

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

Pascal Gutjahr

ICRC 2025 Plot Approval  
May 23, 2025

WG reviewer: Dennis Soldin  
Coll. reviewer: Anatoli Fedynitch  
Technical reviewer: Karolin Hymon  
Wiki: [prompt wiki](#)  
Last update: Uppsala May 14

## Abstract

Atmospheric muons produced in cosmic-ray air showers are classified as conventional muons from pion and kaon decays and prompt muons from heavy hadron decays. Conventional muons dominate at lower energies, and the prompt component becomes more significant at PeV energies and above. Precisely measuring the atmospheric muon flux from a few GeV to several PeV is valuable for advancing our understanding of cosmic-ray interactions and testing hadronic interaction models. Low-energy muons that stop within the IceCube ice array provide valuable information about the energy spectrum of muons from a few 100 GeV up to 10 TeV.

Machine learning techniques are employed to enhance event reconstruction and selection to provide insights into the conventional and prompt components. This contribution presents the unfolding of the energy spectrum of stopping muons in IceCube as well as the unfolding of high-energy muons to probe the prompt component.

**Presenter:** Pascal Gutjahr

**Authors:** Lucas Witthaus and Pascal Gutjahr

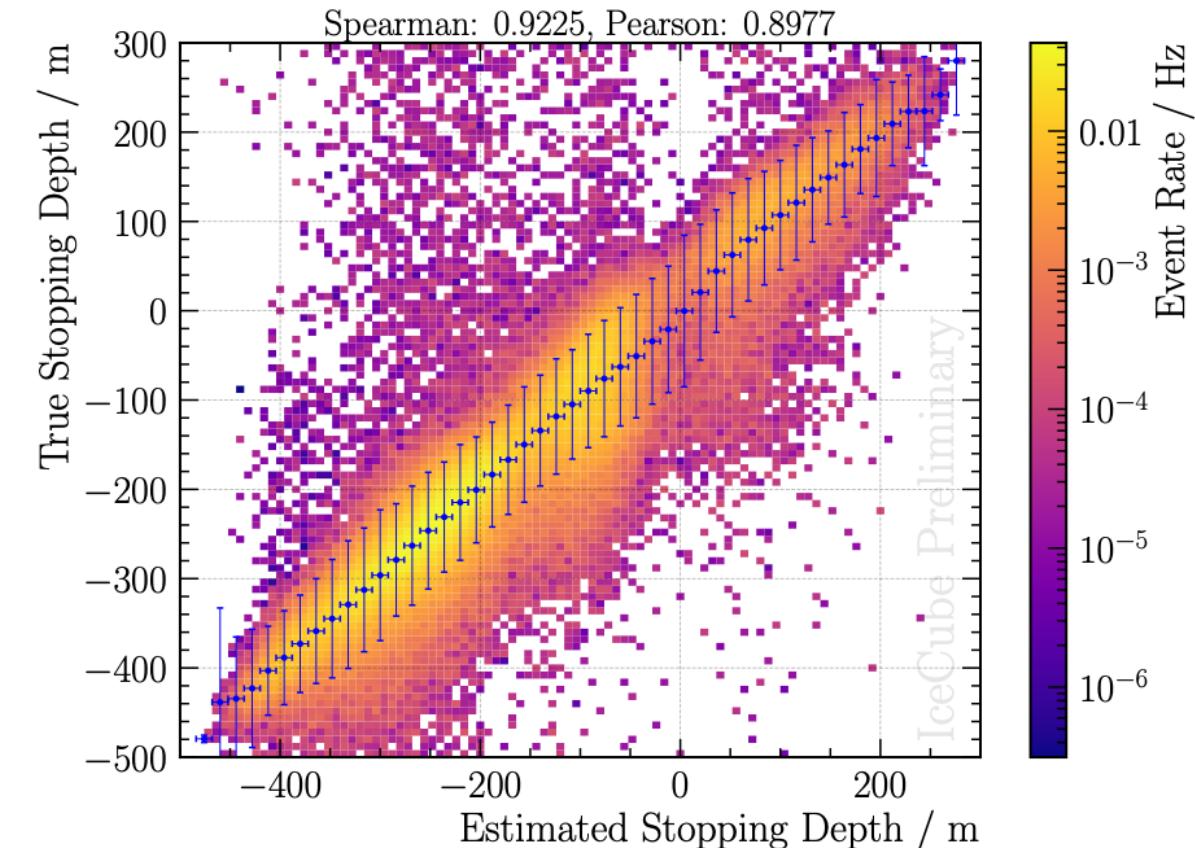
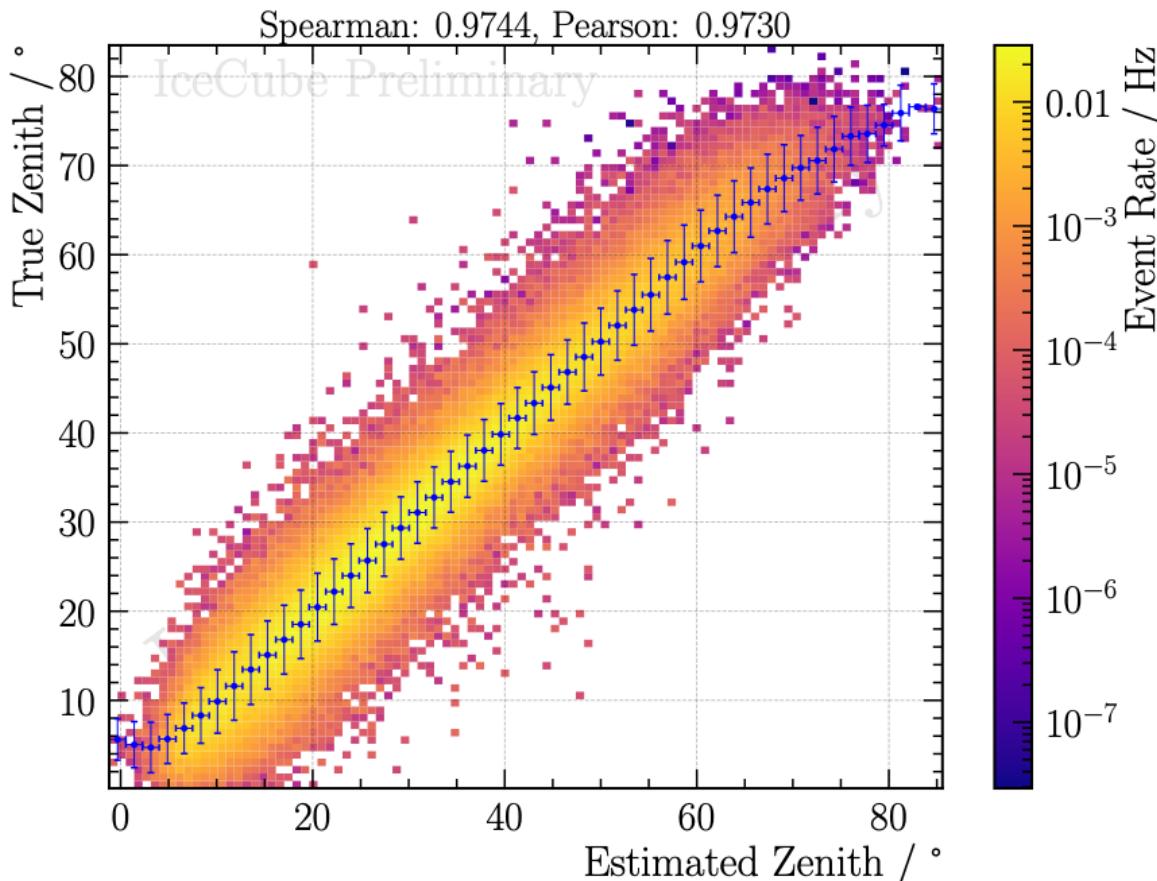
# Outline

1. Introduction / Motivation
  1. Hadronic Interaction Models / Muon Puzzle
  2. Prompt / Conventional
2. Event Selection
  1. Stopping Muons
  2. High Energy Muons
  3. Event Reconstruction (DNN based)
3. Unfolding
  1. Method + Regularization
  2. Acceptance Correction
  3. Systematics
4. Results
  1. Proxy Variable Correlations (Depth + Energy + Zenith)
  2. Data-MC (Depth + Energy + Zenith)
  3. Unfolded Propagation Length (MC + Burnsample)
  4. Unfolded Muon Flux at Surface (MC + Burnsample) – Stopping and High Energy
  5. Robustness Tests (vary spectral index)
5. Conclusion & Outlook

# Disclaimer

- We present a combined analysis – some plots still have different linestyles /colors
- Please focus on the results in the plots
- Style of the plots will be adjusted by us until beginning of next week
- Plots will be added to plot approval wiki

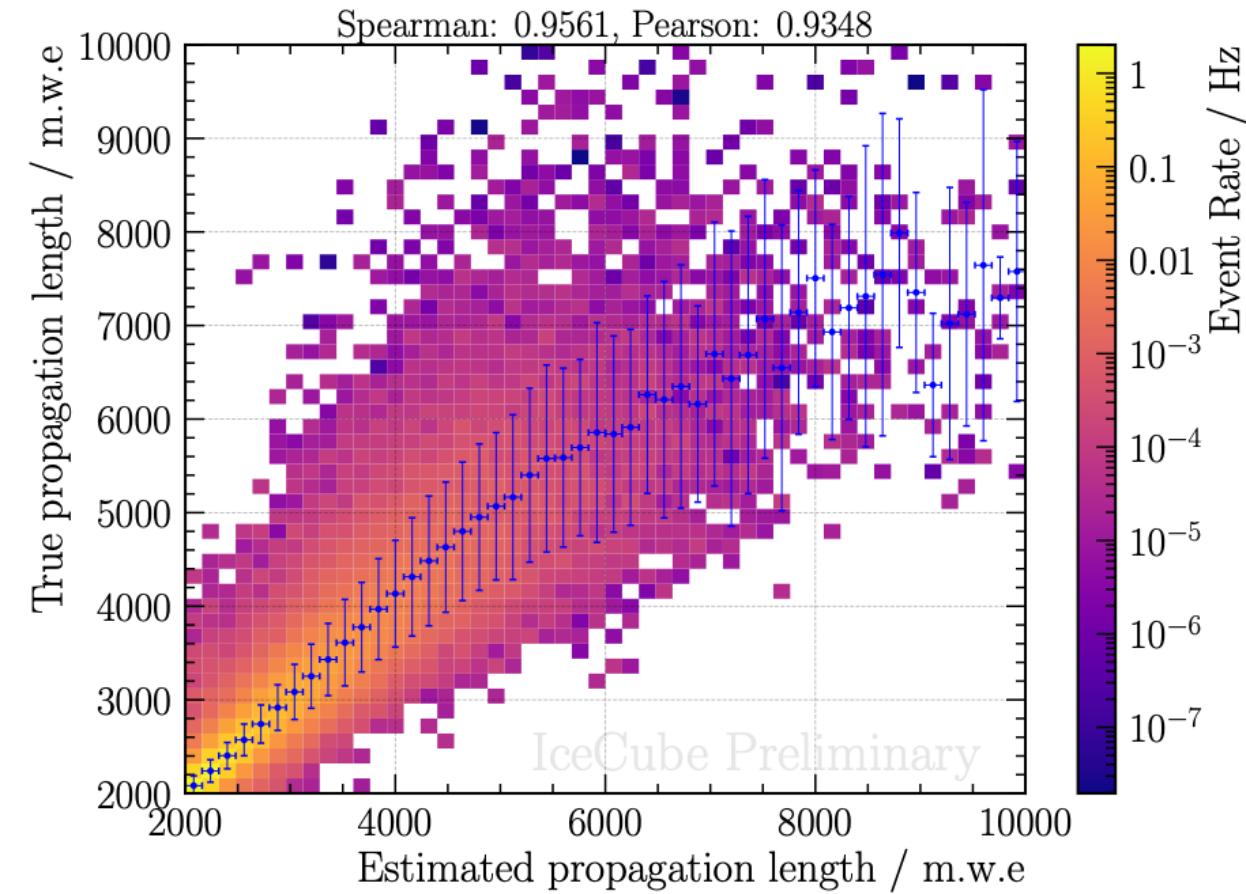
# Reconstructions: Stopping Muons



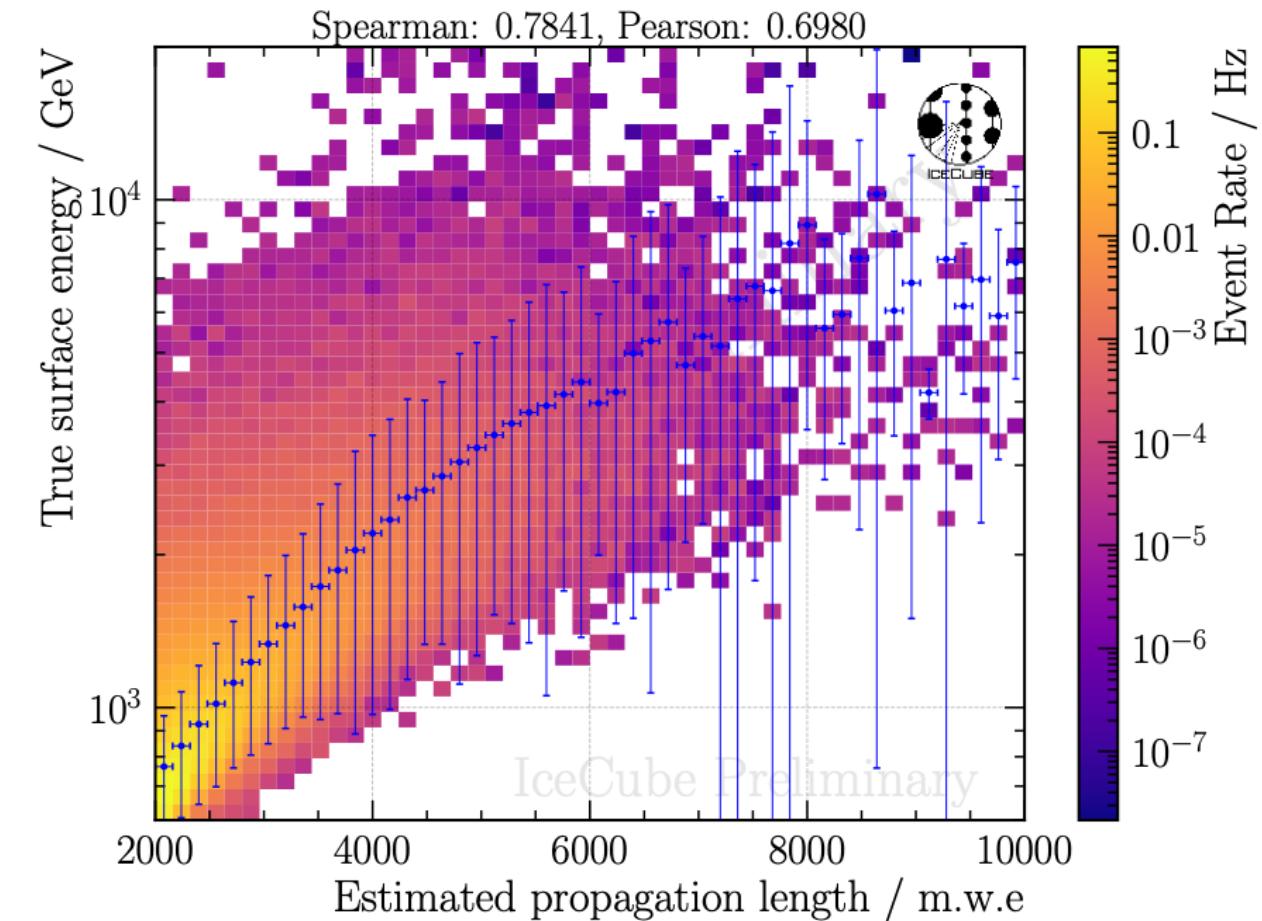
- DNN reconstruction of zenith angle and stopping depth
- Used to calculate the propagation length → proxy variable in unfolding

# Proxy Variable: Stopping Muons

Propagation length



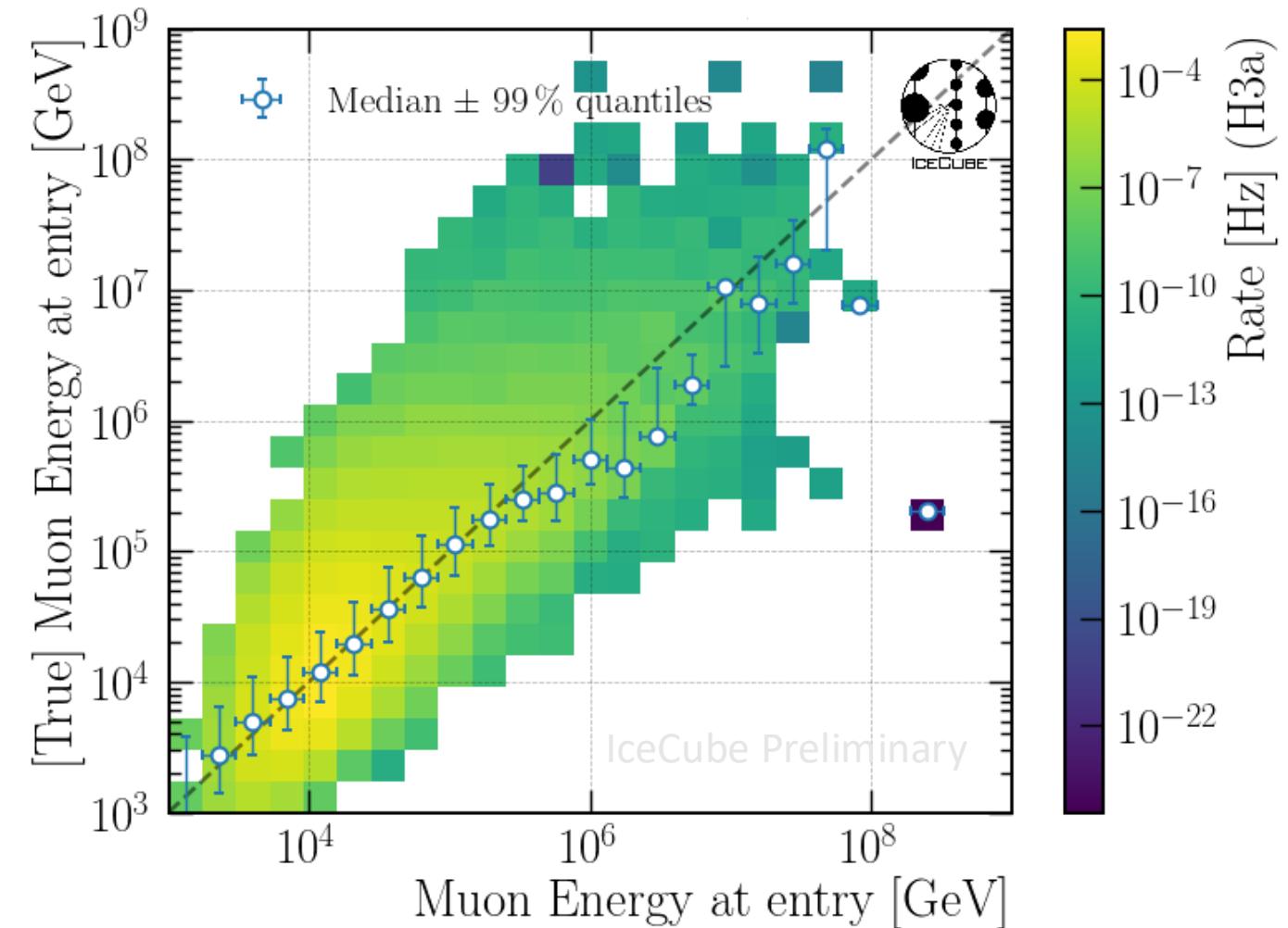
Muon energy at surface



- Correlation between proxy and target variable in unfolding

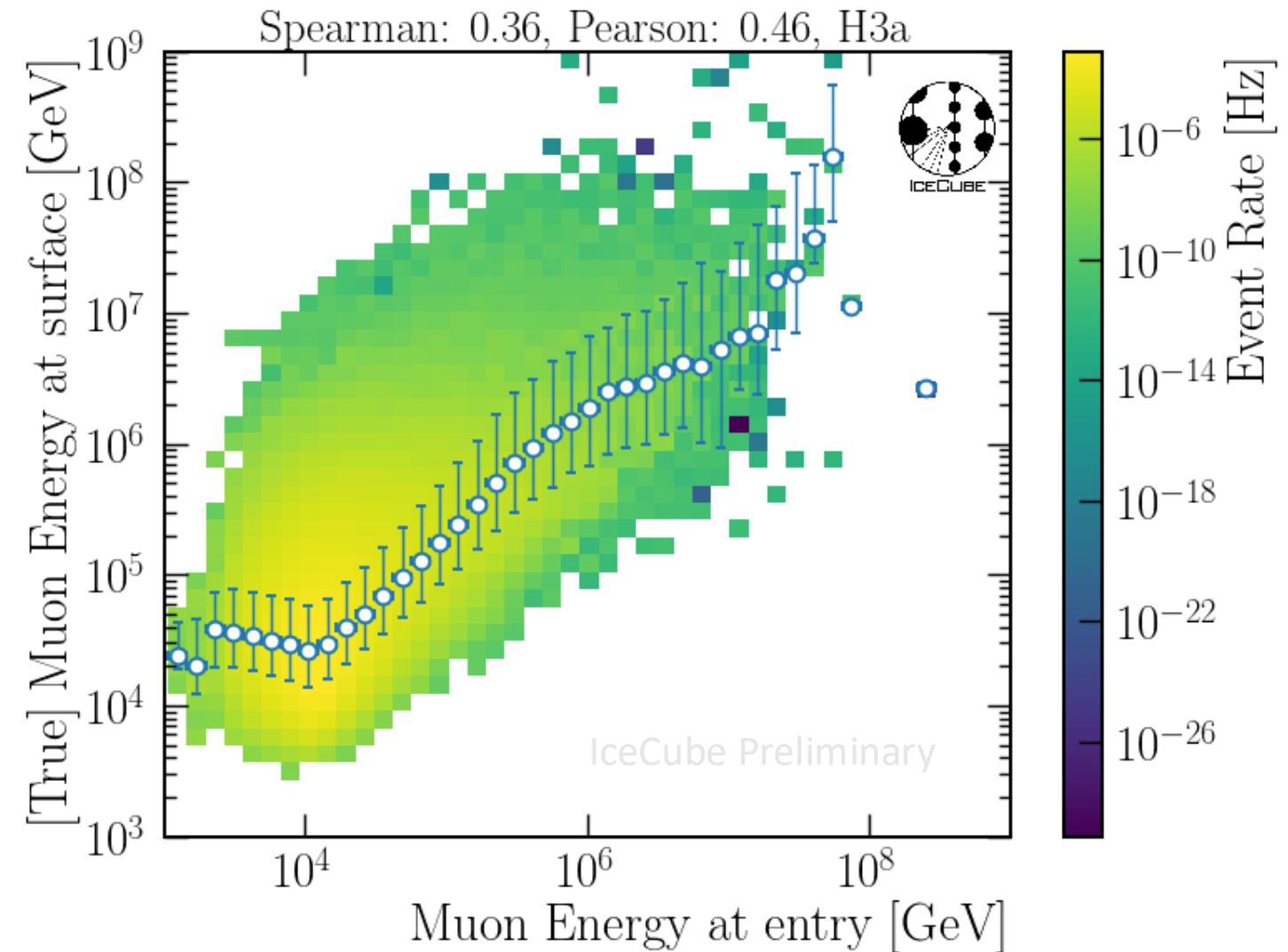
# Reconstruction: High Energy Muons

- DNN reconstruction of leading muon energy at detector entry
- proxy variable in unfolding

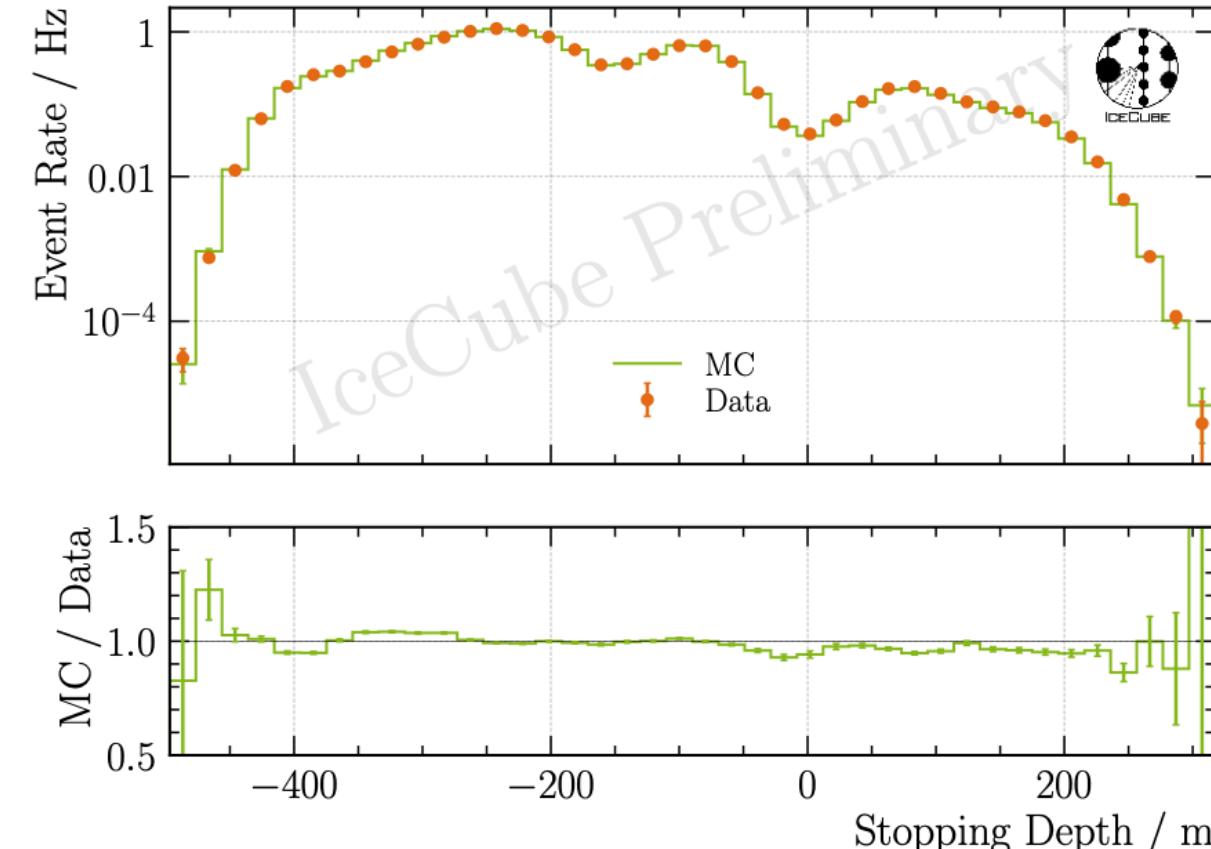
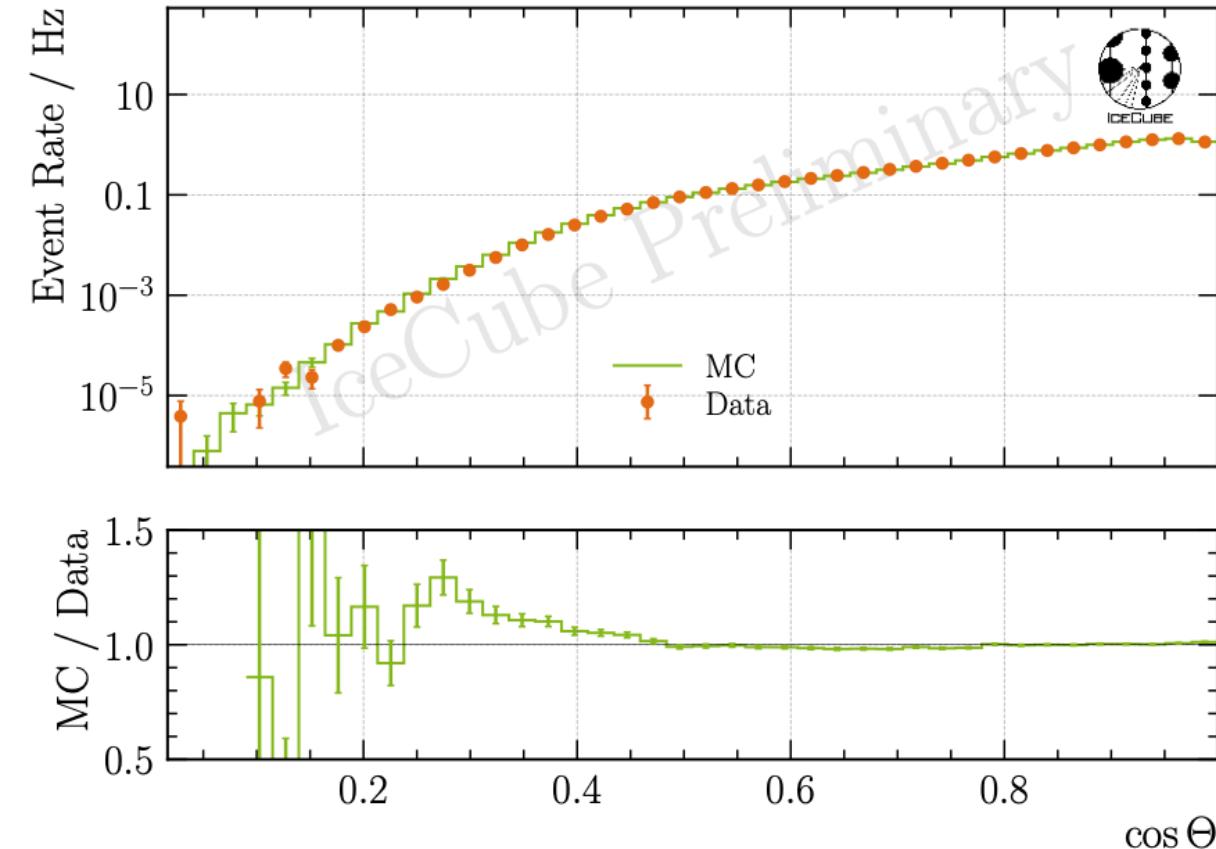


# Proxy Variable: High Energy Muons

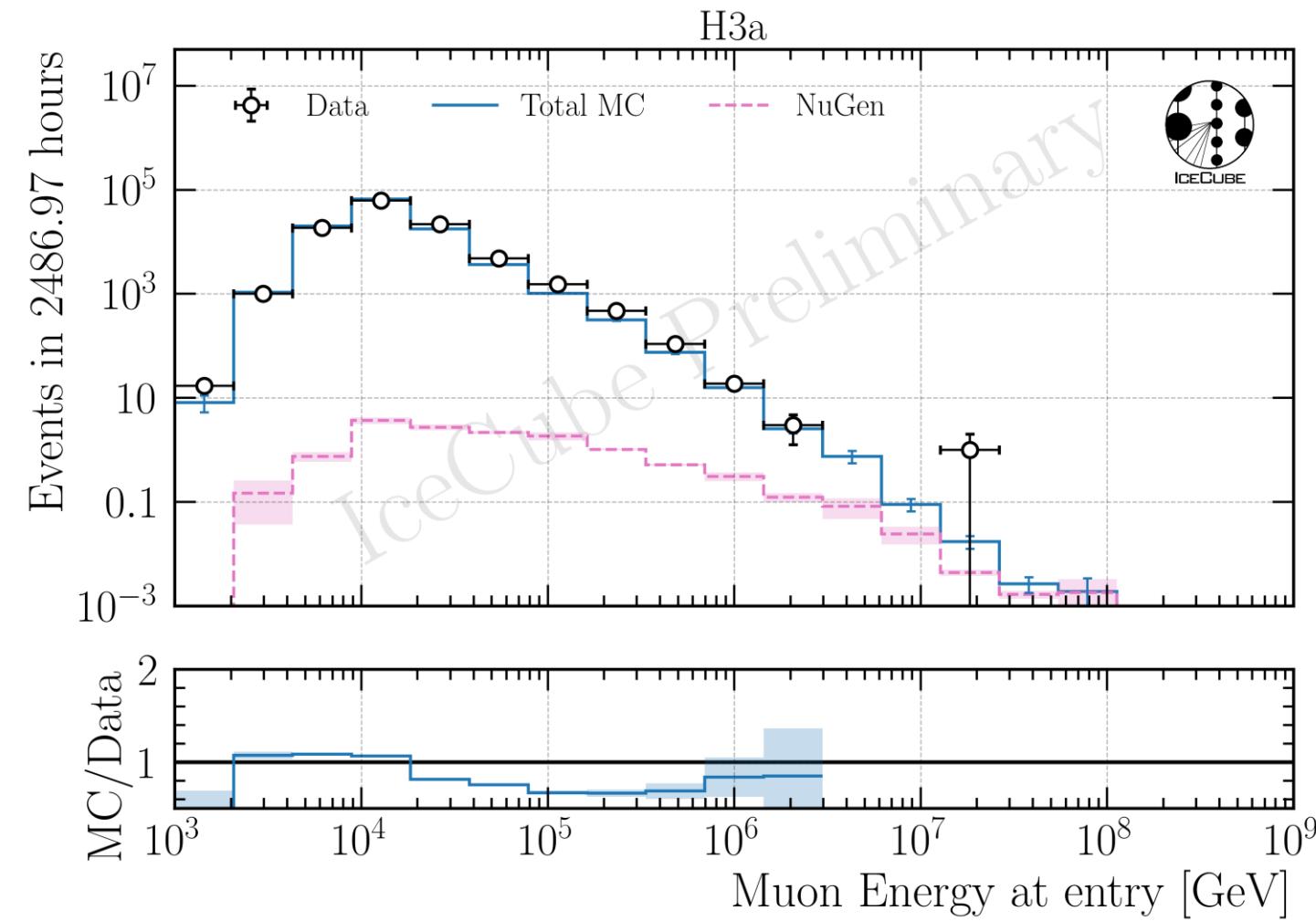
- Correlation between proxy and target variable in unfolding



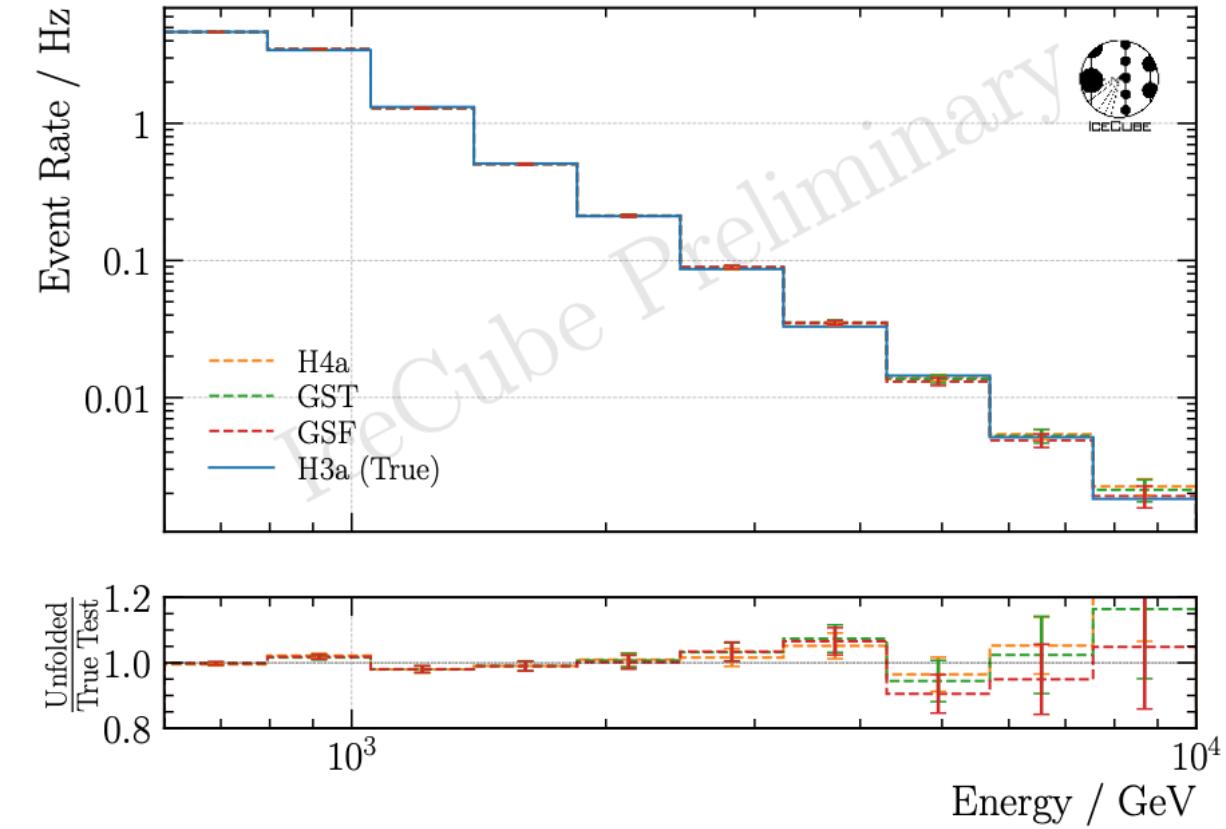
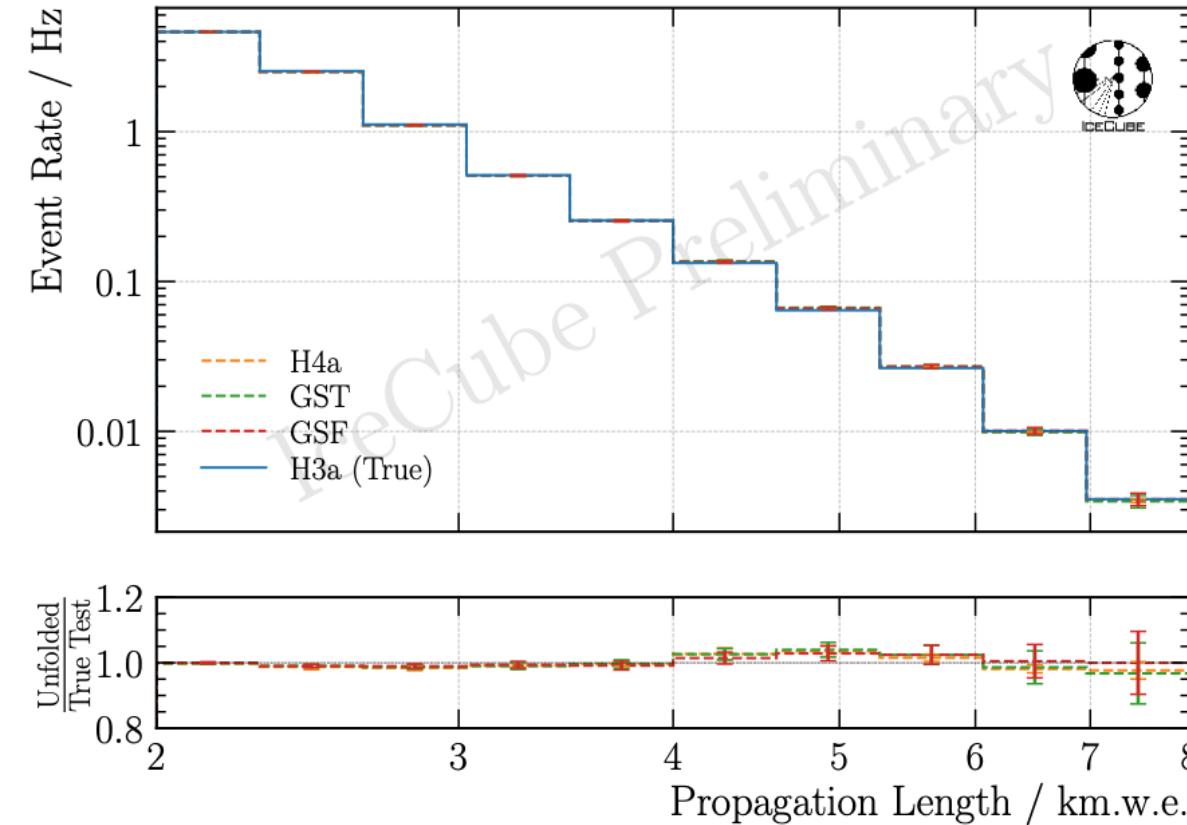
## Data-MC: Stopping Muons



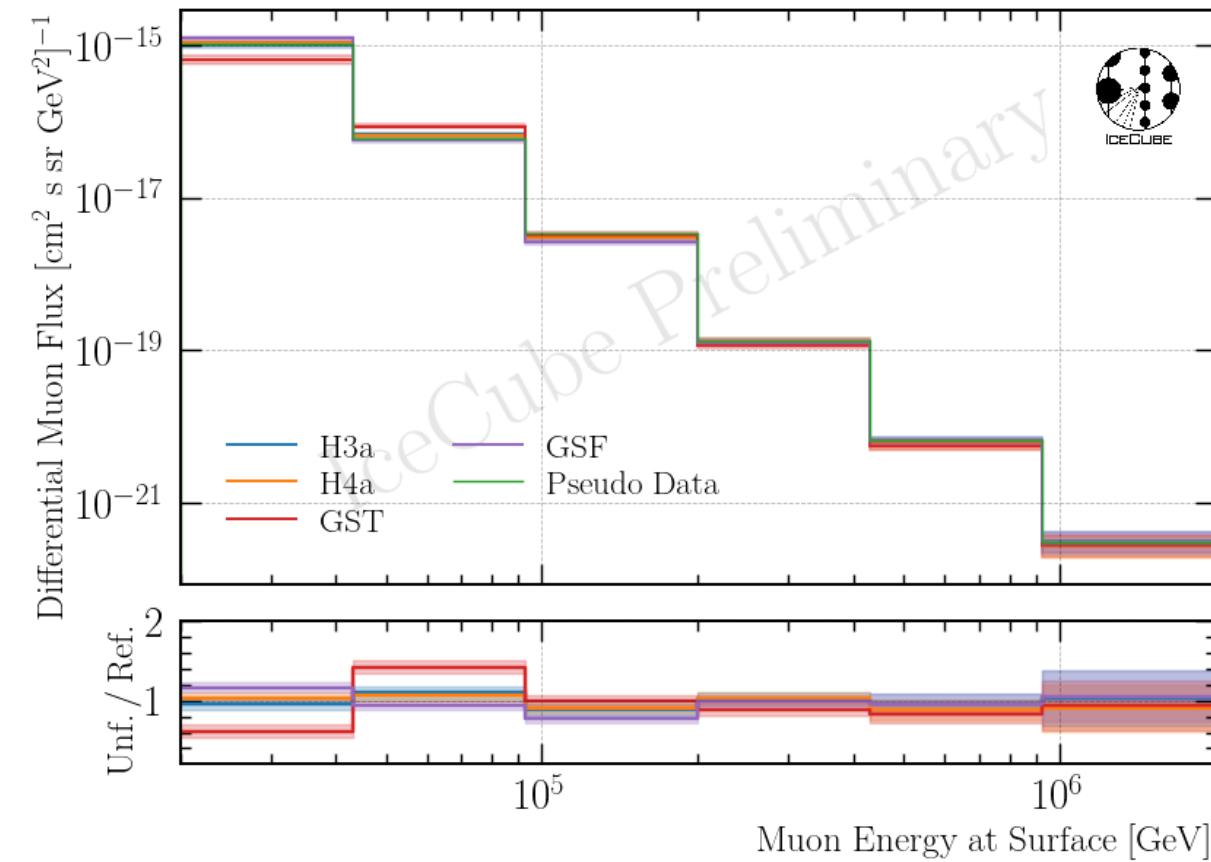
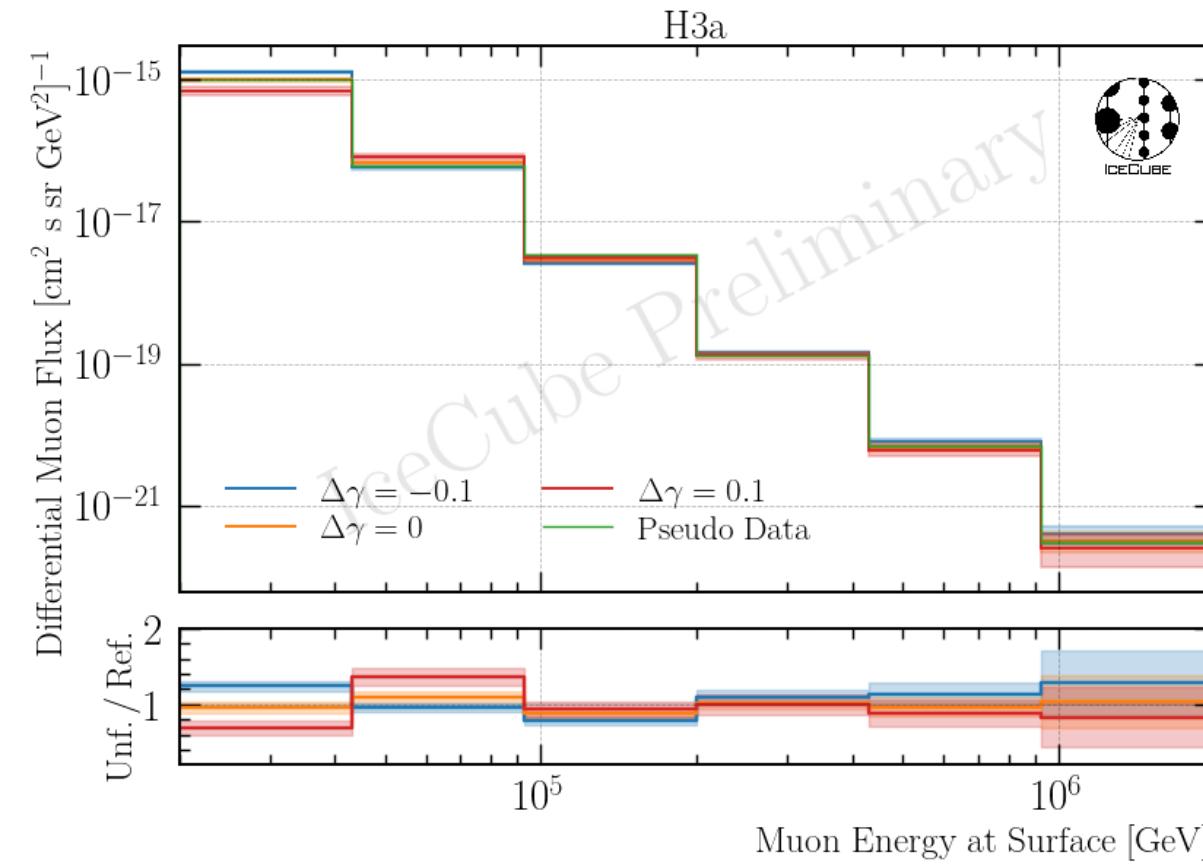
## Data-MC: High Energy Muons



# Robustness Stopping Muons

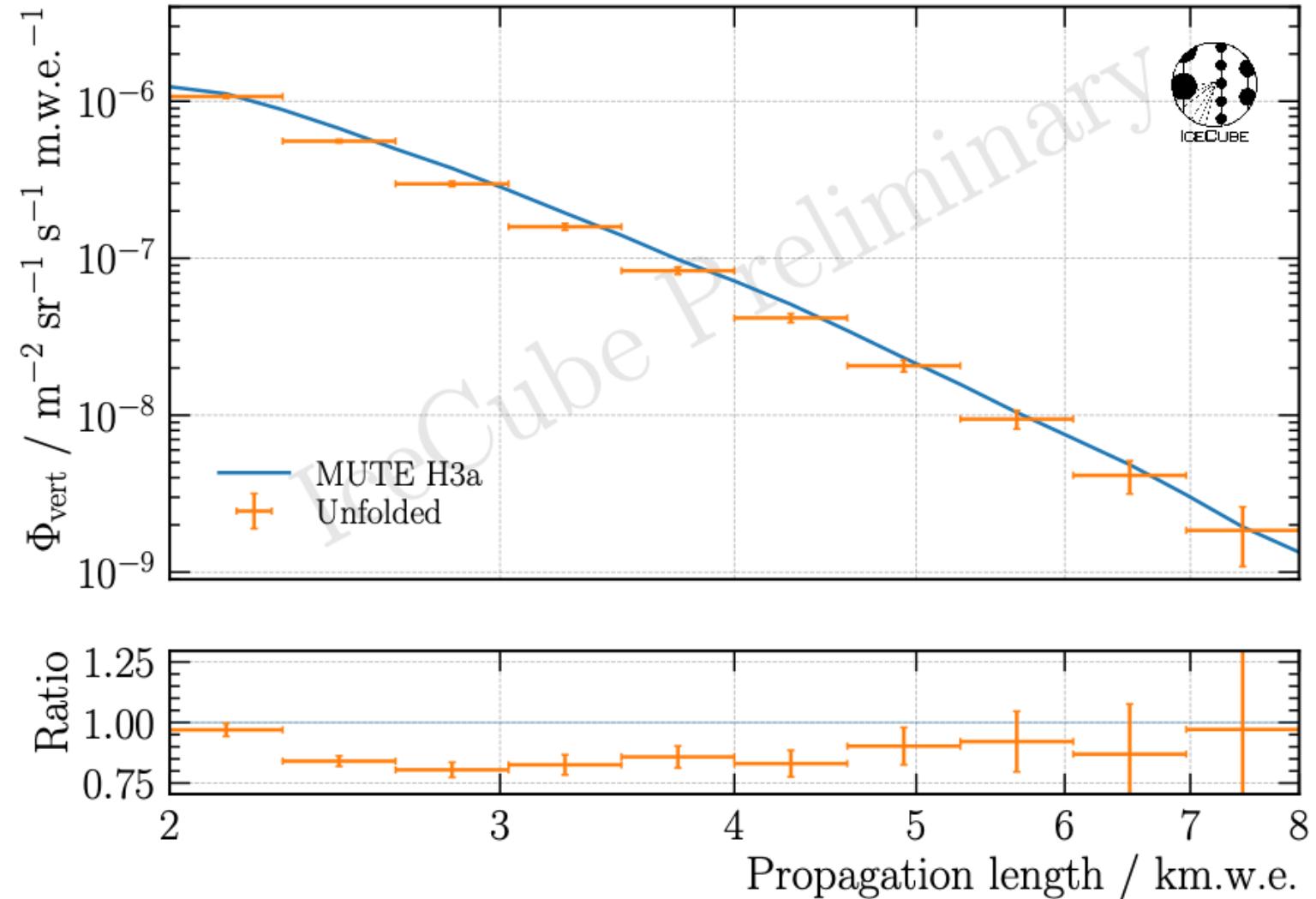


# Robustness High Energy Muons – Starting at 20 TeV



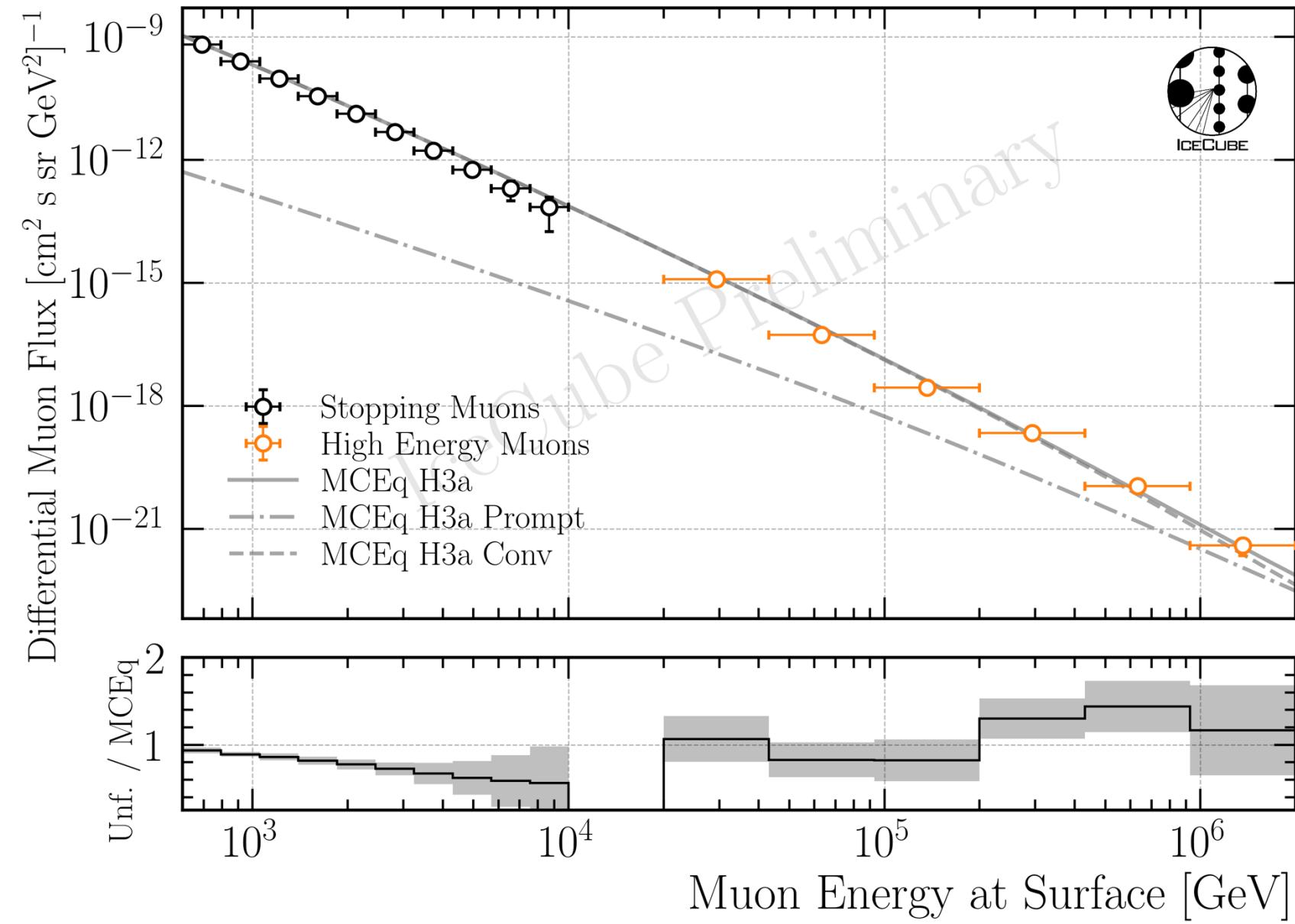
# Unfolding Propagation Length

- Unfolding on burnsample



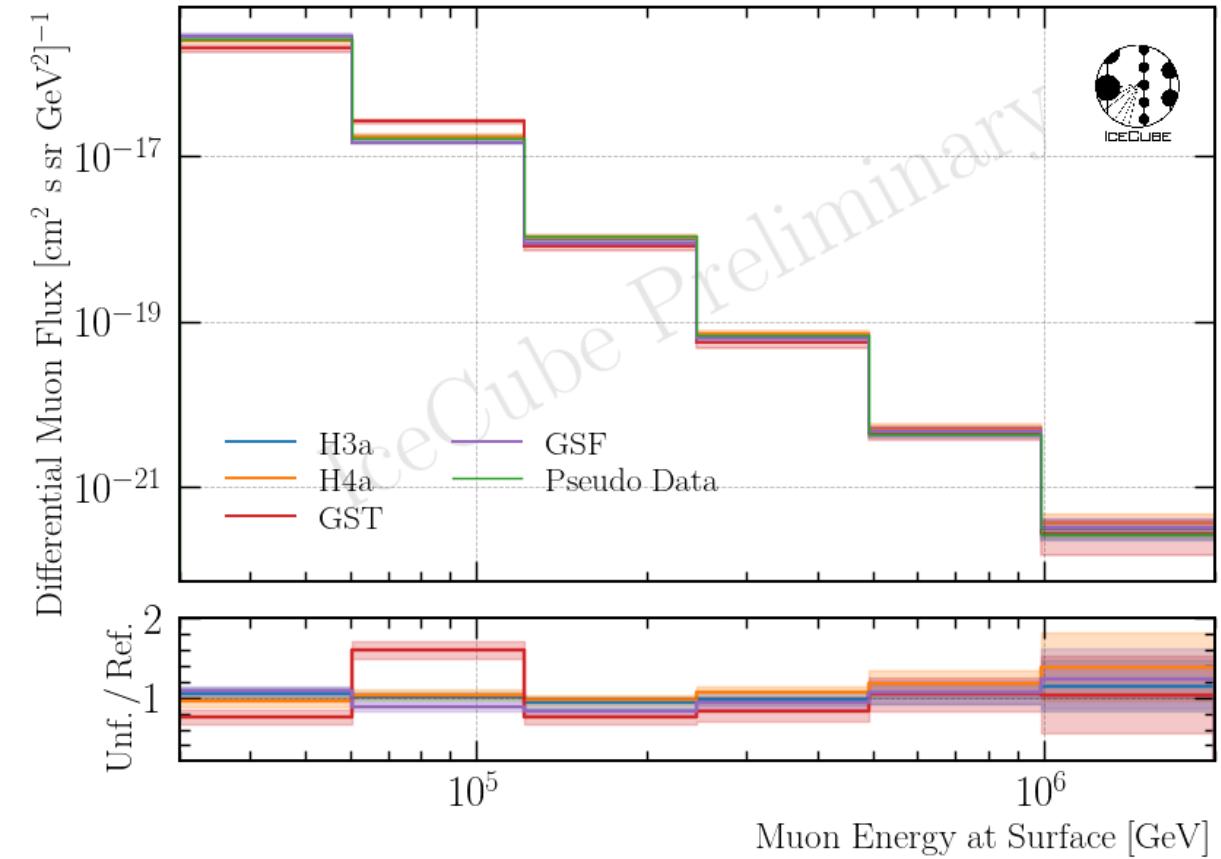
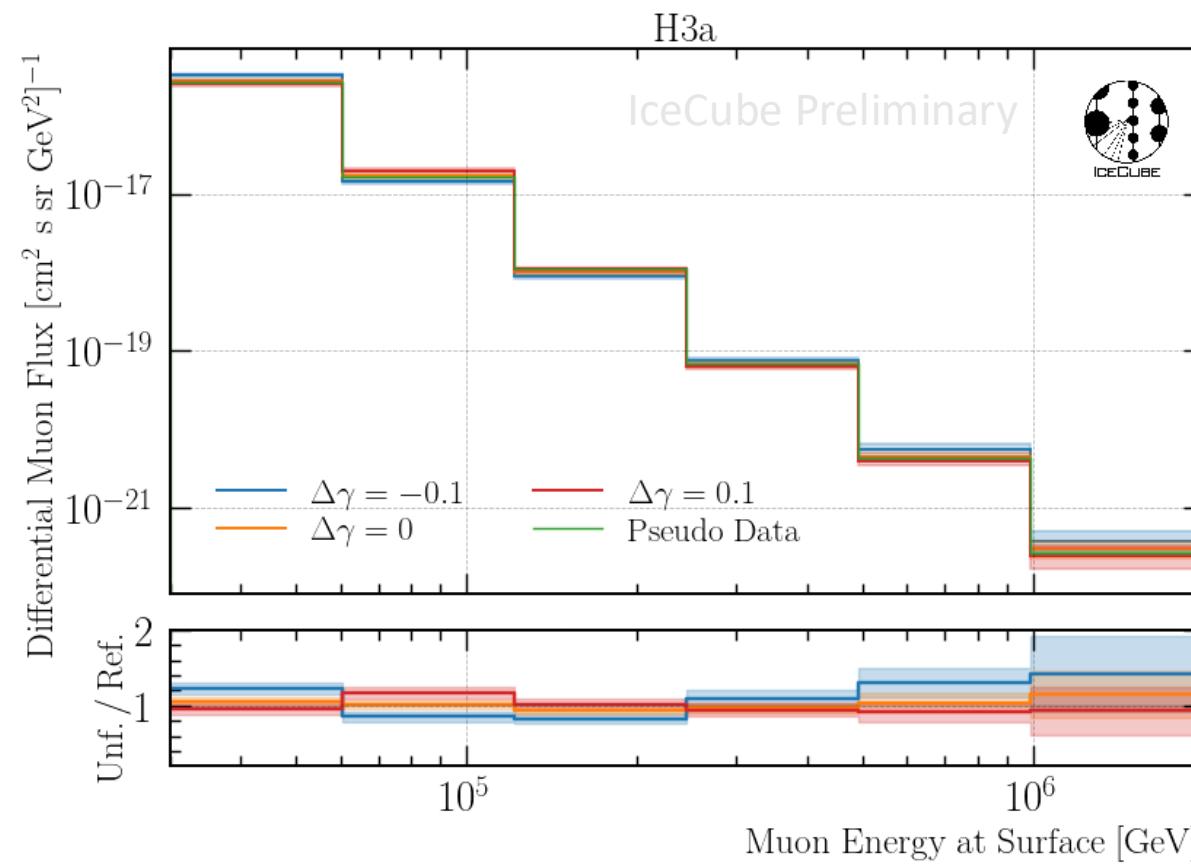
# Unfolding Muon Flux

- Both stopping muons and high energy muons show burnsample unfolding



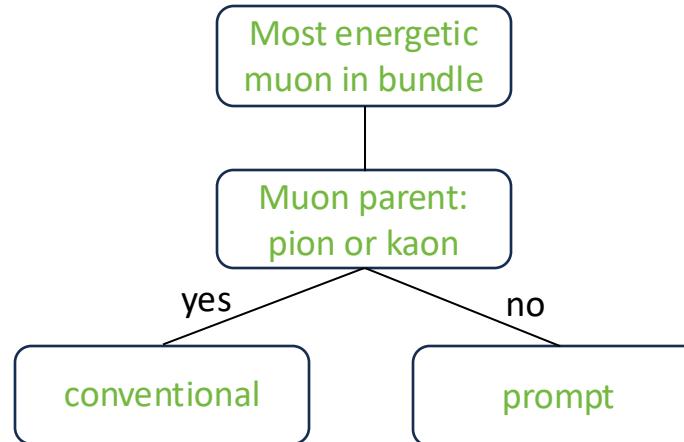
# Thank you for your comments

# Robustness High Energy Muons – Starting at 30 TeV

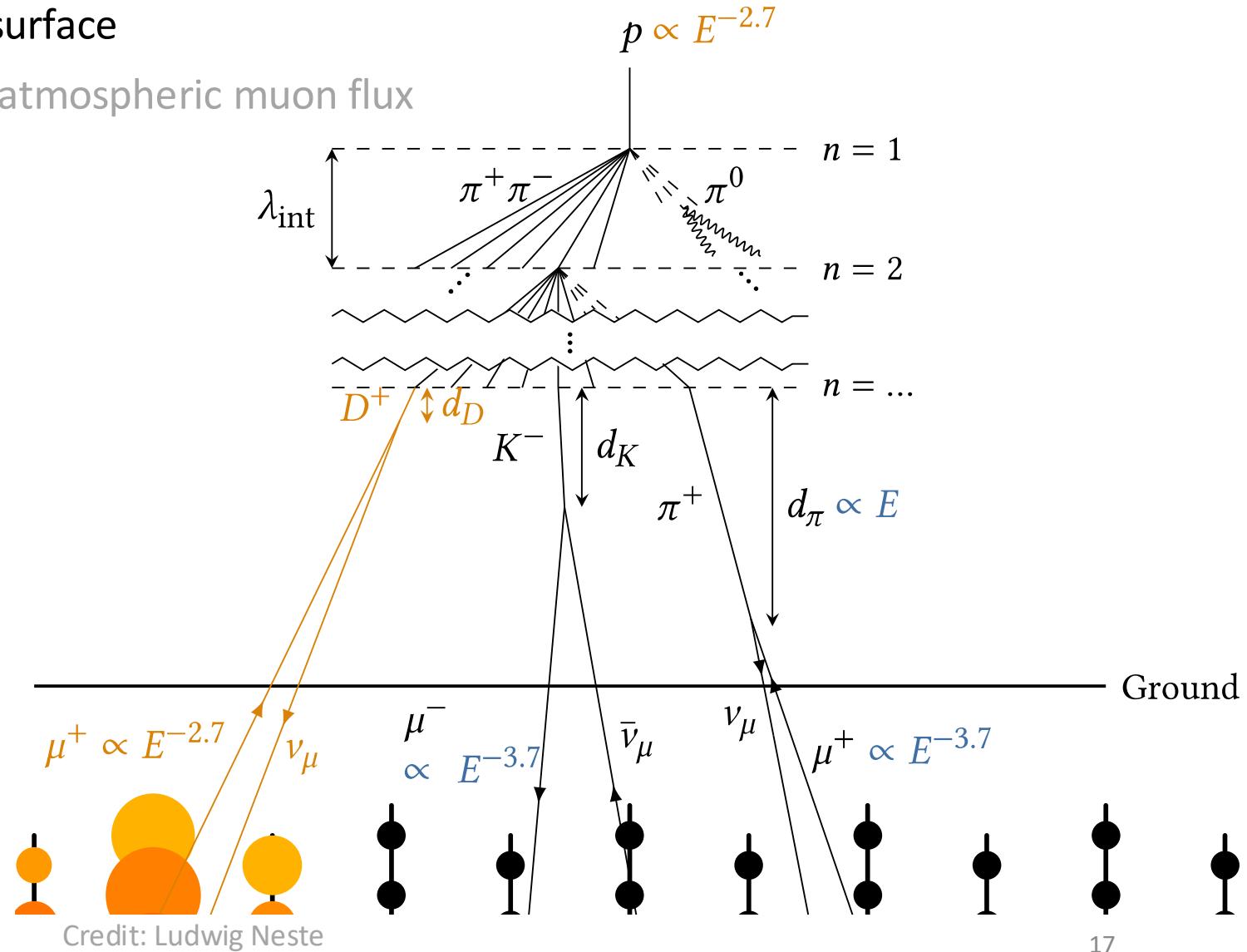


# Analysis Goals: Detect Prompt Muons

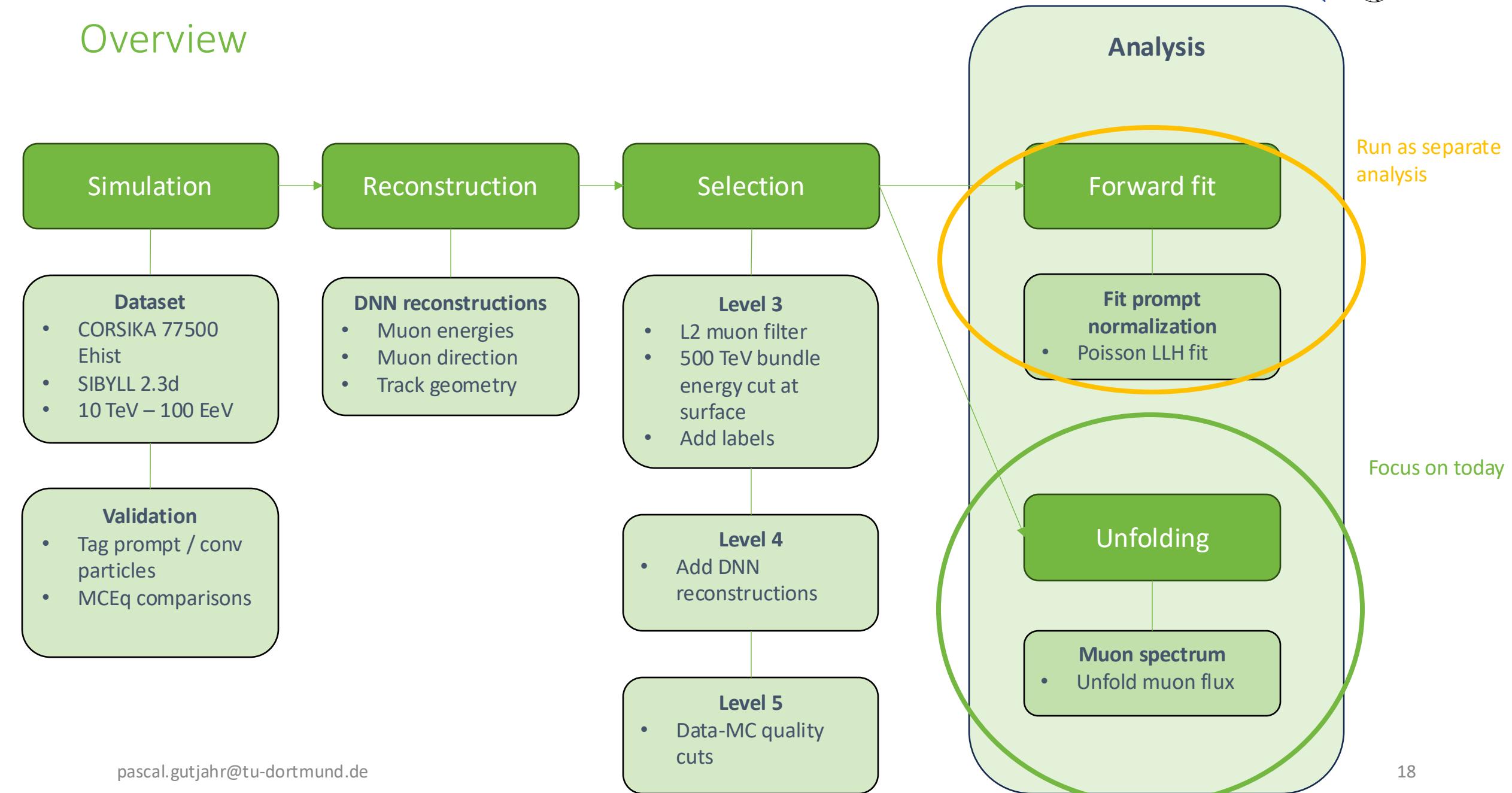
- 1) Unfold a muon energy spectrum at surface
- 2) Measure prompt component of the atmospheric muon flux



Definition leading muon:  
most energetic muon of a muon  
bundle



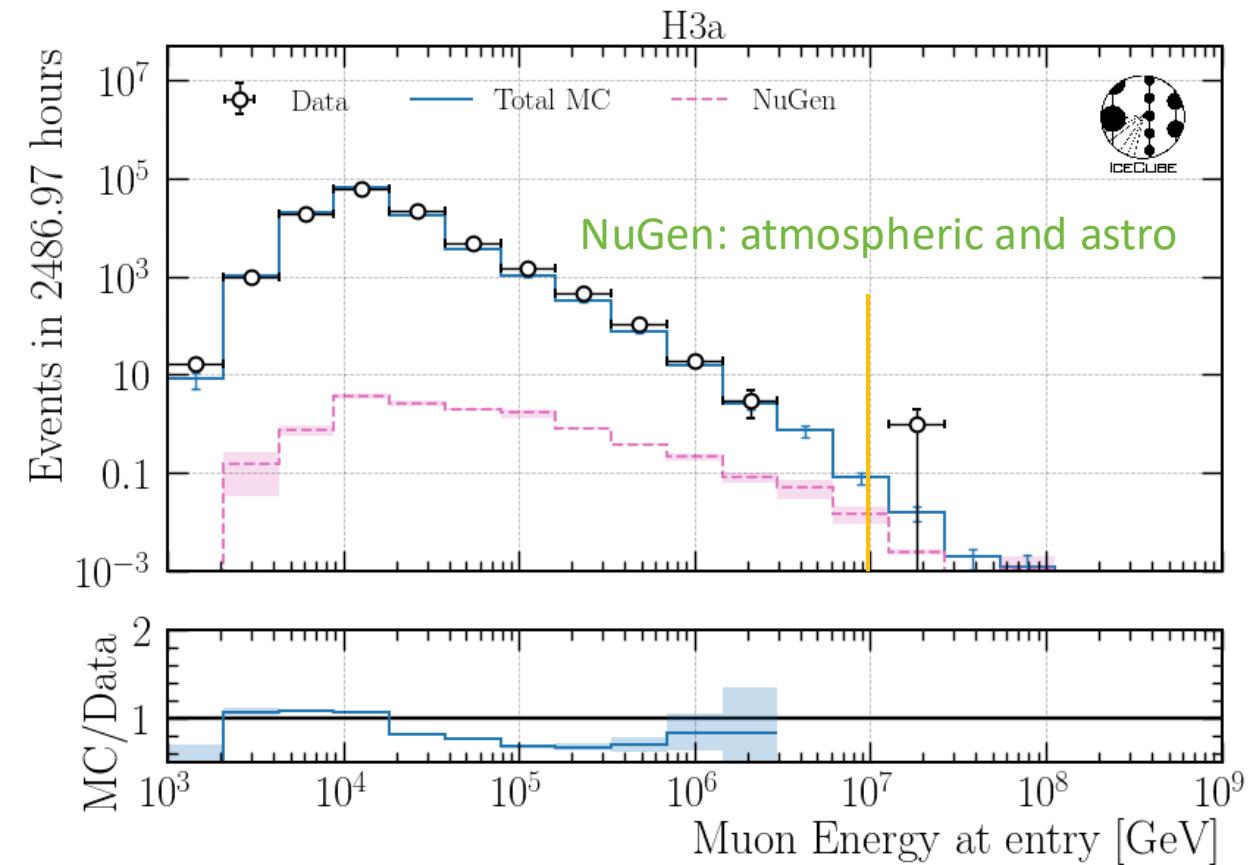
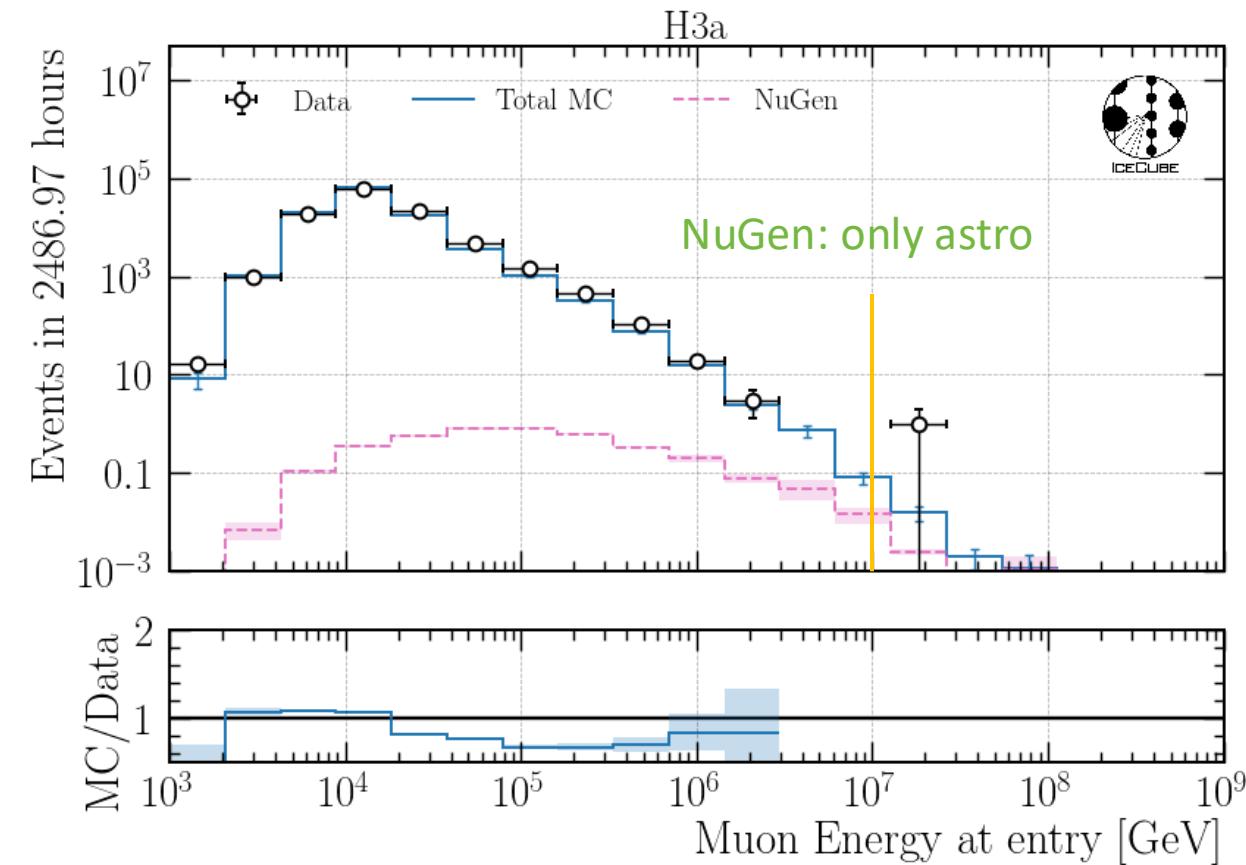
# Overview



# Investigate Neutrino Background

# Impact of Astrophysical Neutrinos – Muon Energy at Entry

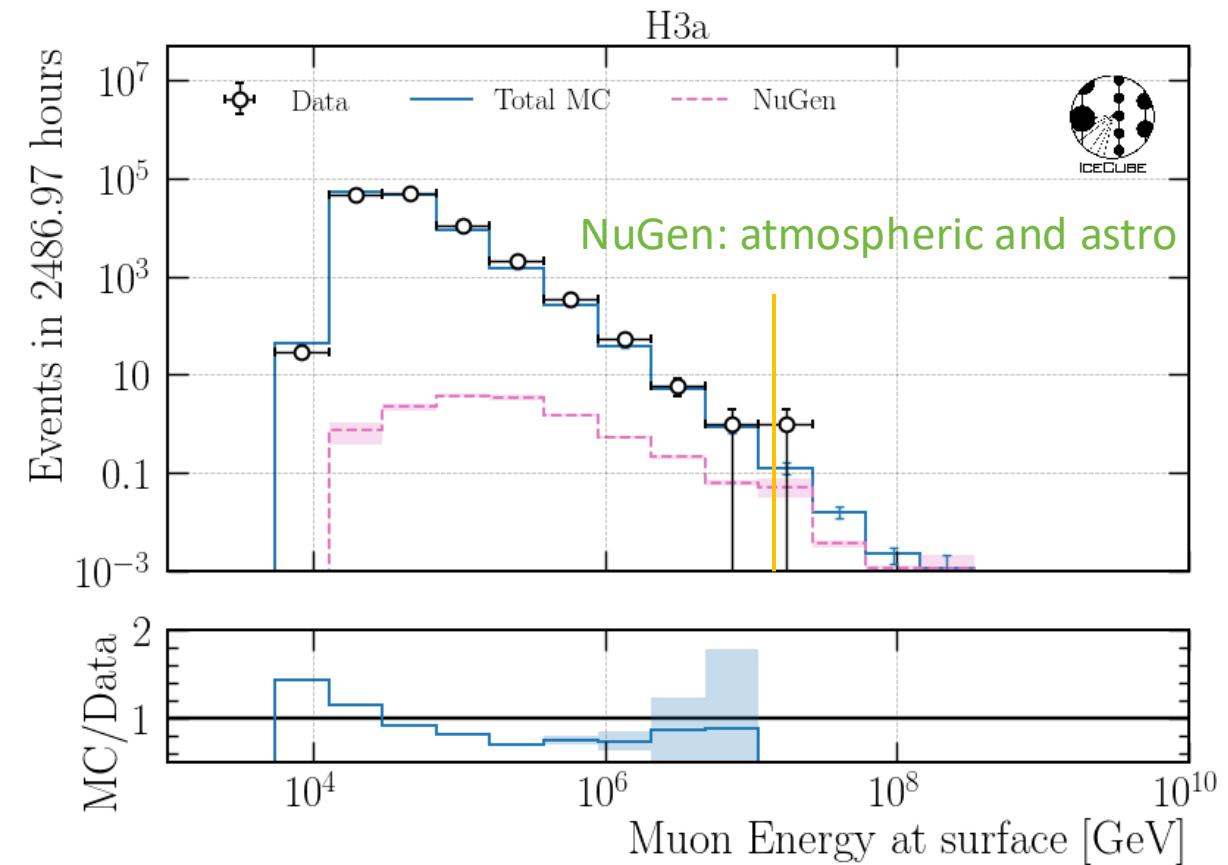
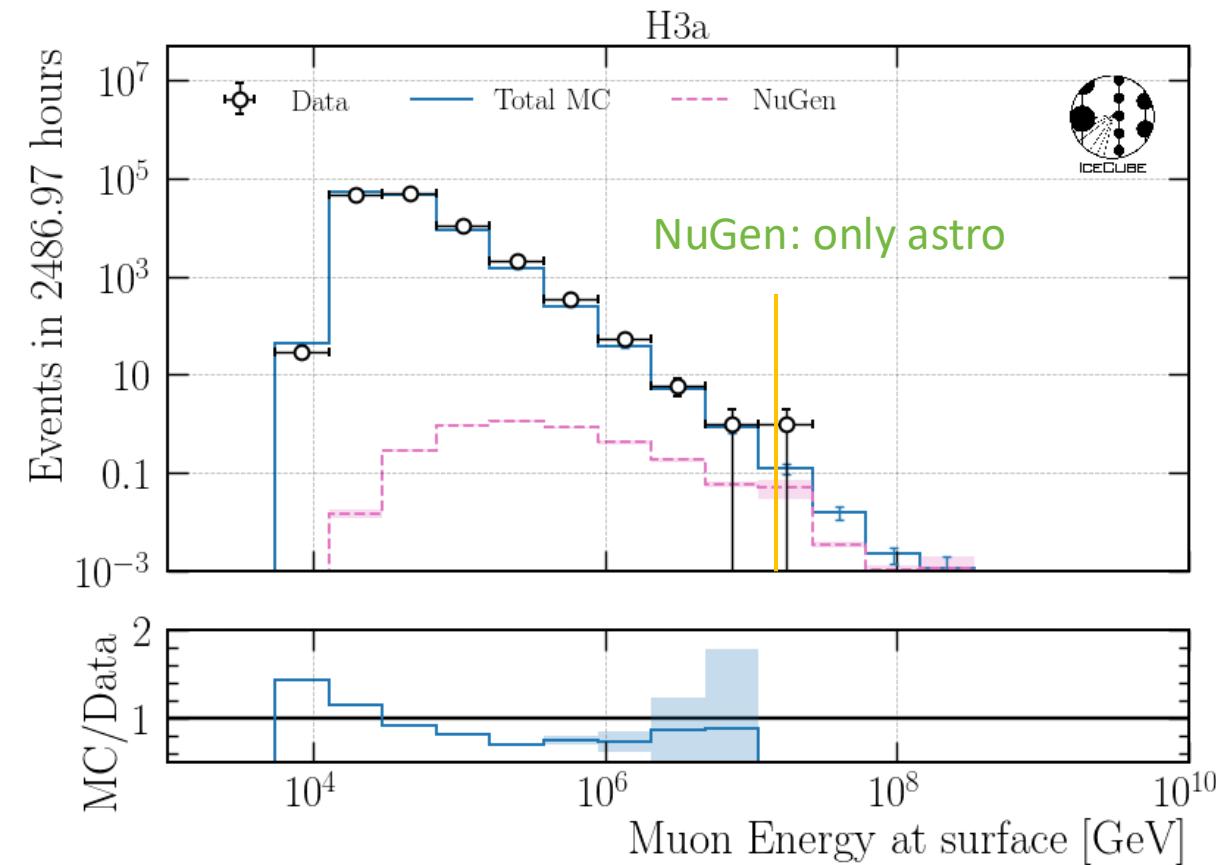
$n = 1.5, \gamma = 2.6$



➤ Neutrinos contribute ~10% to total flux at high energies > 5 PeV

# Impact of Astrophysical Neutrinos – Muon Energy at Surface

$n = 1.5, \gamma = 2.6$



➤ Neutrinos contribute ~50% to total flux at high energies > 5 PeV

# Assume Latest Astrophysical Diffuse Results by IceCube

## Measurement of the astrophysical diffuse neutrino flux in a combined fit of IceCube's high energy neutrino data

### The IceCube Collaboration

(a complete list of authors can be found at the end of the proceedings)

E-mail: [rnaab@icecube.wisc.edu](mailto:rnaab@icecube.wisc.edu), [erik.ganster@icecube.wisc.edu](mailto:erik.ganster@icecube.wisc.edu),  
[zelong.zhang@icecube.wisc.edu](mailto:zelong.zhang@icecube.wisc.edu)

The IceCube Neutrino Observatory has discovered a diffuse neutrino flux of astrophysical origin and measures its properties in various detection channels. With more than 10 years of data, we use multiple data samples from different detection channels for a combined fit of the diffuse astrophysical neutrino spectrum. This leverages the complementary information of different neutrino event signatures. For the first time, we use a coherent modelling of the signal and background, as well as the detector response and corresponding systematic uncertainties. The detector response is continuously varied during the simulation in order to generate a general purpose Monte Carlo set, which is central to our approach. We present a combined fit yielding a measurement of the diffuse astrophysical neutrino flux properties with unprecedented precision.

ArXiv: 2308.00191

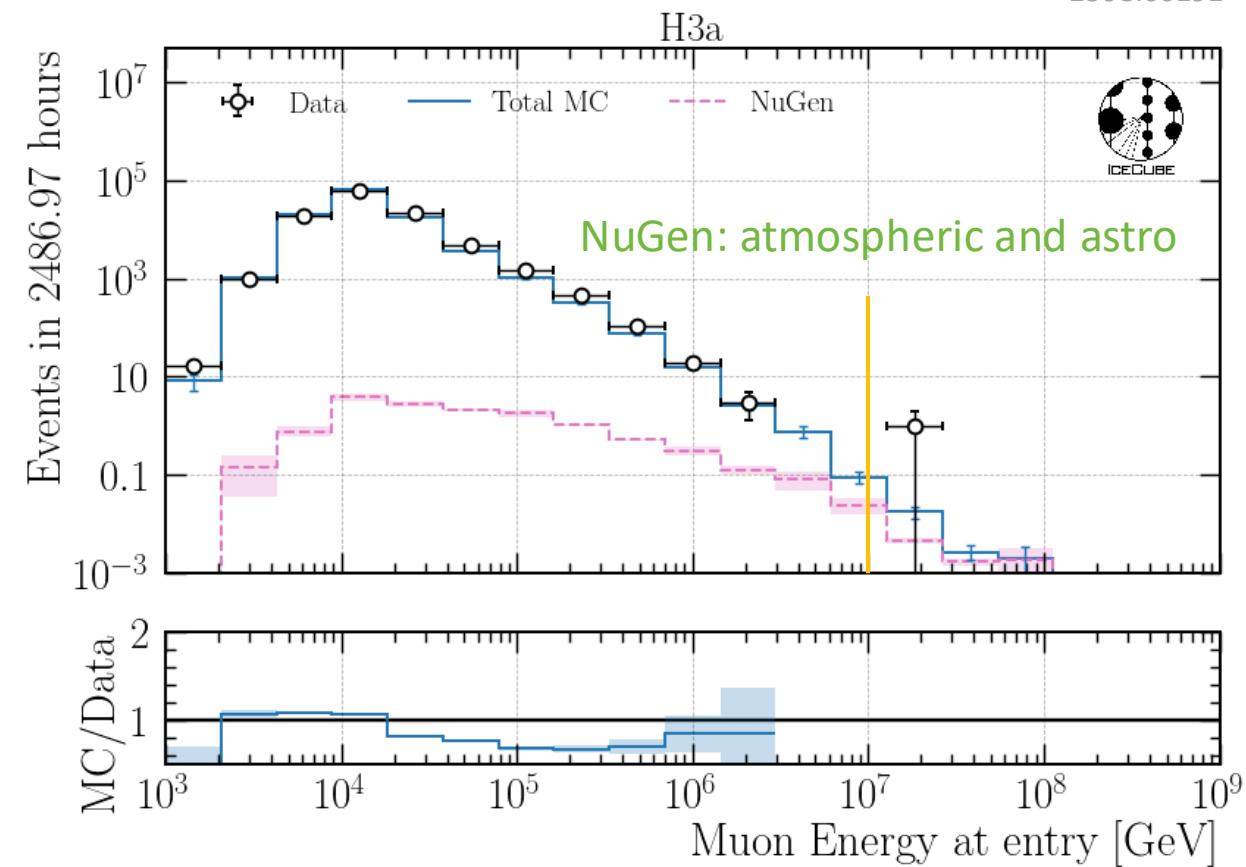
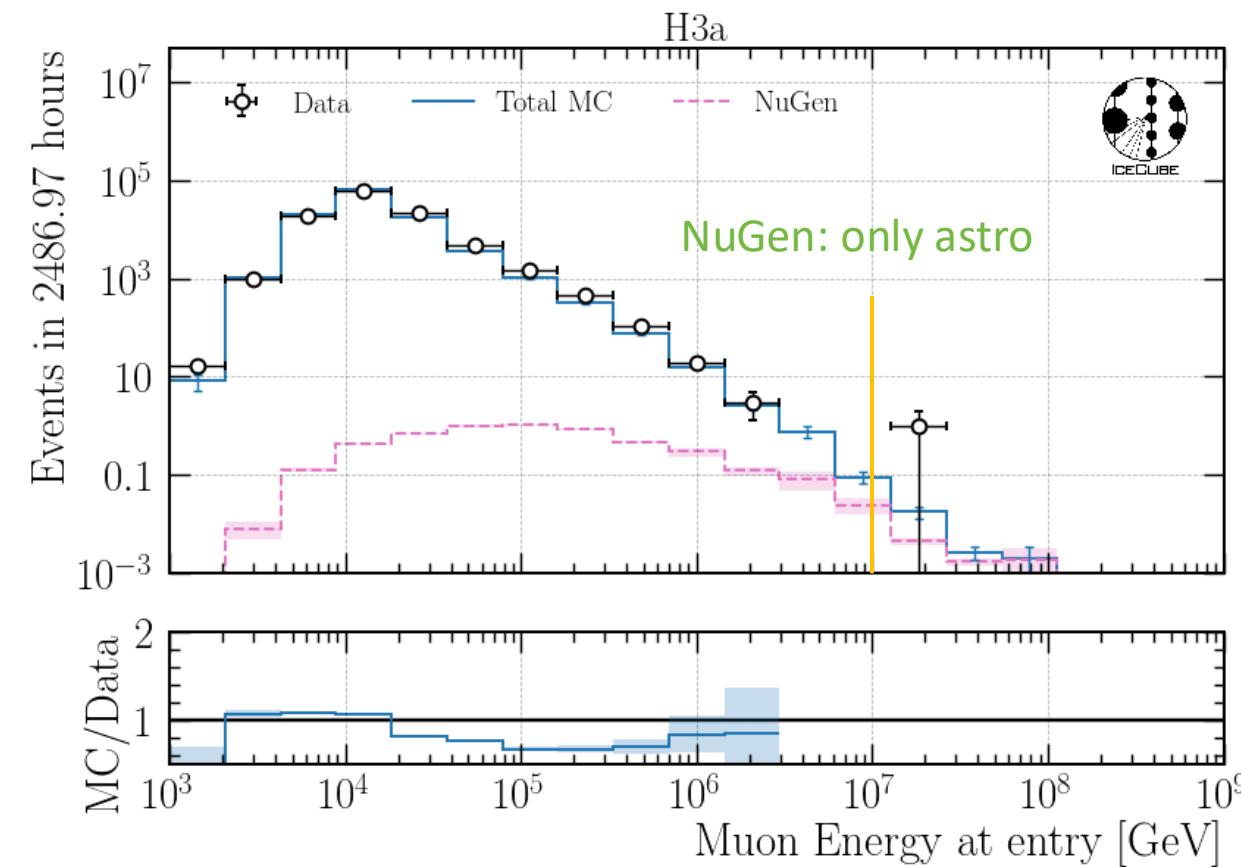
Astrophysical Model	Result	Energy Range (90% CL)	$-2\Delta\log\mathcal{L}$ over SPL
SPL	$\Phi_{@100\text{TeV}}^{\nu+\bar{\nu}} / C = 1.80^{+0.13}_{-0.16}$	2.5 TeV to 6.3 PeV	-
	$\gamma = 2.52^{+0.04}_{-0.04}$		
LogP	$\Phi_{@100\text{TeV}}^{\nu+\bar{\nu}} / C = 2.13^{+0.16}_{-0.19}$	8.0 TeV to 2.2 PeV	16.4
	$\alpha_{LP} = 2.57^{+0.06}_{-0.05}$		
BPL	$\beta_{LP} = 0.23^{+0.10}_{-0.07}$	13.7 TeV to 4.7 PeV	24.7
	$\Phi_{@100\text{TeV}}^{\nu+\bar{\nu}} / C = 1.77^{+0.15}_{-0.11}$		
	$\log_{10}(E_{\text{break}}/\text{GeV}) = 4.39^{+0.09}_{-0.08}$		
	$\gamma_1 = 1.31^{+0.50}_{-1.21}$		
	$\gamma_2 = 2.74^{+0.06}_{-0.07}$		

➤ Test SPL and BPL

# Impact of Astrophysical Neutrinos – Muon Energy at Entry

$n = 1.8, \gamma = 2.52$

2308.00191

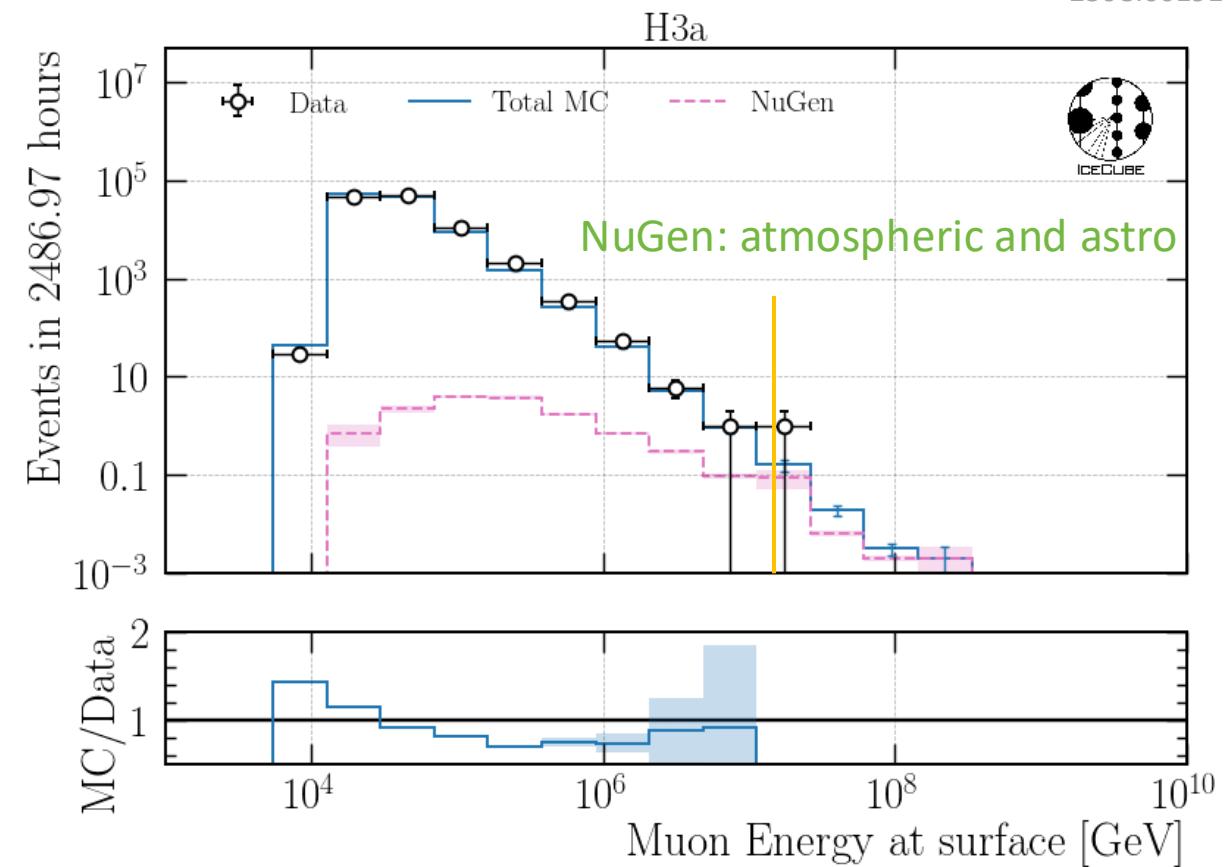
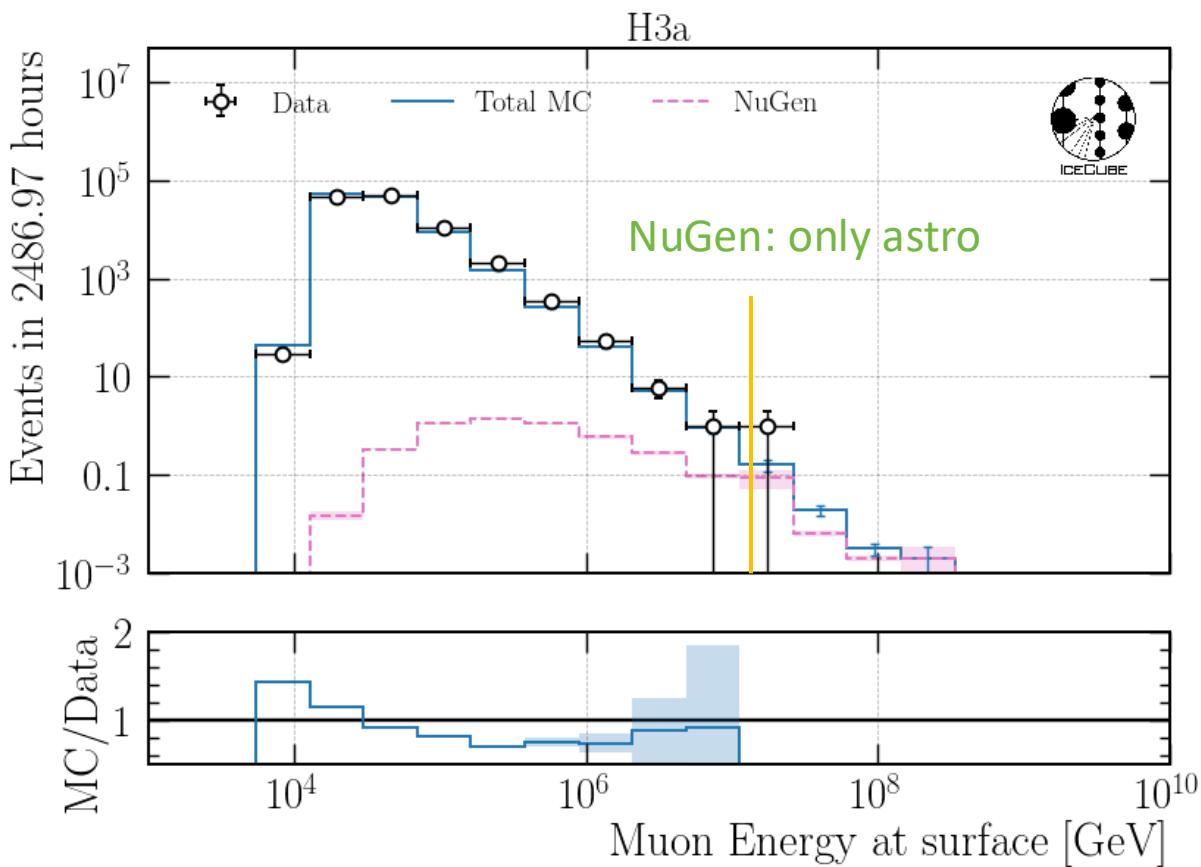


➤ Neutrinos contribute ~10% to total flux at high energies > 5 PeV

# Impact of Astrophysical Neutrinos – Muon Energy at Surface

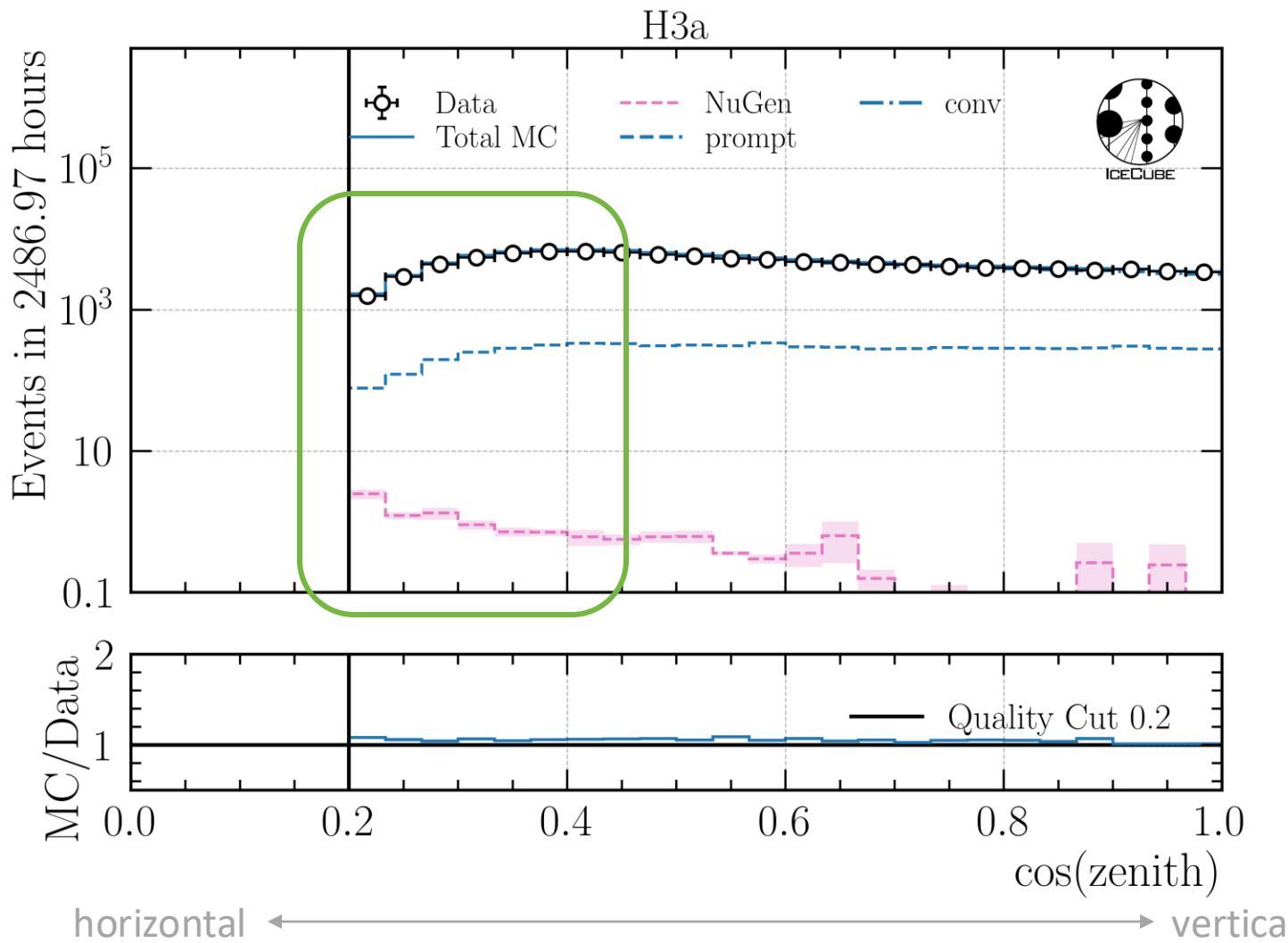
$n = 1.8, \gamma = 2.52$

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➤ Neutrinos contribute ~50% to total flux at high energies > 5 PeV

# Cos(zenith) Distribution

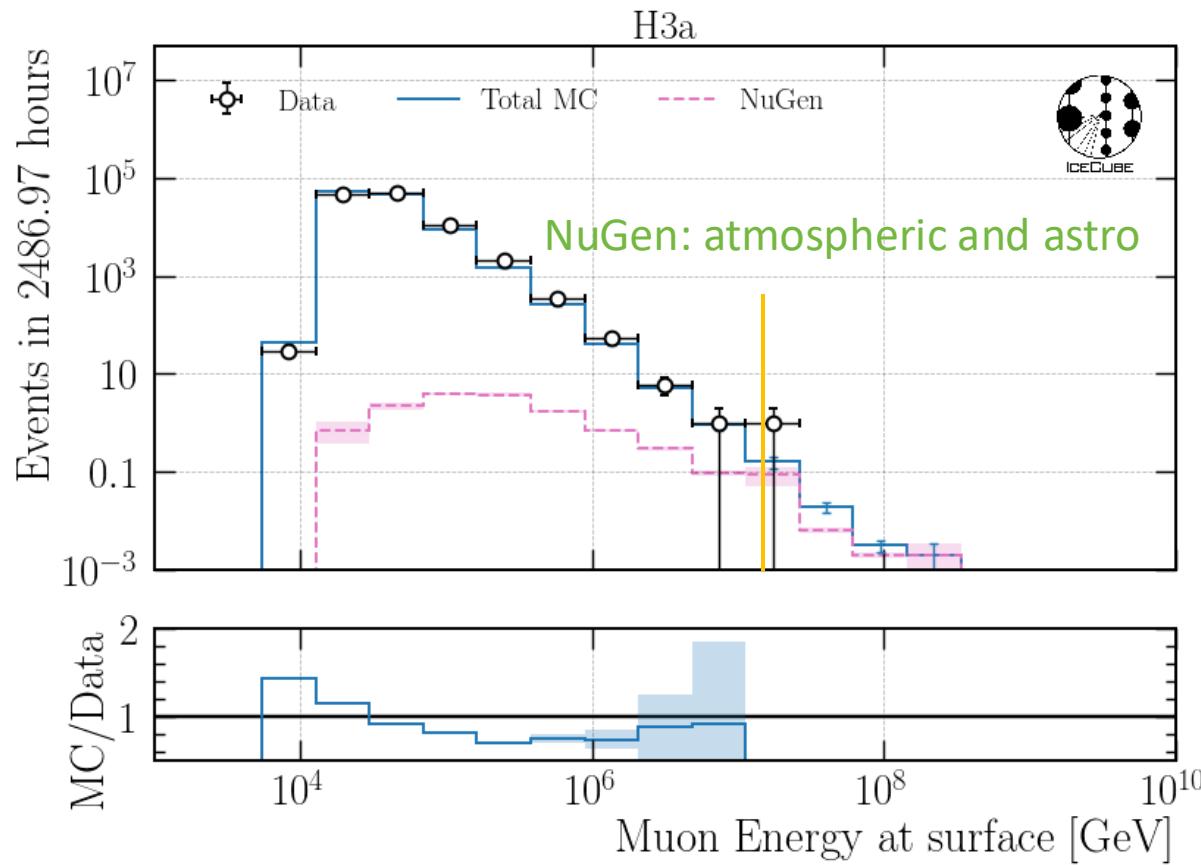
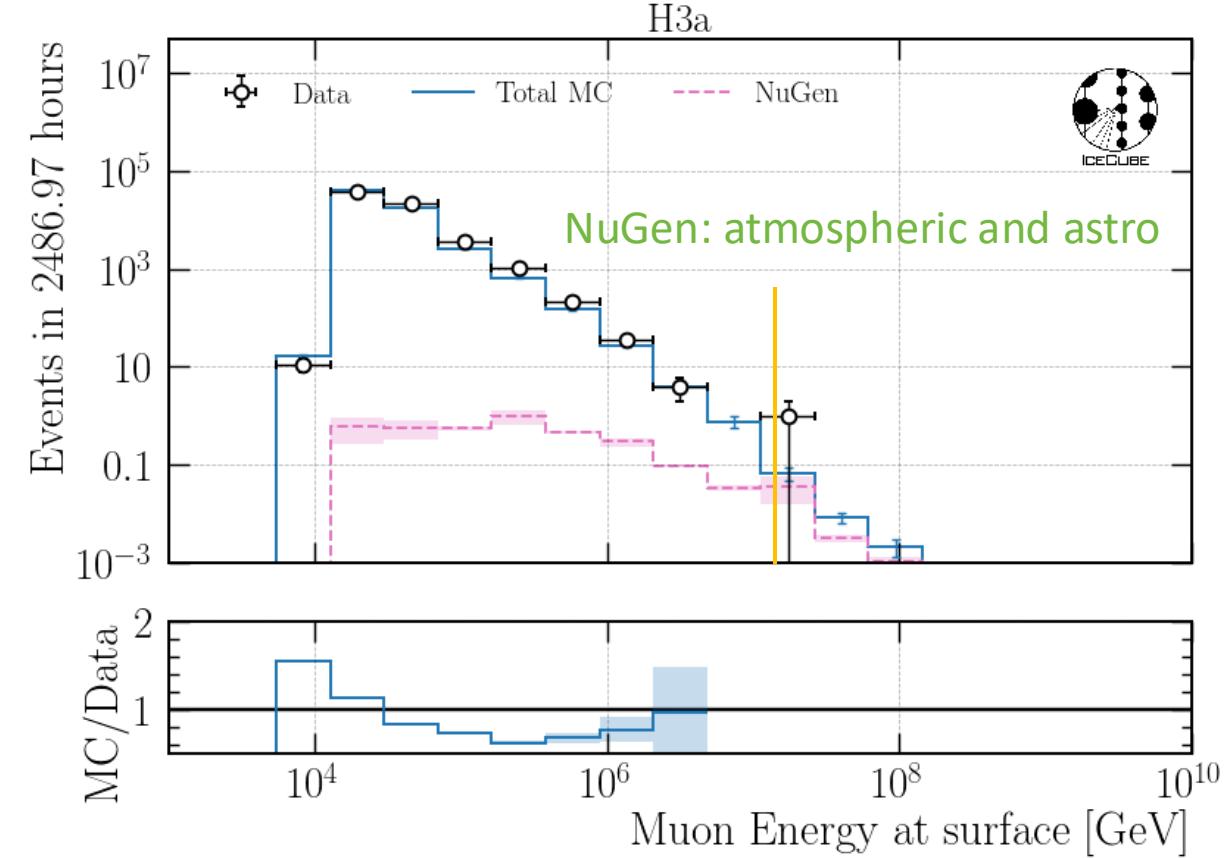


- Expect more neutrinos from the horizon
- Apply stronger zenith cut to remove neutrinos

## Remove Horizontal Events – Muon Energy at Surface

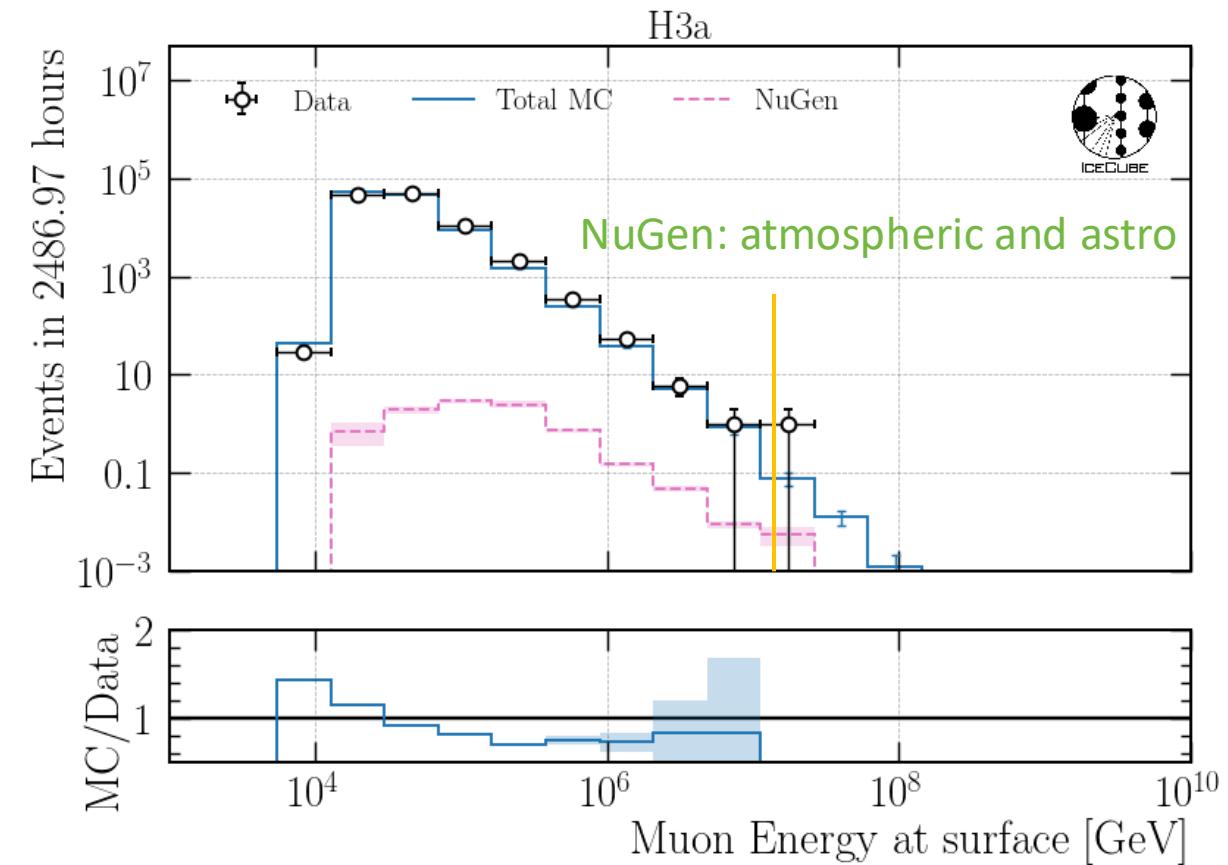
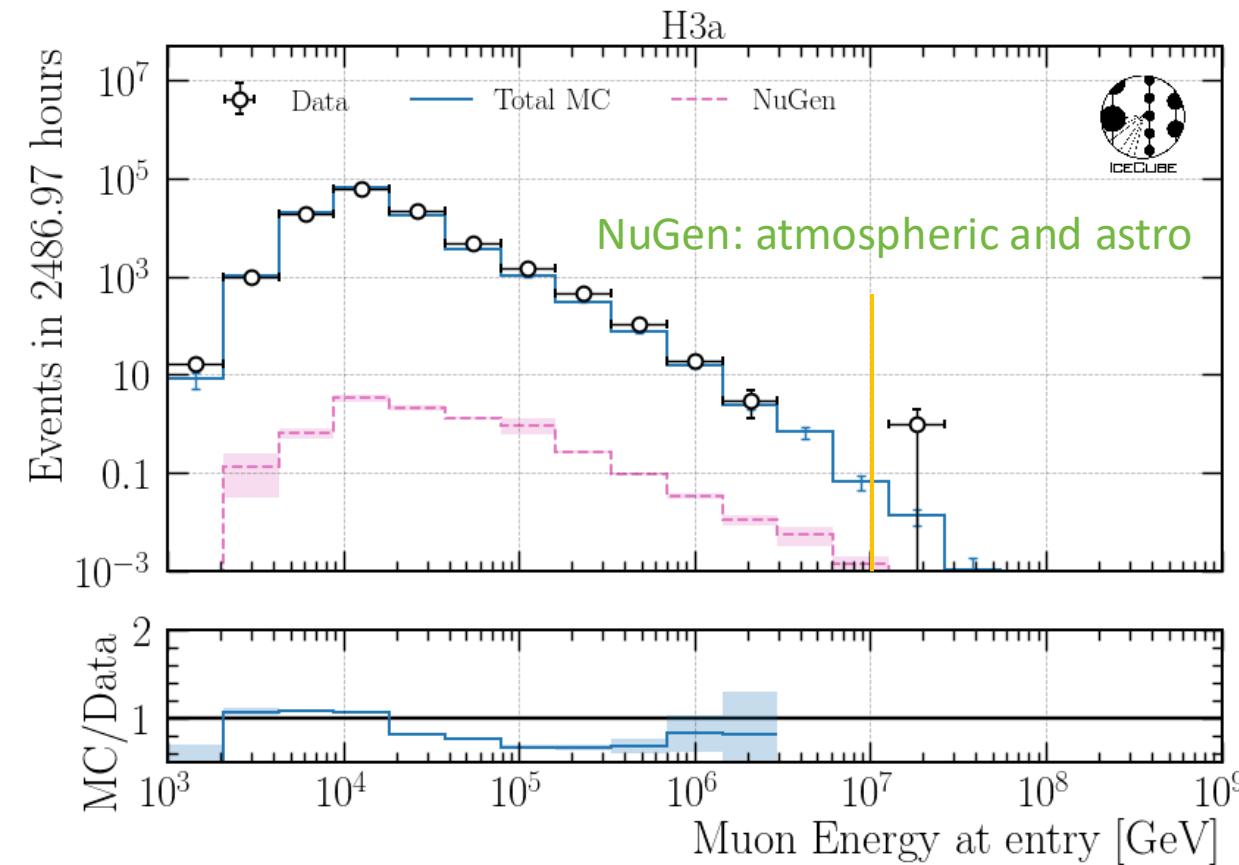
 $n = 1.8, \gamma = 2.52$ 

2308.00191

 $\cos(\theta) > 0.2$  $\cos(\theta) > 0.4$ 

➤ Stronger zenith cut has no significant impact

# Impact of Astrophysical Neutrinos – Muon Energy at Surface/Entry



- For BPL: Neutrinos contribute less than 10%

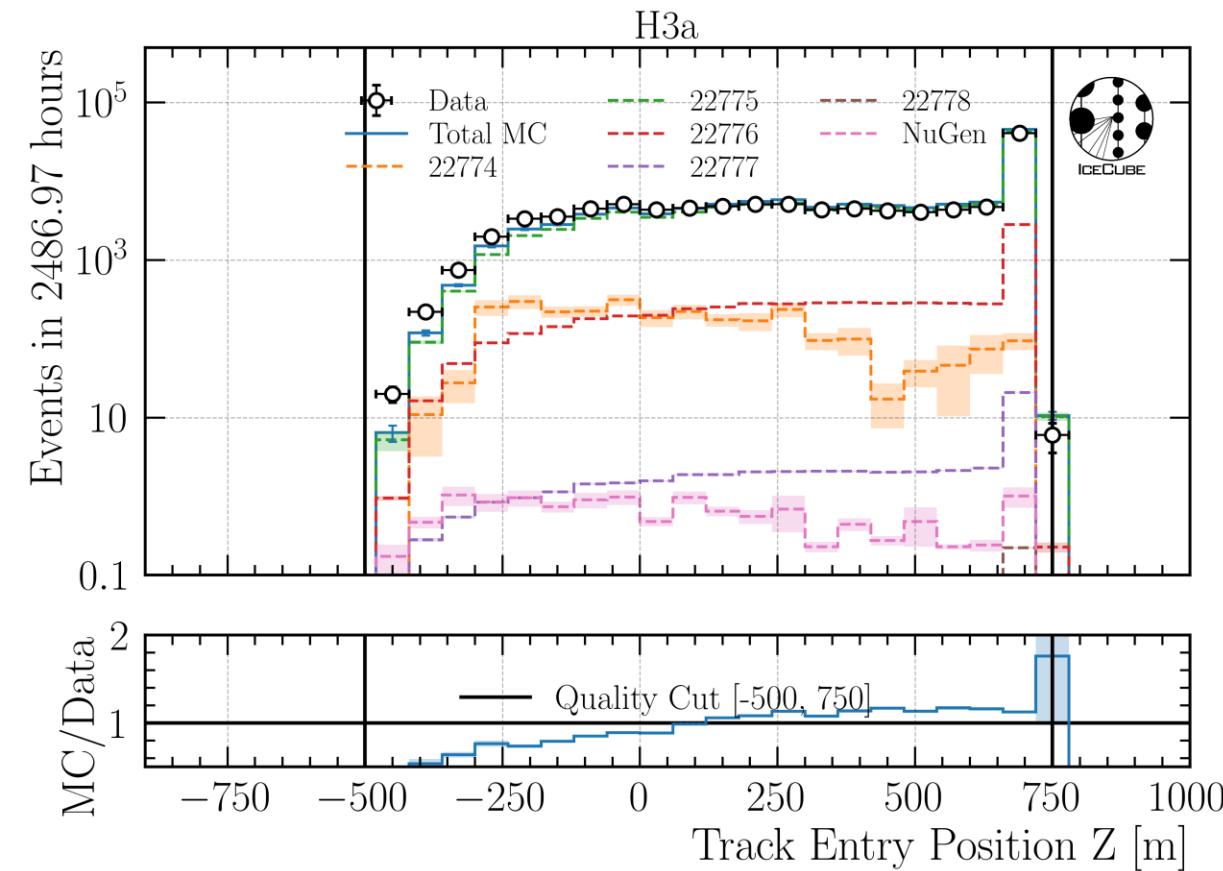
$$n = 1.77, \gamma_1 = 1.31, \gamma_2 = 2.74$$
$$\log_{10}(E_{\text{break}}) = 4.39,$$

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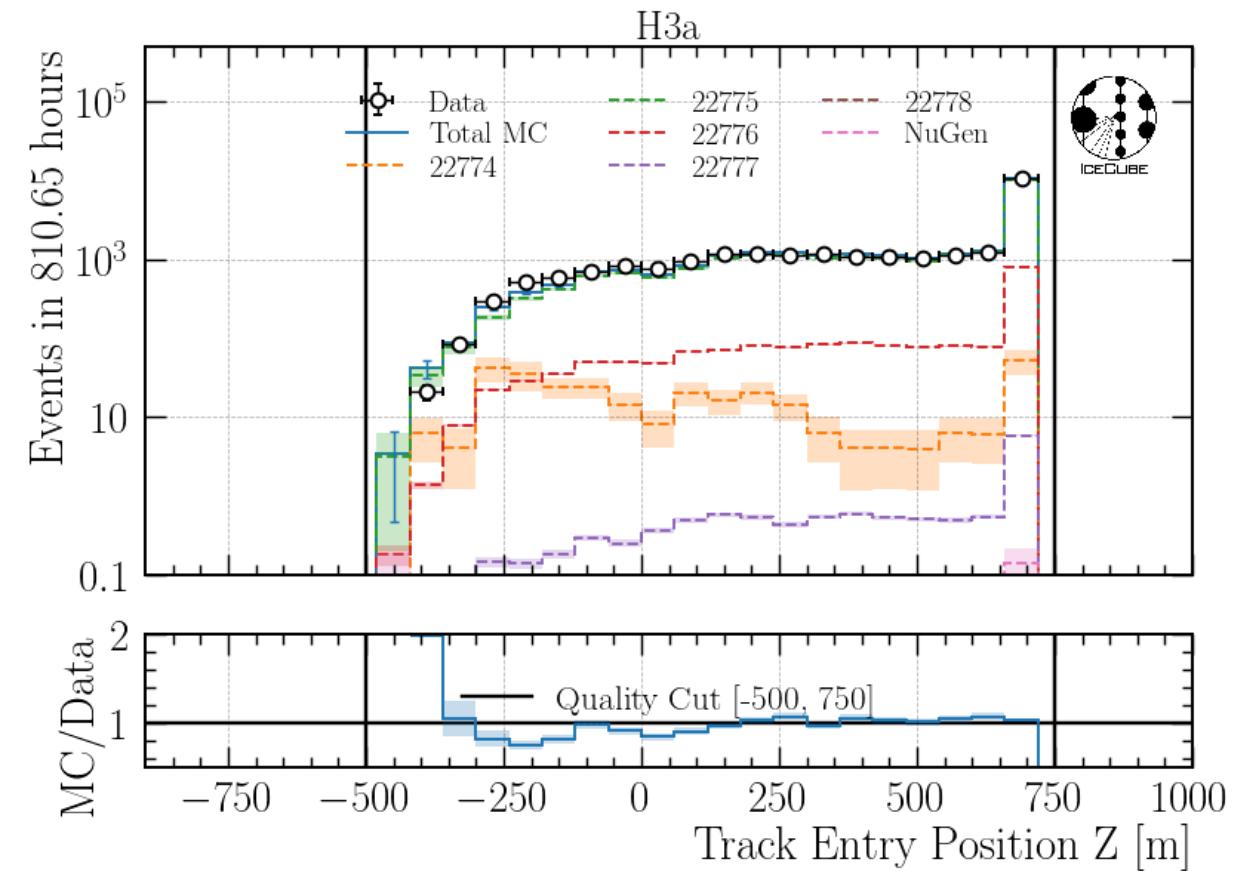
# Z-Vertex Data-MC

- Networks were trained on several old CORSIKA simulation datasets to make them robust
  - Re-train on new ice model spice\_ftp-v3m

# Z-Vertex Data-MC: Entry Position

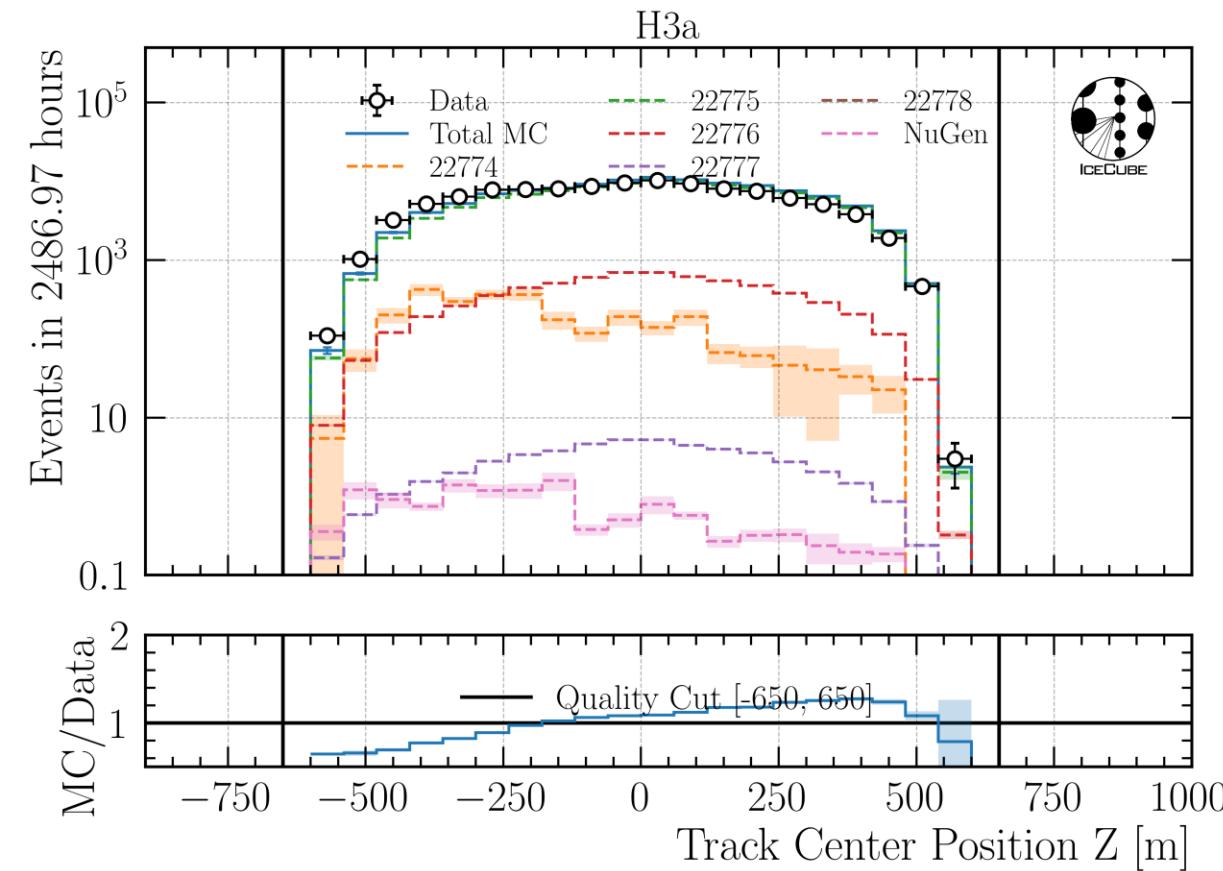


Old ice model

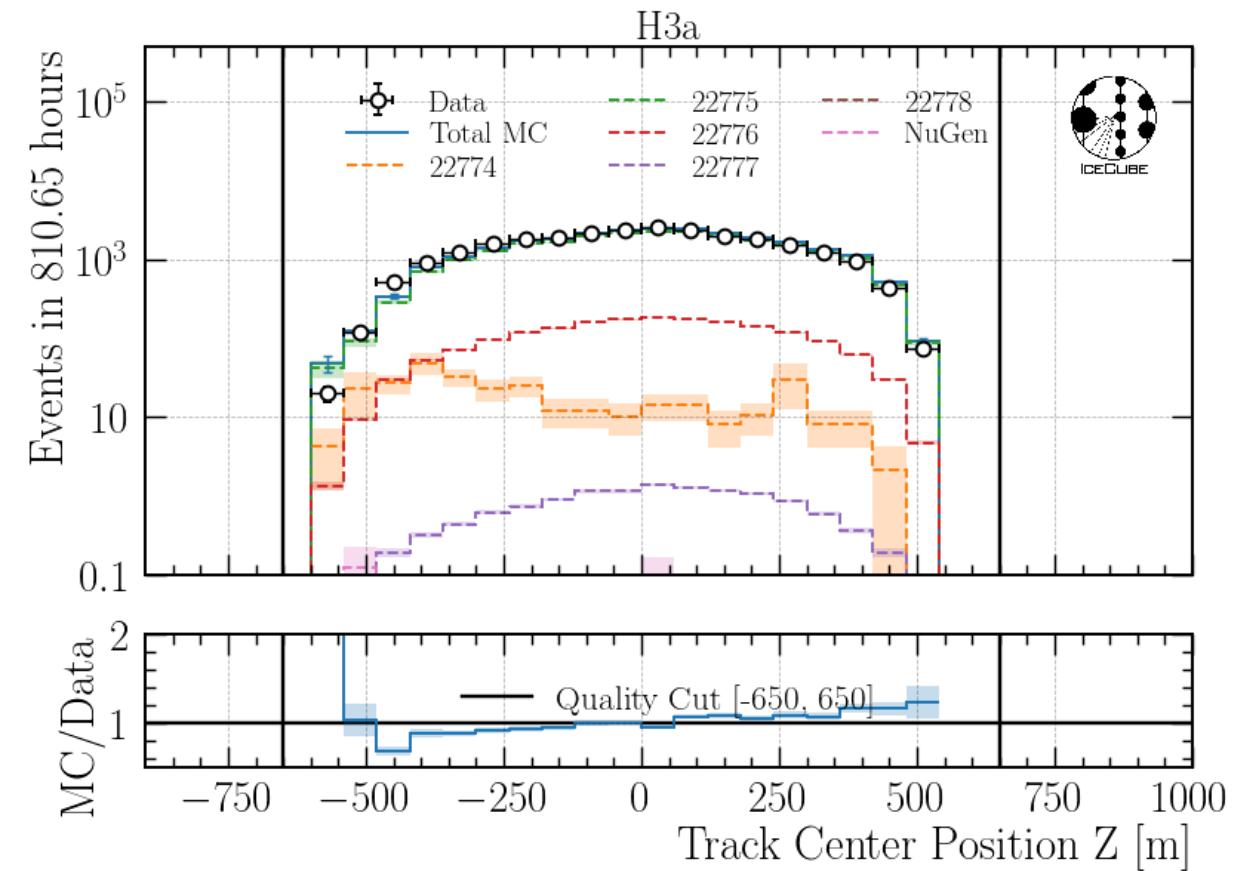


New ice model

## Z-Vertex Data-MC: Center Position

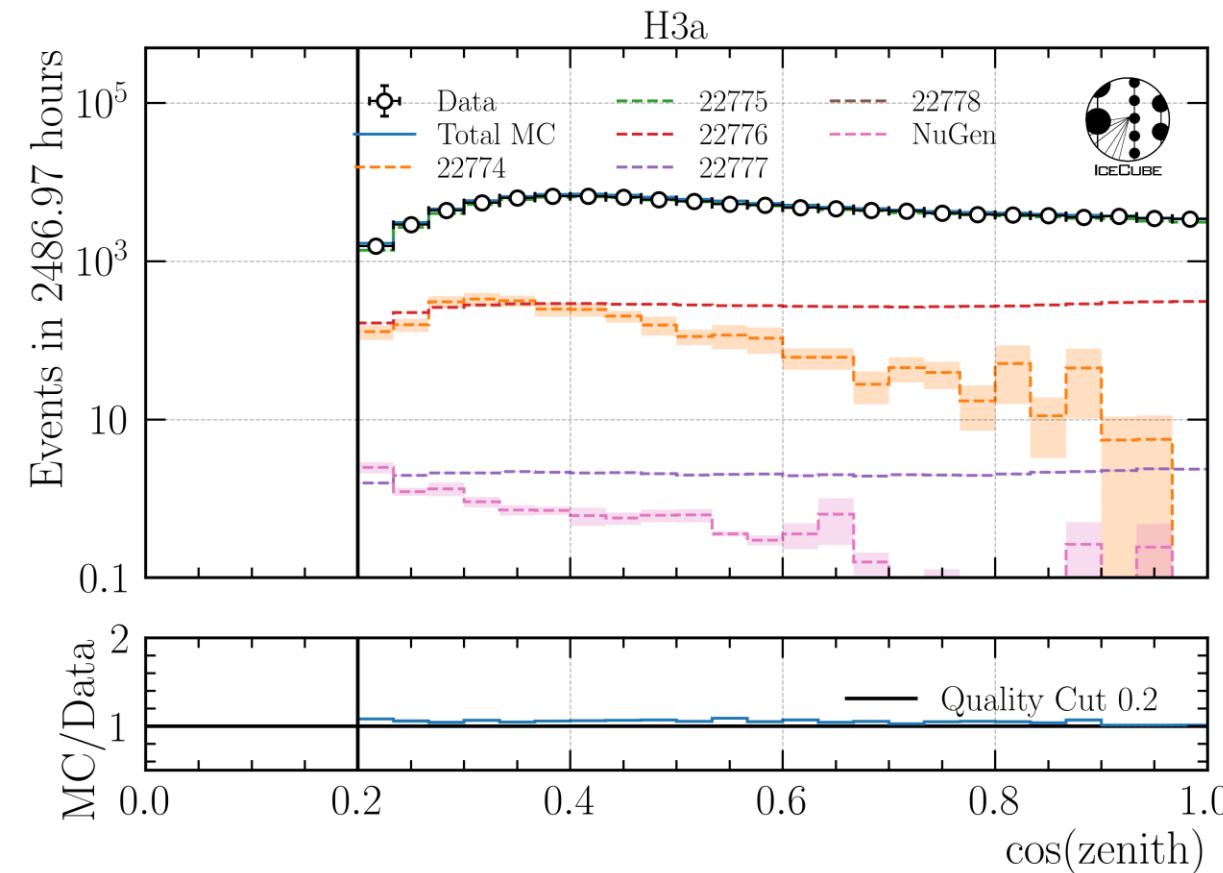


Old ice model



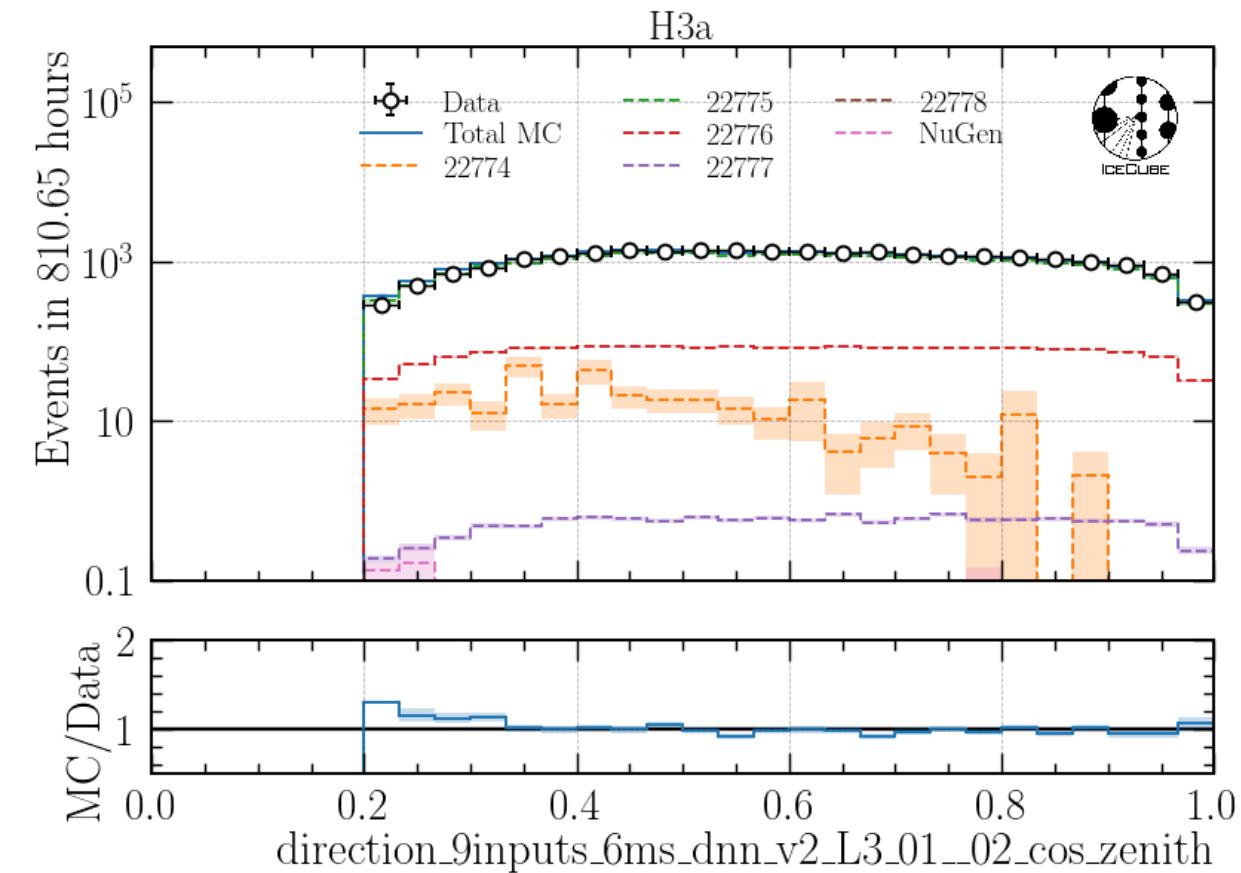
New ice model

# Cos(zenith)



Old ice model

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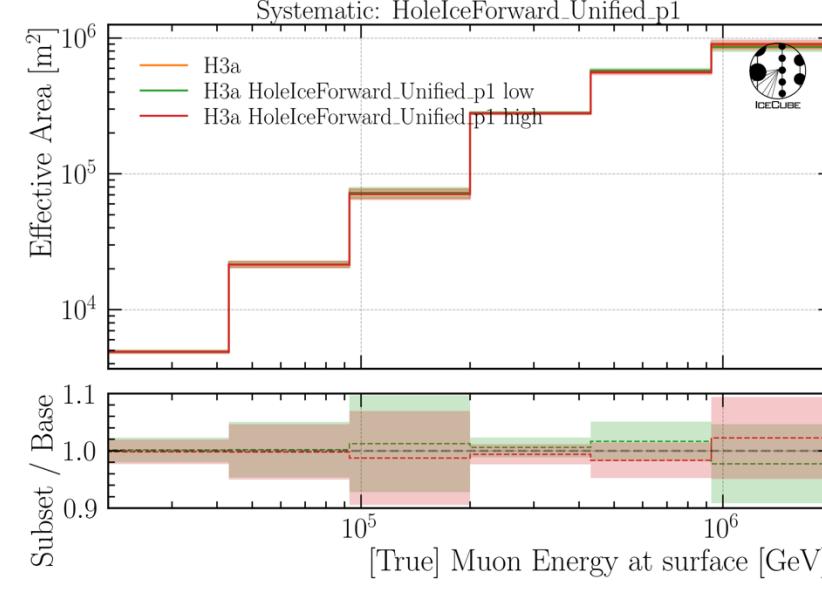
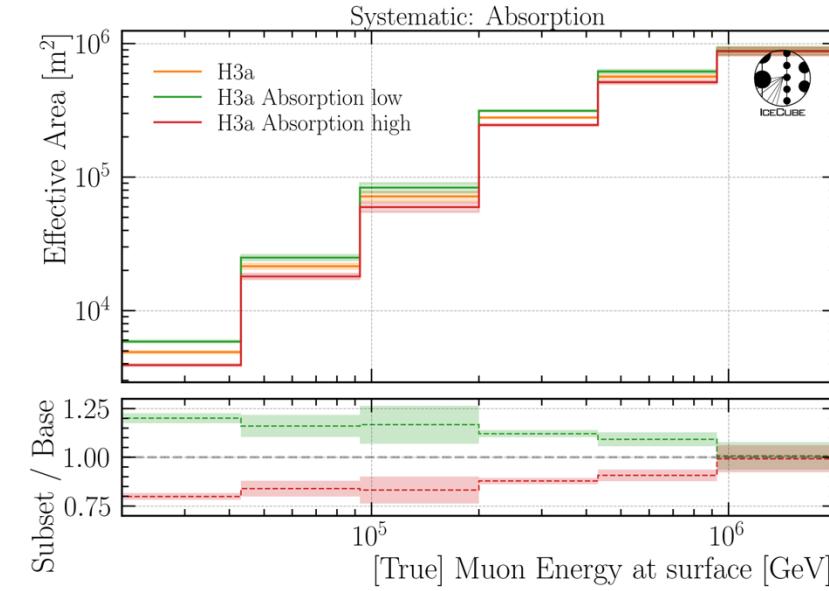
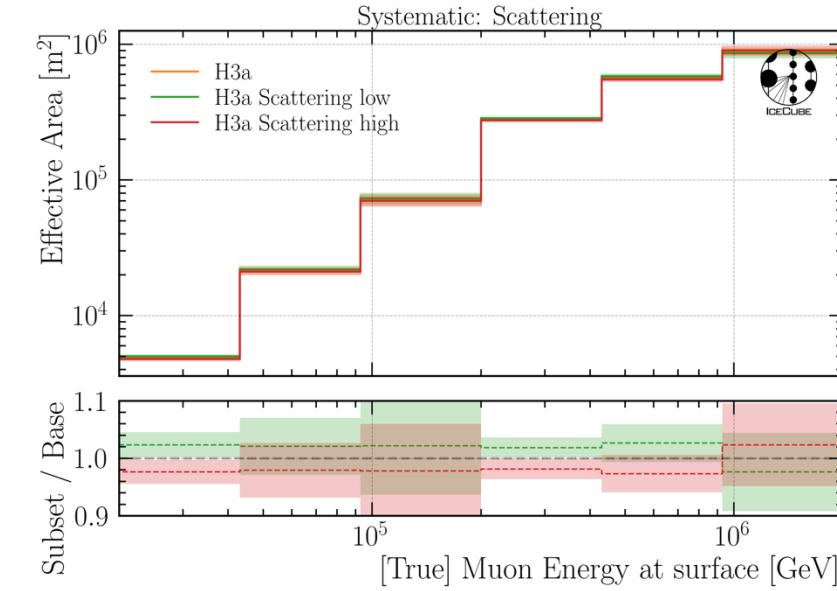
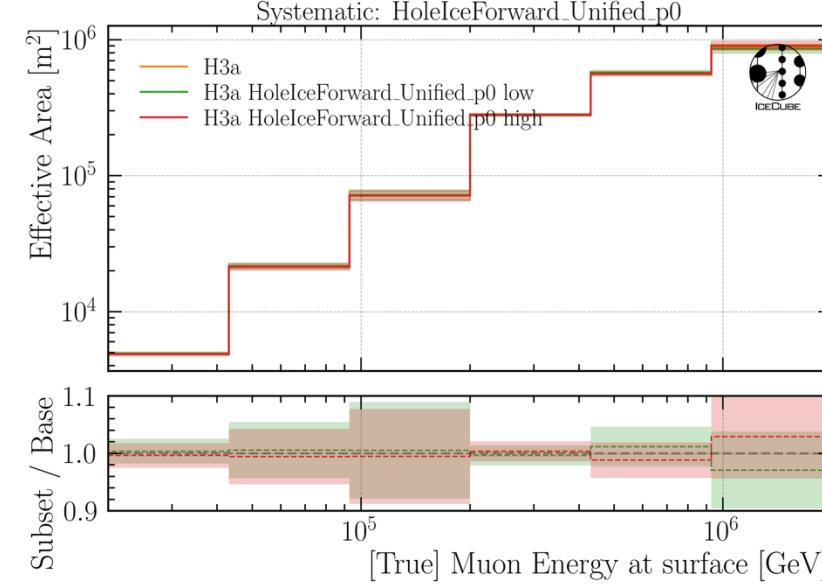
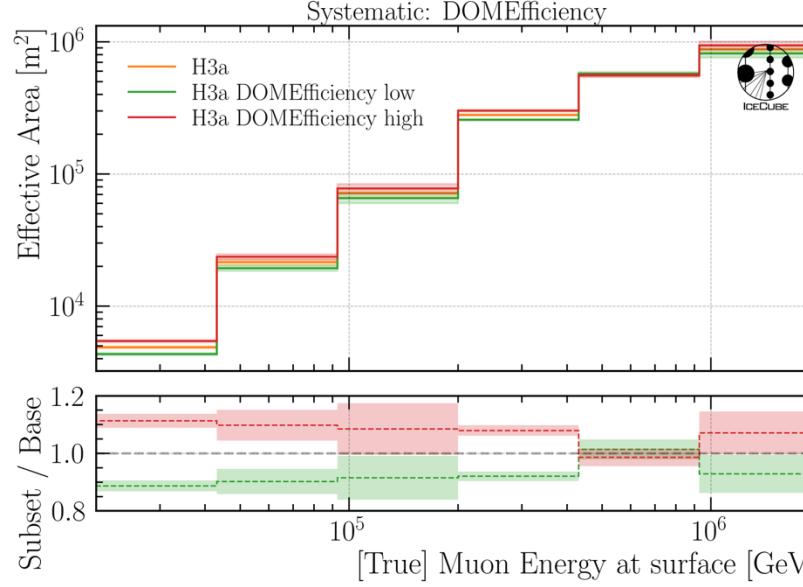
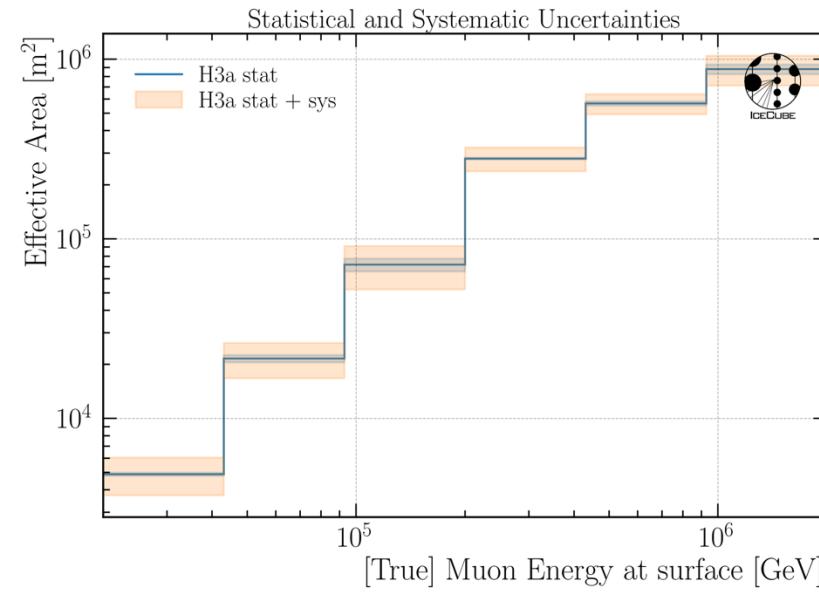
New ice model

- Artefacts observed in zenith reconstruction
- Re-train zenith reco network

# Include Systematic Uncertainties on Effective Area

## Effective Area

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



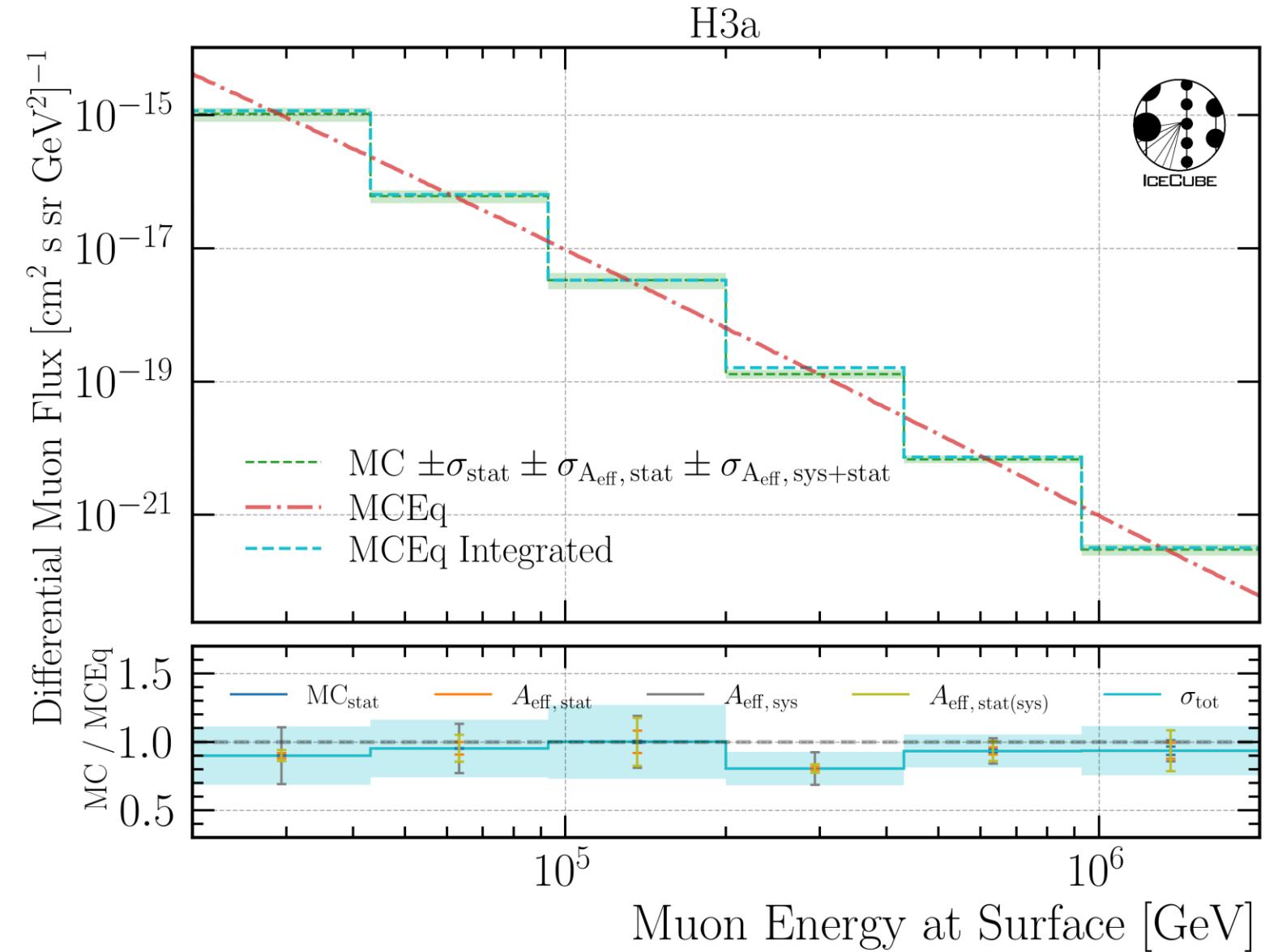
# MCEq vs CORSIKA

## Uncertainties on Flux

- CORSIKA stat.
- Eff. area stat.
- Eff. area sys.
- Eff. area stat. on sys. subset

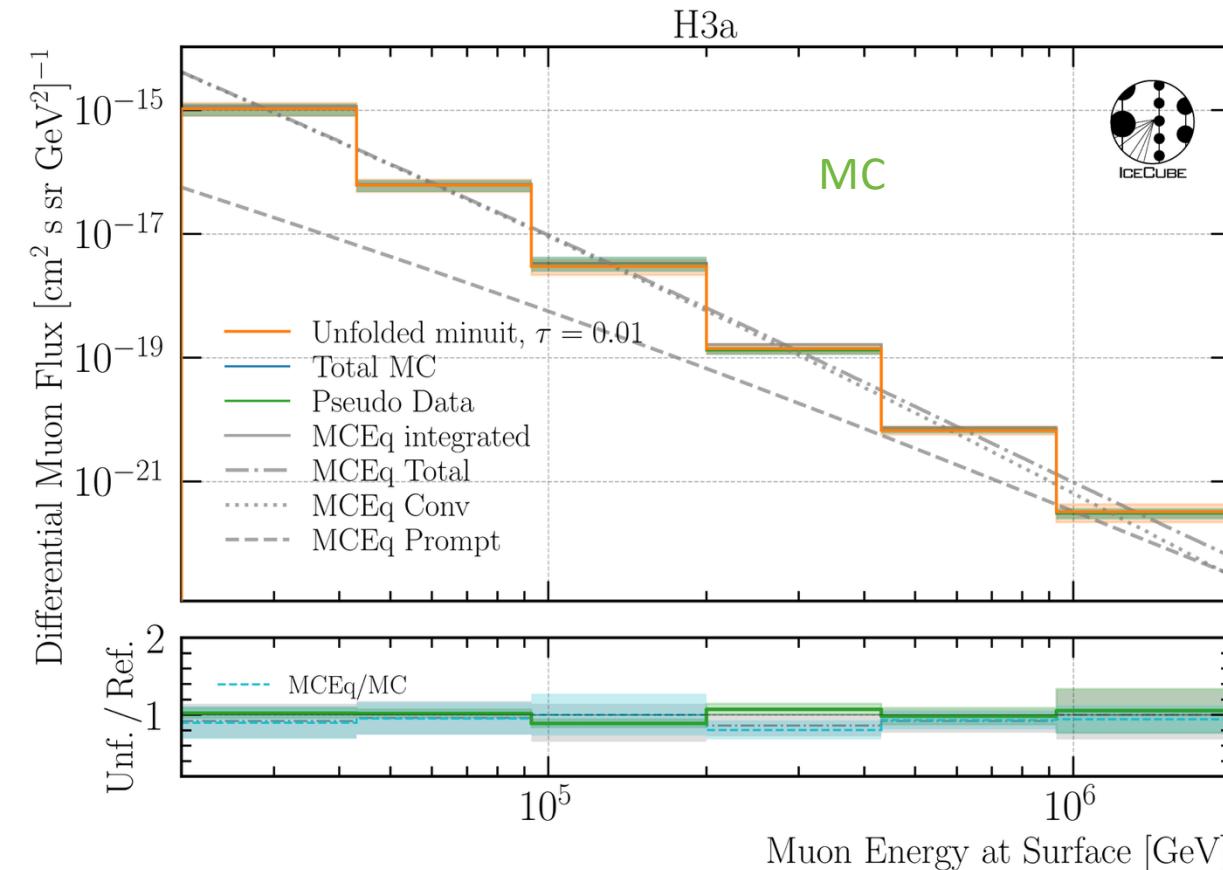
$\chi^2$ –Test (H3a):  
p–value: 0.683

➤ Good agreement between  
MCEq & CORSIKA

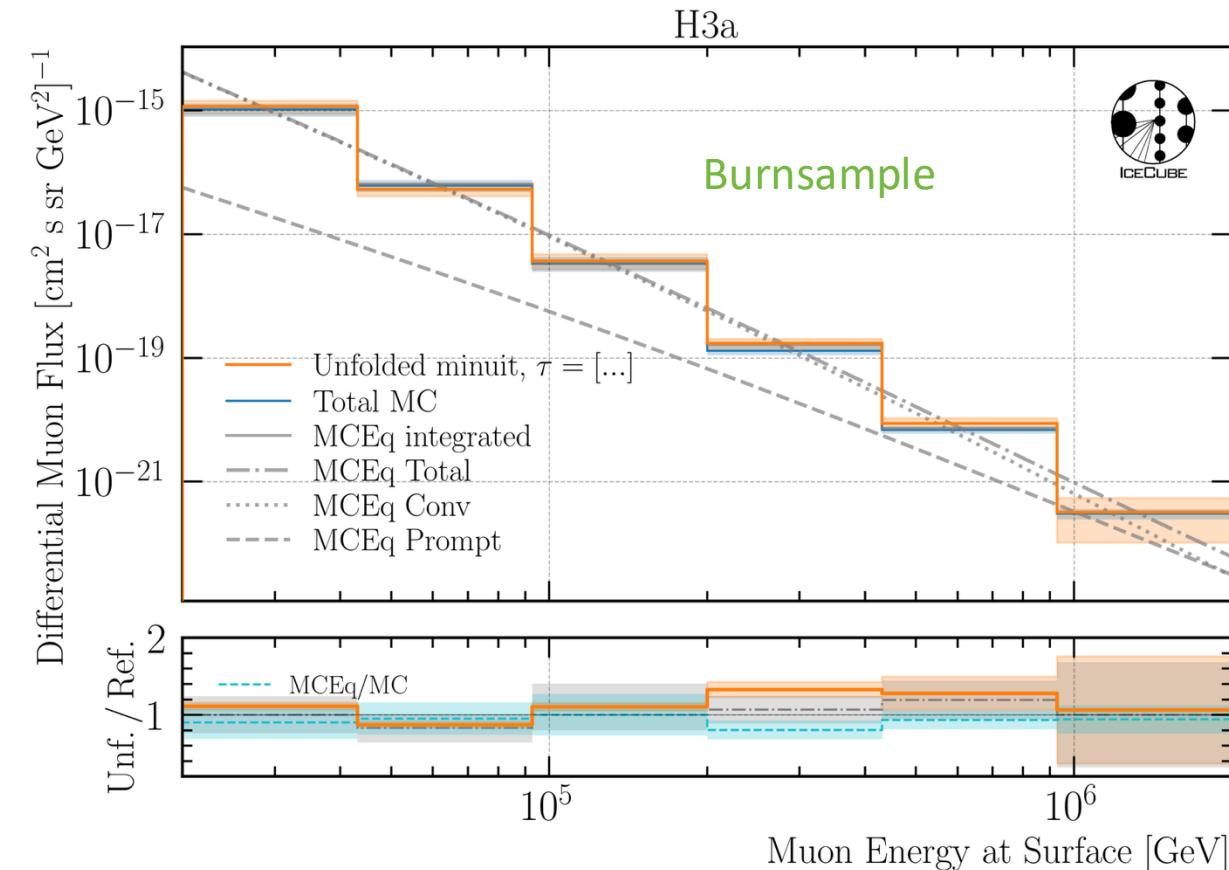


# Unfold Burnsample

# Unfold Burnsample



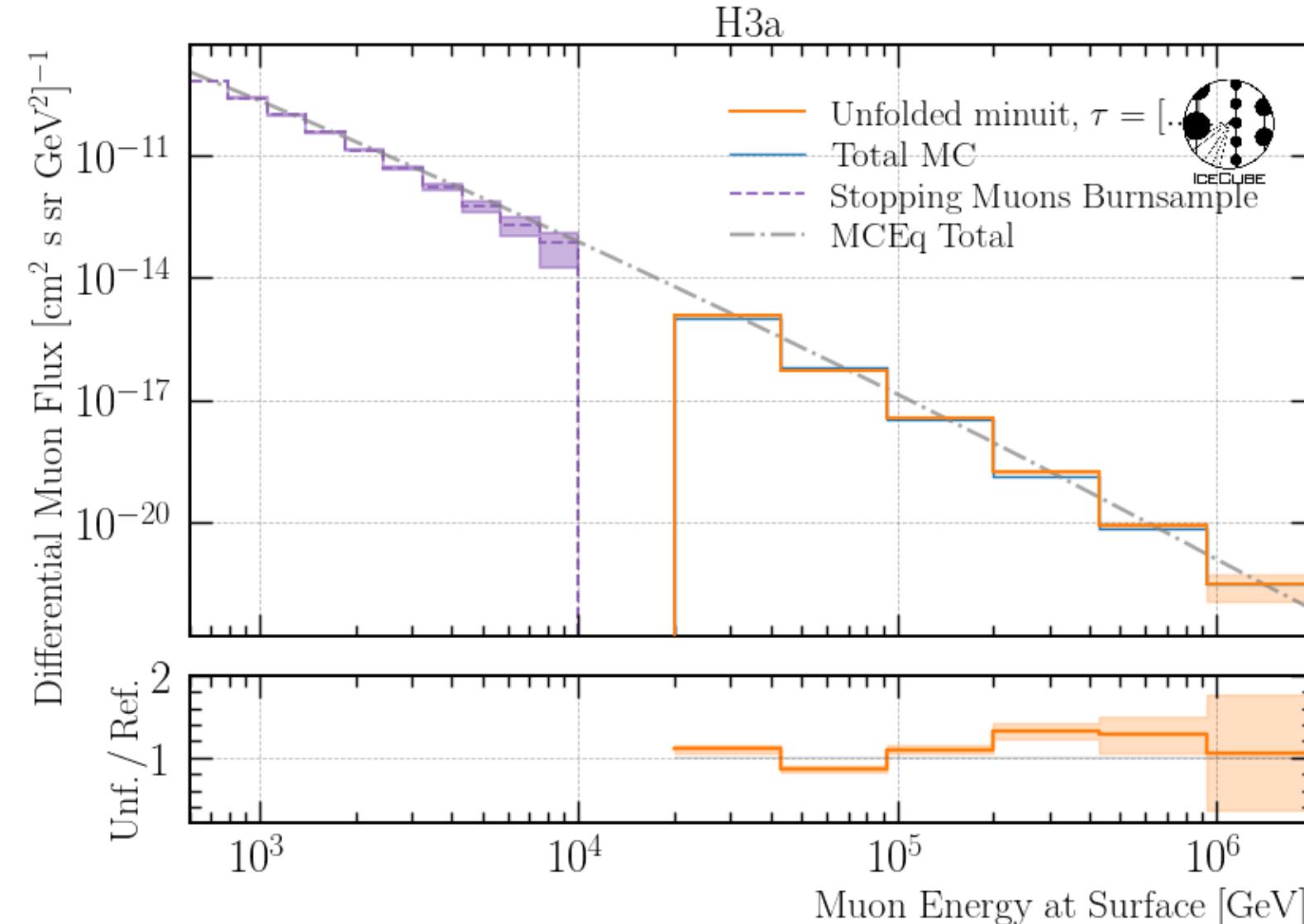
$\chi^2$ – Test (H3a) Conv only:  
p-value: 0.587



## Stopping Muons and Leading Muons

Work in progress

- Use stopping muons to unfold low energy muon spectrum
- Use leading muons to unfold high energy muon spectrum
- Atmospheric muon flux unfolding is promising

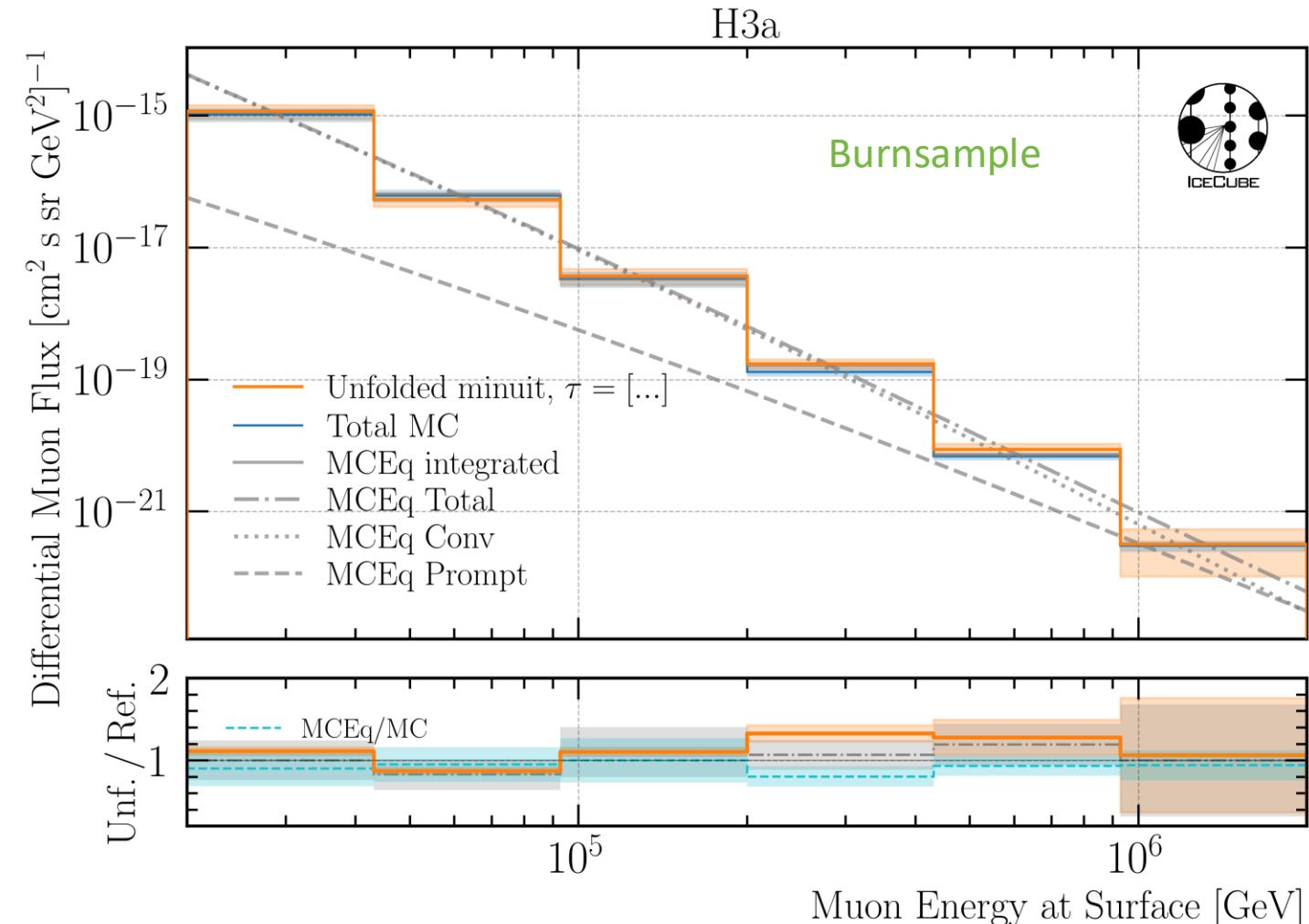


# Conclusion & Outlook

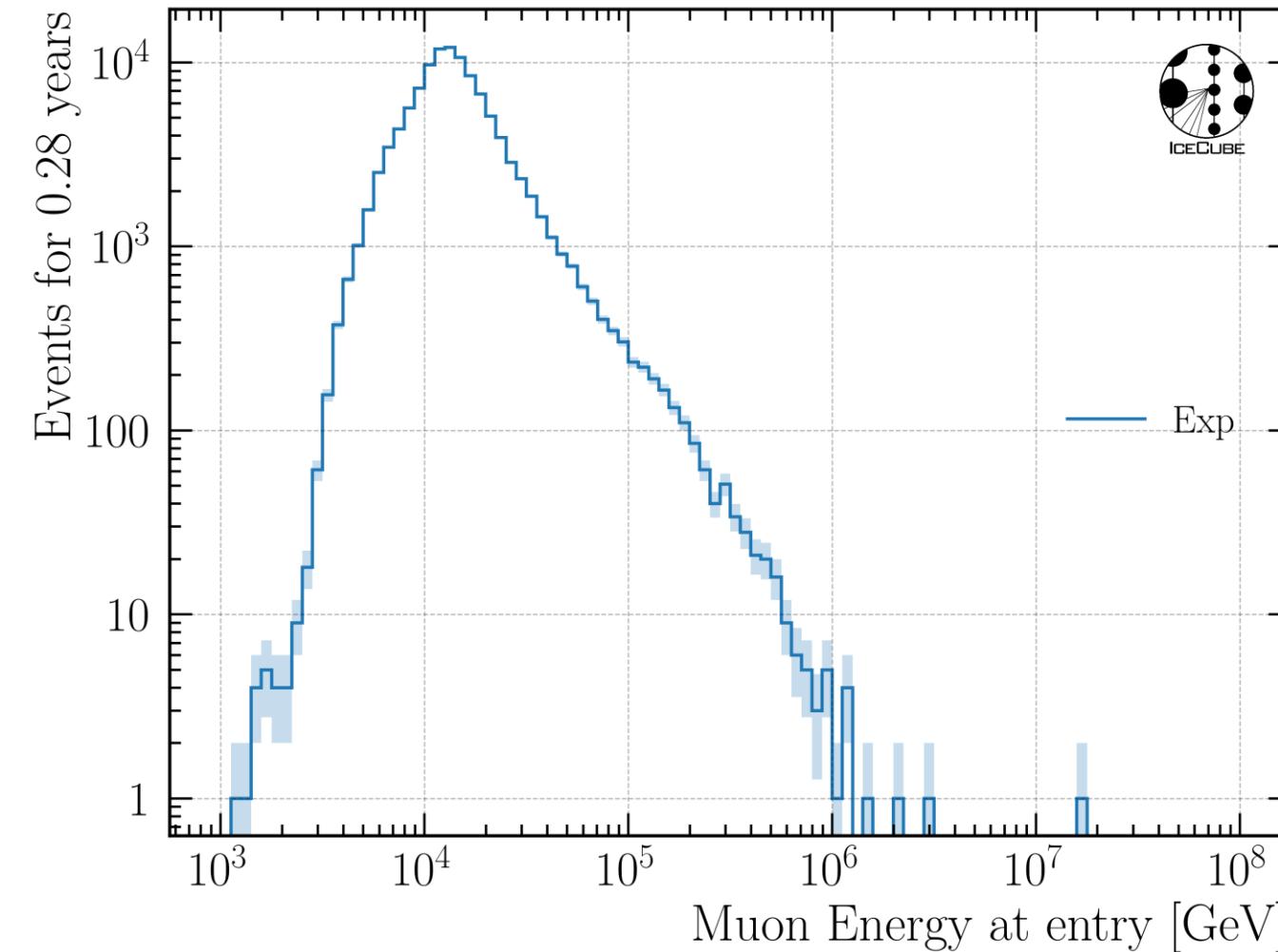
- Neutrino background investigated
  - BPL smaller impact than SPL
- Include uncertainties on effective area
  - statistics & systematics
- Agreement between MCEq & CORSIKA
- Unfolded burnsample up to 2 PeV
- Re-trained DNNs on new ice models
  - z—vertex Data-MC improved

## Outlook

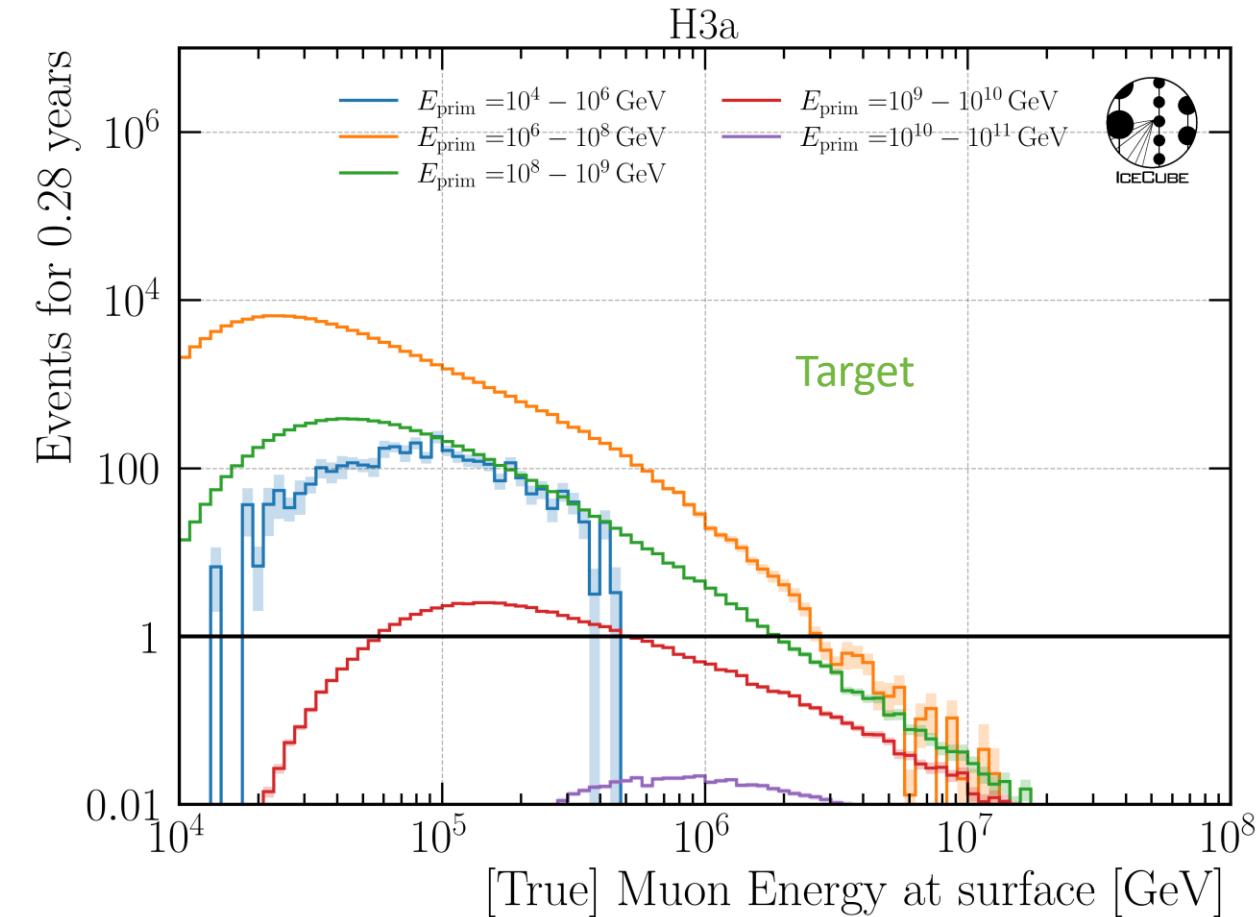
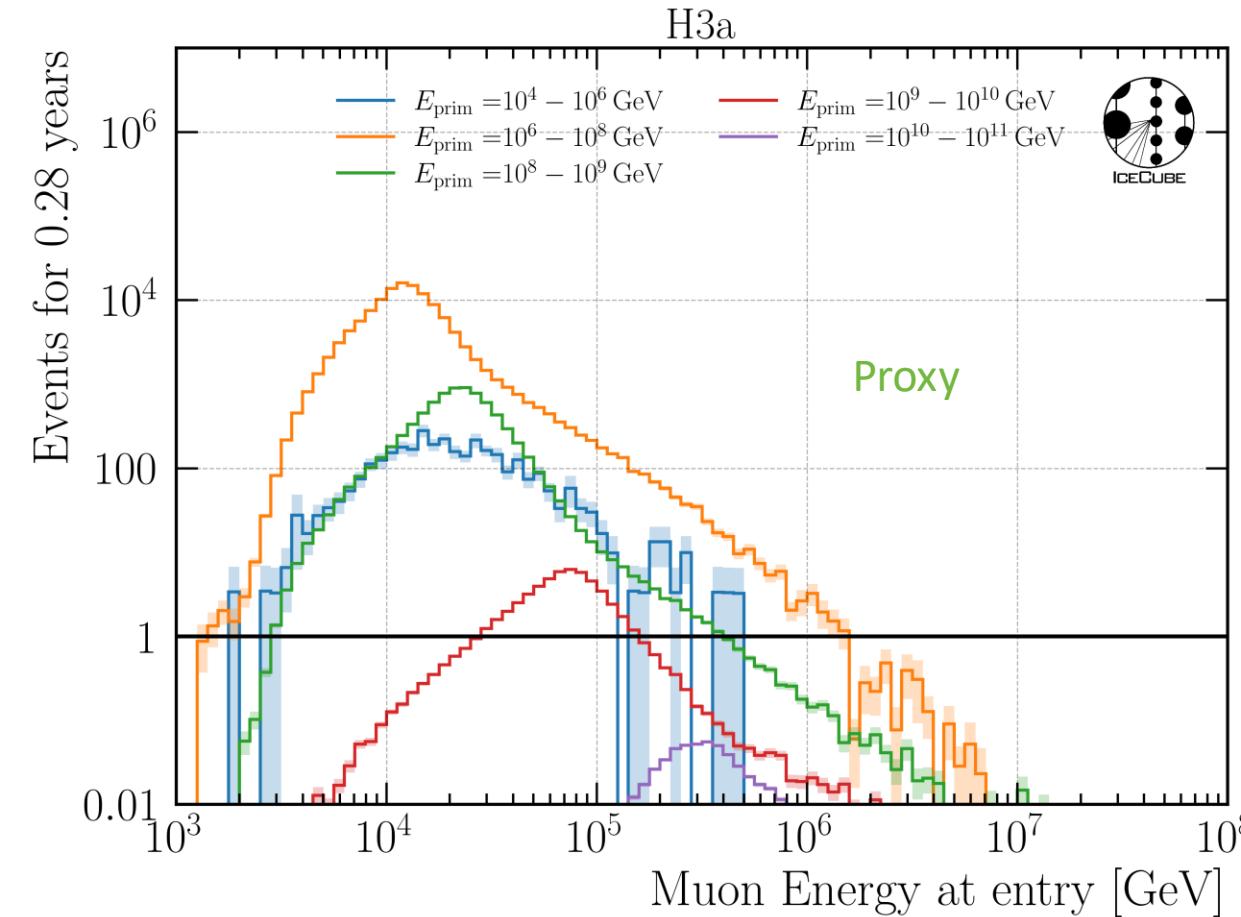
- Unfold for different neutrino background assumptions
- Evaluate new reconstructions in detail
- Unfold on selection with new networks
- Unfold on 12.12 years of data



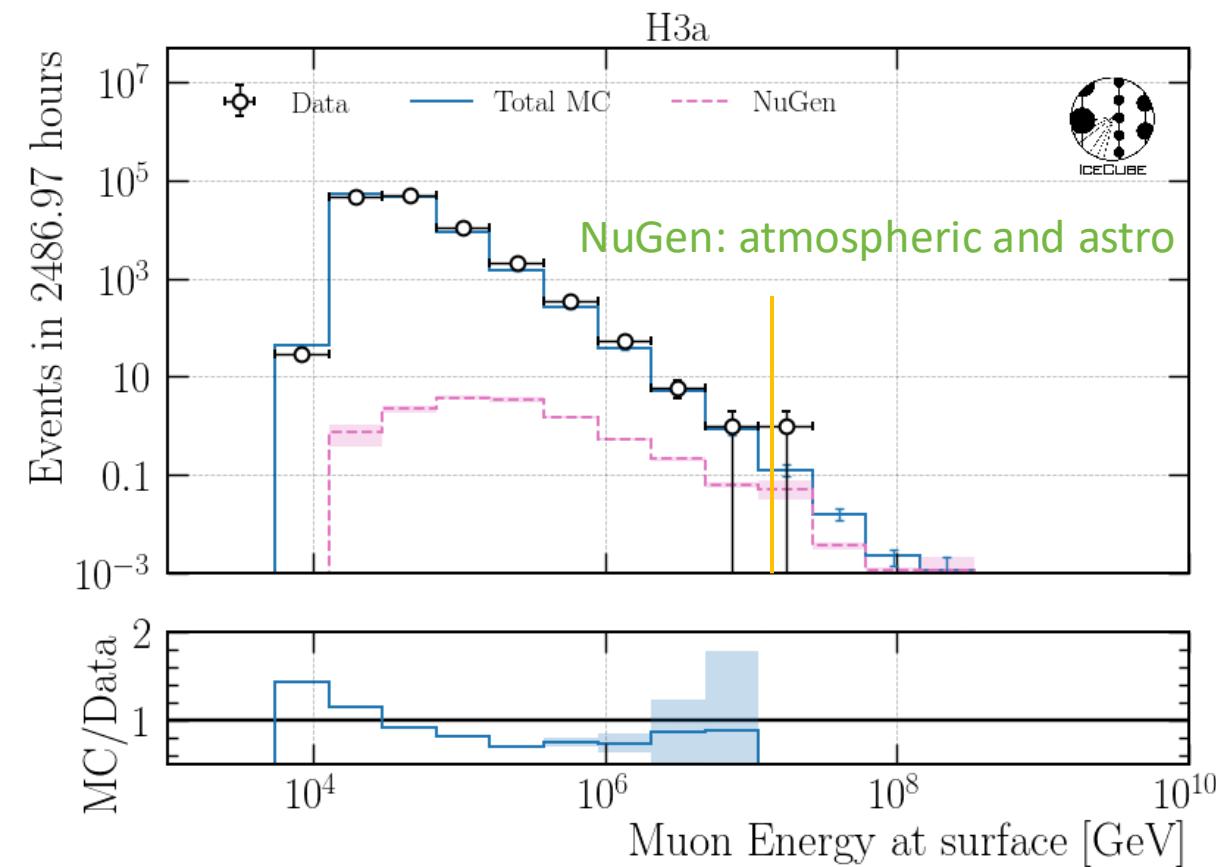
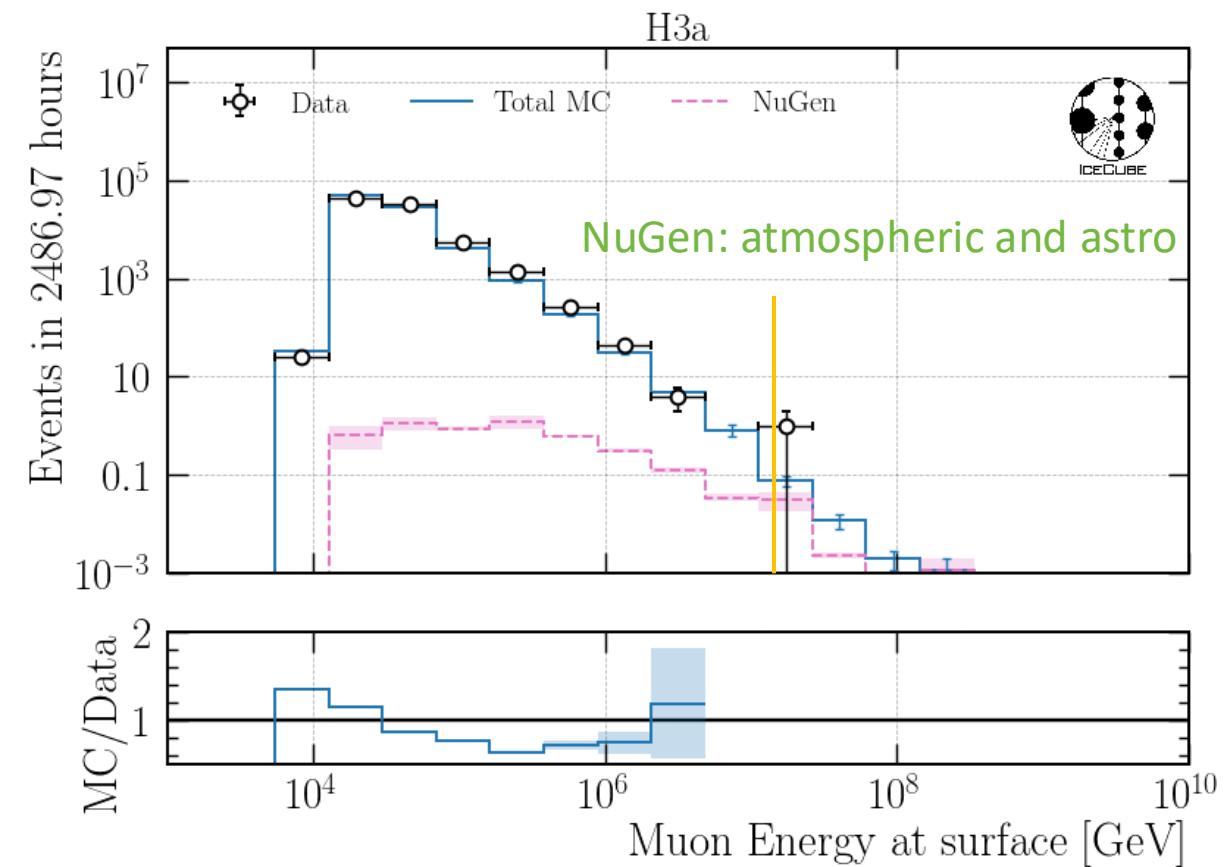
# Burnsample Proxy



## Statistics



## Remove Horizontal Events – Muon Energy at Surface

 $n = 1.5, \gamma = 2.6$  $\cos(\theta) > 0.2$  $\cos(\theta) > 0.4$ 

➤ Stronger zenith cut has no significant impact

# Unblinding Roadmap

- Unblind unfolding of the atmospheric muon flux for ICRC → unblinding request deadline May 1st
  - CRWG review → today
  - Technical review → next 2 weeks
  - Collaboration review → until May 1st
  - ICRC proceedings with unfolded muon flux
- Run forward fit as post-unblinding check → unblind in summer
  - About 1-2 months needed
  - Method is fundamentally different from unfolding → blindness not violated
- Journal paper proposal: includes both the unfolded muon flux and the normalization fit
  - finish first draft in Autumn

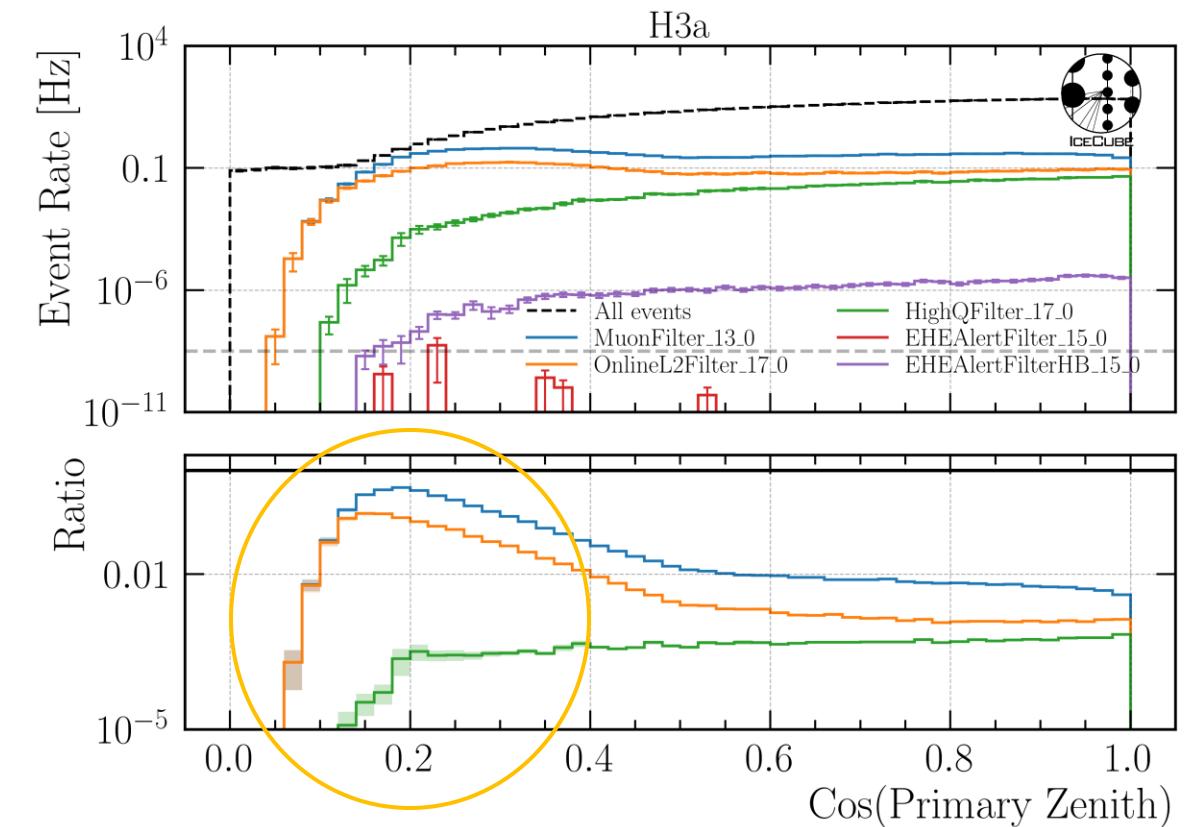
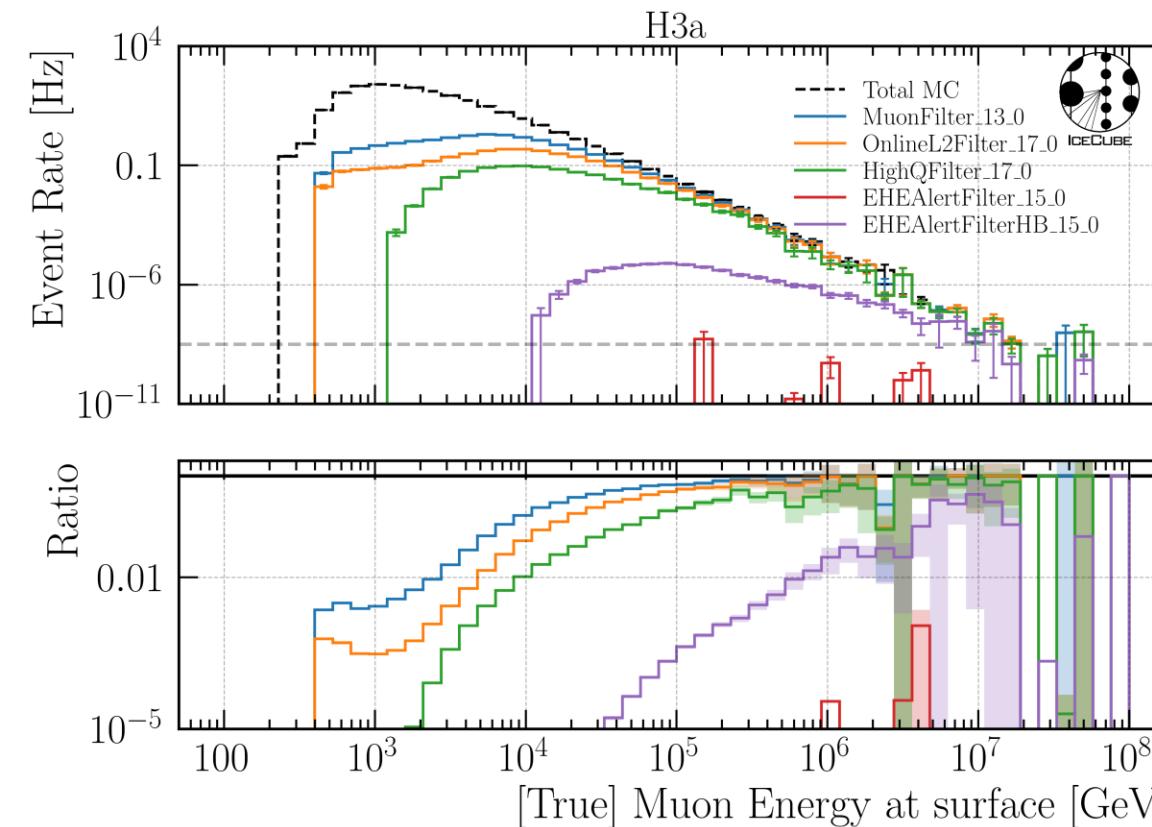
PhD deadline: July

Leander Flottau is working on forward fit  
I'll stay in academia → finish analysis

# CRWG Review

Main questions are addressed here,  
the rest is explained in the [Q&A](#)

# Q: Why do you choose the muon filter?



- HighQFilter: removes more horizontal events → muons travel large distances, not enough energy left to pass high-charge filter
- Goal: keep AMAP high-energy events at surface → muon filter

# Q: Which quantities do you reconstruct and how do you do this?

## Energy

- Bundle energy at entry / surface
- Leading muon energy at entry / surface

## Direction

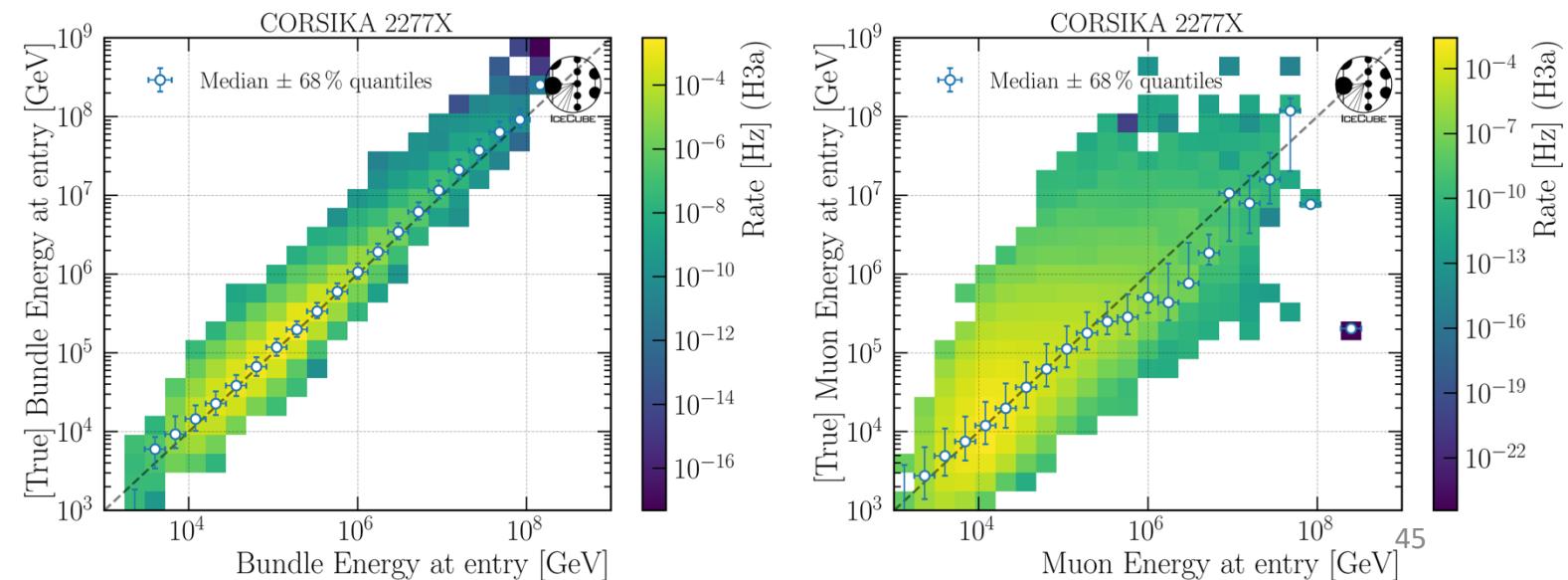
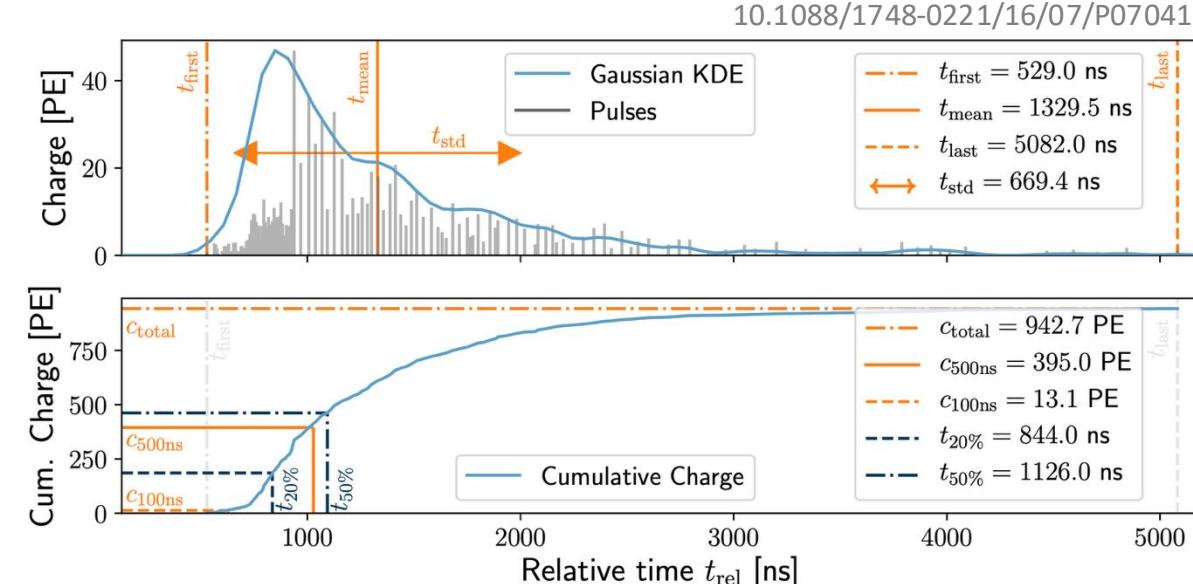
- Zenith / azimuth of leading muon

## Geometry

- Propagation length
- Entry point

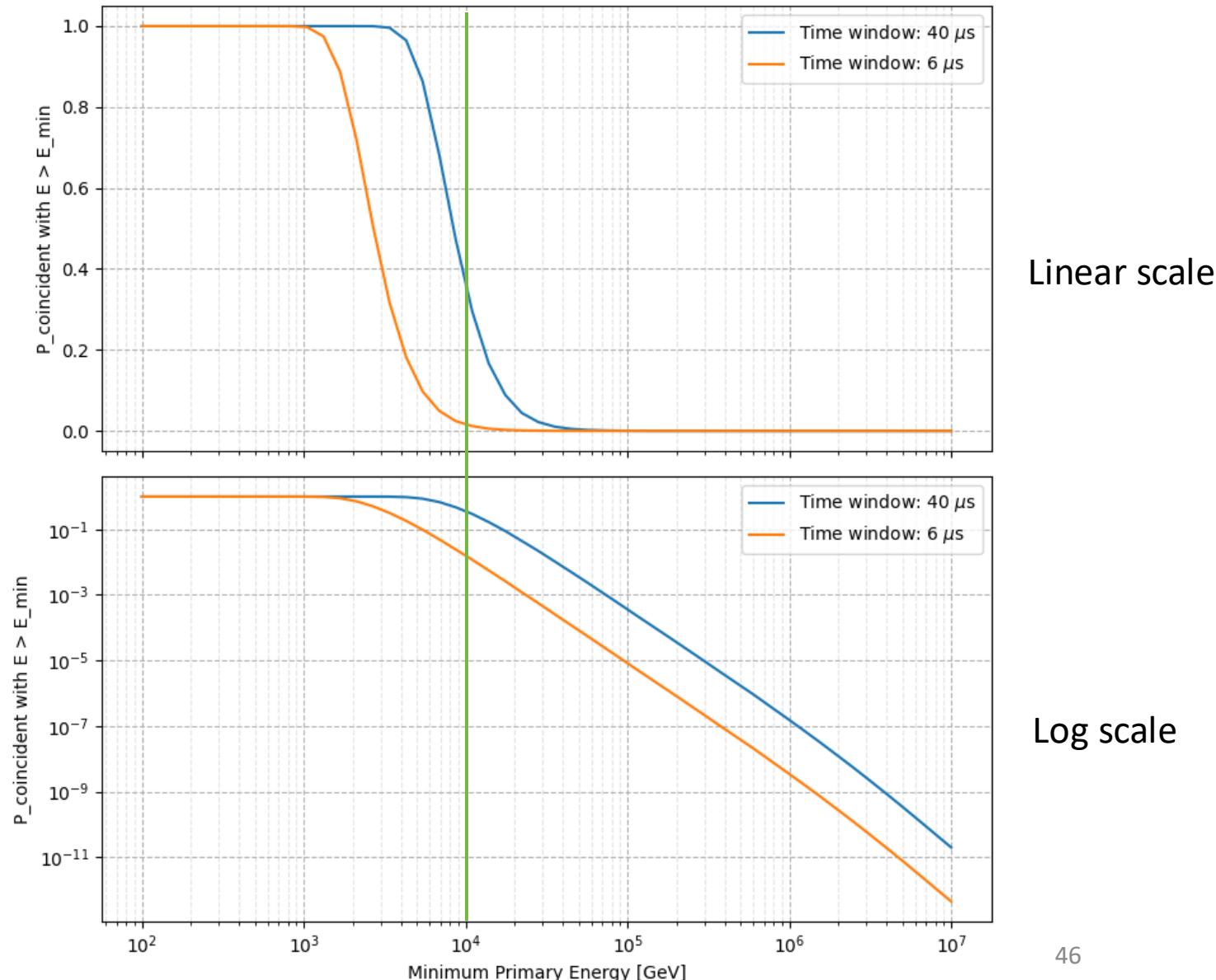
- **dnn\_reco framework**  
(Mirco Hünnefeld)
- Low-level features based on charge and timer per DOM

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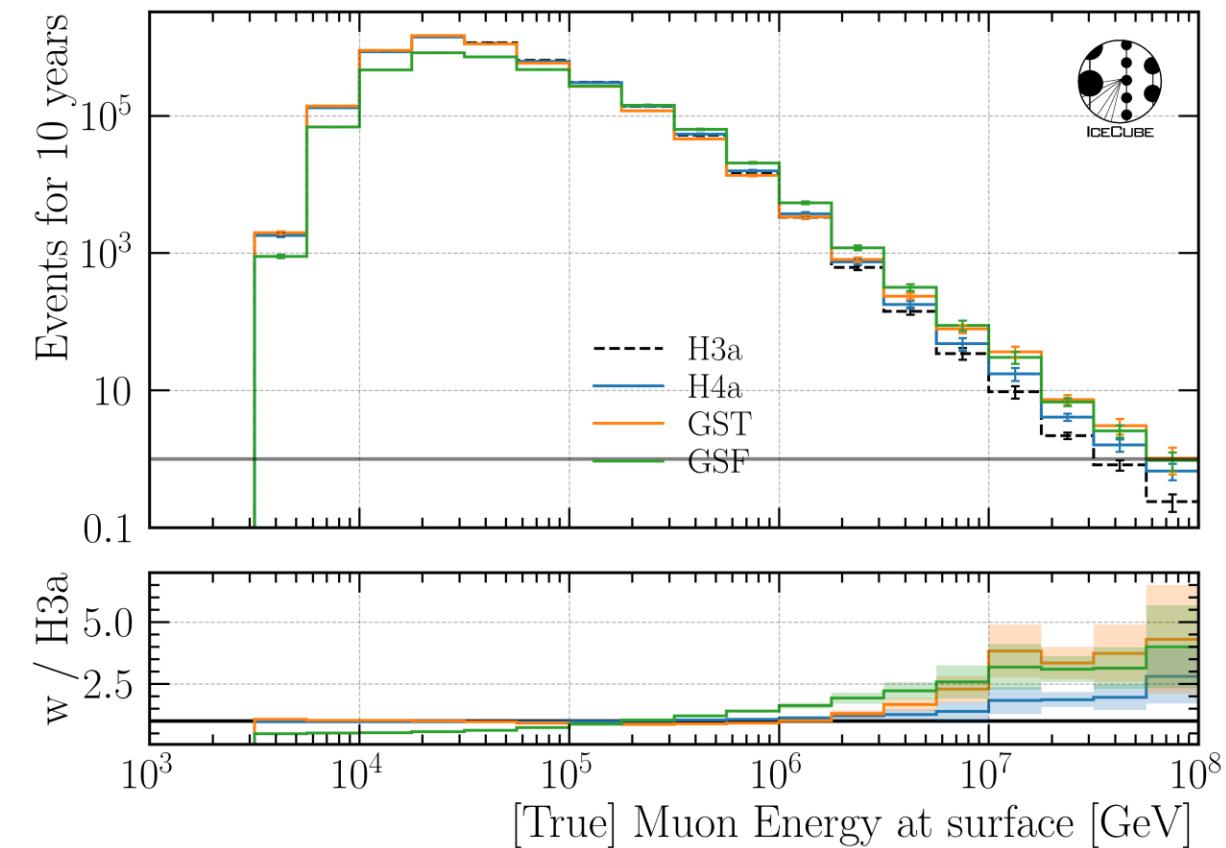
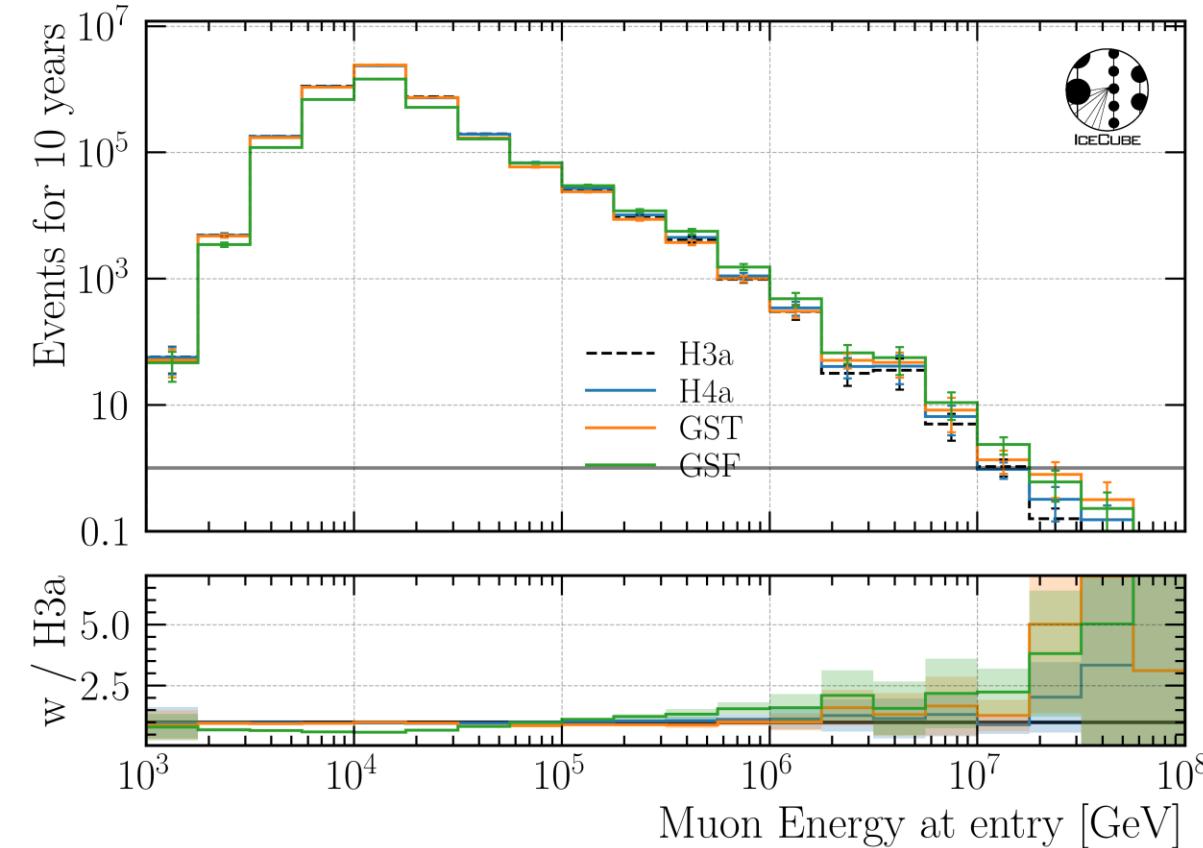


Q: Coincident events are not simulated. Can you show that this does not cause any problems?

- For primary energies above 10 TeV, using a time window of 6  $\mu$ s, the chance for a coincident event is  $\leq 1\%$
- Apply time-window cleaning of 6  $\mu$ s to pulses

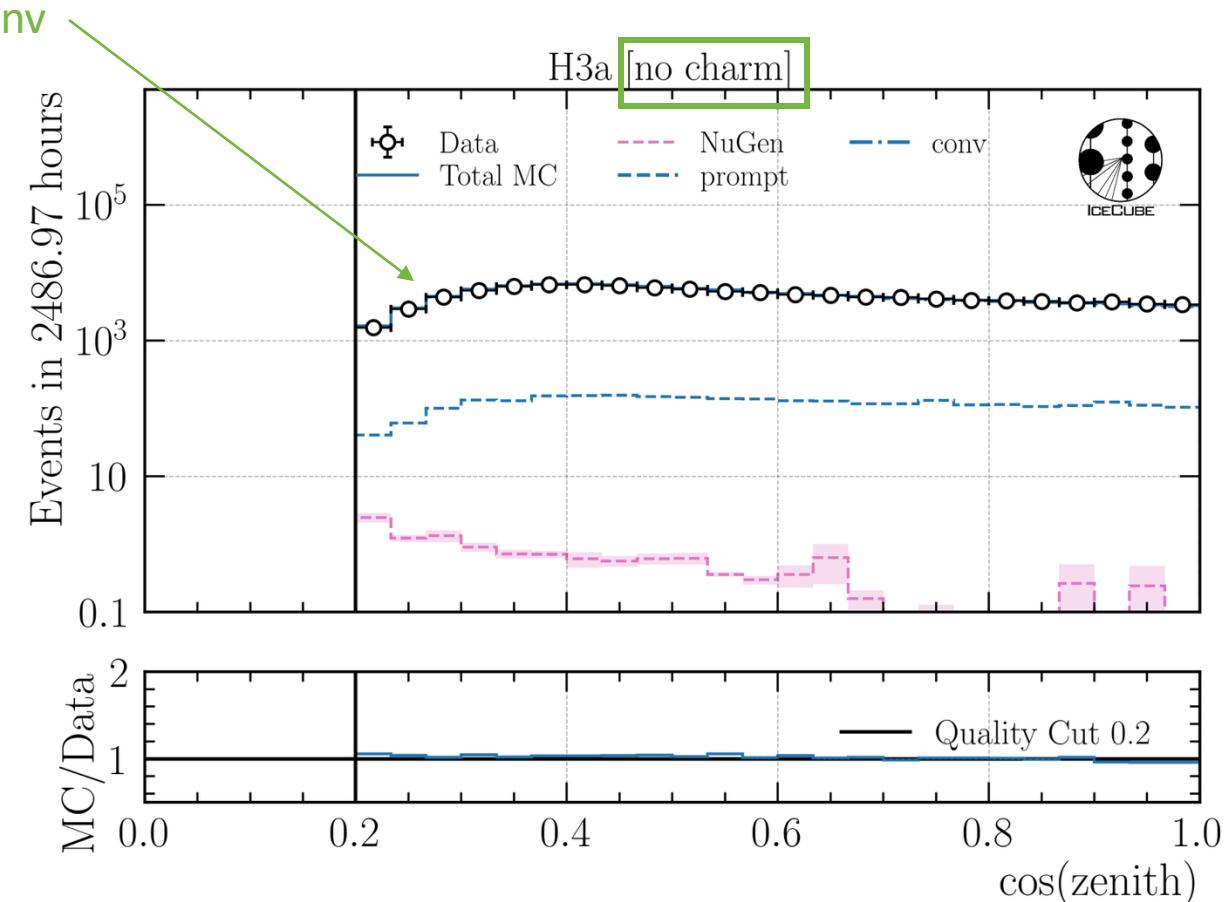
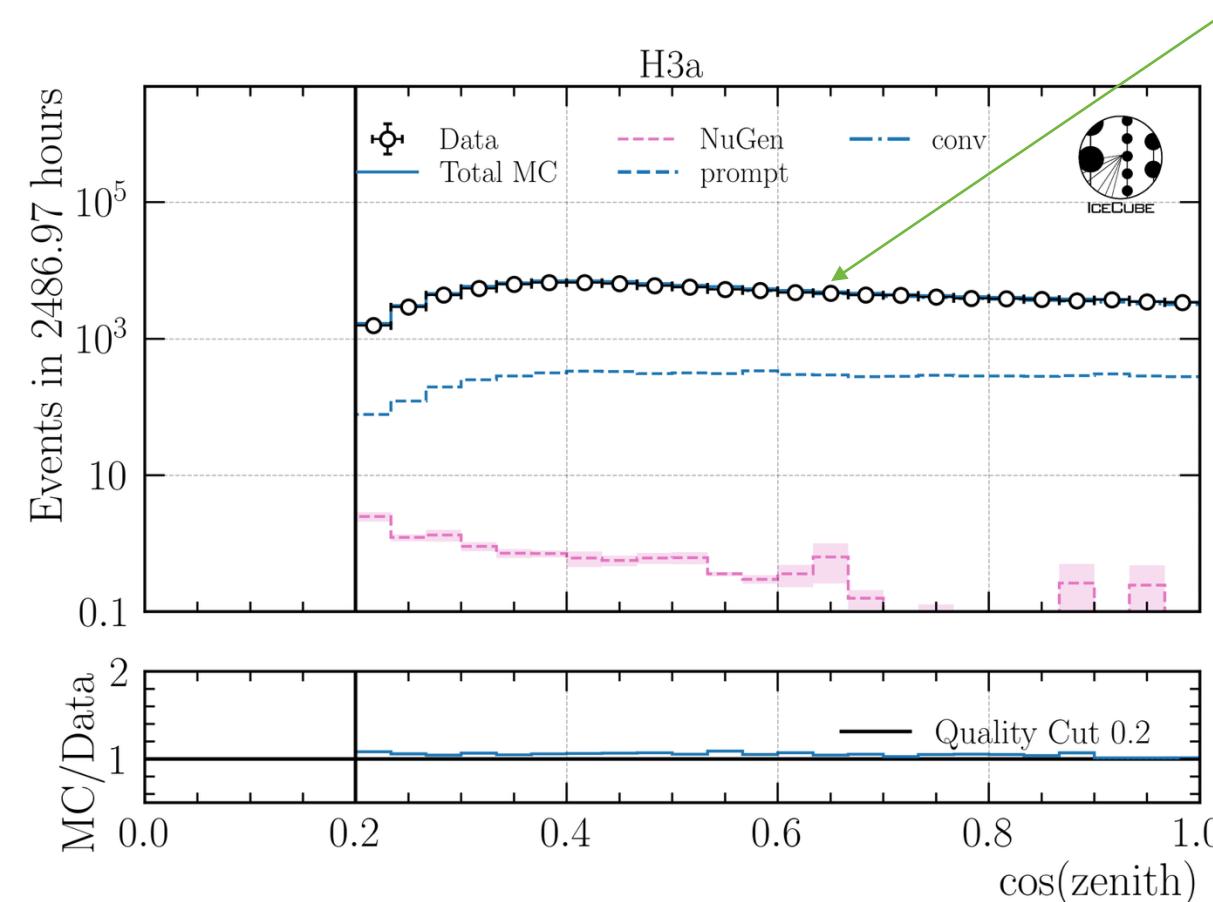


Q: What is the impact of the primary flux on your (most important) distributions?



➤ Primary models diverge towards higher energies

Q: Can you show a zenith distribution with prompt and conv?



- Conv dominates entire distribution by 1-2 orders of magnitude
- Charm has no impact

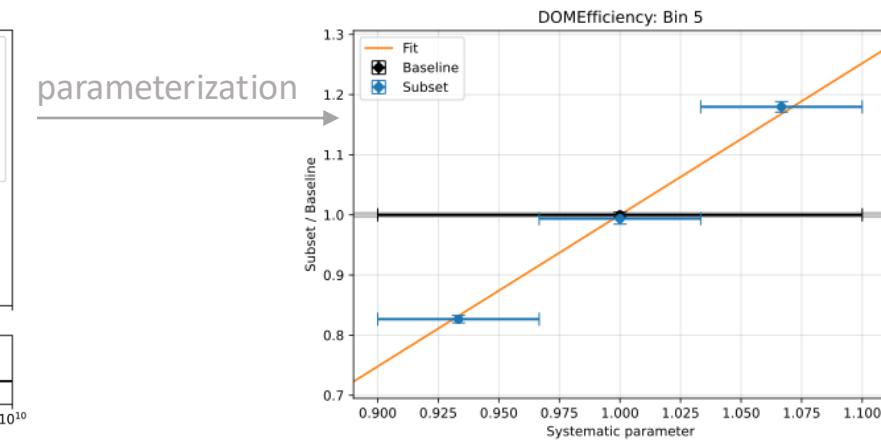
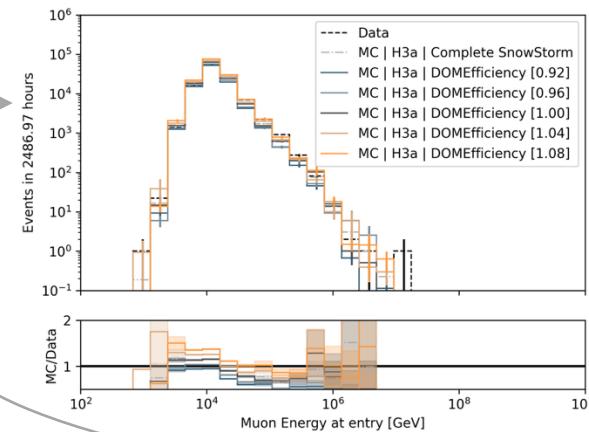
## Q: How do you treat systematics? → here for unfolding

### Ice systematics – Snowstorm

- Vary ice properties
- Relative change of bin content

$$\mathbf{g} = \mathbf{A} \cdot \mathbf{f} \quad \mathbf{A} \rightarrow \mathbf{A}(\vec{\xi})$$

➤ Fit as nuisance parameter



### Cosmic ray primary flux models

- Build matrix for different primary models and show that the result is independent of the input model

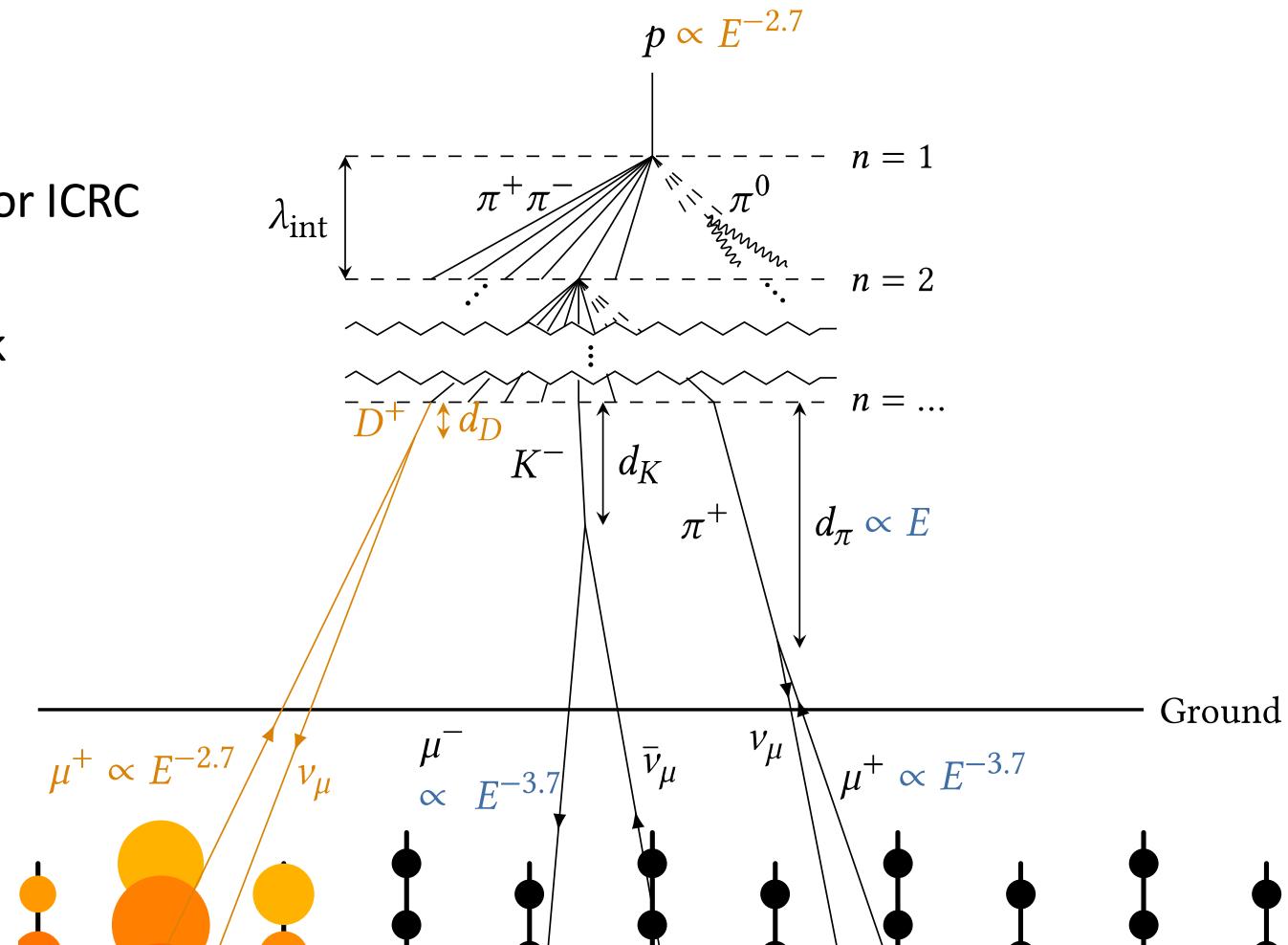
### Hadronic interaction models

- CORSIKA simulations are extensive, we rely on SIBYLL 2.3d (similar to the primary flux, the impact should be negligible)

# Conclusion & Outlook

- Move forward with unblinding the unfolding for ICRC
  - May 1st
- Run normalization fit as post-unblinding check

- Answered CRWG questions
- Finish technical review
- Ask for a collaboration reviewer



Thank you for listening. Do you have more questions?

# Unfolding

# Unfolding in a nutshell

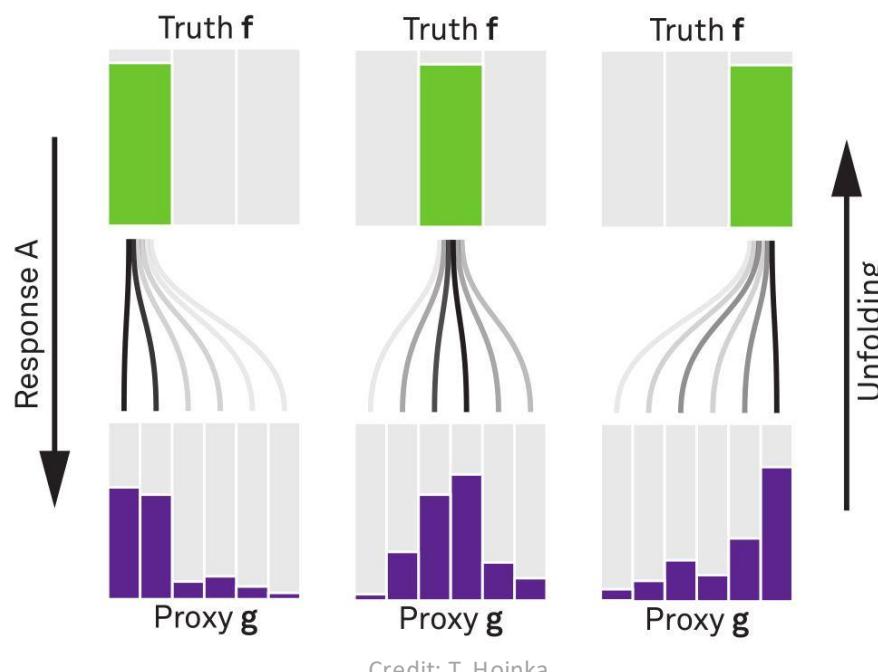
measured proxy

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

detector response

background

true energy distribution



pascal.gutjahr@tu-dortmund.de

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

2. maximum likelihood method:

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

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

3. Tikhonov regularization:

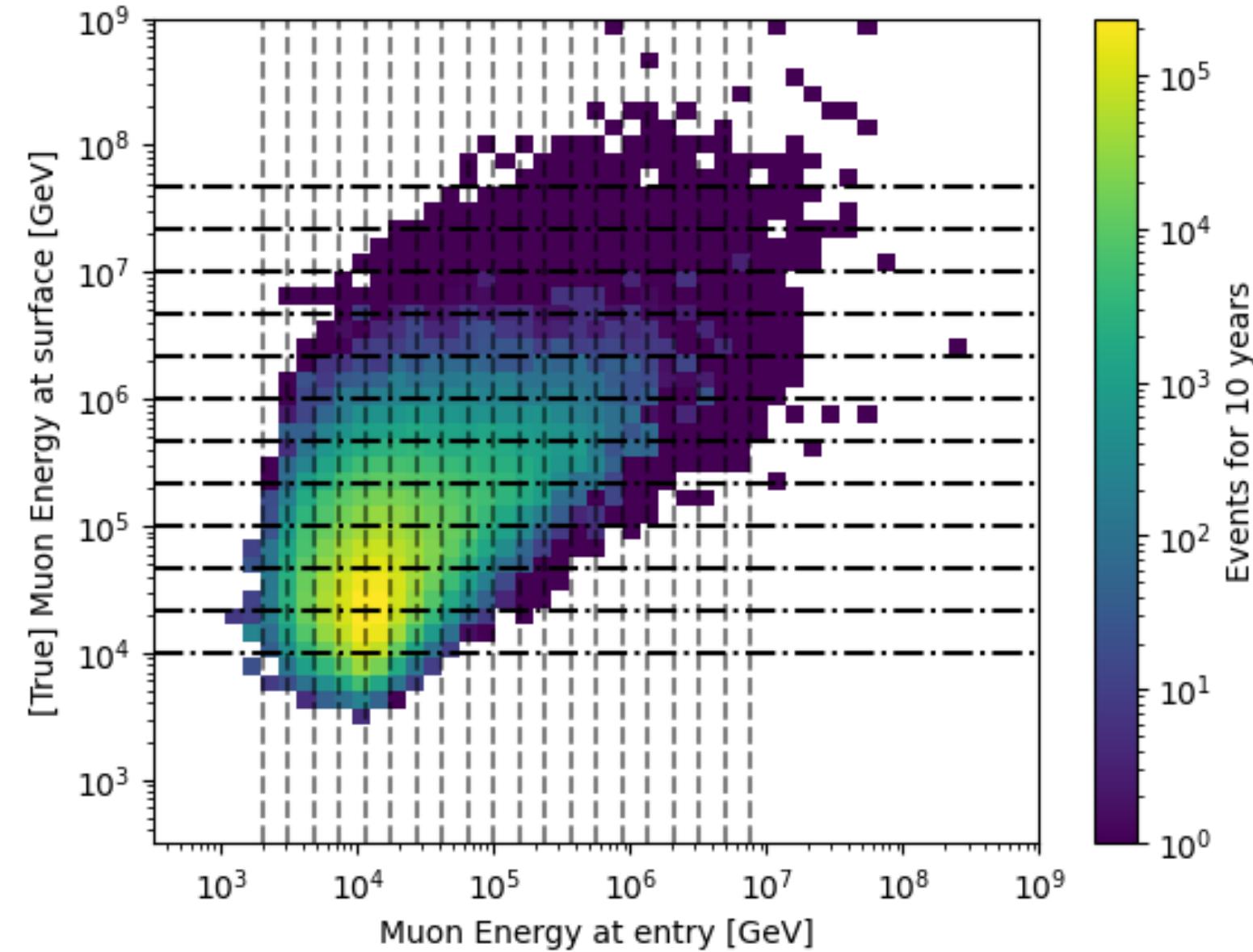
$$t(\vec{f}) = -\frac{1}{2} (\vec{C}\vec{f})^T (\tau I)^{-1} (\vec{C}\vec{f})$$

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



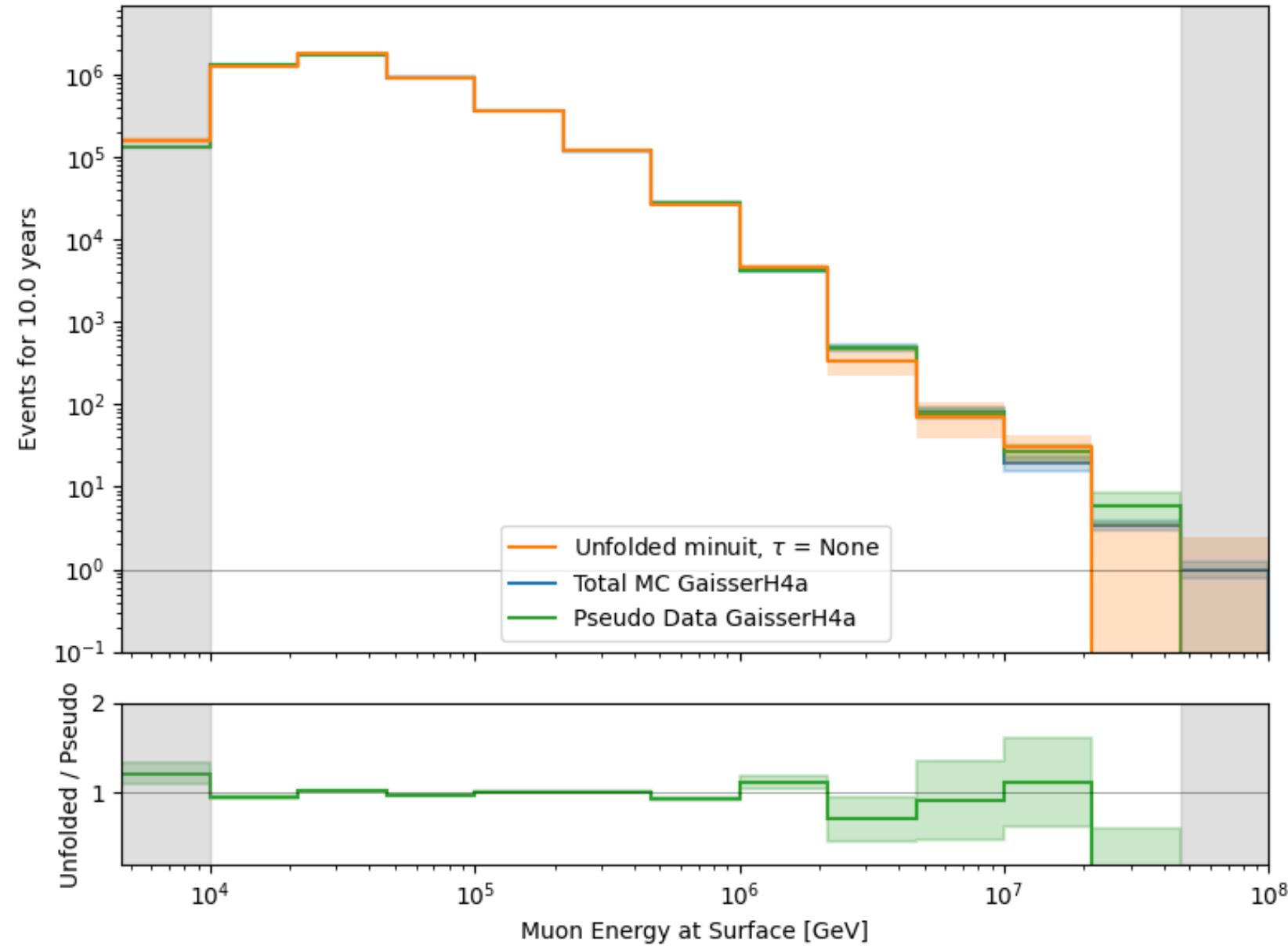
funfolding  
by M. Börner

## Proxy vs Target



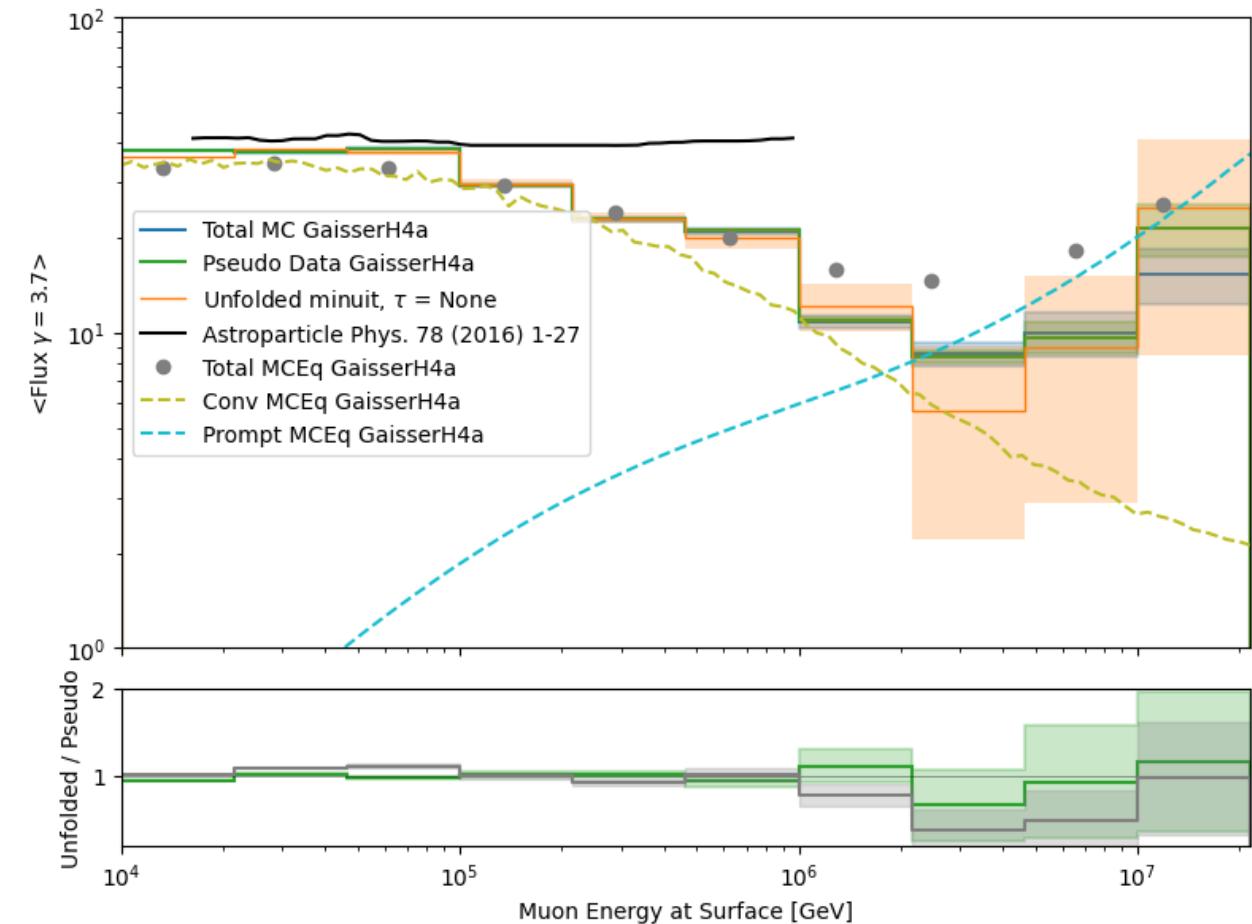
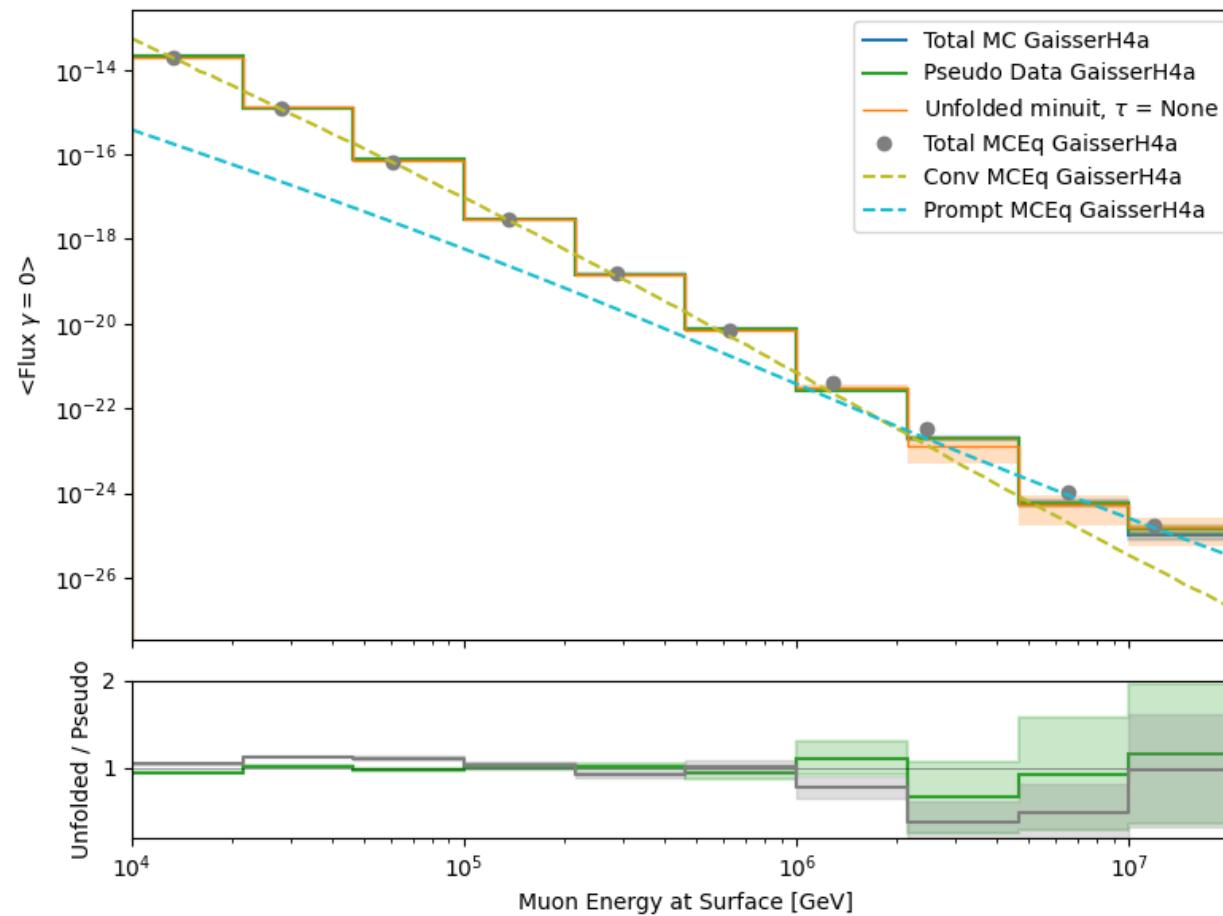
# Unfold Event Rate

## Event Rate



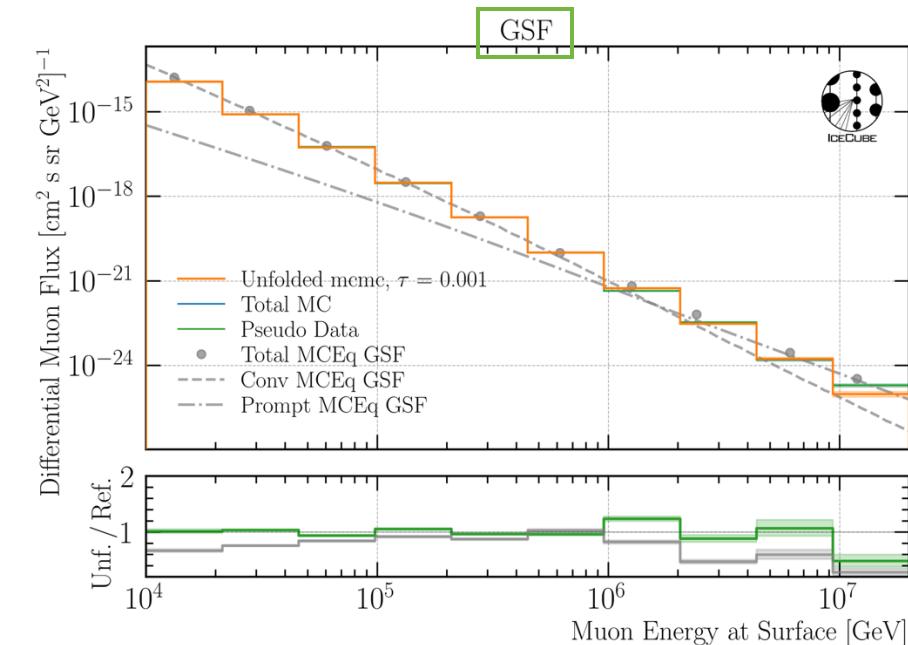
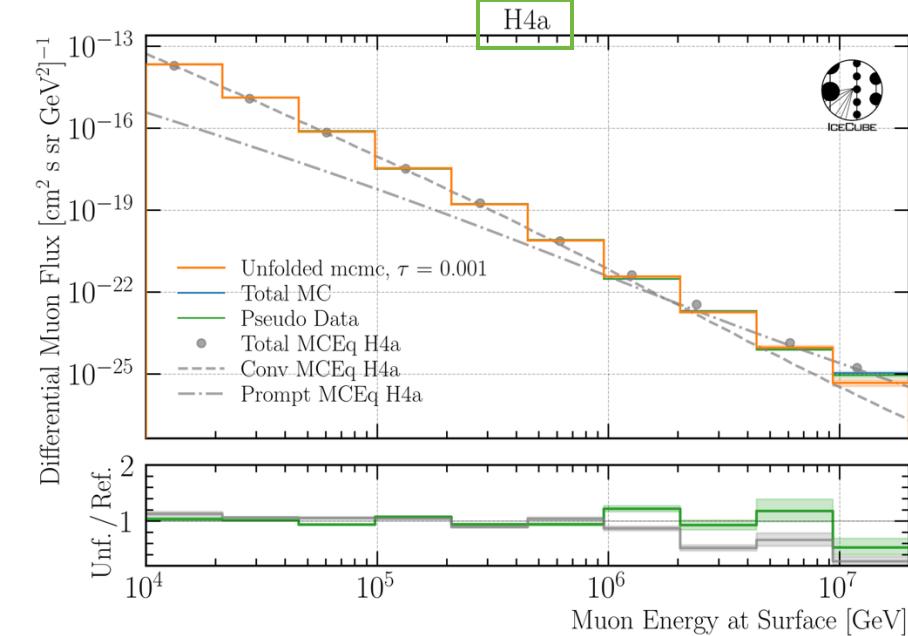
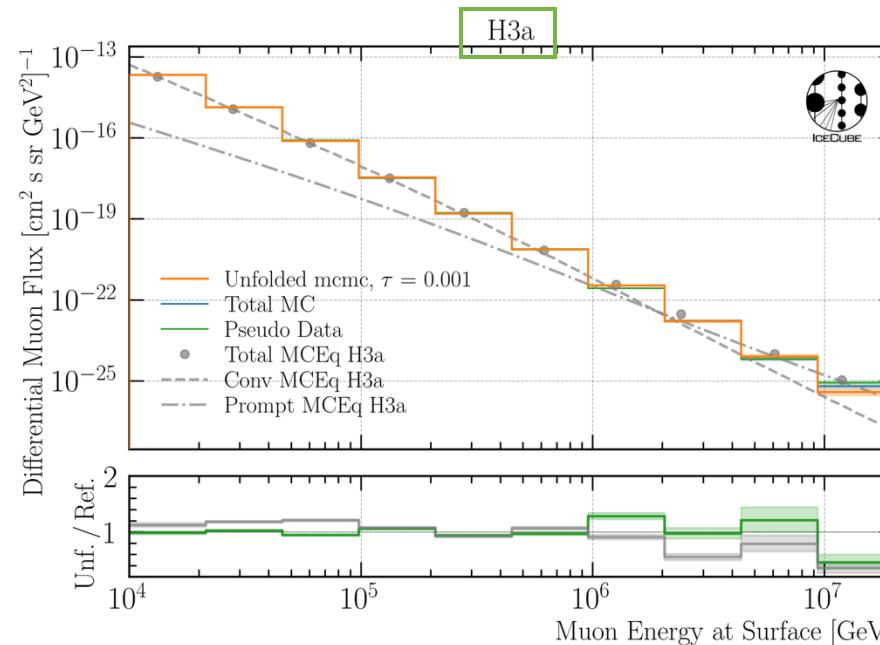
# Unfold Muon Flux

# Muon Flux at Surface



# Check impact of primary input model

- build model on H4a
- unfold H3a, H4a and GSF
- green line should align with 1
- Unfolding independent of input primary flux model

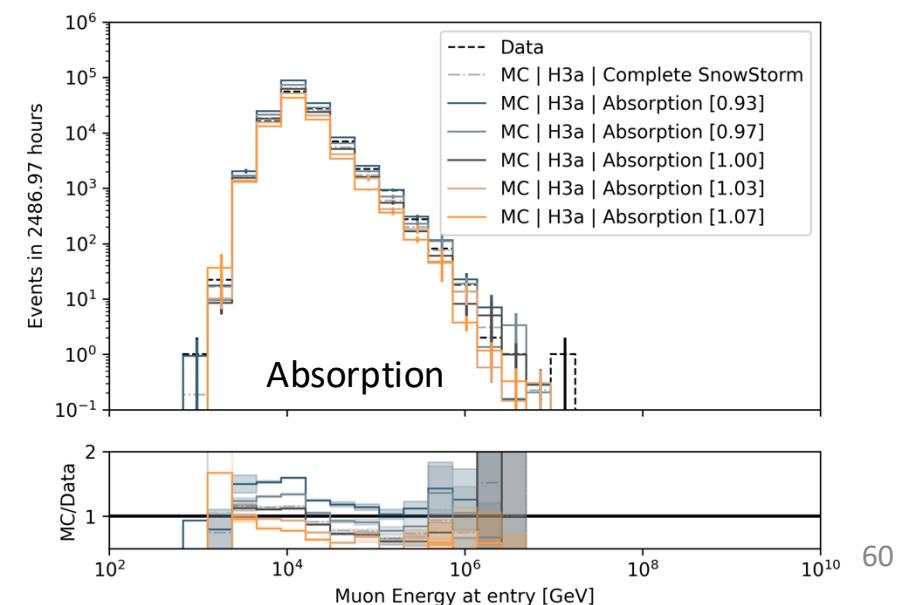
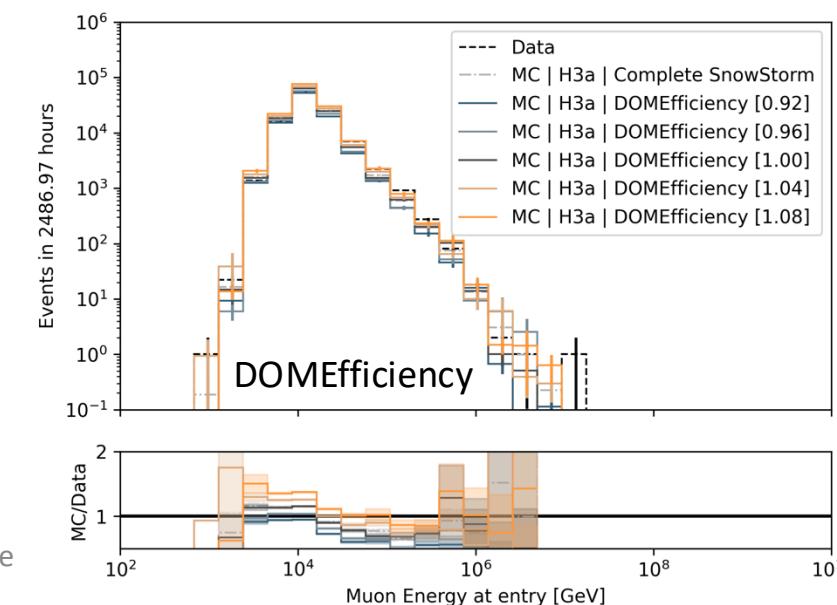
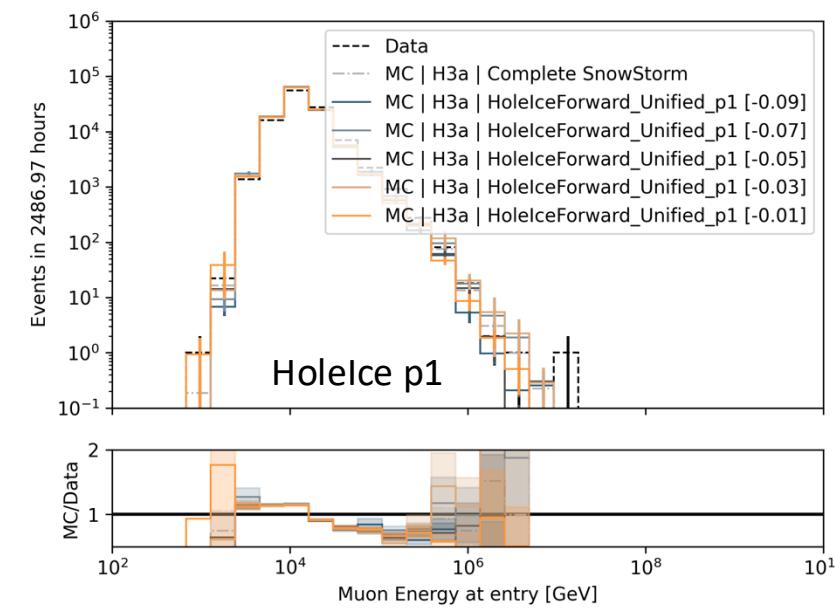
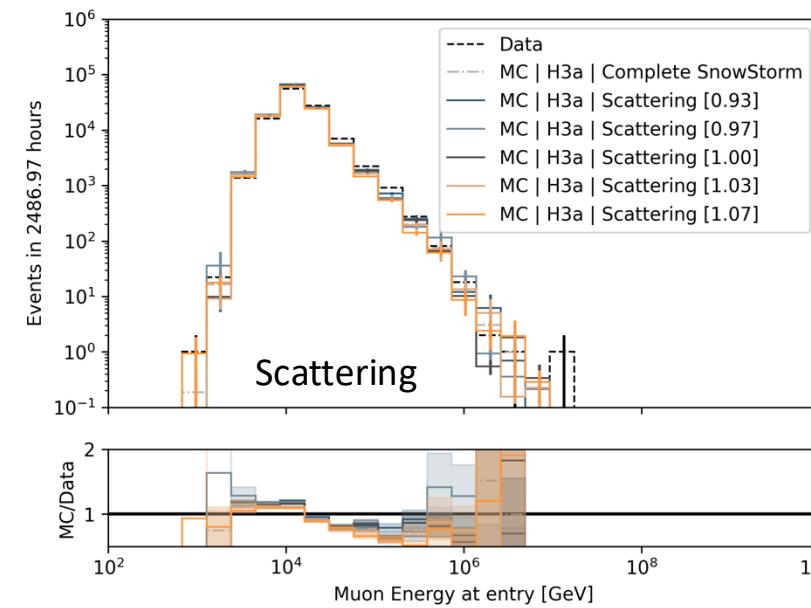
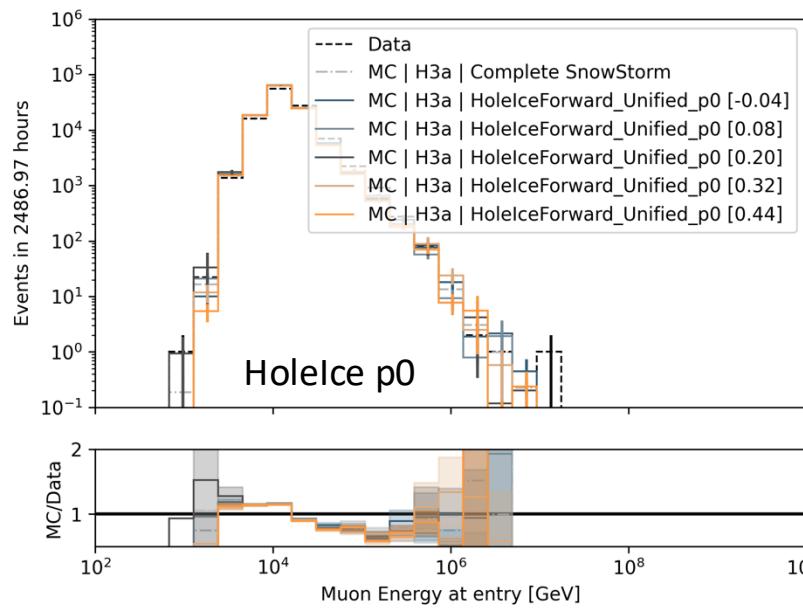


# Ice Systematics

## Snowstorm

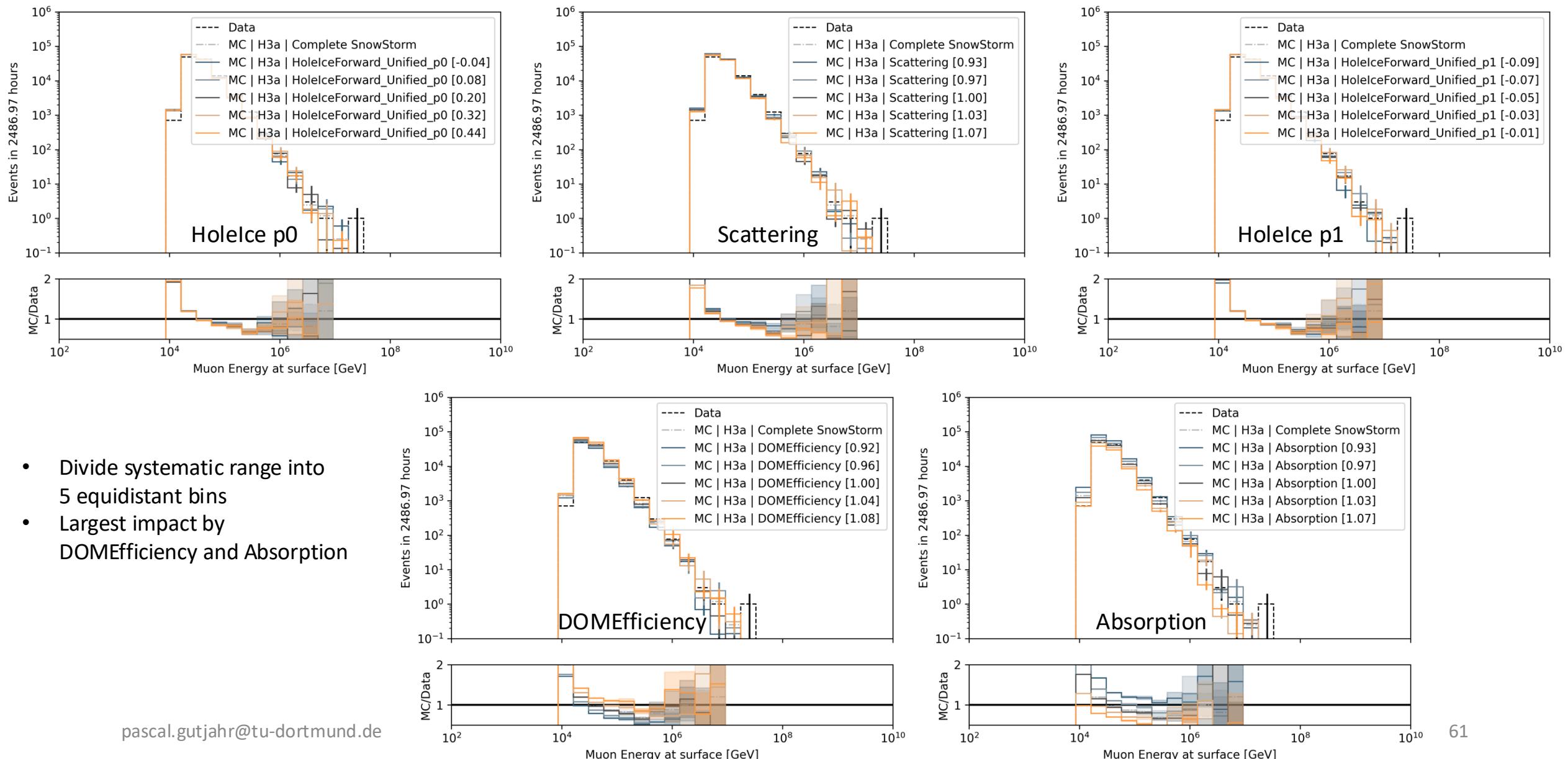
1. Scattering
2. Absorption
3. DOMEfficiency
4. Hole Ice Forward p0
5. Hole Ice Forward p1

# Systematics Impact on Muon Energy at Entry (Proxy)

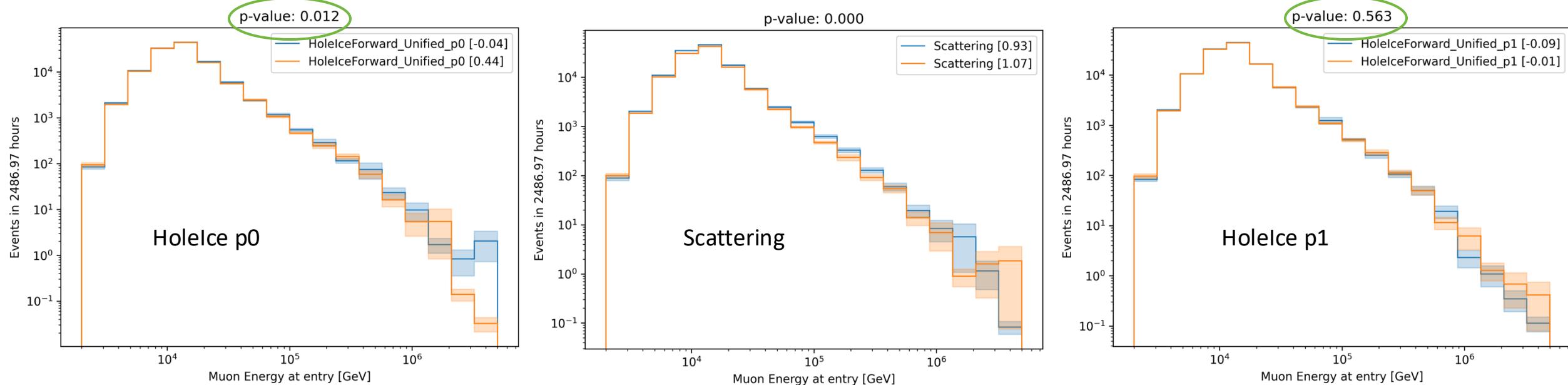


- Divide systematic range into 5 equidistant bins
- Largest impact by DOMEfficiency and Absorption

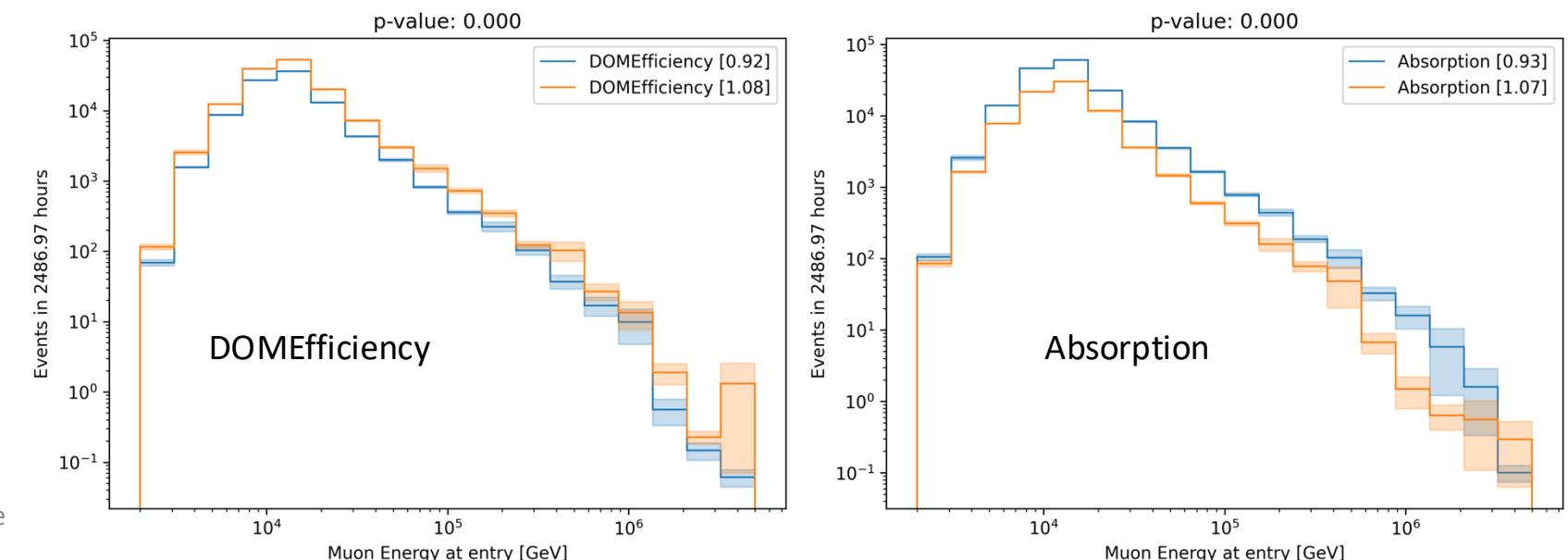
# Systematics Impact on Muon Energy at Surface (Target)



# Chi2 Test: Muon Energy at Entry (Proxy)



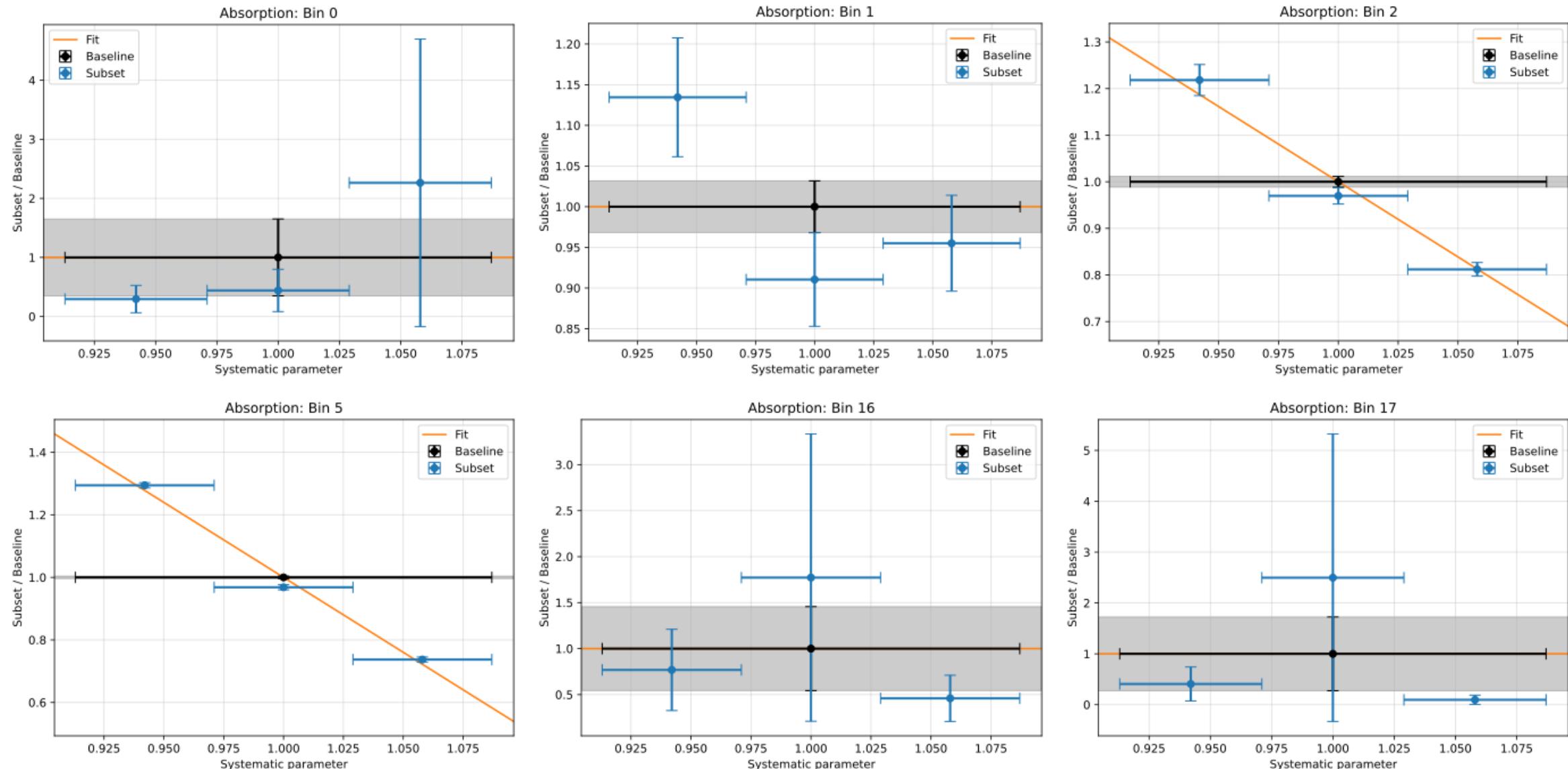
- Chi2 test between lower and upper systematic range bin
- No impact from Hole Ice p1
- Small impact from Scattering and Hole Ice p0



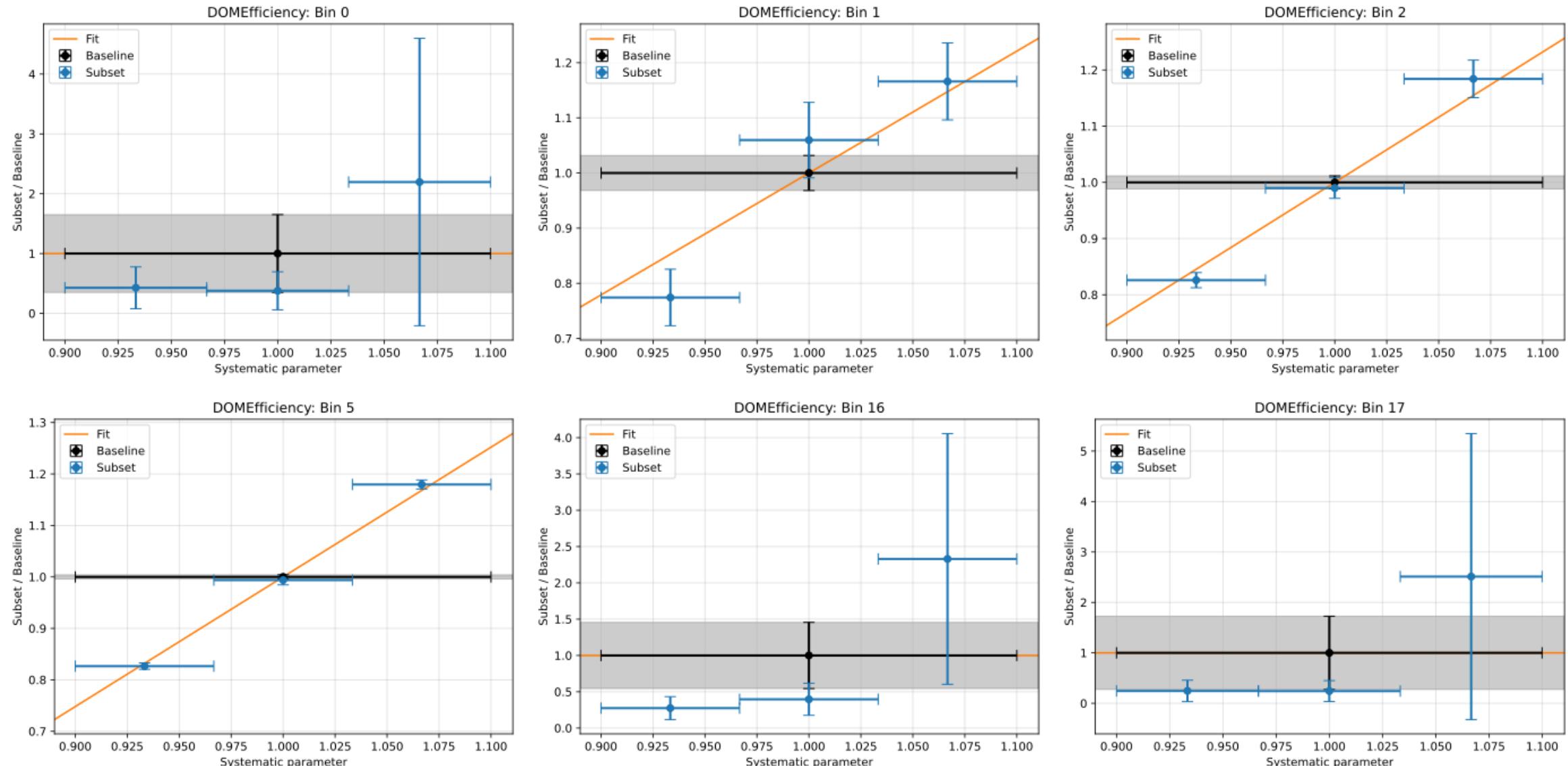
# Parameterize Systematics

- Vary each systematic parameter for each proxy bin  
(18 proxy bins, 3 systematic bins)
  - Fit the relative change of the bin content
1. Chi2 test, if constant  $y = 1$  is compatible with data points ( $p\text{-value} = 0.05$ )
  2. Find linear fit with the lowest slope that is compatible with  $p\text{-value} = 0.2$ 
    1. Require fit is going through (center, 1)

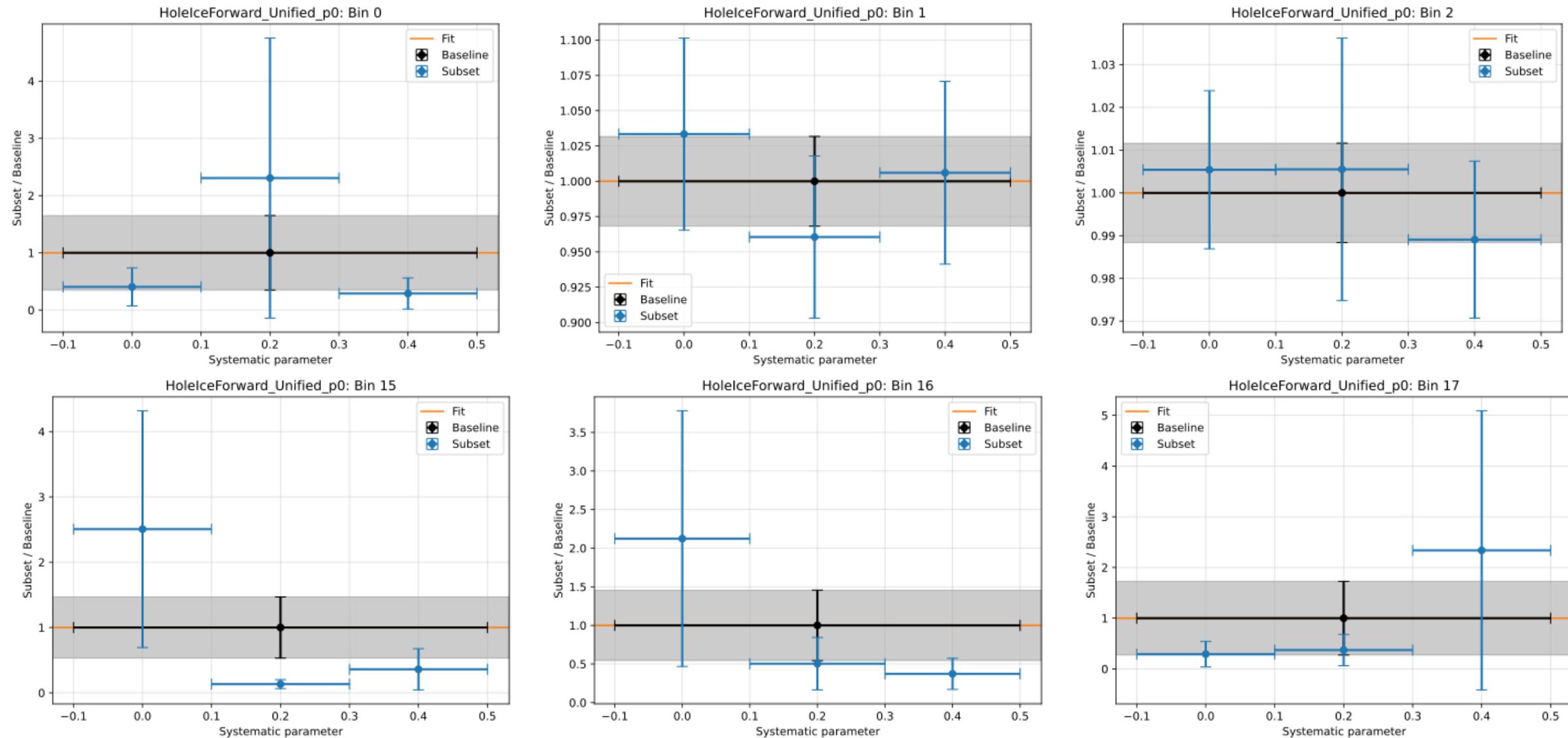
# Absorption



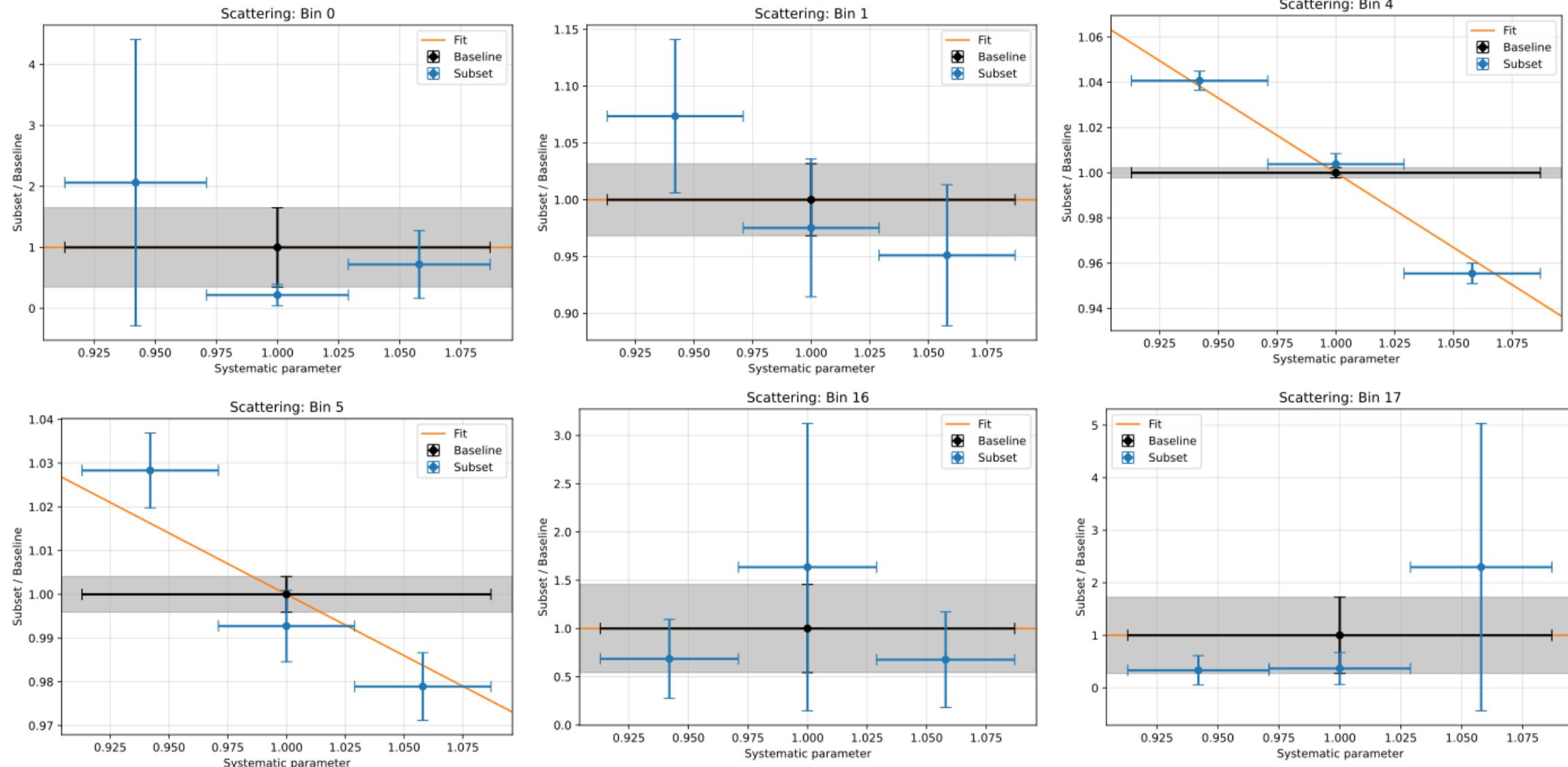
## DOMEfficiency



# Hole Ice p0 → not sensitive enough (same for Hole Ice p1)



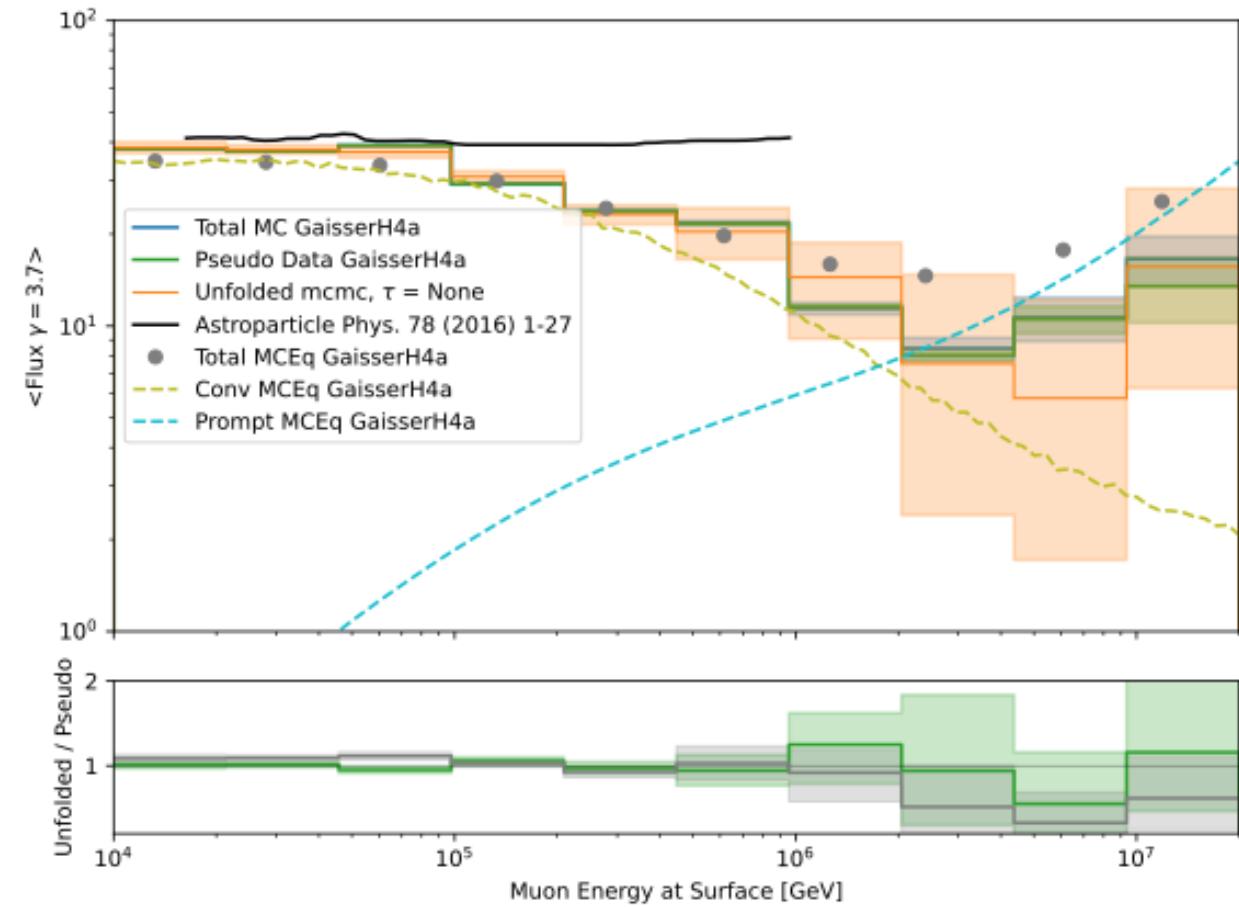
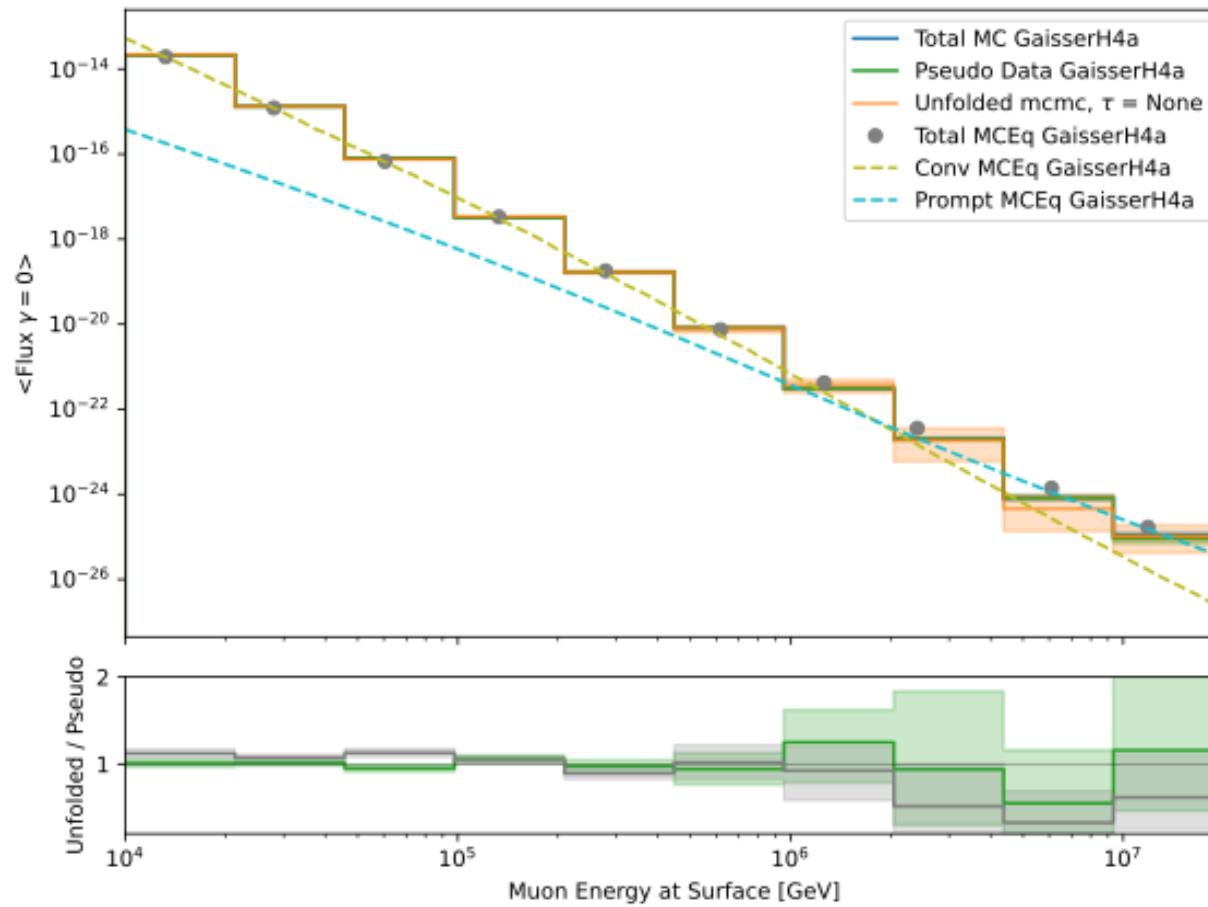
# Scattering



# Unfold Muon Flux with Systematics

No regularization

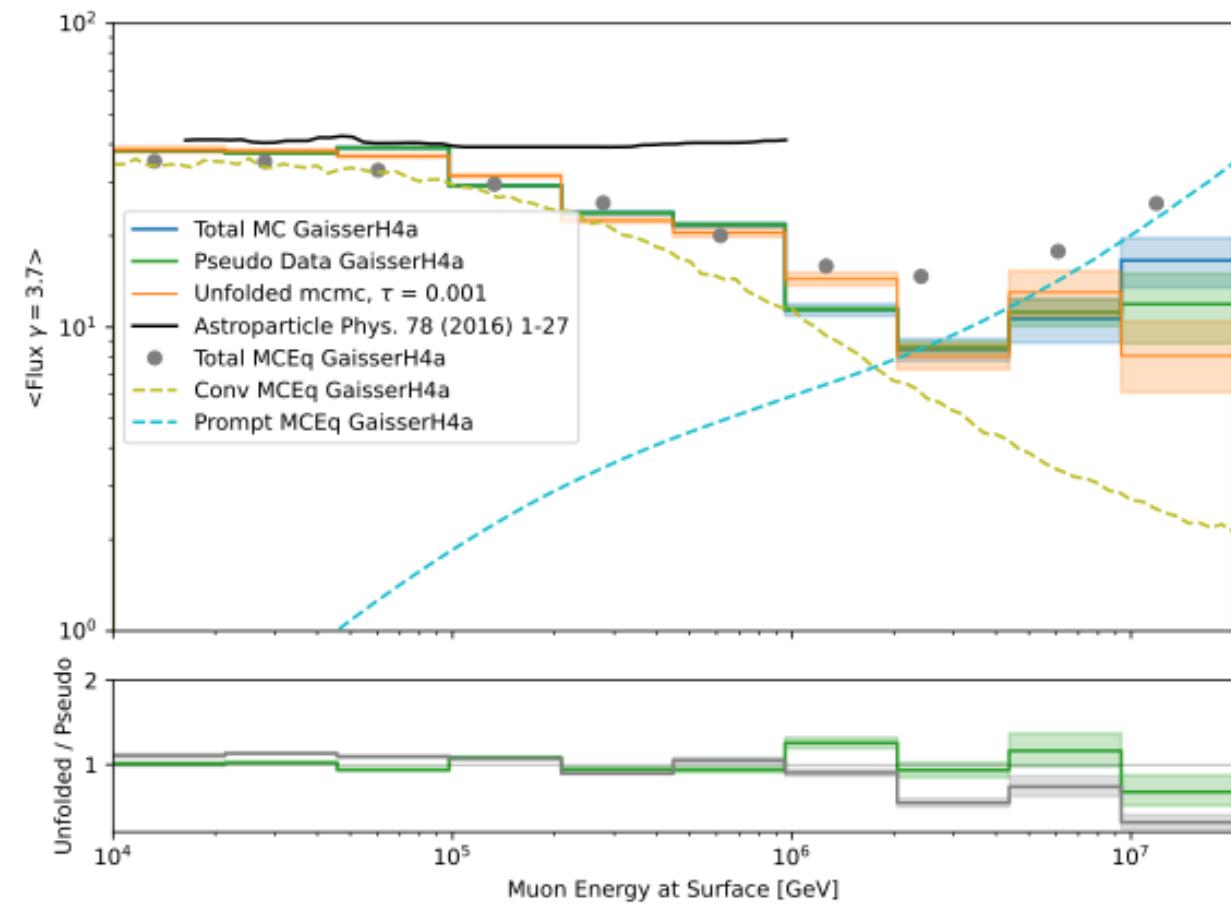
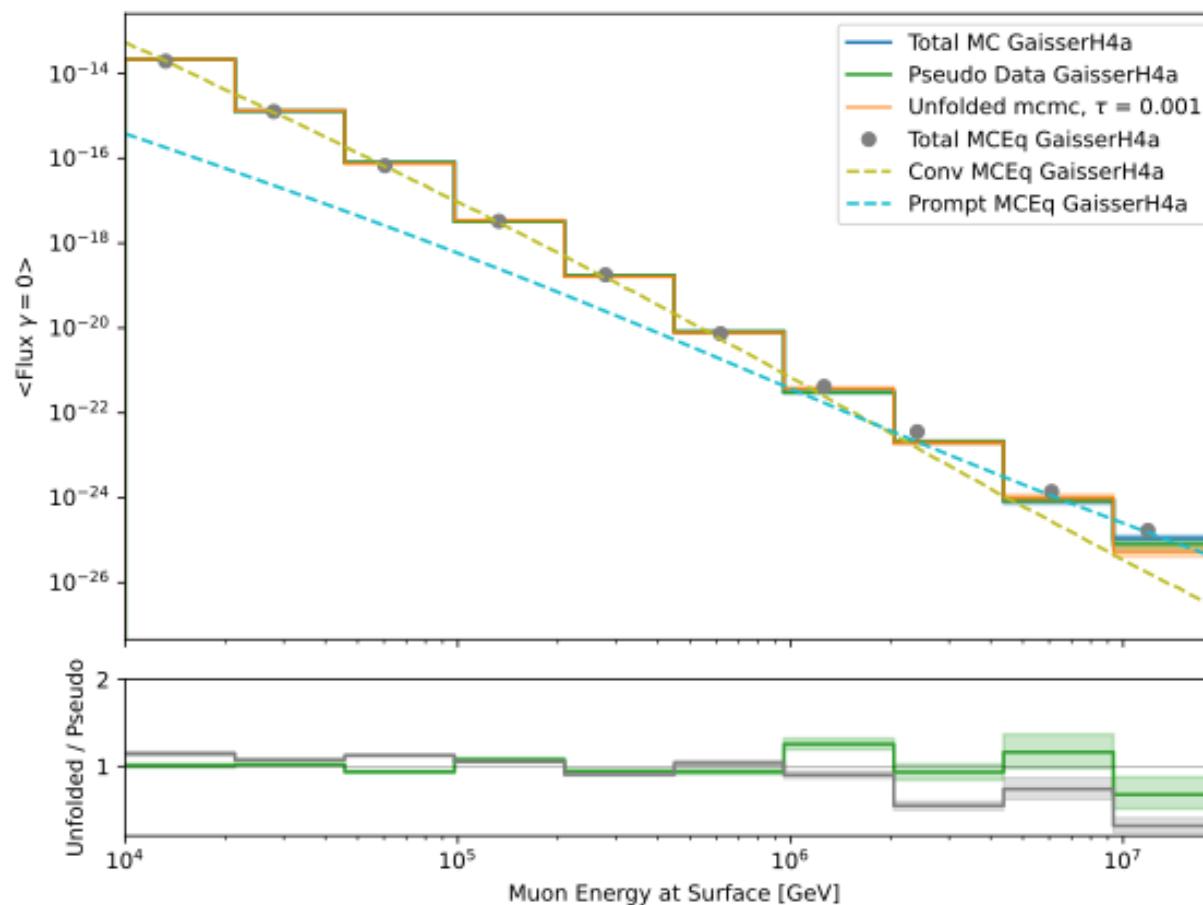
# Muon Flux at Surface (no regularization)

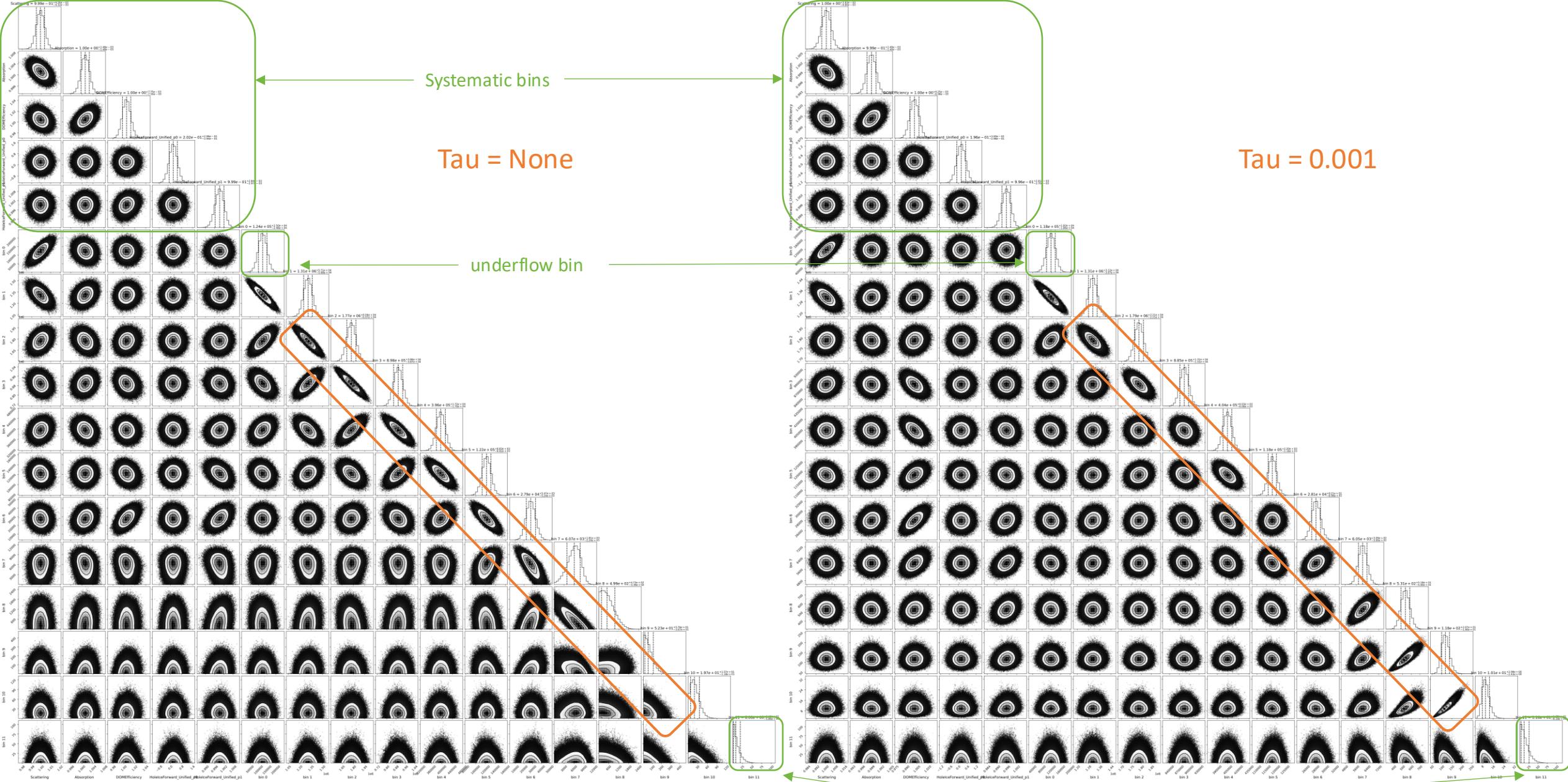


# Unfold Muon Flux with Systematics

With regularization

# Muon Flux at Surface ( $\tau = 0.001$ )





- Regularization minimizes the correlation
  - Find tau with the minimum correlation

# Conclusion

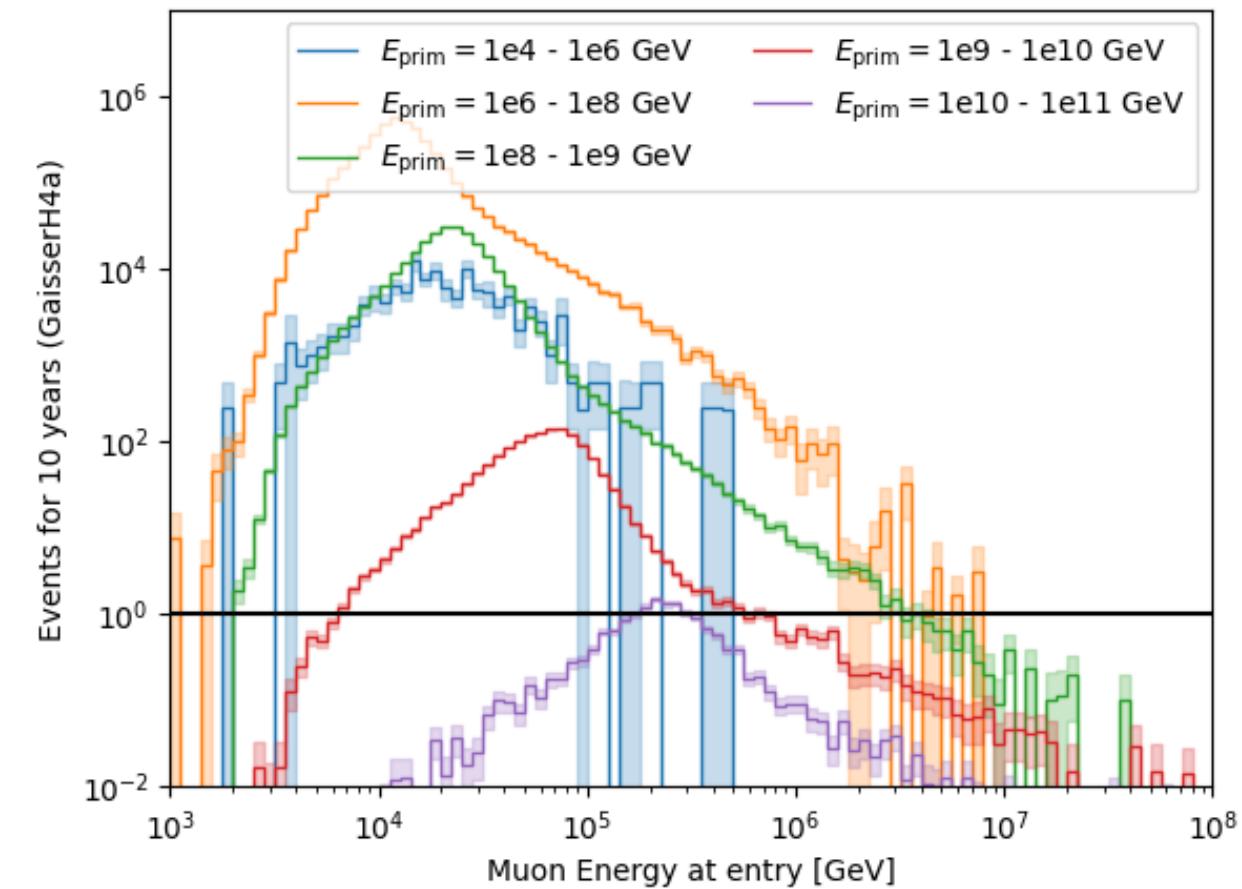
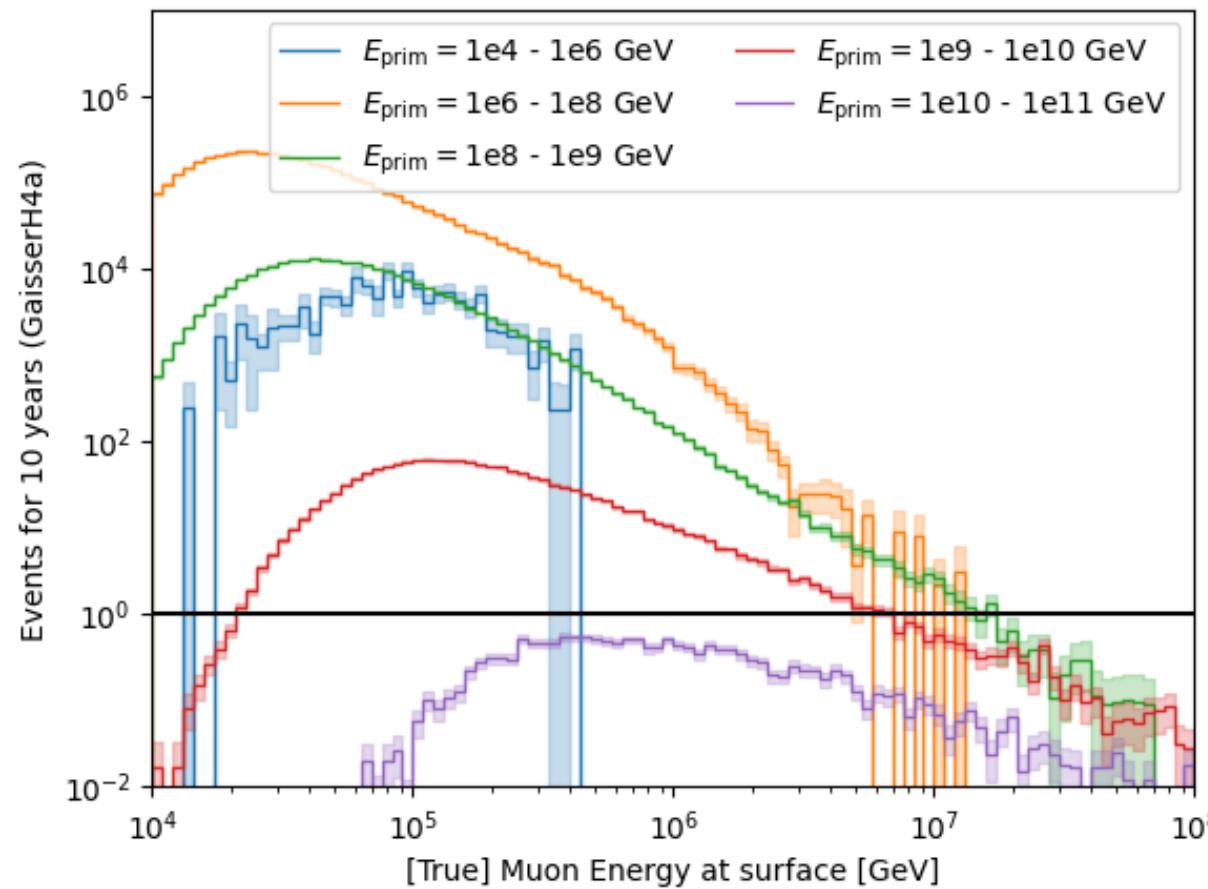
- Unfold muon event rate 
- Unfold muon flux at surface 
- Parameterize ice systematics 
  - Small impact from Scattering, Hole Ice p0 , and Hole Ice p1
  - Linear parameterization of Absorption and DOMEfficiency
- Unfold muon flux with systematics 

## Next steps

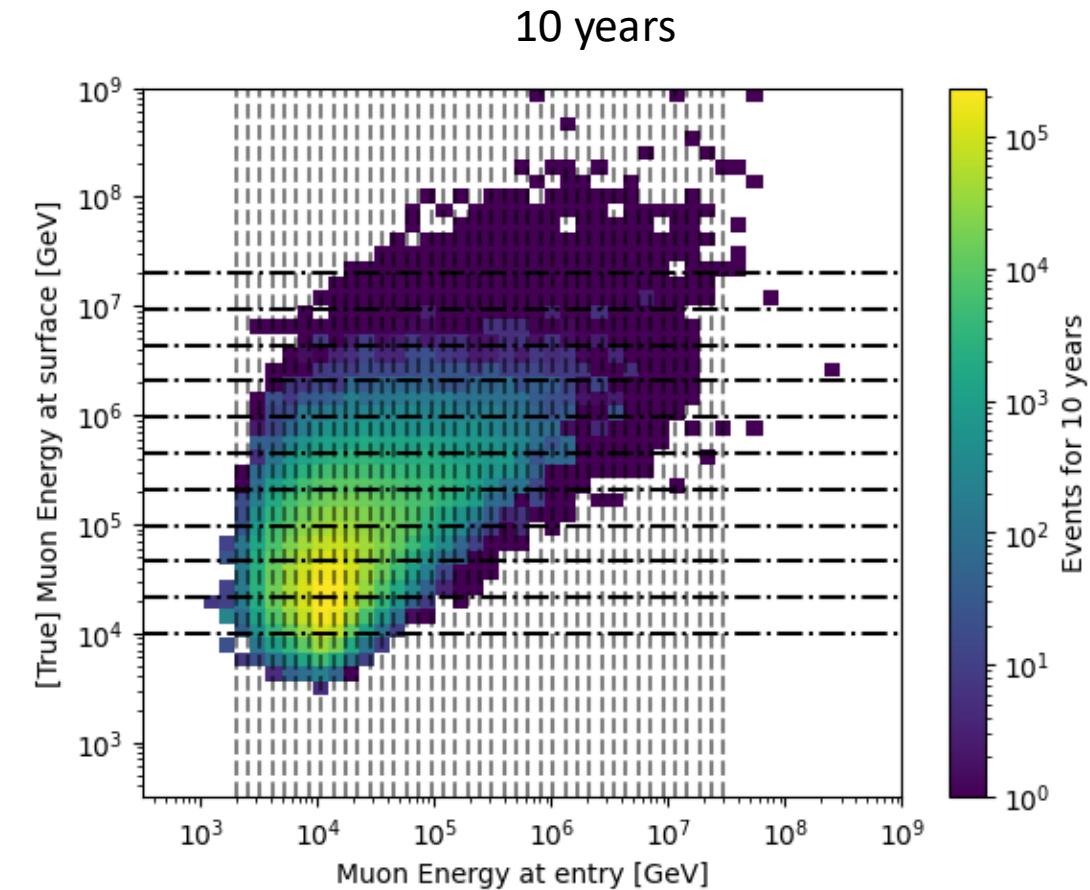
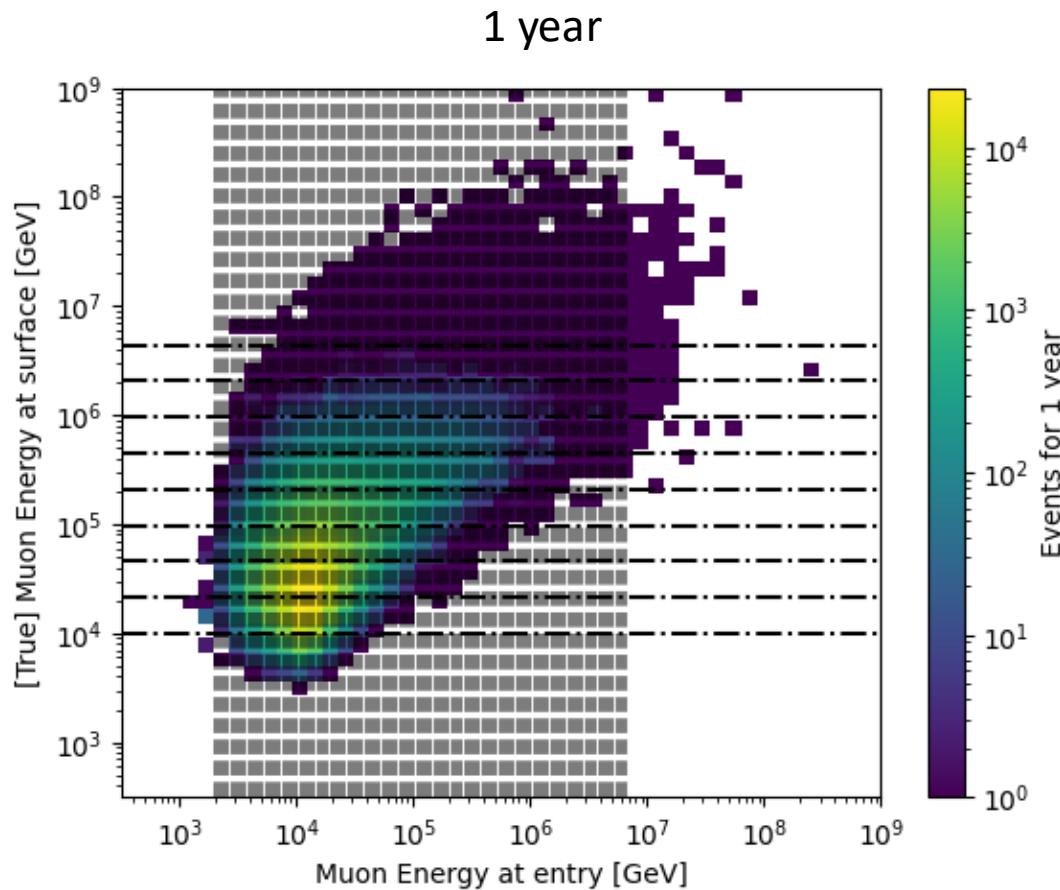
- Test impact of different primary models (spectral index)
- Choose optimal regularization

# Backup

# Relation between primary energy and muon energy at surface and entry

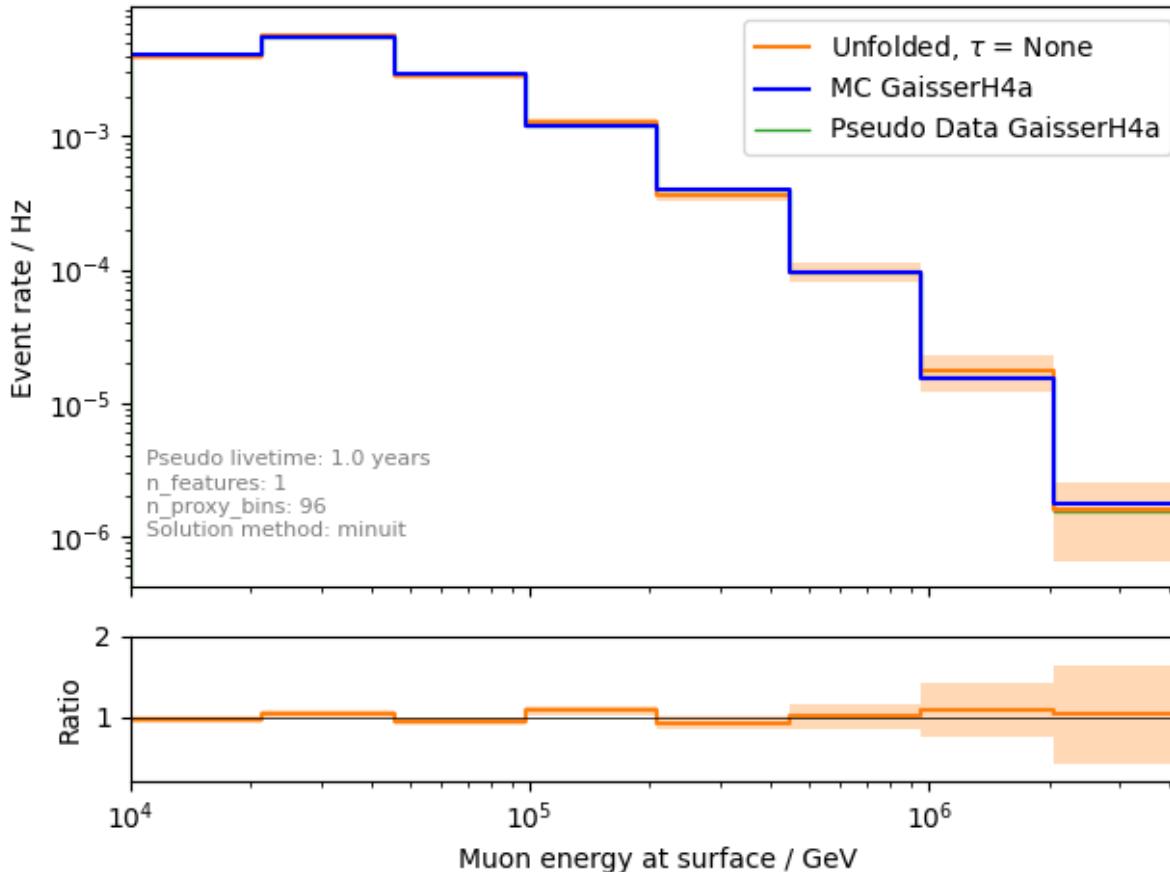


## Proxy vs. target

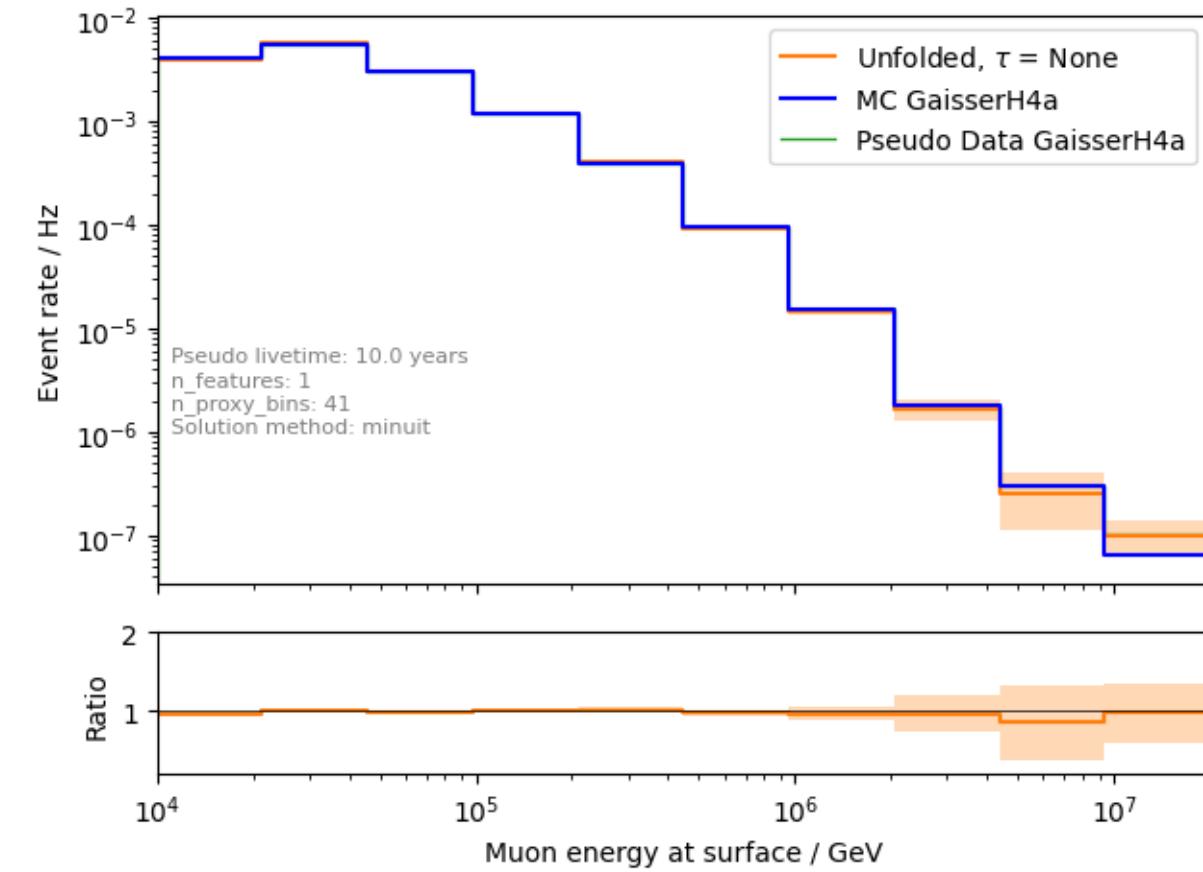


# Unfolding event rate

1 year

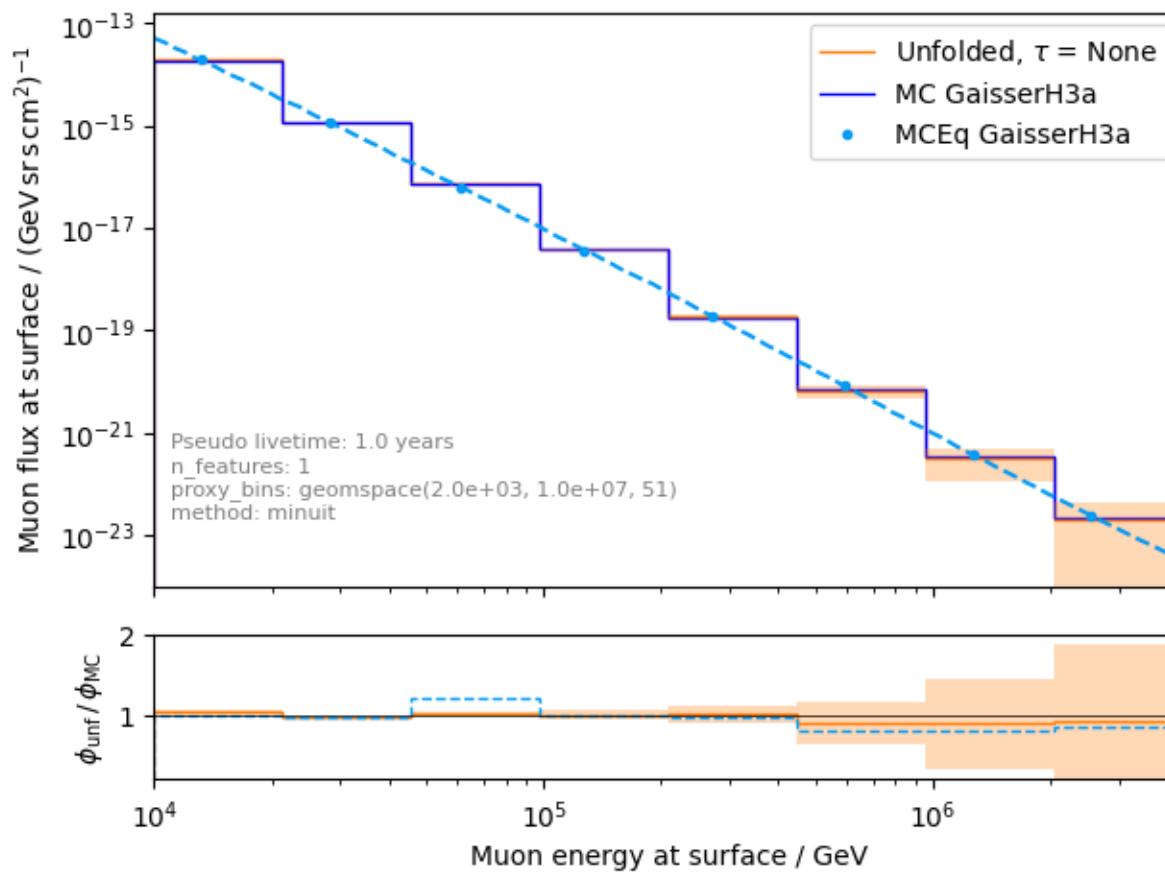


10 years

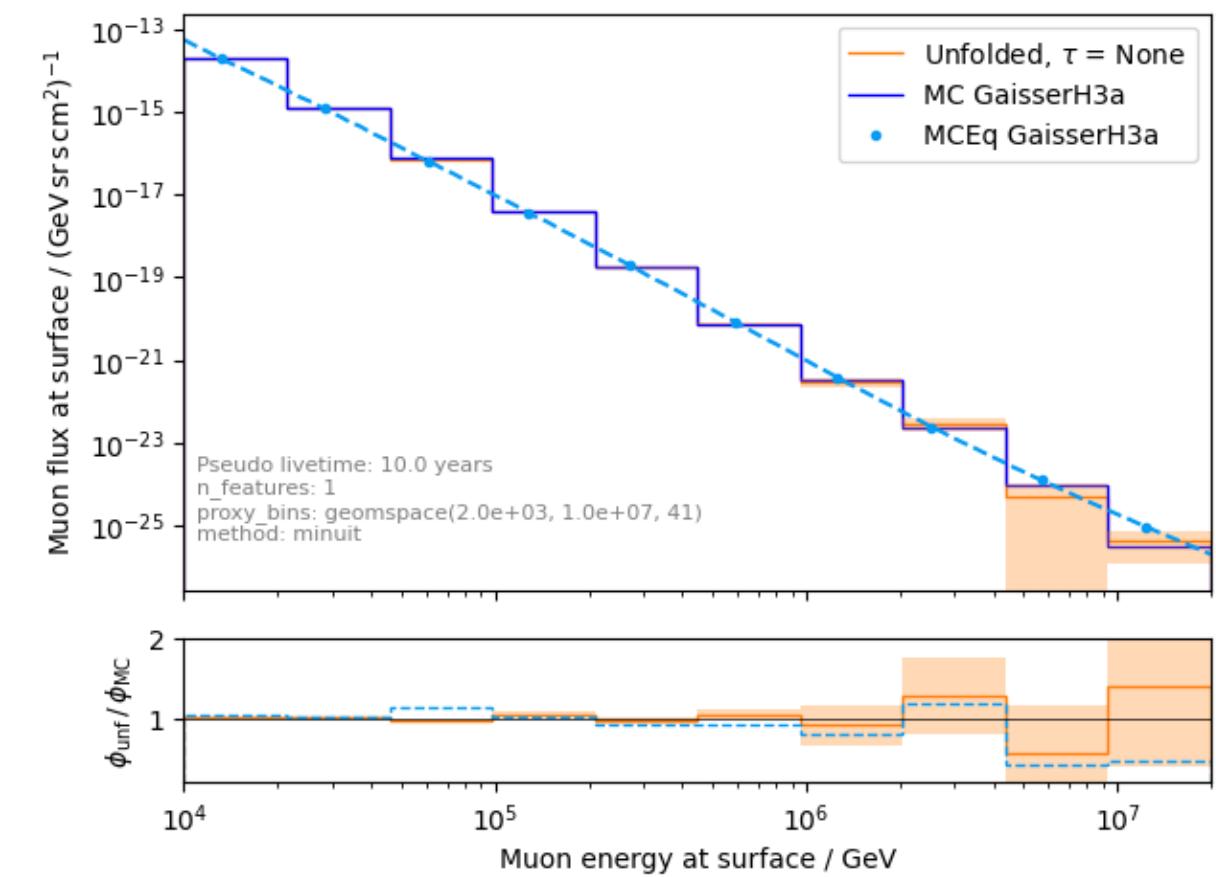


## unfolding of muon flux at surface

1 year



10 years



# Ice systematics

Snowstorm

Absorption

Scattering

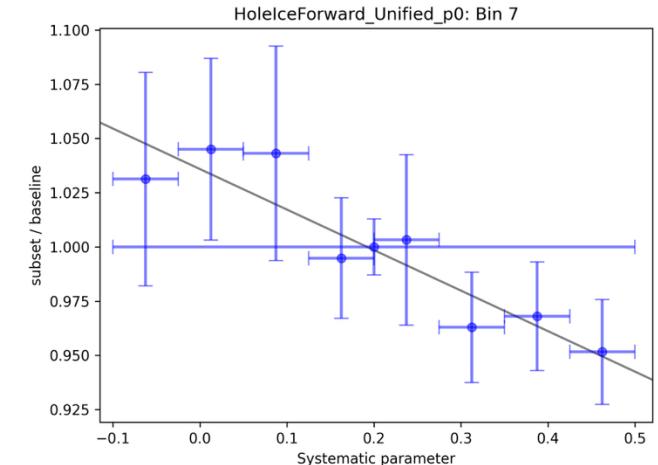
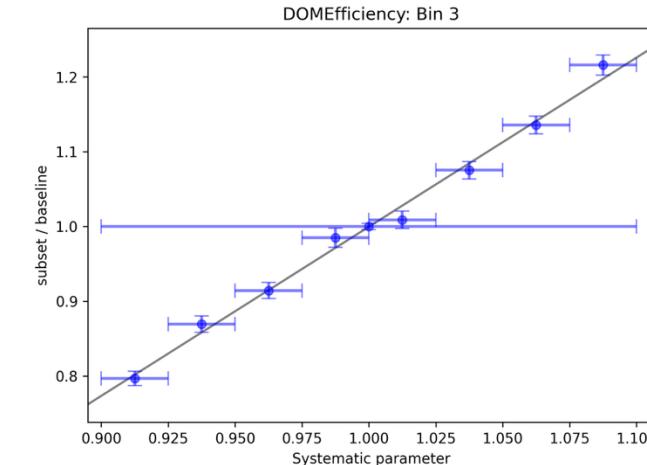
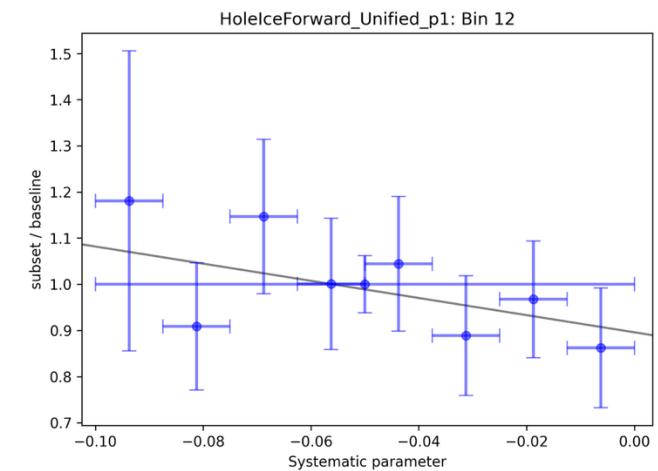
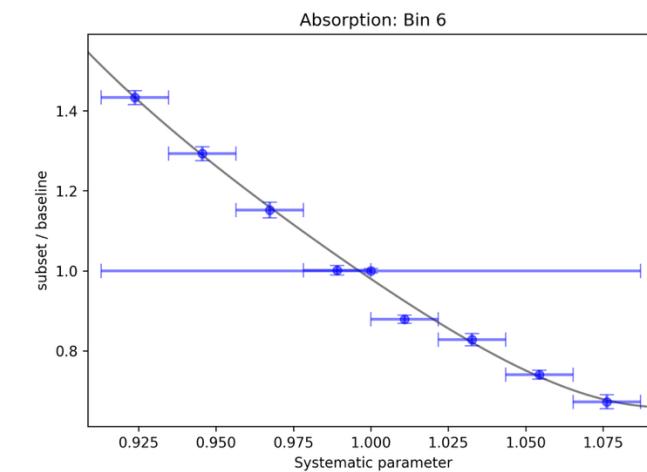
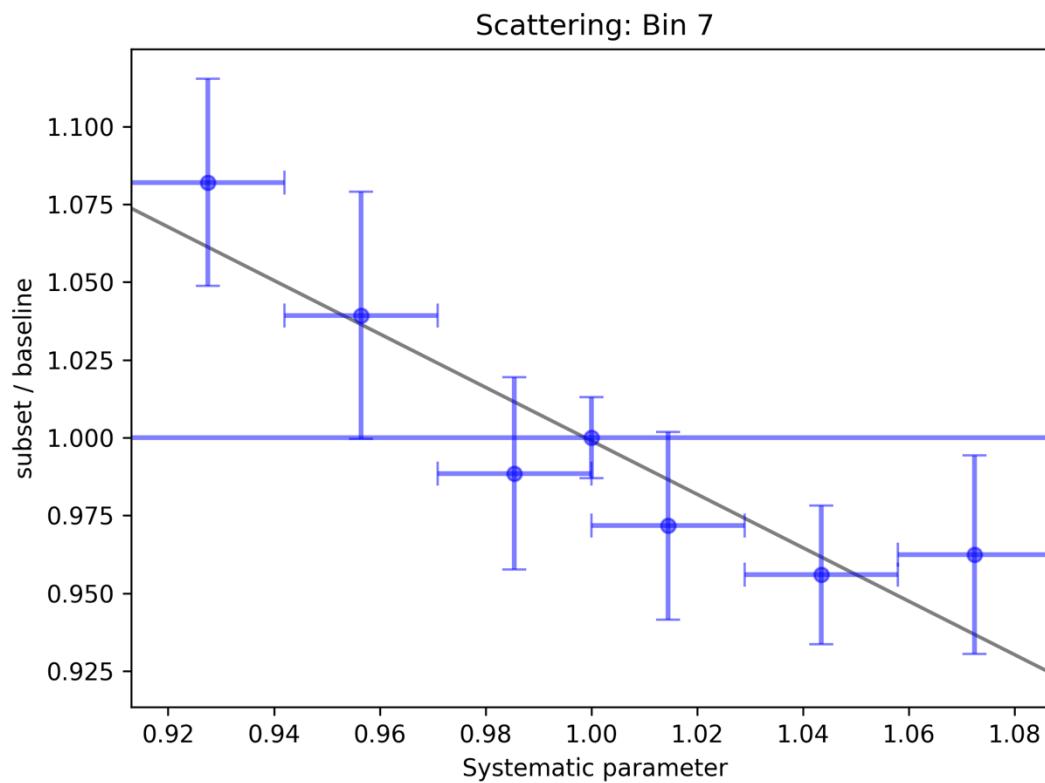
DOMEfficiency

HoleIce 0

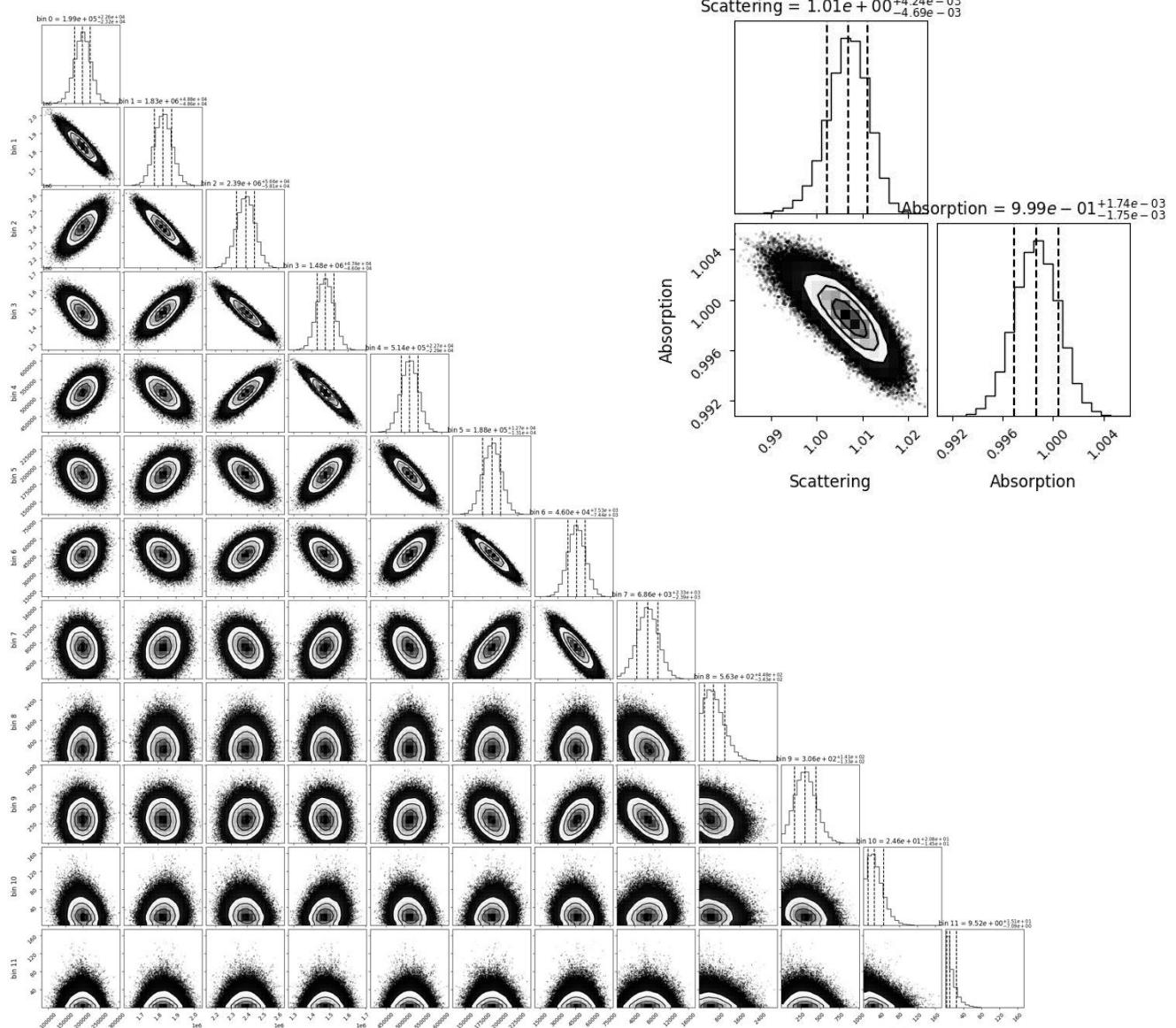
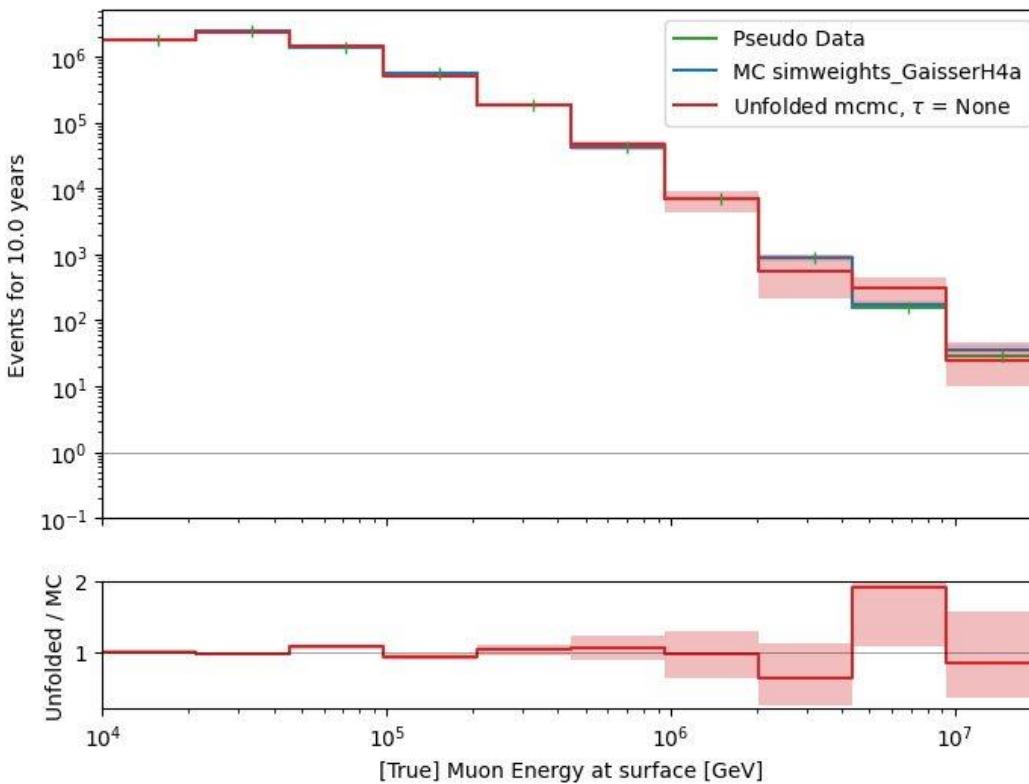
HoleIce 1

# Fit ice systematics:

- Parametrization for systematics in each proxy bin
- Proxy: leading muon energy at entry



# Unfolded event rate with systematics



➤ Use regularization to reduce unphysical oscillations

# Conclusion & outlook

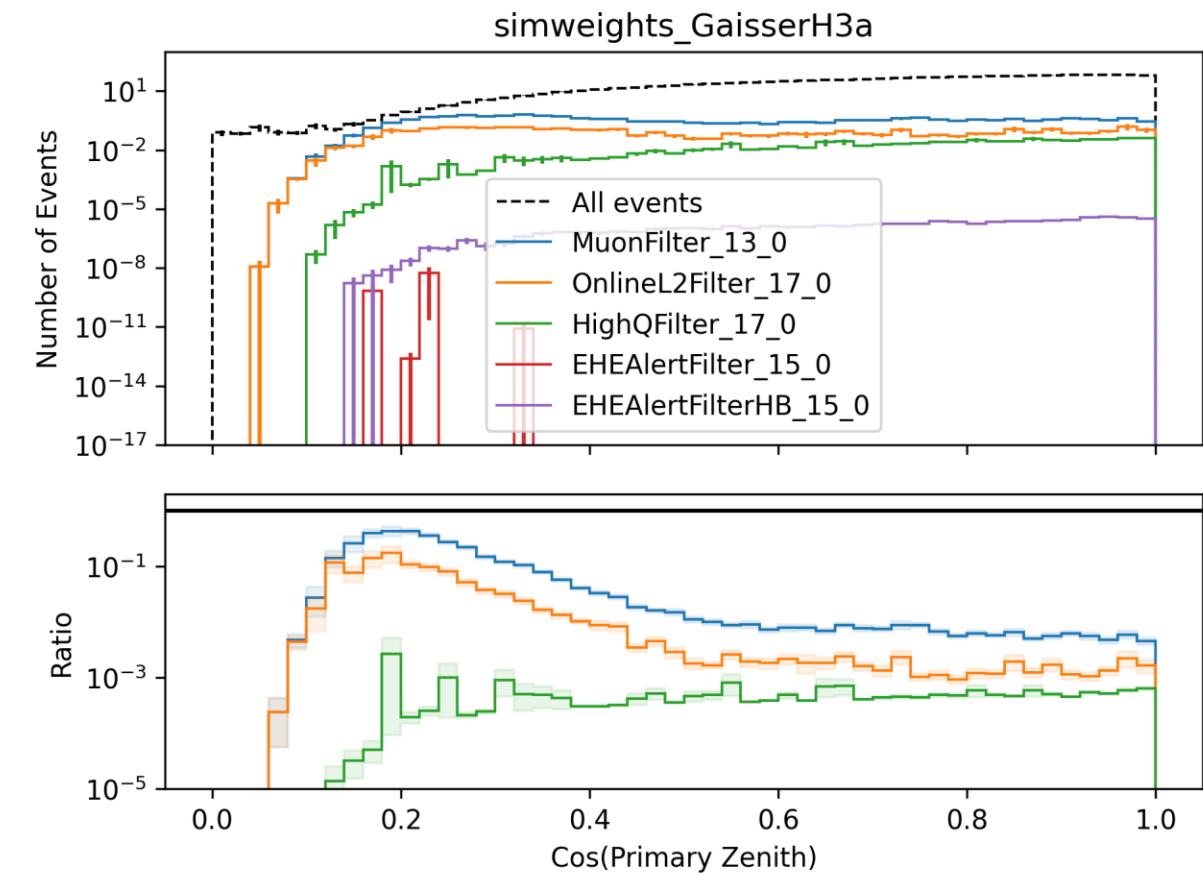
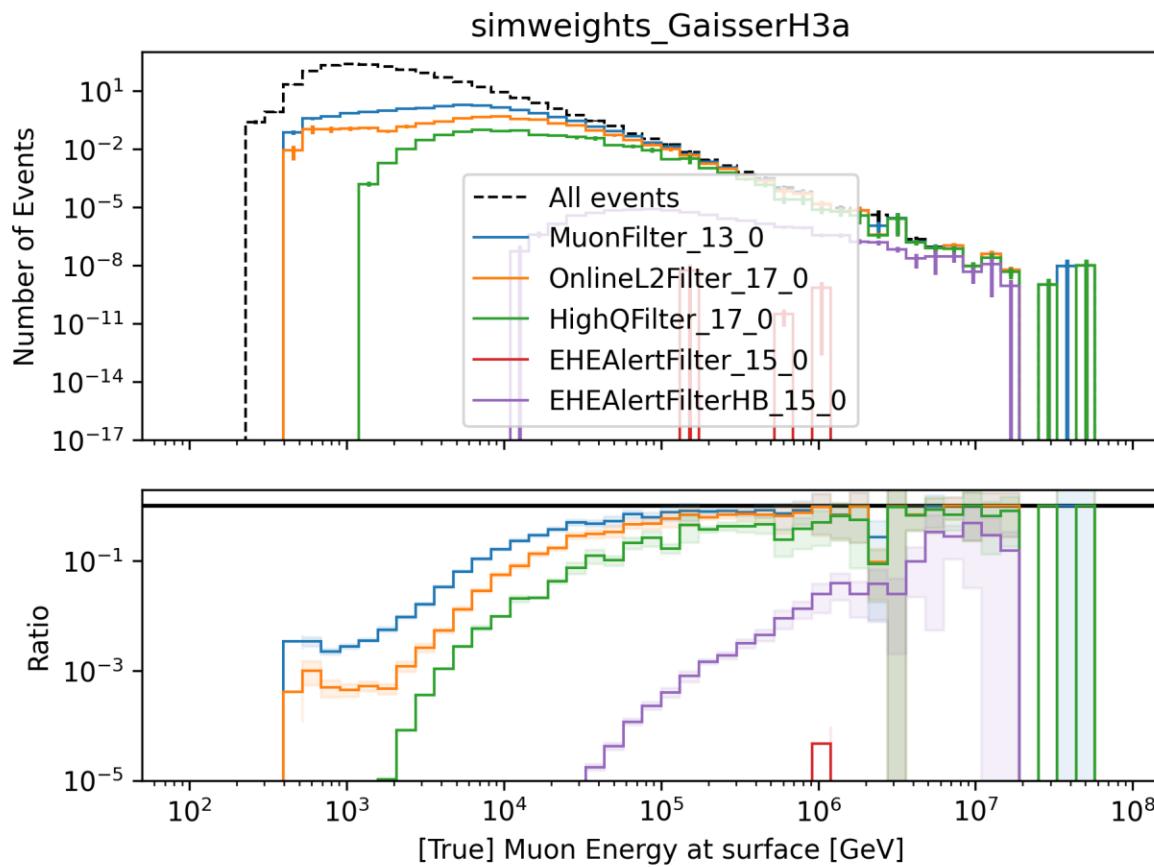
- New CORSIKA simulations with parent information
  - tag prompt and conventional muons
  - validation: agreement with MC Eq
- Add DNN-based reconstructions
- Good data-MC agreement
  - quality cuts defined
  - good agreement in  $\cos(\text{zenith})$  distributions
  - mismatch in z—position → re-weight distributions
- Unfolding is set up
  - systematics can be included, minor investigations
- Fit of prompt normalization is promising
  - systematics need to be included



How ChatGPT illustrates the detection of a prompt muon with IceCube.

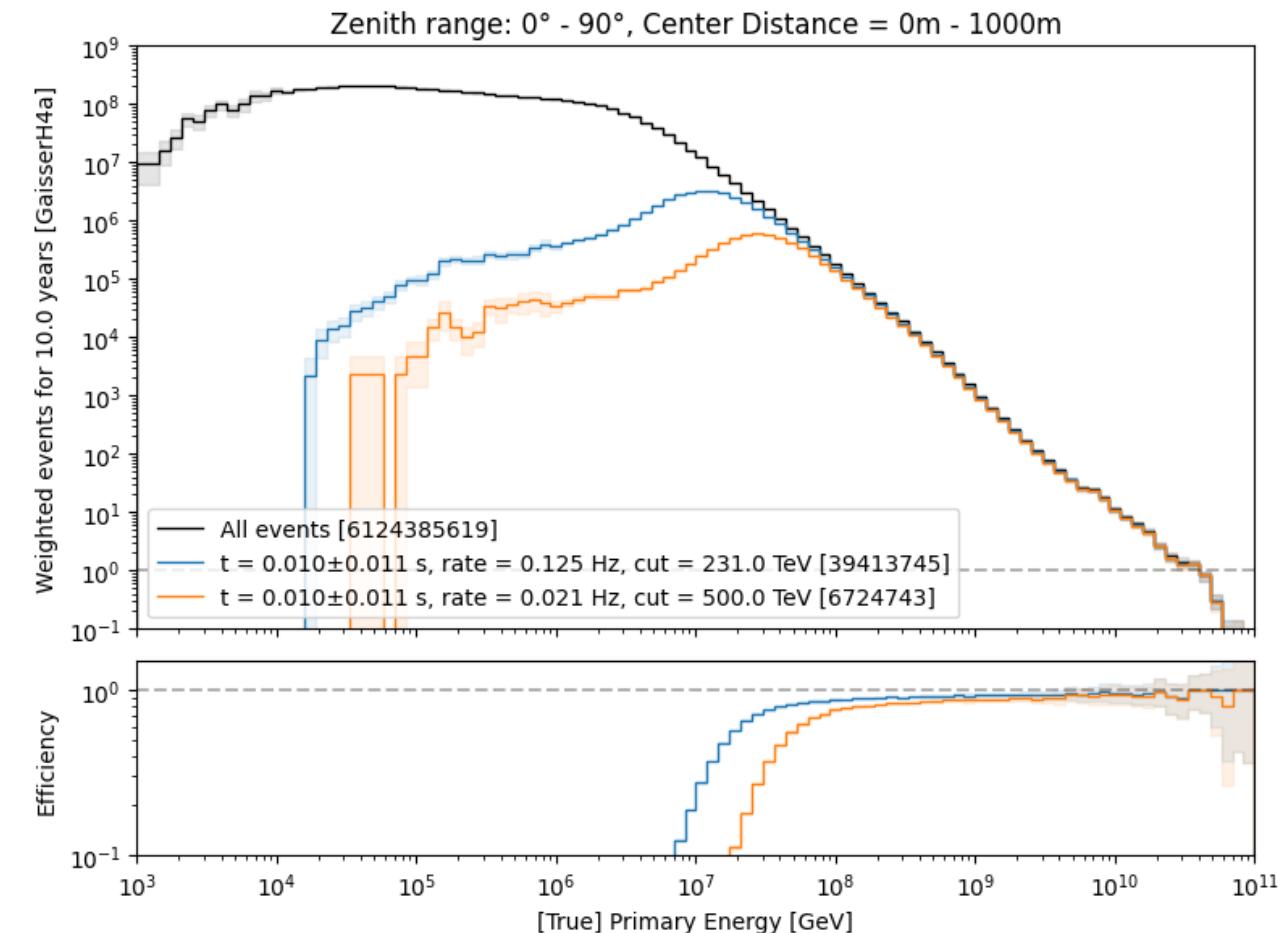
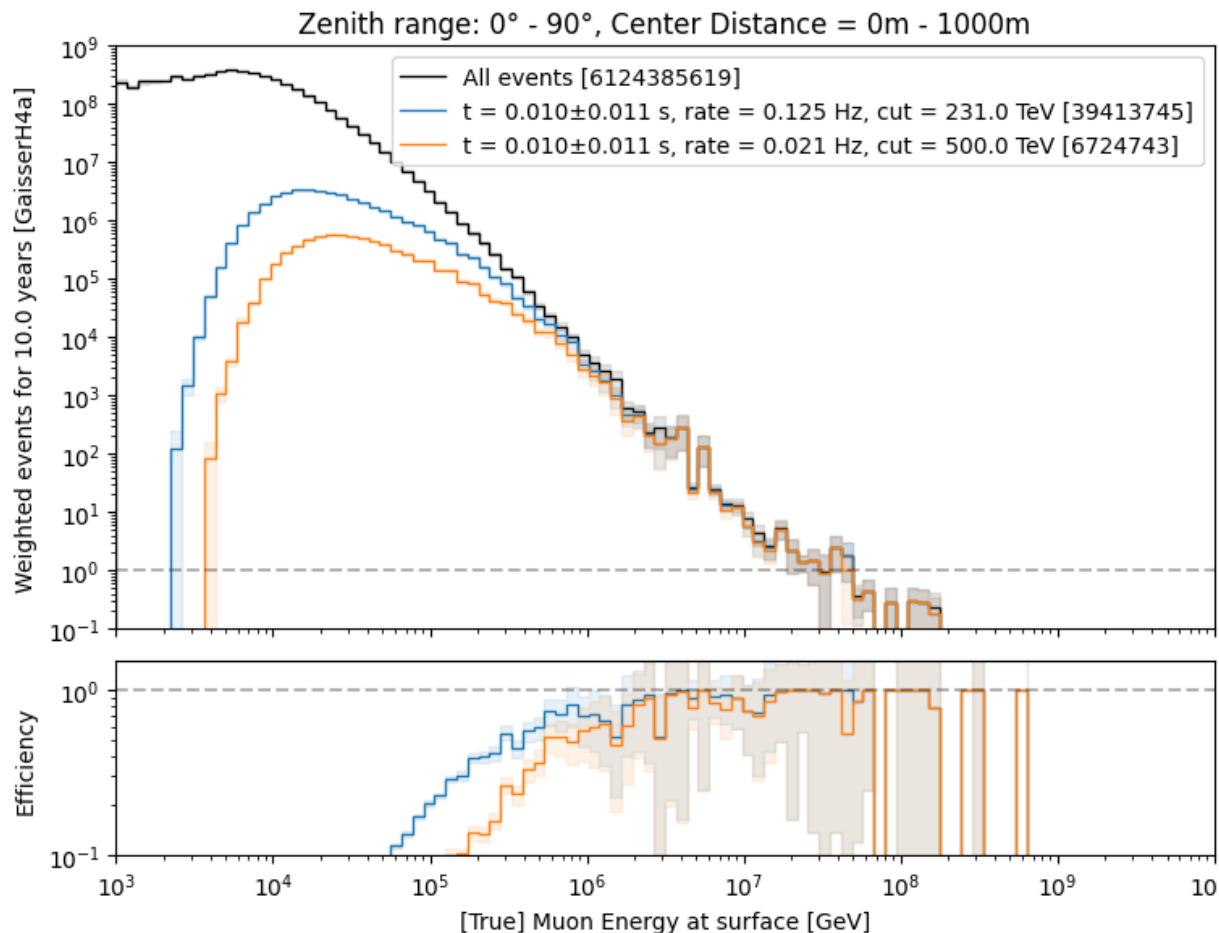
# Selection

# level3: muon filter



- HighQFilter: removes more horizontal events → muons travel large distances, not enough energy left to pass high-charge filter
- Goal: keep AMAP high-energy events at surface → muon filter

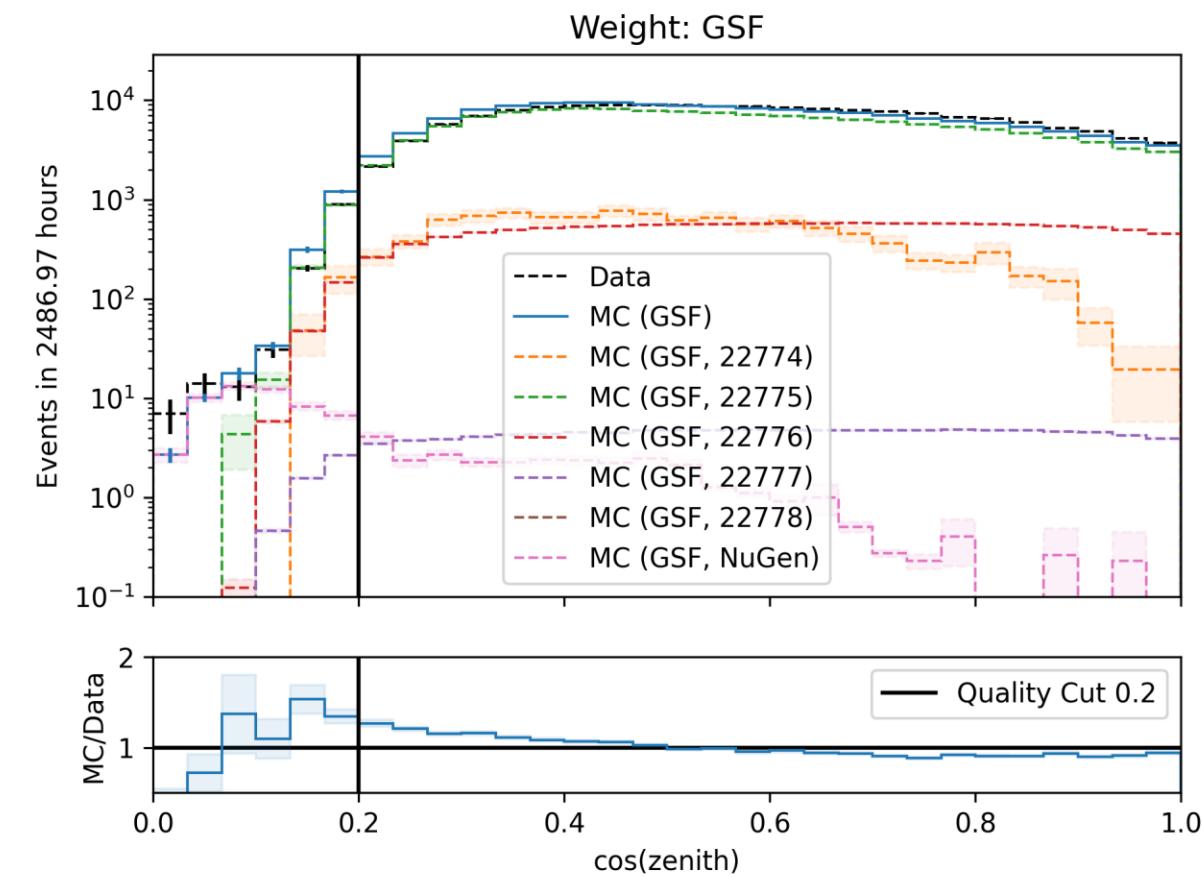
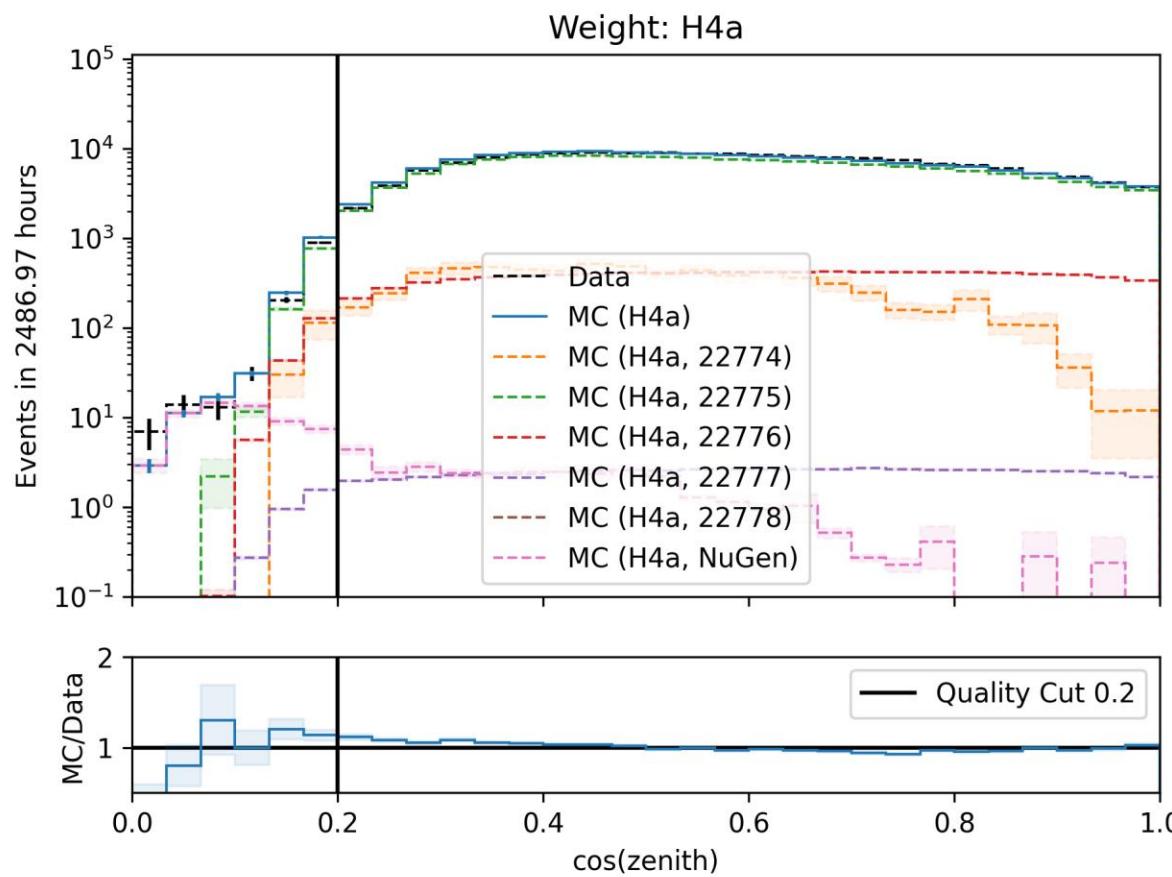
# level3: 500 TeV bundle cut at surface



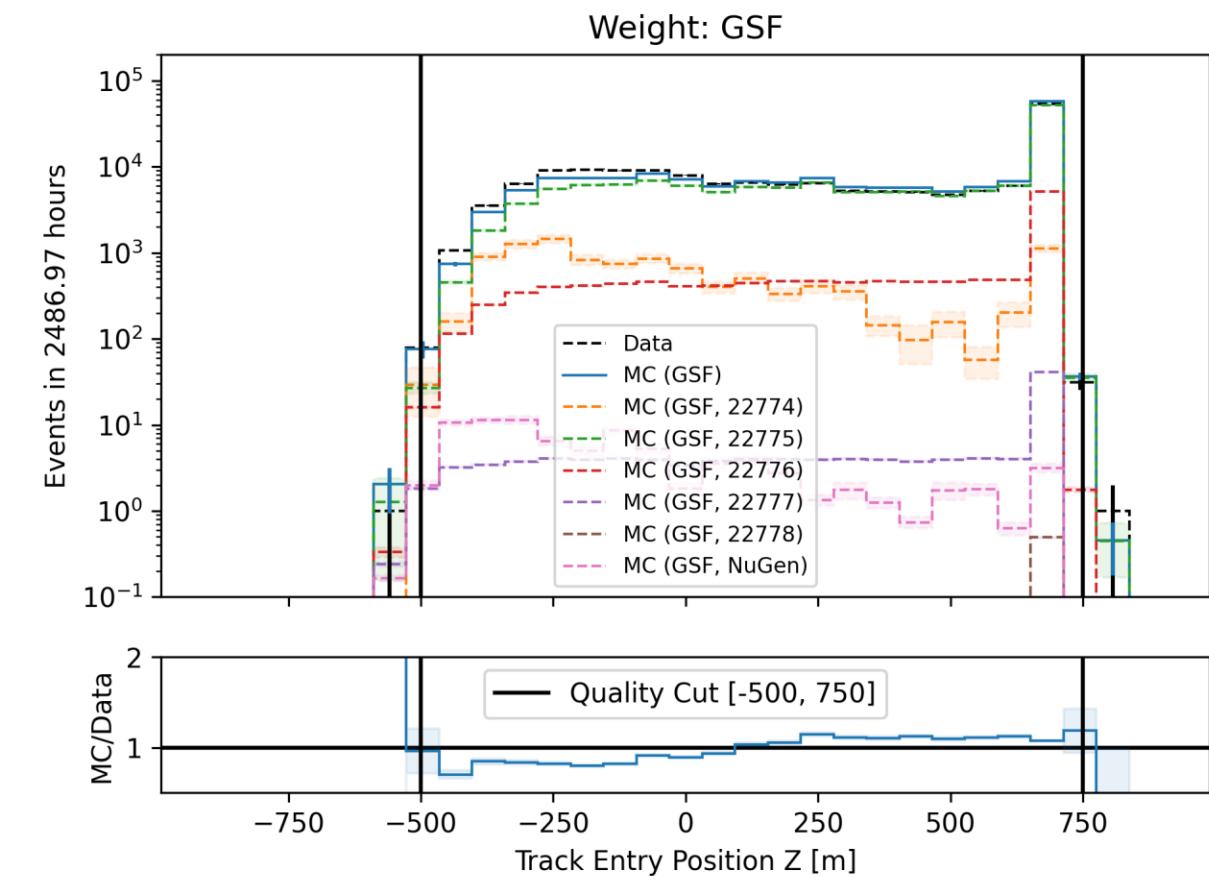
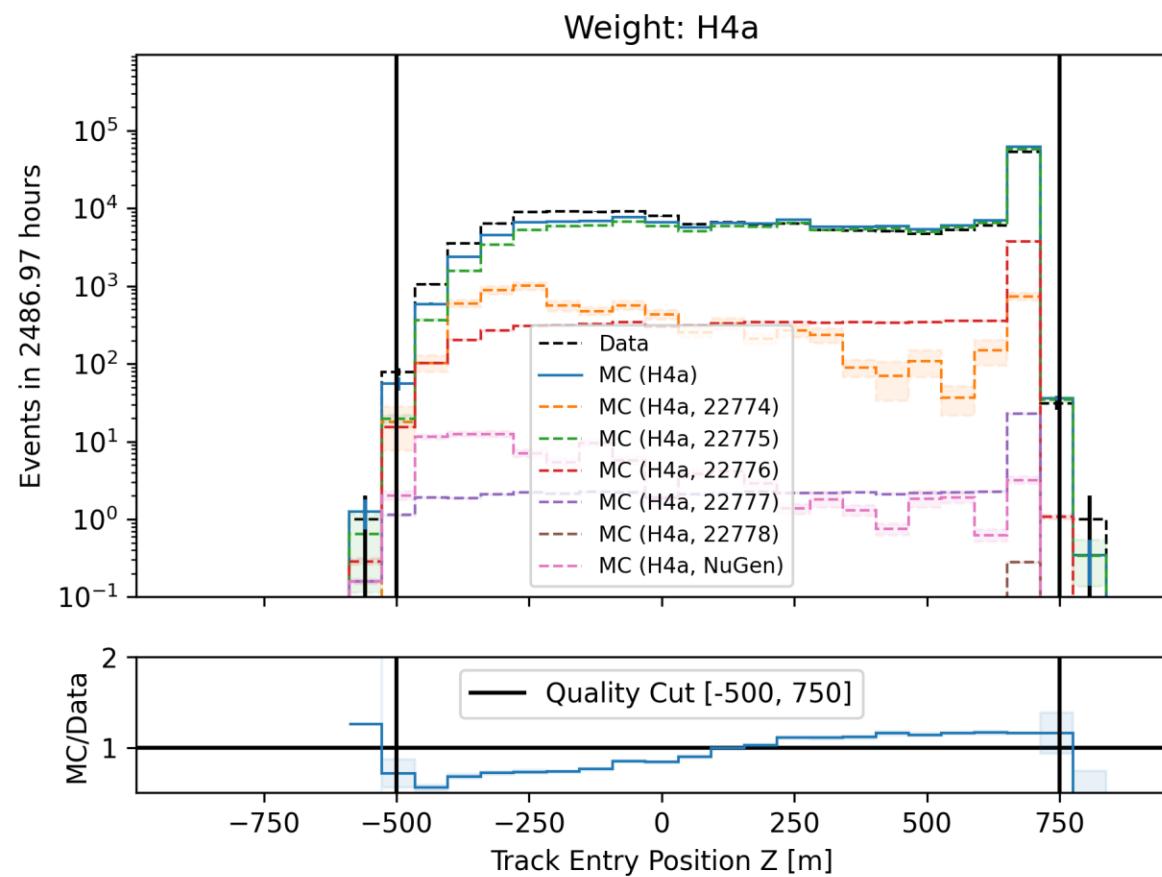
- 6 billion events expected: computationally not feasible → focus on high-energetic events
  - 500 TeV cut: 6.7 Mio events left

# Data-MC

## Cos(zenith)

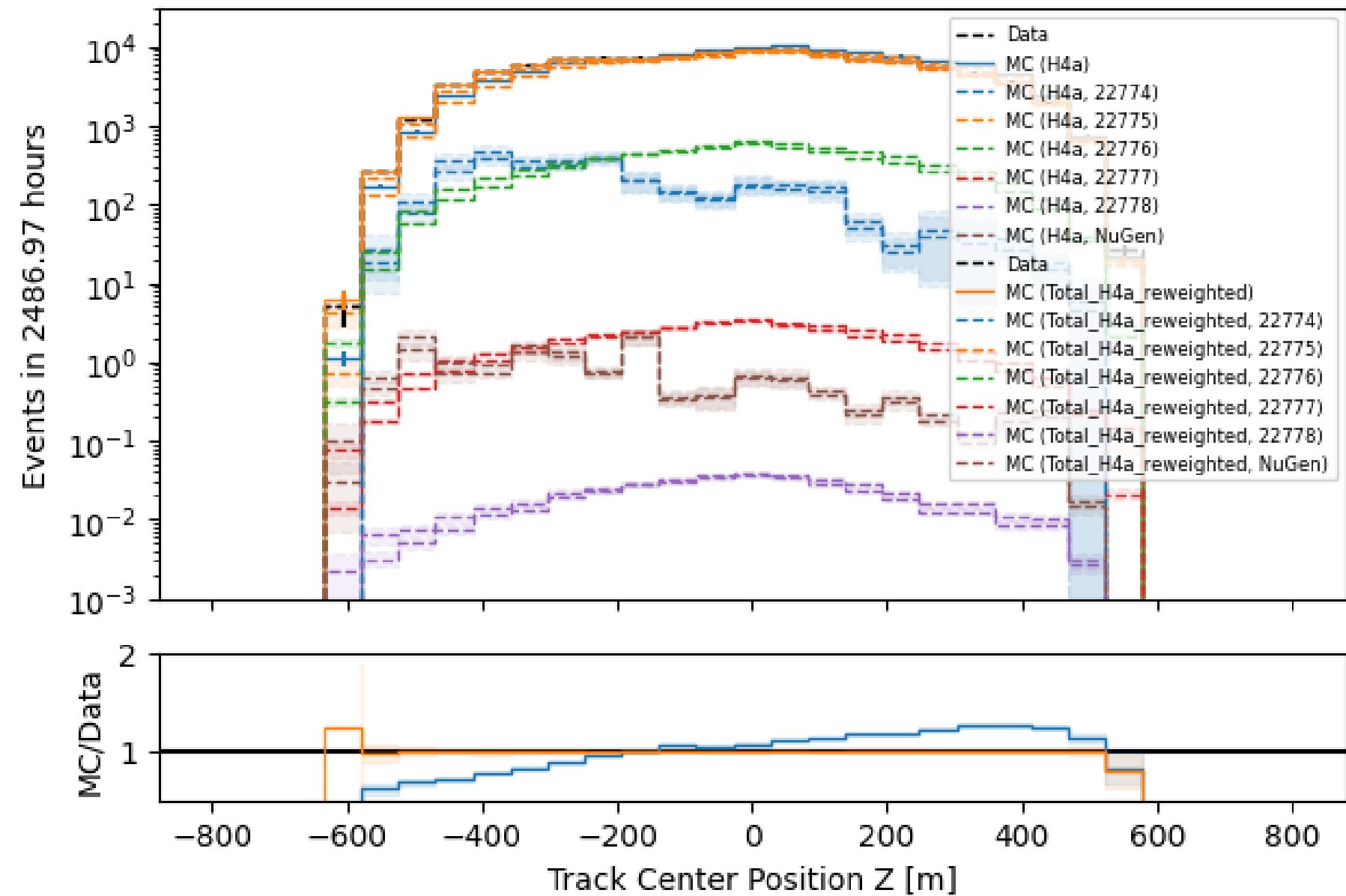


# Entry position z—vertex

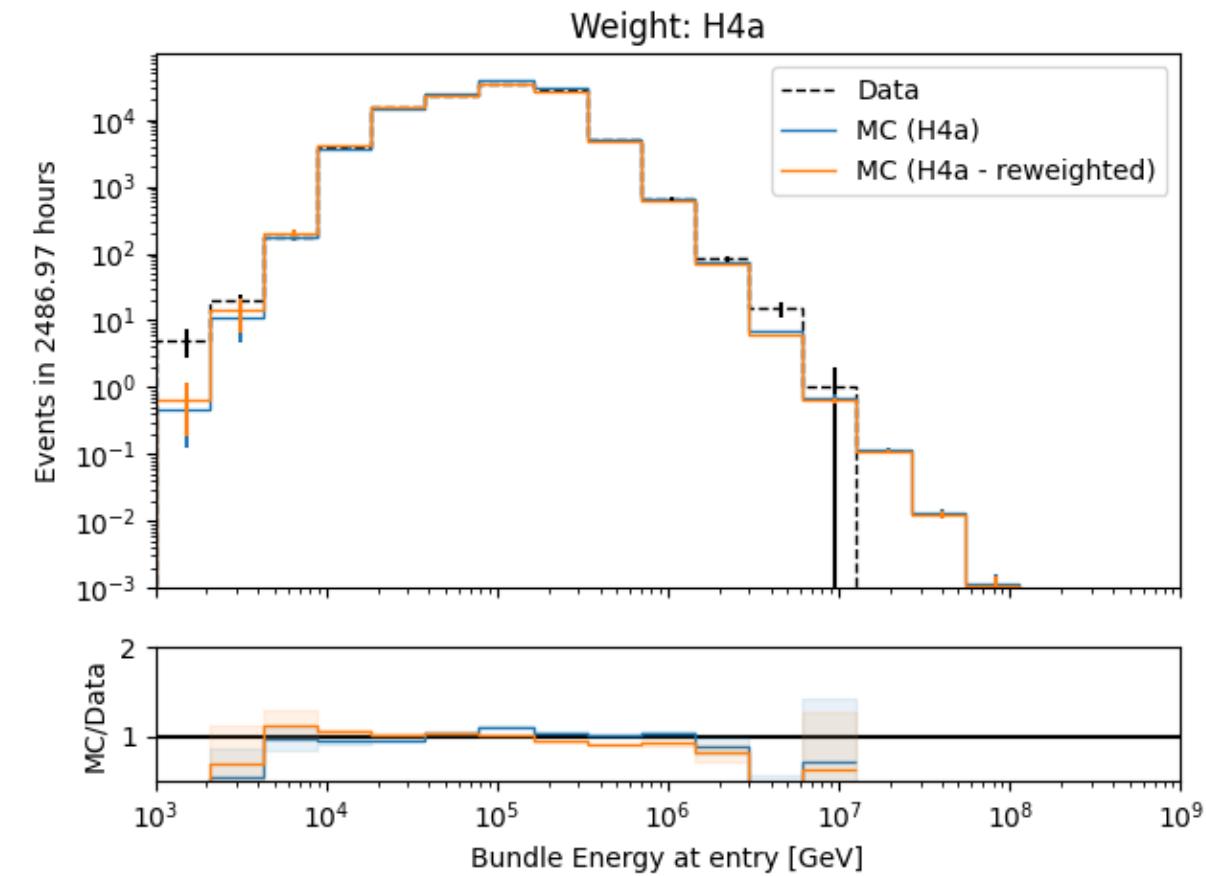
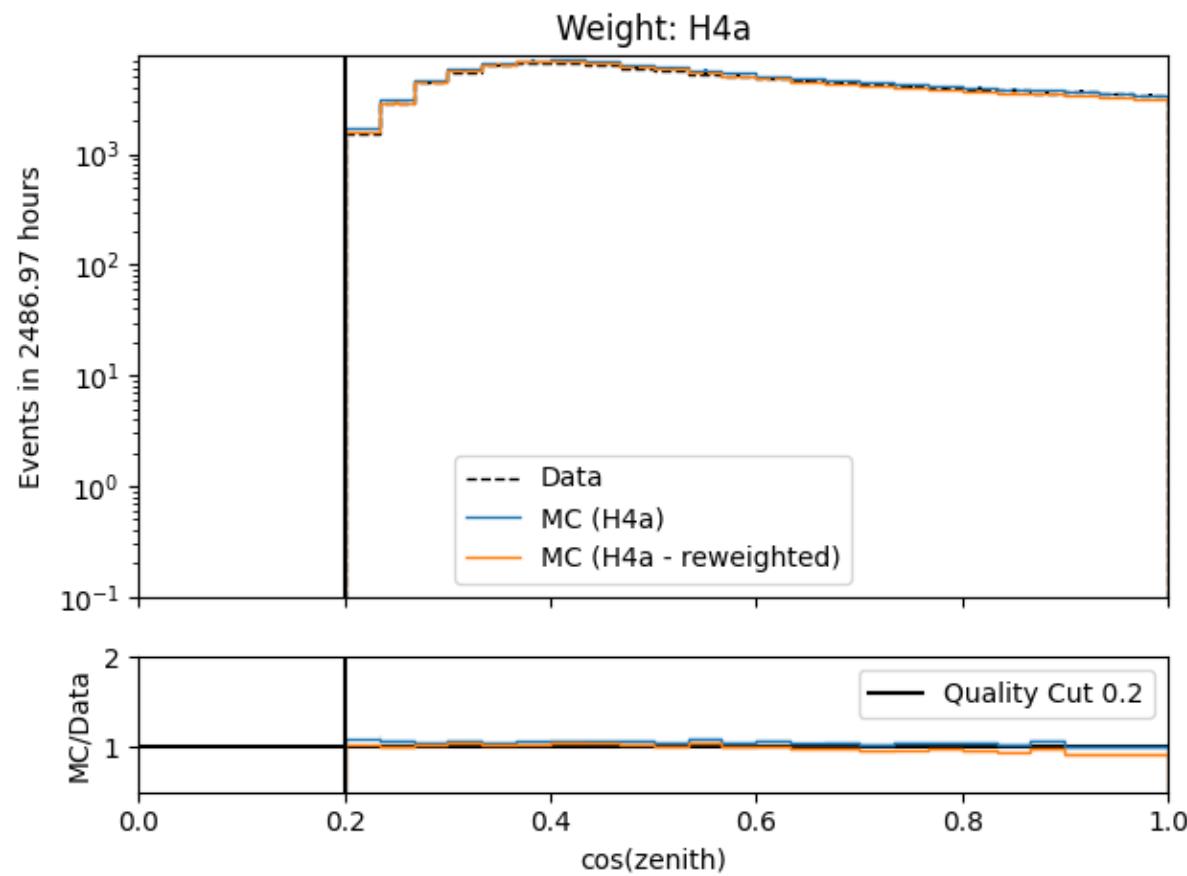


## z—reweighting

- re-weight events to enforce a perfect agreement in the center z—position



# Check z—reweighting



➤ re-weighting has no large effect on  $\cos(\text{zenith})$  and energy

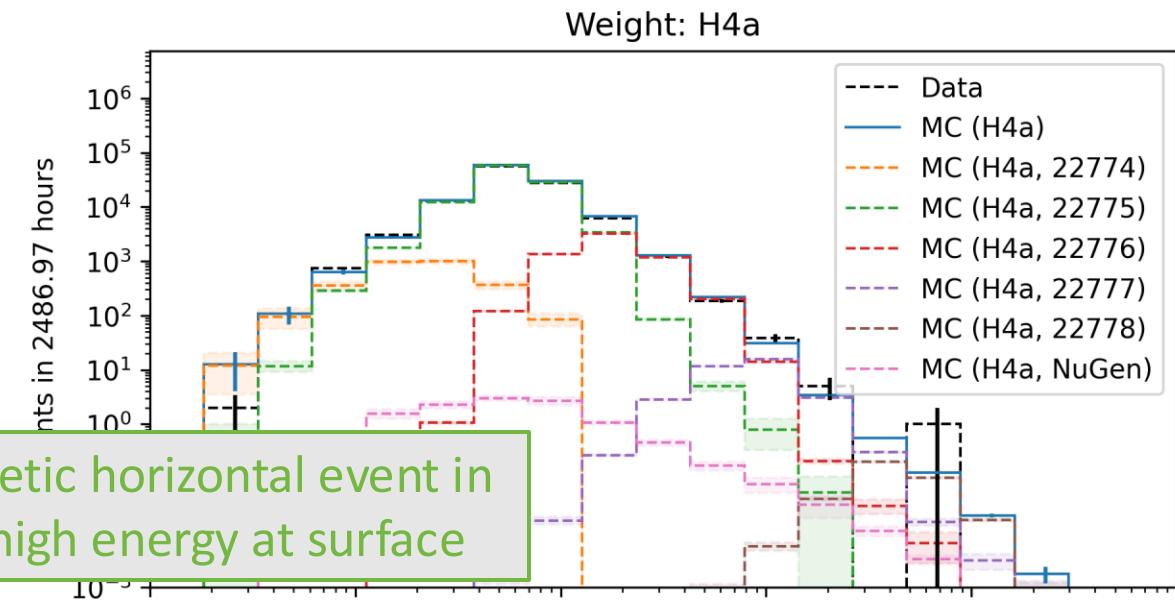
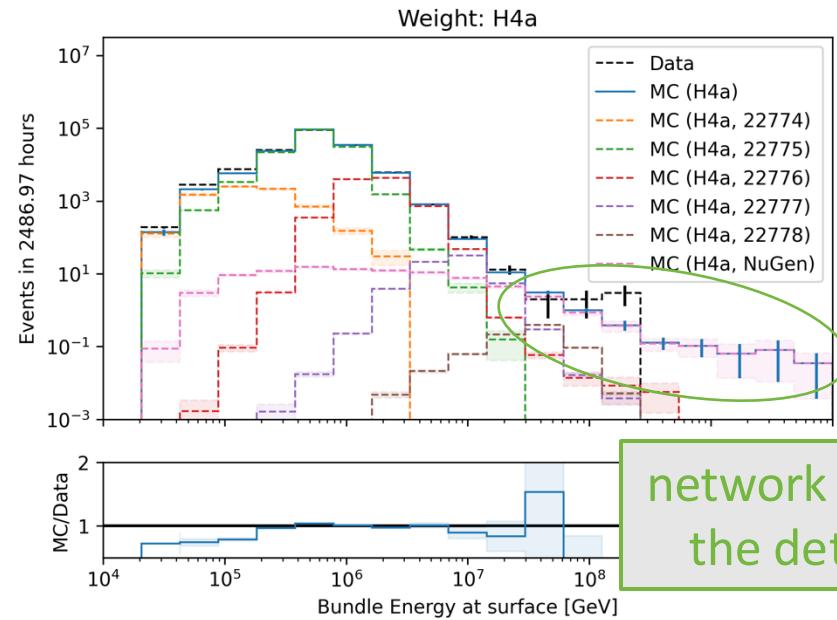
# Level5: quality cuts

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

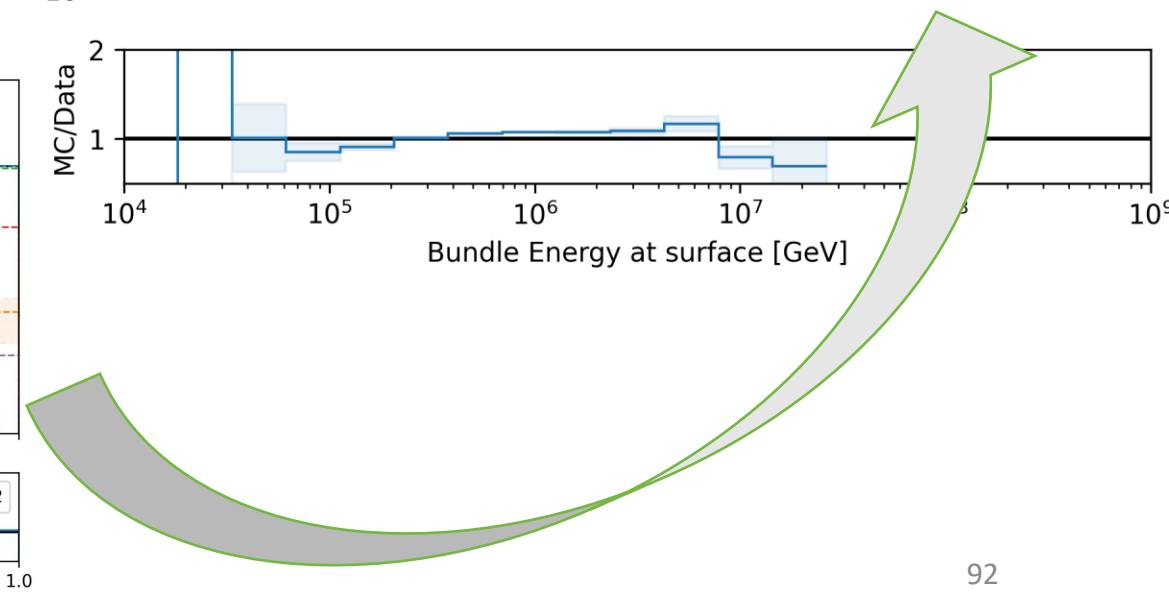
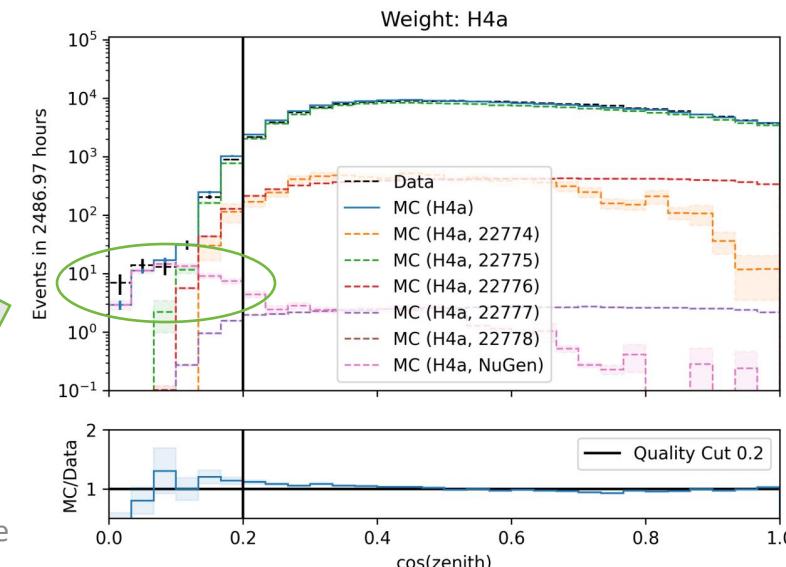
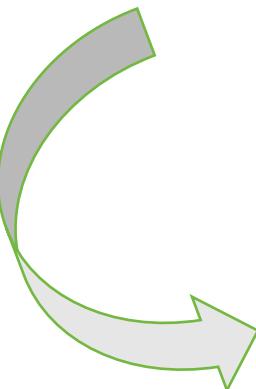
neutrino cuts	>	<
$\cos(\text{zenith})$	0.2	
length	5000 m	15000 m

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

# Level5: quality cuts → removes neutrinos



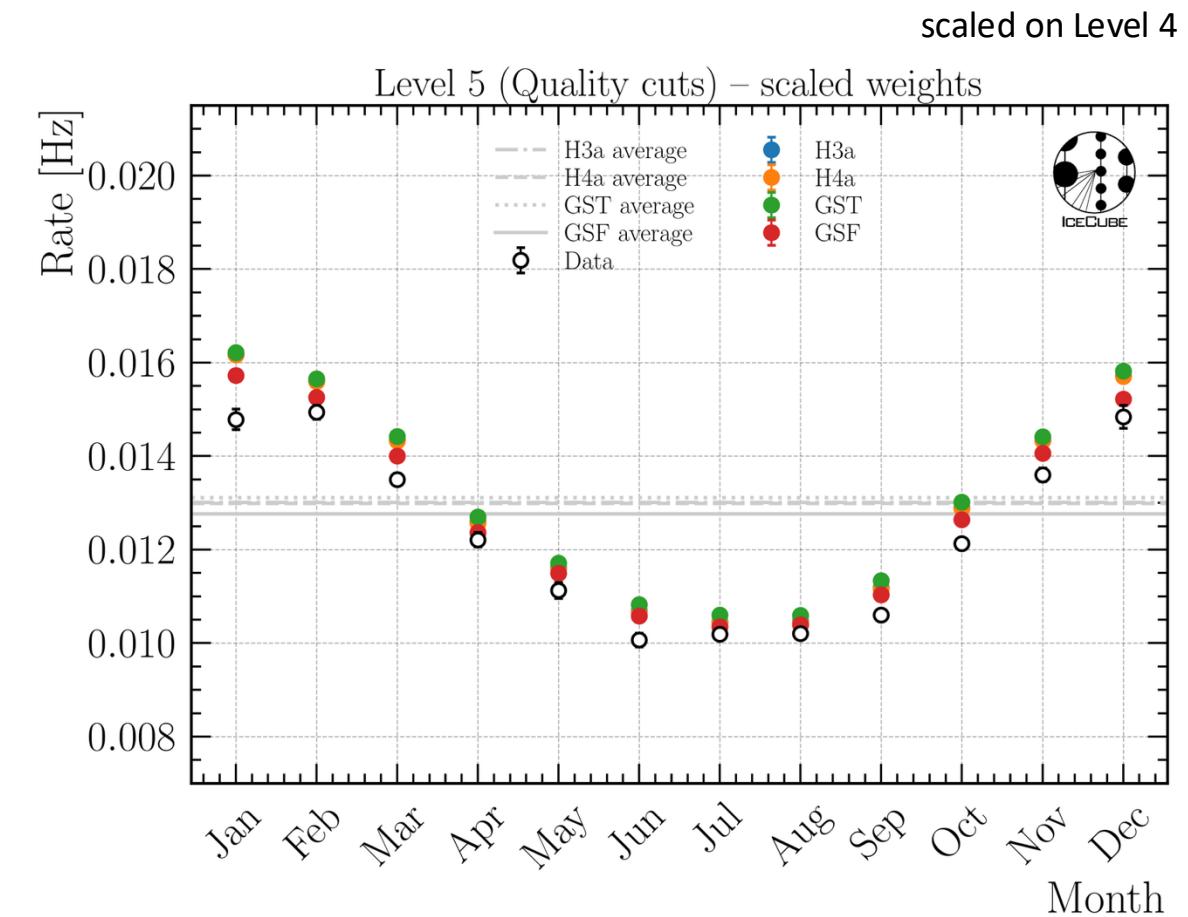
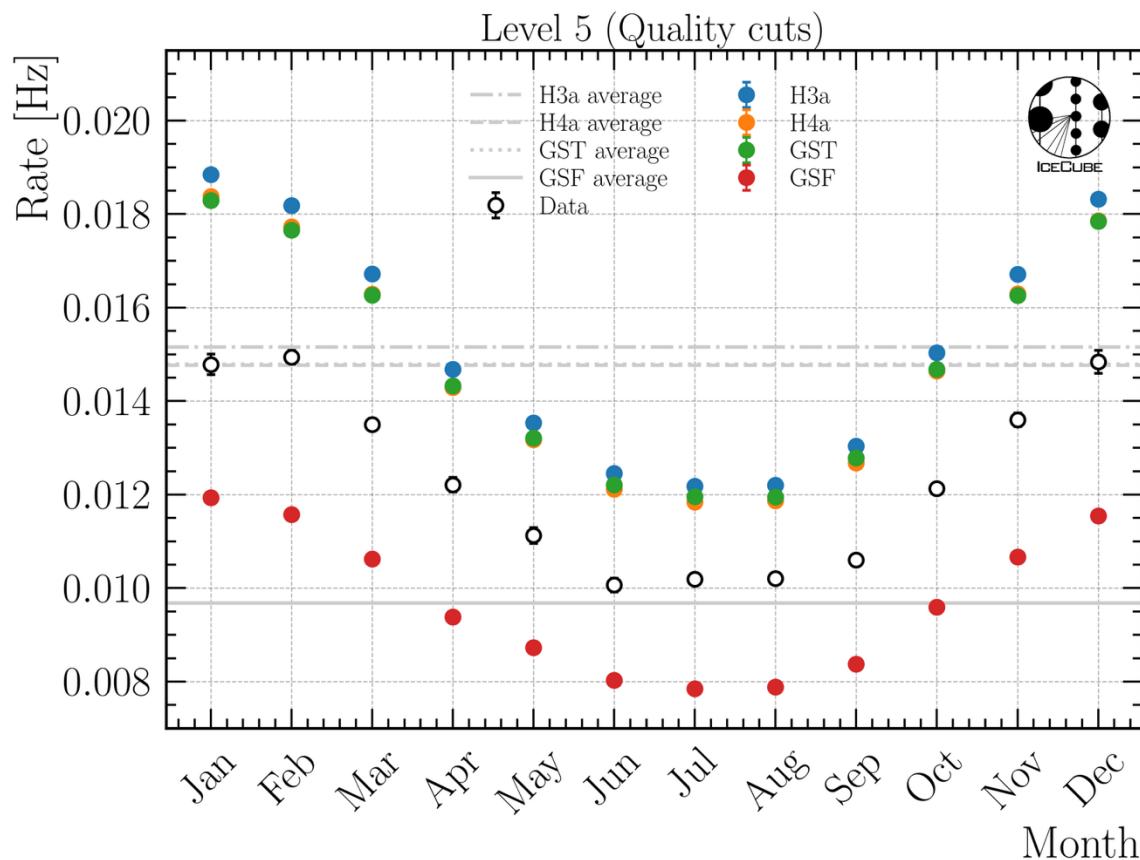
network learns: a high-energetic horizontal event in  
the detector needs a very high energy at surface



# Rates per month

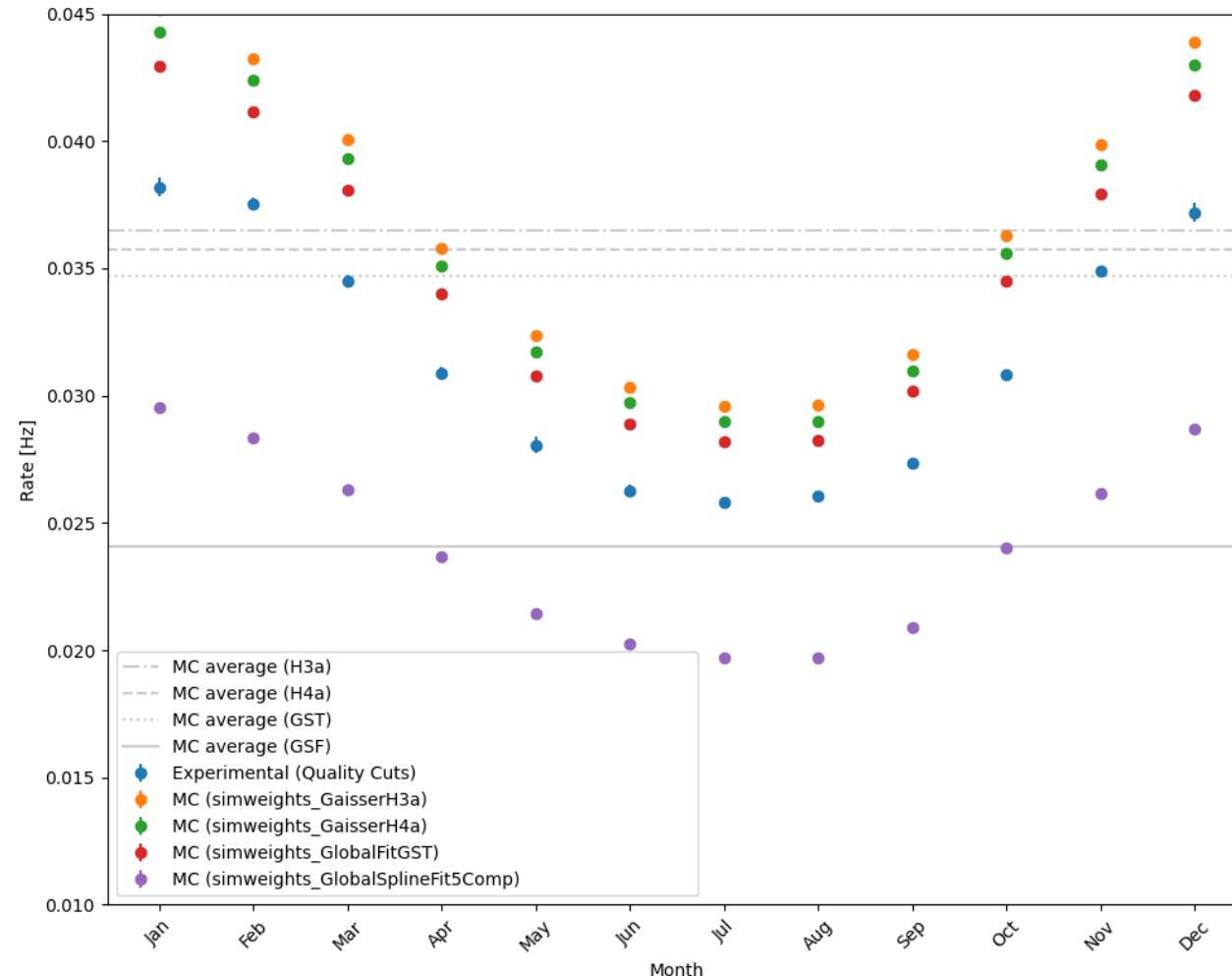
Data-MC

# Rates per month – Level 5

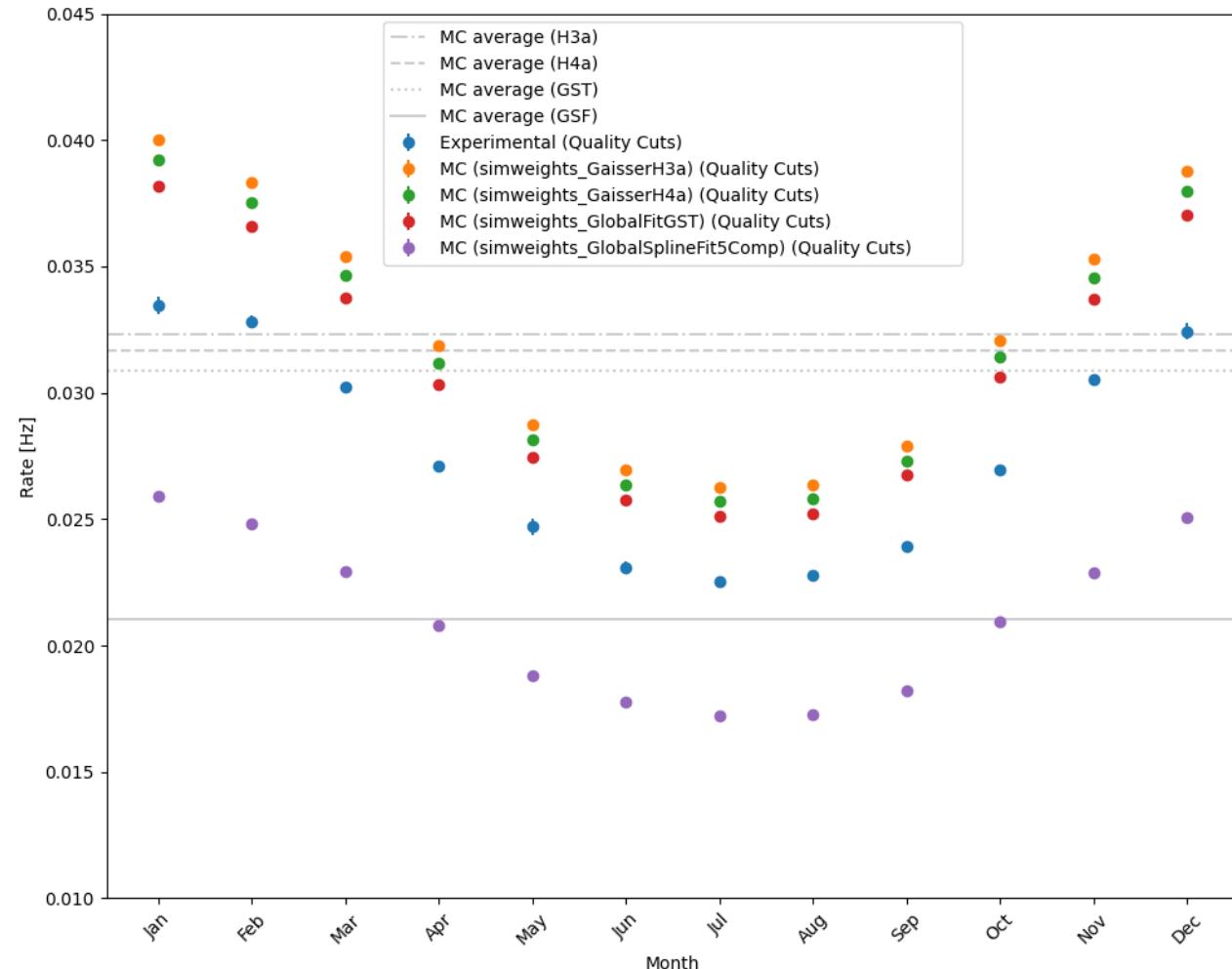


# Rates per month

before quality cuts

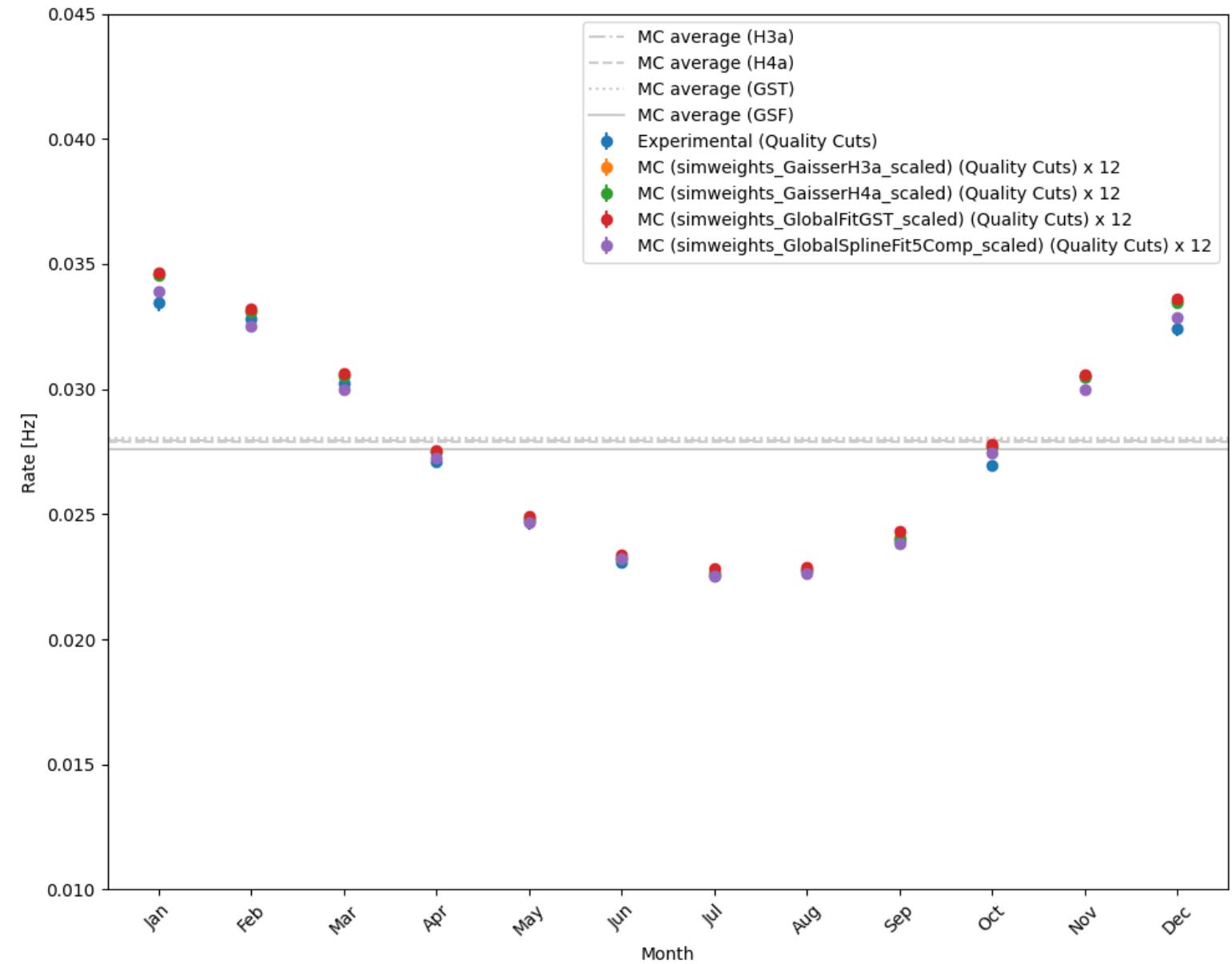


after quality cuts



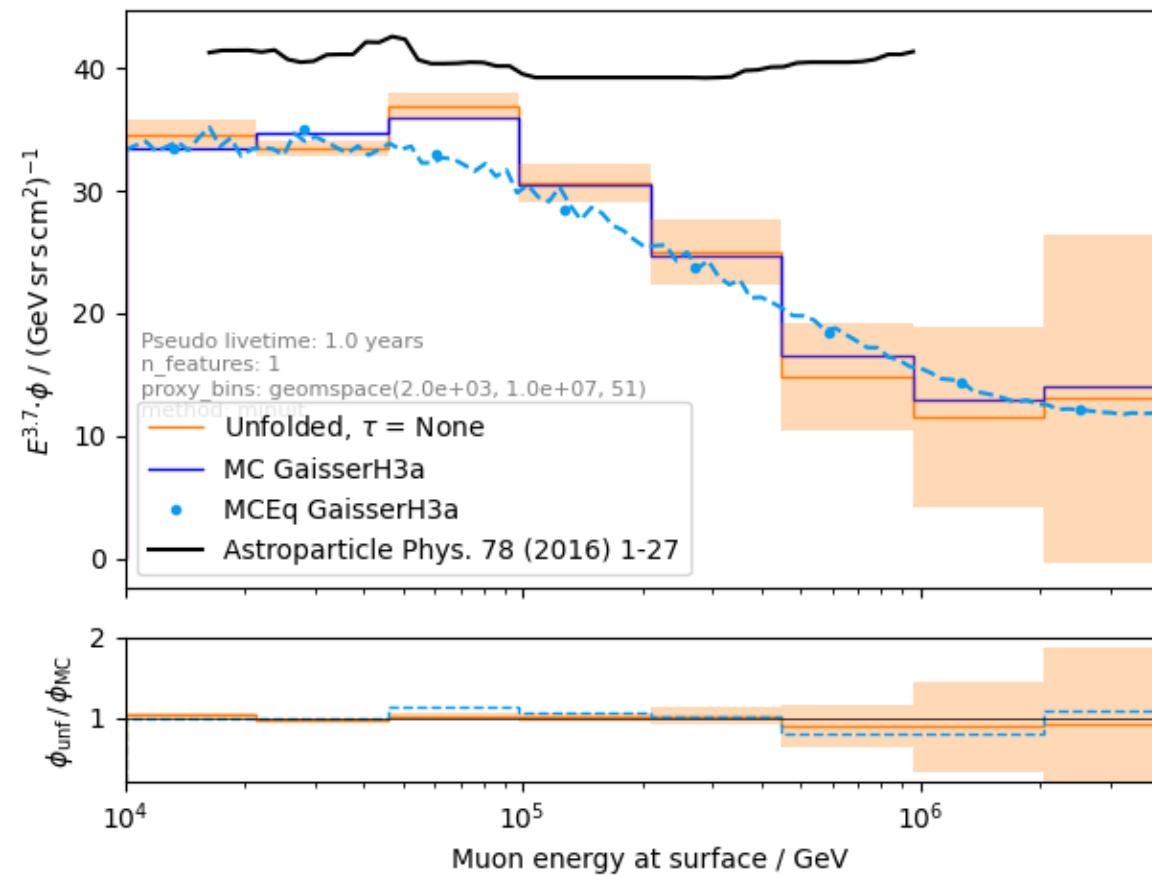
# Rates per month: scaled

- Rates are scaled to the experimental rate to compare the shapes
- Good agreement per month

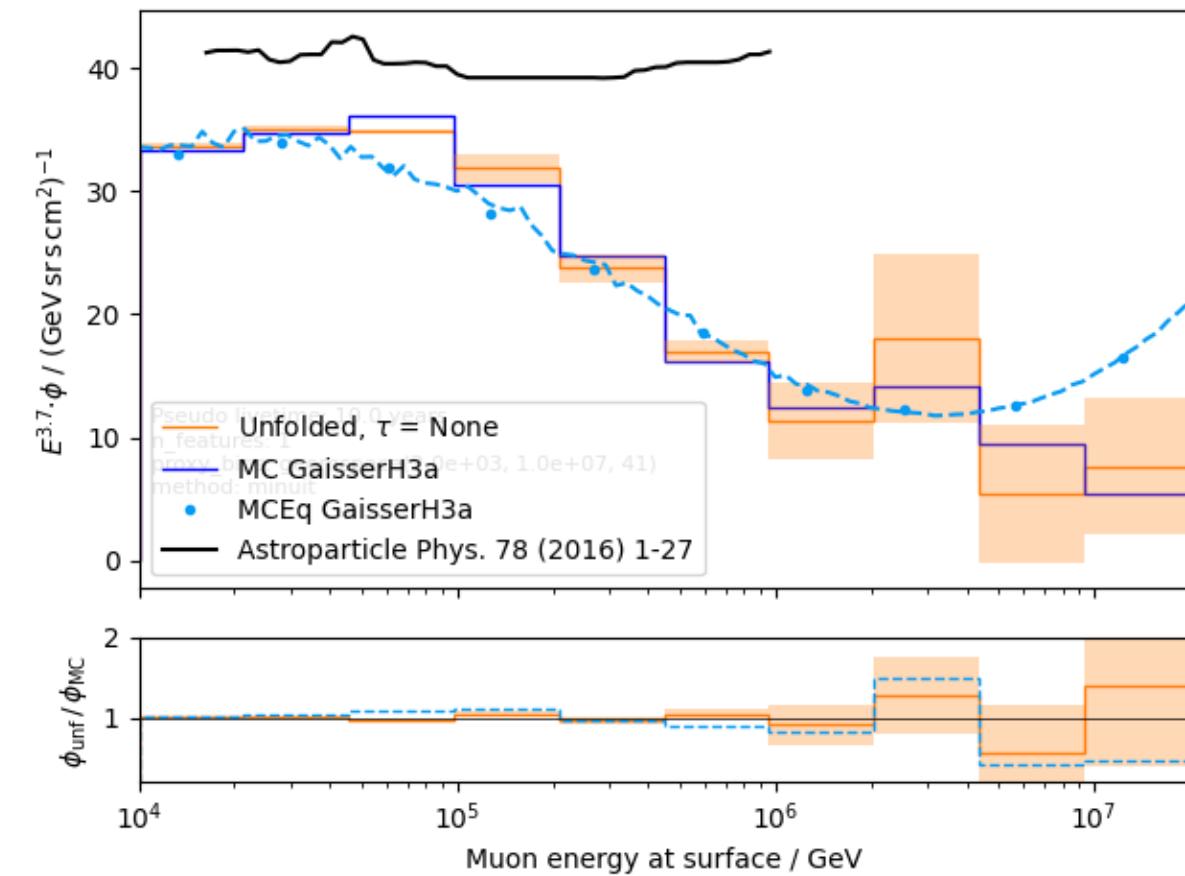


unfolding of muon flux at surface – weighted to  $E^{3.7}$ 

1 year



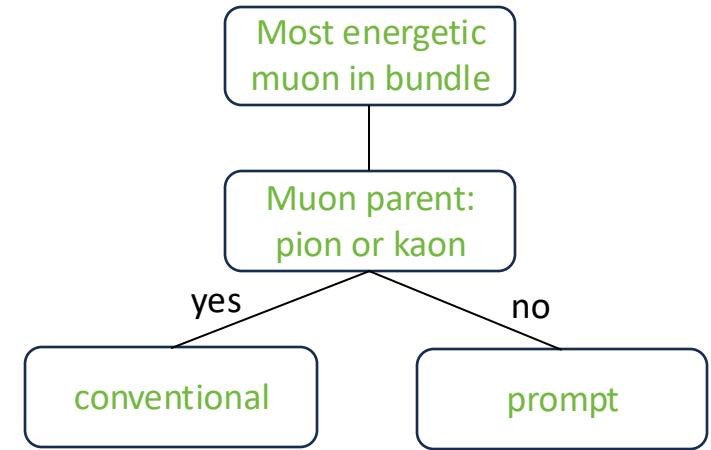
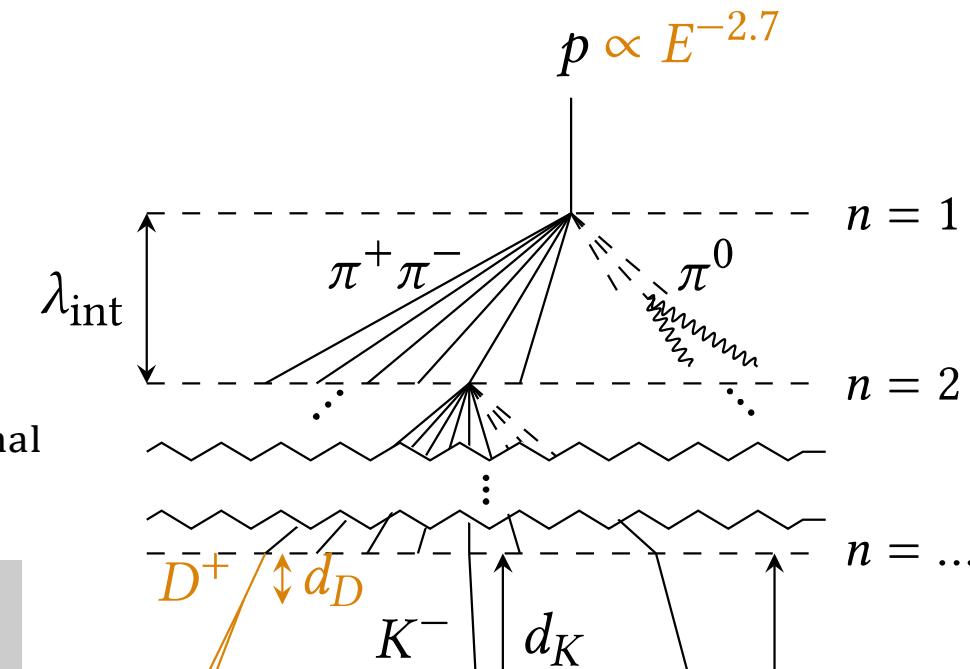
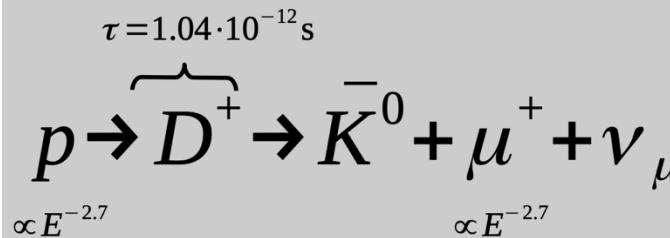
10 years



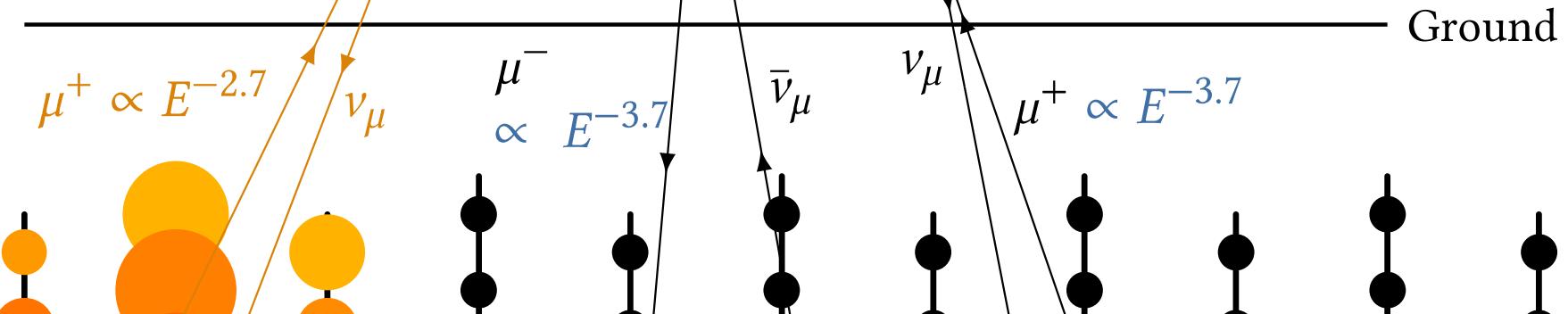
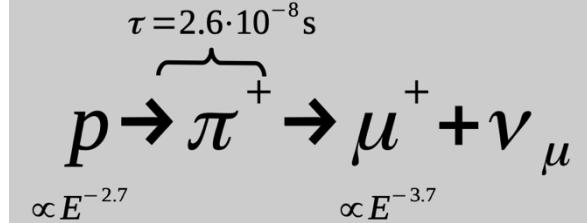
# Muon flux

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

**prompt component:**

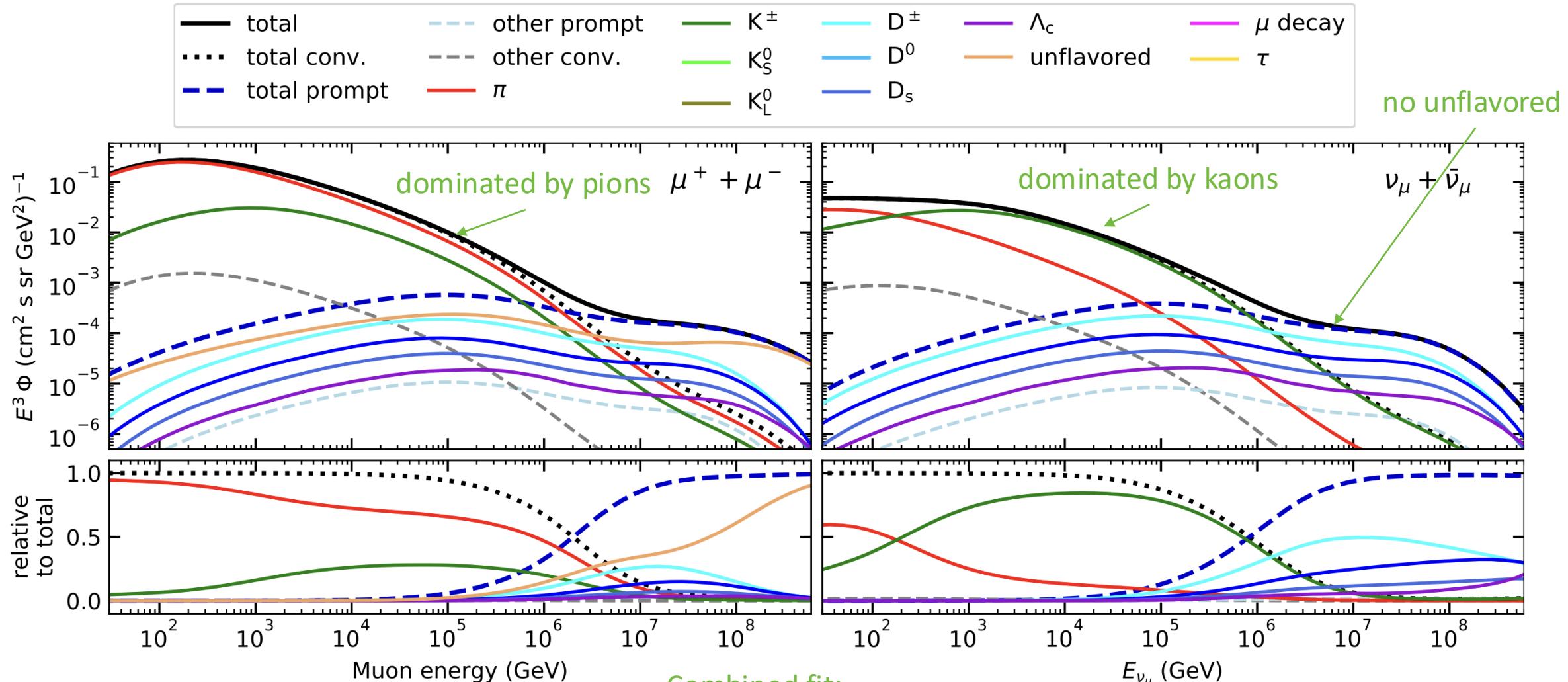


**Conventional component:**



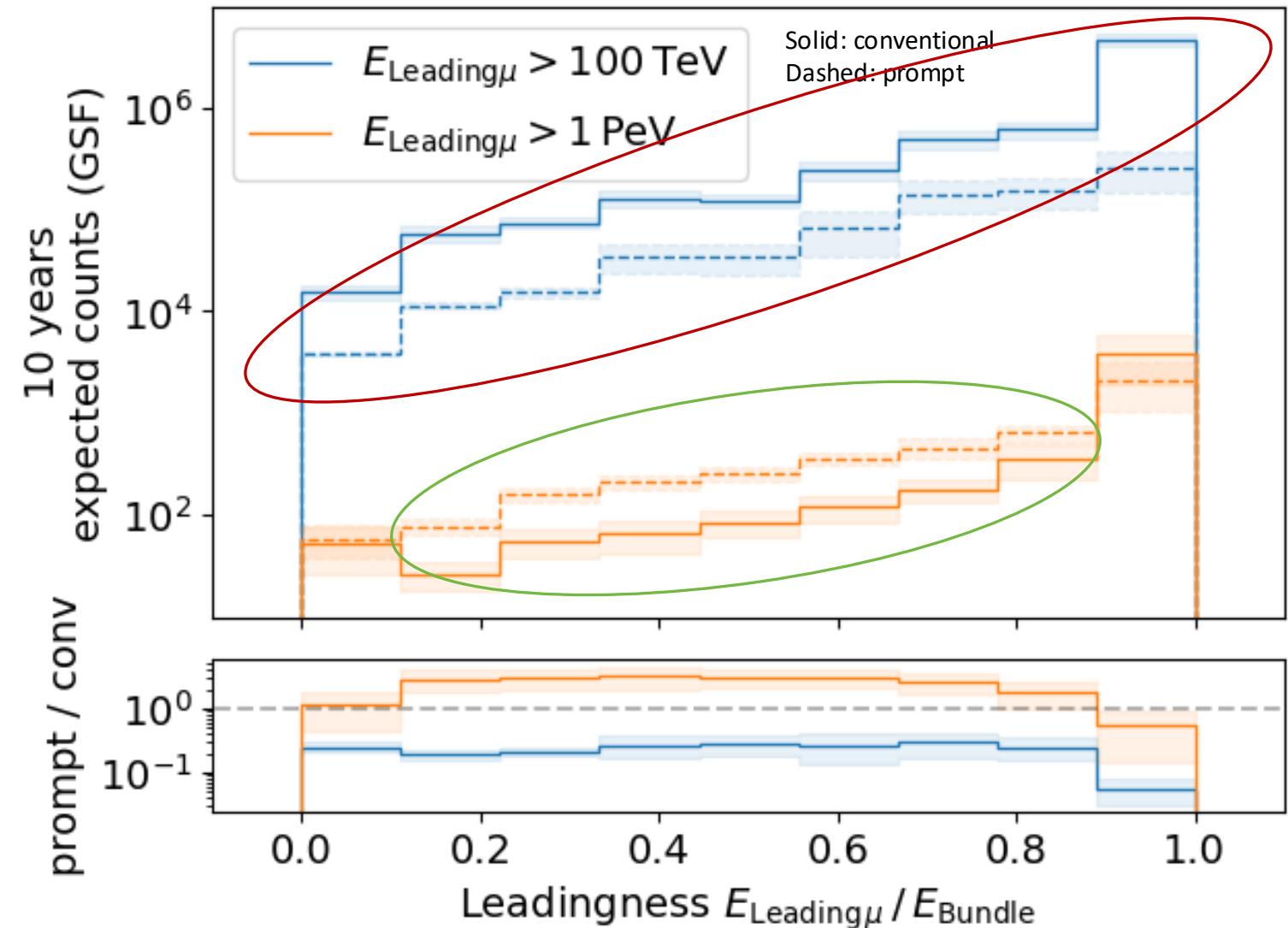
# Prompt atmospheric muons and neutrinos

10.1103/PhysRevD.100.103018



# Leading muon energy fraction

- Prompt dominates for energies  $> 1 \text{ PeV}$
- Leading energy sweet spot:  $0.1 - 0.9$



# Leading muon contribution

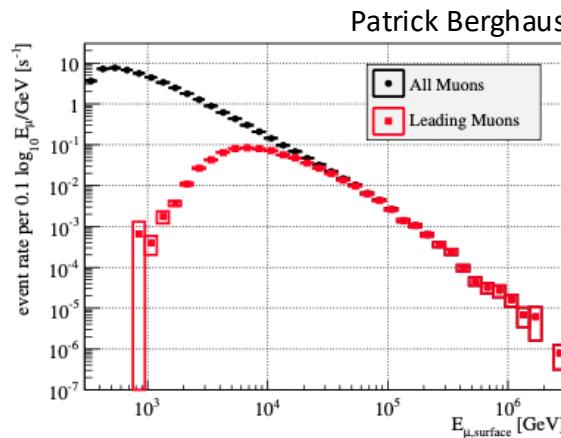
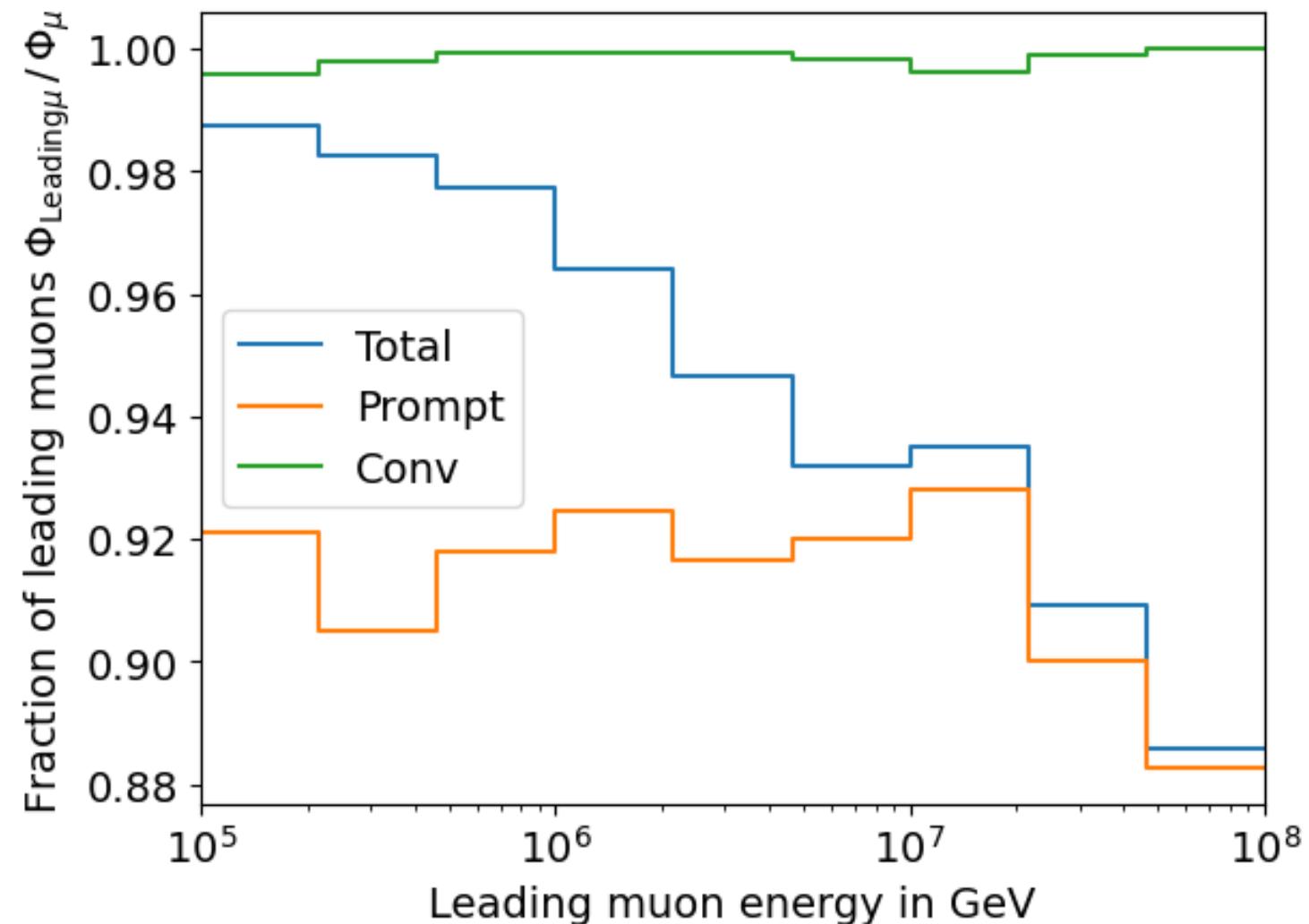


Figure 10: Surface energy distribution for all and most energetic (“leading”) muons in simulated events with a total of more than 1,000 registered photo-electrons in IceCube.

- Muons with energies between 100 TeV and 50 PeV dominate the bundle by more than 90%
  - In average conventional muons are more dominant than prompt
  - But: at high energies, there are more prompt than conventional events
- High leading energy fraction does not lead to more sensitivity to detect prompt

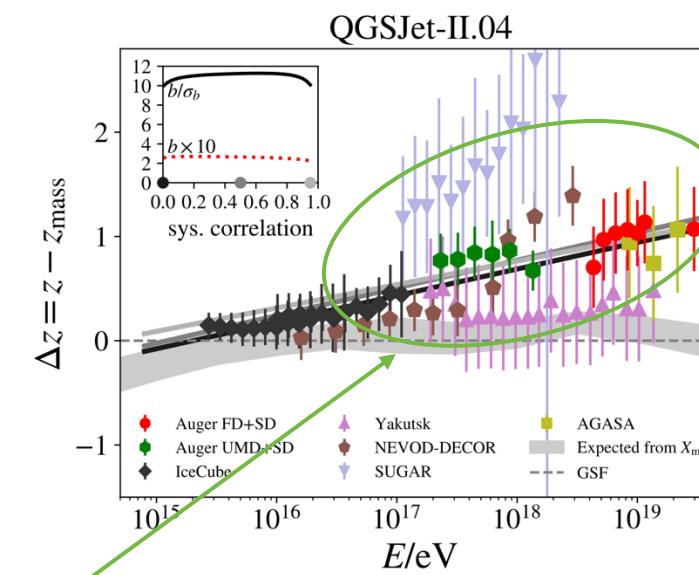
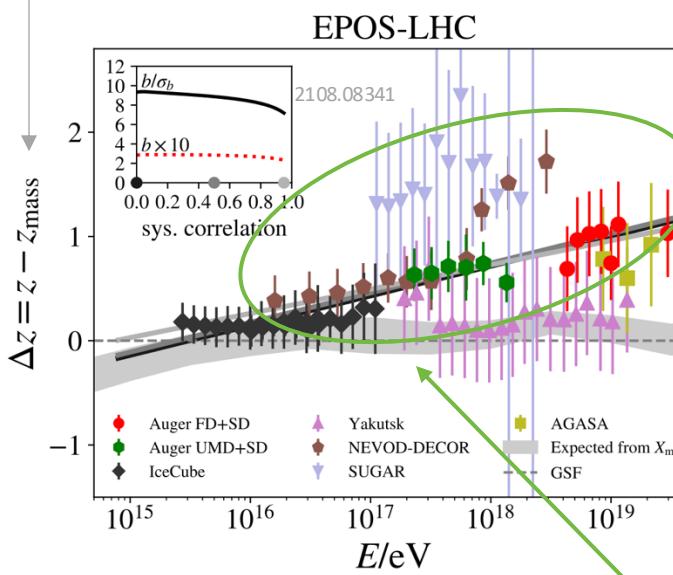


# Muon puzzle and hadronic uncertainties

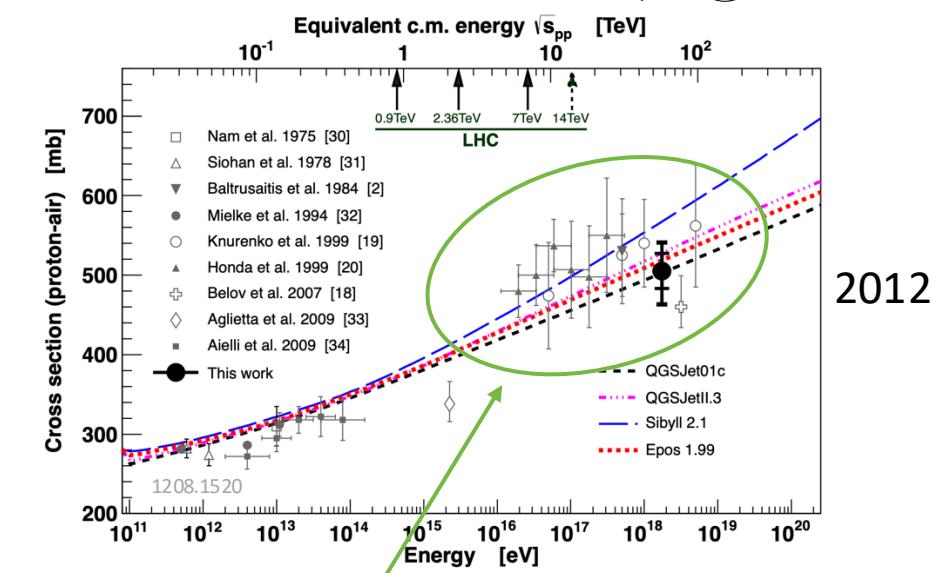
"muon number"

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

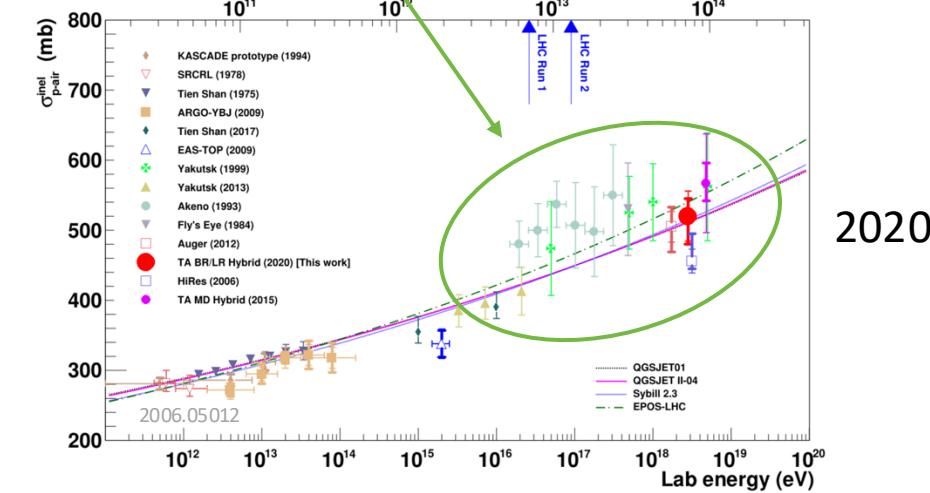
Expected  $z$   
("muon number")



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



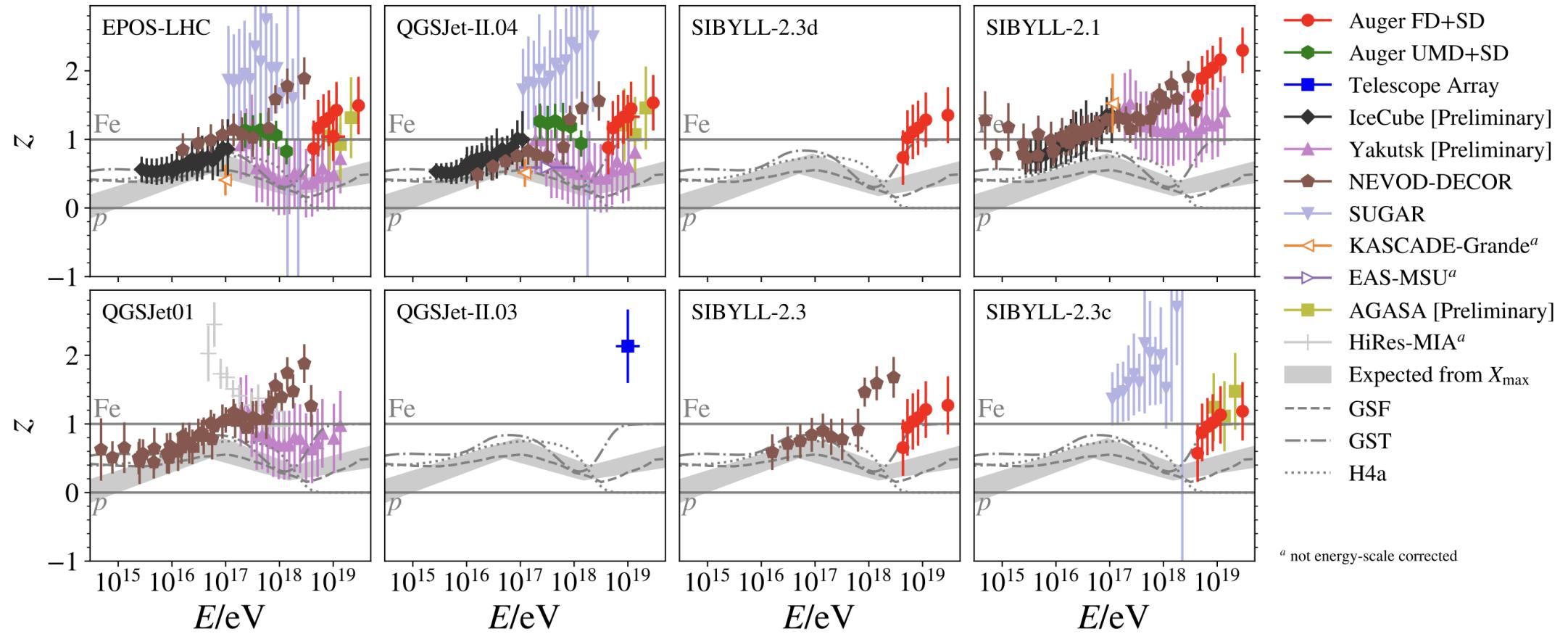
➤ Uncertainties at  $E > 10 \text{ PeV}$



# The Muon Puzzle

"muon number"

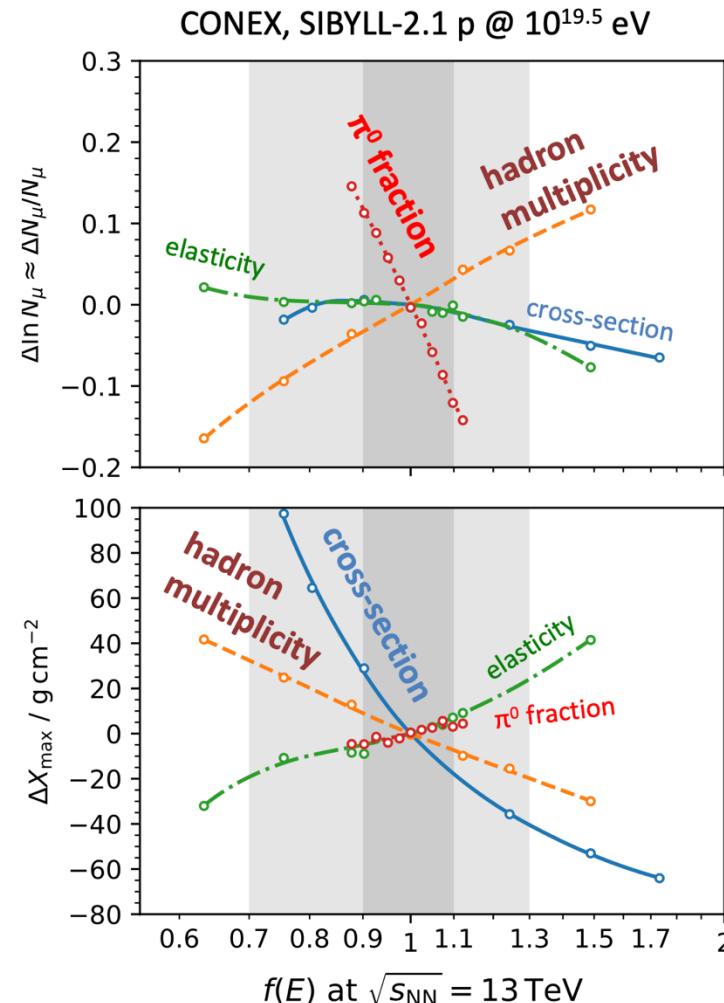
$$z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_p}{\ln\langle N_\mu \rangle_{\text{Fe}} - \ln\langle N_\mu \rangle_p}$$



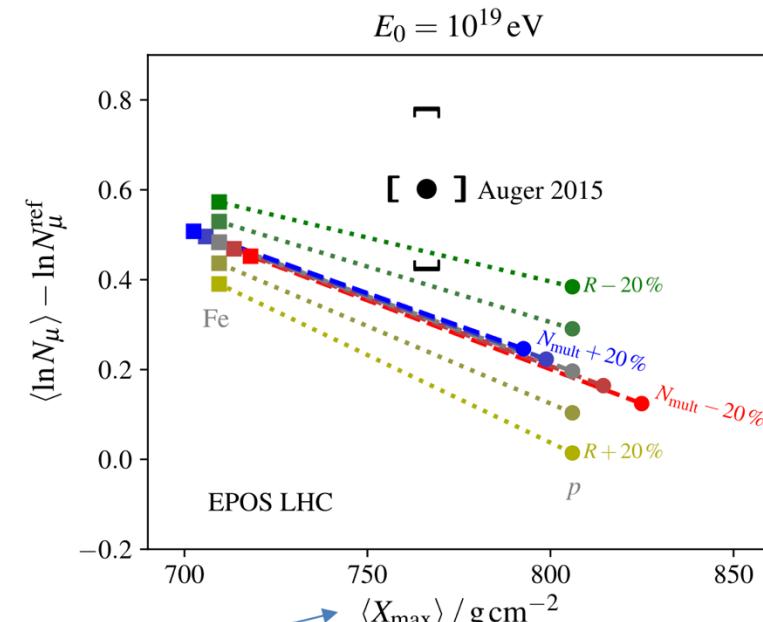
2108.08341

# Possible Solutions

R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026



S. Baur, HD, M. Perlin, T. Pierog, R. Ulrich, K. Werner,  
arXiv:1902.09265

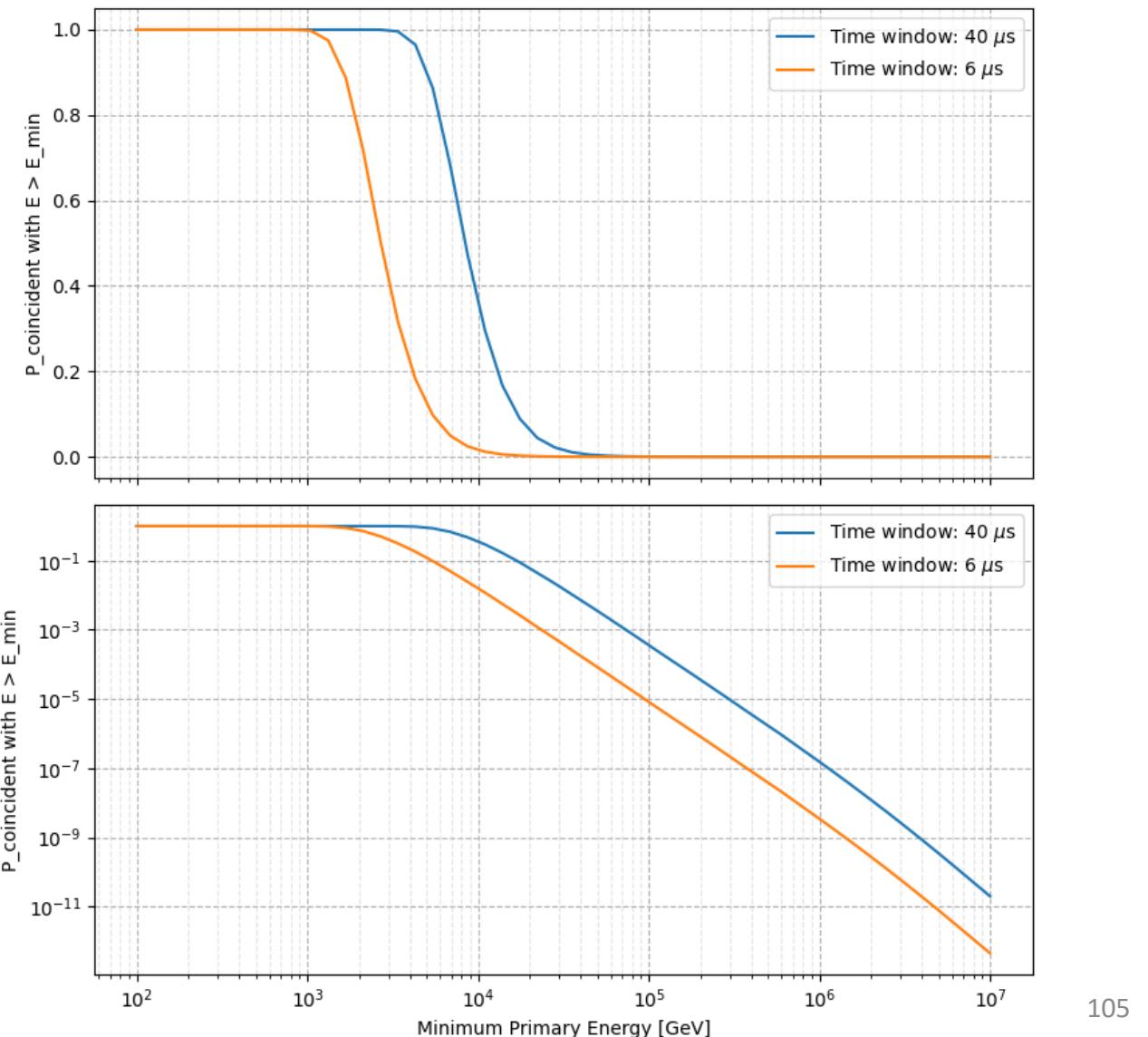


$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

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

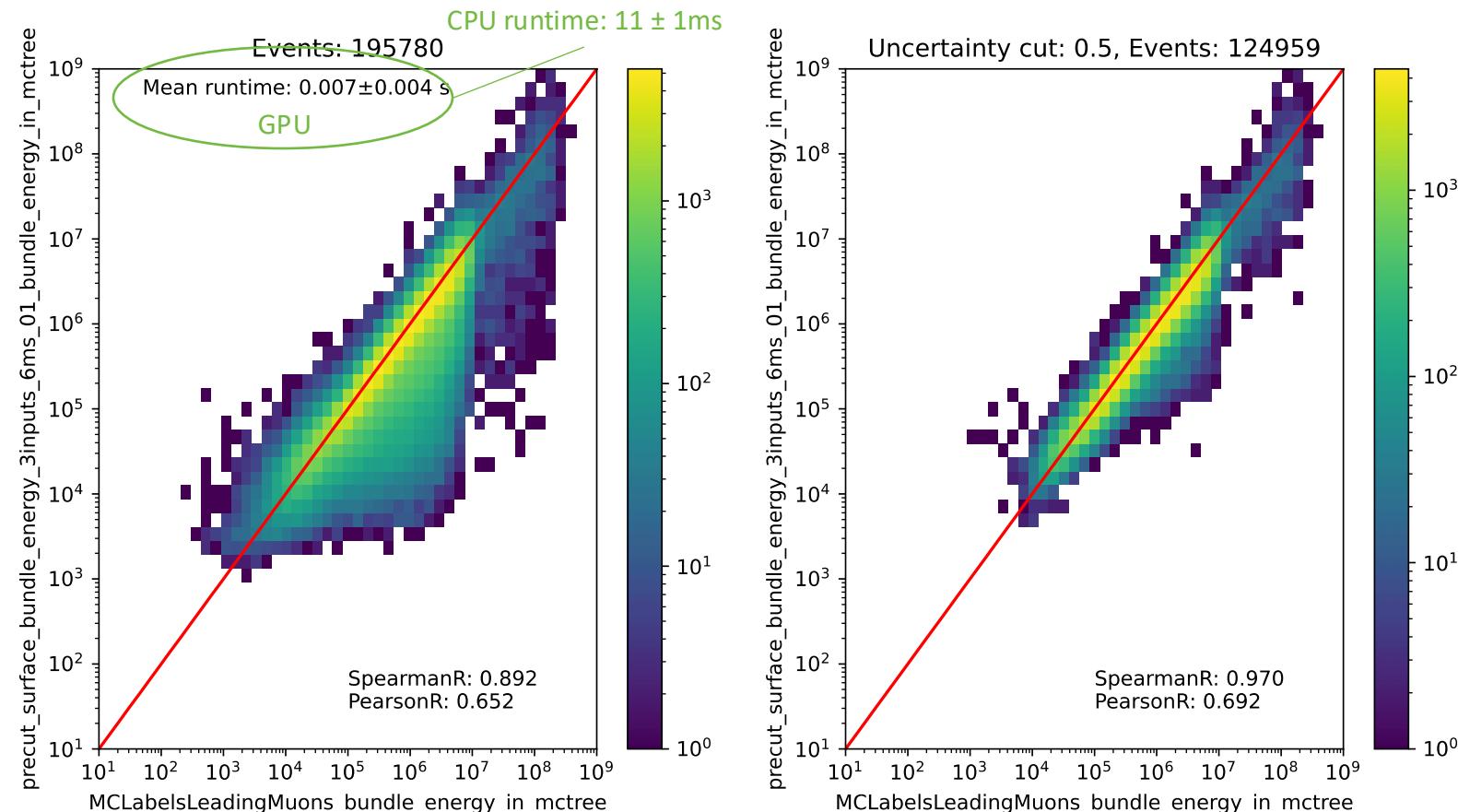
# Simulation w/o coincident events

- for primary energies above 10 TeV, using a time window of 6  $\mu$ s, the chance for a coincident event is  $\leq 1\%$



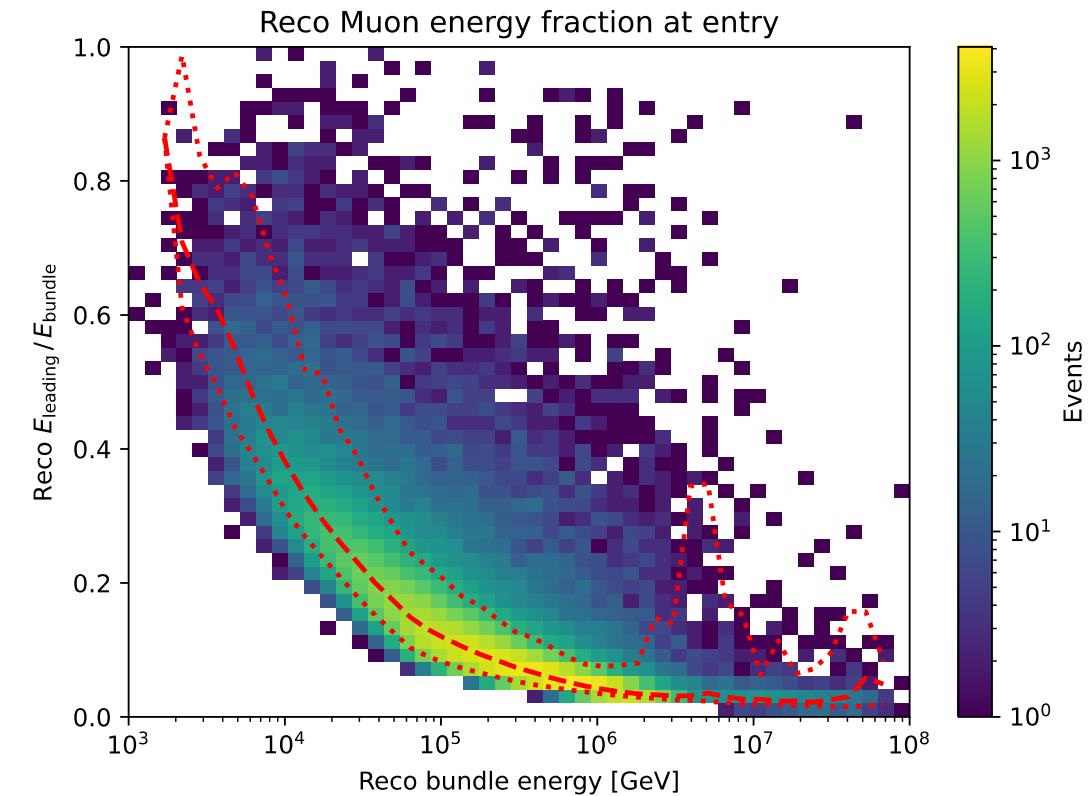
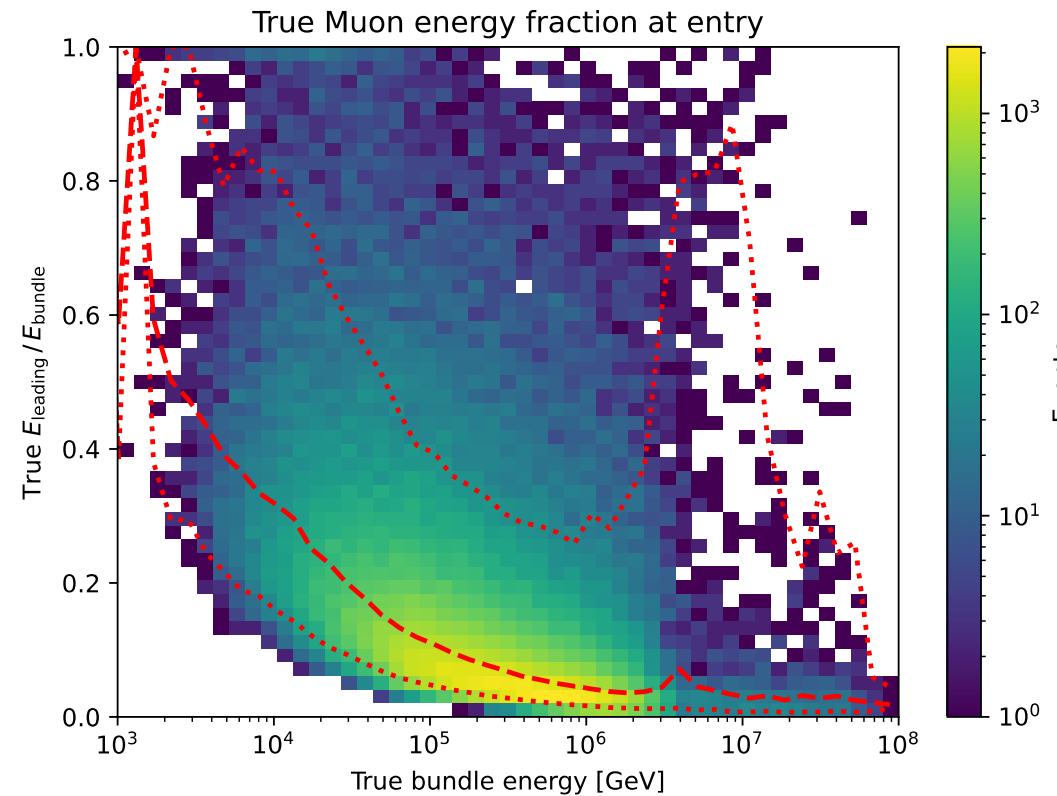
# Bundle energy cut

- Rate after muon filter: 24.62 Hz
- If the process of 1 event needs 1 second, 8h run takes 200h -> needs to be reduced!
- Use small, fast network to remove low energy events -> target rate 125 mHz

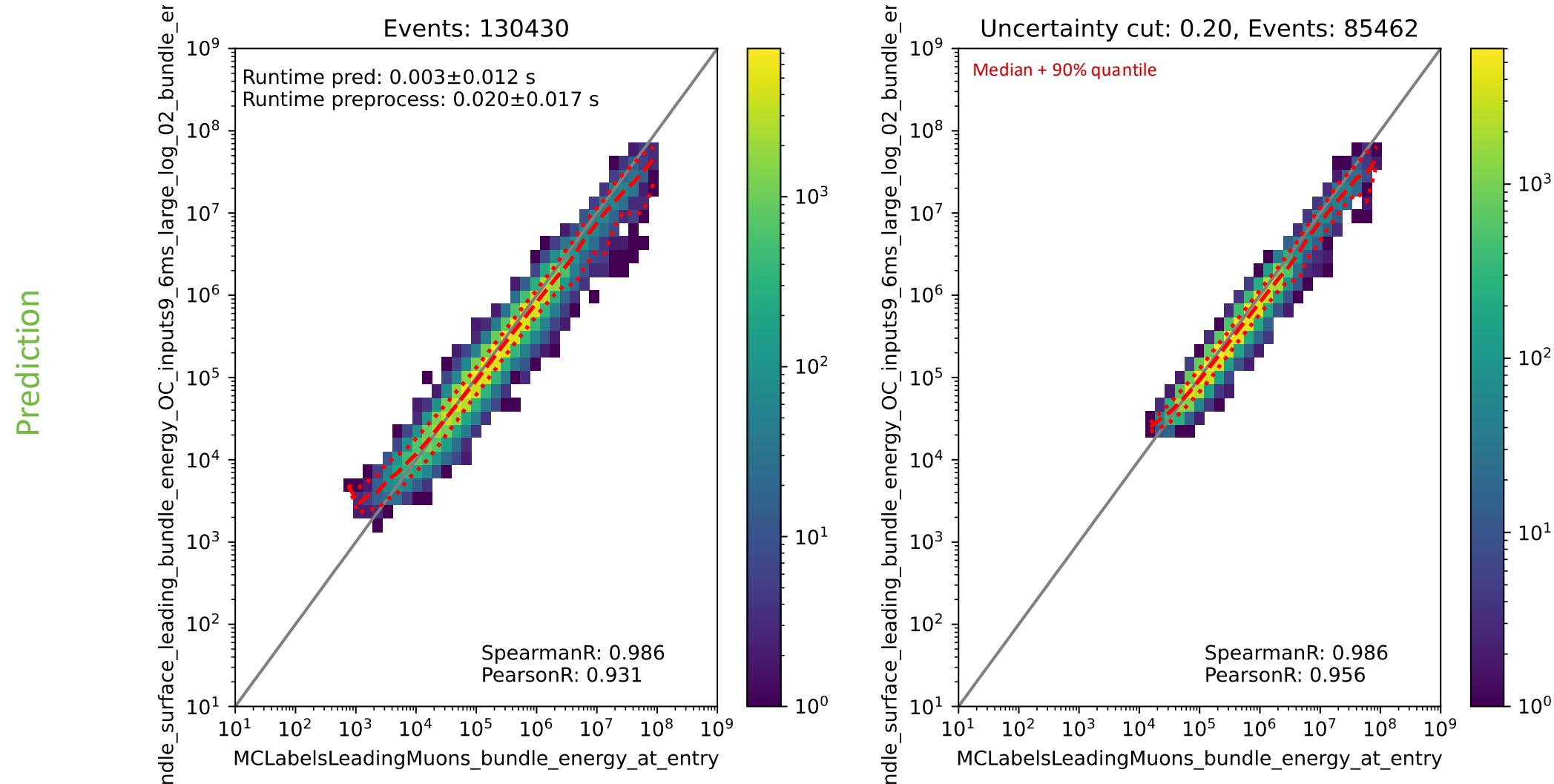


# Leading muon energy fraction - leadingness

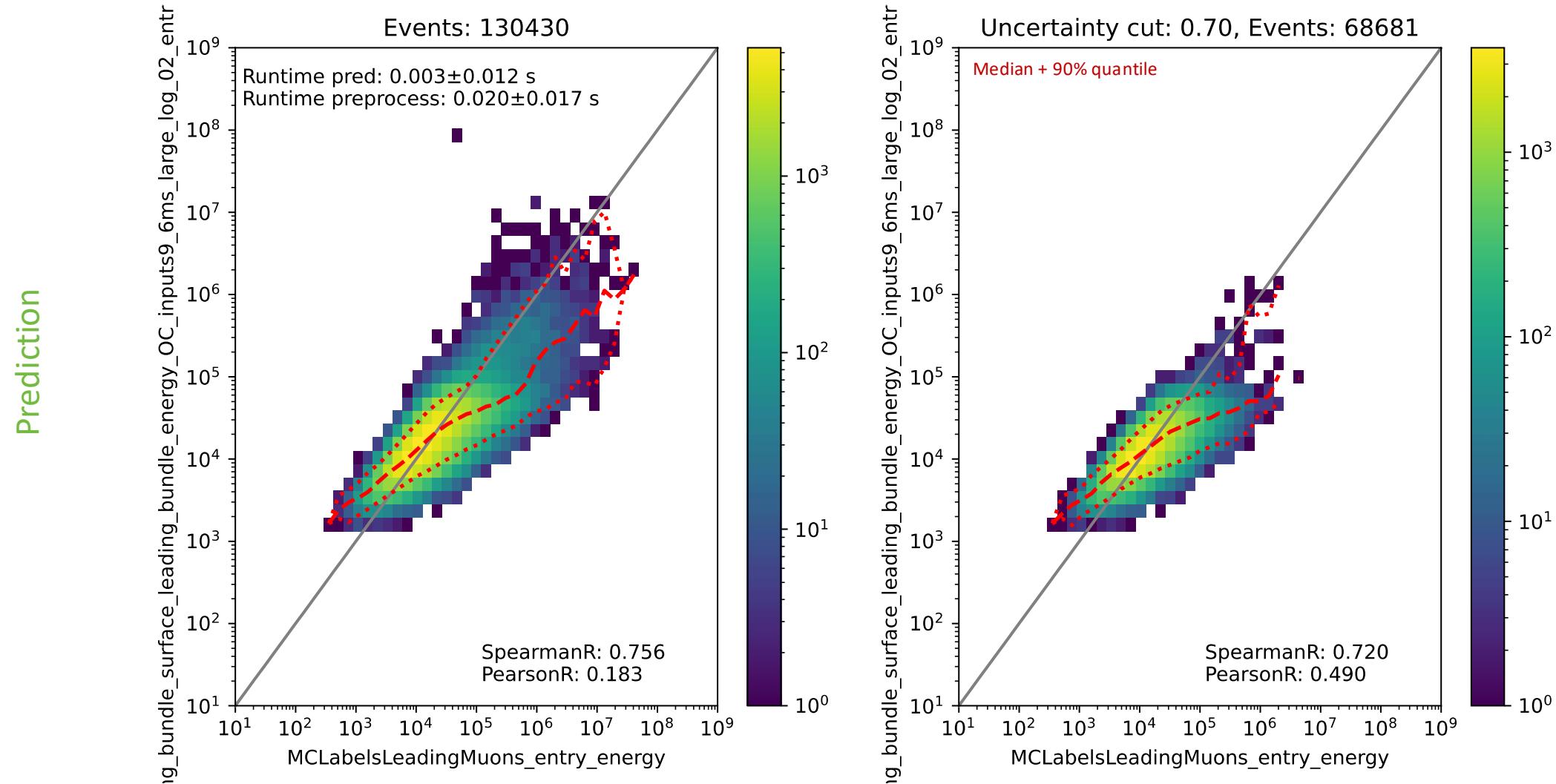
- True muon energy fraction is smeared
- Network tries to predict the median of the distribution



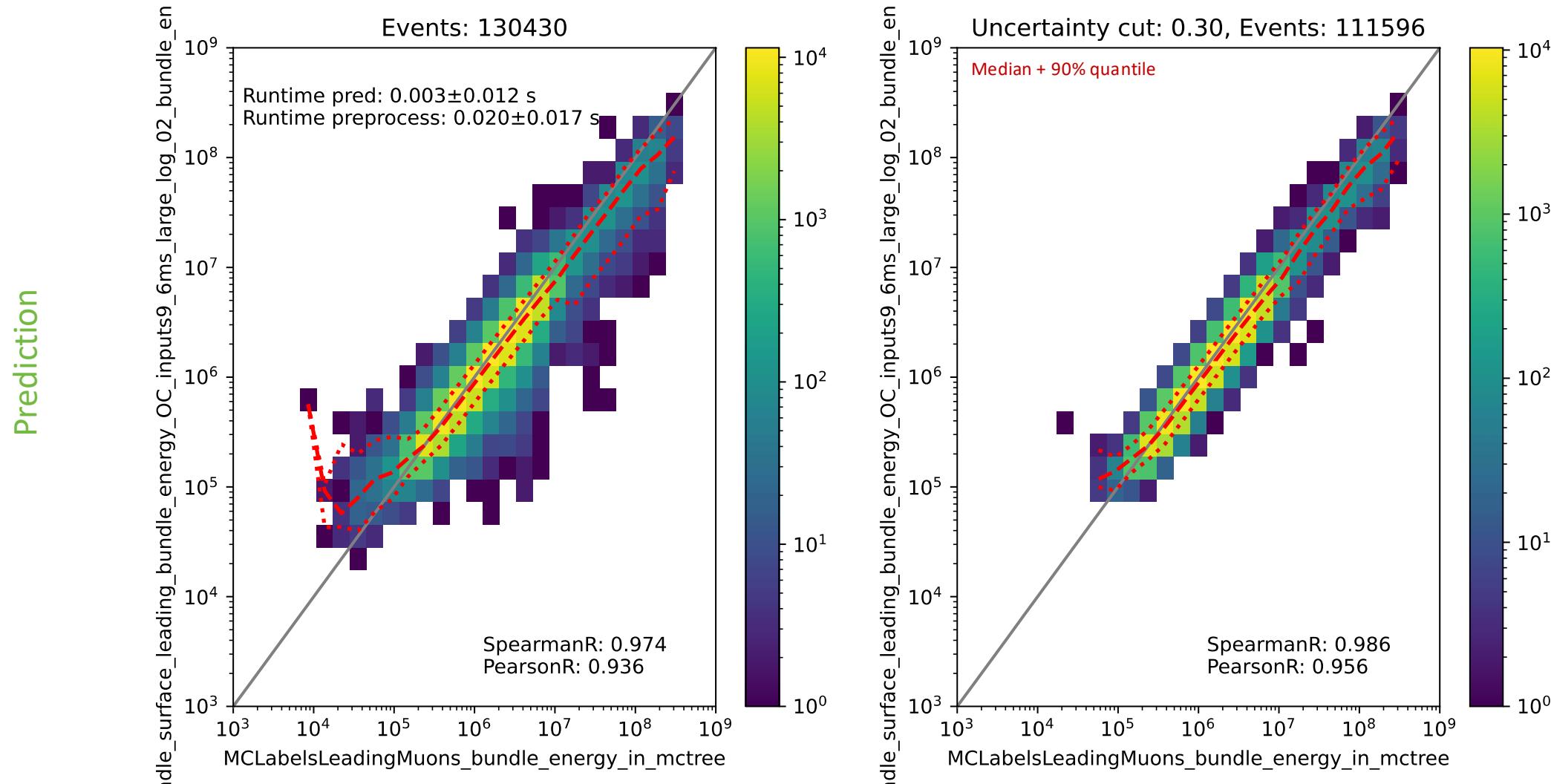
# Bundle energy at entry – 6 $\mu$ s cleaned pulses



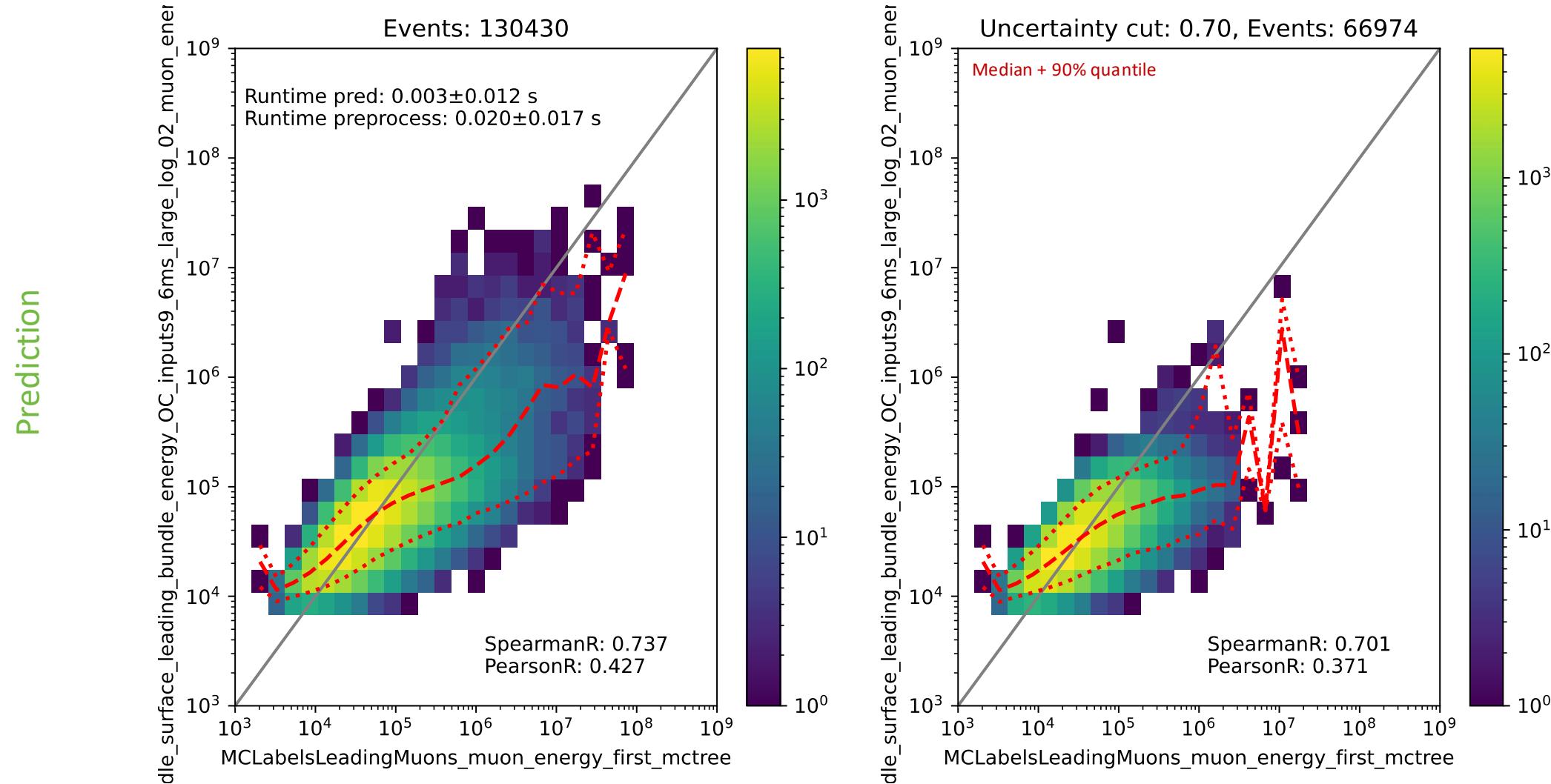
# Leading muon energy at entry – 6 $\mu$ s cleaned pulses



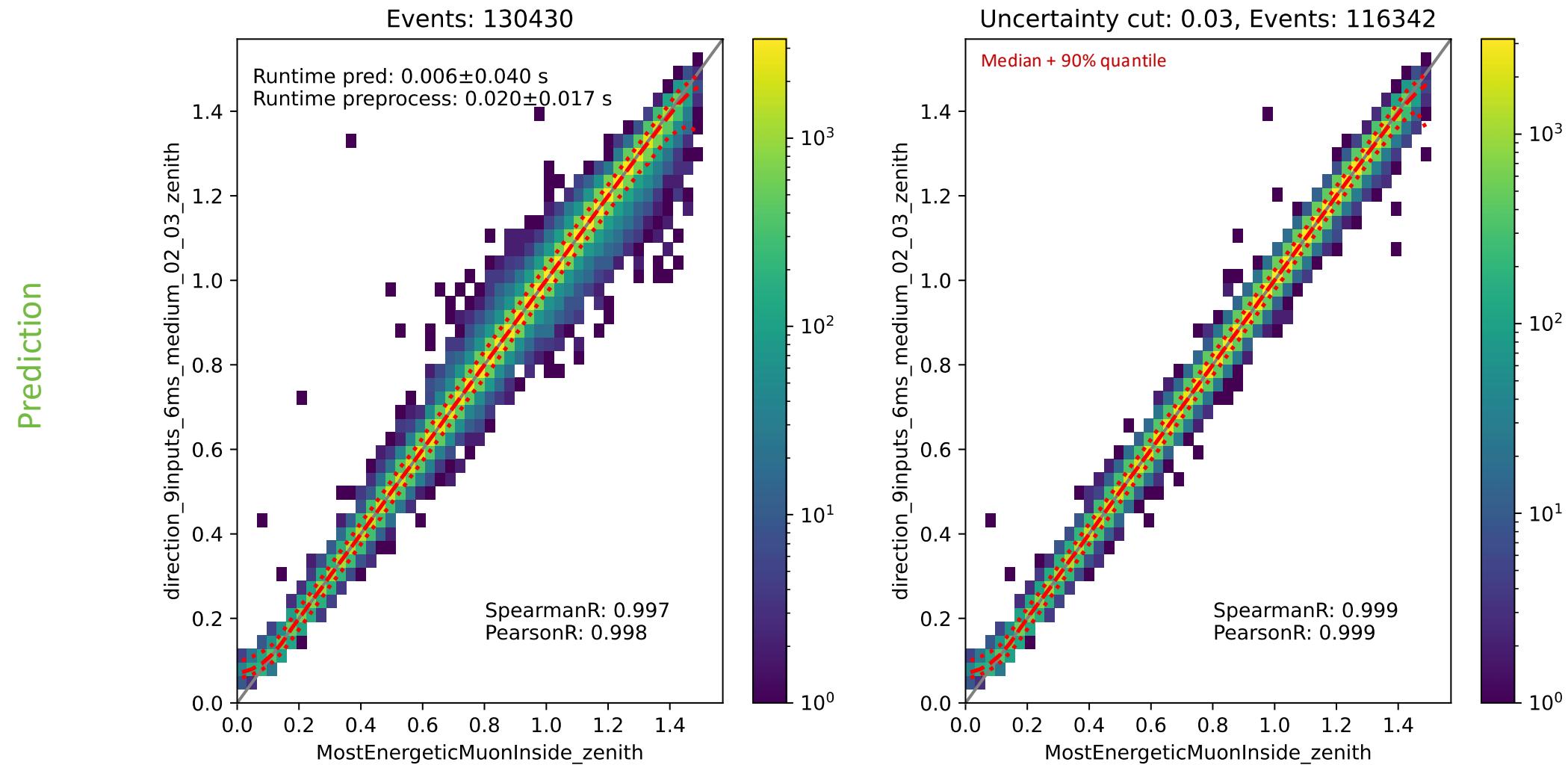
# Bundle energy at surface – 6 $\mu$ s cleaned pulses



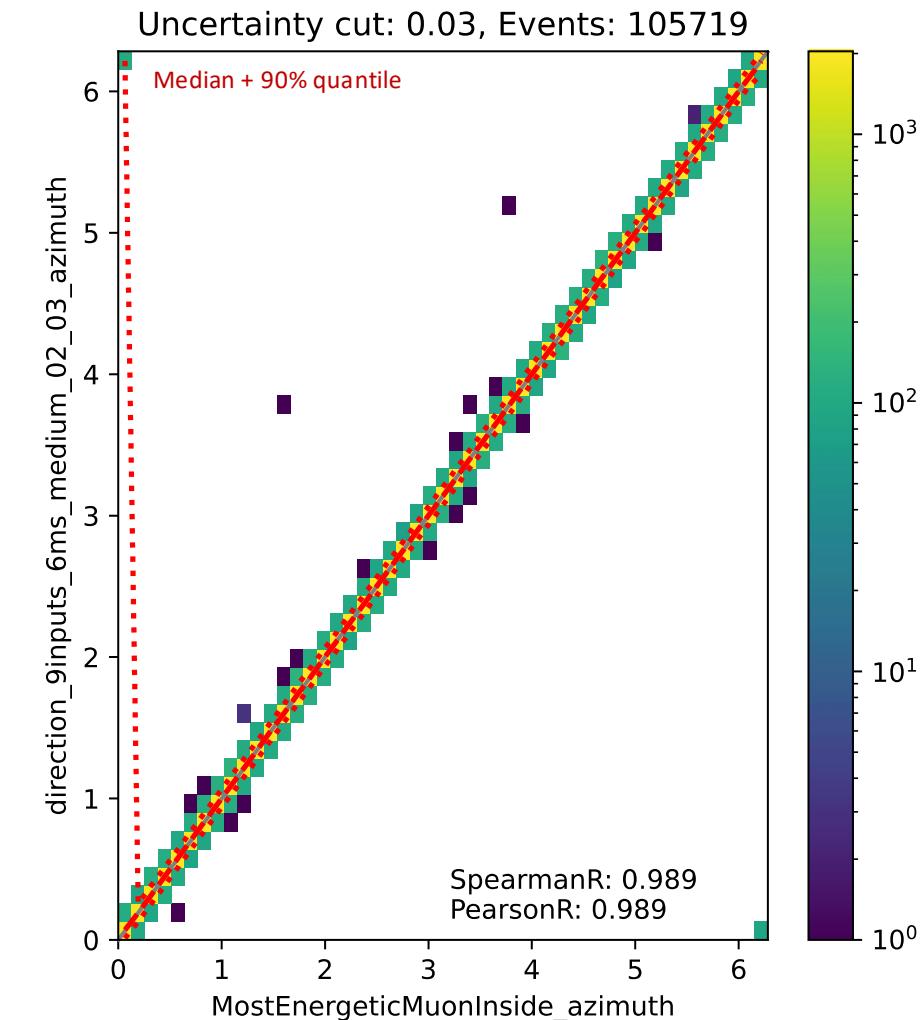
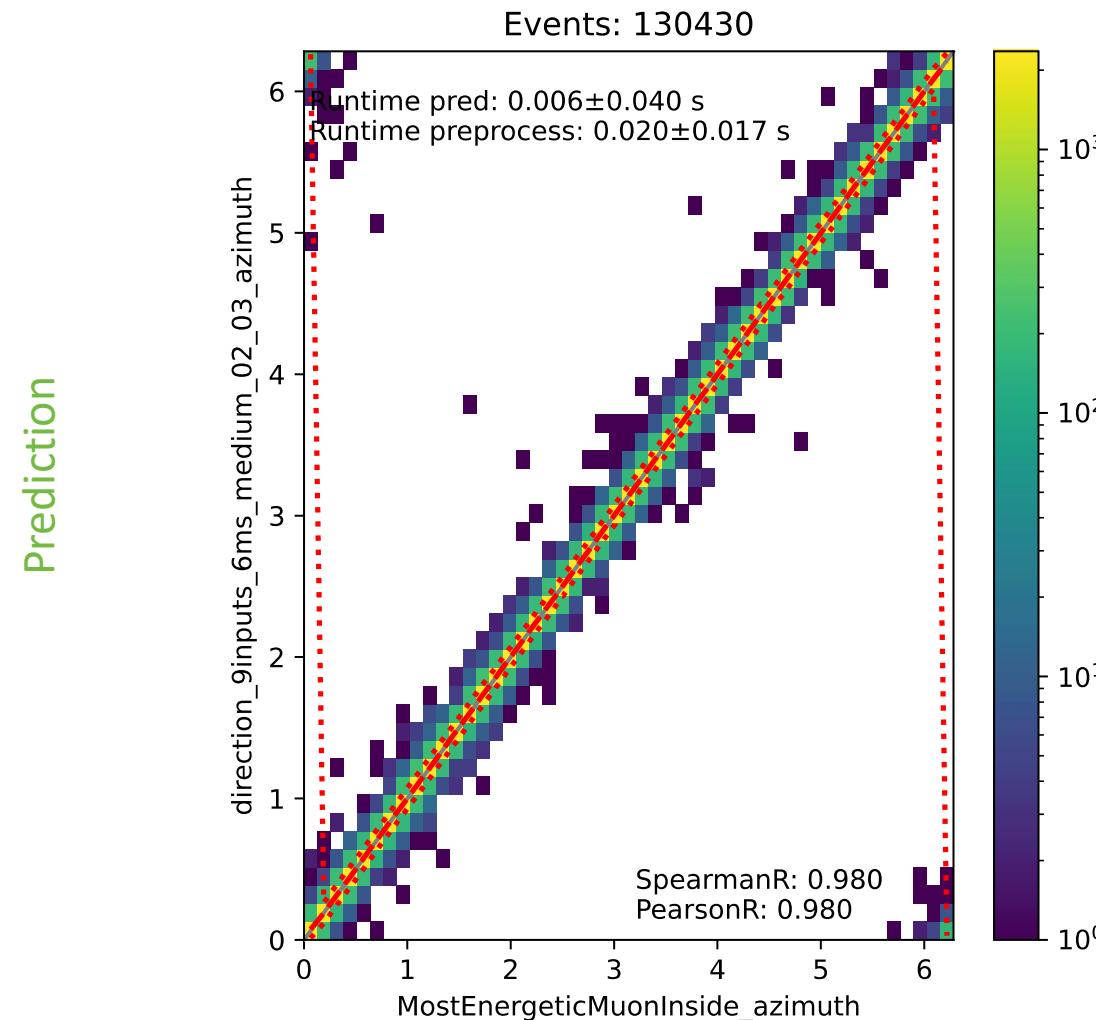
# Leading muon energy at surface – 6 $\mu$ s cleaned pulses



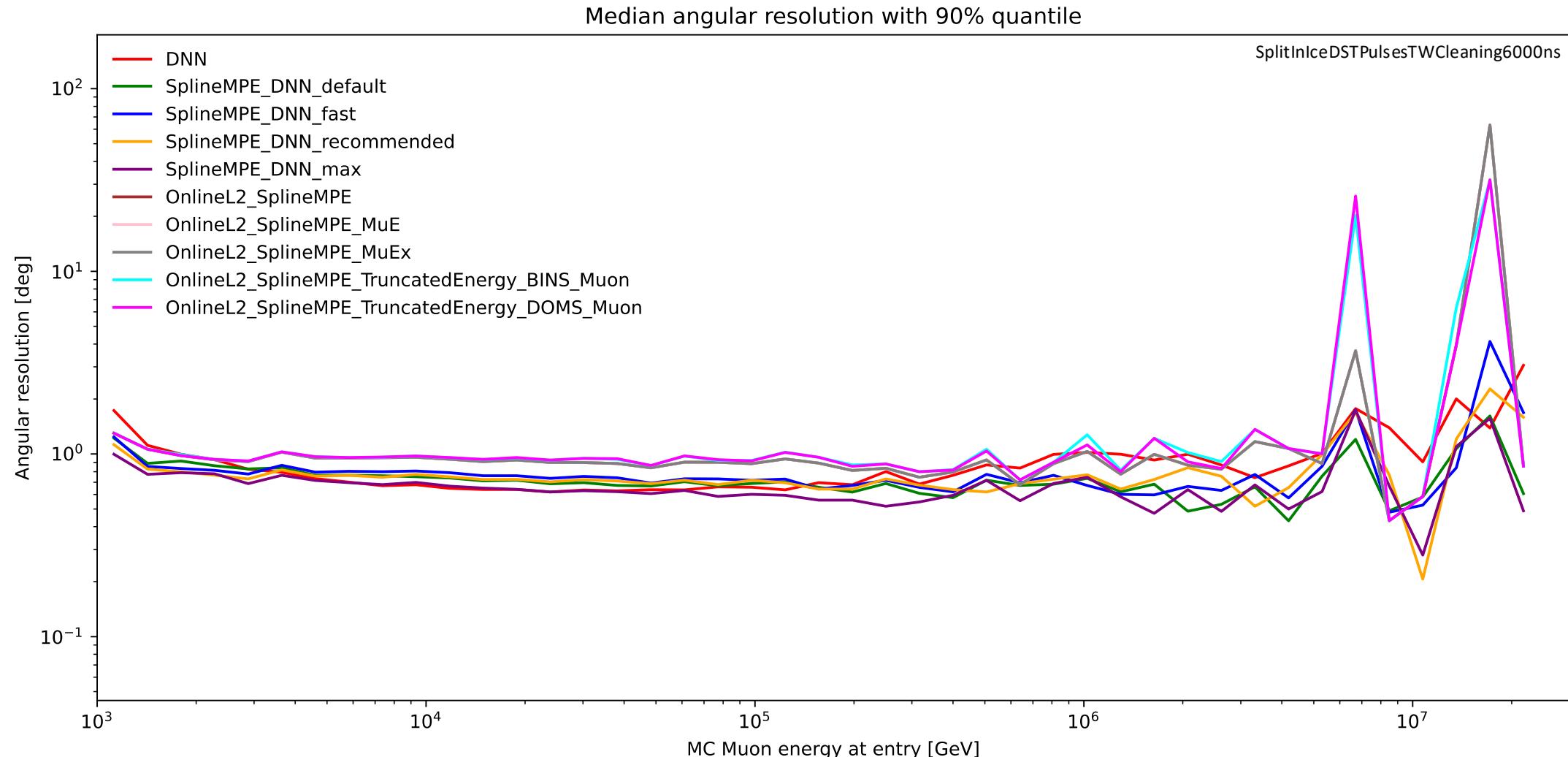
## Zenith – 6 ms cleaned pulses



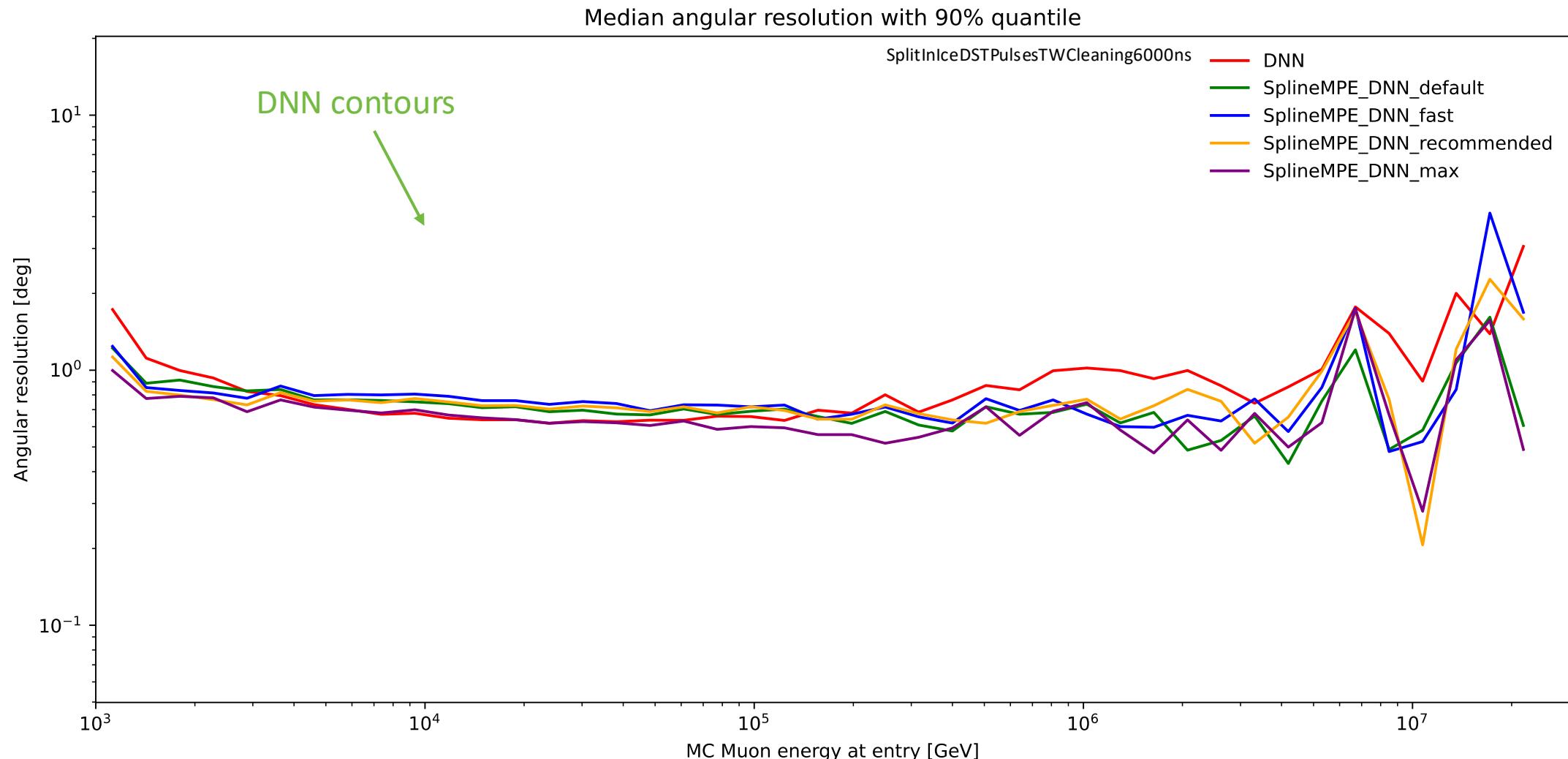
# Azimuth – 6 ms cleaned pulses

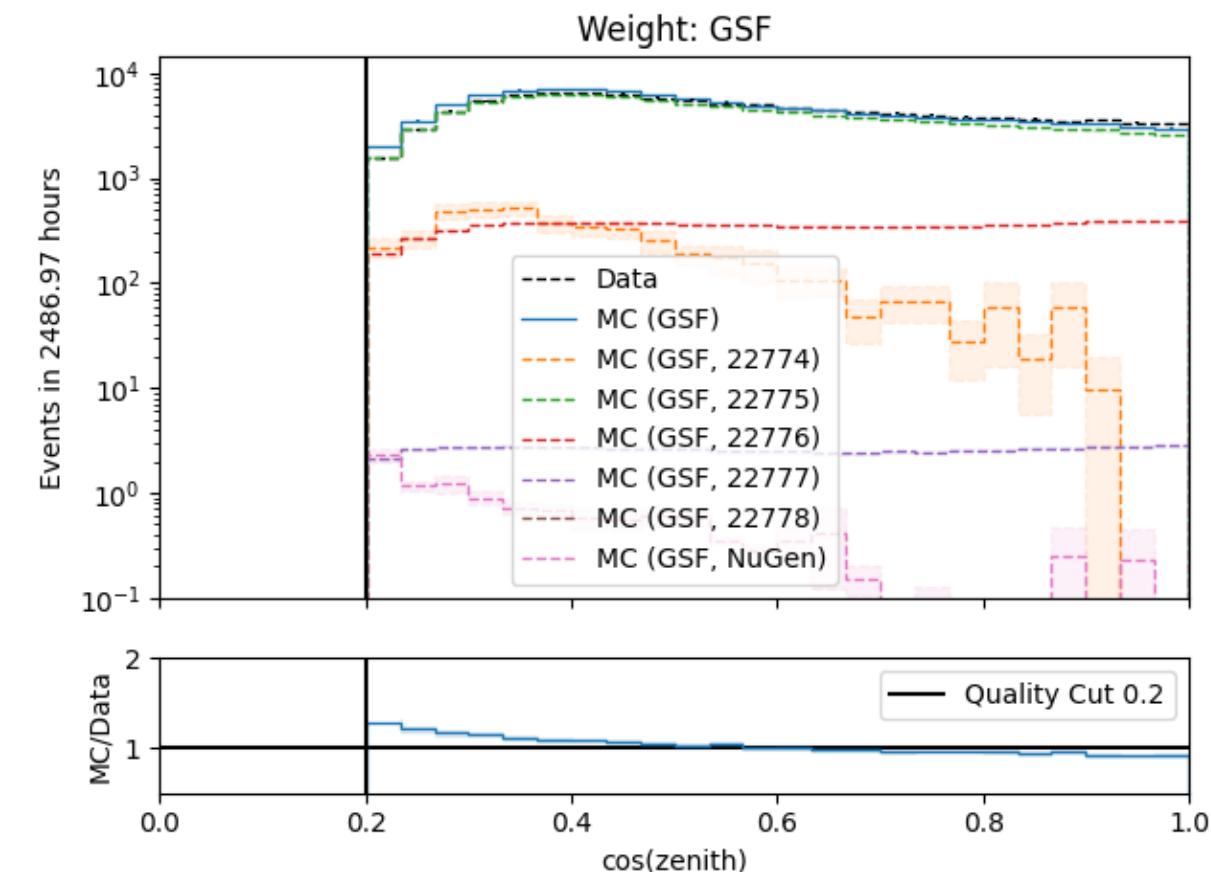
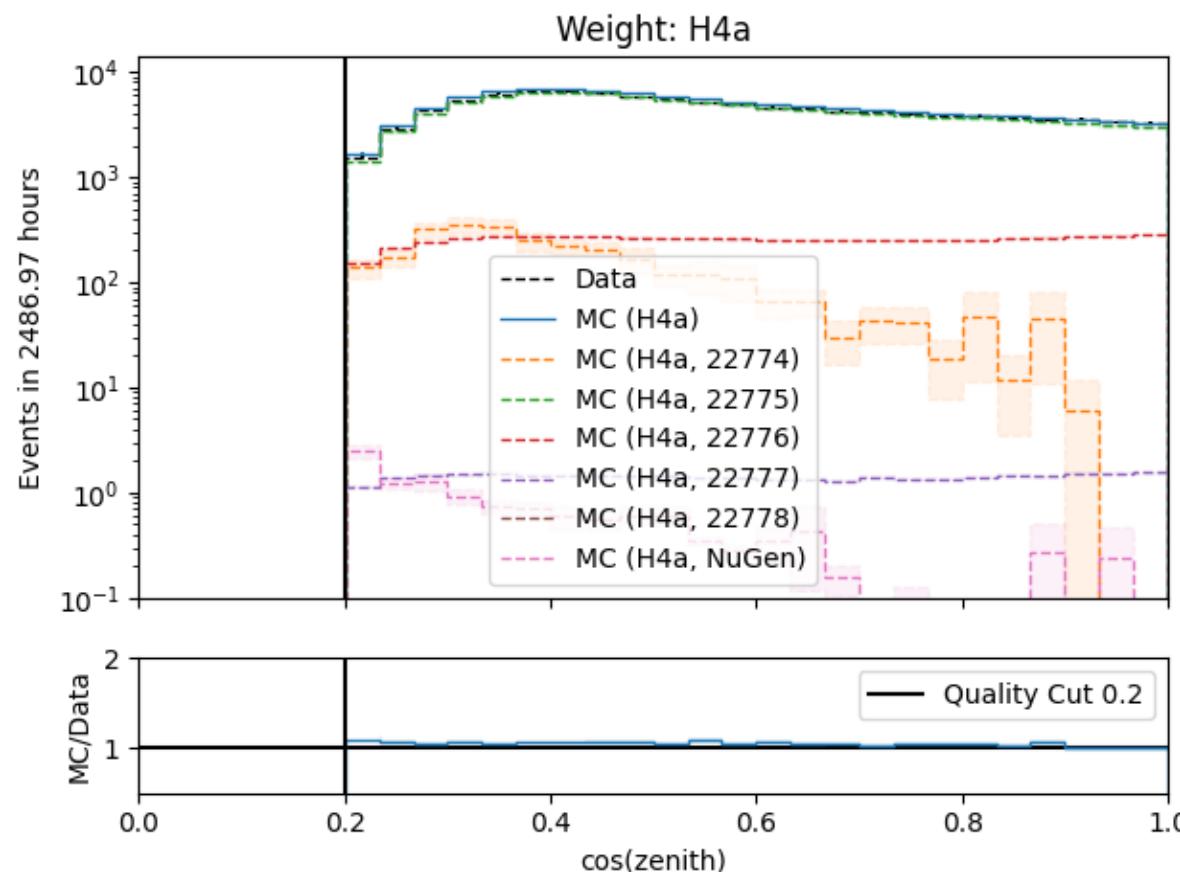


# SplineMPE – DNN and conventional seeds

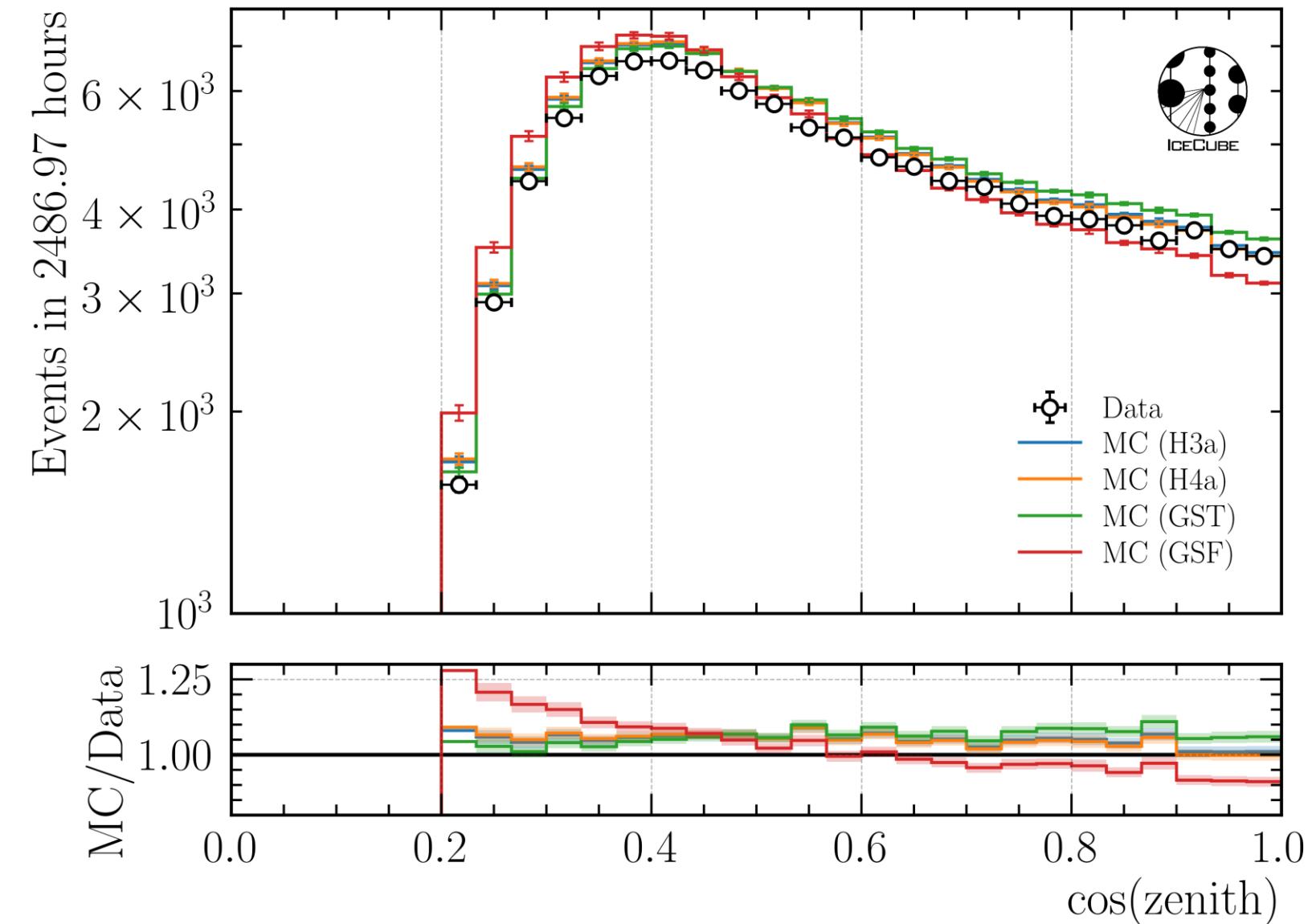


# SplineMPE – DNN seeds



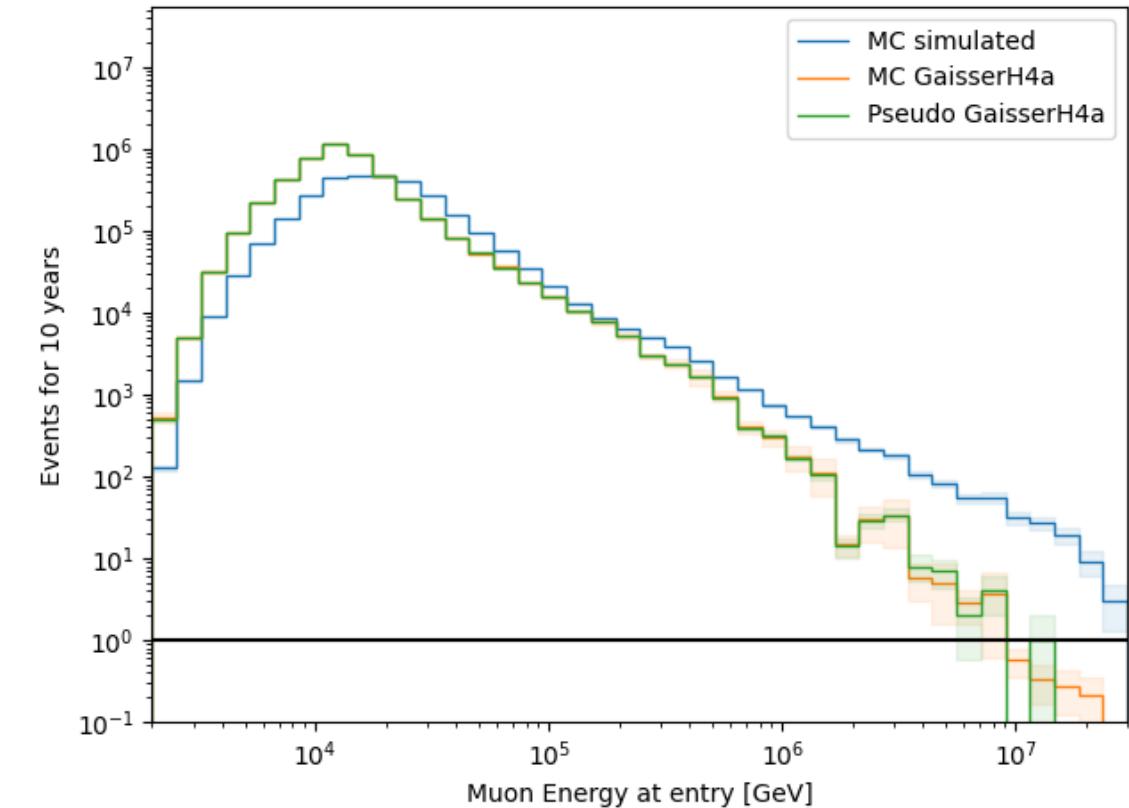
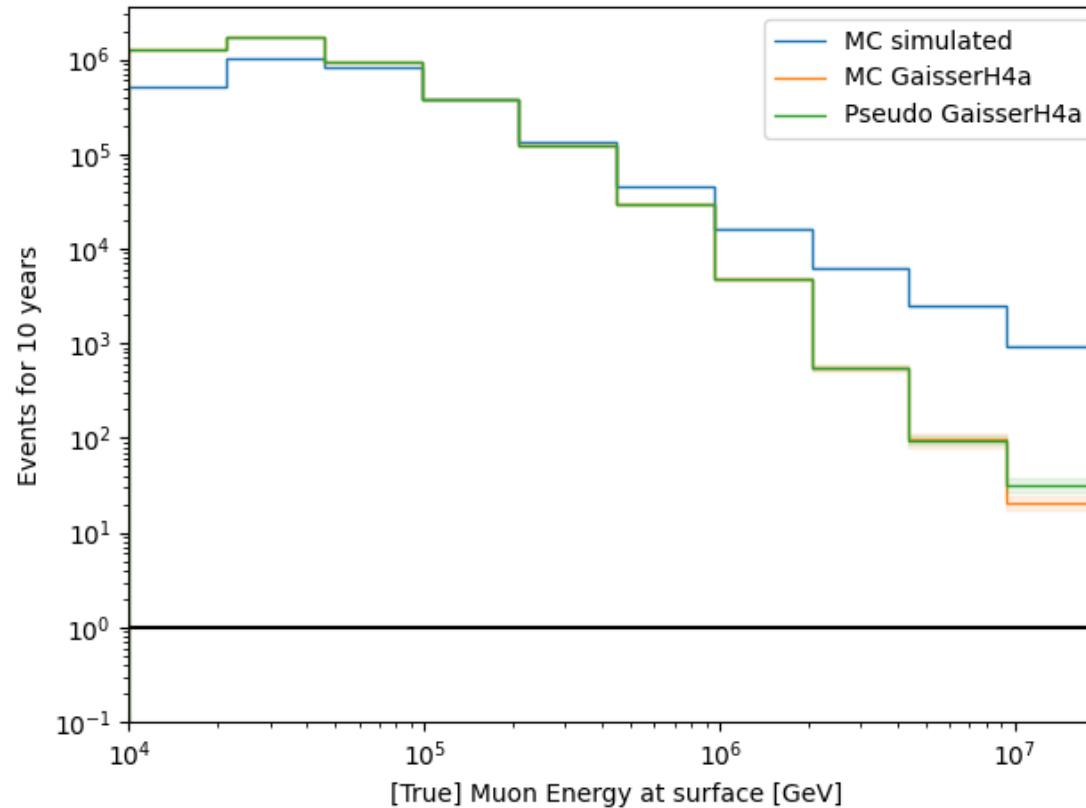
Level5:  $\cos(\text{zenith})$ 

Caution:  
weights are scaled

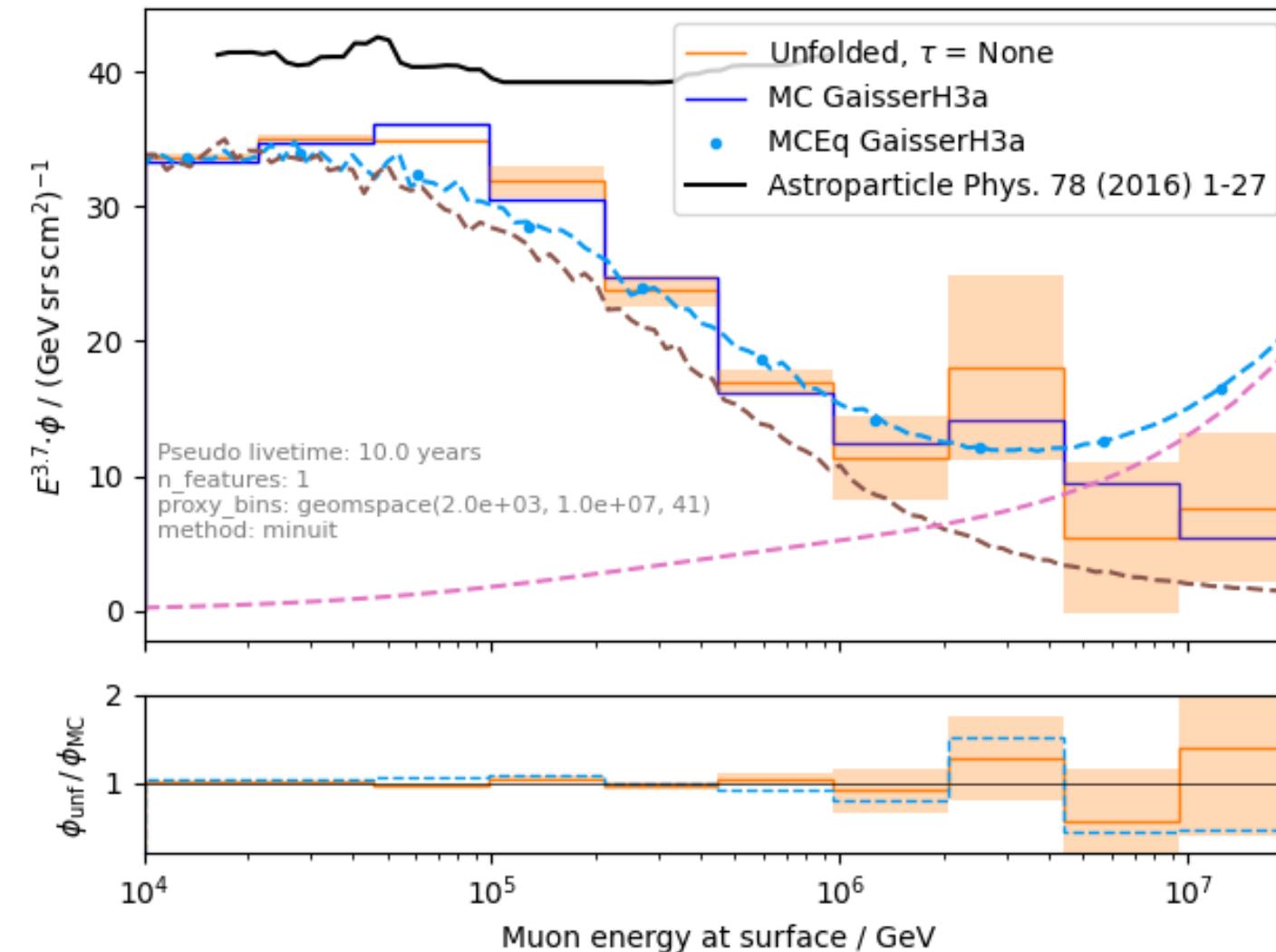
Level5:  $\cos(\text{zenith})$  – all primary models

Caution:  
weights are scaled

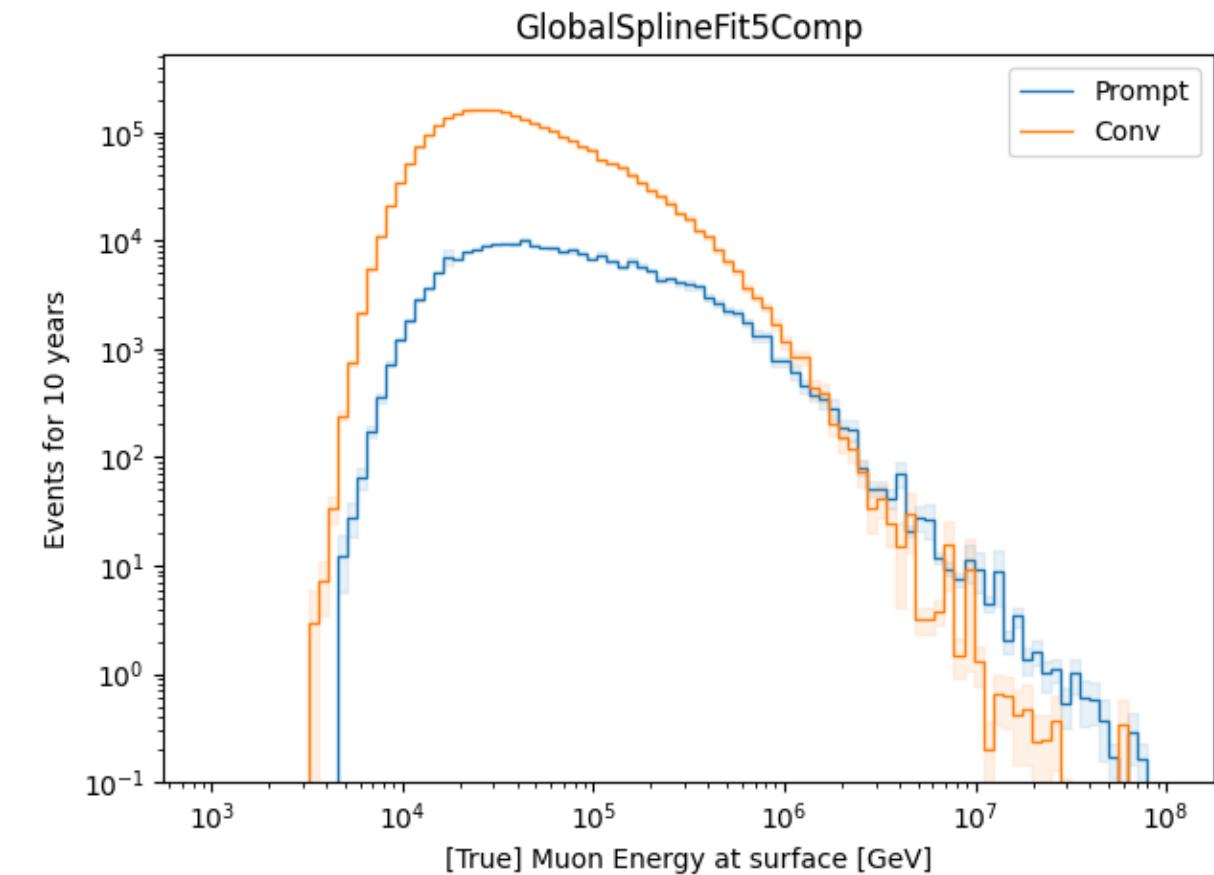
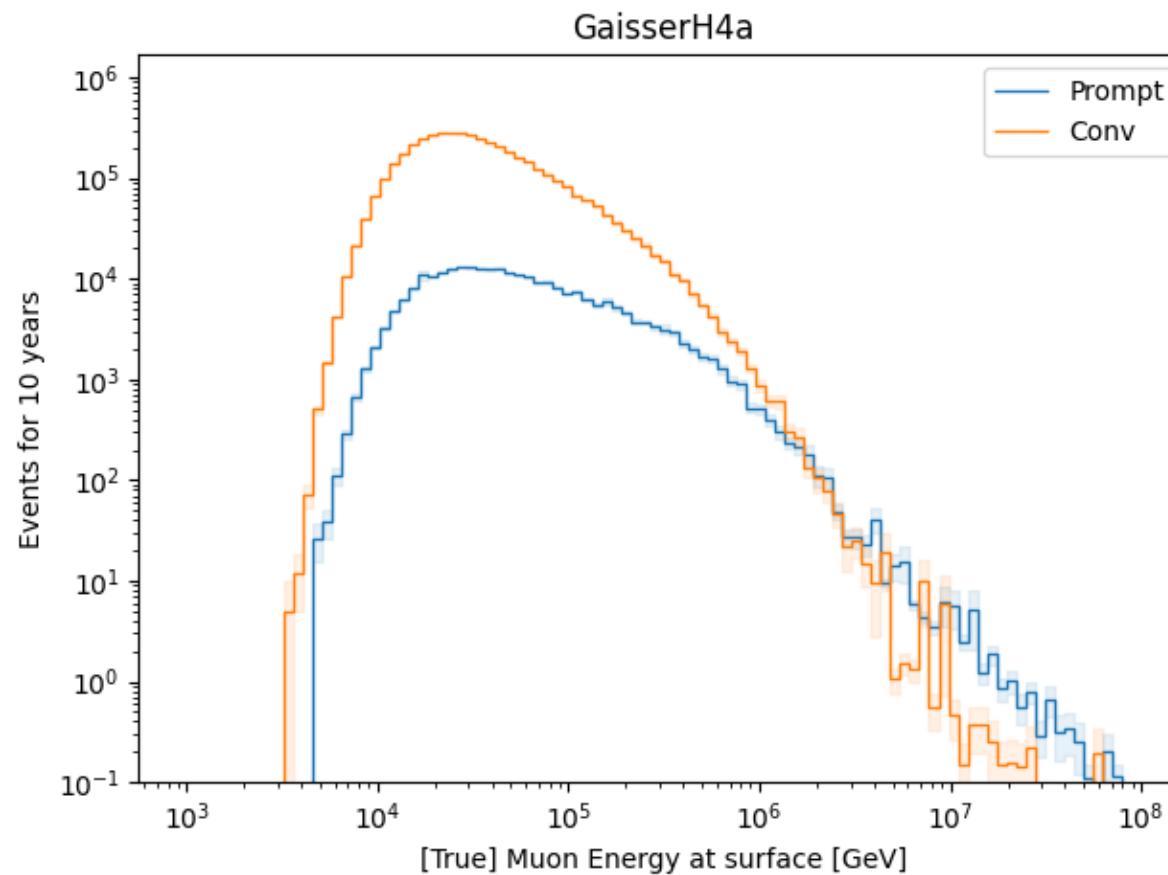
## Proxy and target variable for unfolding – 10 years [H4a]



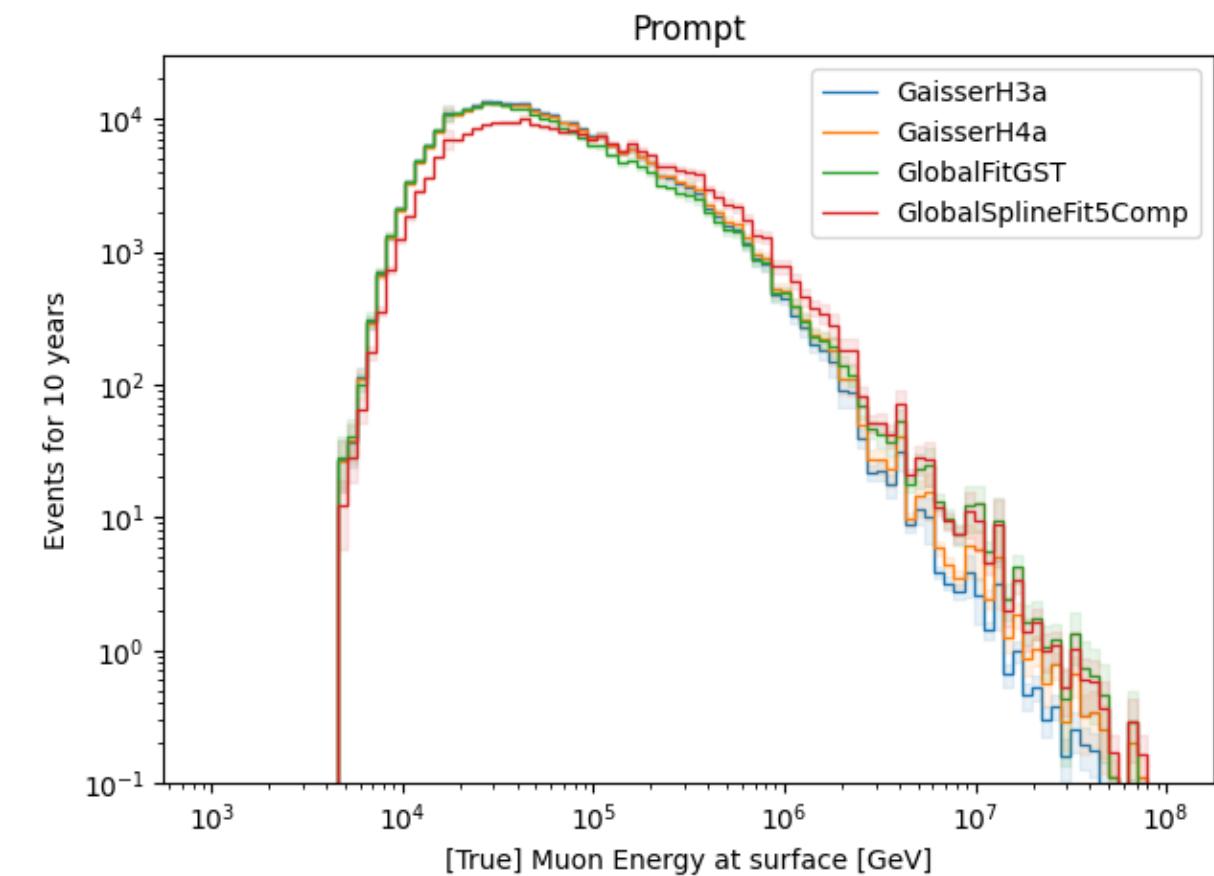
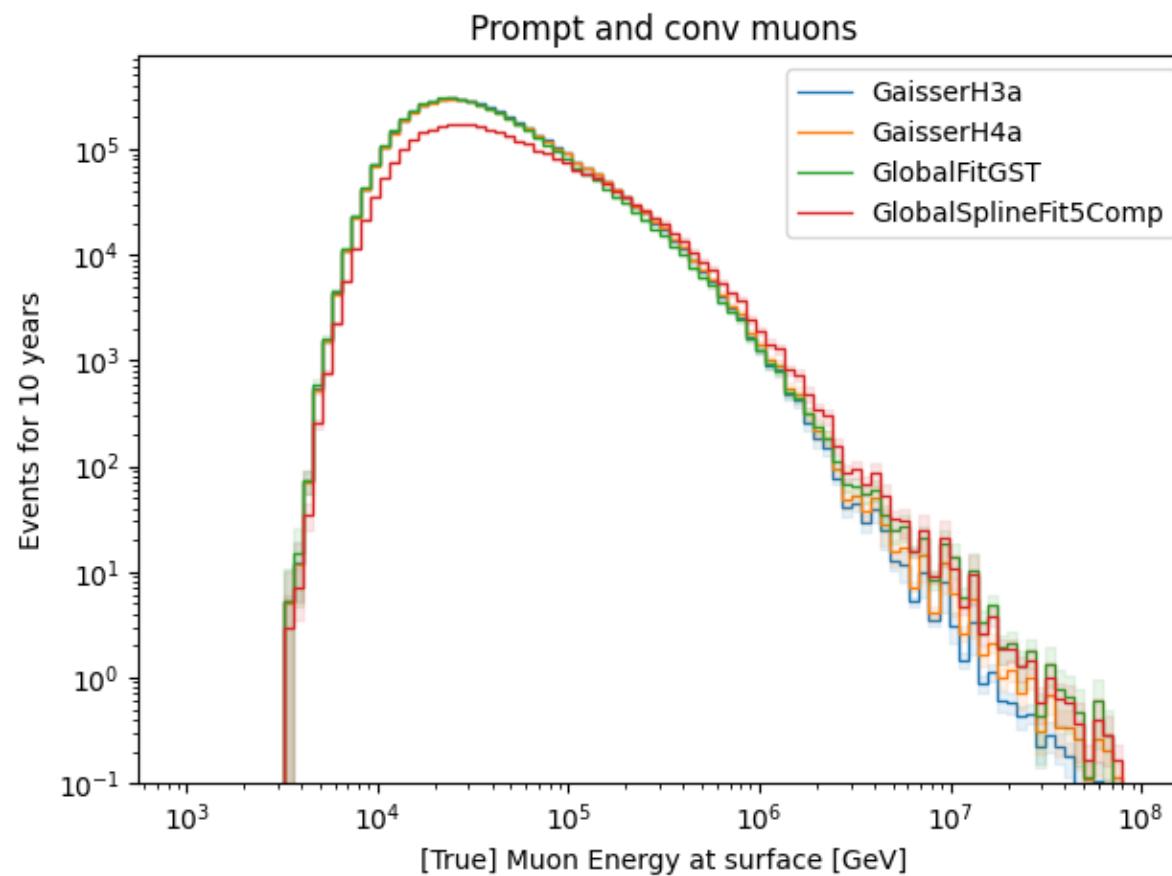
# Unfolding with prompt and conv MCEq



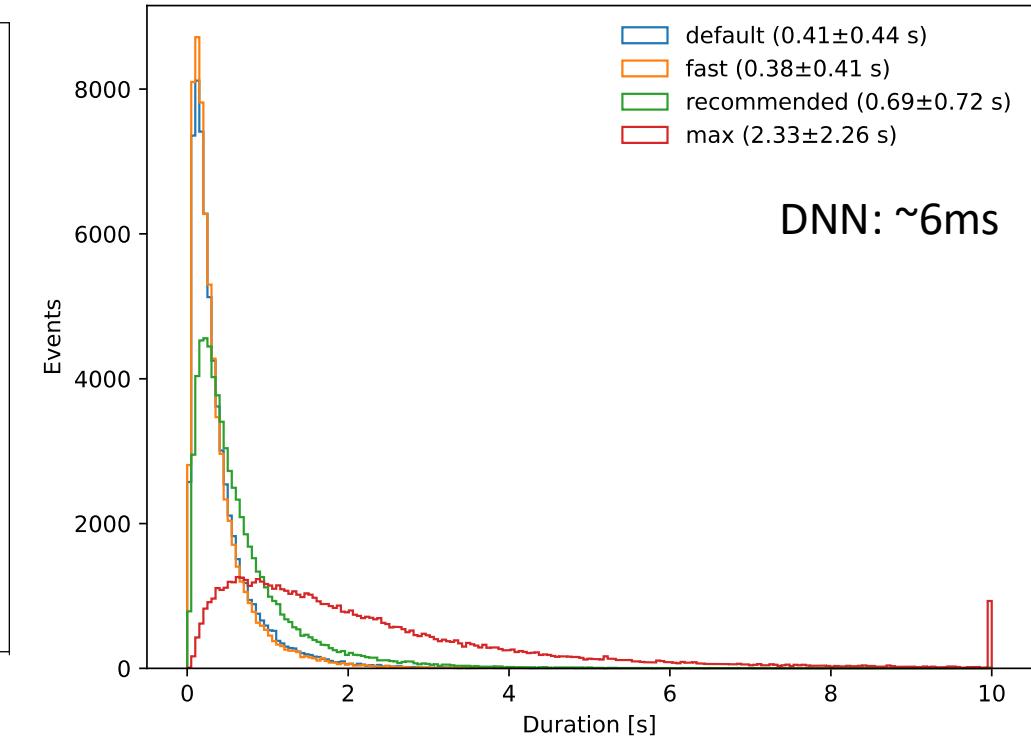
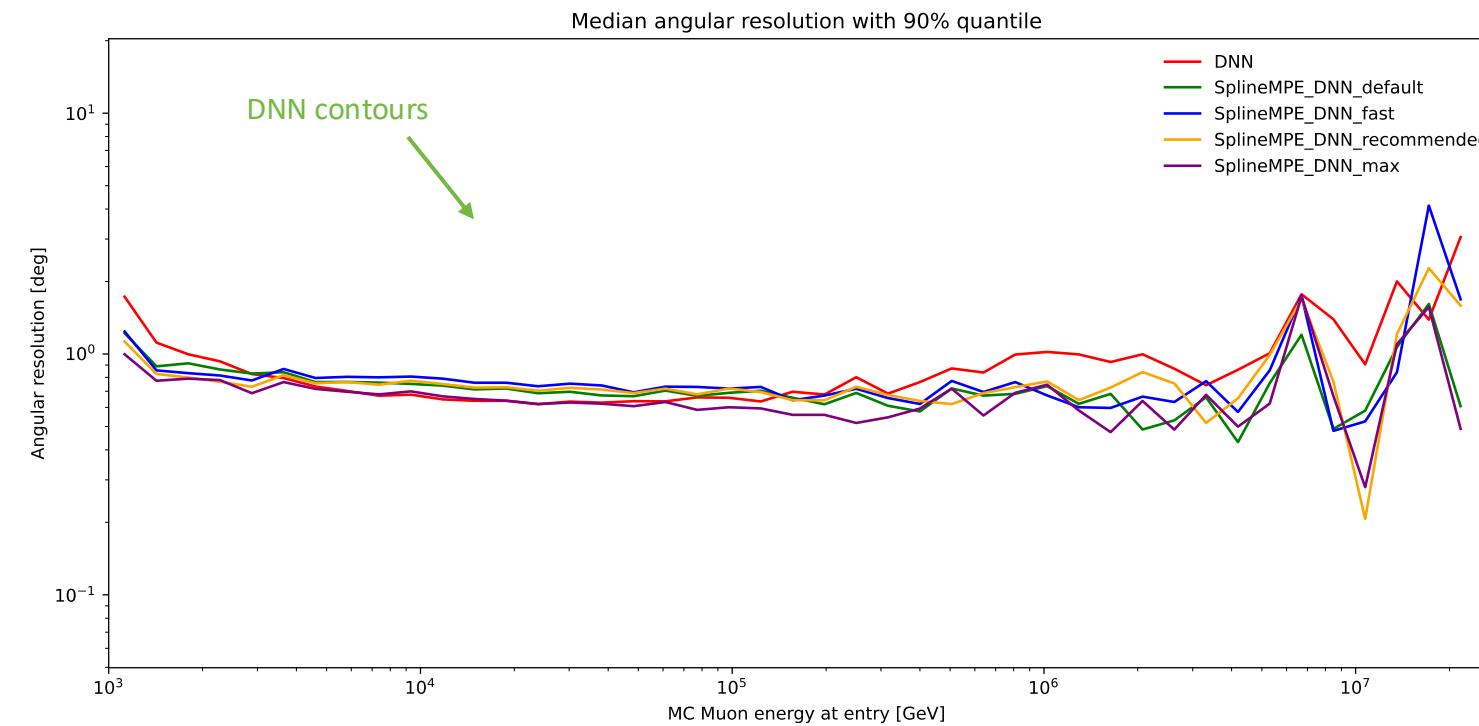
# Prompt and conv: muon energy at surface for 10 years



# Compare all primary fluxes



# Angular reconstructions: DNN vs. SplineMPE

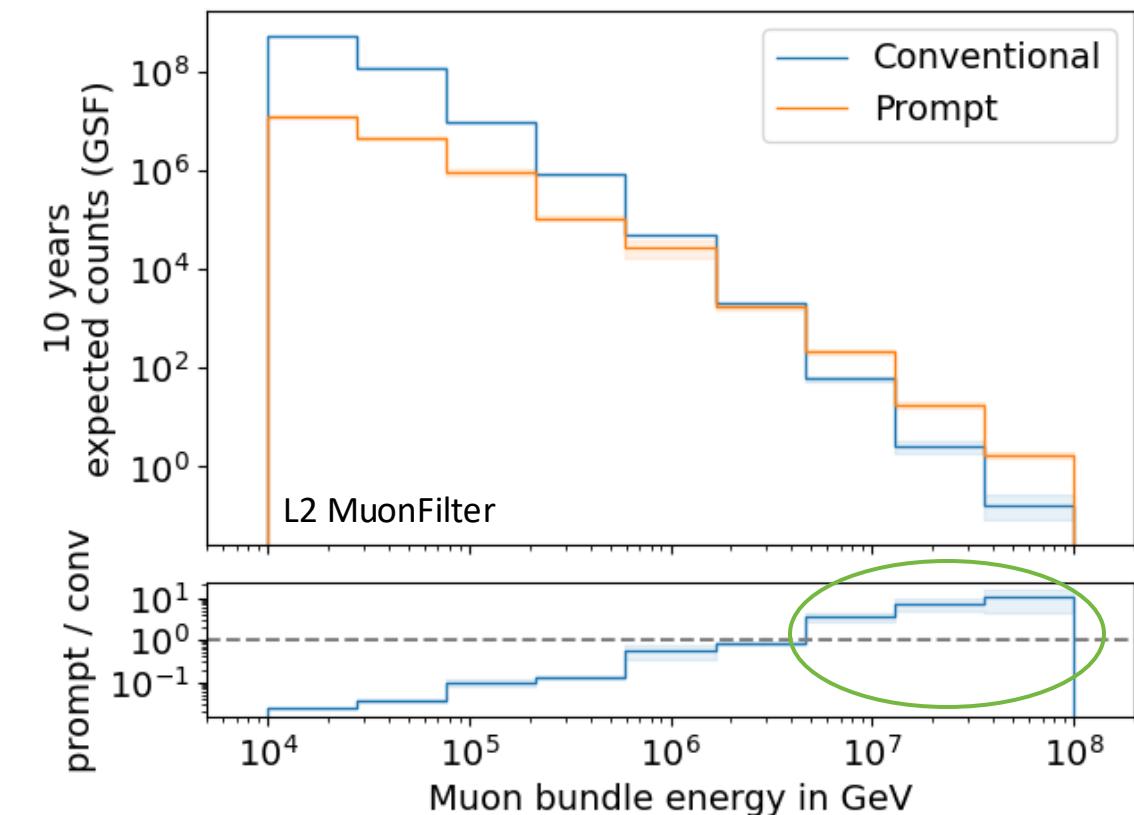
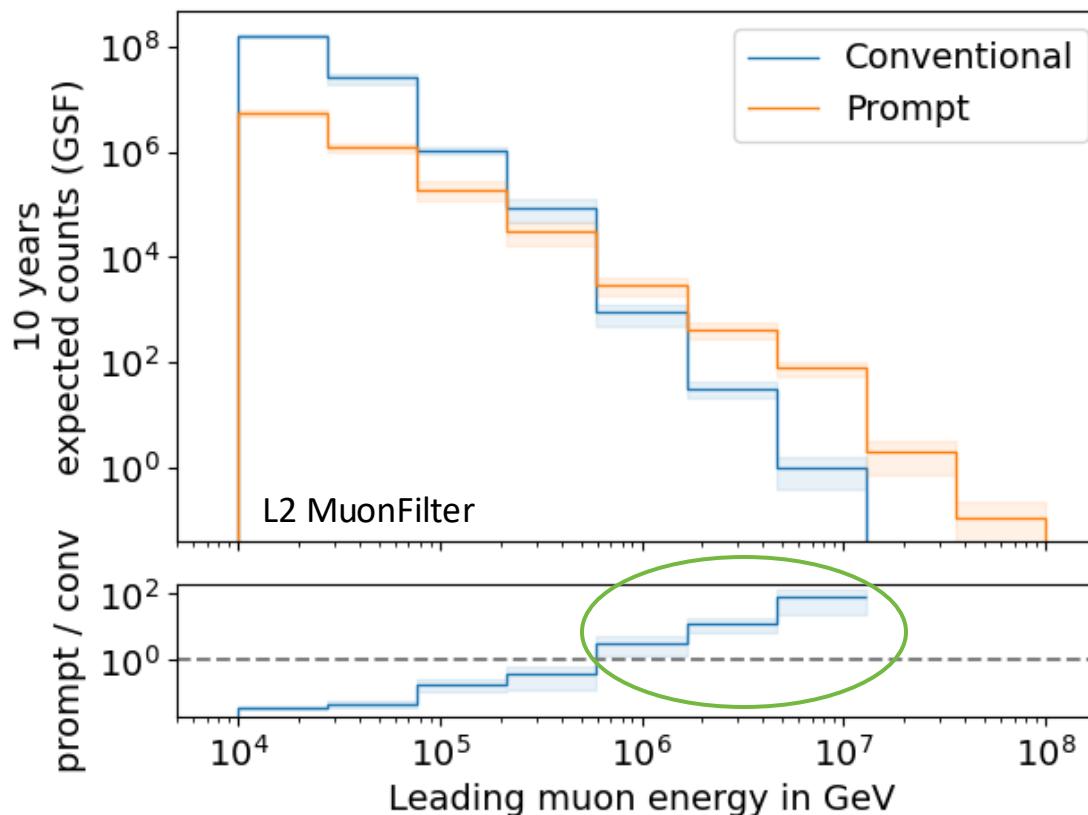


- Only small improvement at energies around 1 PeV
  - Contours are larger
  - Additional runtime
- > Use only DNN reconstruction, since we do not need the best angular resolution

# Forward fit

# Expected muons for 10 years: leading vs. bundle energy (GSF)

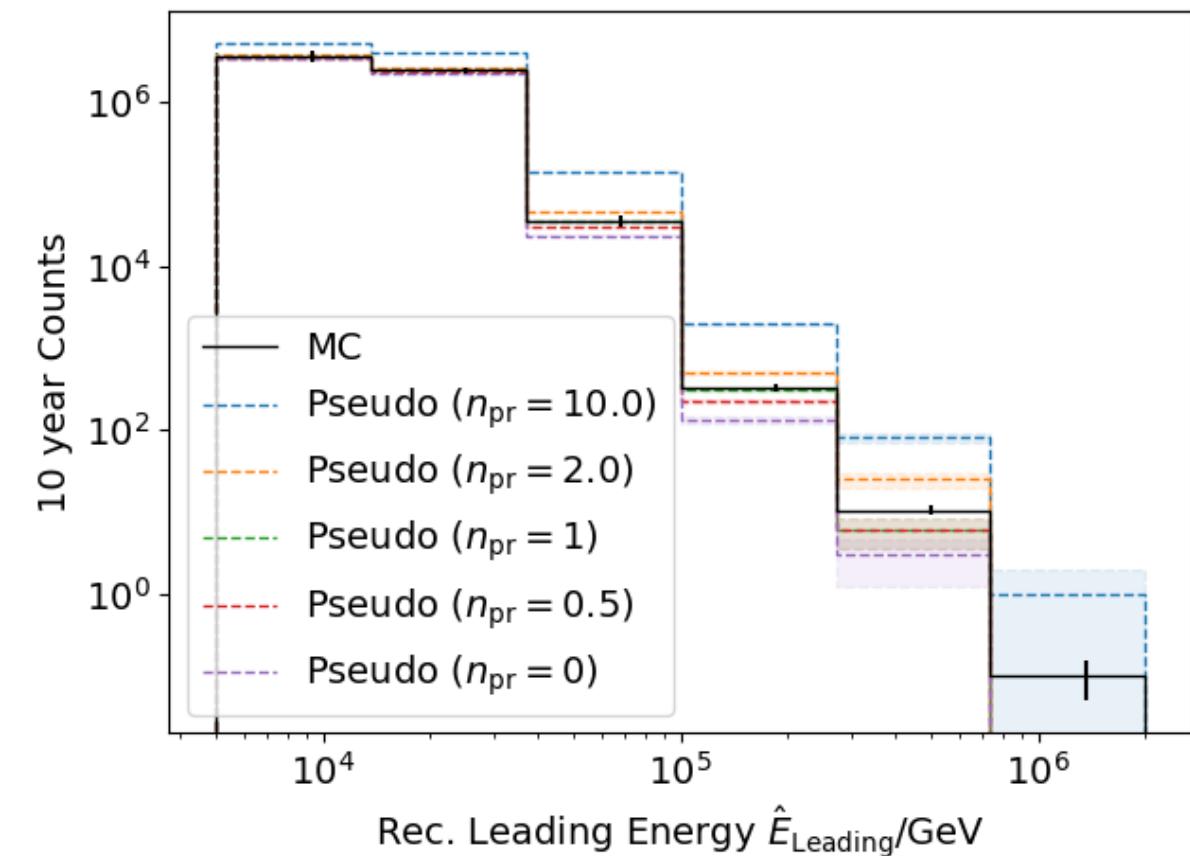
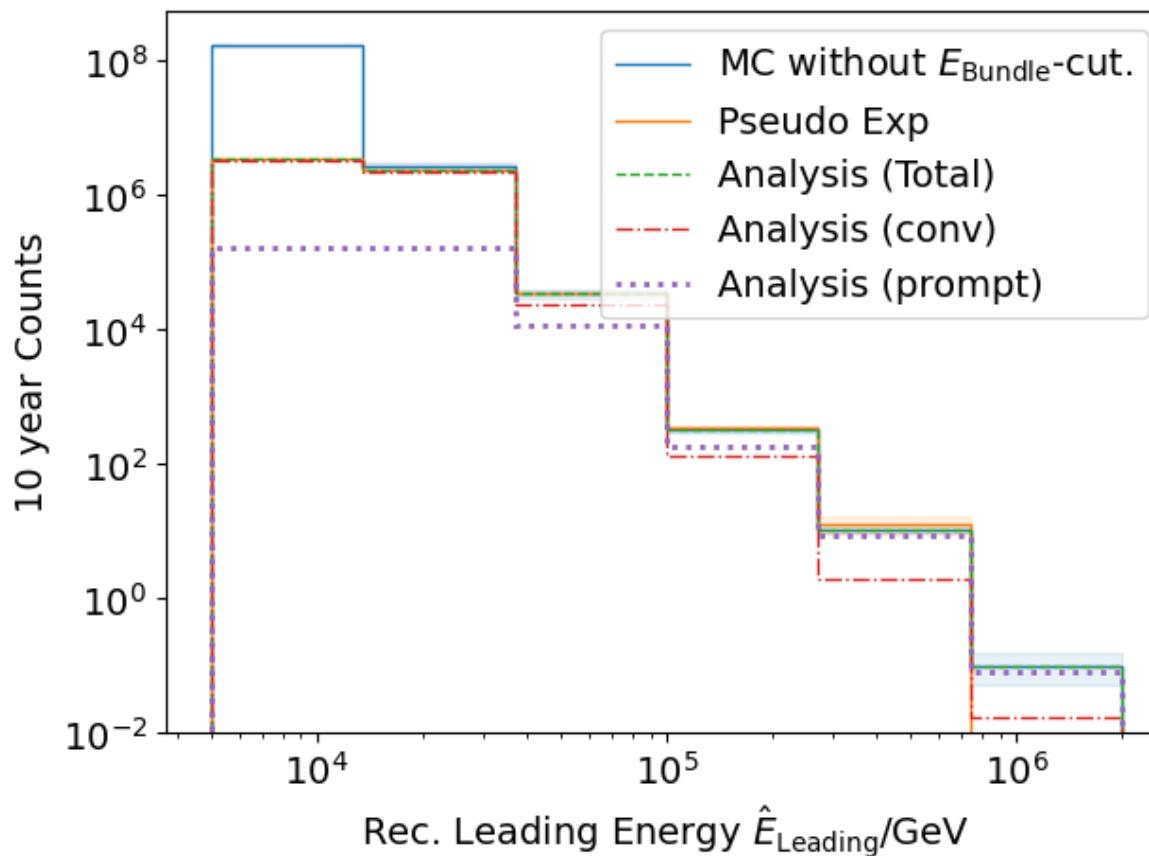
- leading: energy of most energetic muon in a muon bundle
- bundle: sum of energies of all muons of the bundle



- Both leading and bundle energy are sensitive to detect prompt
- Leading muon energy is more sensitive

# Pseudo data sampling

Cuts:  
L2 MuonFilter  
Bundle energy at entry > 100 TeV



➤ Tagging allows scaling of prompt by factor  $n_{\text{pr}}$

# Poisson likelihood fit performed in leading muon energy

Cuts:  
 L2 MuonFilter  
 Bundle energy at entry > 100 TeV

Prompt scaling/normalization

MC counts per bin  $i$

$$C_1^{\text{MC}} = n_{\text{pr}} C_1^{\text{MC,pr}} + n_{\text{conv}} C_1^{\text{MC,conv}}, \dots, C_M^{\text{MC}} = n_{\text{pr}} C_M^{\text{MC,pr}} + n_{\text{conv}} C_M^{\text{MC,conv}}$$

Conv norm = 1

Experimental counts

$$p(C_i) = p_{\text{poisson}}(C_i; \lambda(n_{\text{pr}}) = C_i^{\text{MC}}(n_{\text{pr}})) = \frac{\lambda(n_{\text{pr}})^{C_i} e^{-\lambda(n_{\text{pr}})}}{C_i!}$$

Maximize likelihood

$$\mathcal{L}(n_{\text{pr}}) = \prod_{i=1}^M p(C_i; n_{\text{pr}})$$

Easier:  
 minimize negative  
 log-likelihood

$$-\ln \mathcal{L} = -\sum_{i=1}^M C_i \ln \lambda(n_{\text{pr}}) - \lambda(n_{\text{pr}}) - \ln C_i!$$

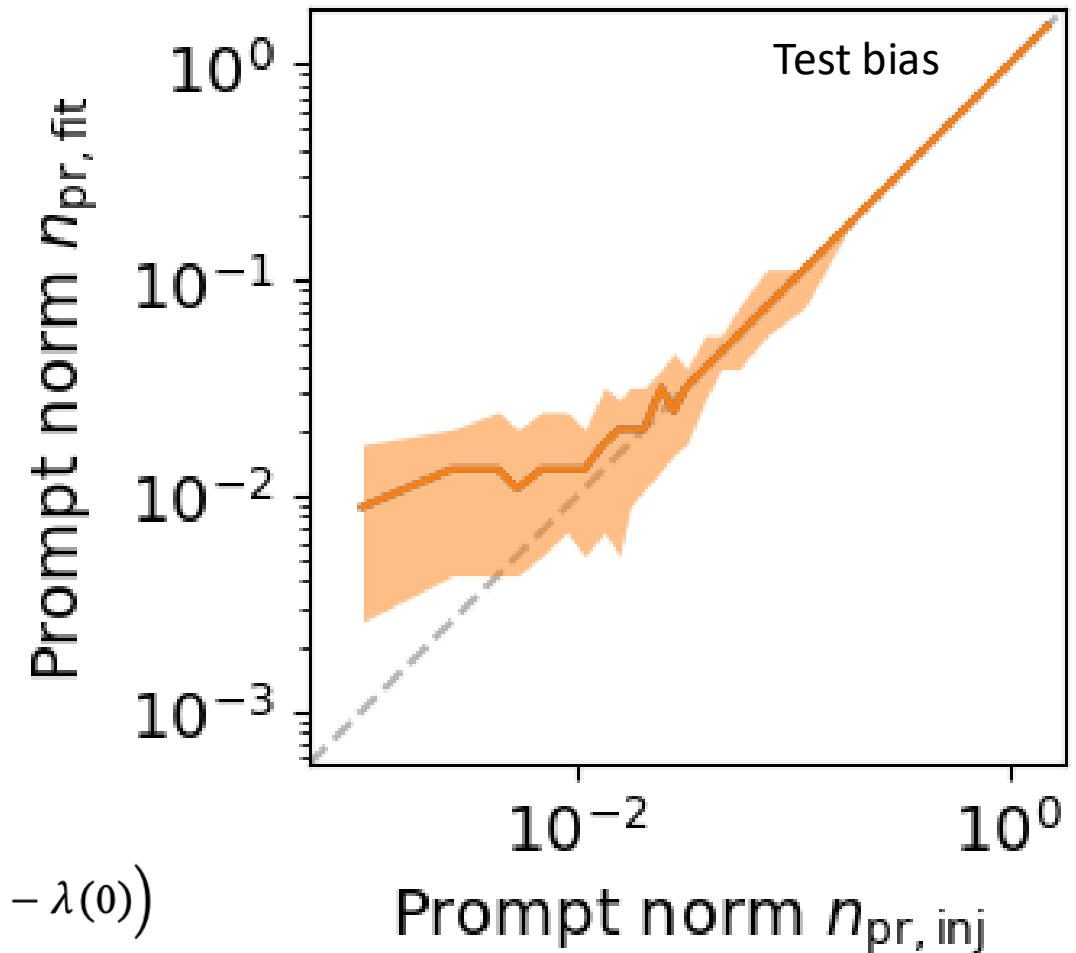
With a constant conv norm:  
 bin counts depend only on prompt norm  
 = expectation value per bin

$\Lambda = -2 \ln \frac{\mathcal{L}(n_{\text{pr}} = \hat{n}_{\text{pr}})}{\mathcal{L}(n_{\text{pr}=0})} = -2 \sum_{i=1}^M C_i (\ln \lambda(\hat{n}_{\text{pr}}) - \ln \lambda(0)) - (\lambda(n_{\text{pr}}) - \lambda(0))$

Test statistic for Wilks' theorem

Null hypothesis: no prompt

pascal.gutjahr@tu-dortmund.de



➤ Bias starts at a prompt  
 normalization of ~0.1

# Discovery potential and sensitivity

Expectation for 1 year:

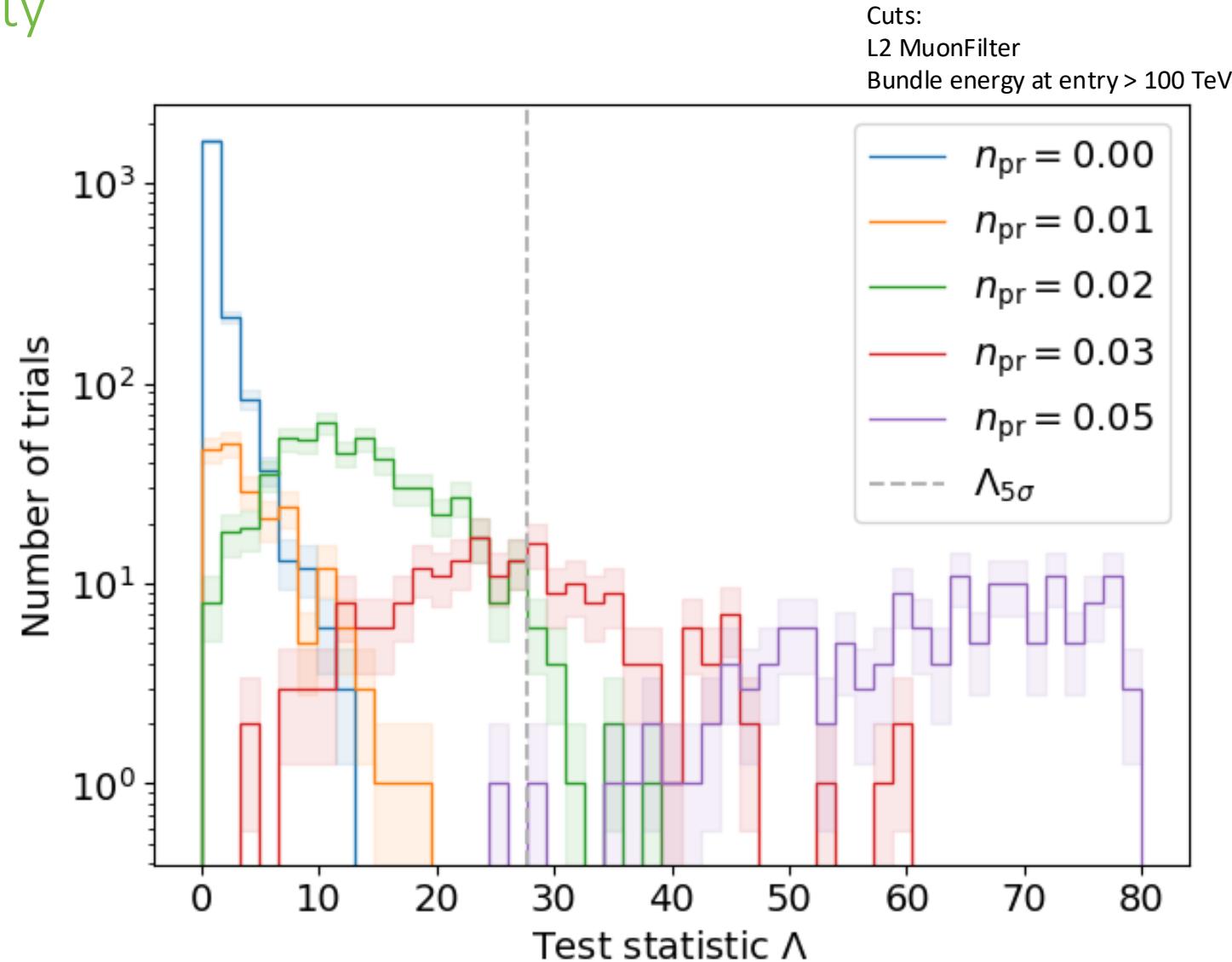
- 5 sigma discovery potential:  $0.102 \pm 0.005$
- Sensitivity:  $0.024 \pm 0.001$

Expectation for 10 years:

- 5 sigma discovery potential:  $0.032 \pm 0.001$
- Sensitivity:  $0.007 \pm 0.000$

Caution:

- Limited MC statistics -> events are oversampled in pseudo dataset
- No systematic uncertainties



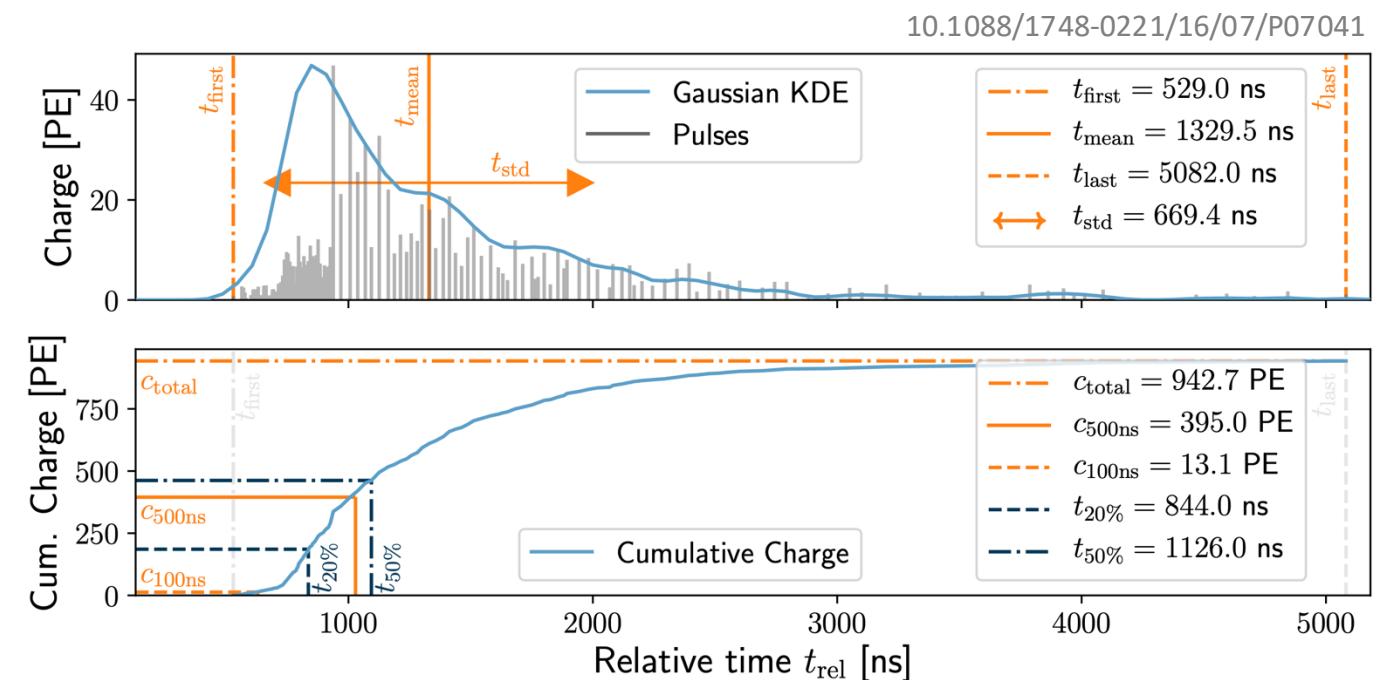
# Input data per DOM

## 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



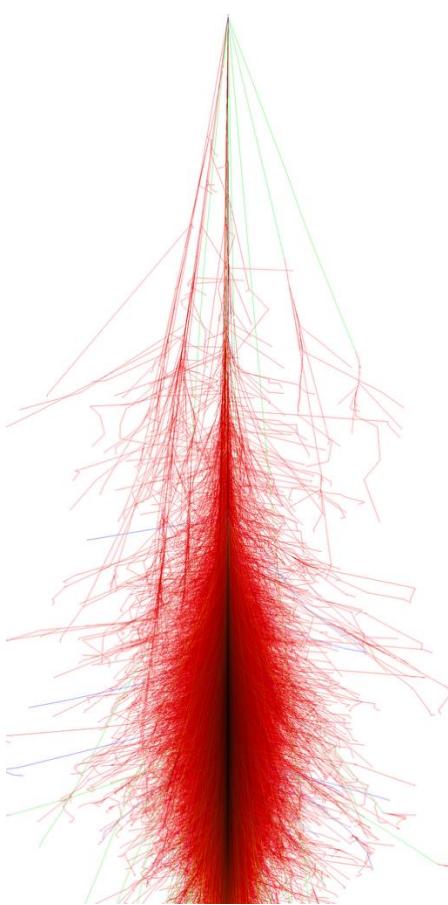
## Input pulses

- SplitInIceDSTPulses
- SplitInIceDSTPulsesTWCleaning6000ns
- (DNN framework performs an internal cleaning)

## Training datasets

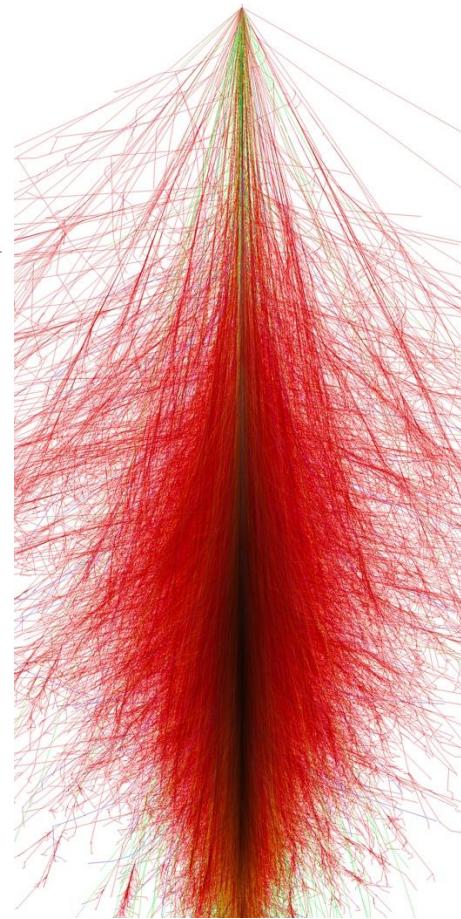
- 20904
- 21962
- 22020
- 22187

## Air shower – 10 TeV

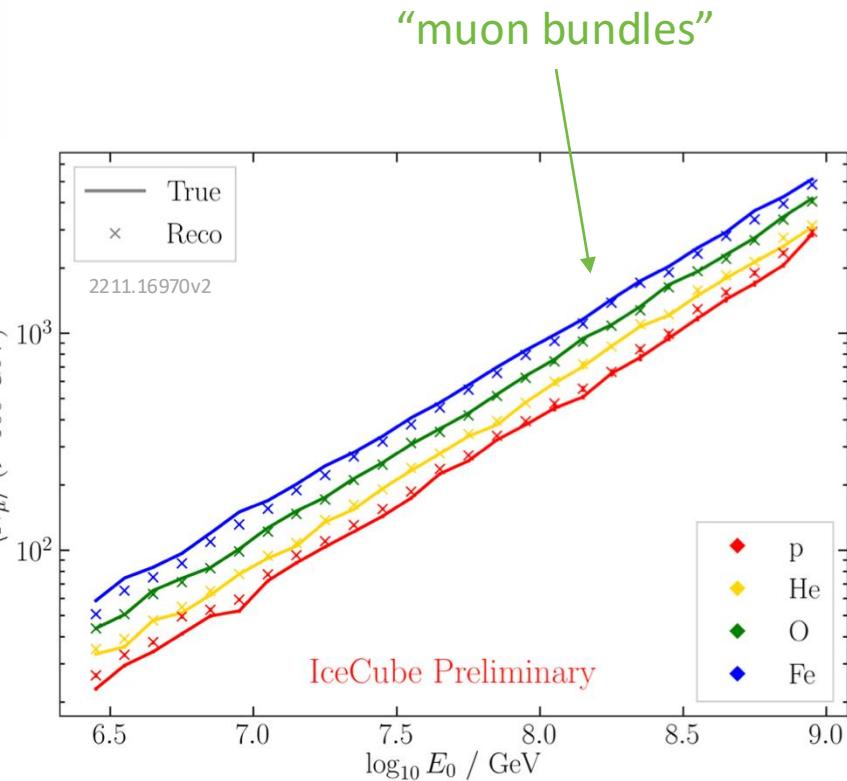
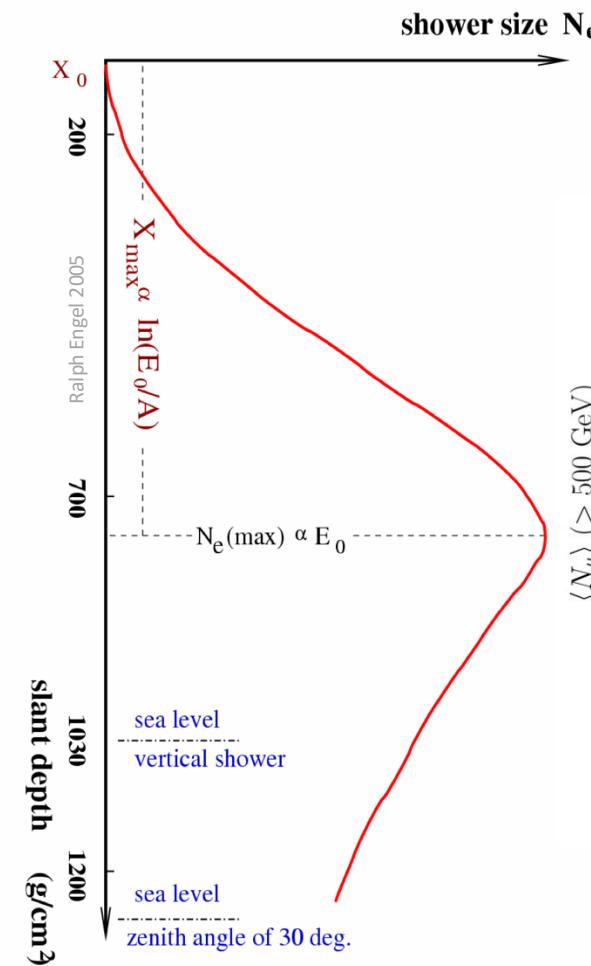


Proton

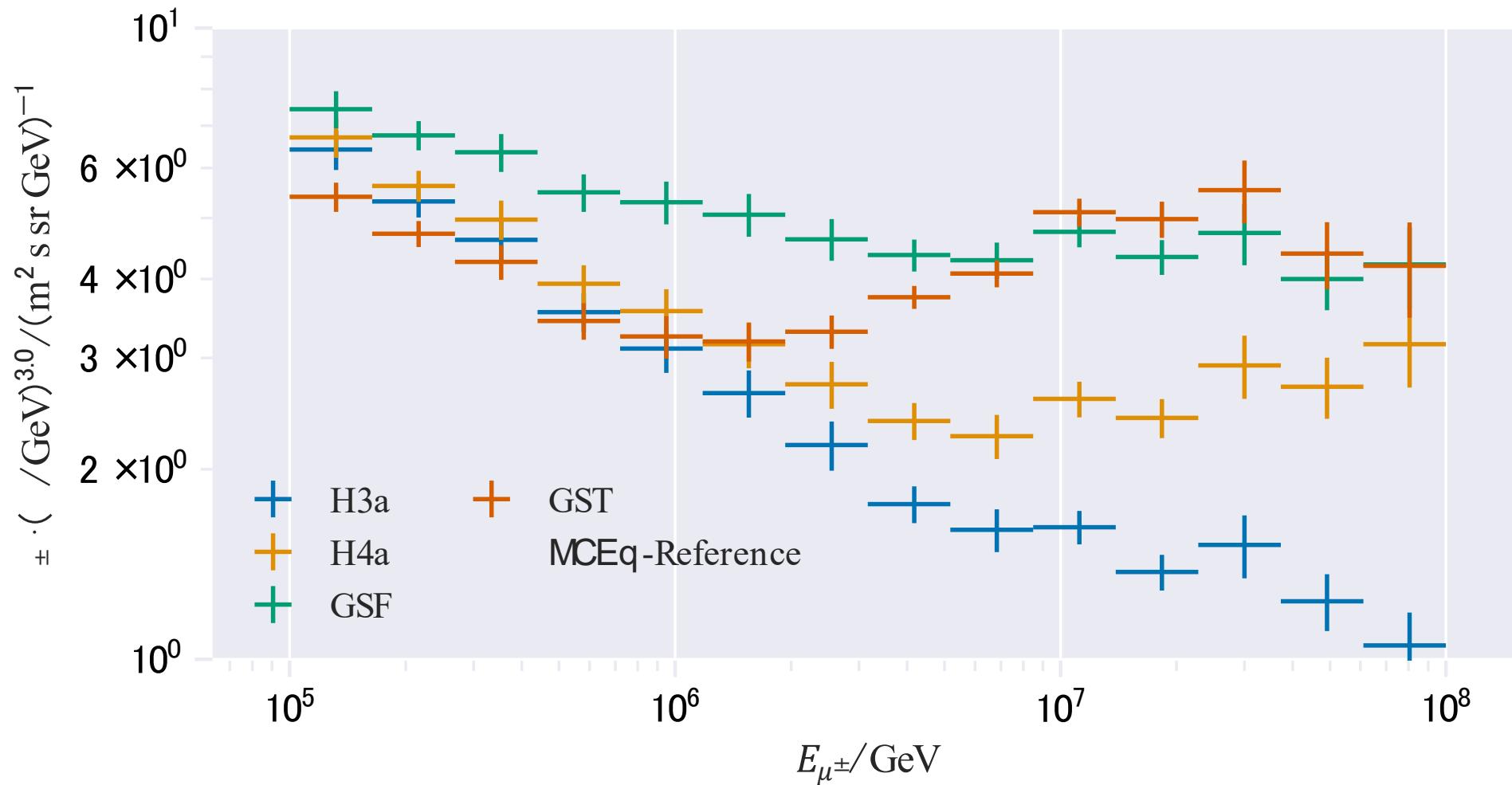
zeuthen.desy.de



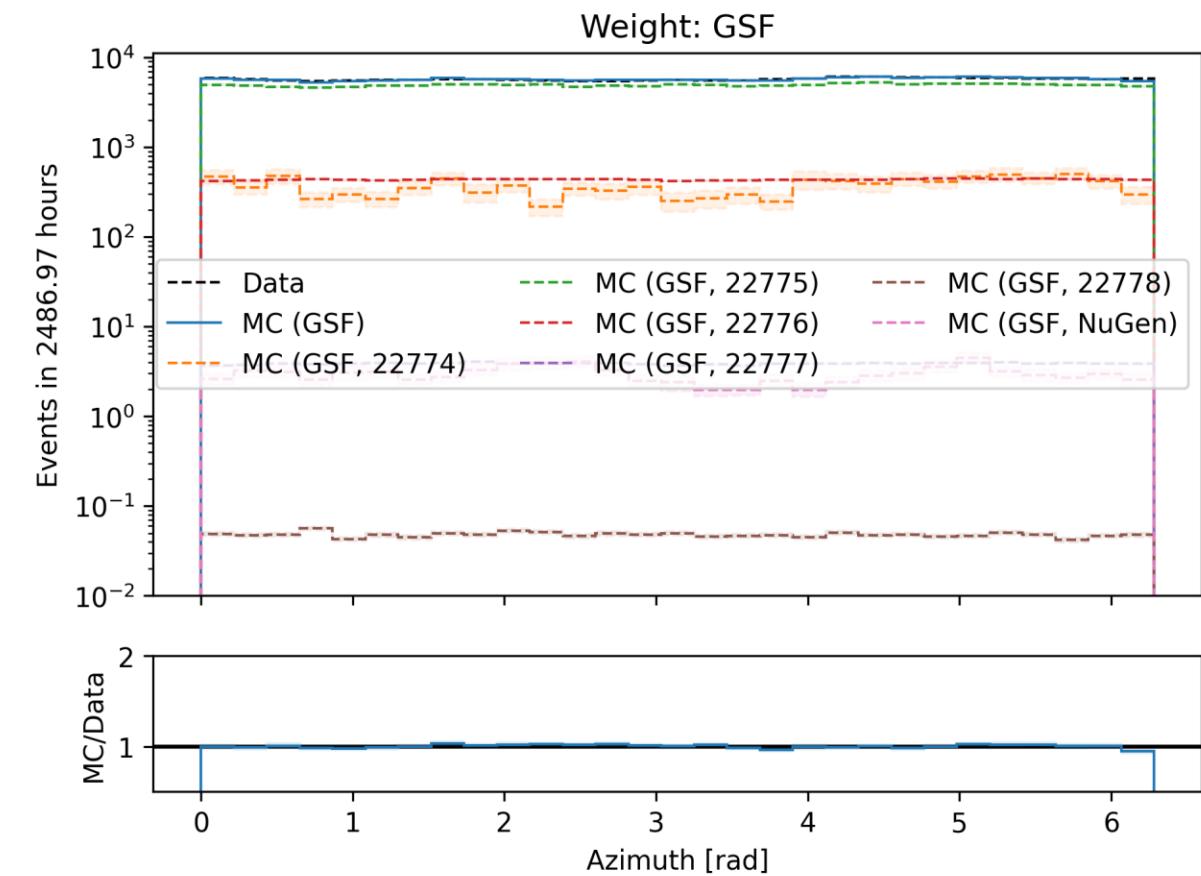
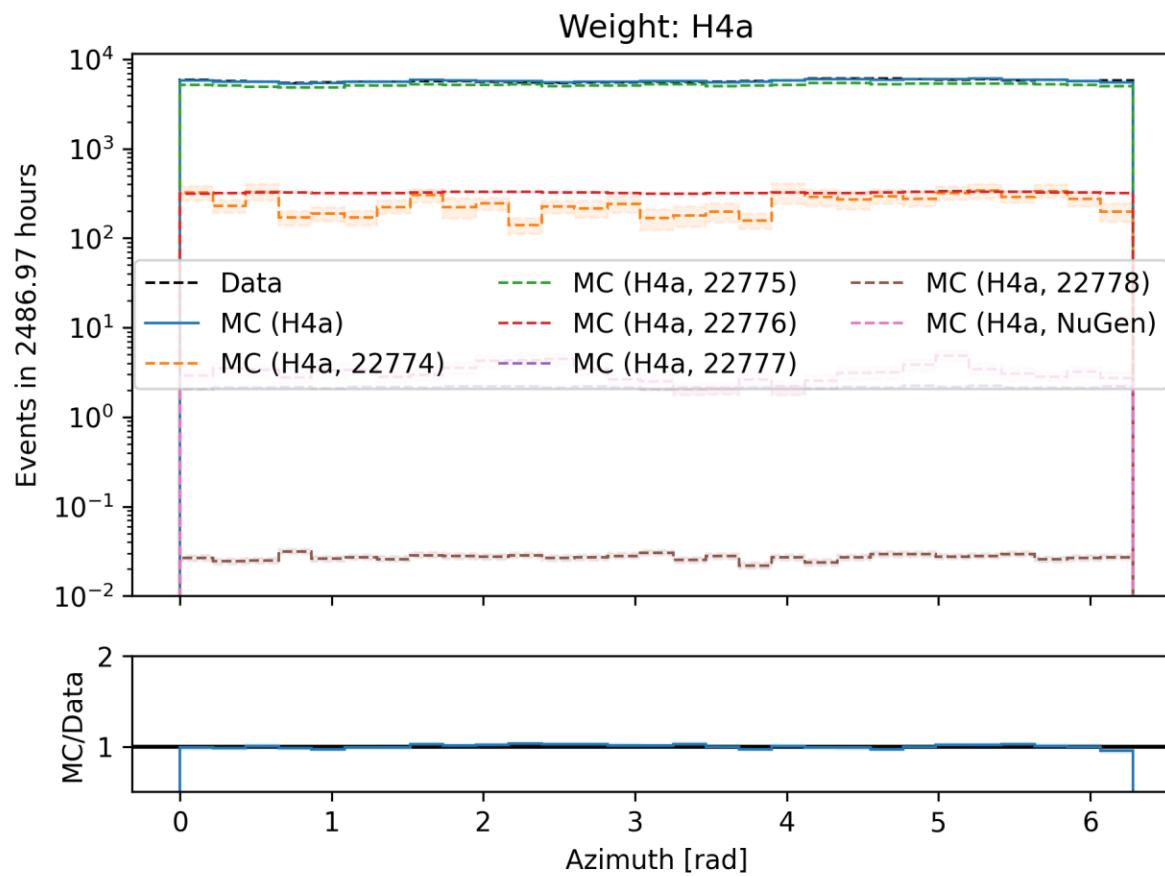
Iron



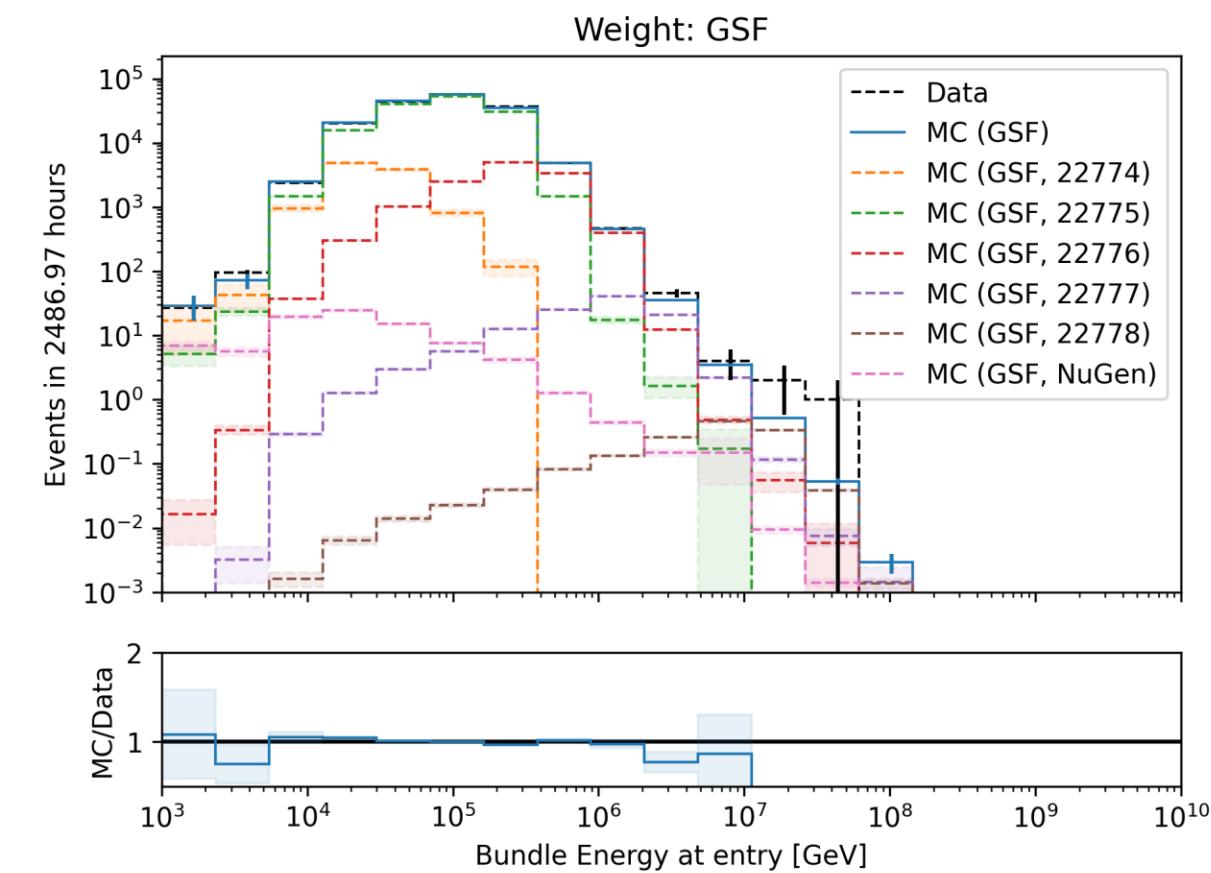
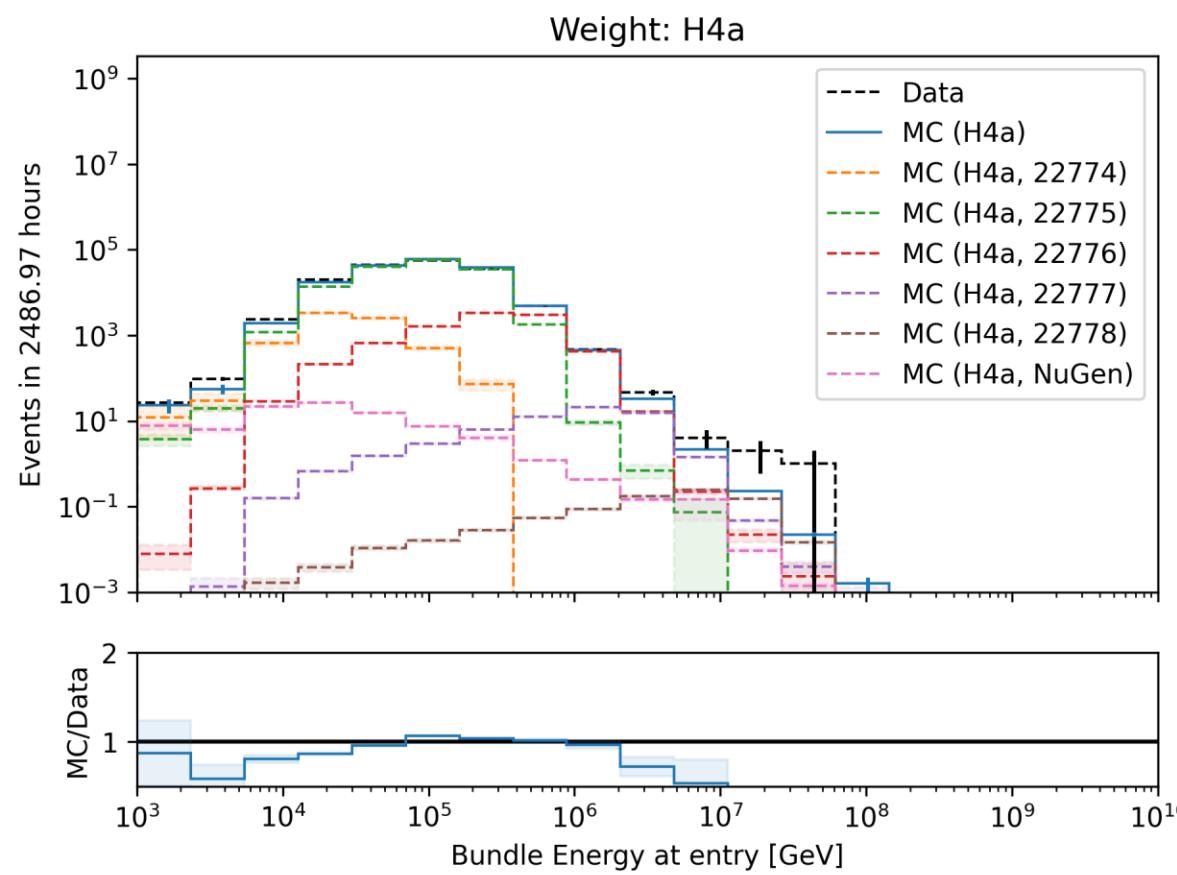
## Agreement for different primary models



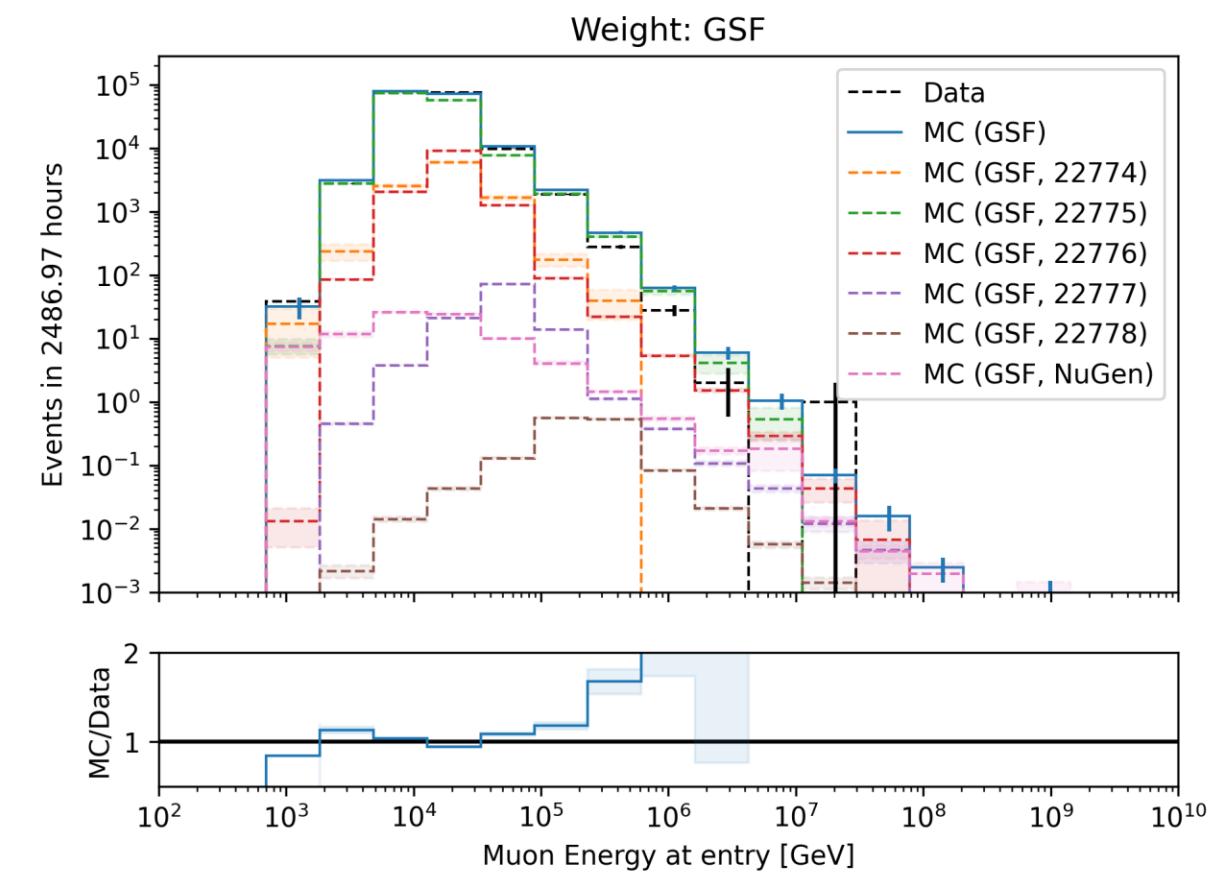
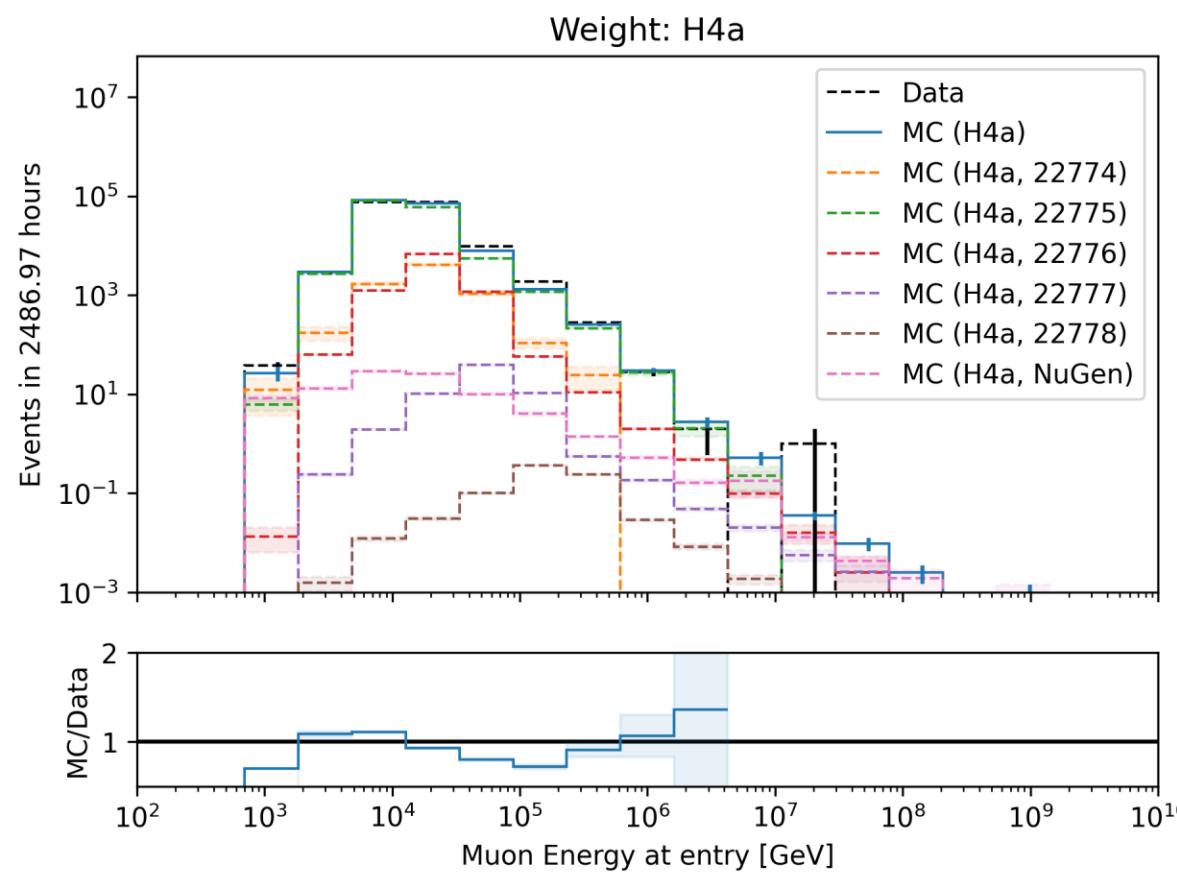
## Azimuth



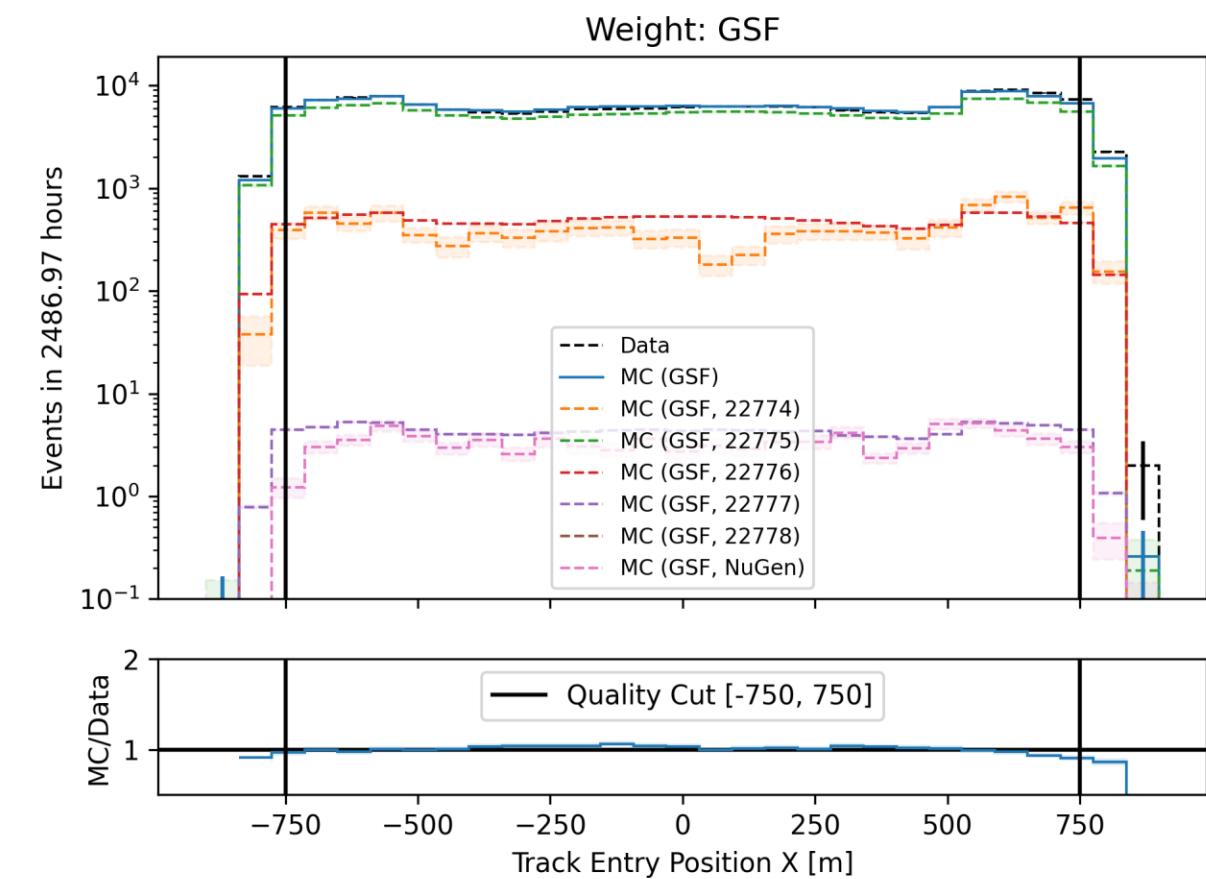
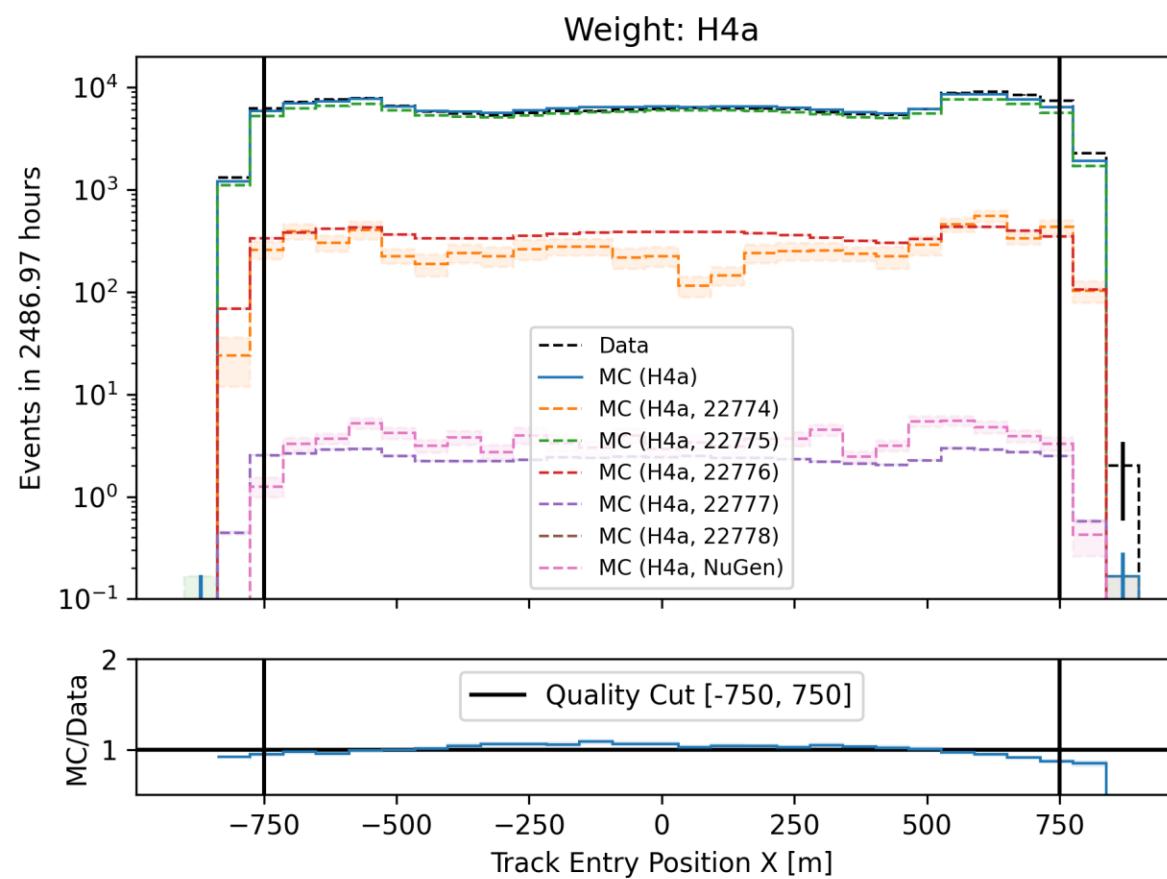
# Bundle energy at entry



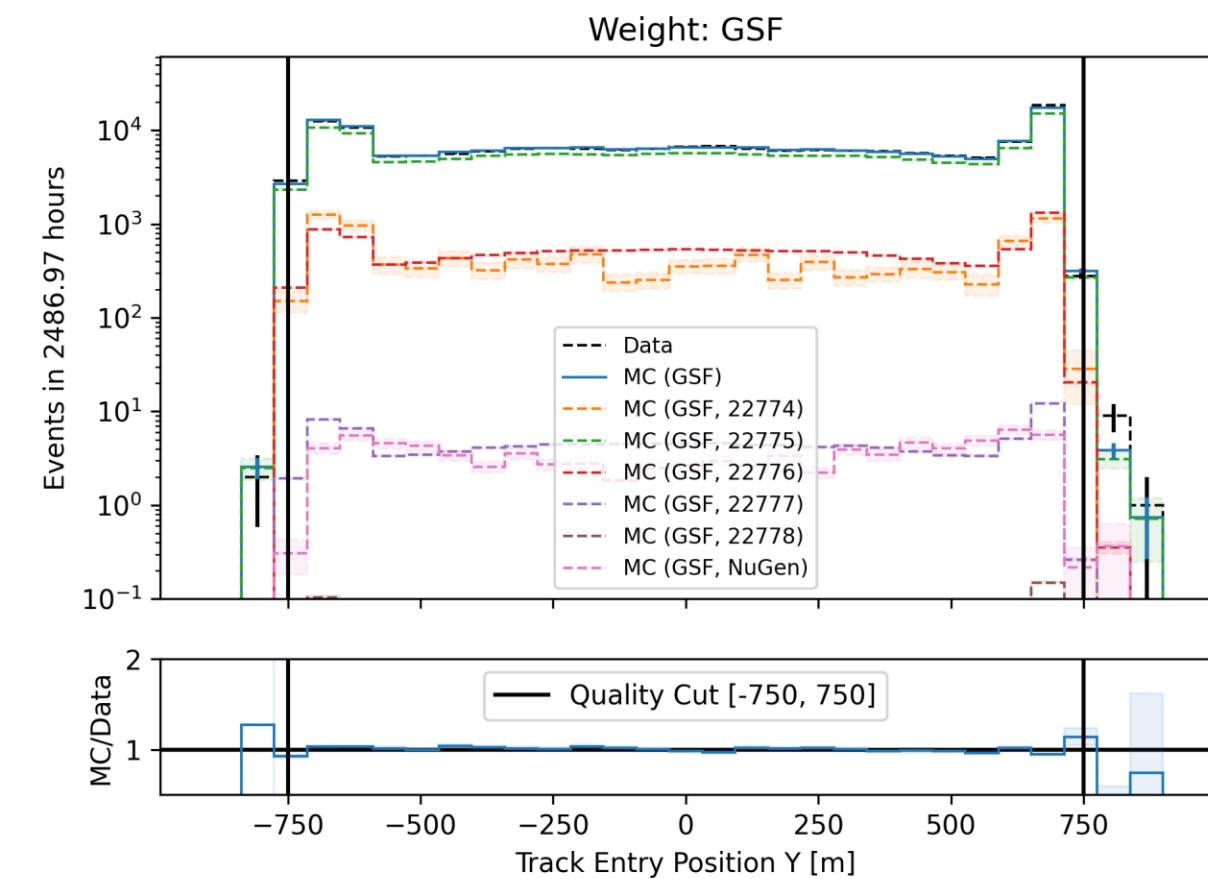
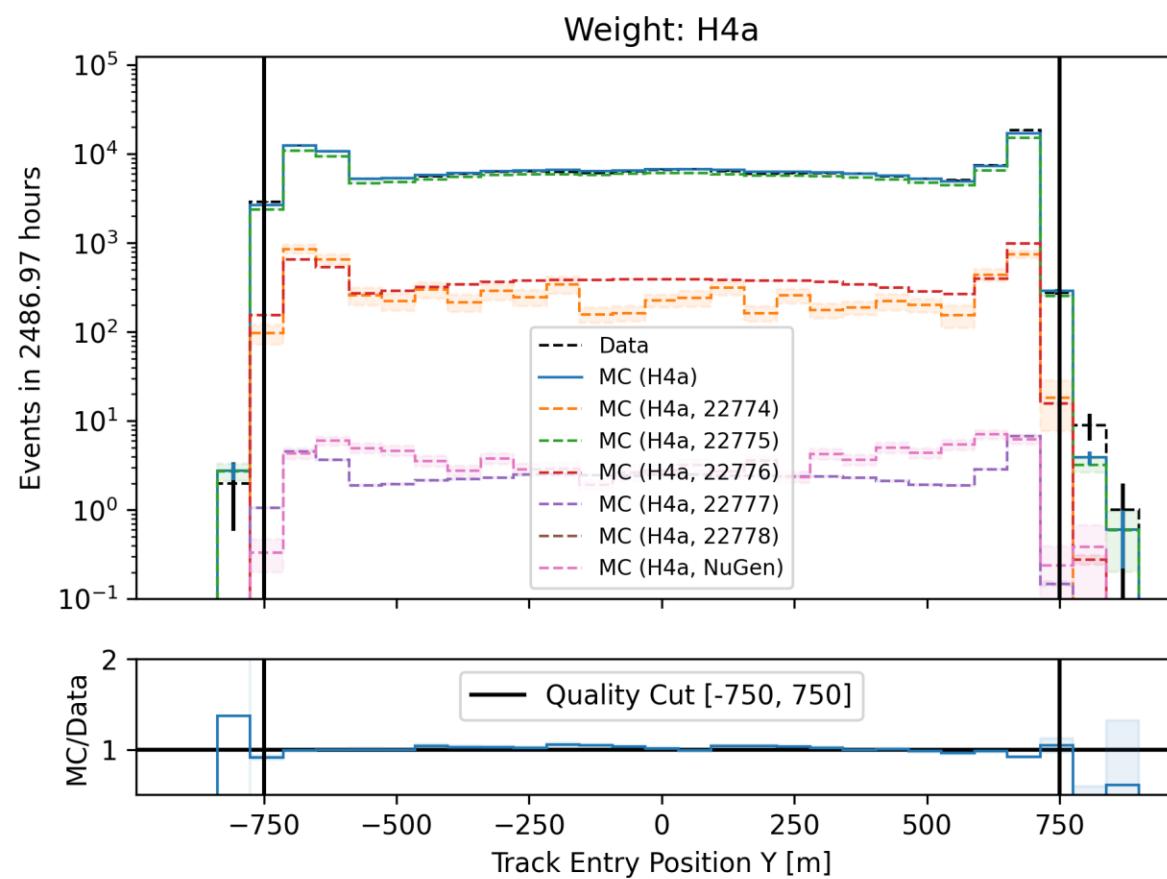
# Leading muon energy at entry



# Entry position x–vertex



# Entry position y-vertex



# DNN reconstructions

# 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

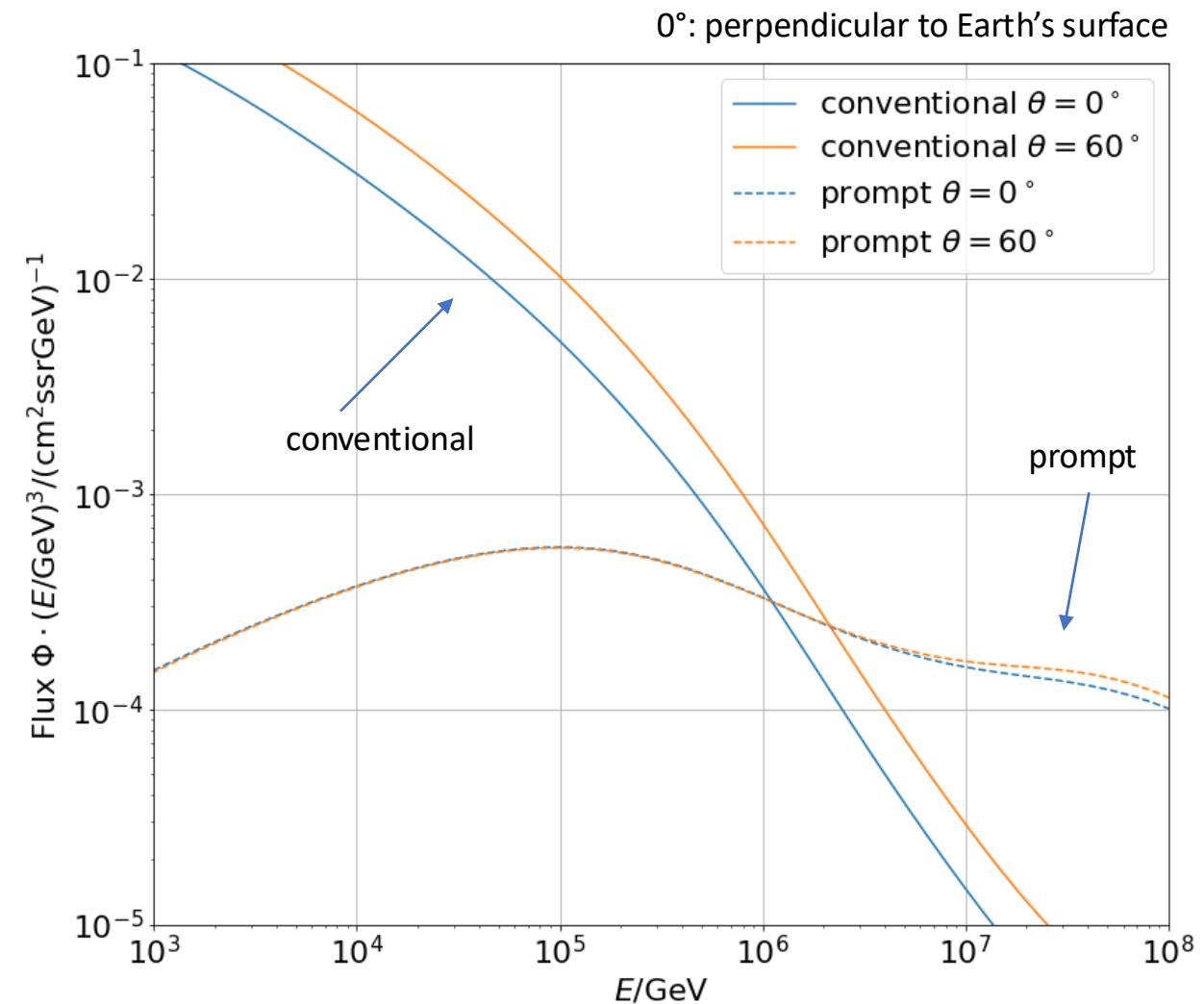
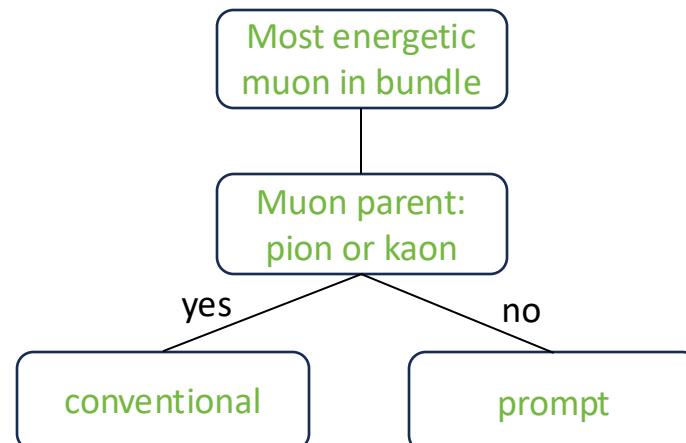
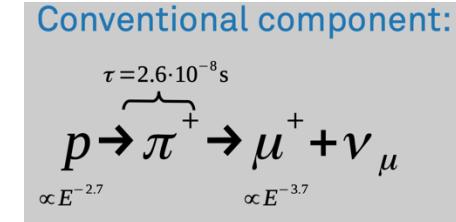
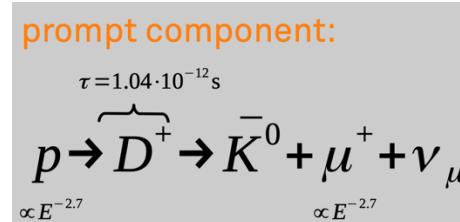
- `Length`: Propagation length of muon in the ice
- `LengthInDetector`: Propagation length of muon in the detector
- `center_pos_x`: Closest x position of muon to center of the detector
- `center_pos_y`: Closest y position of muon to center of the detector
- `center_pos_z`: Closest z position of muon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

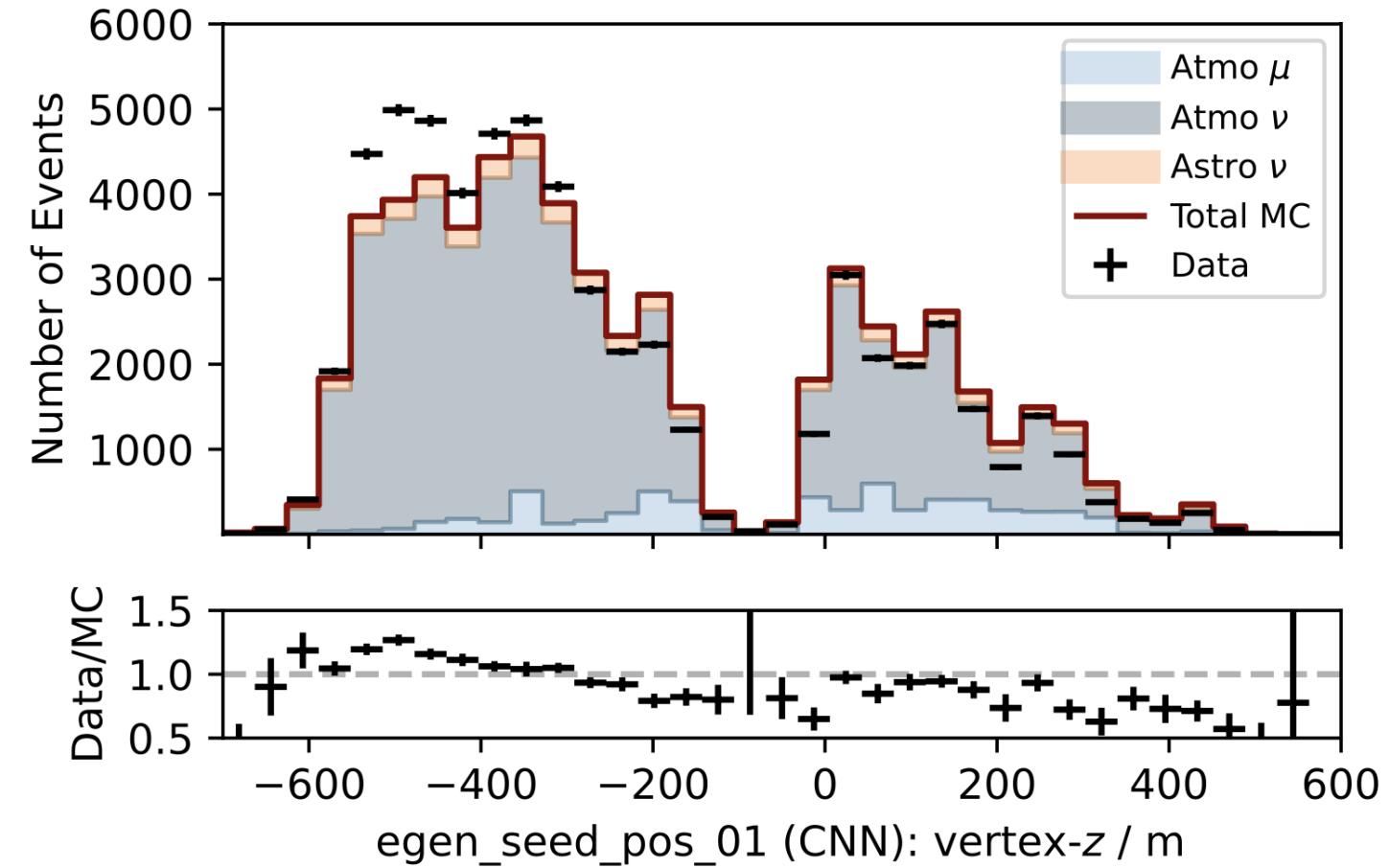
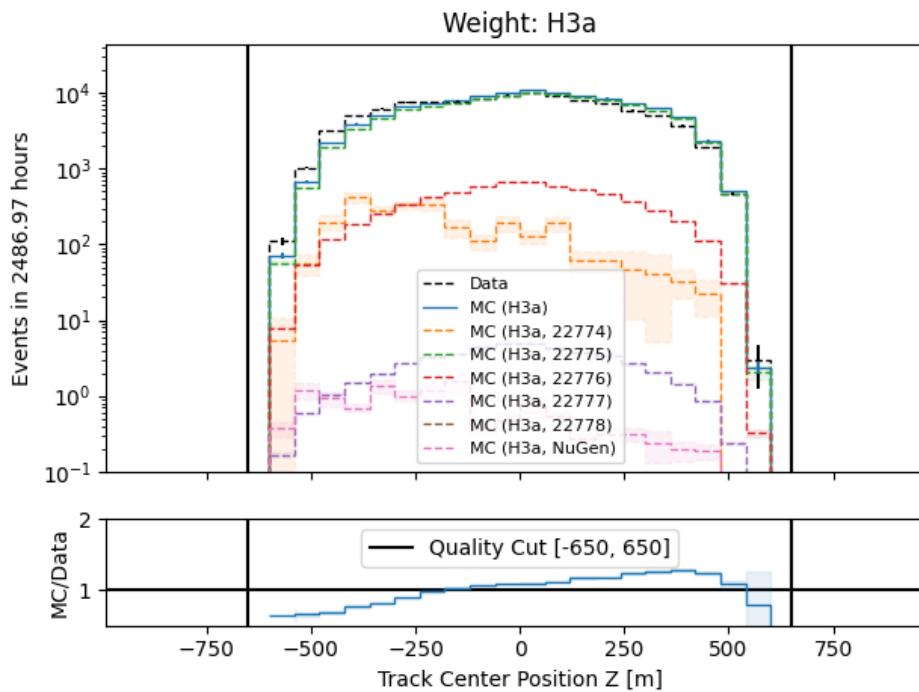
# Muon flux: Prompt spectrum

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

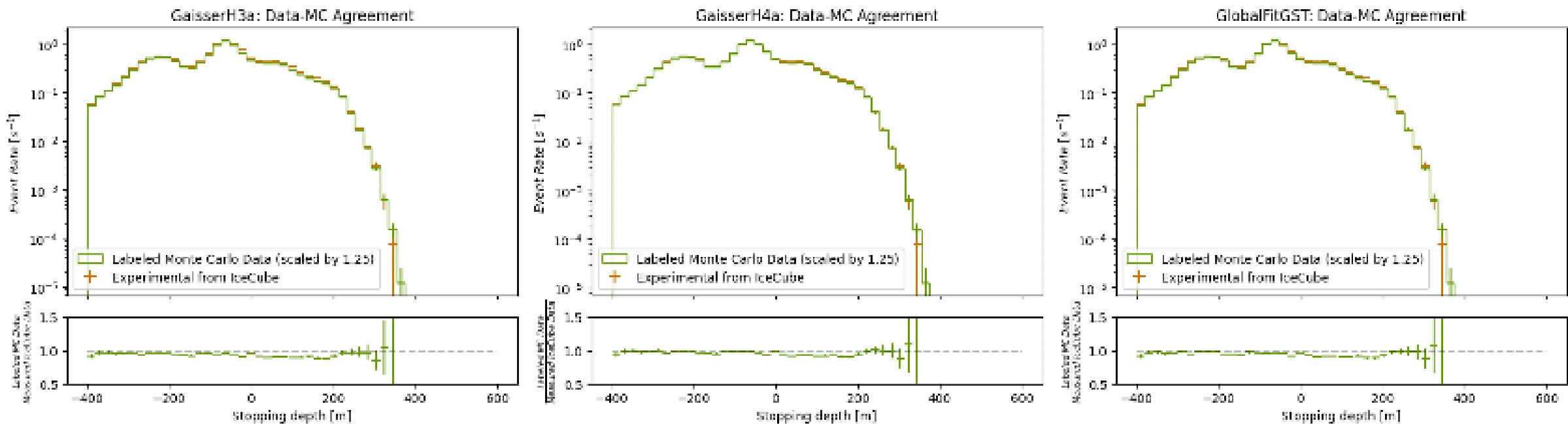


# Neutrino: z-vertex

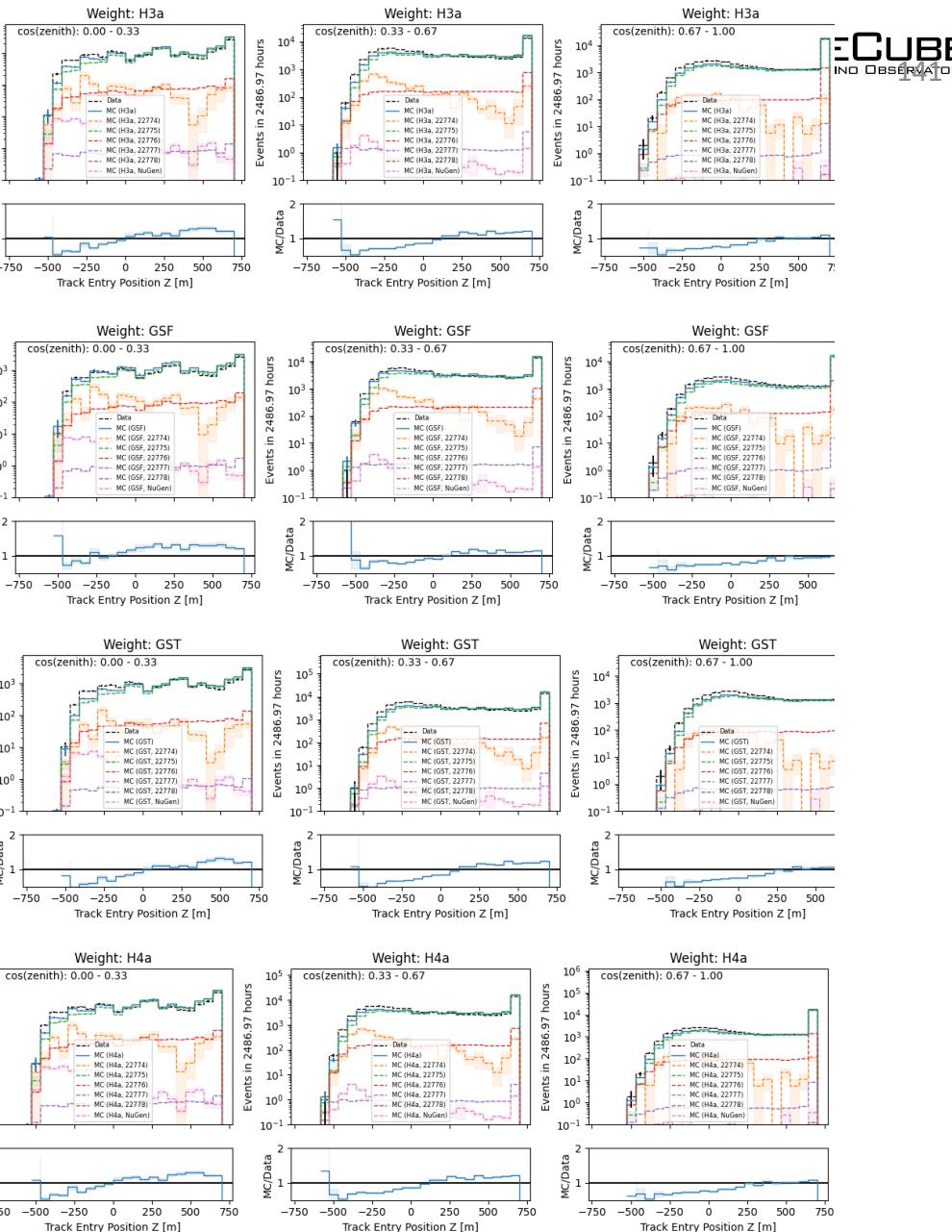
- Dissertation Mirco
- Same shape mismatch for neutrinos as for muons



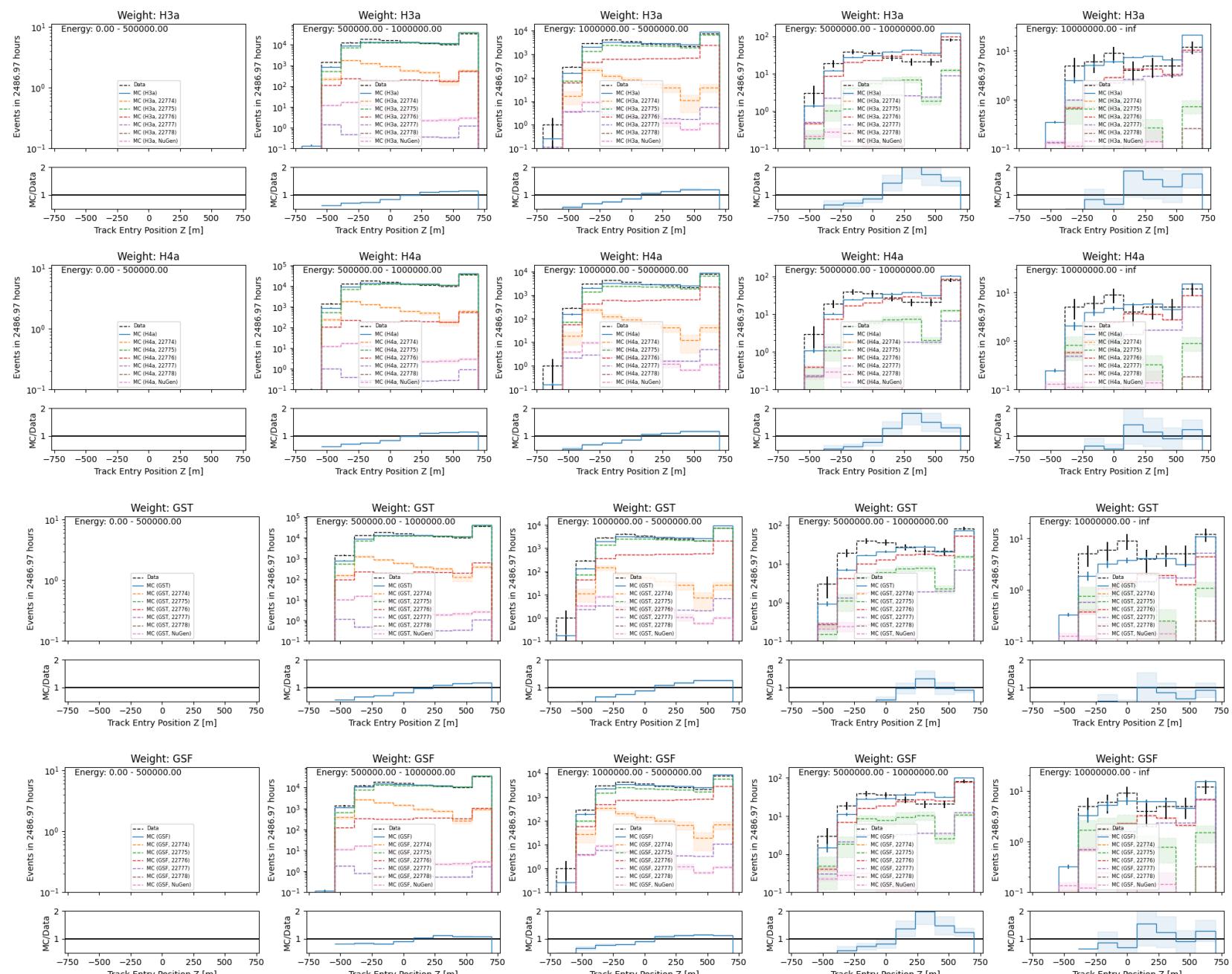
# Stopping muons



# Entry position z - different cos(zenith)



Entry position z  
- different cuts on  
bundle energy at  
surface

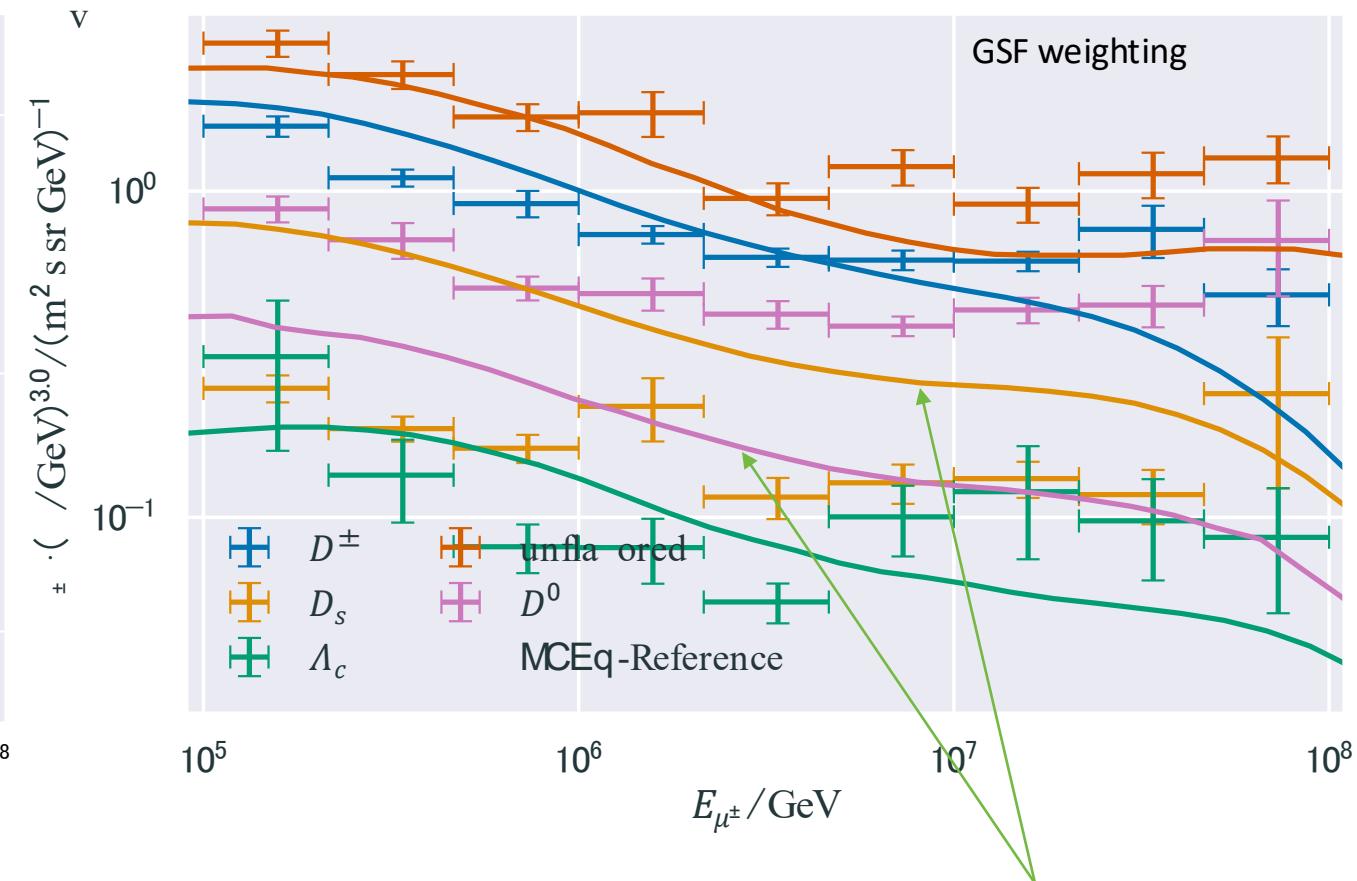
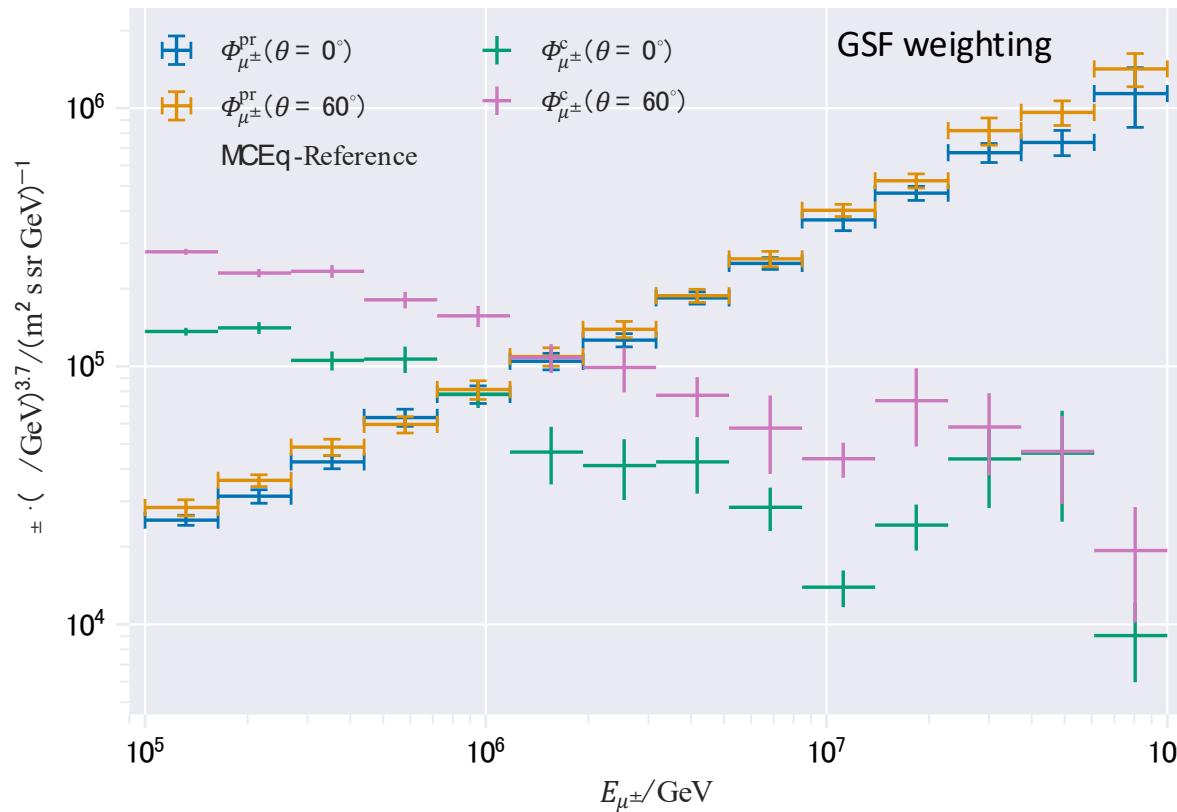


# New CORSIKA simulation

with extended history option for information about the parent particles

# CORSIKA 7 tagging and MCEq comparison

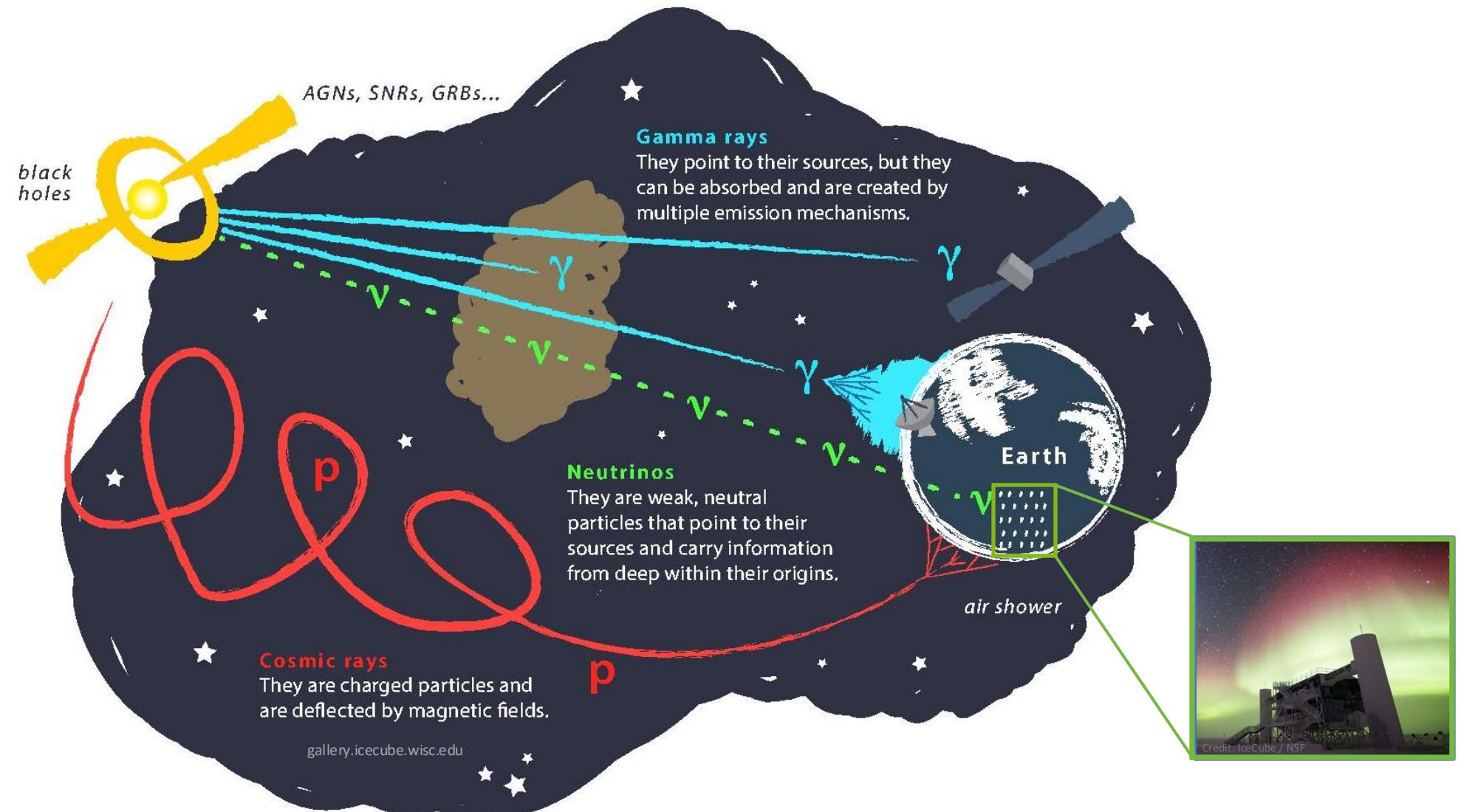
MCEq: tool to numerically solve the cascade equations that describes the evolution of particle densities as they propagate through a gaseous, dense medium  
<https://github.com/mceq-project/MCEq>



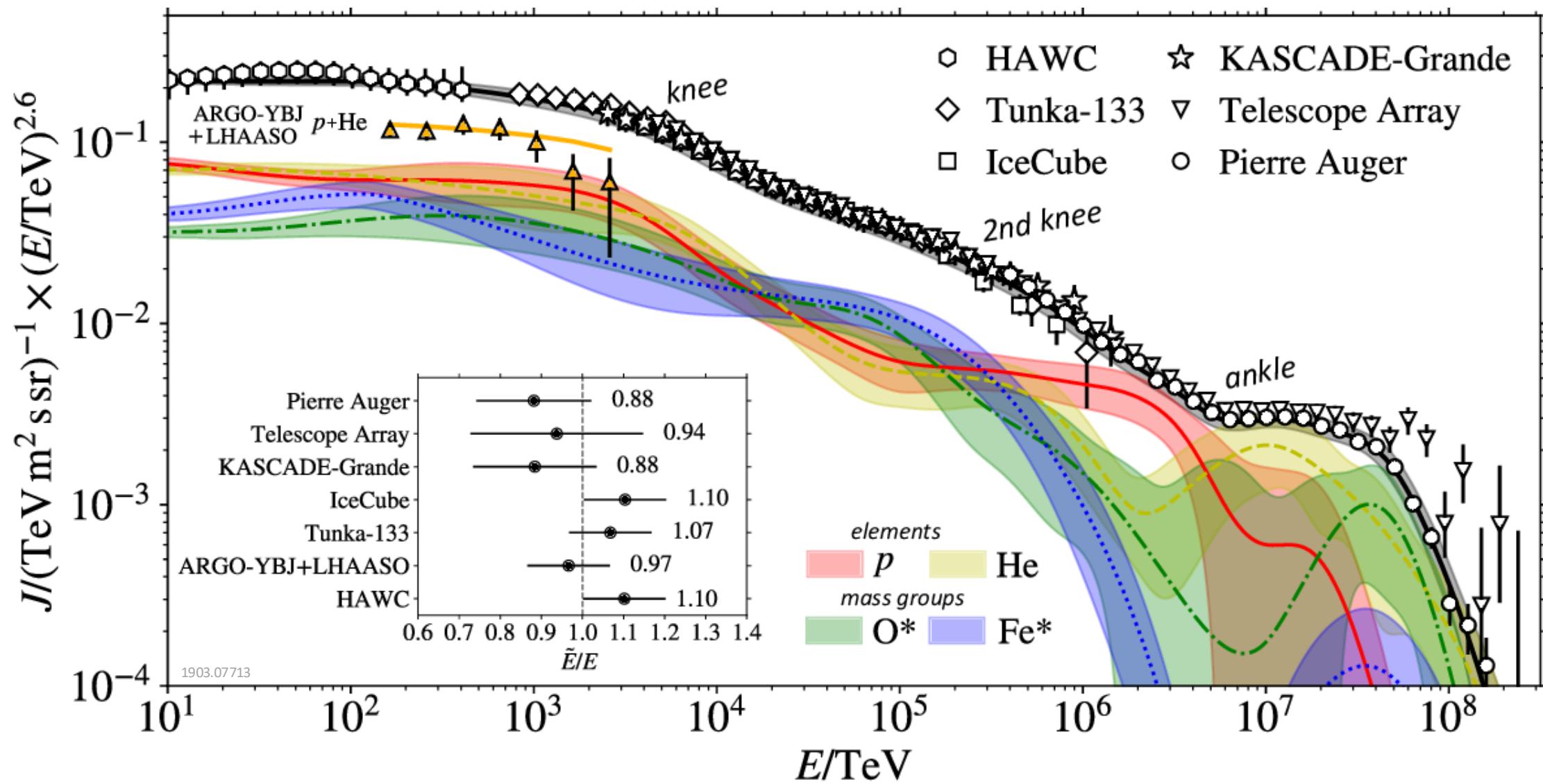
➤ Good agreement in total prompt and conv muon flux

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

# Astroparticle physics



## Cosmic ray flux



## Reconstruction of leading muon at entry (99% quantiles)

