

## Unblinding Request:

# Unfolding the Atmospheric Muon Flux with IceCube

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WG: Dennis

Coll.: Anatoli

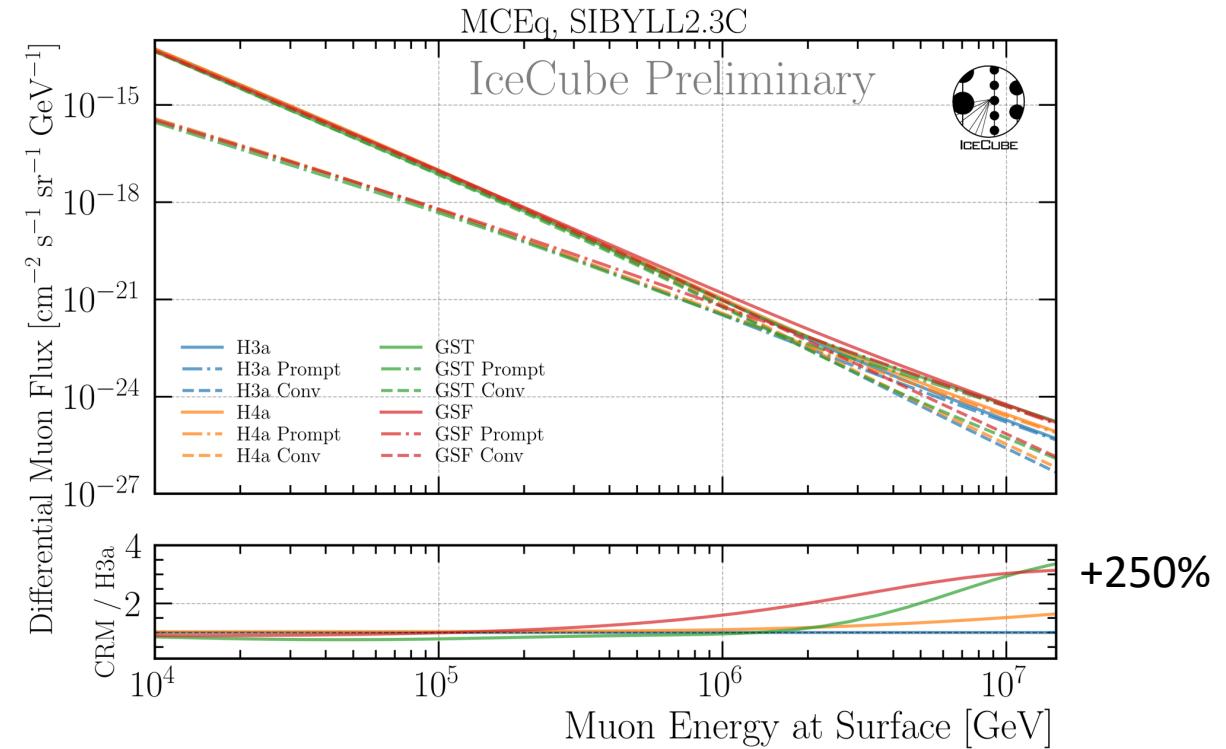
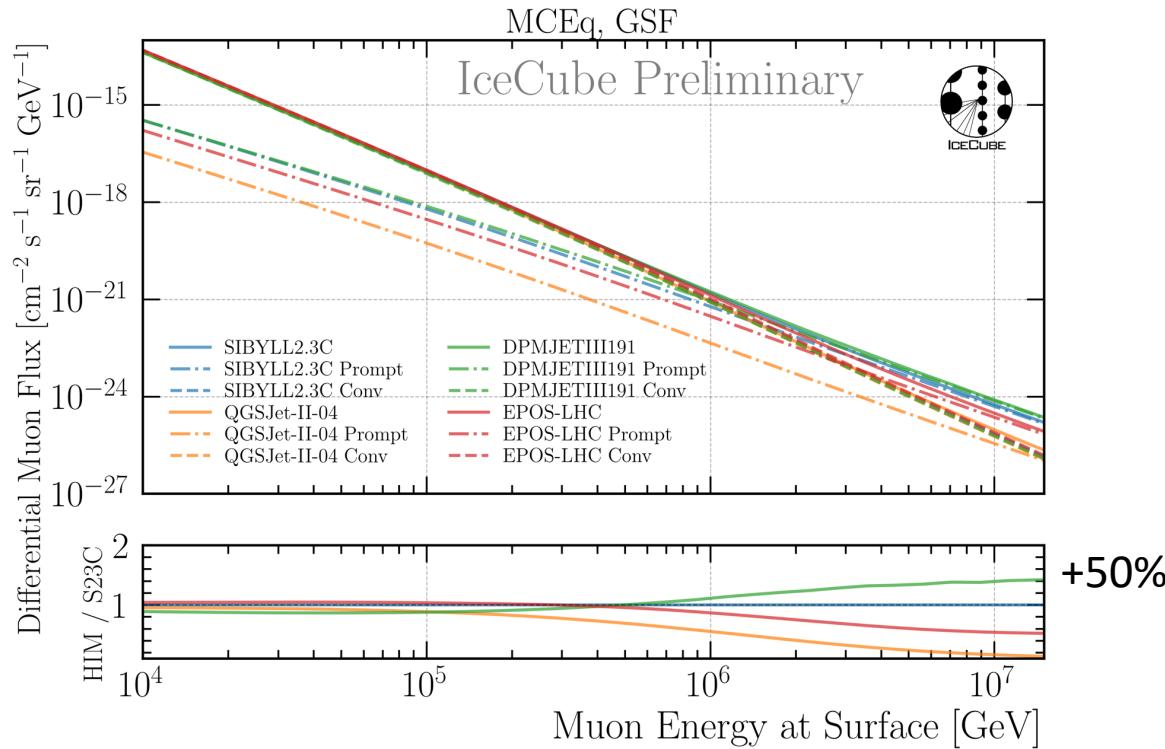
Tech: Karolin

[wiki page](#)

Analysis Call

December 04, 2025

# Impact of Hadronic Interaction Models?



- 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)

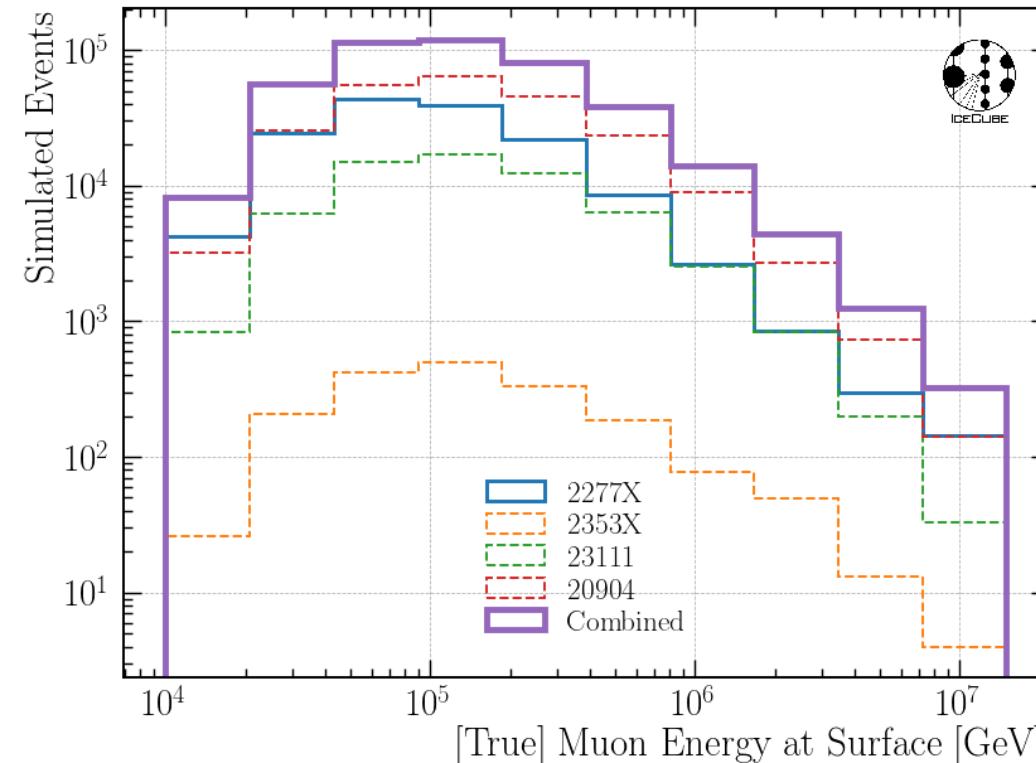
23111 (Lucas dataset)

20904 (Standard CORSIKA)

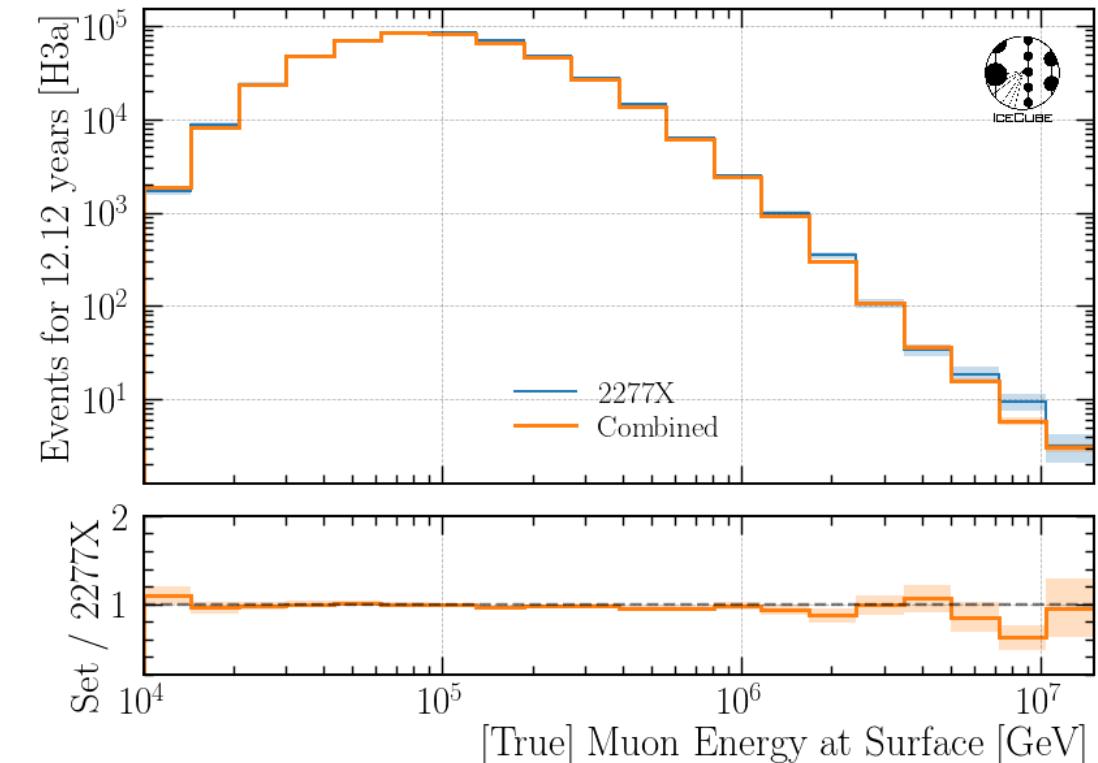
→ Increase MC statistics

# Combine Several CORSIKA Datasets

simulated

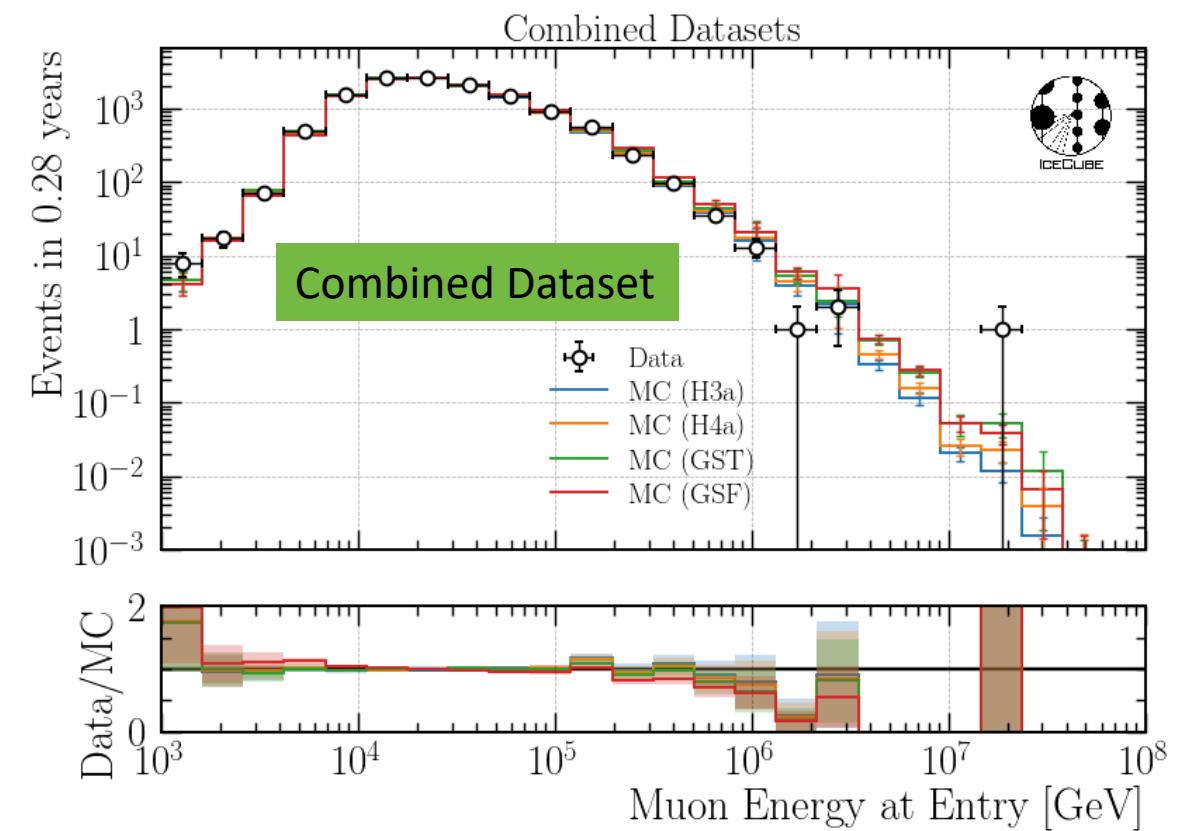
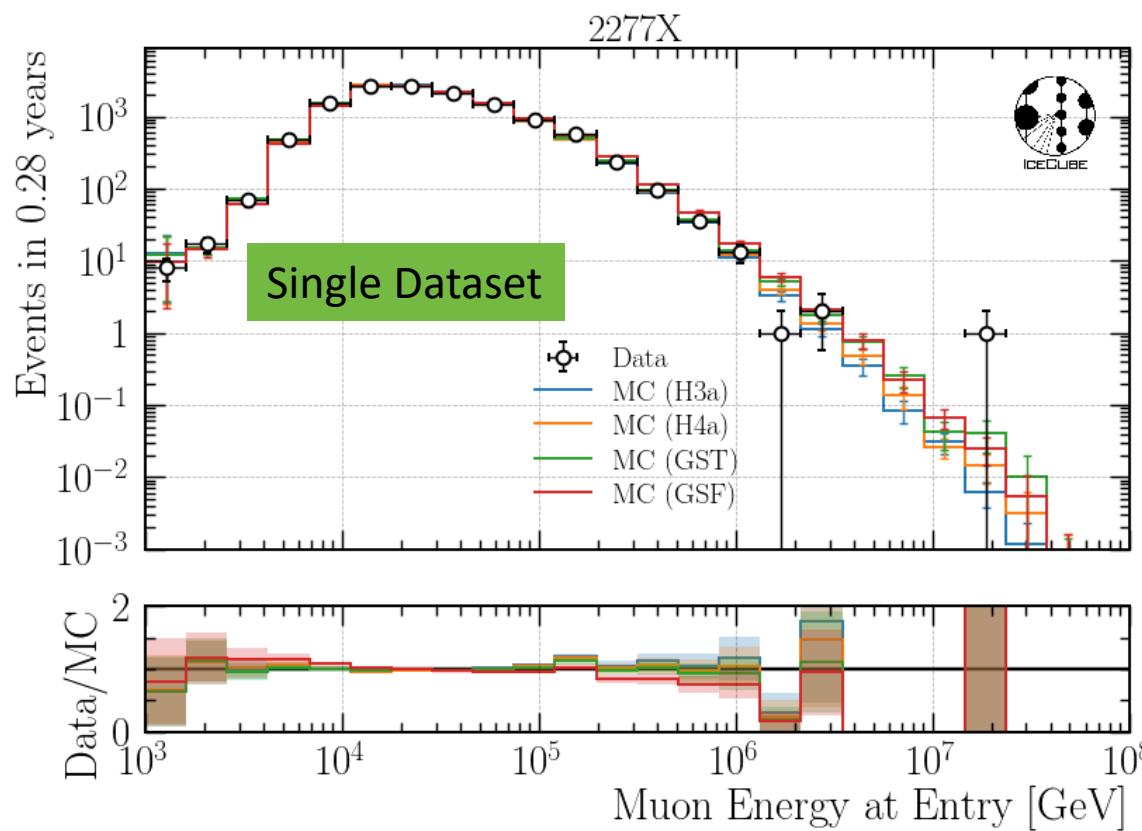


weighted



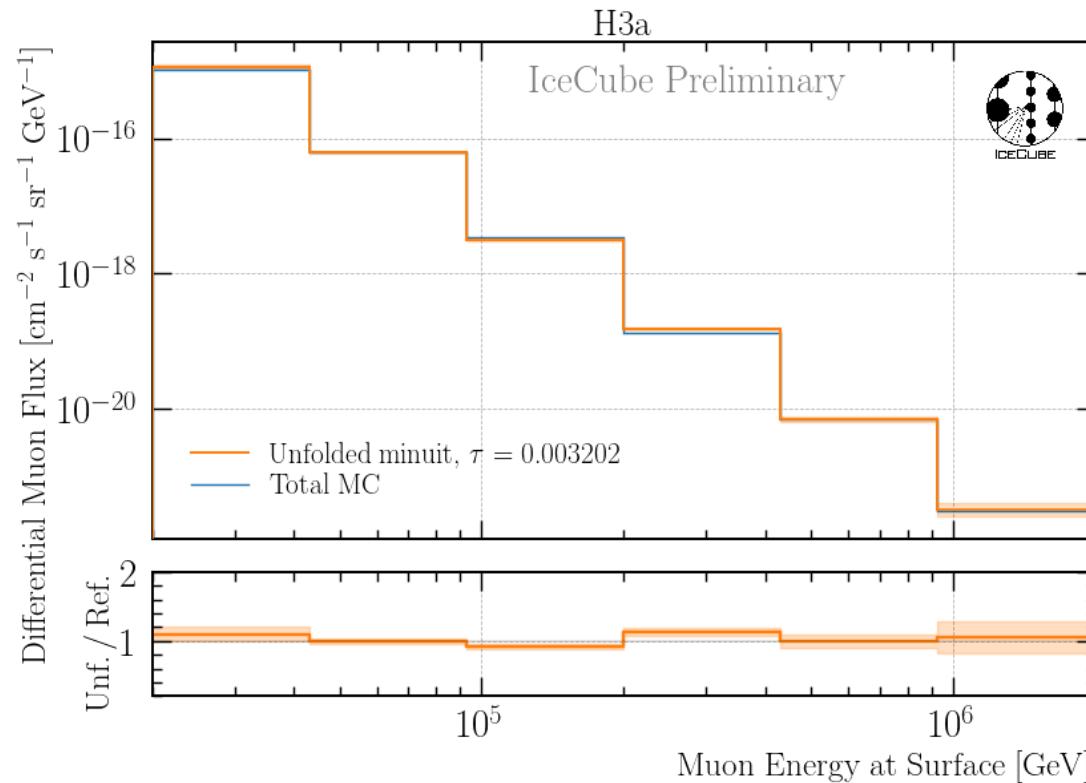
- Before: Only 2277X
- After: All sets → better statistics
- Weighting works

# Check Data-MC on Burnsample

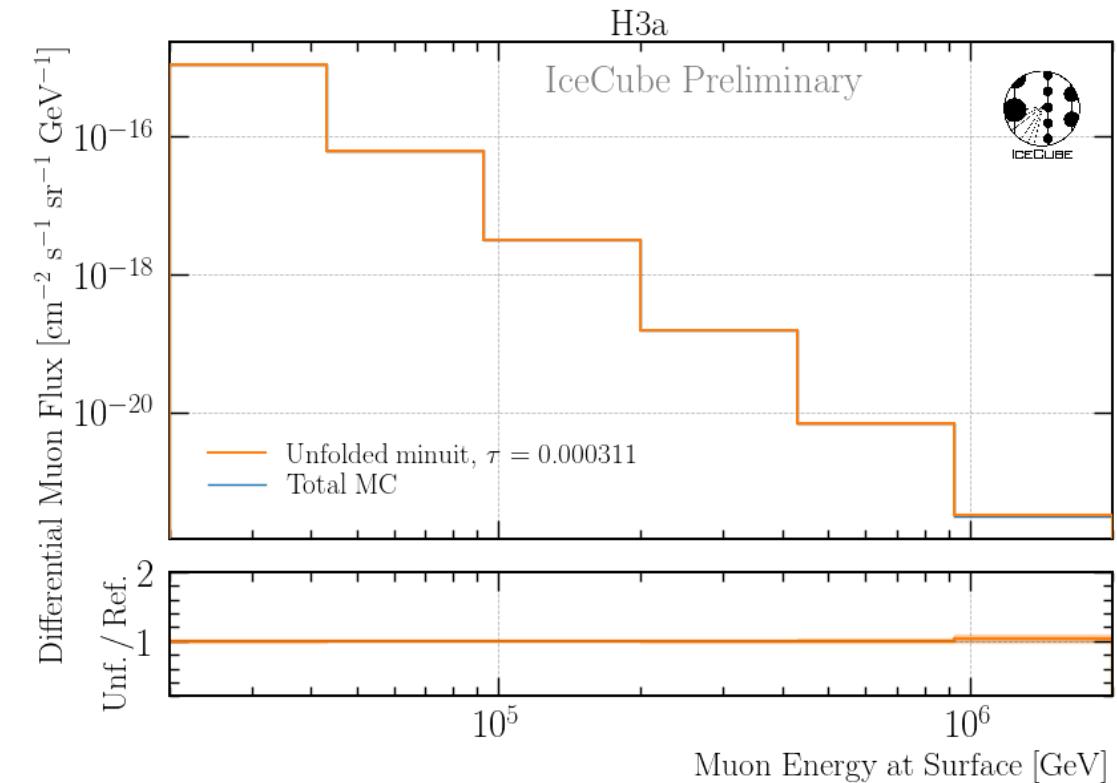


- Same agreement between 2277X and combined datasets

# Compare Burnsample Unfolding Bias



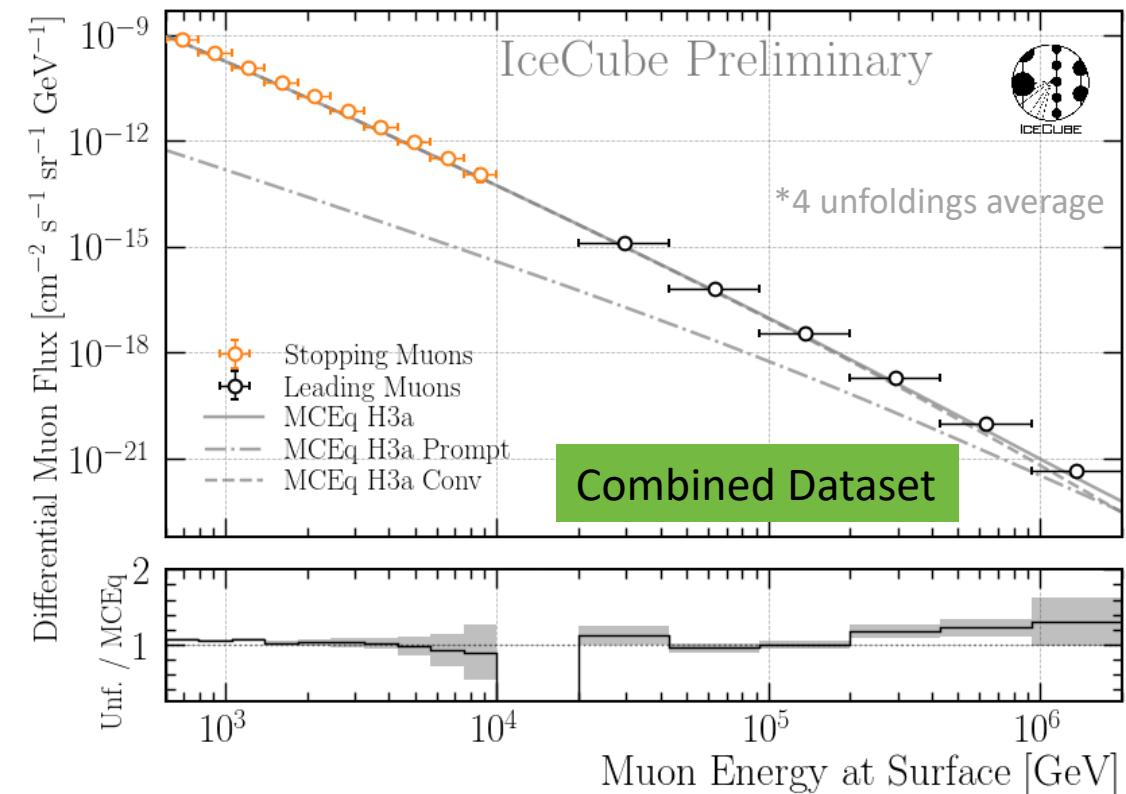
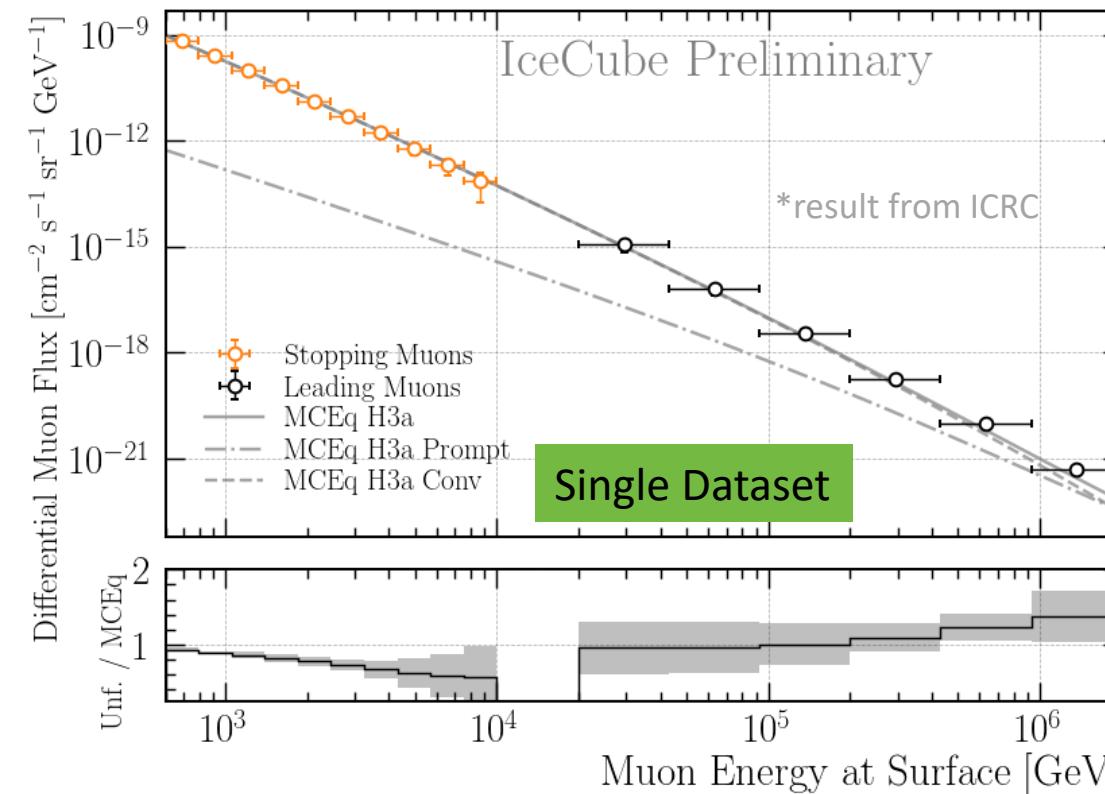
Single Dataset



Combined Dataset

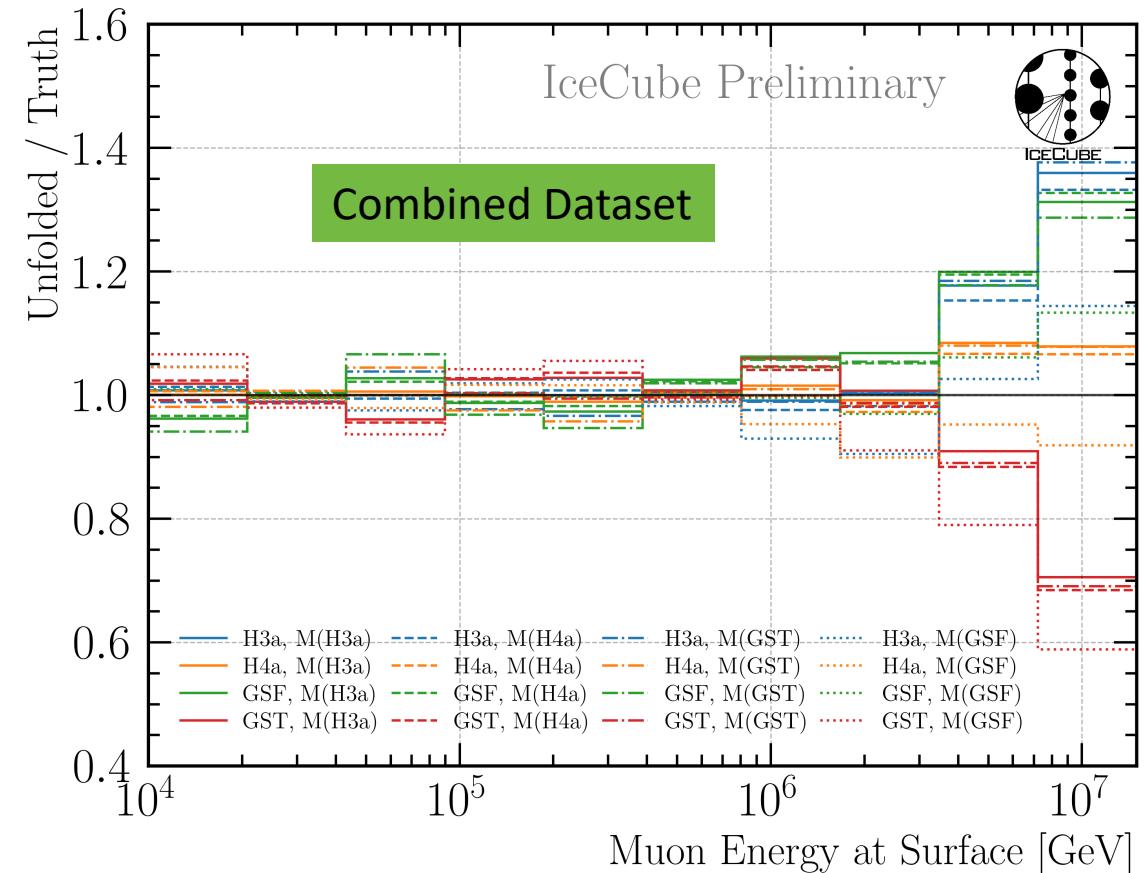
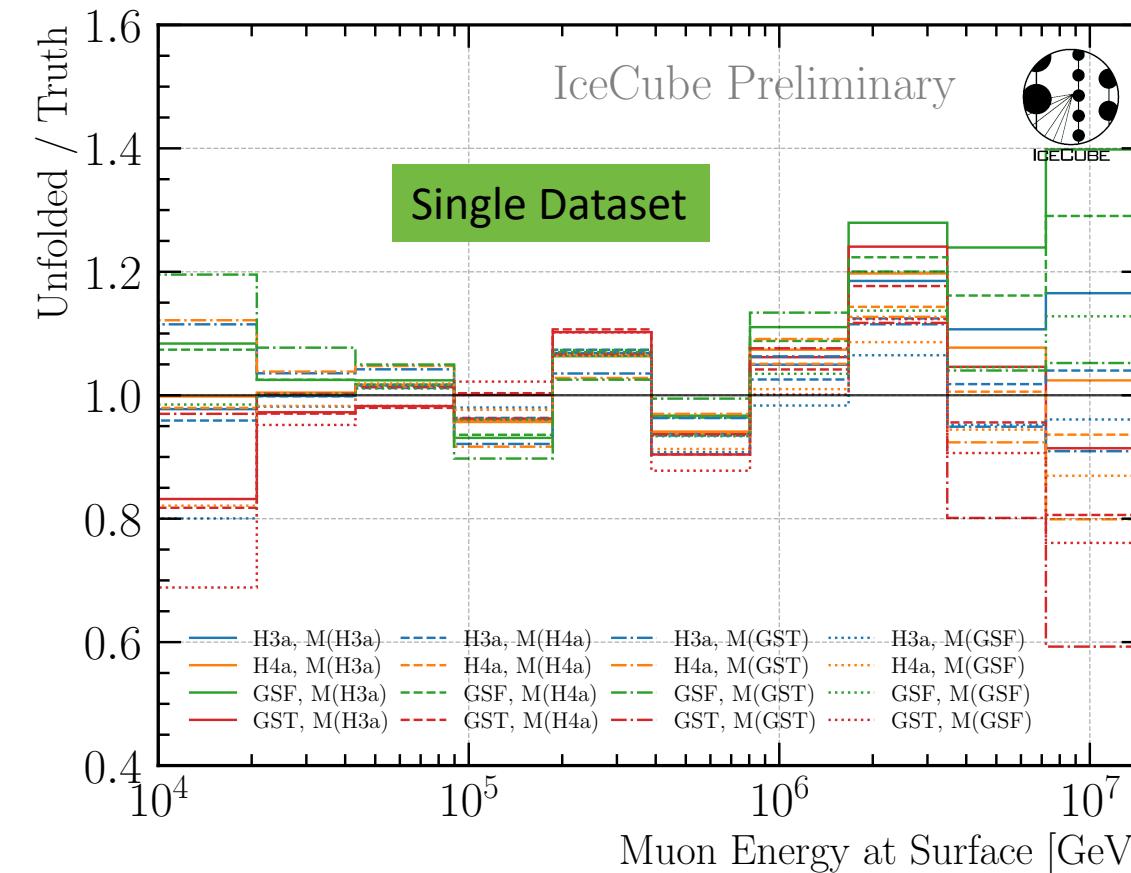
# Compare Burnsample Unfolding

Stopping muon unfolding has improved since ICRC  
→ Unblinding request soon



- Same result for 2277X unfolding and combined unfolding

# Compare “Unfolding Bias”



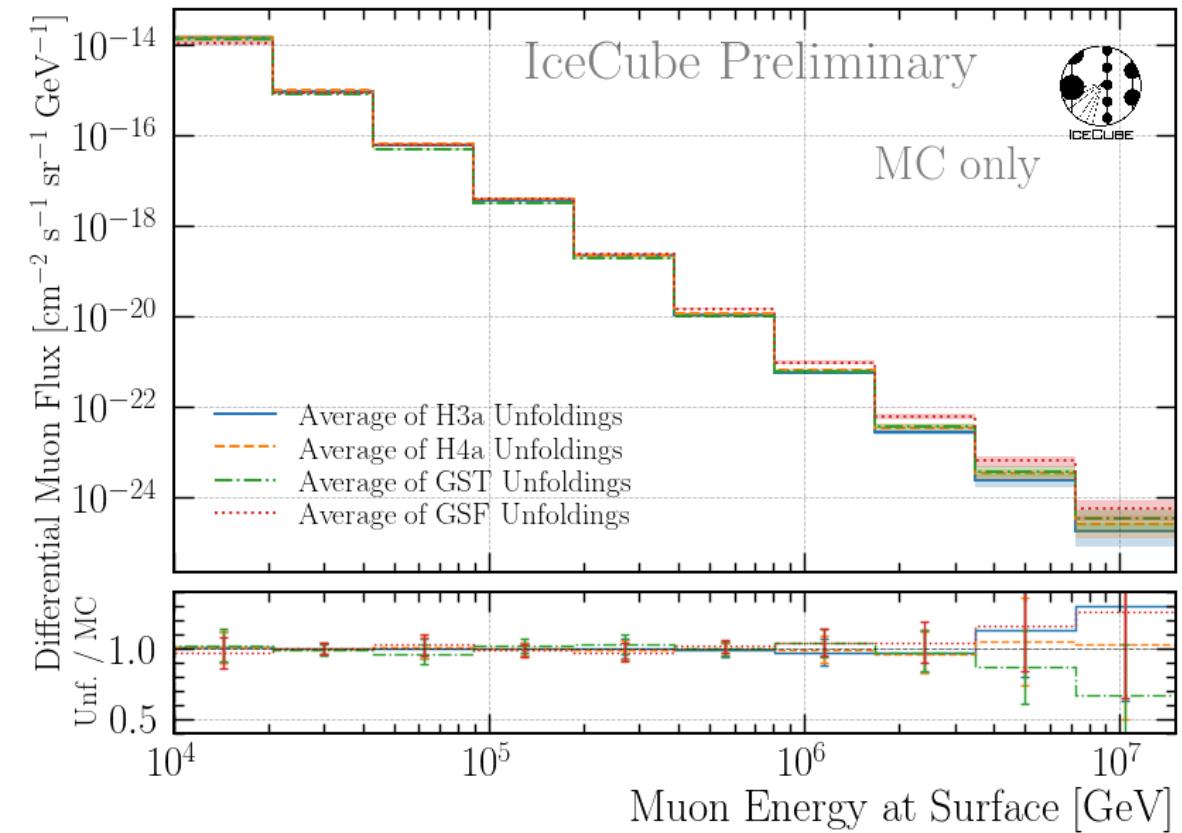
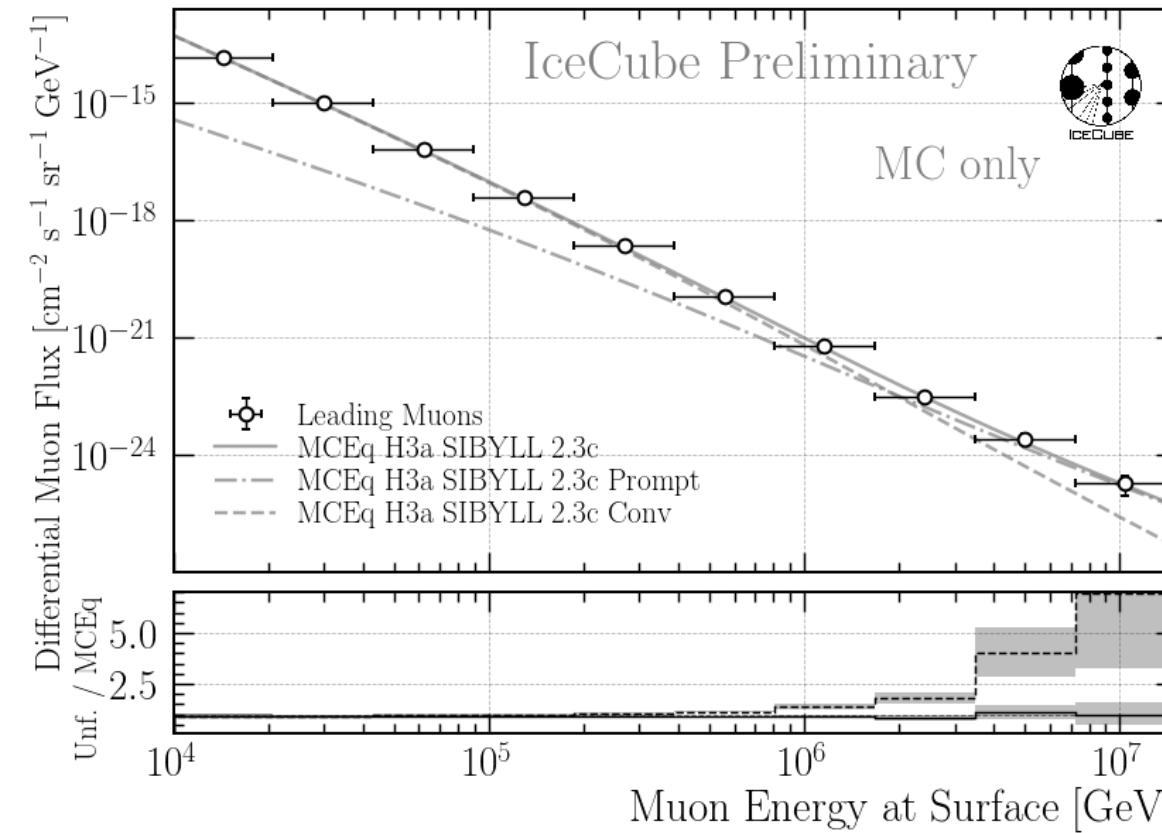
- Combining datasets improves injection recovery

## Summary

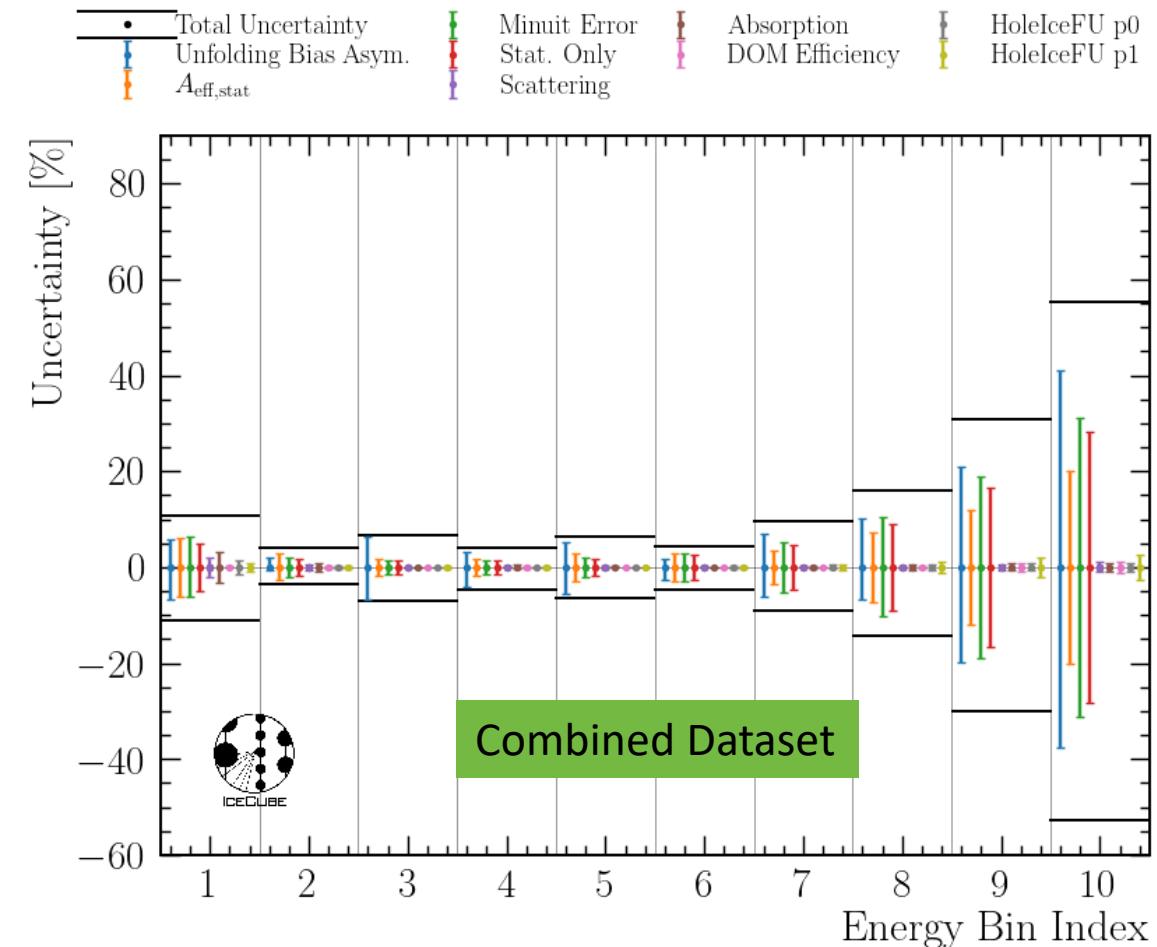
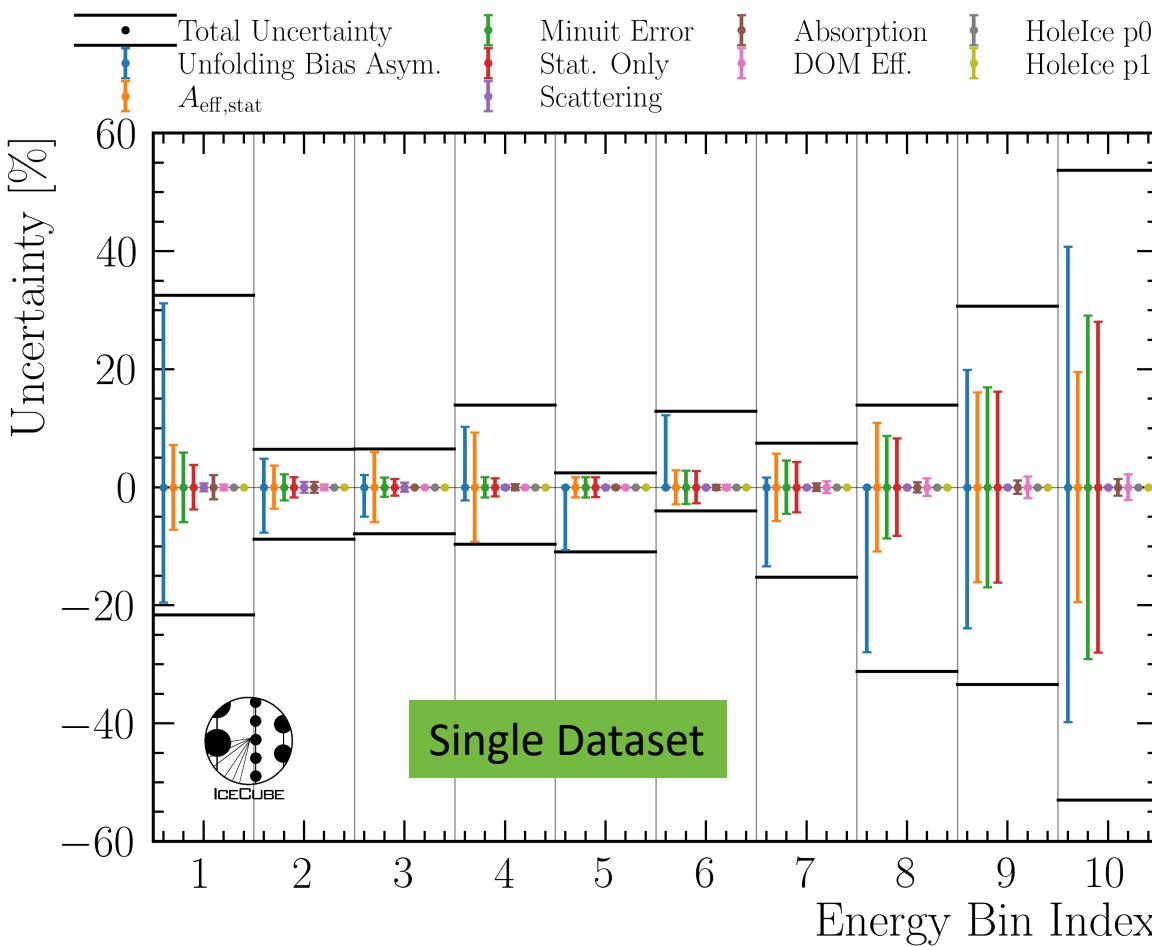
- HIM impact: smaller than primary model impact
  - Specific simulations take too many resources → not feasible
- Combine multiple CORSIKA datasets
  - Better statistics
  - Same data—MC agreement
  - Better injection recovery
  - Burns sample unfolding compatible with ICRC result
  - Use combined datasets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

# Backup

# MC Unfolding with Combined Datasets

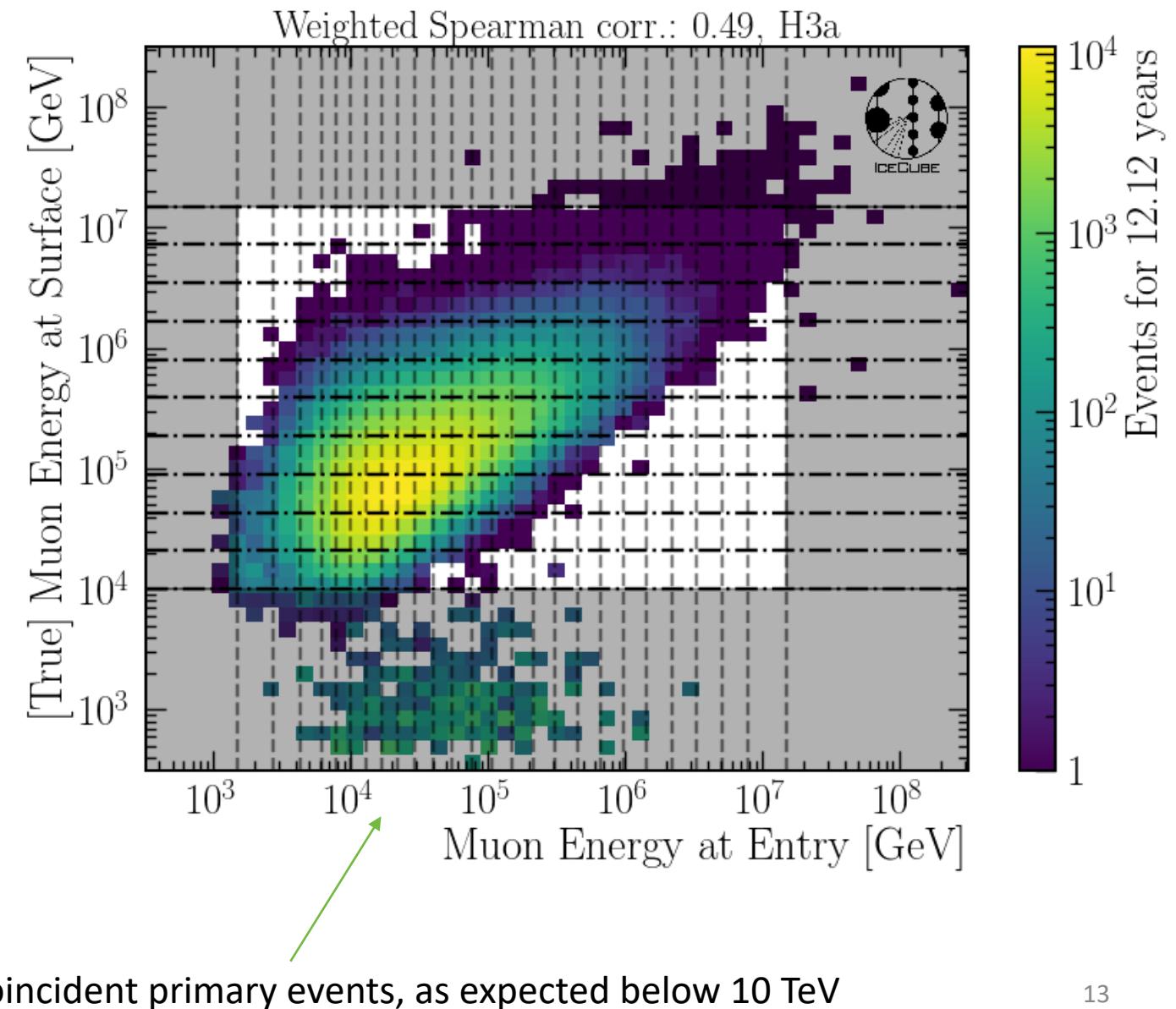


# Comparison Uncertainties per Bin

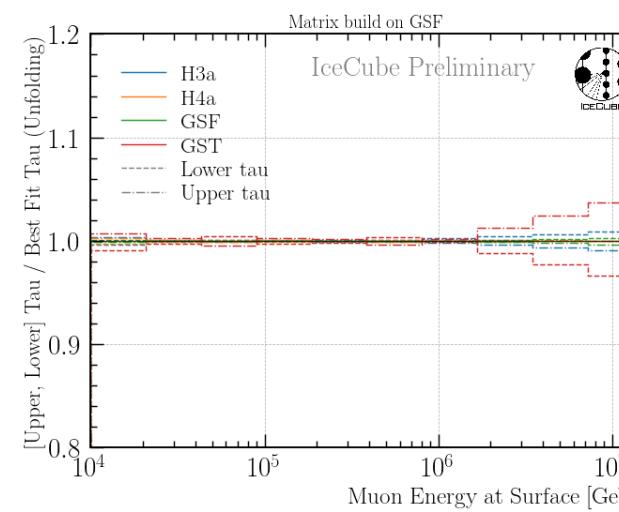
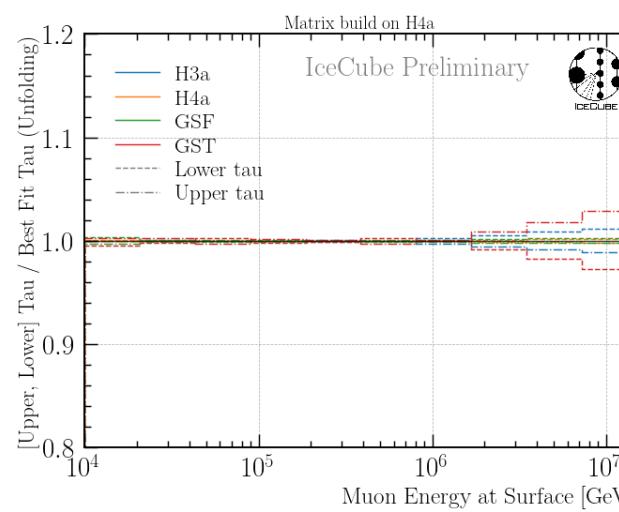
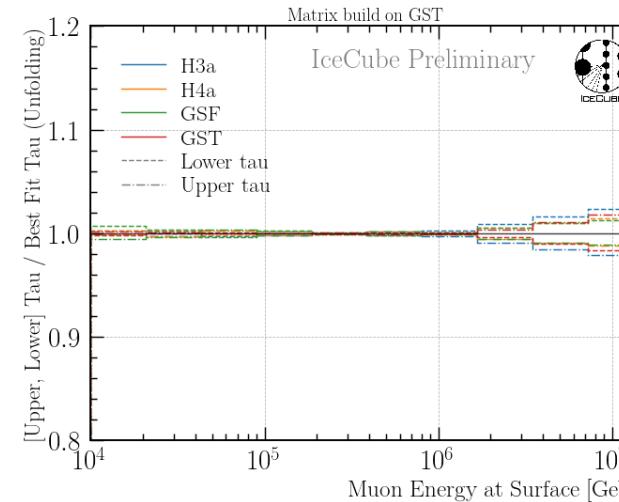
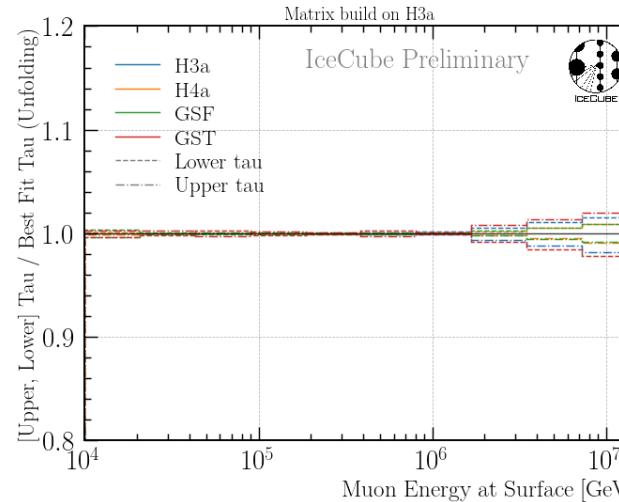


# Target – Pseudo Correlation

- shaded area indicates analysis binning

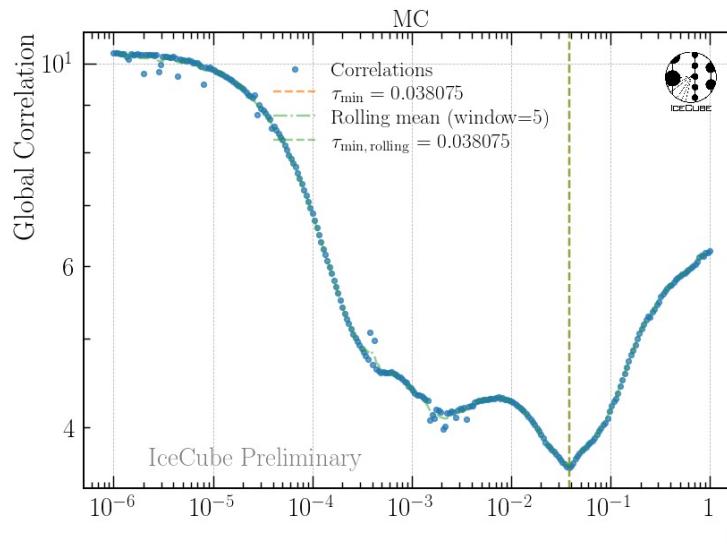


# Regularization Impact

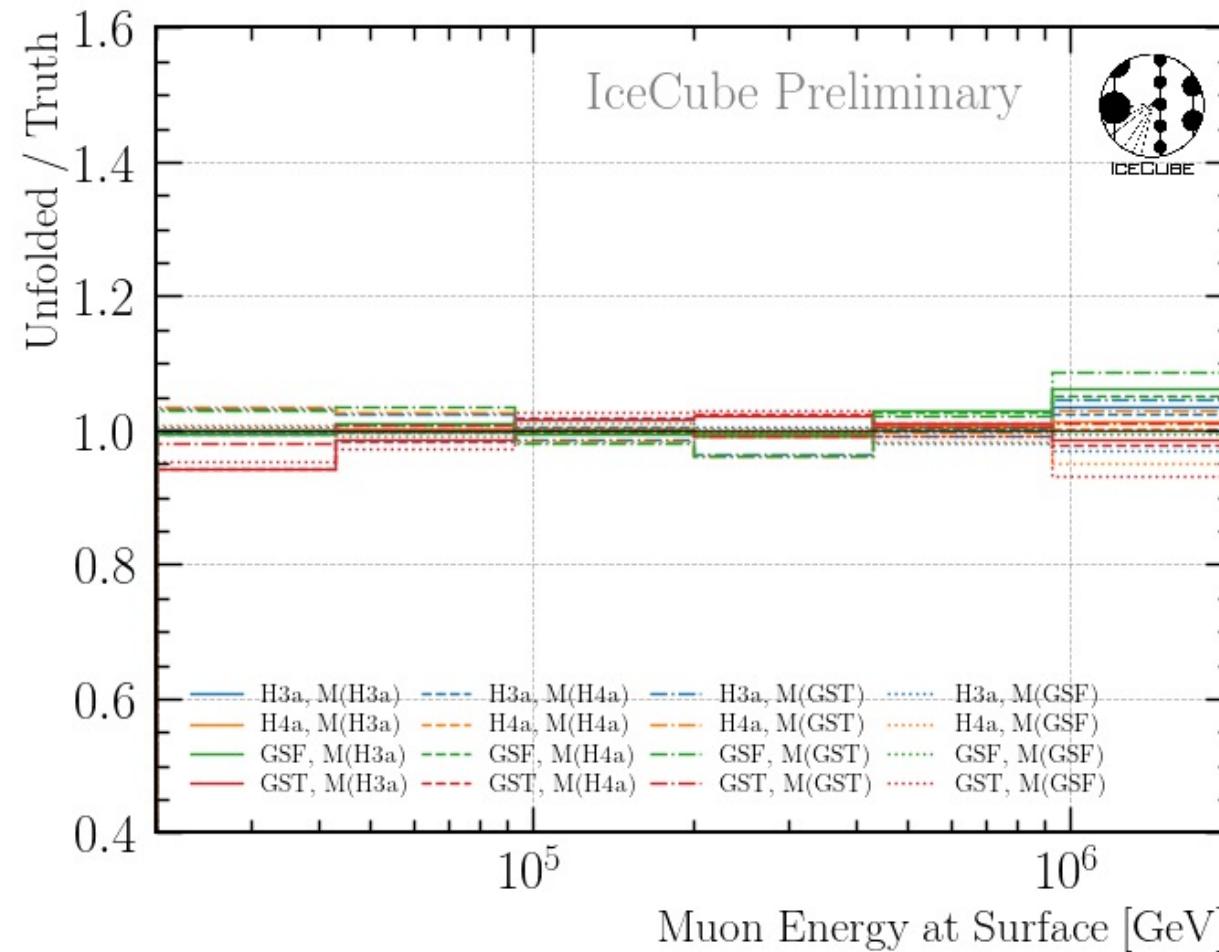


- regularization impact below 5%

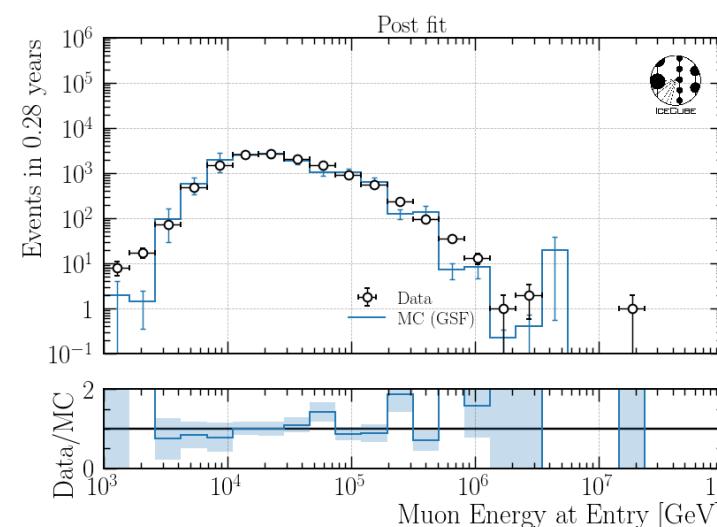
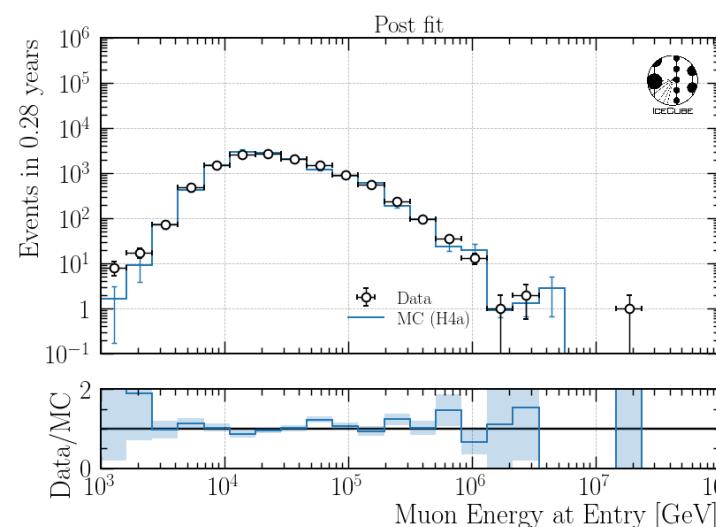
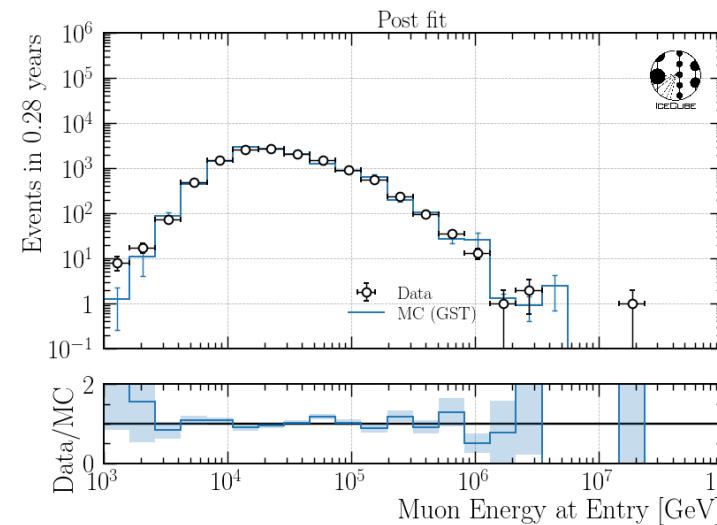
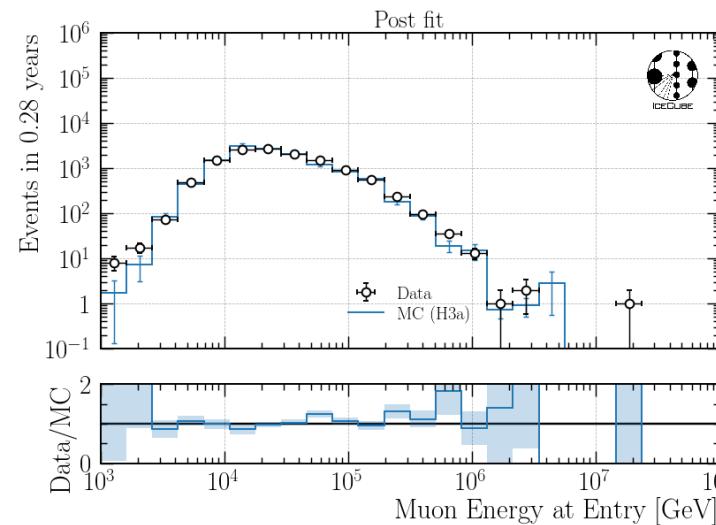
# Compare Burnsample Unfolding Global Correlation



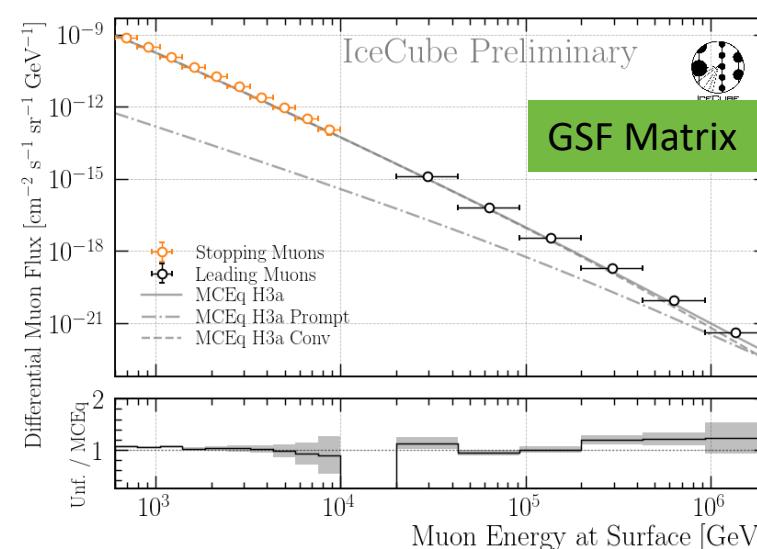
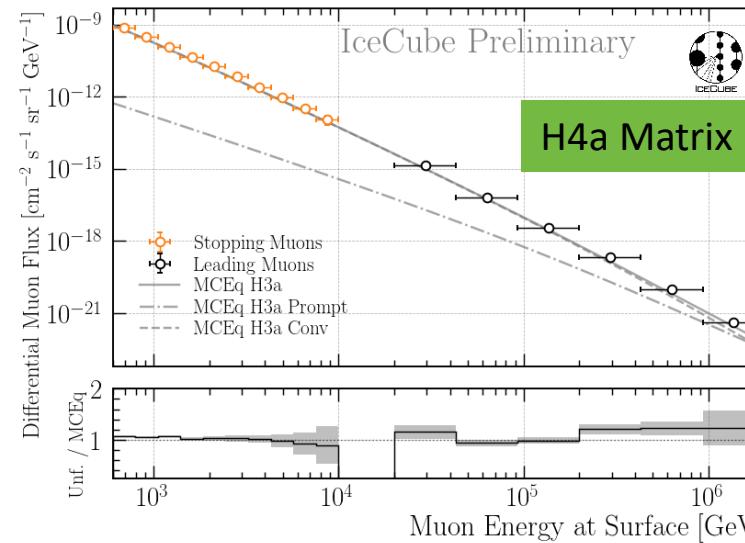
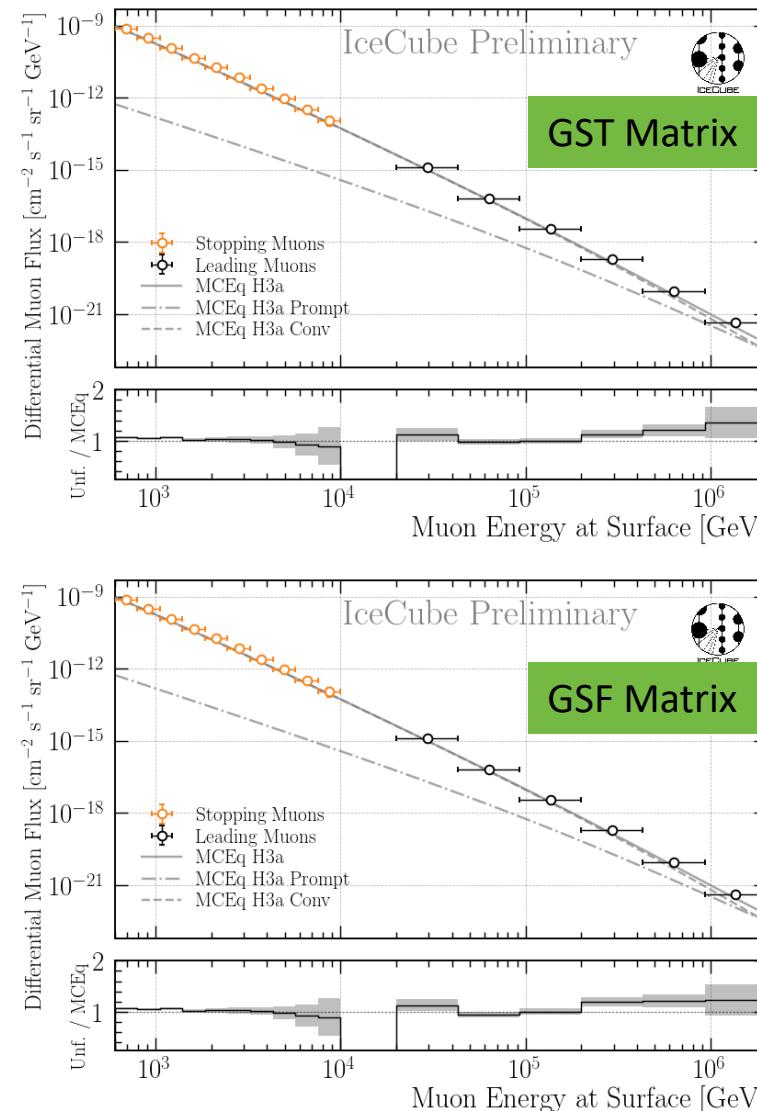
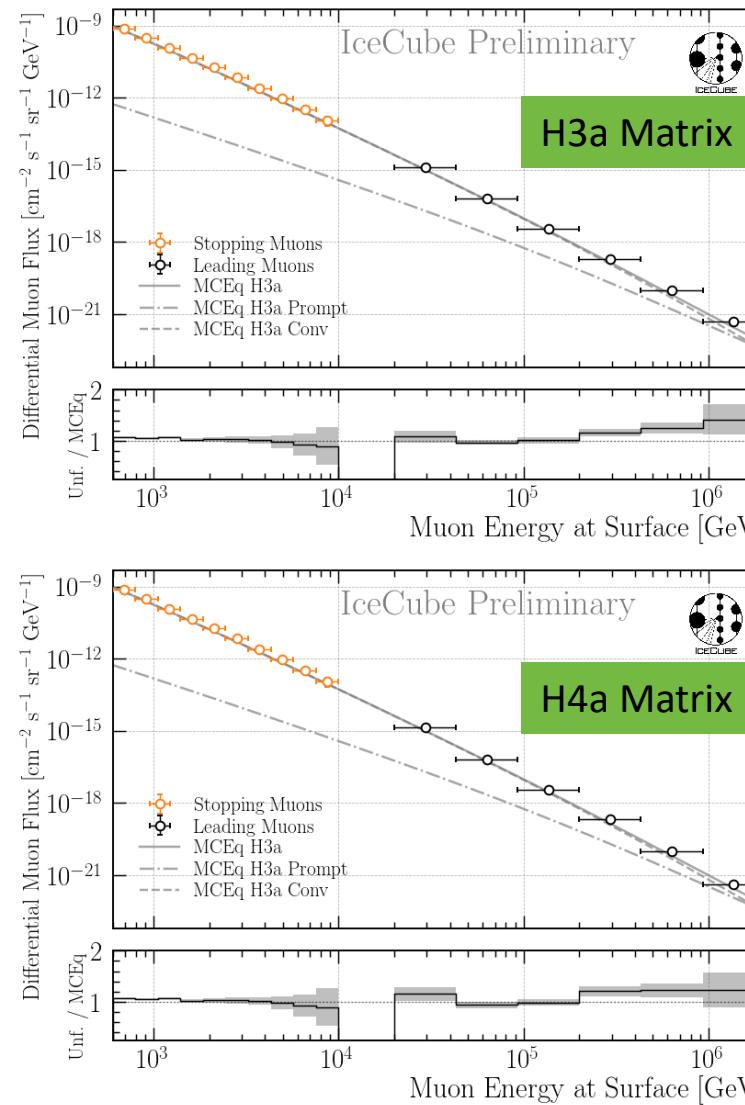
# Unfolding Bias on Burnsample with Combined Datasets



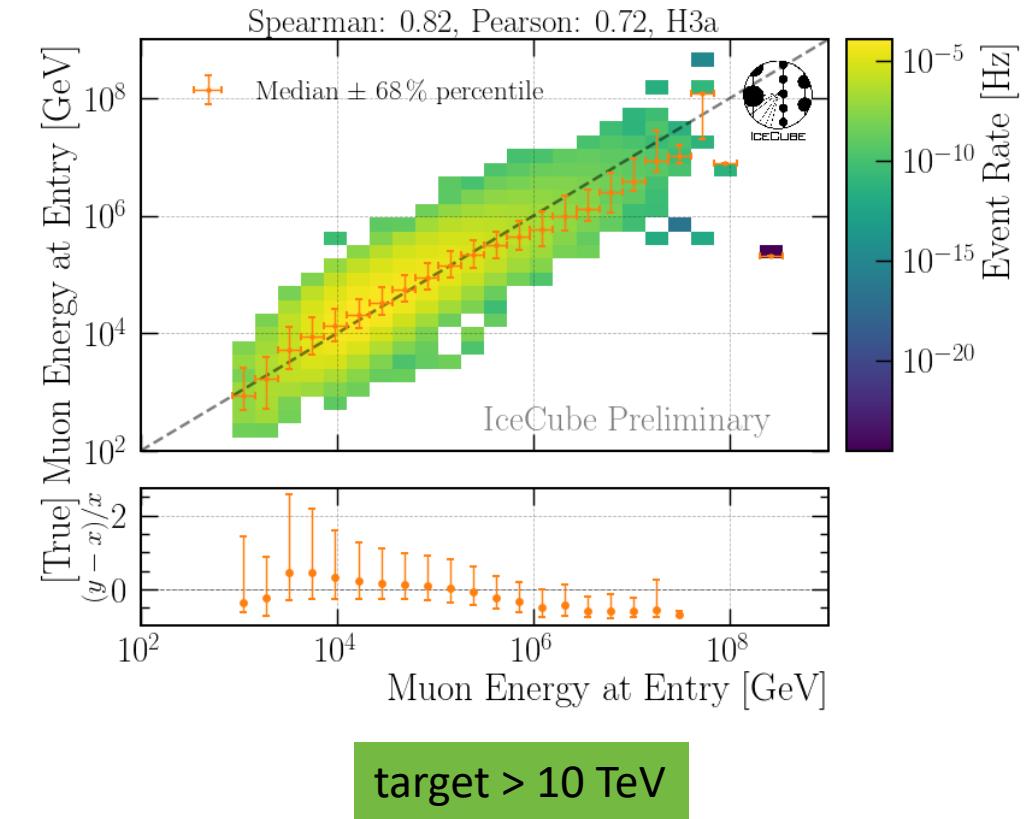
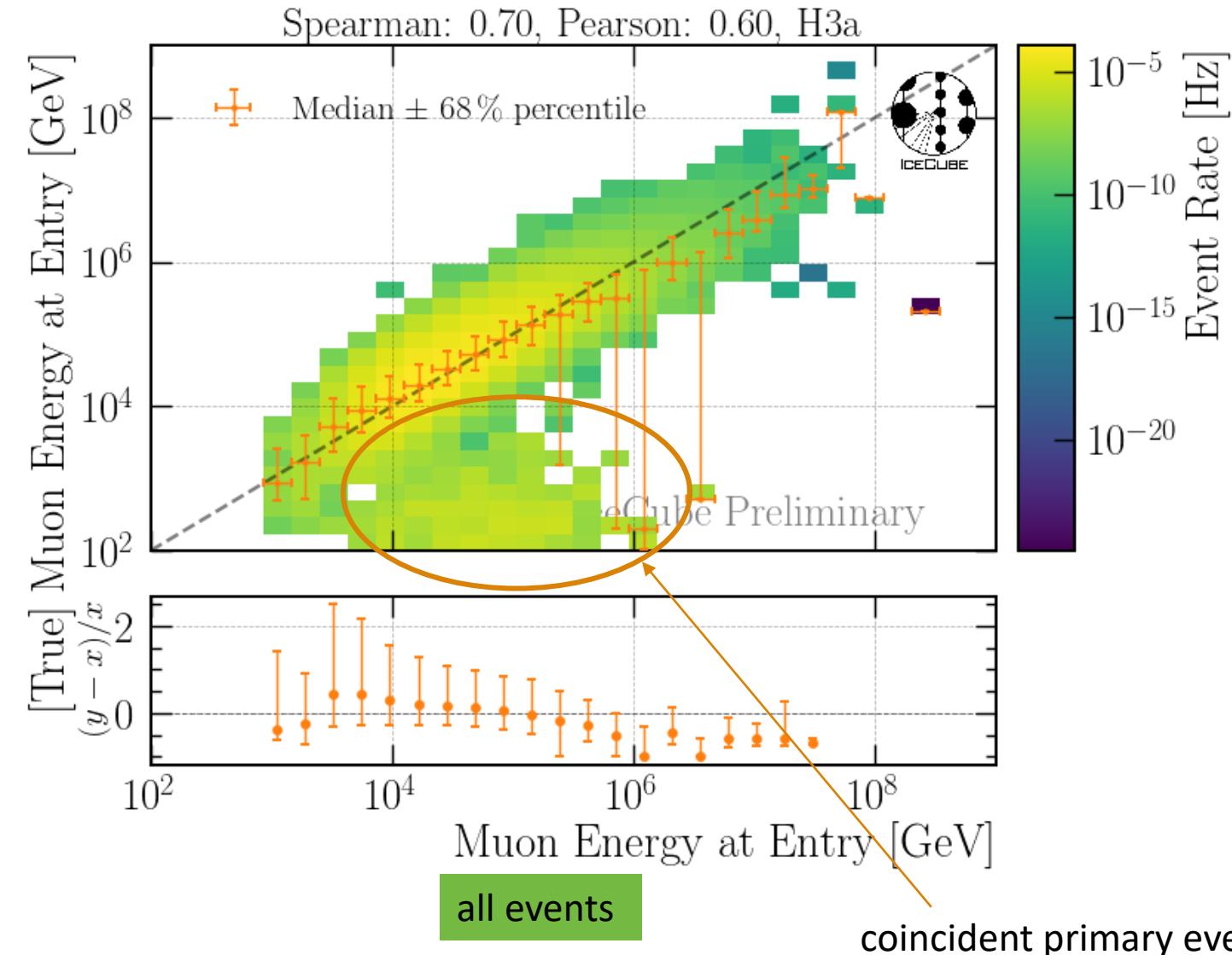
# Data-MC Post Fit for 4 Burnsample Unfoldings with Combined Datasets



# 4 Burnsample Unfolding Results with Combined Datasets



# Reconstruction Performance on Combined Dataset

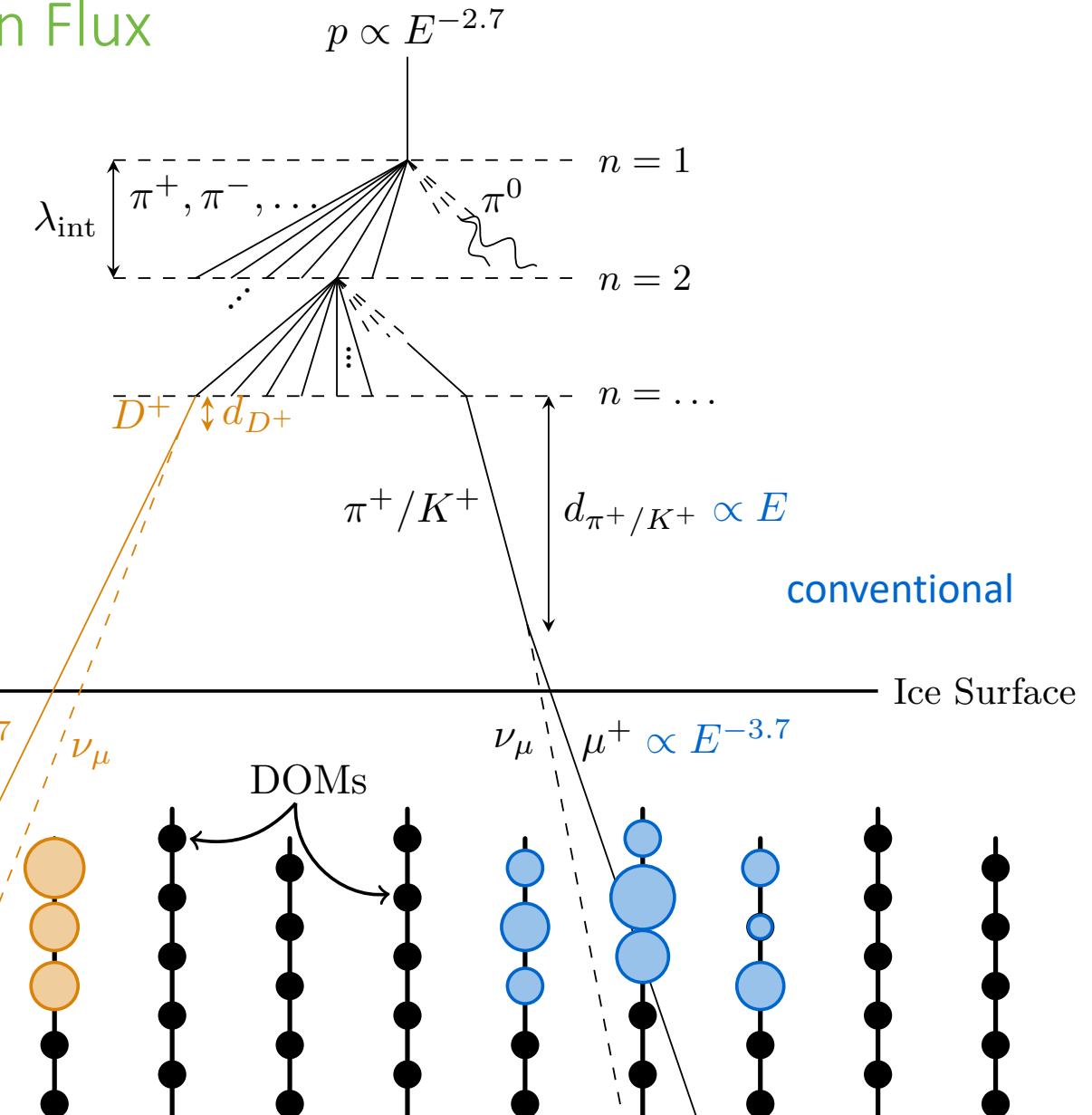


# Normalization Fit MC Full Sample

```
[LikelihoodFitter] Using diagonal symmetric uncertainties.  
=====  
LIKELIHOOD FIT SUMMARY  
=====  
  
Mode: Diagonal symmetric uncertainties  
  
Best-Fit Parameters:  
    Prompt normalization:      0.832565 ± 0.165685  
    Conventional normalization: 0.989772 ± 0.022720  
  
 $\chi^2 = 0.70$     ndof = 8     $\chi^2/\text{ndof} = 0.087$   
    Goodness-of-fit p-value: 0.9995  
    Parameter correlation: -0.6947  
  
=====  
HYPOTHESIS TEST:  $H_0$ : prompt normalization = 0  
=====  
 $\Delta\chi^2 = 12.625$   
p (one-sided, boundary-corrected) = 1.902833e-04  
significance approx ≈ 3.55σ  
significance exact = 3.55σ  
→ Reject  $H_0$  at 95 % CL → evidence for prompt component.  
=====
```

# Cosmic Ray Air Shower – Muon Flux

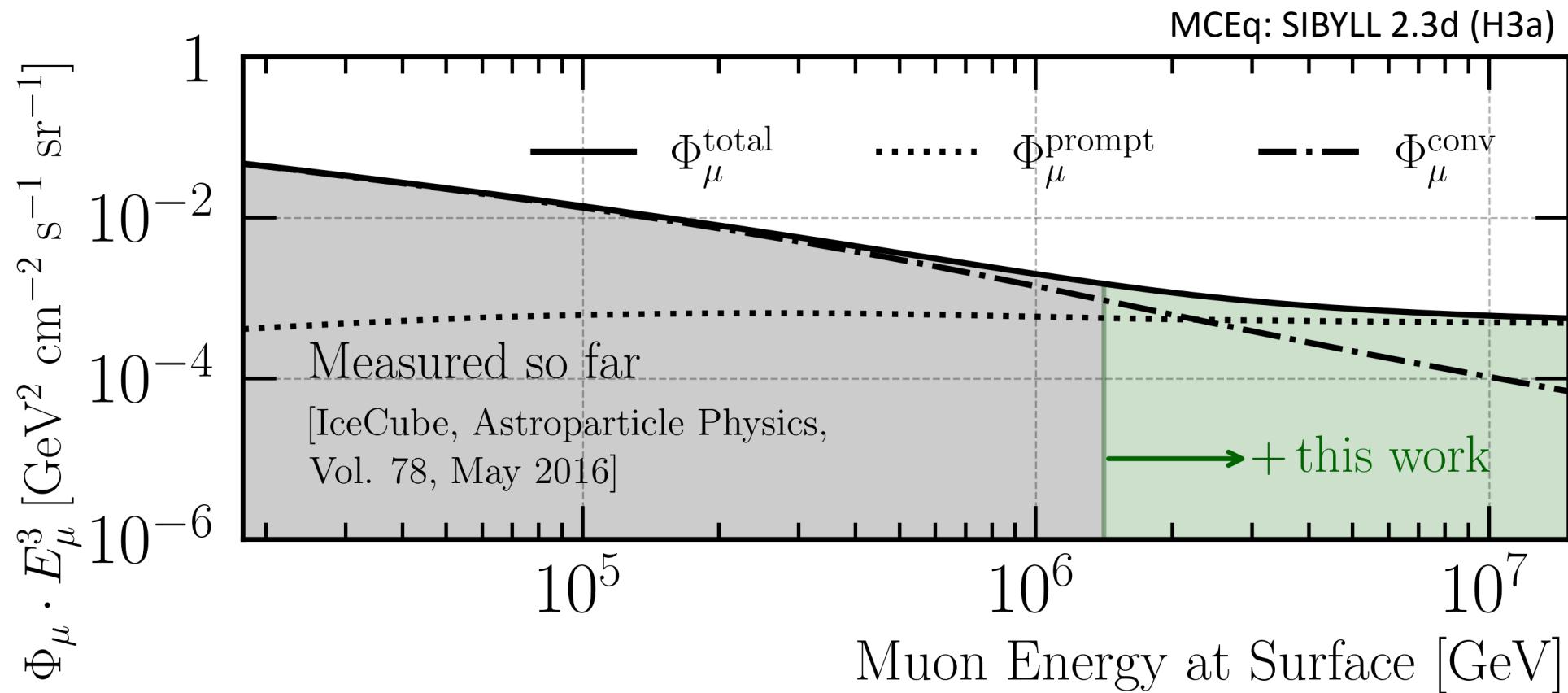
- Measure muon flux at surface
- Characterize prompt and conventional component



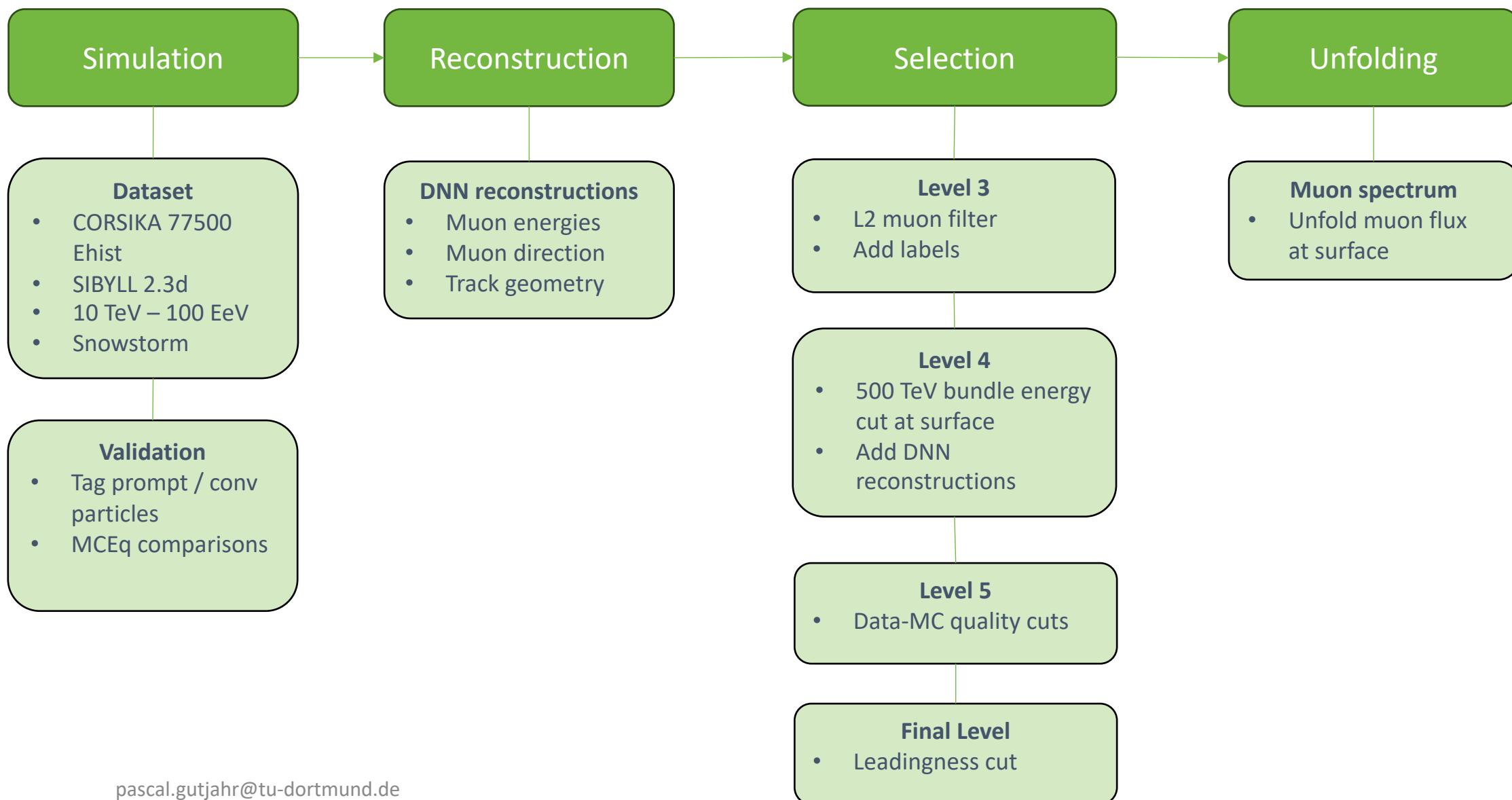
Conventional Muon:  
Parent is pion or kaon

Prompt Muon:  
„Rest“

# Goal: Measure Muon Flux at Surface



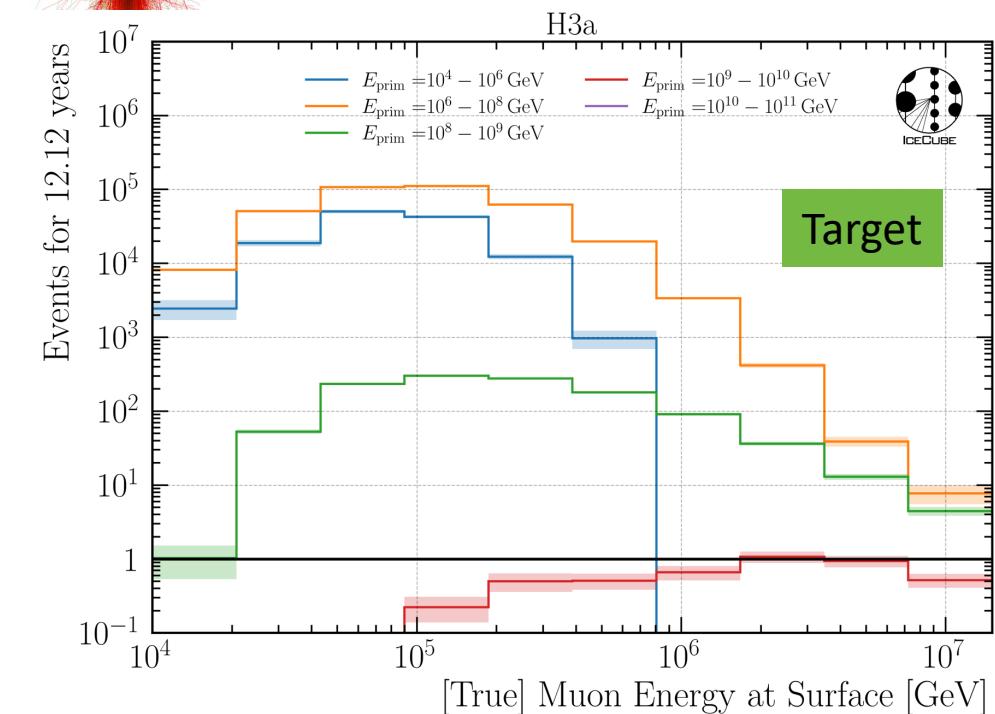
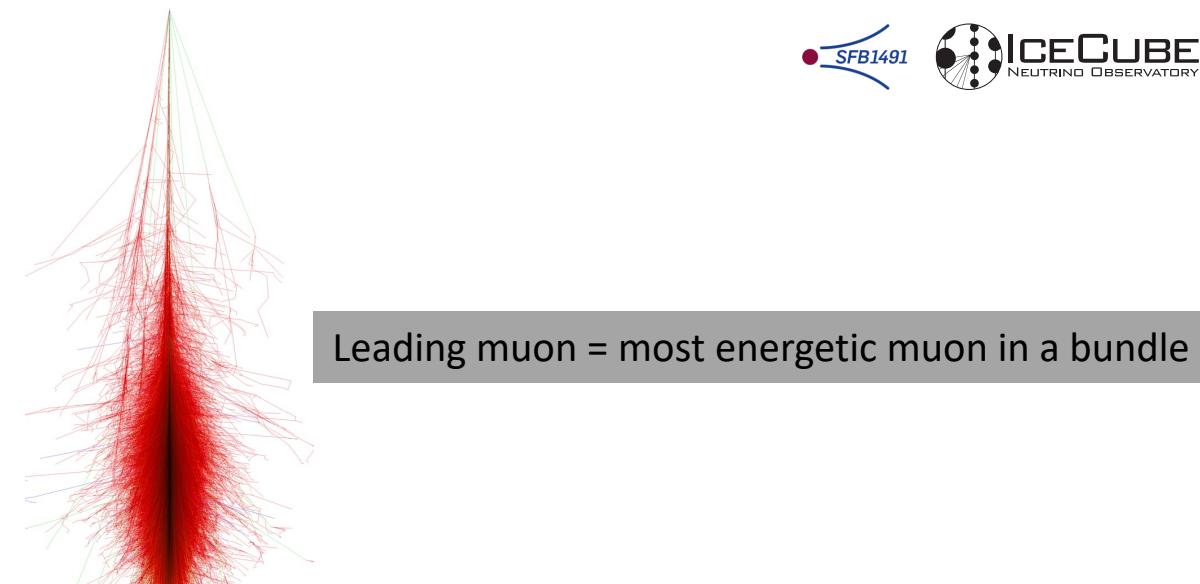
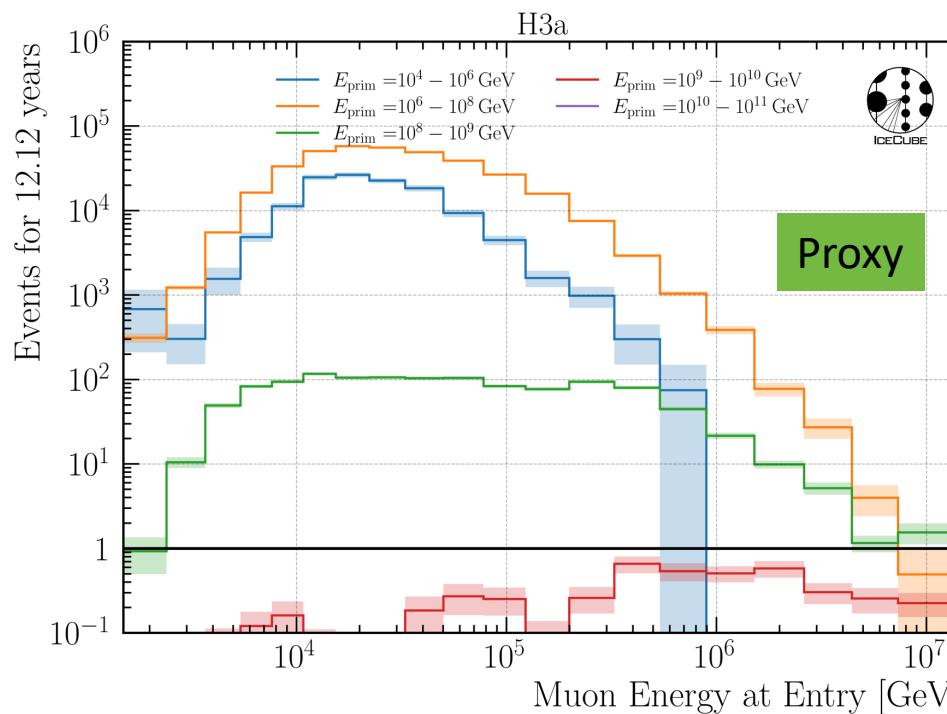
# Overview



# Simulation

# New CORSIKA Simulation

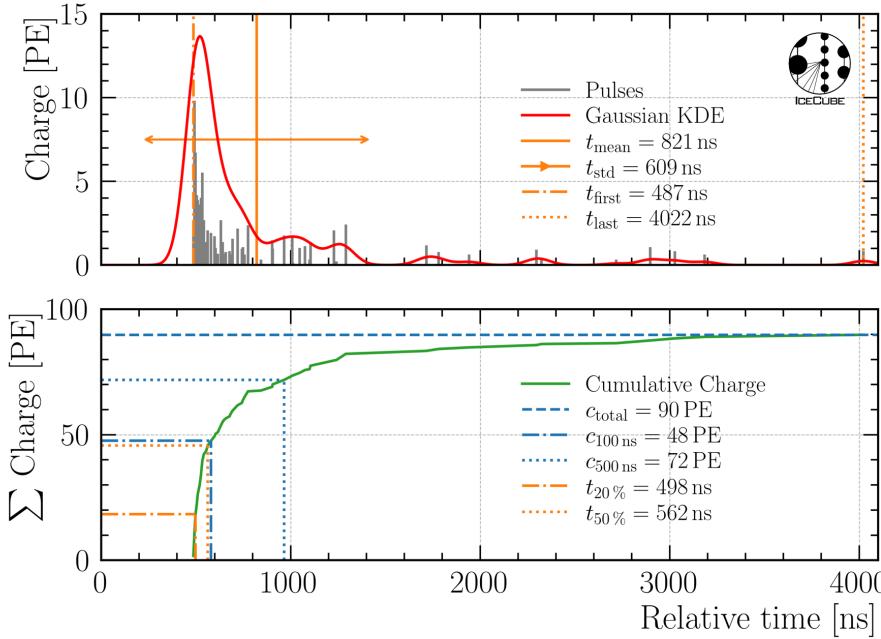
- Extended history → get muon parent information
- Official iceprod datasets: 22774 – 8
- Primary energy: 10 TeV – 1e11 GeV
- HIM: SIBYLL 2.3d



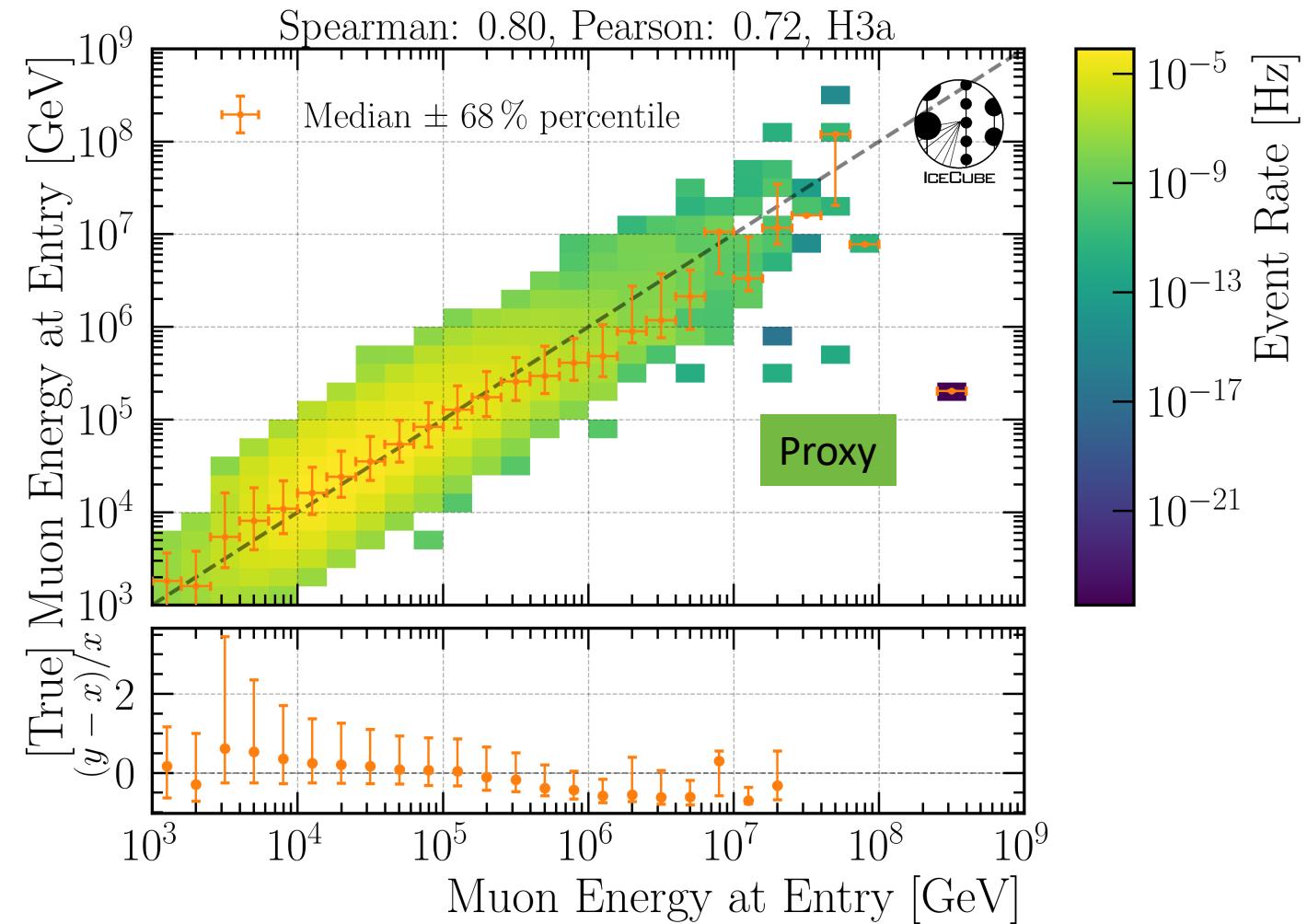
# Reconstruction

# CNN Reconstructions

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



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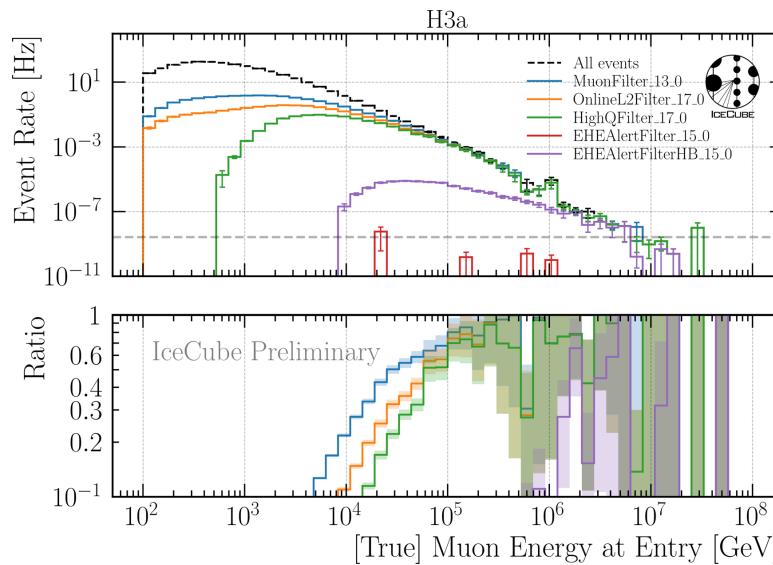
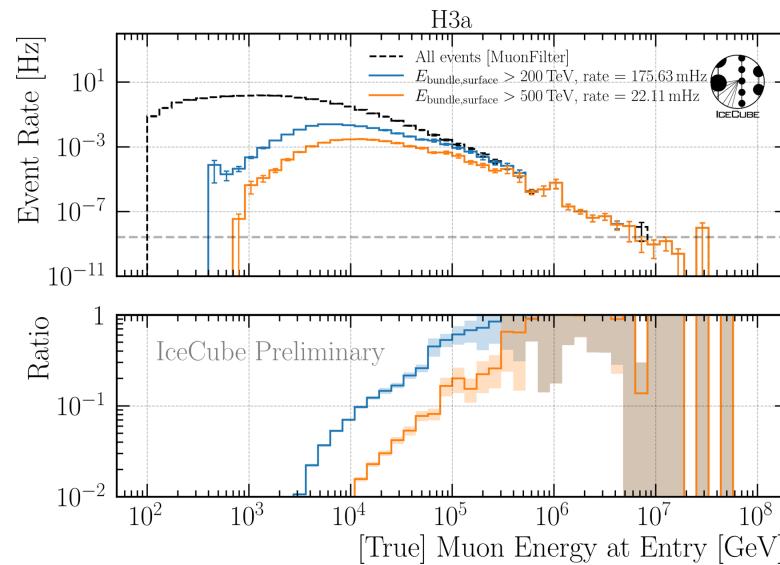
27

# Selection

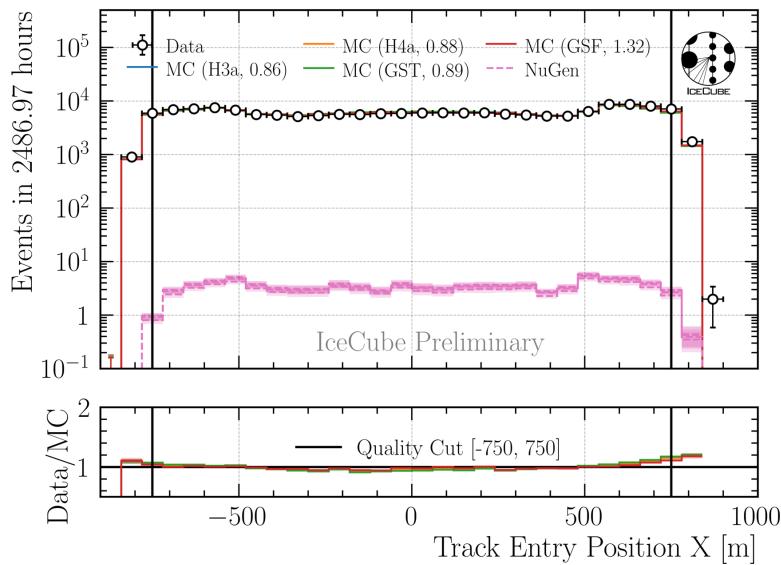
## Selection

Details: [wiki/selection](#)

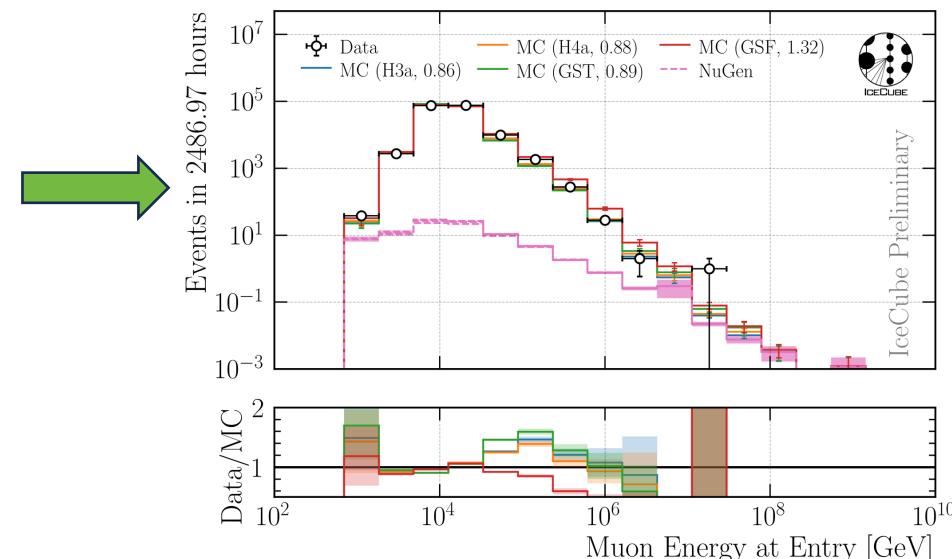
## Level 3: MuonFilter

Level 4:  $E > 500 \text{ TeV}$  bundle Energy a surface

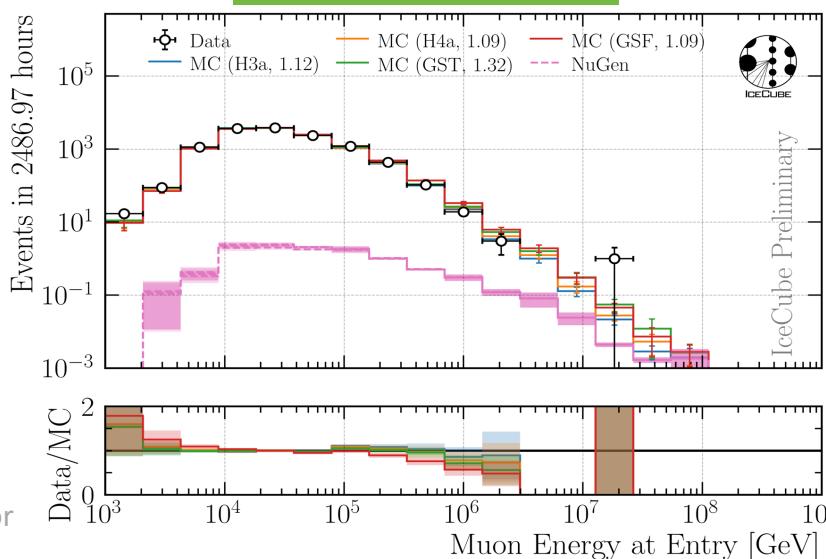
## Level 5: 23 Data/MC Quality Cuts

Final Level:  $L > 40 \%$ 

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



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



# Unfolding

# Unfolding in a nutshell

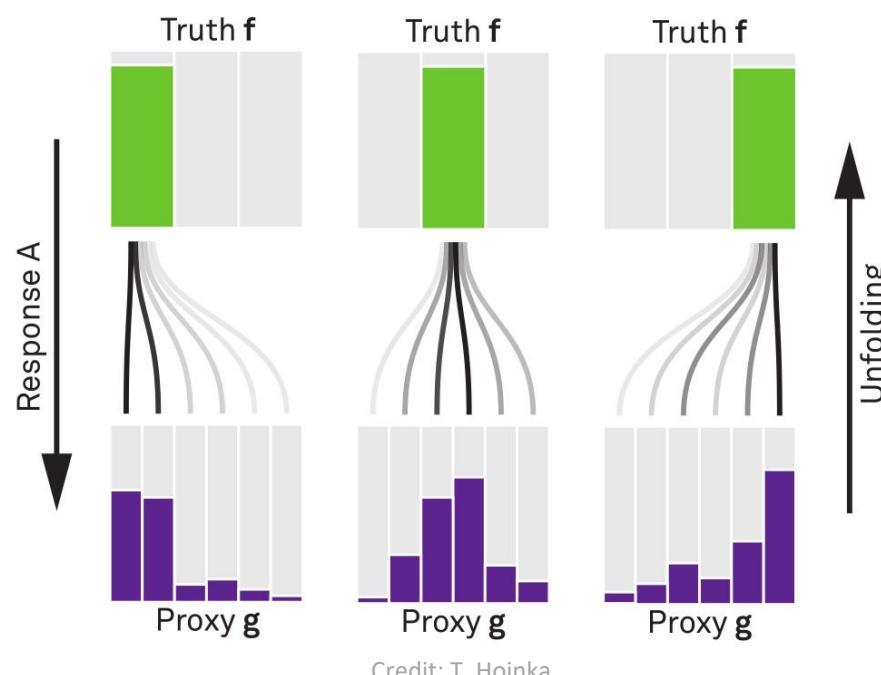
measured proxy

detector response

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

background

true energy distribution



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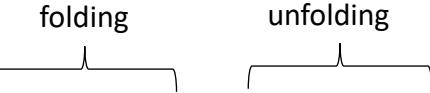
1. Discretized form:  $\vec{g} = A\vec{f} \leftrightarrow \vec{f} = A^{-1}\vec{g}$

2. Maximum likelihood method:

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

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

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



3. Tikhonov regularization:

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

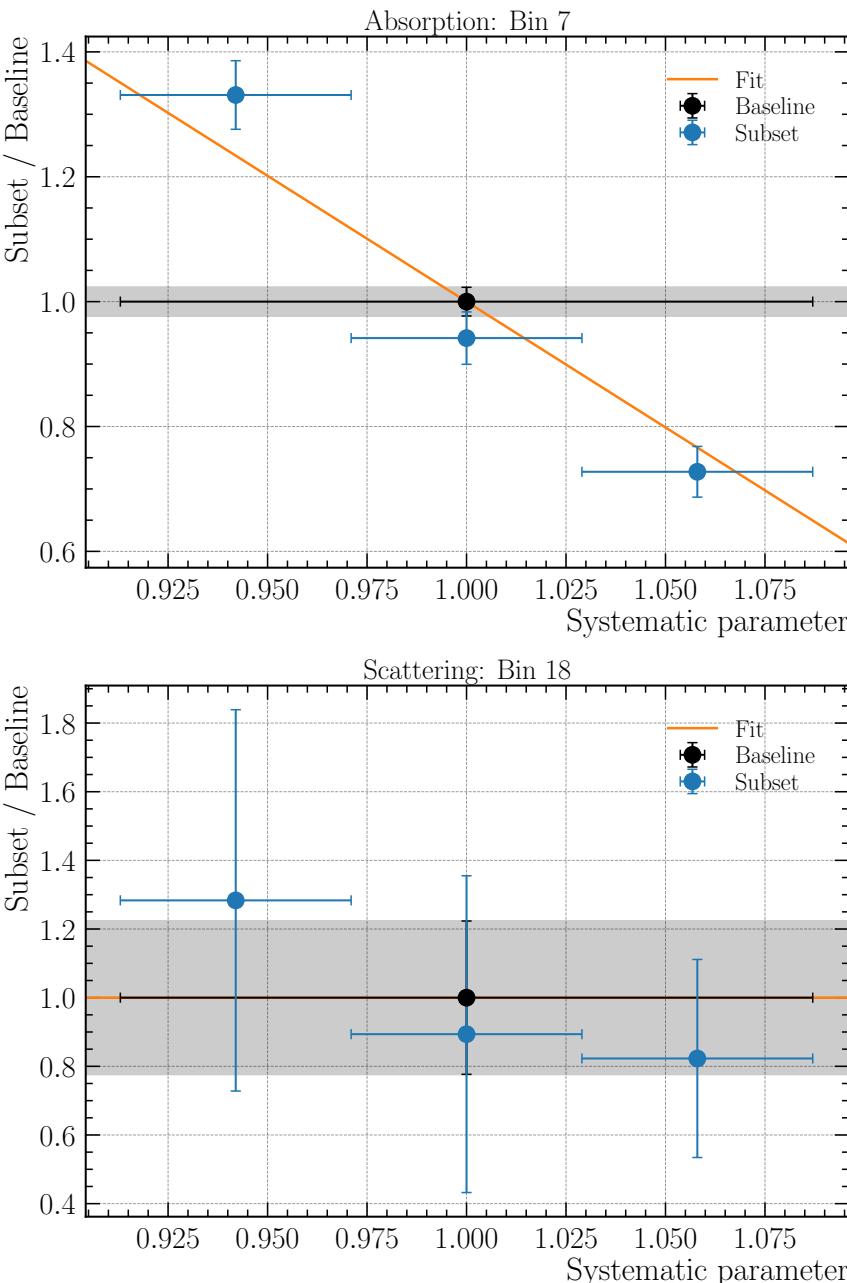
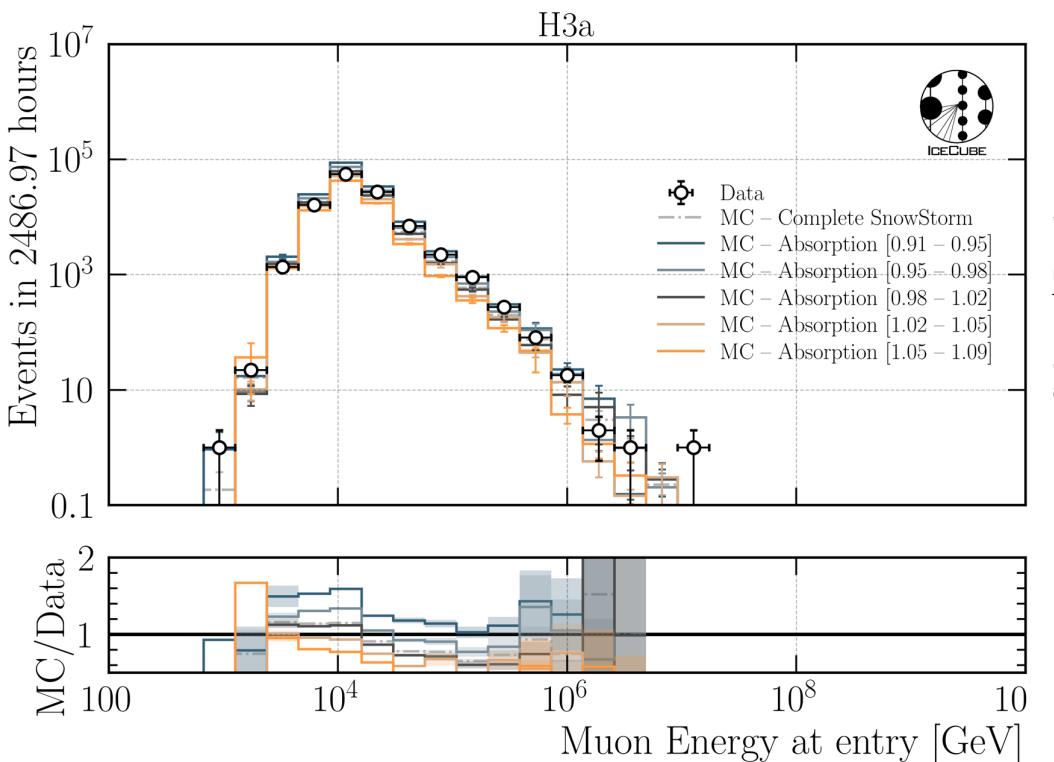


[funfolding](#)  
by M. Börner

# 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

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

- with solid angle

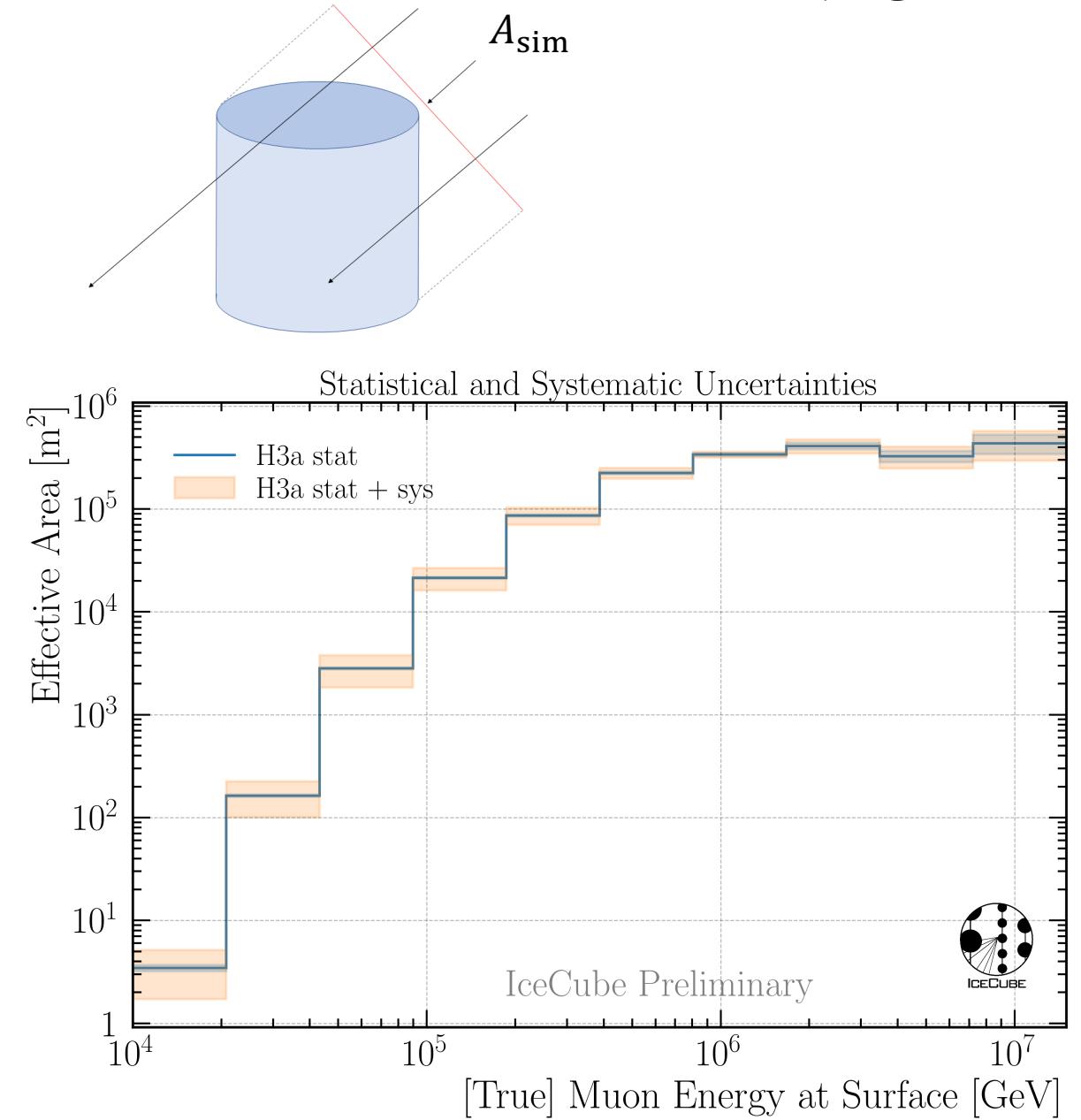
$$\Omega_i = 2\pi (\cos(\Omega_{\min,i}) - \cos(\Omega_{\max,i}))$$

- and effective area

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

final level events

generation level events

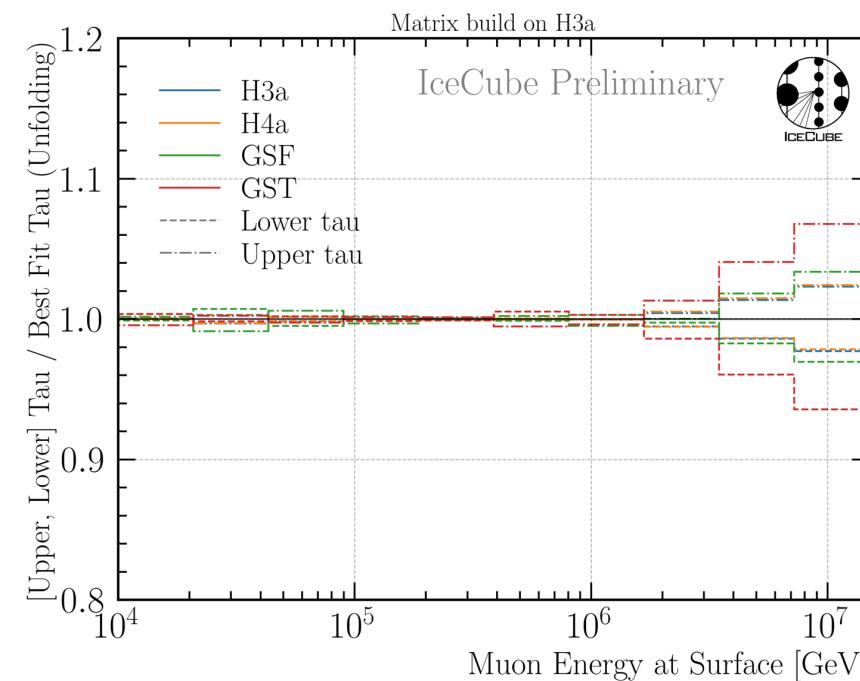
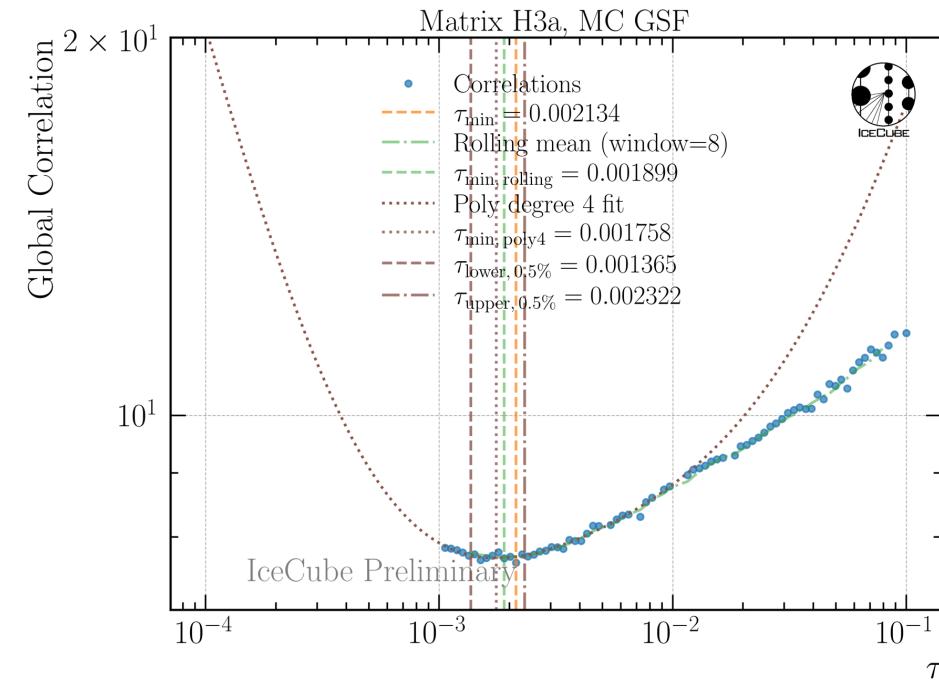


# Regularization

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

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

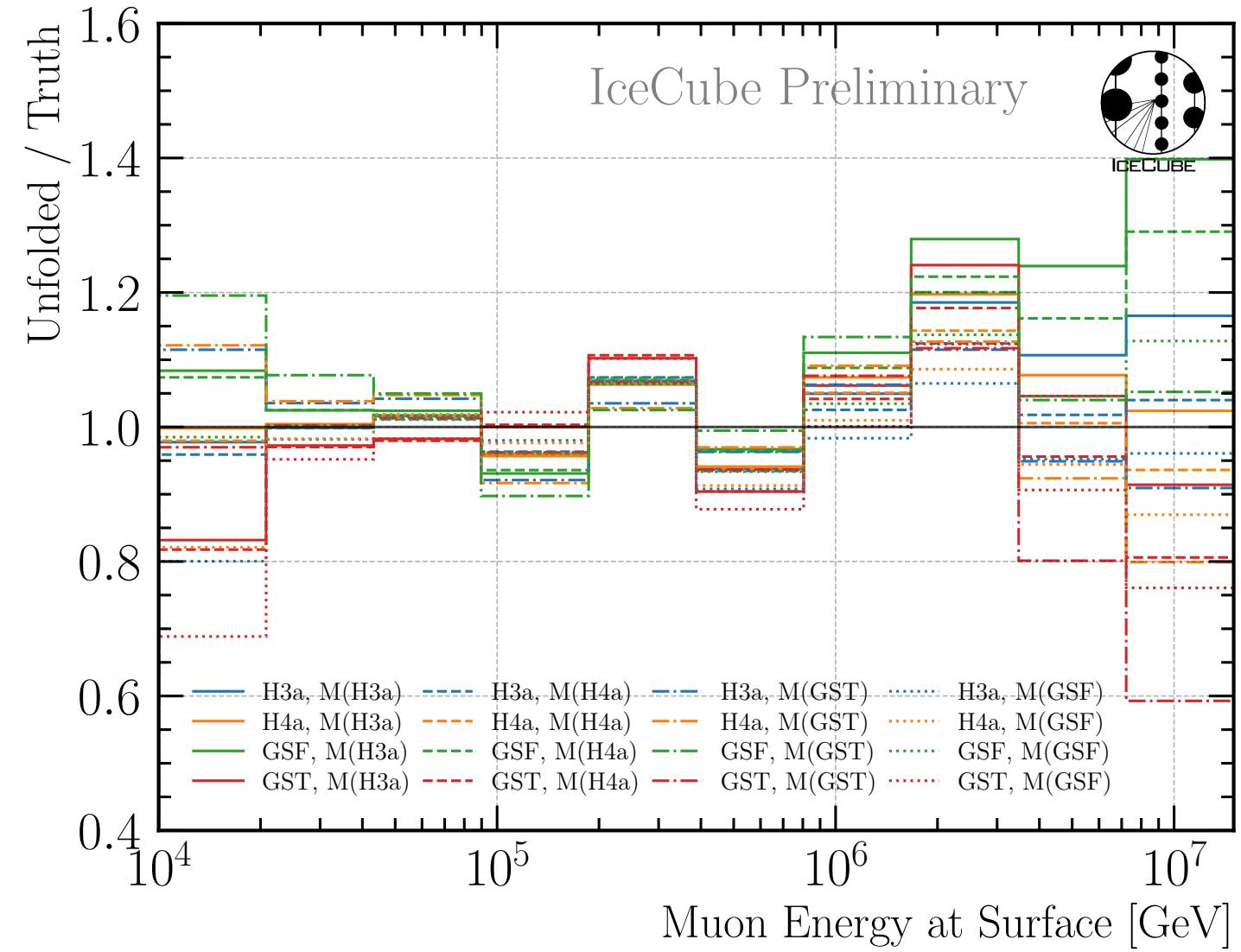
- Fit are only accepted, when minuit minimization is valid
  - Sometimes fits fail
- Fit polynomial from  $10^{-3} - 10^{-2}$  to determine minimum



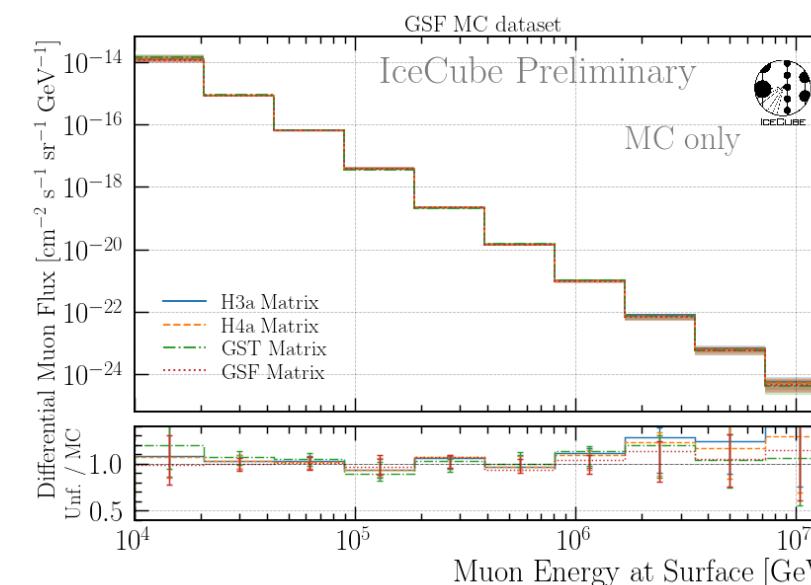
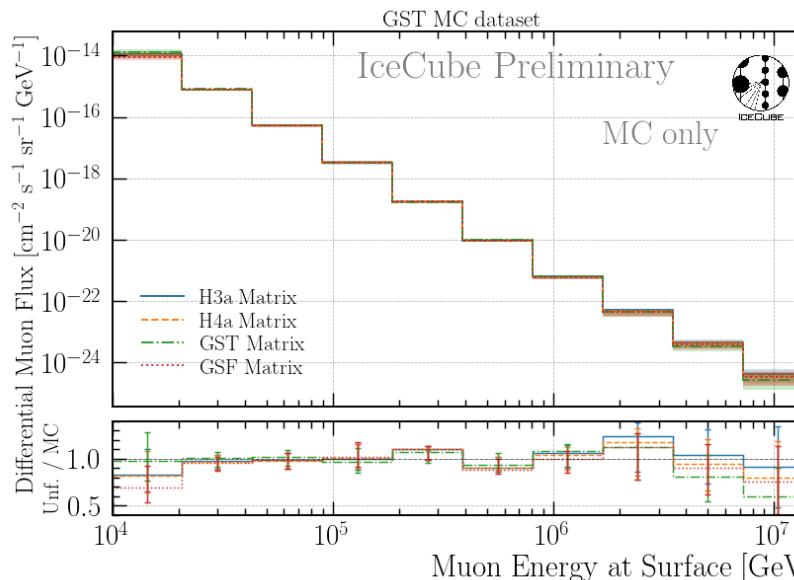
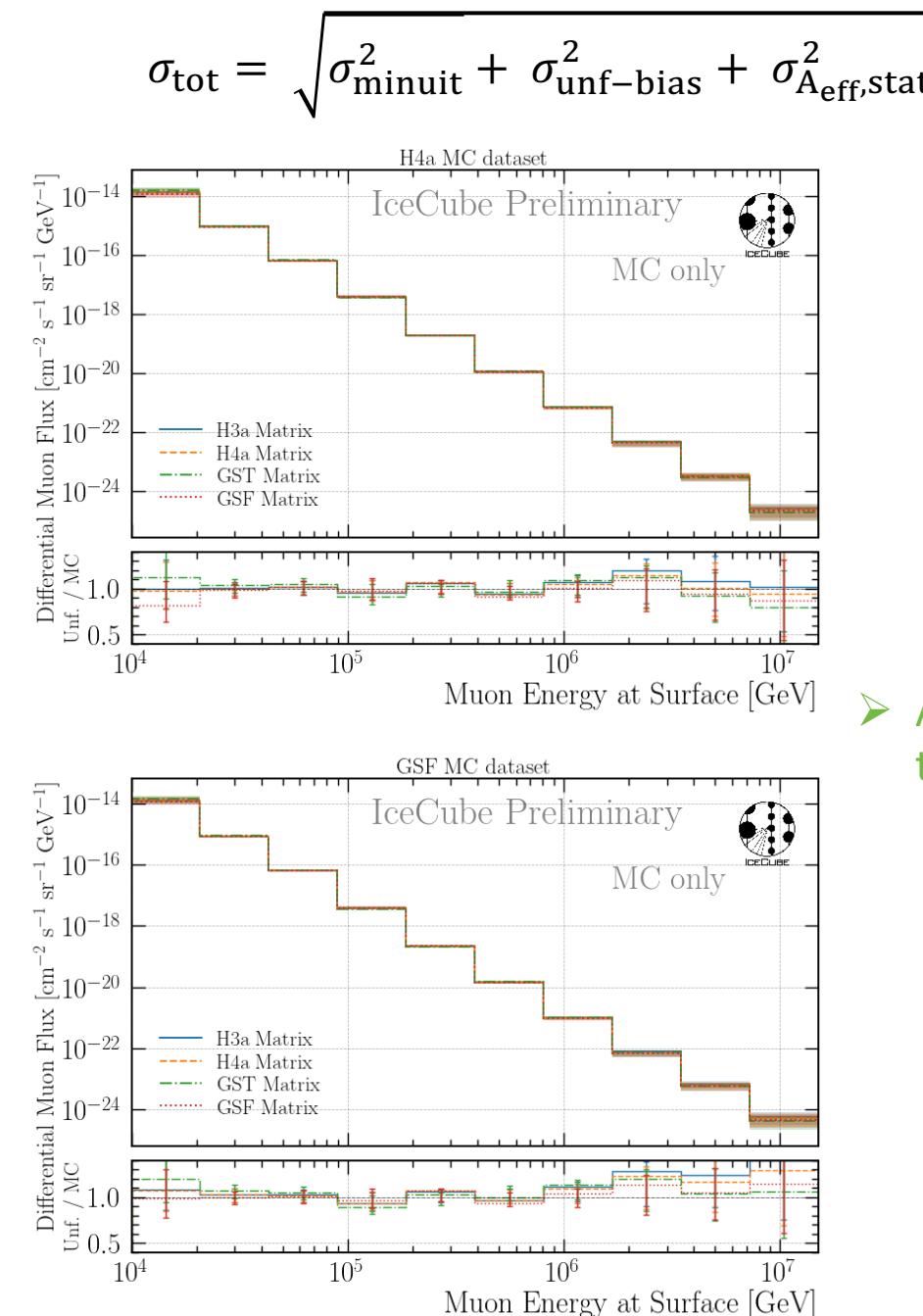
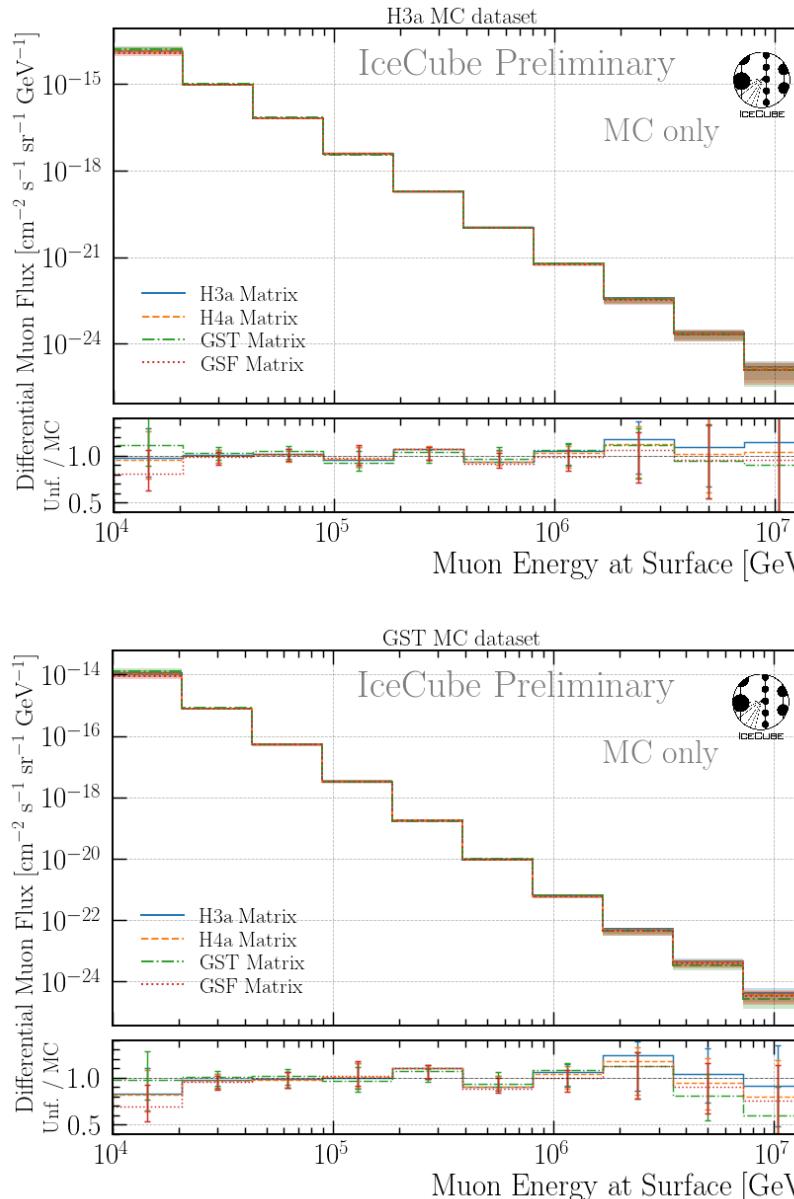
# “Method Bias”

# 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



➤ 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

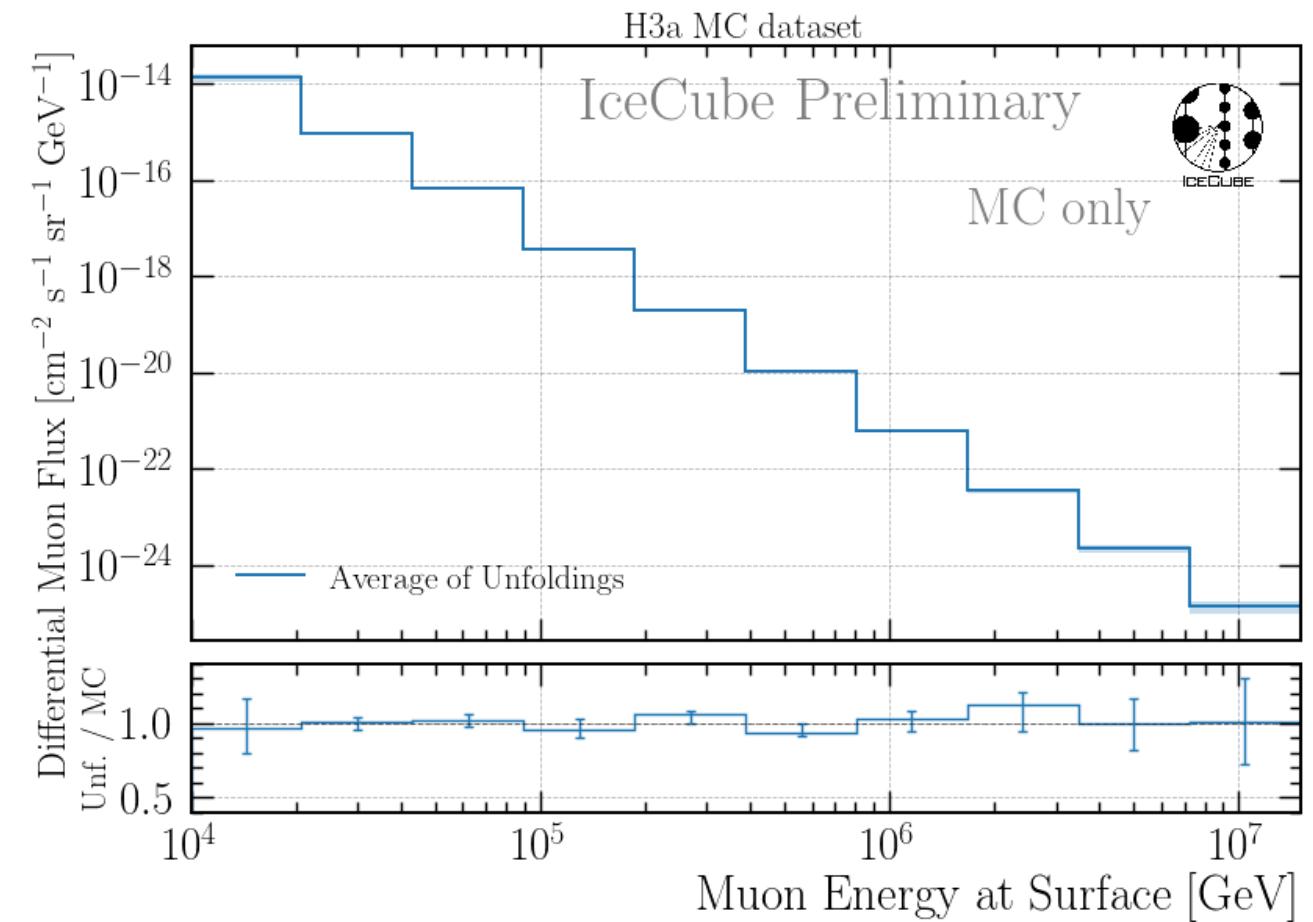
$$\sigma_{\text{tot}} = \sqrt{\sigma_{\text{unf}}^2 + \sigma_{\text{spread}}^2}$$

with

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

total uncertainty of  
the 4 unfoldings

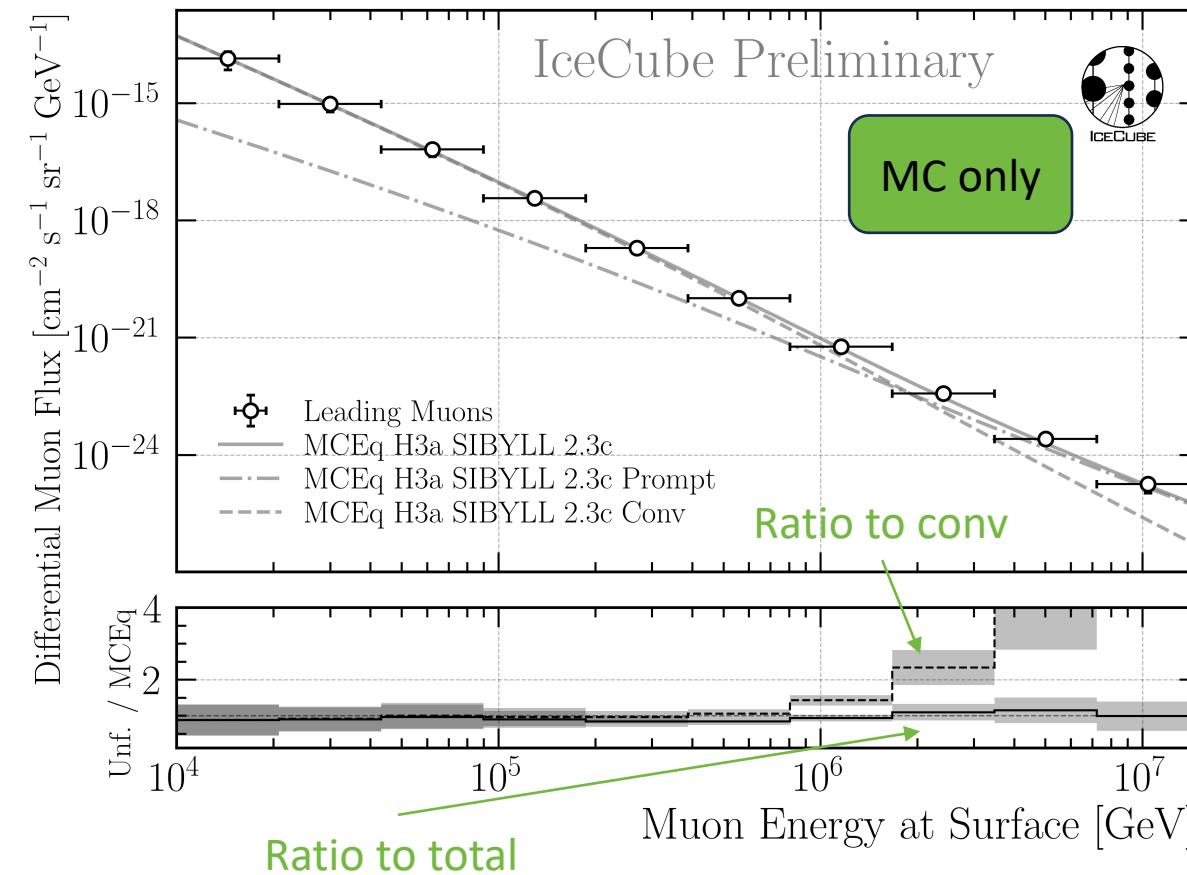
$$\sigma_{\text{spread}} = \text{std}(f_i)$$



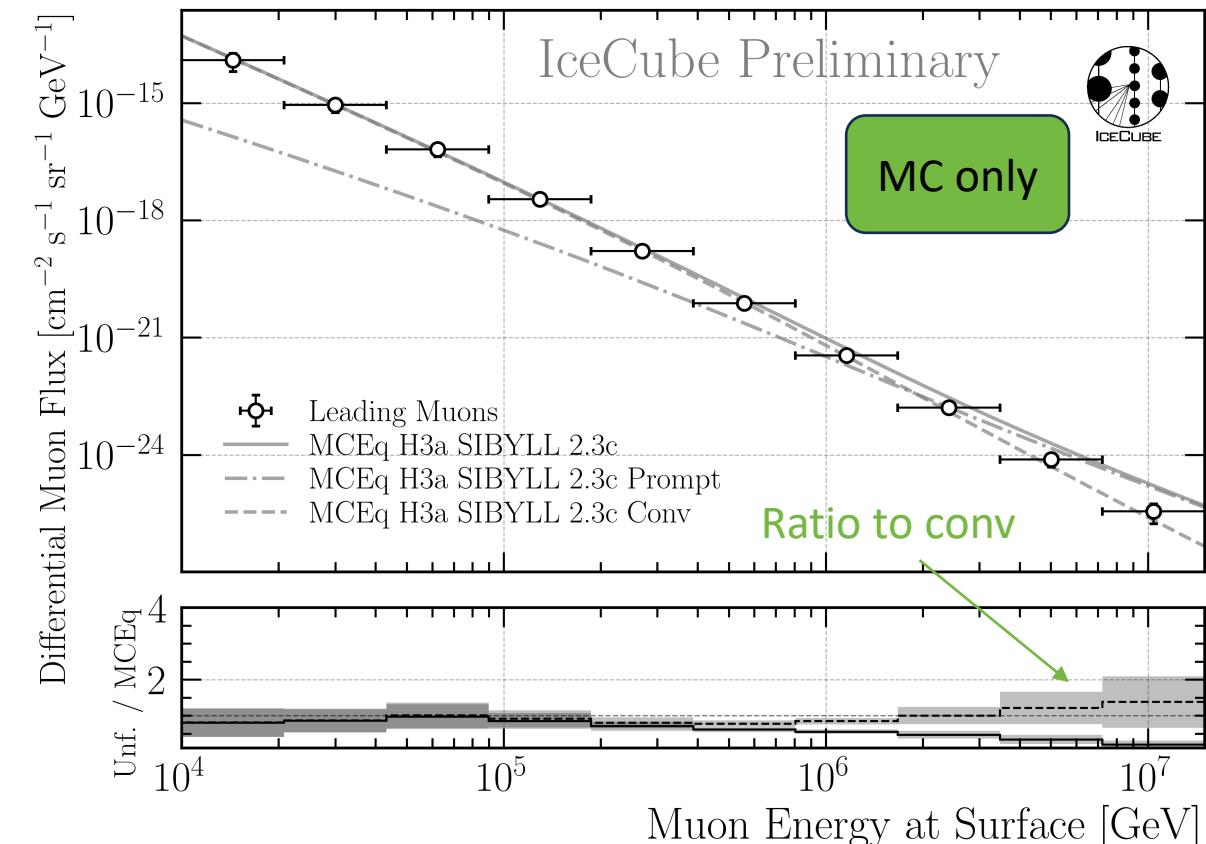
# Sensitive to Prompt?

# Prediction: 12 Years of IceCube Data Unfolding

Pseudo Sample has prompt



Pseudo Sample has NO prompt



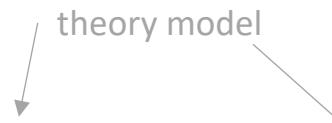
➤ Unfolding is sensitive to the prompt component

# Flux Characterization

# Chi2 Likelihood Fit

## Fit normalizations

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



## Significance test for prompt

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

[LikelihoodFitter] Using full covariance matrix.

Maximum bin correlation: 0.254

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## LIKELIHOOD FIT SUMMARY

---

Mode: Full covariance matrix (10x10)

### Best-Fit Parameters:

Prompt normalization:  $1.163869 \pm 0.312284$

Conventional normalization:  $0.993129 \pm 0.042122$

$\chi^2 = 1.00$  ndof = 8  $\chi^2/\text{ndof} = 0.125$

Goodness-of-fit p-value: 0.9982

Parameter correlation: -0.6352

---

### HYPOTHESIS TEST: $H_0: \text{prompt normalization} = 0$

---

$\Delta\chi^2 = 6.945$

p (one-sided, boundary-corrected) = 4.202486e-03

significance approx  $\approx 2.64\sigma$

significance exact =  $2.64\sigma$

$\rightarrow$  Reject  $H_0$  at 95 % CL  $\rightarrow$  evidence for prompt component.

# Burnsample Unfolding

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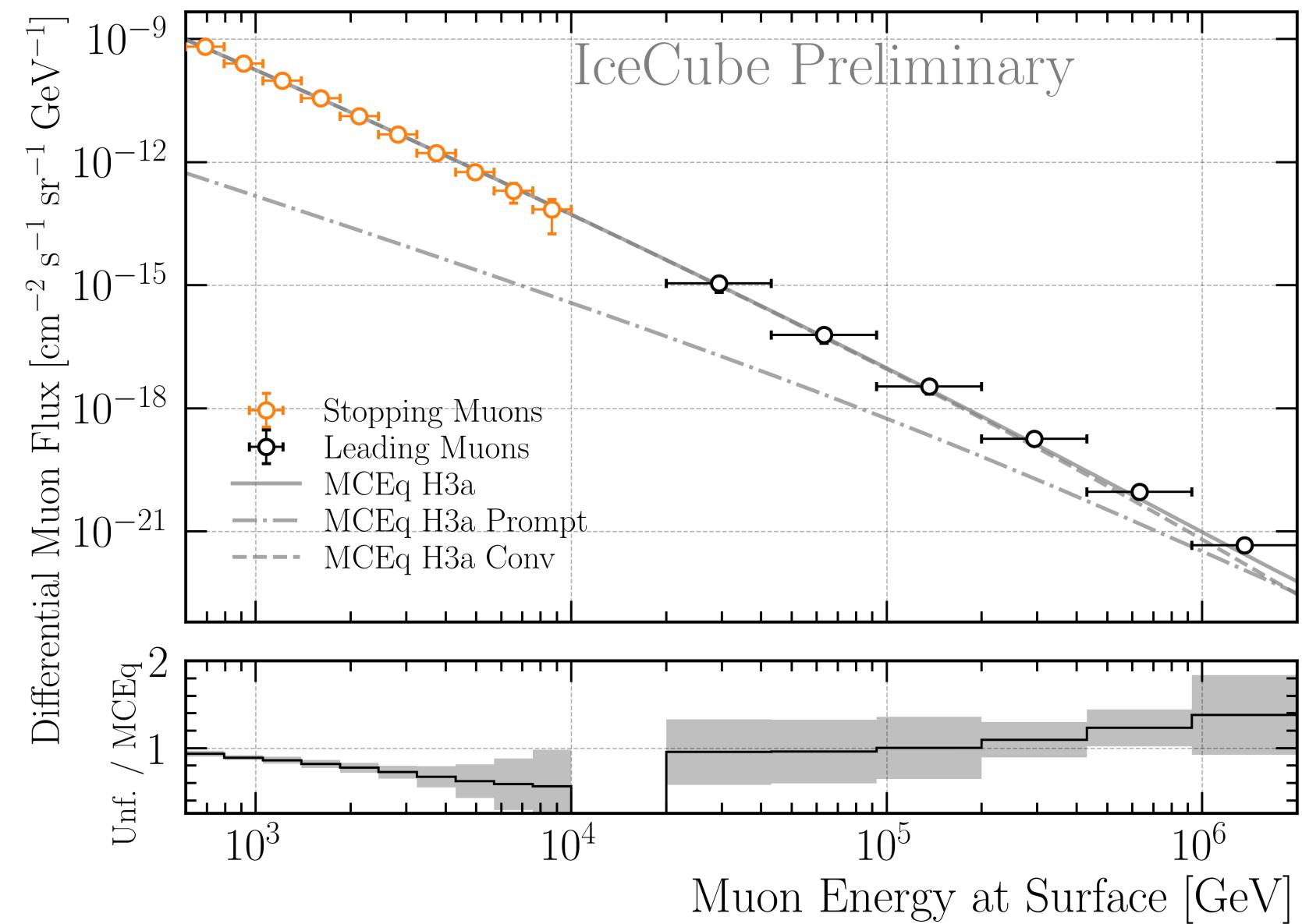
## Leading muons

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

## Stopping muons

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

[ICRC PoS 281](#)



# 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

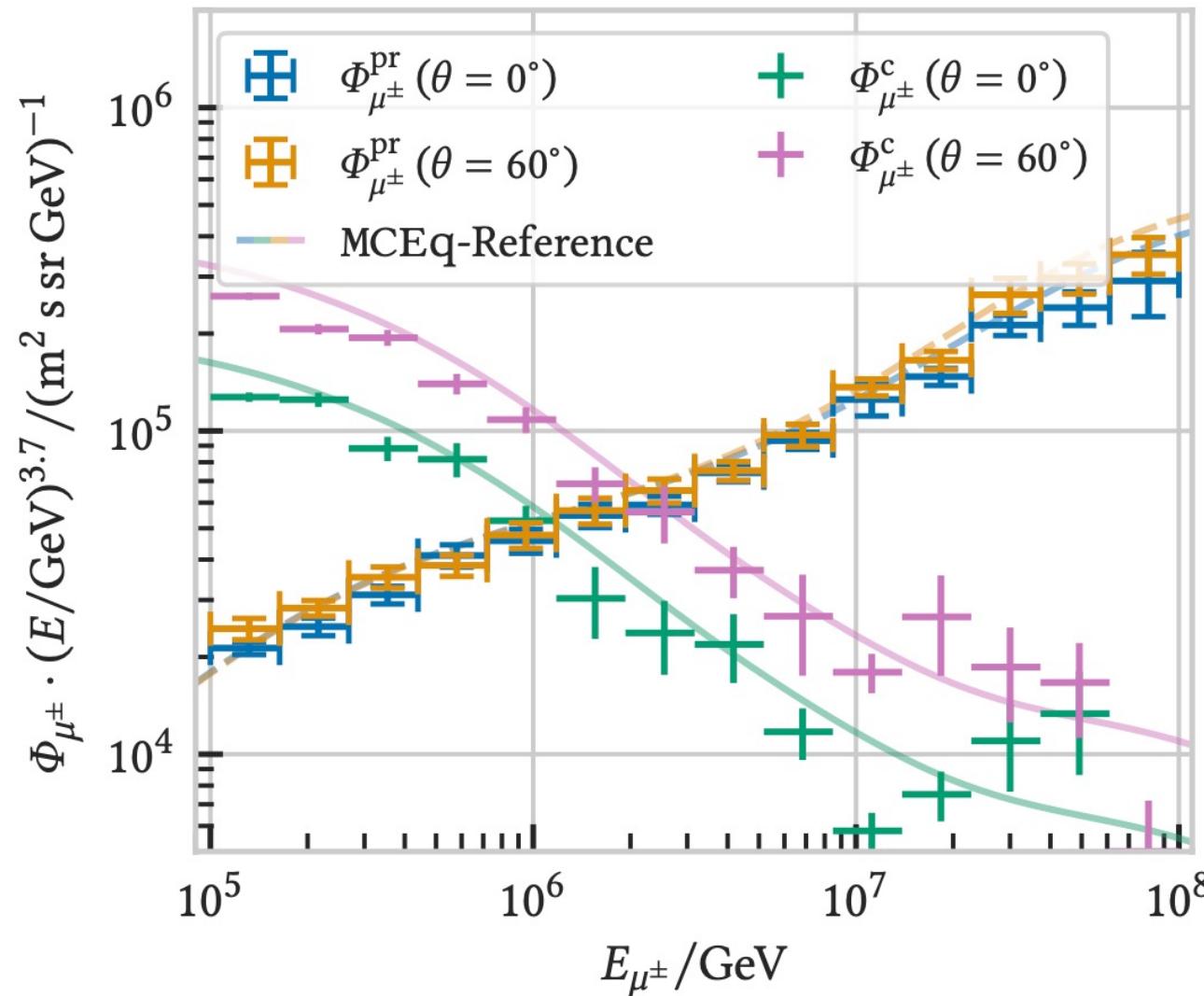
## Post-unblinding checks

- 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

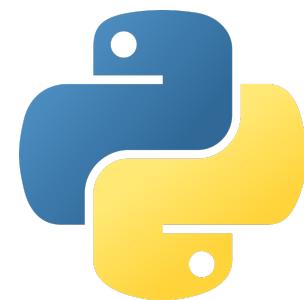


MCEq: tool to numerically solve the cascade equations that describes the evolution of particle densities as they propagate through a gaseous, dense medium  
<https://github.com/mceq-project/MCEq>

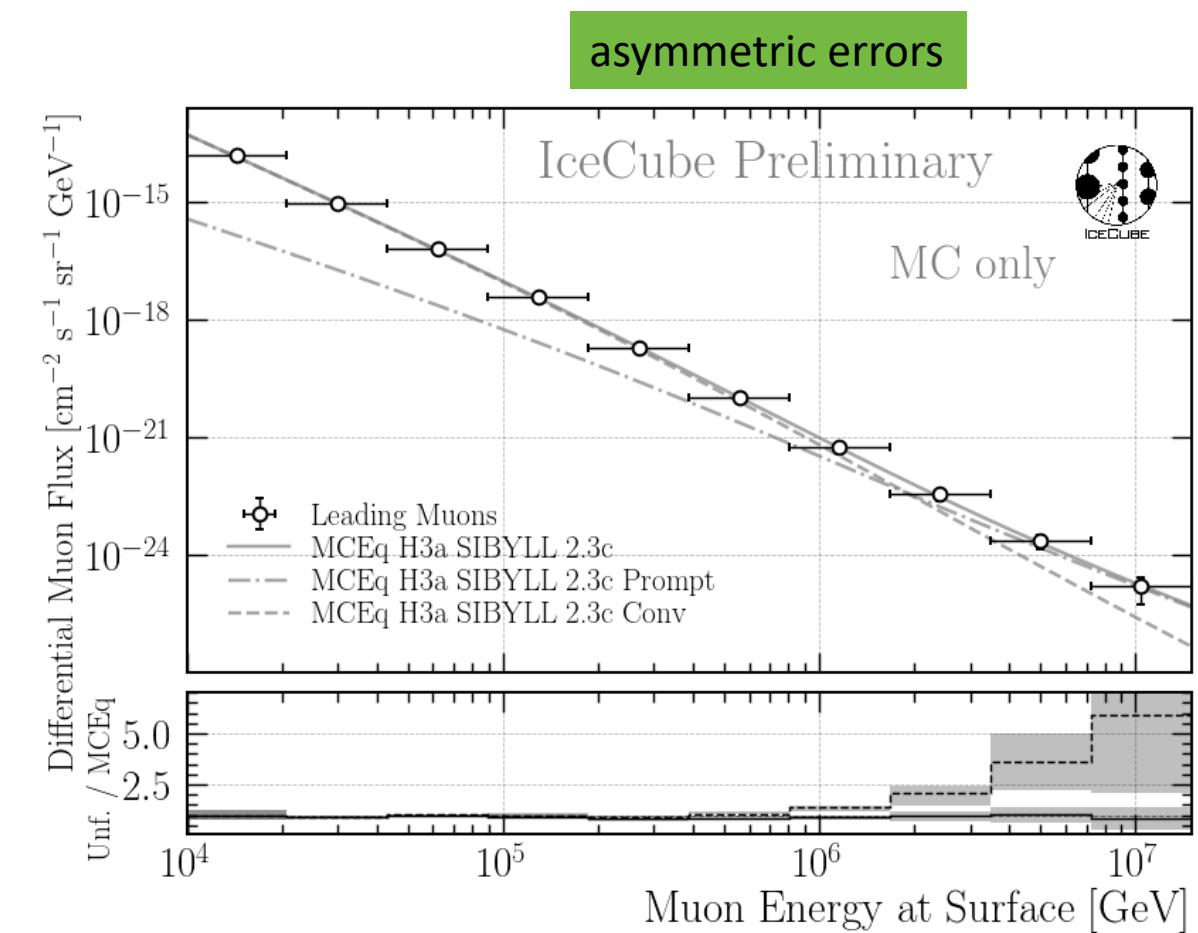
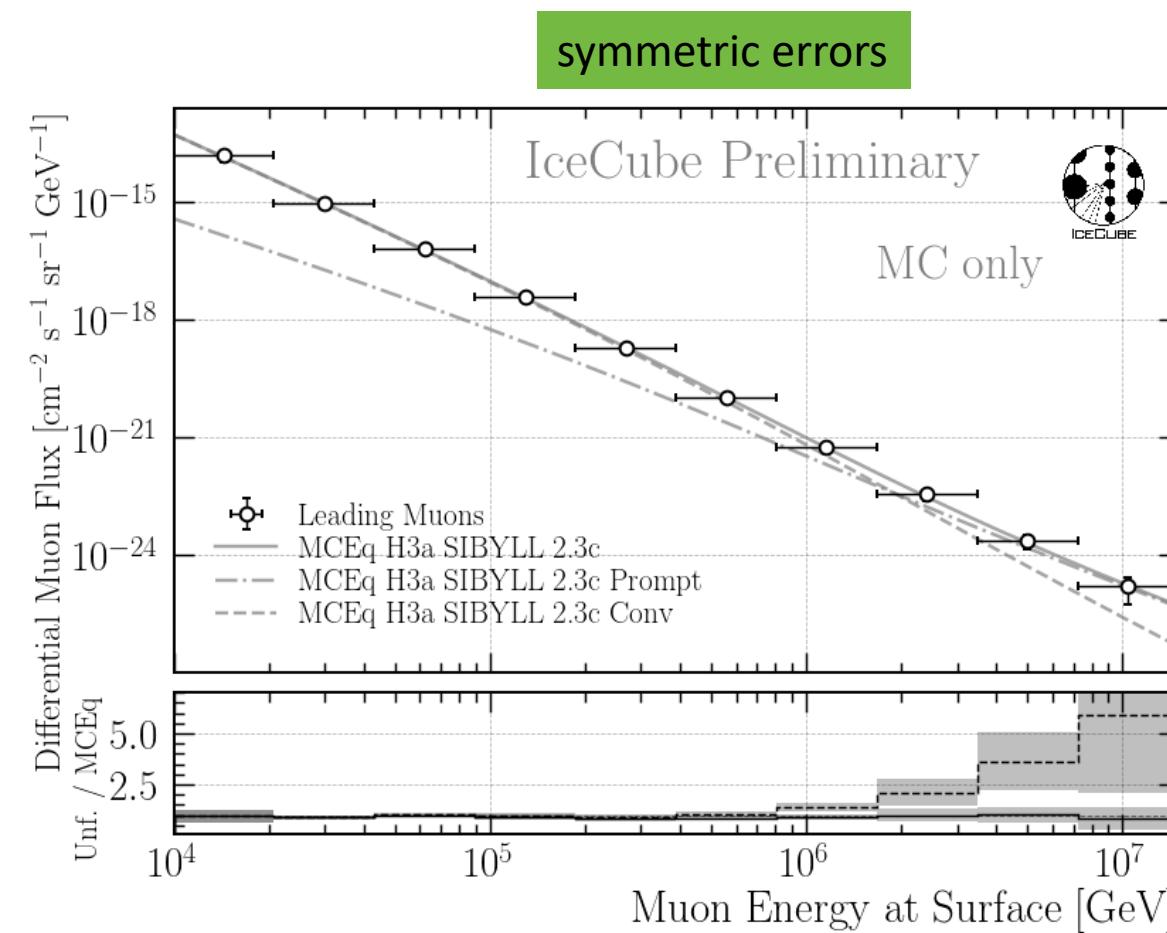
➤ Good agreement for inclusive flux

Python package developed – PANAMA

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

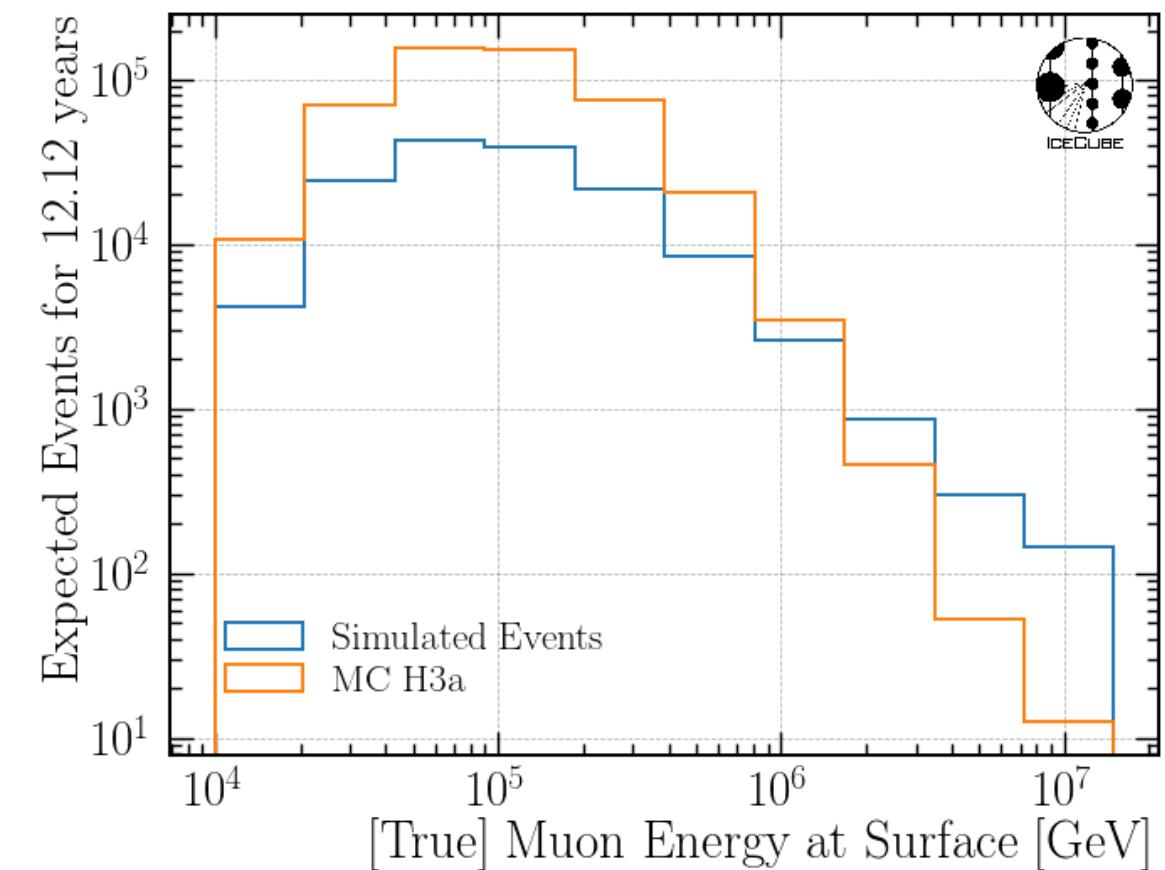
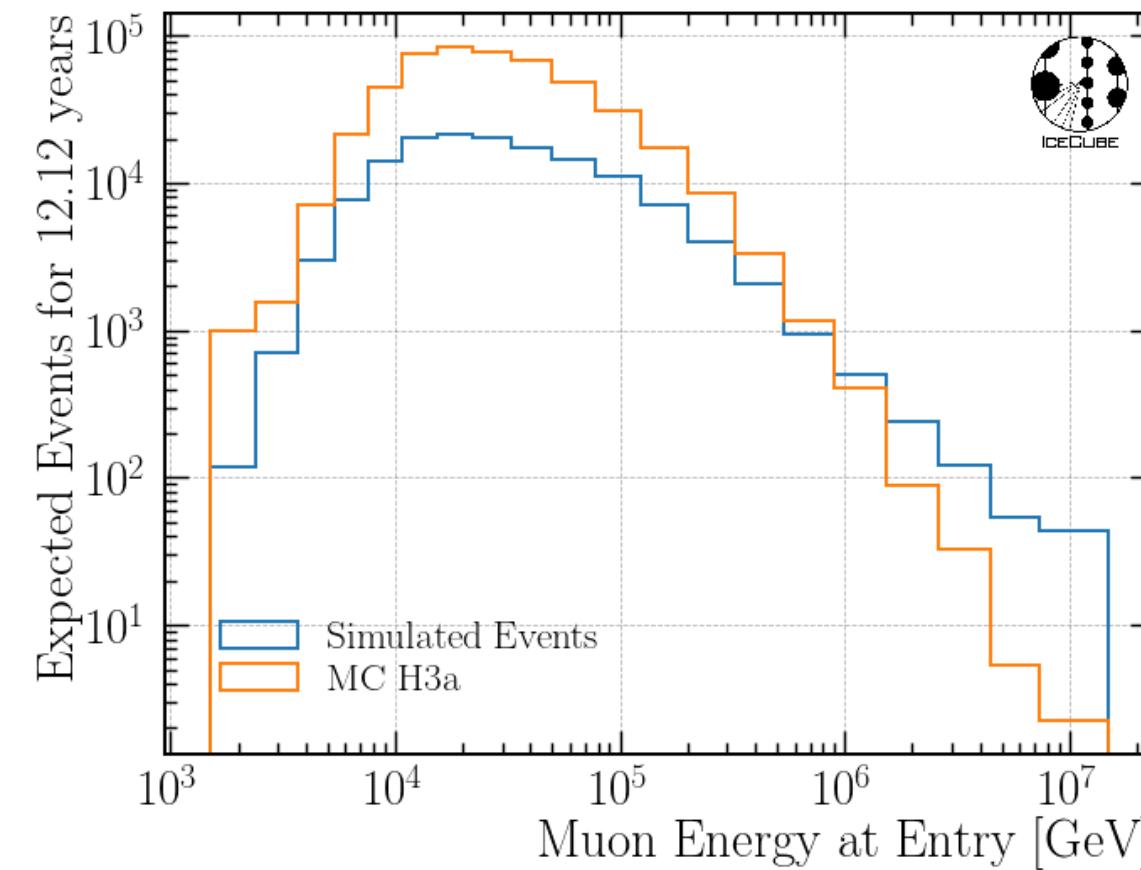


## 12 Years Prediction



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

## MC Statistics on Final Level



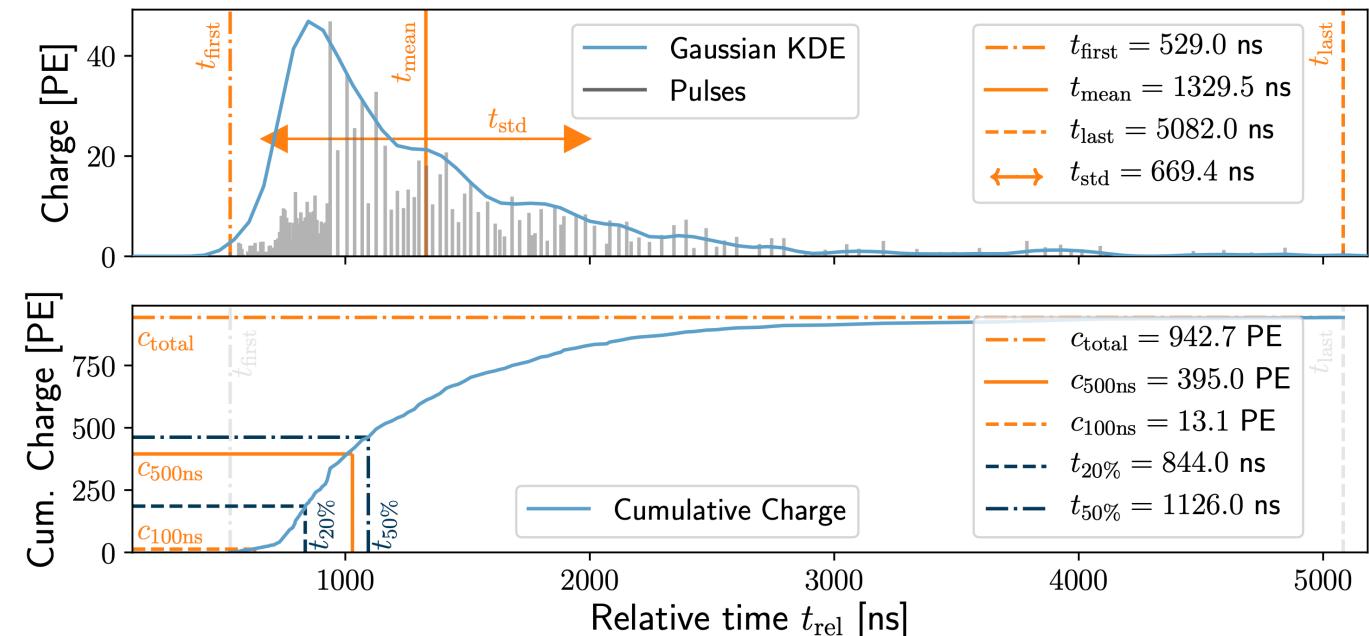
# Input data per DOM

## 3 inputs

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

## 9 inputs

- $t_{\text{last}}$ : 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
- $t_{\text{mean}}$ : Mean time
  - Charge weighted mean time of all pulses relative to total time offset
- $c_{500\text{ns}}$ : Charge at 500ns
  - Sum of charge after 500ns
- $c_{100\text{ns}}$ : Charge at 100ns
  - Sum of charge after 100ns

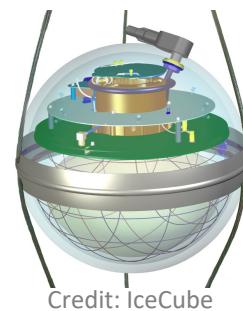


## Input pulse cleaning

- 6000 ns

## Training data

- Different simulations for robustness



# Reconstructed properties

## Energy

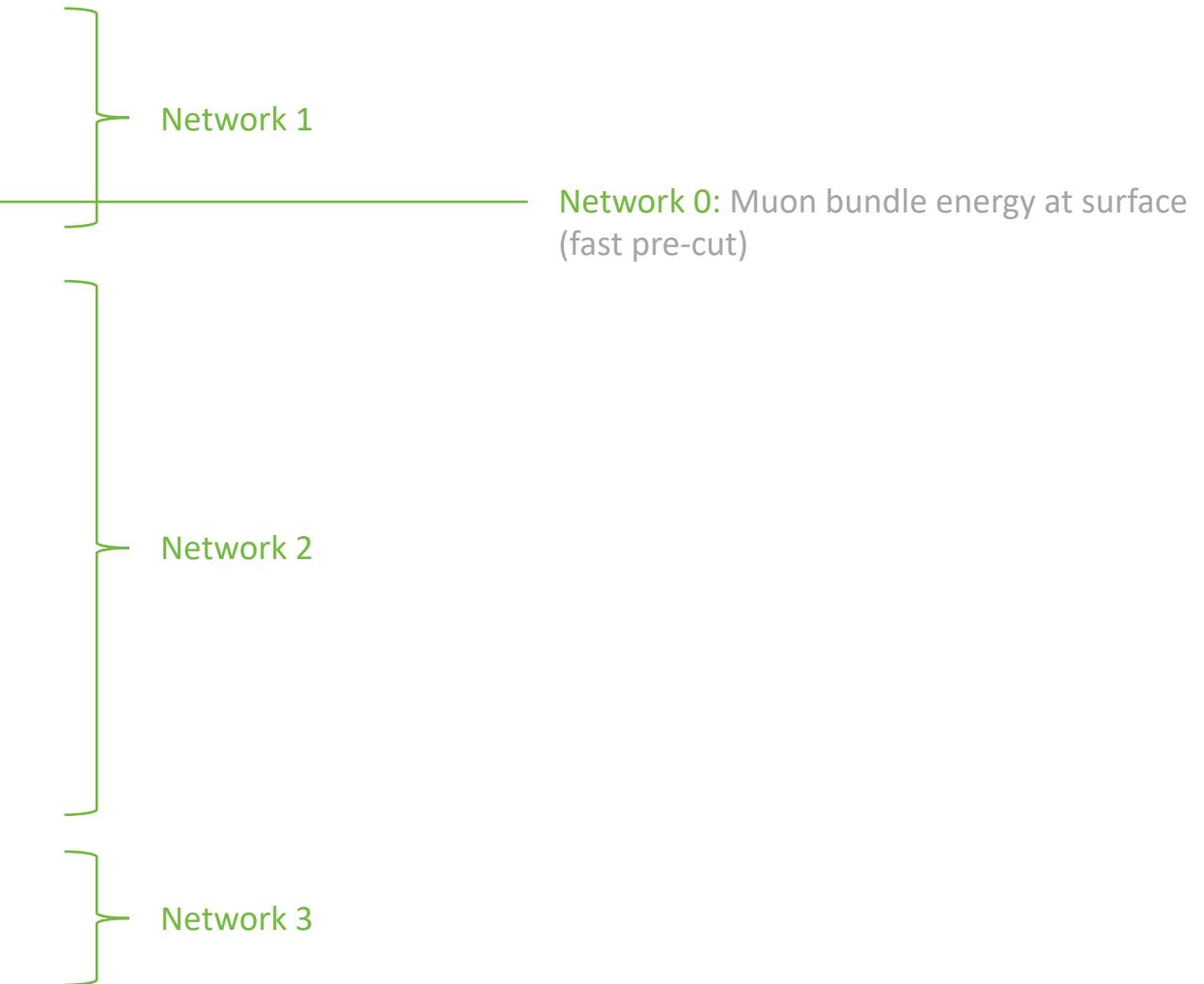
- `entry_energy`: Leading muon energy at the detector entry
- `bundle_energy_at_entry`: Muon bundle energy at the detector entry
- `muon_energy_first_mctree`: Leading muon energy at surface
- `bundle_energy_in_mctree`: Muon bundle energy at surface

## Track geometry

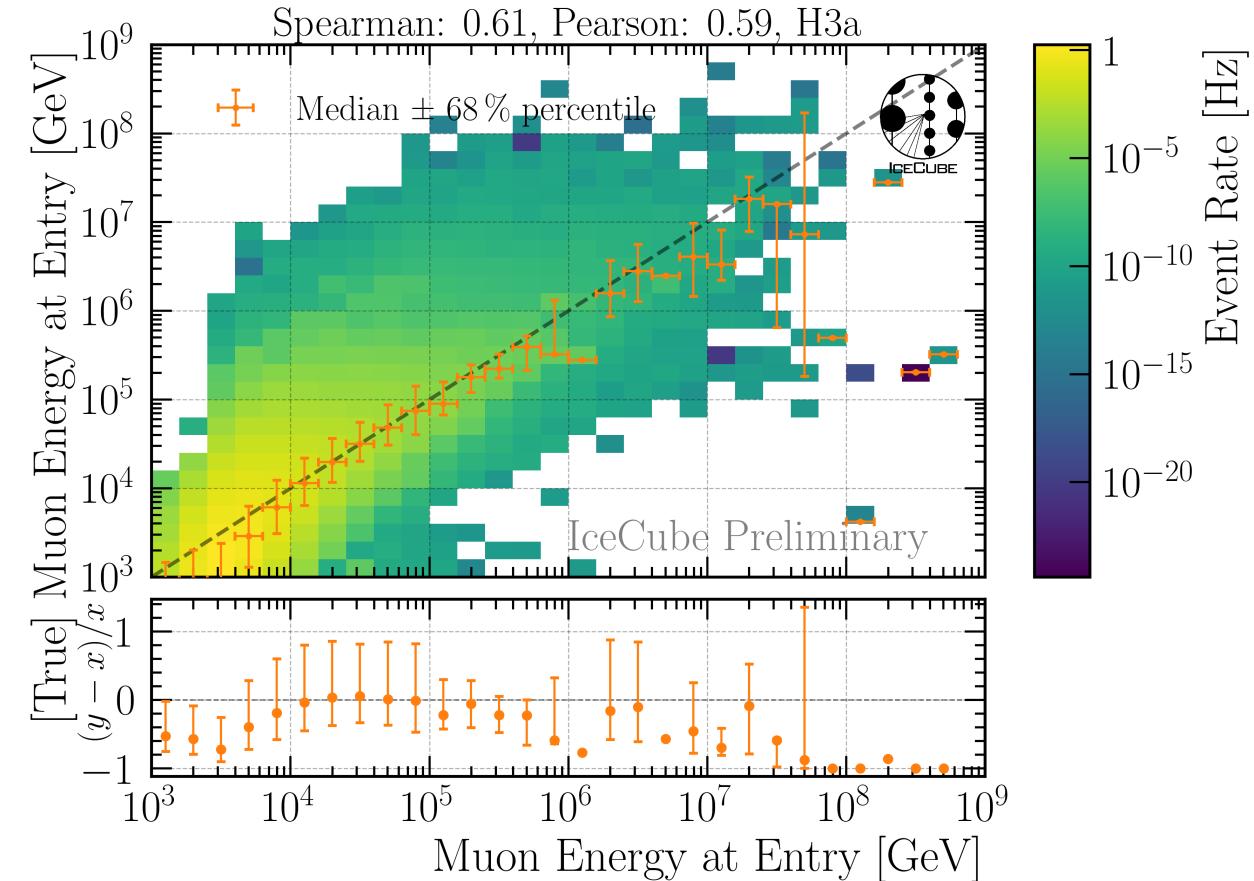
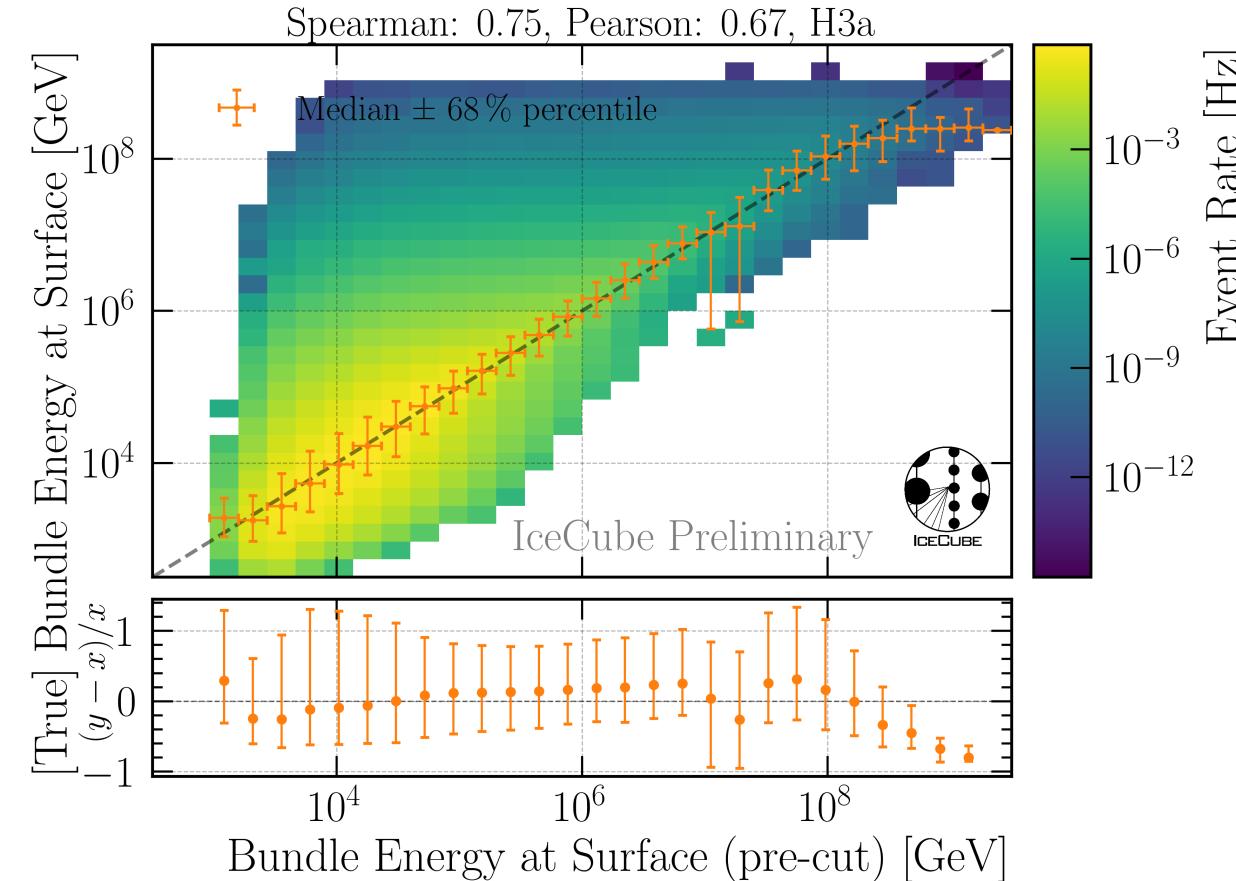
- `Length`: Propagation length of muon in the ice
- `LengthInDetector`: Propagation length of muon in the detector
- `center_pos_x`: Closest x position of muon to center of the detector
- `center_pos_y`: Closest y position of muon to center of the detector
- `center_pos_z`: Closest z position of muon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

## Direction

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

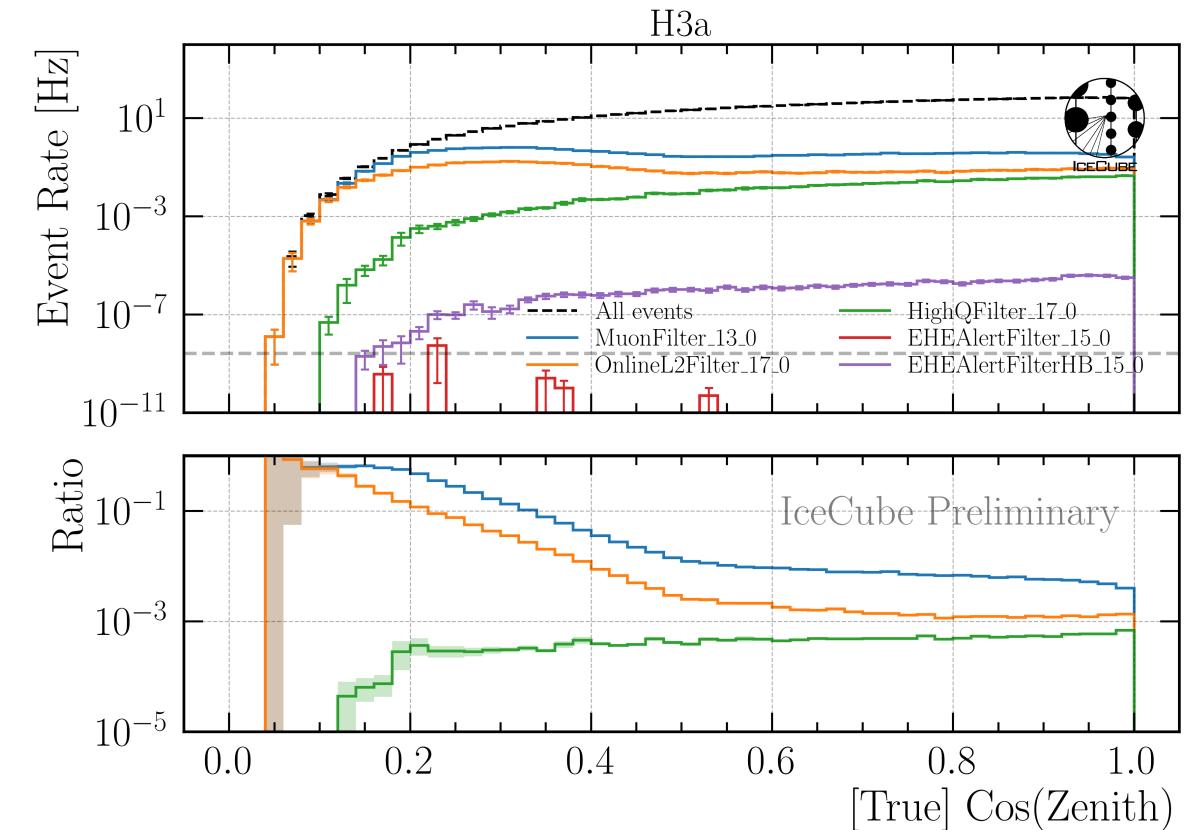
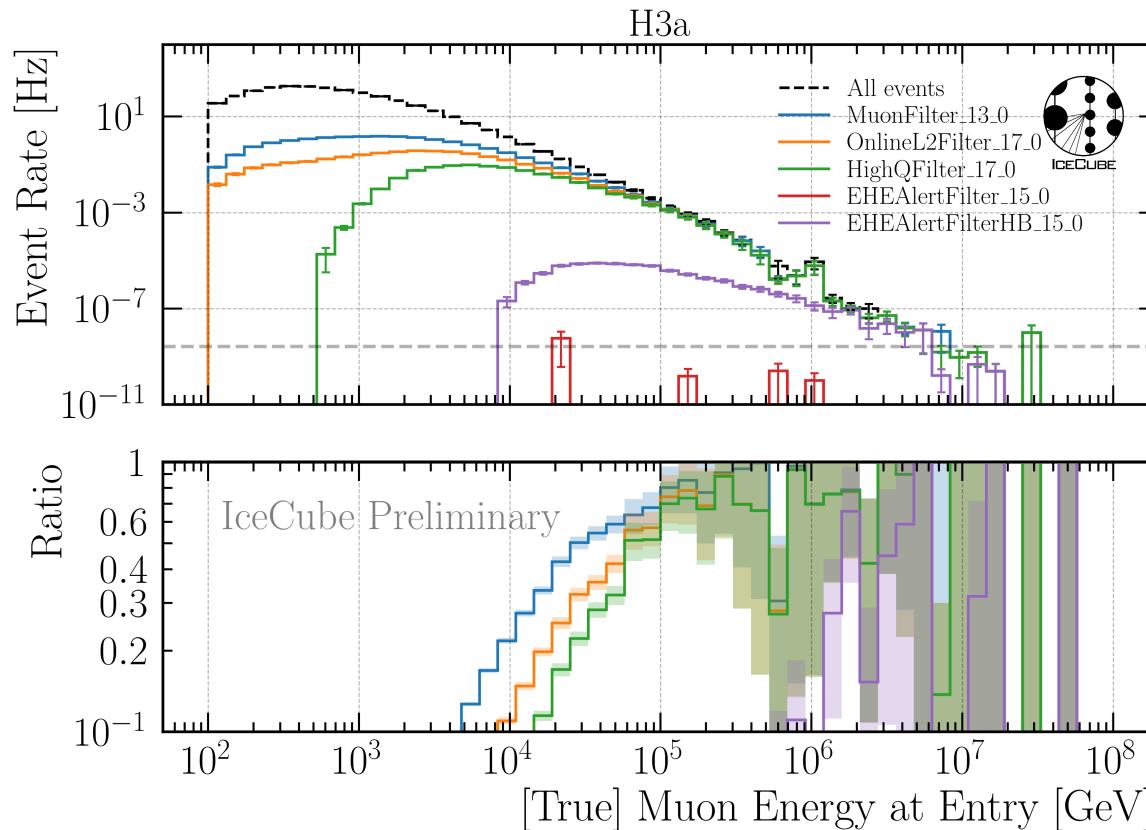


# Energy Reconstructions



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

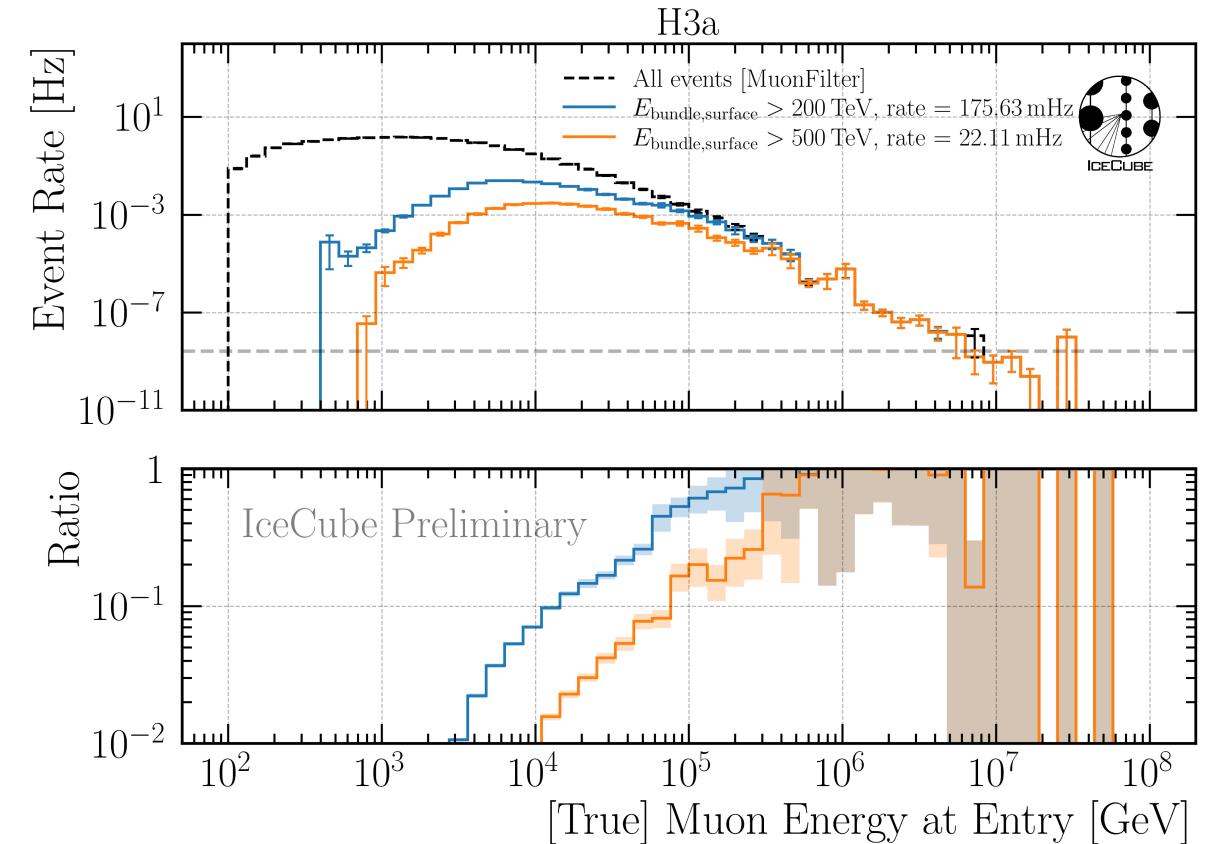
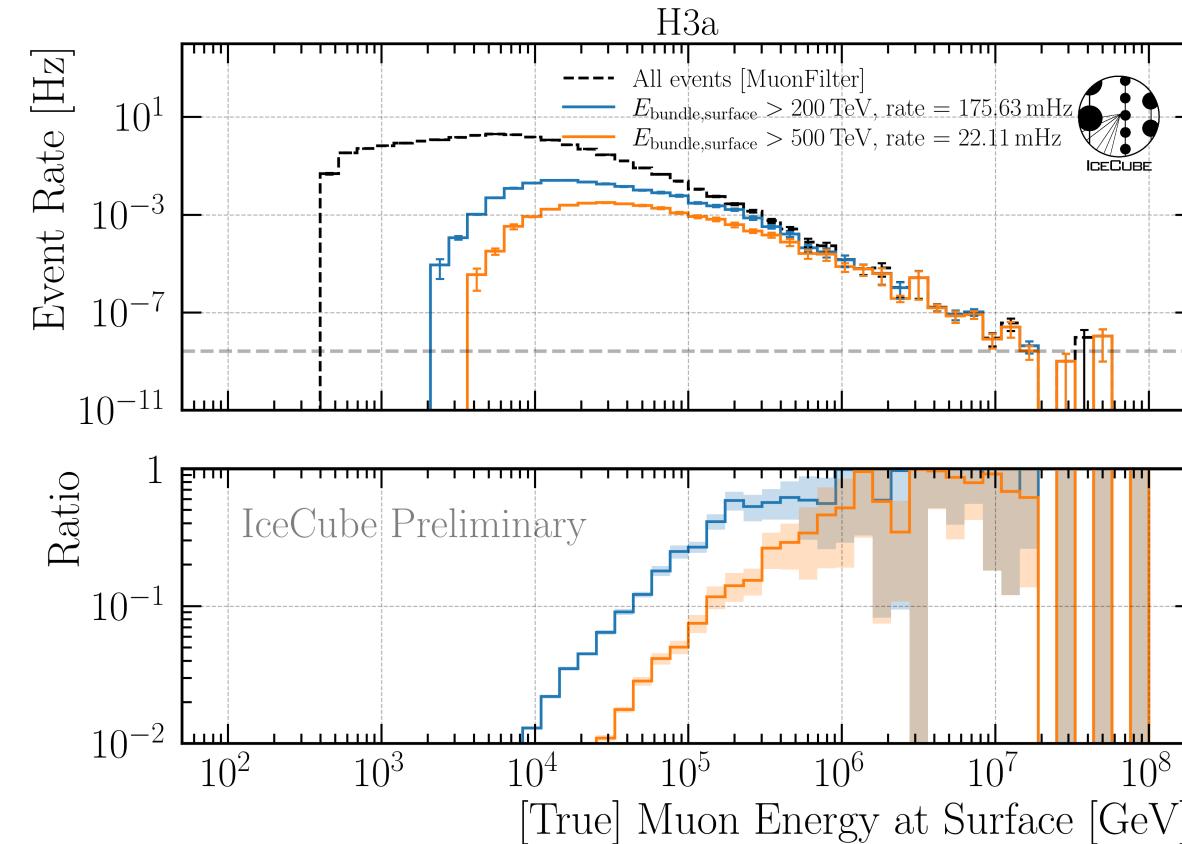
# Level 3: Muon Filter



Muon filter: zenith-dependent charge and quality cut

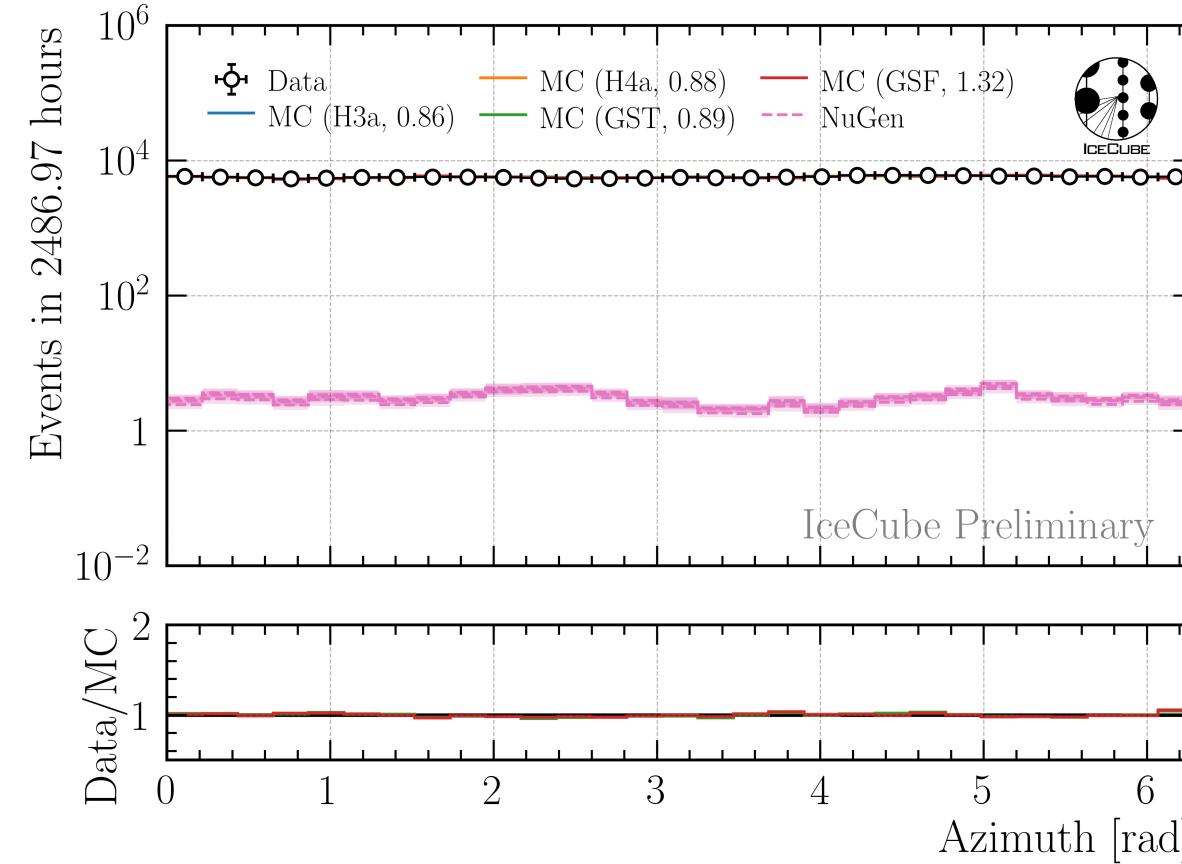
➤ Choose muon filter to select as many high-energy muons as possible

## Level 4: Energy Cut



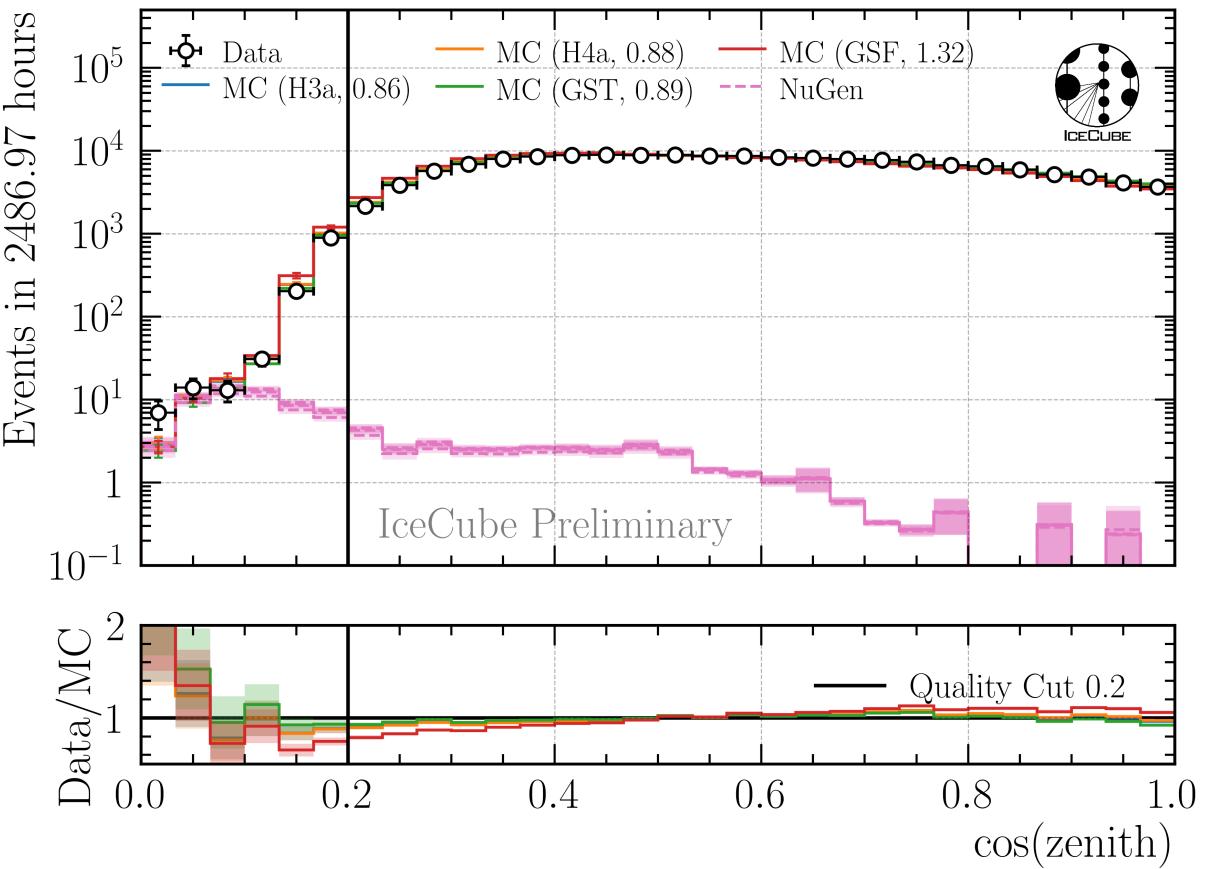
- 6 billion events expected in 10 years → computationally not feasible
- focus on high-energetic events
- Remove low-energy muons: bundle energy at surface > 500 TeV

# Level 5: Data/MC Quality Cuts



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

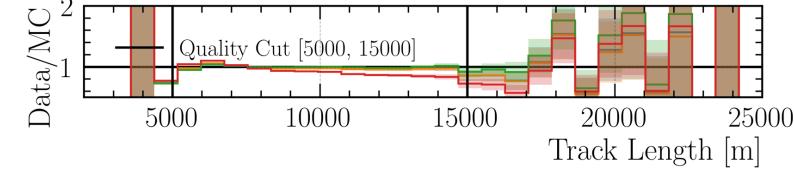
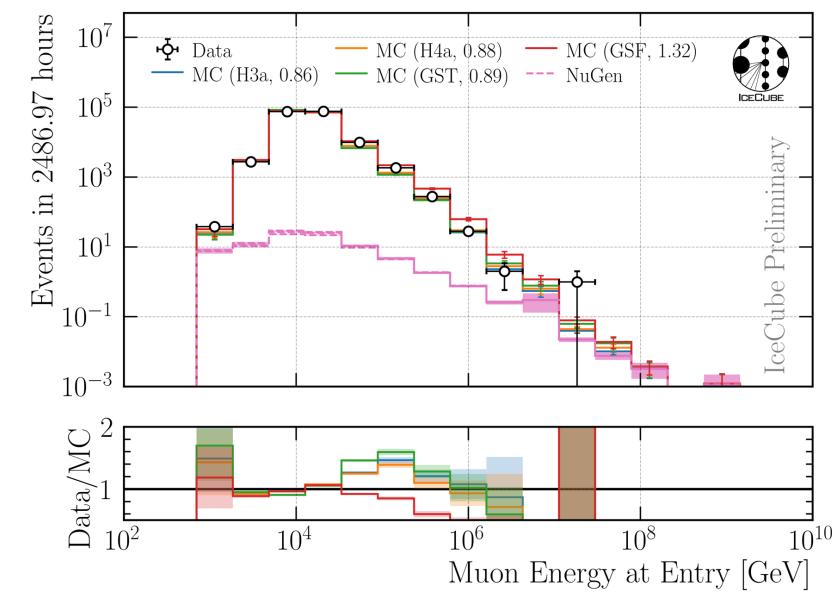
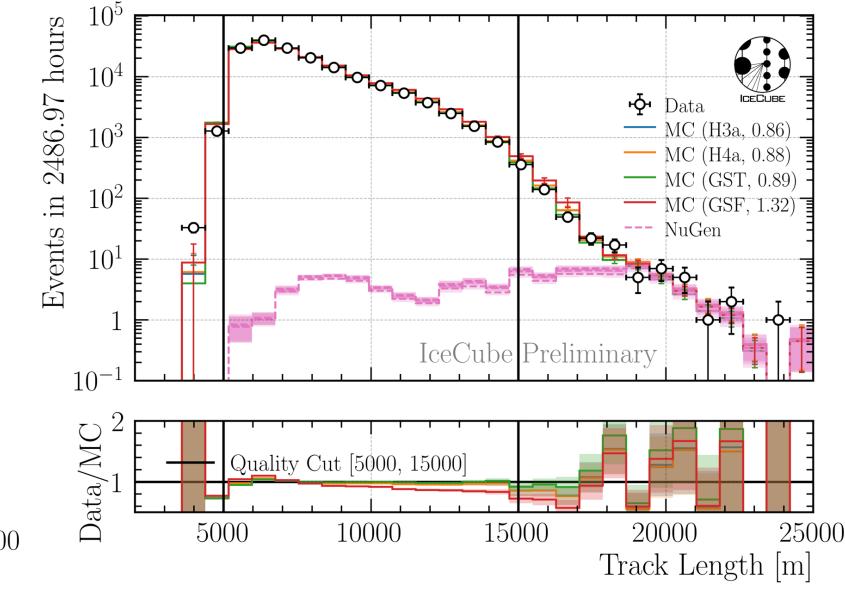
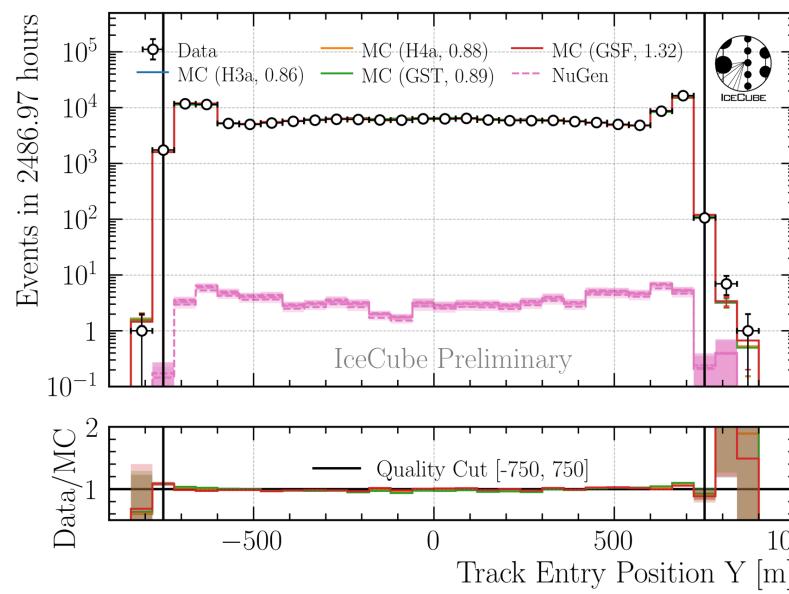
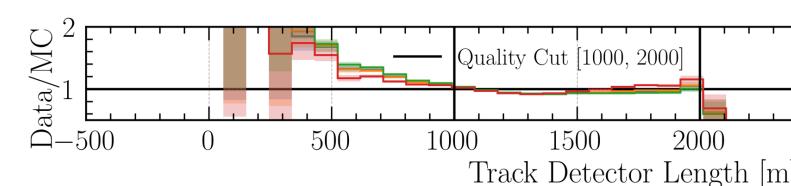
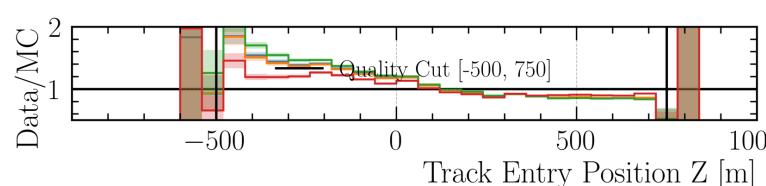
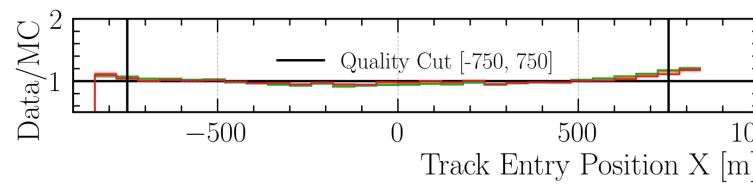
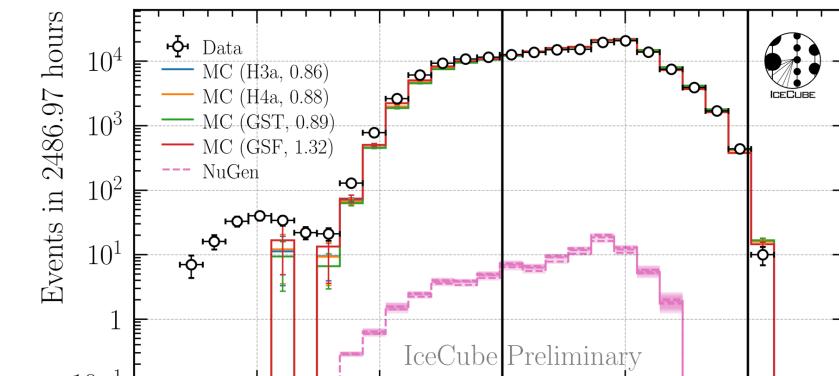
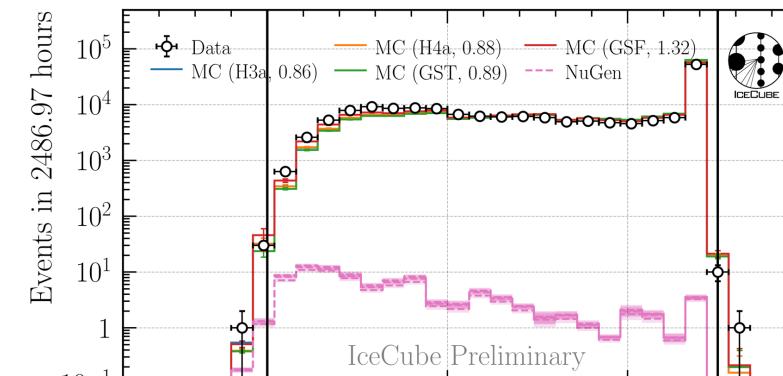
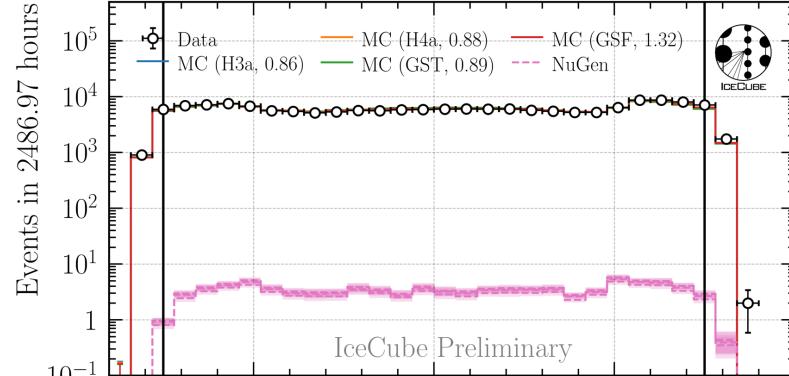
IceCube Collaboration PoS ICRC2023 1064



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

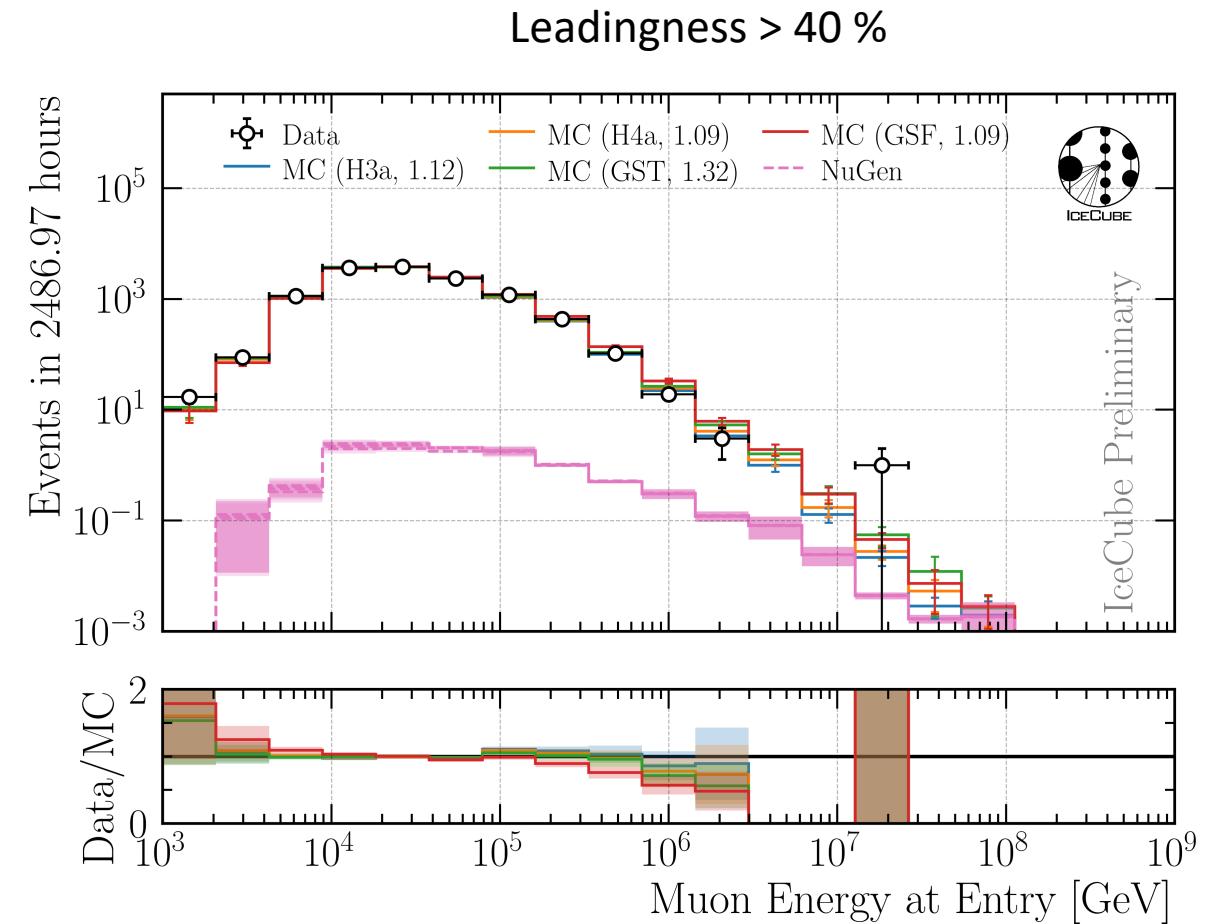
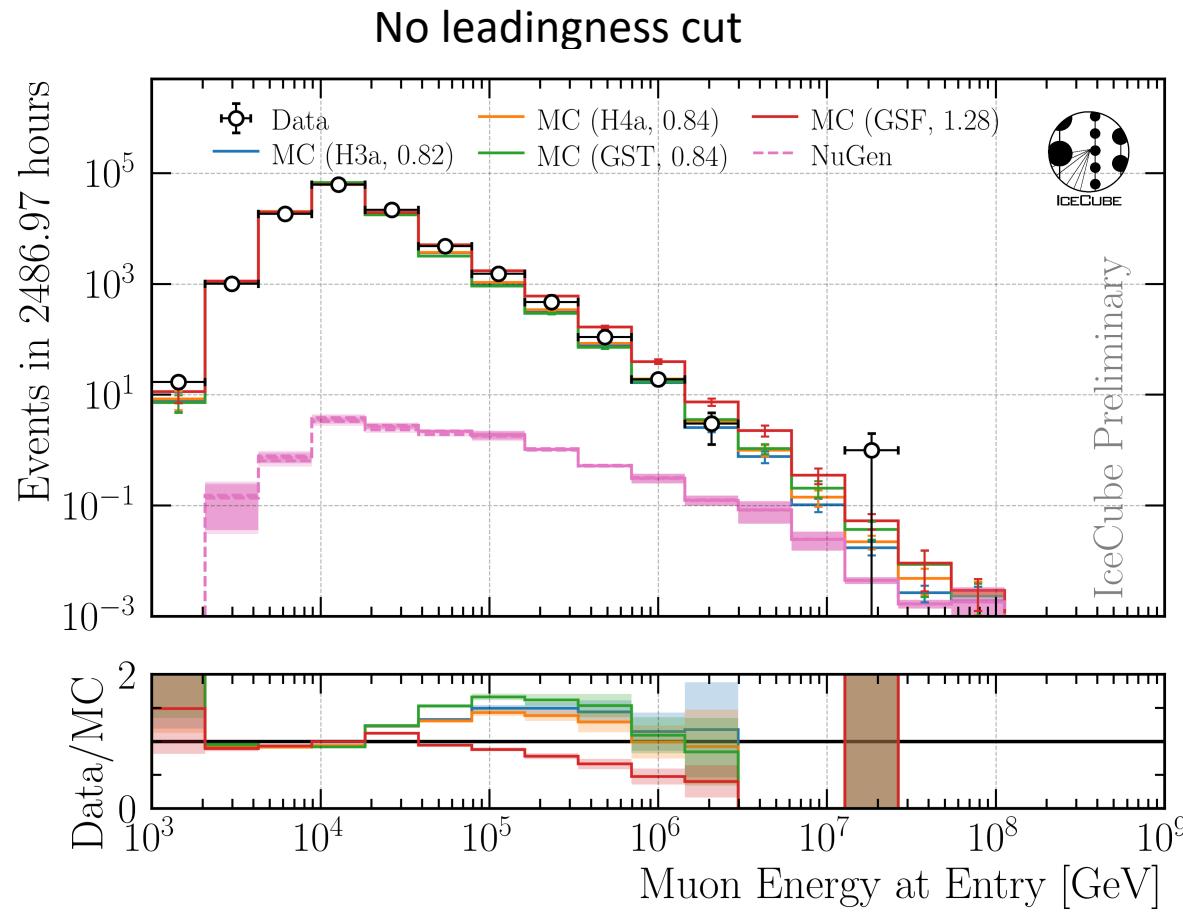
- Remove outliers
- Depth—dependent slope (no analysis relevance)
- CR—model impact on energy reconstruction
- 23 quality cuts in total

# Level 5: Data/MC Quality Cuts



## Final Level: Leadingness &gt; 40 %

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



➤ Improve Data/MC by leadingness cut

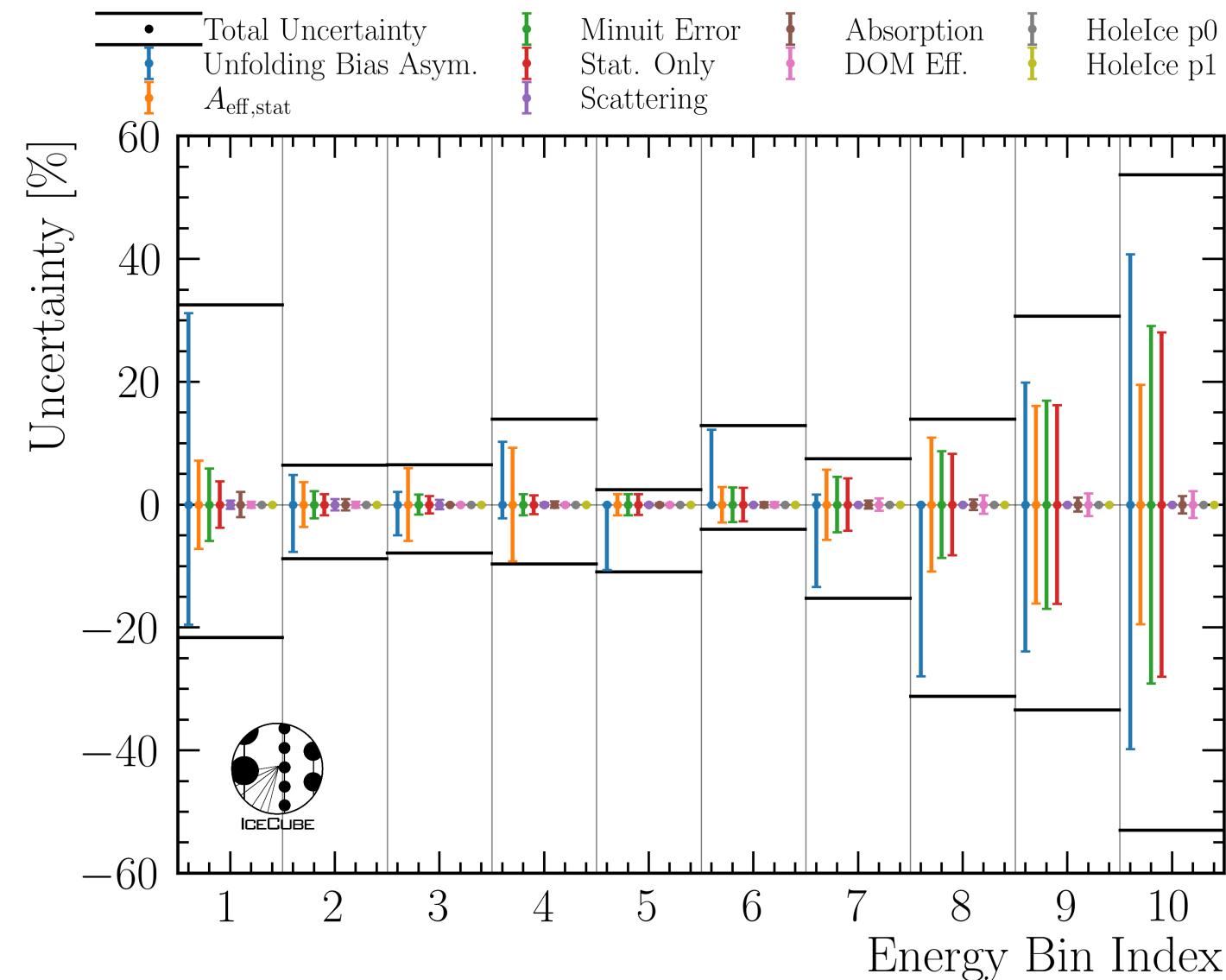
# Level5: quality cuts

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

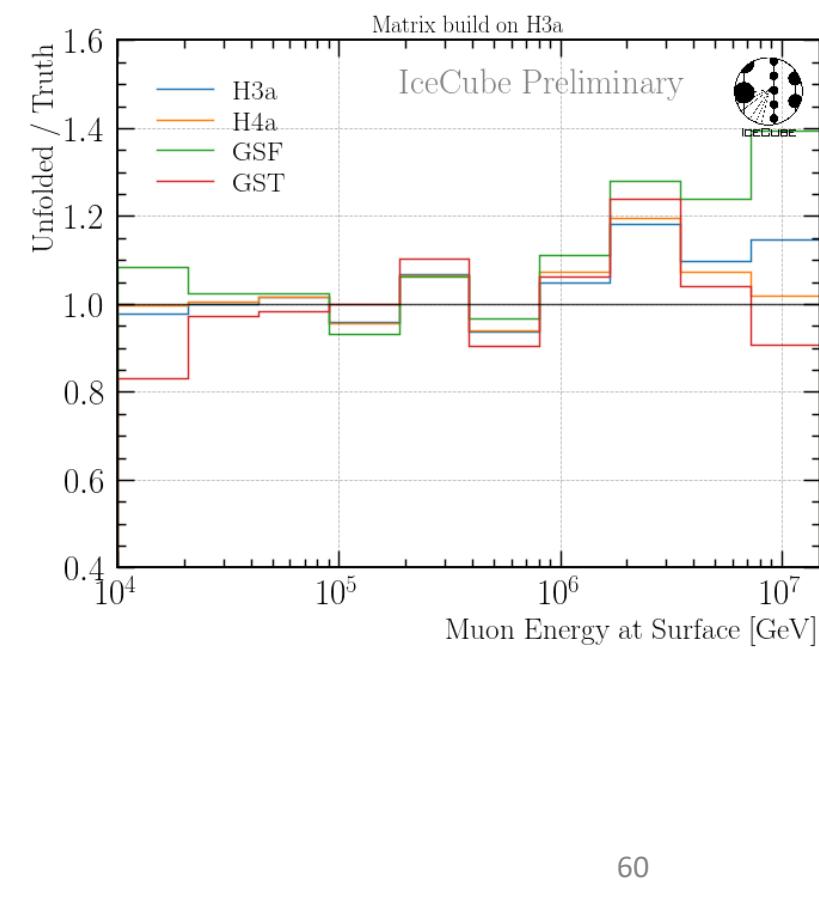
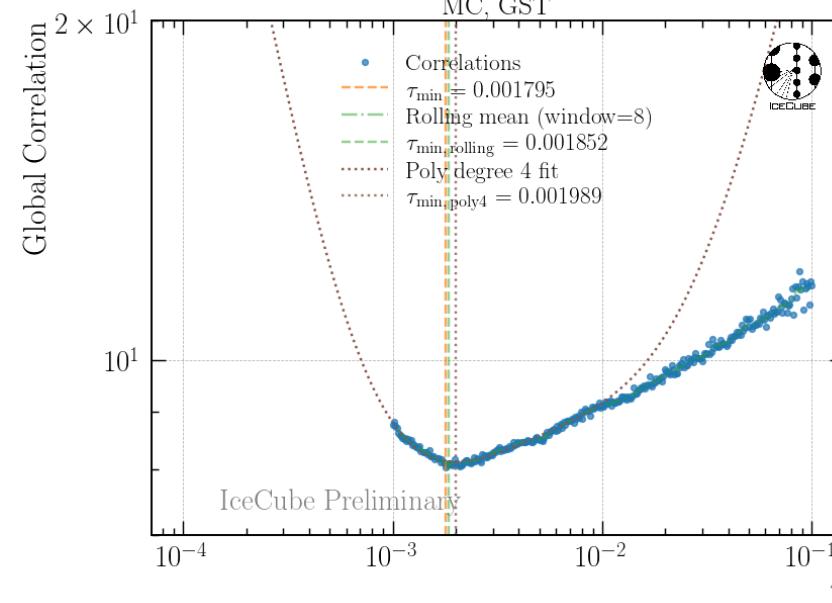
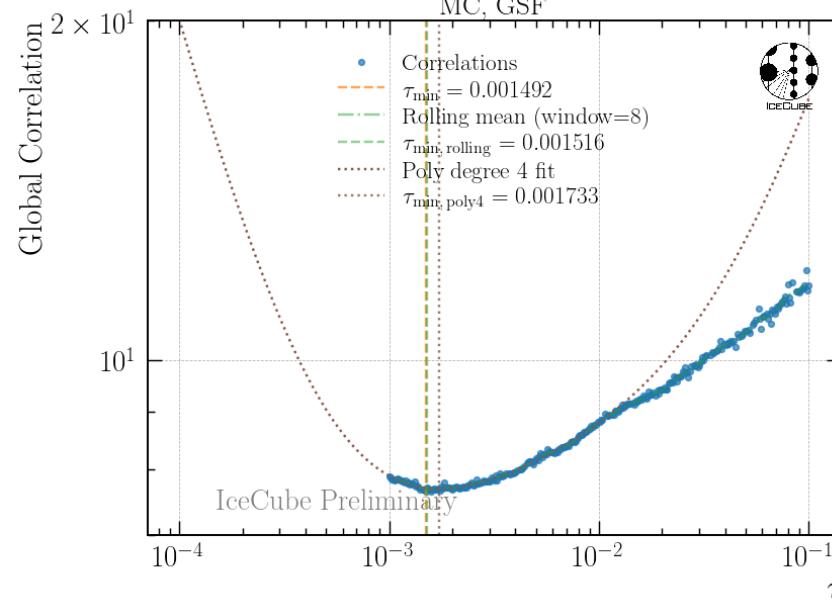
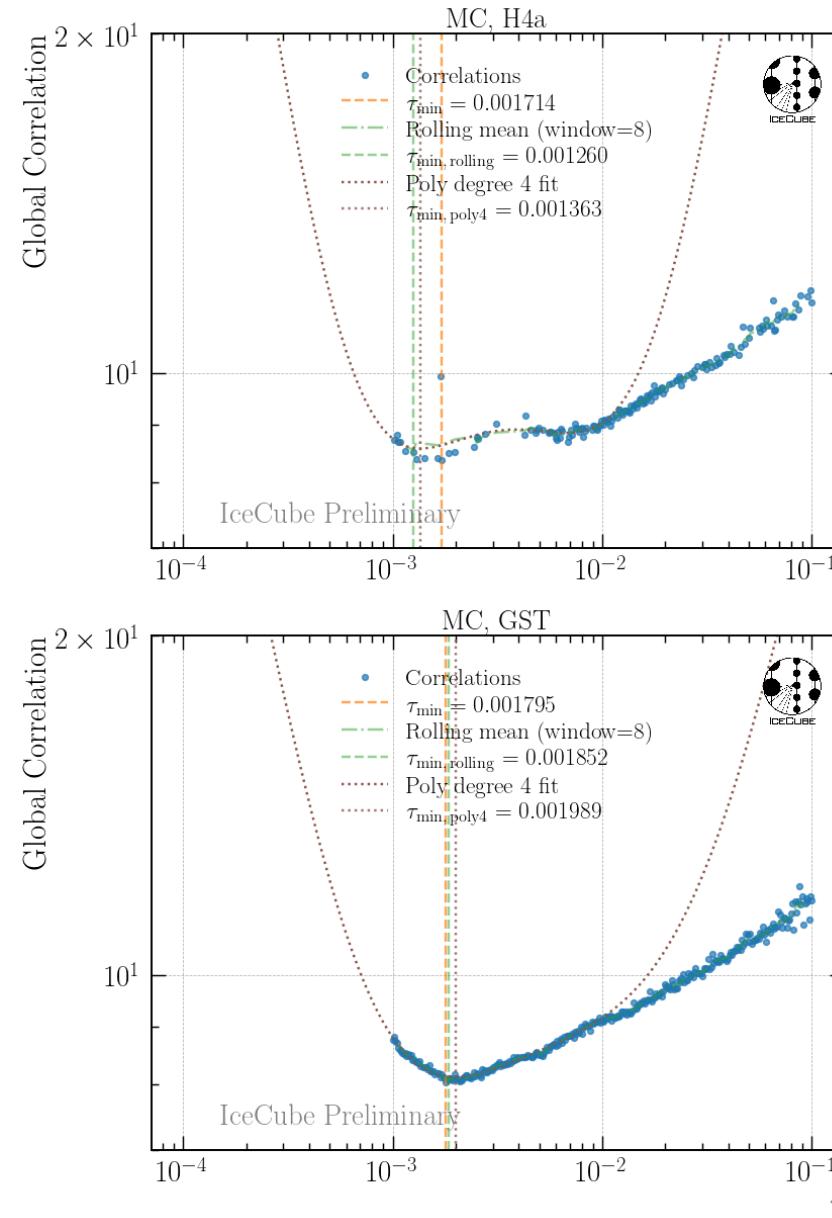
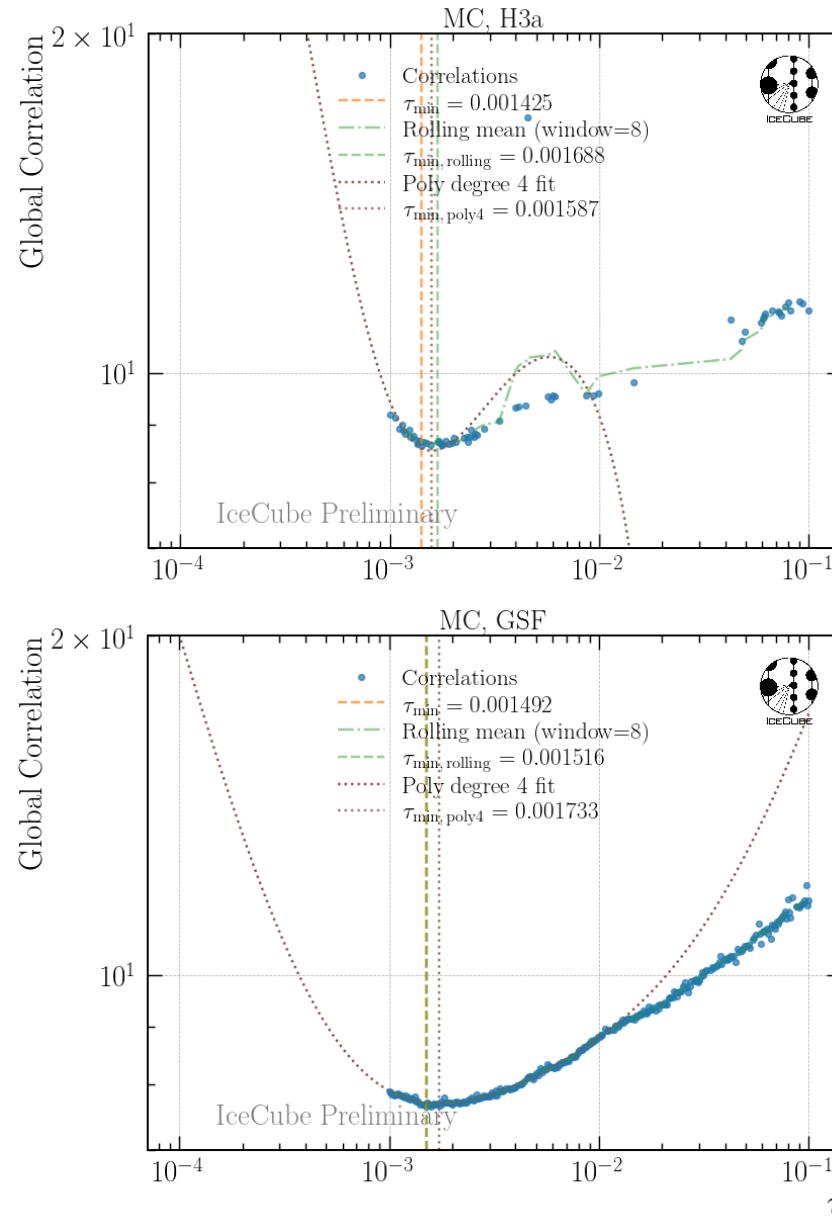
uncertainty cuts	<
bundle energy at entry	$0.9 \log_{10}(\text{GeV})$
bundle energy at surface	$2.0 \log_{10}(\text{GeV})$
zenith	0.1 rad
azimuth	0.2 rad
entry pos x, y, z	42 m
center pos x, y, z	50 m
entry pos time	200 ns
center pos time	600 ns
length in detector	160 m
length	2000 m

# Uncertainties per Bin



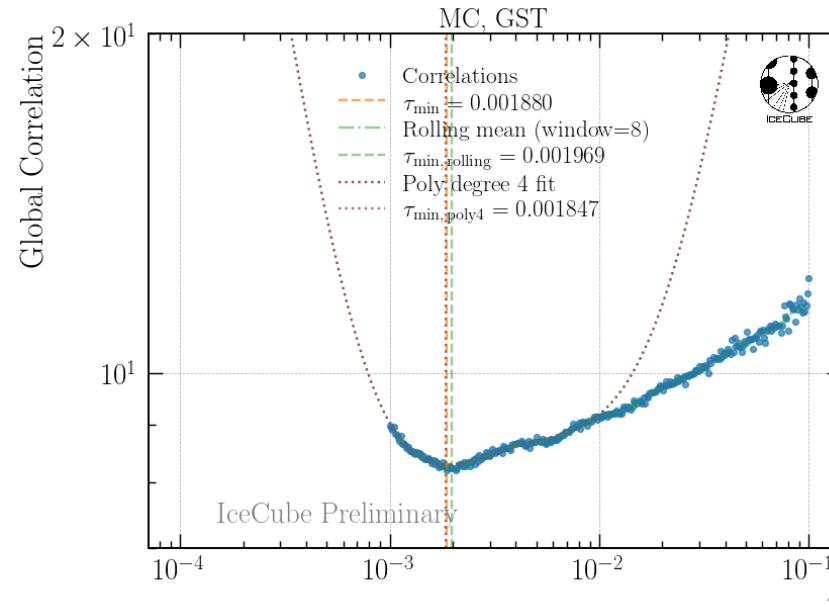
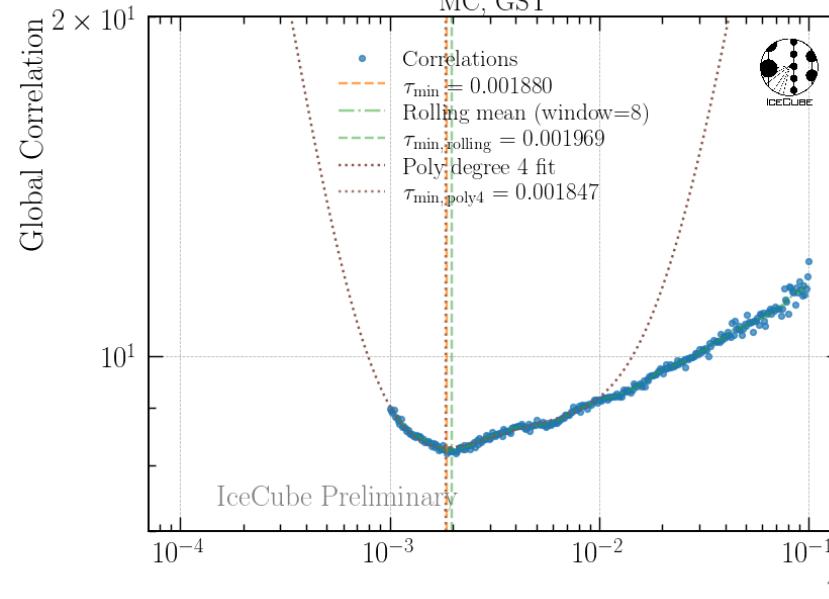
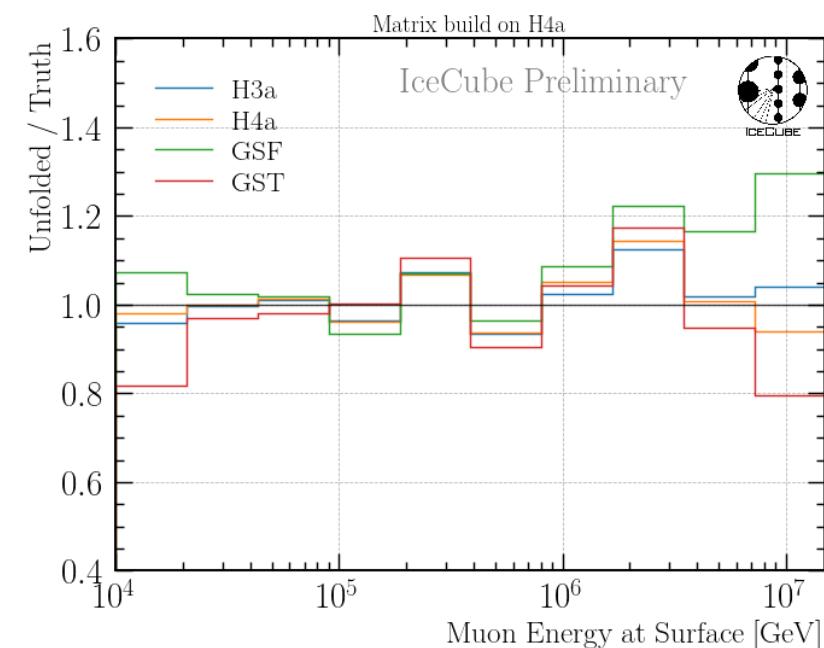
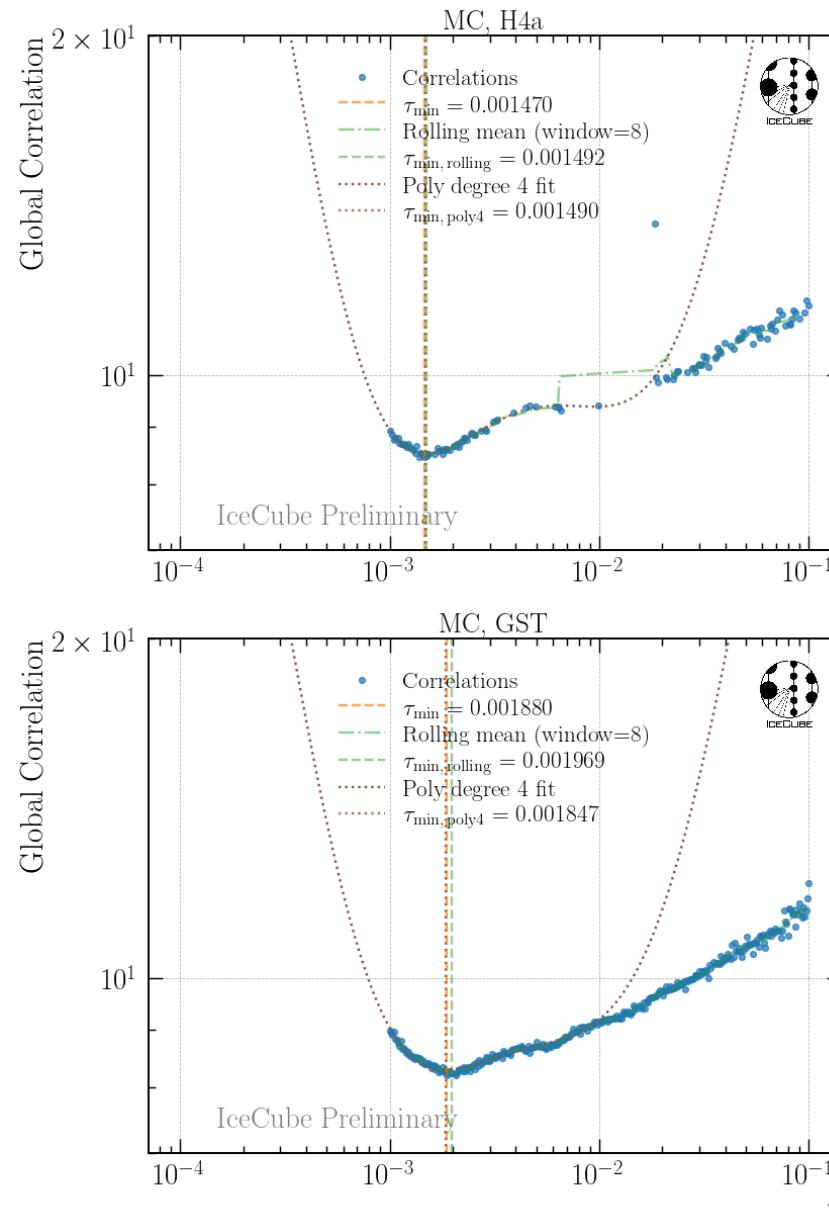
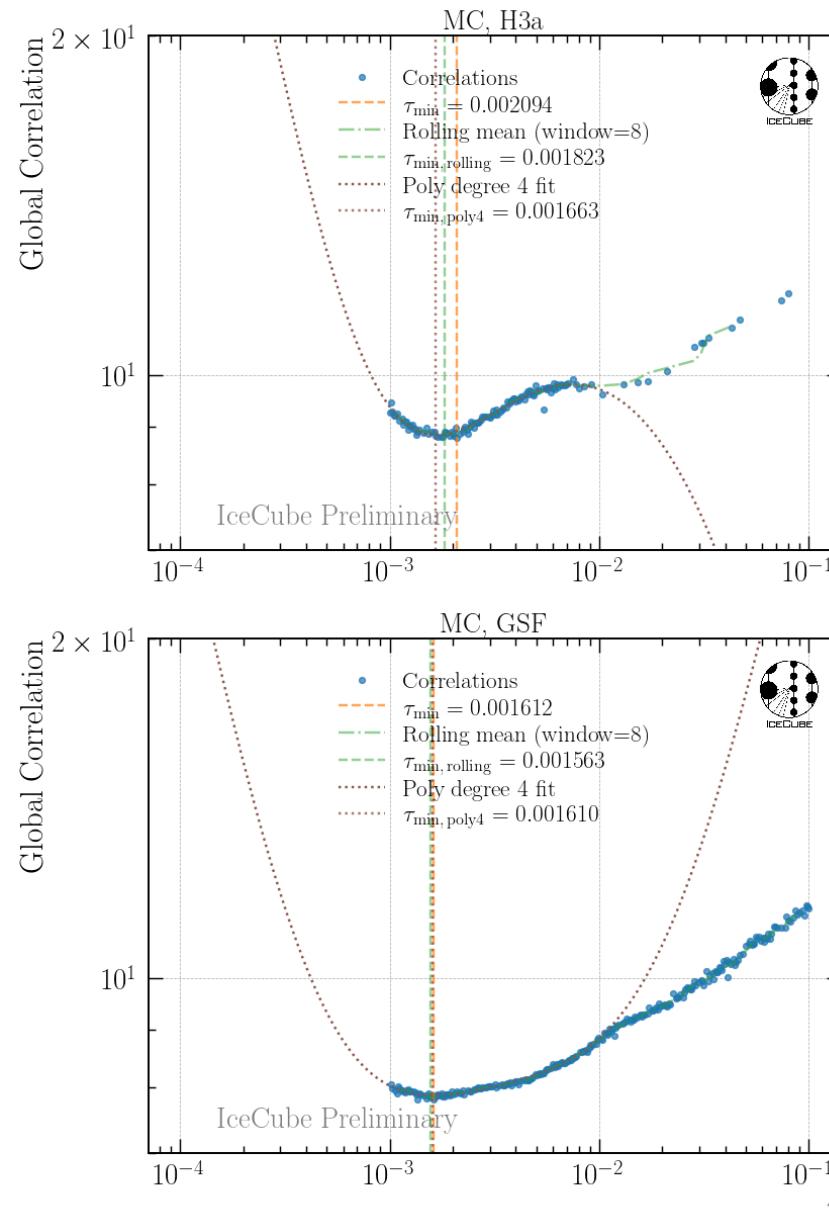
- Fit  $\tau \in 10^{-3} - 10^{-2}$

## H3a Unfolding Bias



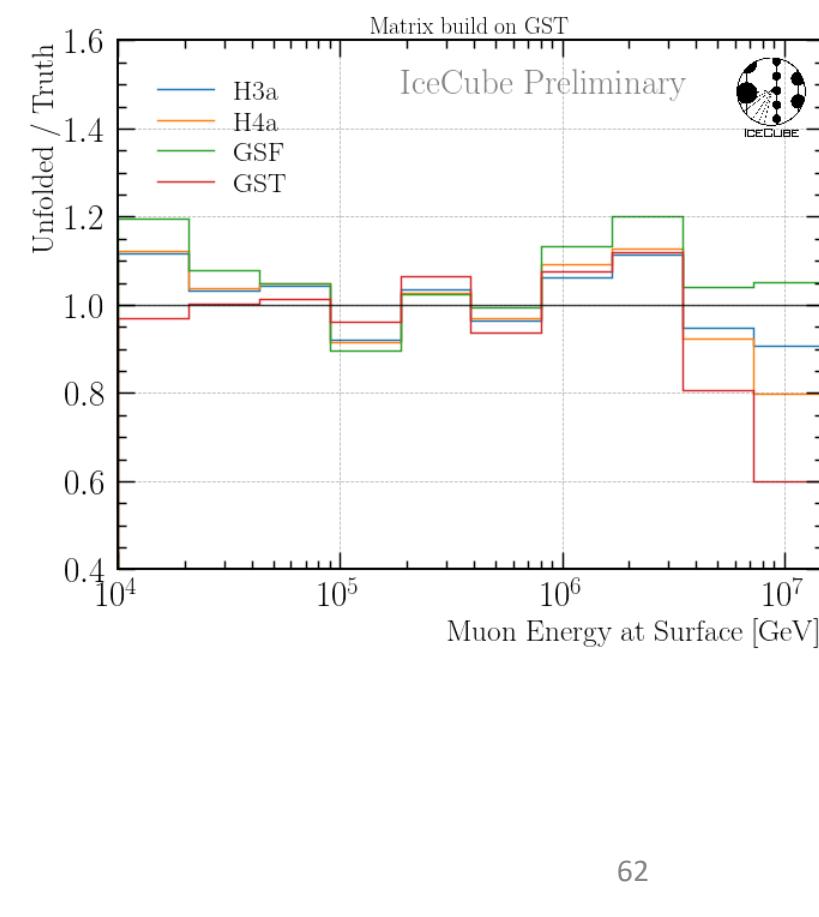
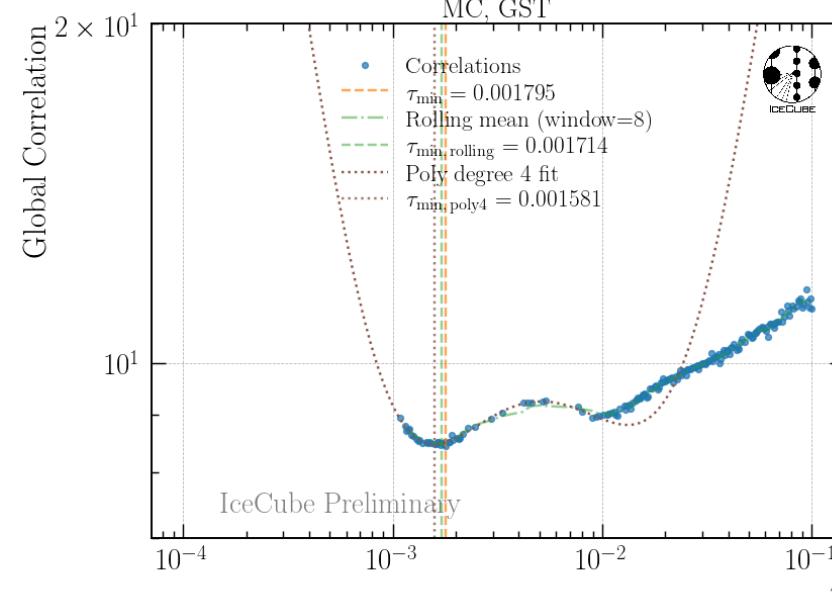
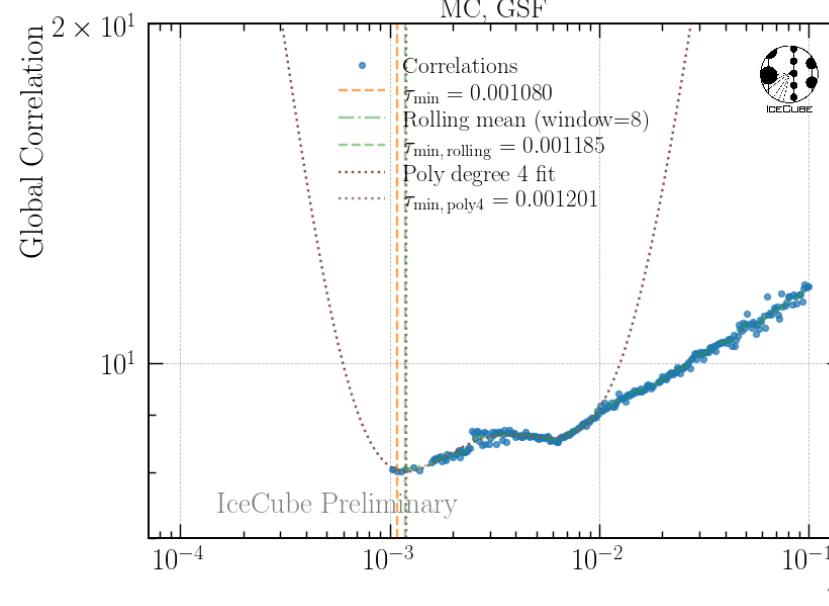
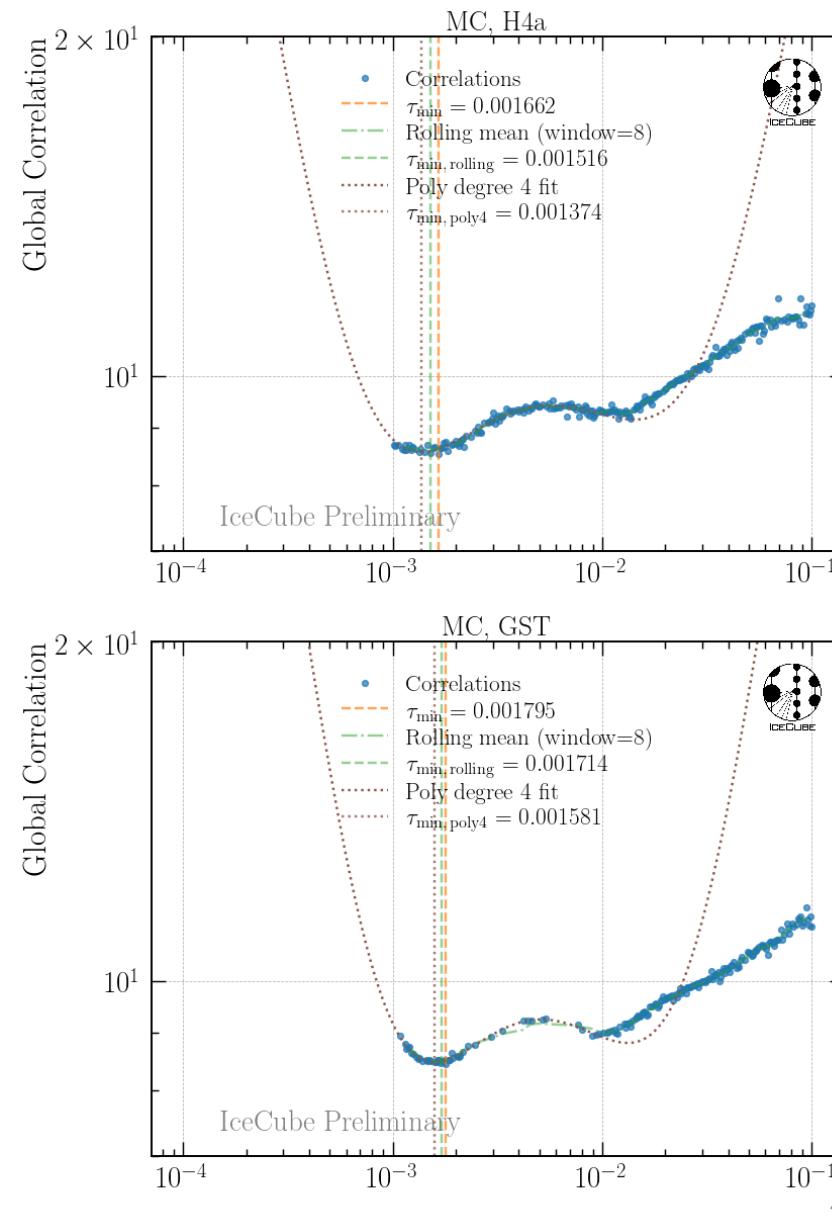
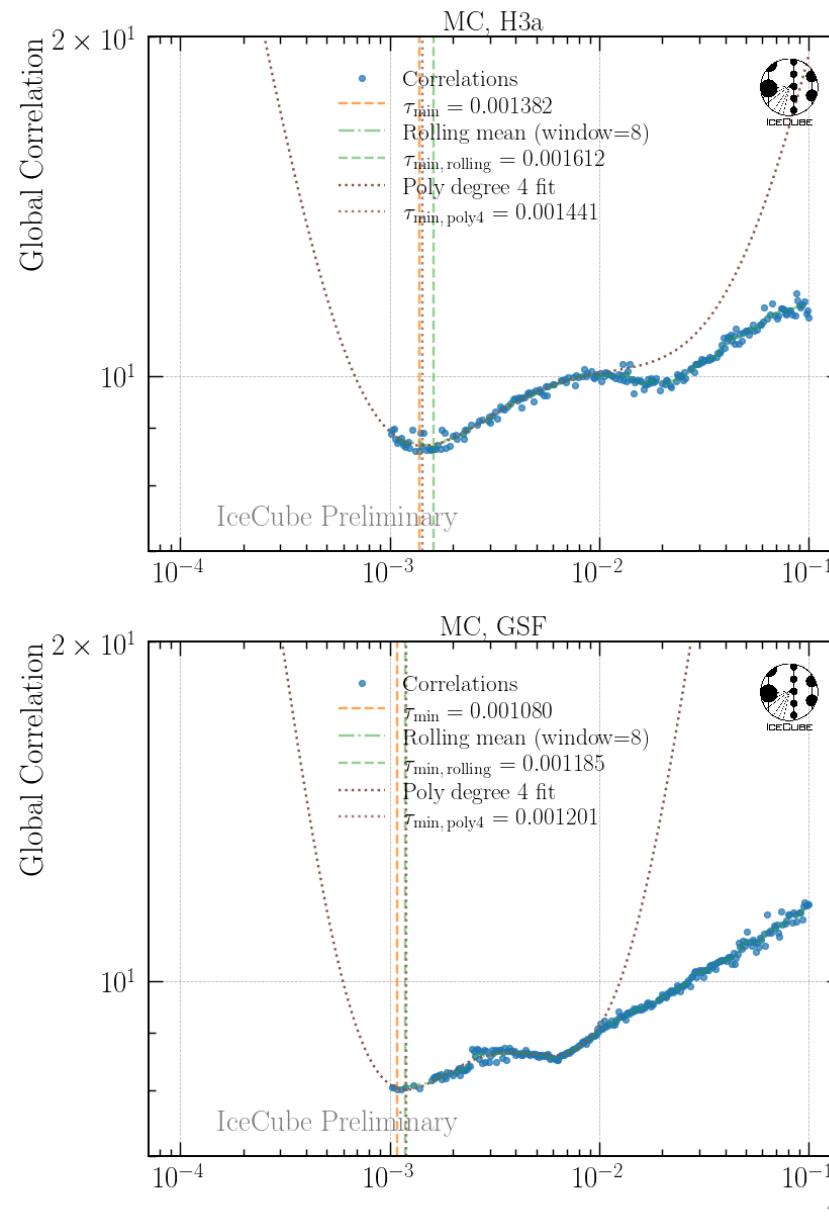
- Fit  $\tau \in 10^{-3} - 10^{-2}$

## H4a Unfolding Bias



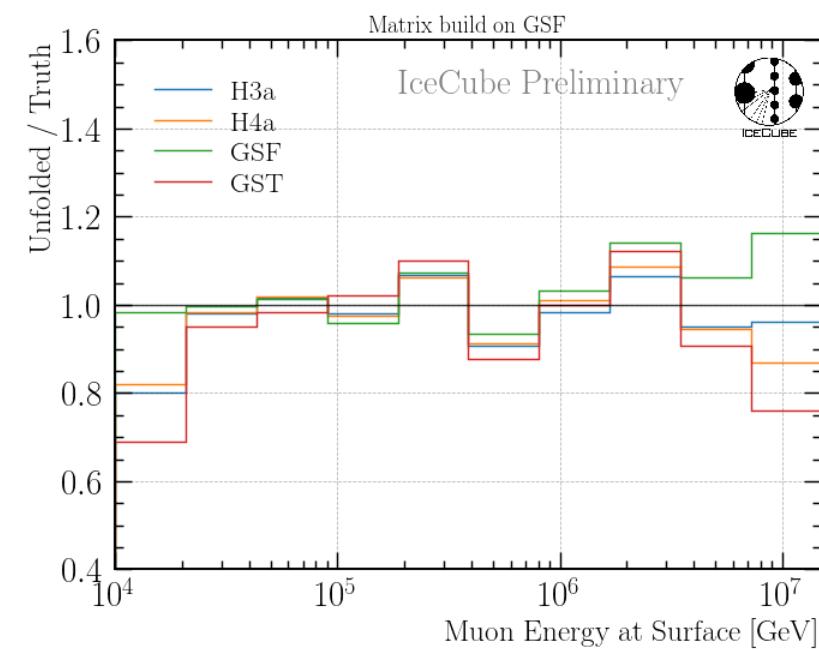
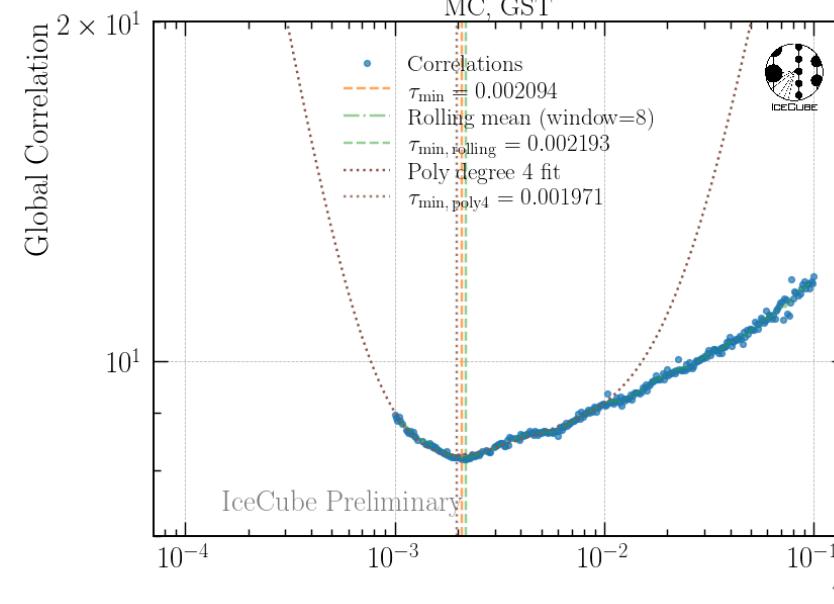
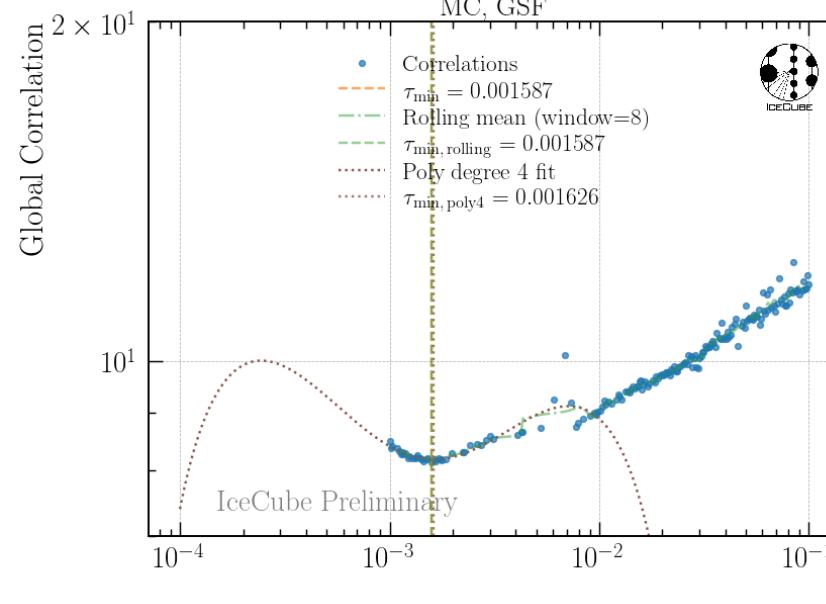
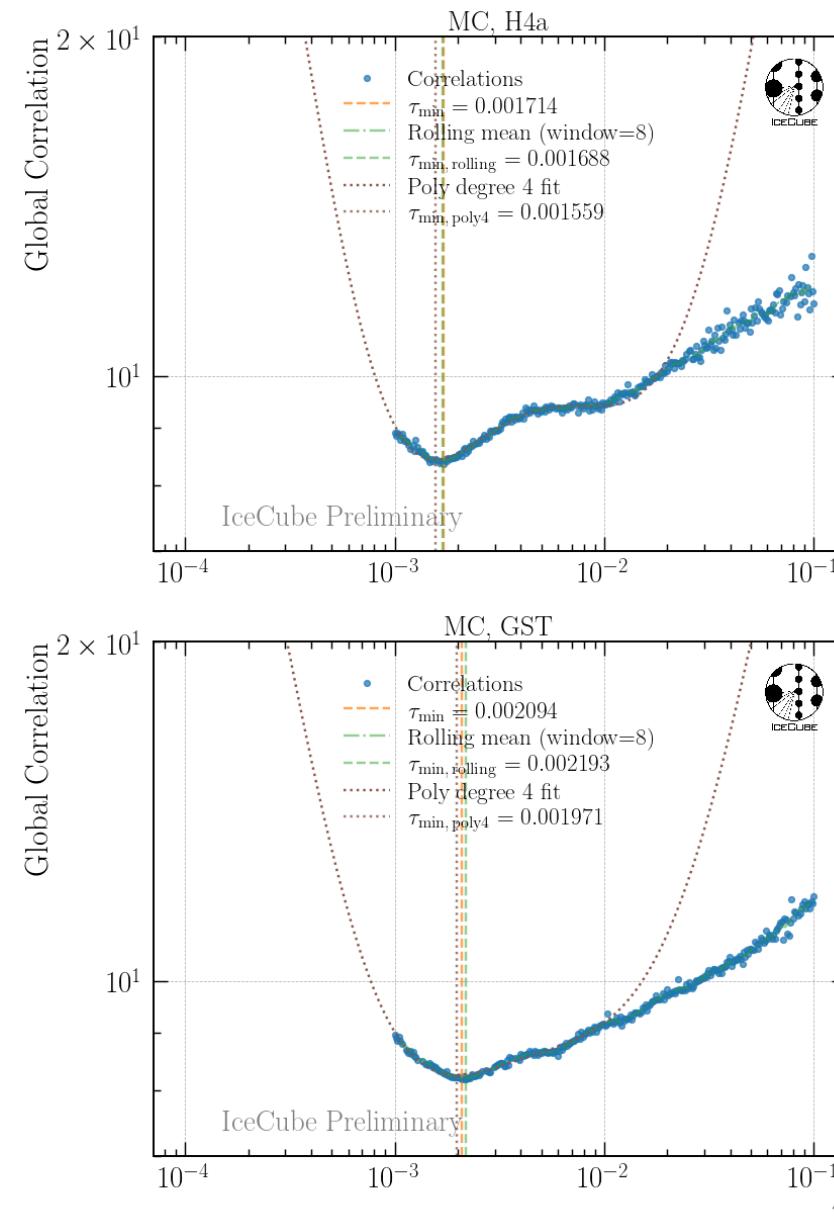
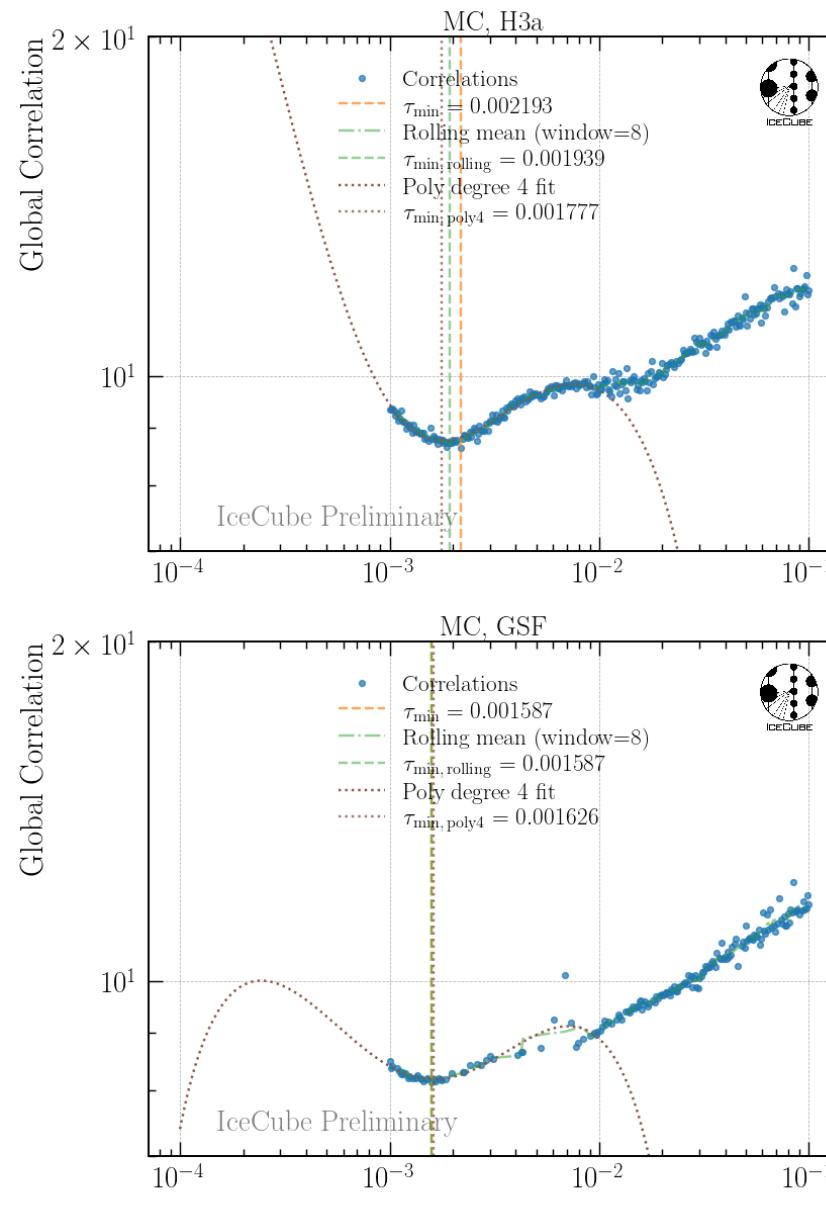
- Fit  $\tau \in 10^{-3} - 10^{-2}$

## GST Unfolding Bias

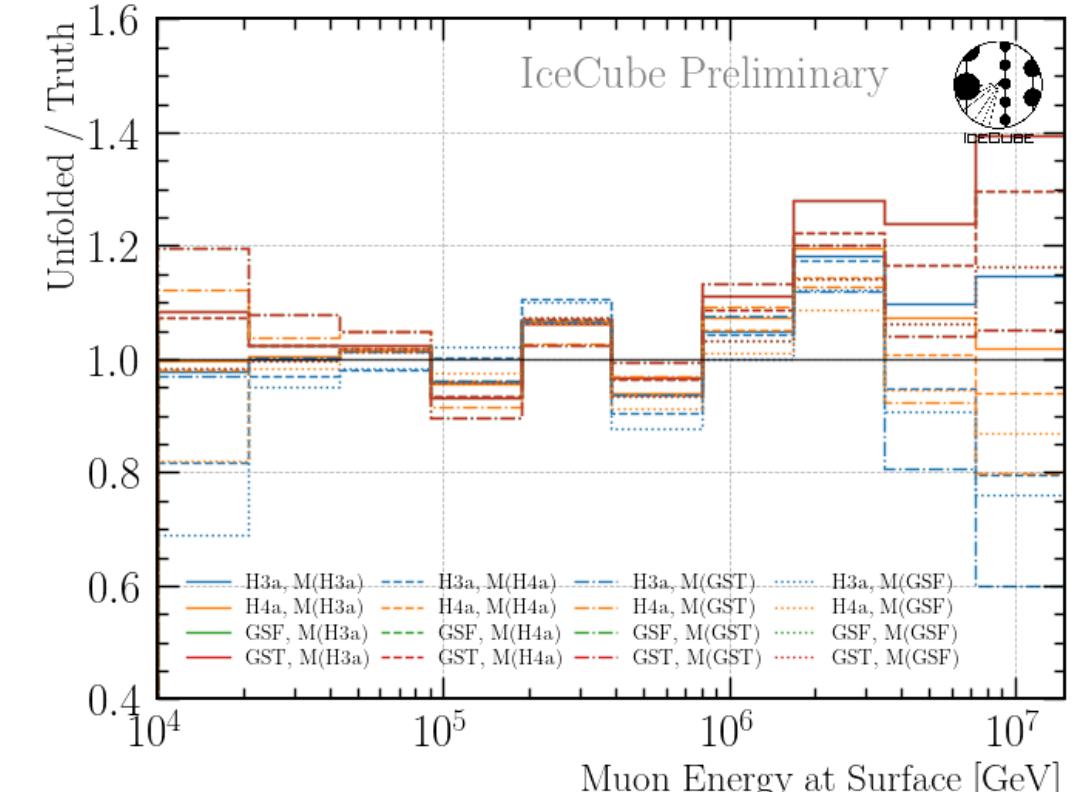
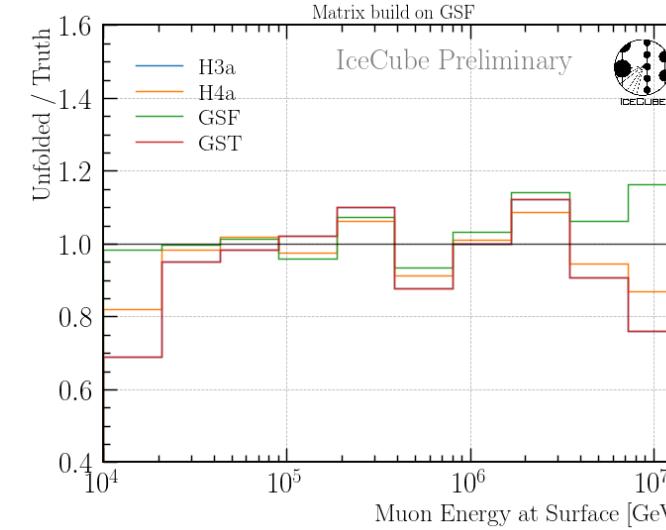
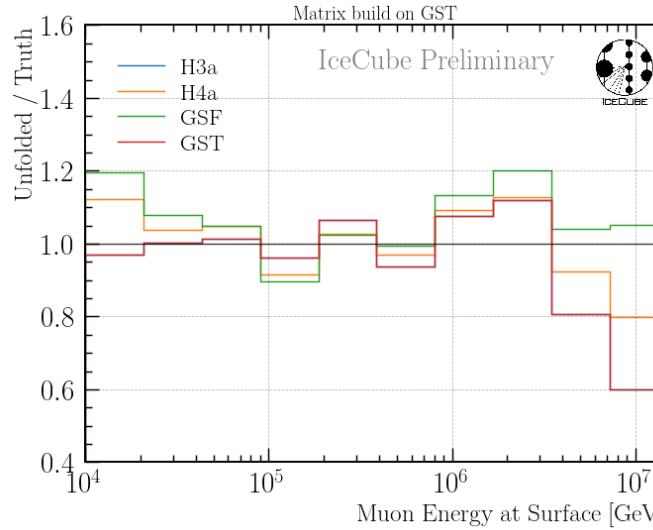
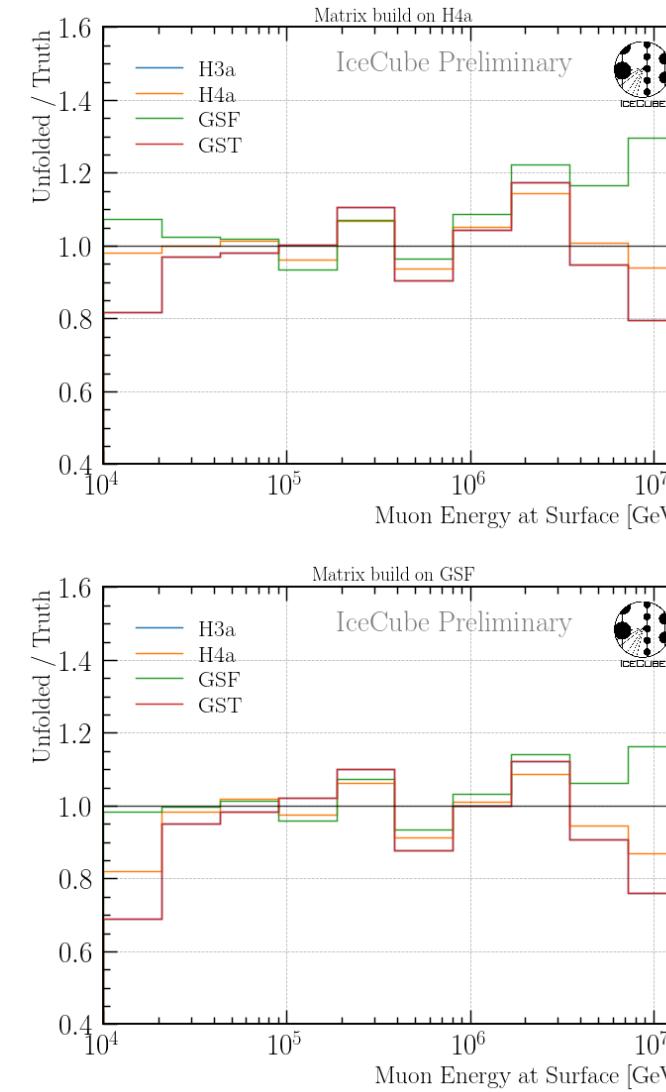
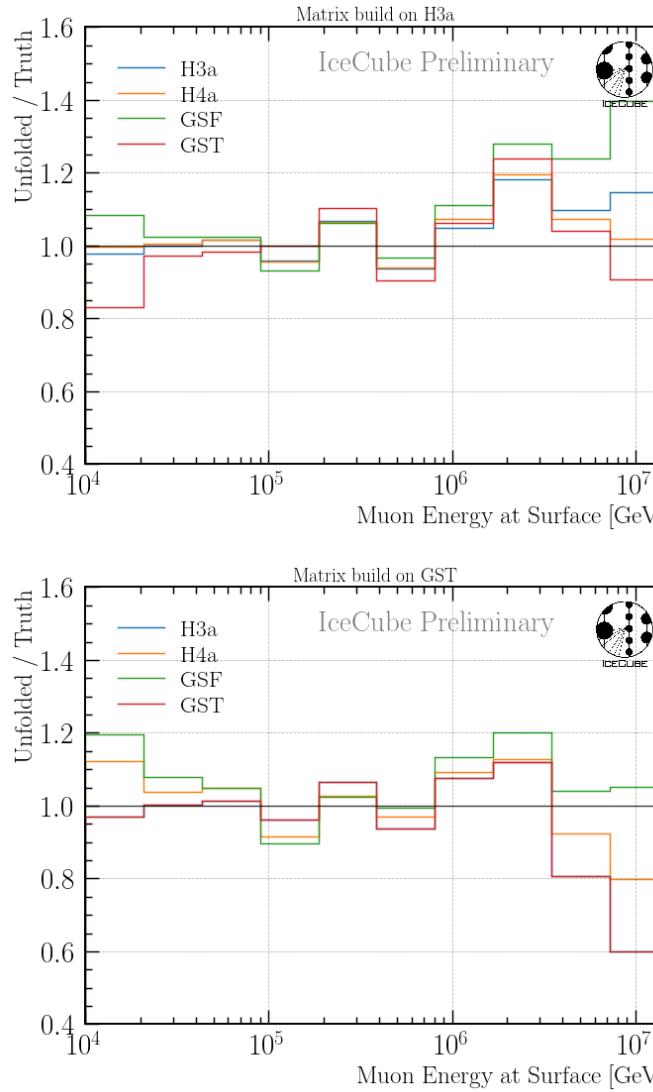


- Fit  $\tau \in 10^{-3} - 10^{-2}$

# GSF Unfolding Bias

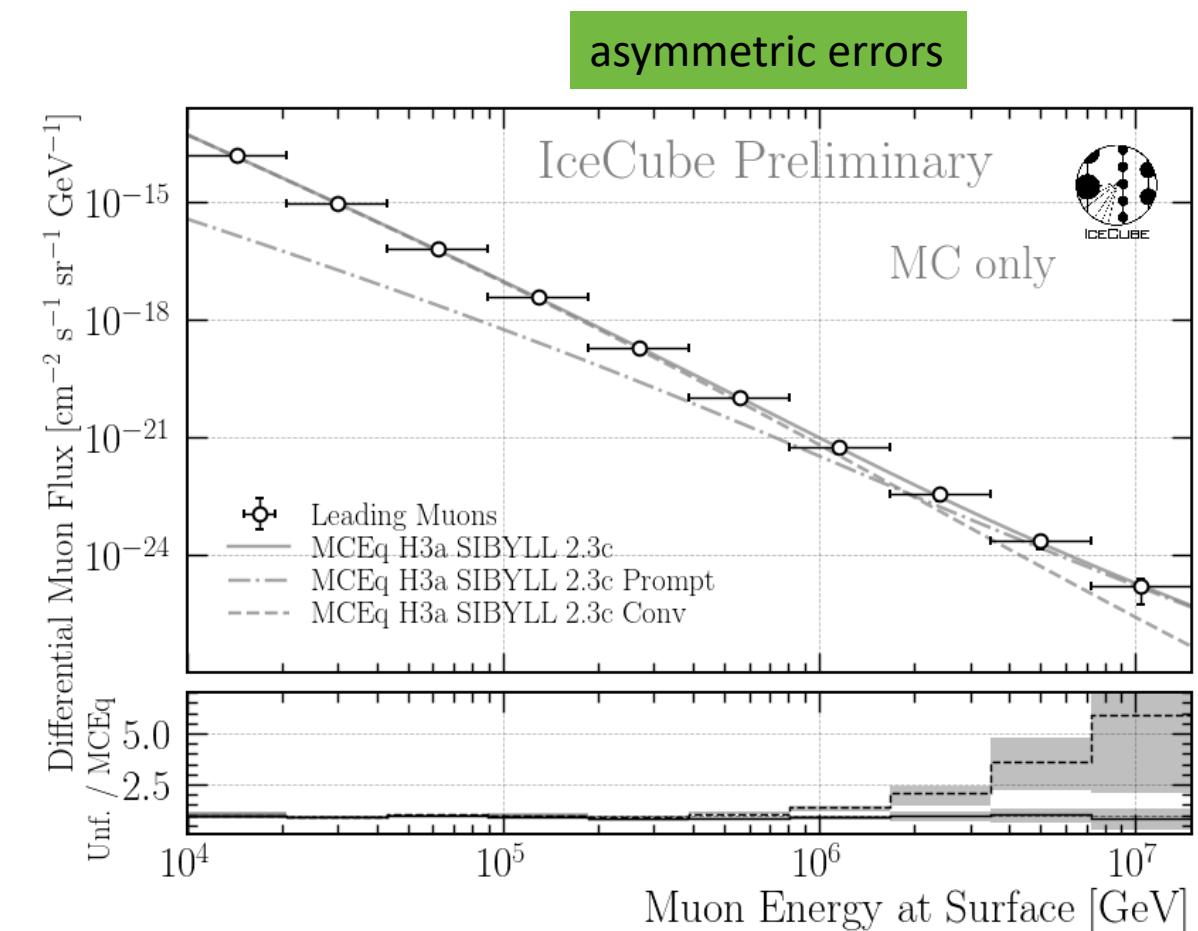
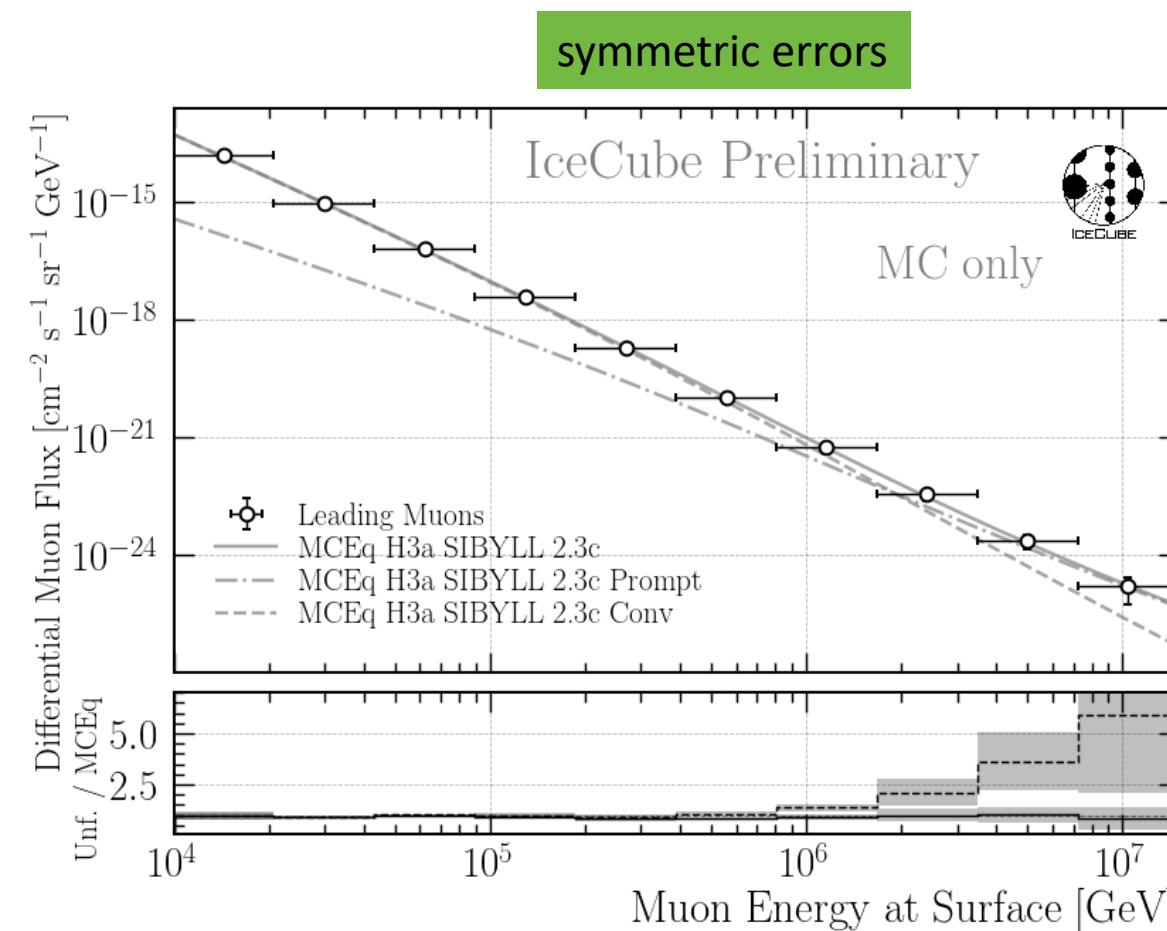


# Unfolding Bias for All Models



➤ Add these biases as an uncertainty to the unfolding result

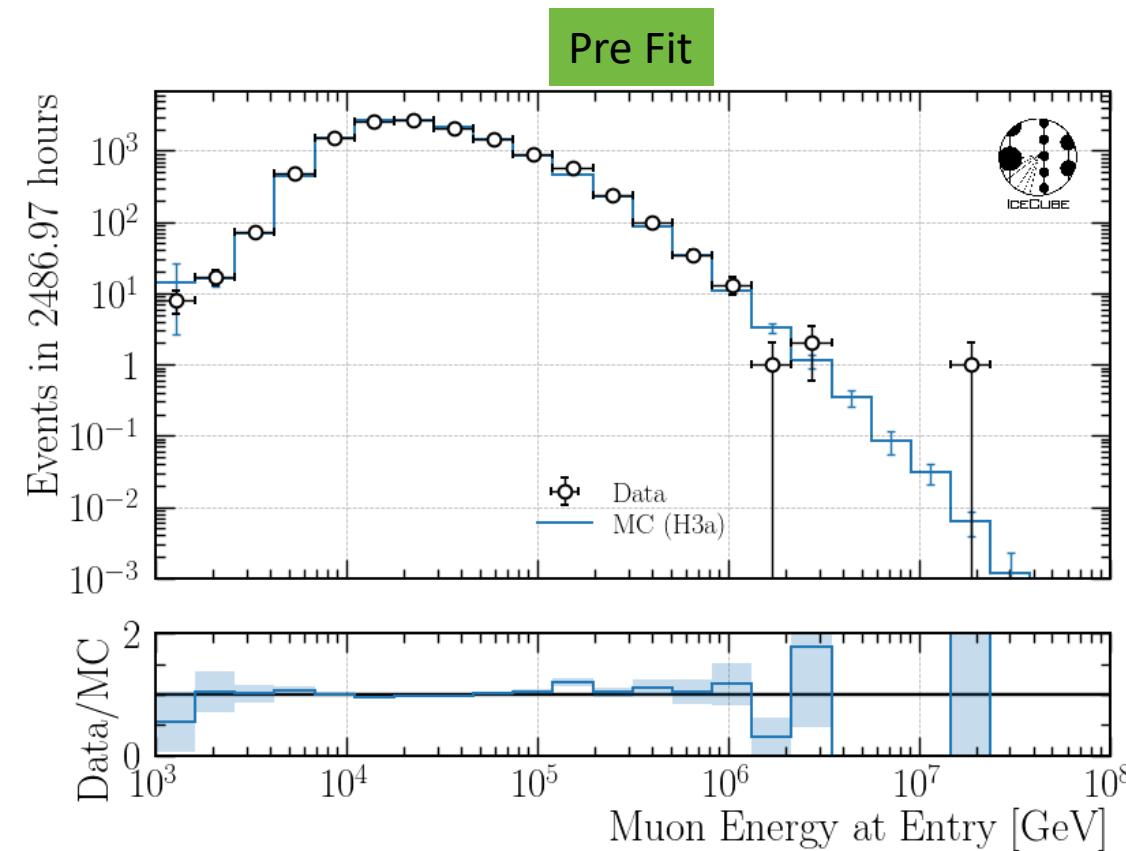
## 12 Years Prediction



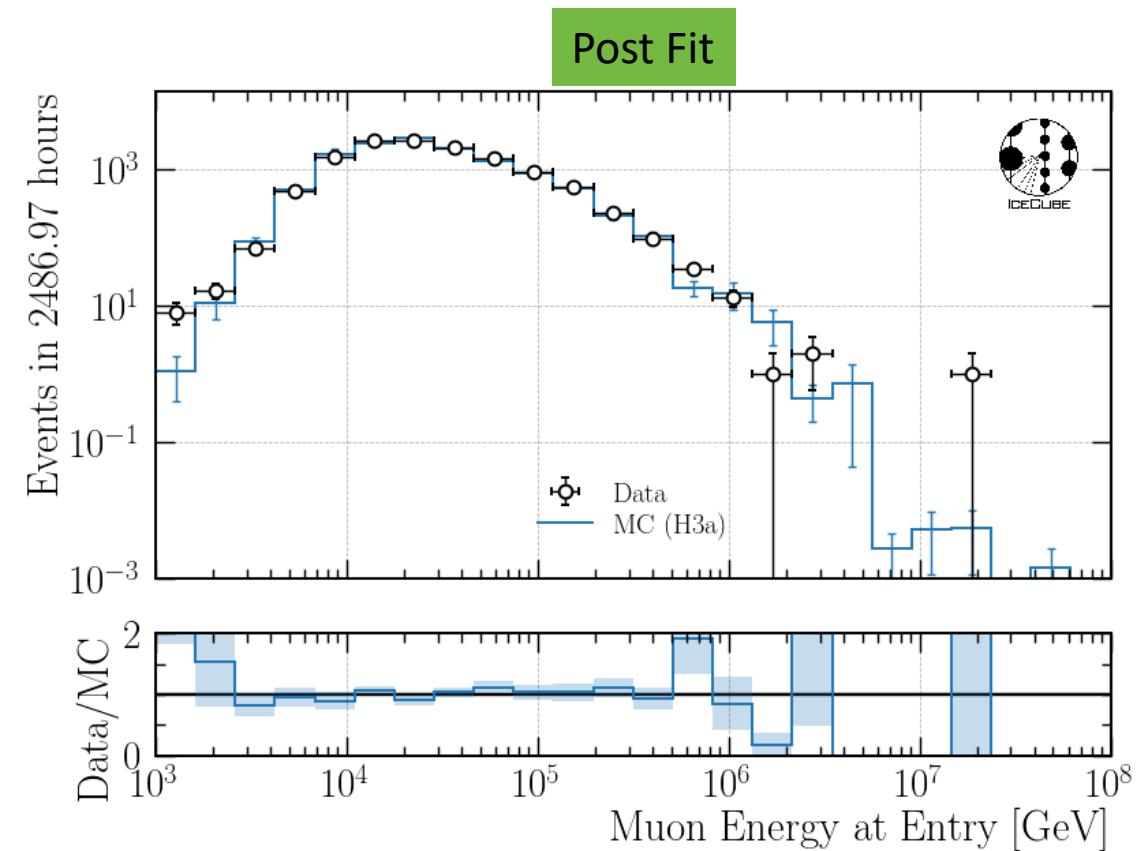
$$\sigma_{\text{tot}} = \sqrt{\sigma_{\text{minuit}}^2 + \sigma_{\text{unf-bias}}^2 + \sigma_{A_{\text{eff}},\text{stat}}^2}$$

# Data—MC Pre/Post Fit

# Data-MC: Burnsample



- include entire Snowstorm dataset



- re-weight to best fit systematics

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	

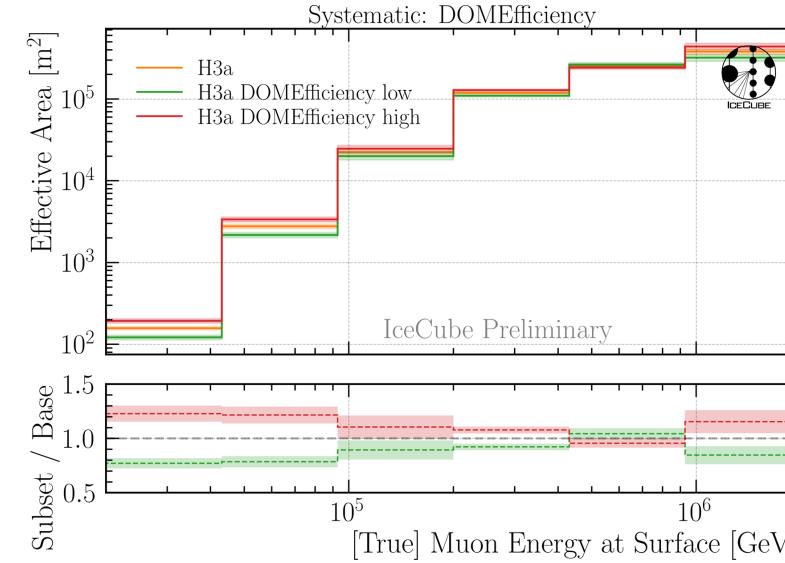
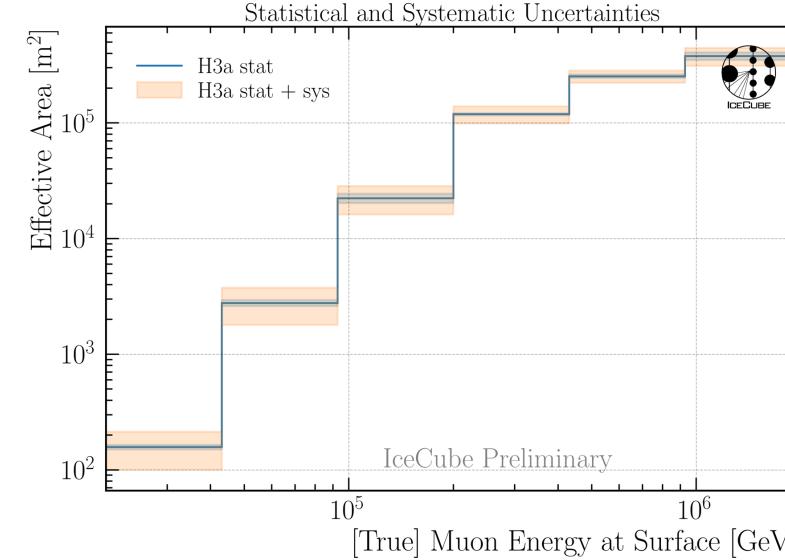
# Minuit output

	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 (-0.421)	-1.320718 (0.211)	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 (-0.080)	-1.65e3 (-0.037)	1.02e3 (-0.244)	-14.3596 (-0.303)	2.565423 (-0.311)	-4.189896 (0.000)	0.01 (-0.000)	-0.0013
x5	-0.08e6 (-0.116)	0 (0.034)	-0.4e6 (-0.118)	1.4e6 (0.267)	-0.4e6 (-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 (0.000)	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 (0.000)	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 (0.000)	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 (0.936)	100 (-0.727)	-100 (-0.727)	6.8e-3 (0.023)	-3.941e-3 (-0.092)	7.366e-3 (0.108)	-0.00 (0.000)	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 (-0.711)	-50 (-0.15)	2.1e-3 (0.015)	-1.390e-3 (-0.069)	2.506e-3 (0.079)	-0.00 (0.000)	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 (-0.10)	-2.0e-3 (0.034)	920e-6 (-0.049)	-2.090e-3 (-0.049)	0.00 (0.000)	-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 (-0.091)	5e-6 (0.091)	0.040e-3 (0.443)	-0 (0.000)	0 (0.000)
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 (-0.437)	-6e-6 (-0.437)	0e-6 (0.000)	-0e-6 (-0.000)
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 (-0.437)	-0 (0.000)	-0 (0.000)
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 (0.000)	-0.00 (0.000)	-0.00 (0.000)	-0.00 (0.000)	0.00 (0.000)	-0 (0.000)	0e-6 (-0e-6)	-0 (0.000)	0.0912 (-0.0000)	-0.0000	
x16	0.0006	-0.0008 (0.000)	0.0011 (0.000)	0.0003 (-0.000)	-0.0013 (-0.000)	-0.0002 (-0.000)	0.0001 (0.000)	0.0001 (0.000)	0.0000 (0.000)	0.0000 (0.000)	0.0000 (0.000)	-0.0000 (0.000)	0 (0.000)	-0e-6 (-0e-6)	0 (0.000)	-0.0000 (0.00253)	

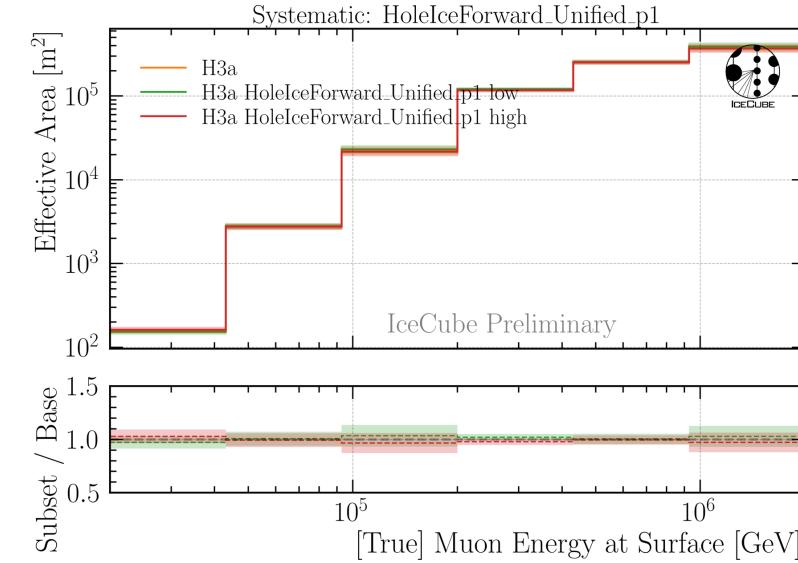
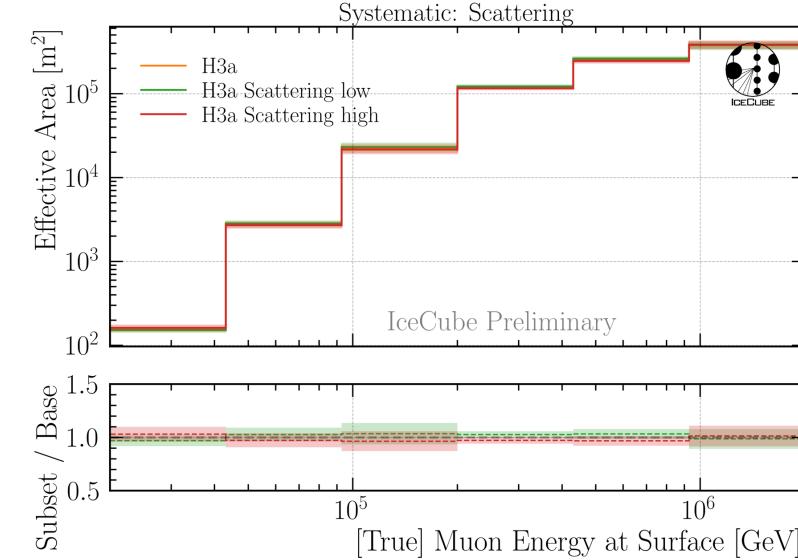
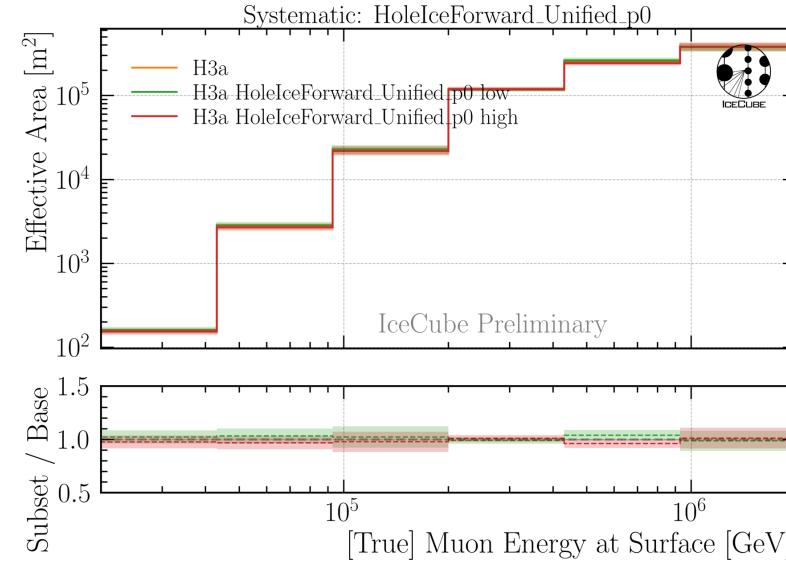
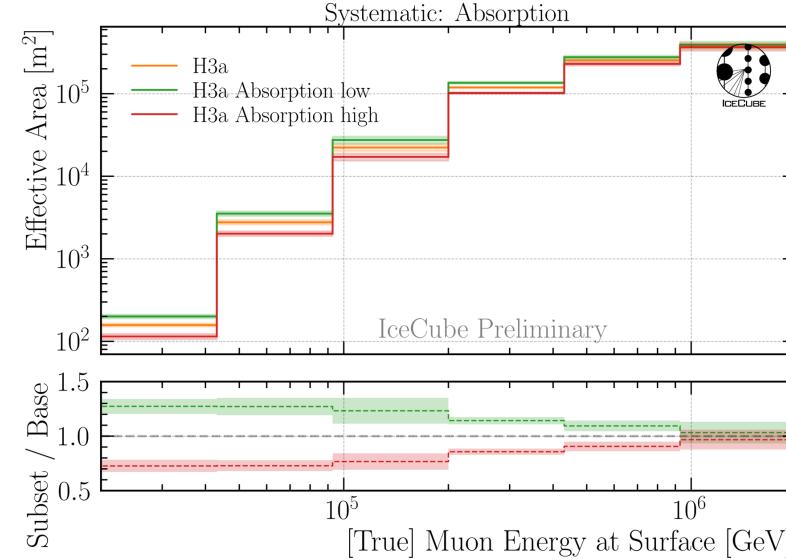
# Muon Flux Unfolding

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

# Ice & Detector Systematics



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



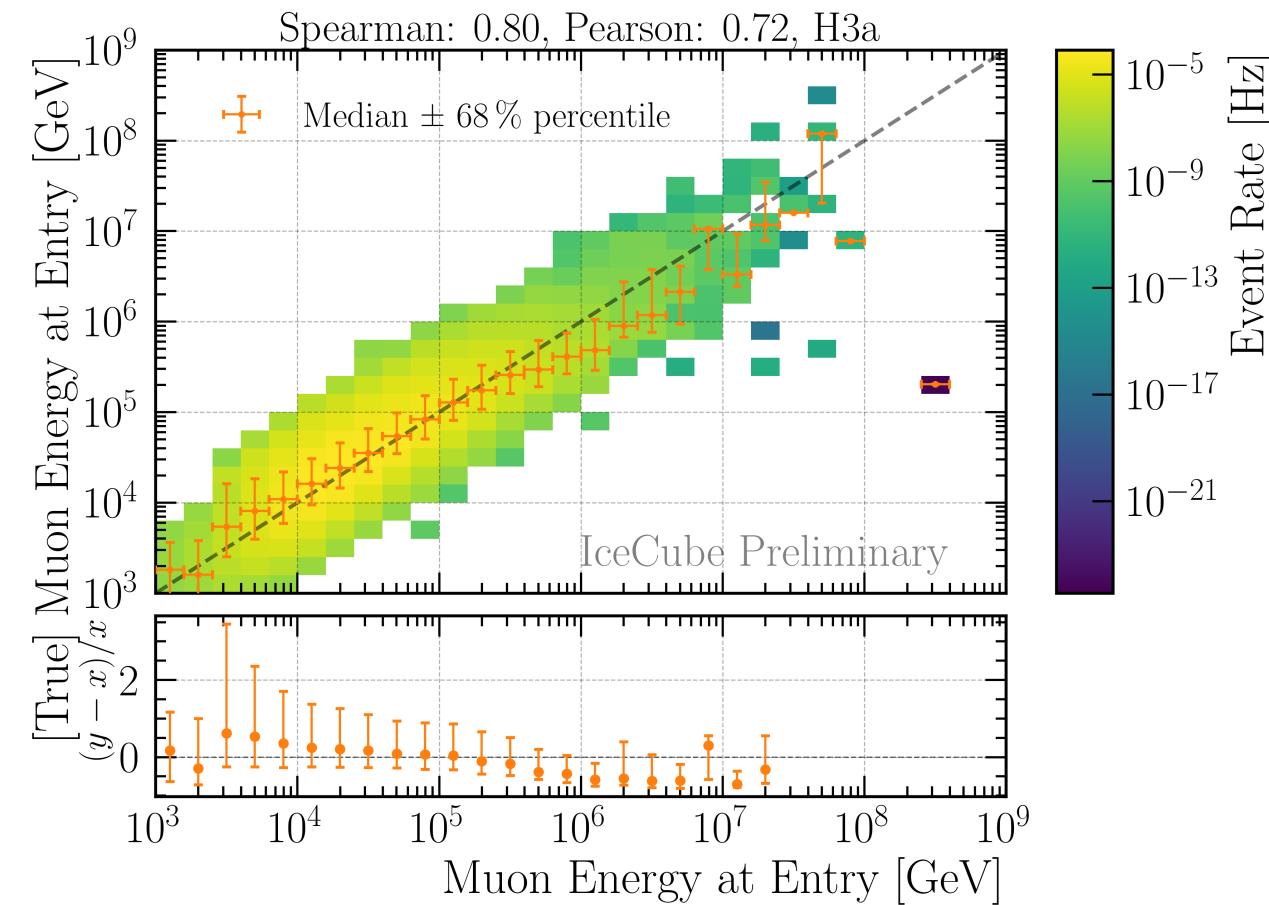
pascal.gutjahr@tu-dortmund.de

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

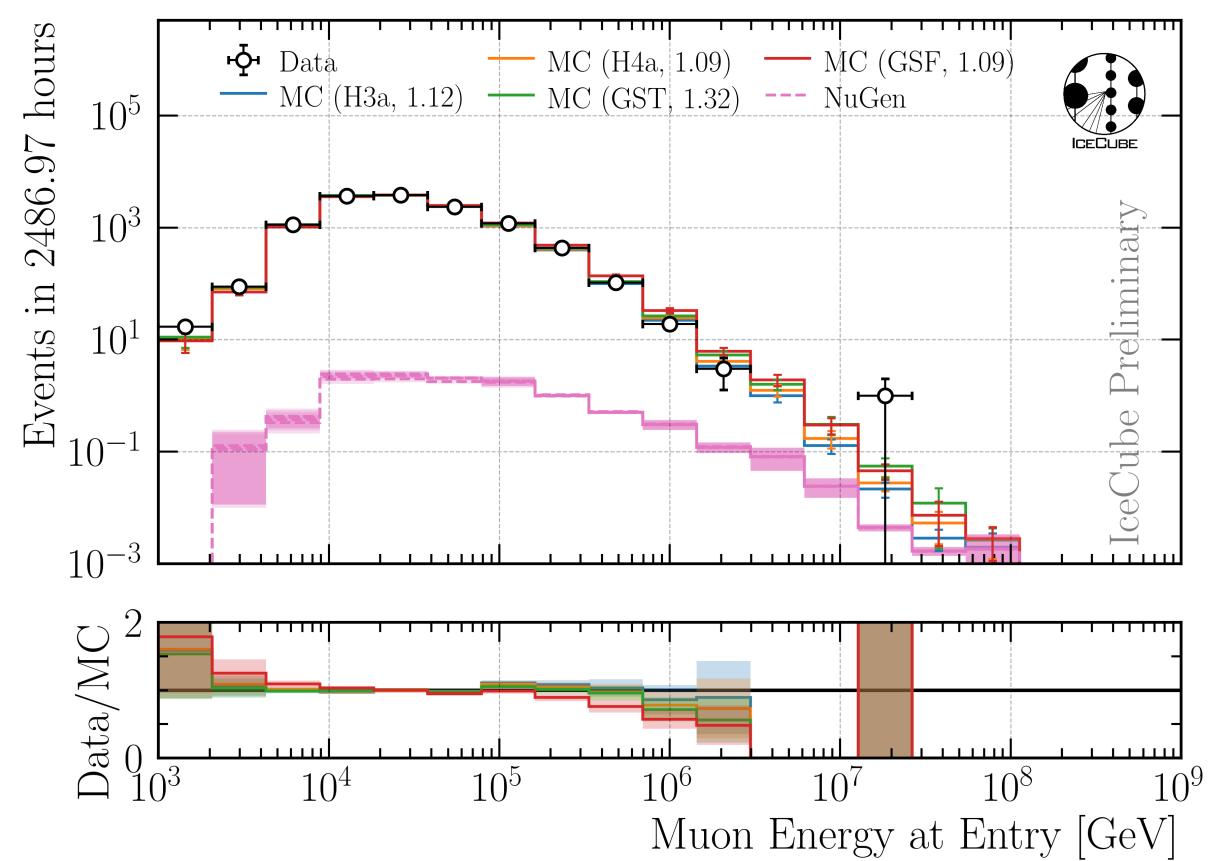
$$\sigma_{\text{tot}} = \sqrt{\sigma_{\text{stat}}^2 + \sum_i \sigma_i^2}, i: \text{scat, abs, DOME, holeice p0, p1}$$

# Reconstruction and Data—MC: Leading Muons

- Good reconstruction of leading muon energy → proxy

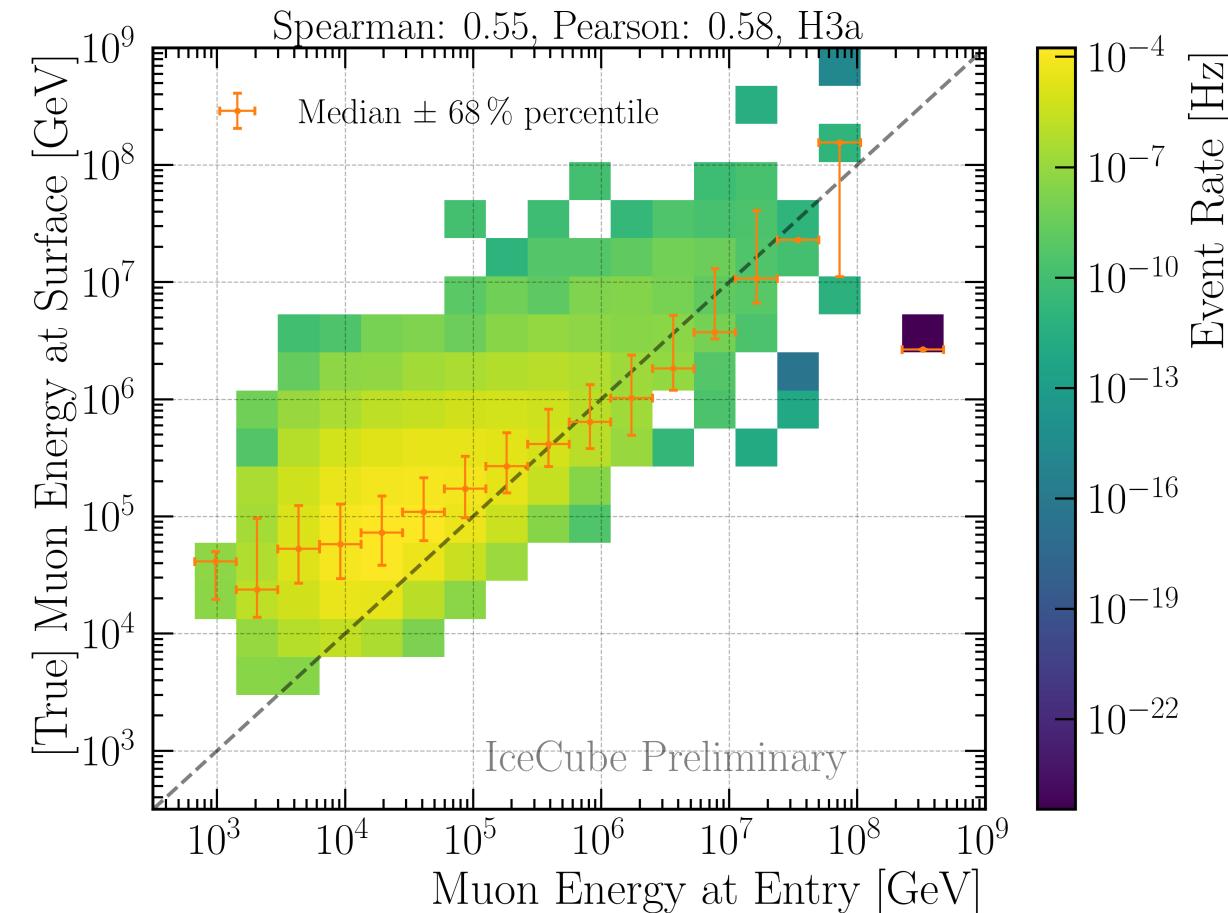


- Good data—MC agreement
- Global offset → upscale MC by 12%

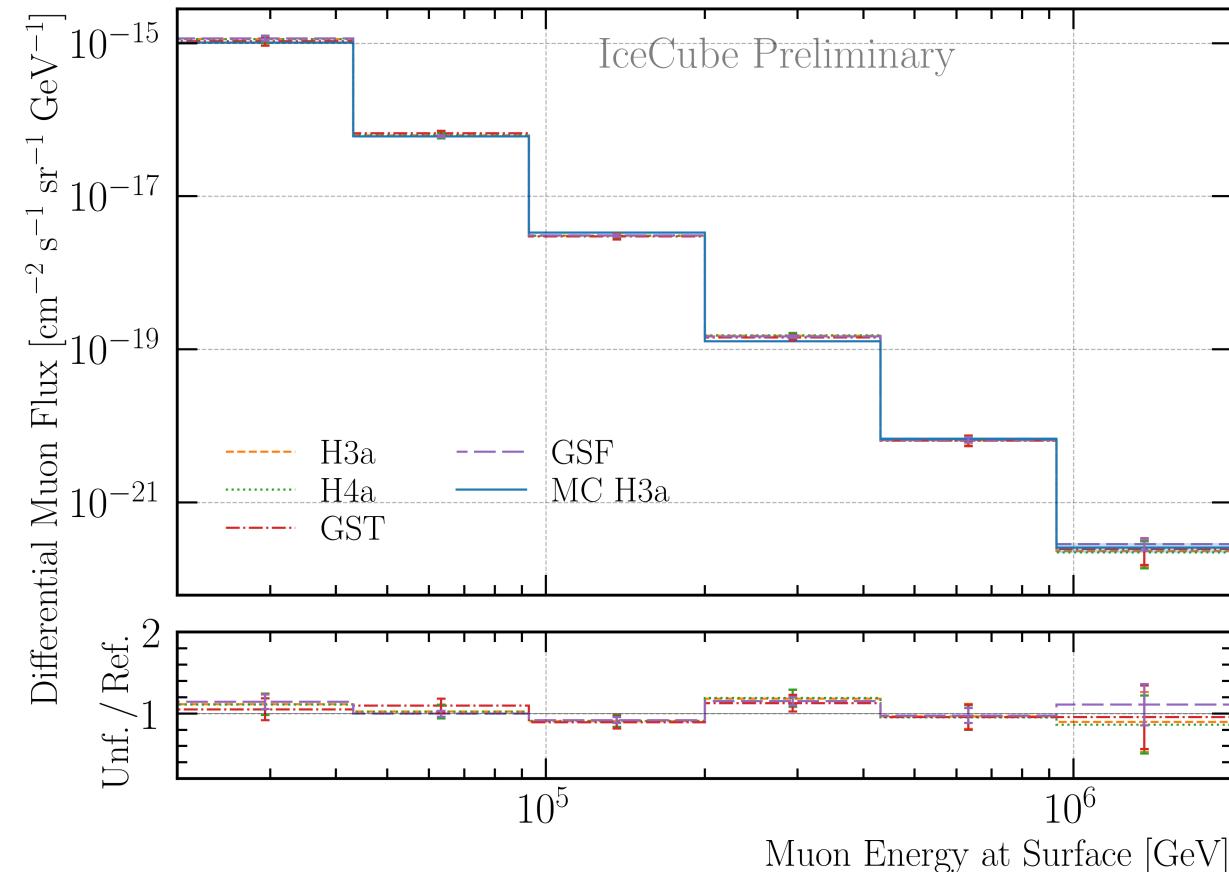


# Correlation and Robustness Test: Leading Muons

- Correlation between proxy and target



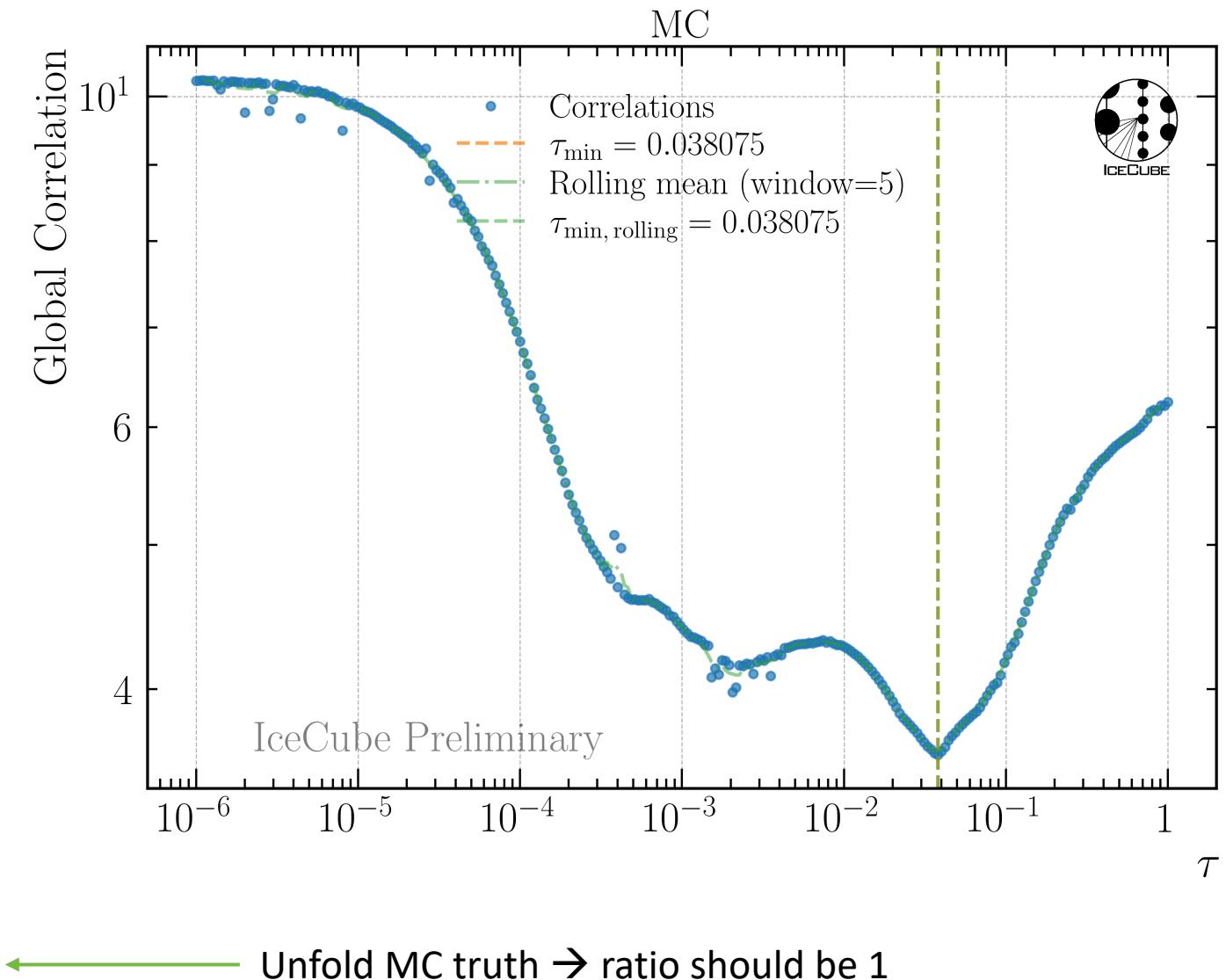
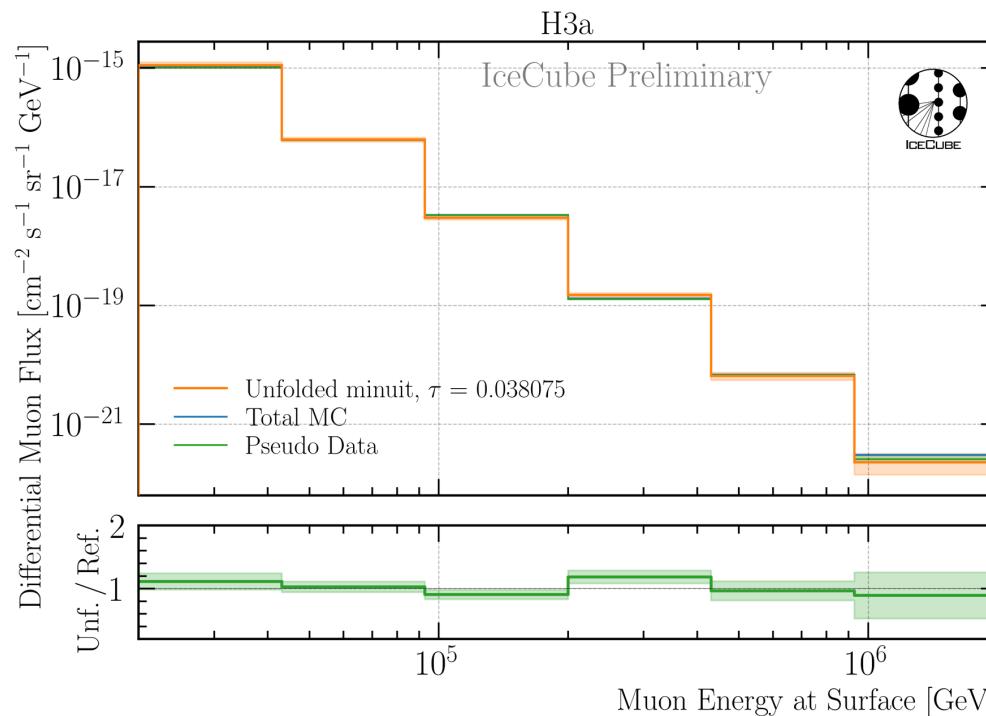
- Build unfolding matrix on H3a, H4a, GST & GSF
- Unfold H3a as test set
- Results are within uncertainties → robust



# Determine Regularization

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

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



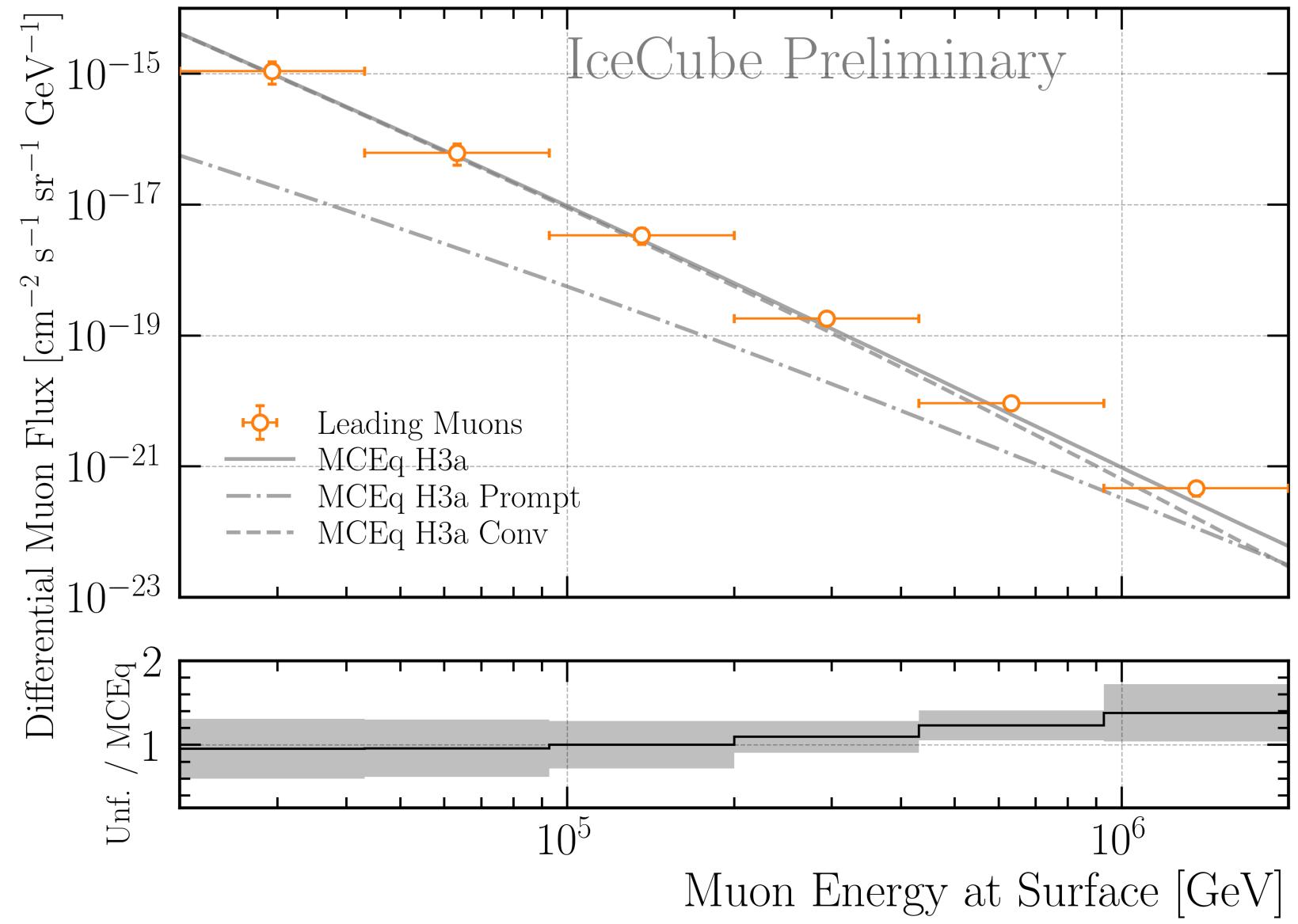
Unfold MC truth → ratio should be 1

Burnsample

# Burnsample Unfolding

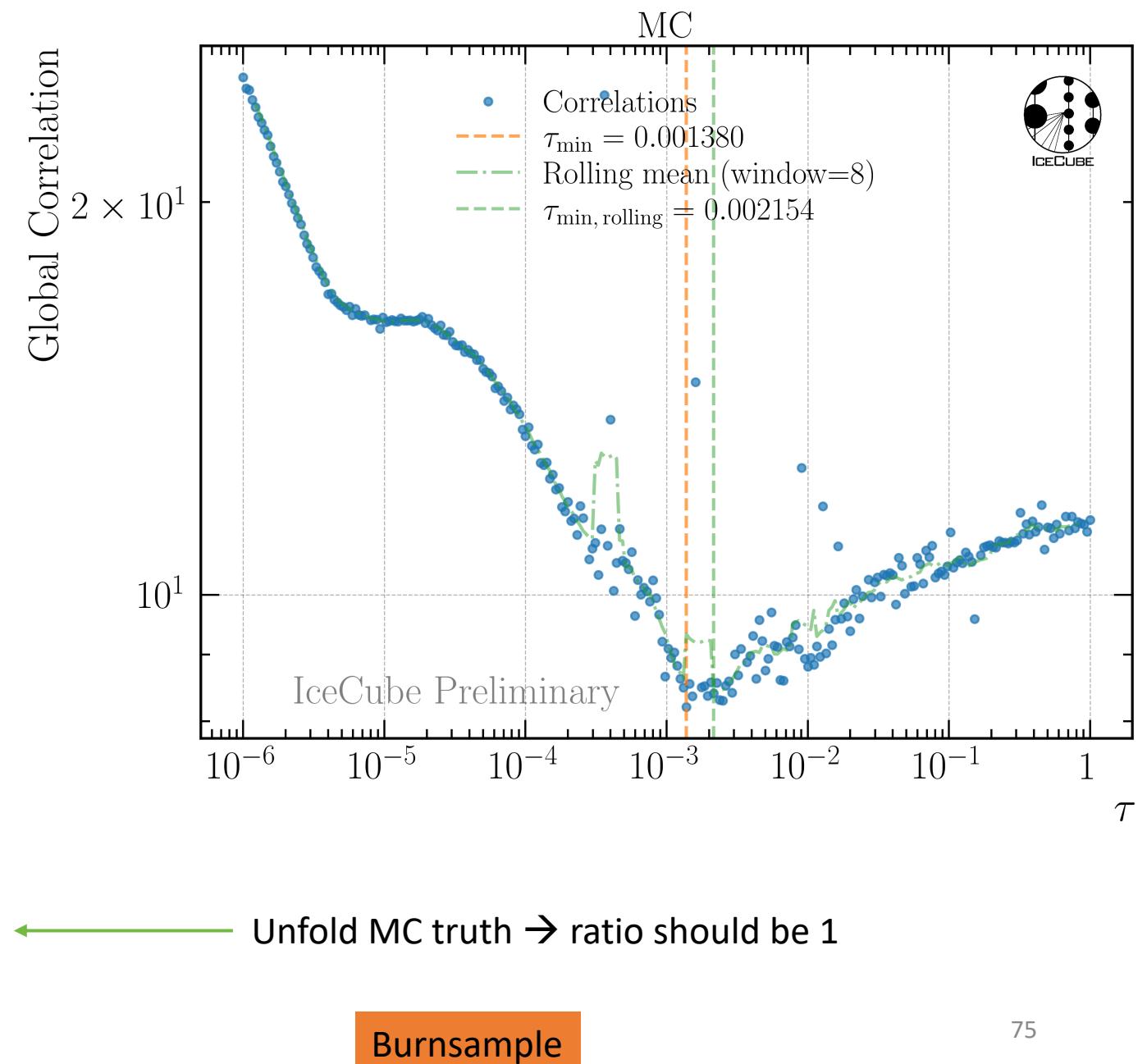
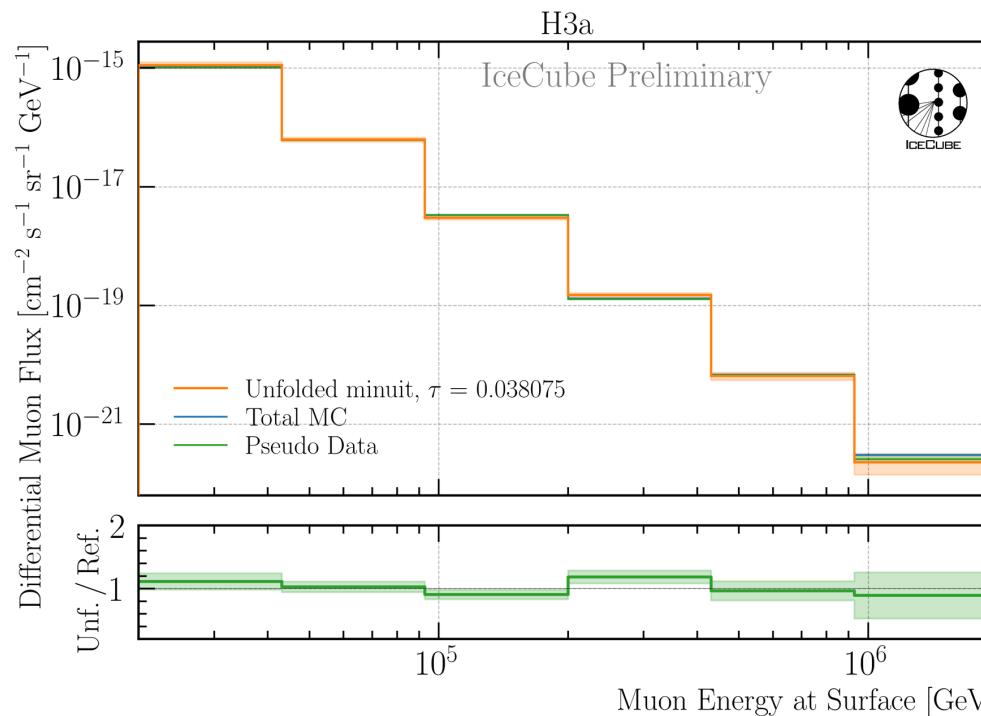
## Leading muons

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



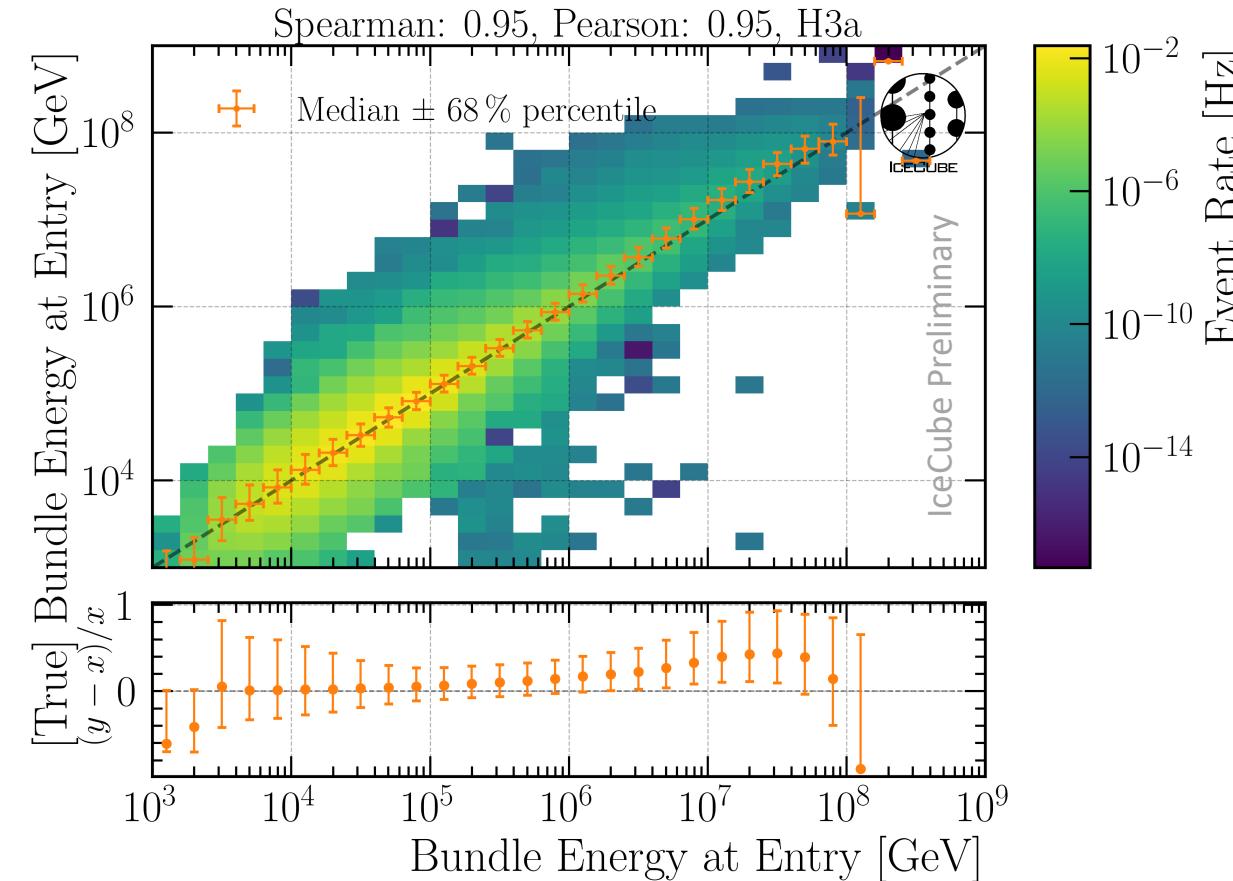
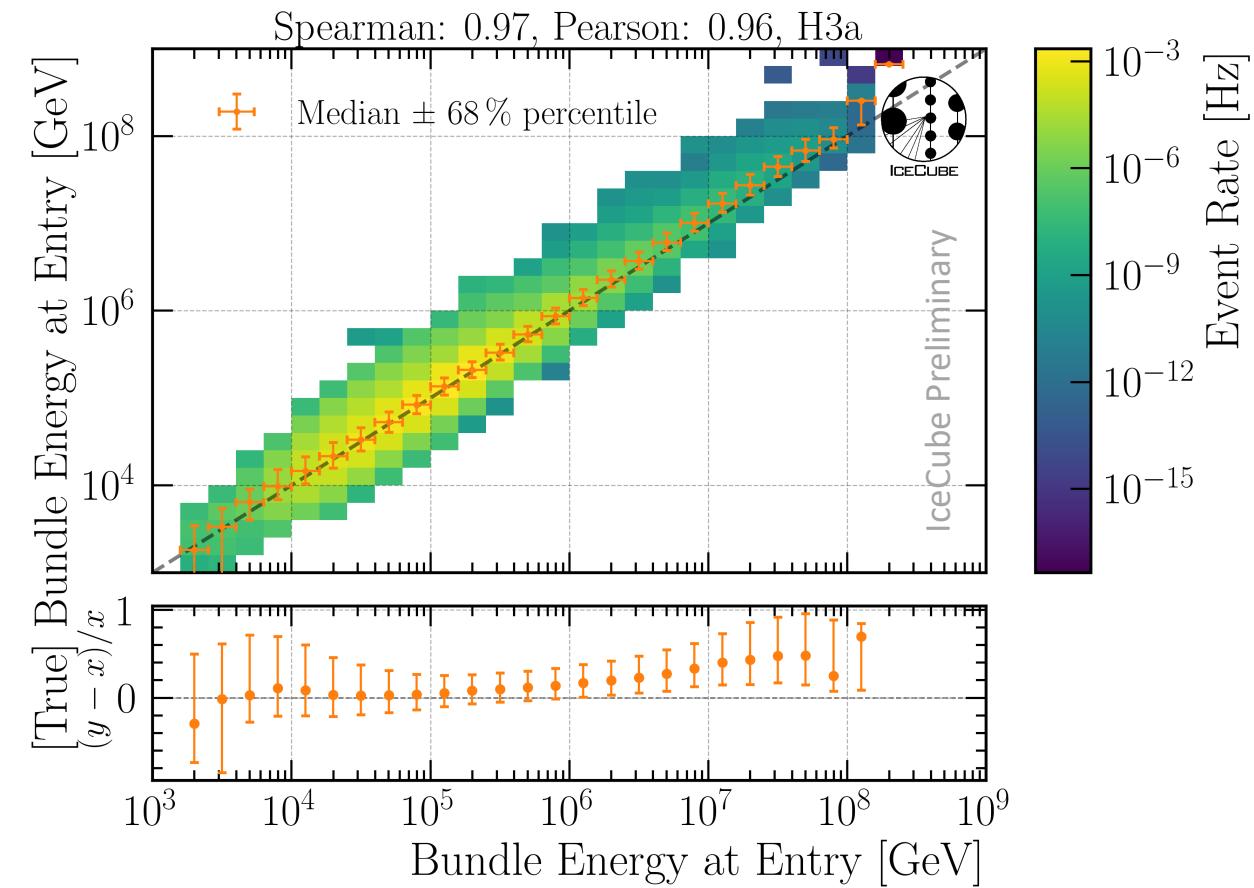
# Determine Regularization

- Find regularization  $\tau$  with minimal bin-to-bin correlation
  - LLH minimization (unfolding) provides full covariance matrix  $V$
- Minimize global correlation  $\rho = \sum_{i > i} V_{ij}$

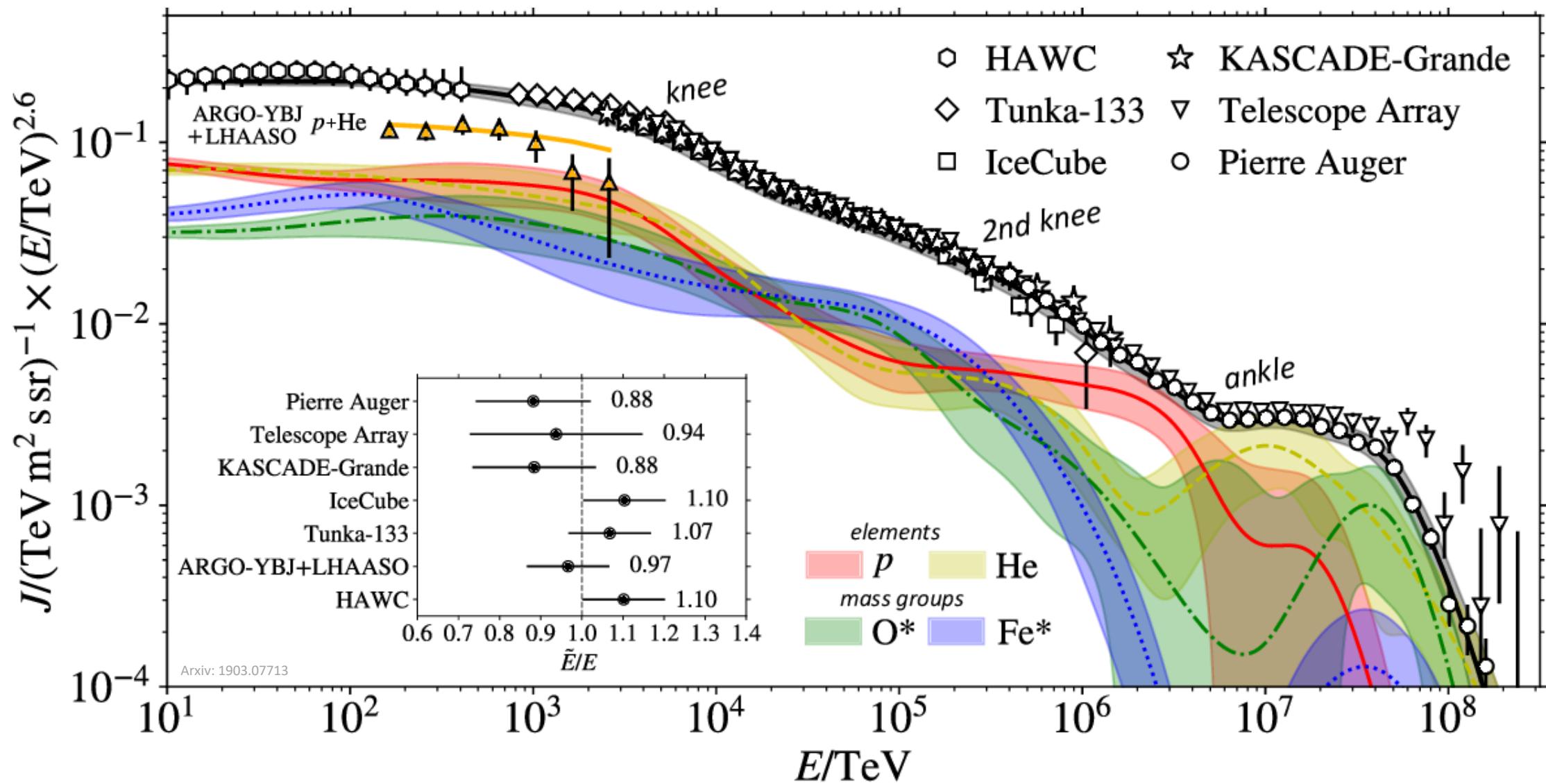


Burnsample

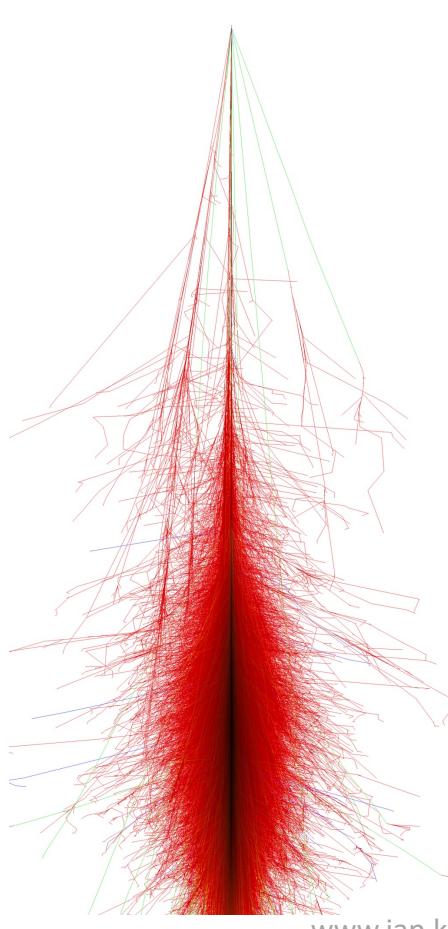
# Bundle Energy Reconstruction

**Level 4****Level 5**

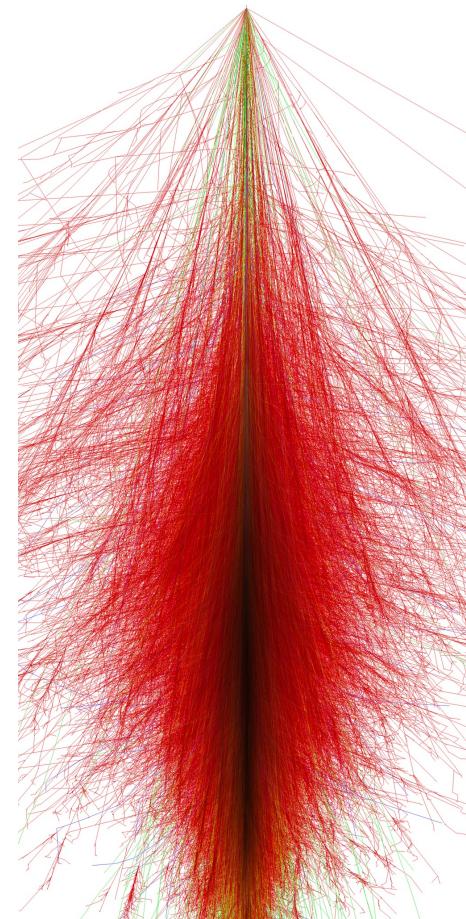
## Cosmic ray flux



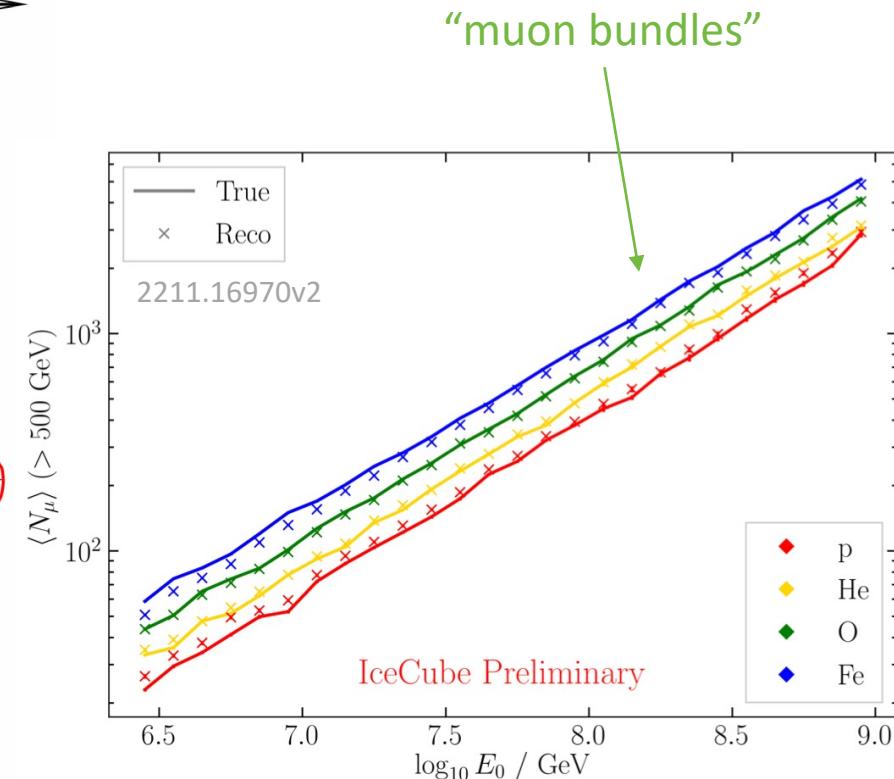
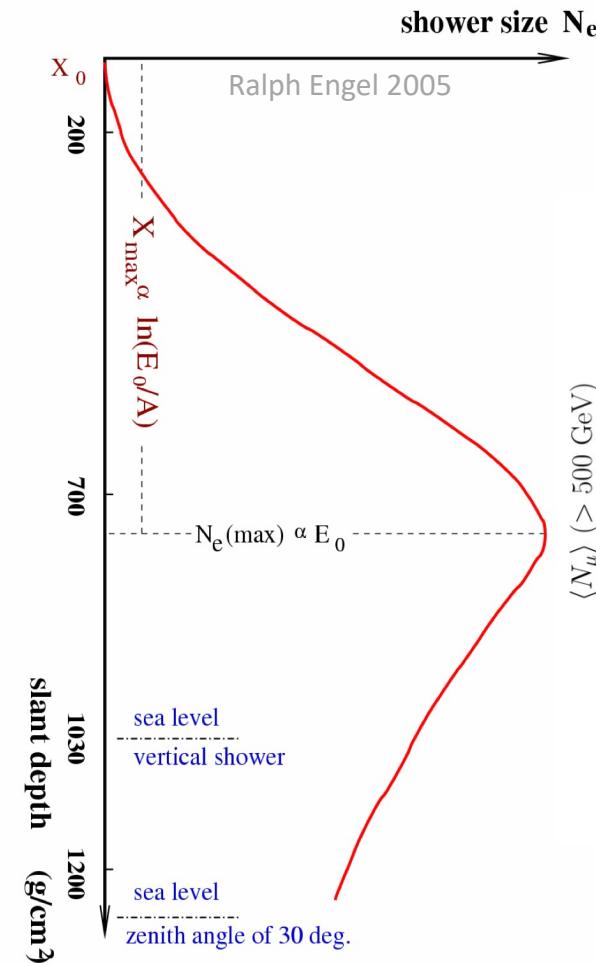
## Air shower – 10 TeV



Proton

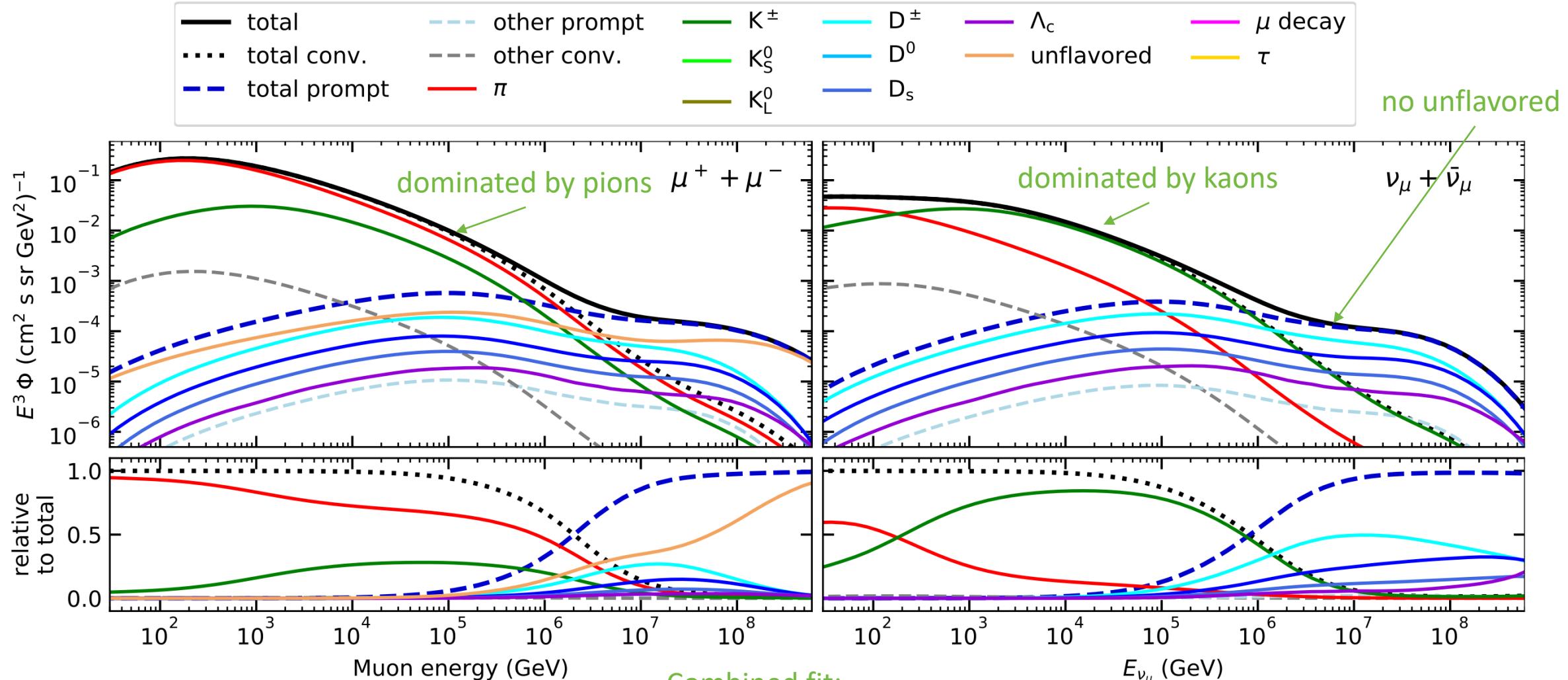


Iron



# Prompt atmospheric muons and neutrinos

10.1103/PhysRevD.100.103018

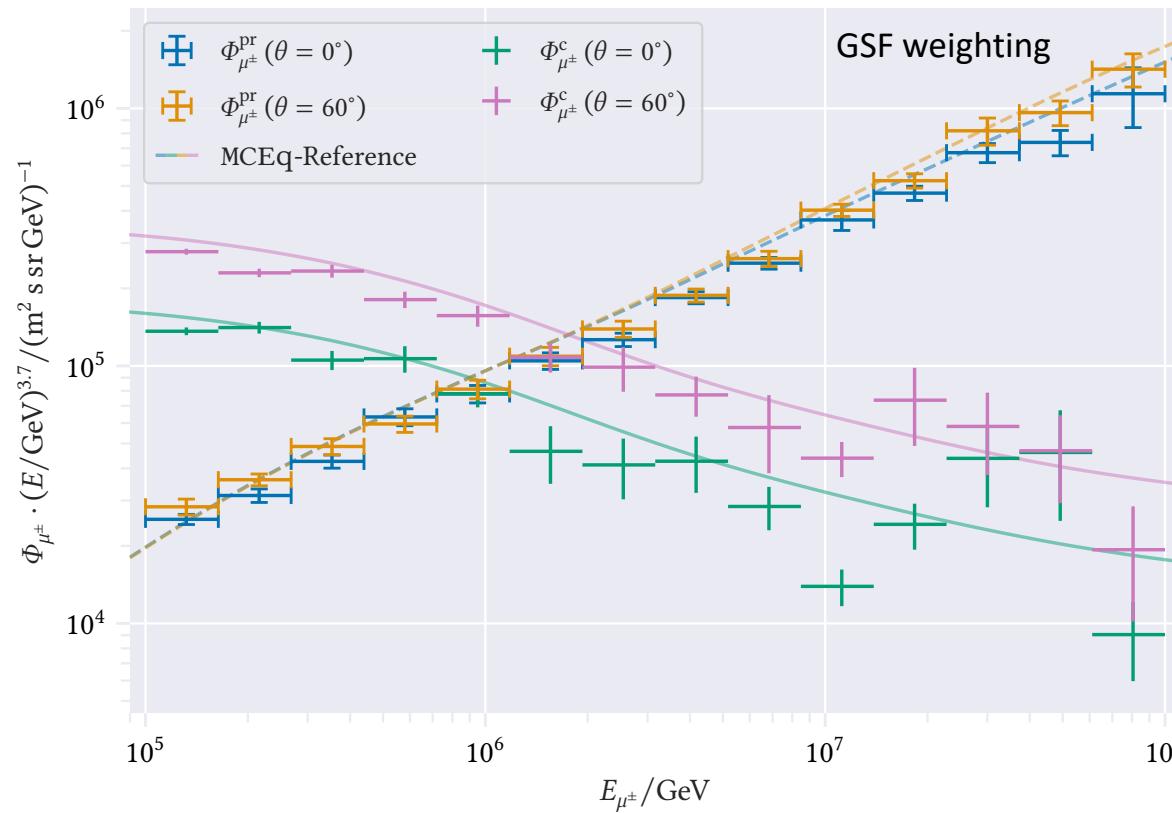


Combined fit:

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

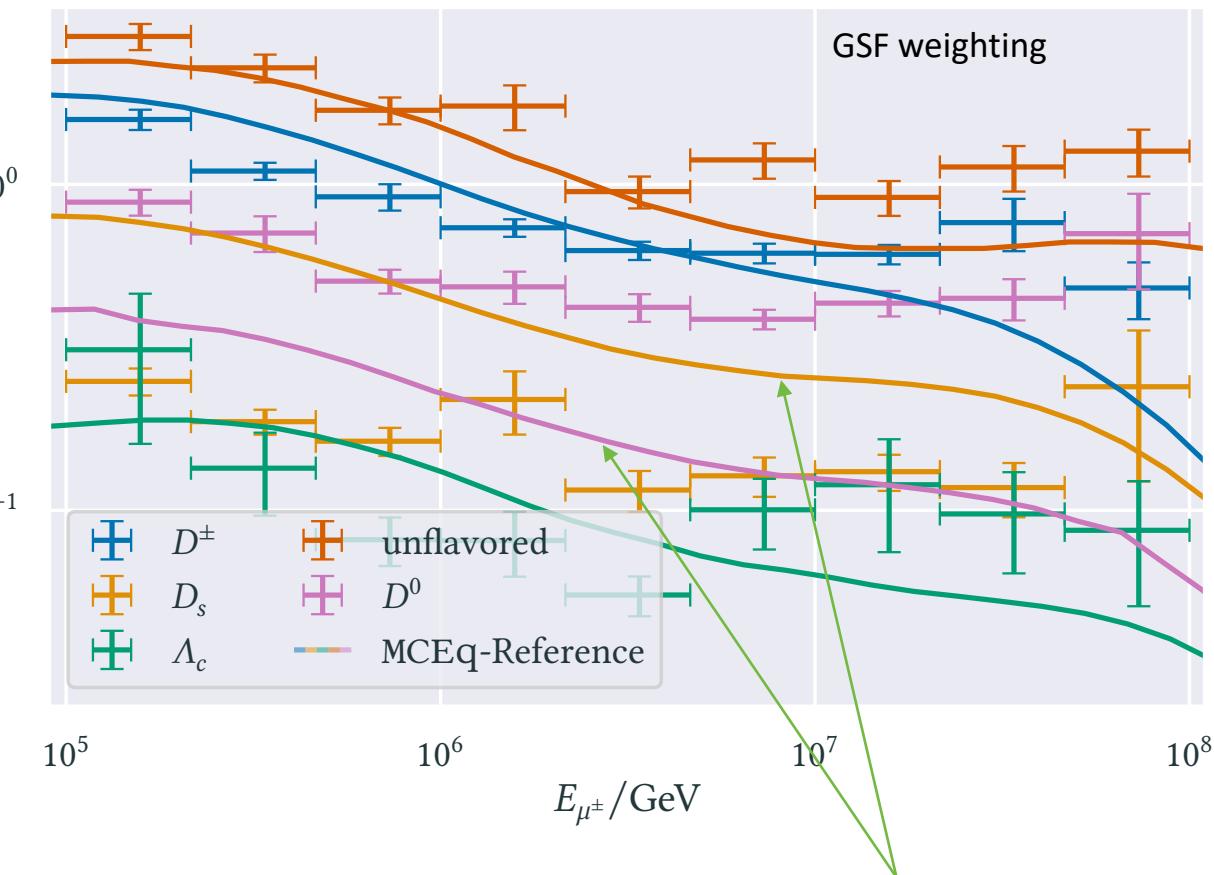
# CORSIKA 7 tagging and MCEq comparison

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

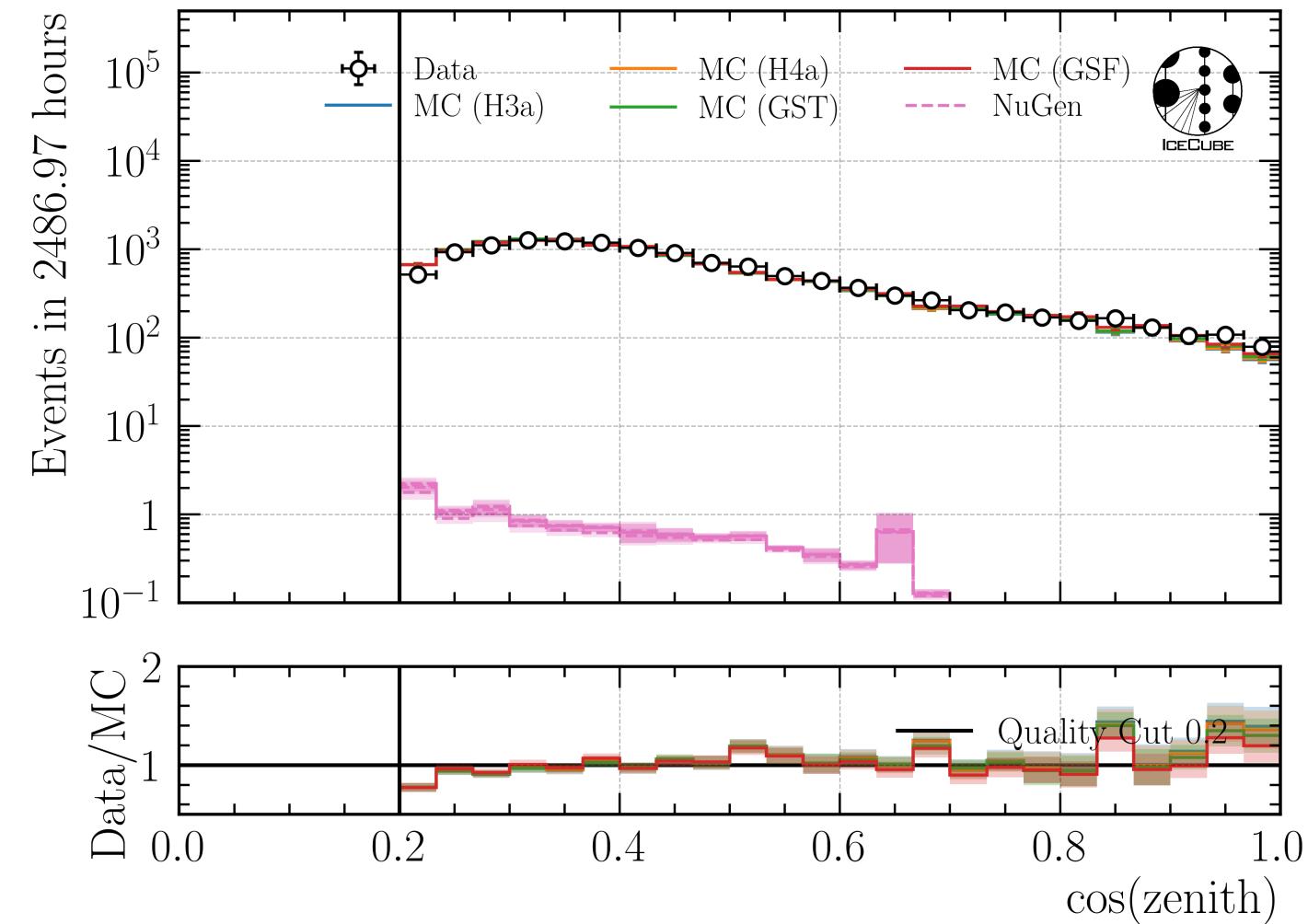


- Good agreement in total prompt and conv muon flux

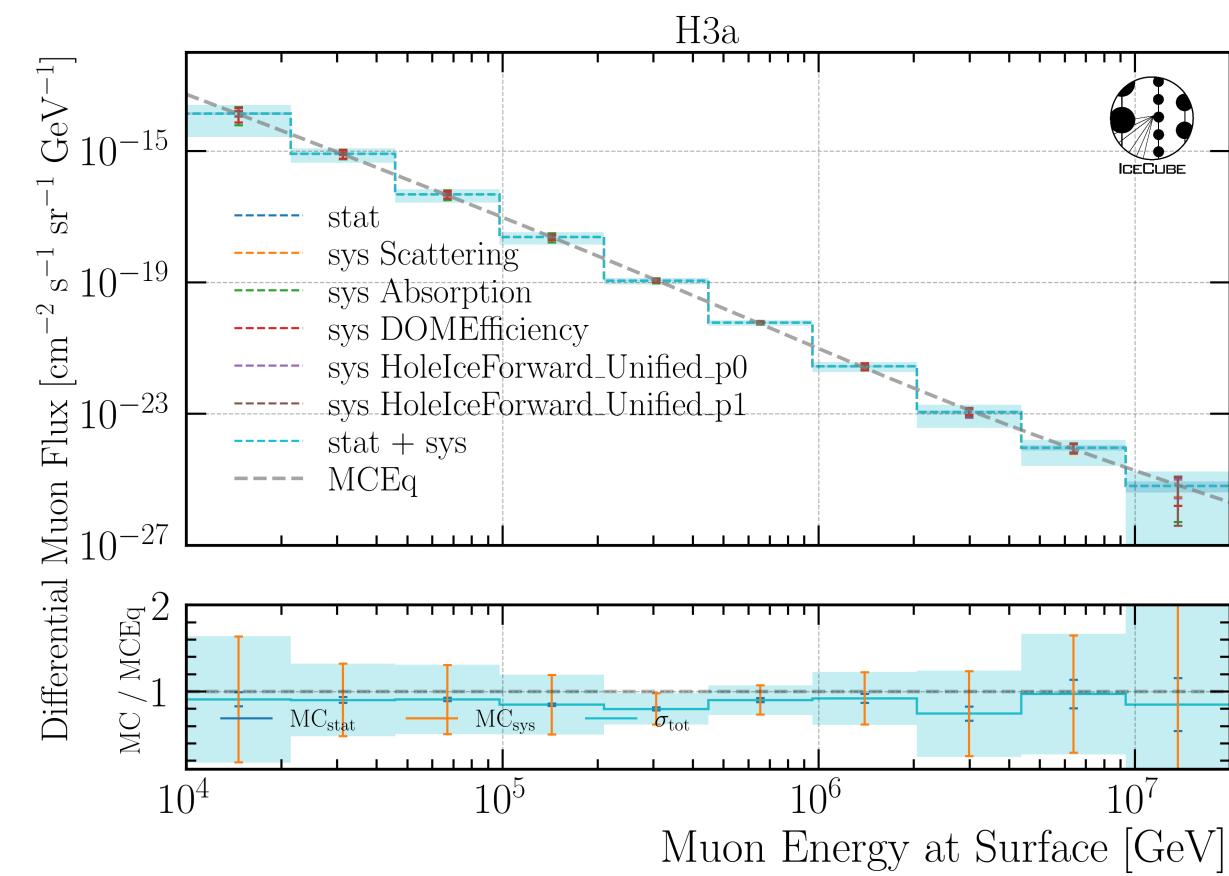
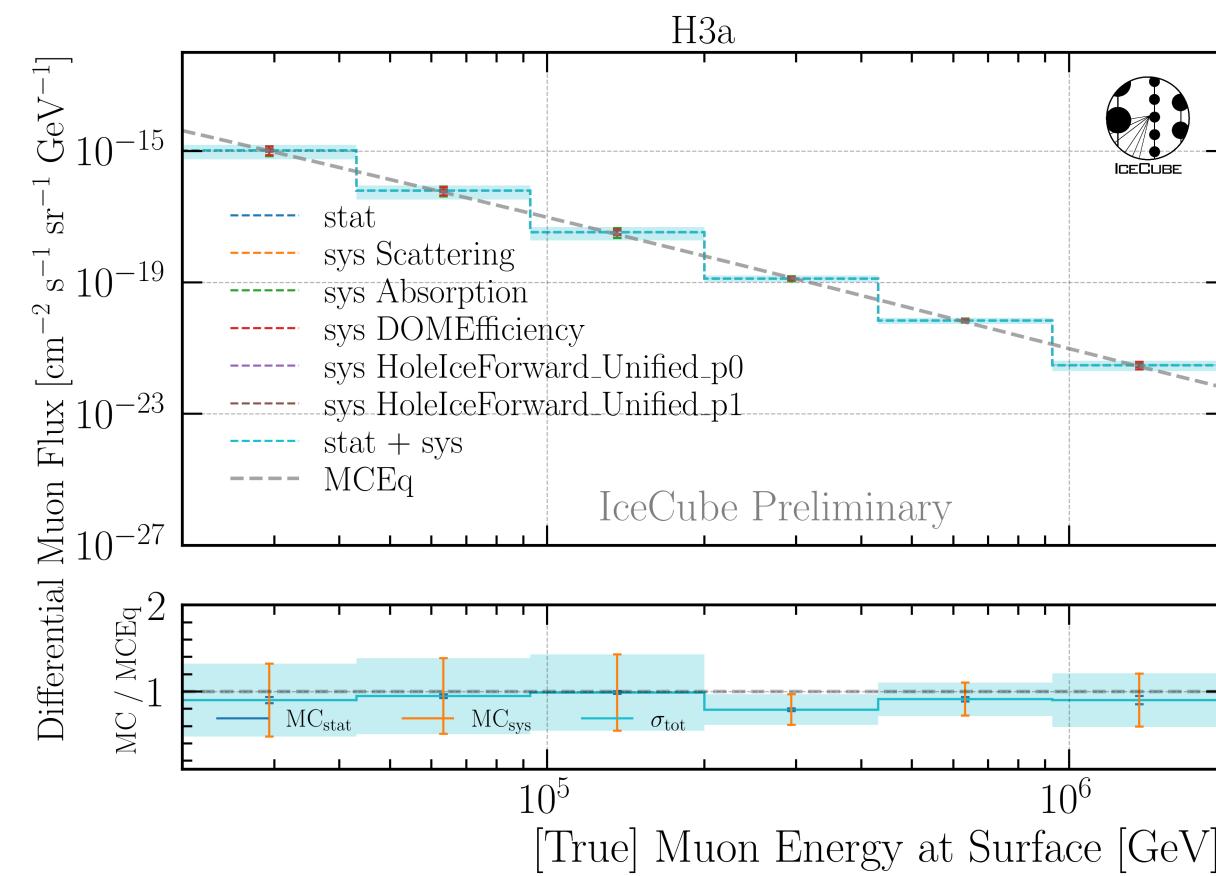
mention panama



- \$D^0\$ and \$D\_s\$ are swapped here but this is fixed in MCEq

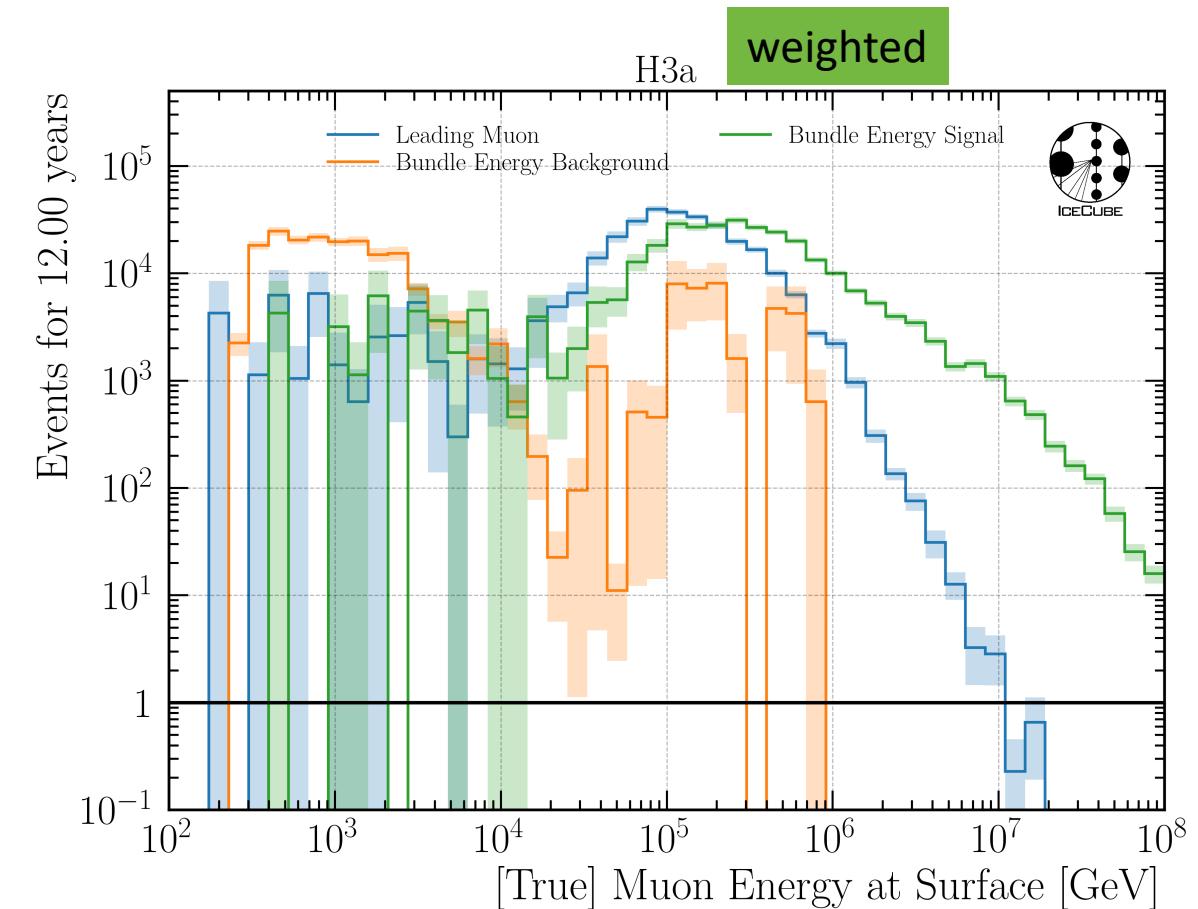
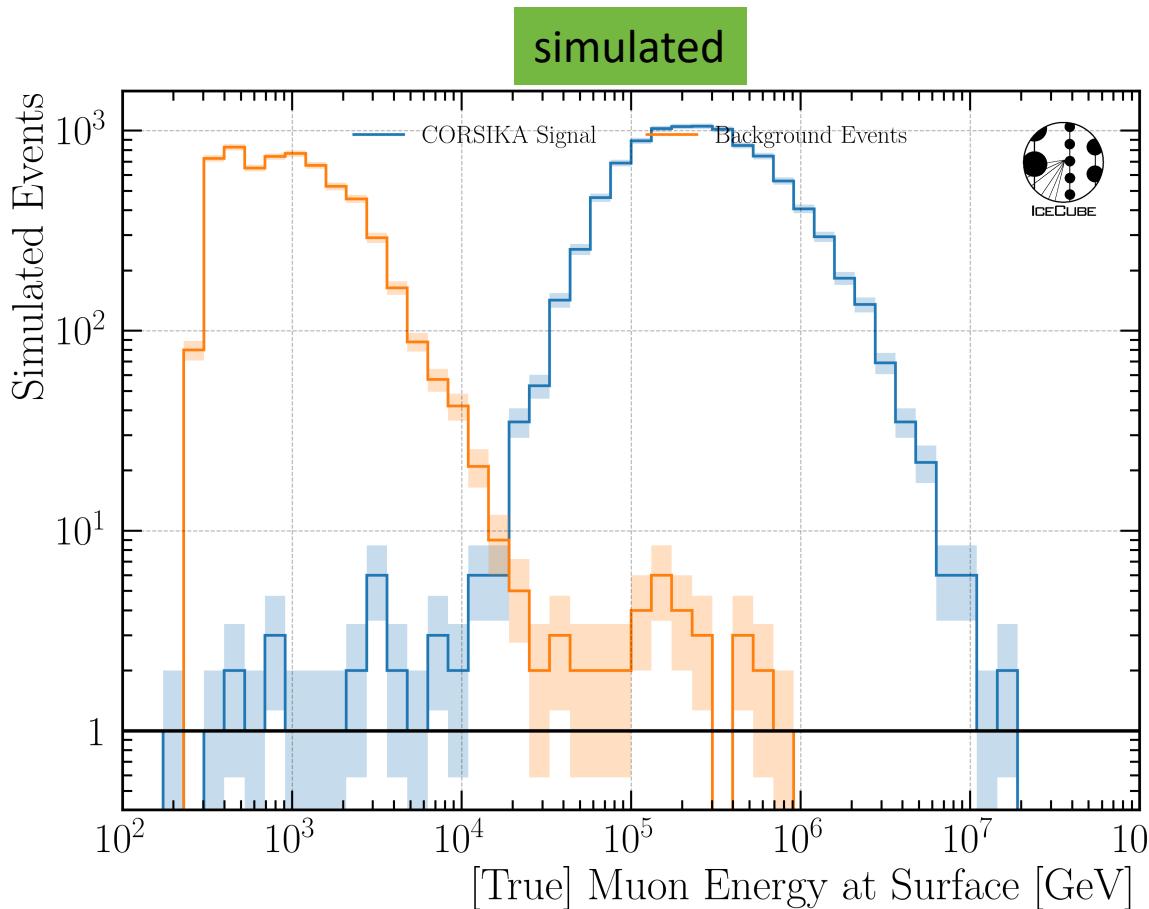
Final Level  $\cos(\text{zenith})$ 

## MCEq vs CORSIKA



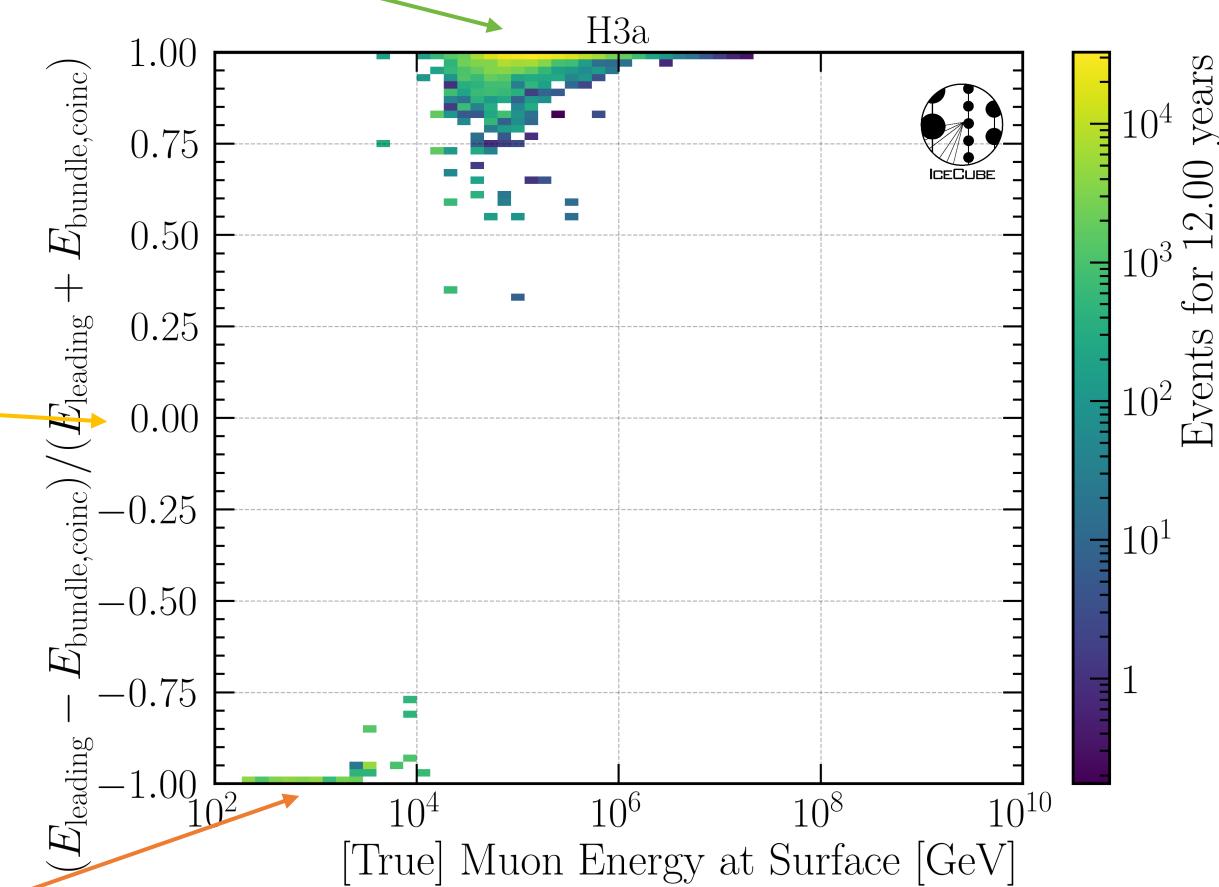
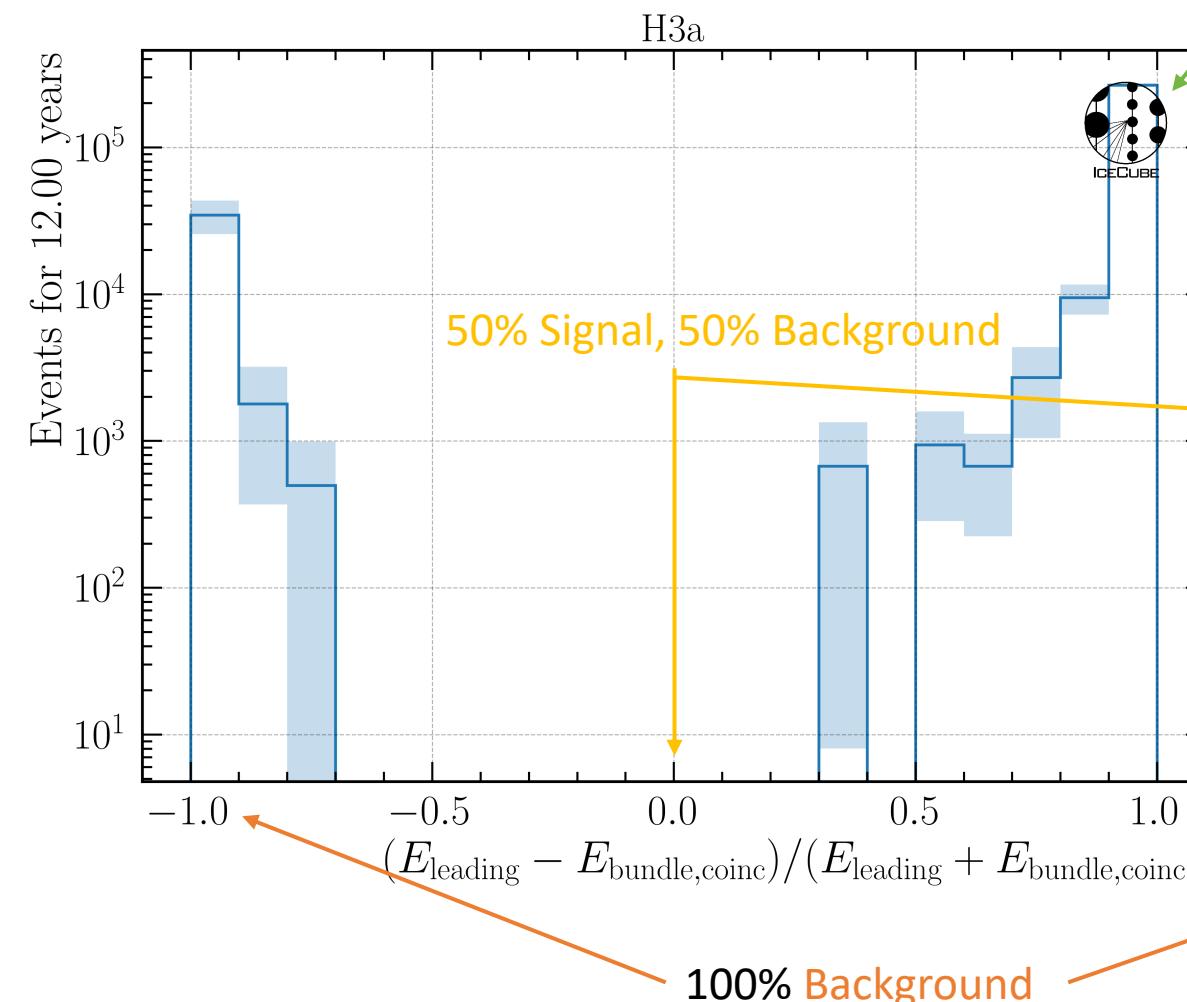
# Coincident Events with 22615

# Muon Energy at Surface



- 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



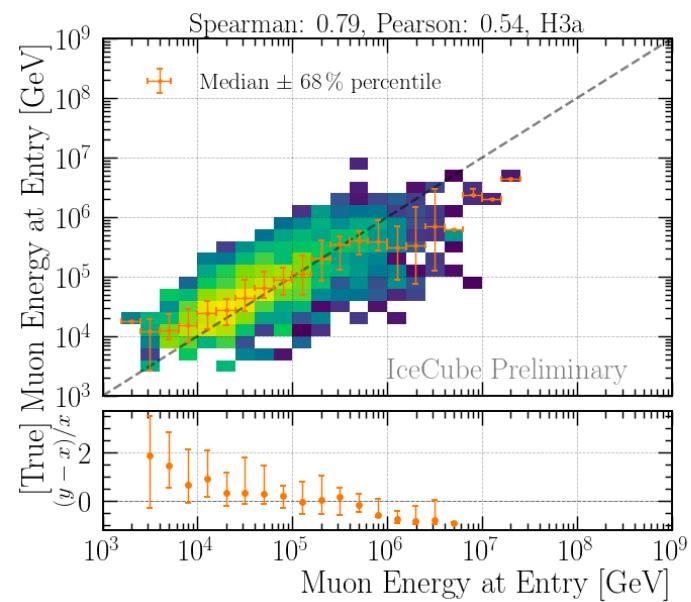
➤ above 10 TeV, no background dominated events

## Estimate Rates with H3a

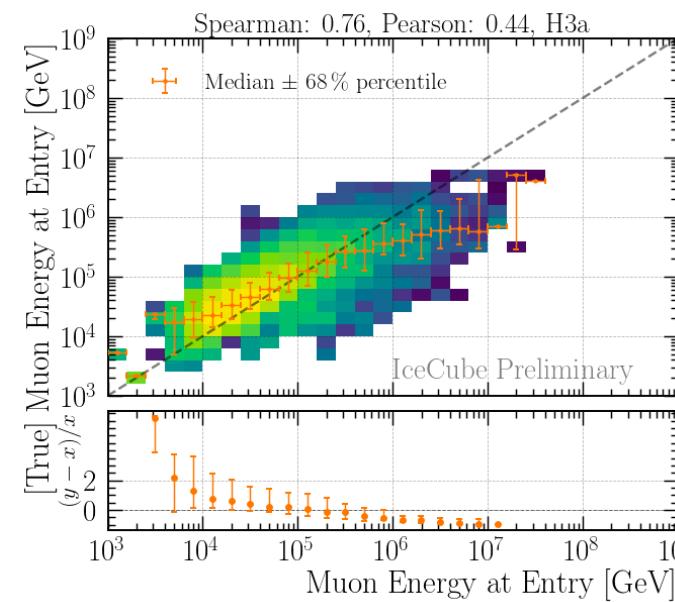
- Signal rate: 0.84 mHz (total event rate)
  - Background rate: 0.68 mHz (event rate with at least 1 coincident primary)
  
  - Signal rate: 0.74 mHz (leading muon energy at surface > 10 TeV)
  - Background rate: 0.58 mHz (event rate with at least 1 coincident primary & lead. muon E. > 10 TeV)
  
  - 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 has 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

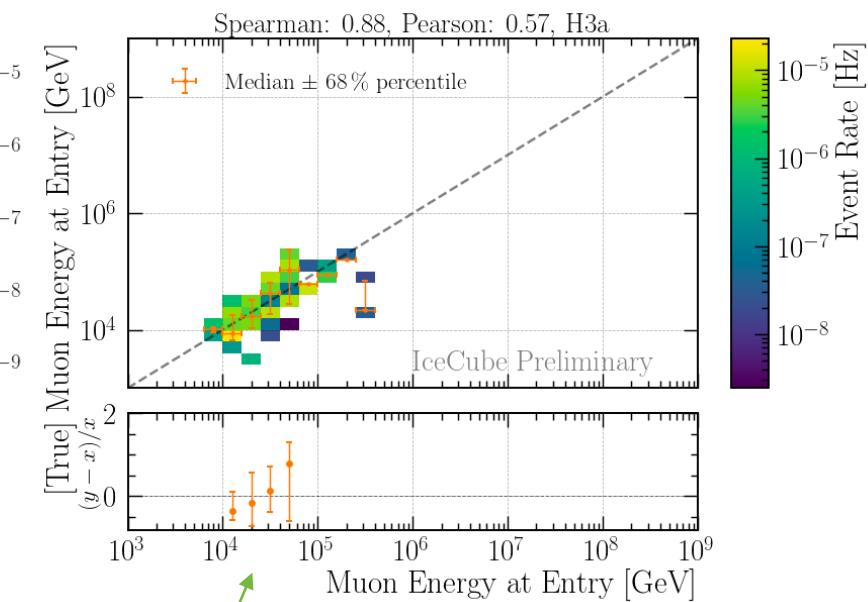
no background event



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



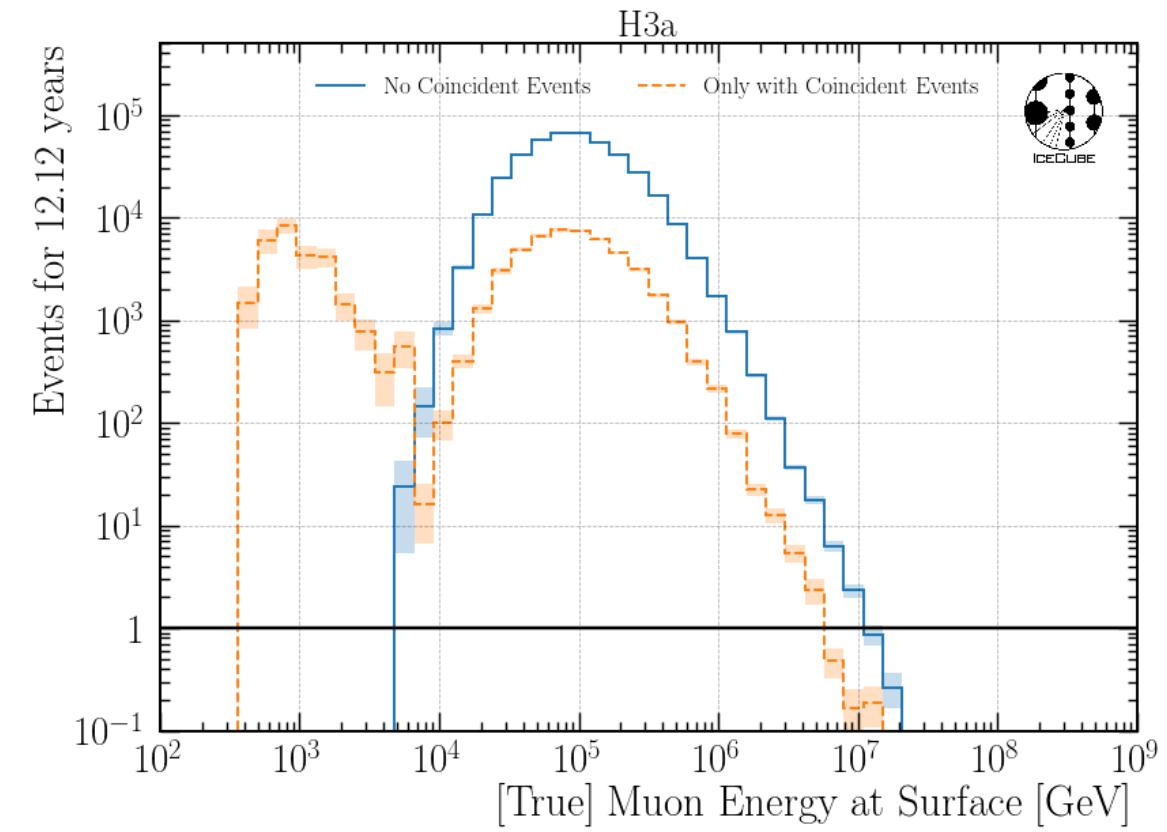
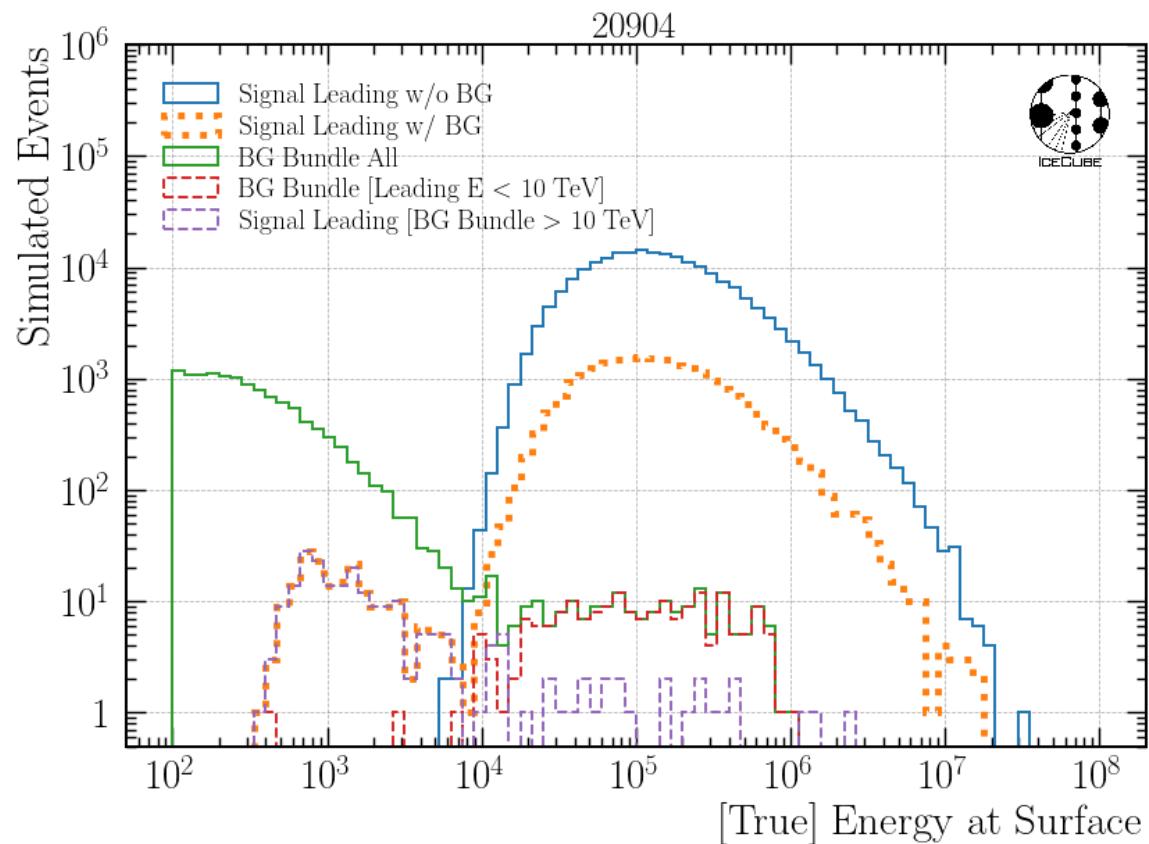
$\frac{\text{bundle energy at surface}}{\text{leading energy at surface}} > 0.1$



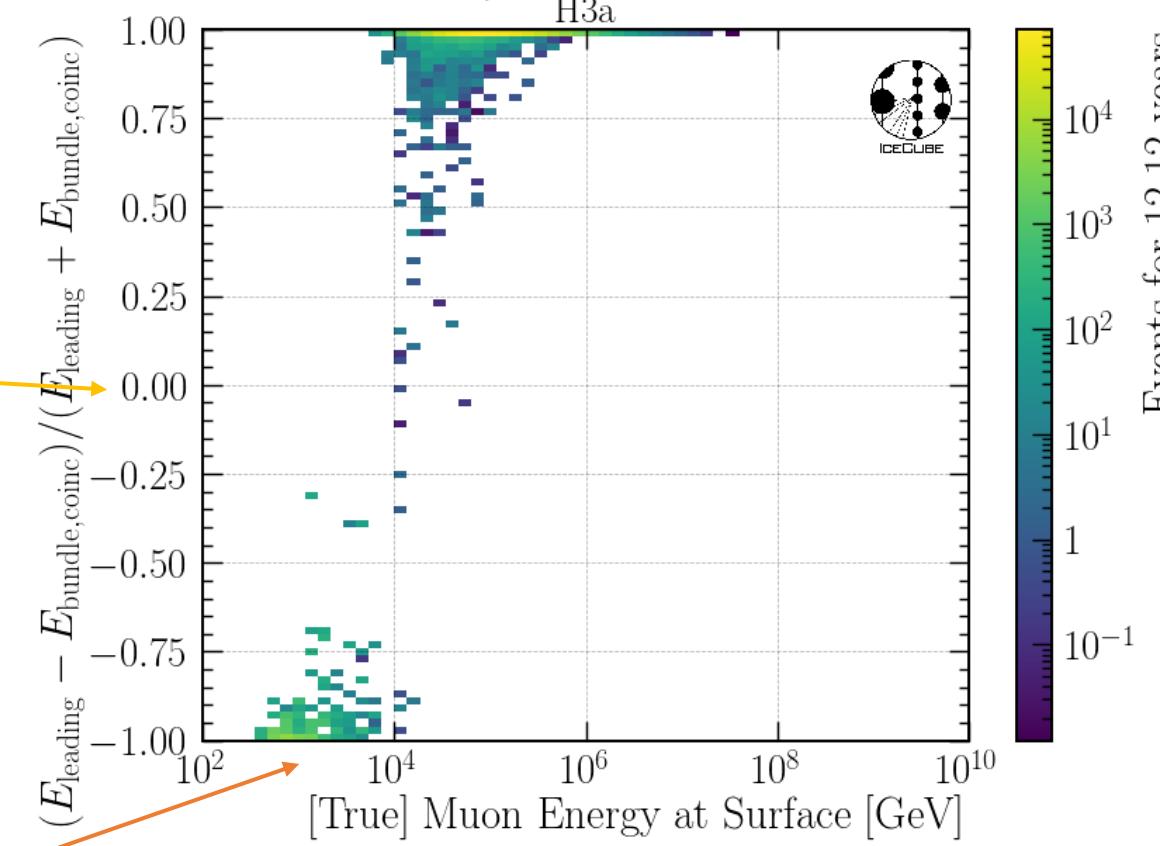
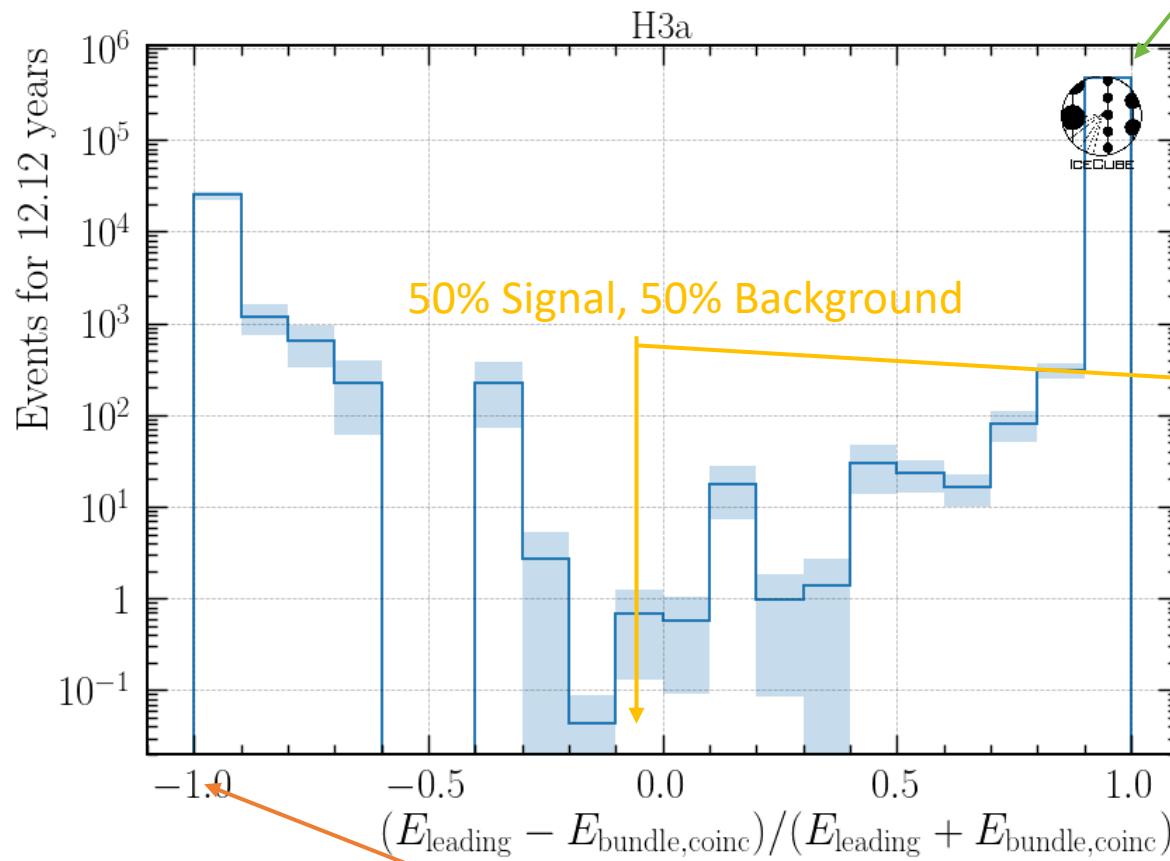
- sufficient energy reconstruction for events with background

# Coincident Events with 20904

# True MC Distributions



# Coincidence: Muons on Event Level



➤ 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 has 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

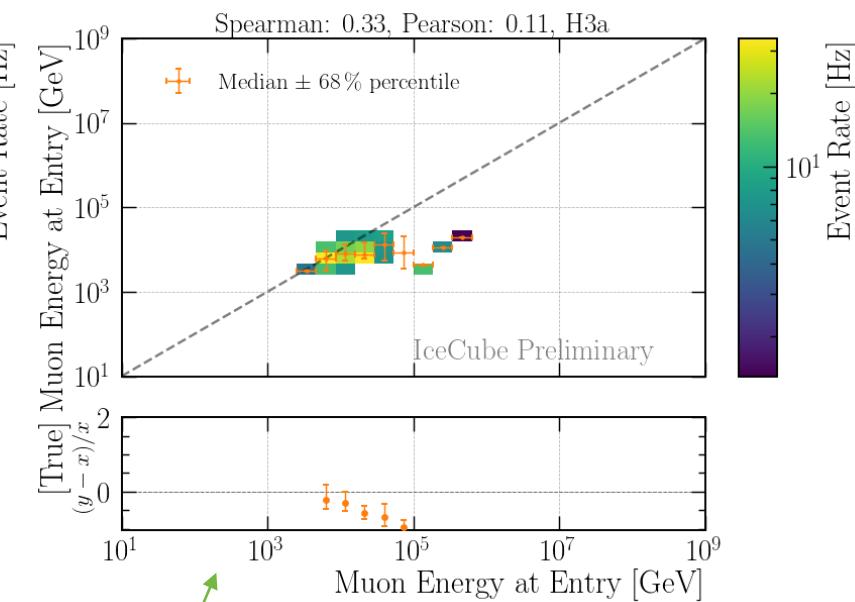
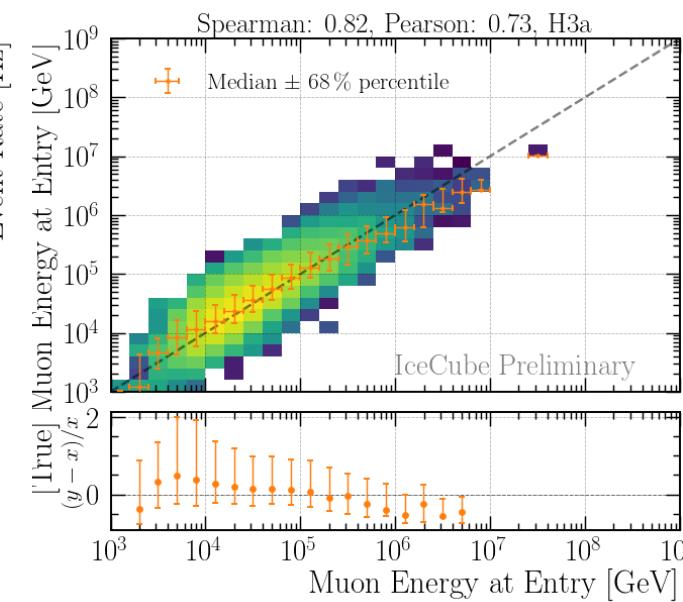
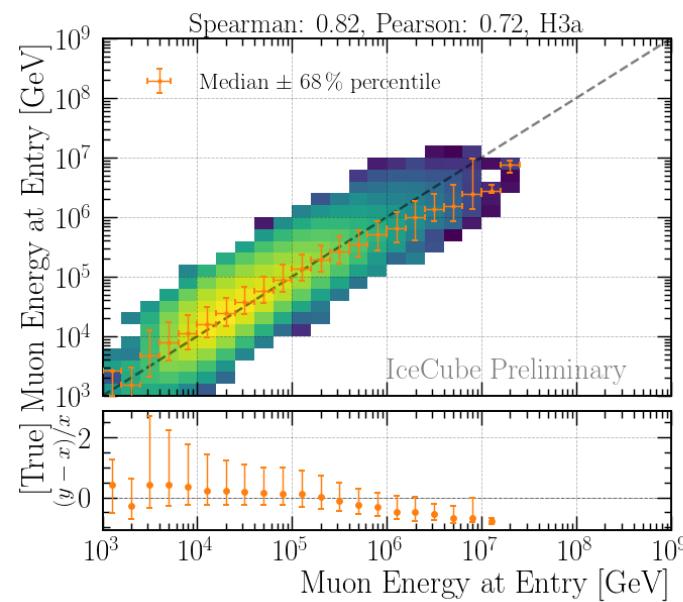
# Reconstructions: Coincident Events

no background event

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

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

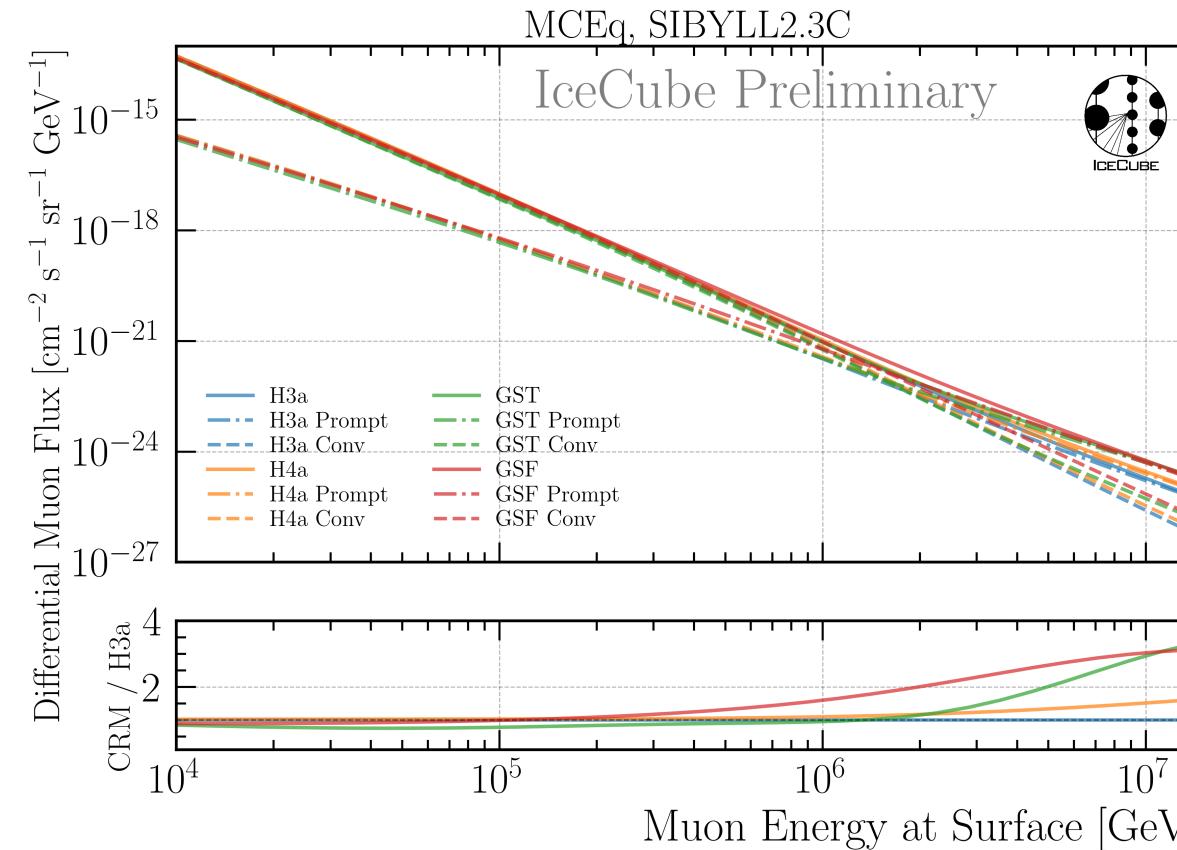
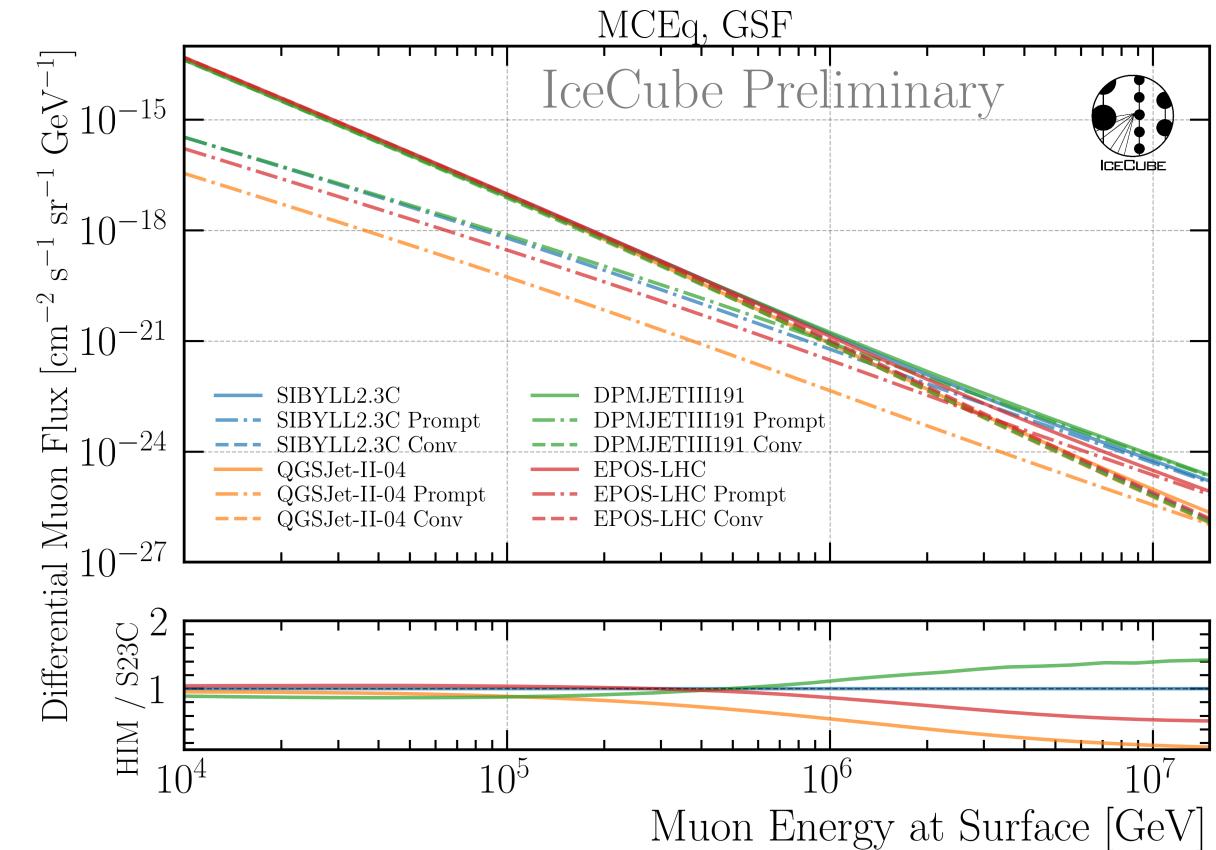
leading energy at surface  $> 10 \text{ TeV}$



20904

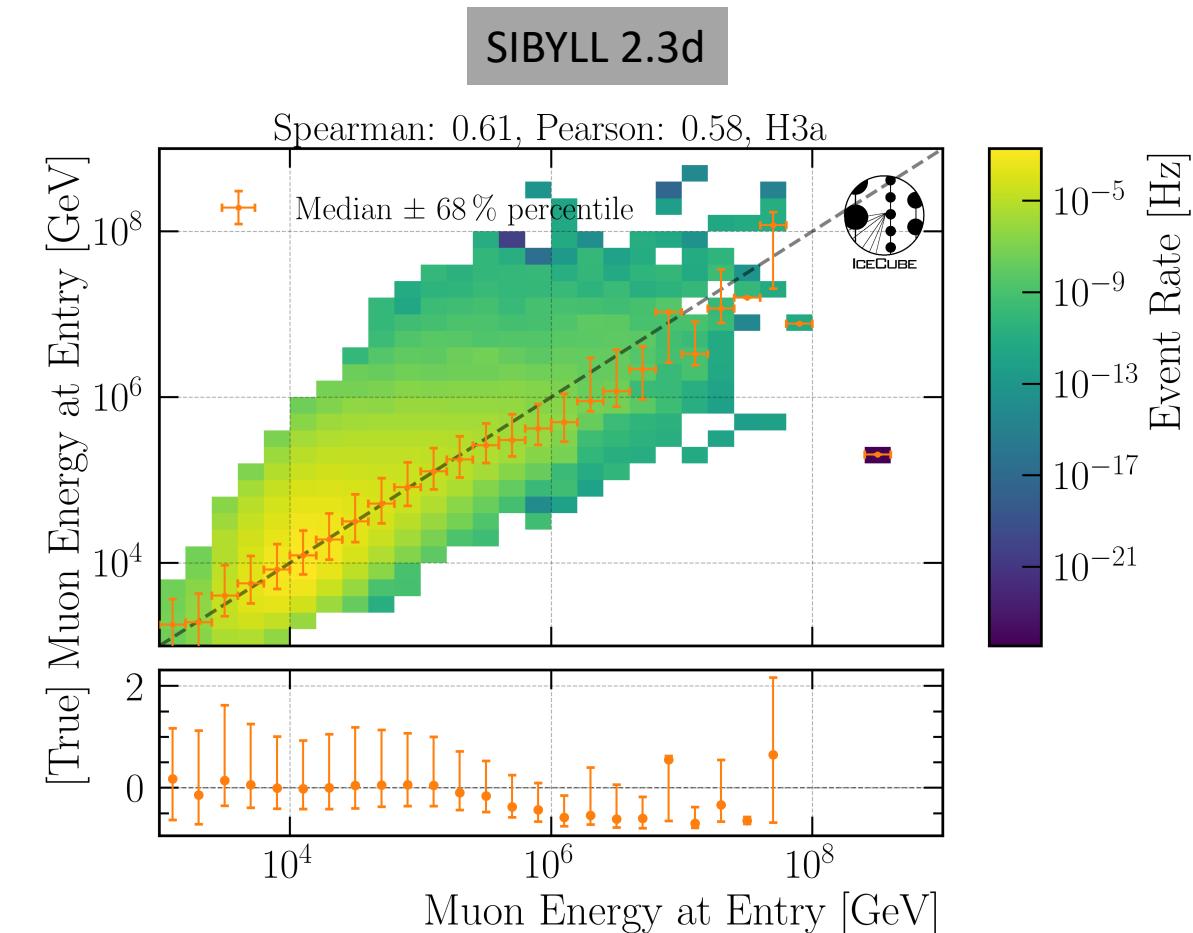
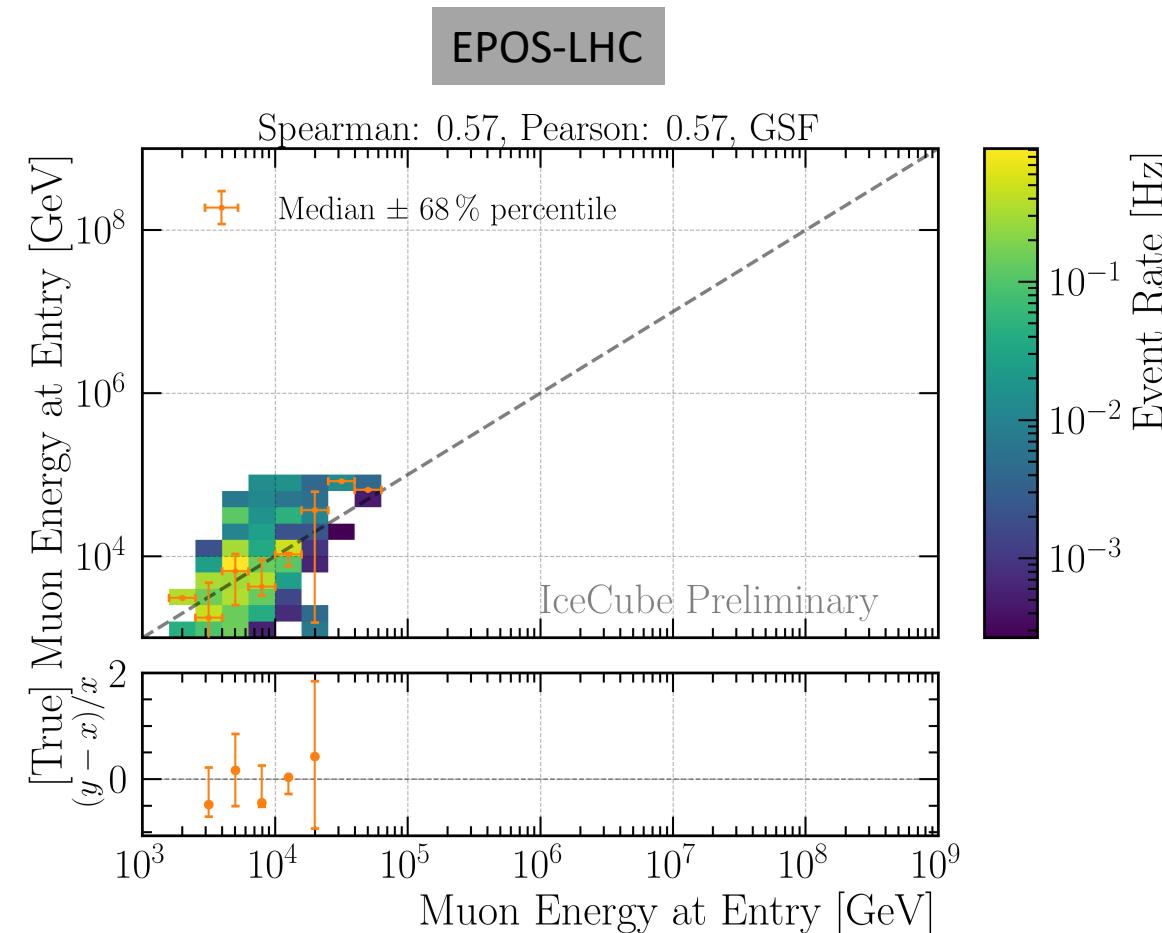
- sufficient energy reconstruction for events with background

# Estimate Impact of Hadronic Interaction Model

**Different CR Models****Different Hadronic 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]



- IceTop simulations for proton and iron
- 23198 and 23201
- Primary energy  $> 1\text{e}7$