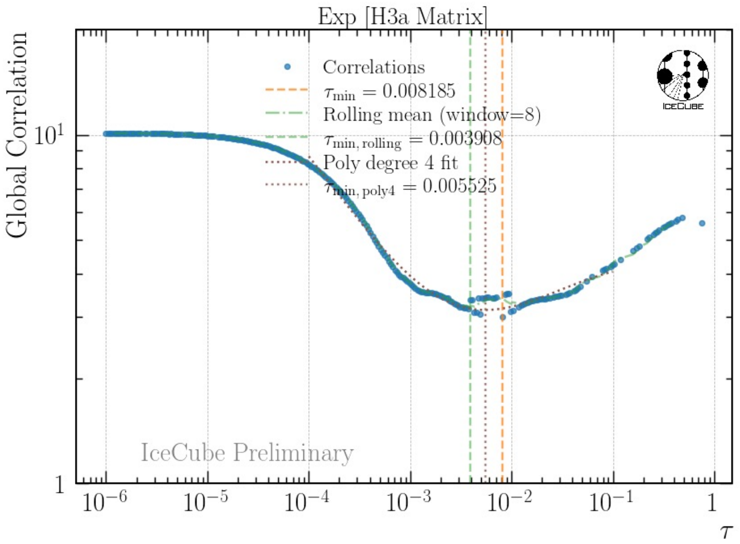
Compare Burnsample Unfolding Global Correlation





MC



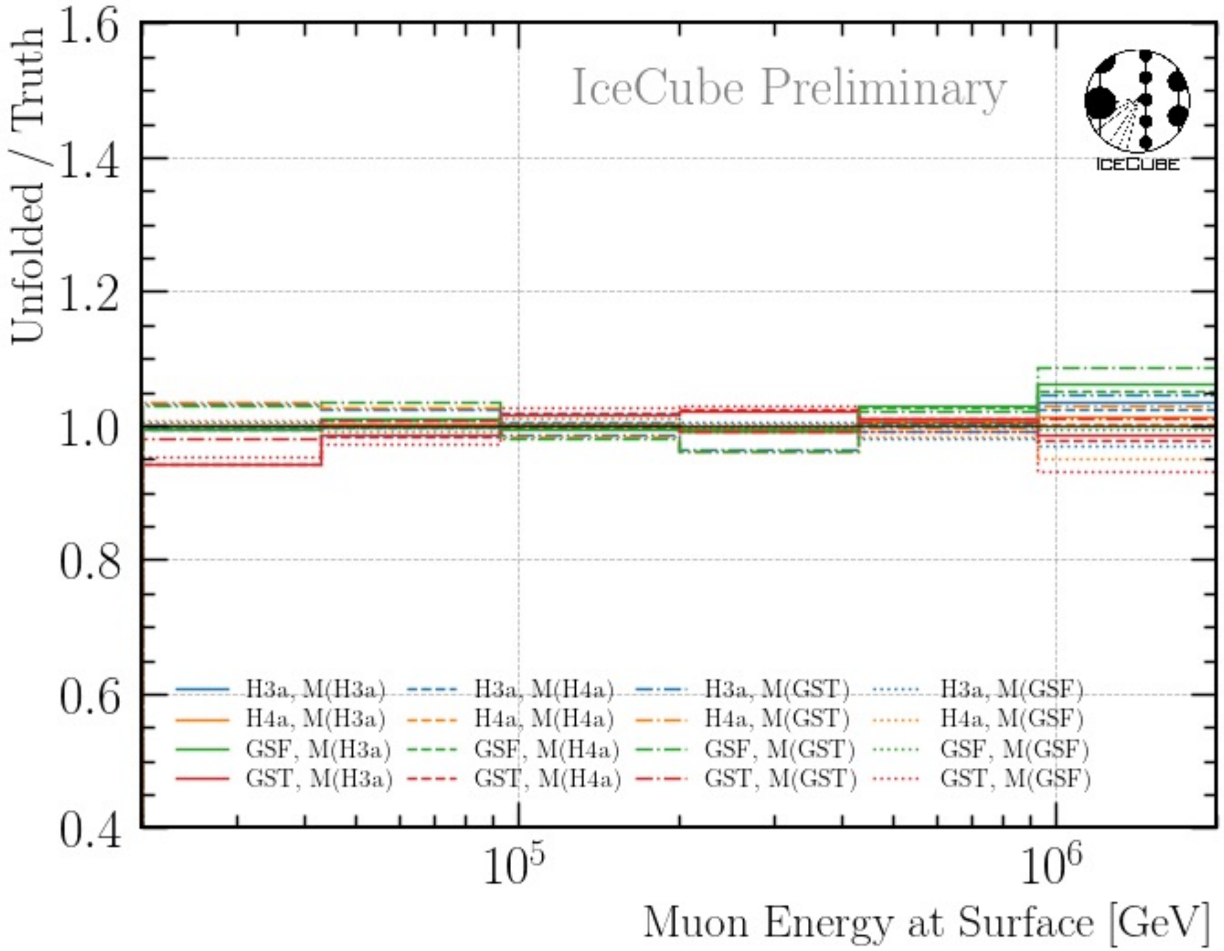


Burnsample

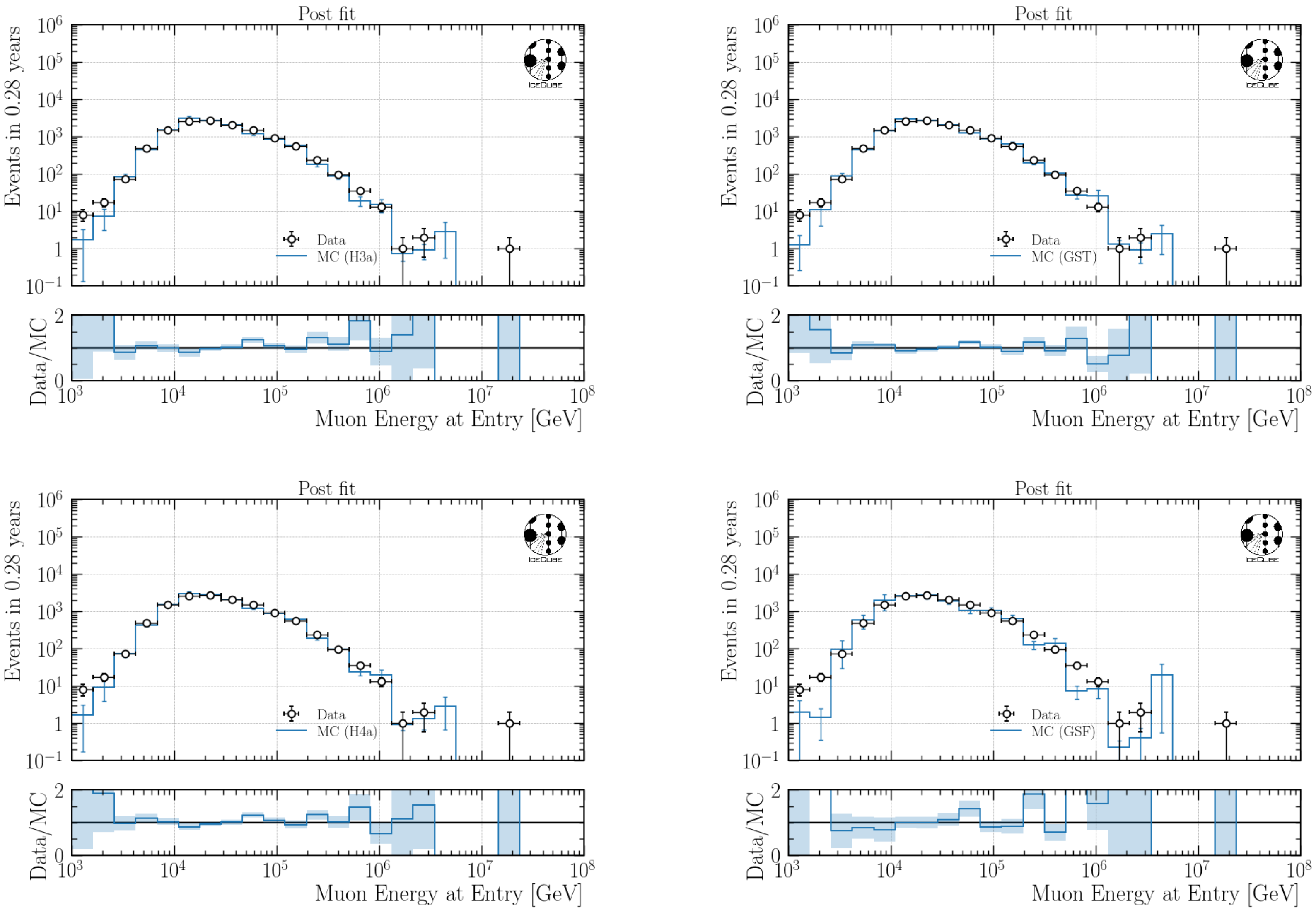
Single Dataset

Combined Dataset

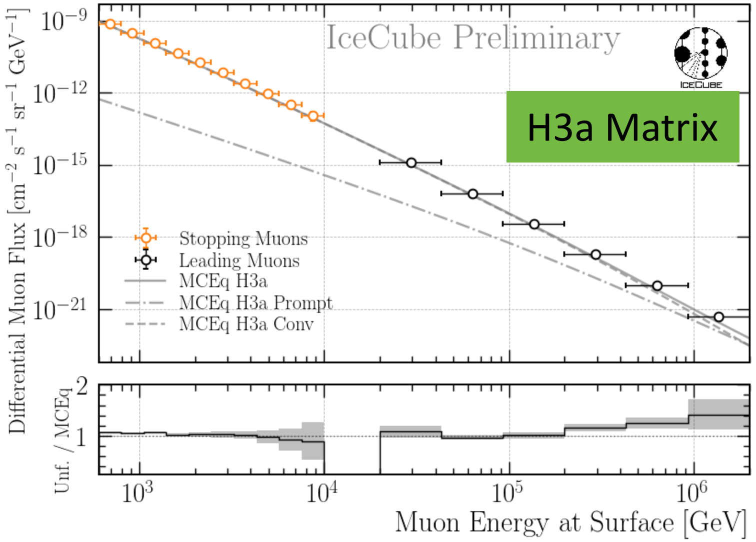
Unfolding Bias on Burnsample with Combined Datasets

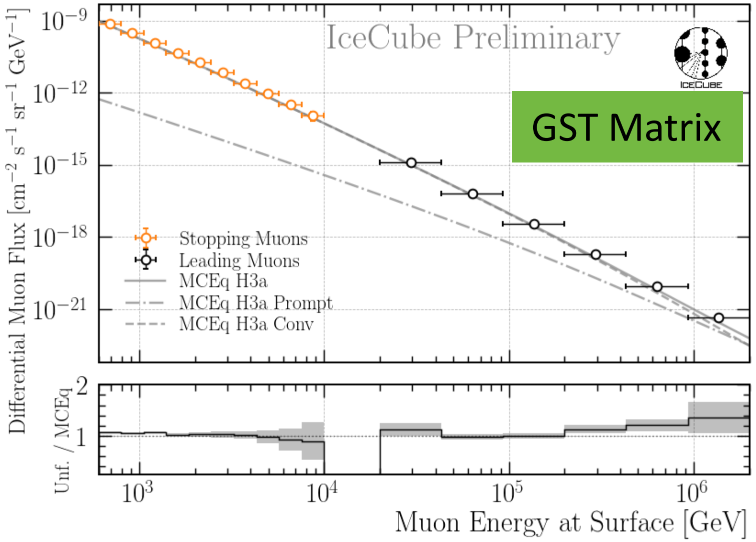


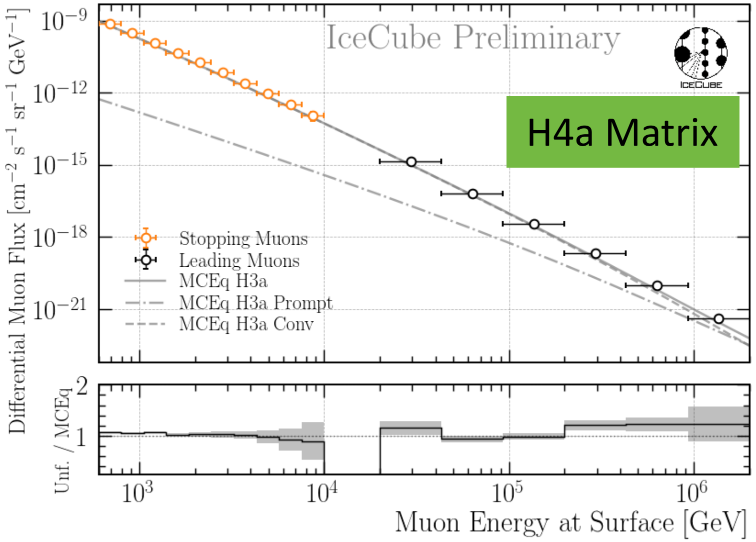
Data-MC Post Fit for 4 Burnsample Unfoldings with Combined Datasets

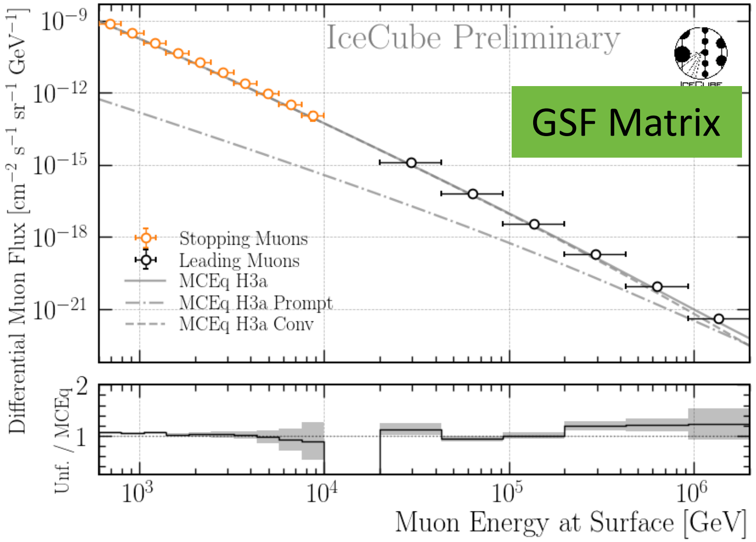


4 Burnsample Unfolding Results with Combined Datasets

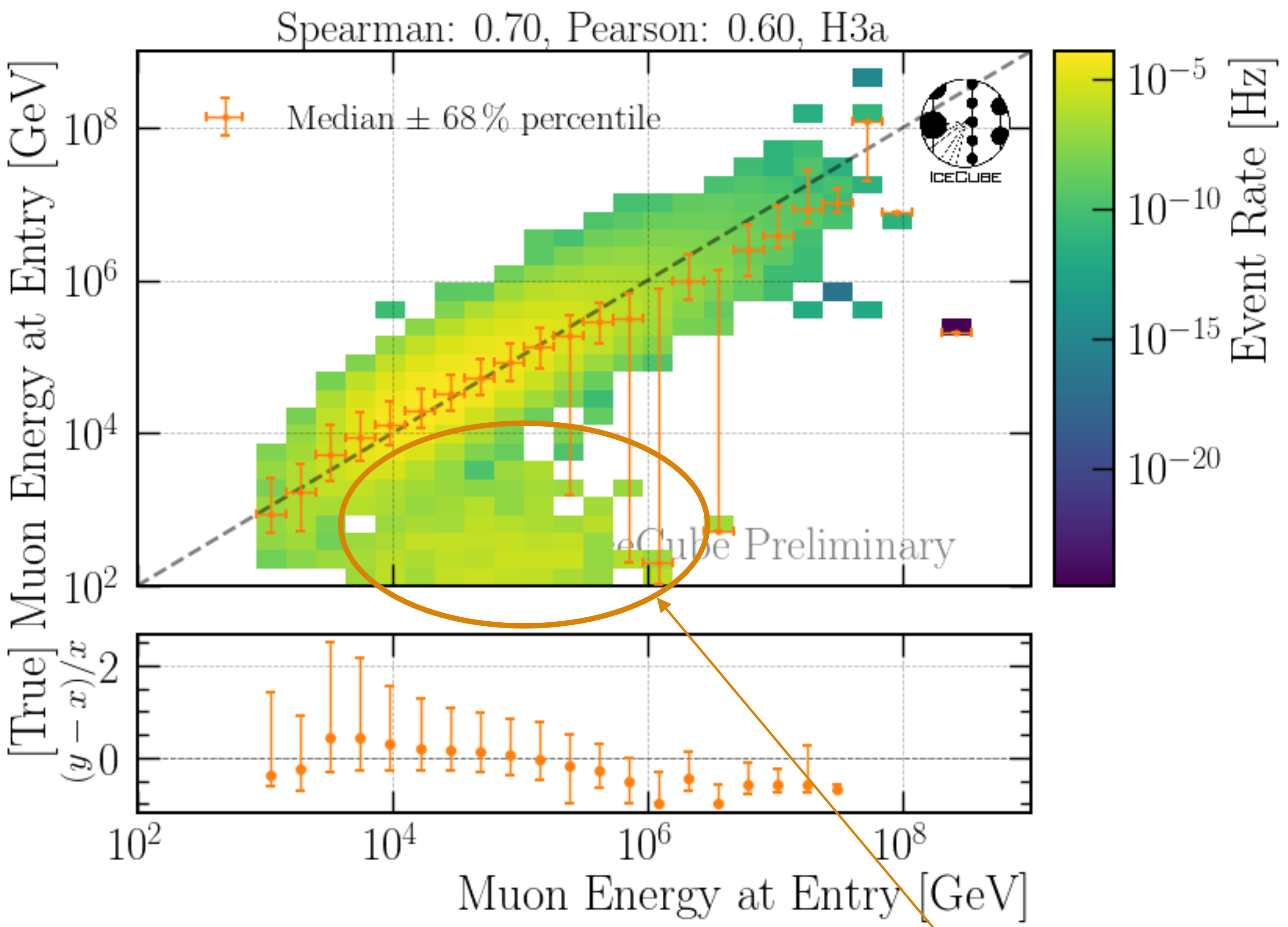








Reconstruction Performance on Combined Dataset

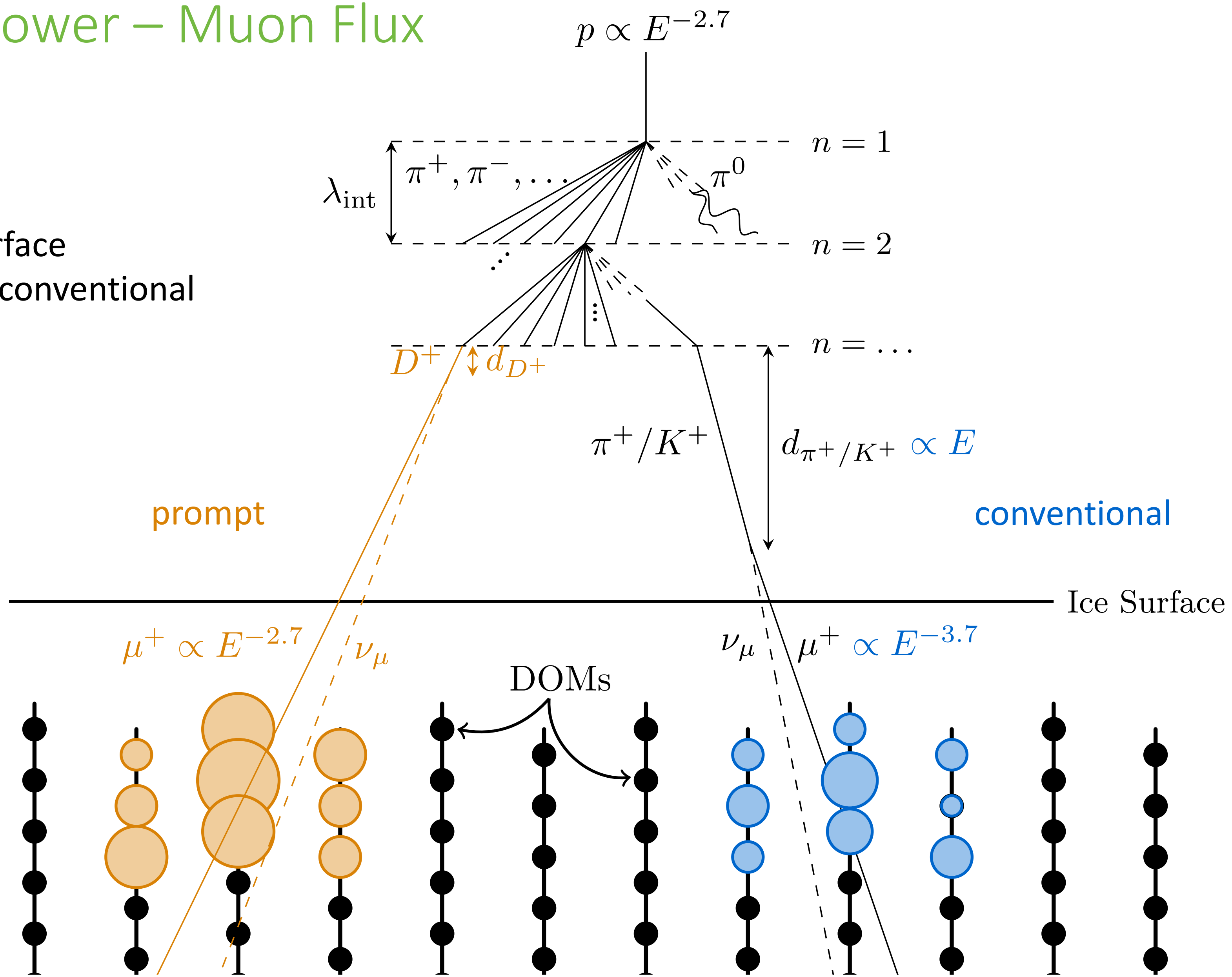


all events

coincident primary events

Cosmic Ray Air Shower – Muon Flux

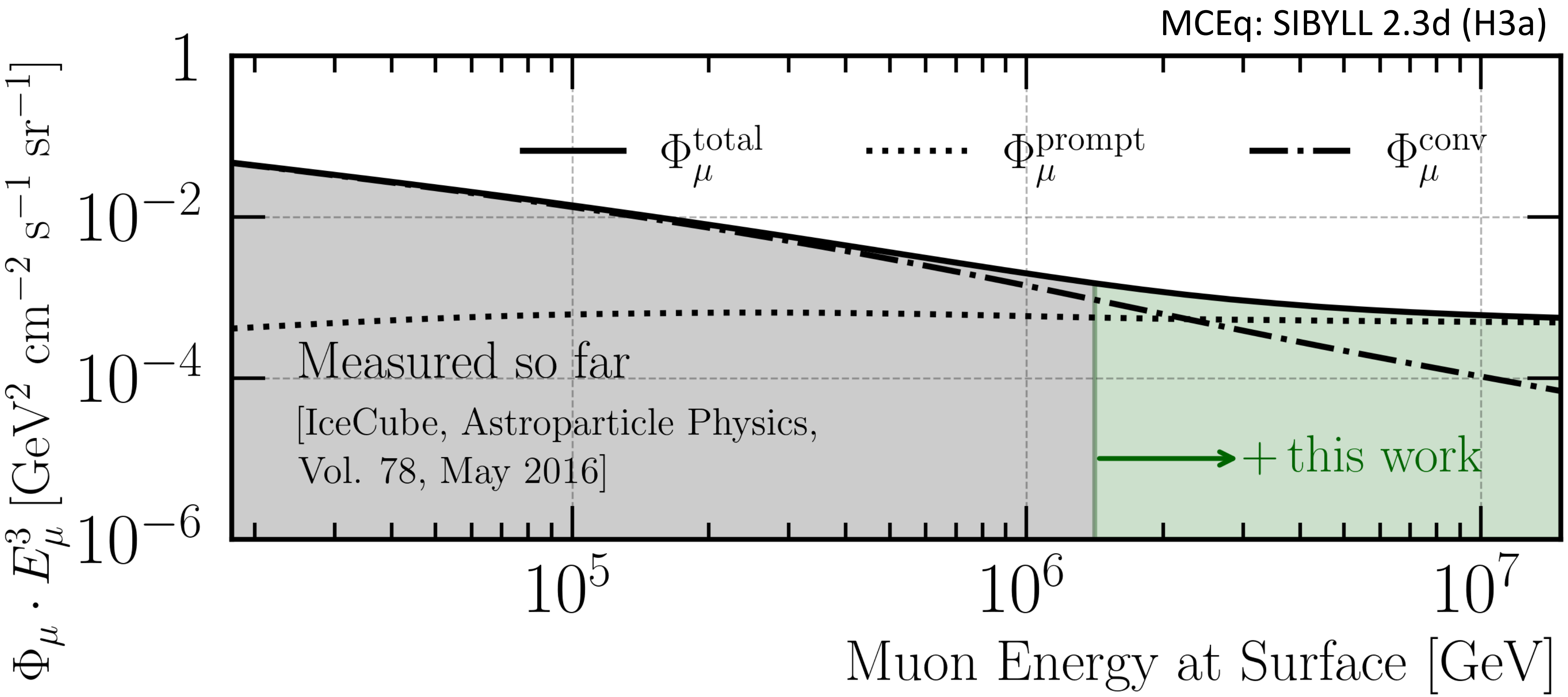
- Measure muon flux at surface
- Characterize prompt and conventional component



Conventional Muon:
Parent is pion or kaon

Prompt Muon:
„Rest“

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

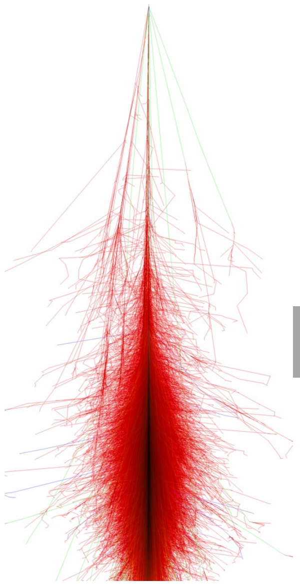
Unfolding

Muon spectrum
- Unfold muon flux at surface

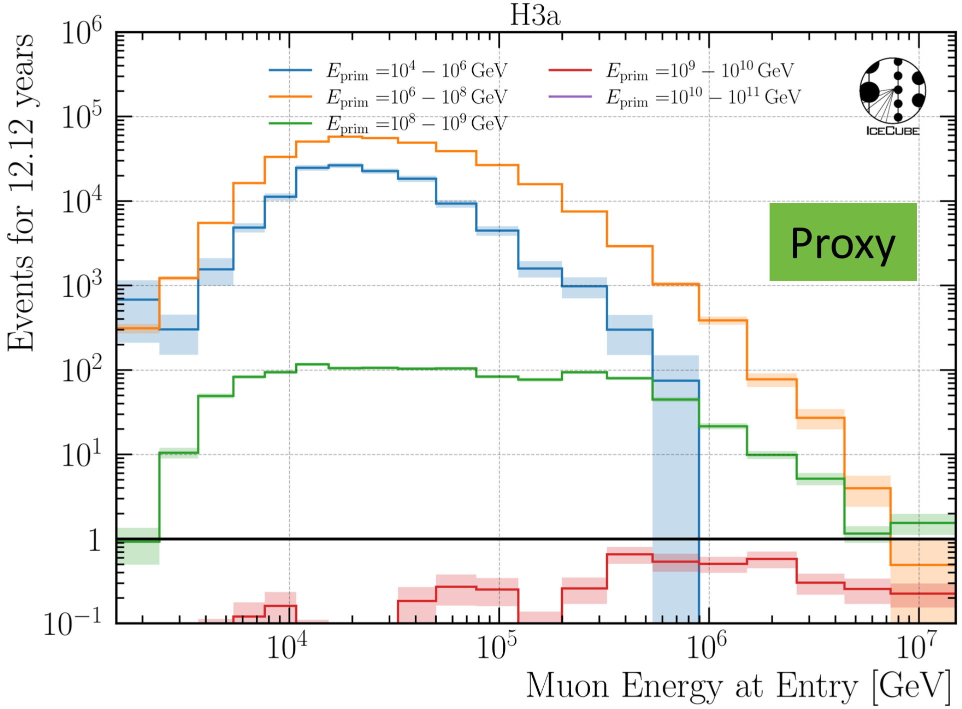
Simulation

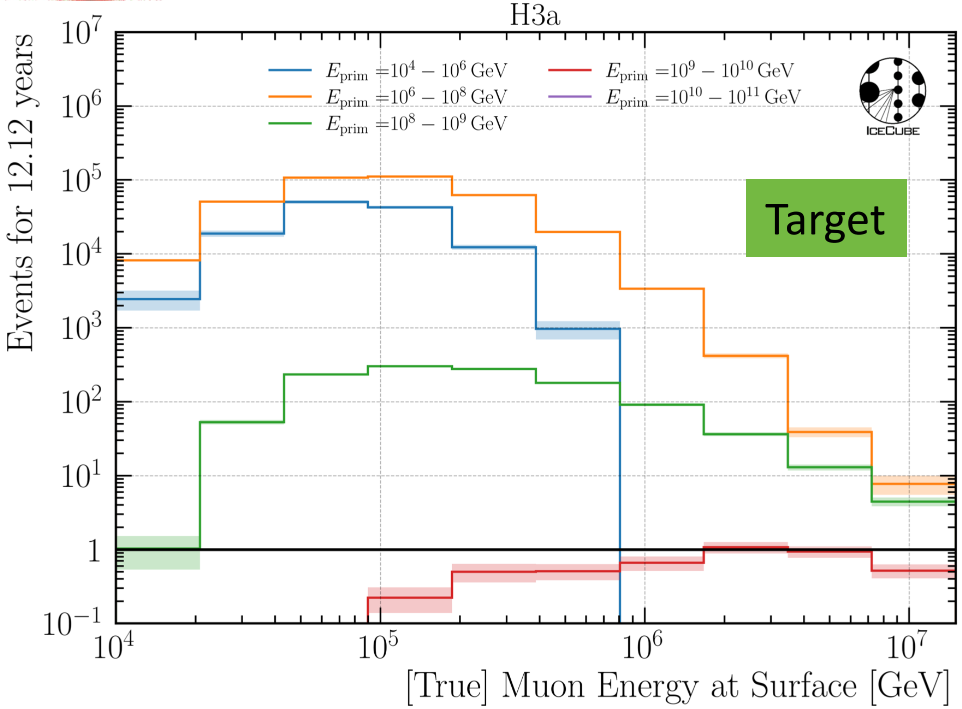
New CORSIKA Simulation

- Extended history → get muon parent information
- Official iceprod datasets: 22774 – 8
- Primary energy: 10 TeV – 1e11 GeV
- HIM: SIBYLL 2.3d



Leading muon = most energetic muon in a bundle



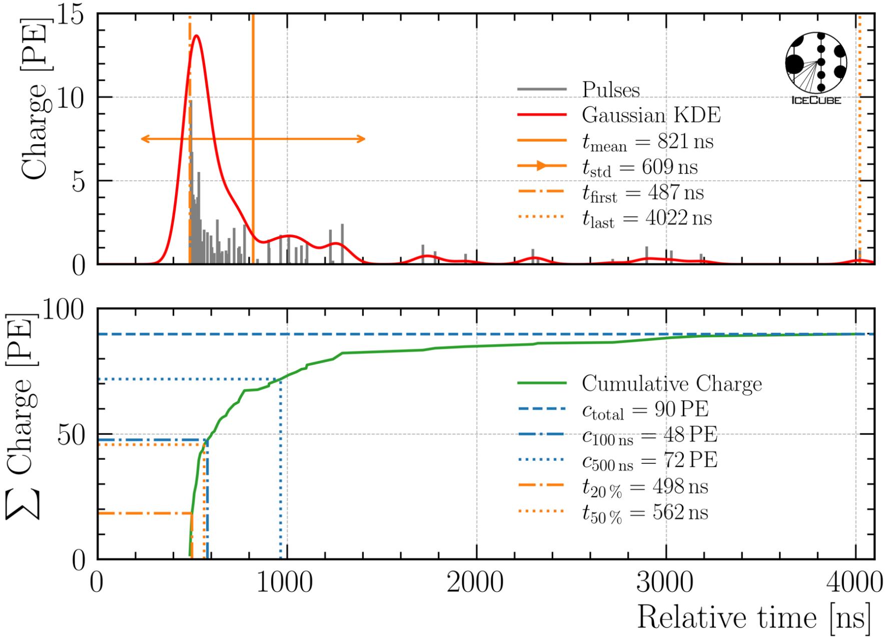


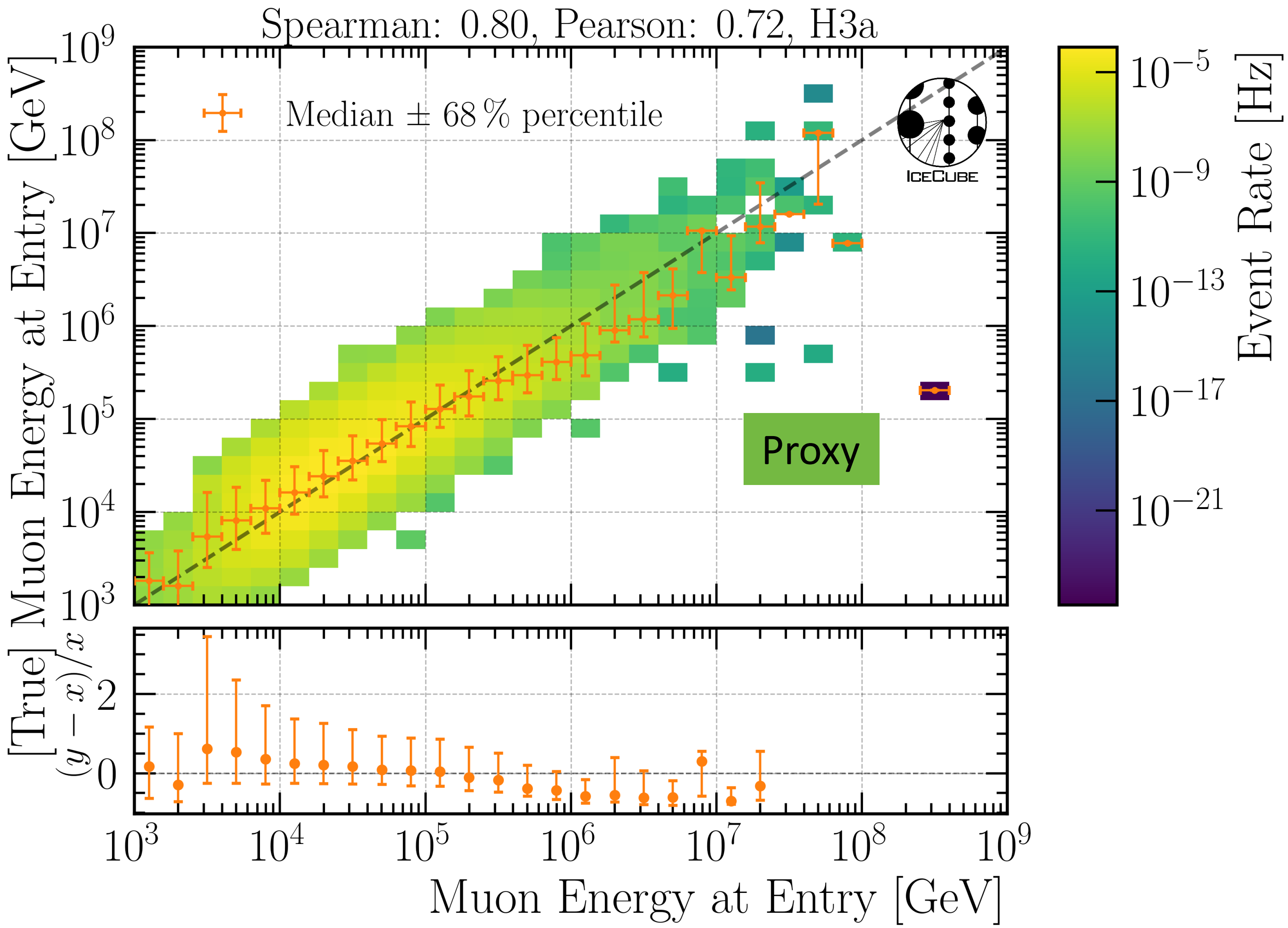
*22875 is simulated from 600 GeV – 10 TeV, but not used in this analysis
→ from the simulated statistics, no event made it into the final selection stage

Reconstruction

CNN Reconstructions

- dnn_reco
- Train on multiple CORSIKA datasets
- 3 / 9 features
- SplitInIceDSTPulses
- 6000ns pulse cleaning
- Energies, directions, track geometries



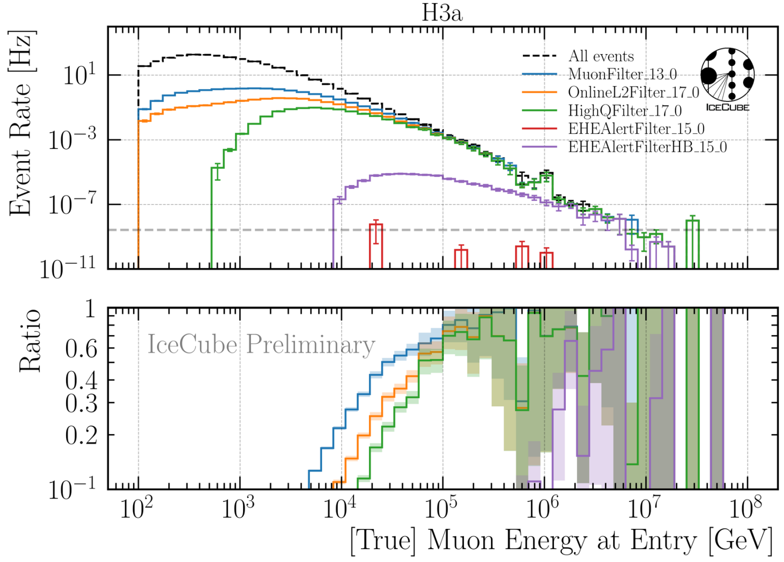


Selection

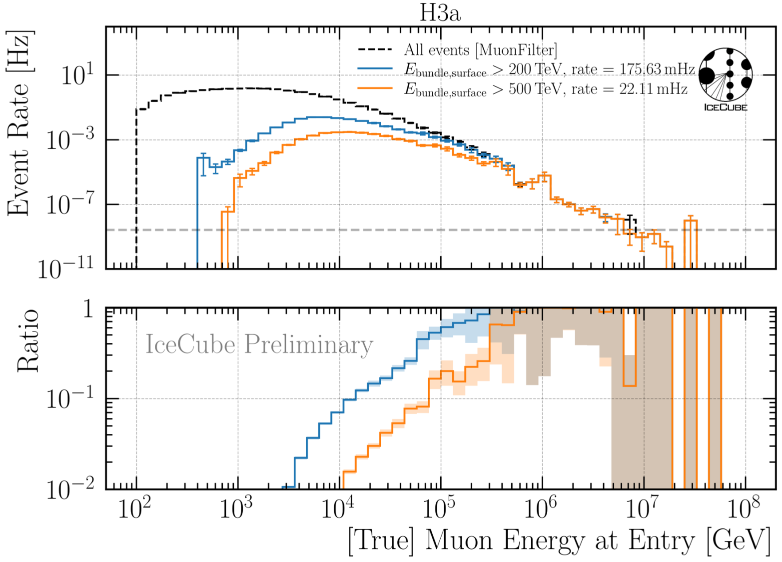
Selection

Details: wiki/selection

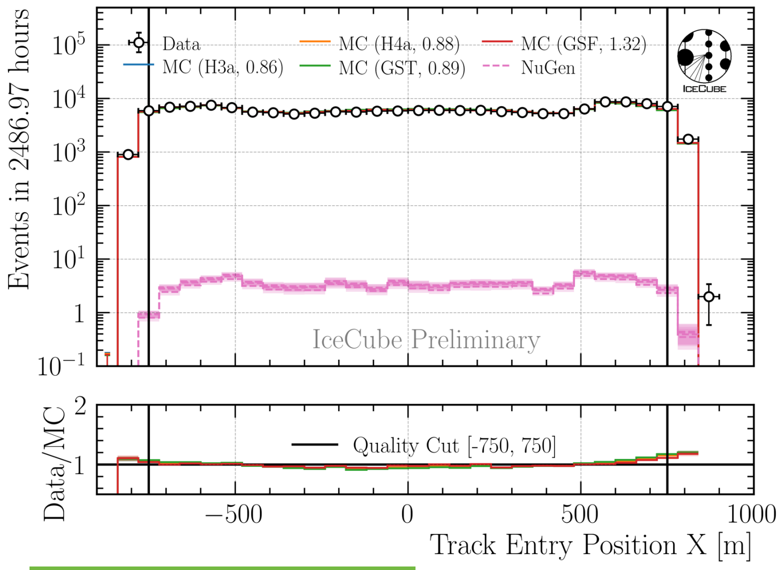
Level 3: MuonFilter

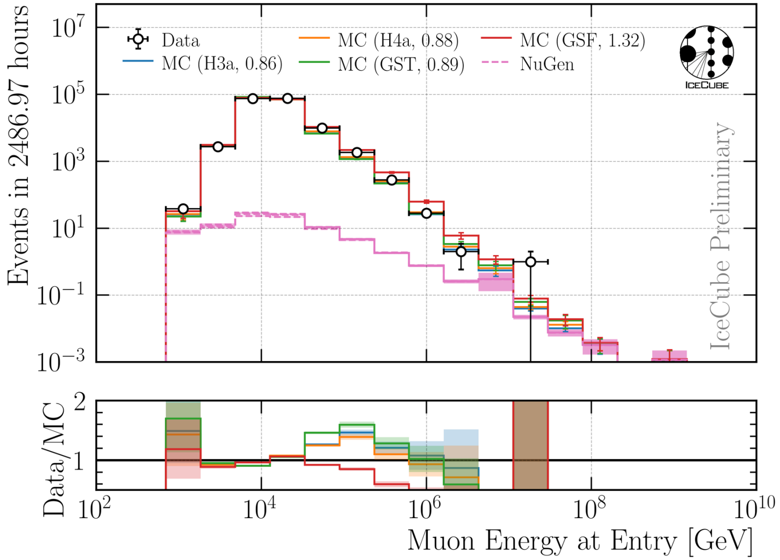


Level 4: E > 500 TeV bundle Energy a surface



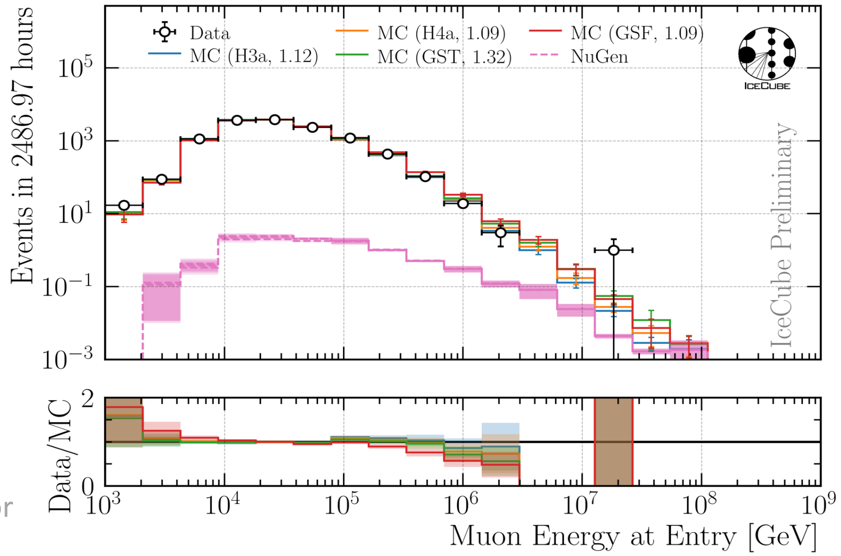
Level 5: 23 Data/MC Quality Cuts





$$L = \frac{\text{Leading Energy at Entry}}{\text{Bundle Energy at Entry}} > 40\ \%$$

Final Level: L > 40 %



*numbers in brackets mark a scaling factor to match the total number of data events

Unfolding

Unfolding in a nutshell

measured proxy

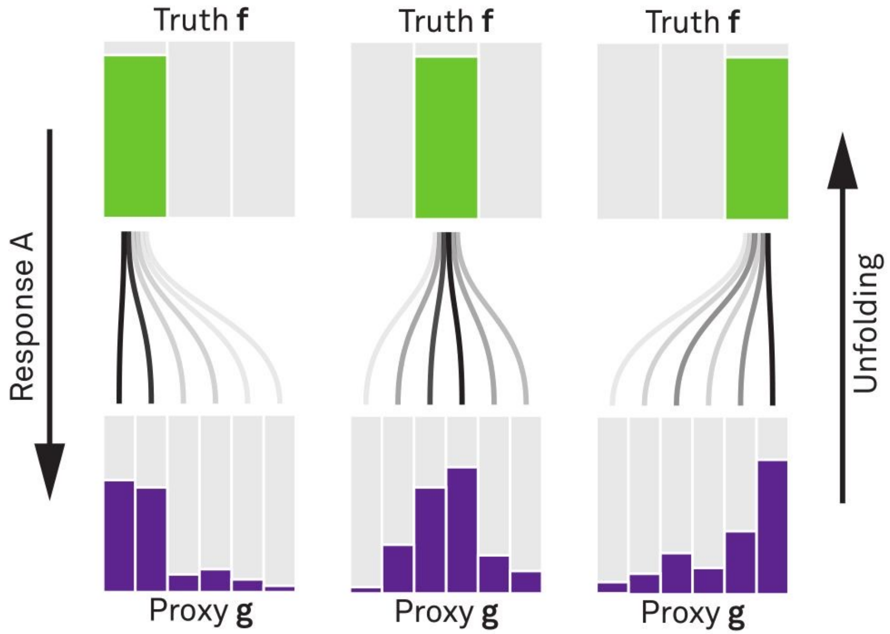
detector response

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



Credit: T. Hoinka

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:

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

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

GitHub

funfolding

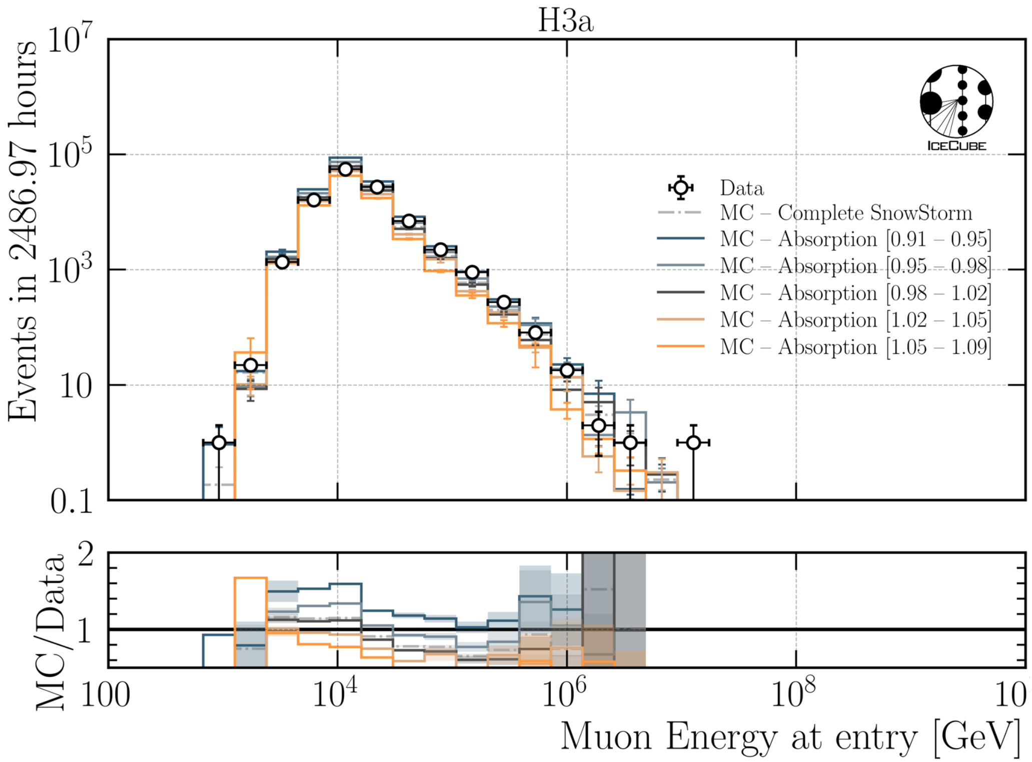
by M. Börner

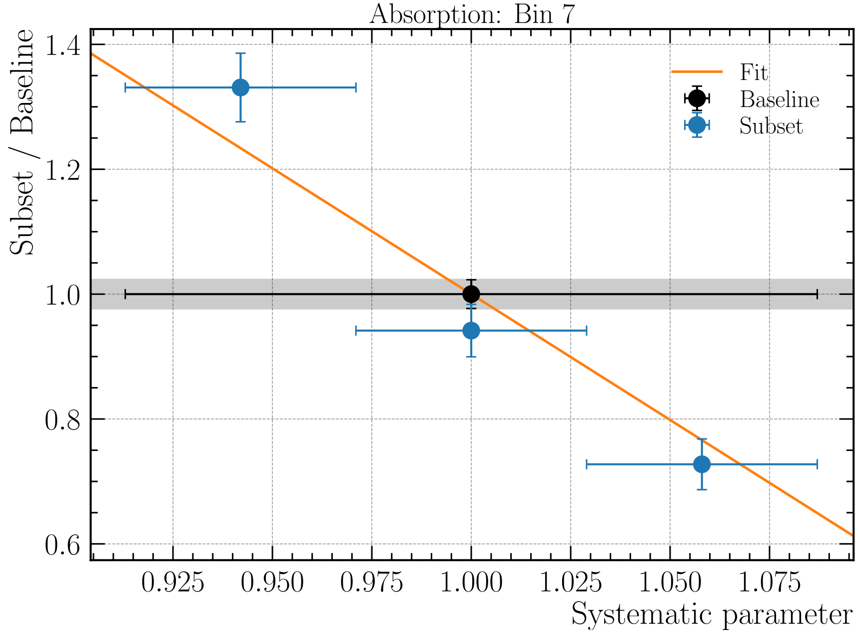
SnowStrom In-Ice Systematics

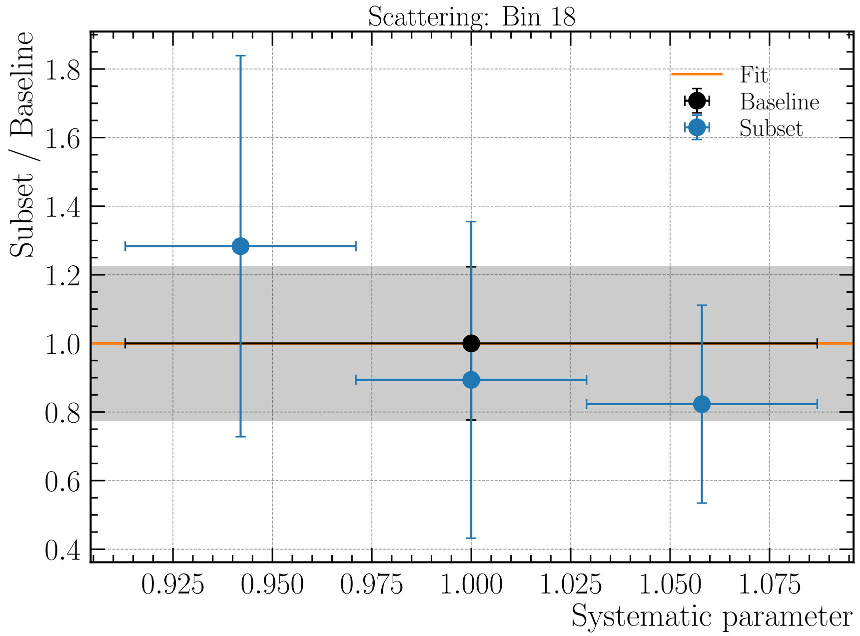
Systematic	Sampling Distribution	Sampling Range
Scattering	uniform	[0.913, 1.087]
Absorption	uniform	[0.913, 1.087]
DOM Efficiency	uniform	[0.9, 1.1]
HoleIce Forward p0	uniform	[-0.1, 0.5]
HoleIce Forward p1	uniform	[-0.1, 0.0]

- Parameterize impact of systematic for each proxy bin (leading muon at entry)
- 5 systematics x 20 bins = 100 fits
- Many bins have large uncertainties
  → set to constant
- Mainly impacted by Absorption and DOM efficiency

➢ Included as nuisance parameters in the unfolding







Event Rate to Flux → Effective Area

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

$$\phi_i = \frac{N_i}{T \, \Delta E_i \, \Omega_i \, A_{\mathrm{eff},i}}$$

- with solid angle

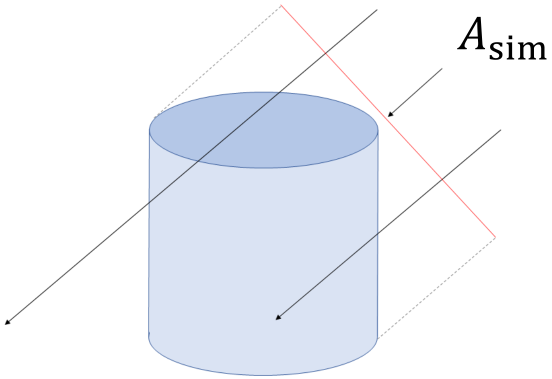
$$\Omega_i = 2\pi \left(\cos(\Omega_{\mathrm{min},i}) - \cos(\Omega_{\mathrm{max},i})\right)$$

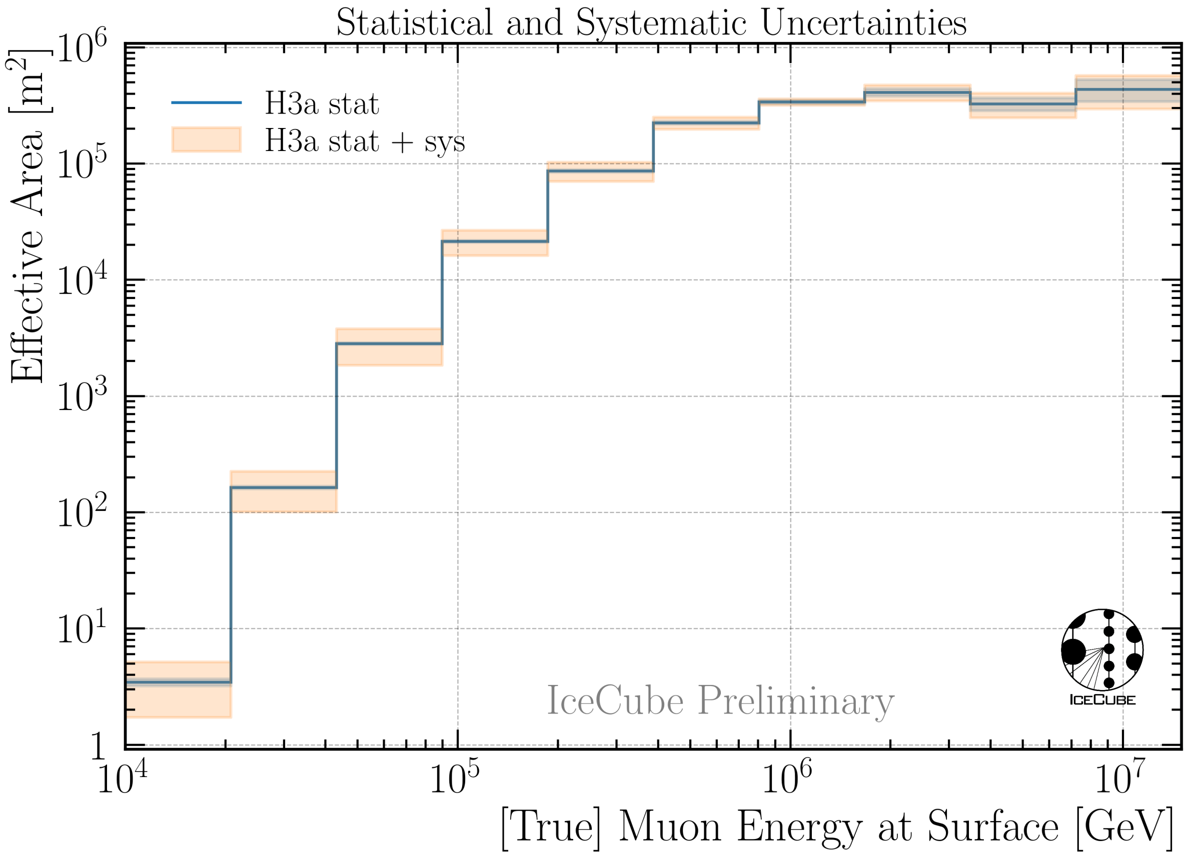
- and effective area

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

final level events

generation level events

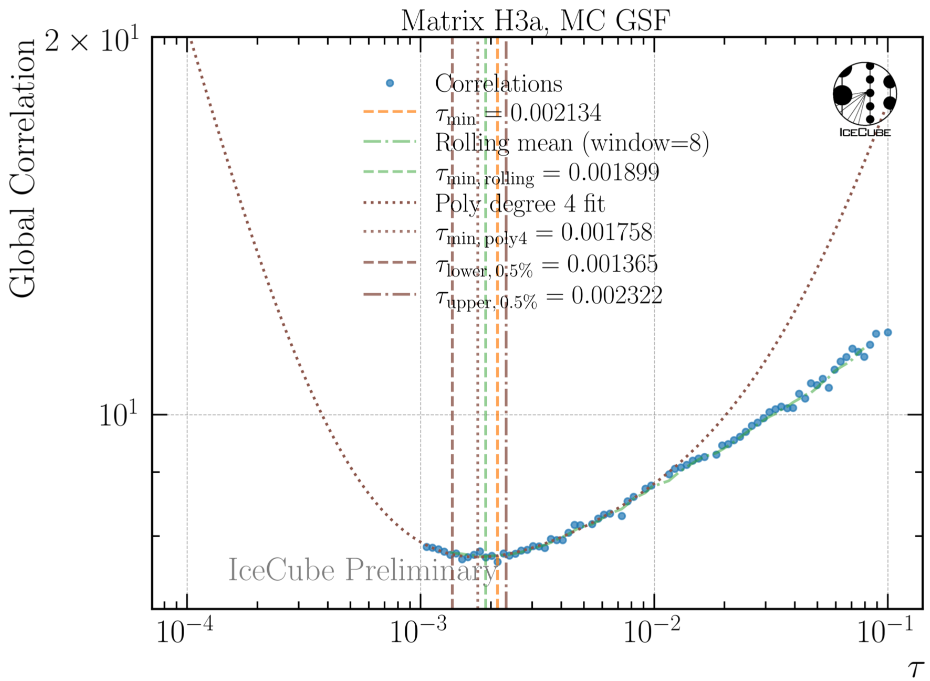




Regularization

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

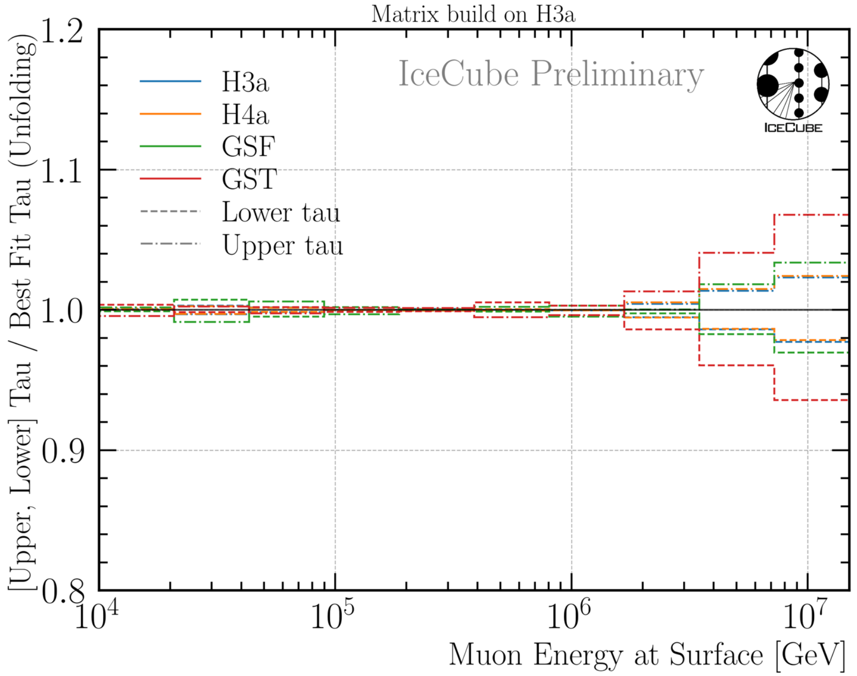
➢ Minimize global correlation $$\rho = \sum_{i>j} V_{ij}$$



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

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

impact of tau variation < 10 %
→ negligible in comparison to statistical uncertainty



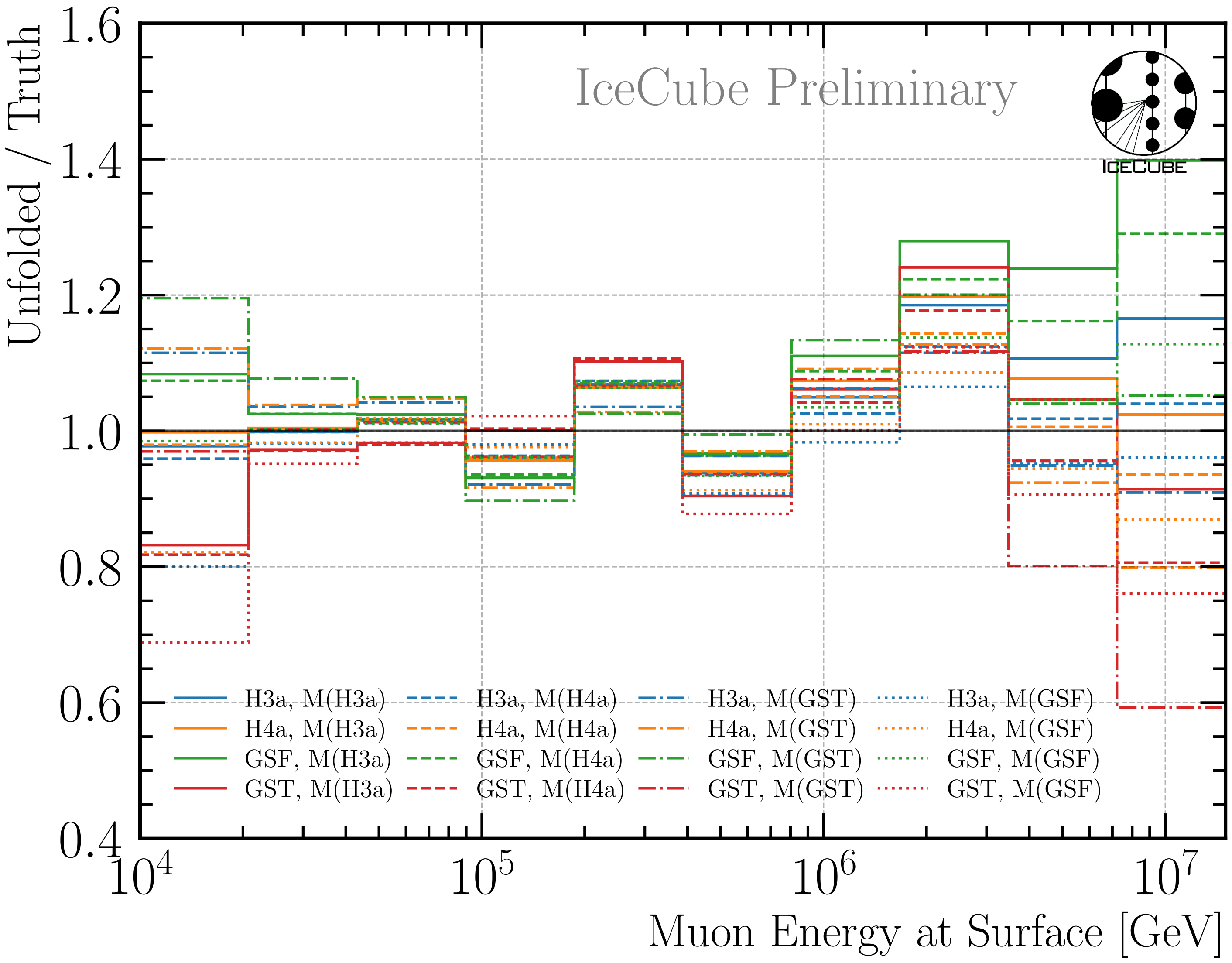
“Method Bias”

Uncertainties: “Unfolding Bias”

- Train unfolding on H3a, H4a, GSF, GST
- Unfold 4 MC weighted datasets for the 4 primary models
- Divide each unfolding by its true MC distribution
- 16 unfoldings in total

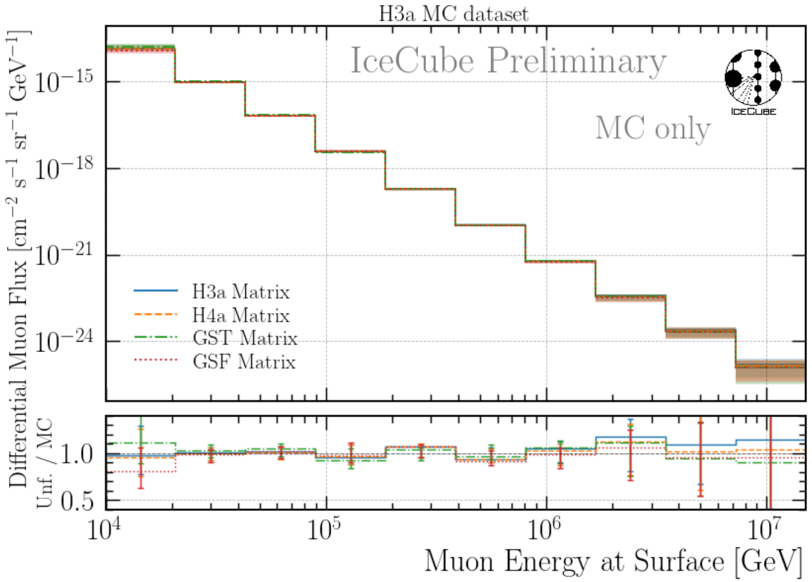
- ➢ Ratio of 1 expected
- ➢ Offset to 1 → bias

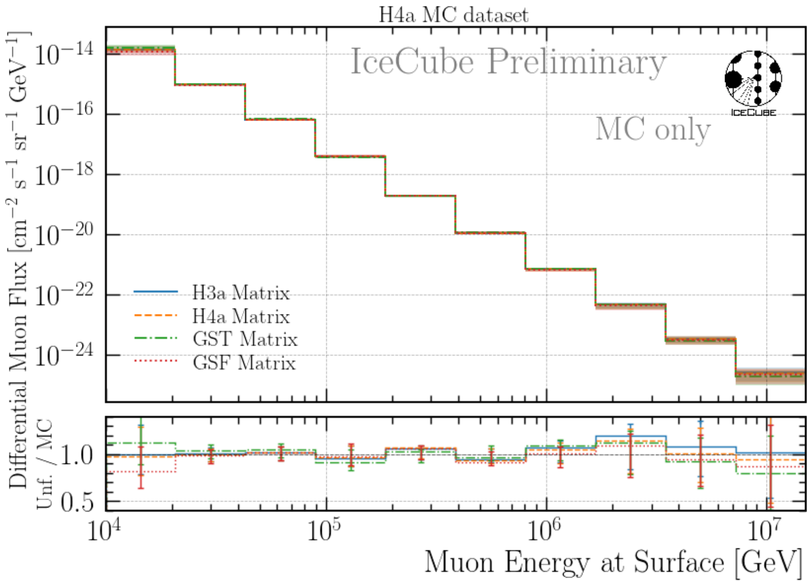
- ➢ Maximum distance to true distribution
- ➢ Add these biases as an uncertainty to the unfolding result

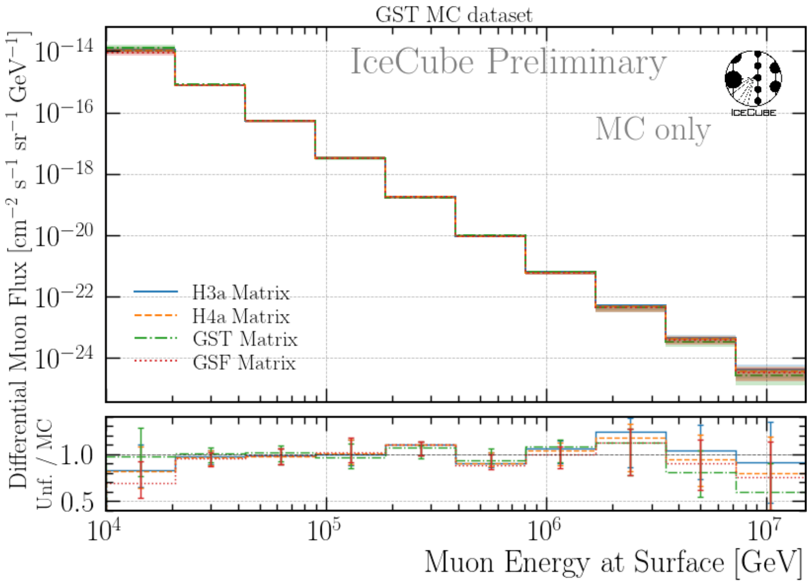


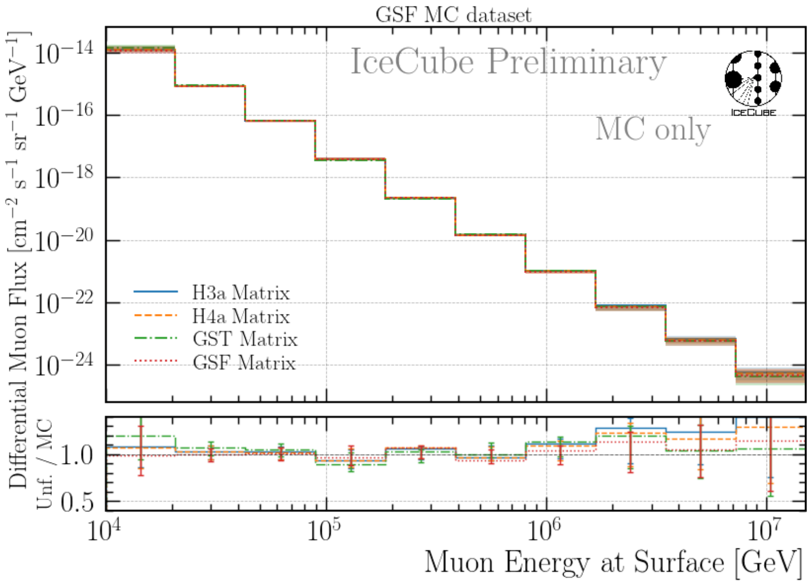
Include Uncertainties

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









- All test unfoldings agree with the truth within the uncertainties

Nominal / Best Fit → Average of 4 Unfoldings

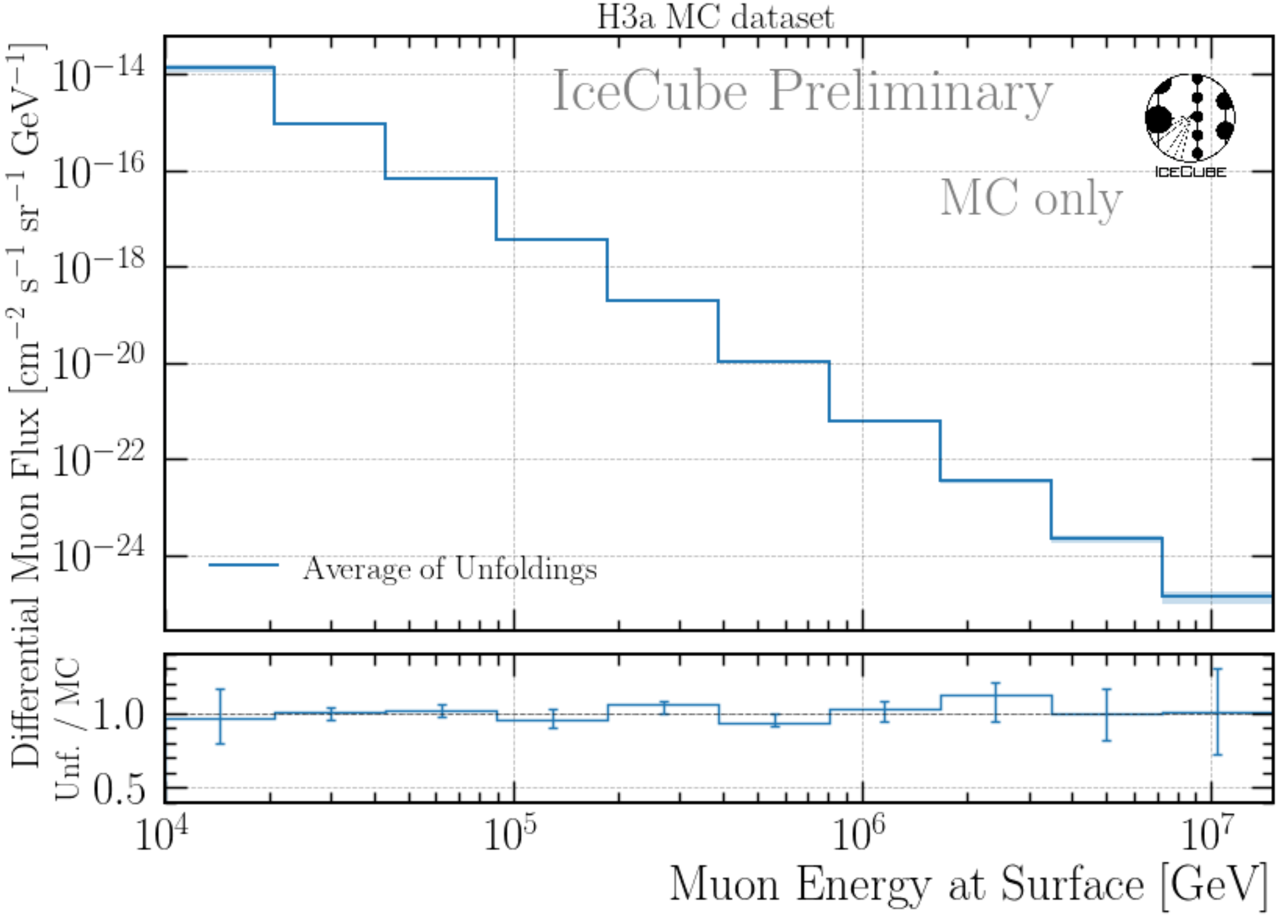
- Unfold H3a test dataset with all 4 primary models
- Build average
- $\sigma_{\text{tot}} = \sqrt{\sigma_{\text{unf}}^2 + \sigma_{\text{spread}}^2}$

with

- $\sigma_{\text{unf}} = \frac{\sqrt{\sum \sigma_{\text{tot,j}}^2}}{N}$

total uncertainty of the 4 unfoldings

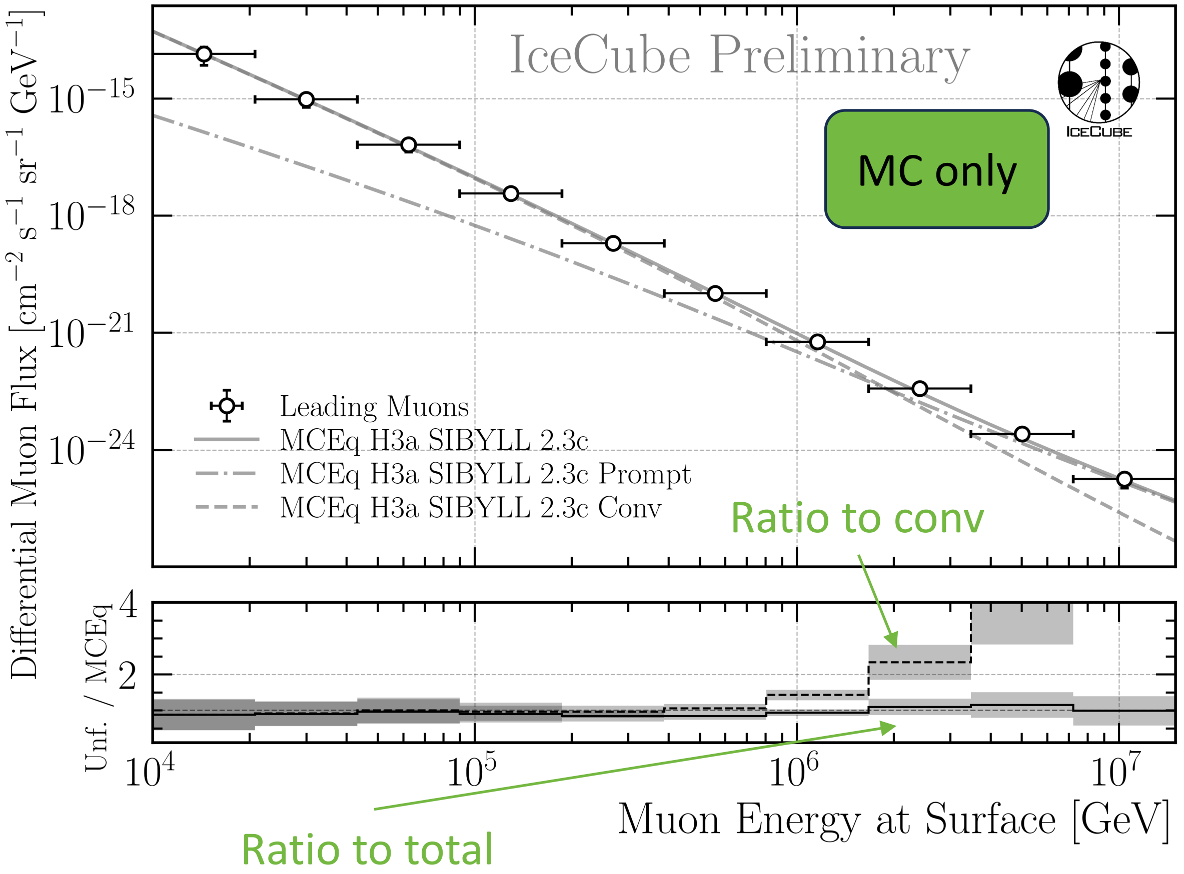
- $\sigma_{\text{spread}} = \text{std}(f_i)$



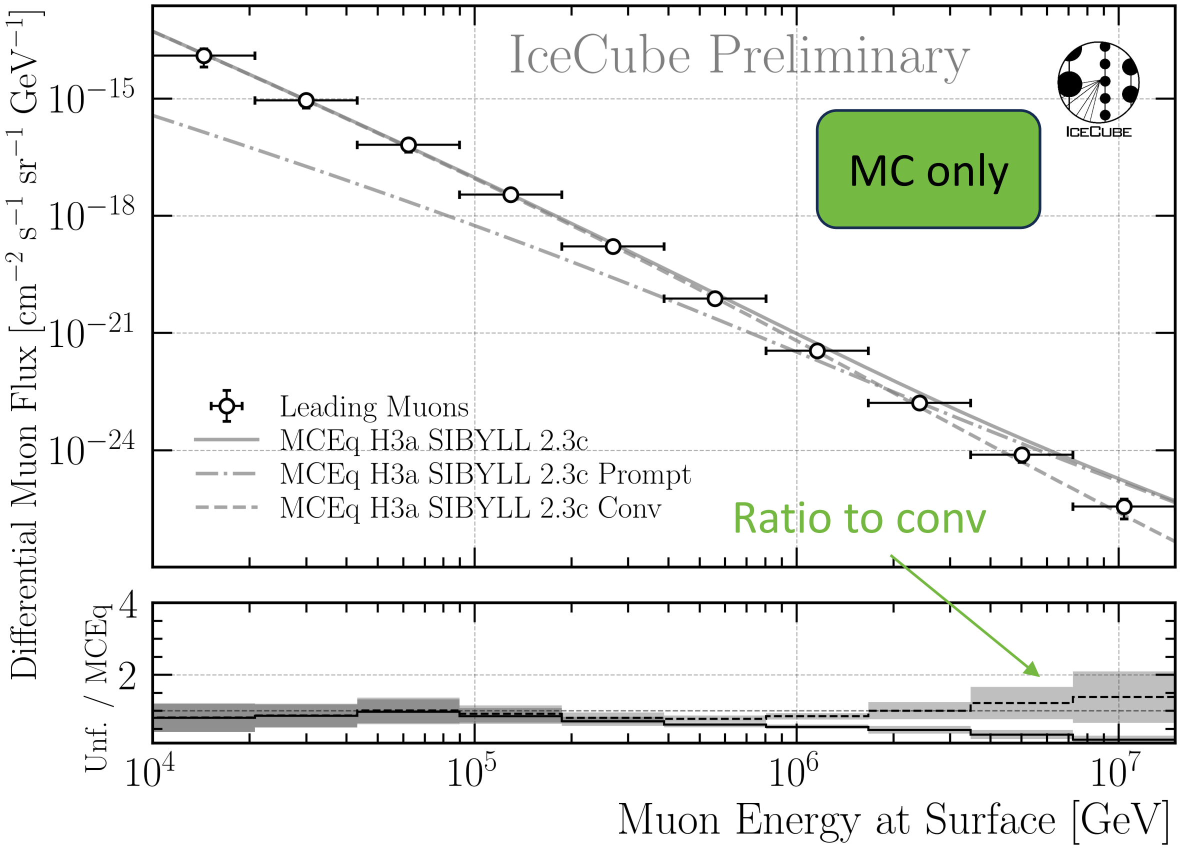
Sensitive to Prompt?

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

Flux Characterization

Chi2 Likelihood Fit

Fit normalizations

theory model

- $\mu_i(N_{\text{prompt}}, N_{\text{conv}}) = N_{\text{prompt}} \times f_{\text{prompt},i} + N_{\text{conv}} \times f_{\text{conv},i}$
- $r_i = m_i - \mu_i$
- $\chi^2 = r^{\text{T}} C^{-1} r$
  - $C = C_{\text{minuit}} + \text{diag}(\sigma^2_{\text{unf\_bias}}) + \text{diag}(\sigma^2_{\text{A}_{\text{eff}},\text{stat}})$
- minimize with scipy minimize → $N_{\text{prompt}}, N_{\text{conv}}$

Significance test for prompt

- $H_0 : N_{\text{prompt}} = 0, \quad H_1 : N_{\text{prompt}}, N_{\text{conv}}$ free
- $\chi_0^2 = \chi^2(N_{\text{prompt}} = 0, N_{\text{conv}})$
- $\chi_1^2 = \chi^2(N_{\text{prompt}}, N_{\text{conv}})$
- $TS = \Delta\chi^2 = \chi_0^2 - \chi_1^2$
- $p = \sqrt{2}\,\text{erfc}\left(\sqrt{\frac{TS}{2}}\right)$
- $Z = \sqrt{TS}$

```
[LikelihoodFitter] Using full covariance matrix.
  Maximum bin correlation: 0.254
======================================================================
LIKELIHOOD FIT SUMMARY
======================================================================

Mode: Full covariance matrix (10×10)

Best-Fit Parameters:
  Prompt normalization:        1.163869 ± 0.312284
  Conventional normalization:  0.993129 ± 0.042122

χ² = 1.00    ndof = 8    χ²/ndof = 0.125
  Goodness-of-fit p-value: 0.9982
  Parameter correlation: -0.6352

----------------------------------------------------------------------
HYPOTHESIS TEST: H₀: prompt normalization = 0
----------------------------------------------------------------------
  Δχ² = 6.945
  p (one-sided, boundary-corrected) = 4.202486e-03
  significance approx ≈ 2.64σ
  significance exact  = 2.64σ
  → Reject H₀ at 95 % CL → evidence for prompt component.
======================================================================
```

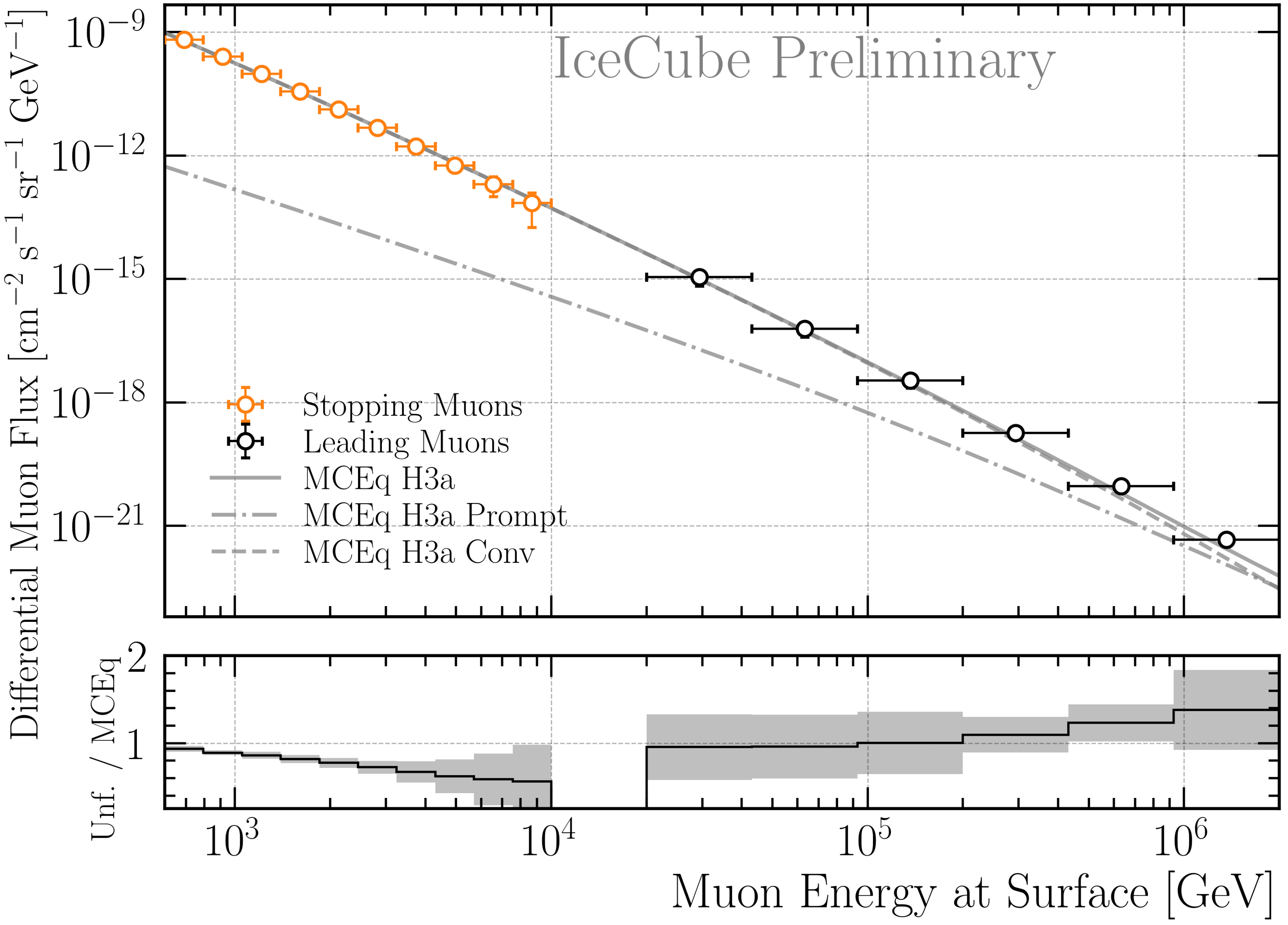
Burnsample Unfolding

Burnsample Unfolding

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

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

ICRC PoS 281



*Stopping muon analysis done by Lucas Witthaus

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

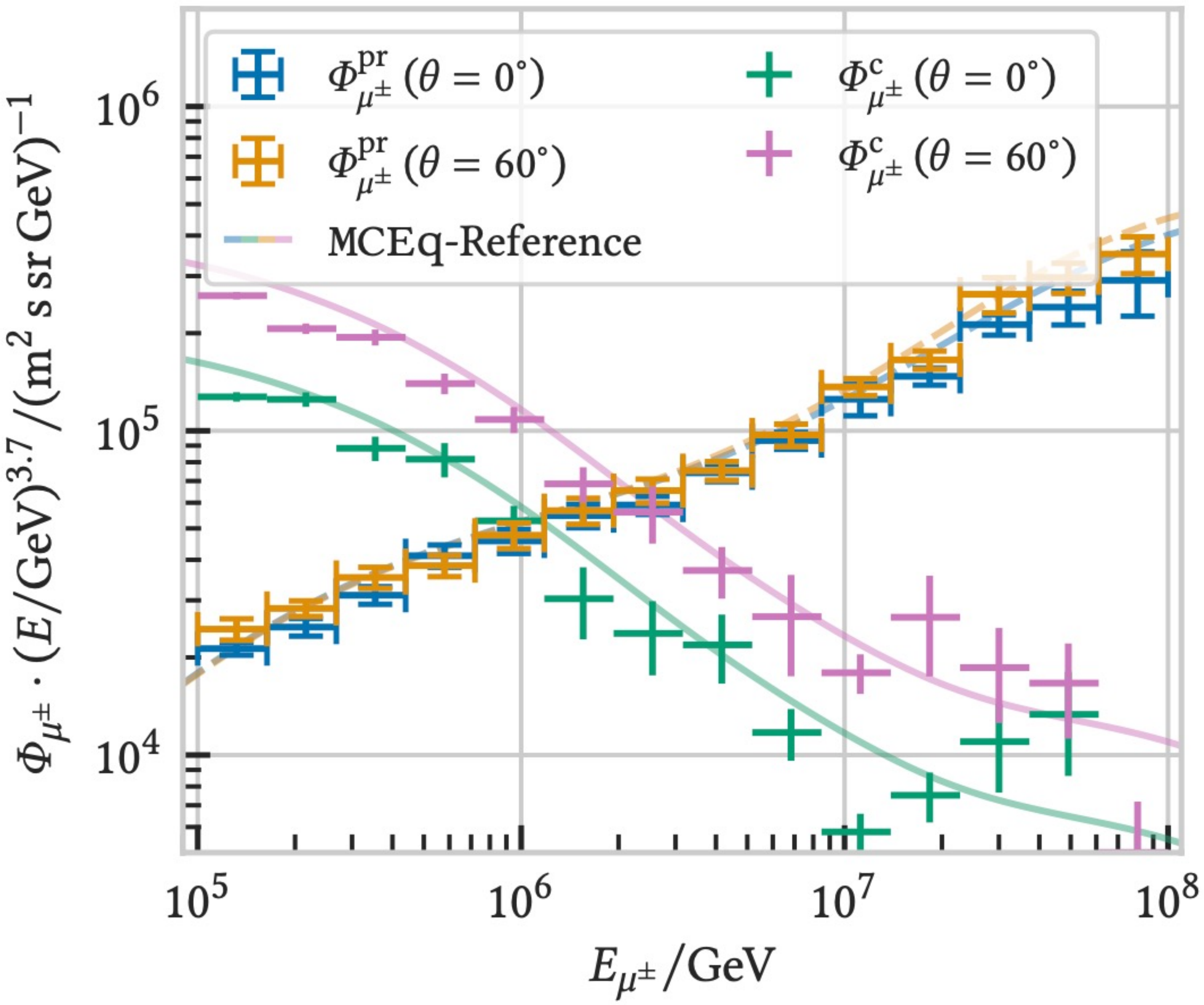
- Check the data-MC agreement for proxy variable (leading energy)
  - Pre-fit (on the entire Snowstorm dataset)
  - Post-fit (re-weight to fitted systematics)
- Divide total dataset in 3 subsets á 4 years to analyze systematic impacts over the years
- Divide dataset into 4 seasons

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

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

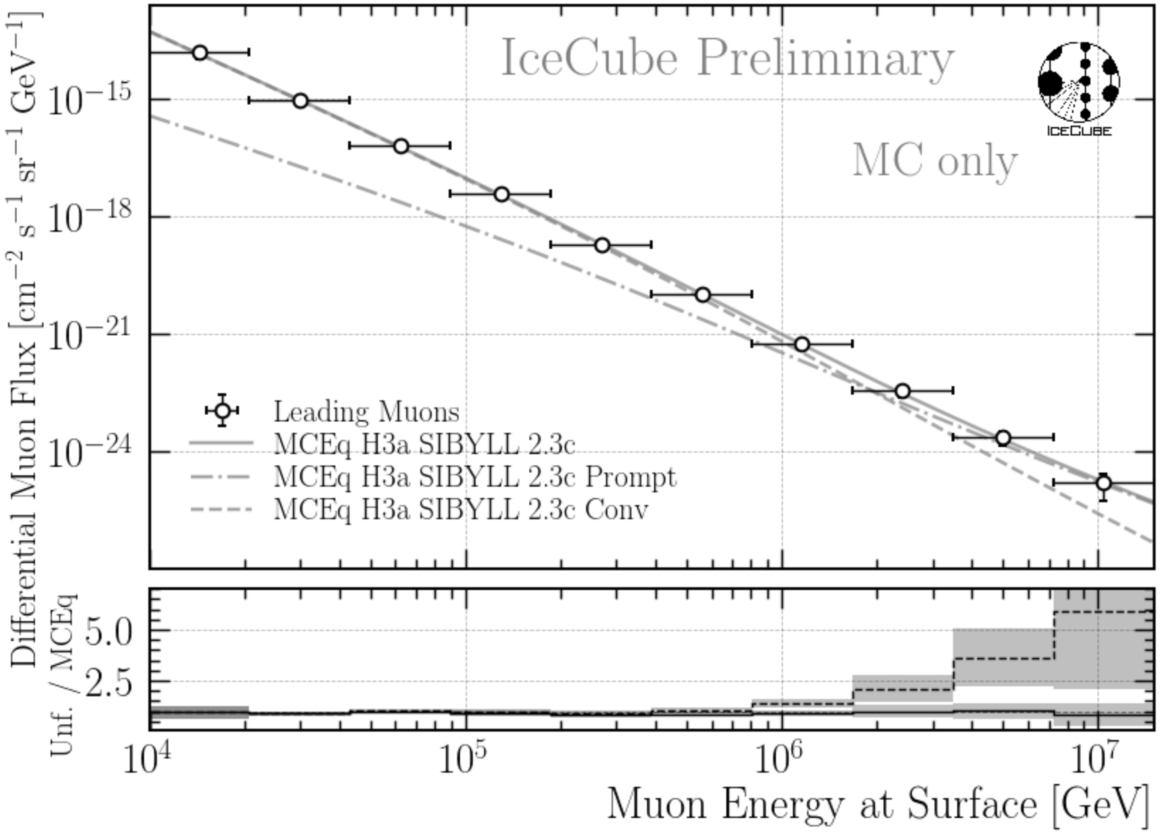
- Execute CORSIKA 7 (multi core)
- Read DAT files → pandas DataFrames
- Parse EHIST option
- Calculate primary weightings

https://github.com/The-Ludwig/PANAMA

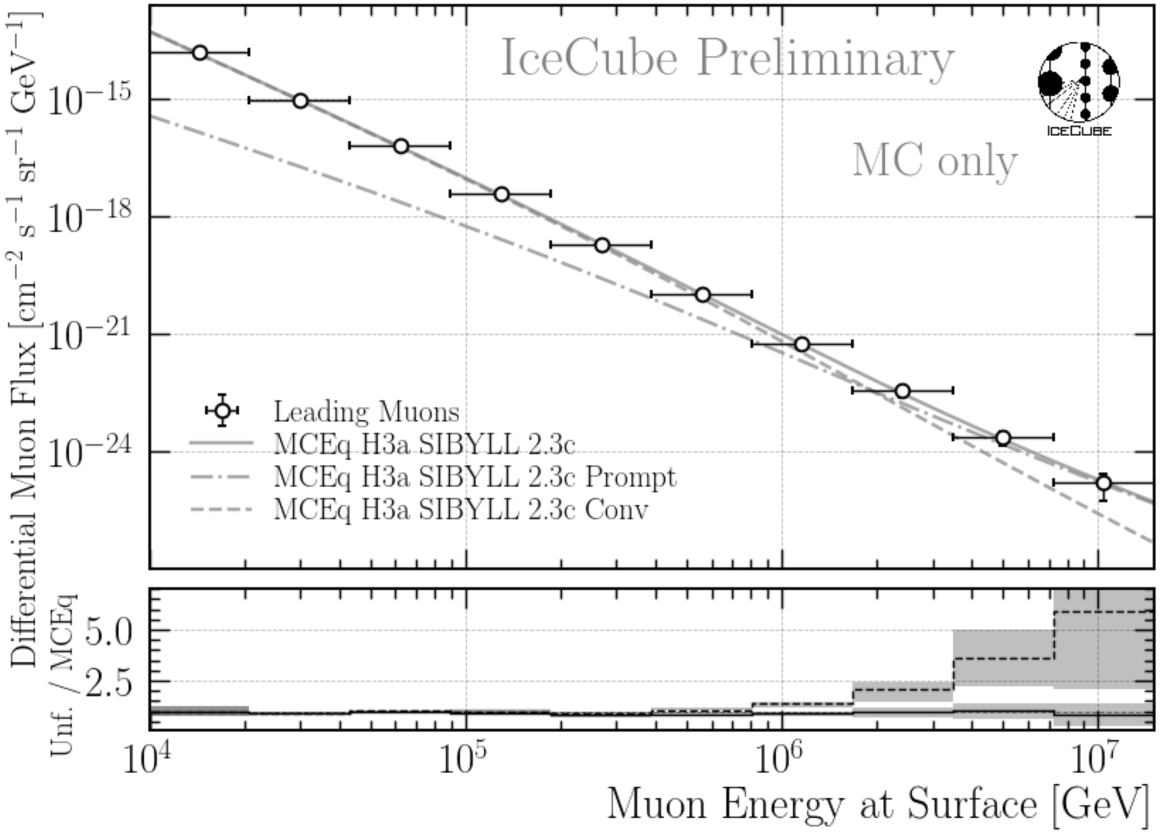
Neste & Gutjahr et al., EPJ C, 85, 759 (2025)

12 Years Prediction

symmetric errors



asymmetric errors



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

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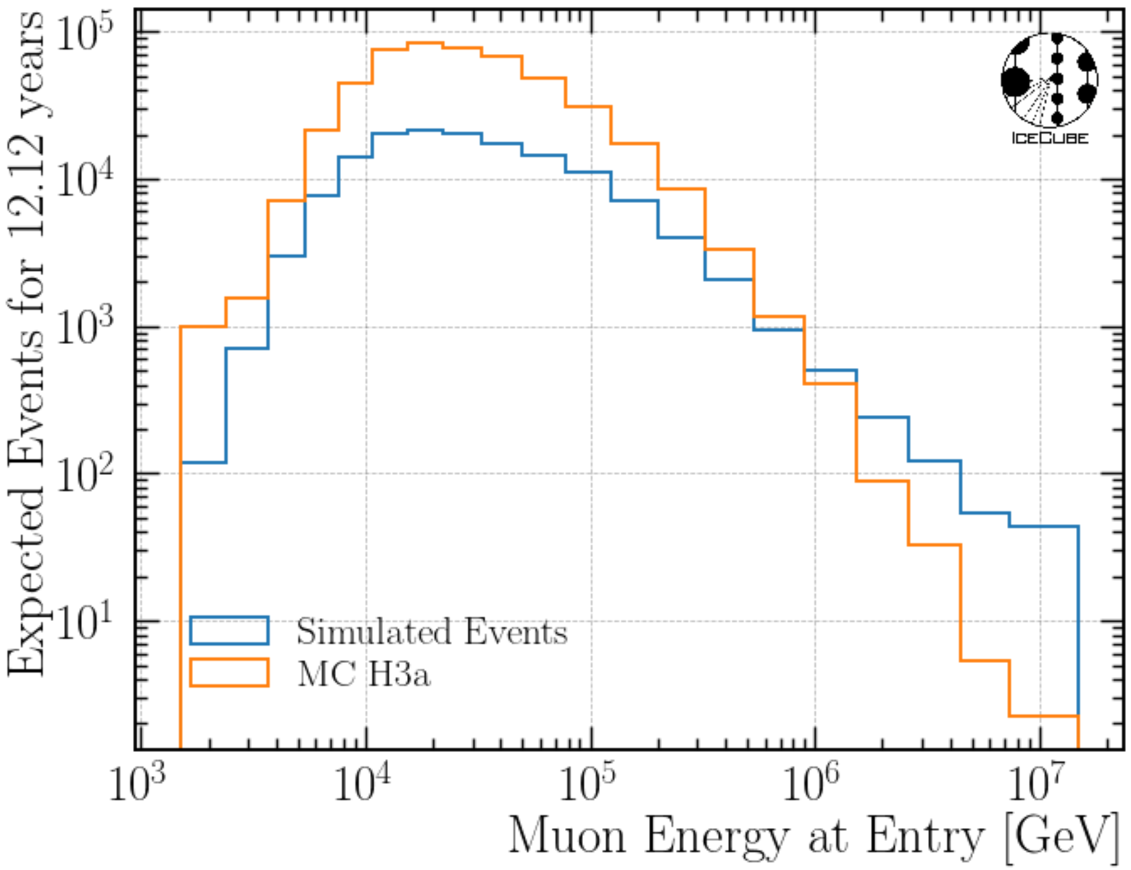
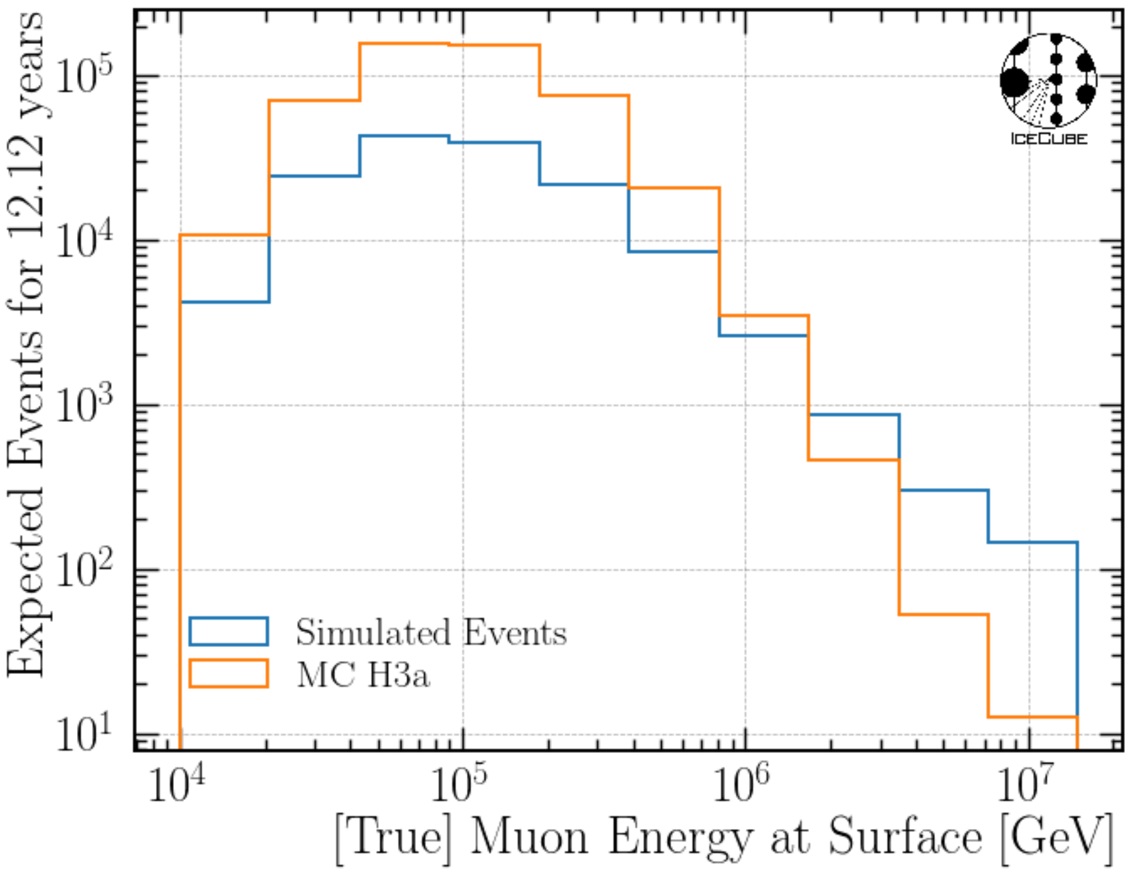
ICECUBE NEUTRINO OBSERVATORY

MC Statistics on Final Level





Input data per DOM

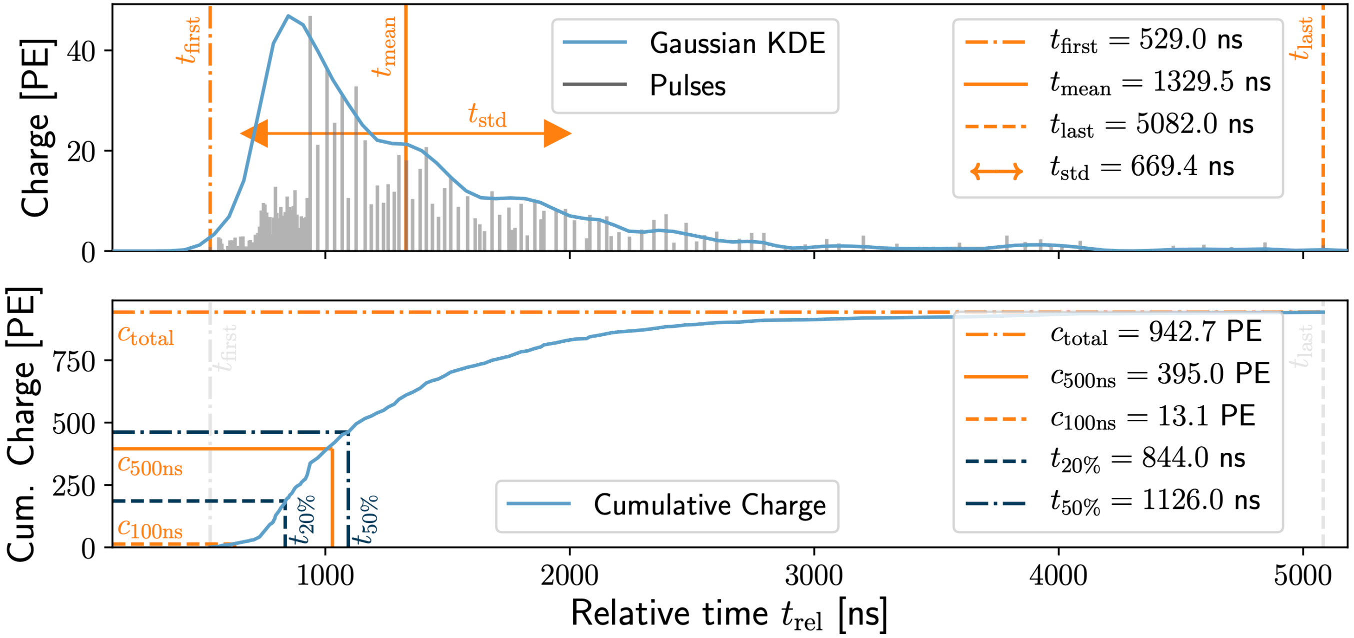
10.1088/1748-0221/16/07/P07041

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

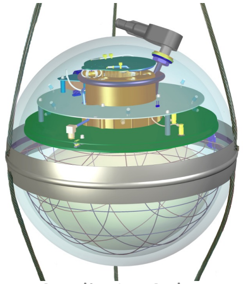


Input pulse cleaning

- 6000 ns

Training data

- Different simulations for robustness



Credit: IceCube

pascal.gutjahr@tu-dortmund.de

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

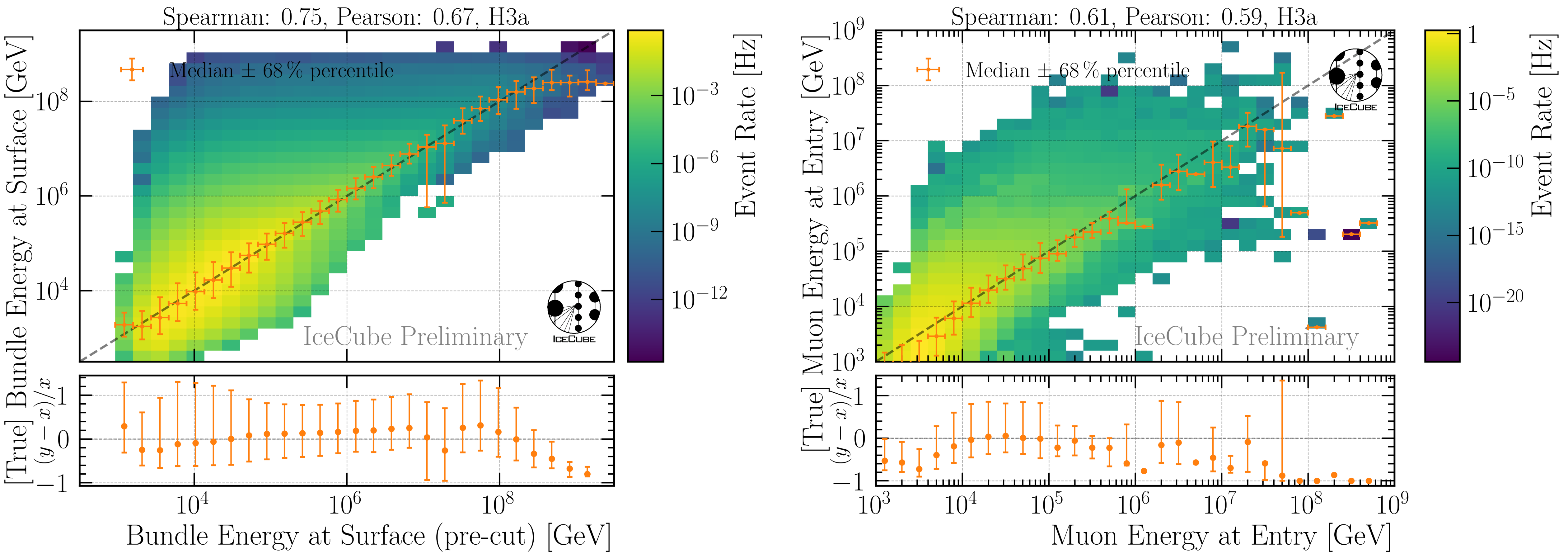
Network 2

Direction

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

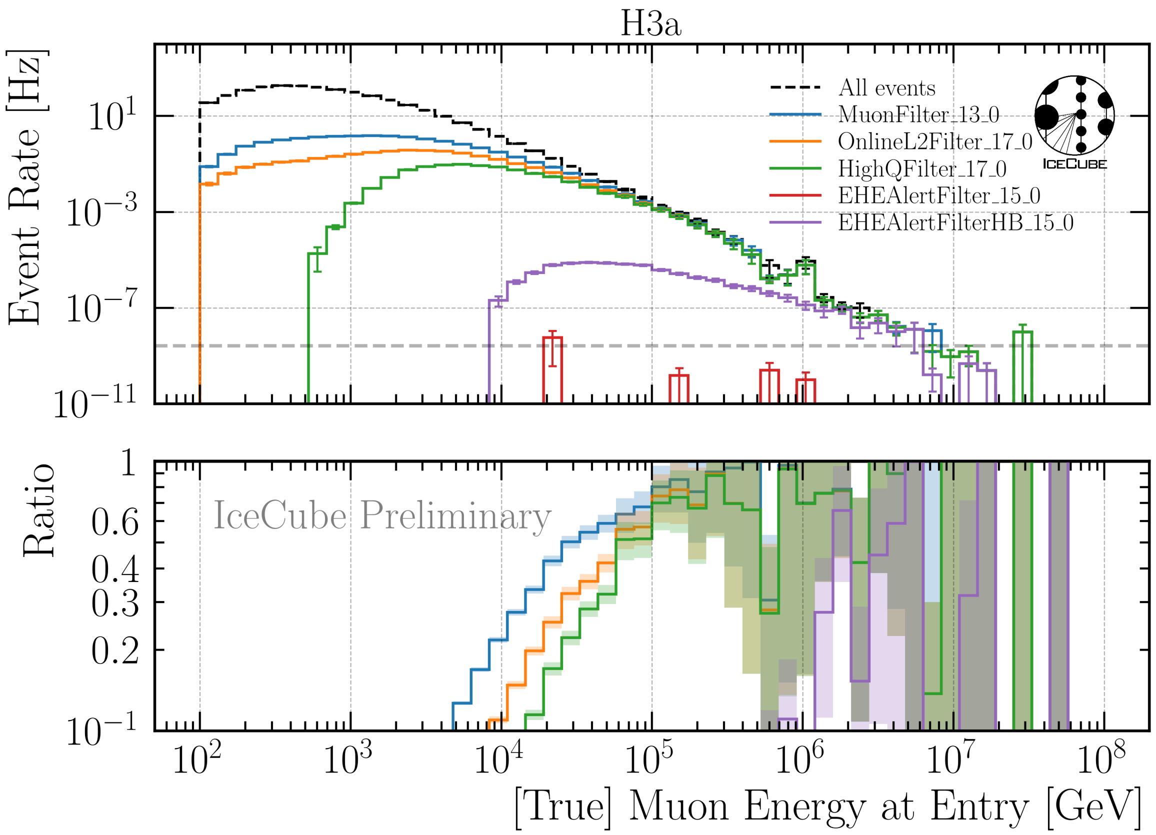
Network 3

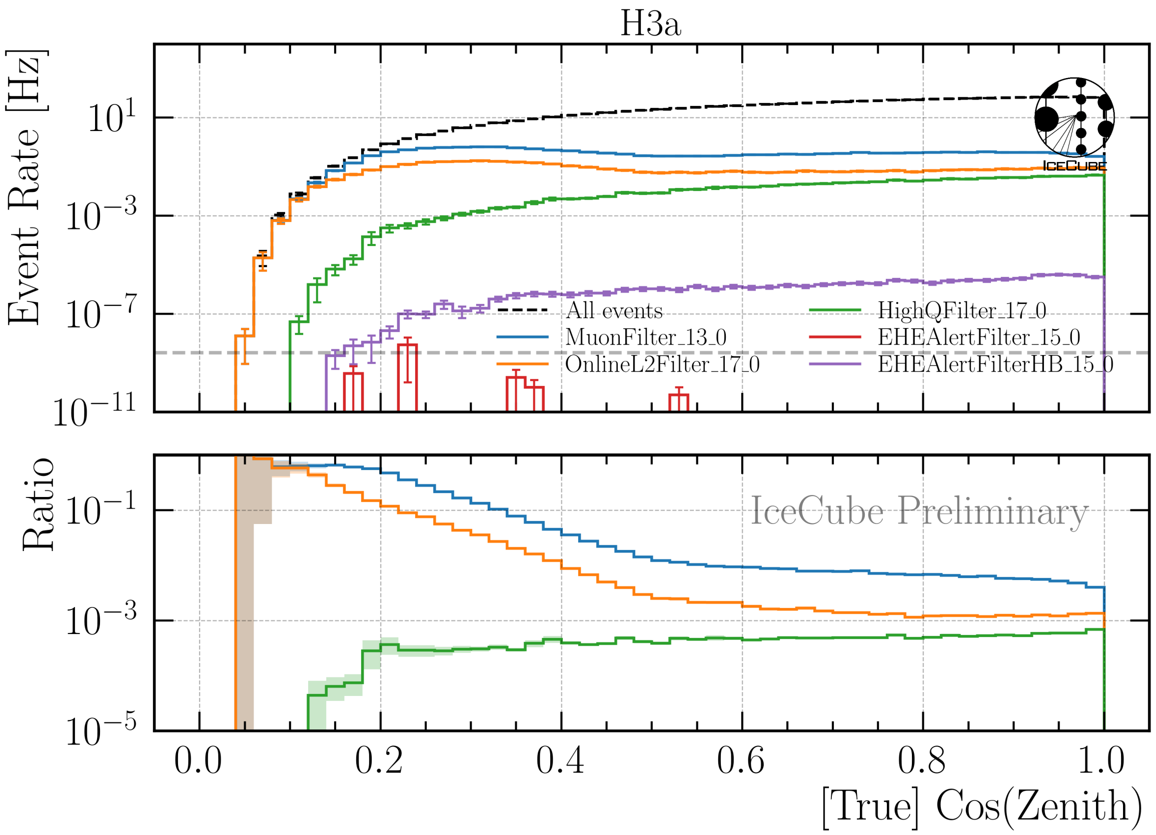
Energy Reconstructions



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

Level 3: Muon Filter

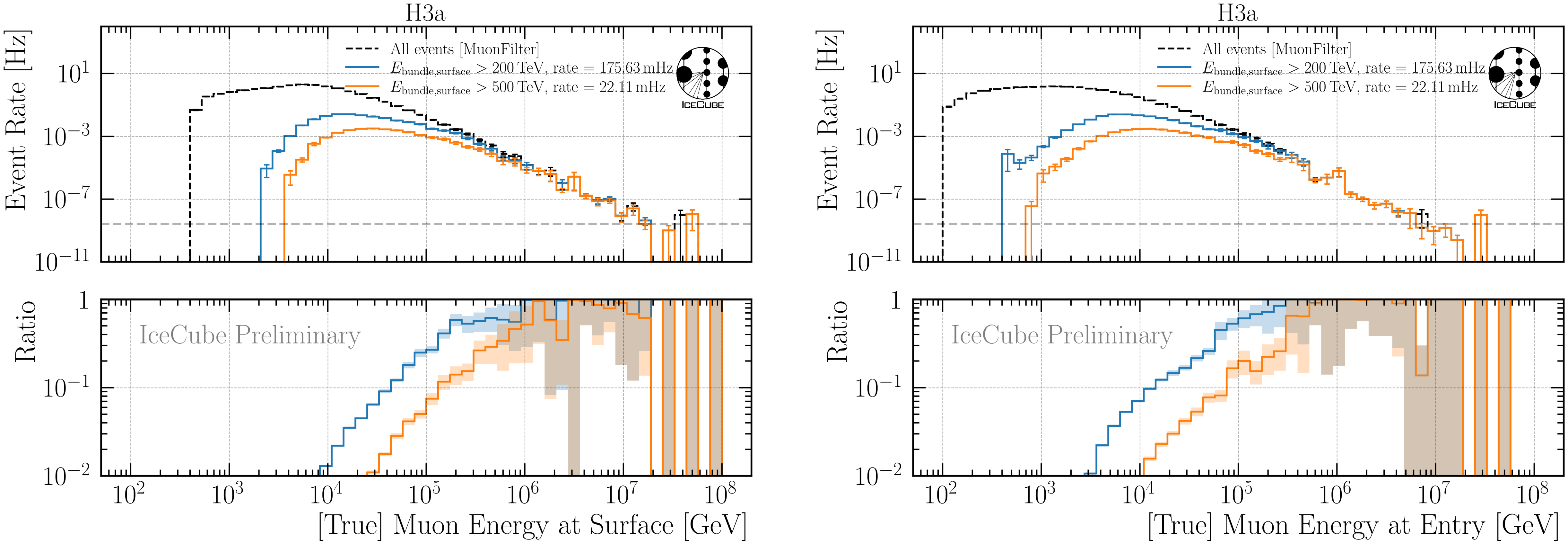




Muon filter: zenith-dependent charge and quality cut

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

Level 4: Energy Cut

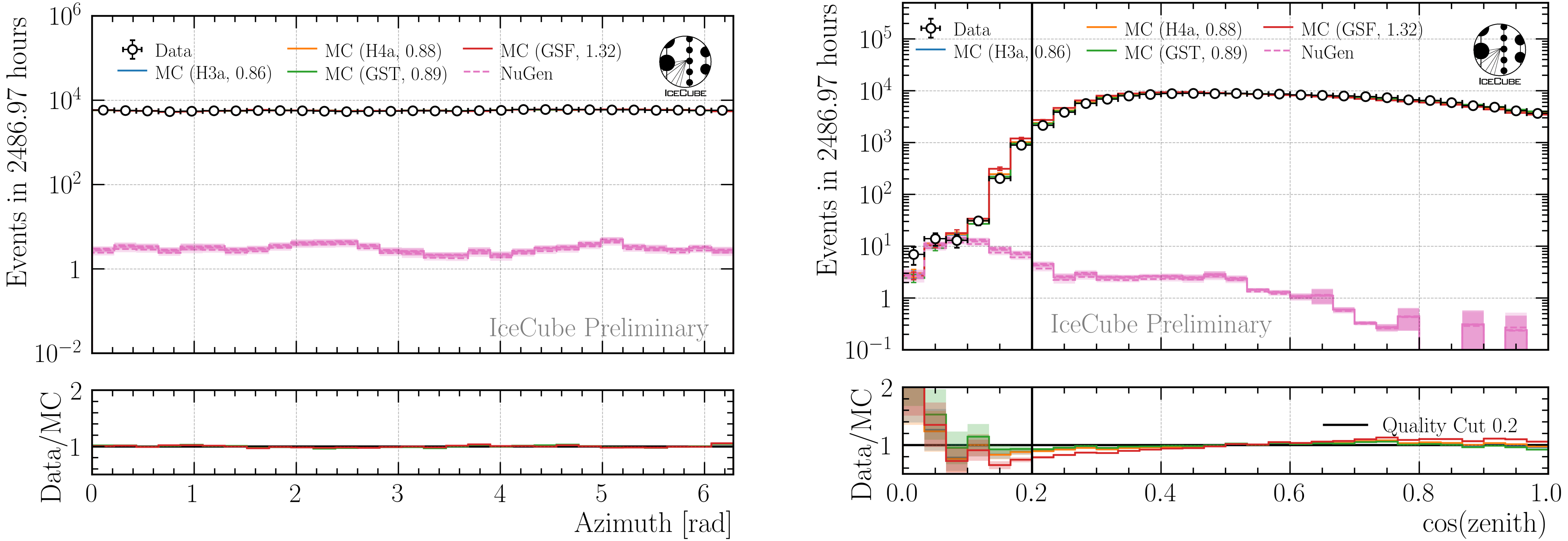


- 6 billion events expected in 10 years → computationally not feasible
- focus on high-energetic events
- Remove low-energy muons: bundle energy at surface > 500 TeV

Level 5: Data/MC Quality Cuts

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

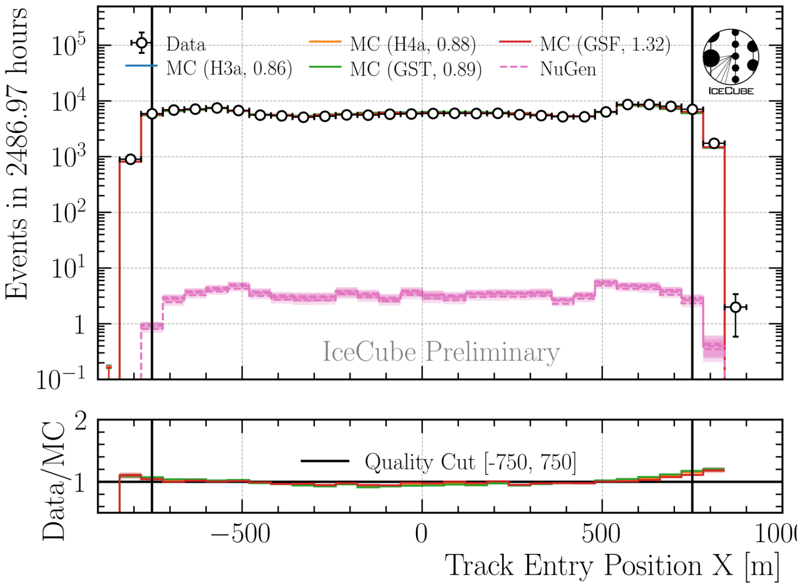
IceCube Collaboration PoS ICRC2023 1064

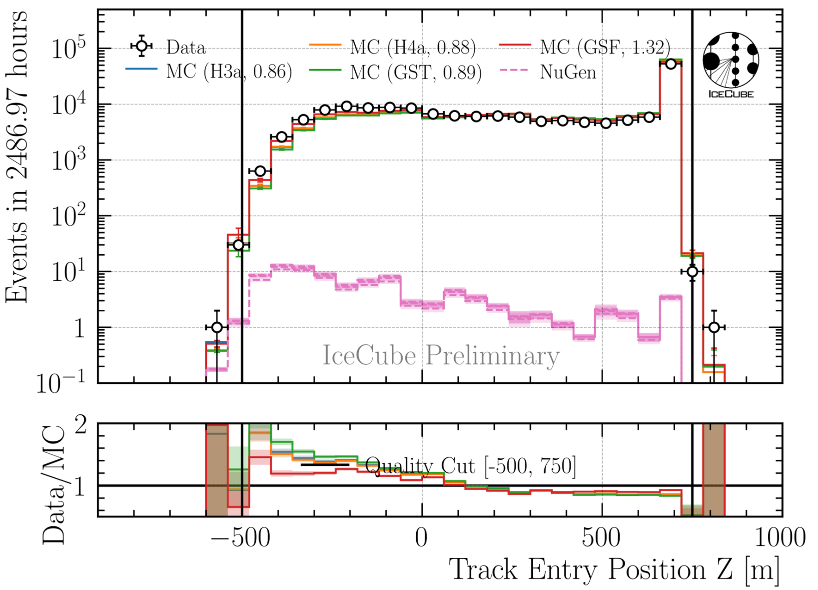


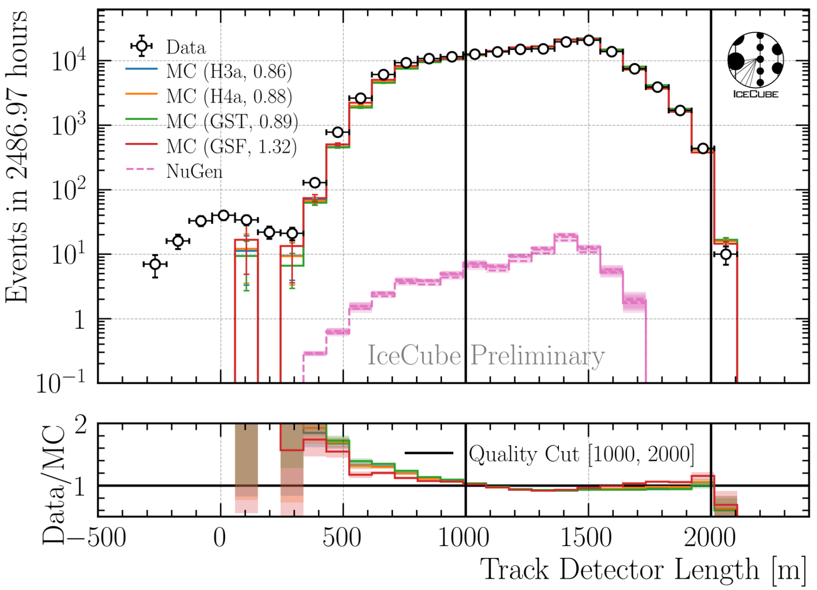
- Good directional reconstruction
- Cut: cos(zenith) > 0.2

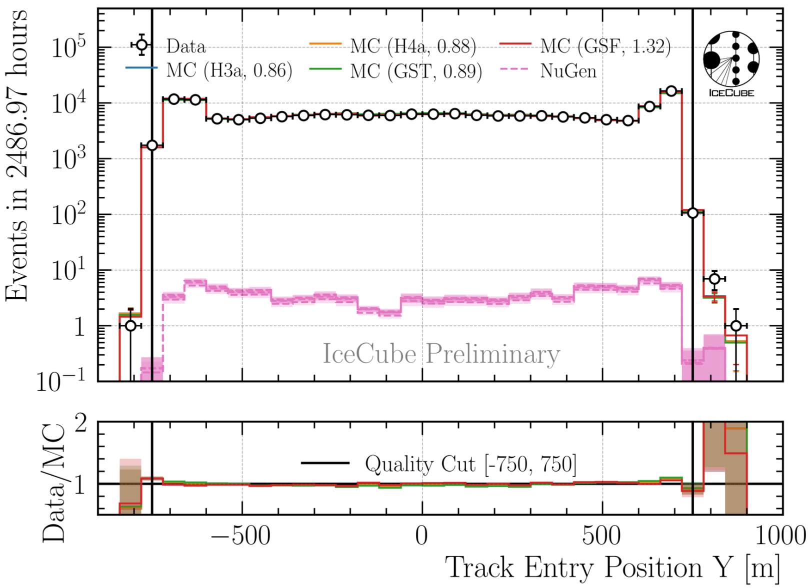
Level 5: Data/MC Quality Cuts

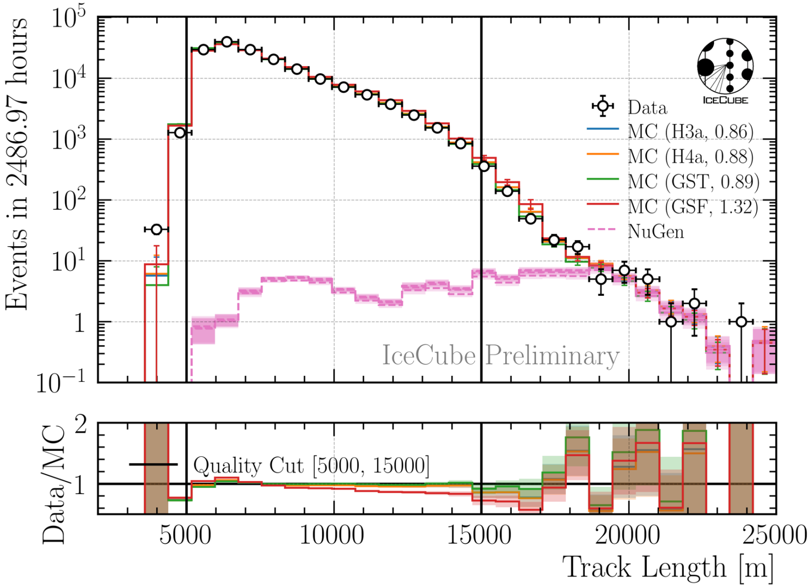
- Remove outliers
- Depth—dependent slope (no analysis relevance)
- CR—model impact on energy reconstruction
- 23 quality cuts in total

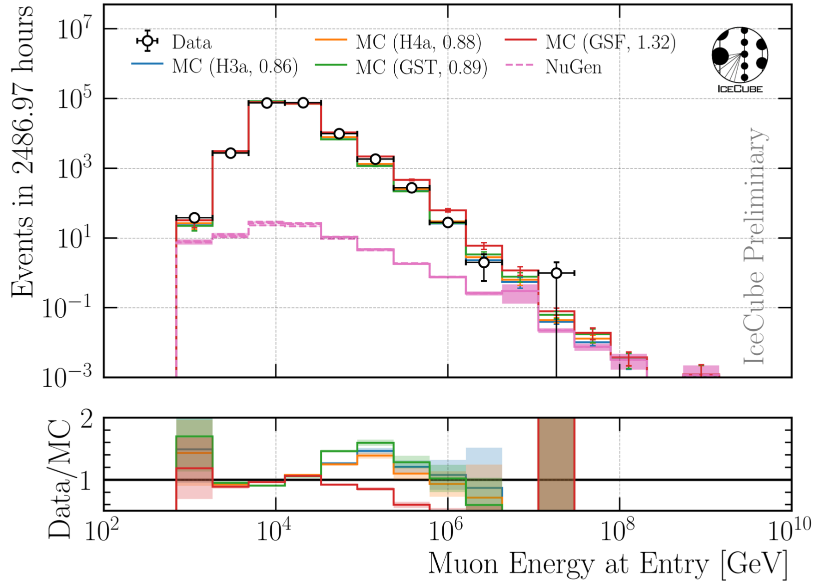








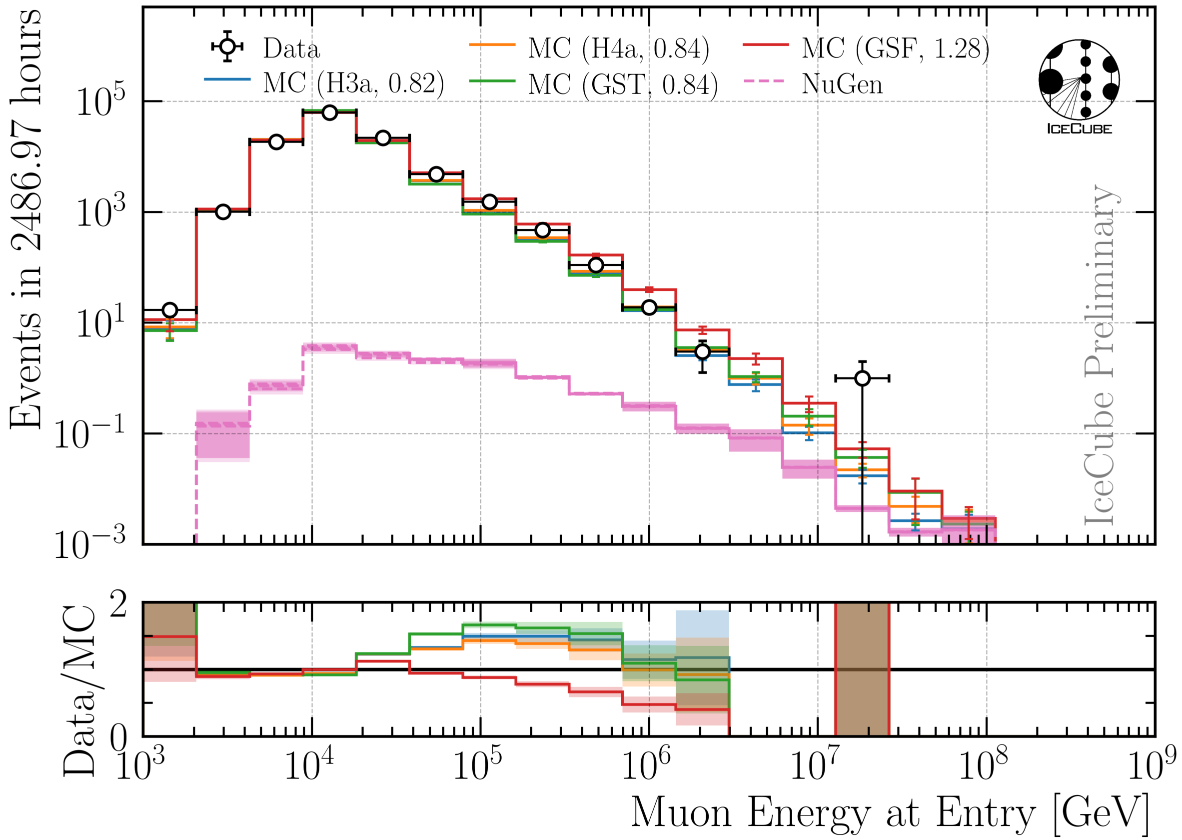




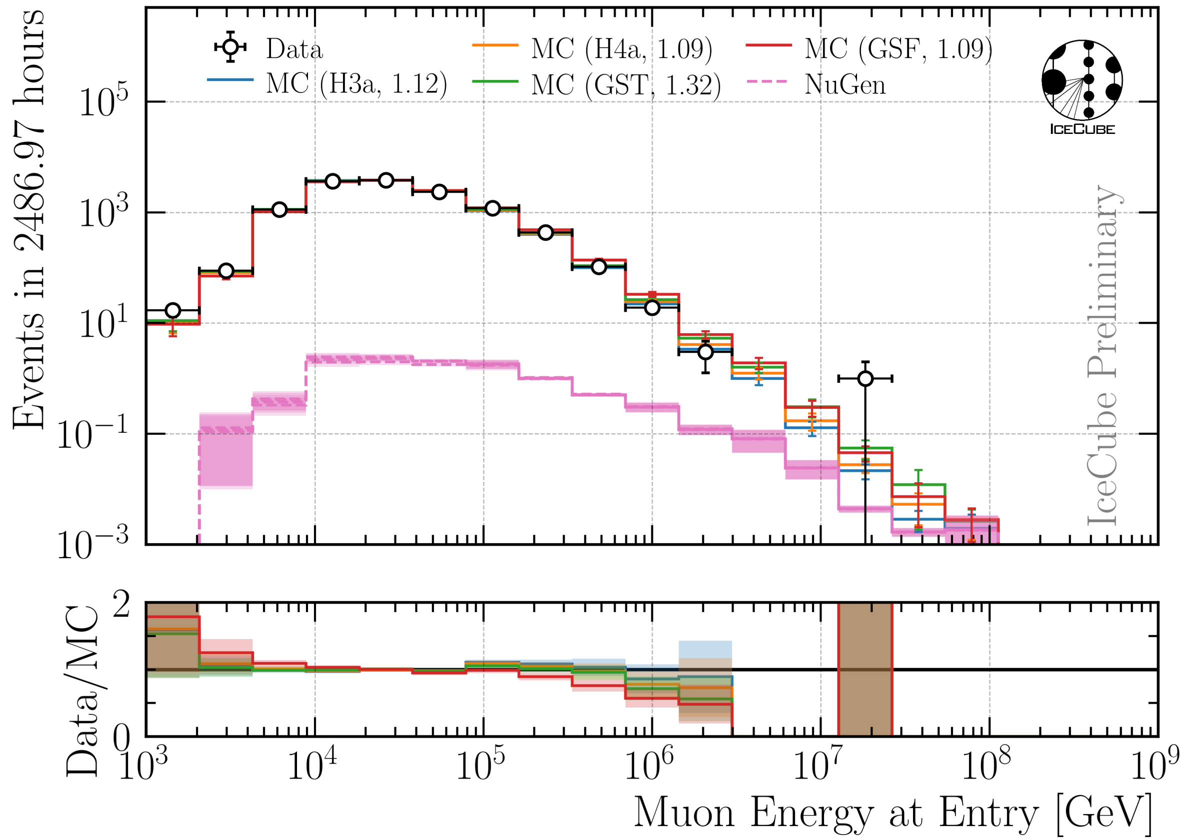
Final Level: Leadingness > 40 %

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

No leadingness cut



Leadingness > 40 %



➢ Improve Data/MC by leadingness cut

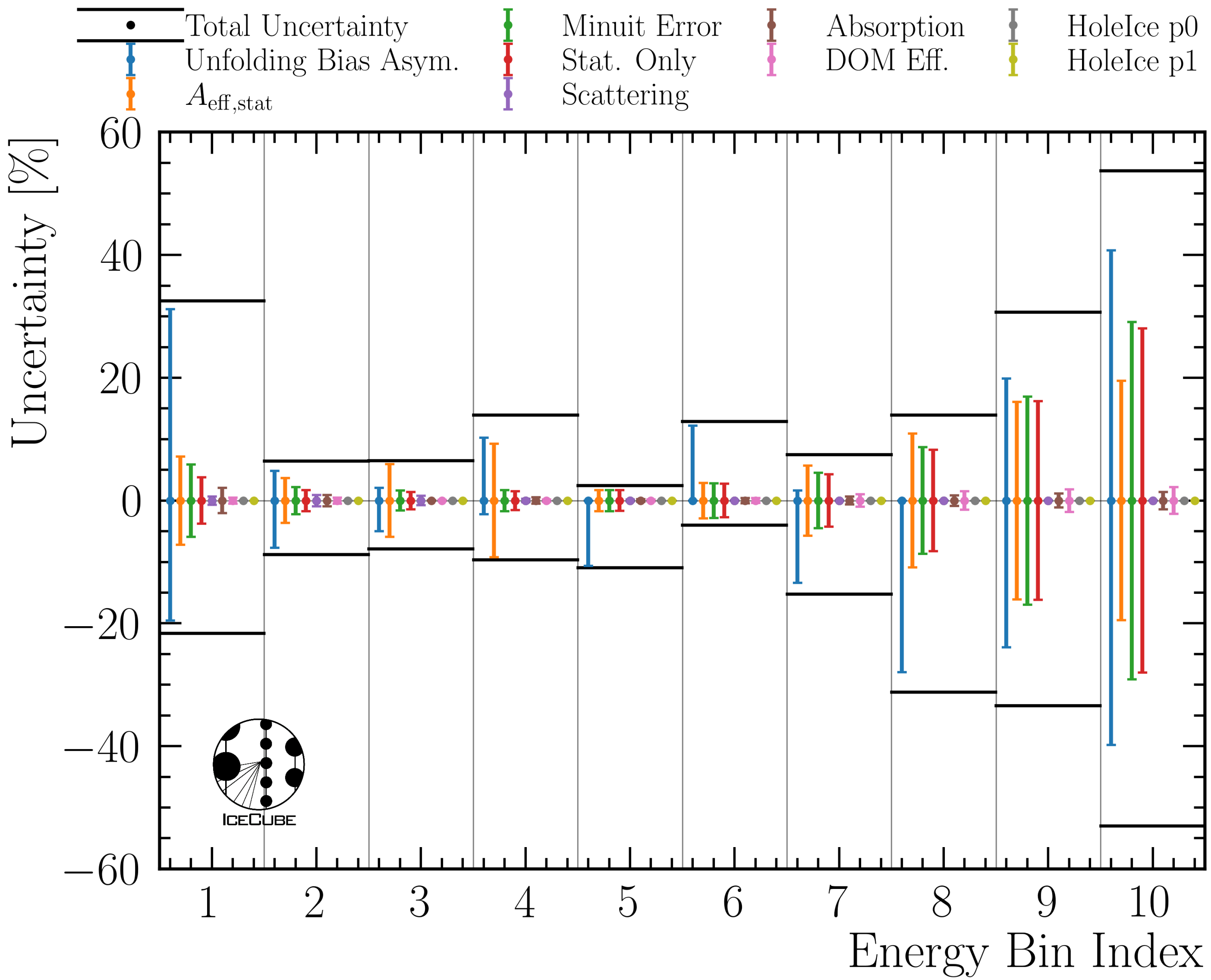
Level5: quality cuts

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

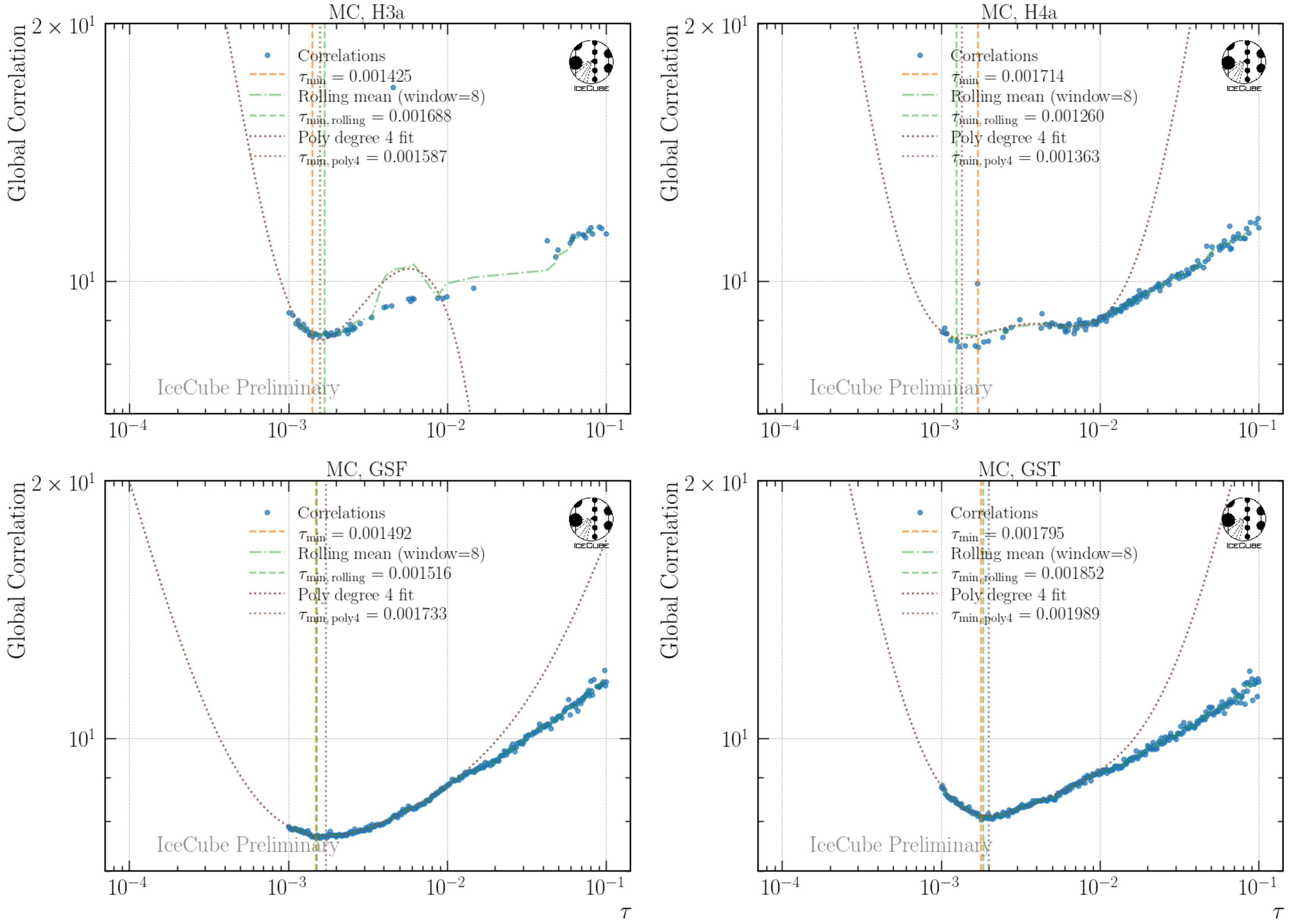
uncertainty cuts	<
bundle energy at entry	0.9 log10(GeV)
bundle energy at surface	2.0 log10(GeV)
zenith	0.1 rad
azimuth	0.2 rad
entry pos x , y, z	42 m
center pos x, y, z	50 m
entry pos time	200 ns
center pos time	600 ns
length in detector	160 m
length	2000 m

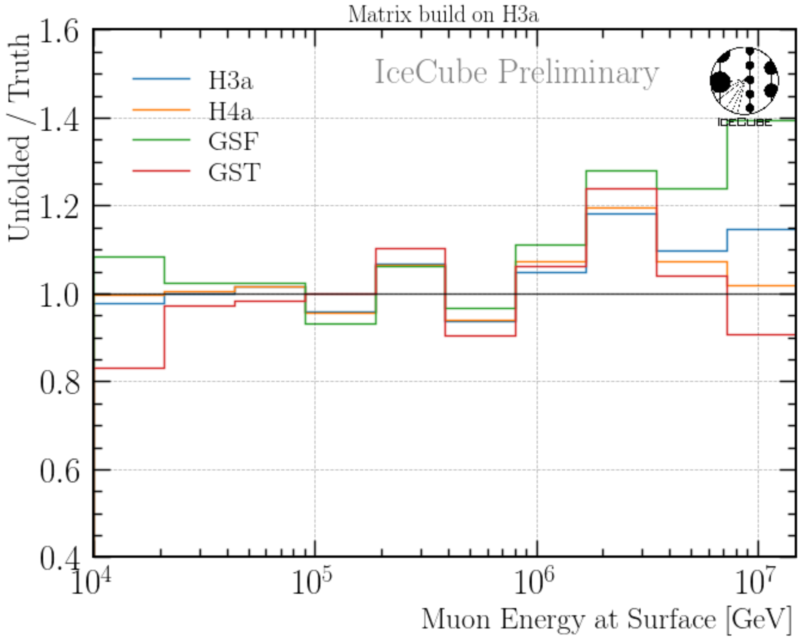
Uncertainties per Bin



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

H3a Unfolding Bias





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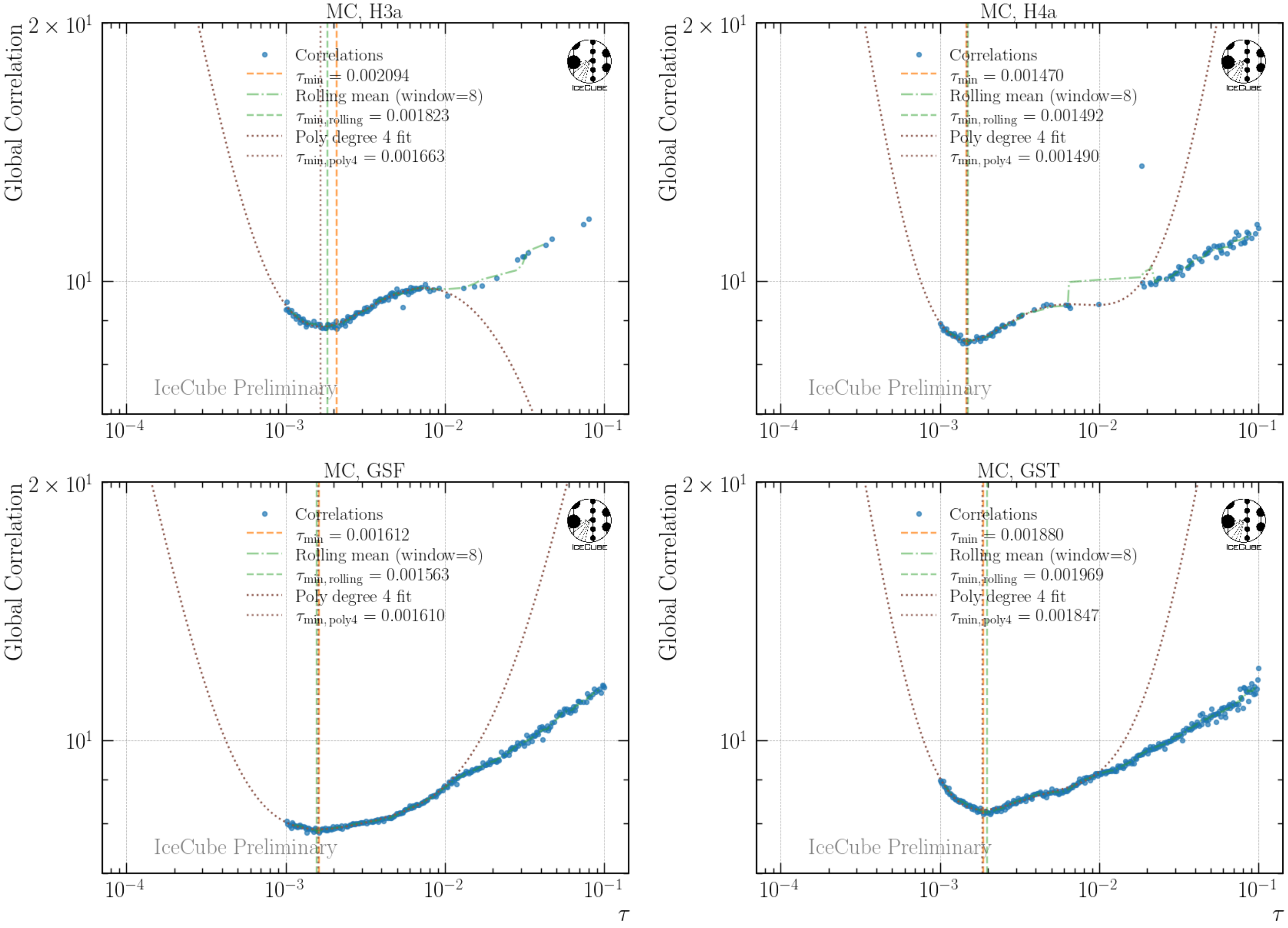
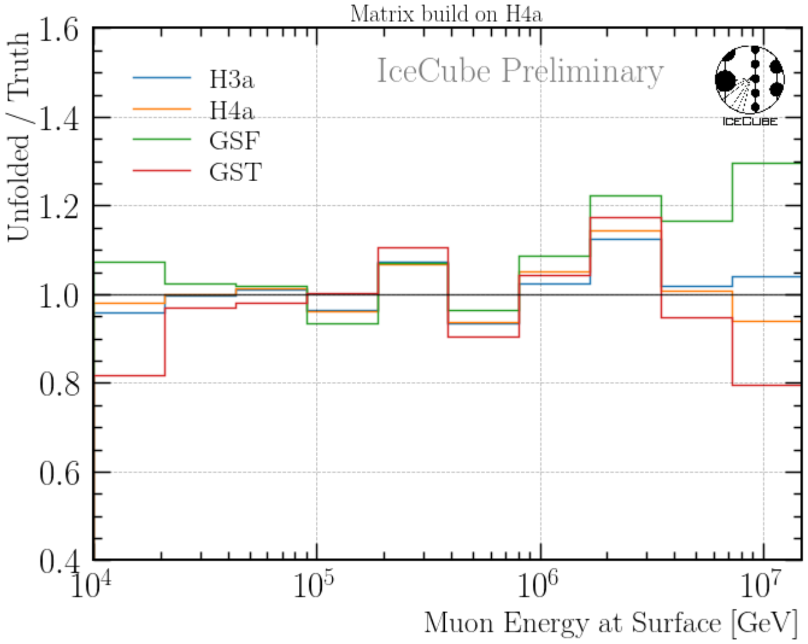
H4a Unfolding Bias

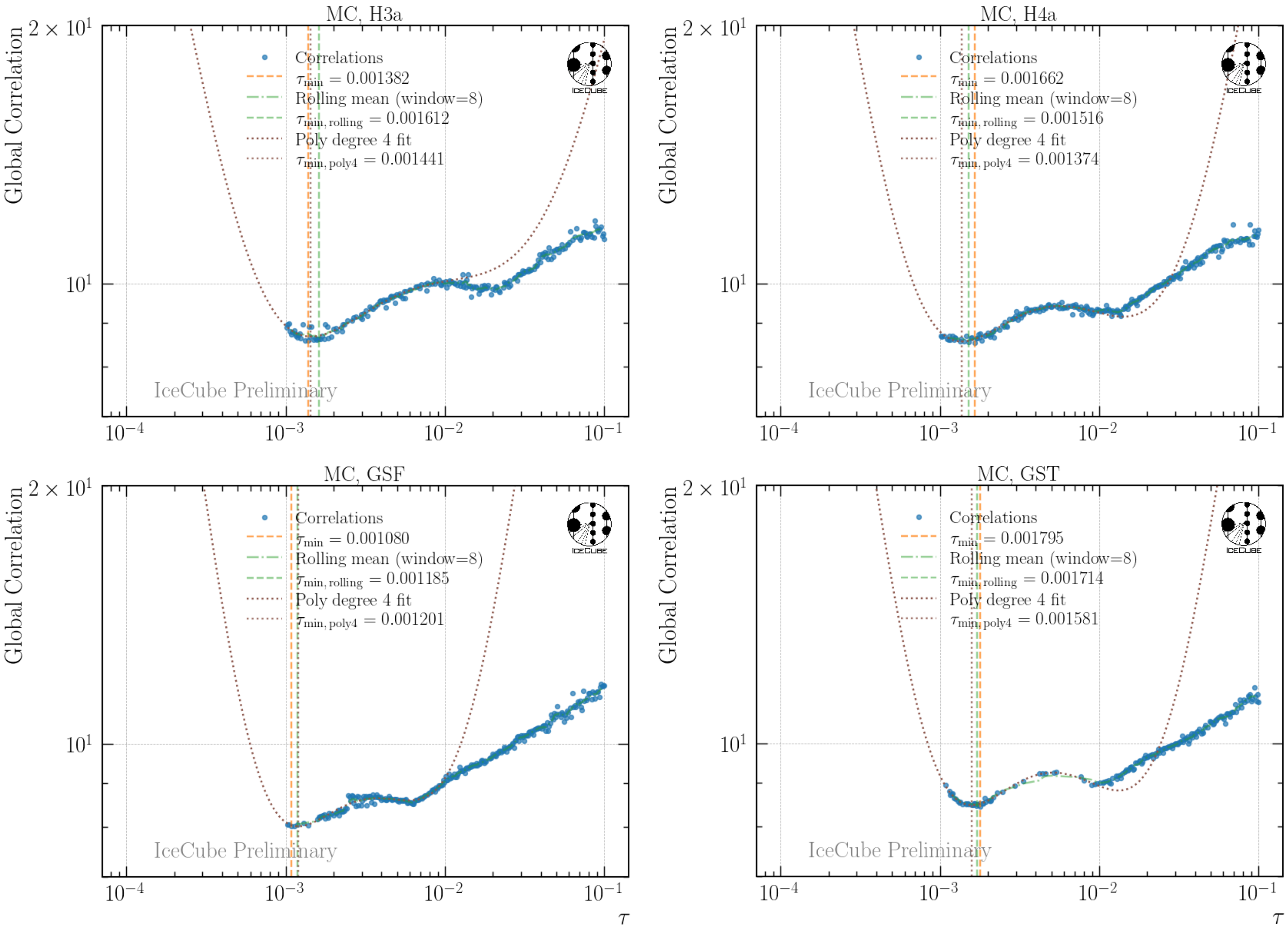
- Fit $\tau \in 10^{-3} - 10^{-2}$

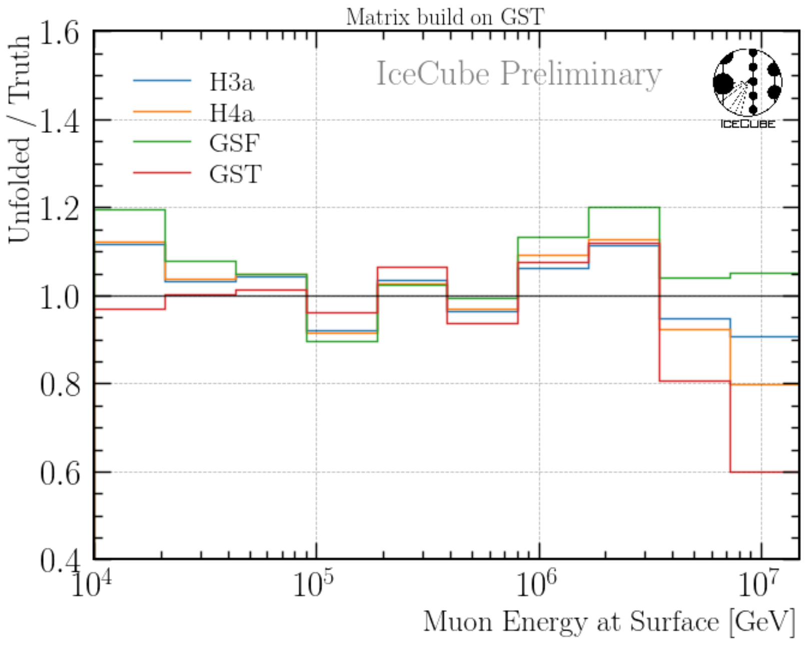




Fit $\tau \in 10^{-3} - 10^{-2}$

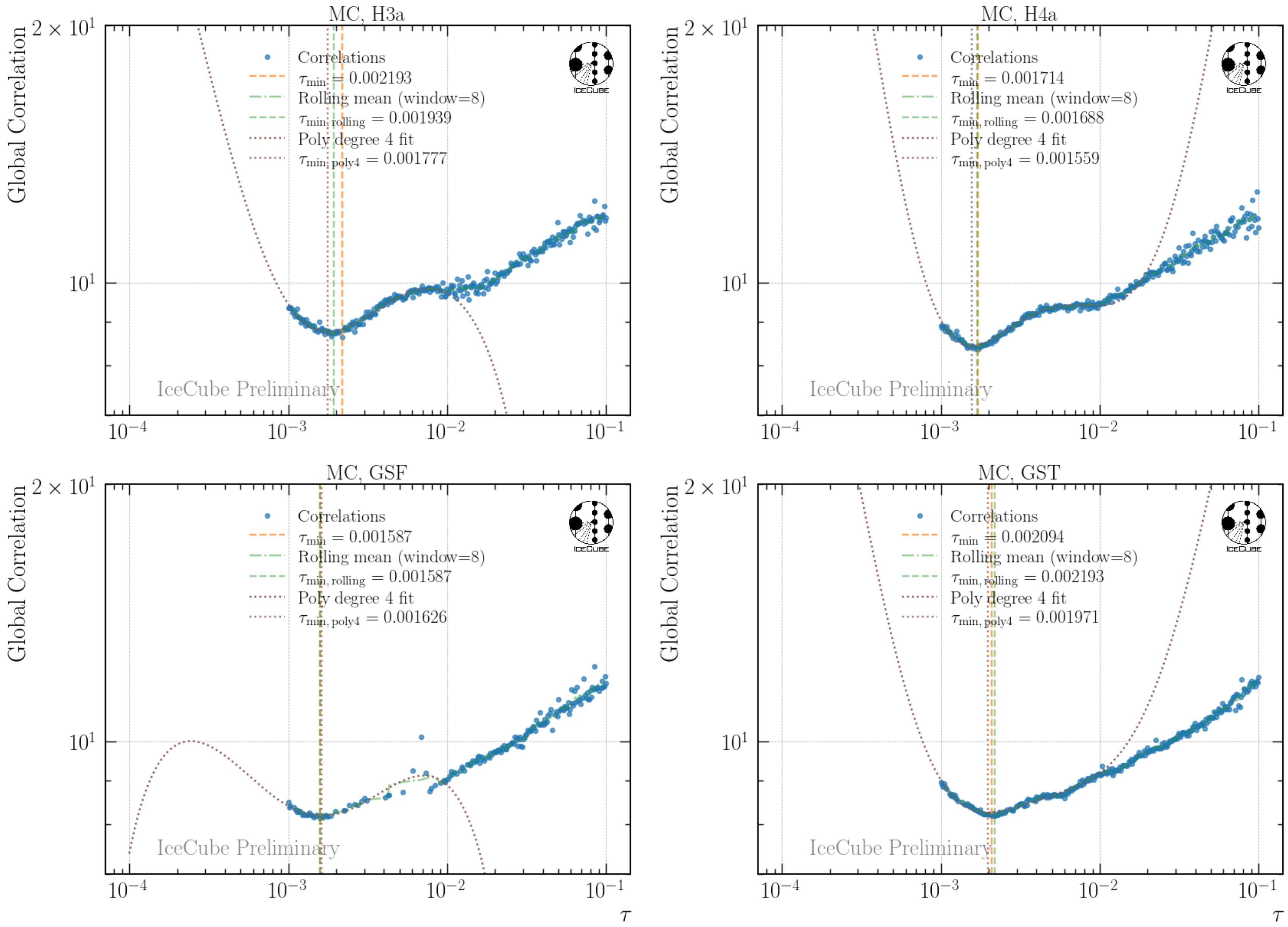
GST Unfolding Bias

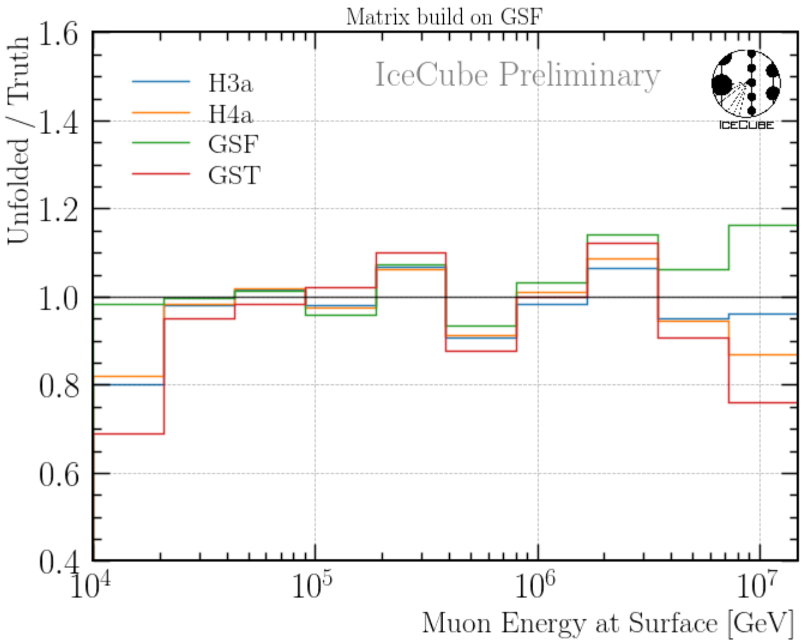




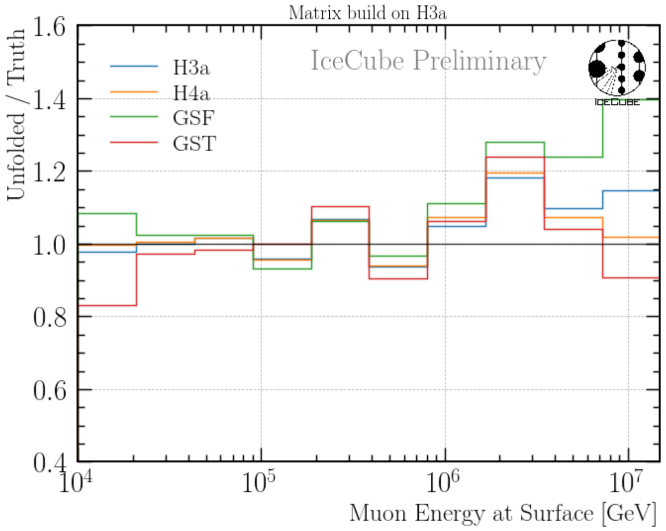
GSF Unfolding Bias

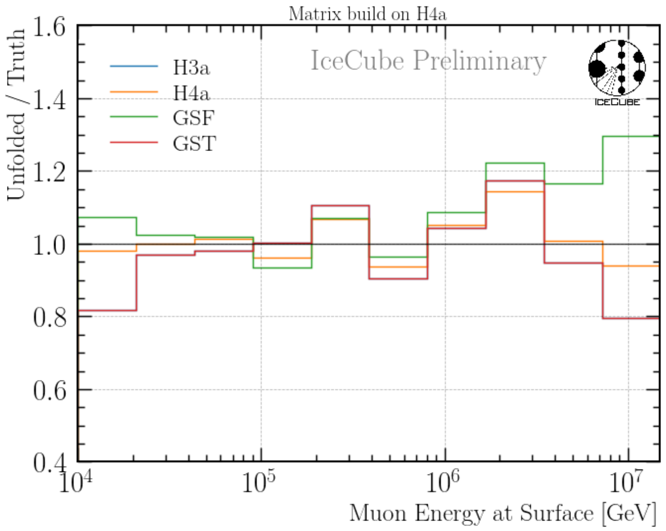
- Fit $\tau \in 10^{-3} - 10^{-2}$

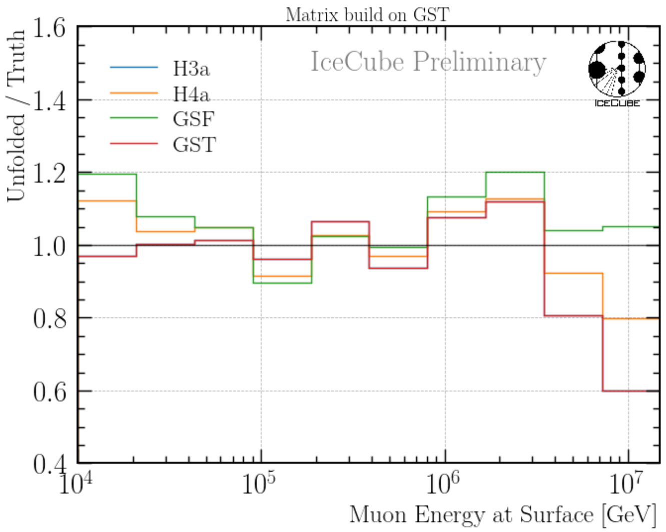


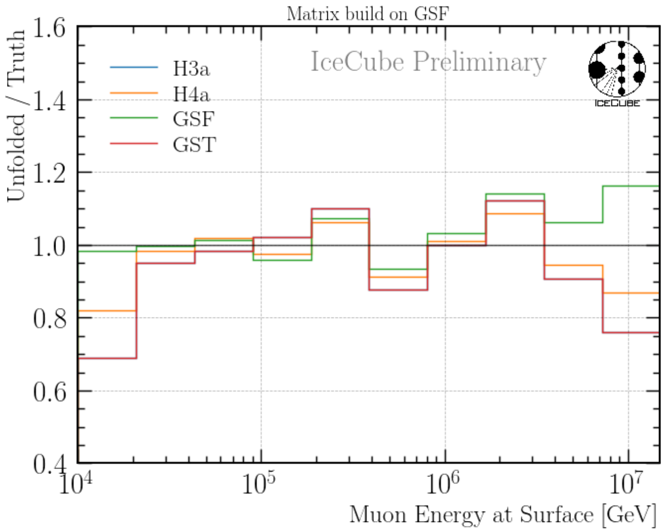


Unfolding Bias for All Models

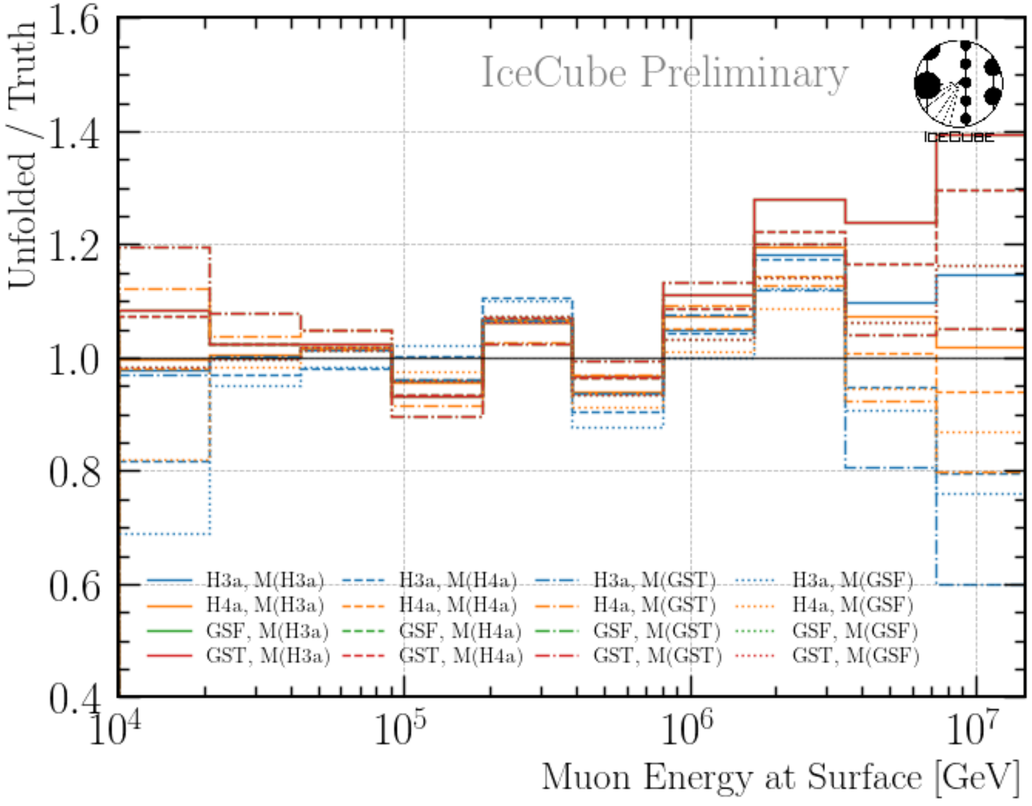








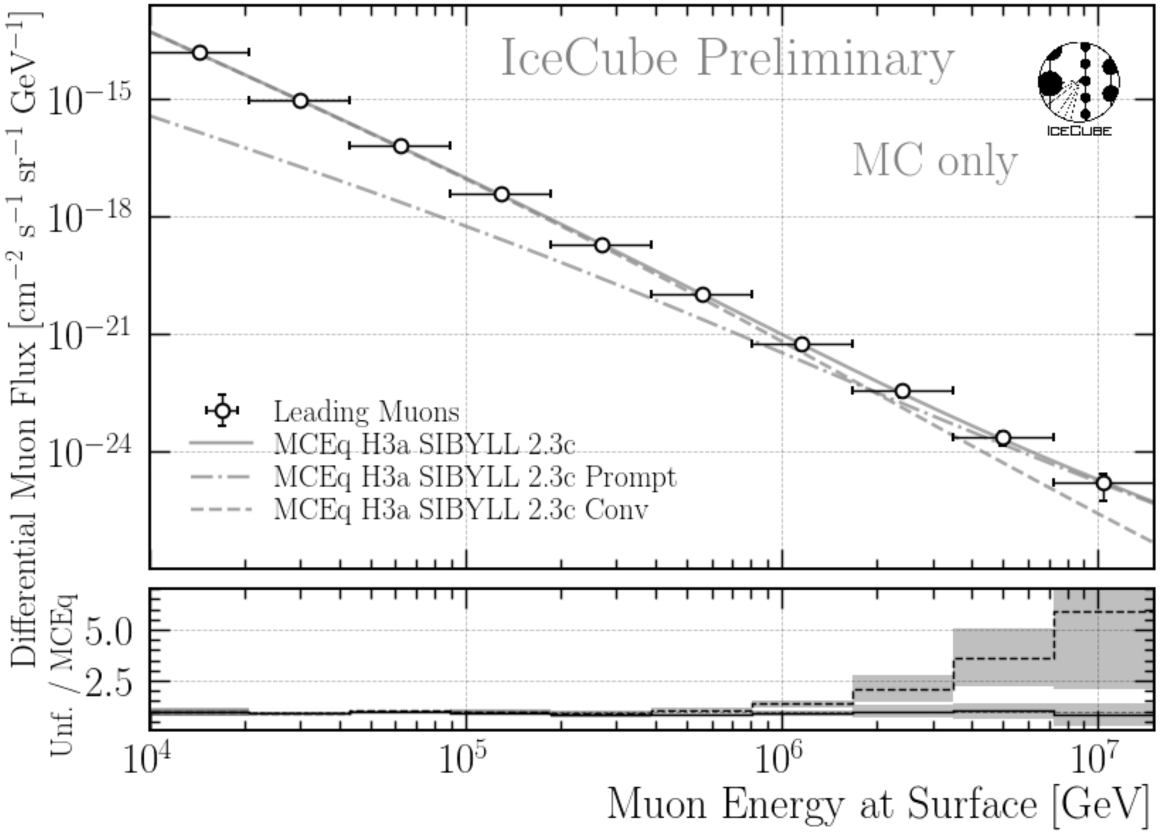
Summary



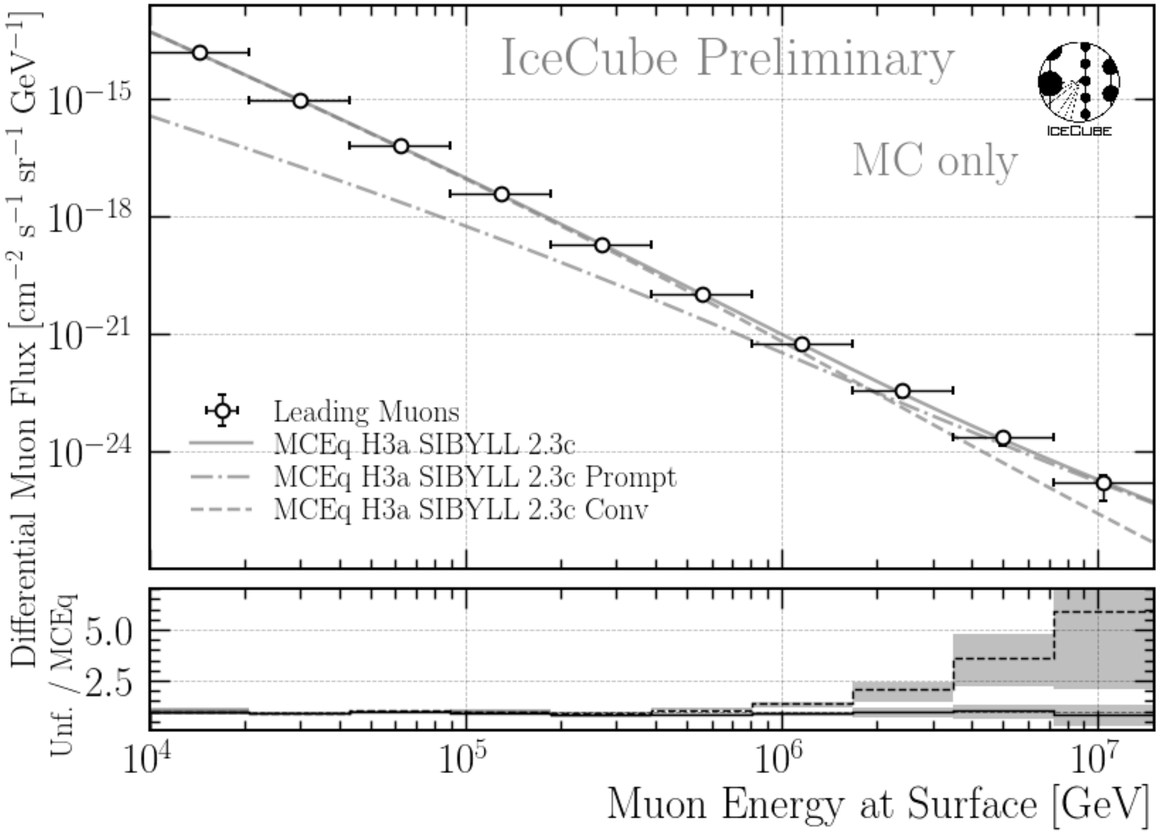
- Add these biases as an uncertainty to the unfolding result

12 Years Prediction

symmetric errors



asymmetric errors

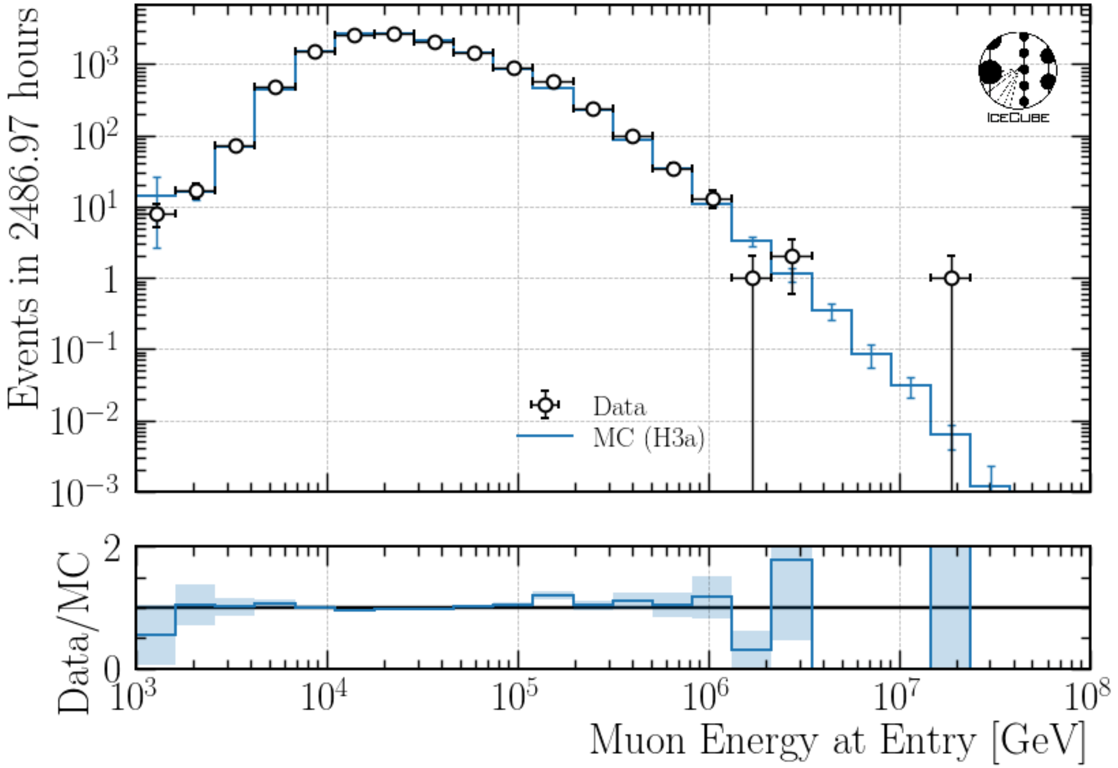


$$\sigma_{\text{tot}} = \sqrt{\sigma^2_{\text{minuit}} + \sigma^2_{\text{unf-bias}} + \sigma^2_{A_{\text{eff}},\text{stat}}}$$

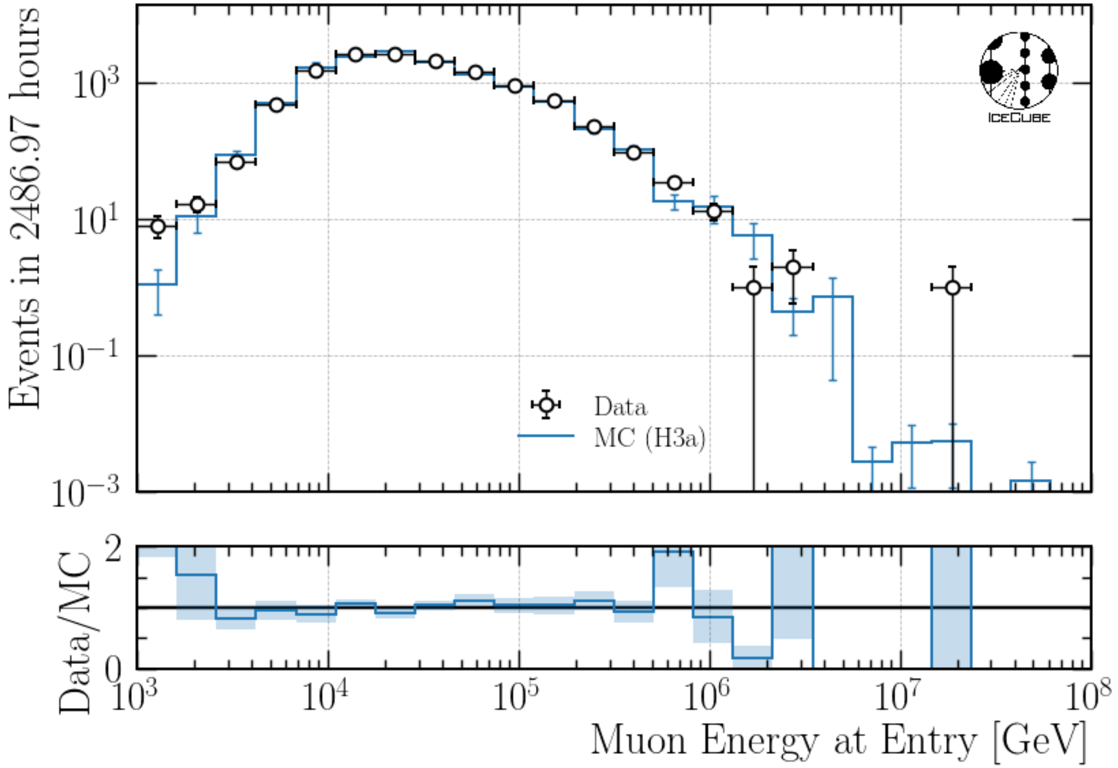
Data—MC Pre/Post Fit

Data-MC: Burnsample

Pre Fit



Post Fit



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

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	

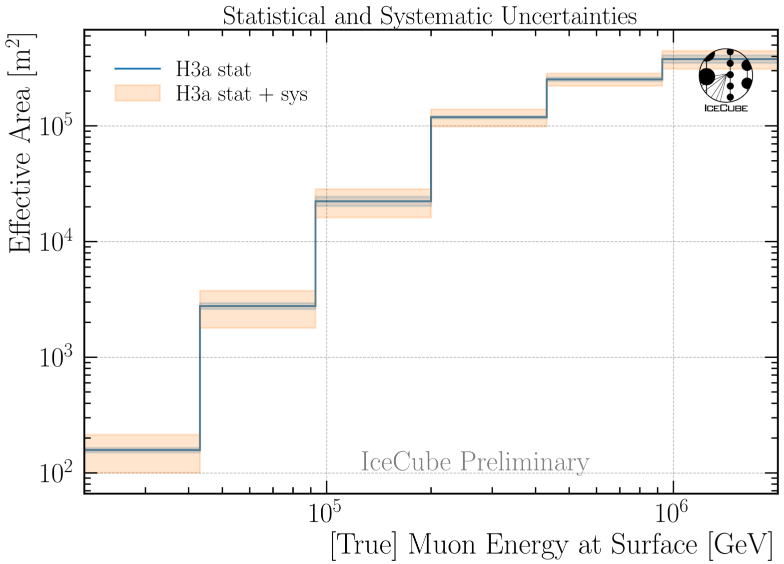
	x0	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13	x14	x15	x16
x0	1.74e+05	-0.21e6 (-0.725)	0.24e6 (0.321)	0.16e6 (0.126)	-0.35e6 (-0.287)	-0.08e6 (-0.116)	0.05e6 (0.158)	0.02e6 (0.196)	3.3e3 (0.136)	0.52e3 (0.084)	180 (0.061)	-130 (-0.033)	1.6651 (0.201)	-737.090e-3 (-0.615)	1.199859 (0.630)	-0.00 (-0.000)	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

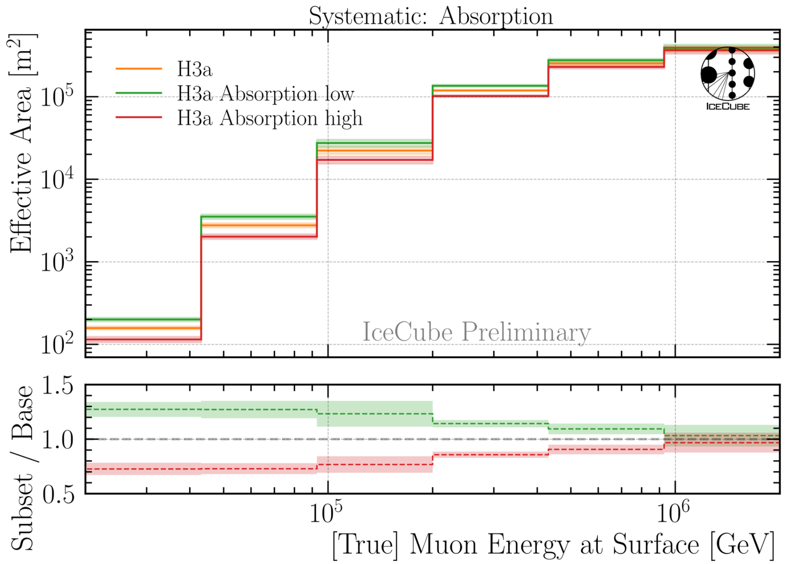
Muon Flux Unfolding

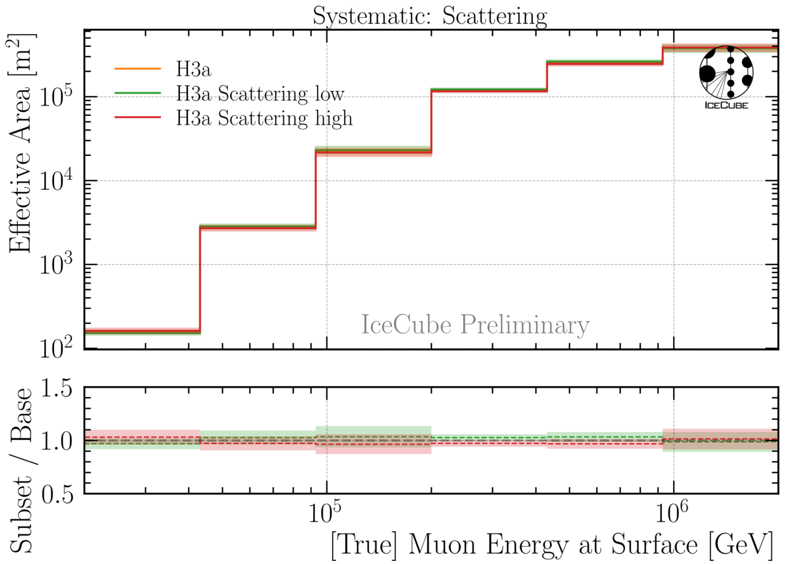
- ❑ Effective area
- ❑ Systematics
- ❑ Proxy that correlates with target
- ❑ Regularization
- ➢ Unfolding

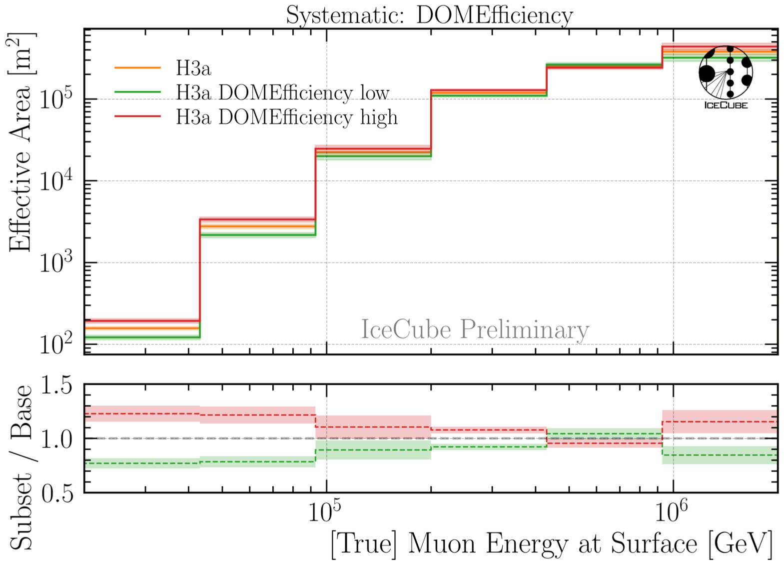
Ice & Detector Systematics

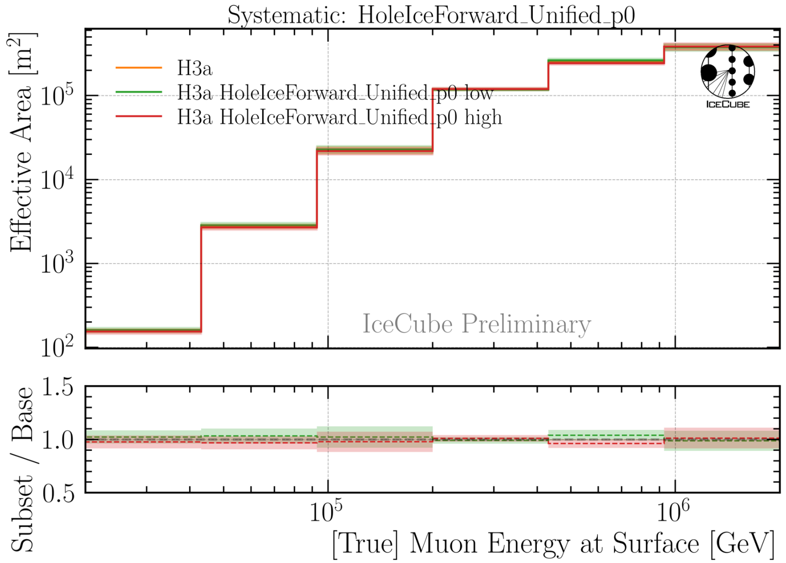
$$\sigma_{sys,i} = \max(A_{low}, A_{high}) - A_{base}$$

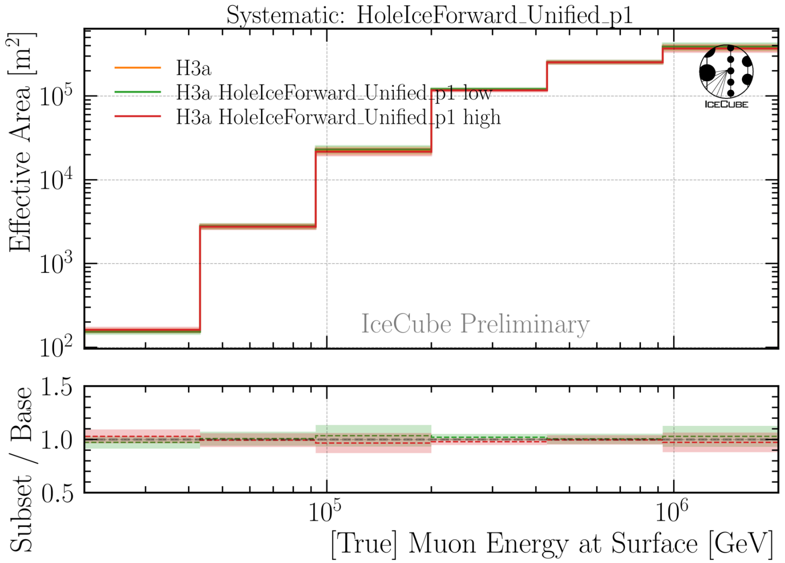










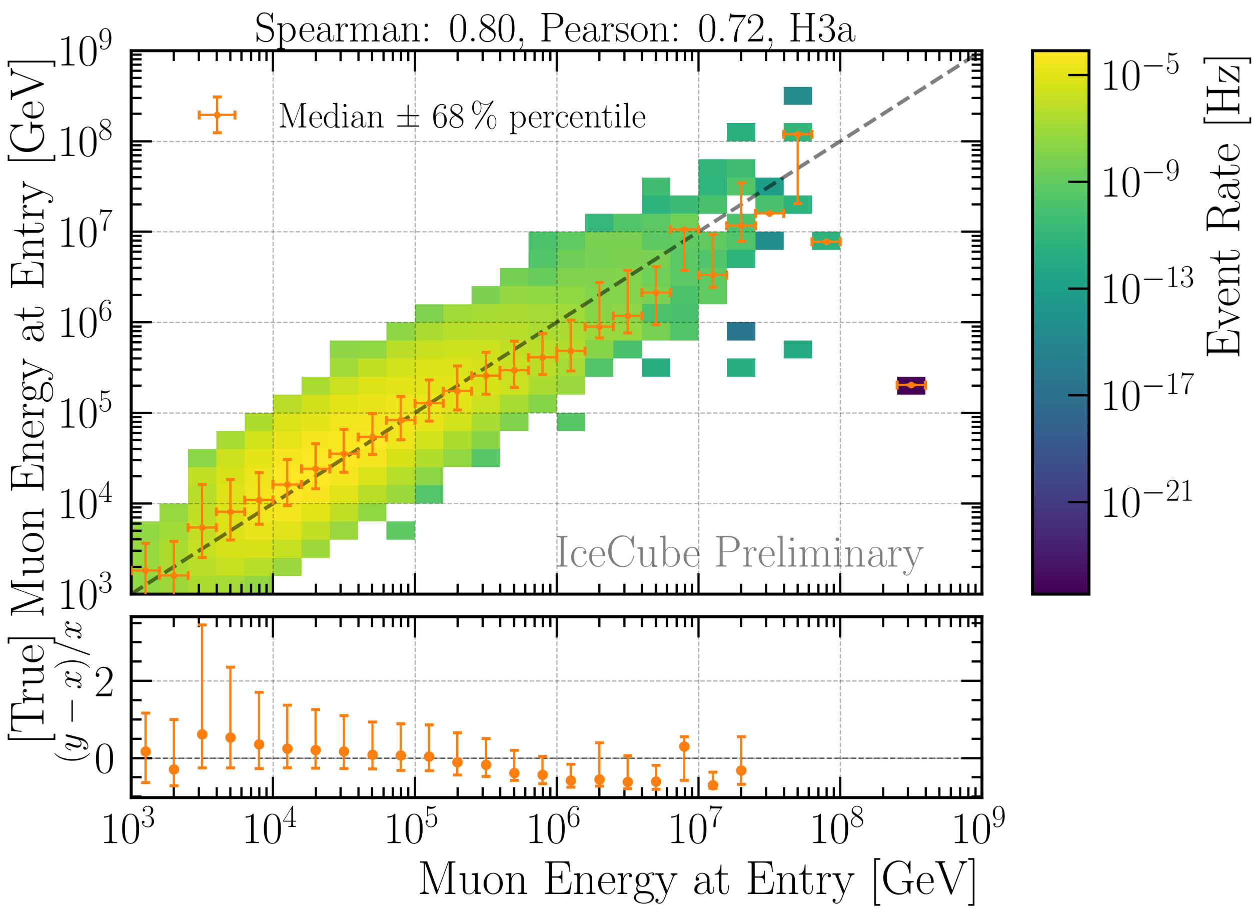


- Baseline: entire set
- Subset: above/below center

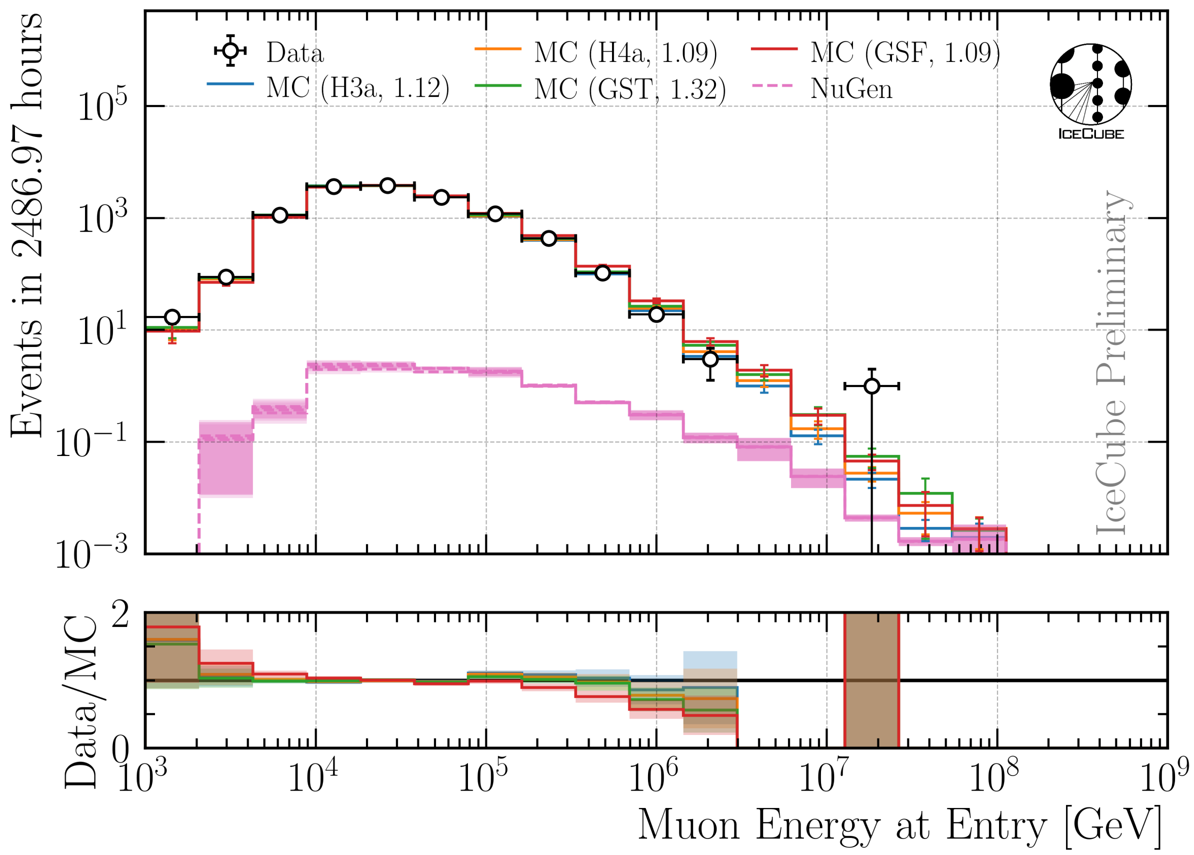
$$\sigma_{tot} = \sqrt{\sigma_{stat}^2 + \sum \sigma_i^2}, \; i\text{: scat, abs, DOME, holeice p0, p1}$$

Reconstruction and Data—MC: Leading Muons

- Good reconstruction of leading muon energy → proxy

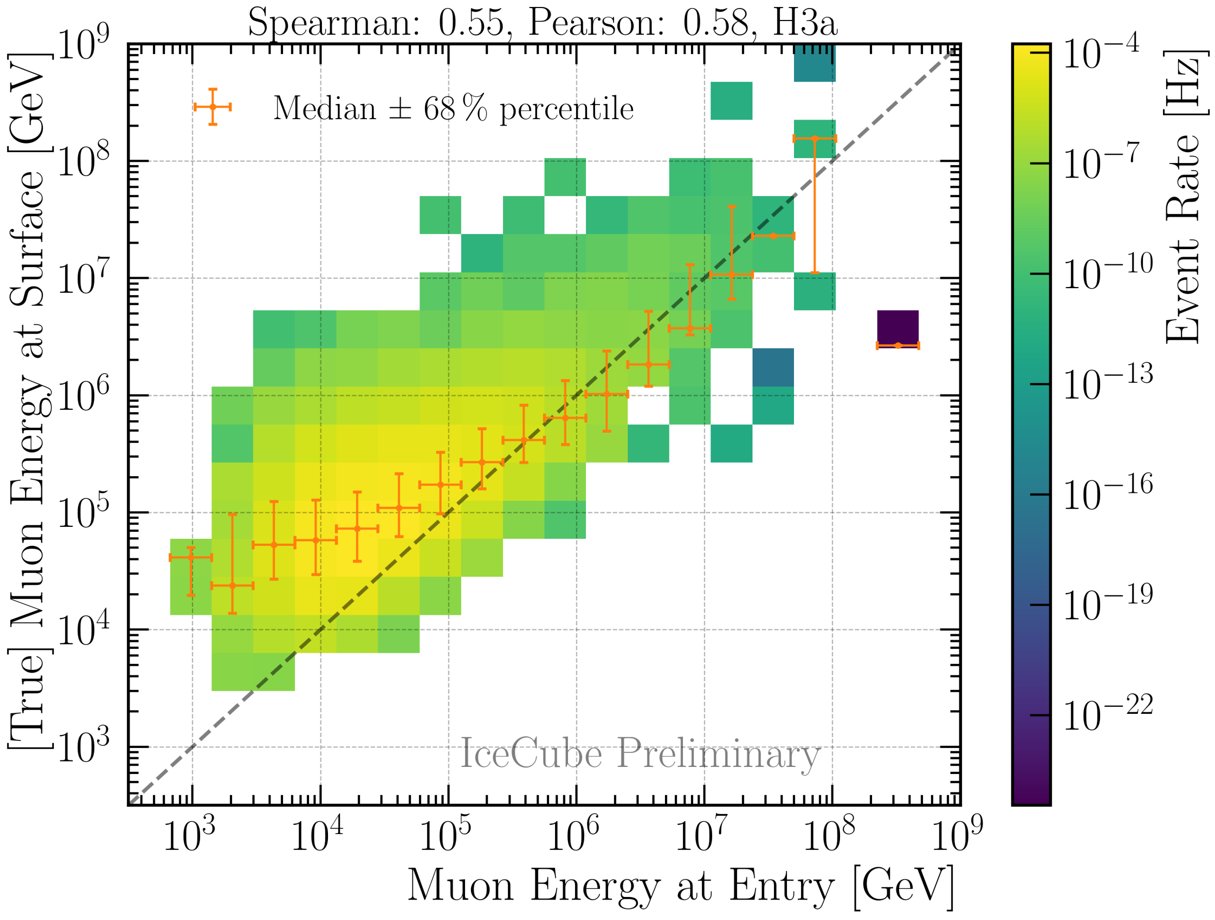


- Good data—MC agreement
- Global offset → upscale MC by 12%

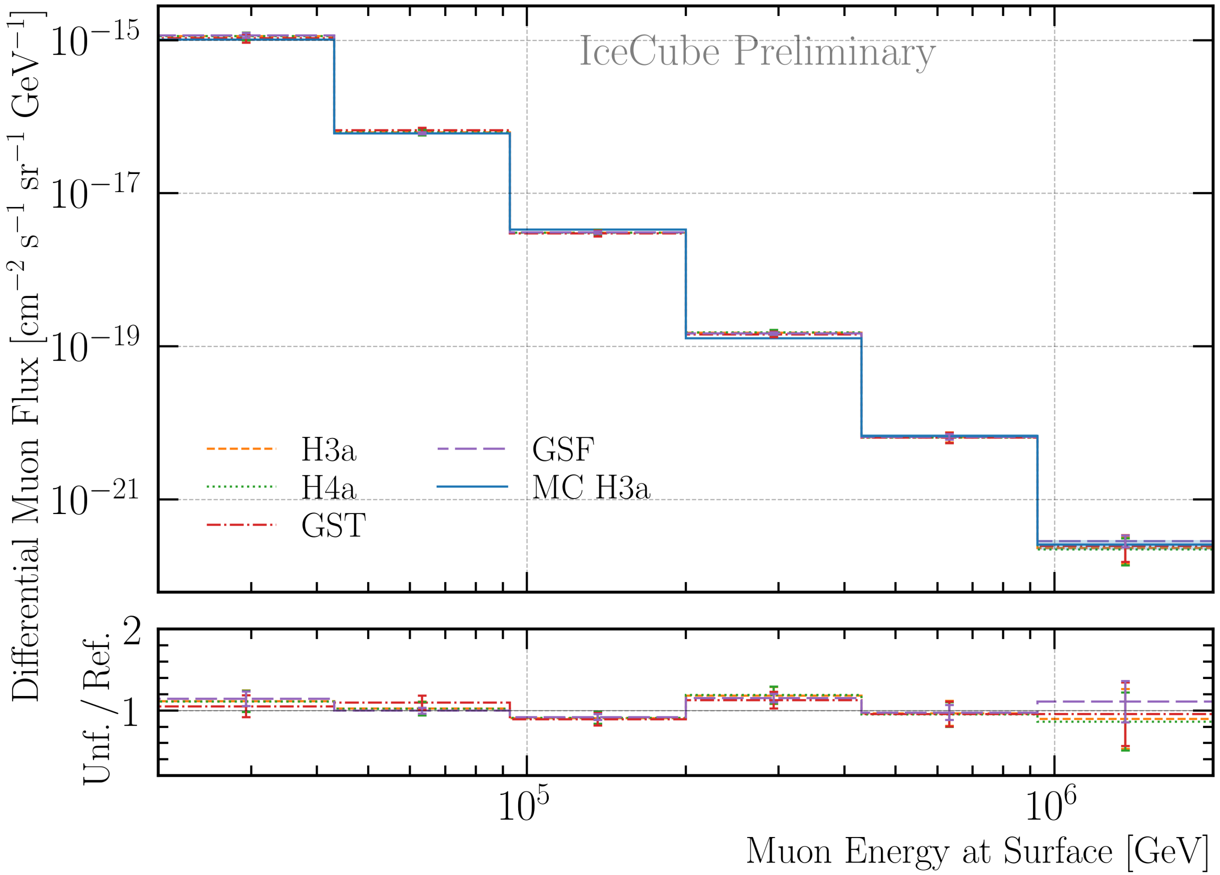


Correlation and Robustness Test: Leading Muons

- Correlation between proxy and target



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

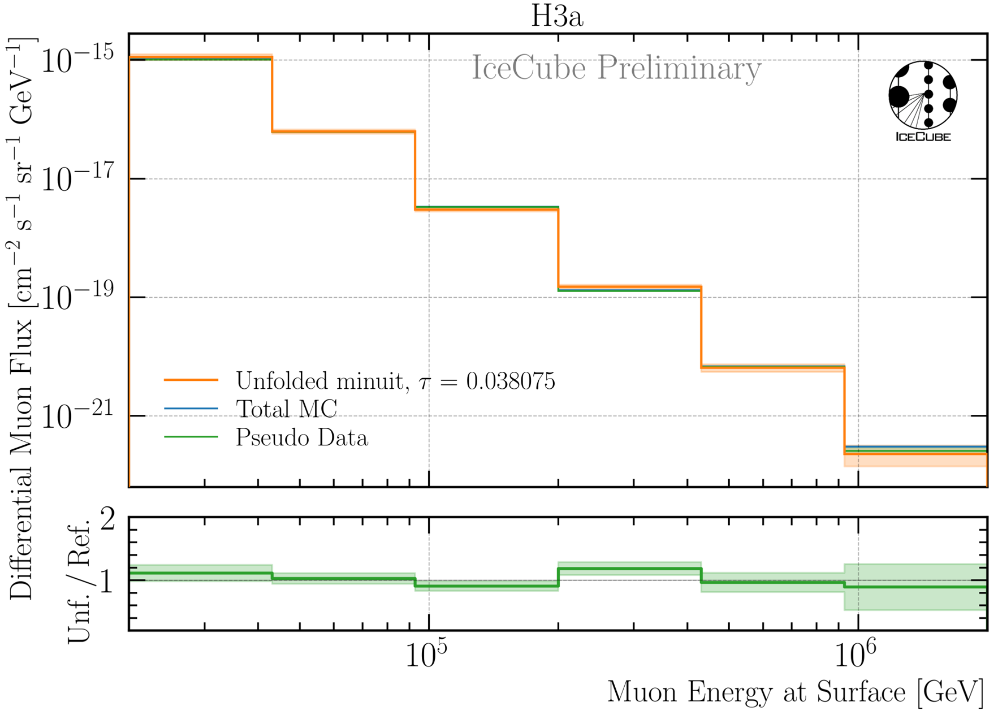


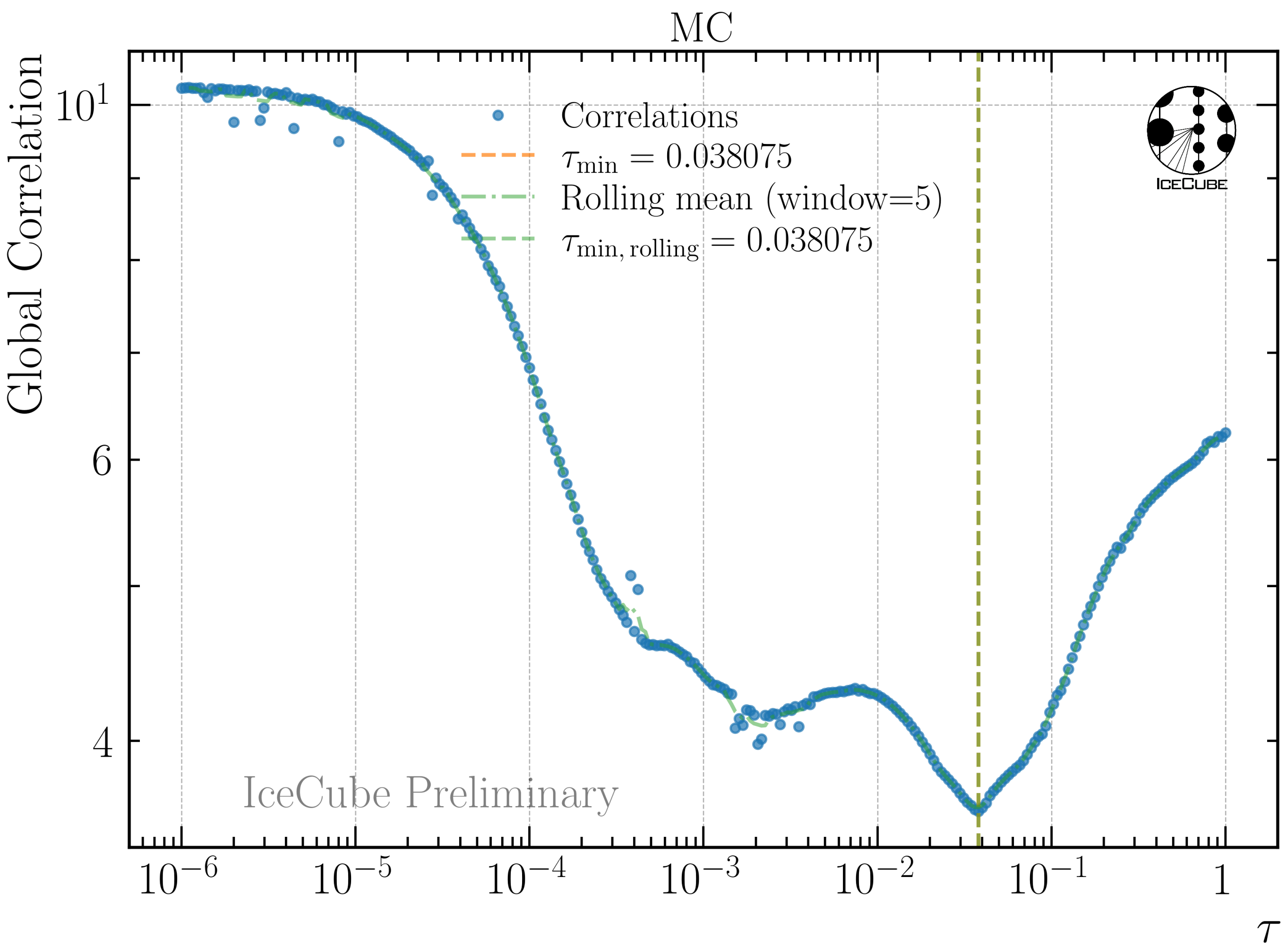
Burnsample

Determine Regularization

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

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

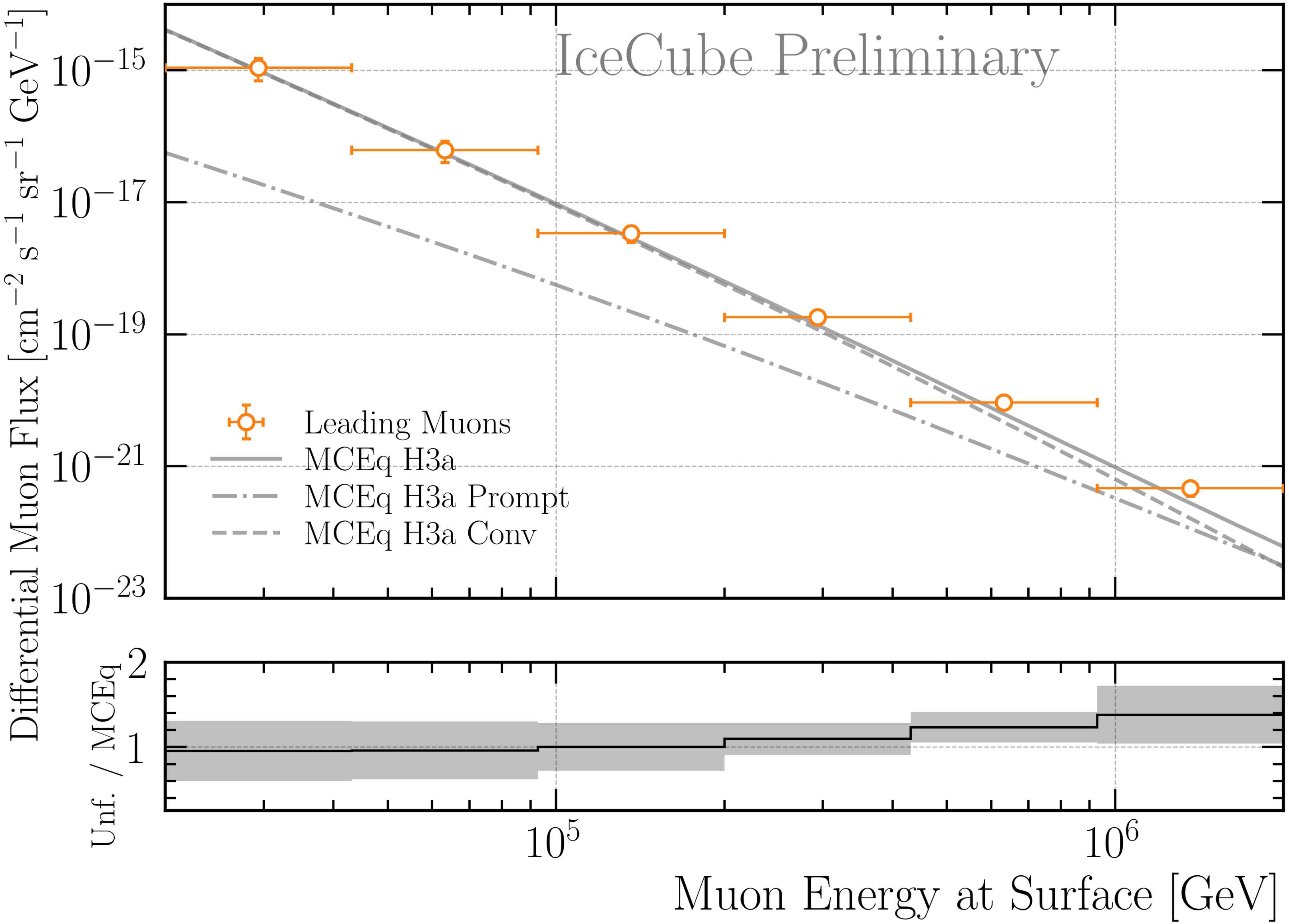




Unfold MC truth → ratio should be 1

Burnsample

Burnsample Unfolding



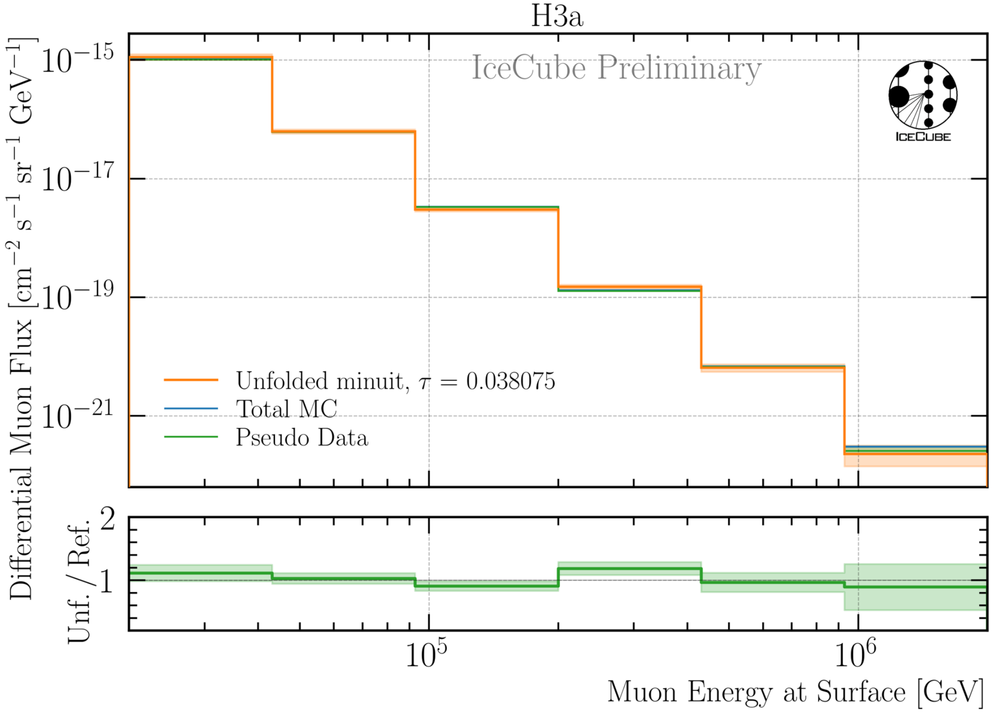
Leading muons

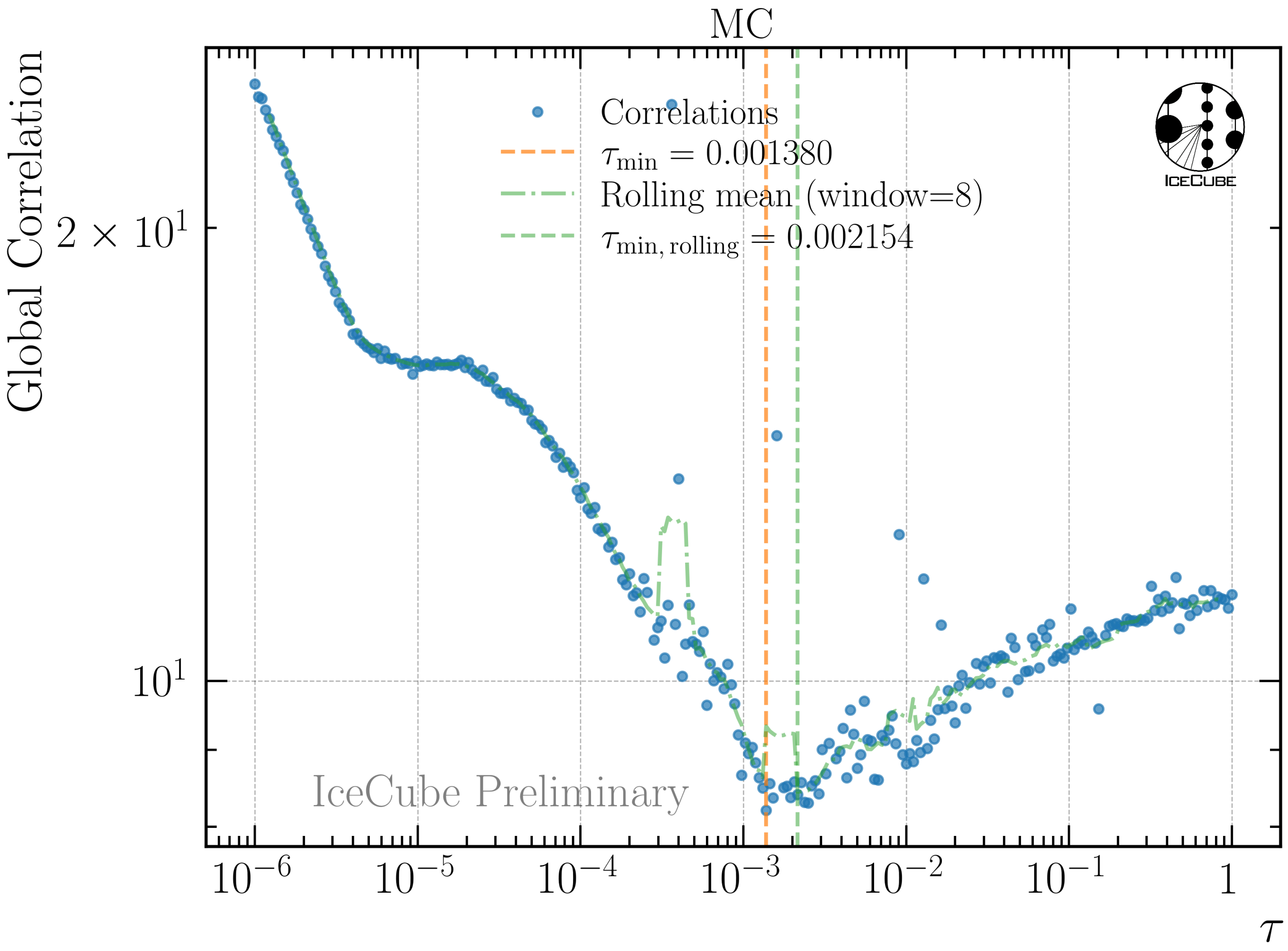
- 2487 h IceCube data
- 12754 events
- Agrees with MCEq

Determine Regularization

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

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



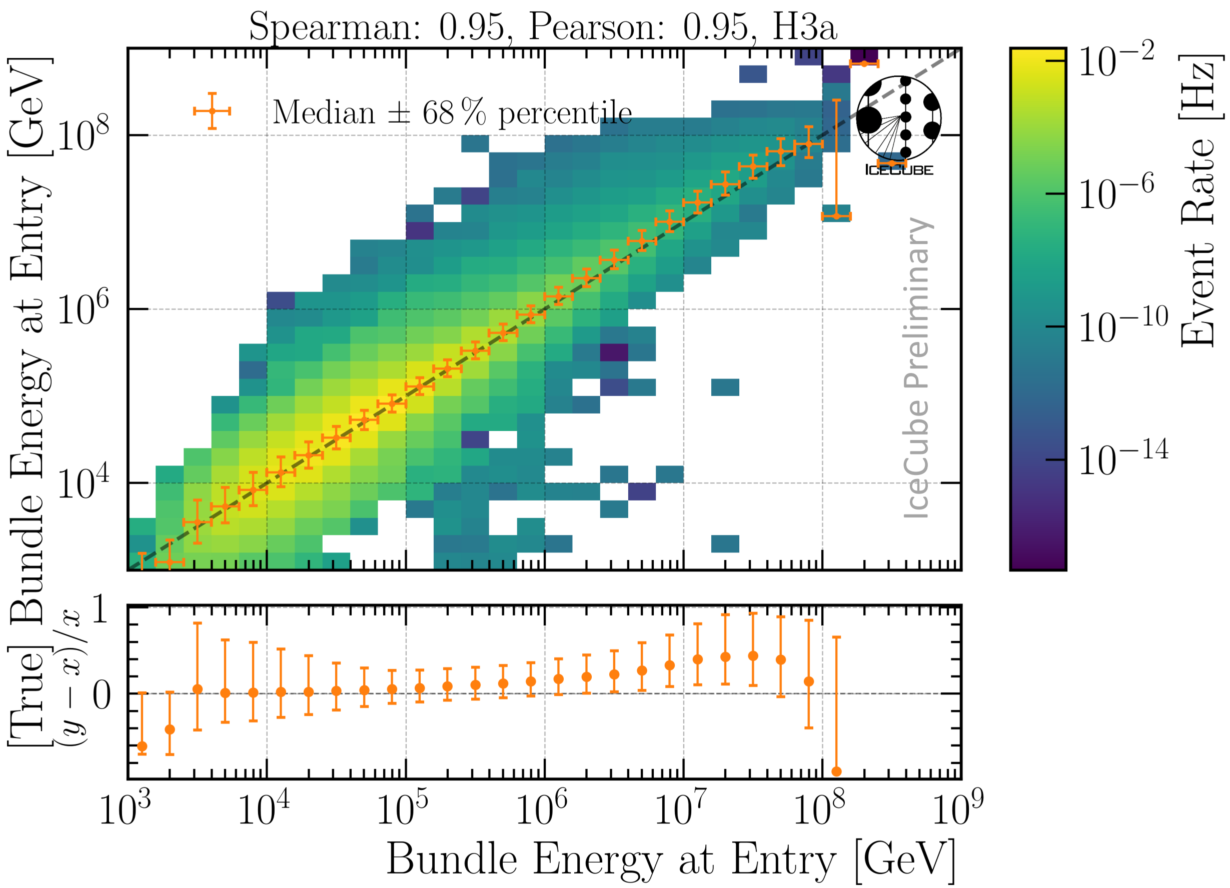


Unfold MC truth → ratio should be 1

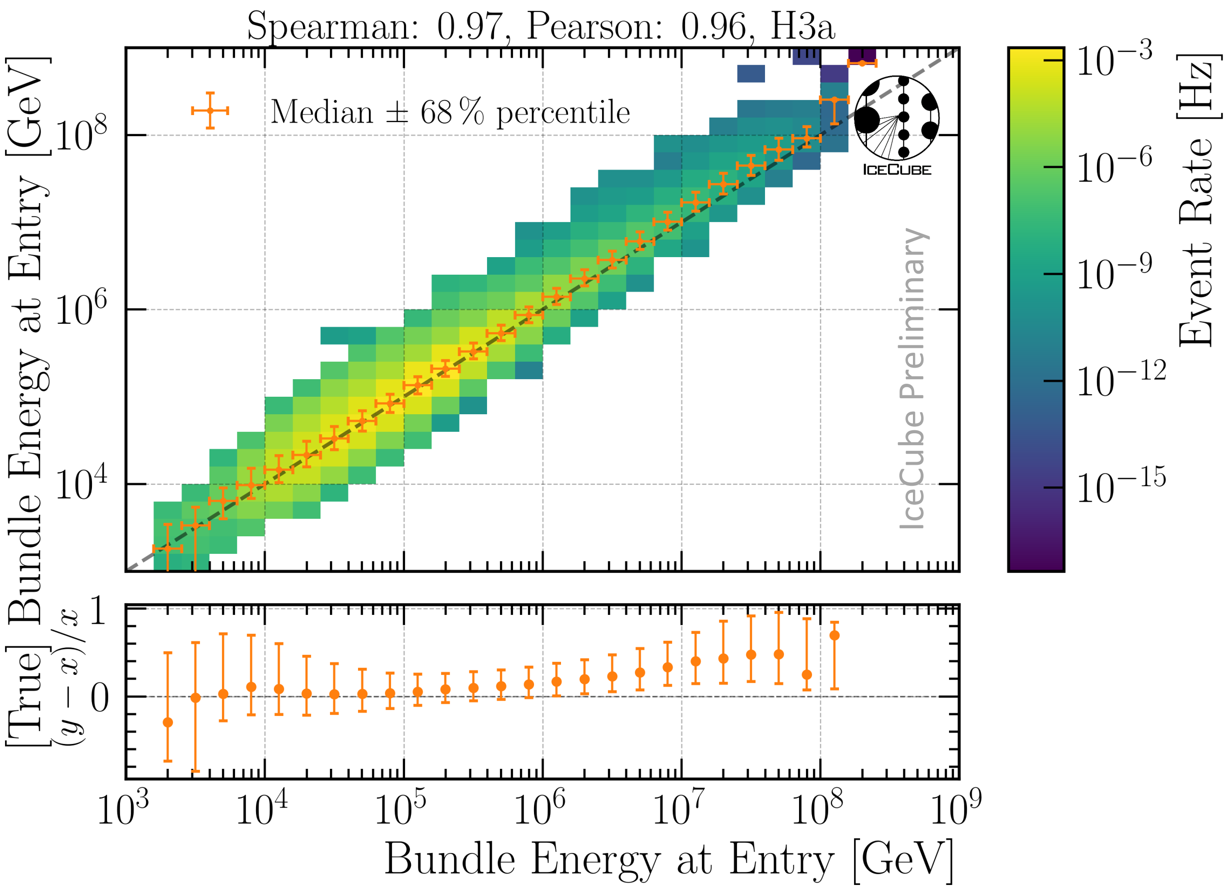
Burnsample

Bundle Energy Reconstruction

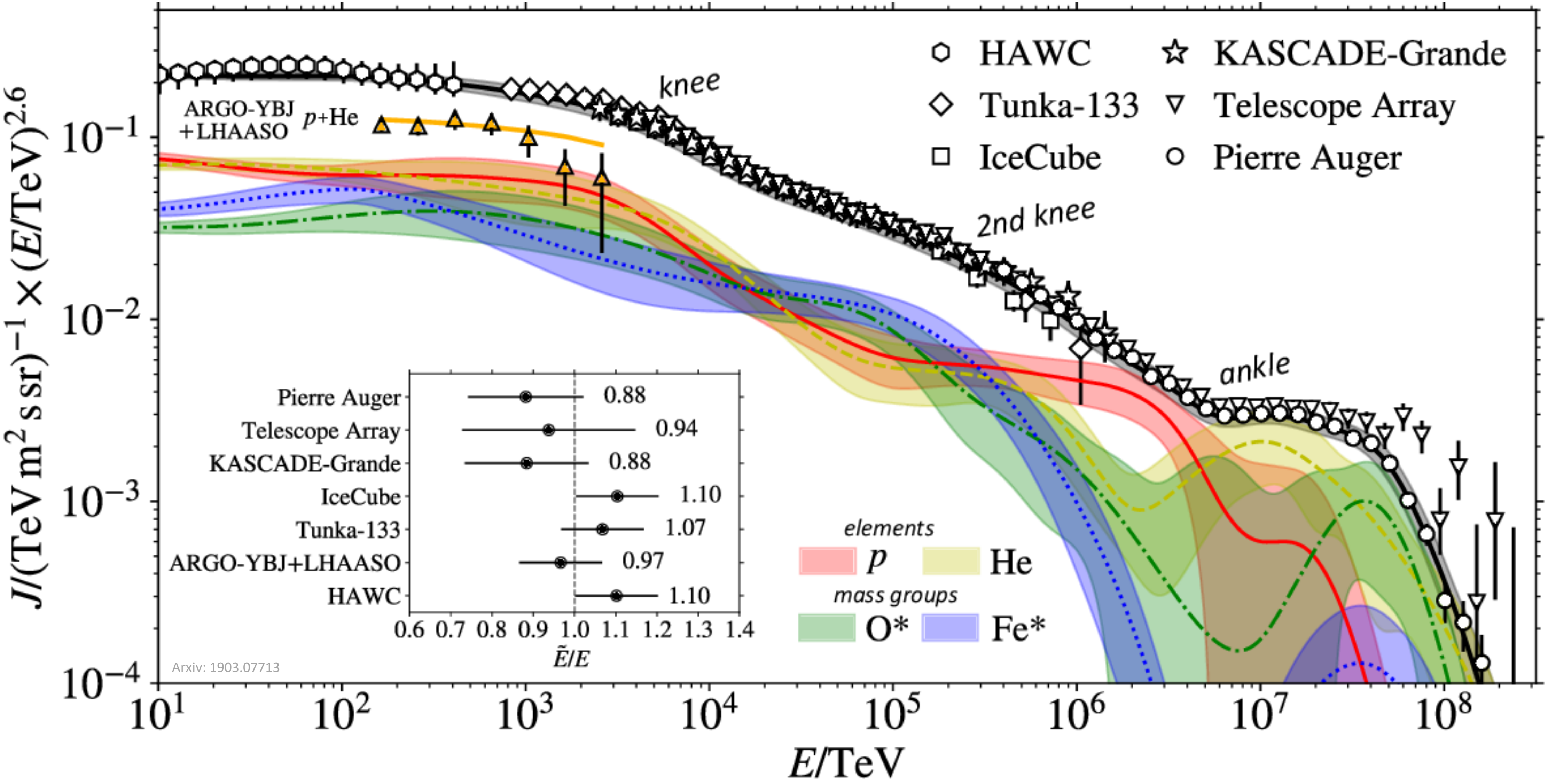
Level 4



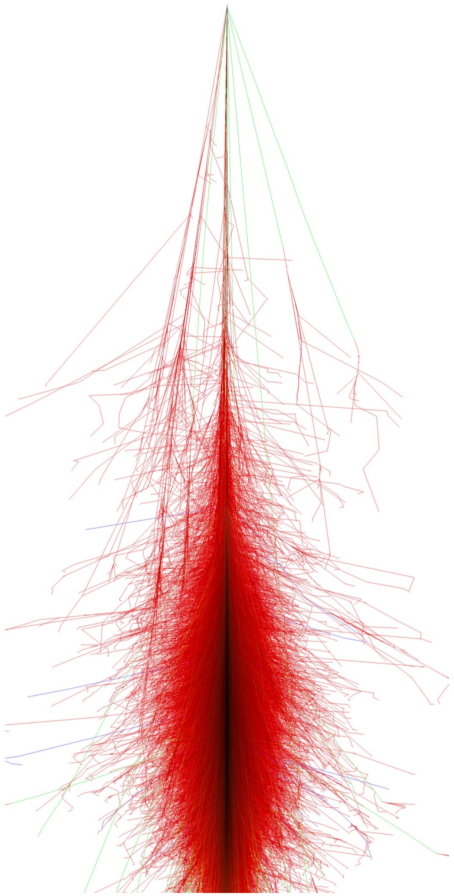
Level 5



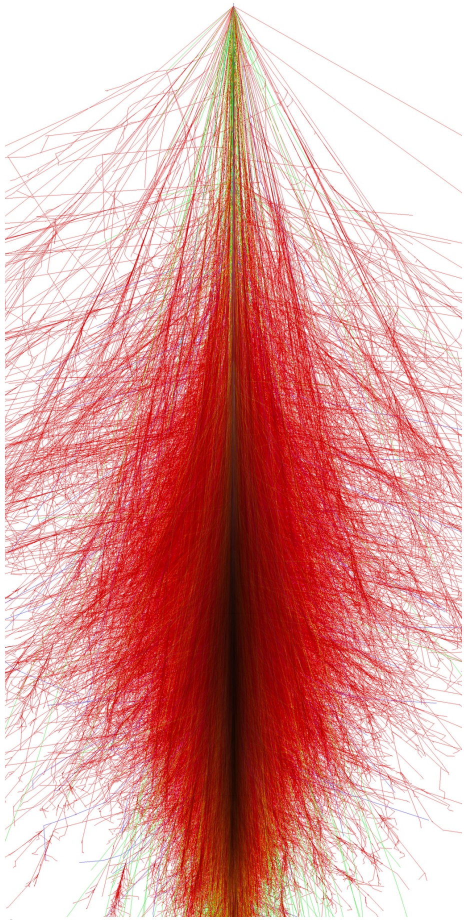
Cosmic ray flux



Air shower – 10 TeV

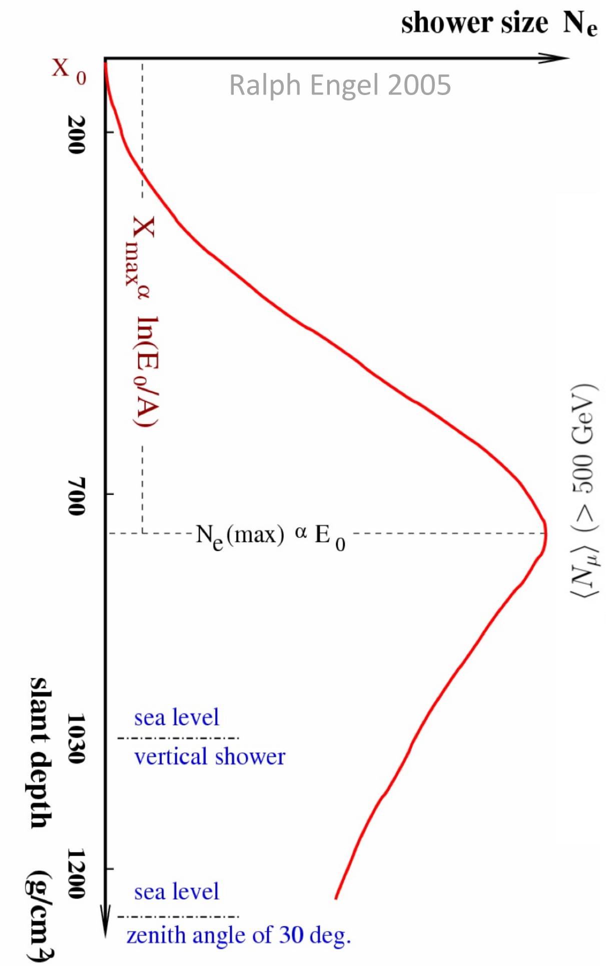


Proton

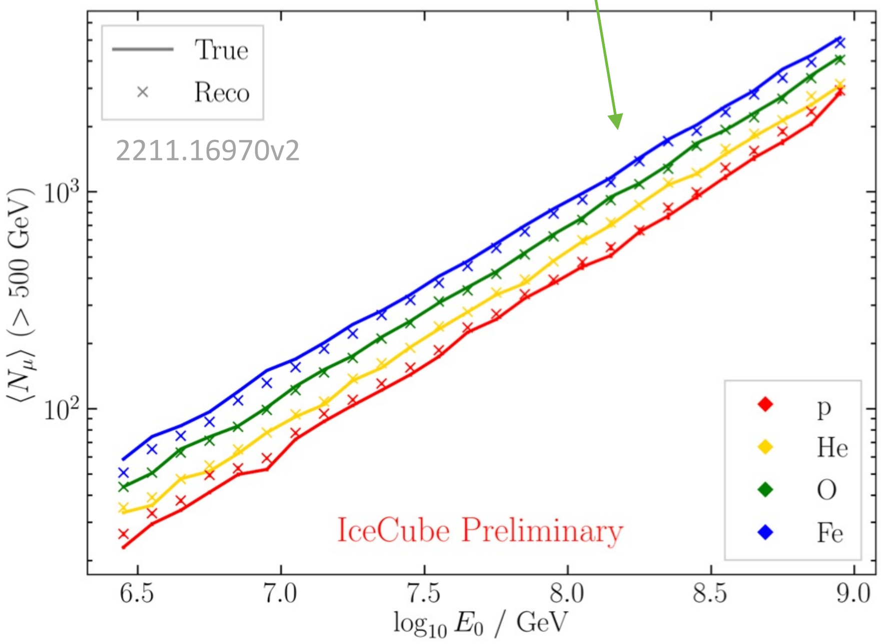


Iron

www.iap.kit.edu/corsika

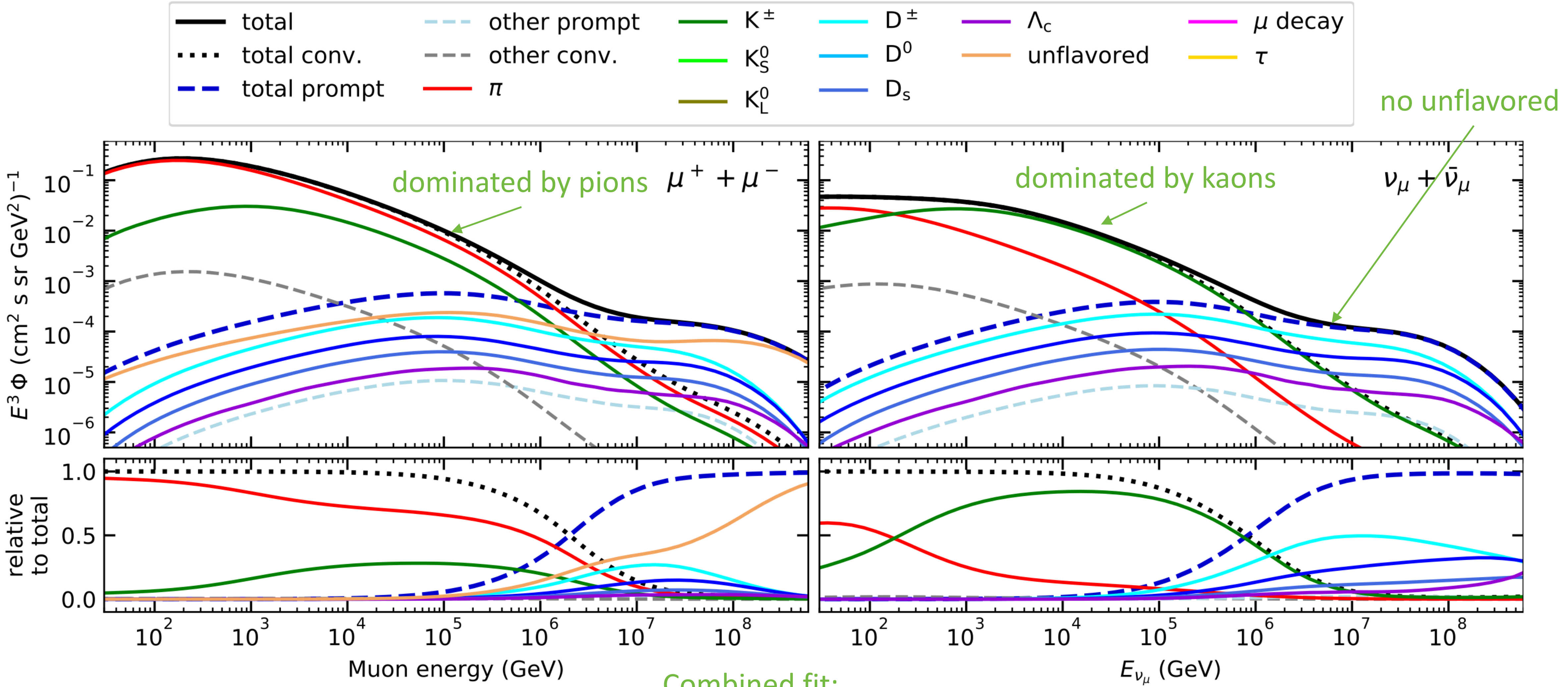


“muon bundles”



Prompt atmospheric muons and neutrinos

10.1103/PhysRevD.100.103018



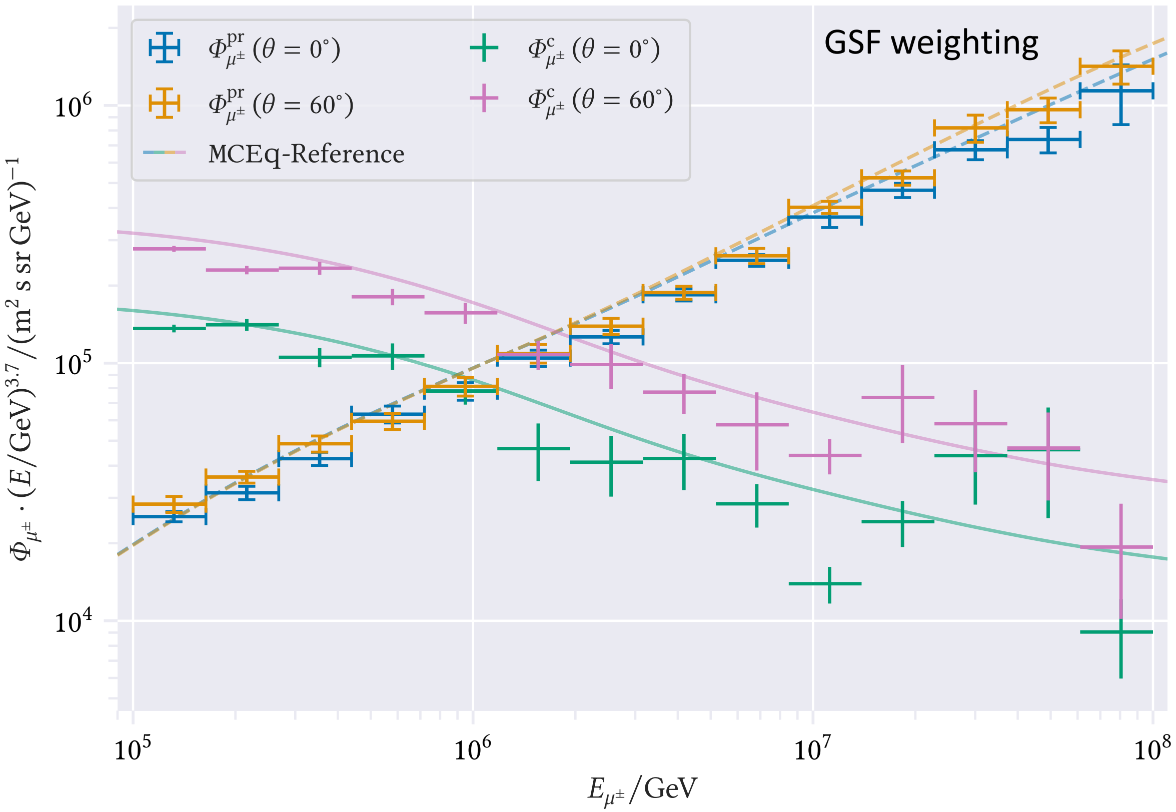
Combined fit:

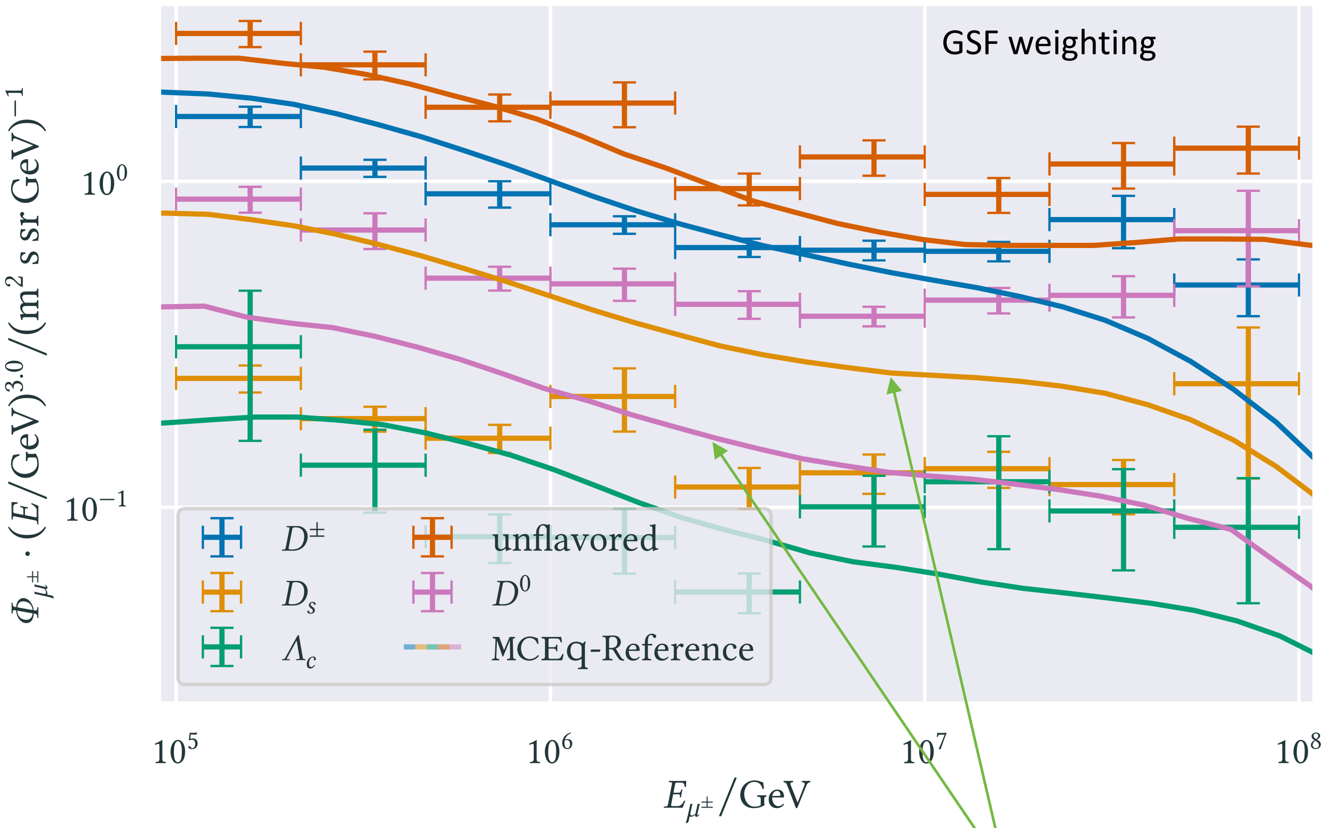
- ➢ handle on pion/kaon ratio
- ➢ handle on charmed mesons

dortmund university BERKELEY LAB SFB1491 ICECUBE NEUTRINO OBSERVATORY

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



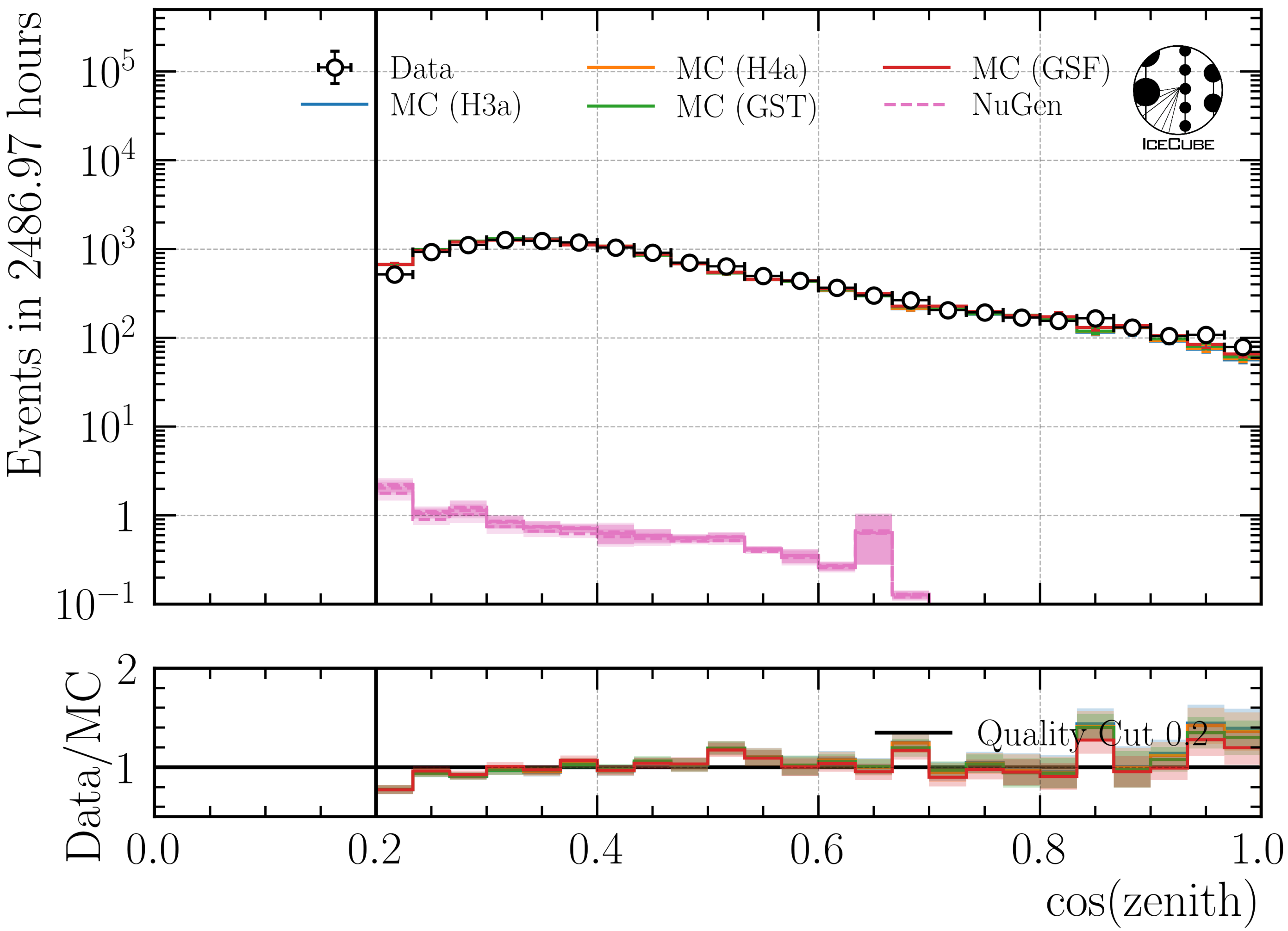


- Good agreement in total prompt and conv muon flux

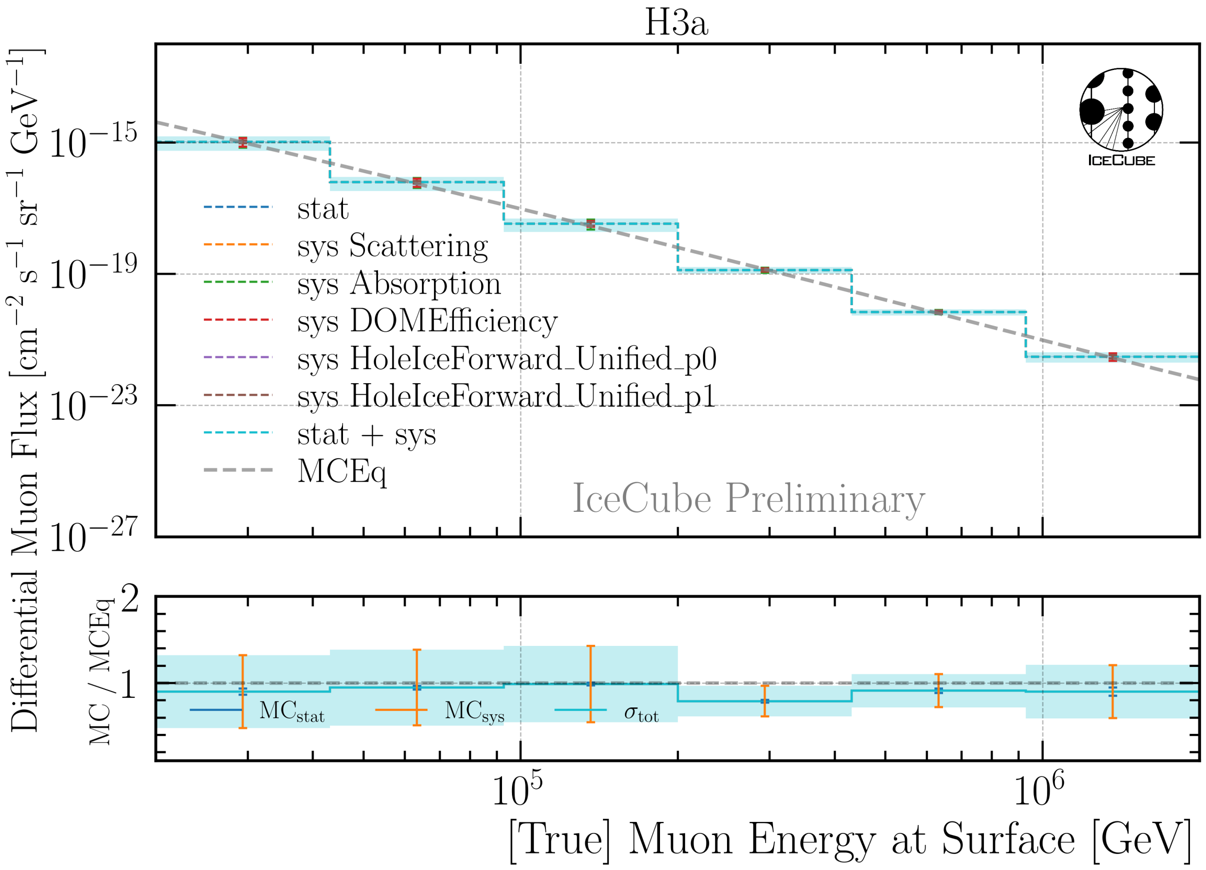
- D^0 and D_s are swapped here but this is fixed in MCEq

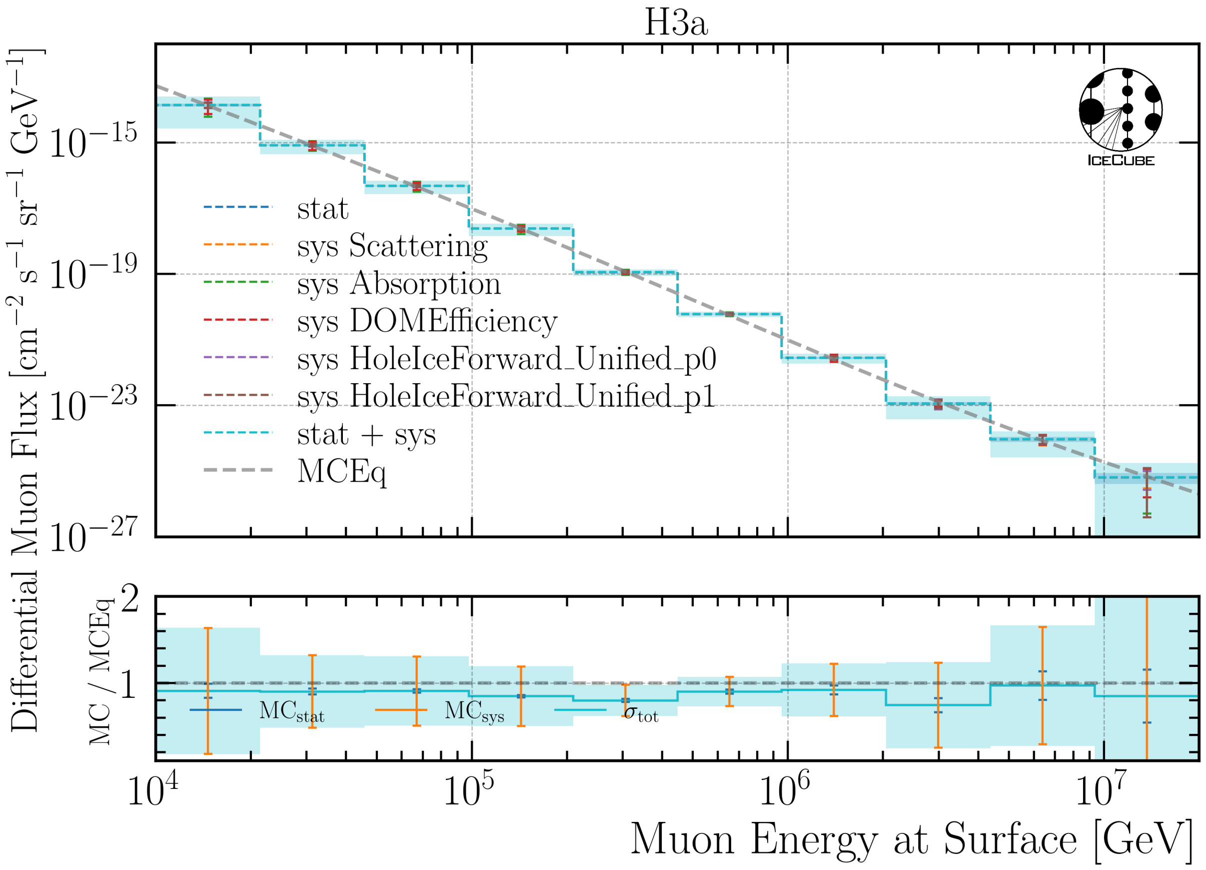
mention panama

Final Level cos(zenith)



MCEq vs CORSIKA

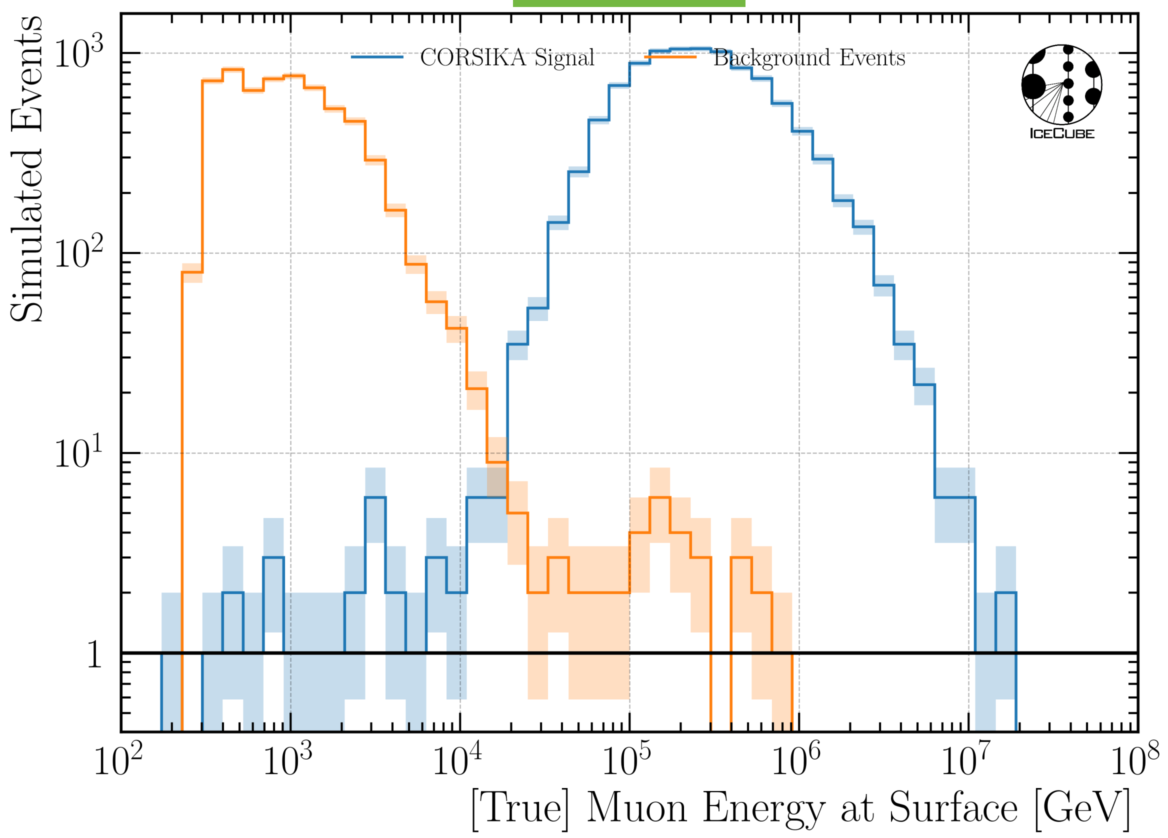




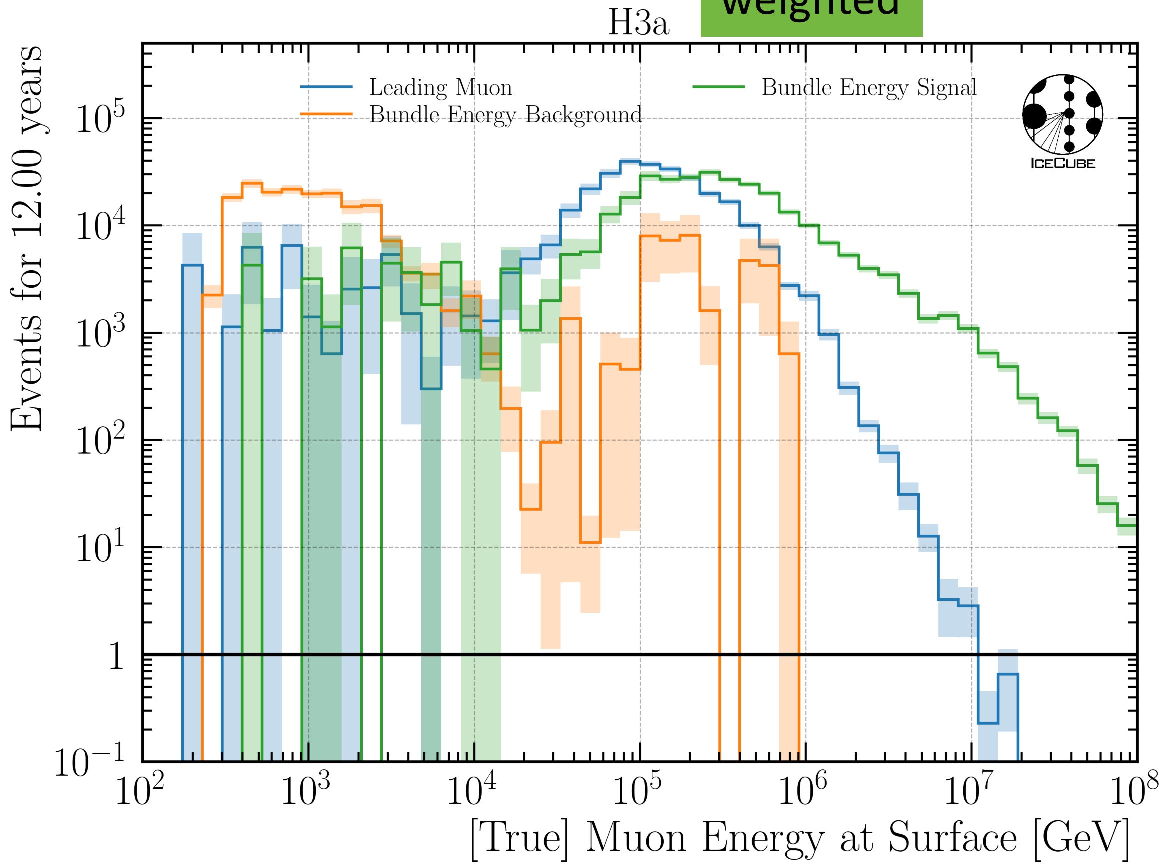
Coincident Events with 22615

Muon Energy at Surface

simulated



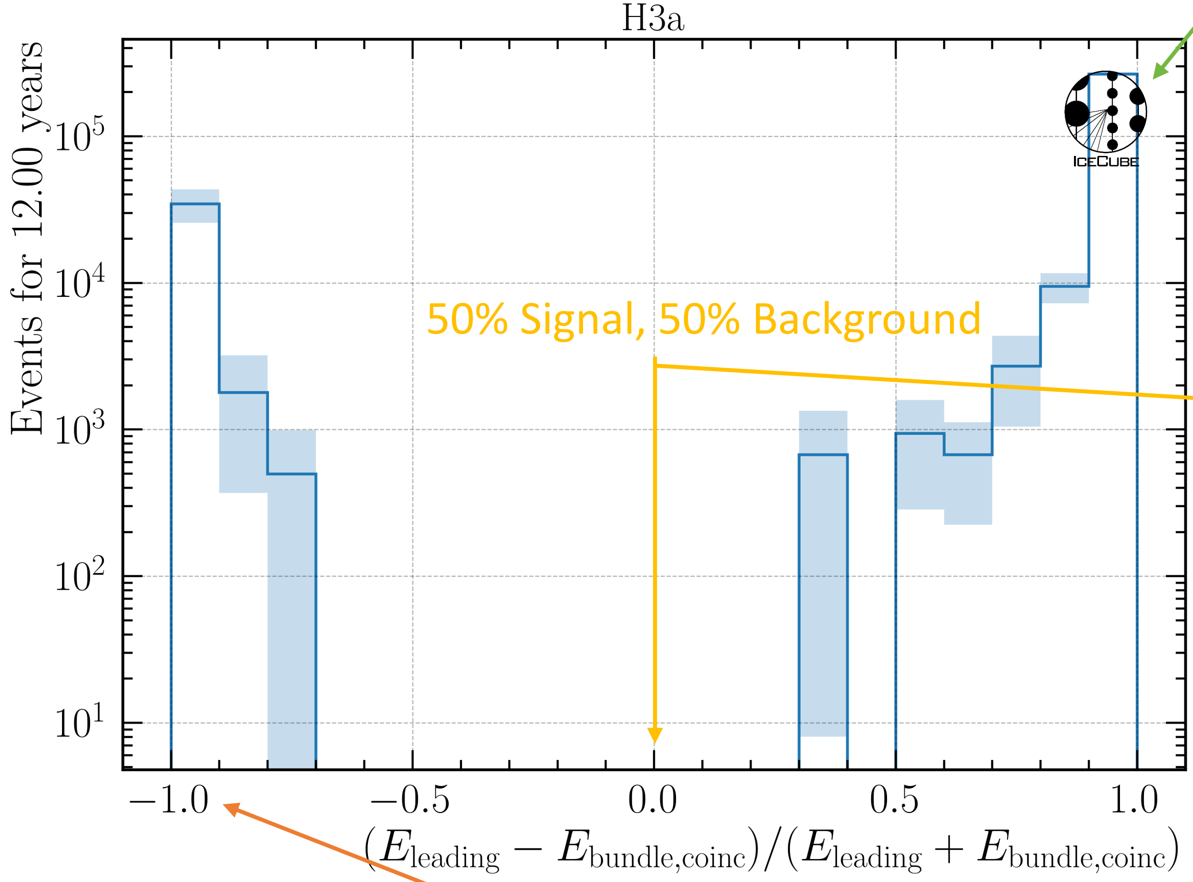
weighted



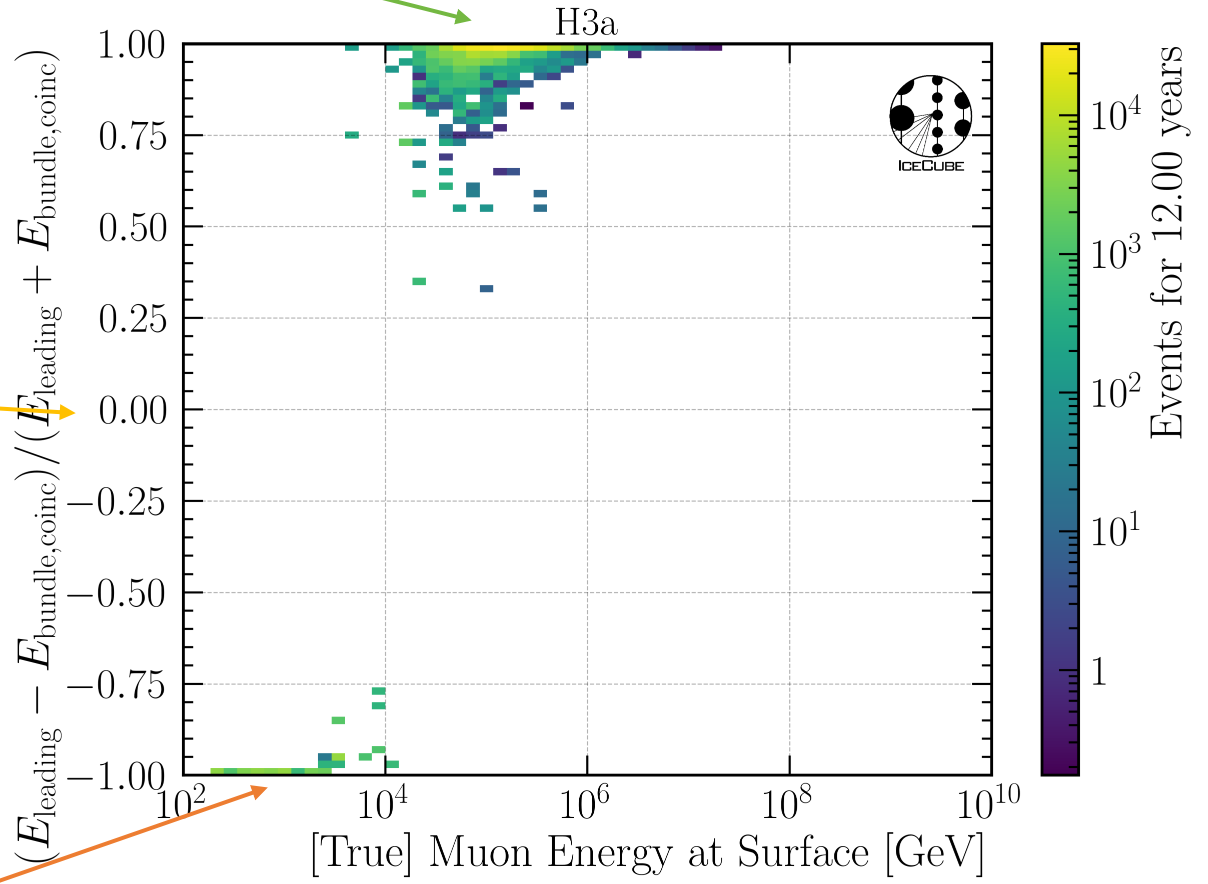
- Leading Muon: most energetic muon in tree
- Bundle Energy Signal: sum of all muons of "signal" primary
- Bundle Energy Background: sum of all muons of coincident primaries

Coincidence: Muons on Event Level

100% Signal



50% Signal, 50% Background



100% Background

- above 10 TeV, no background dominated events

Estimate Rates with H3a

- Signal rate: 0.84 mHz (total event rate)
- Background rate: 0.68 mHz (event rate with at least 1 coincident primary)

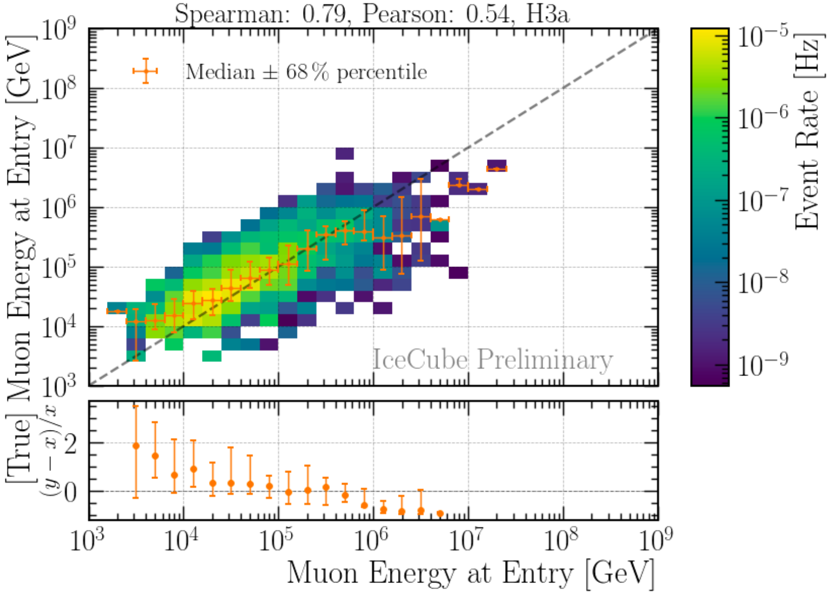
- Signal rate: 0.74 mHz (leading muon energy at surface > 10 TeV)
- Background rate: 0.58 mHz (event rate with at least 1 coincident primary & lead. muon E. > 10 TeV)

- Signal rate: 0.74 mHz (leading muon energy at surface > 10 TeV)
- Background rate: 0.02 mHz (event rate with at least 1 coincident primary & lead. muon E. > 10 TeV & coincident muon bundle energy at surface hast at least 10% of leading muon energy)

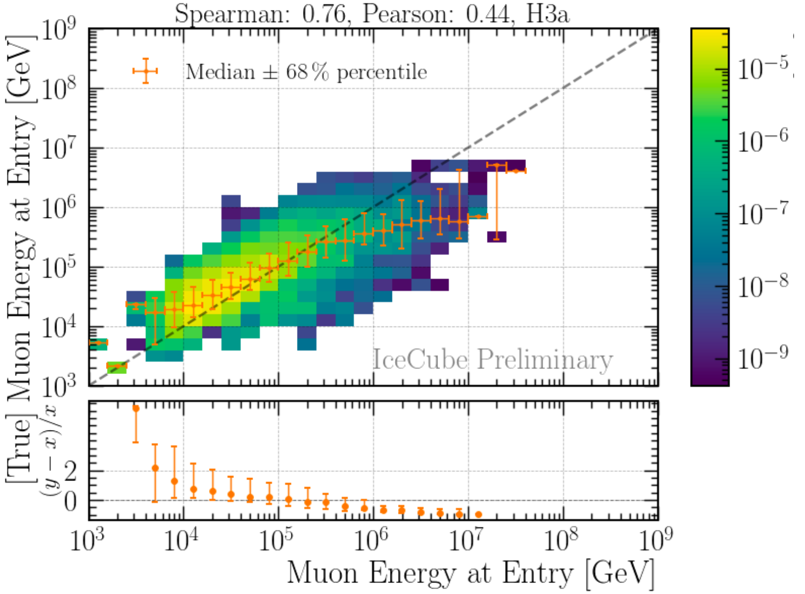
- ➢ The light of the background events overlaps with the signal → no chance to separate
- ➢ A 10% bundle energy contribution would shift the measured light up by roughly 10% → within the uncertainties of the energy prediction
- ➢ Networks have been trained on MC with coincident events → they are able to subtract a little light in case they assume there is a background event, however, this is not quantified

Reconstructions: Coincident Events

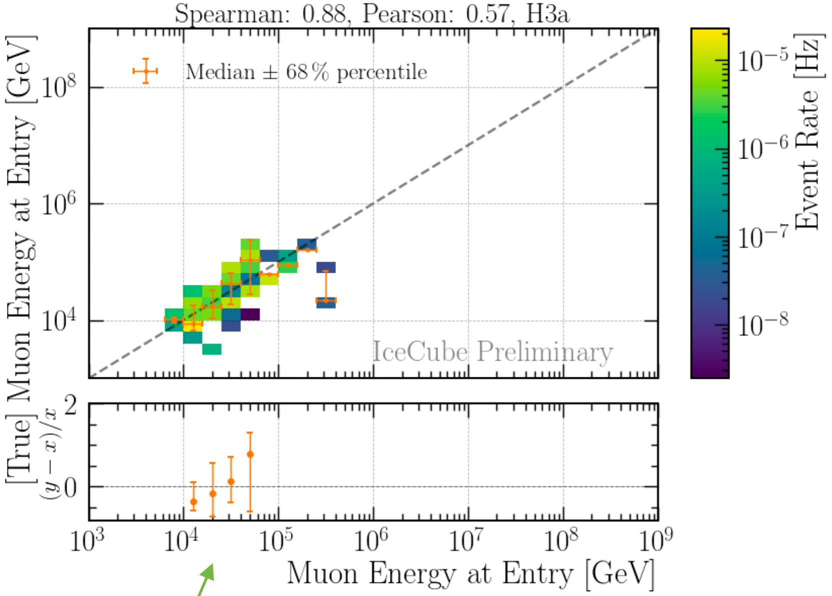
no background event



$\frac{\text{bundle energy at surface}}{\text{leading energy at surface}} < 0.1$



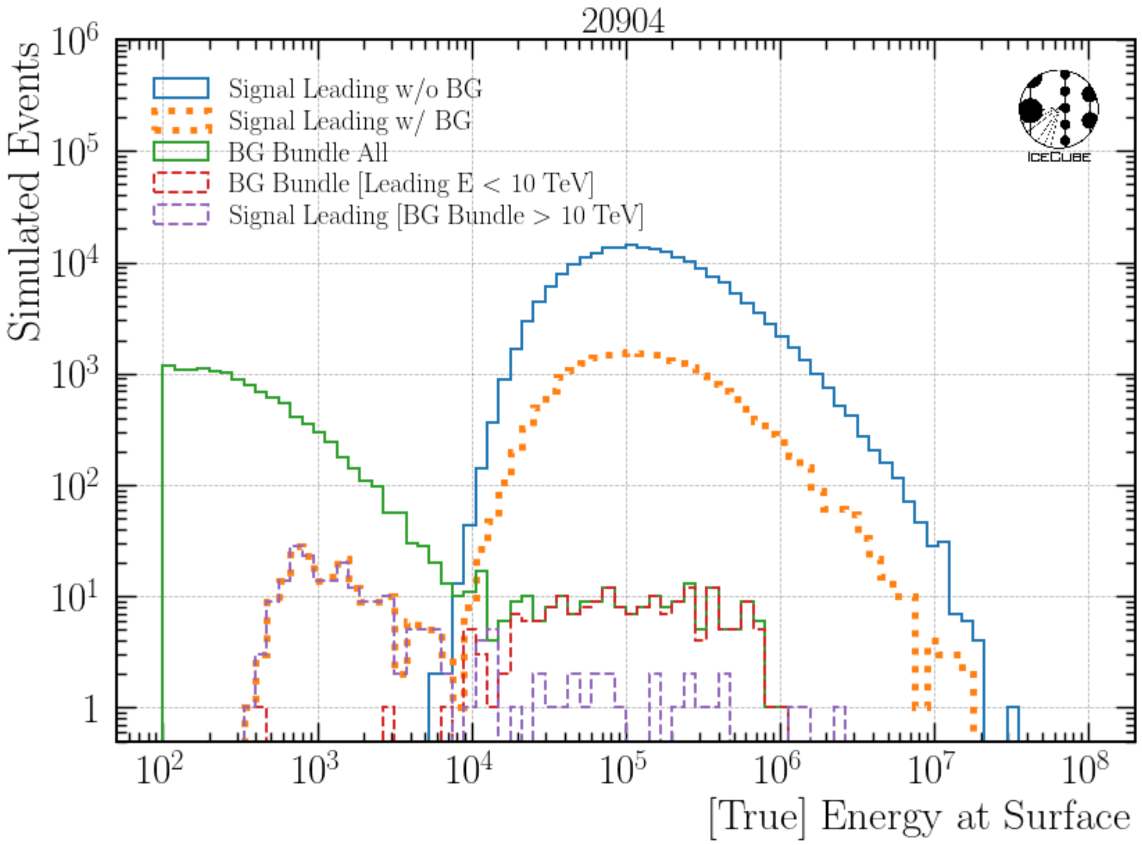
$\frac{\text{bundle energy at surface}}{\text{leading energy at surface}} > 0.1$

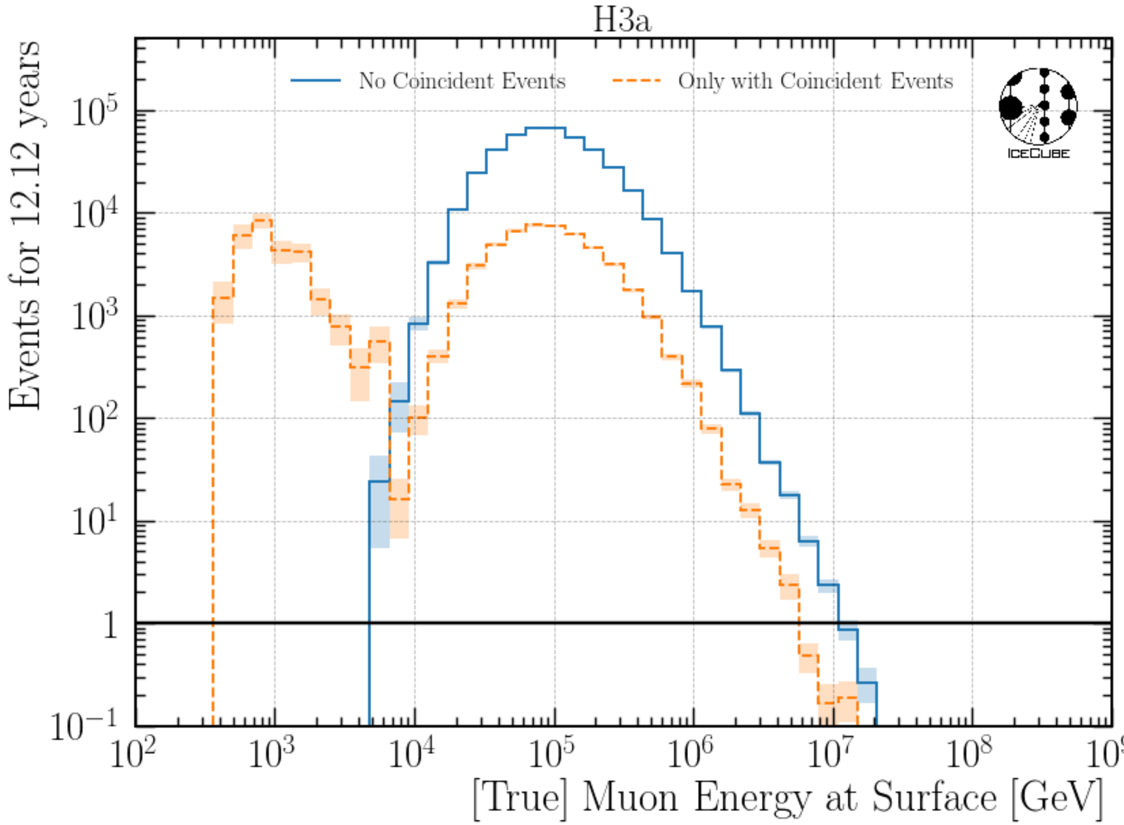


- sufficient energy reconstruction for events with background

Coincident Events with 20904

True MC Distributions

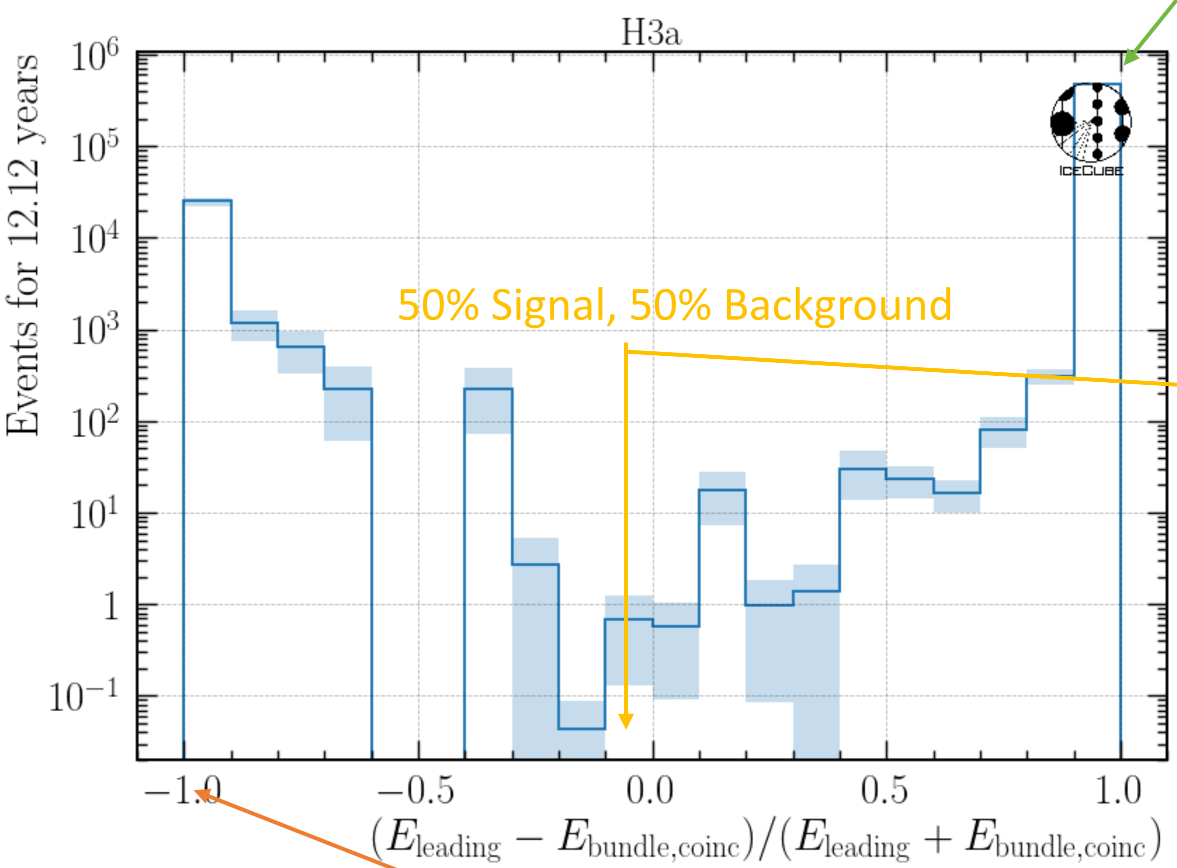


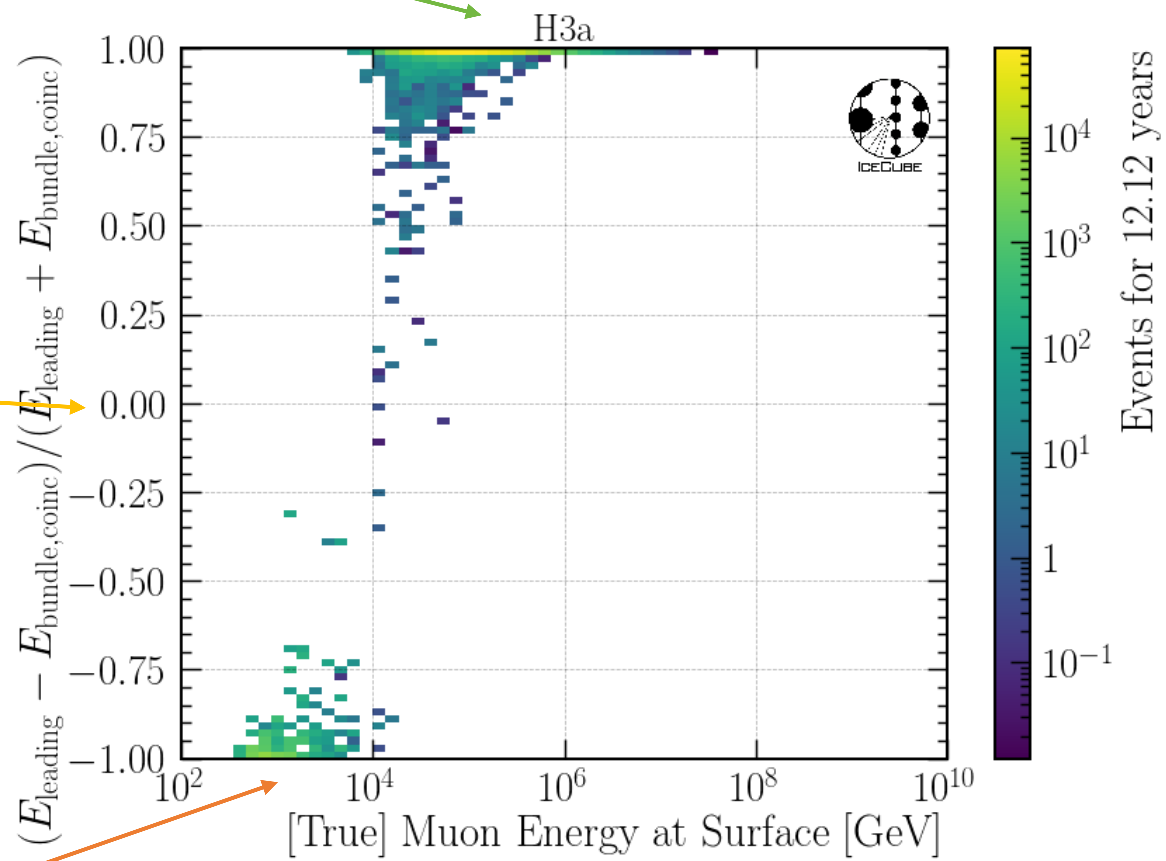


Coincidence: Muons on Event Level

100% Signal

50% Signal, 50% Background





100% Background

- ➢ above 10 TeV, no background dominated events

Estimate Rates with H3a

- Signal rate: 1.31 mHz (total event rate)
- Background rate: 0.20 mHz (event rate with at least 1 coincident primary)

- Signal rate: 1.24 mHz (leading muon energy at surface > 10 TeV)
- Background rate: 0.13 mHz (event rate with at least 1 coincident primary & lead. muon E. > 10 TeV)

- Signal rate: 1.242 mHz (leading muon energy at surface > 10 TeV)
- Background rate: 0.001 mHz (event rate with at least 1 coincident primary & lead. muon E. > 10 TeV & coincident muon bundle energy at surface hast at least 10% of leading muon energy)

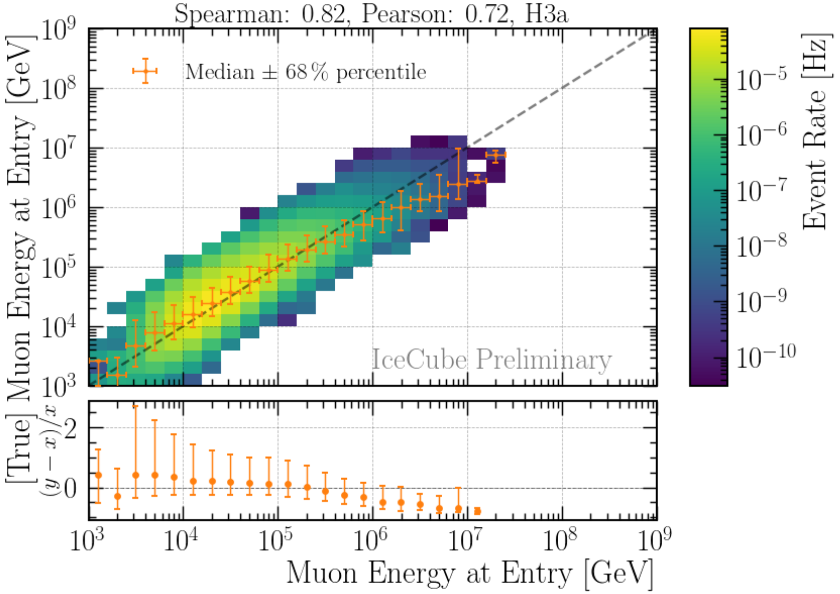
➢ The light of the background events overlaps with the signal → no chance to separate

➢ A 10% bundle energy contribution would shift the measured light up by roughly 10% → within the uncertainties of the energy prediction

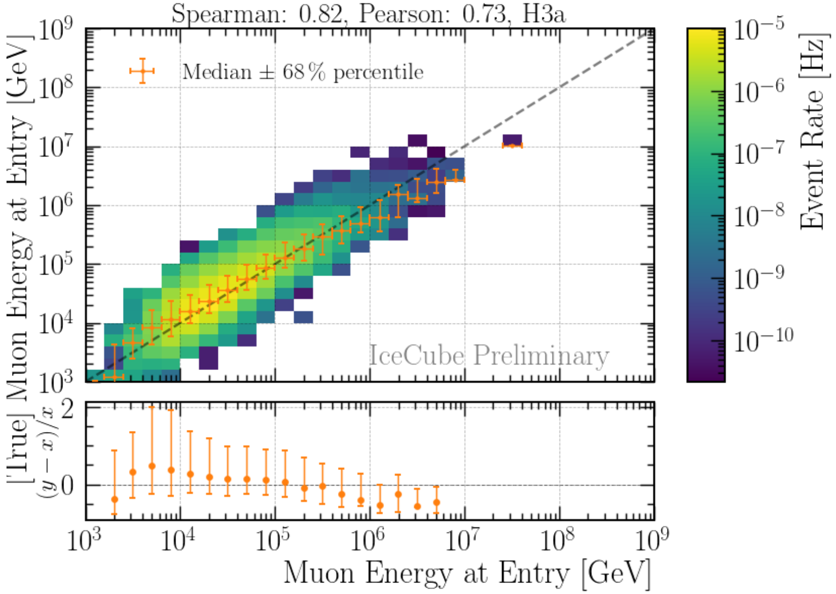
➢ Networks have been trained on MC with coincident events → they are able to subtract a little light in case they assume there is a background event, however, this is not quantified

Reconstructions: Coincident Events

no background event

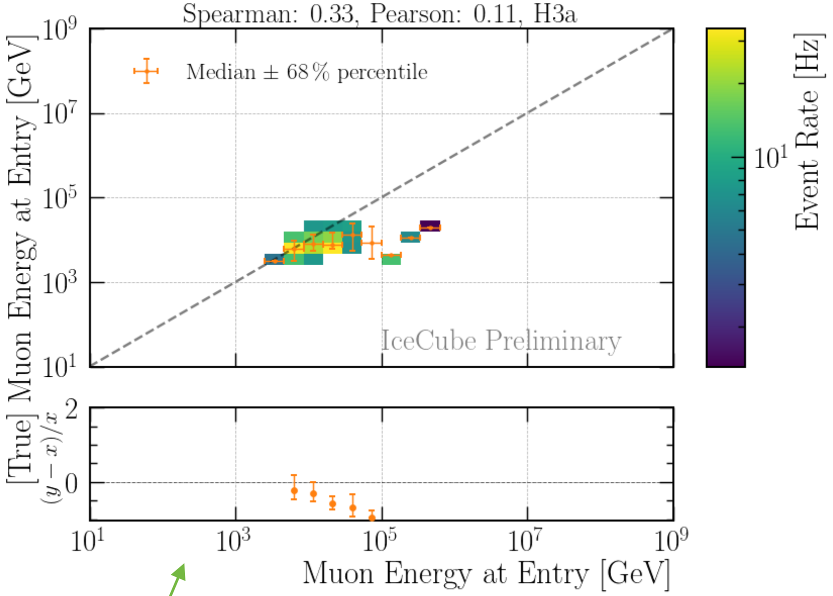


$$\frac{\text{bundle energy at surface}}{\text{leading energy at surface}} < 0.1$$



$$\frac{\text{bundle energy at surface}}{\text{leading energy at surface}} > 0.1$$

leading energy at surface > 10 TeV

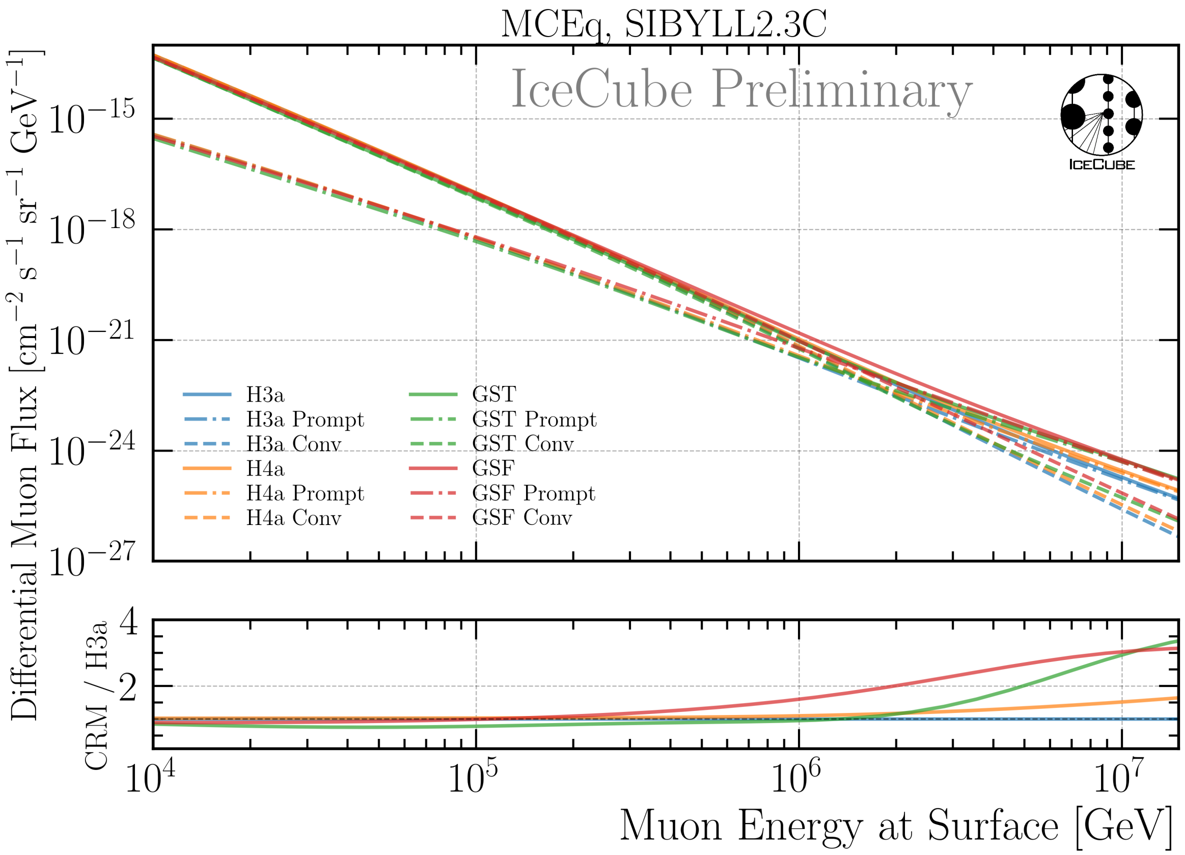


20904

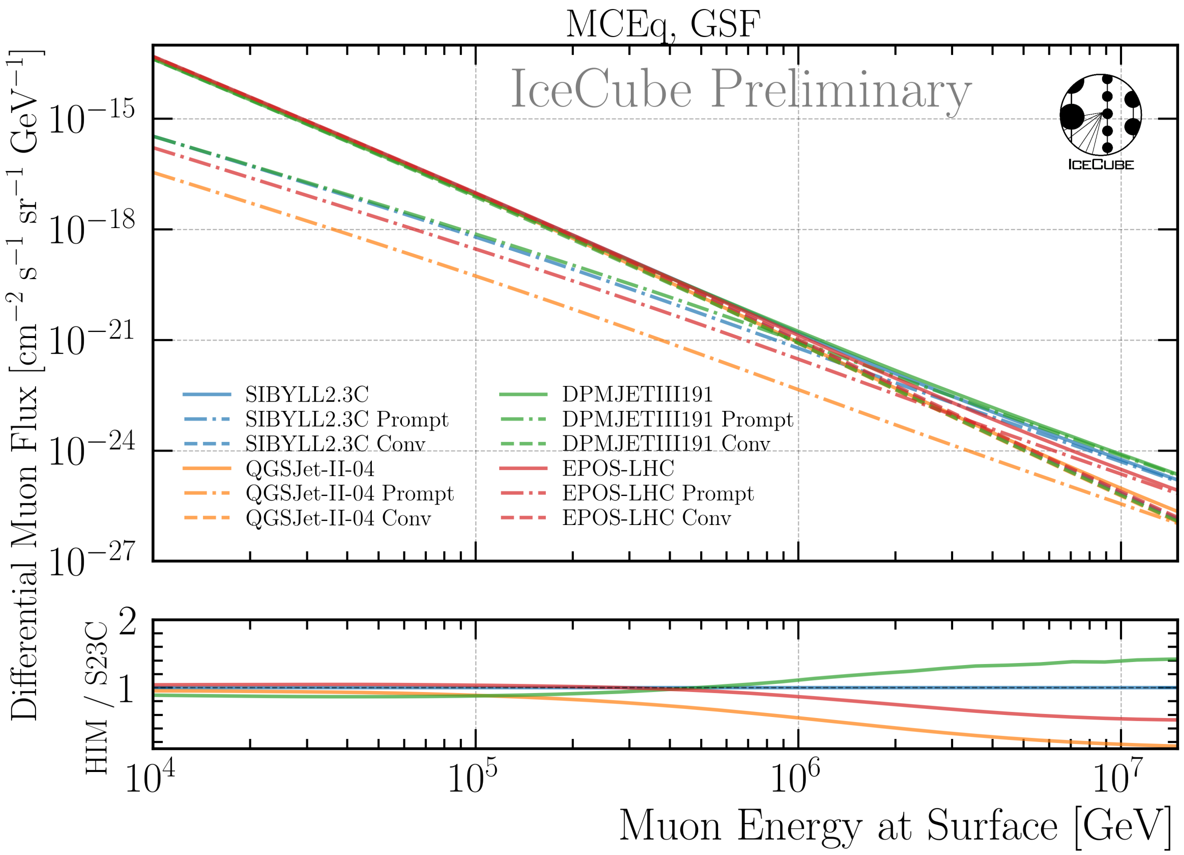
- sufficient energy reconstruction for events with background

Estimate Impact of Hadronic Interaction Model

Different CR Models



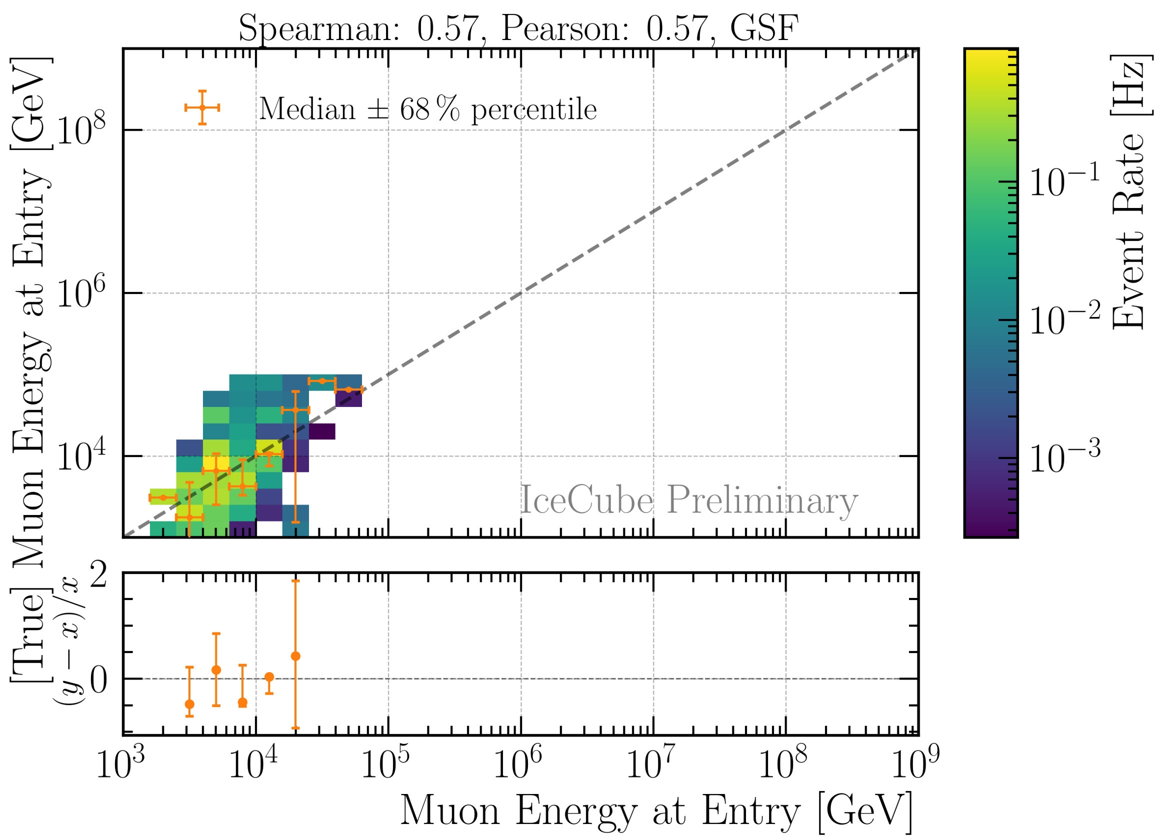
Different Haronic Models



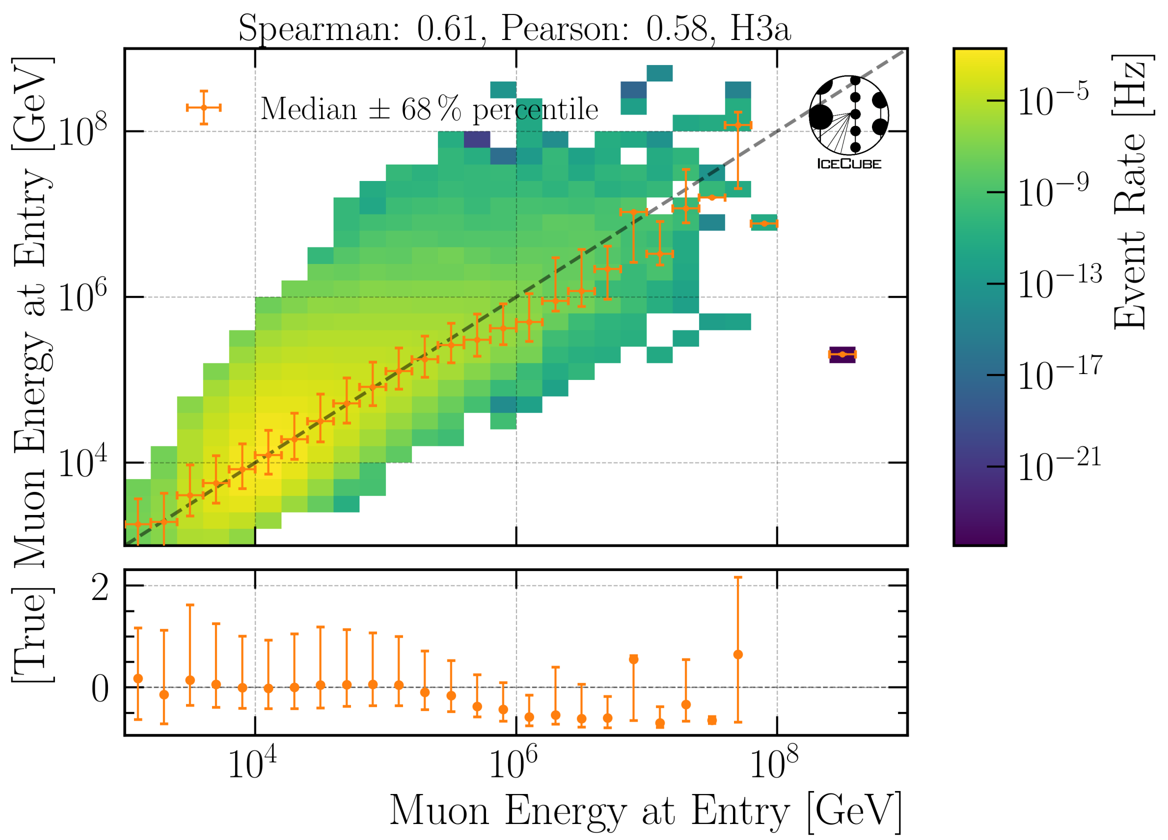
- Not all hadronic models include charm
- Impact of HIM smaller than CRM
- Hadronic Model impact is negligible

Reconstruction: EPOS-LHC vs SIBYLL 2.3d [Level 5]

EPOS-LHC



SIBYLL 2.3d



- IceTop simulations for proton and iron
- 23198 and 23201
- Primary energy > 1e7