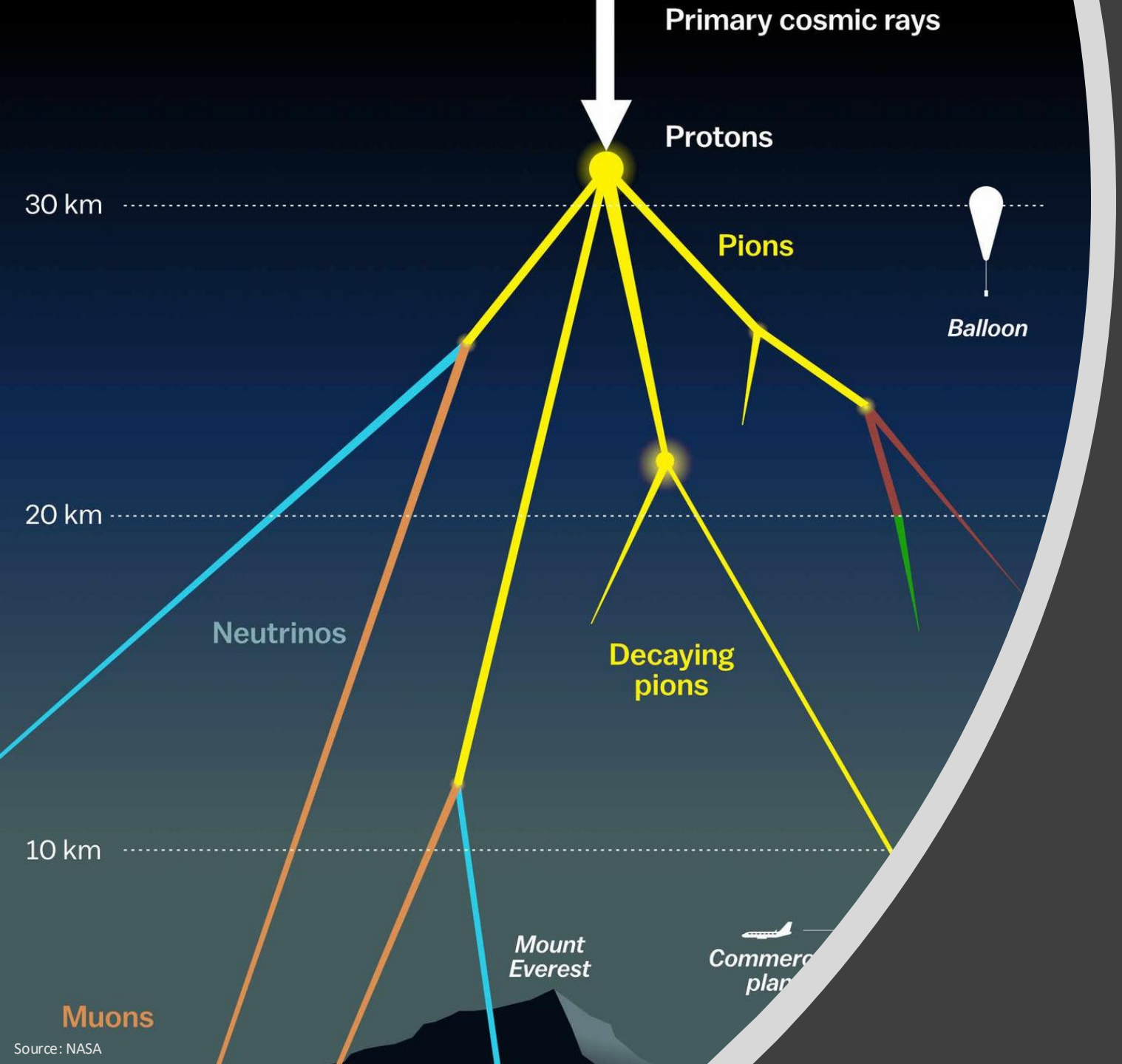


Prompt Muons Update - Leadingness Cut

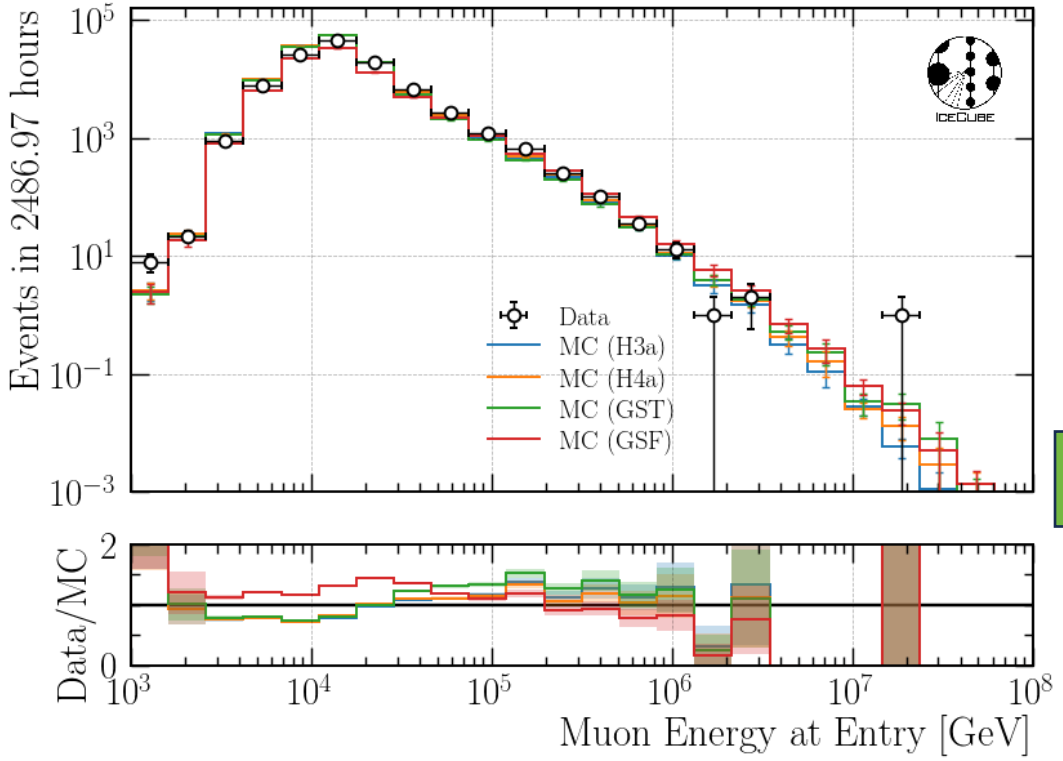
Pascal Gutjahr

June 27, 2025

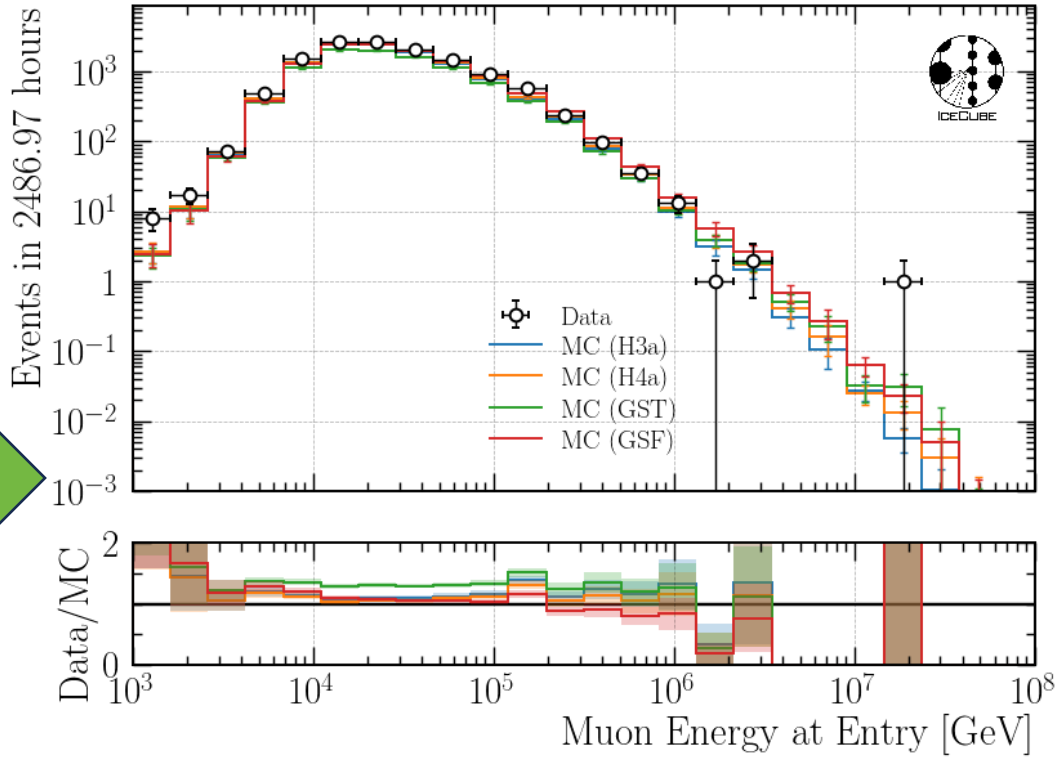
WG reviewer: Dennis Soldin
Coll. reviewer: Anatoli Fedynitch
Technical reviewer: Karolin Hymon
Wiki: prompt wiki
Last update: Uppsala May 14

Data—MC Proxy Variable

$$\text{Leadingness} = \frac{\text{Leading Energy}}{\text{Bundle Energy}}$$



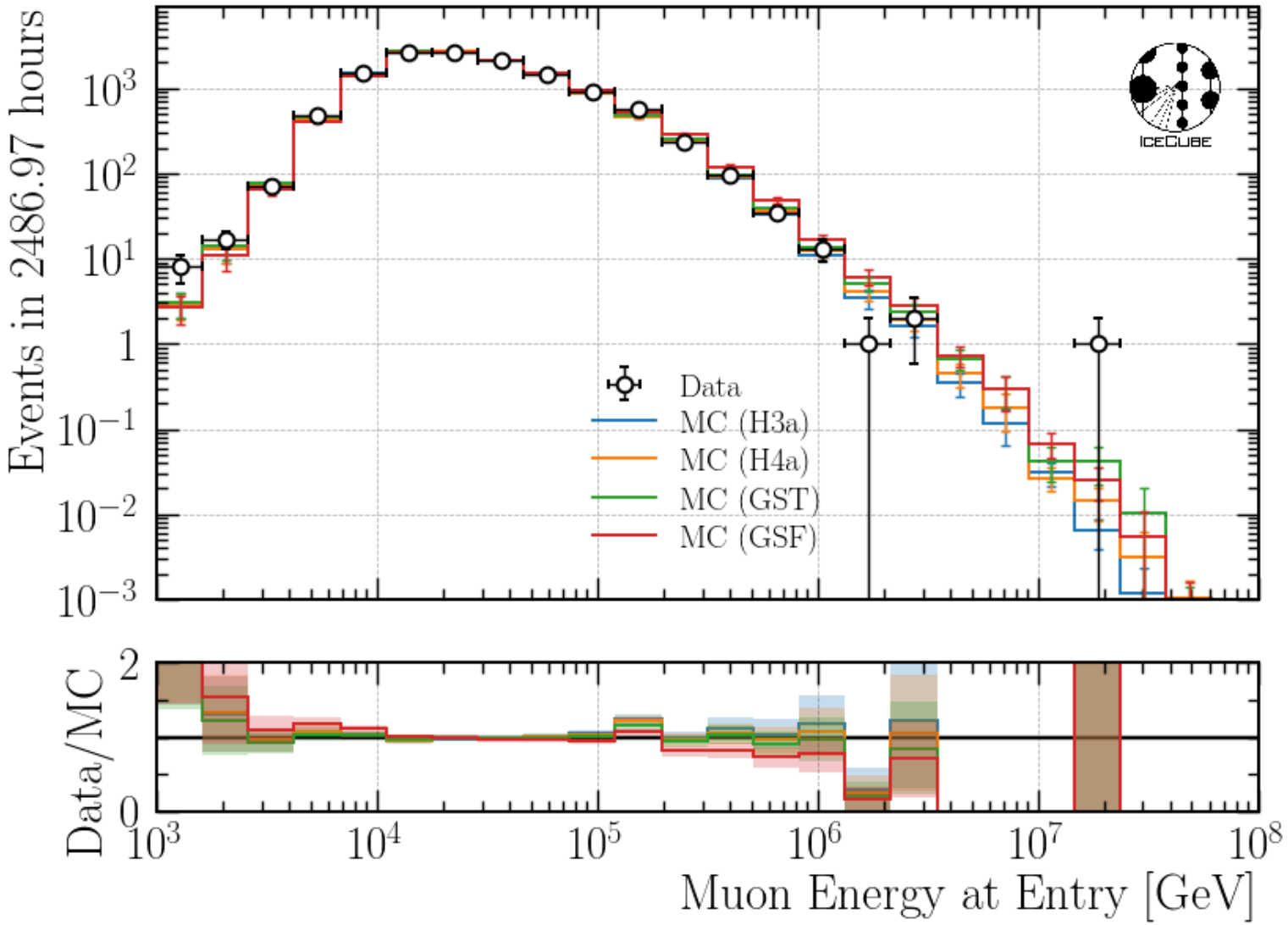
Leadingness > 40%



Data—MC Proxy Variable: Leadingness > 40 %

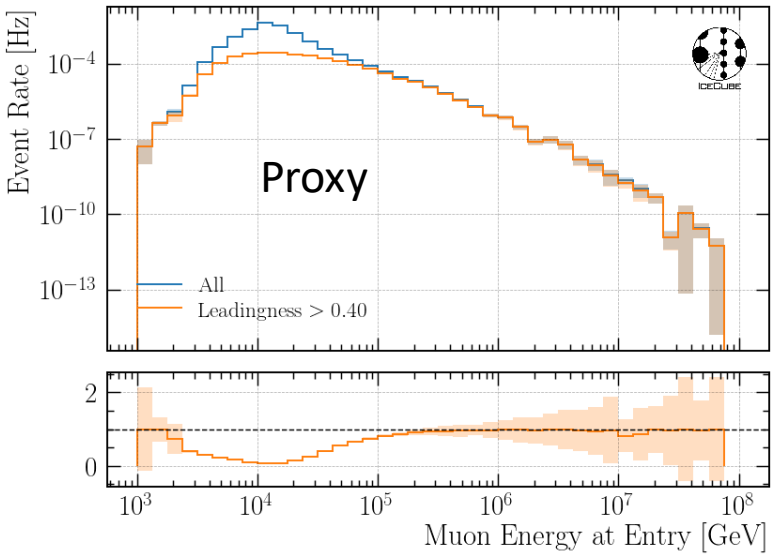
Nomalizations:

- H3a: + 12 %
- H4a: + 9%
- GST: + 32%
- GSF: + 9%

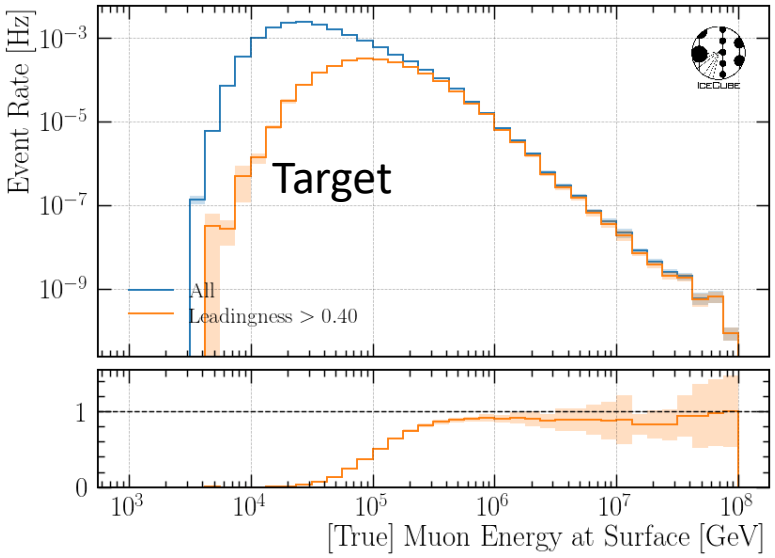


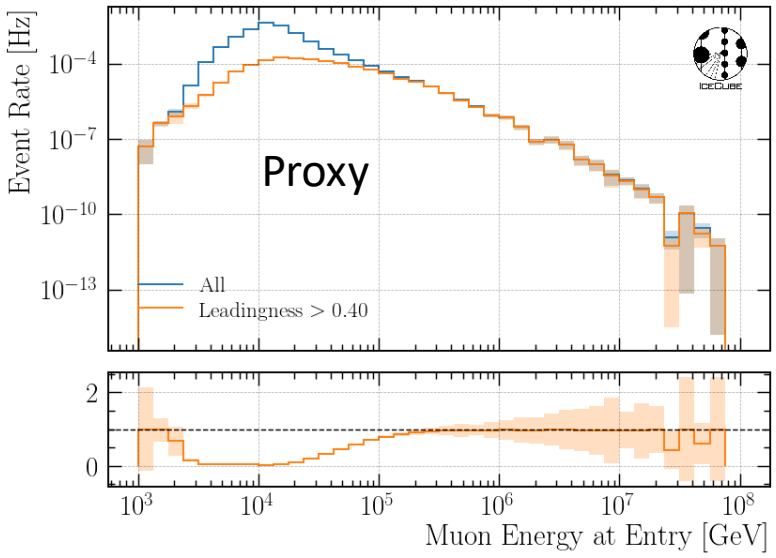
- MC shapes agree with data
- Total normalization has NO impact on unfolding

Proxy & Target Distributions Before/After cut (True & Reco)

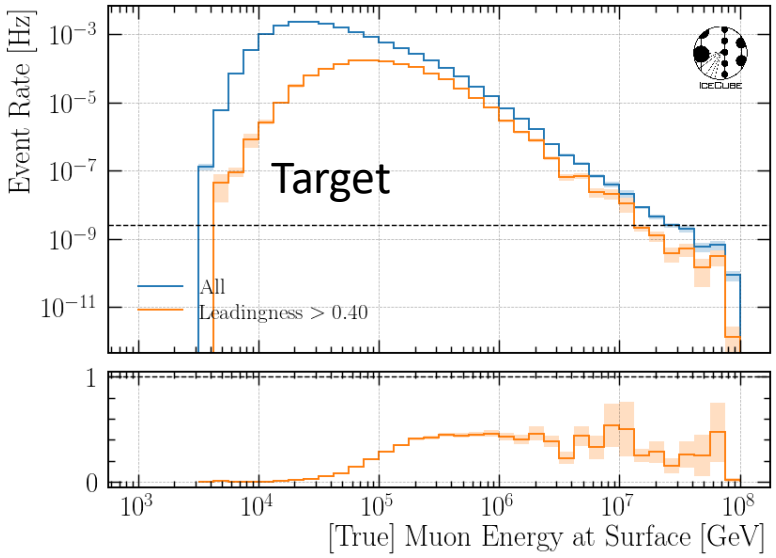


Cut on TRUE leadingness

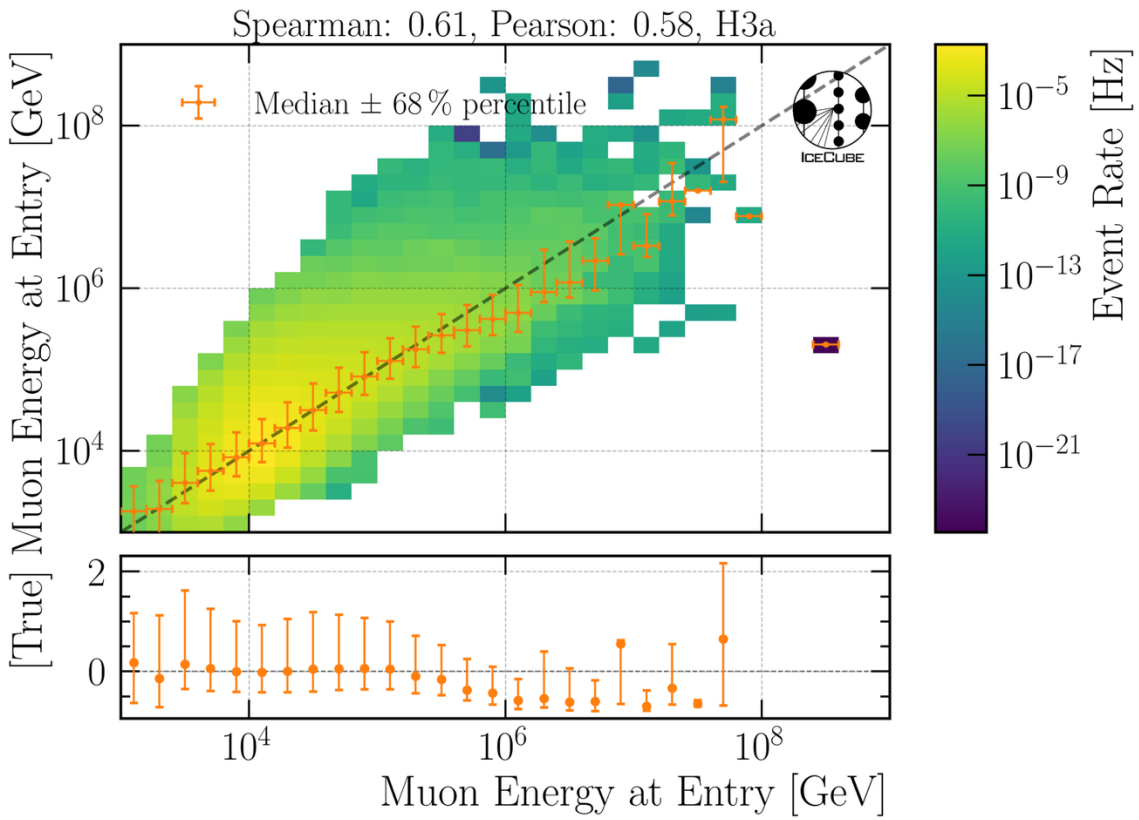


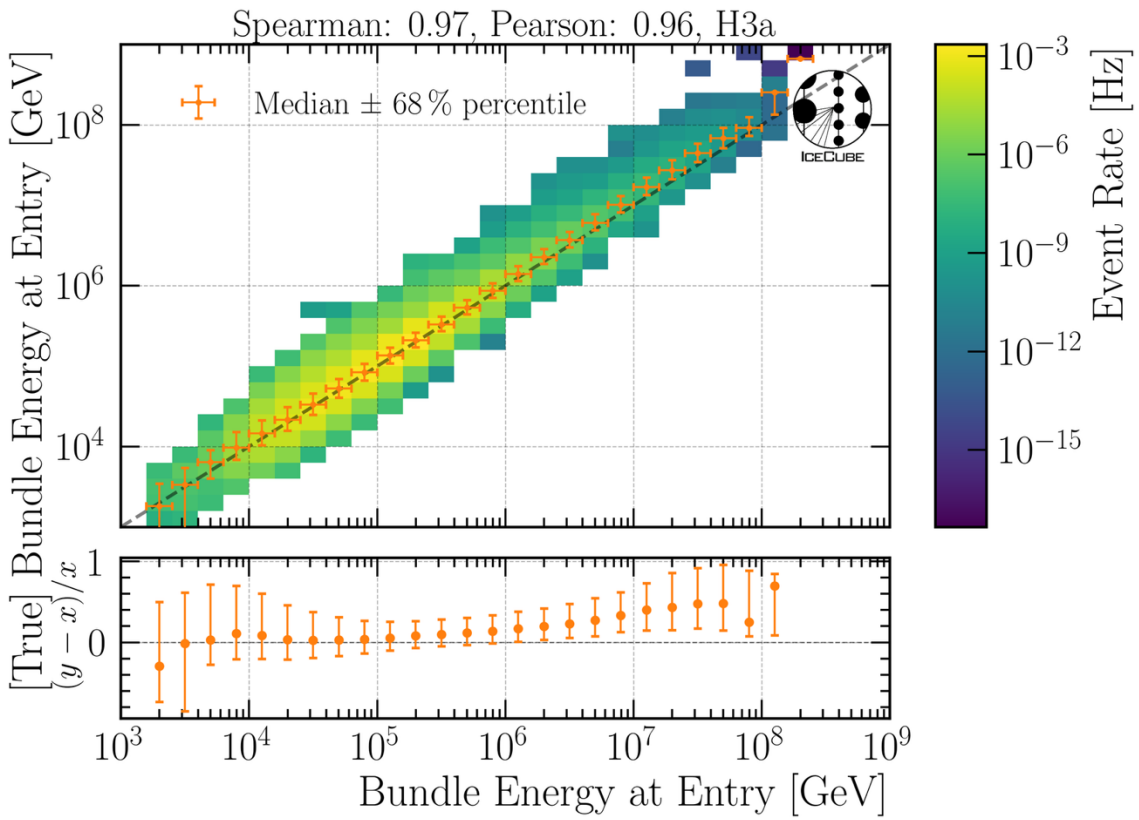


Cut on PRED leadingness

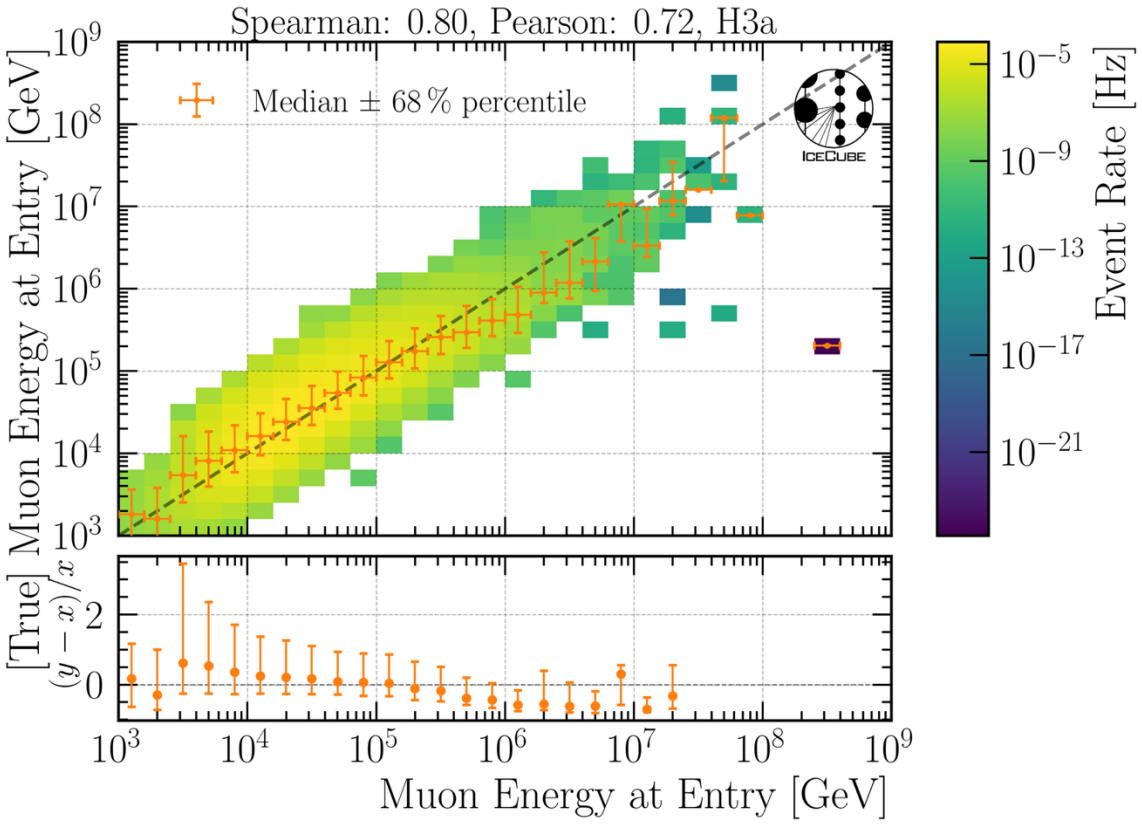


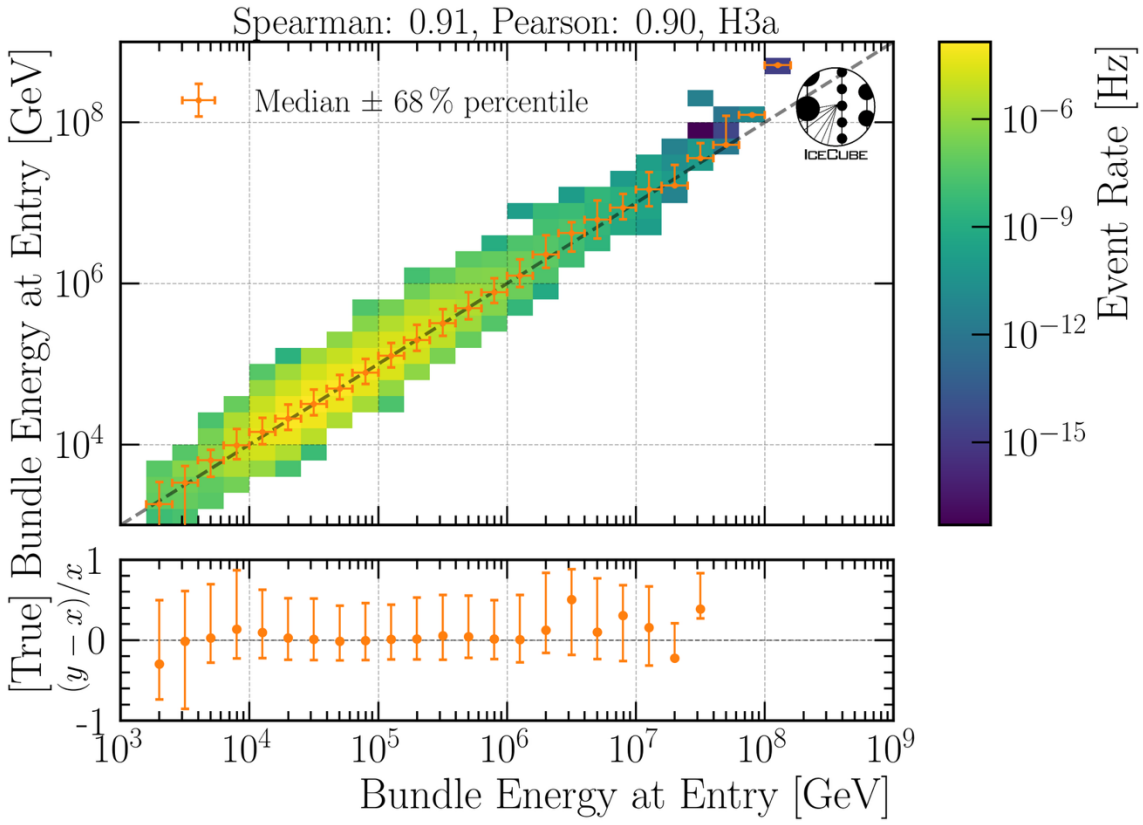
Reconstructions for Leadingness: Level 5





Reconstructions after Leadingness cut: Final Level

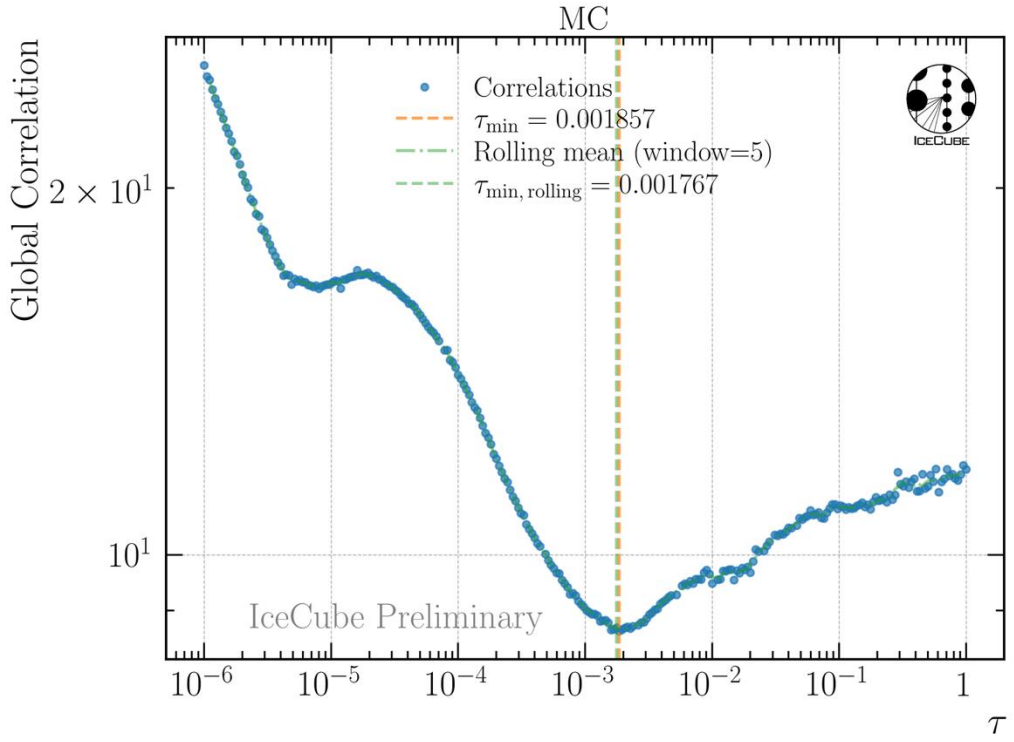


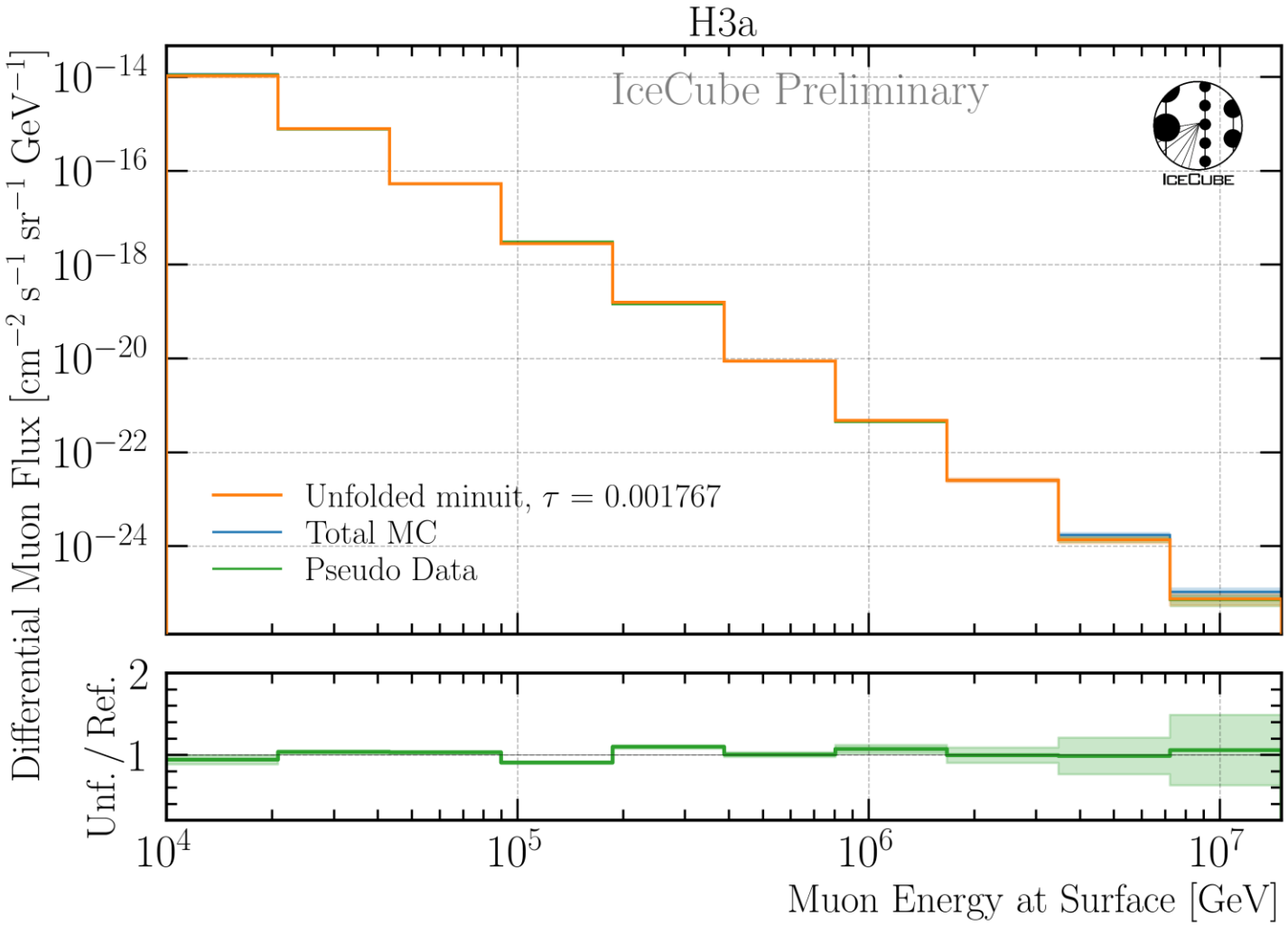


➢ Improved reconstructions

Unfolding on 12.12 years MC Pseudo data

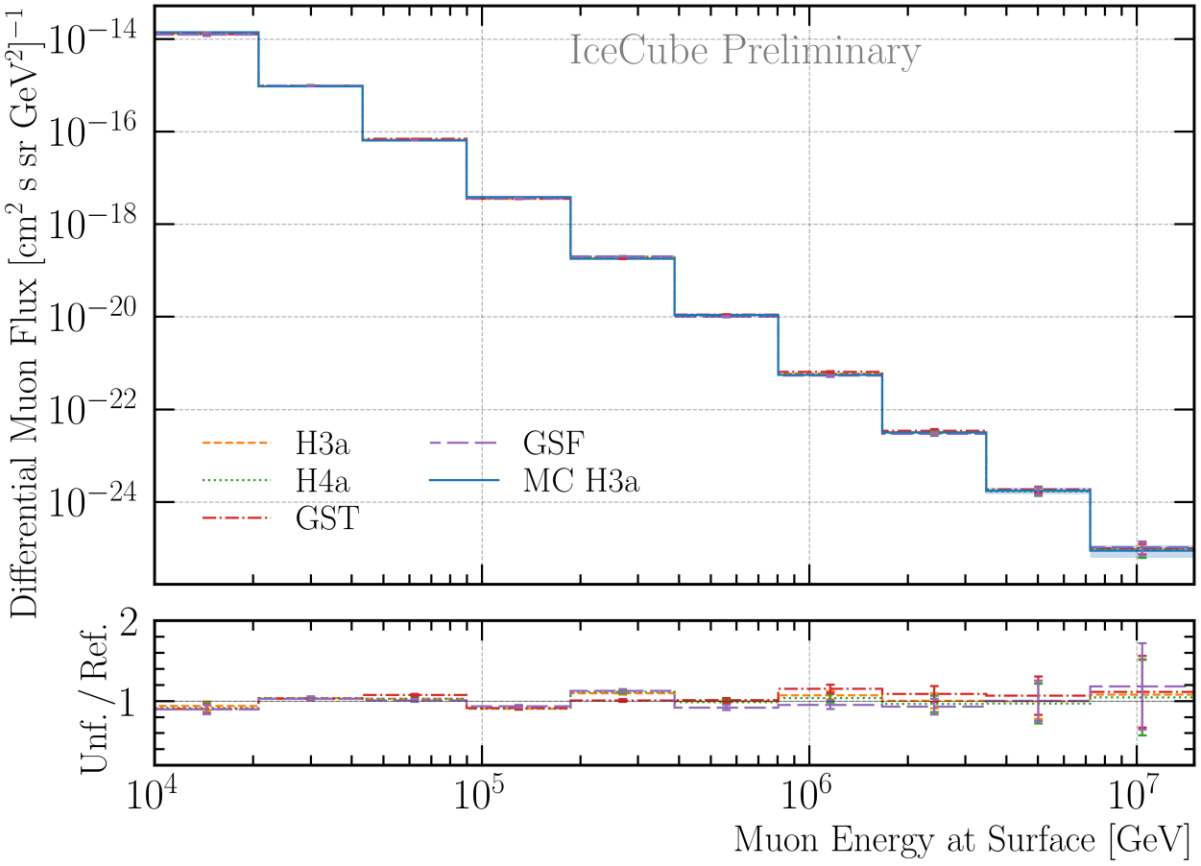
- Find reguluraization with minimal correlation: $\rho = \sum_i \sqrt{1 - \left(\mathbf{V}_{ii} \cdot \mathbf{V}_{ii}^{-1}\right)}$
  (V: Covariance Matrix)



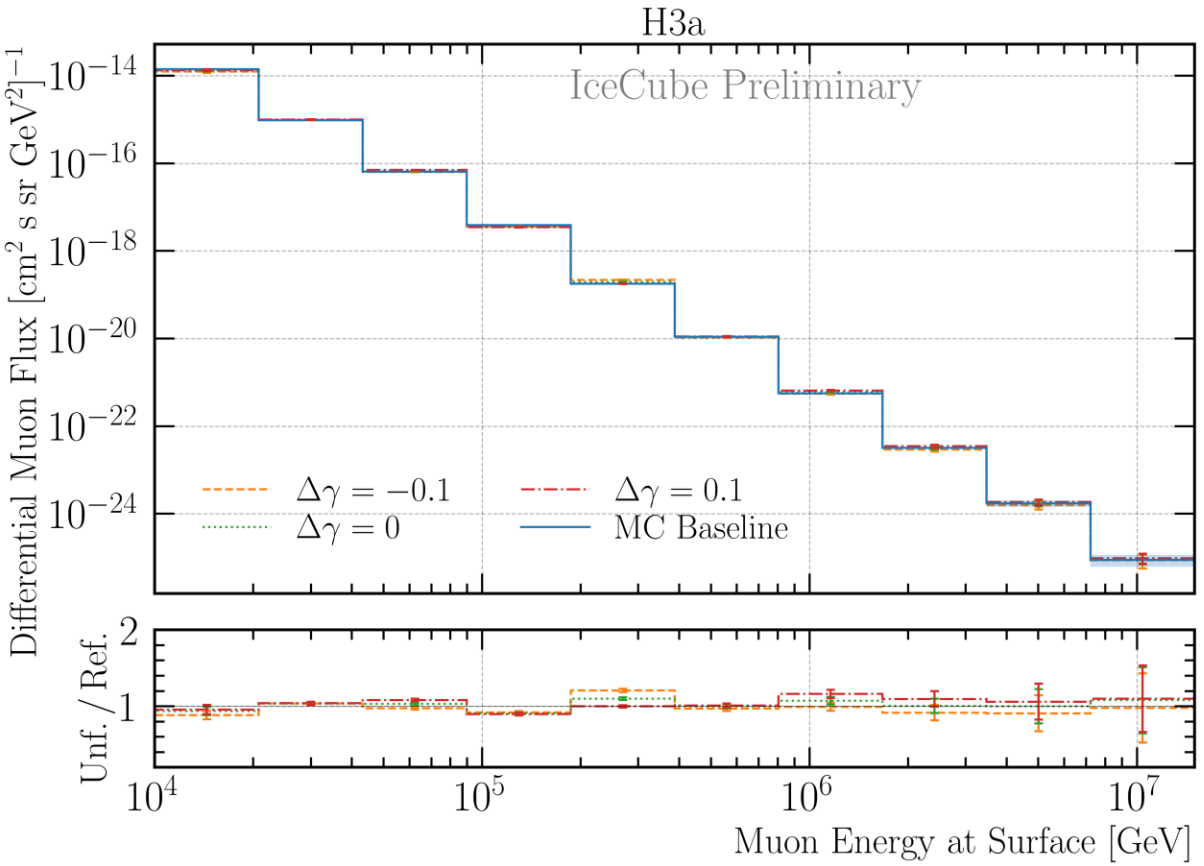


Robustness Tests

- Build unfolding matrix on H3a, H4a, GST and GSF
- Unfold H3a as “test data”

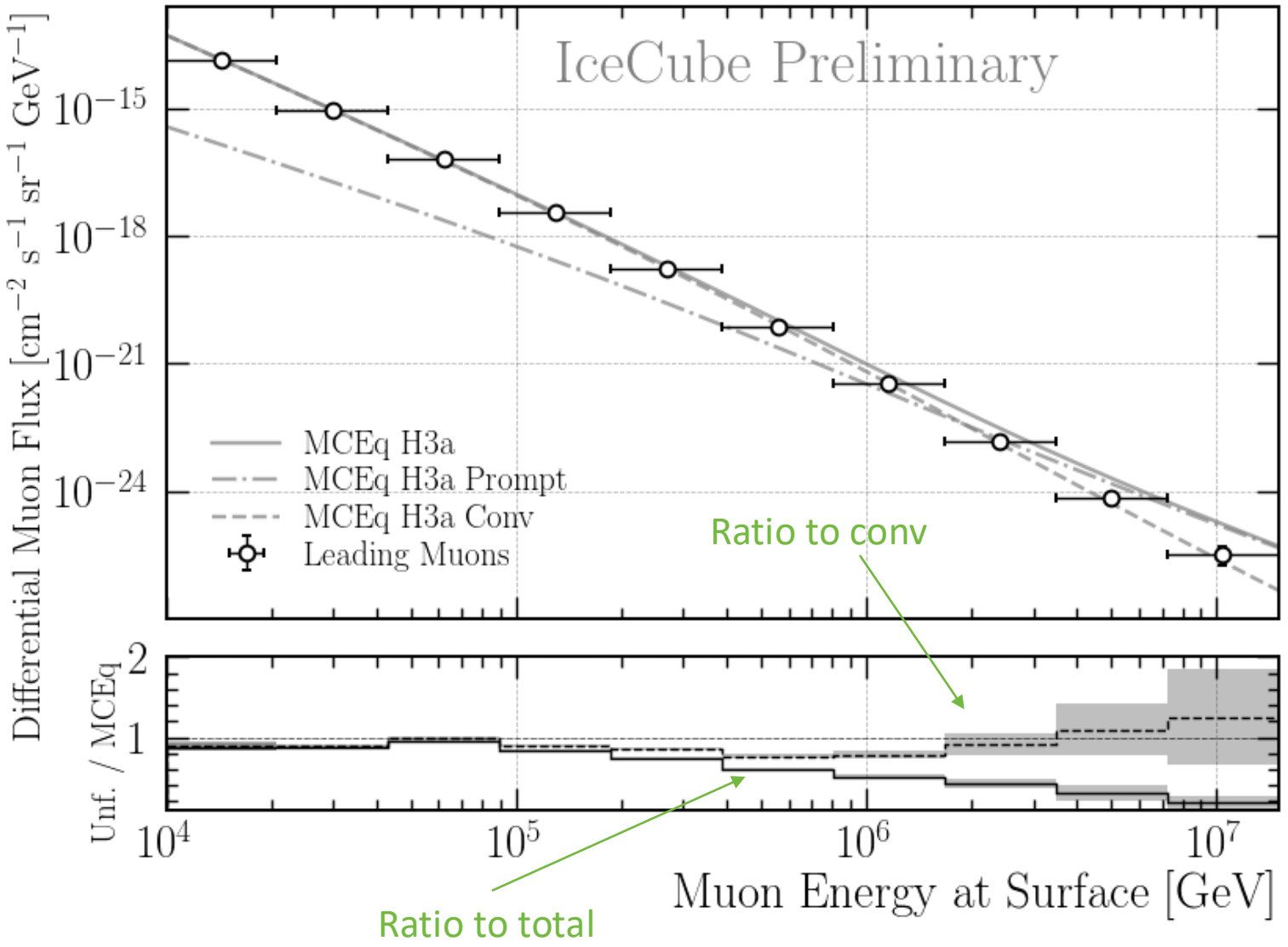


- Build unfolding matrix on H3a with $\gamma \pm 0.1$
- Unfold H3a as “test data”



Test: Pseudo Data set includes ONLY conv

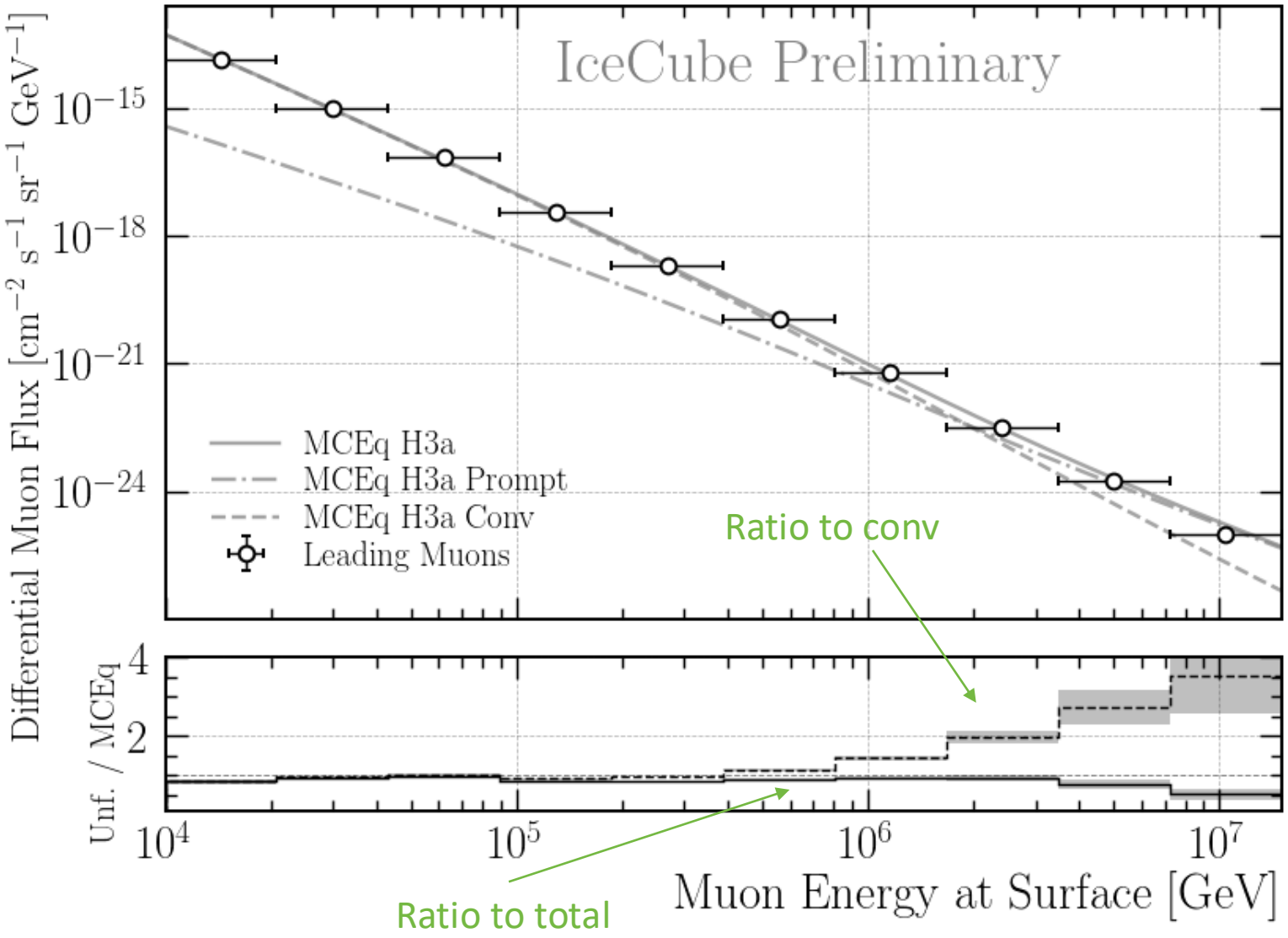
- Expectation:
  Unfolding agrees with conventional
- Works as expected



No effective area are uncertainties shown

Test: Pseudo data includes prompt & conv

- Expectation:
  Unfolding agrees with total
- Works as expected



No effective area are uncertainties shown

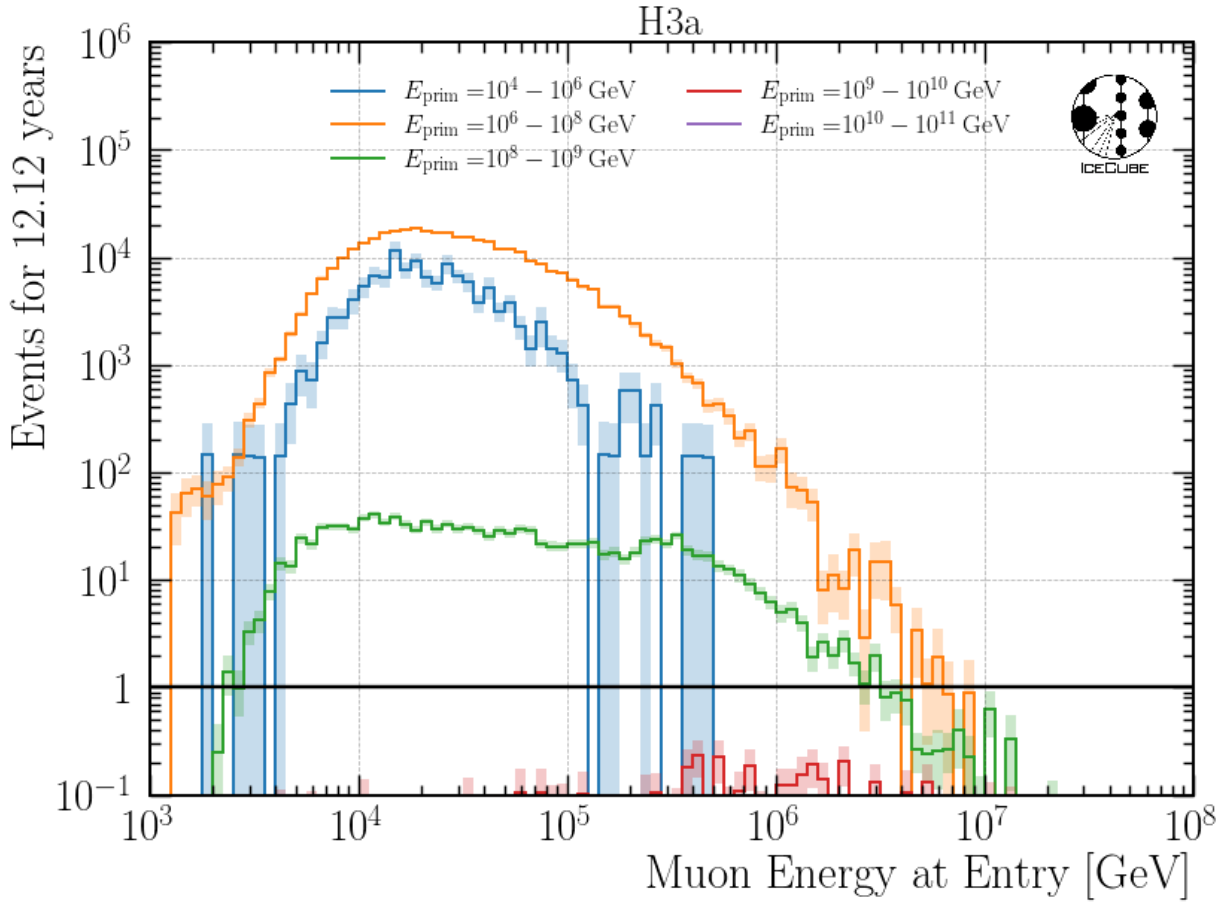
Conclusion

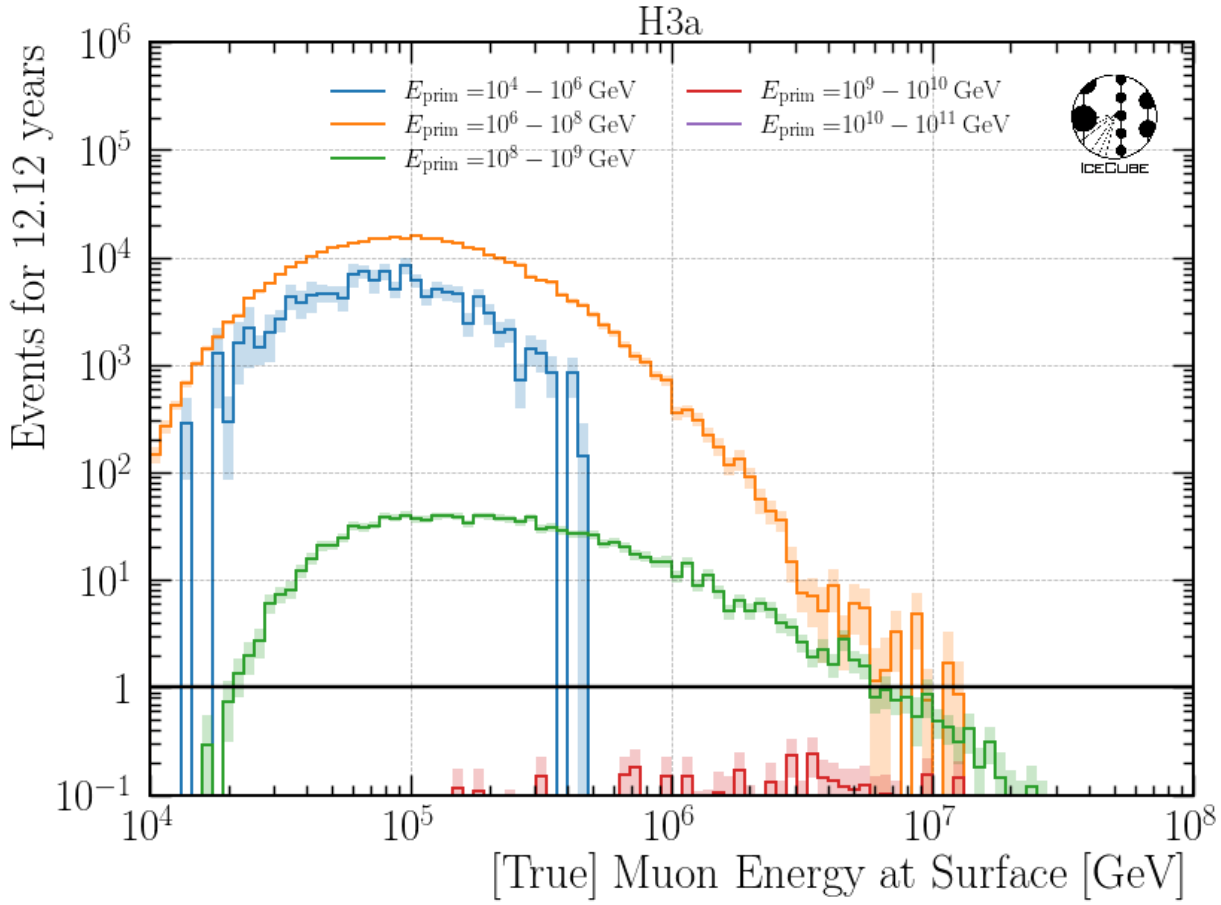
- Leadingness > 40 % improves data—MC of proxy variable
  - Additional cut → Final Level
  - Better reconstructions
  - Better correlation
- Unfolding works on MC for 12.12 years of data
- Robustness for different primary mass compositions and $\gamma \pm 0.1$ presented
- Algorithm is sensitive to prompt
  - When injecting conv only → conv is revovered
  - When injecting conv and prompt → total is recovered

Binning – info for myself

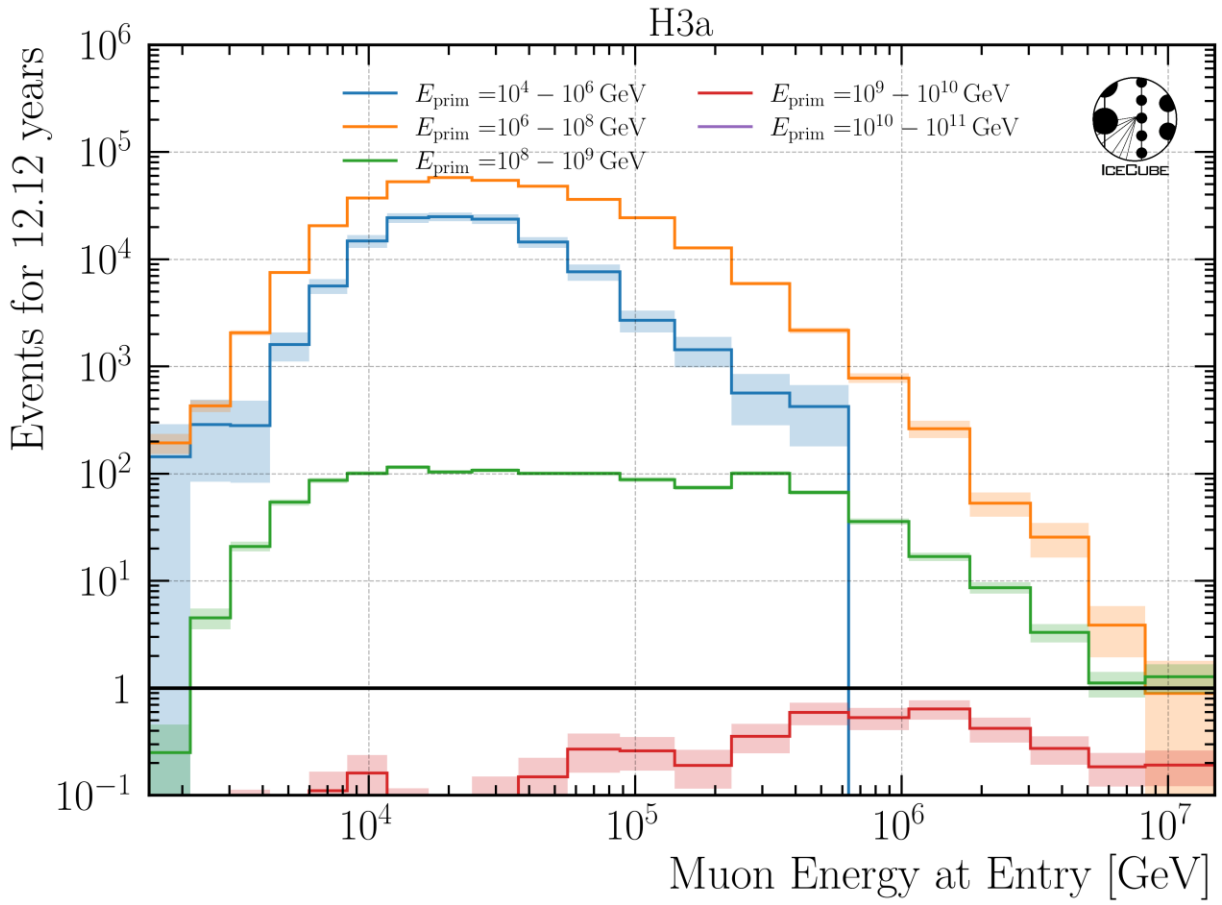
- Plots in these slides have been created with the proxy resolution binning k = 1
- Proxy: bins = np.geomspace(1.5e3, 1.5e7, 11)
- Unf: unf_bins = np.geomspace(1e4, 1.5e7, 11)
- Test set: H3a, seed 42

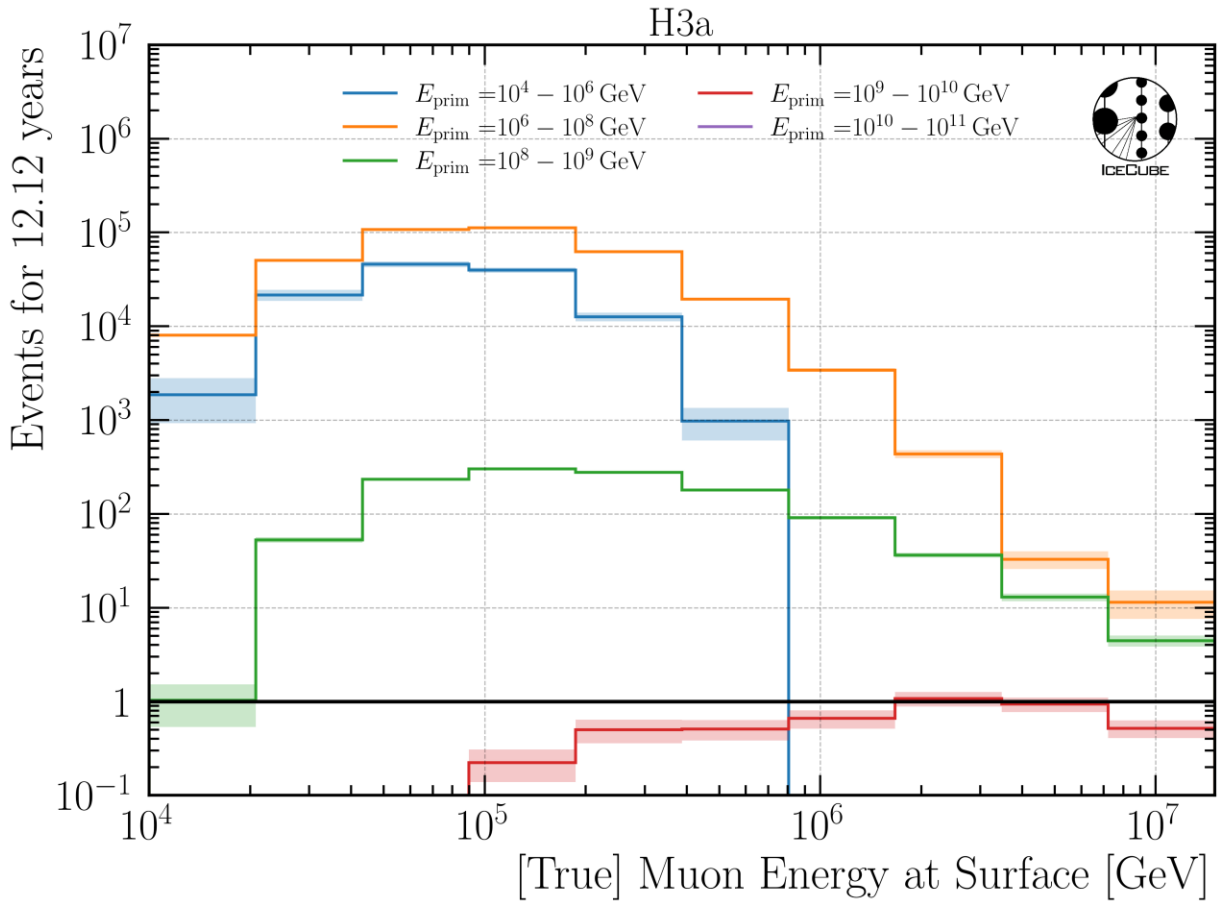
Final Level Statistics





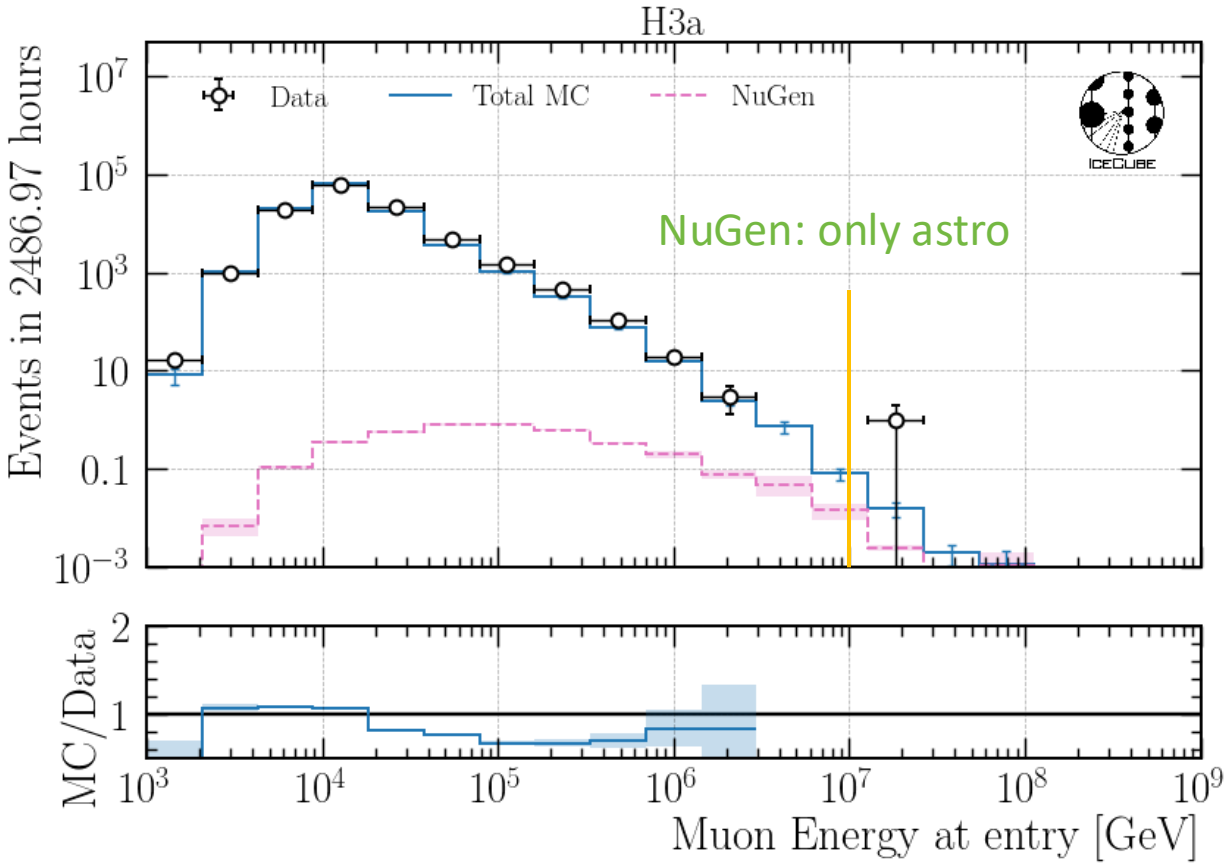
Final Level Statistics: Proxy & Target Binning

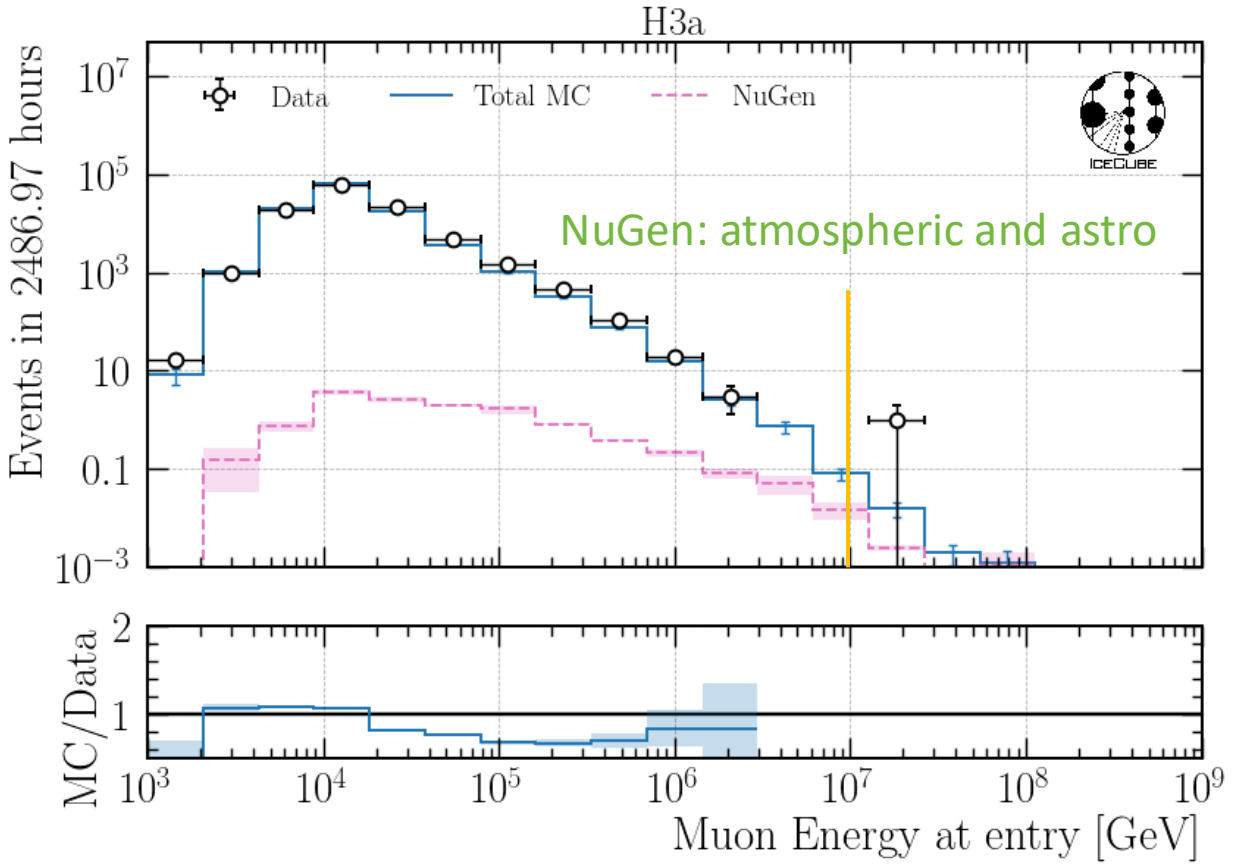




Impact of Astrophysical Neutrinos – Muon Energy at Entry

$n = 1.5, \gamma = 2.6$





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

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, erik.ganster@icecube.wisc.edu, 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

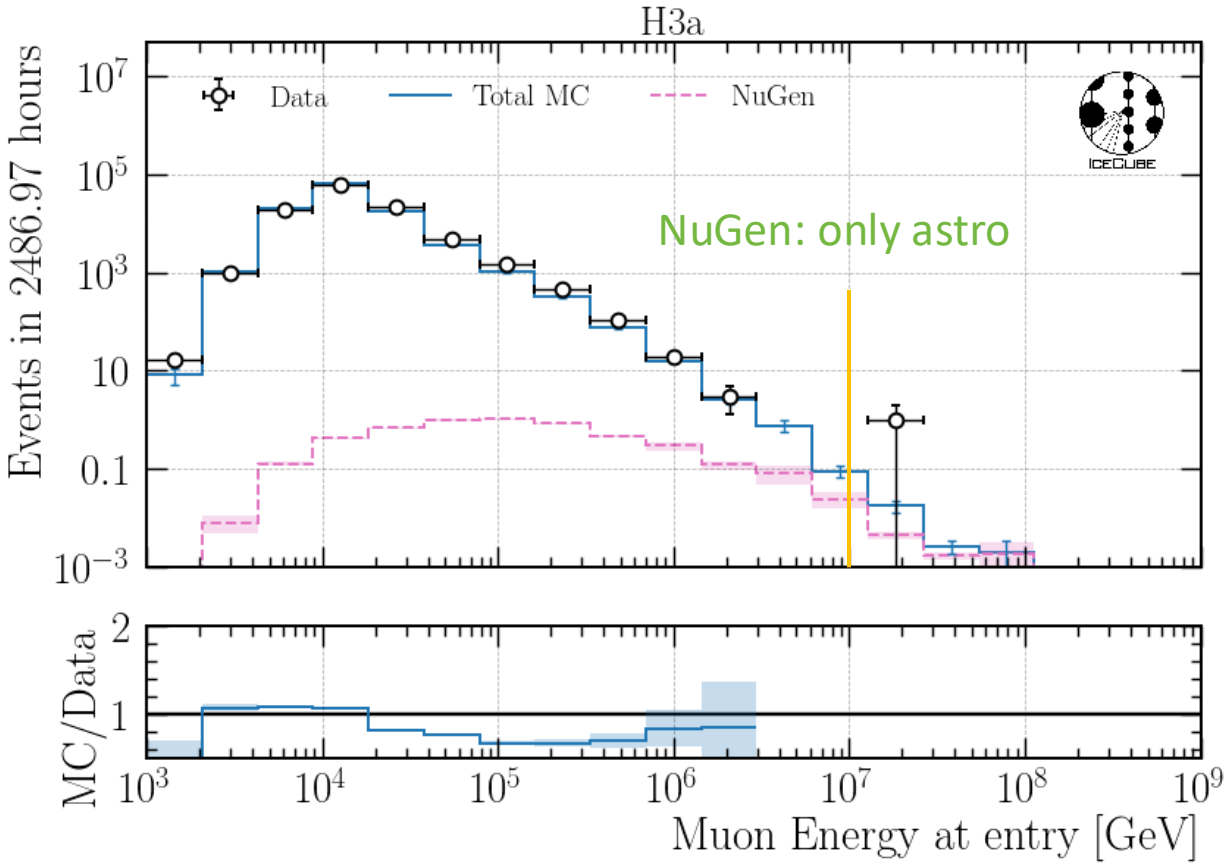
Astrophysical Model	Result	Energy Range (90% CL)	$-2\Delta\log\mathcal{L}$ over SPL
SPL	$\Phi^{\nu+\bar{\nu}}_{@100\text{TeV}} / C = 1.80^{+0.13}_{-0.16}$ $\gamma = 2.52^{+0.04}_{-0.04}$	2.5 TeV to 6.3 PeV	-
LogP	$\Phi^{\nu+\bar{\nu}}_{@100\text{TeV}} / C = 2.13^{+0.16}_{-0.19}$ $\alpha_{\text{LP}} =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

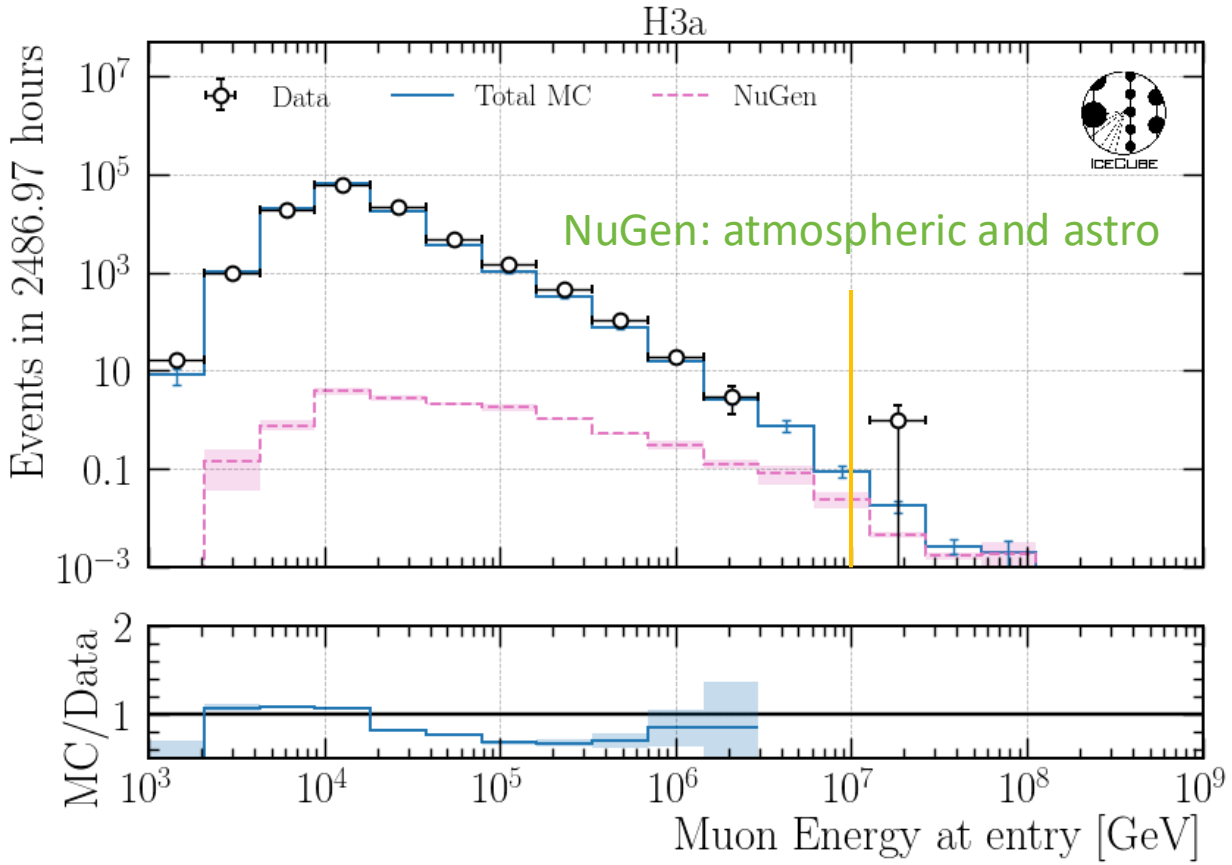
➢ Test SPL and BPL

Impact of Astrophysical Neutrinos – Muon Energy at Entry

$n = 1.8, \gamma = 2.52$

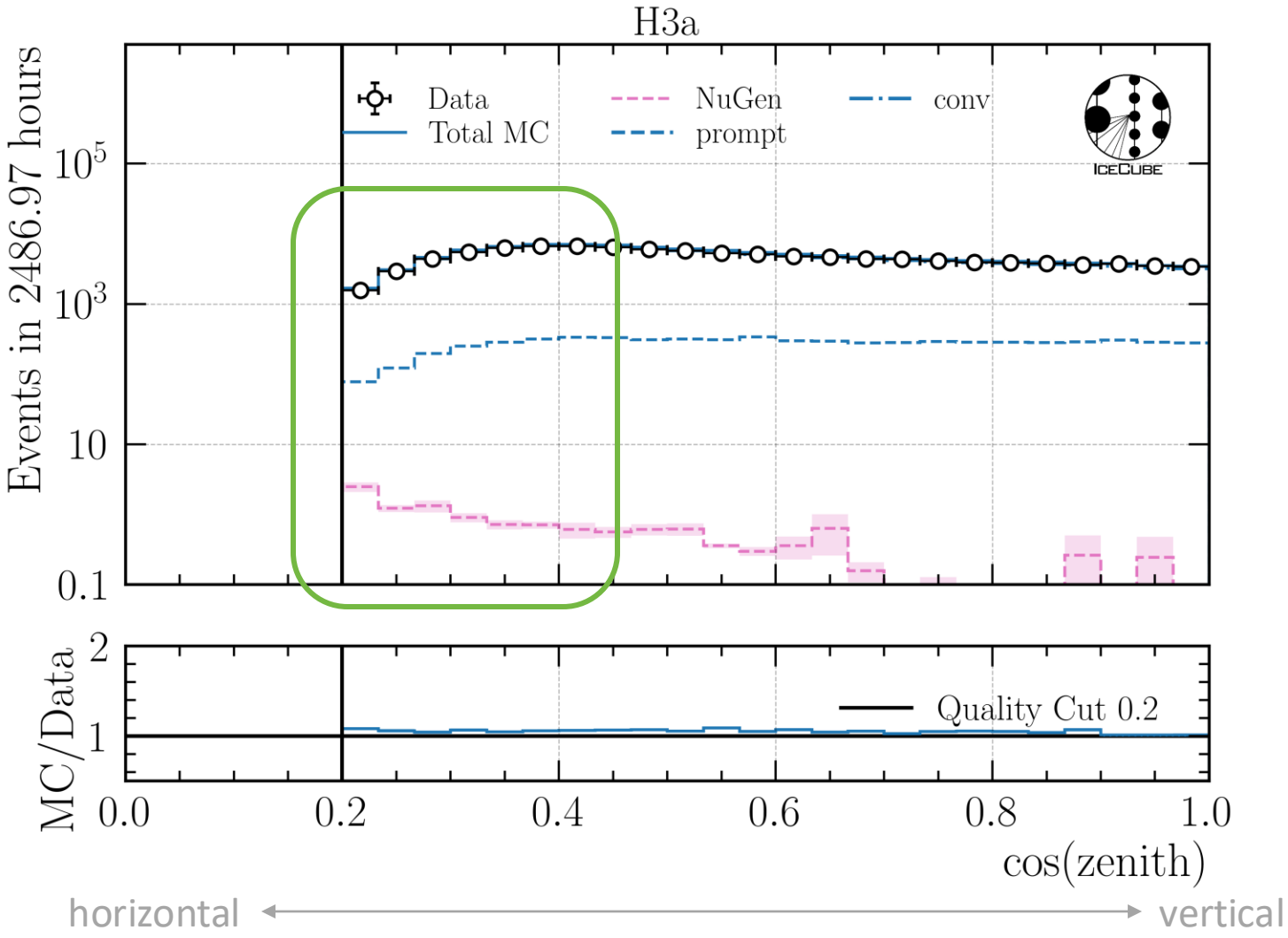
2308.00191





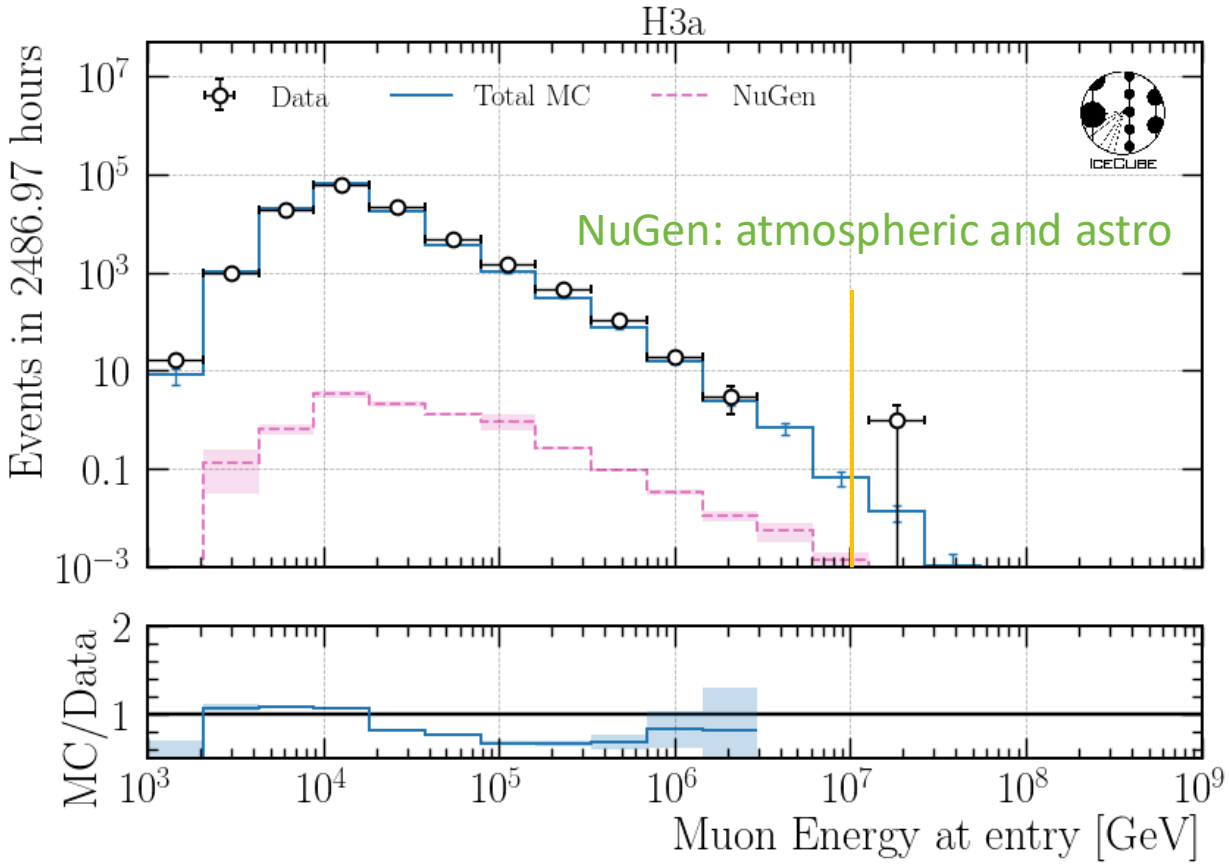
- Neutrinos contribute ~10% to total flux at high energies > 5 PeV

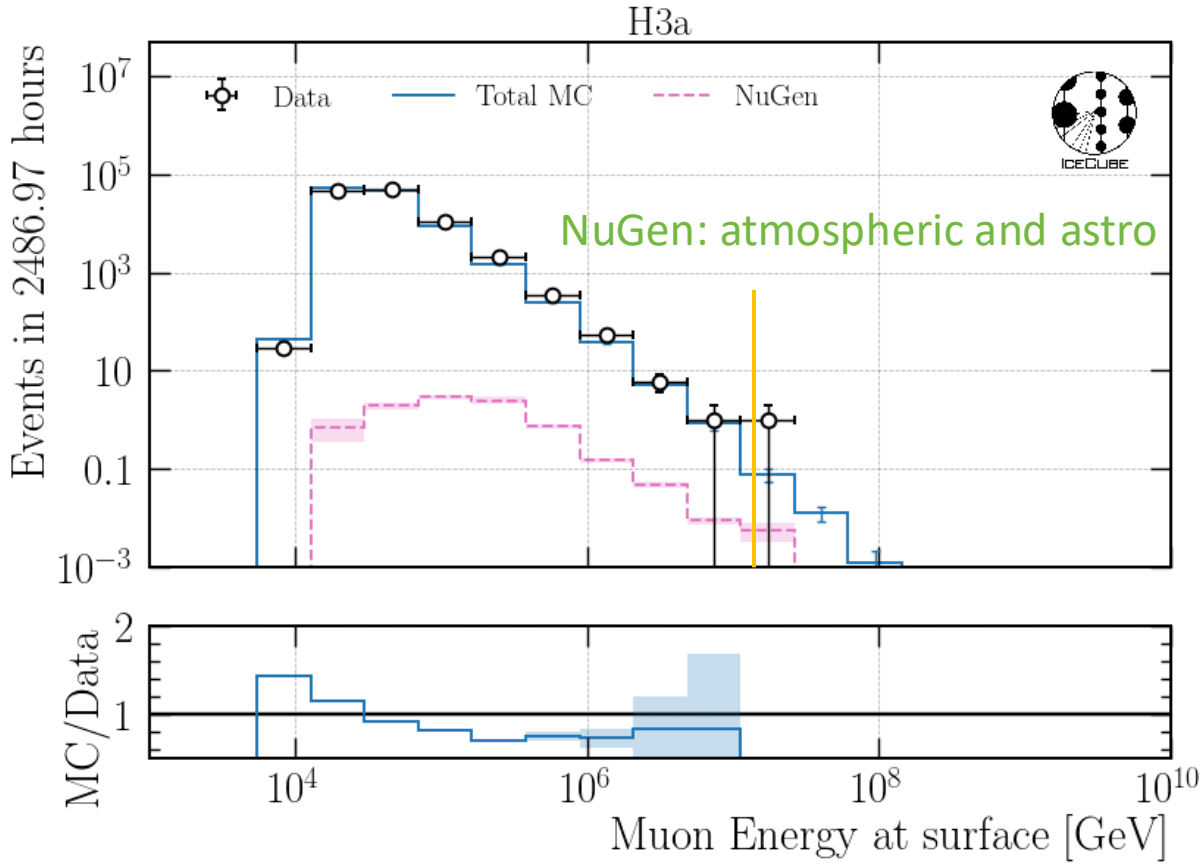
Cos(zenith) Distribution



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

Impact of Astrophysical Neutrinos – Muon Energy at Surface/Entry





- For BPL: Neutrinos contribute less than 10%

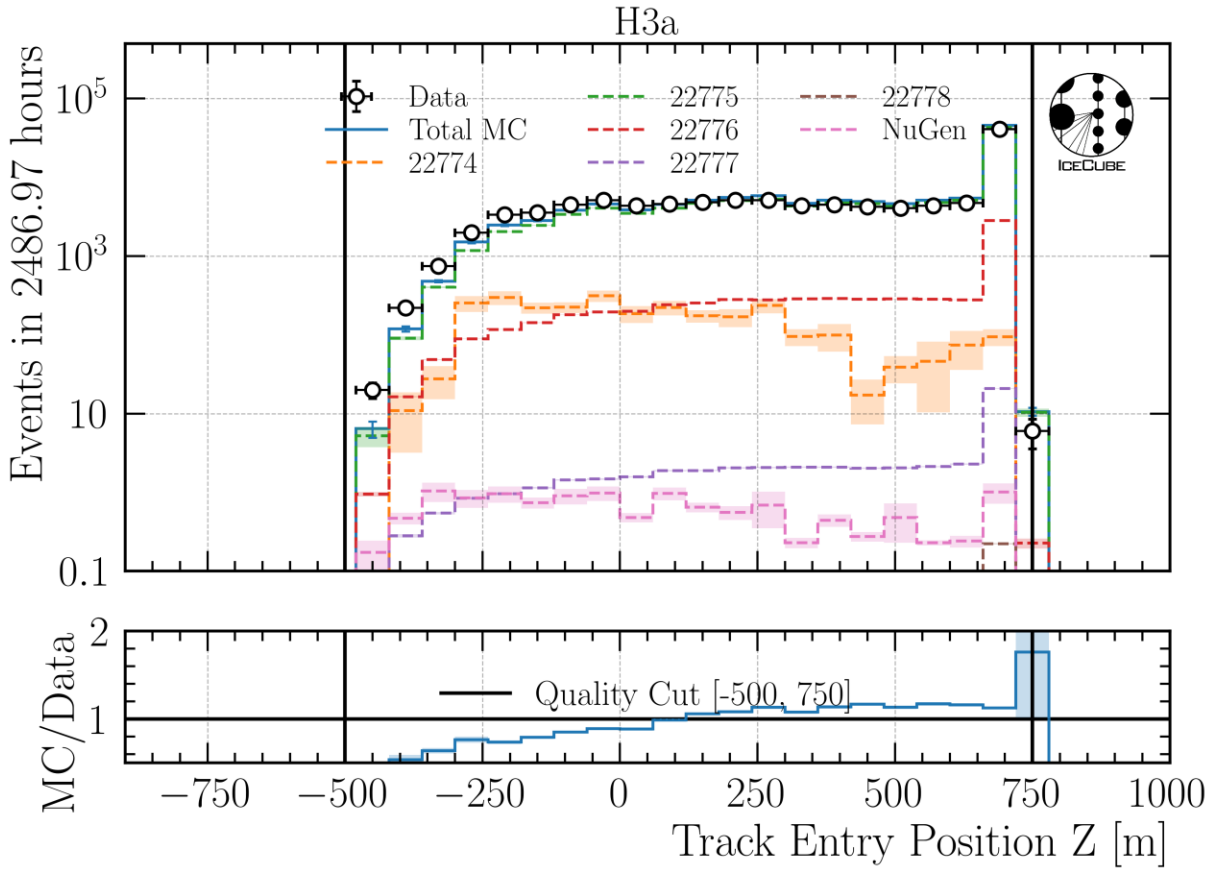
$n = 1.77, \gamma_1 = 1.31, \gamma_2 = 2.74$
$\log10(E_{\text{break}}) = 4.39,$

2308.00191

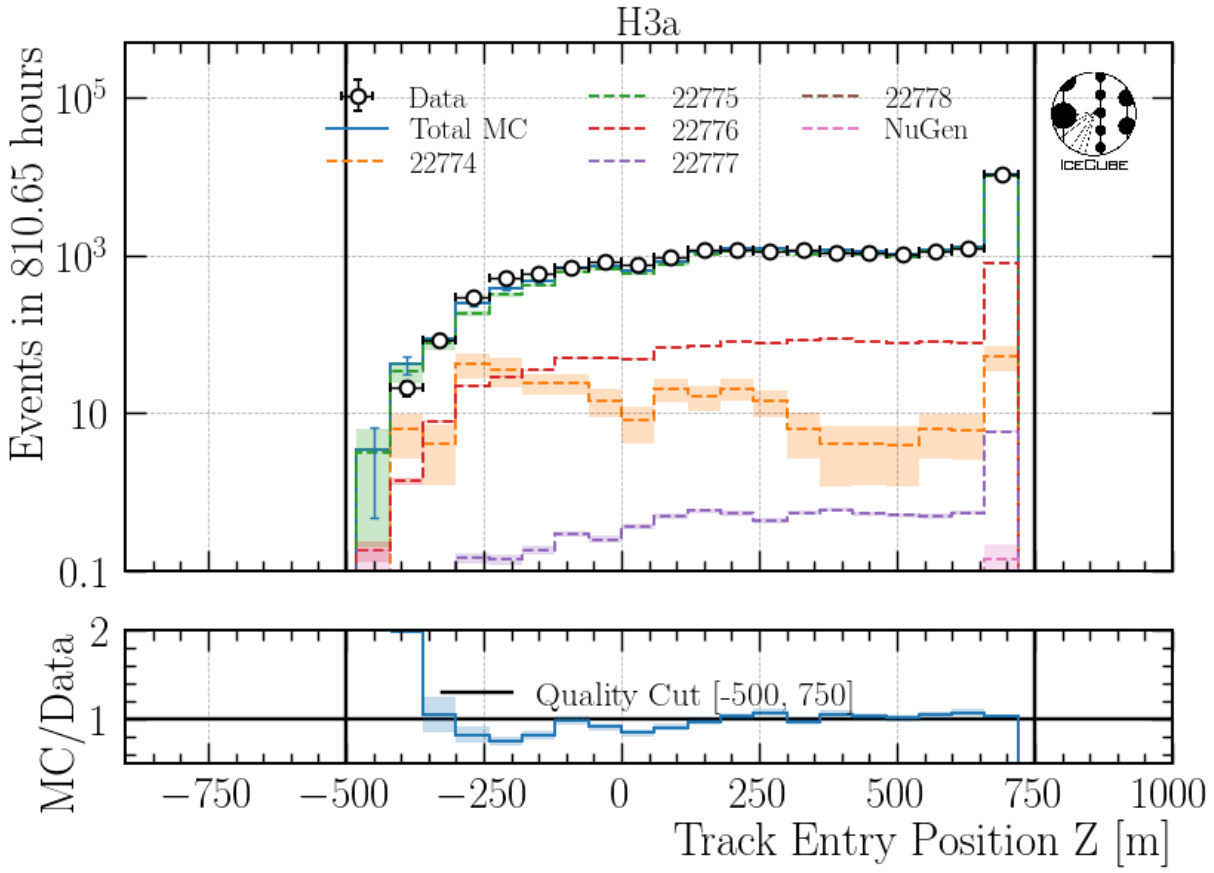
Z—Vertex Data-MC

- 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

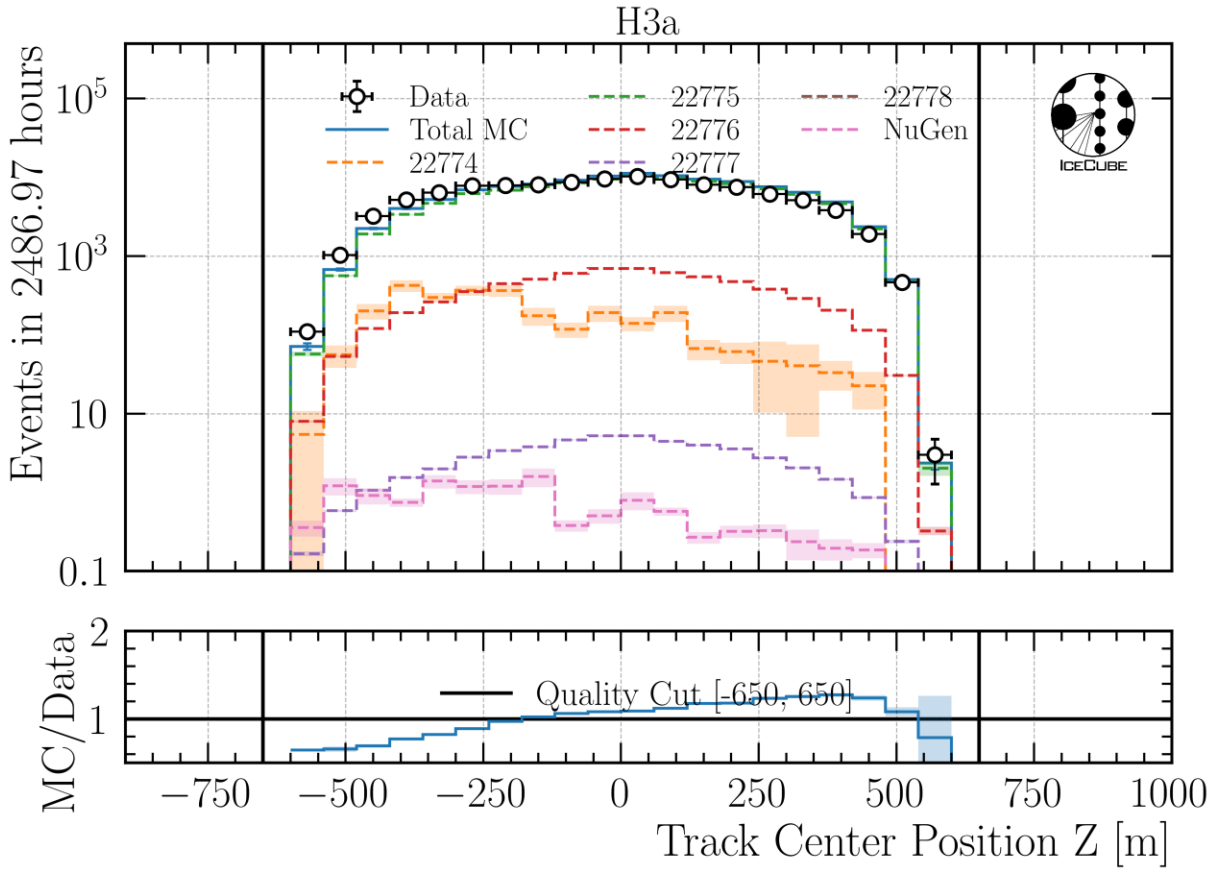


Old ice model

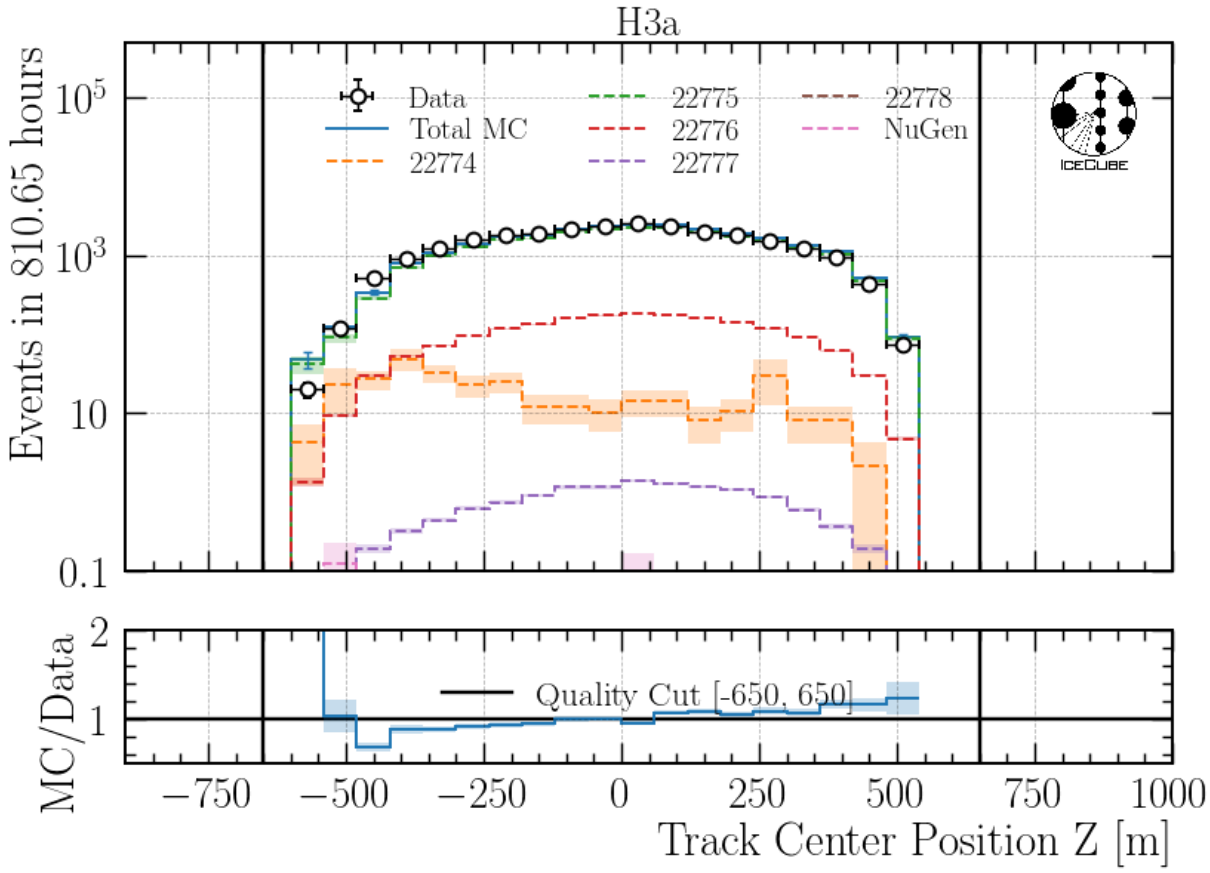


New ice model

Z—Vertex Data-MC: Center Position

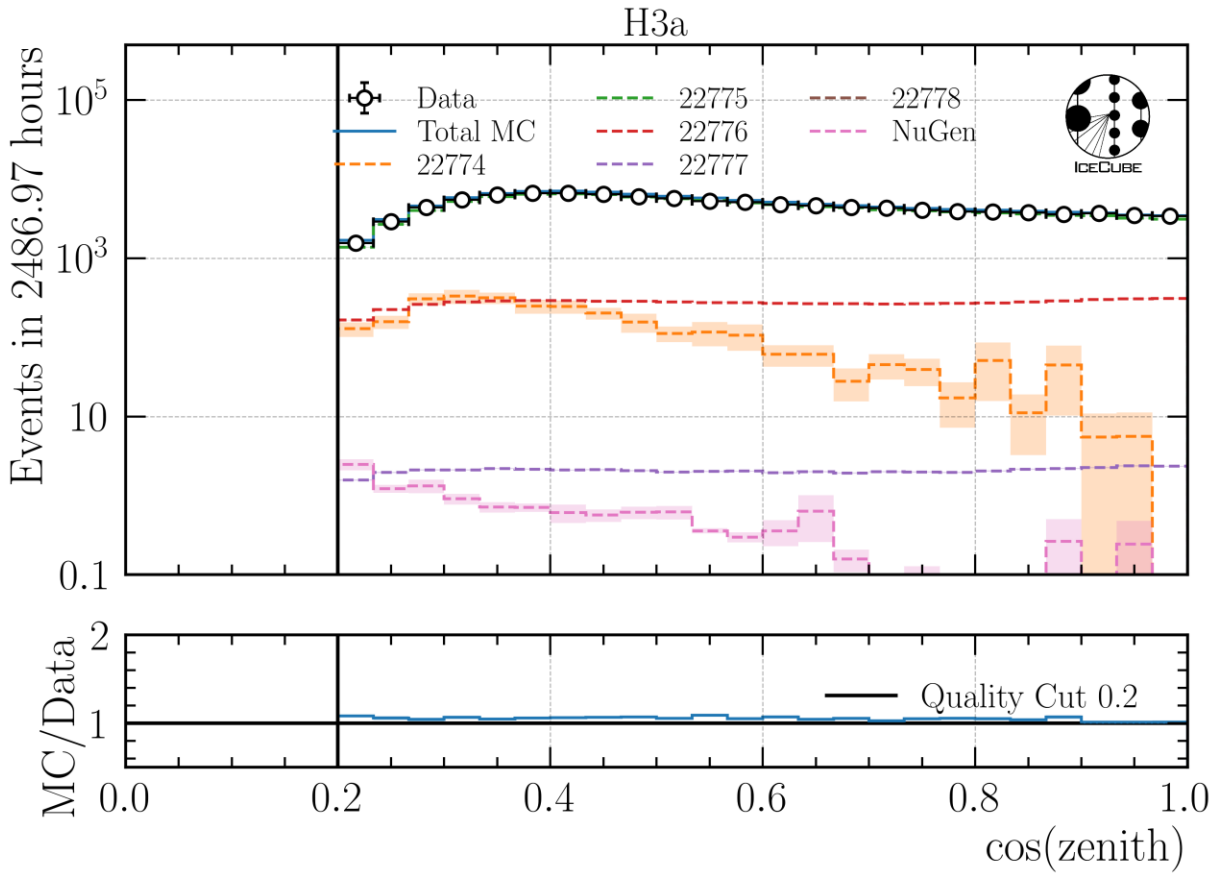


Old ice model

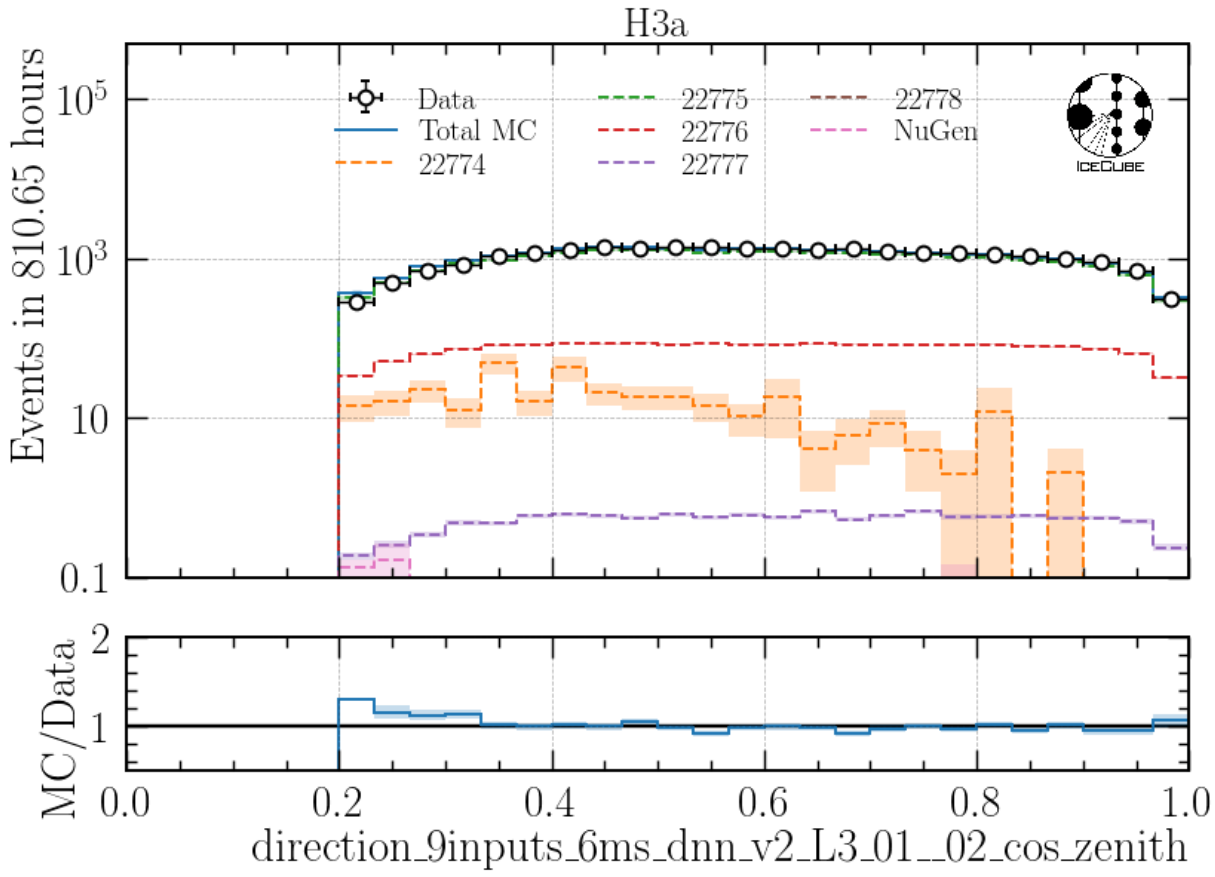


New ice model

Cos(zenith)



Old ice model



New ice model

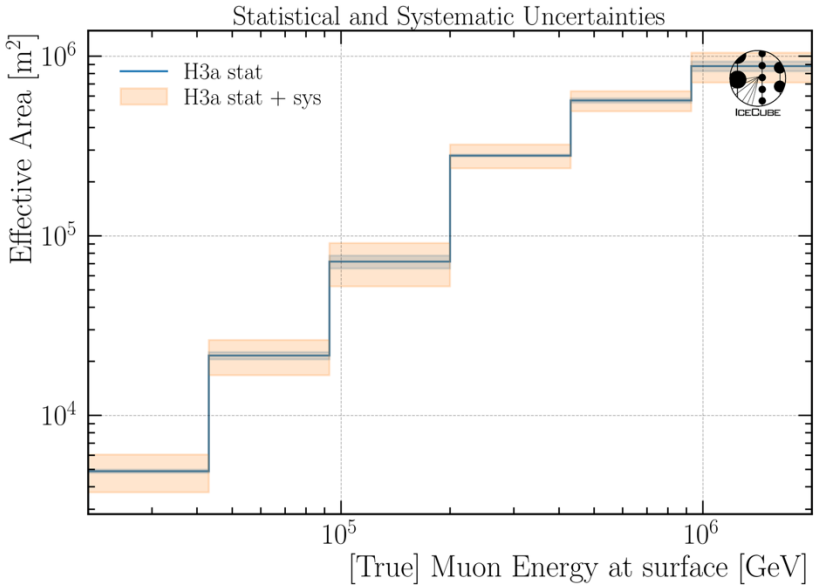
- Artefacts observed in zenith reconstruction

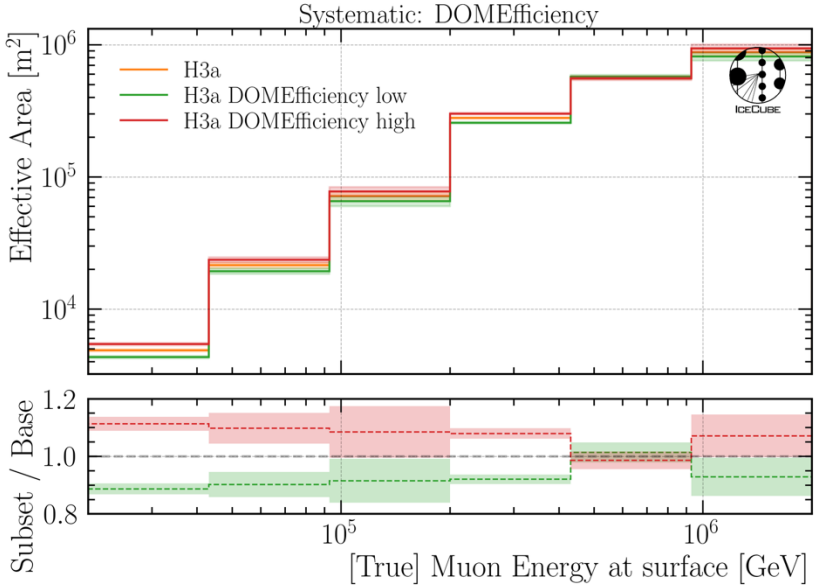
➢ Re-train zenith reco network

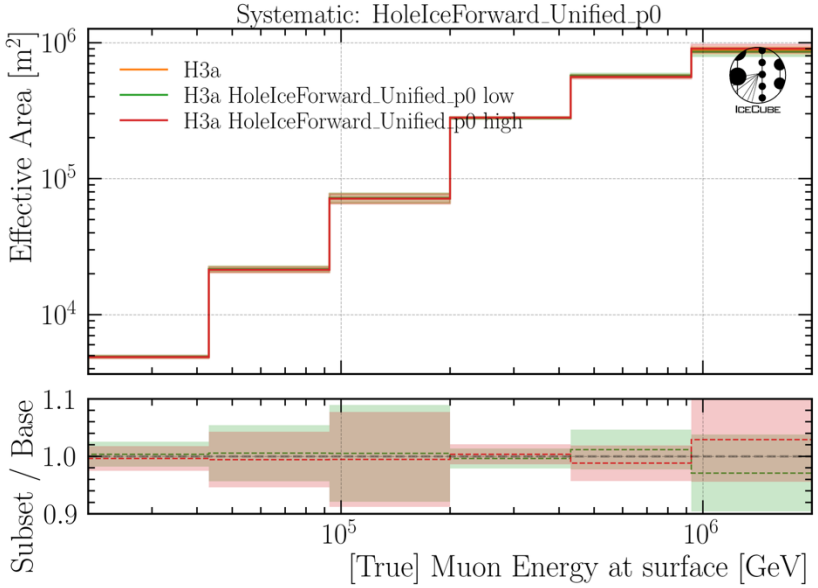
Include Systematic Uncertainties on Effective Area

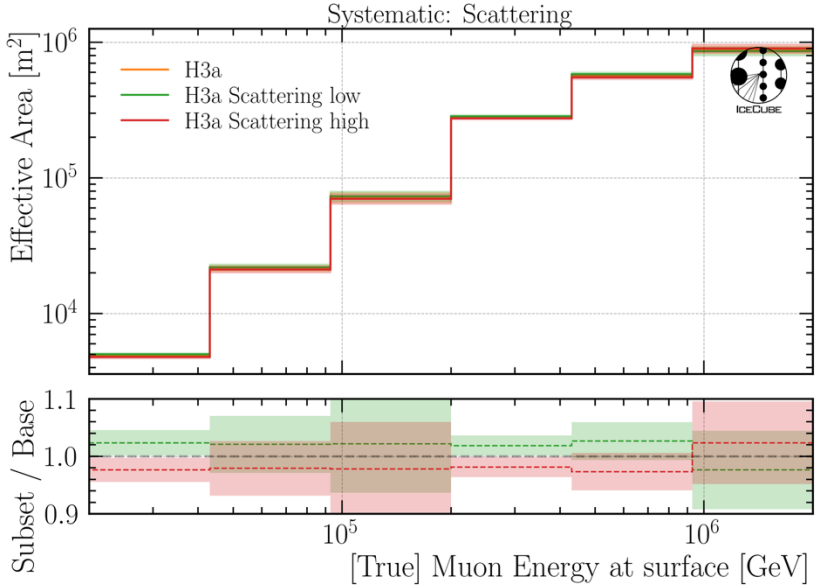
Effective Area

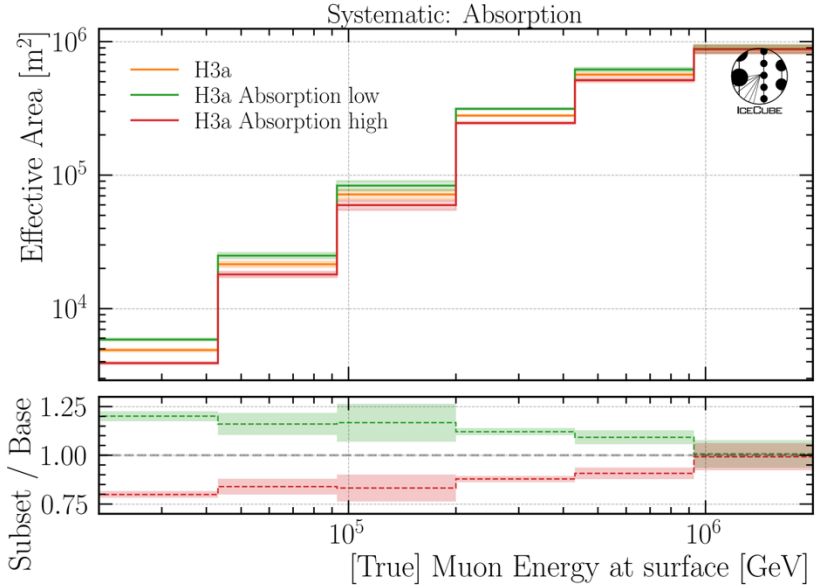
- Baseline: entire set
- Subset: above/below median

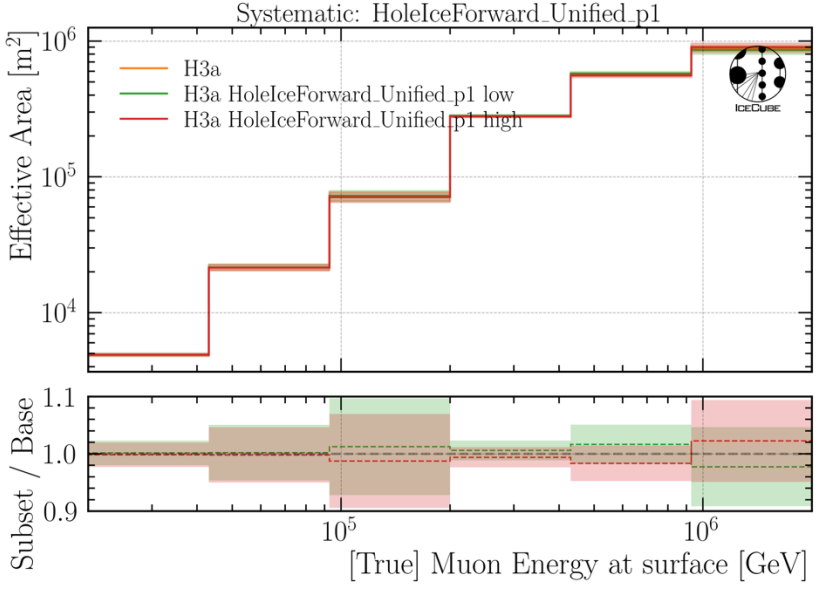












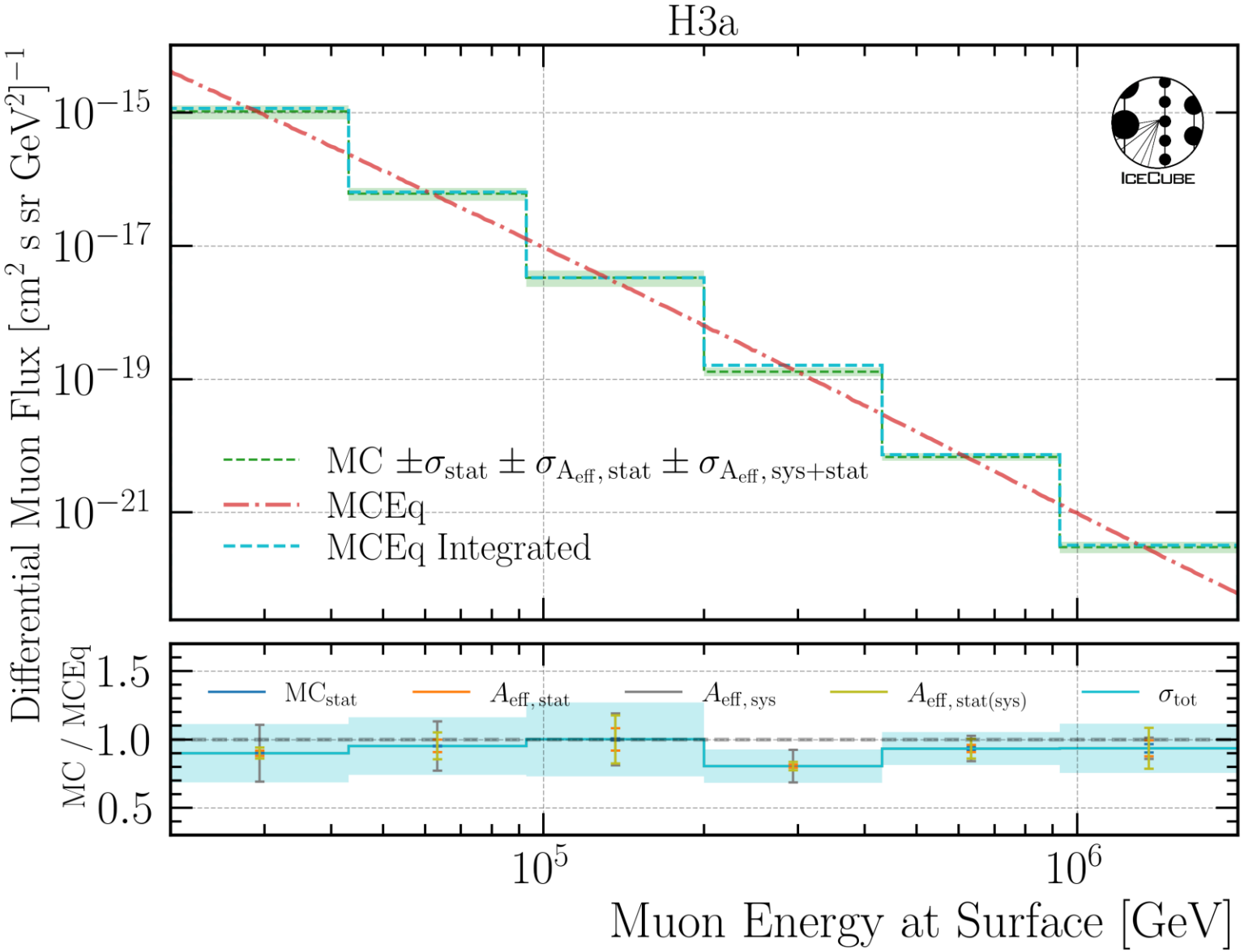
MCEq vs CORSIKA

Uncertainties on Flux

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

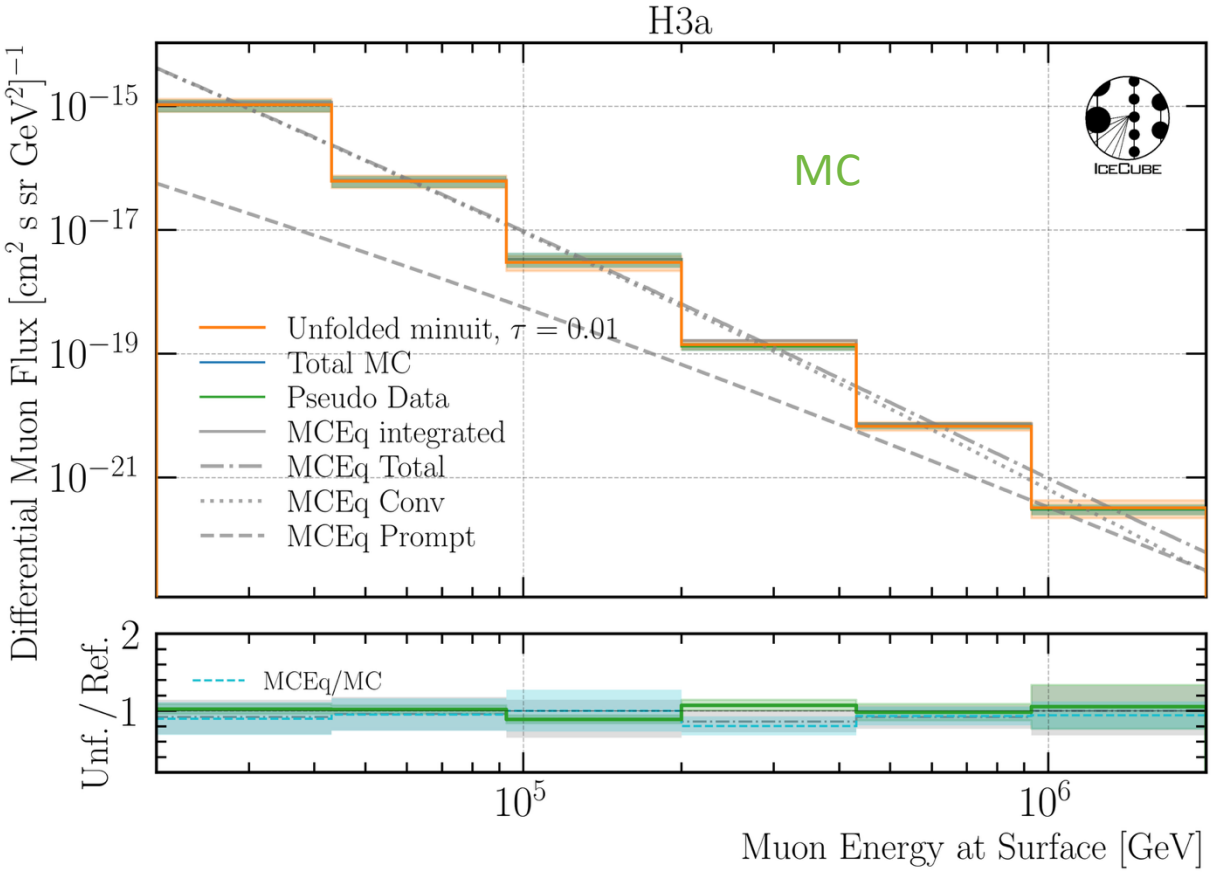
χ^2– Test (H3a):
p—value: 0.683

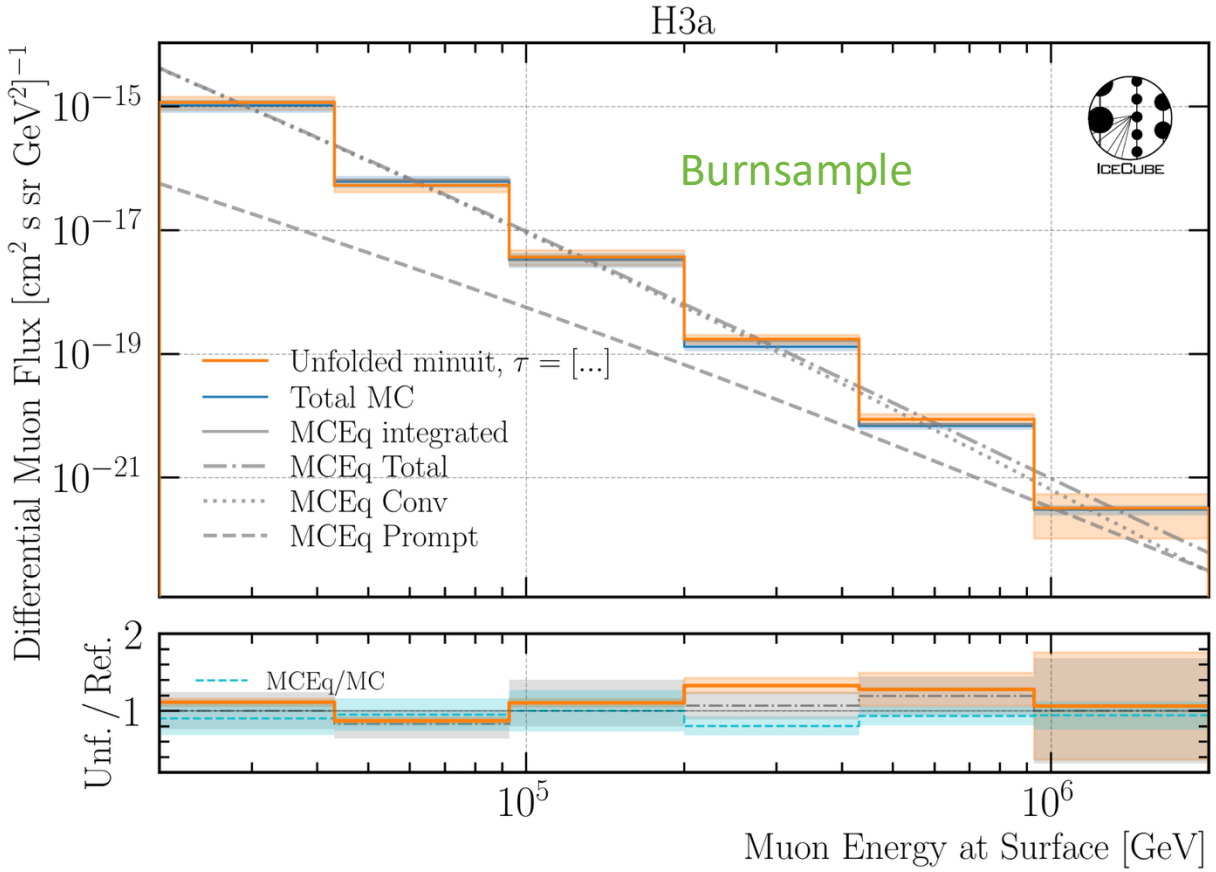
➢ Good agreement between MCEq & CORSIKA



Unfold Burnsample

Unfold Burnsample





χ^2– Test (H3a) Conv only:
p—value: 0.587

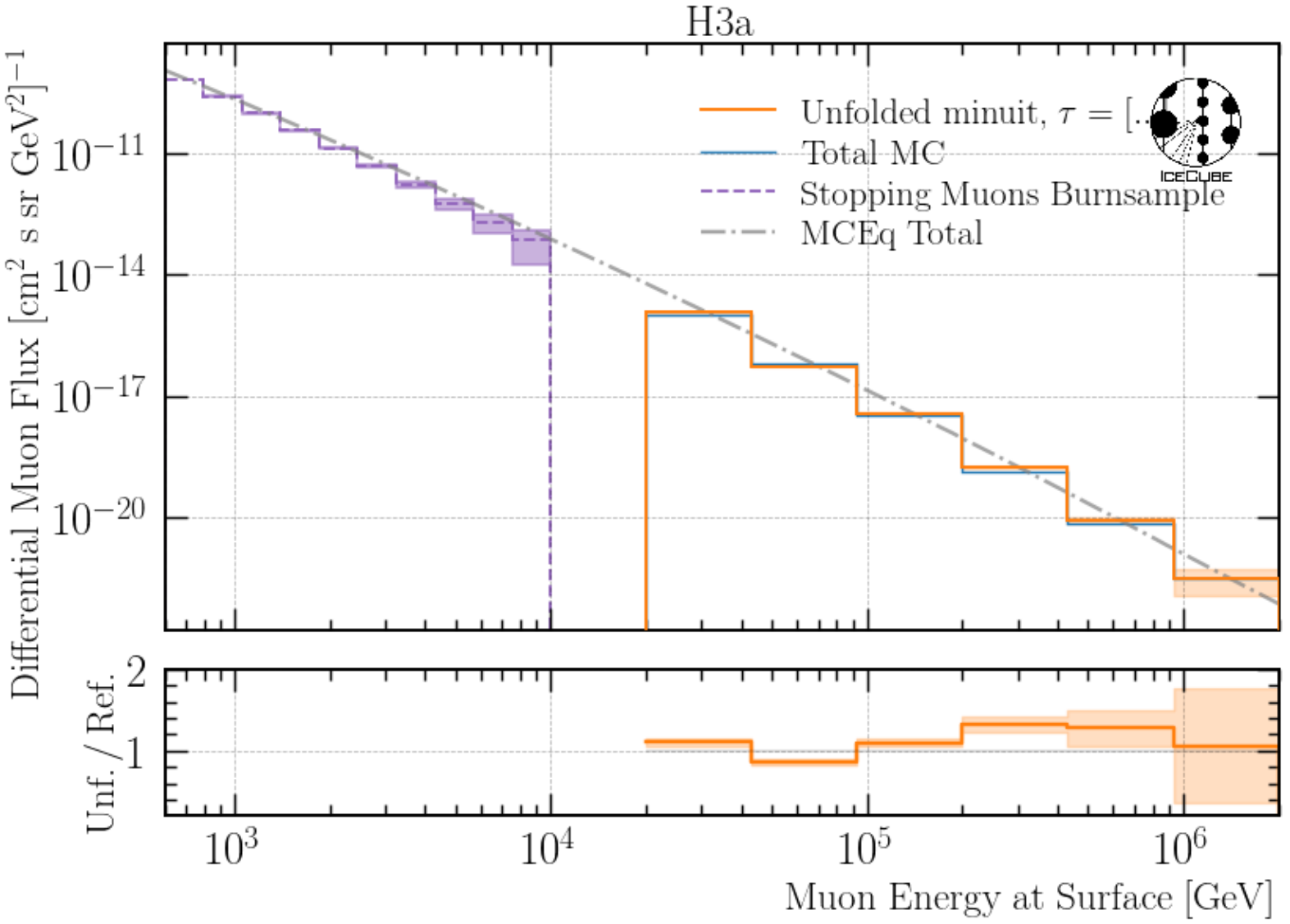
➢ Unfolding works on MC & burnsample

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



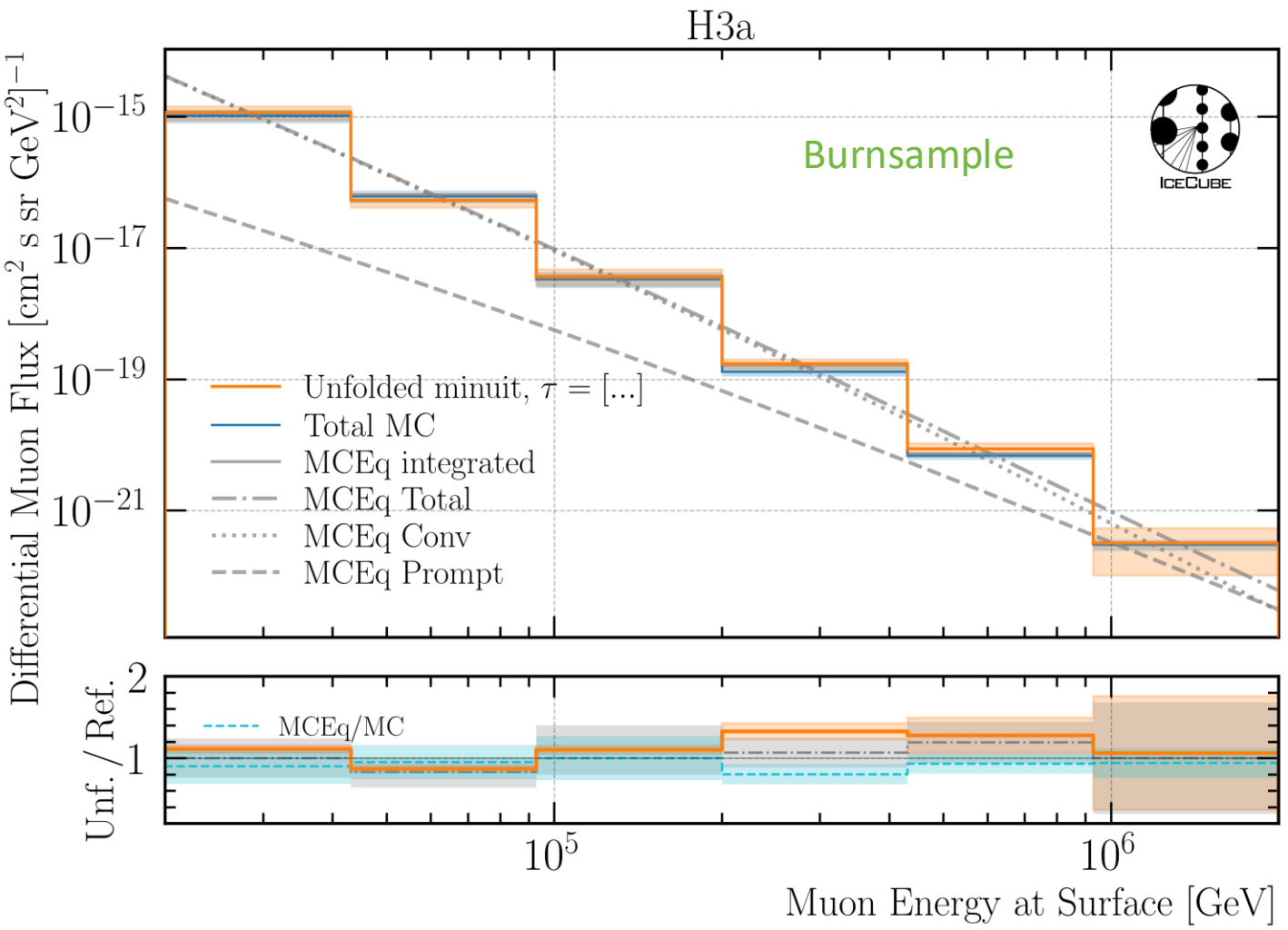
Conclusion & Outlook

- 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

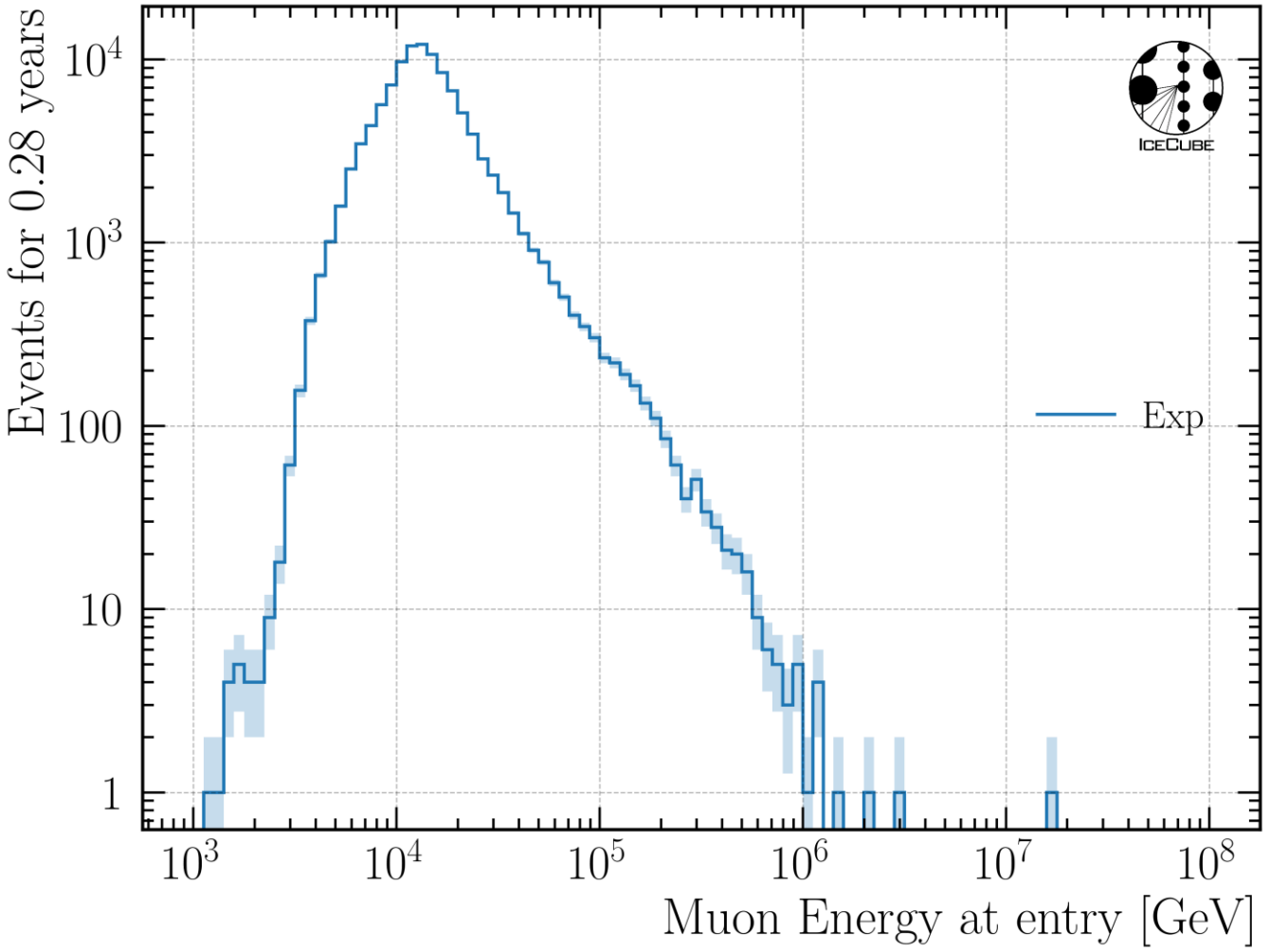
Outlook

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

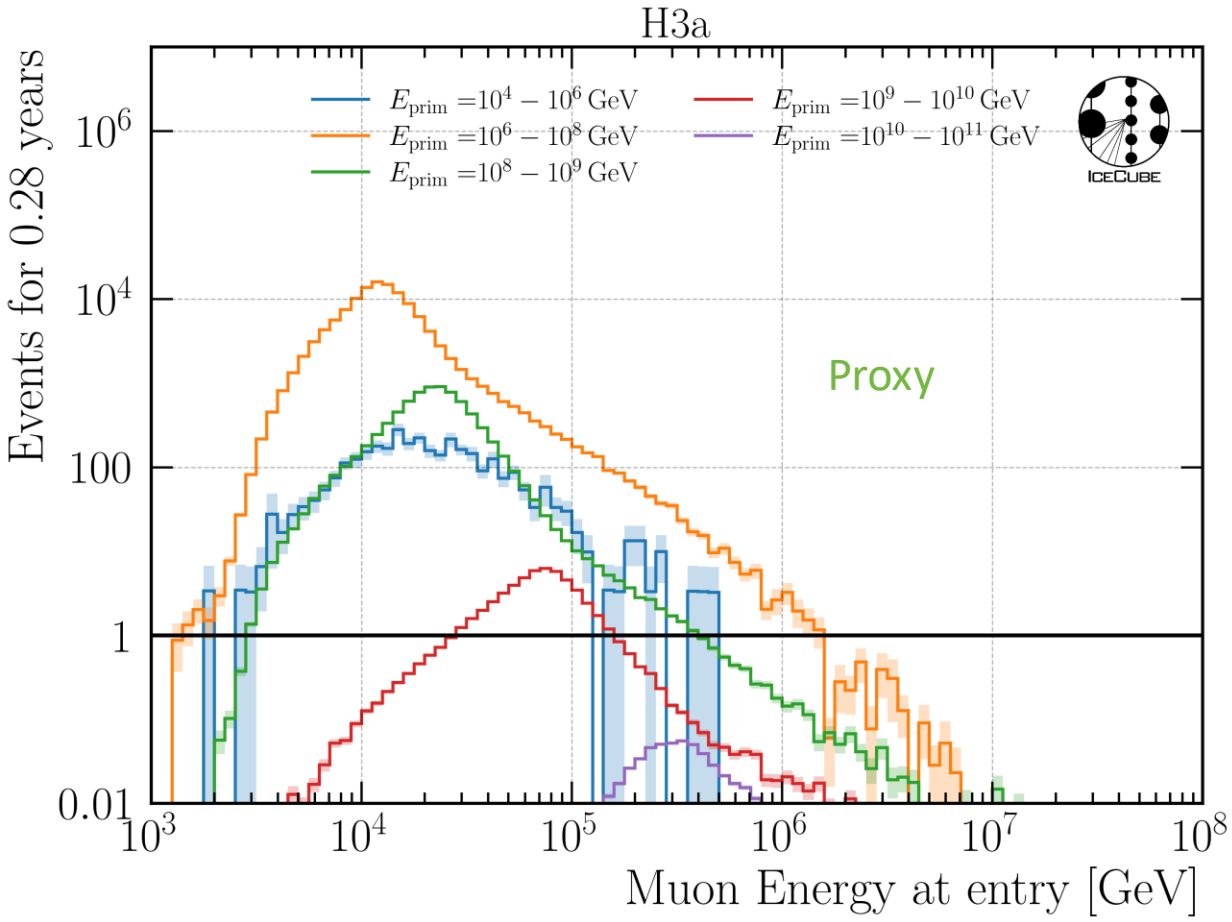
➢ Unfold on 12.12 years of data

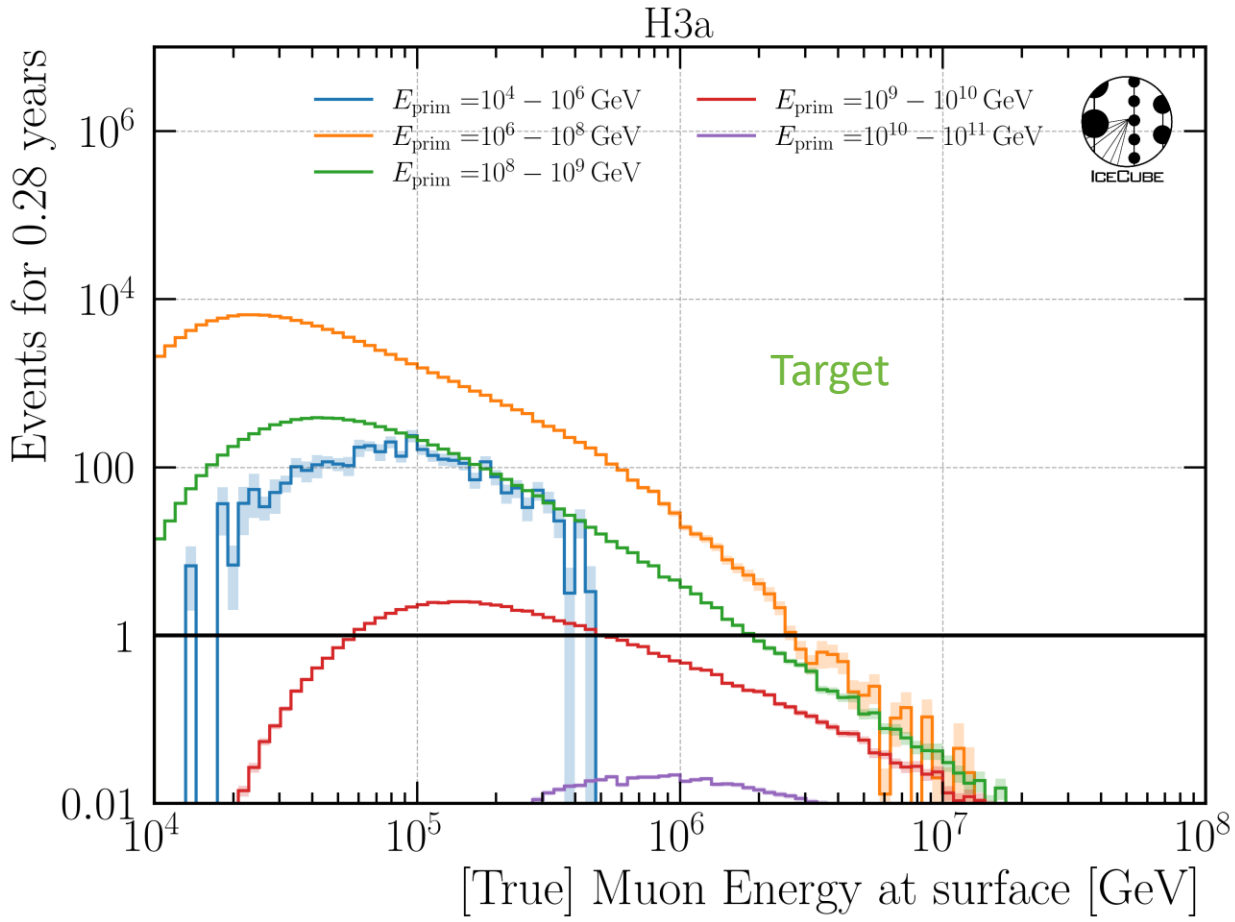


Burnsample Proxy

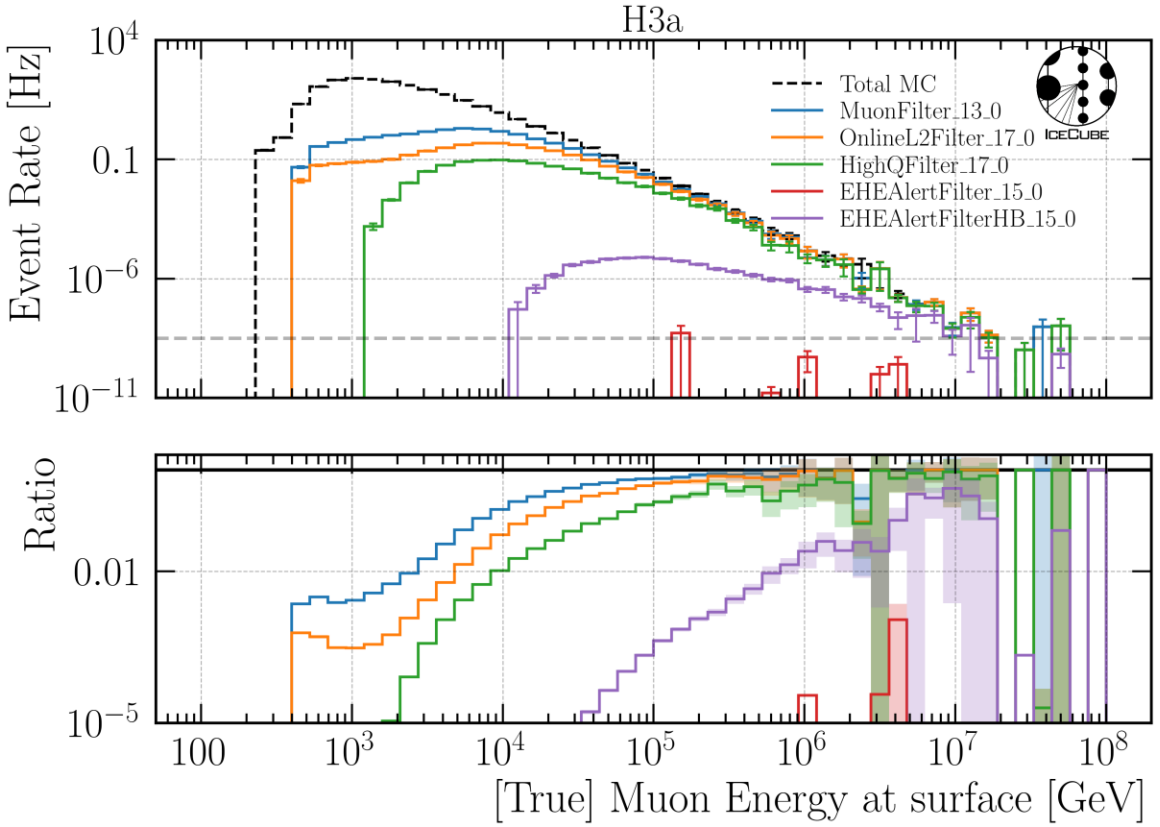


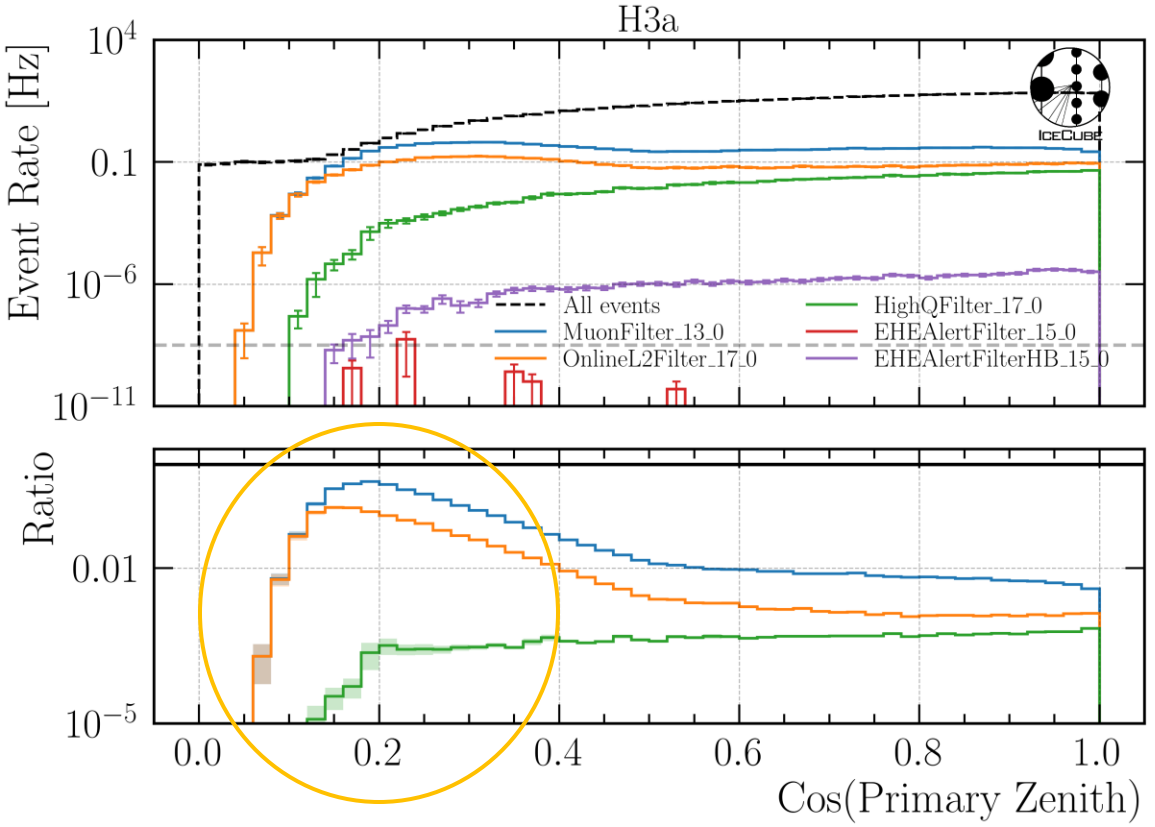
Statistics


H3a
$E_{\mathrm{prim}} = 10^4 - 10^6$ GeV
$E_{\mathrm{prim}} = 10^6 - 10^8$ GeV
$E_{\mathrm{prim}} = 10^8 - 10^9$ GeV
$E_{\mathrm{prim}} = 10^9 - 10^{10}$ GeV
$E_{\mathrm{prim}} = 10^{10} - 10^{11}$ GeV
IceCube
Proxy
Events for 0.28 years
Muon Energy at entry [GeV]


H3a
$E_{\mathrm{prim}} = 10^4 - 10^6$ GeV
$E_{\mathrm{prim}} = 10^6 - 10^8$ GeV
$E_{\mathrm{prim}} = 10^8 - 10^9$ GeV
$E_{\mathrm{prim}} = 10^9 - 10^{10}$ GeV
$E_{\mathrm{prim}} = 10^{10} - 10^{11}$ GeV
IceCube
Target
Events for 0.28 years
[True] Muon Energy at surface [GeV]

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?

10.1088/1748-0221/16/07/P07041

Energy

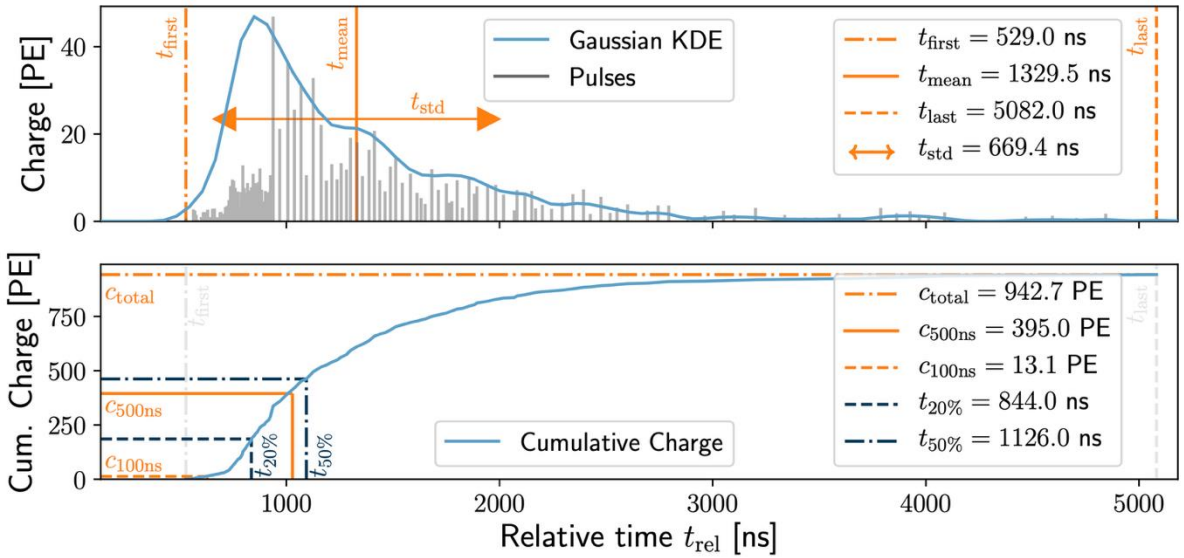
- Bundle energy at entry / surface
- Leading muon energy at entry / surface

Direction

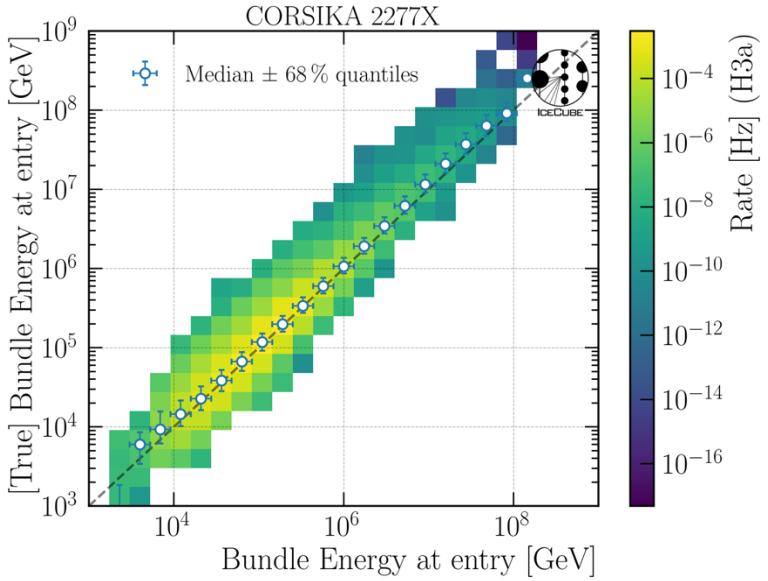
- Zenith / azimuth of leading muon

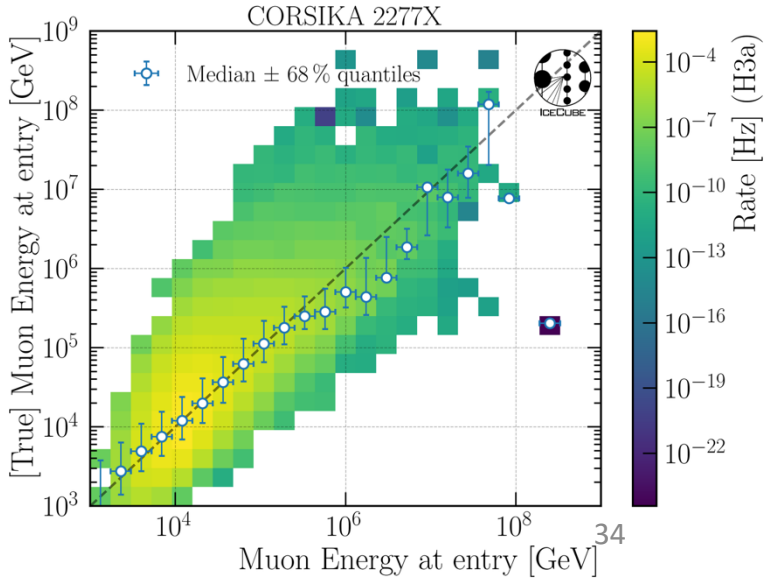
Geometry

- Propagation length
- Entry point



- dnn_reco framework (Mirco Hünnefeld)
- Low-level features based on charge and timer per DOM





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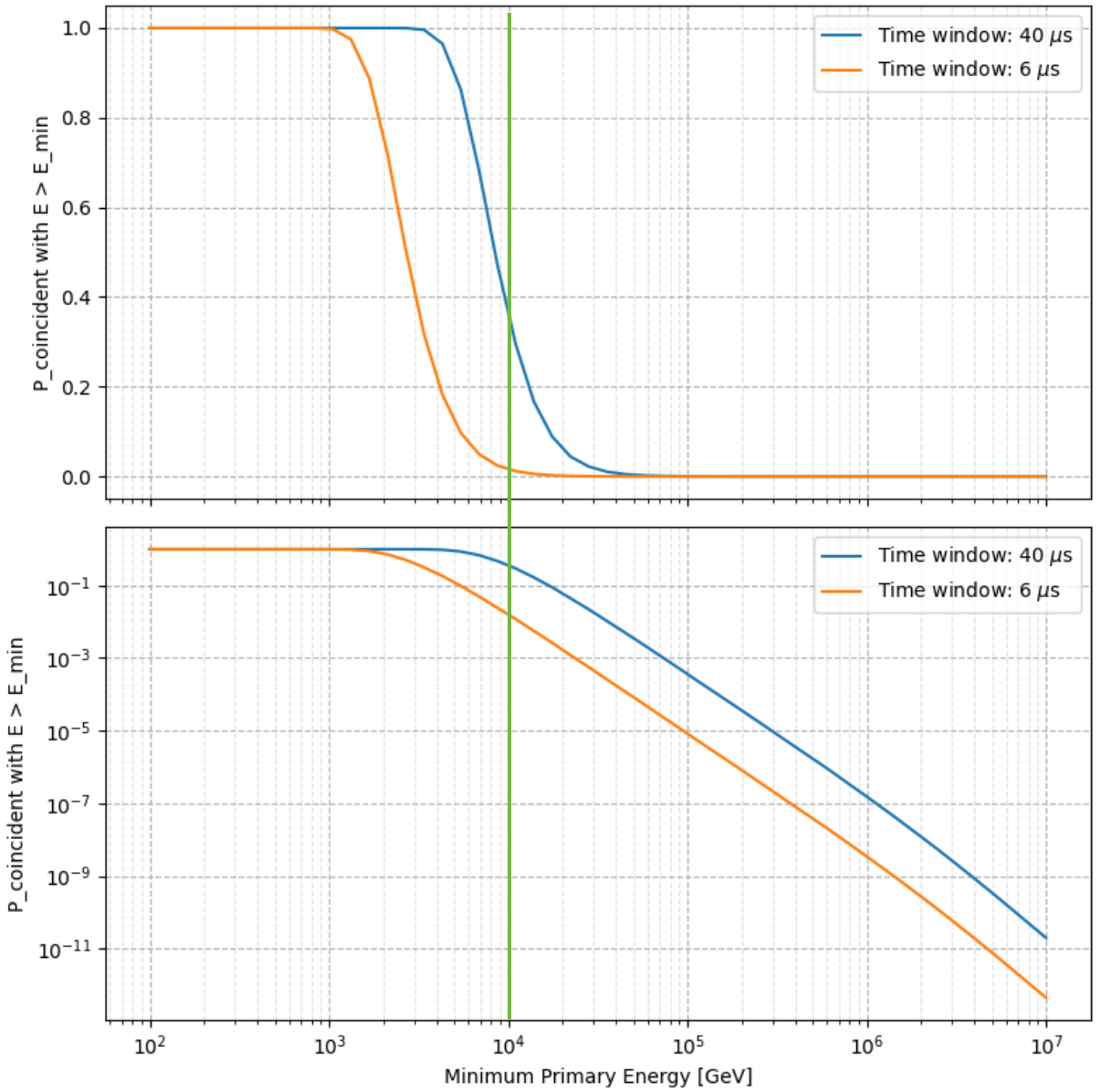
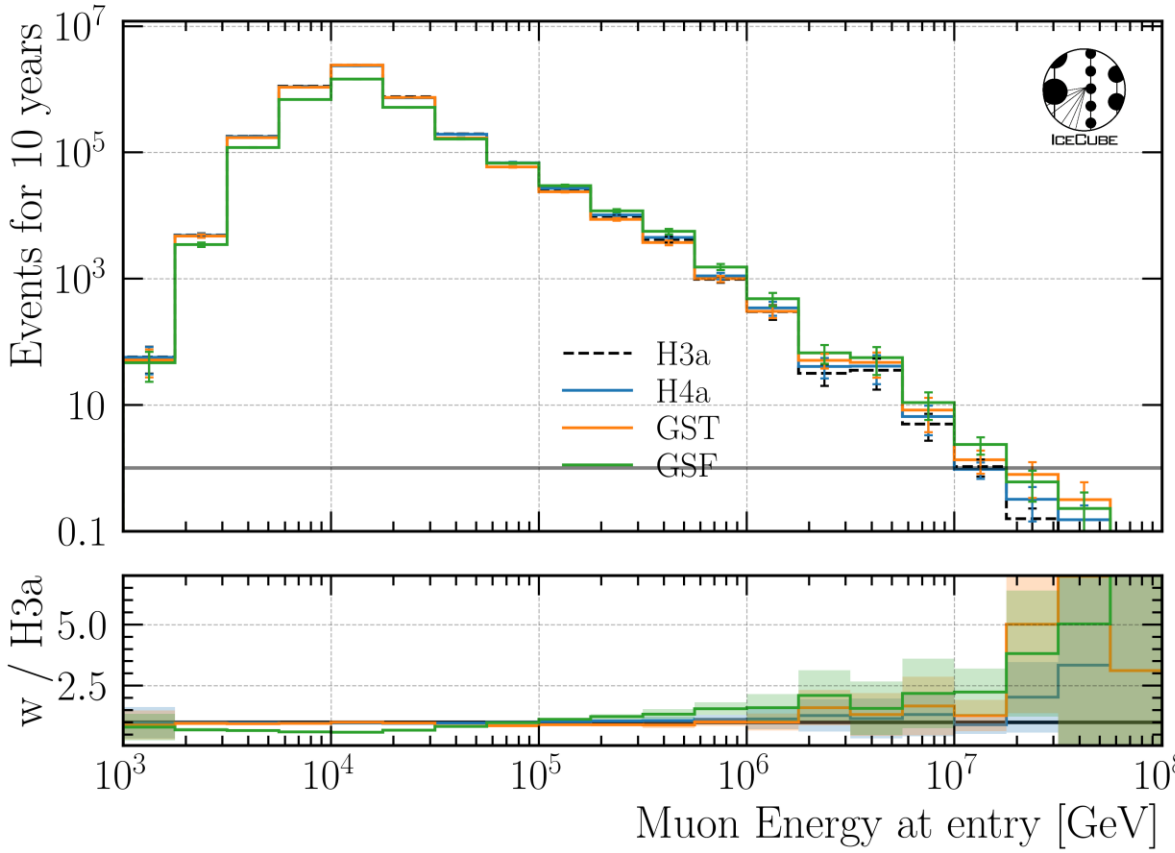
Q: Coincident events are not simulated. Can you show that this does not cause any problems?

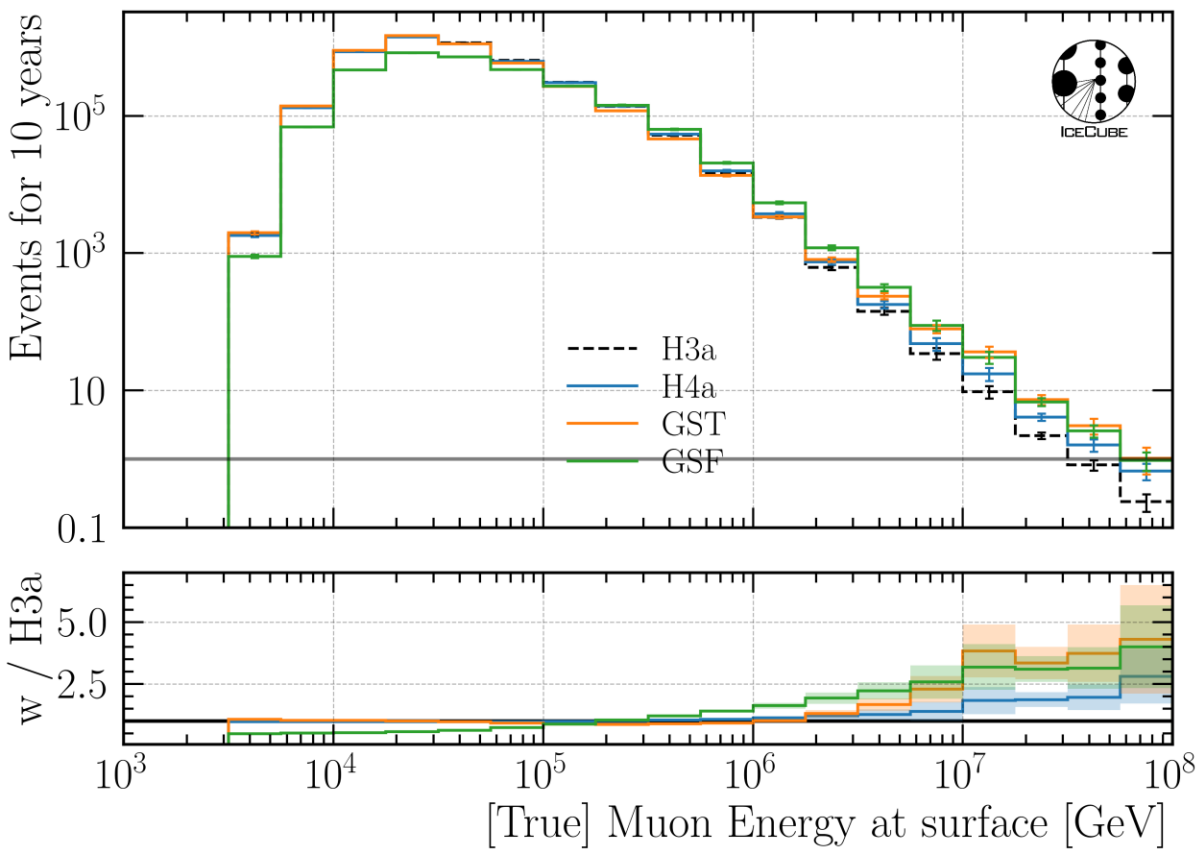
- For primary energies above 10 TeV, using a time window of 6 µs, the chance for a coincident event is ≤ 1 %

➢ Apply time-window cleaning of 6 µs to pulses



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





➢ Primary models diverge towards higher energies