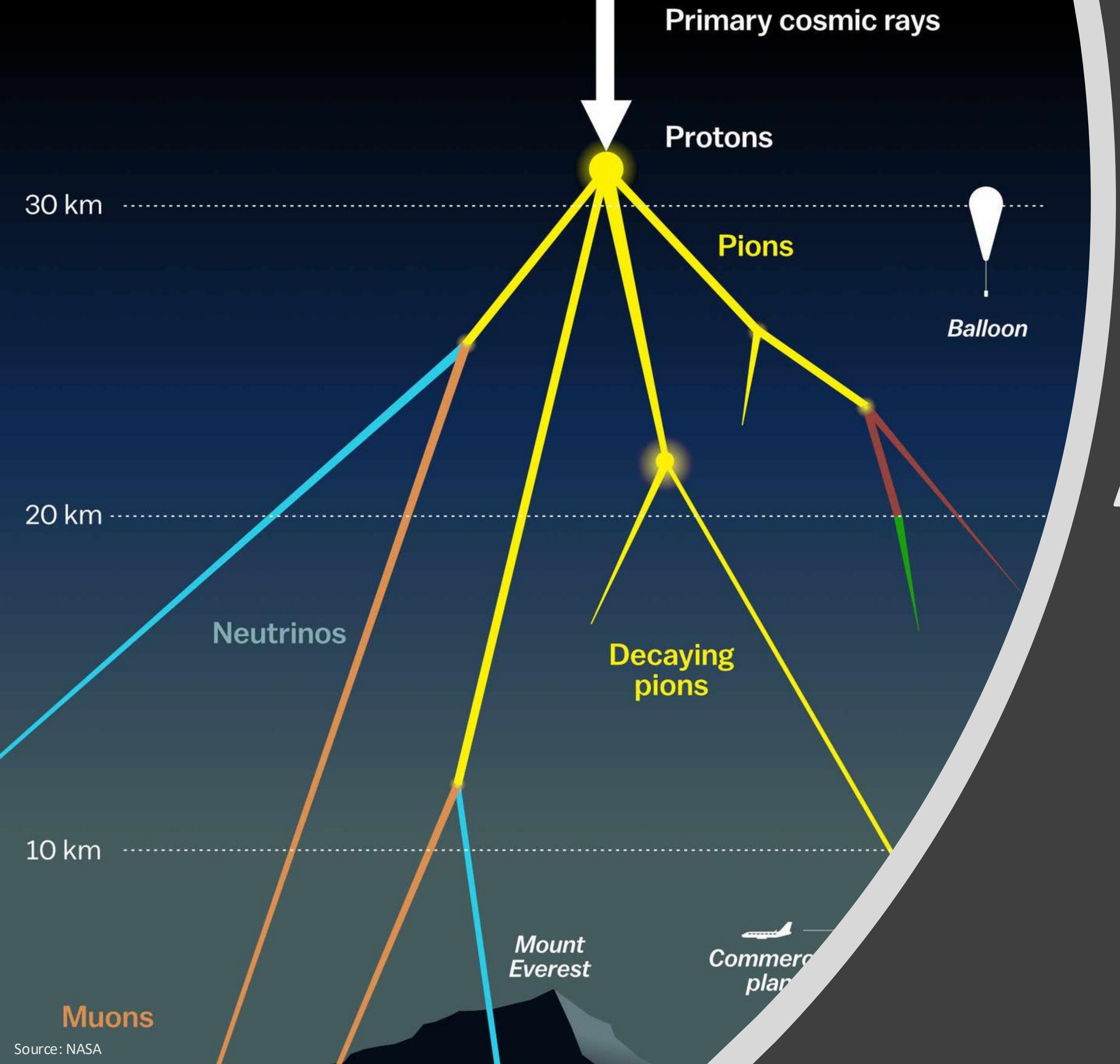


Unfolding the Atmospheric Muon Flux

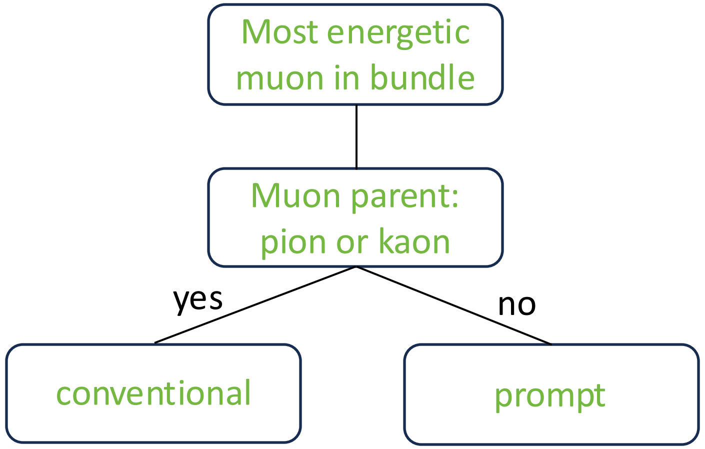
Pascal Gutjahr

IceCube Spring Meeting Uppsala
May 14, 2025

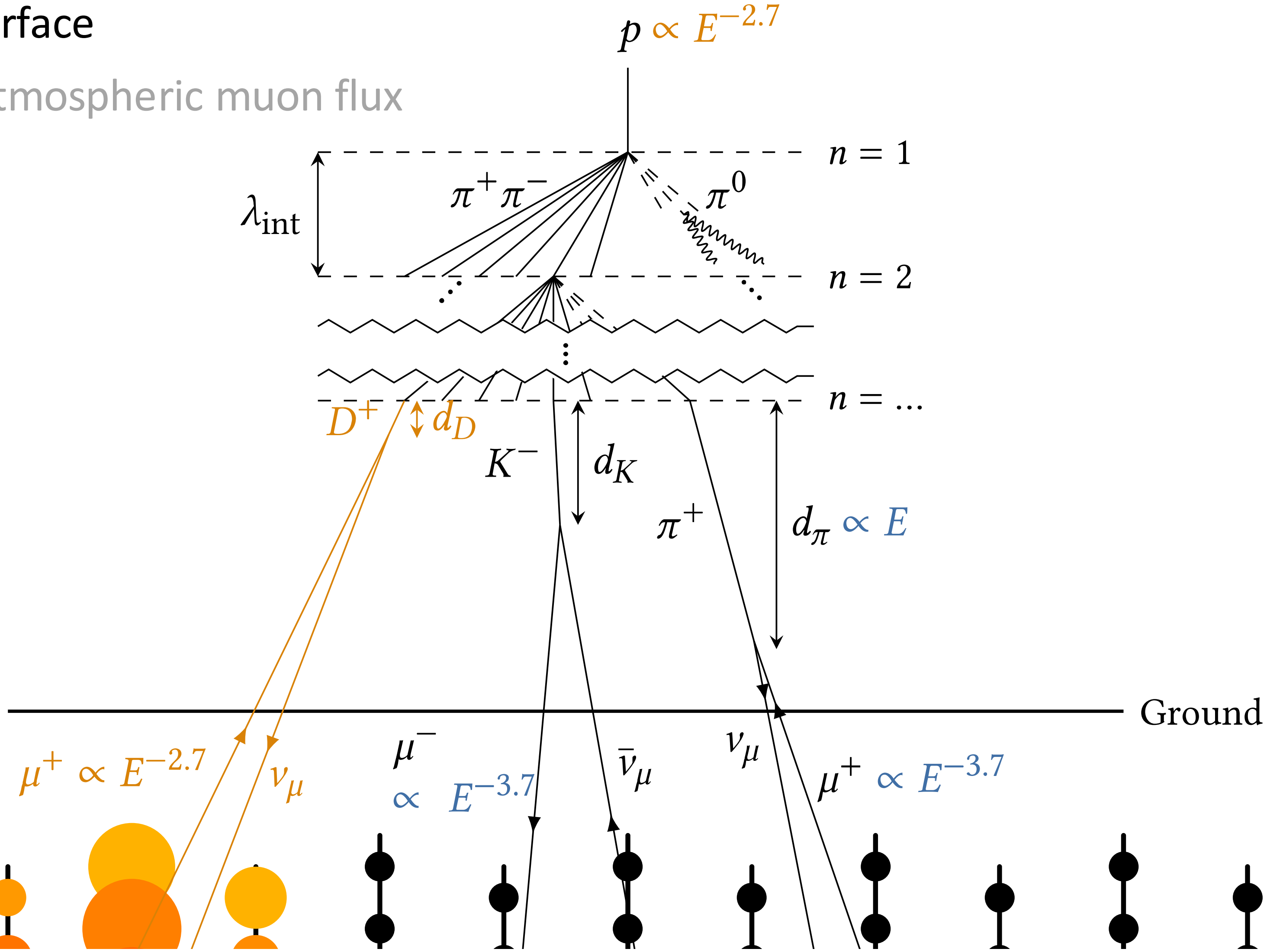
WG reviewer: Dennis Soldin
Coll. reviewer: Anatoli Fedynitch
Technical reviewer: Karolin Hymon
Wiki: prompt wiki
Last update: CR call April 11

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



Credit: Ludwig Neste

Overview

Analysis

Run as separate analysis

Simulation → **Reconstruction** → **Selection** → **Forward fit** / **Unfolding**

Simulation

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

Validation
- Tag prompt / conv particles
- MCEq comparisons

Reconstruction

DNN reconstructions
- Muon energies
- Muon direction
- Track geometry

Selection

Level 3
- L2 muon filter
- 500 TeV bundle energy cut at surface
- Add labels

Level 4
- Add DNN reconstructions

Level 5
- Data-MC quality cuts

Forward fit

Fit prompt normalization
- Poisson LLH fit

Focus on today

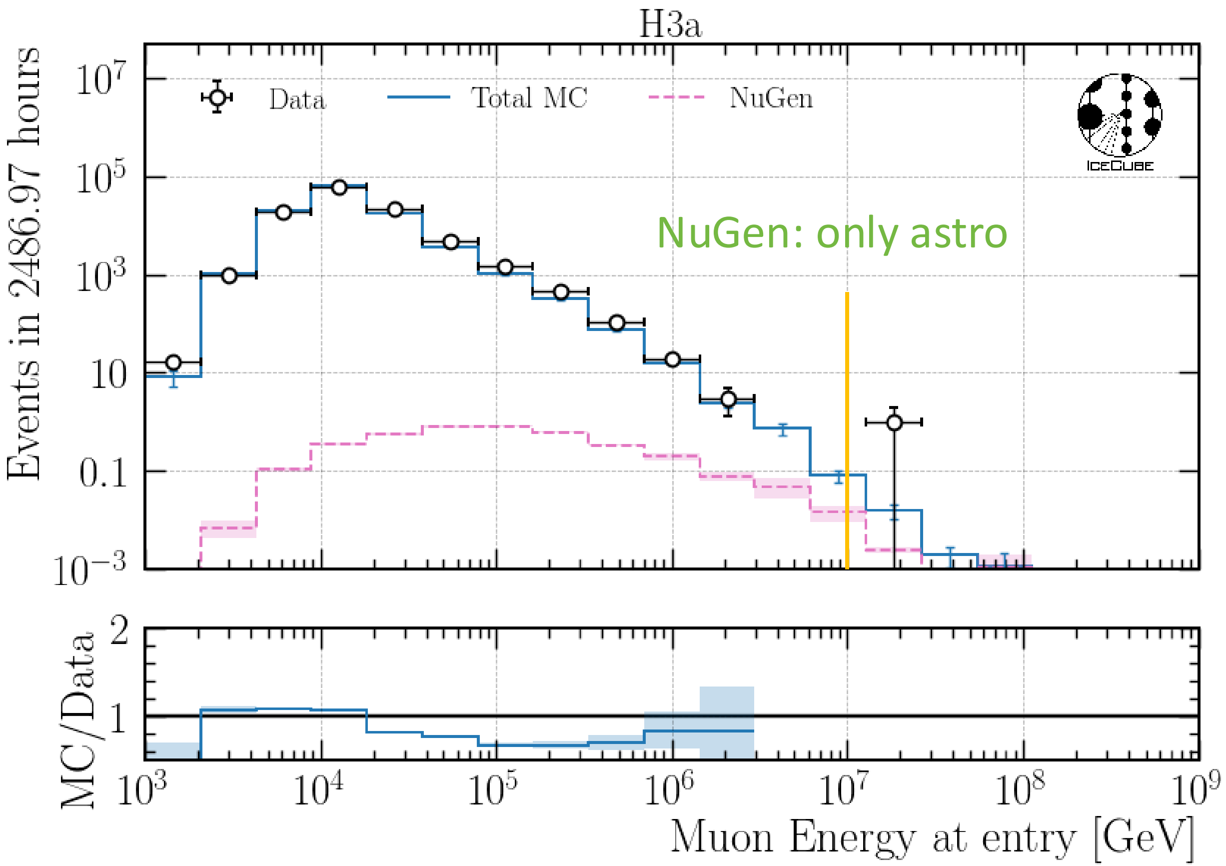
Unfolding

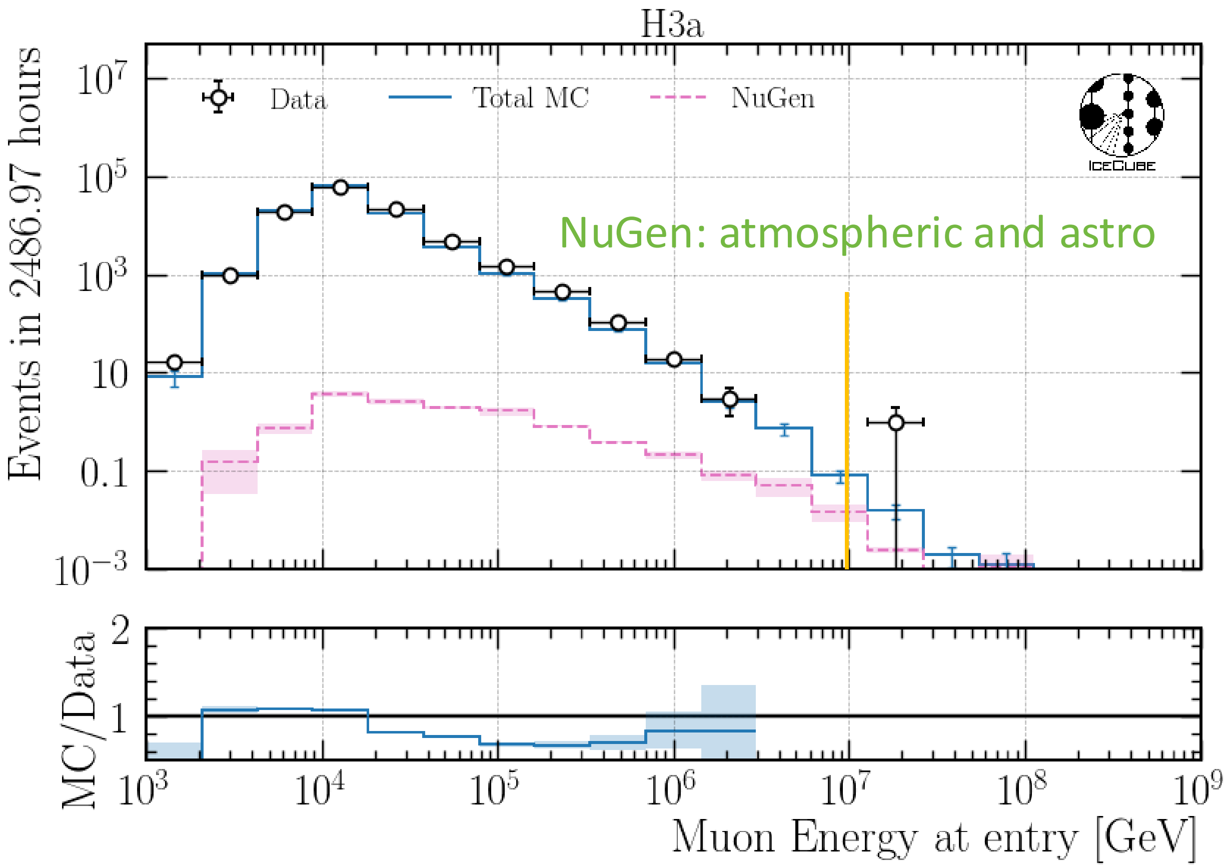
Muon spectrum
- Unfold muon flux

Investigate Neutrino Background

Impact of Astrophysical Neutrinos – Muon Energy at Entry

$n = 1.5, \gamma = 2.6$

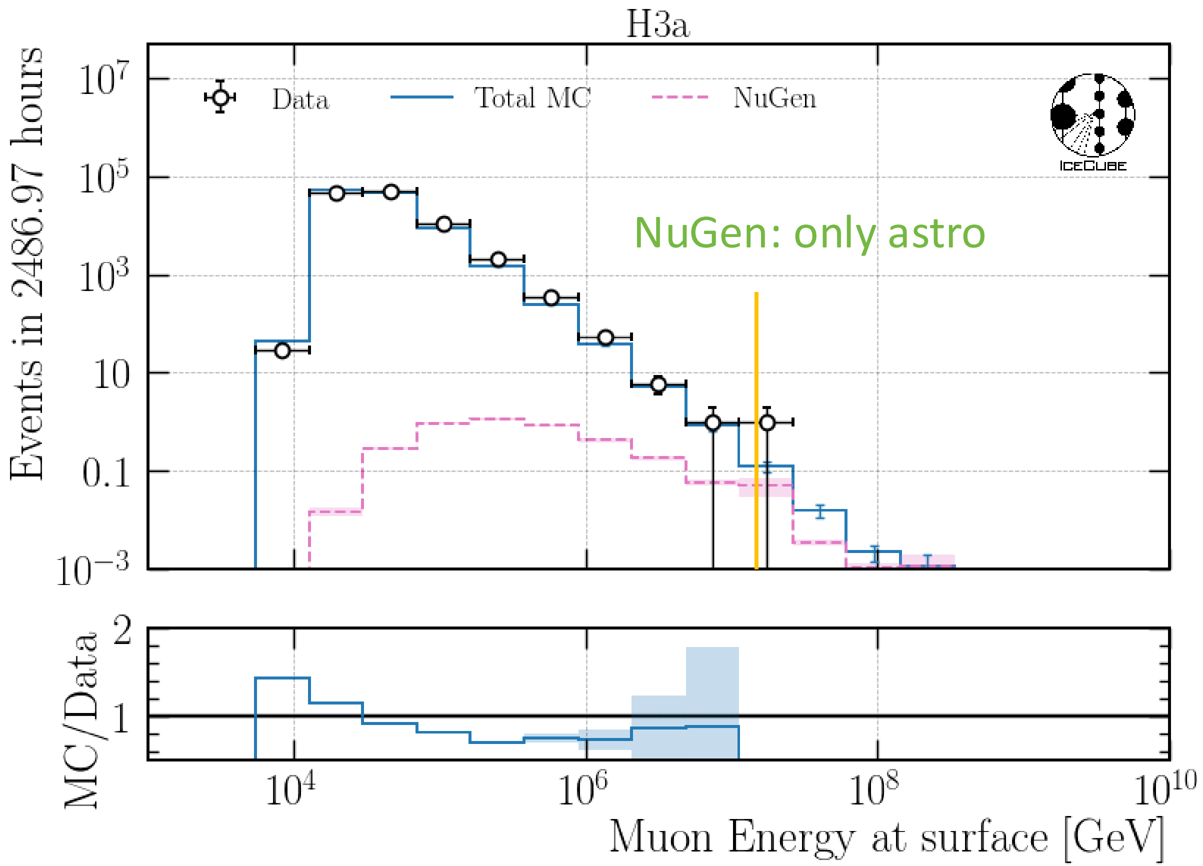


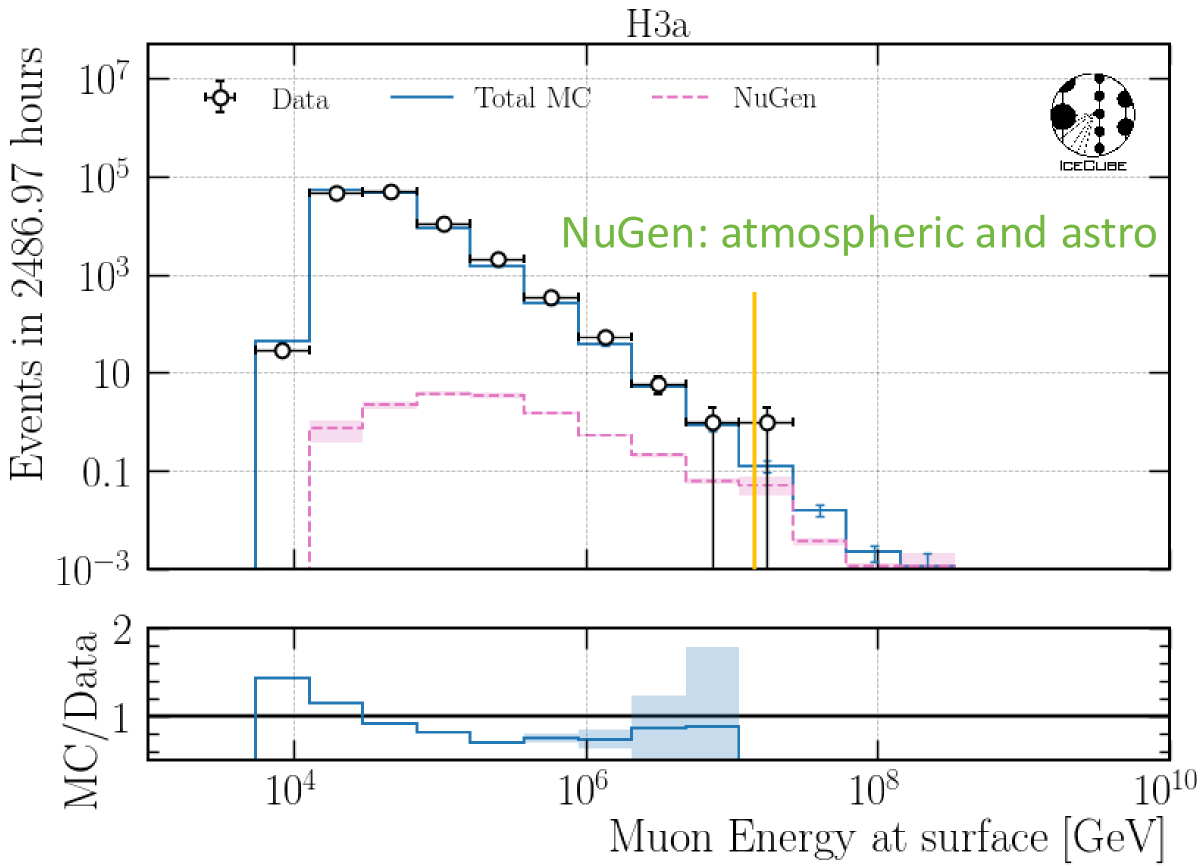


- Neutrinos contribute ~10% to total flux at high energies > 5 PeV

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, 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.

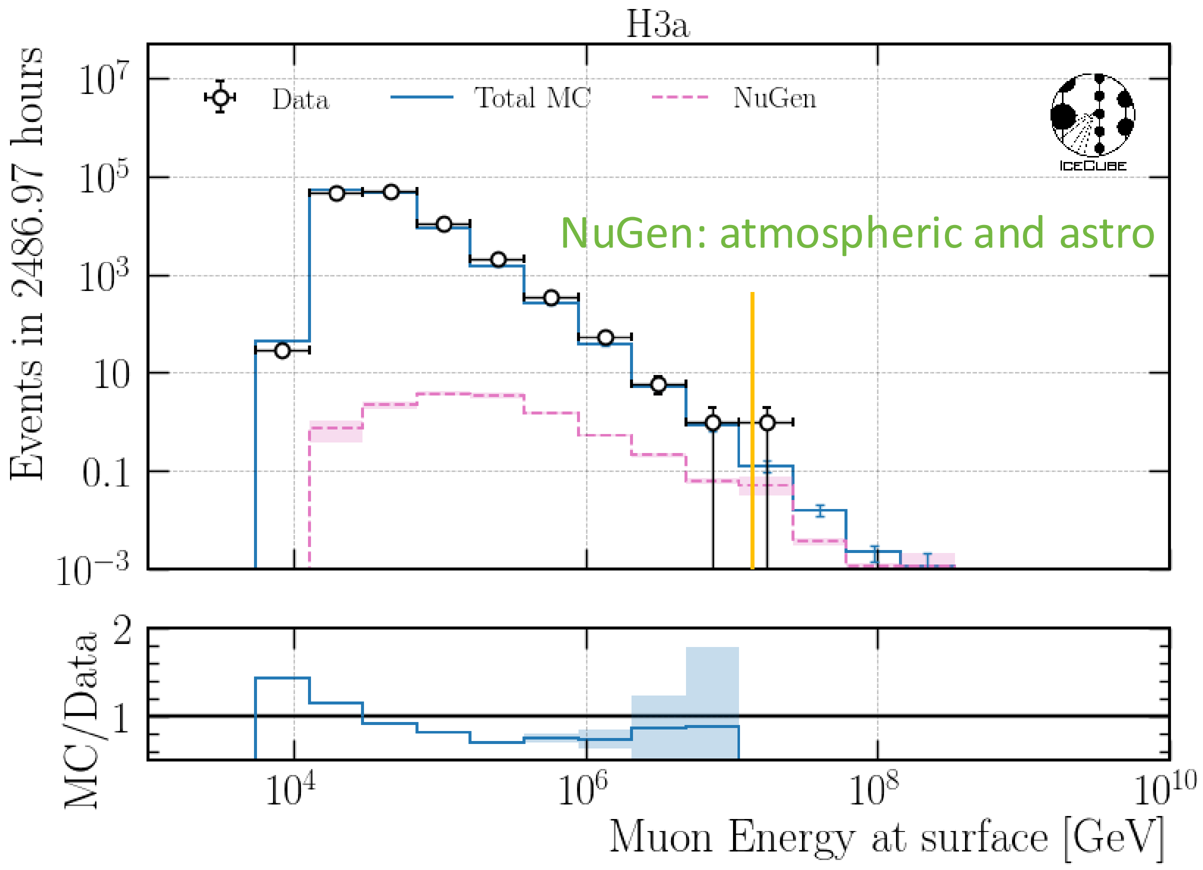
ArXiv: 2308.00191

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

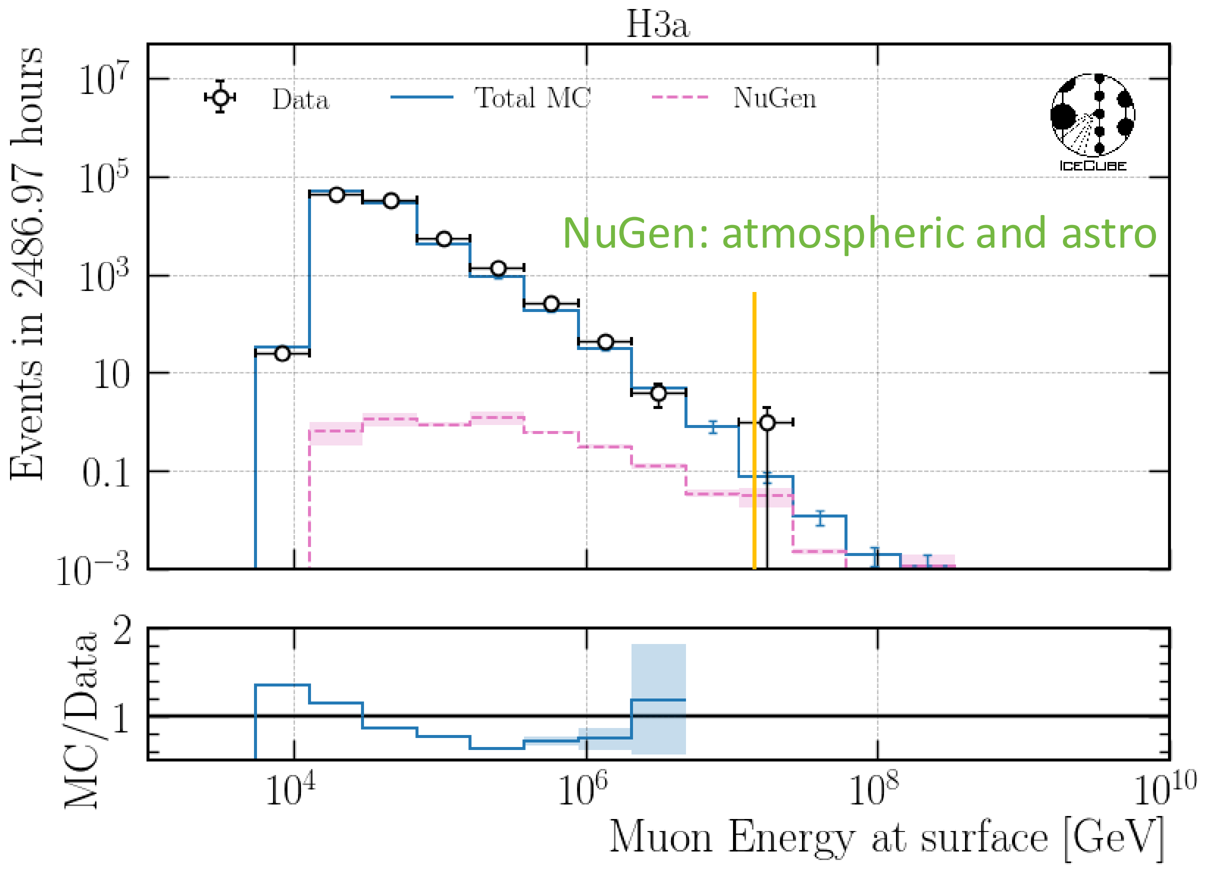
➢ Test SPL and BPL

Remove Horizontal Events – Muon Energy at Surface

n = 1.5, γ = 2.6



$\cos(\boldsymbol{\theta}) > 0.2$



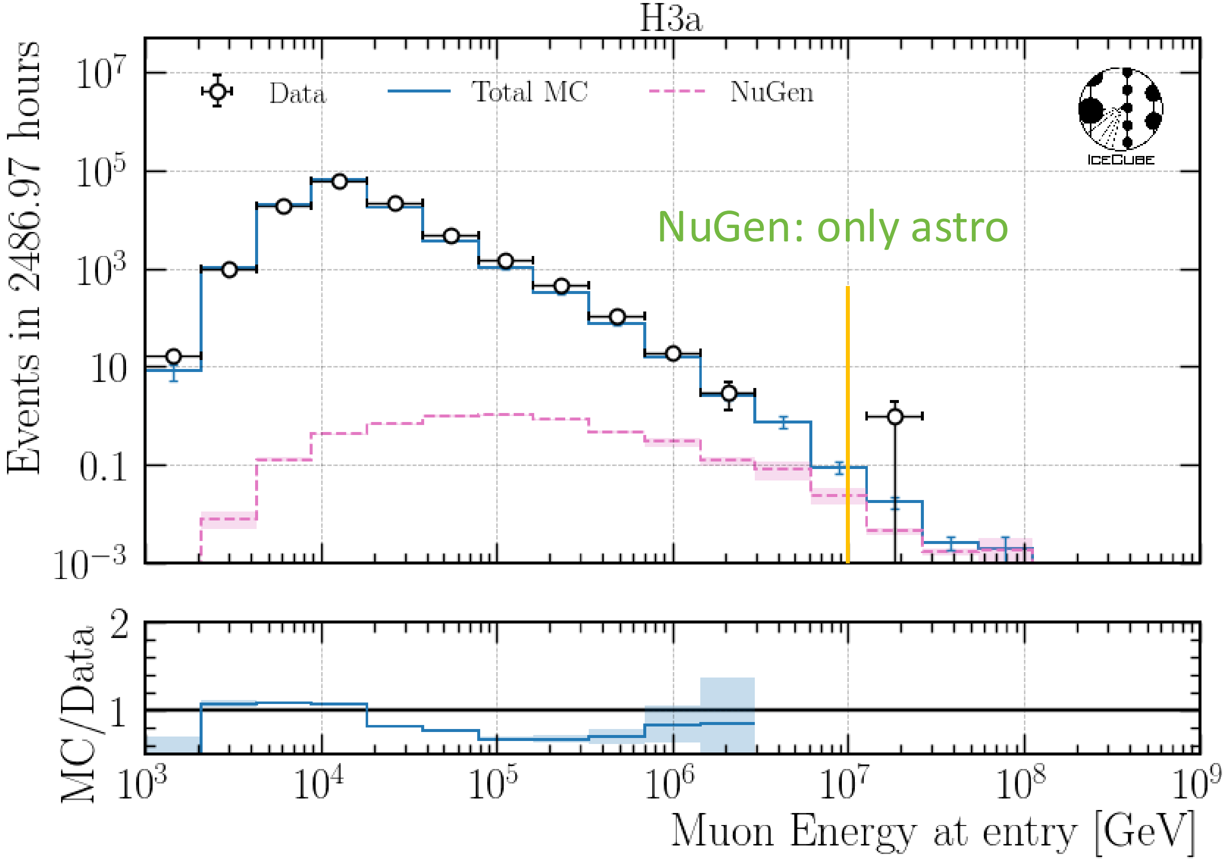
$\cos(\boldsymbol{\theta}) > 0.4$

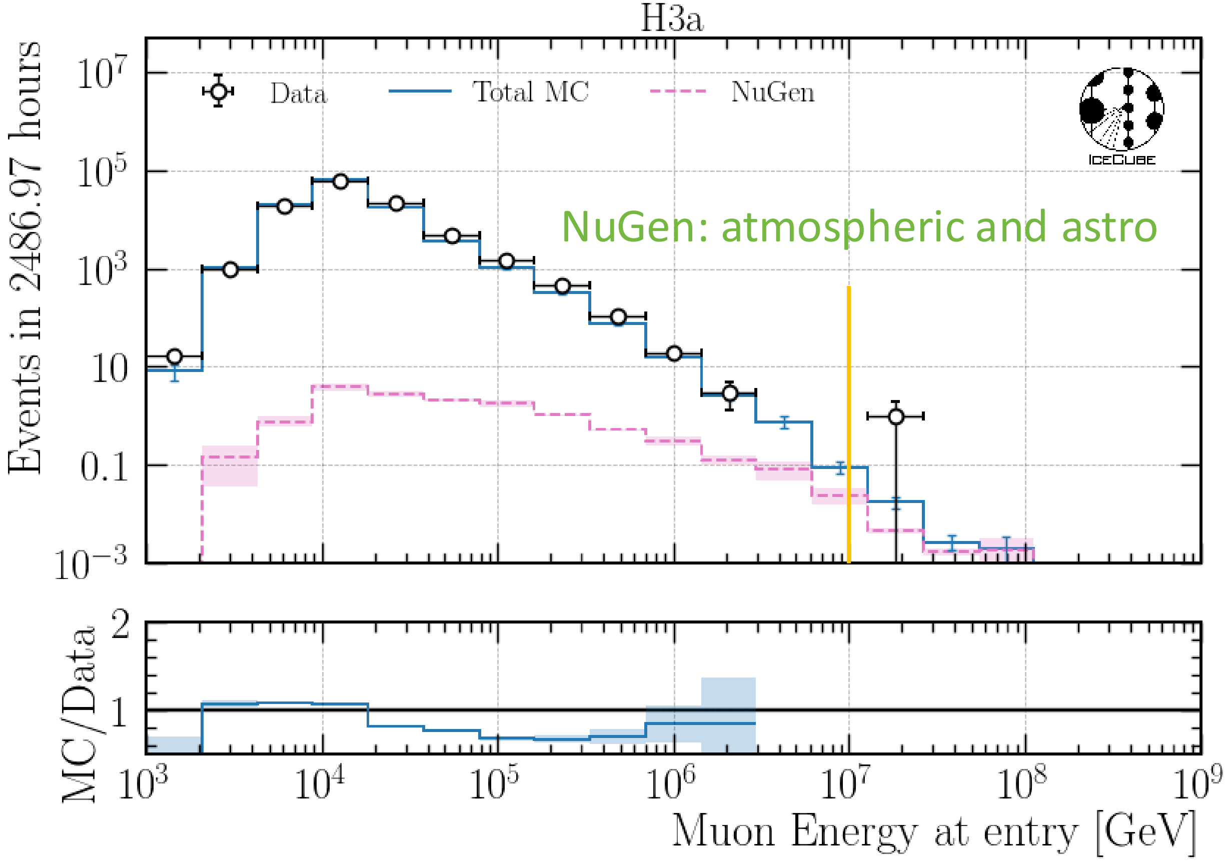
- Stronger zenith cut has no significant impact

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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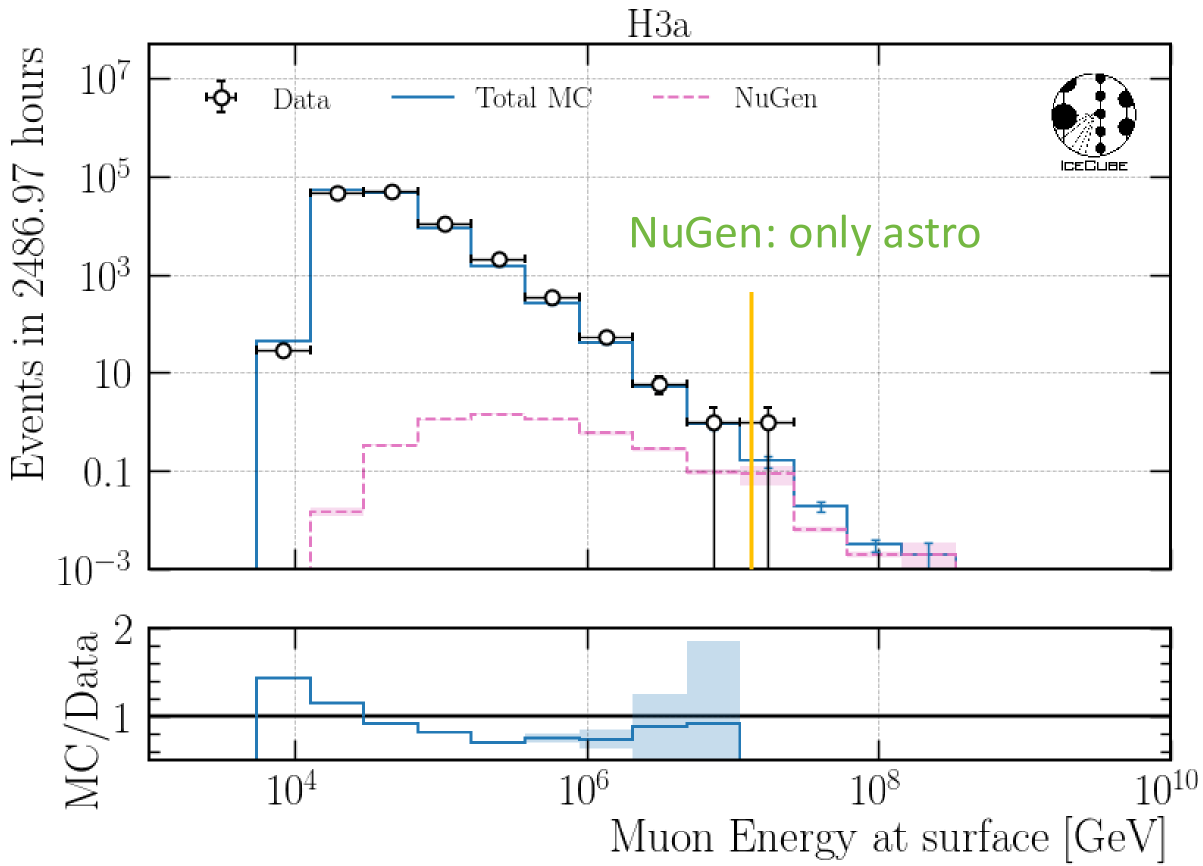
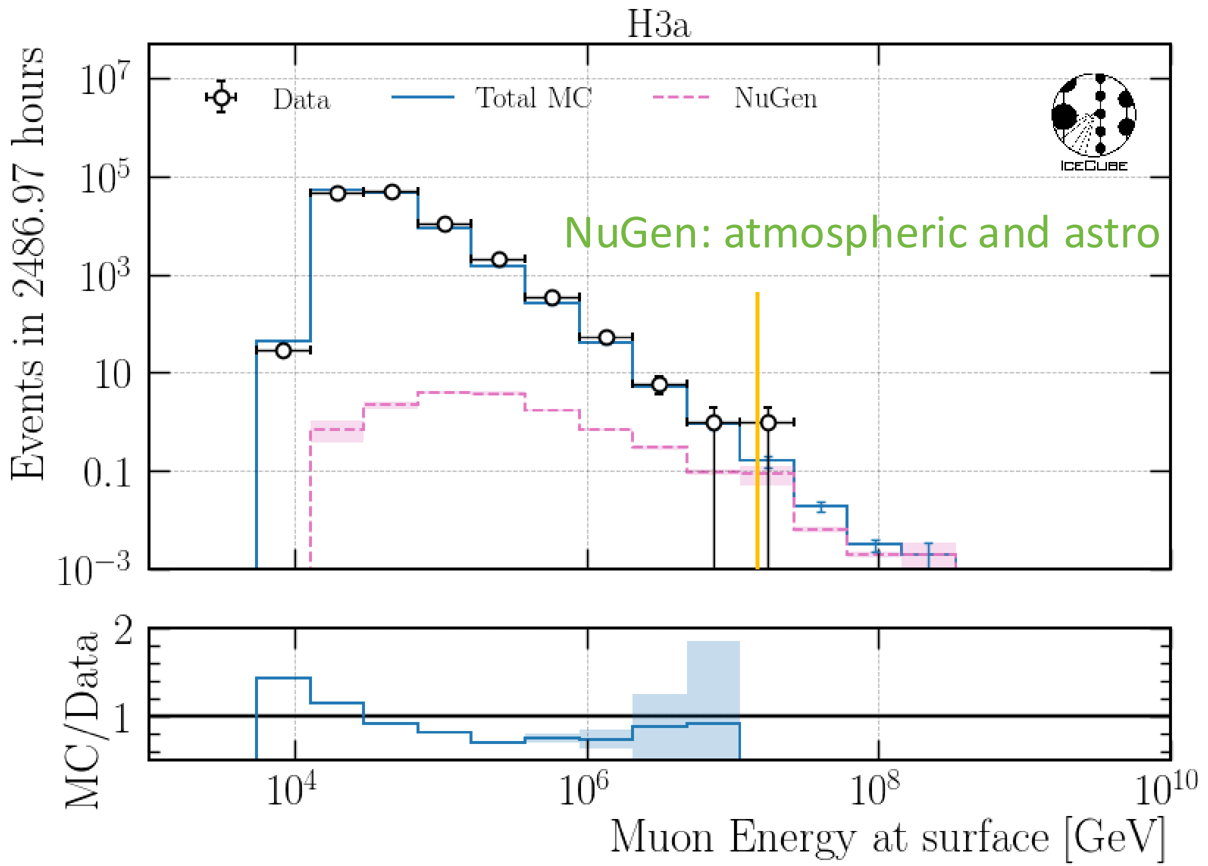
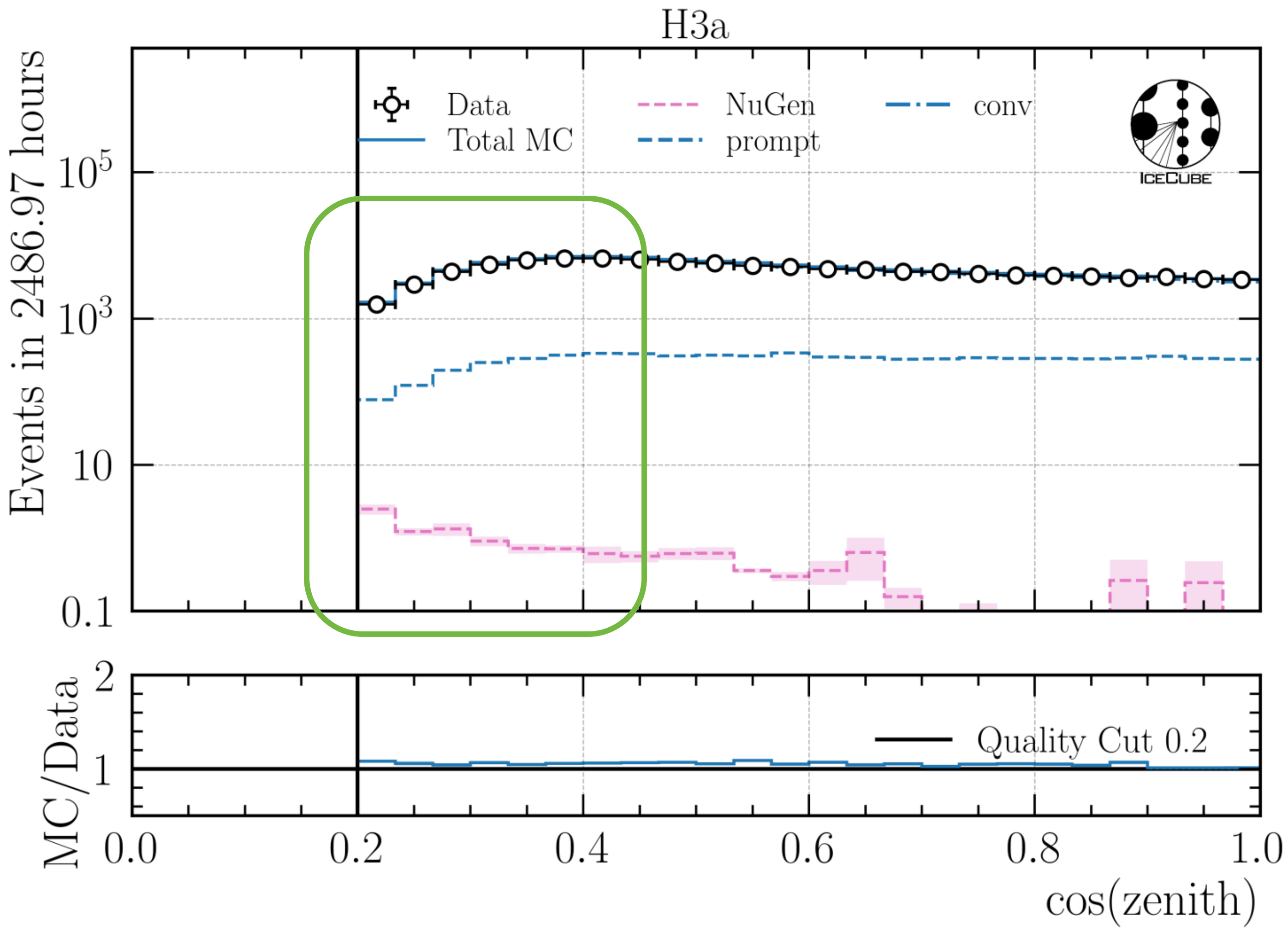




➢ Neutrinos contribute ~50% to total flux at high energies > 5 PeV

Cos(zenith) Distribution



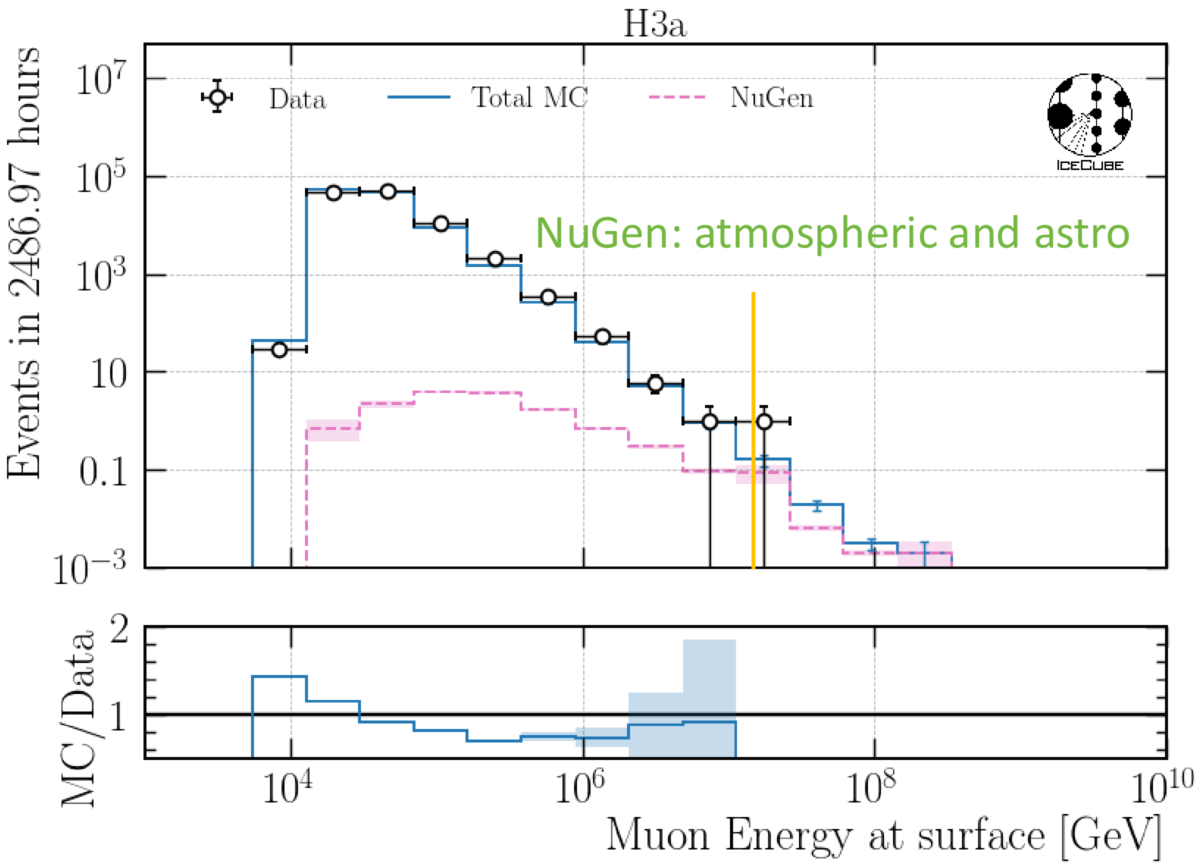
horizontal ⟷ vertical

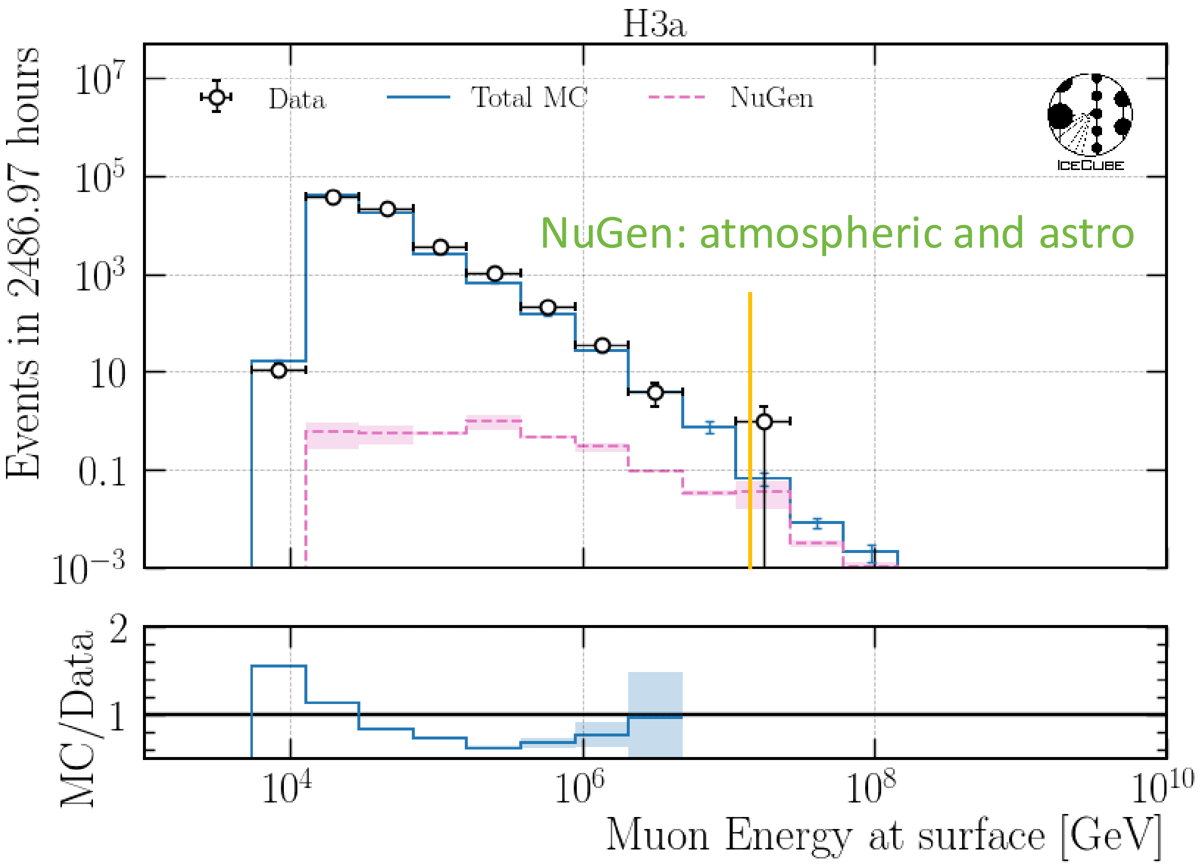
- Expect more neutrinos from the horizon
- ➢ Apply stronger zenith cut to remove neutrinos

Remove Horizontal Events – Muon Energy at Surface

$n = 1.8, \gamma = 2.52$

2308.00191



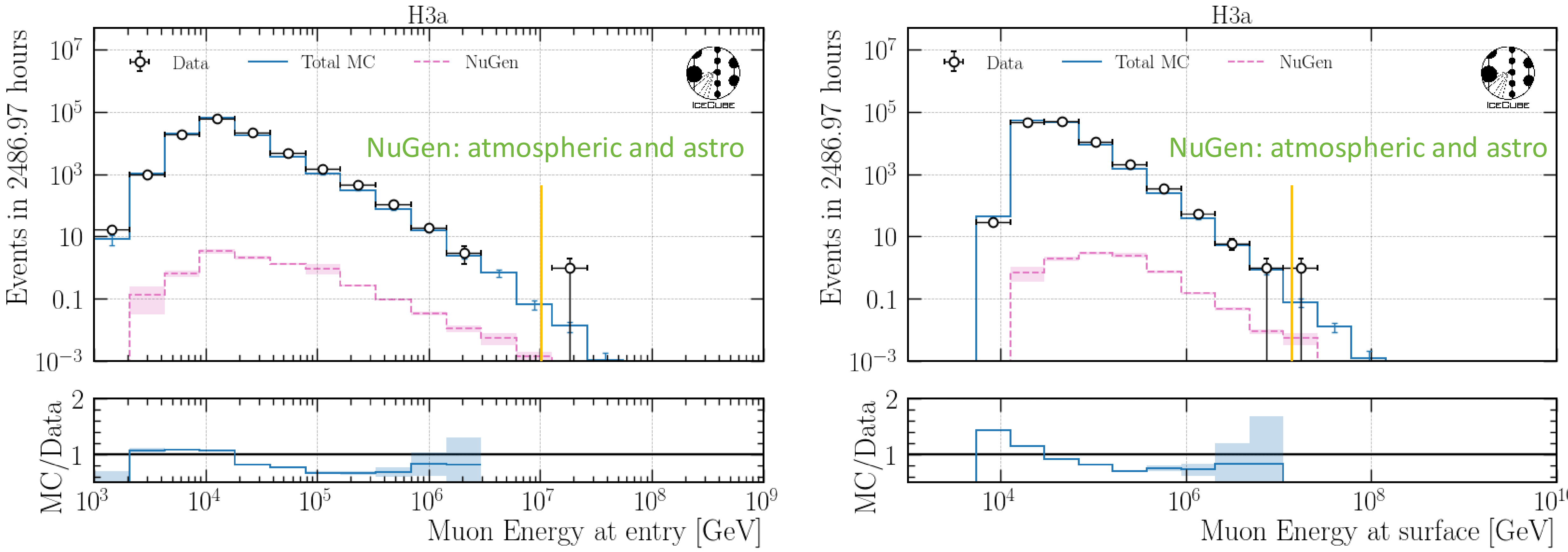


$\cos(\boldsymbol{\theta}) > 0.2$

$\cos(\boldsymbol{\theta}) > 0.4$

➢ Stronger zenith cut has no significant impact

Impact of Astrophysical Neutrinos – Muon Energy at Surface/Entry



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

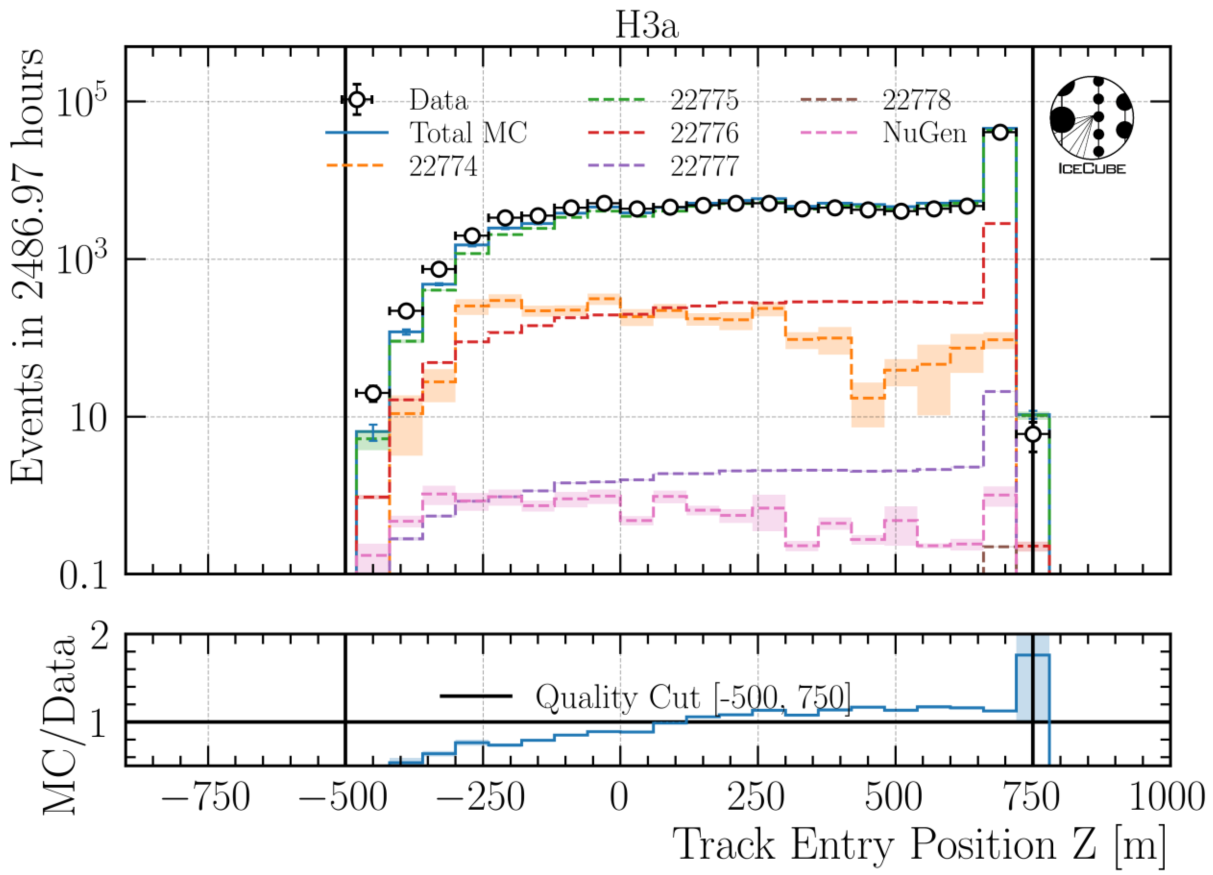
- For BPL: Neutrinos contribute less than 10%

2308.00191

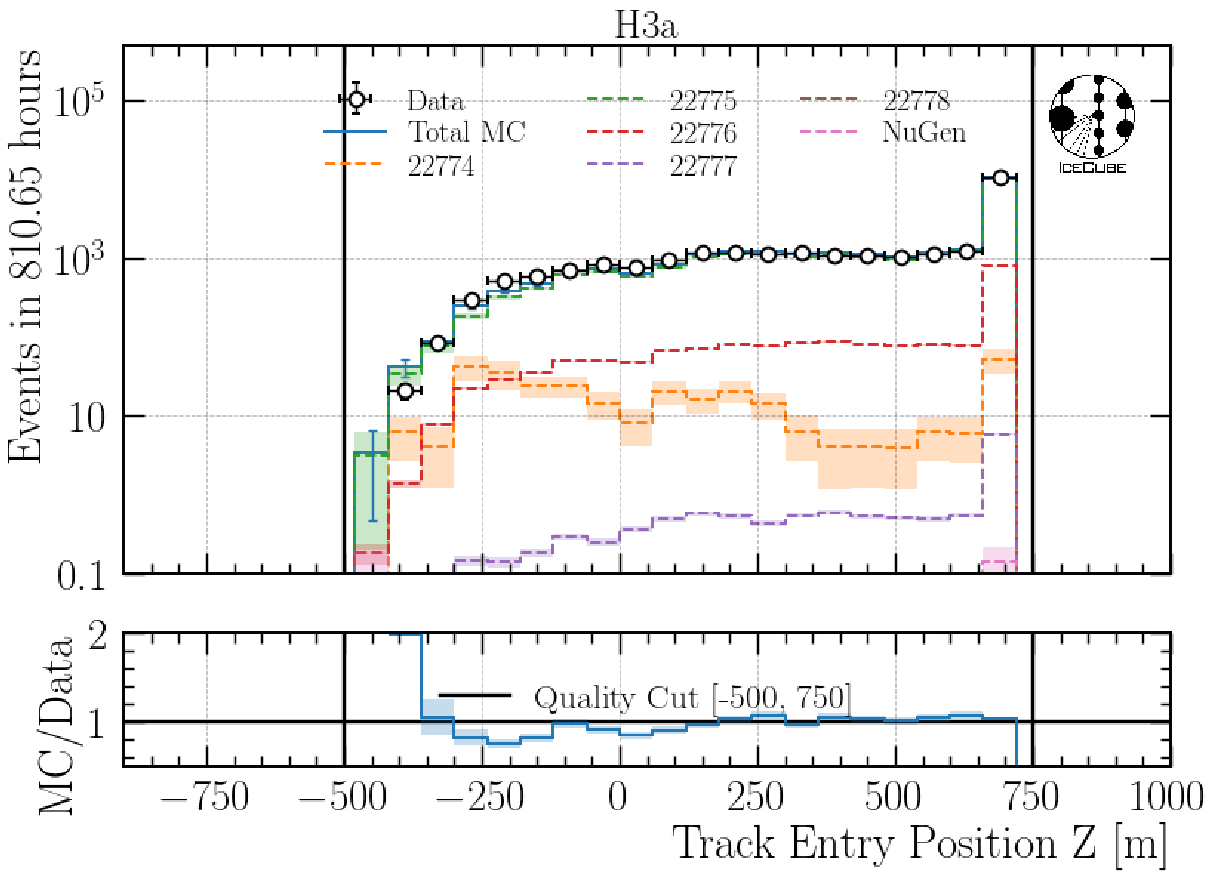
Z—Vertex Data-MC

- 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

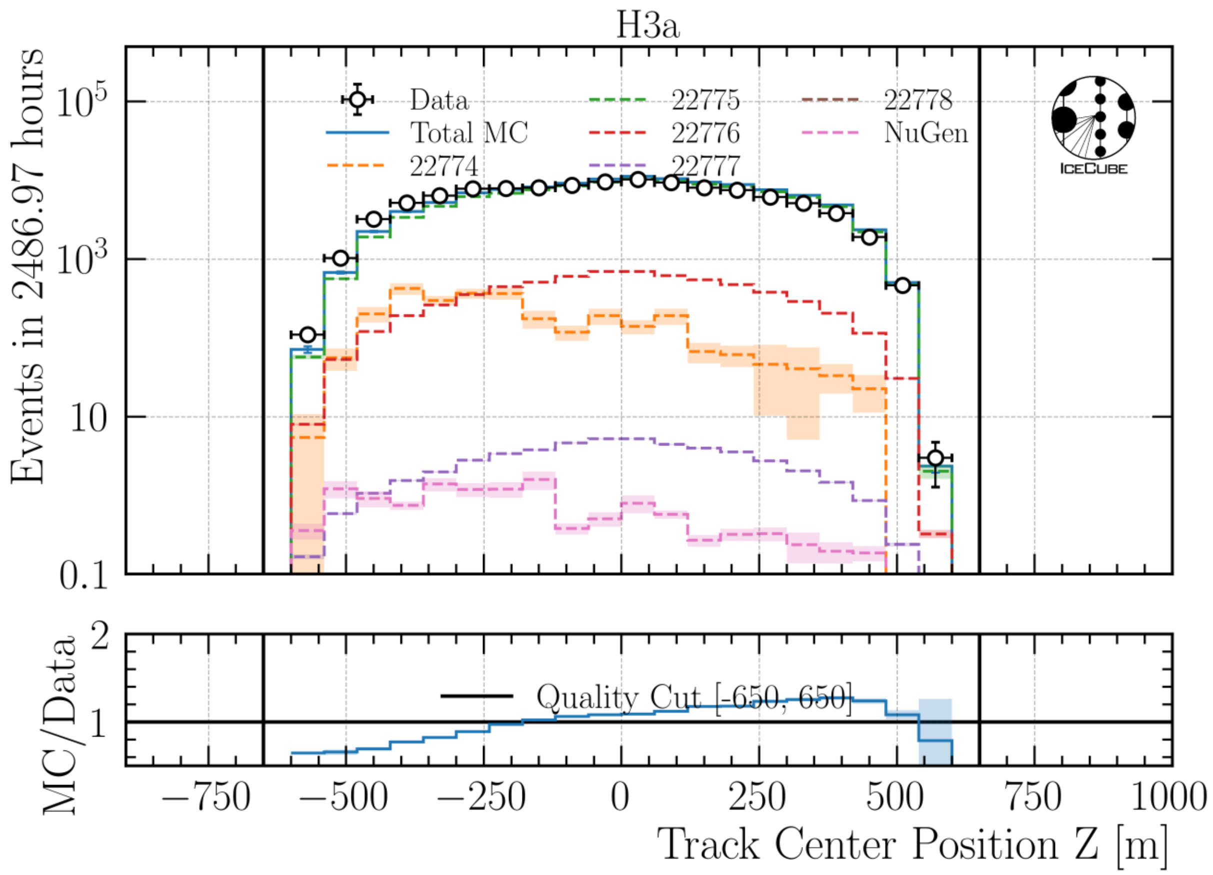


Old ice model

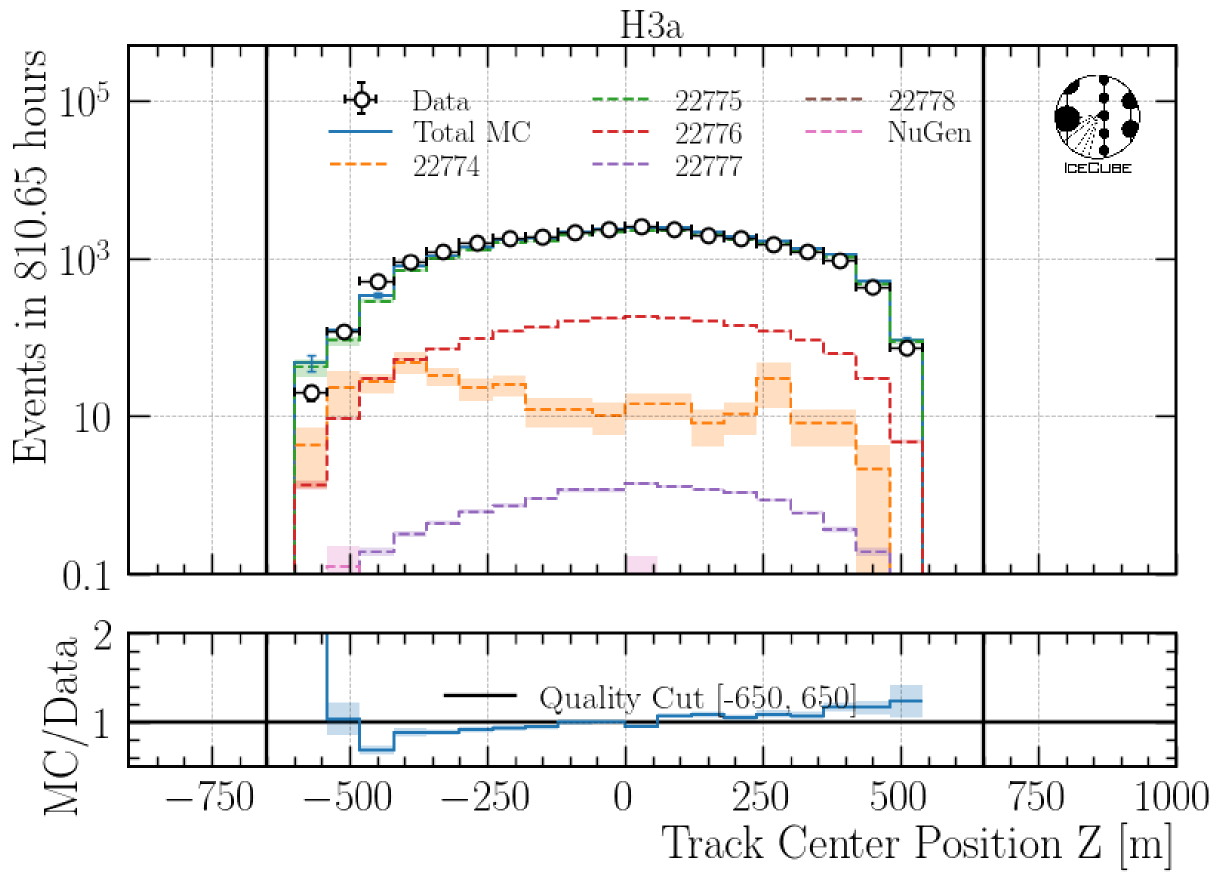


New ice model

Z—Vertex Data-MC: Center Position

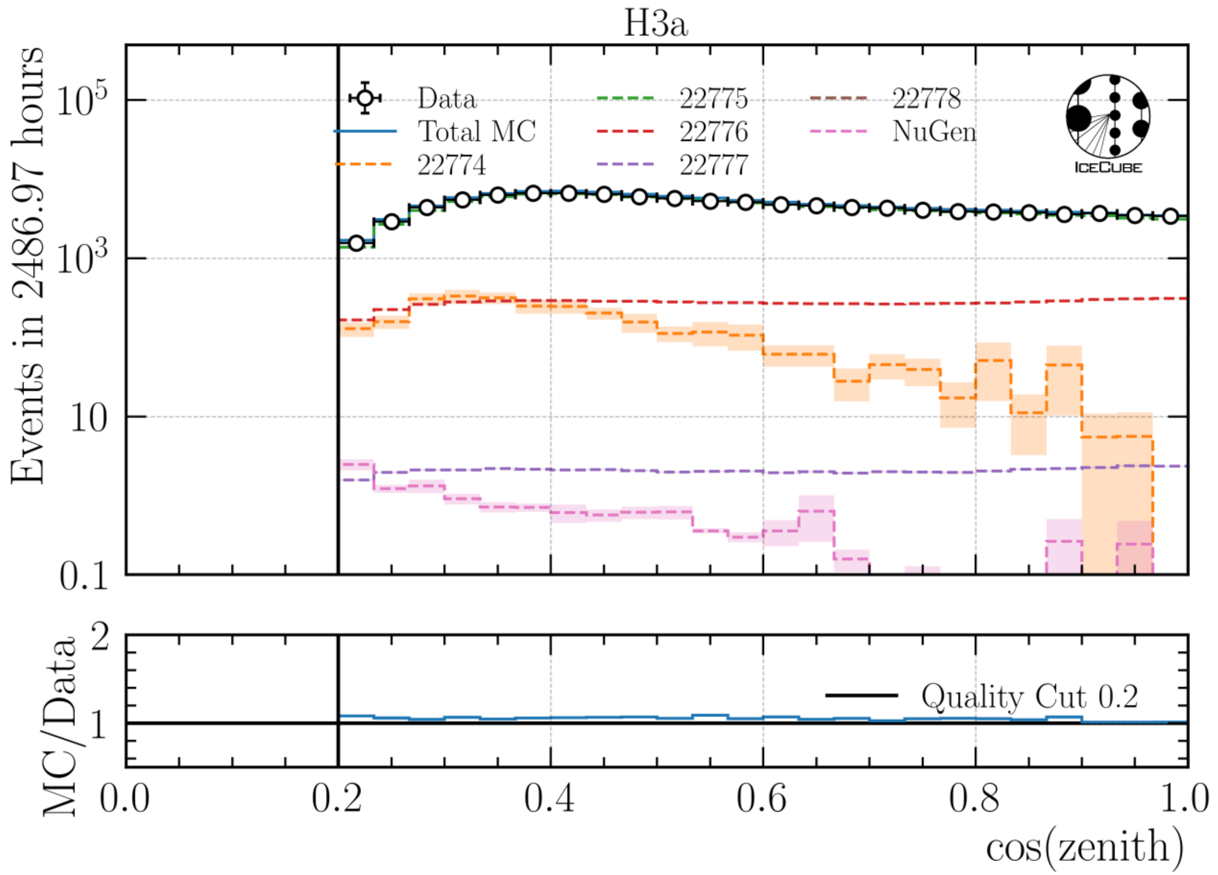


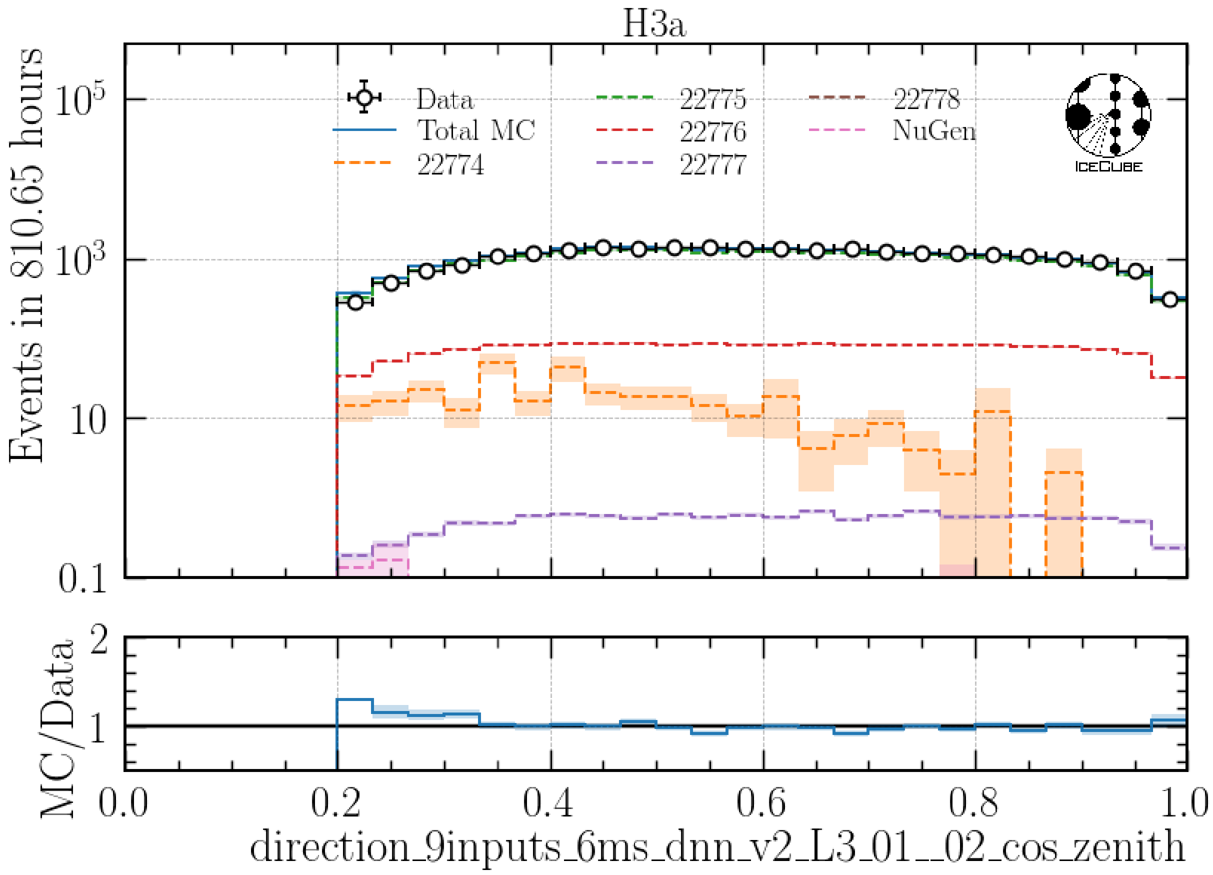
Old ice model



New ice model

Cos(zenith)





Old ice model

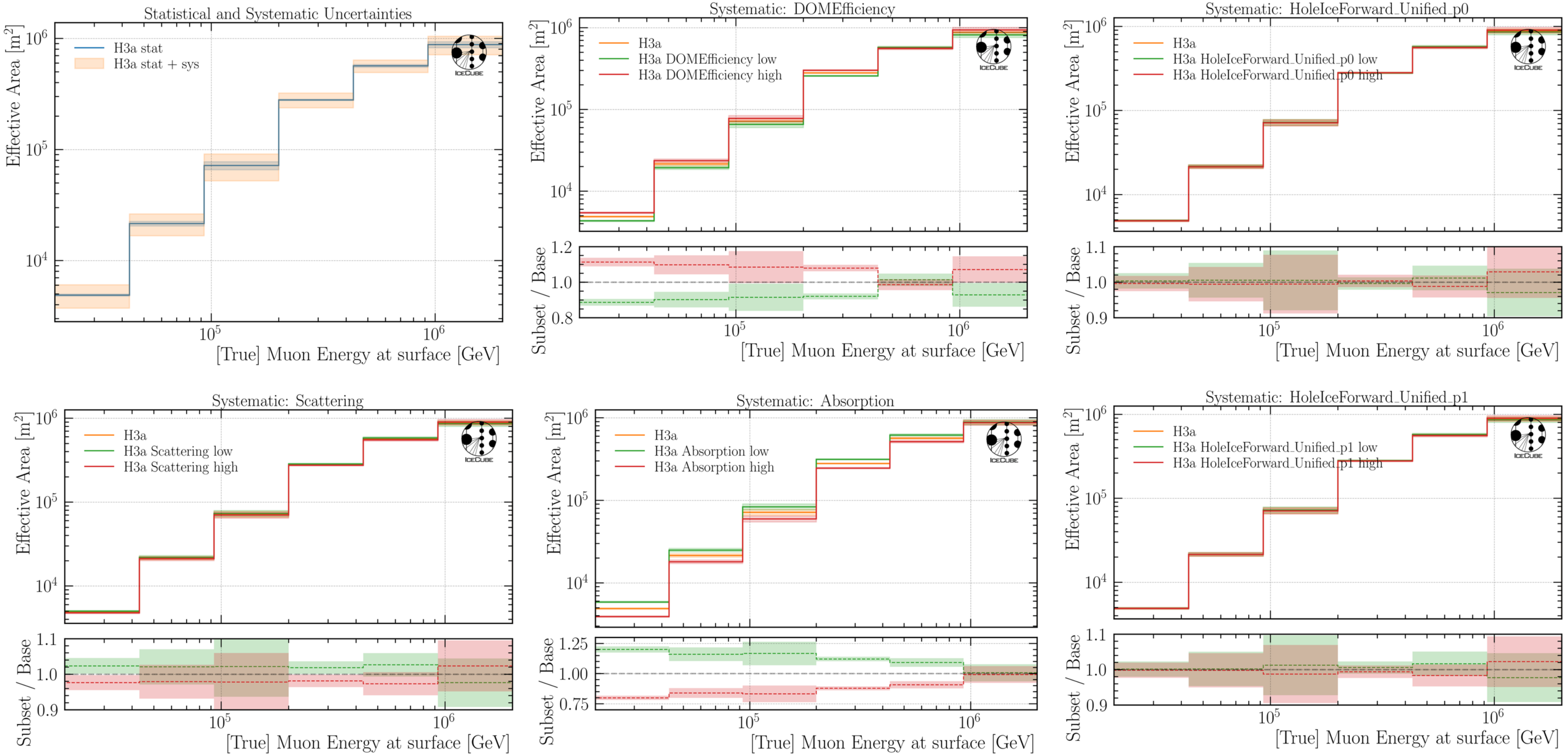
New ice model

- 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



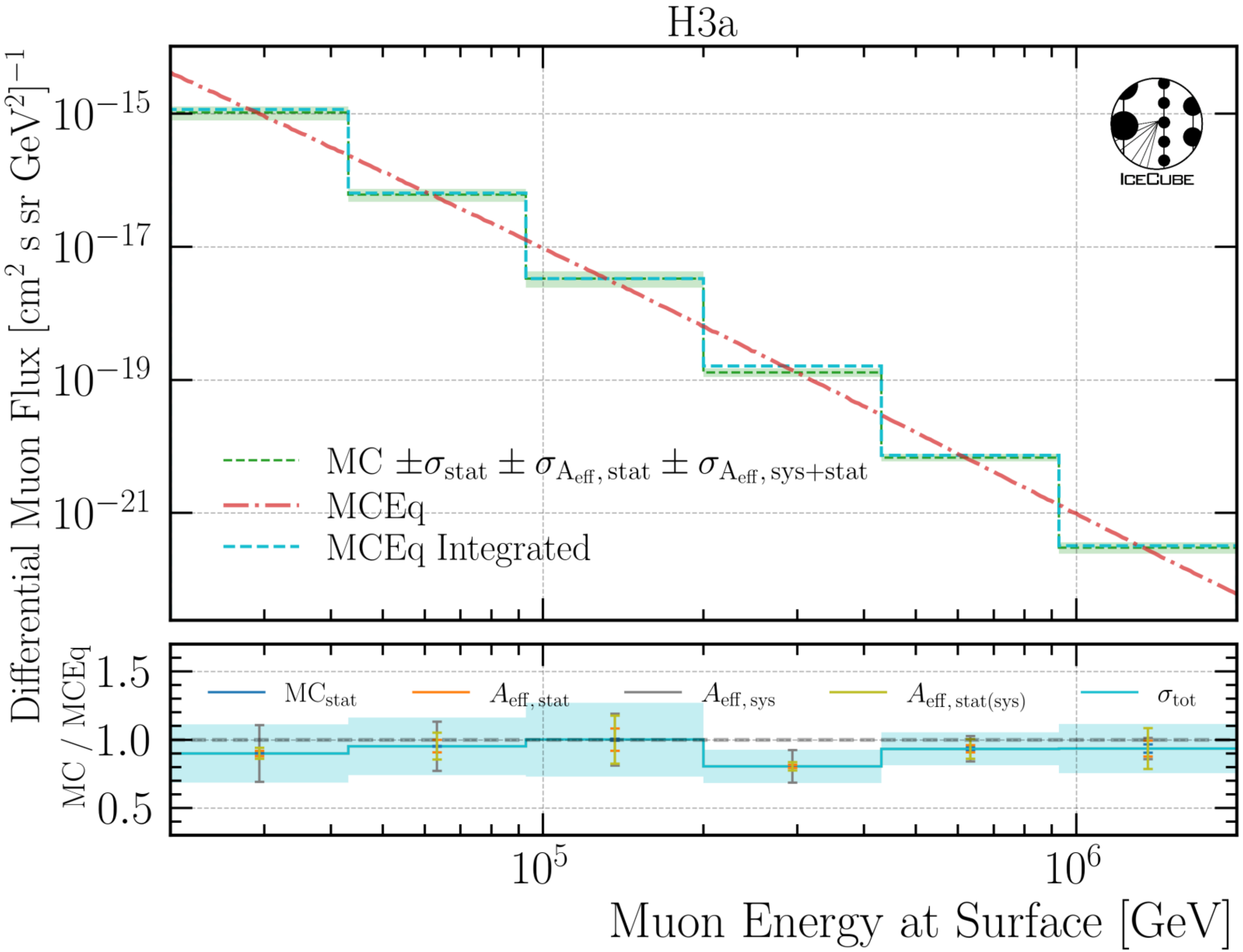
MCEq vs CORSIKA

Uncertainties on Flux

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

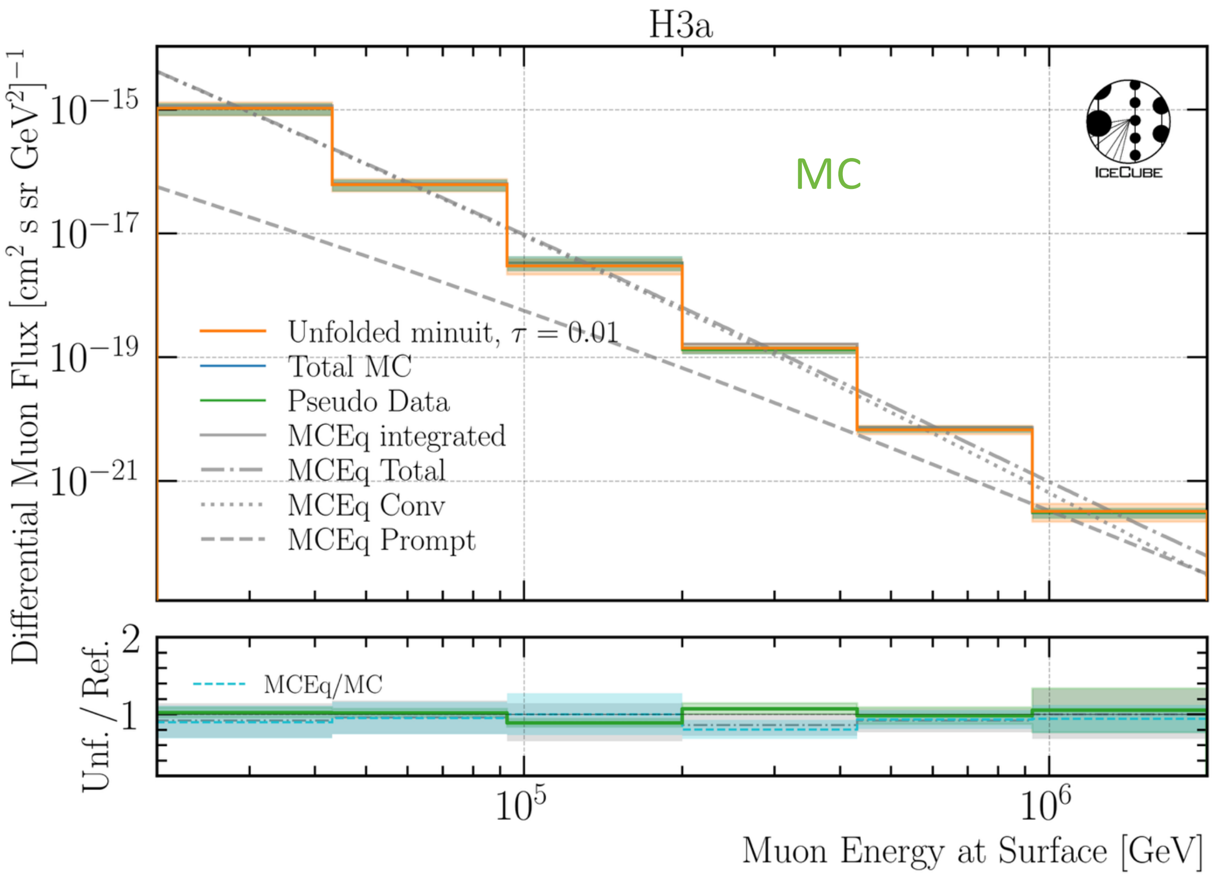
χ^2– Test (H3a):
p—value: 0.683
→ -0.48 **σ**

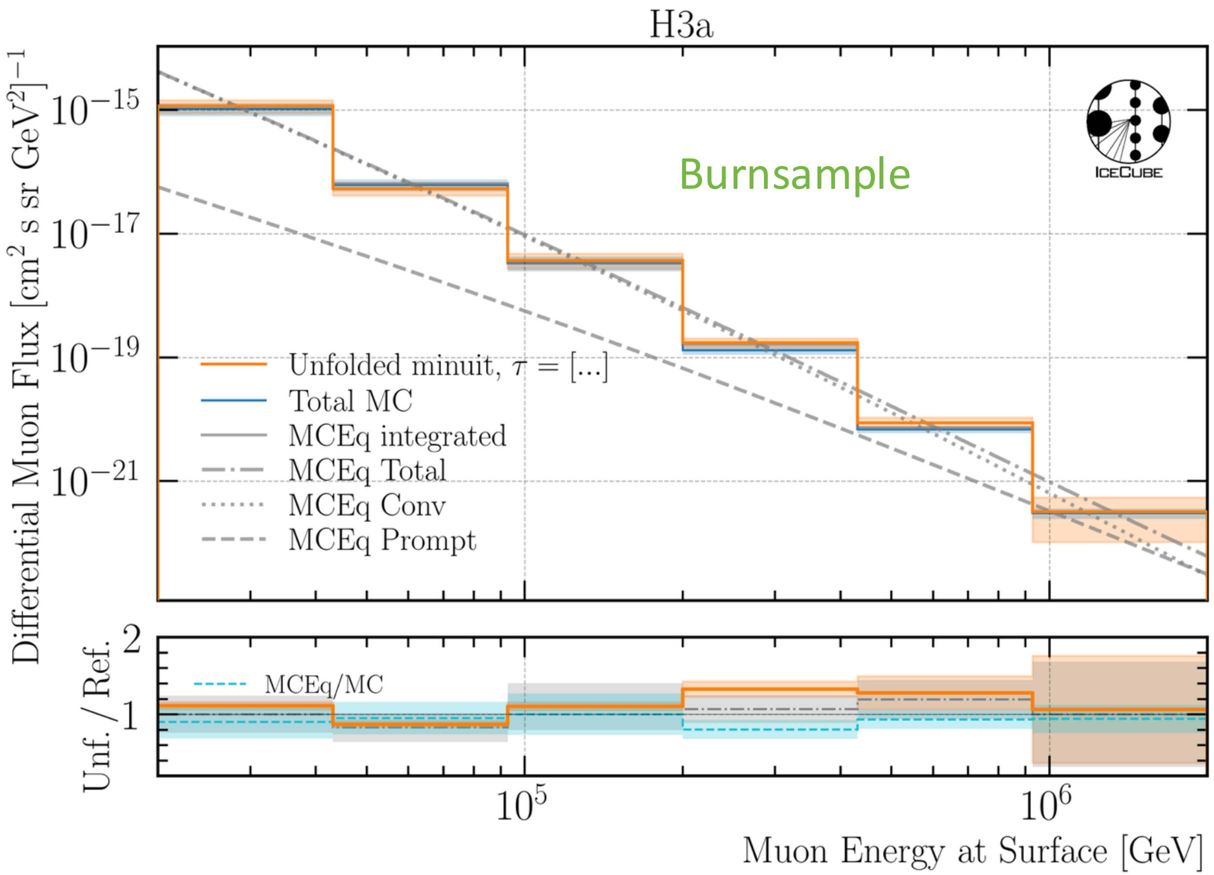
➢ Good agreement between MCEq & CORSIKA



Unfold Burnsample

Unfold Burnsample





χ^2– Test (H3a):
p—value: 0.587
→ -0.22 **σ**

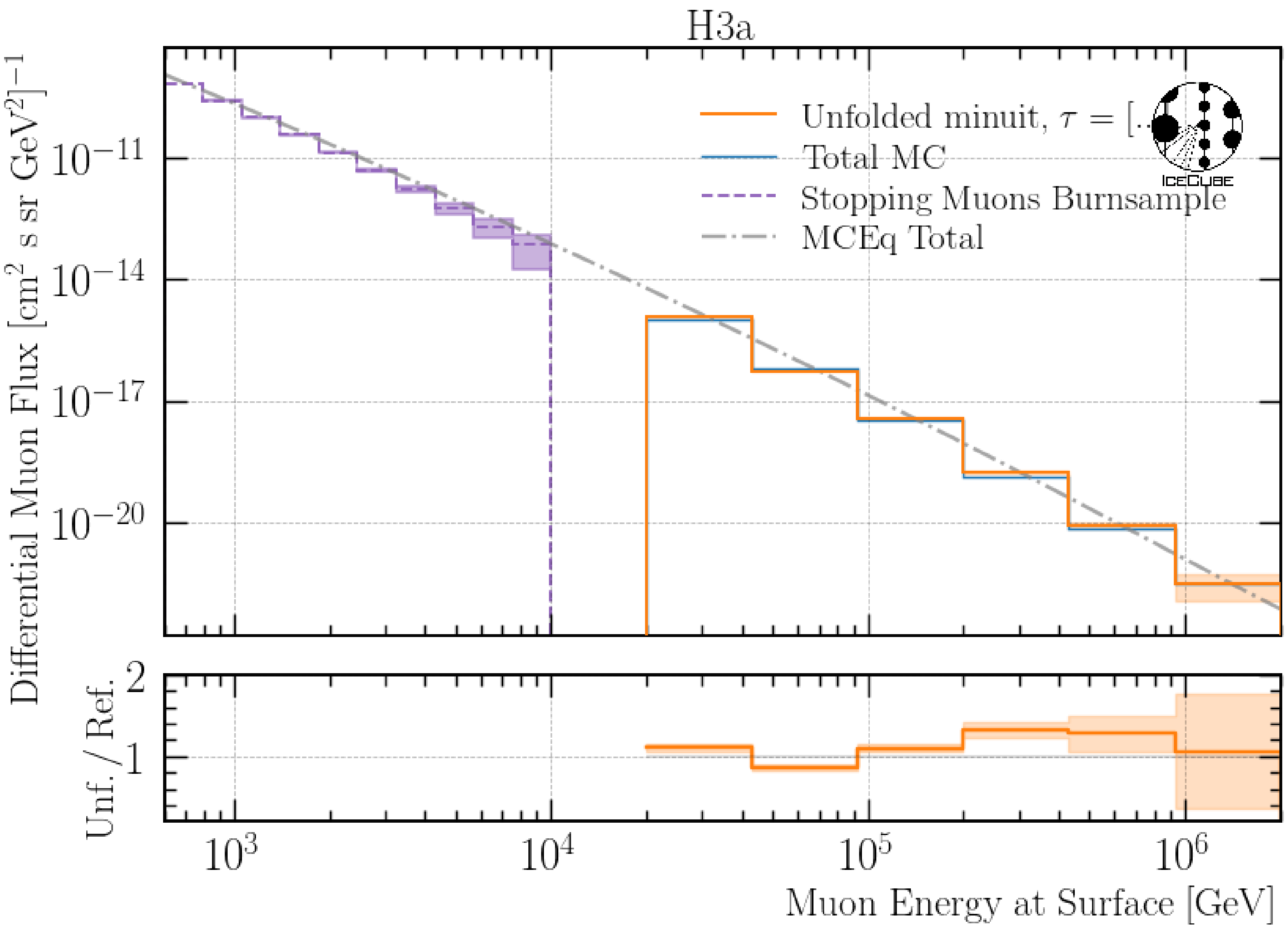
➢ Unfolding works on MC & burnsample

Stopping Muons and Leading Muons

Work in progress

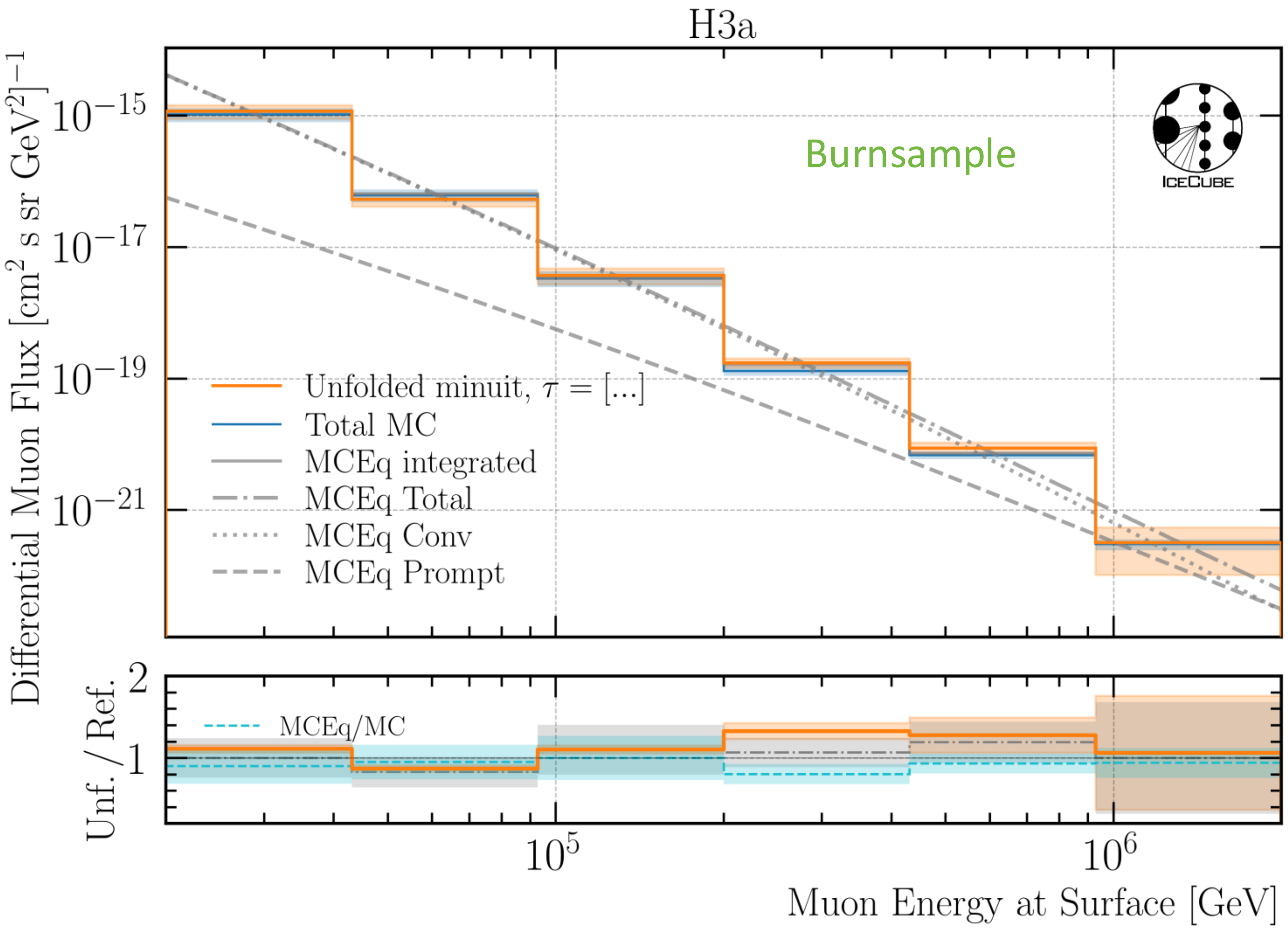
- Use stopping muons to unfold low energy muon spectrum
- Use leading muons to unfold high energy muon spectrum

➢ 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



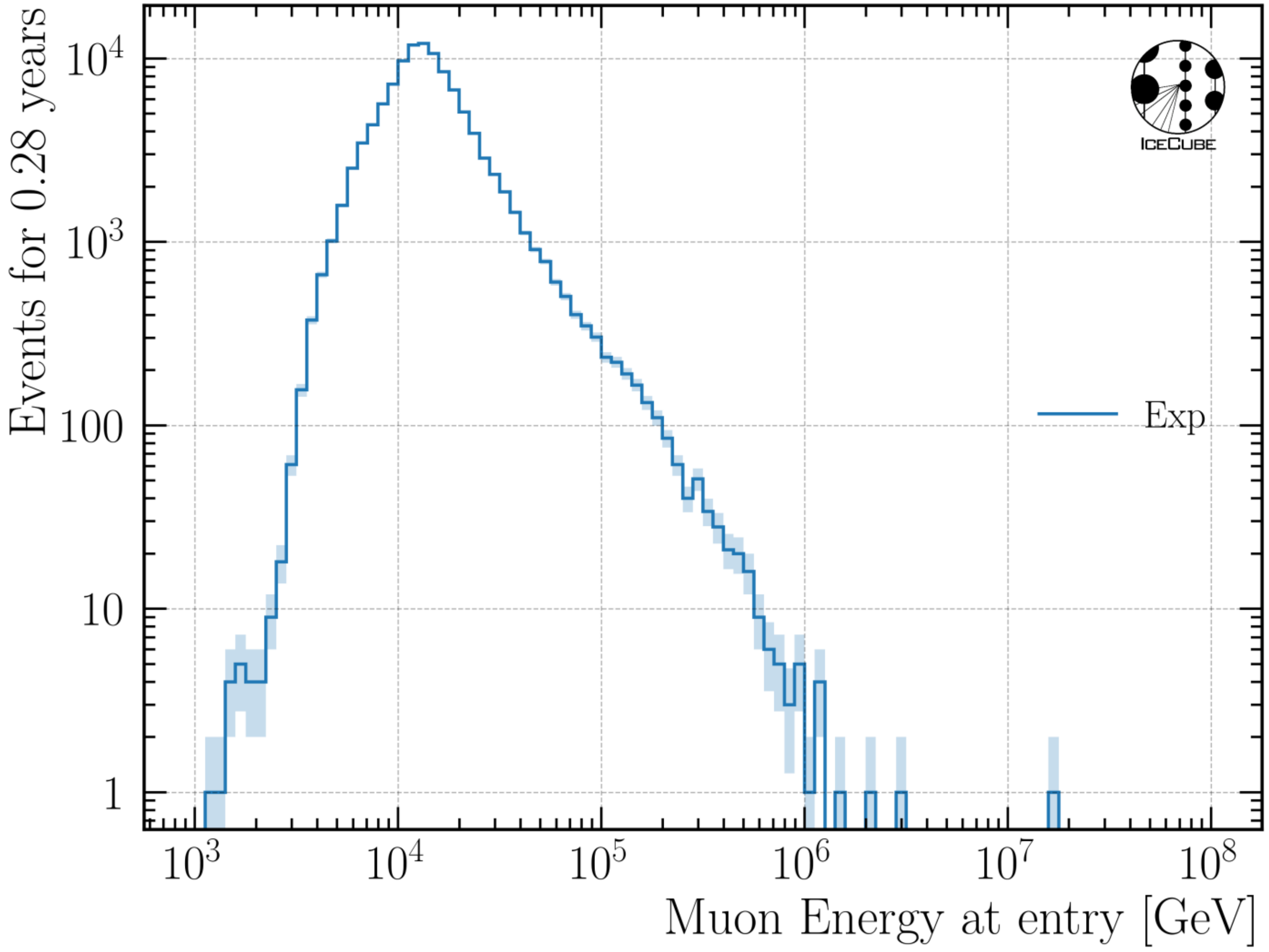
Outlook

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

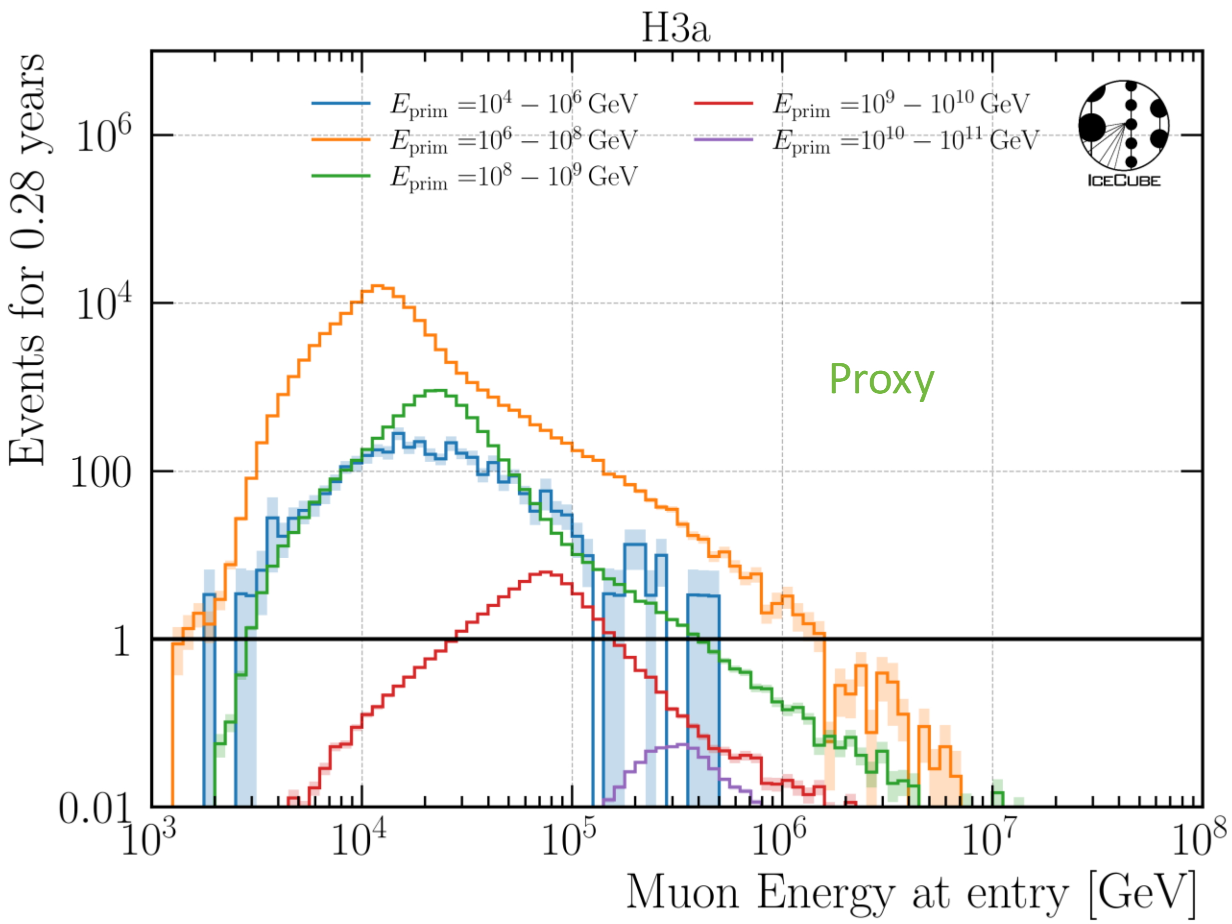
➢ Unfold on 12.12 years of data

Thank you for your attention!

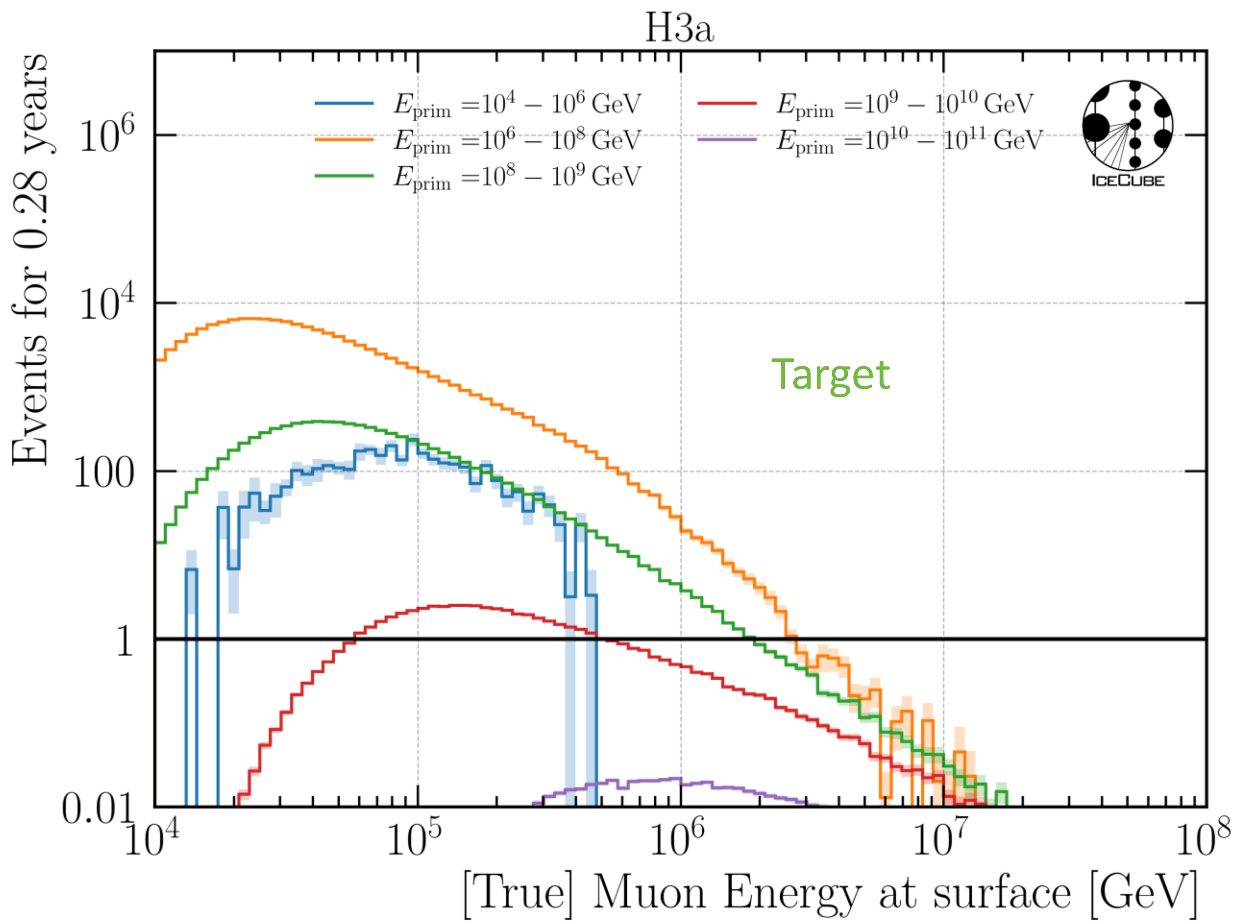
Burnsample Proxy



Statistics



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



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

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

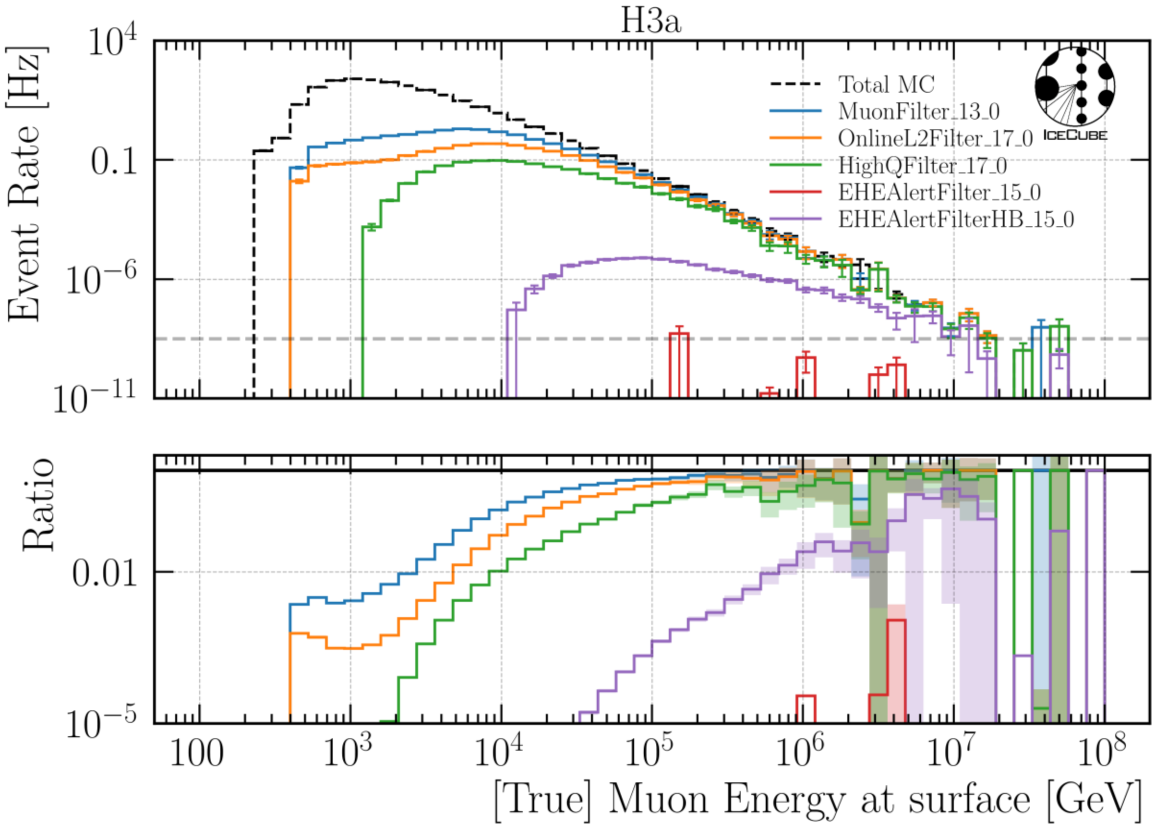
PhD deadline: July
Leander Flottau is working on forward fit
I'll stay in academia → finish analysis

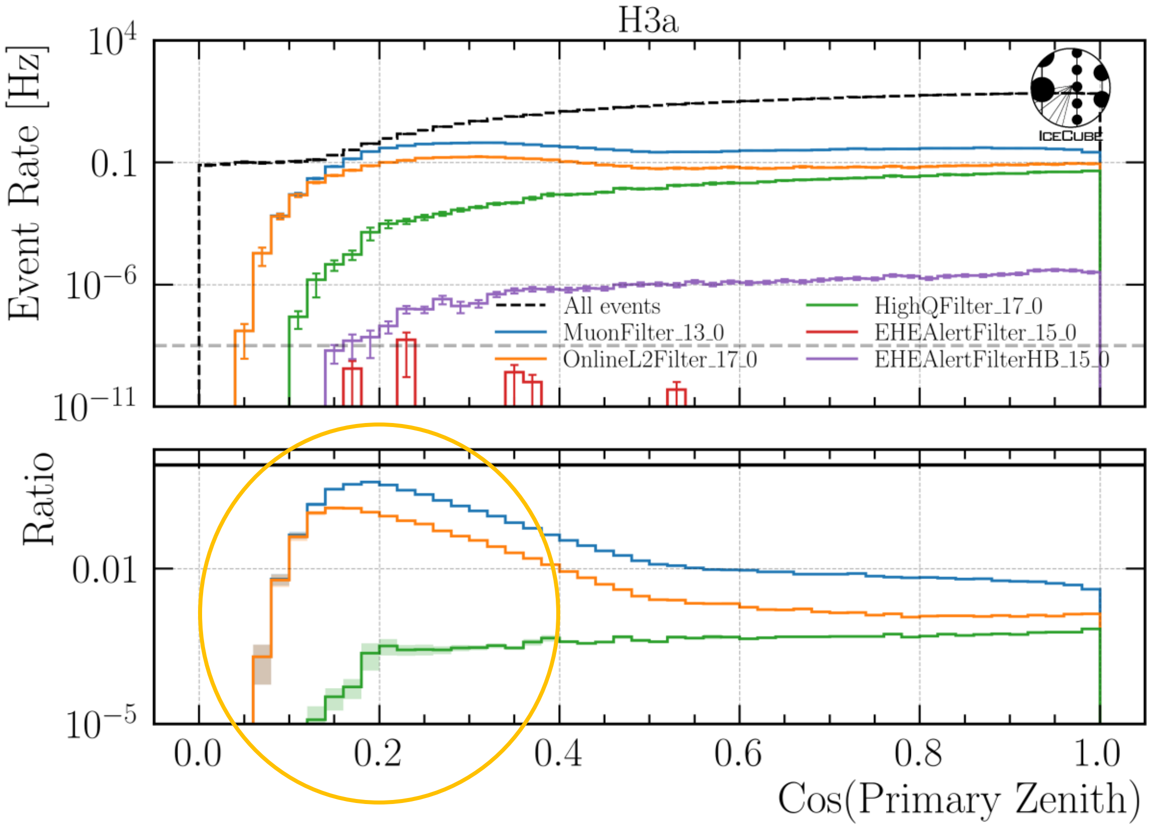
CRWG Review

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

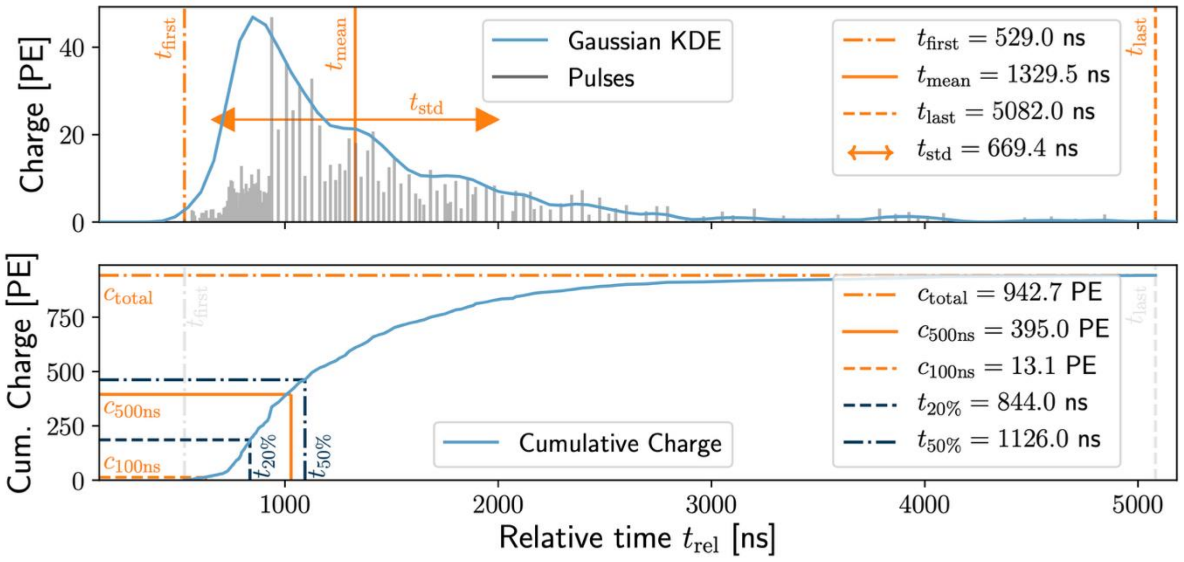
Q: Which quantities do you reconstruct and how do you do this?

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

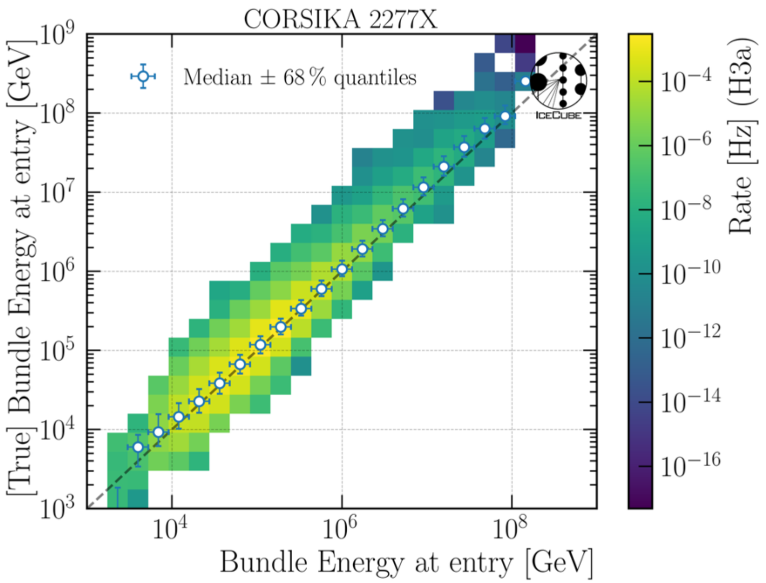
Direction
- Zenith / azimuth of leading muon

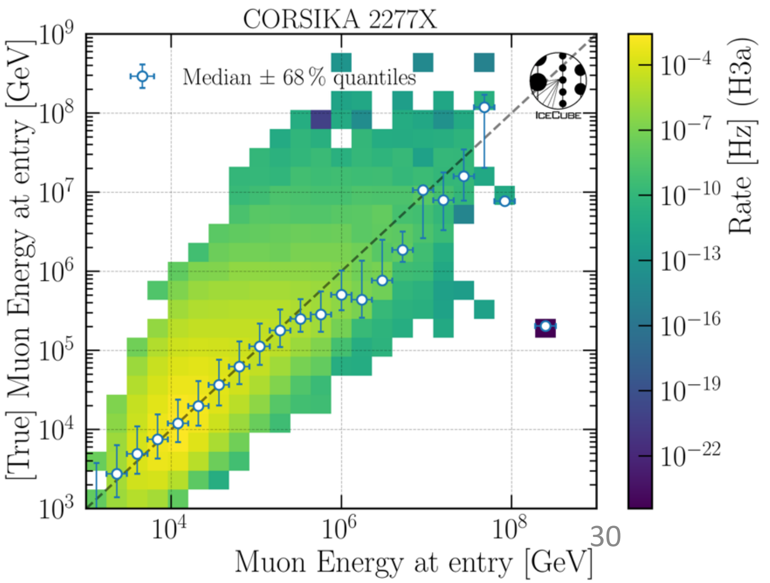
Geometry
- Propagation length
- Entry point

10.1088/1748-0221/16/07/P07041



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



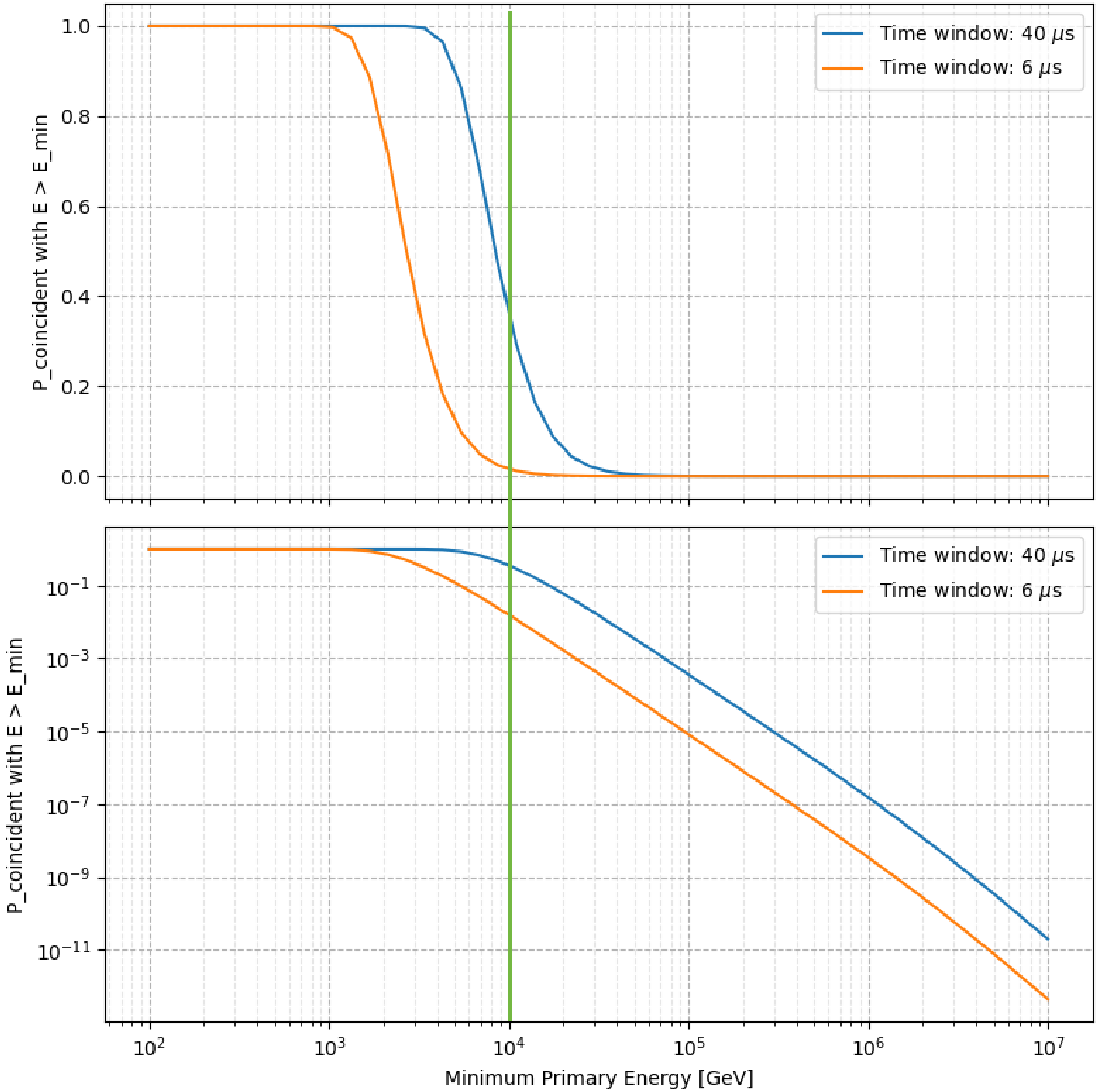


pascal.gutjahr@tu-dortmund.de

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 %

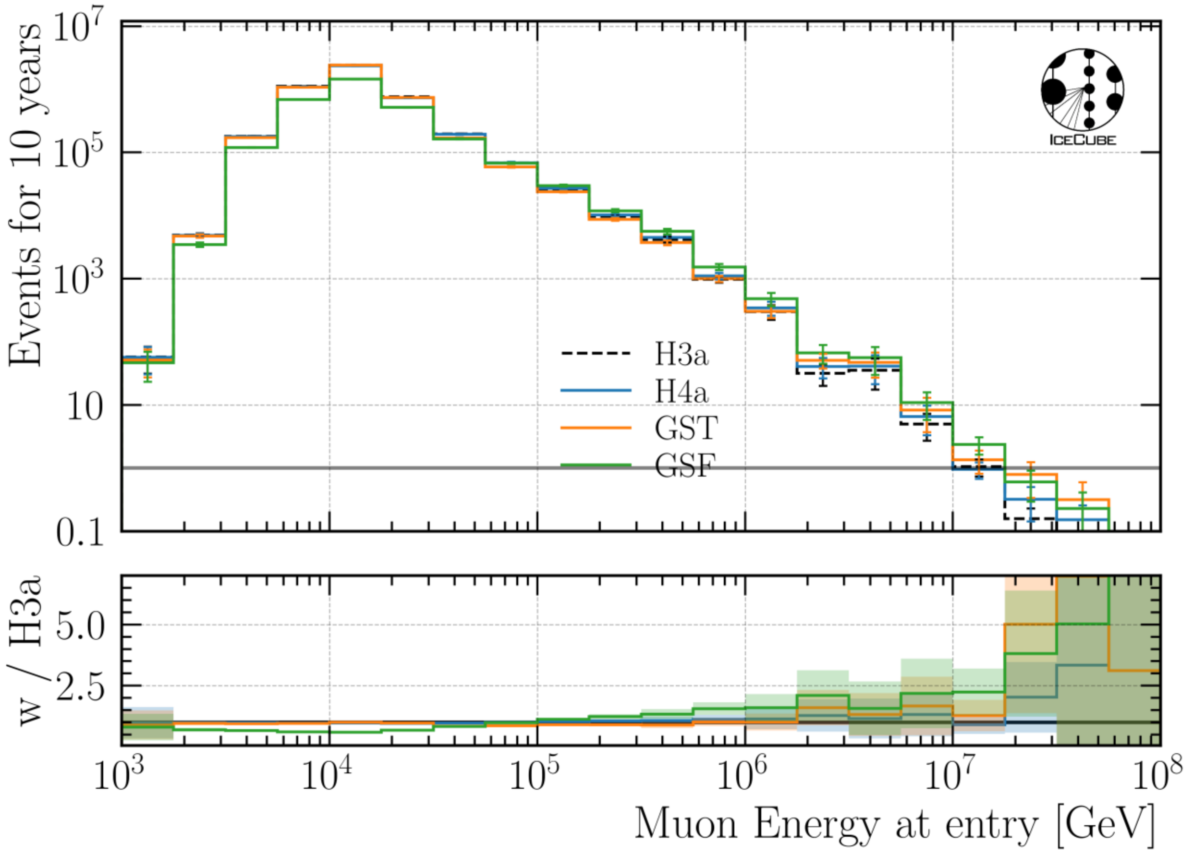
➢ Apply time-window cleaning of 6 µs to pulses

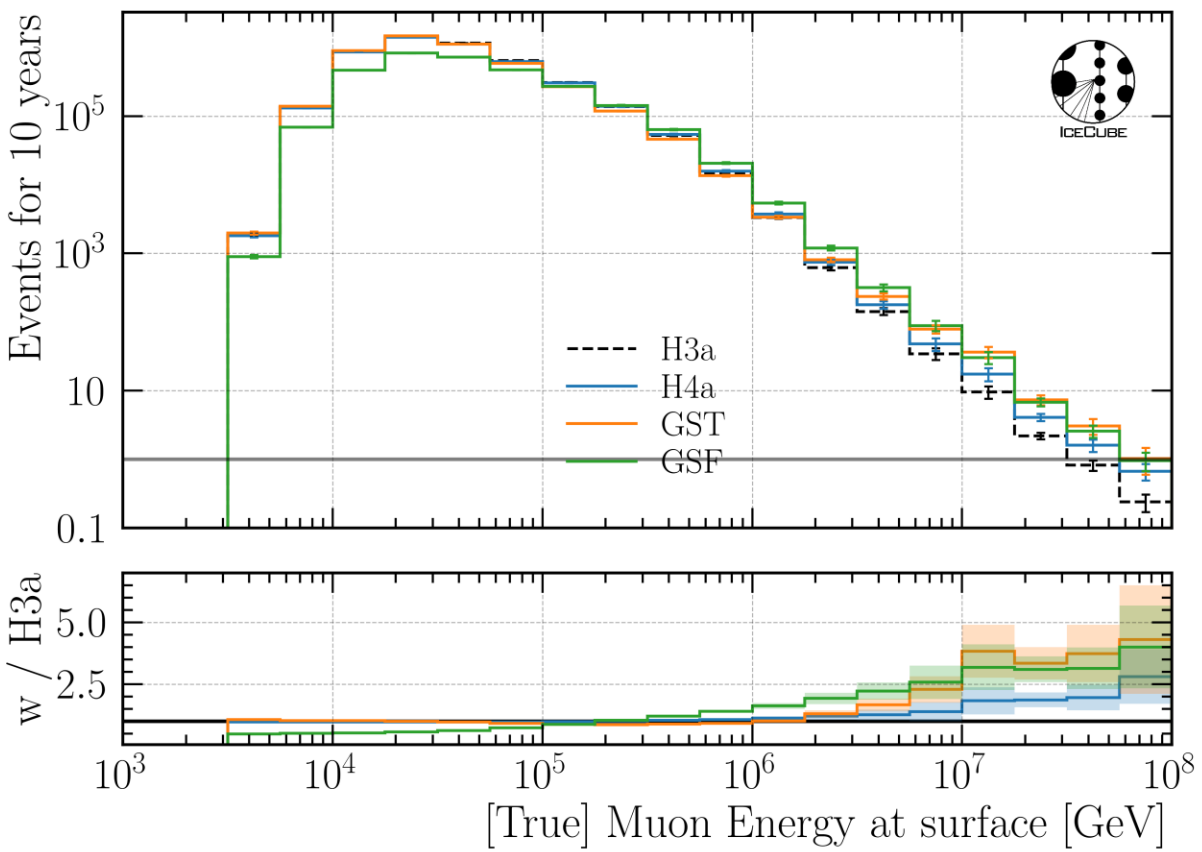


Linear scale

Log scale

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

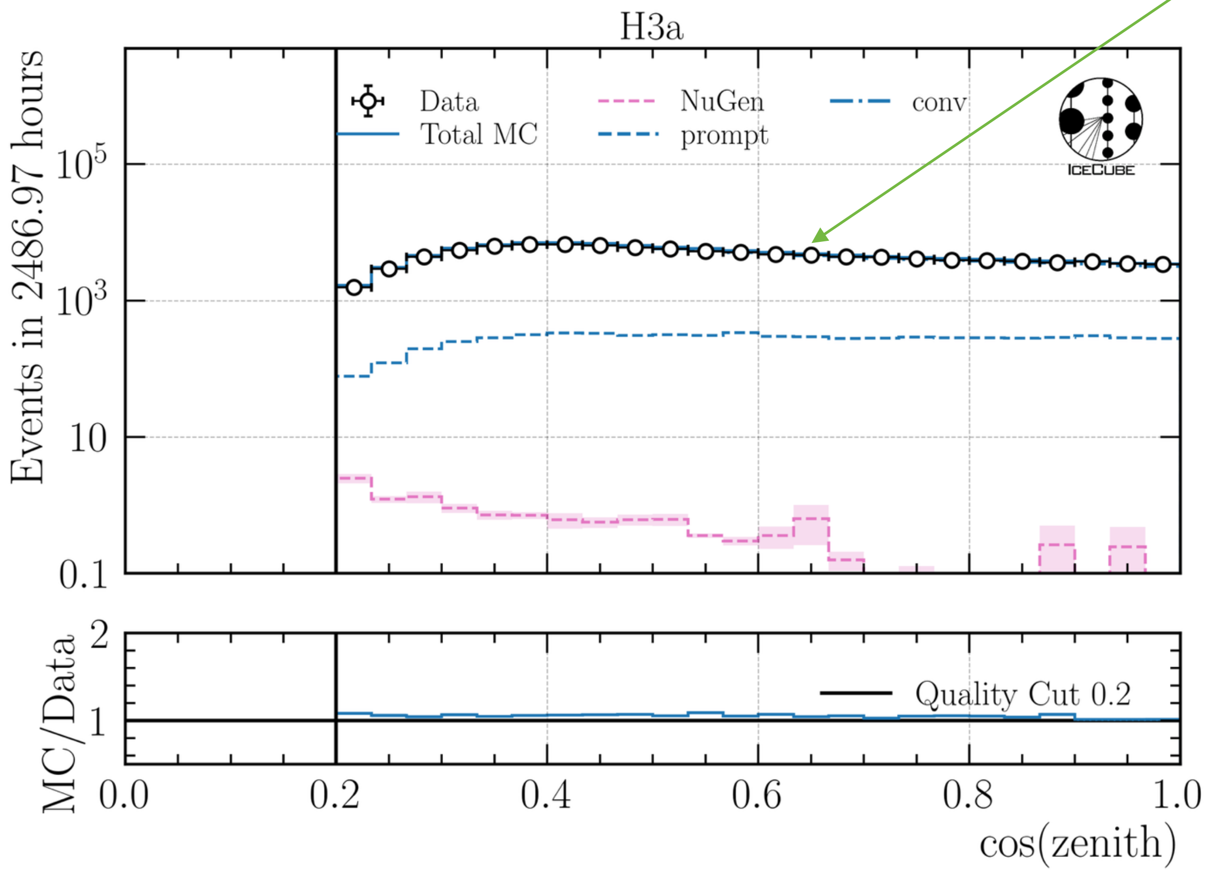


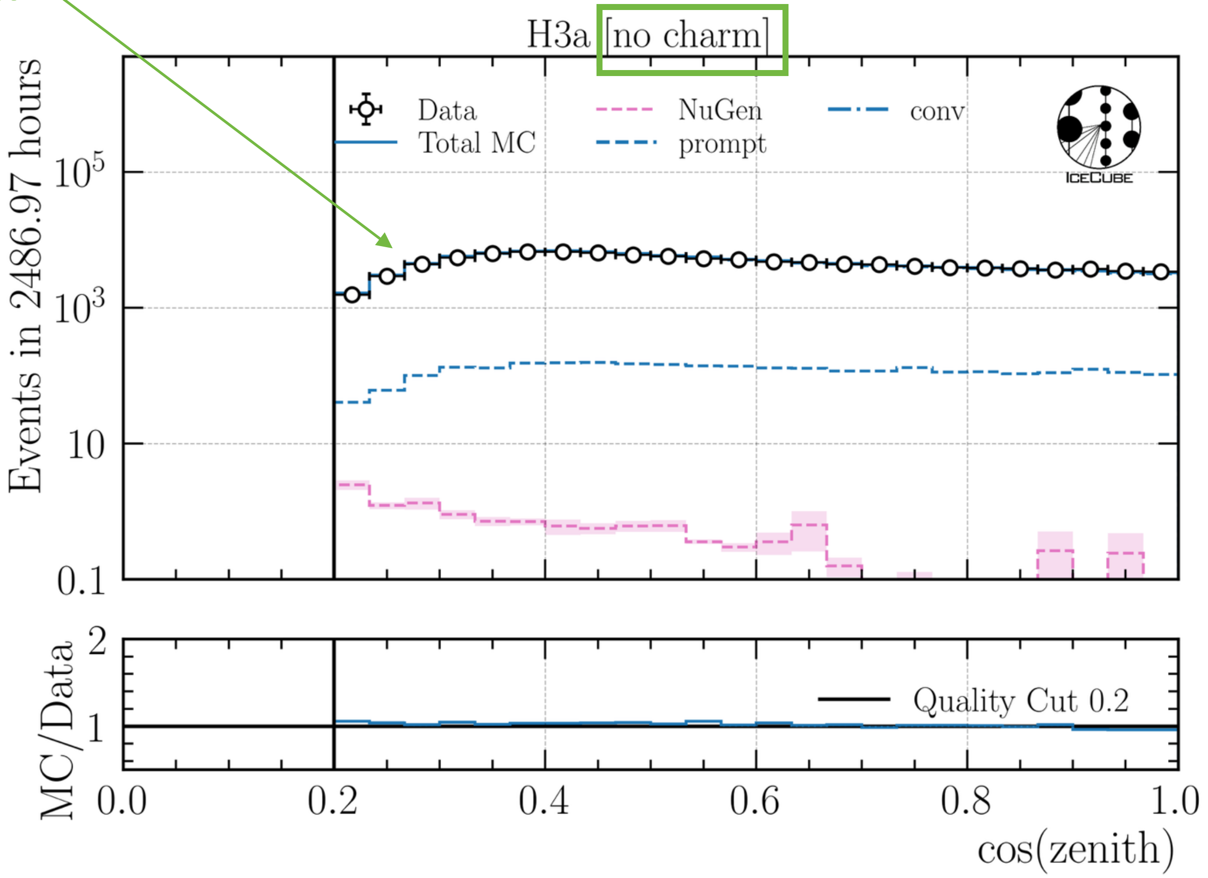


- Primary models diverge towards higher energies

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

conv





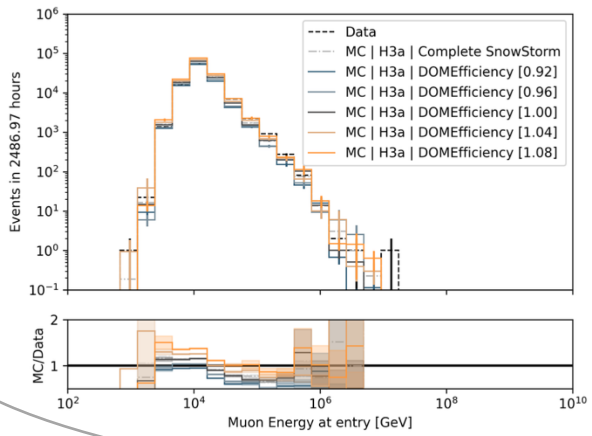
- Conv dominates entire distribution by 1-2 orders of magnitude
- Charm has no impact

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

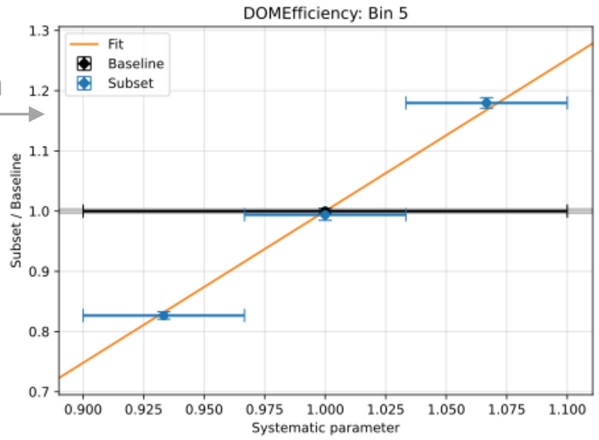
Ice systematics – Snowstorm

- Vary ice properties
- Relative change of bin content

impact on proxy



parameterization



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

➢ 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)

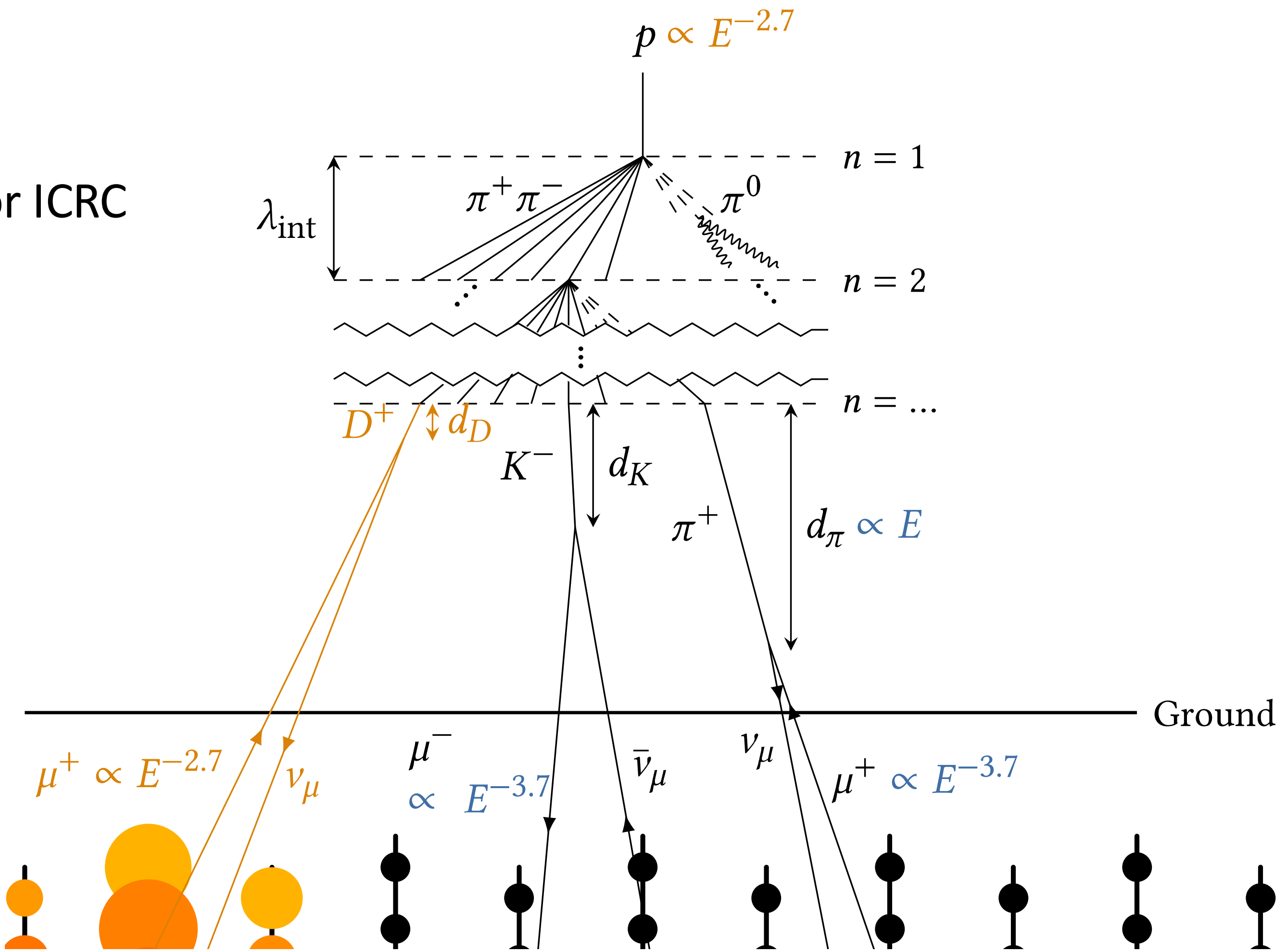
Conclusion & Outlook

- 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

detector response

background

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

true energy distribution

1. discretized form: $\underbrace{\vec{g} = A\vec{f}}_{\text{folding}} \leftrightarrow \underbrace{\vec{f} = A^{-1}\vec{g}}_{\text{unfolding}}$

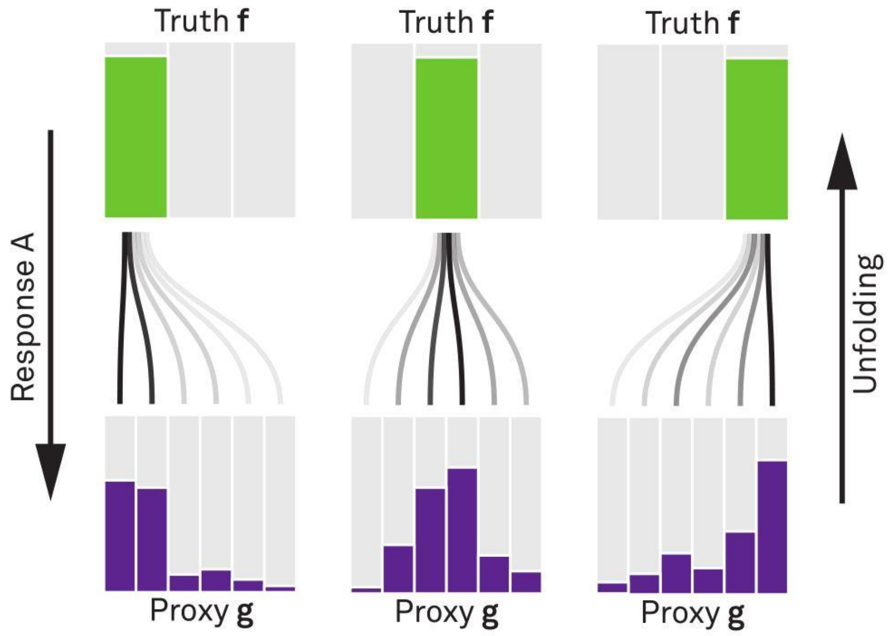
2. maximum likelihod method:

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

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

3. Thikonov regularization:

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

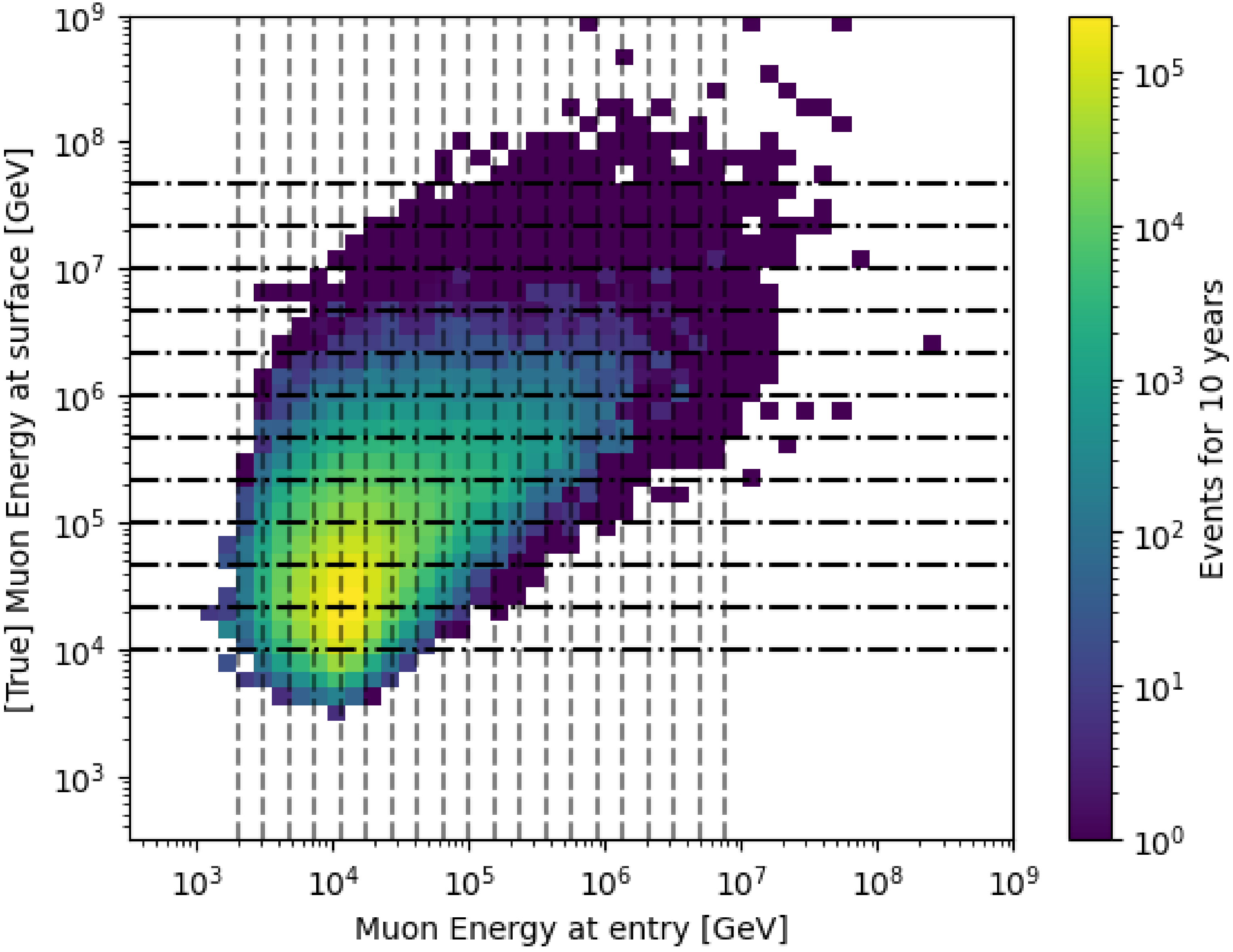


Credit: T. Hoinka

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

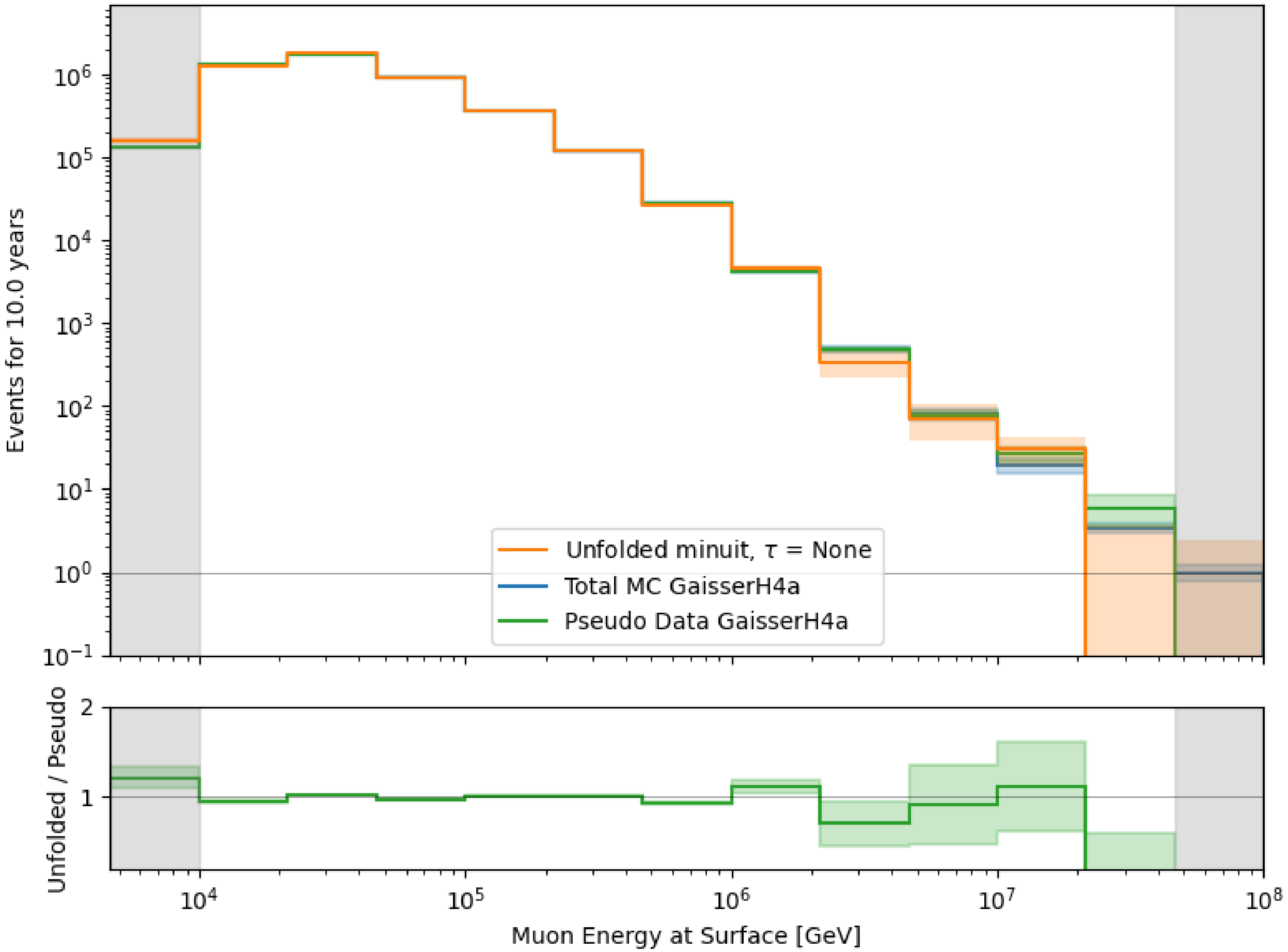
GitHub **funfolding** by M. Börner

Proxy vs Target



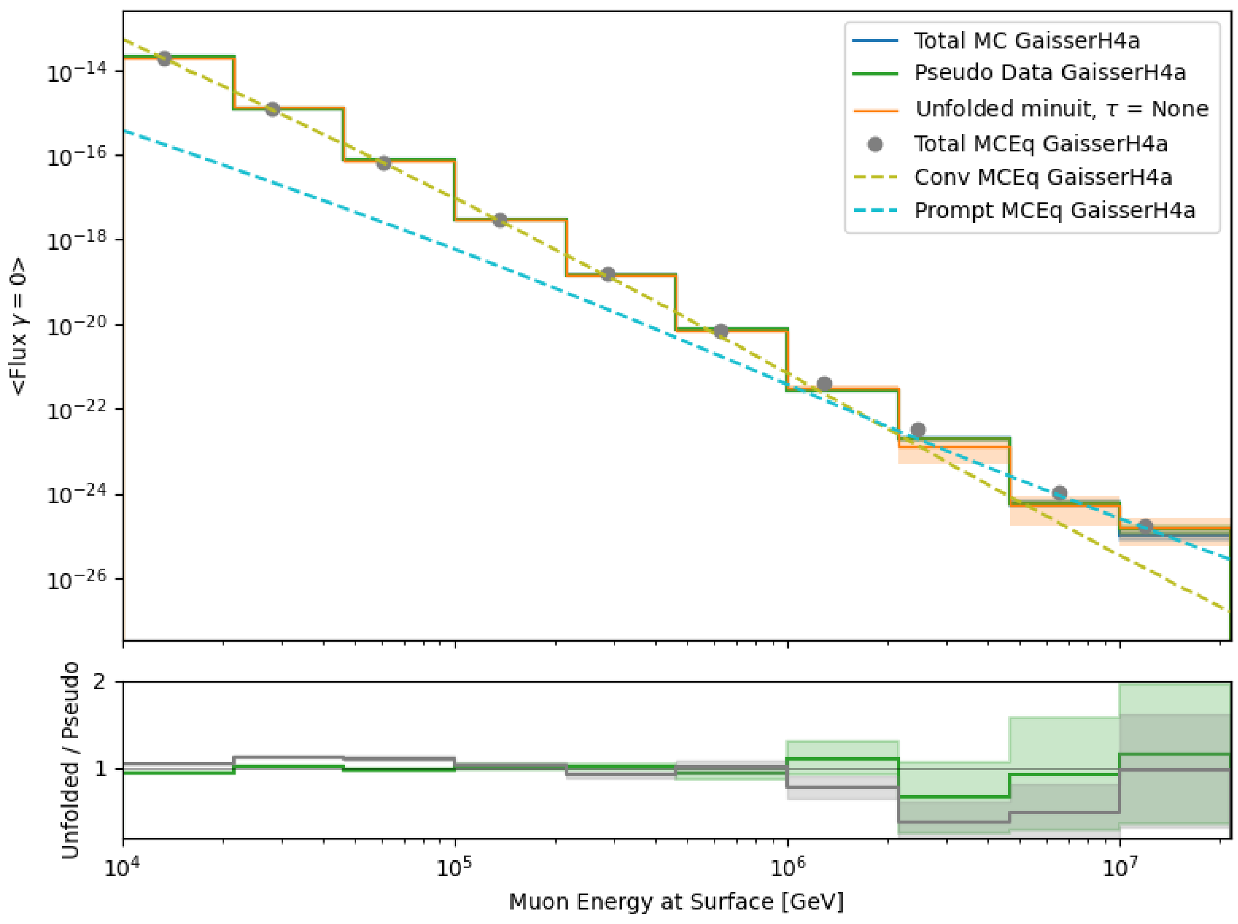
Unfold Event Rate

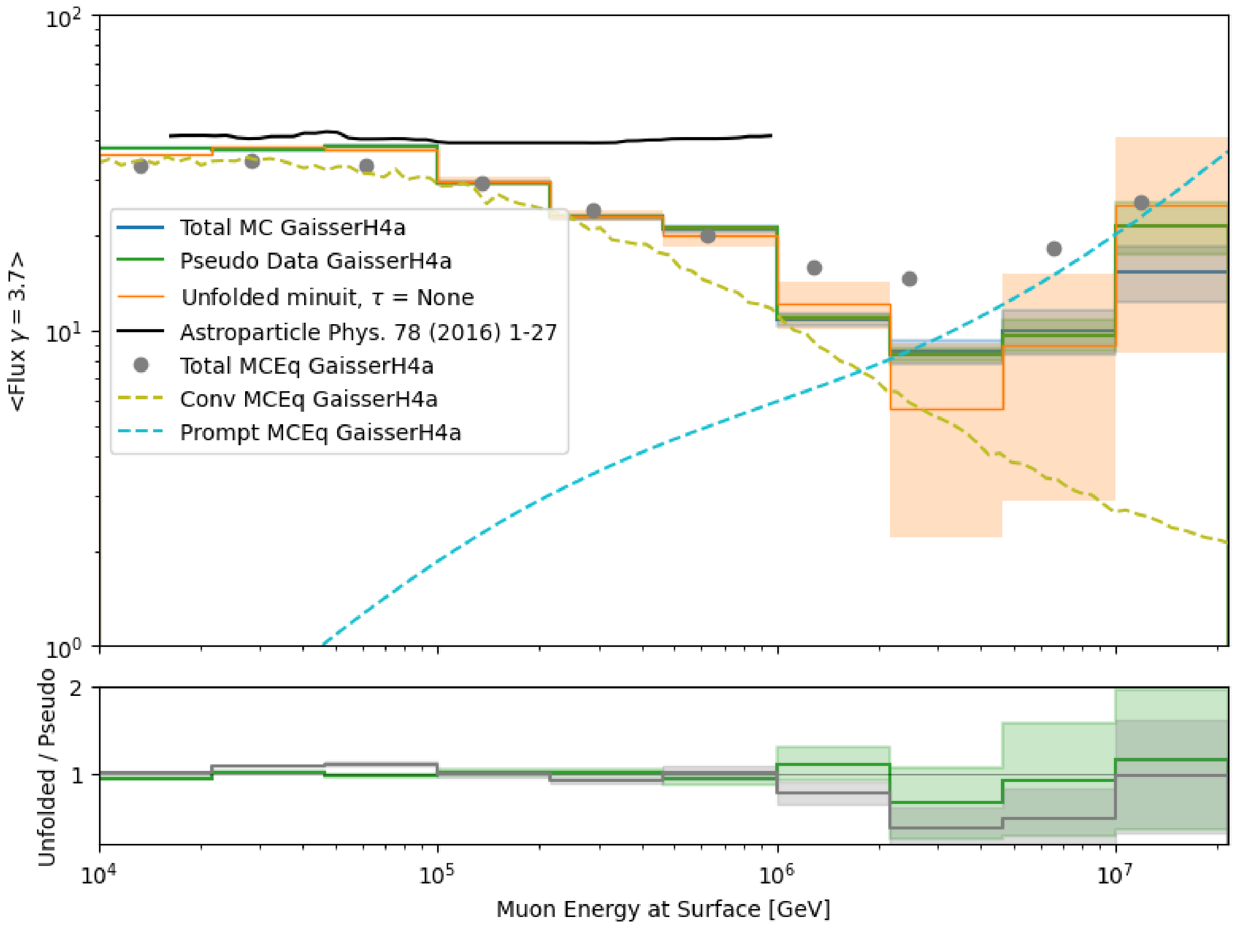
Event Rate


Events for 10.0 years
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
Unfolded minuit, τ = None
Total MC GaisserH4a
Pseudo Data GaisserH4a
Unfolded / Pseudo
2
1
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
Muon Energy at Surface [GeV]

Unfold Muon Flux

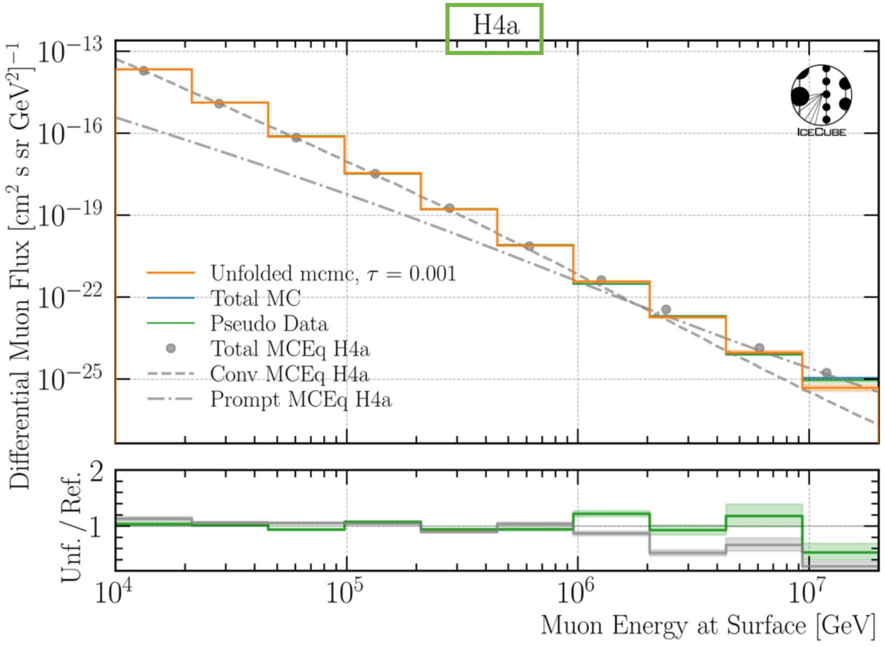
Muon Flux at Surface

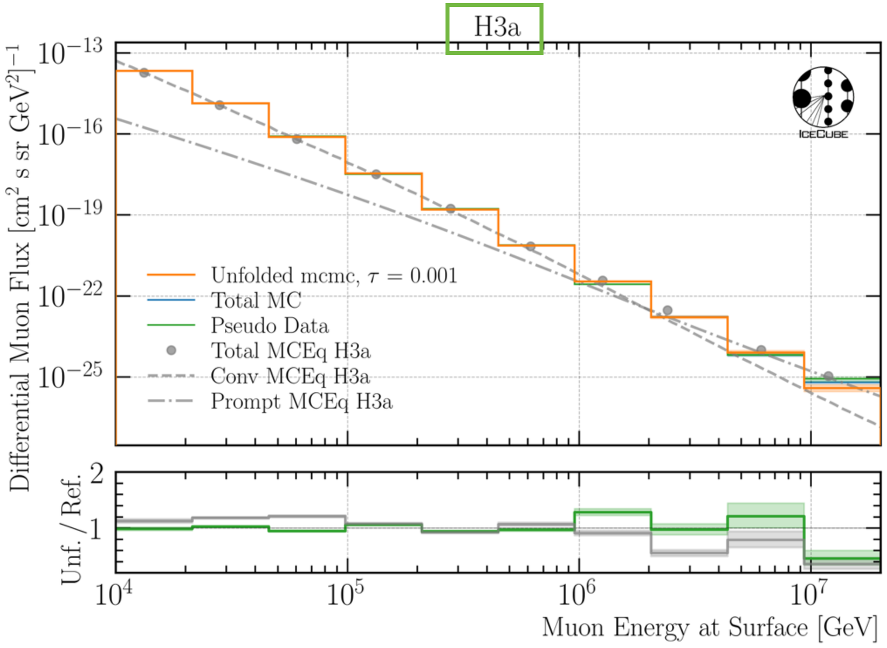


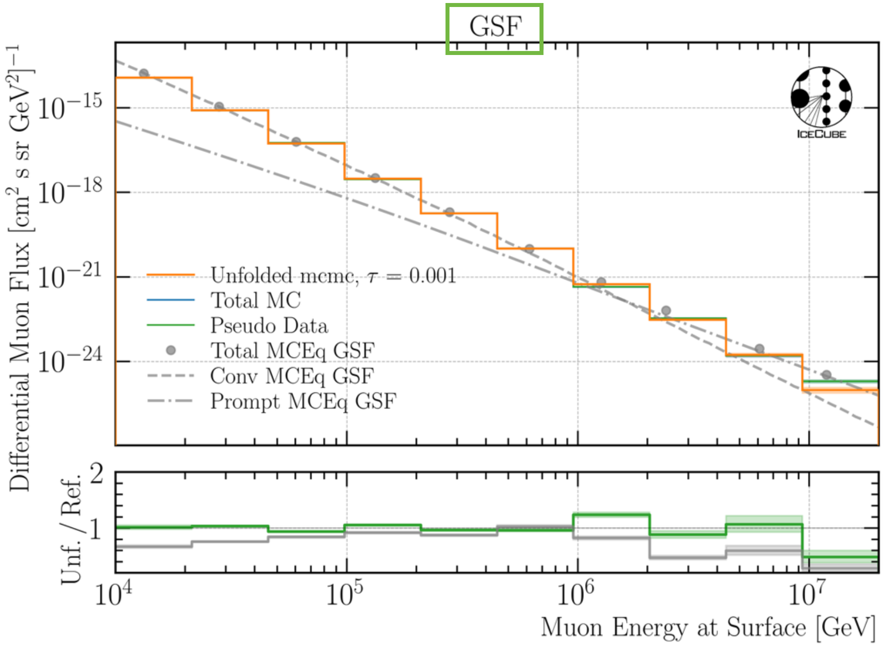


Check impact of primary input model

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







- grey ratio to MCEq depends on the expectation value per bin, here this is calculated based on H4a

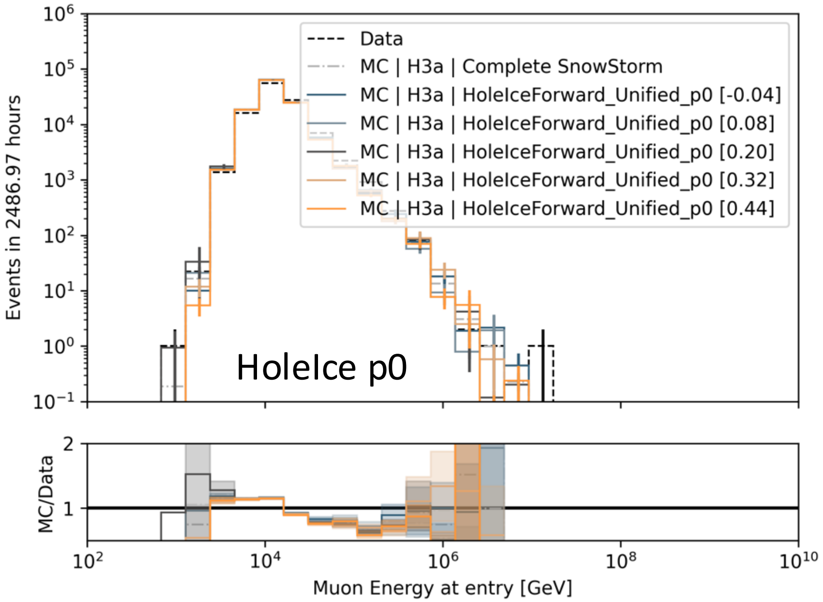
→ this leads to minor deviations for H3a and GSF

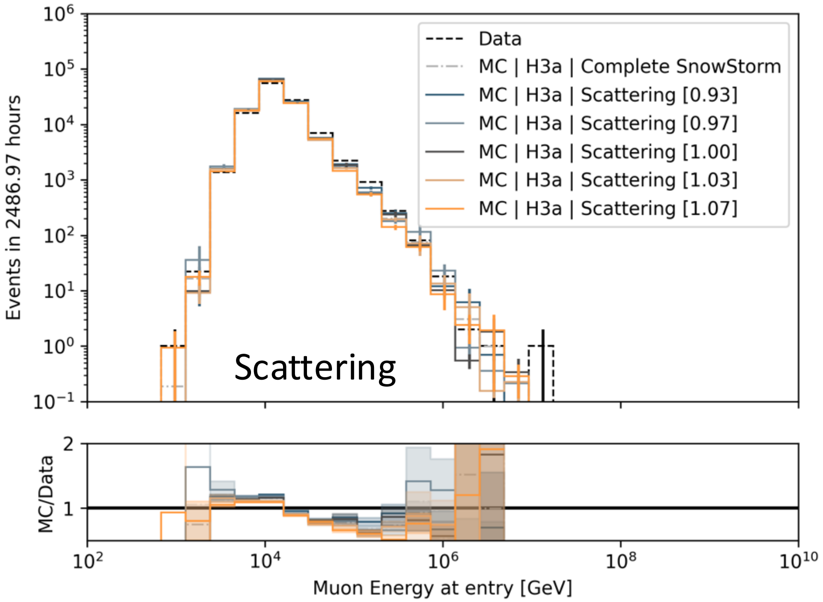
Ice Systematics

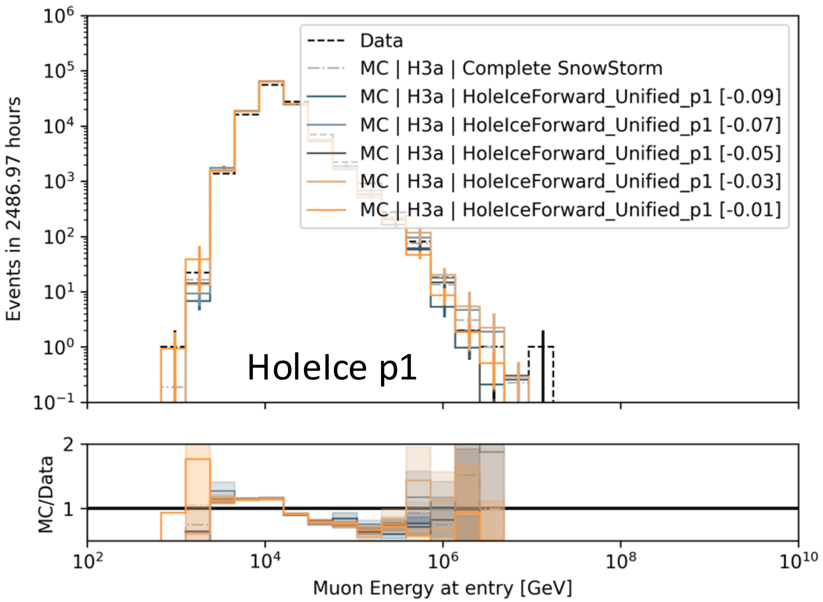
Snowstorm

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

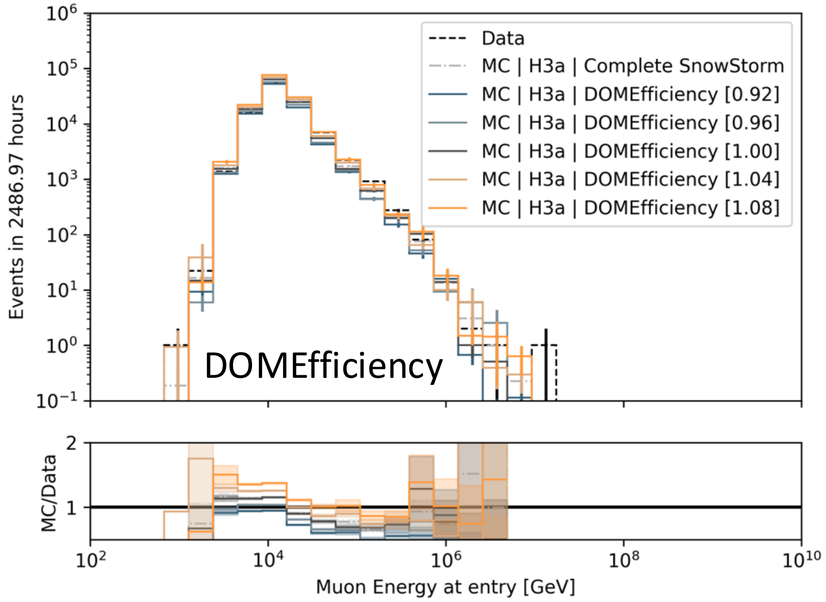
Systematics Impact on Muon Energy at Entry (Proxy)

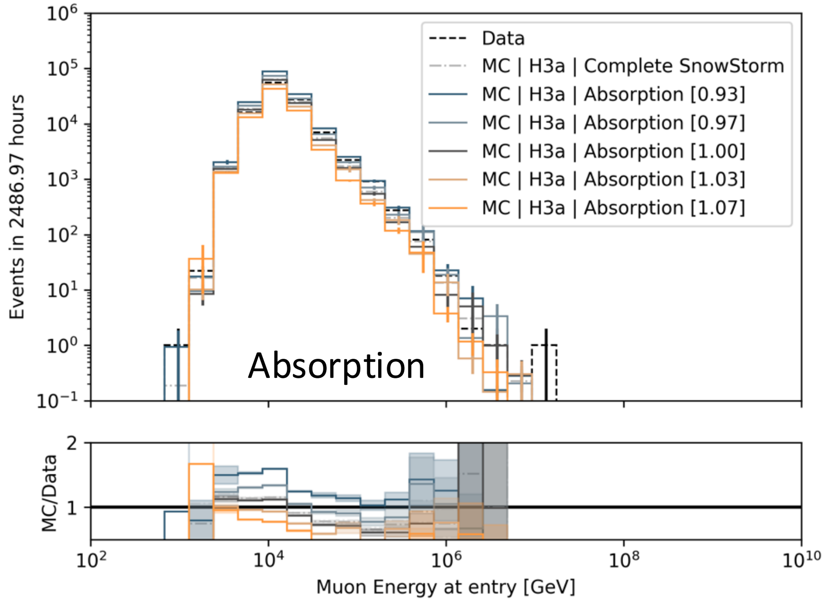




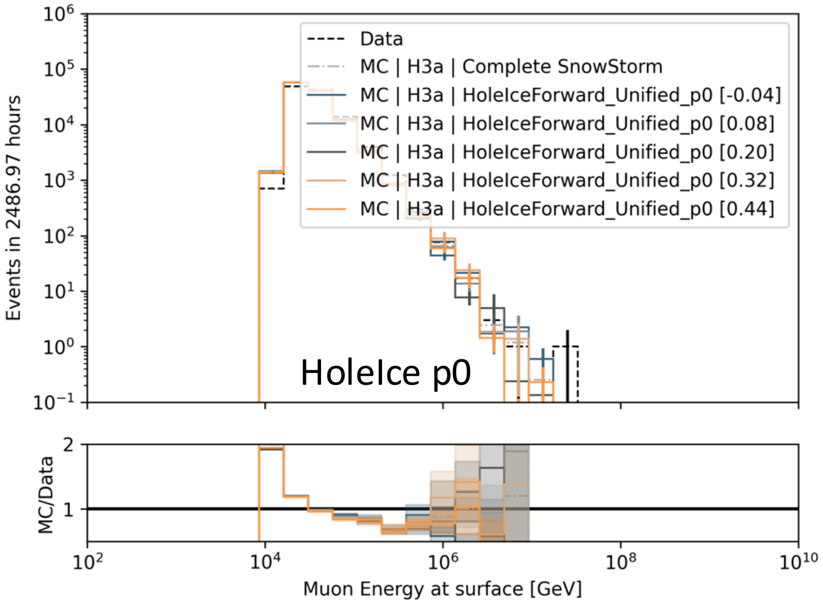


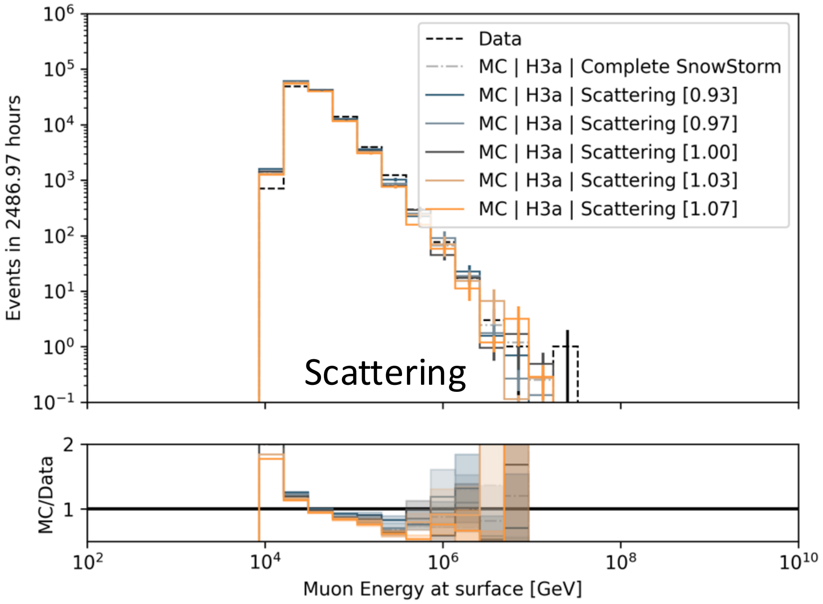
- Divide systematic range into 5 equidistant bins
- Largest impact by DOMEfficiency and Absorption

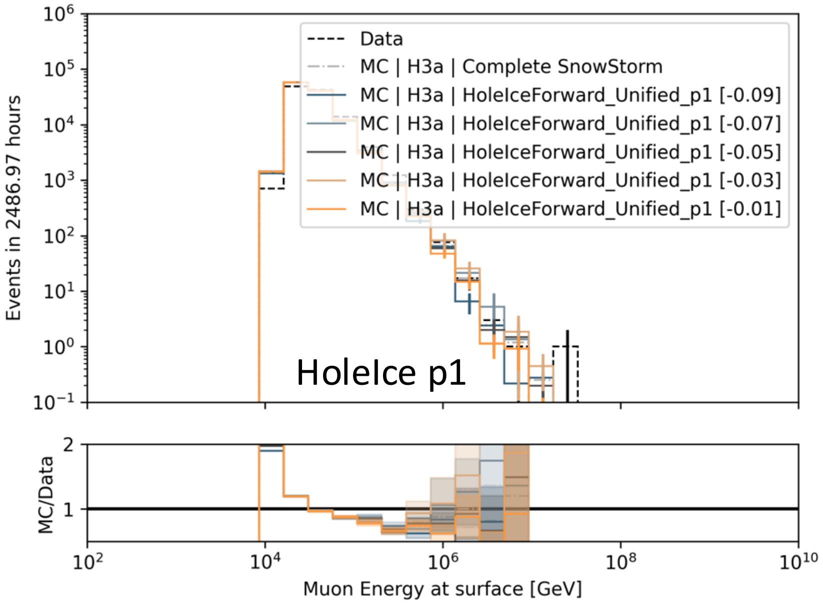




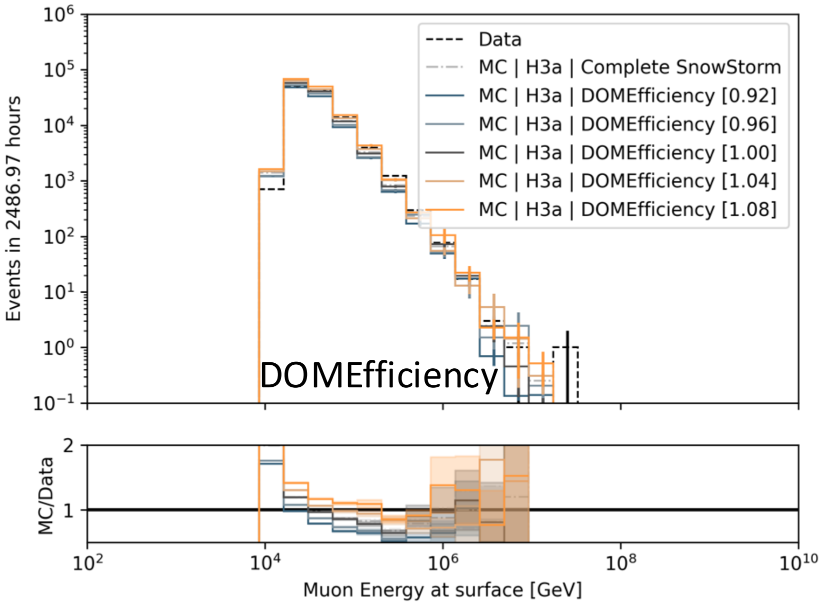
Systematics Impact on Muon Energy at Surface (Target)

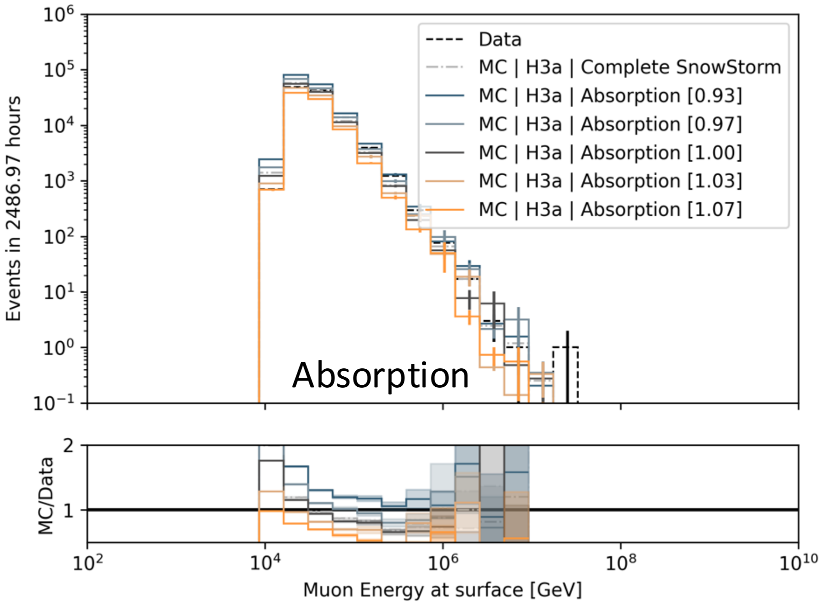




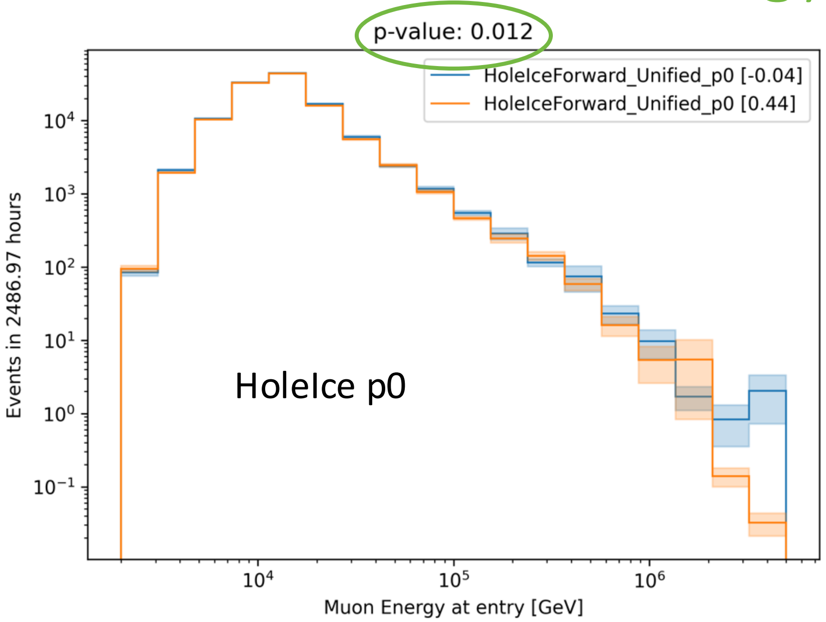


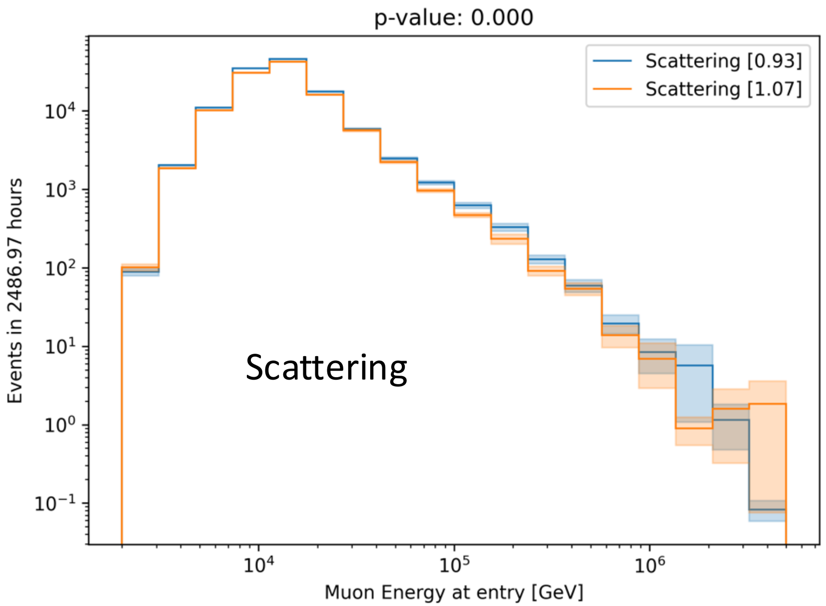
- Divide systematic range into 5 equidistant bins
- Largest impact by DOMEfficiency and Absorption

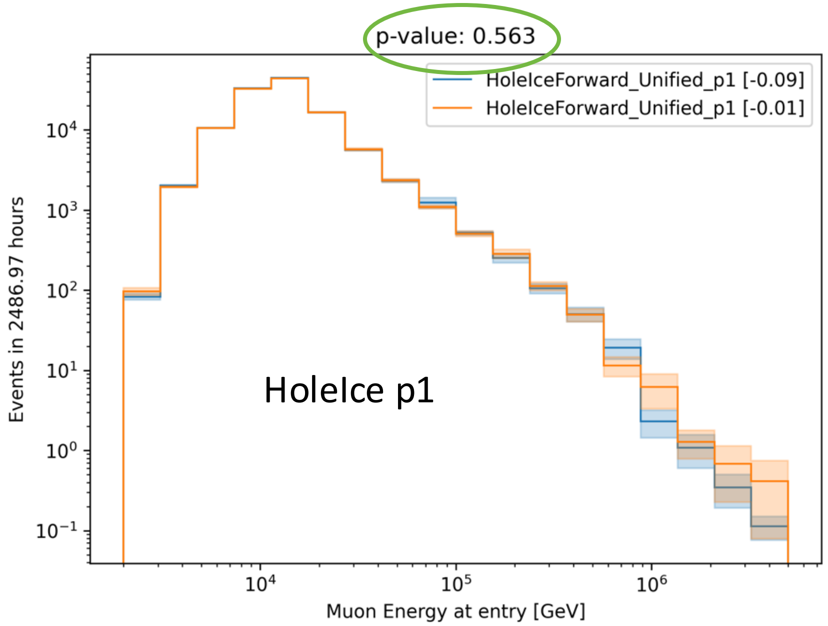




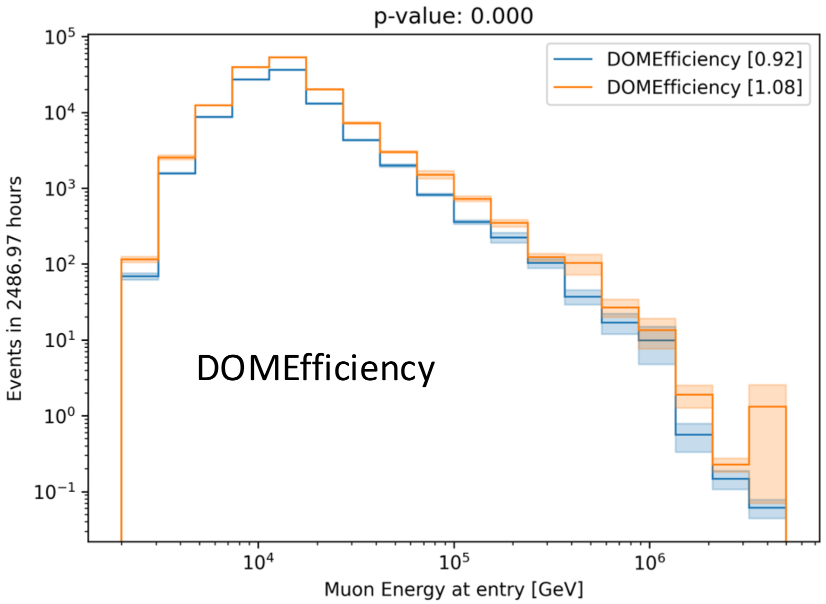
Chi2 Test: Muon Energy at Entry (Proxy)

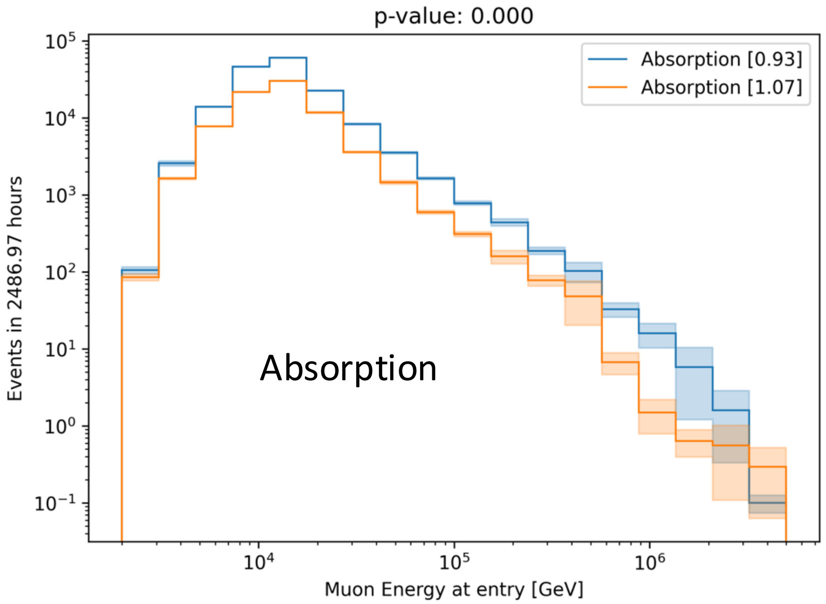






- Chi2 test between lower and upper systematic range bin
- No impact from Hole Ice p1
- Small impact from Scattering and Hole Ice p0





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-value = 0.05)
2. Find linear fit with the lowest slope that is compatible with p-value = 0.2
    1. Require fit is going through (center, 1)

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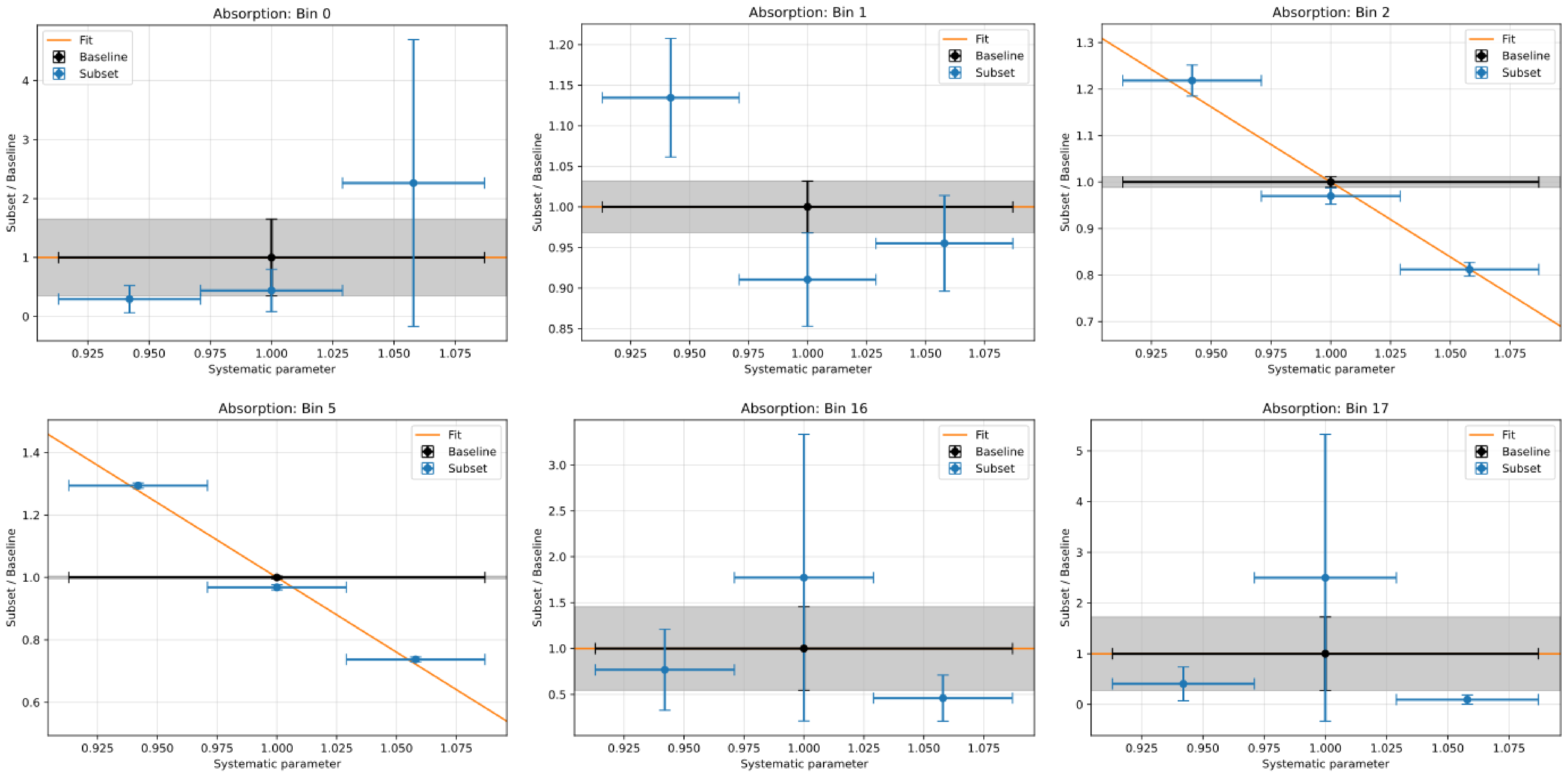
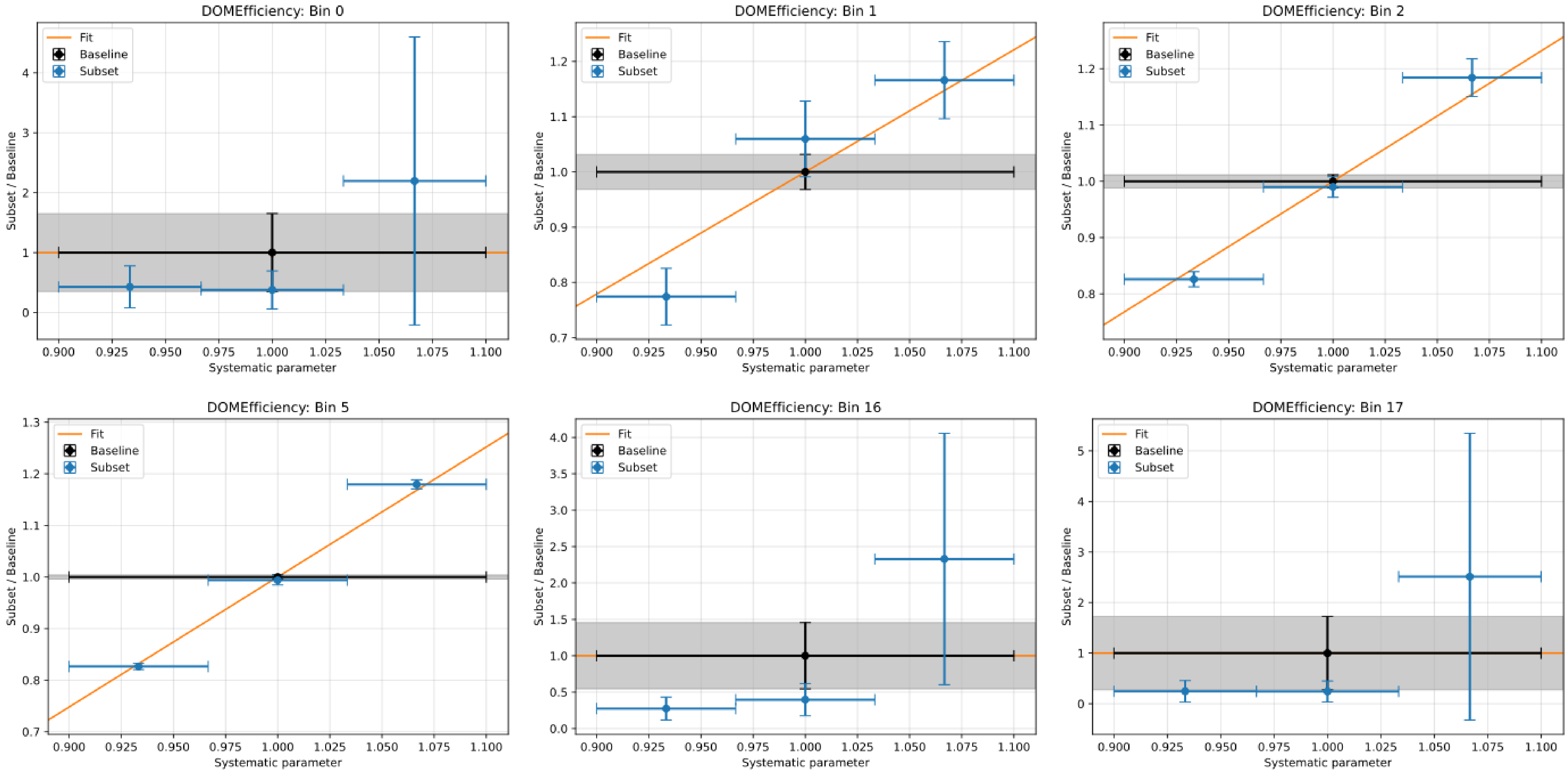
Absorption

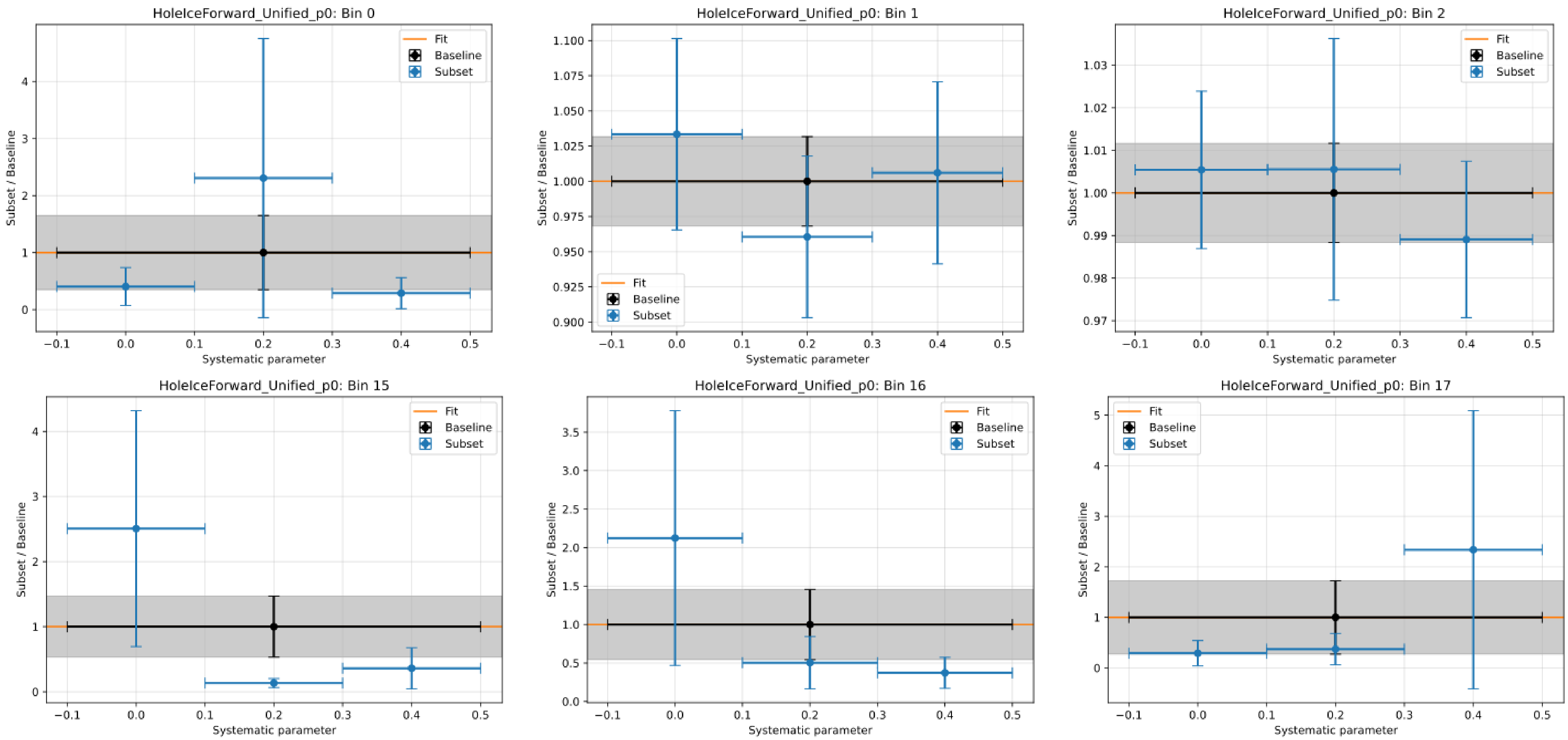


DOMEfficiency

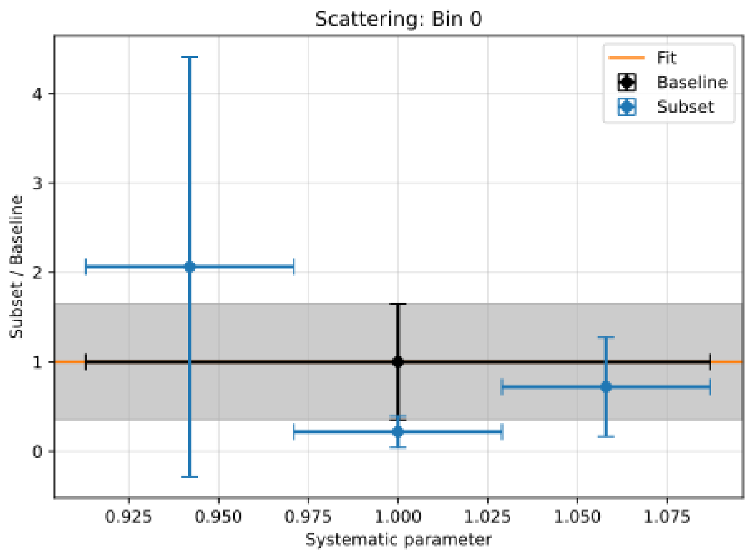


pascal.gutjahr@tu-dortmund.de

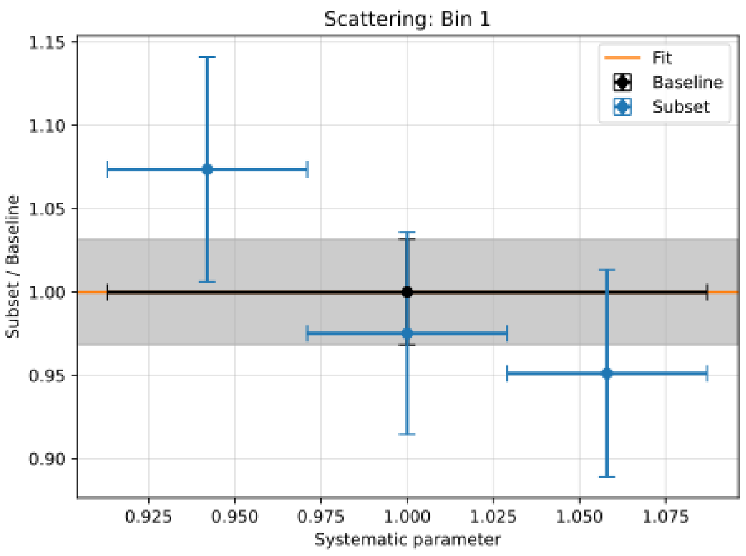
Hole Ice p0 → not sensitive enough (same for Hole Ice p1)



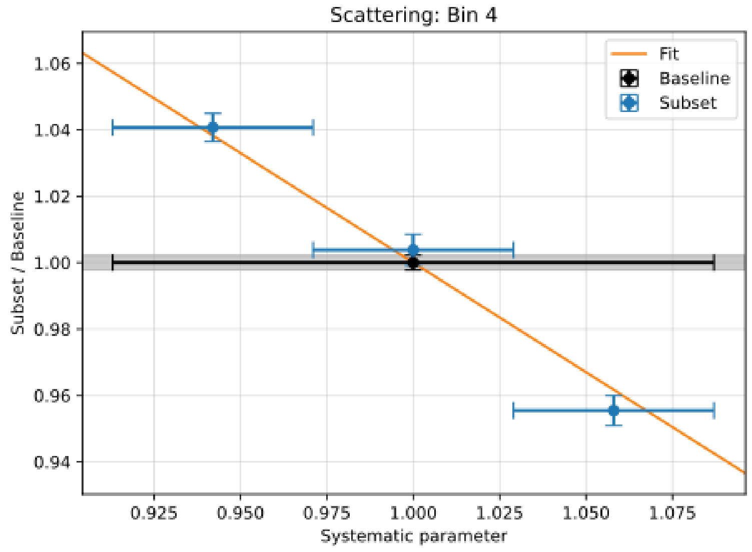
Scattering



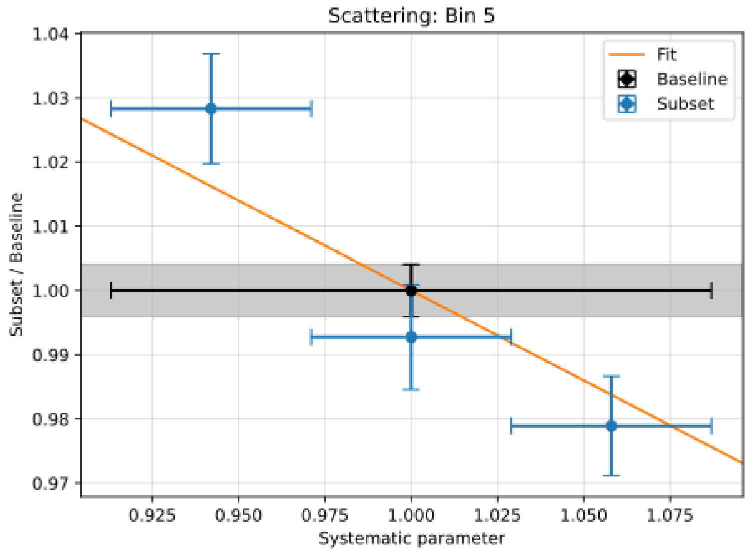
Scattering: Bin 0
Fit
Baseline
Subset
Subset / Baseline
Systematic parameter



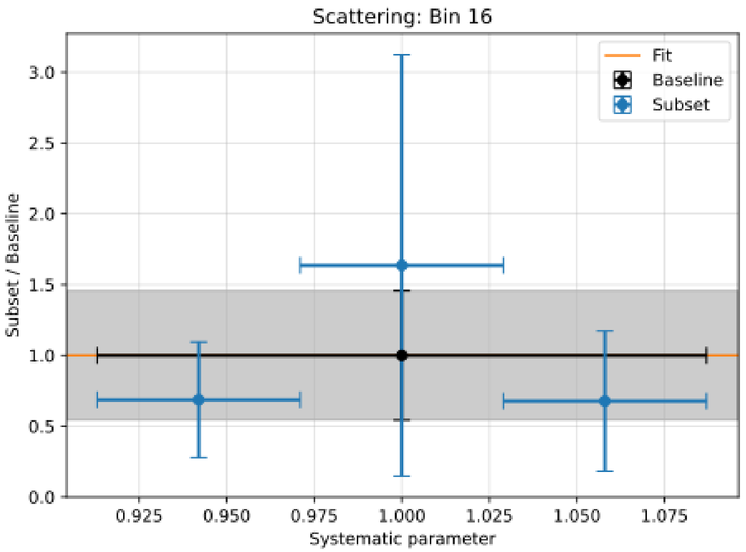
Scattering: Bin 1
Fit
Baseline
Subset
Subset / Baseline
Systematic parameter



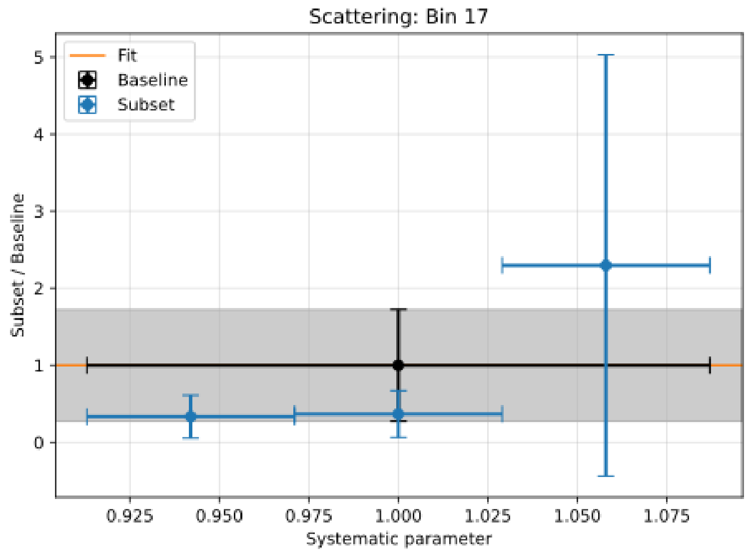
Scattering: Bin 4
Fit
Baseline
Subset
Subset / Baseline
Systematic parameter



Scattering: Bin 5
Fit
Baseline
Subset
Subset / Baseline
Systematic parameter



Scattering: Bin 16
Fit
Baseline
Subset
Subset / Baseline
Systematic parameter

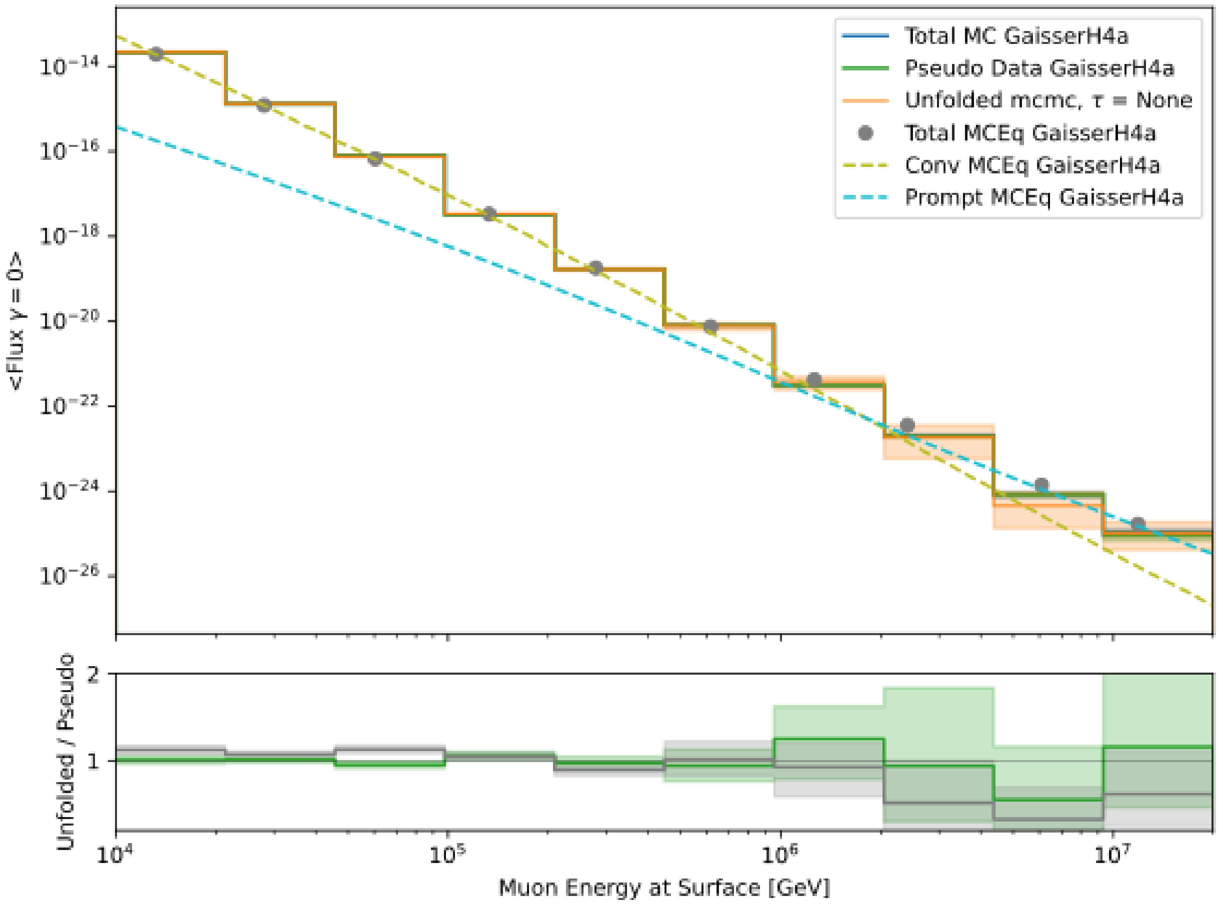


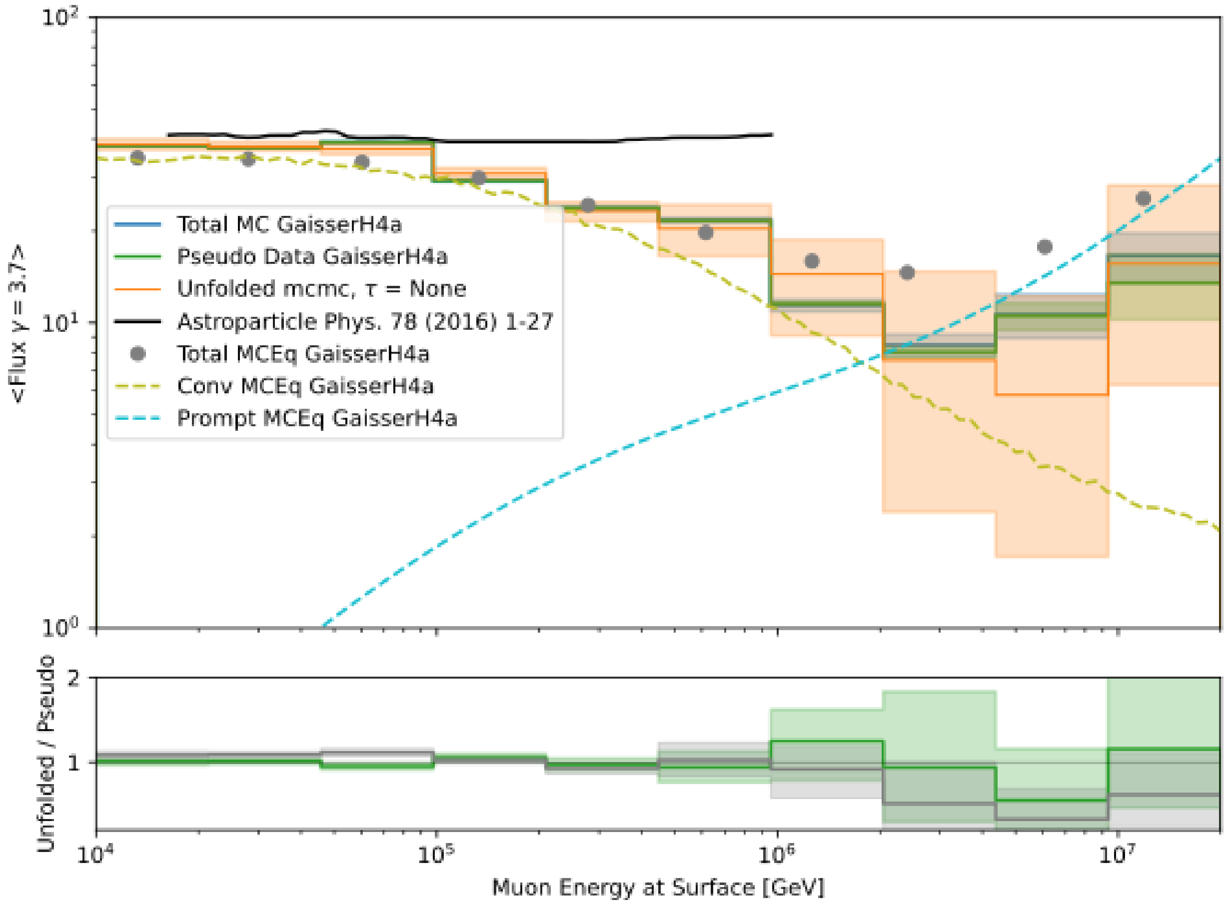
Scattering: Bin 17
Fit
Baseline
Subset
Subset / Baseline
Systematic parameter

Unfold Muon Flux with Systematics

No regularization

Muon Flux at Surface (no regularization)

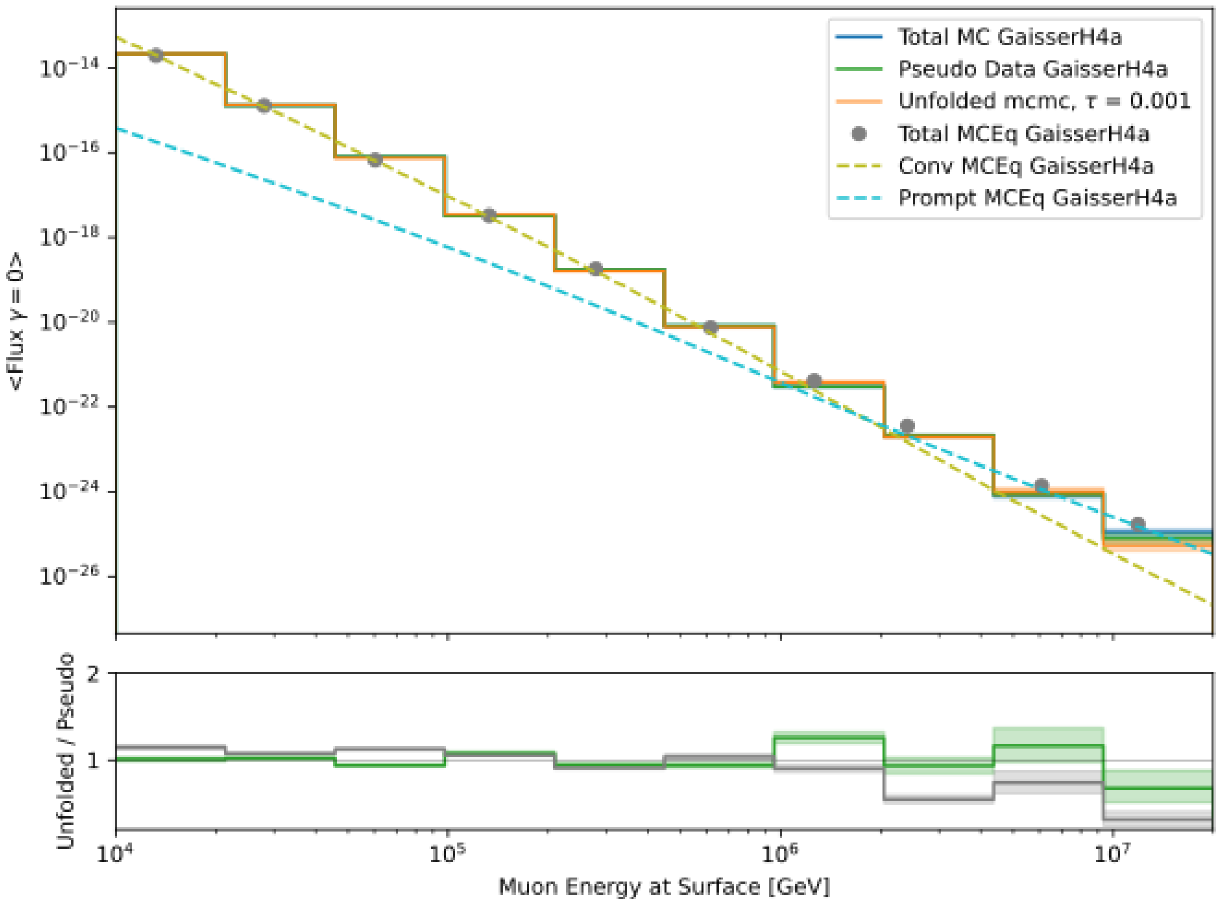


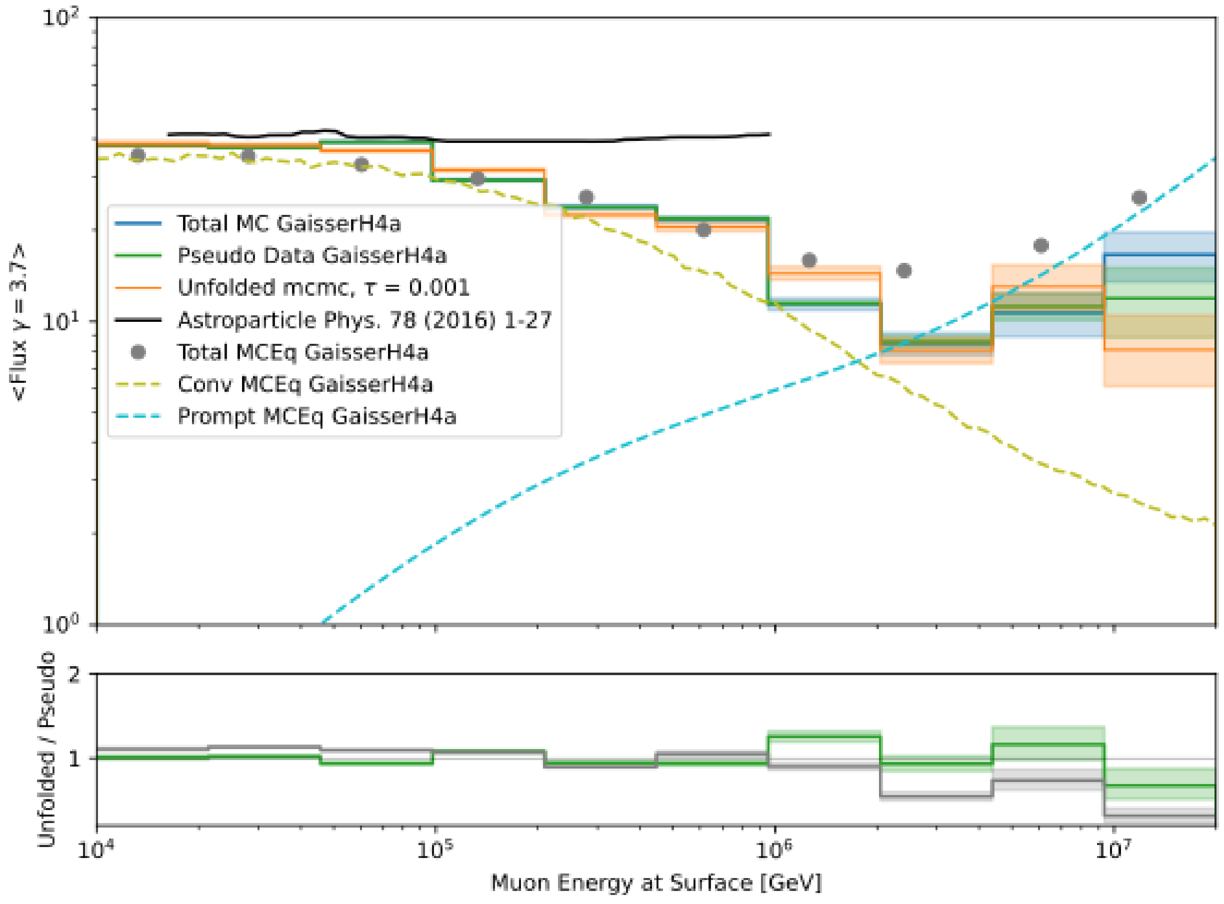


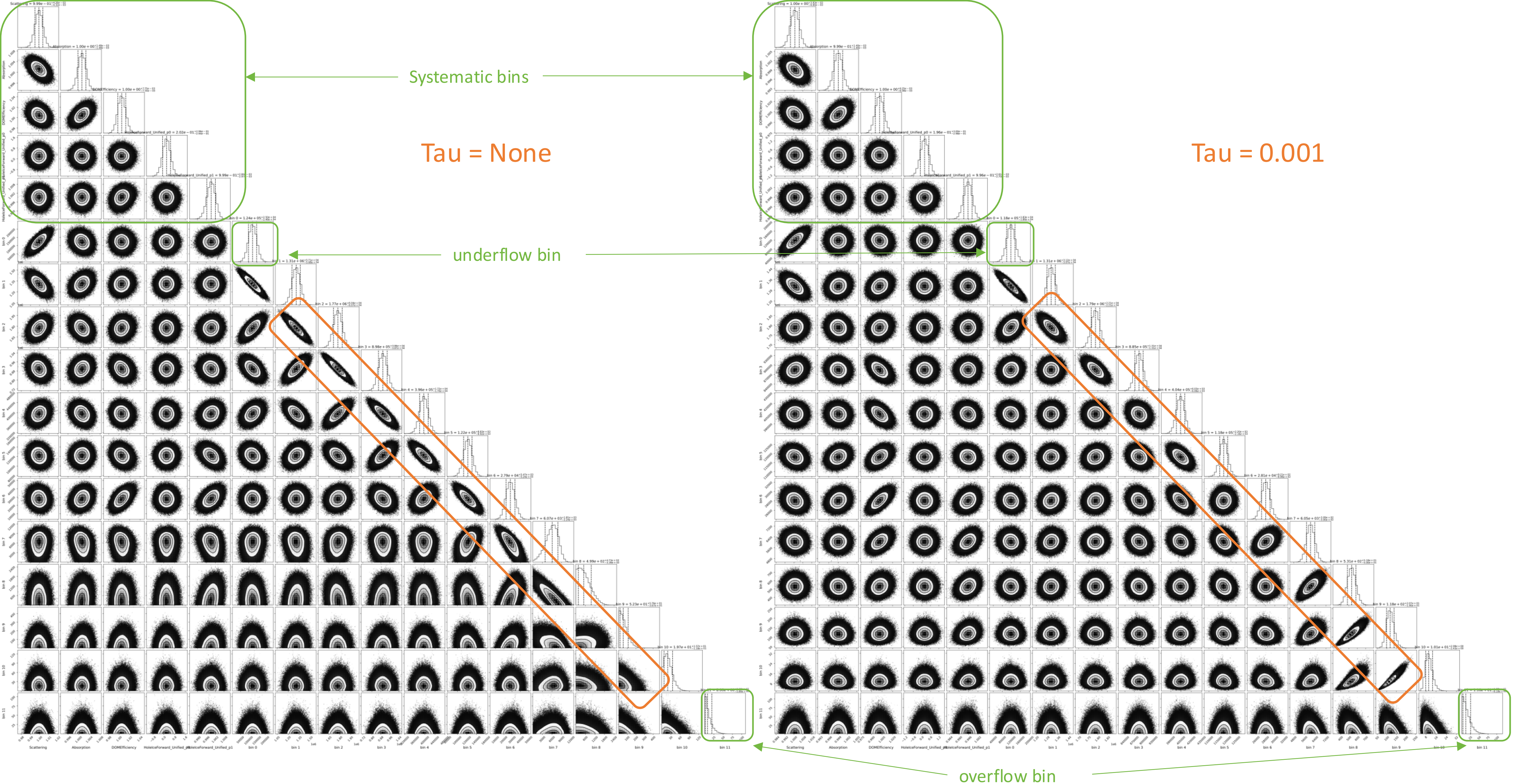
Unfold Muon Flux with Systematics

With regularization

Muon Flux at Surface (Tau = 0.001)







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

Conclusion

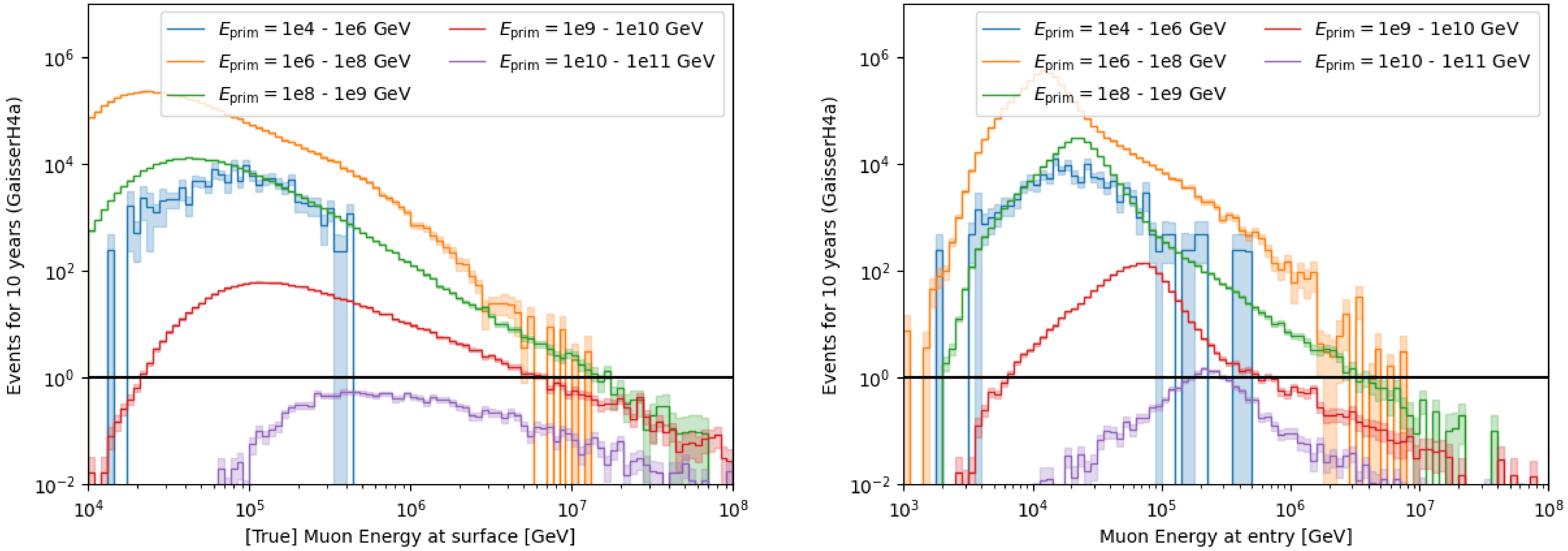
- Unfold muon event rate ✅
- Unfold muon flux at surface ✅
- Parameterize ice systematics ✅
  - Small impact from Scattering, Hole Ice p0 , and Hole Ice p1
  - Linear parameterization of Absorption and DOMEfficiency
- Unfold muon flux with systematics ✅

Next steps

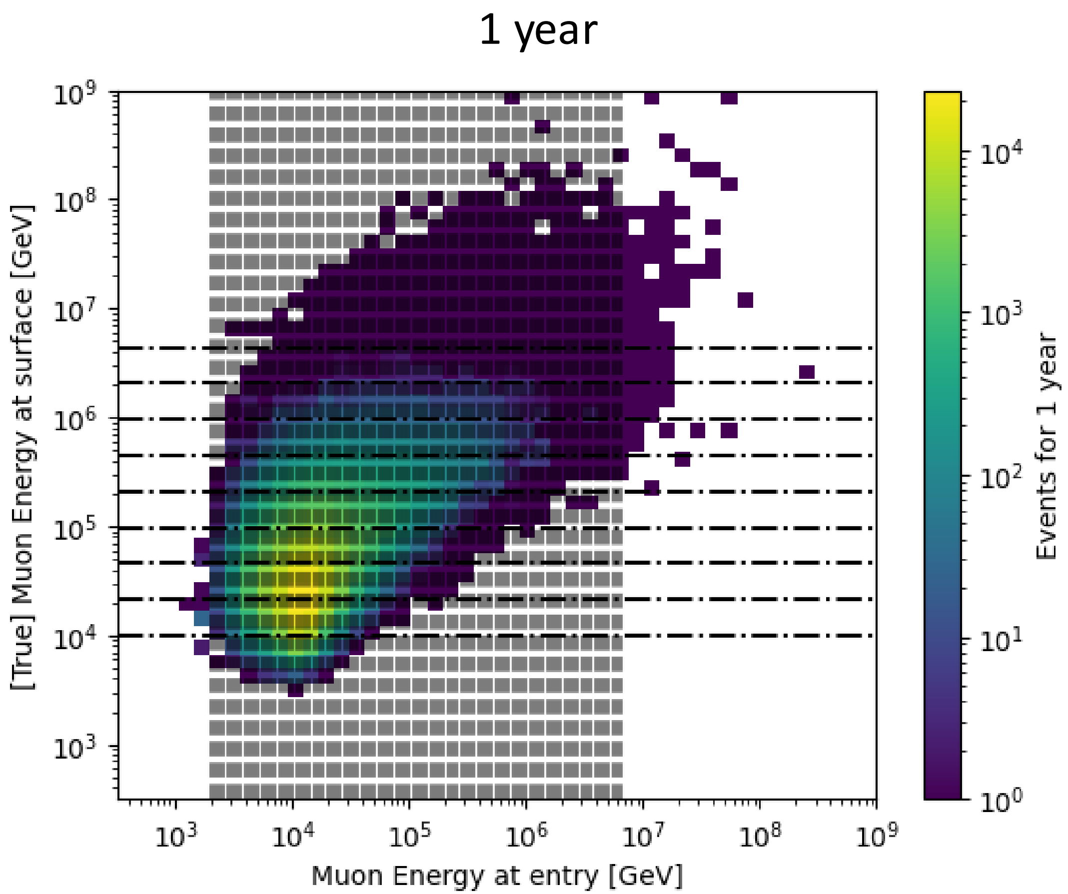
- Test impact of different primary models (spectral index)
- Choose optimal regularization

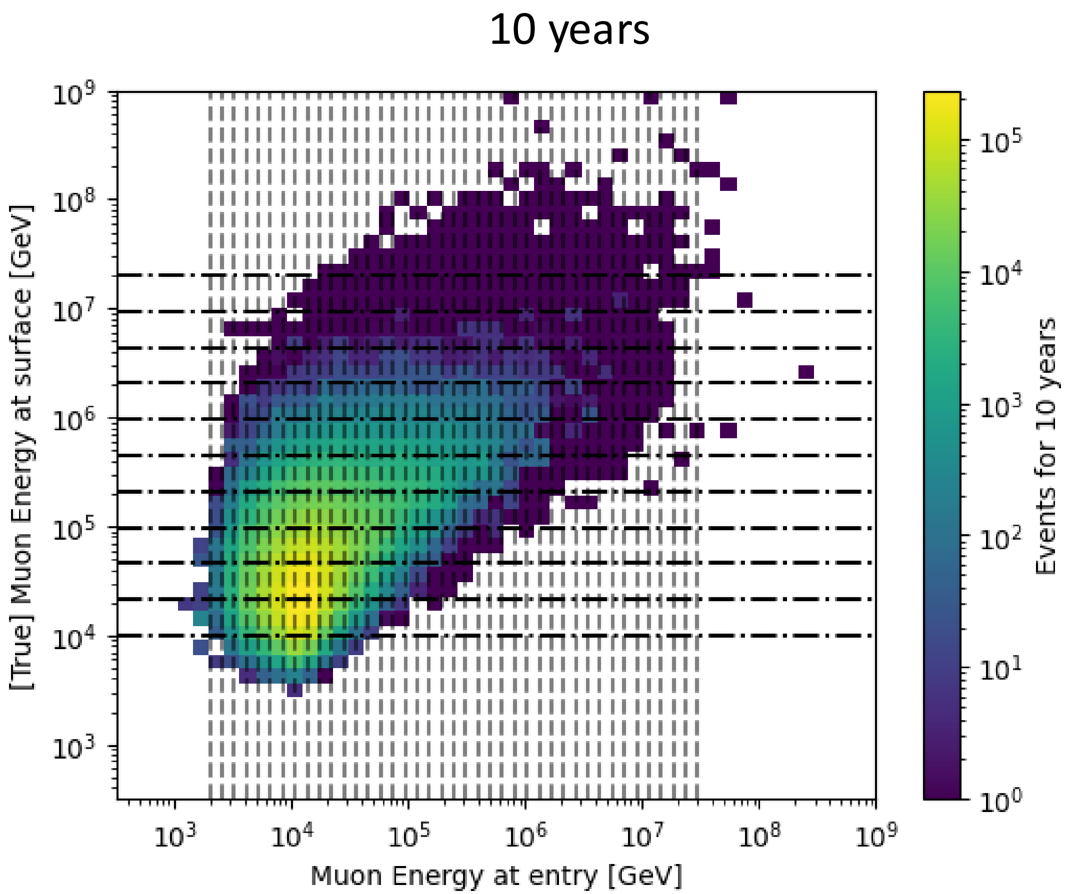
Backup

Relation between primary energy and muon energy at surface and entry



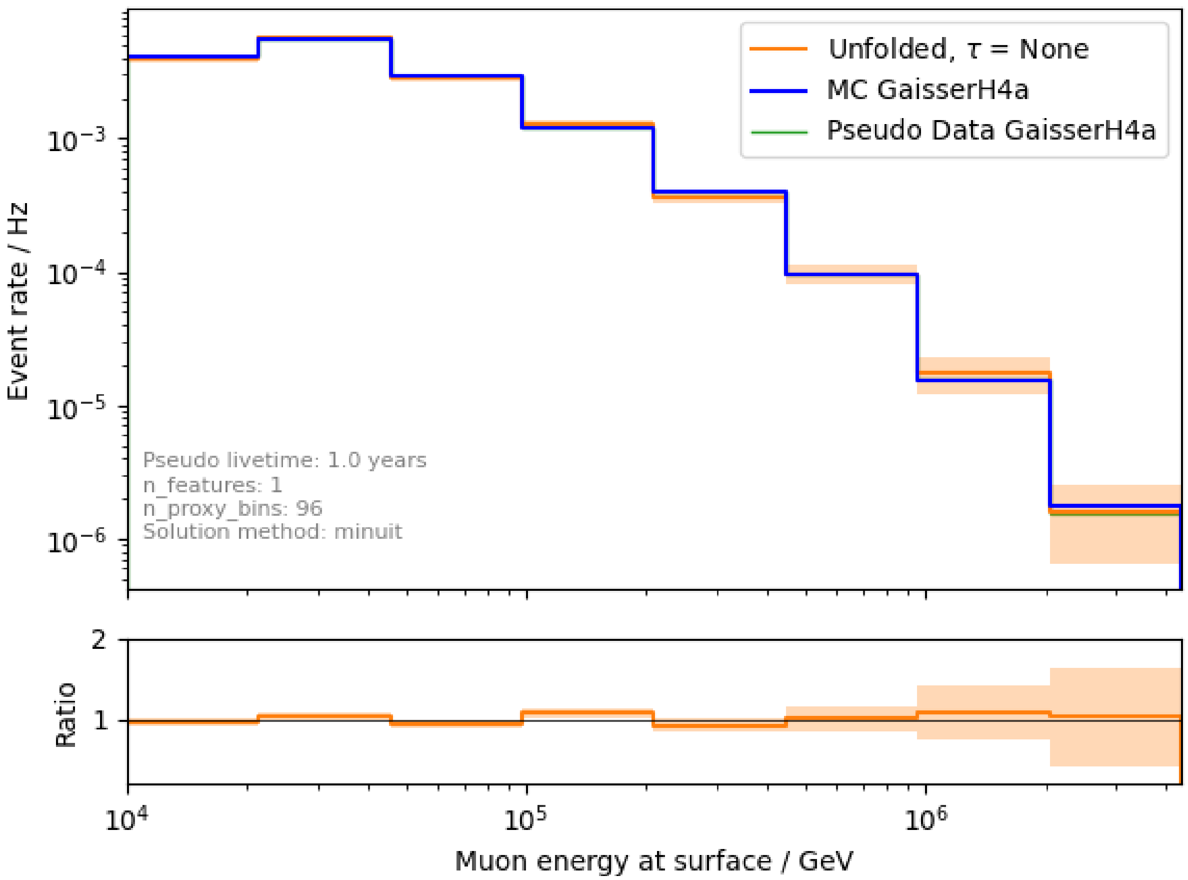
Proxy vs. target



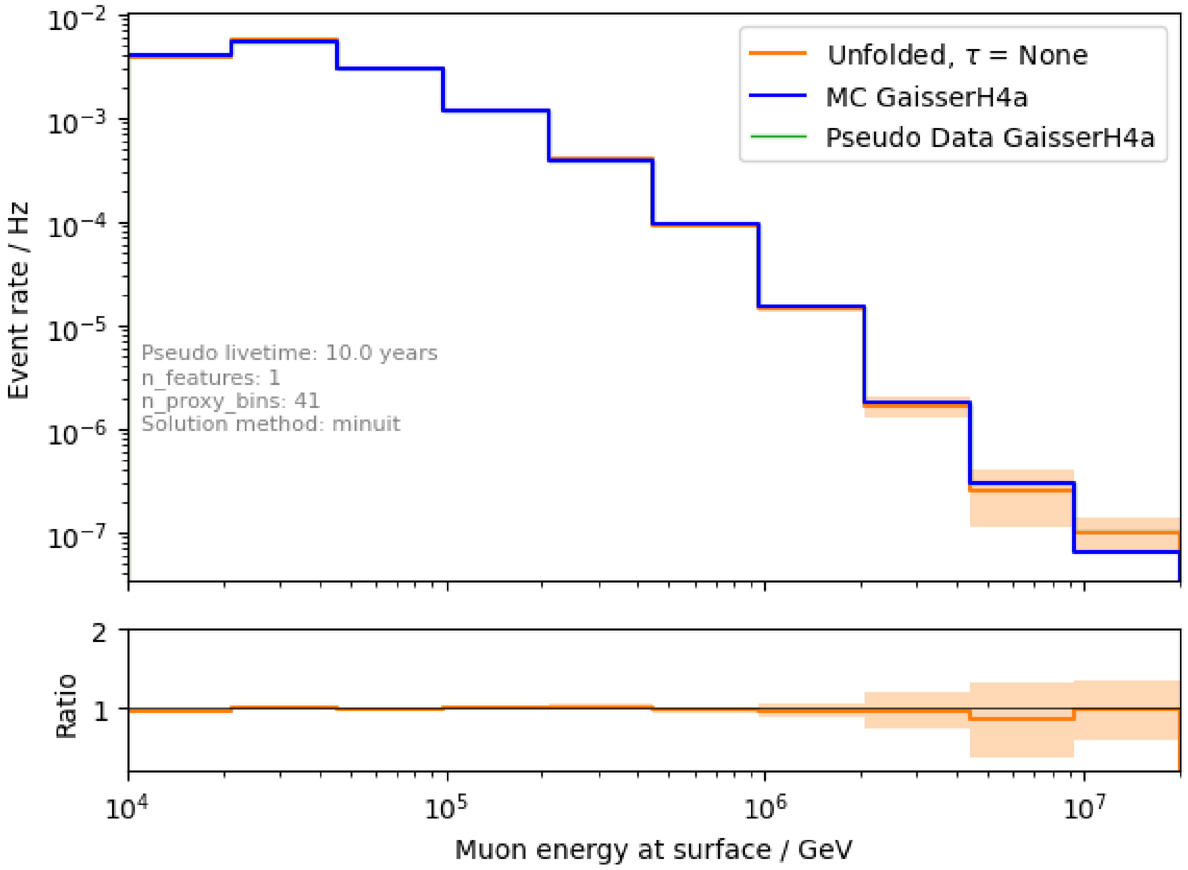


Unfolding event rate

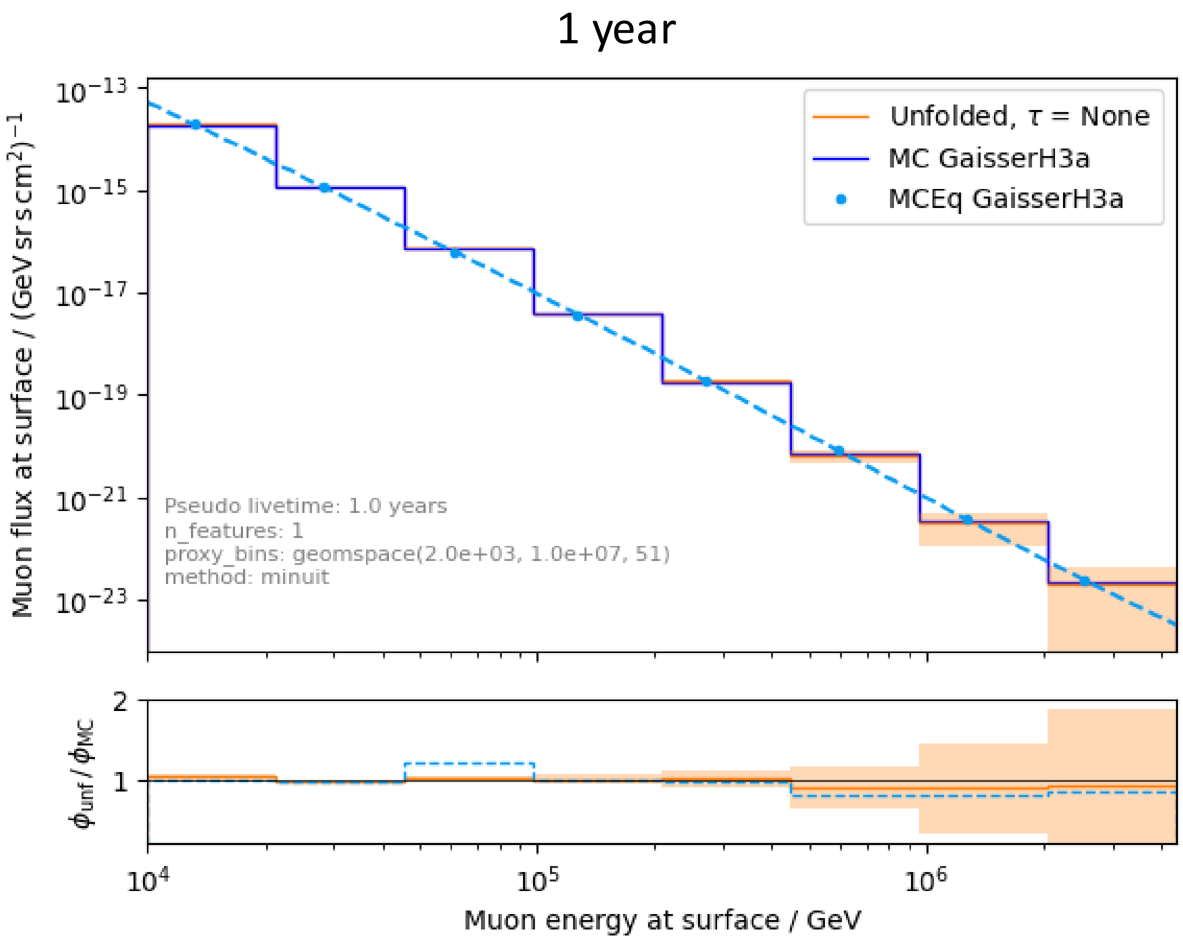
1 year

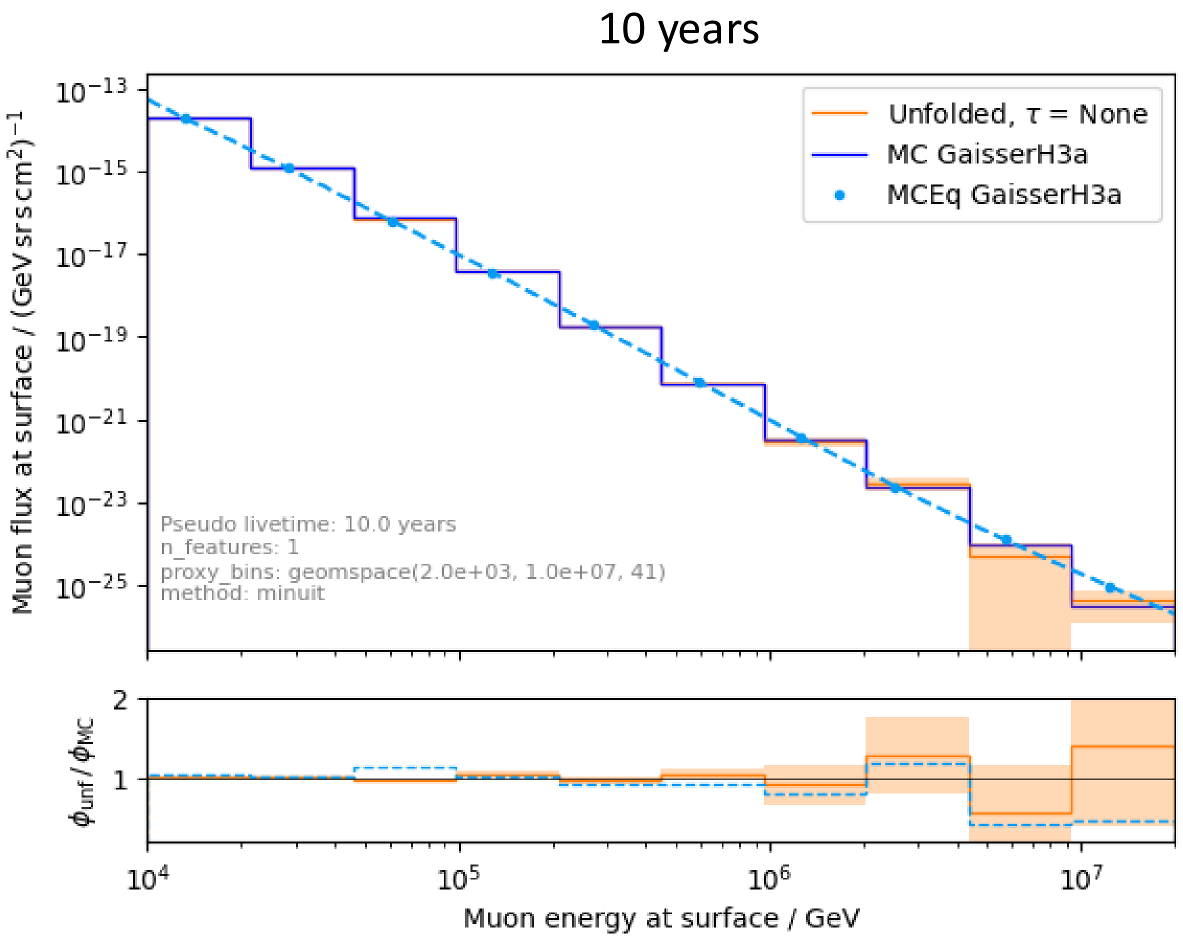


10 years



unfolding of muon flux at surface





Ice systematics

Snowstorm

Absorption

Scattering

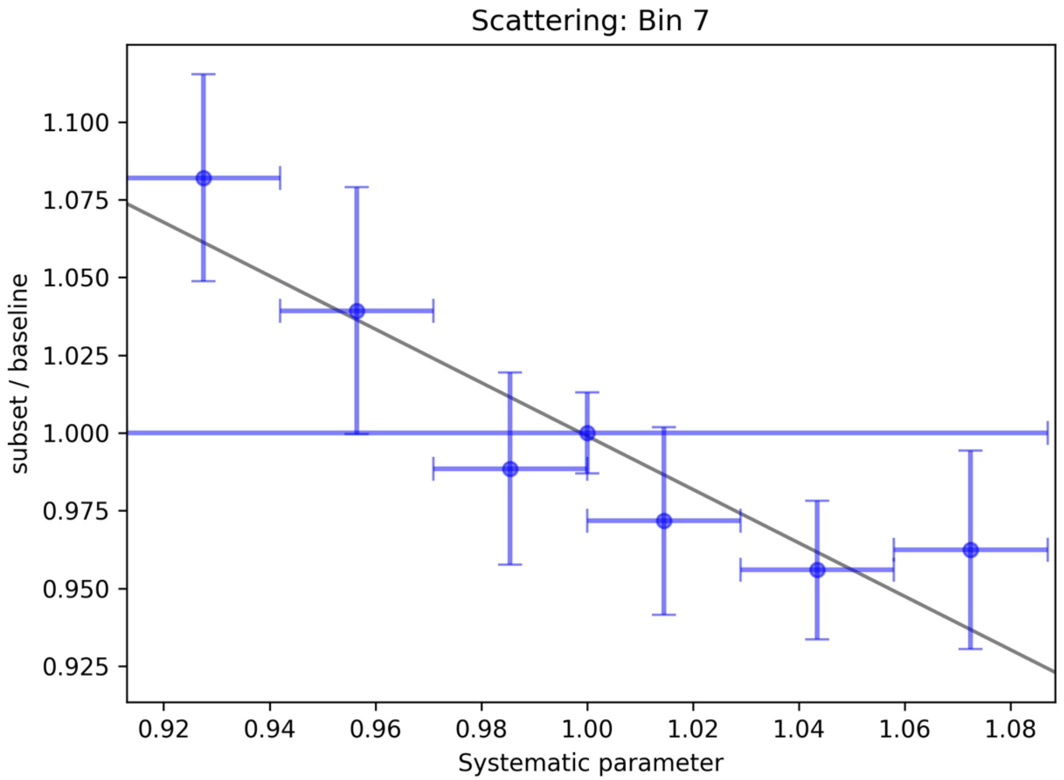
DOMEfficiency

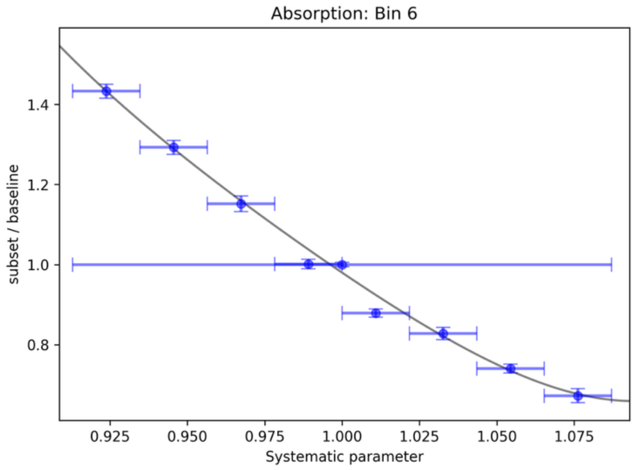
HoleIce 0

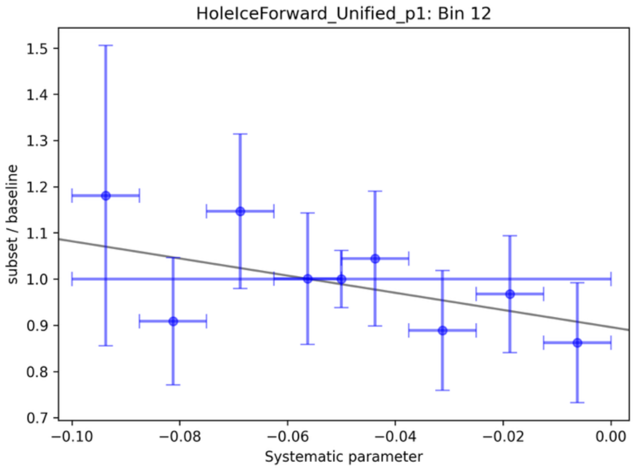
HoleIce 1

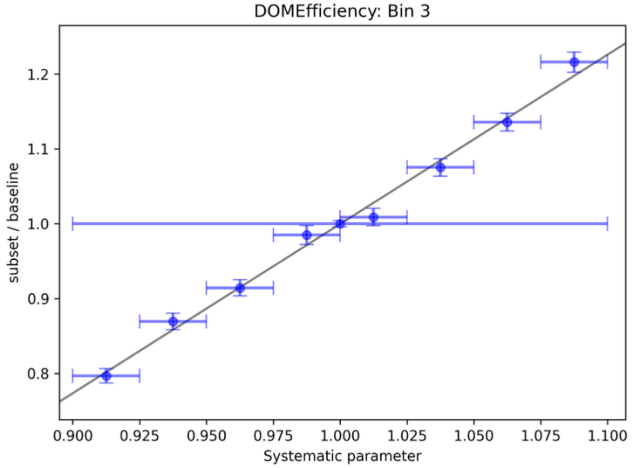
Fit ice systematics:

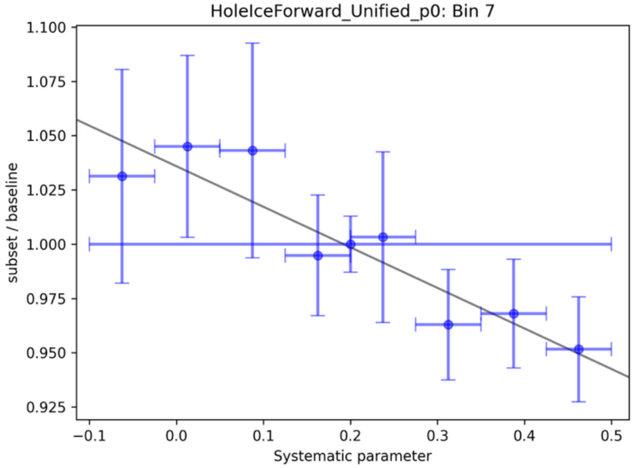
- Parametrization for systematics in each proxy bin
- Proxy: leading muon energy at entry





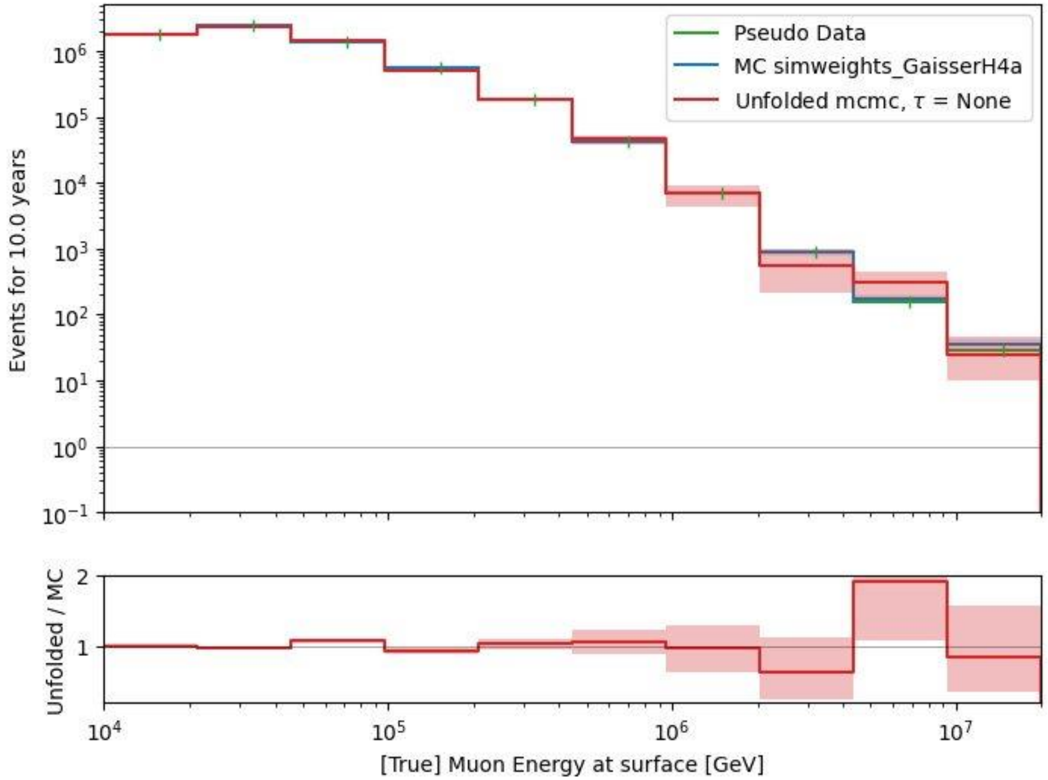


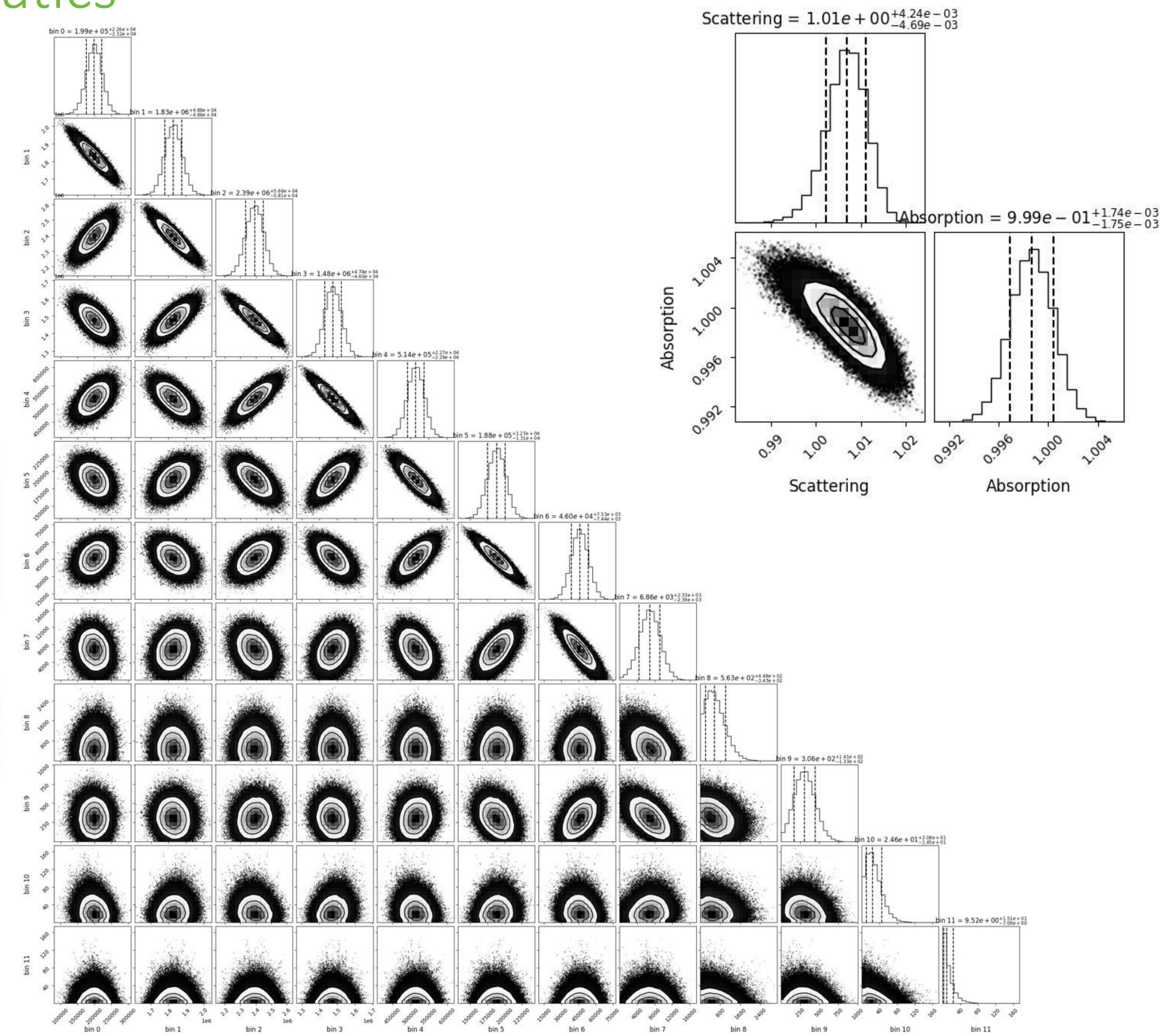




➢ This is done for each systematic and every proxy bin work in progress

Unfolded event rate with systematics





➢ Use regularization to reduce unphyiscal oscillations

Conclusion & outlook

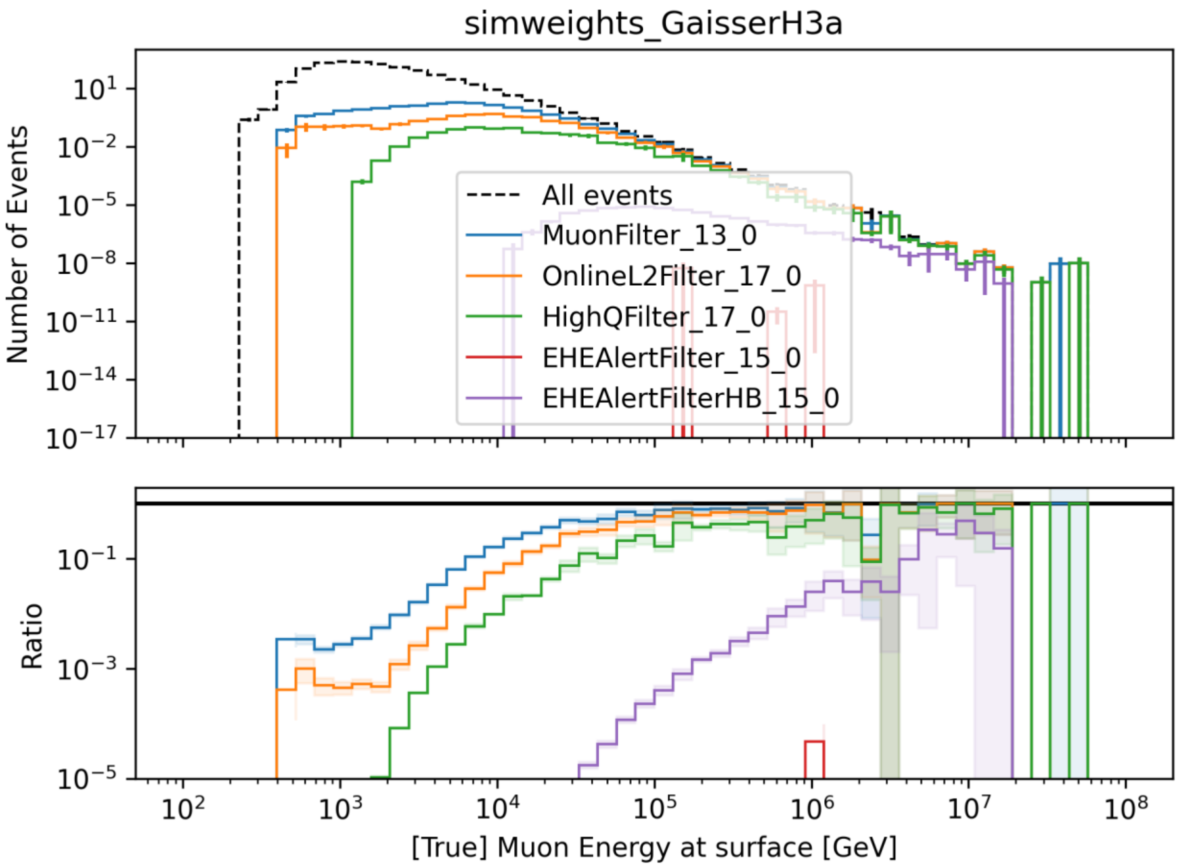
- New CORSIKA simulations with parent information
  - tag prompt and conventional muons
  - validation: agreement with MCEq
- Add DNN-based reconstructions
- Good data-MC agreement
  - quality cuts defined
  - good agreement in cos(zenith) distributions
  - mismatch in z—position → re-weight distributions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

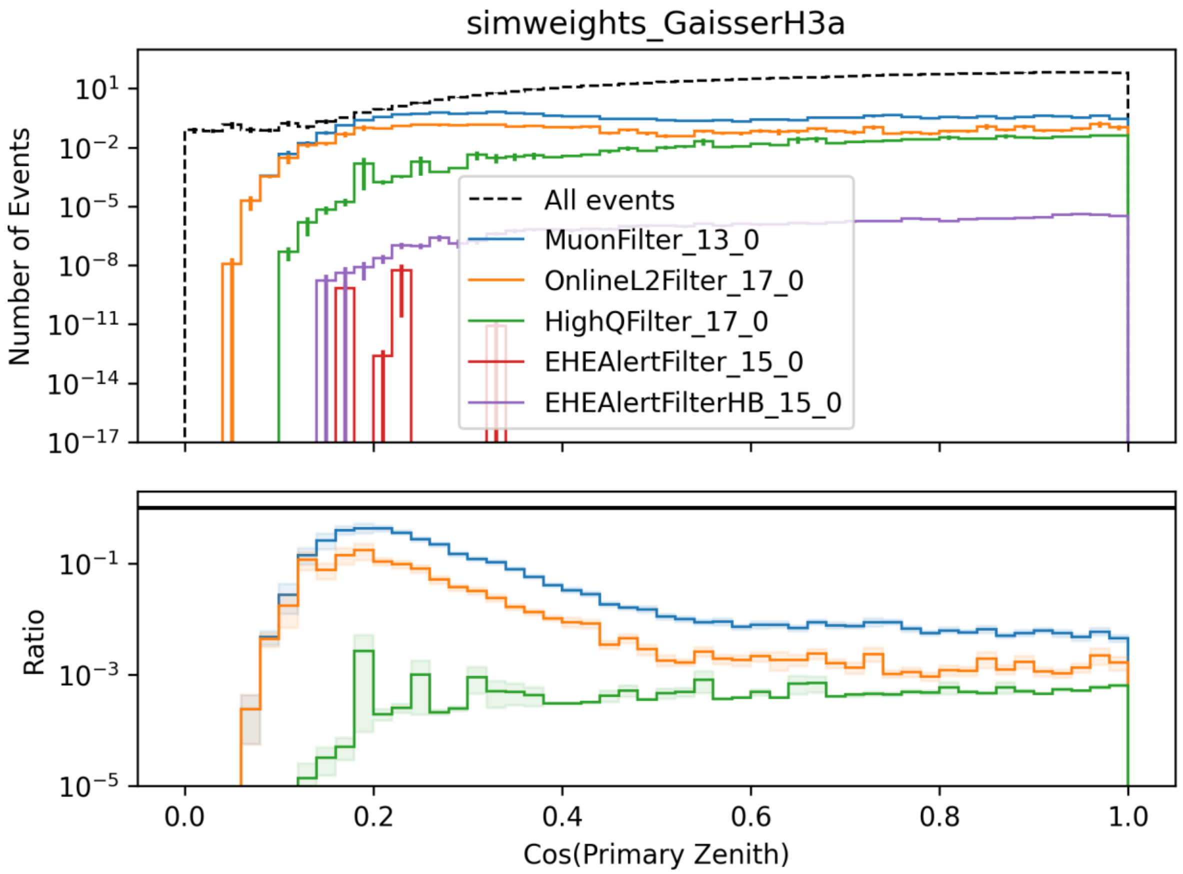
How ChatGPT illustrates the detection of a prompt muon with IceCube.

Thank you for your attention!

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

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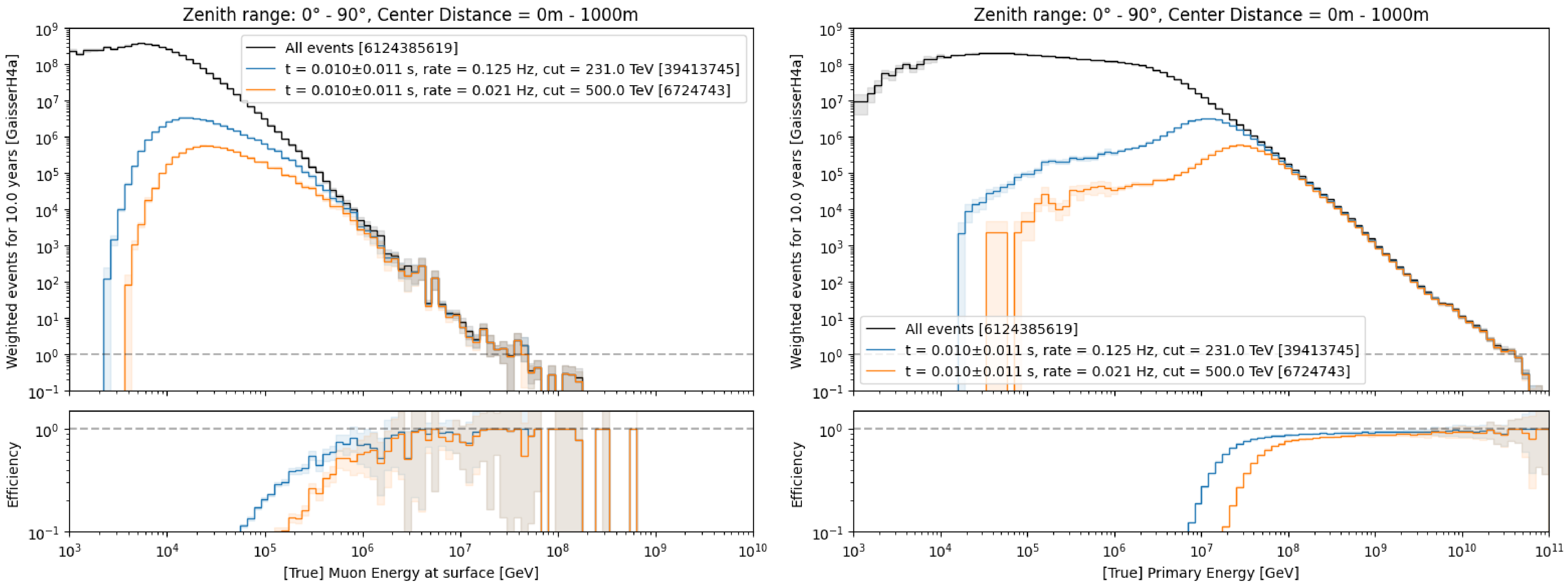
level3: 500 TeV bundle cut at surface

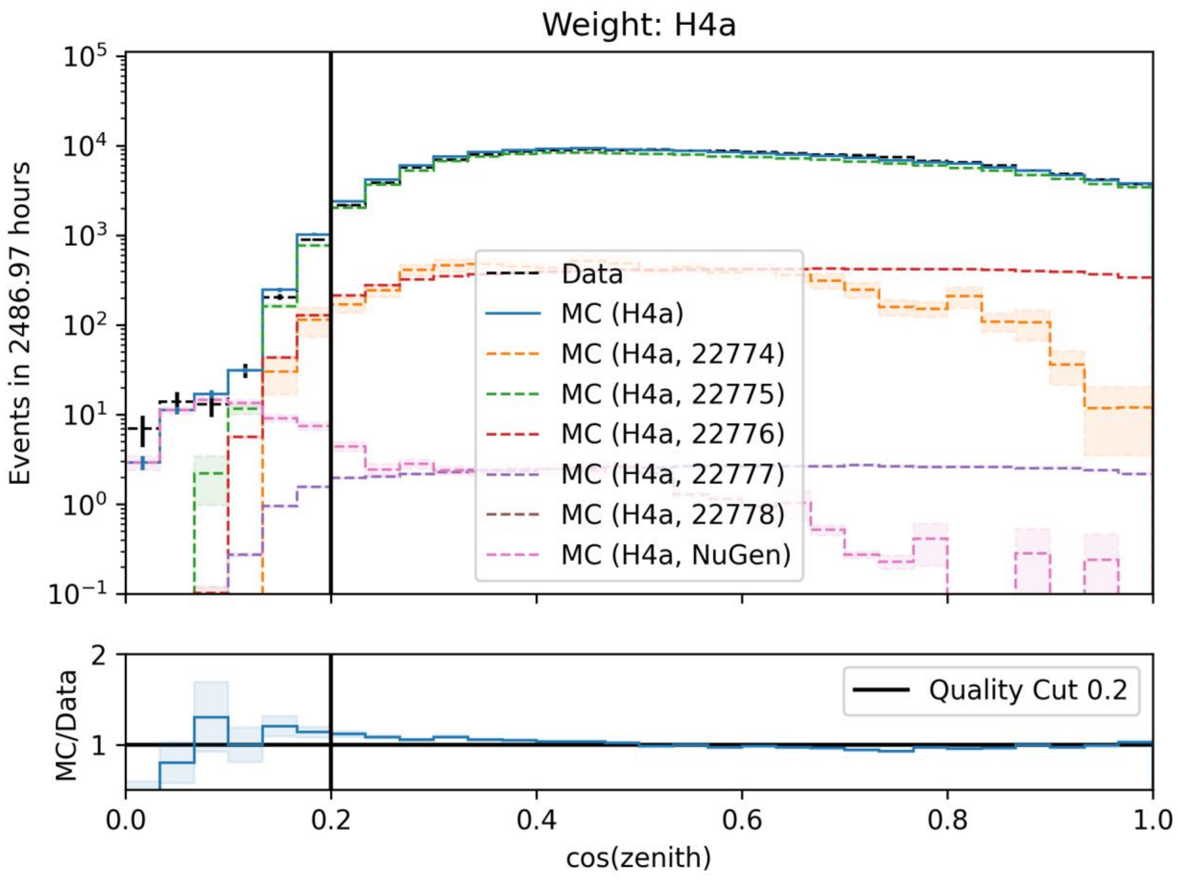


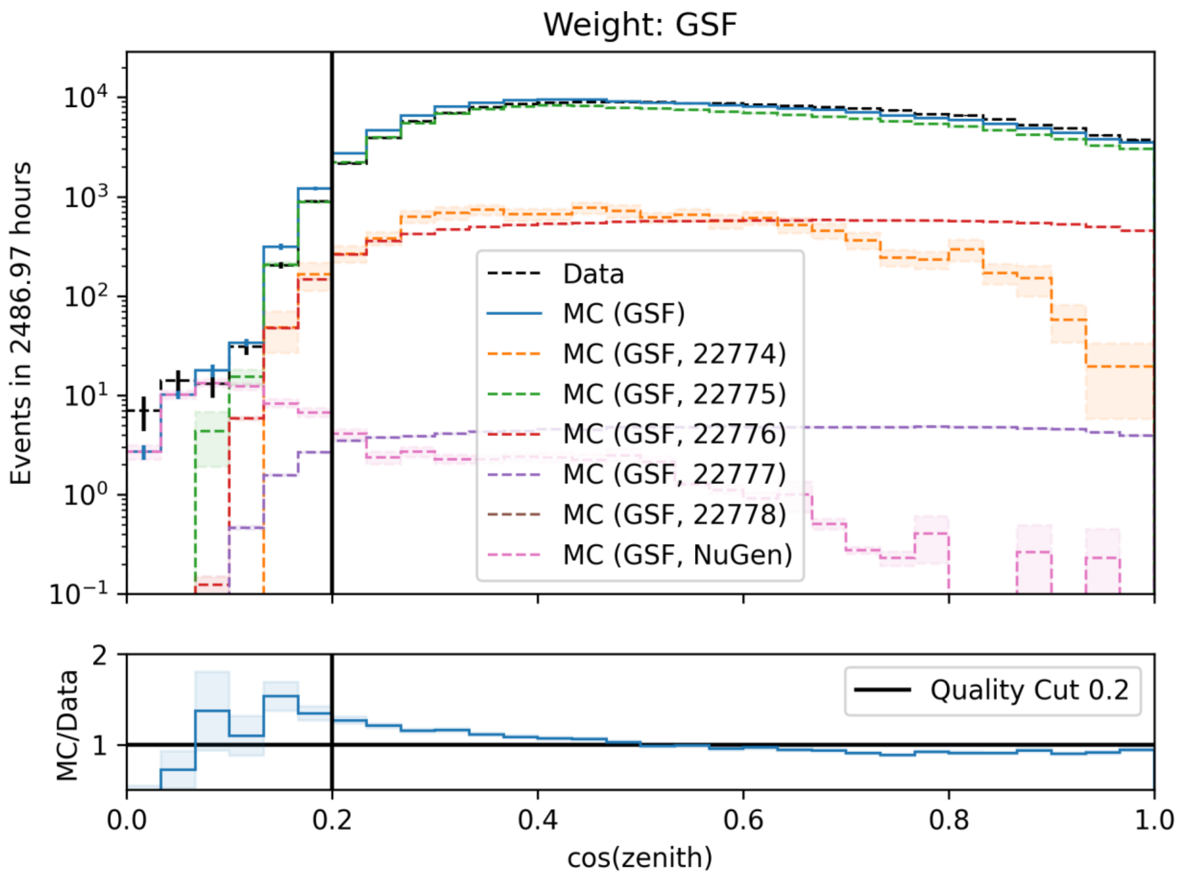
- 6 billion events expected: computationally not feasible → focus on high-energetic events
  - 500 TeV cut: 6.7 Mio events left

use fast pre-cut network to estimate bundle energy at surface

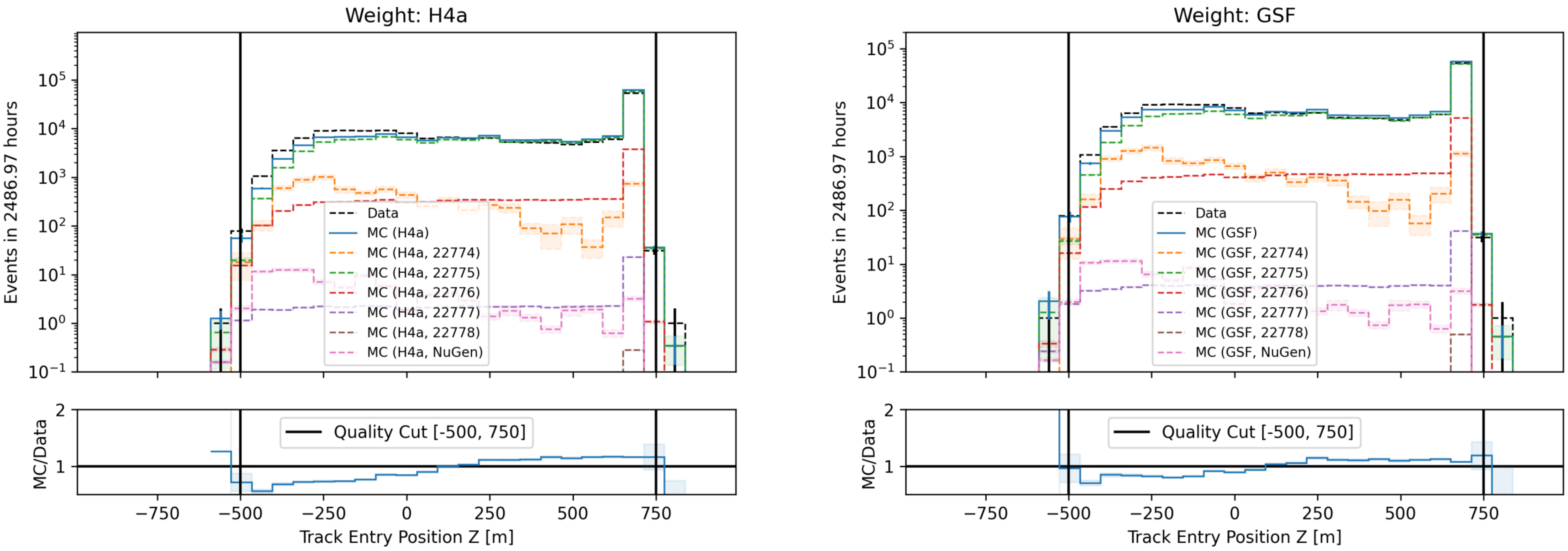
Data-MC

Cos(zenith)


Weight: H4a
Events in 2486.97 hours
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Data
MC (H4a)
MC (H4a, 22774)
MC (H4a, 22775)
MC (H4a, 22776)
MC (H4a, 22777)
MC (H4a, 22778)
MC (H4a, NuGen)
MC/Data
1
2
Quality Cut 0.2
0.0
0.2
0.4
0.6
0.8
1.0
cos(zenith)

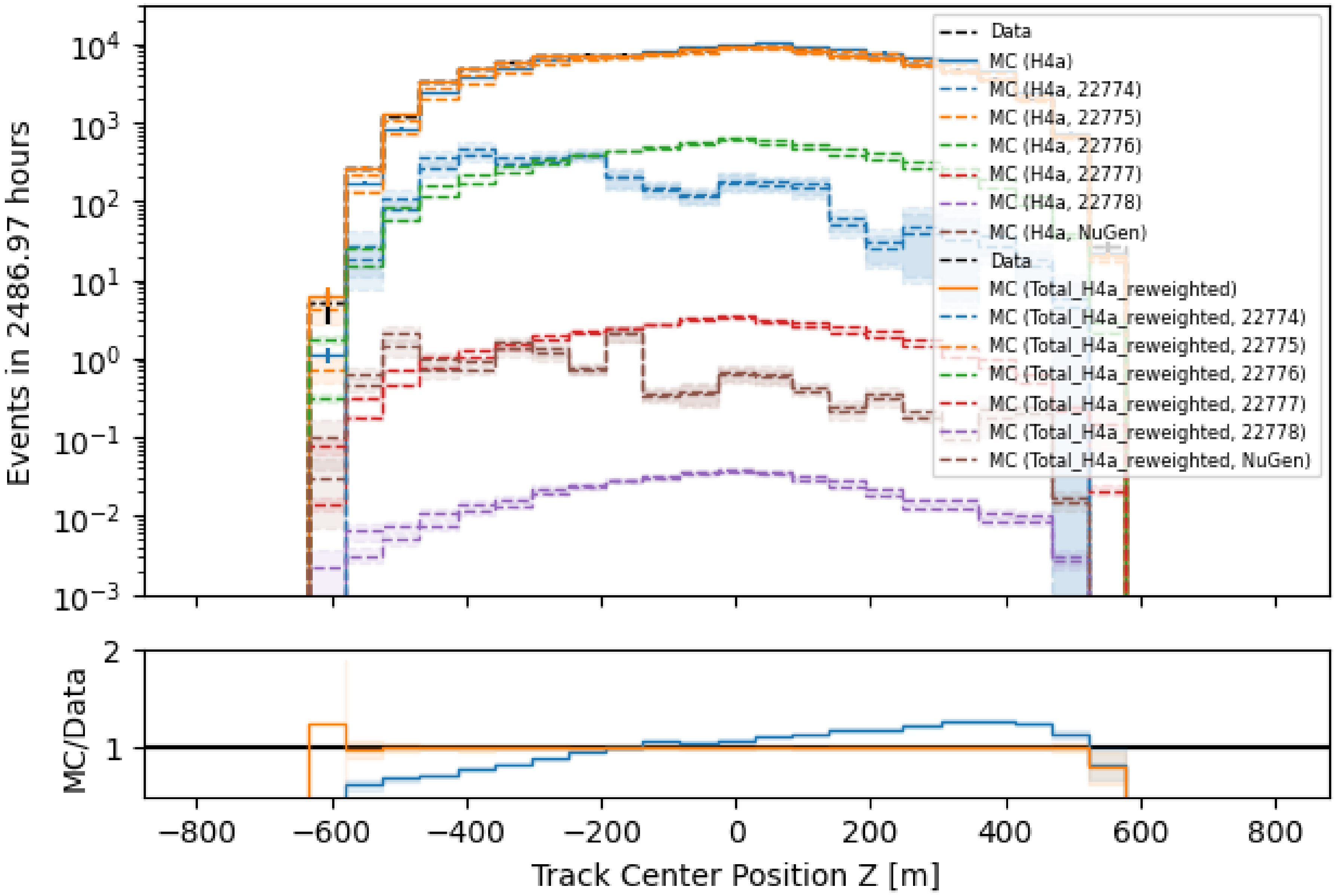

Weight: GSF
Events in 2486.97 hours
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Data
MC (GSF)
MC (GSF, 22774)
MC (GSF, 22775)
MC (GSF, 22776)
MC (GSF, 22777)
MC (GSF, 22778)
MC (GSF, NuGen)
MC/Data
1
2
Quality Cut 0.2
0.0
0.2
0.4
0.6
0.8
1.0
cos(zenith)

Entry position z—vertex

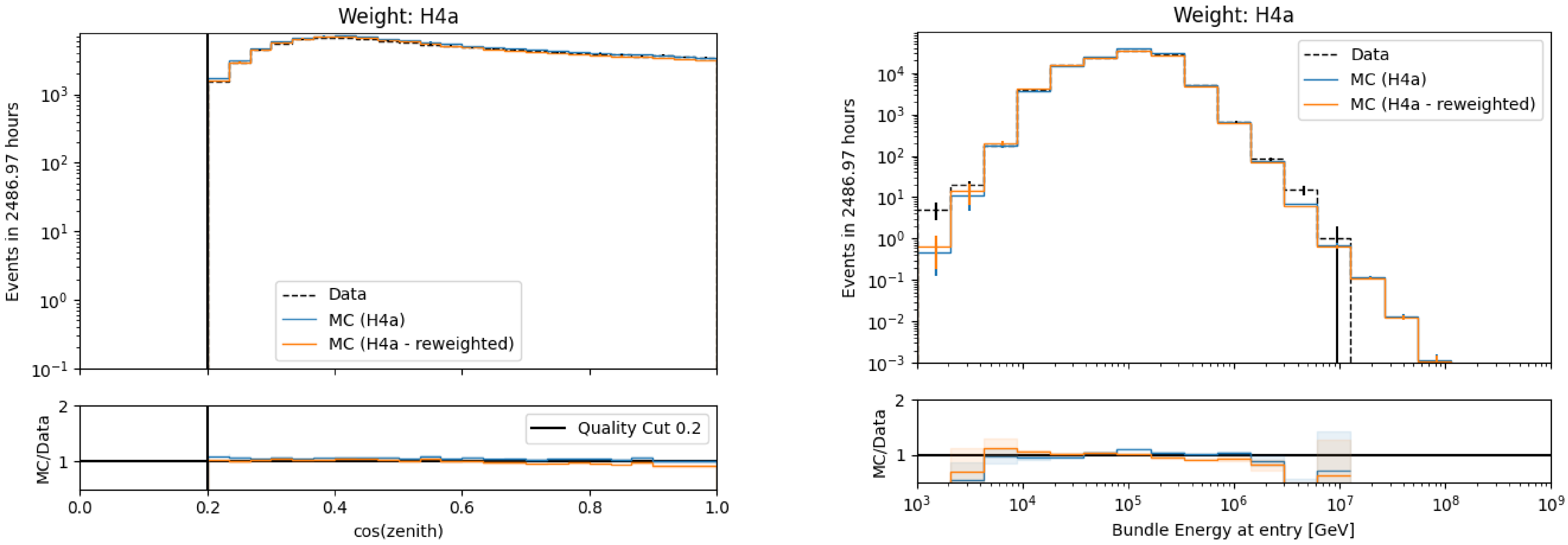


z—reweighting

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



Check z—reweighting



- ➢ re-weighting has no large effect on cos(zenith) and energy

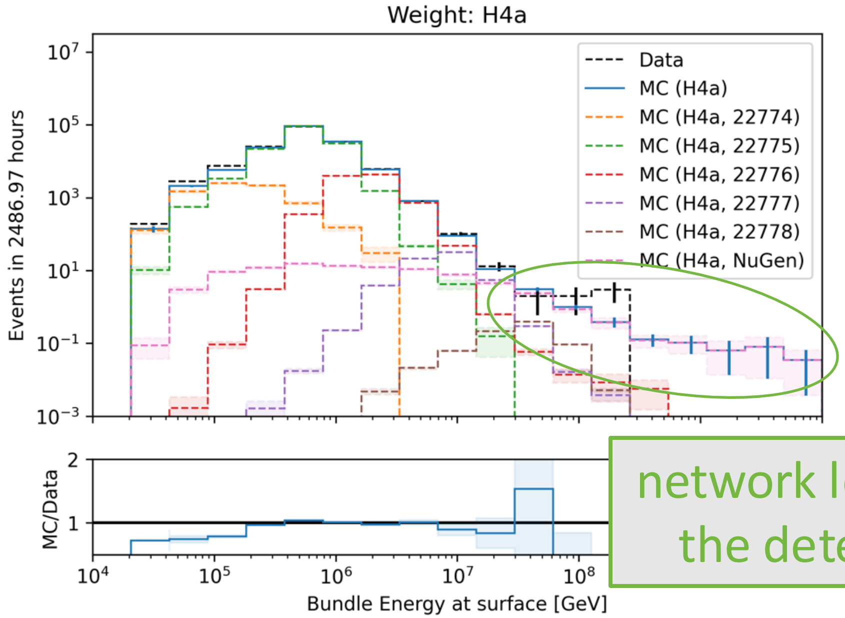
Level5: quality cuts

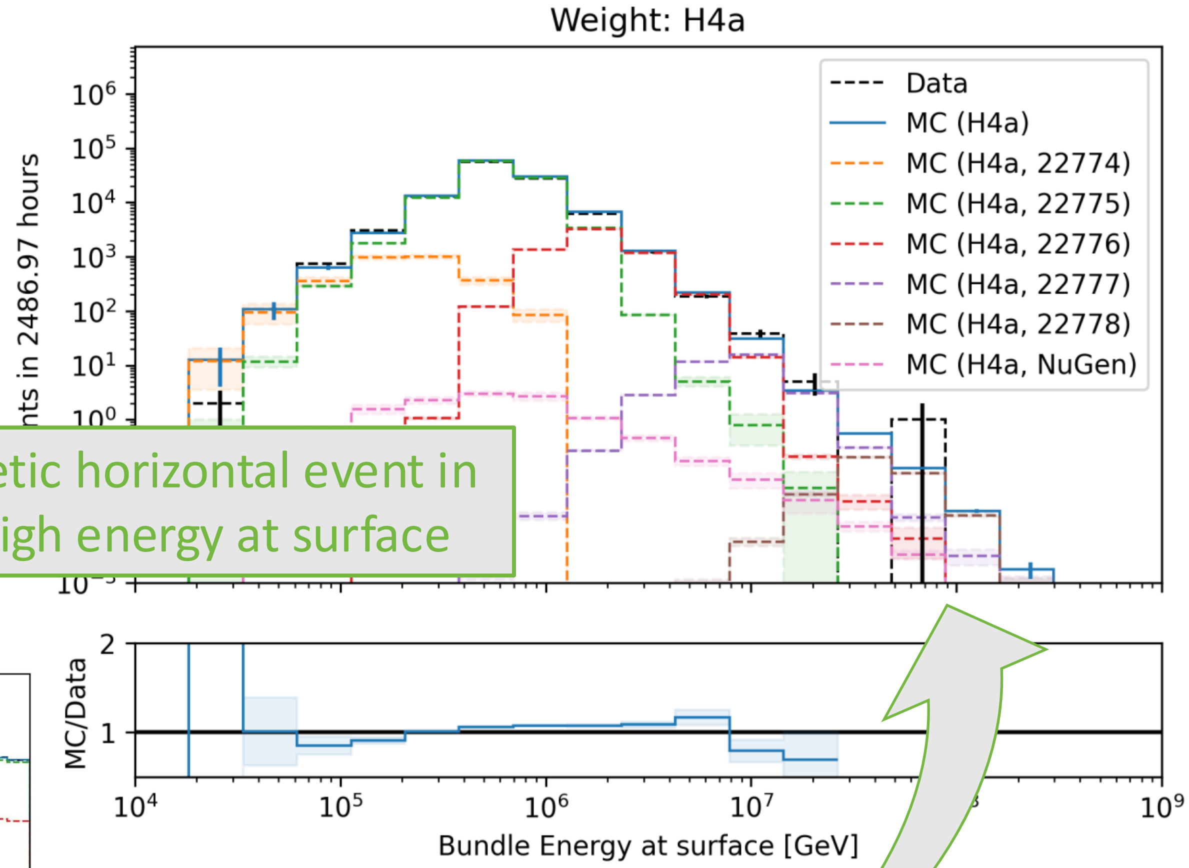
containment cuts	>	<
length in detector	1000 m	2000 m
entry pos x, y	-750 m	750 m
entry pos z	-500 m	750 m
center pos x, y	-550 m	550 m
center pos z	-650 m	650 m

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

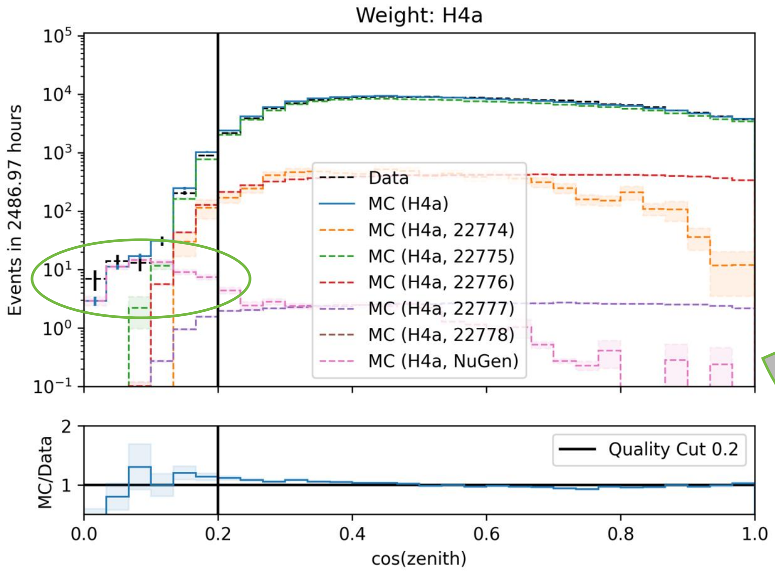
uncertainty cuts	<
bundle energy at entry	0.9 log10(GeV)
bundle energy at surface	2.0 log10(GeV)
zenith	0.1 rad
azimuth	0.2 rad
entry pos x , y, z	42 m
center pos x, y, z	50 m
entry pos time	200 ns
center pos time	600 ns
length in detector	160 m
length	2000 m

Level5: quality cuts → removes neutrinos





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

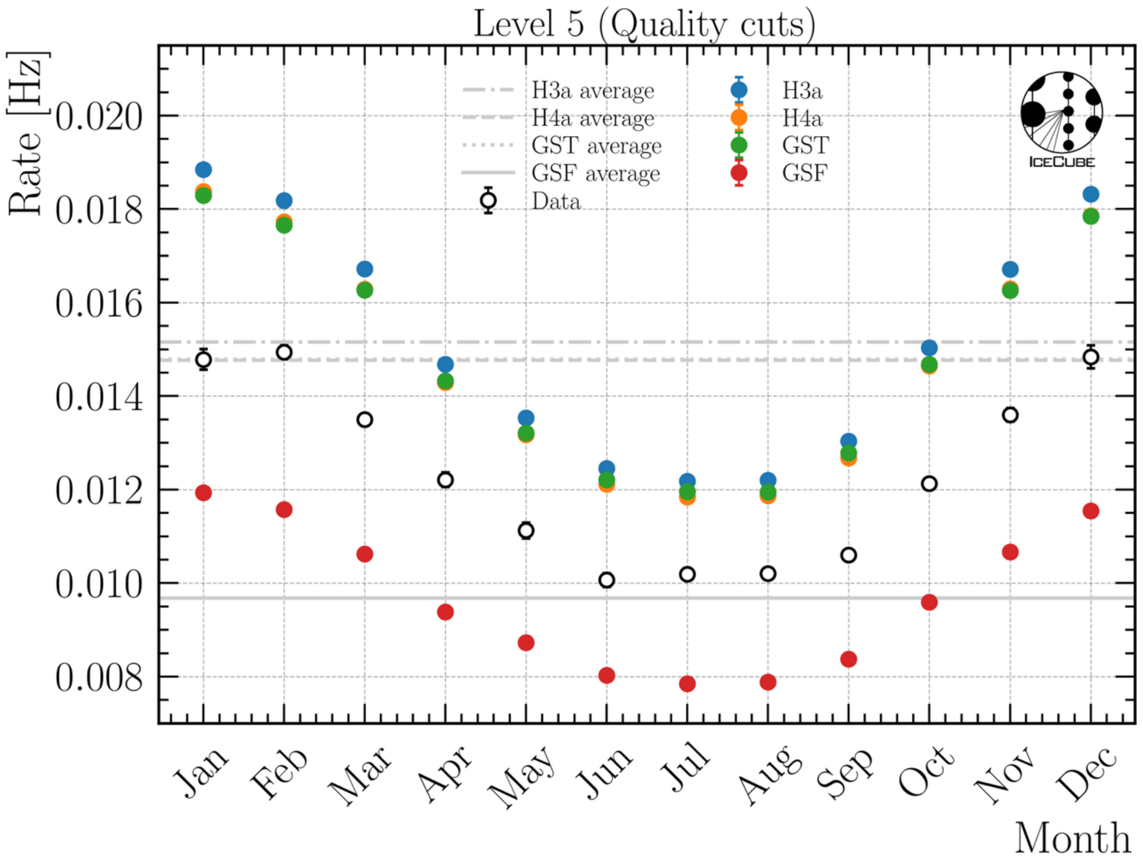


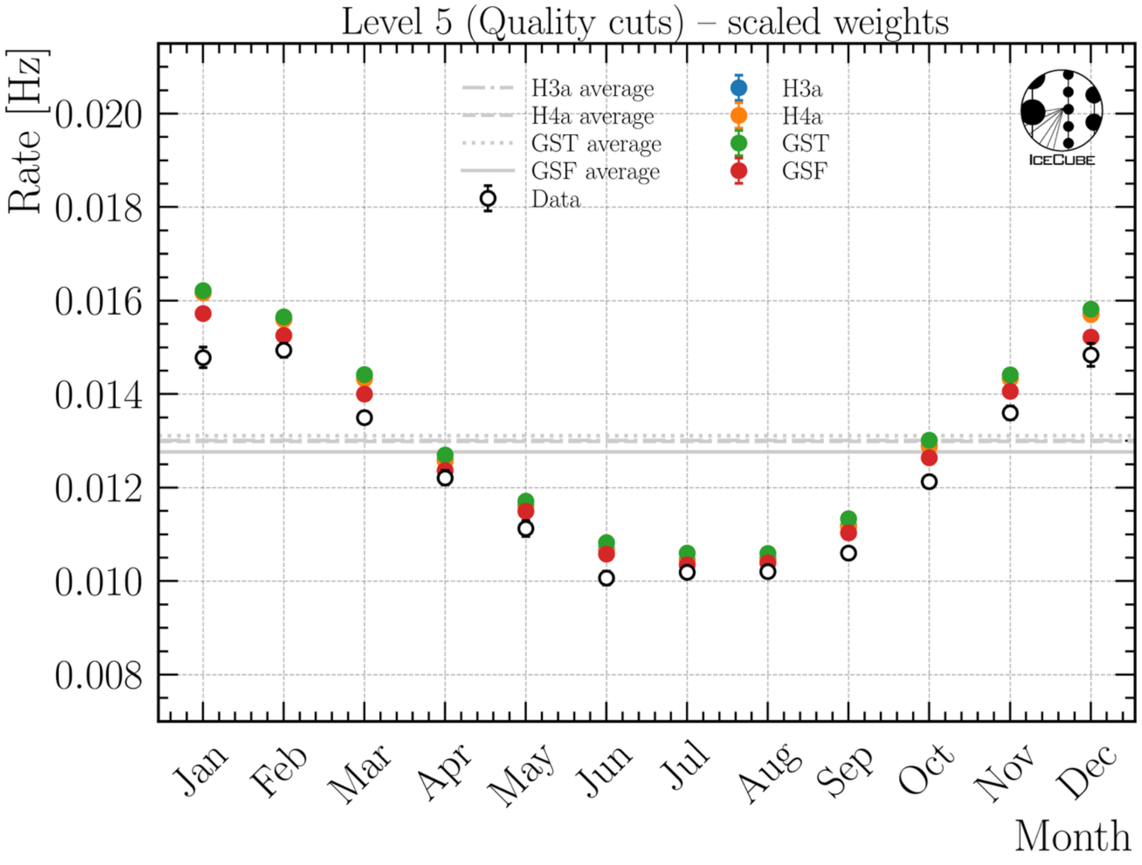
Rates per month

Data-MC

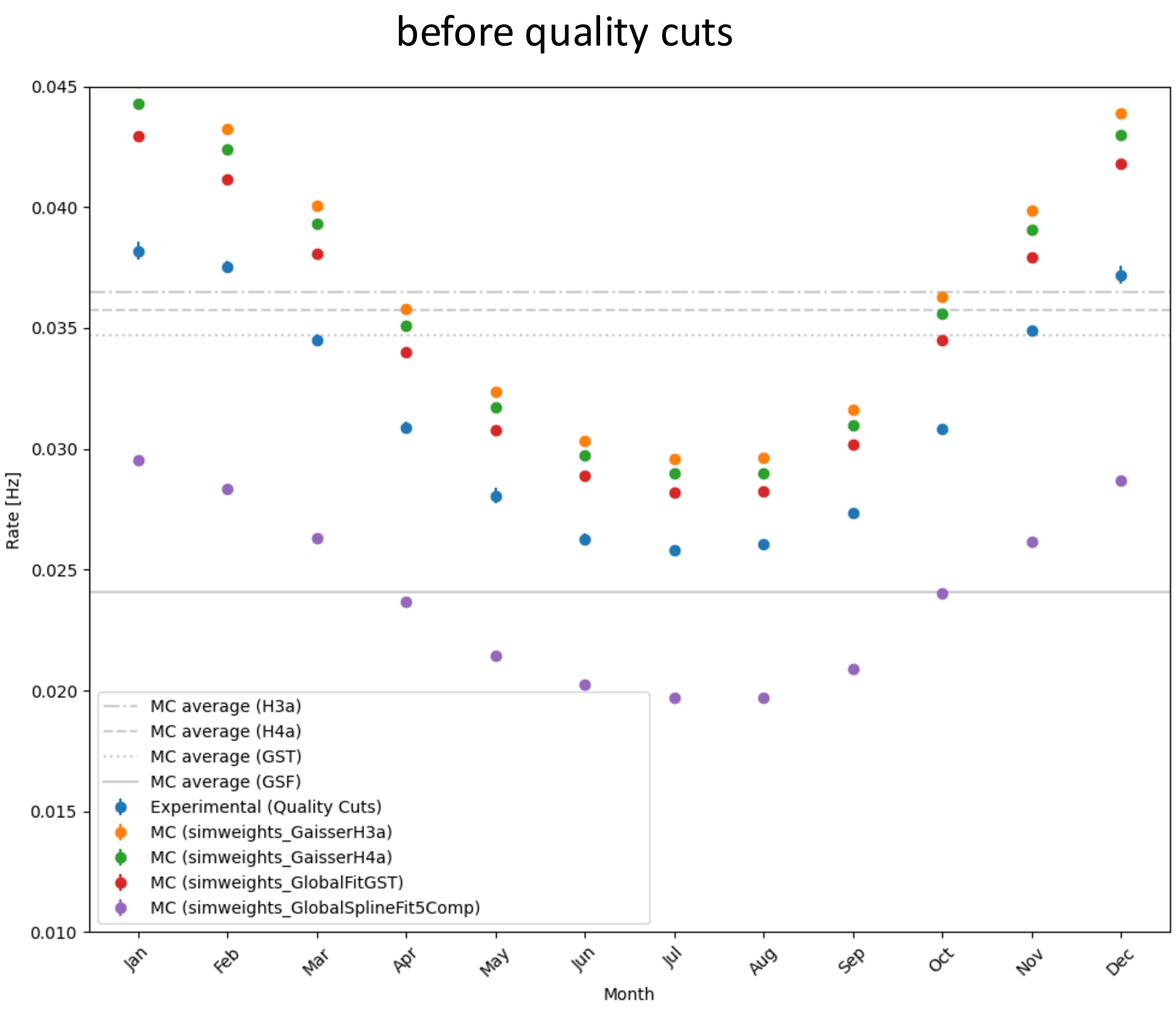
Rates per month – Level 5

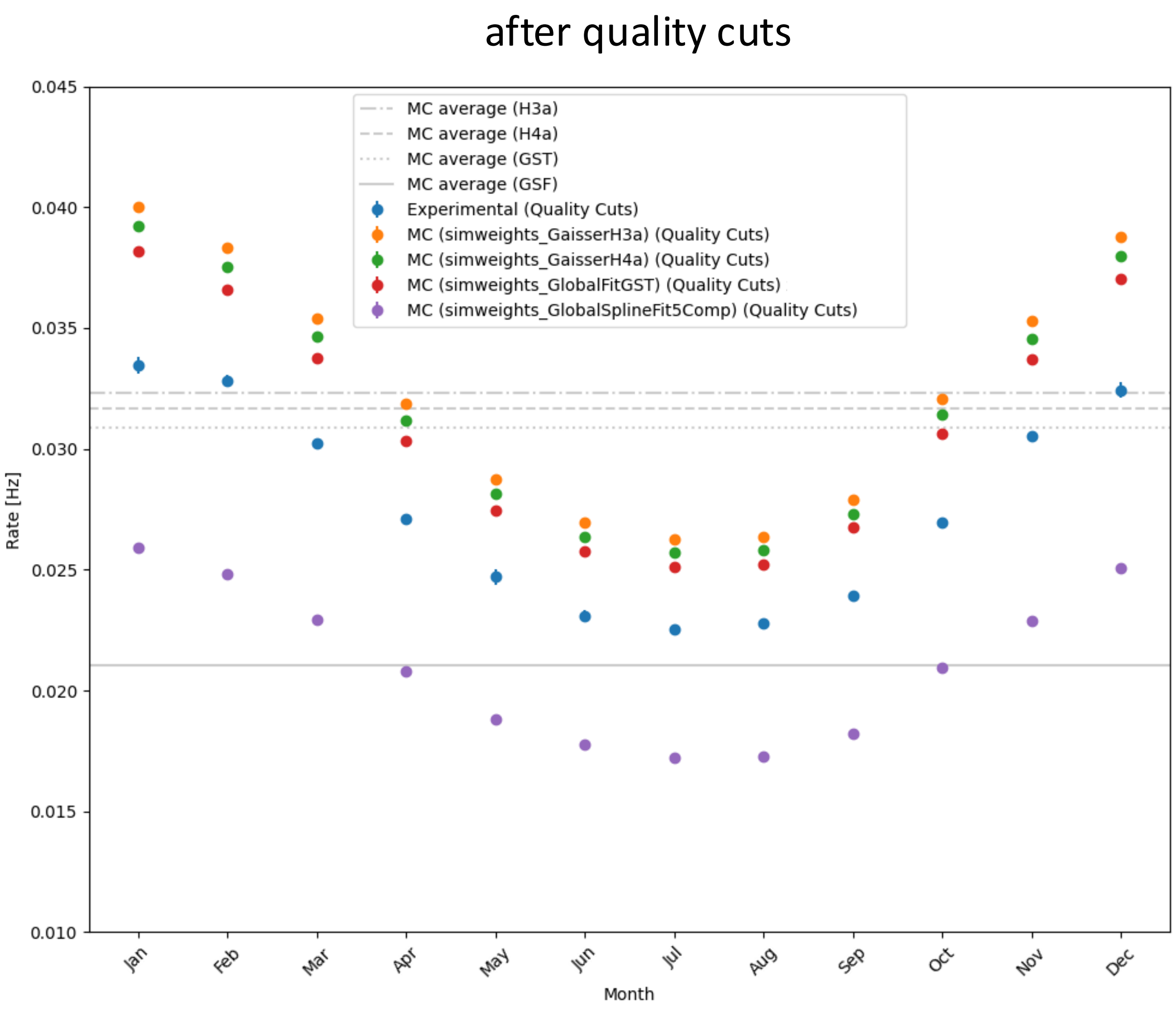
scaled on Level 4





Rates per month

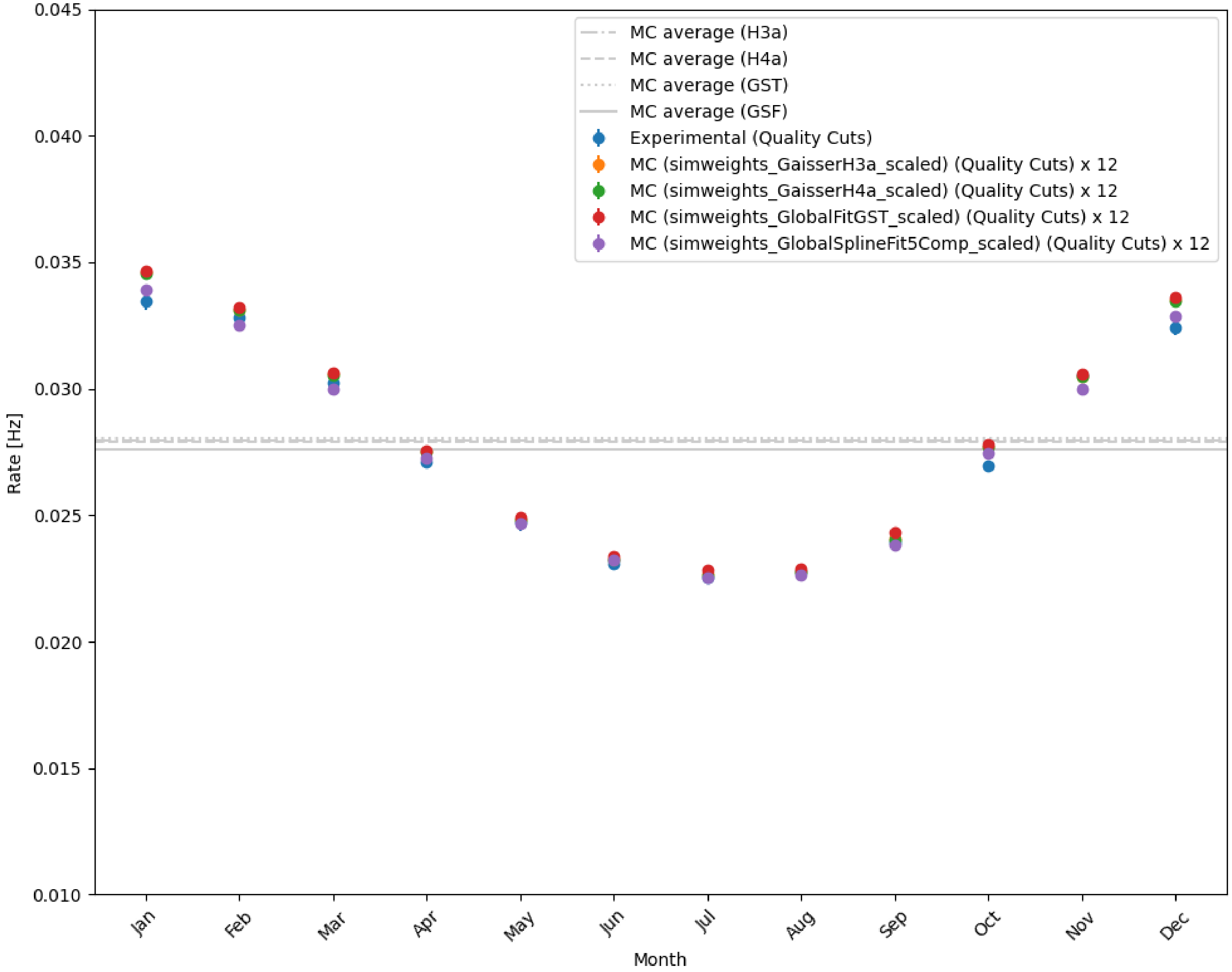




- total offset in rate per month

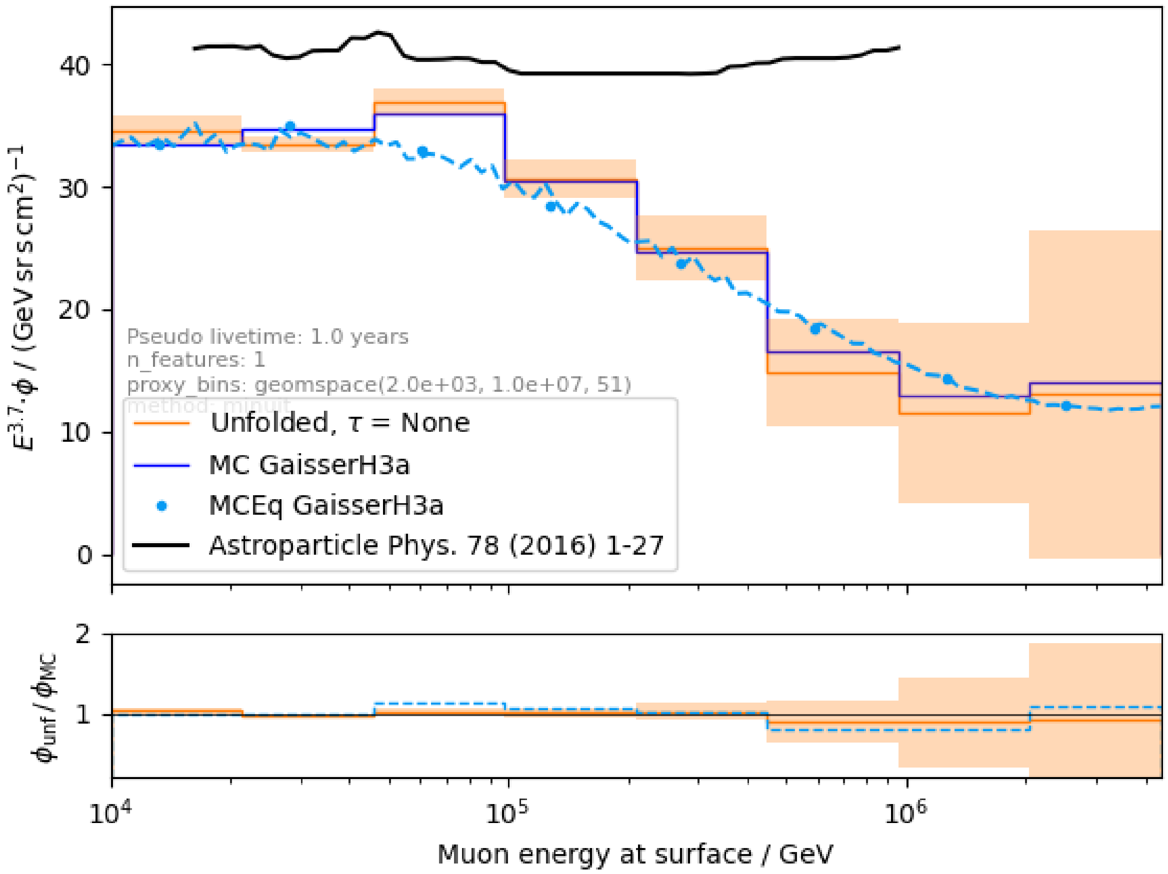
Rates per month: scaled

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

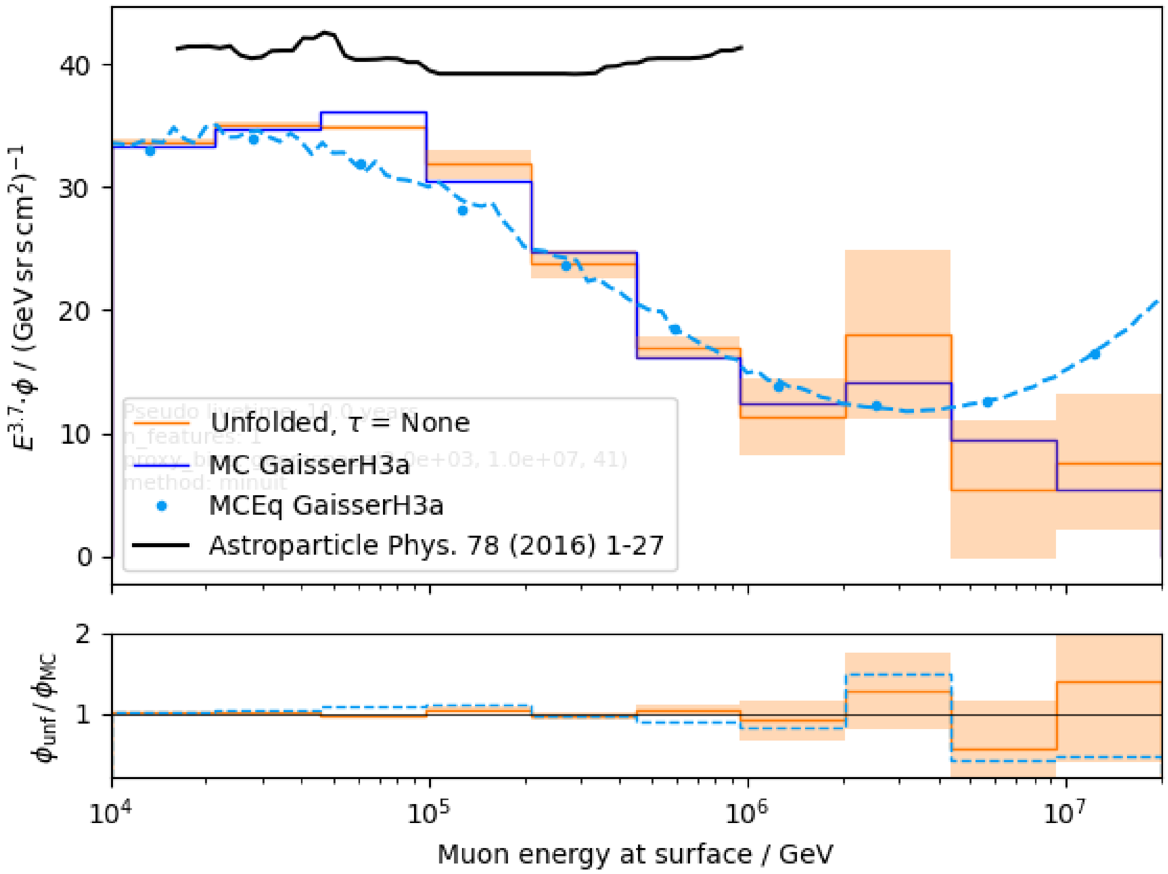


unfolding of muon flux at surface – weighted to $E^{3.7}$

1 year

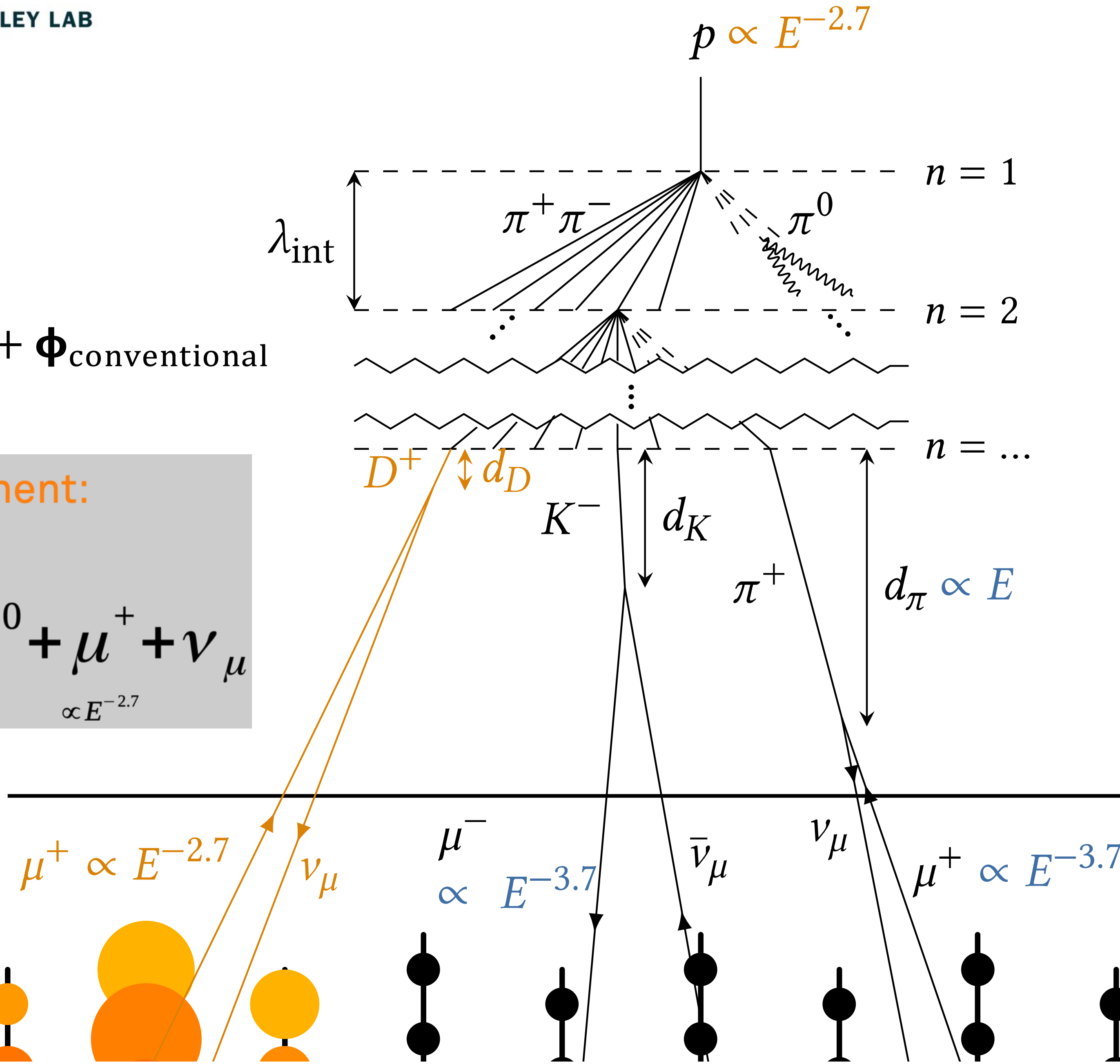


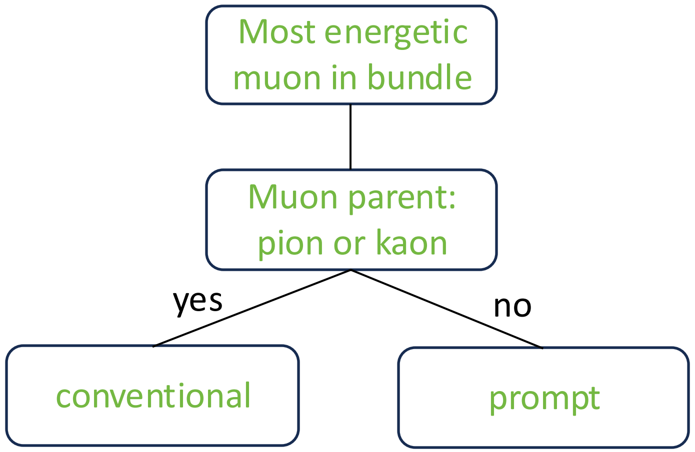
10 years



Muon flux

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





prompt component:

$$\underset{\propto E^{-2.7}}{p} \rightarrow \overbrace{D^+}^{\tau = 1.04\cdot 10^{-12}\,\mathrm{s}} \rightarrow \bar{K}^0 + \underset{\propto E^{-2.7}}{\mu^+} + \nu_\mu$$

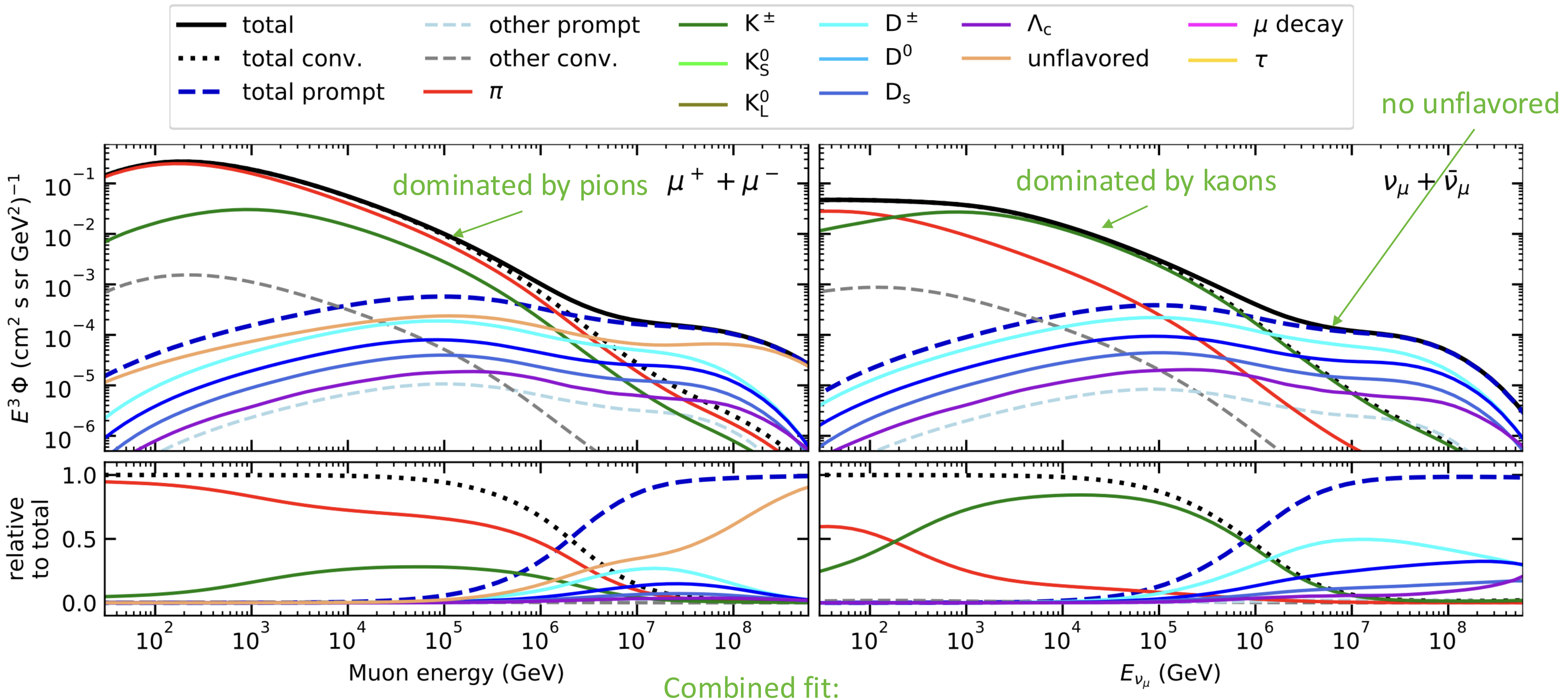
Conventional component:

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

Credit: Ludwig Neste

Prompt atmospheric muons and neutrinos

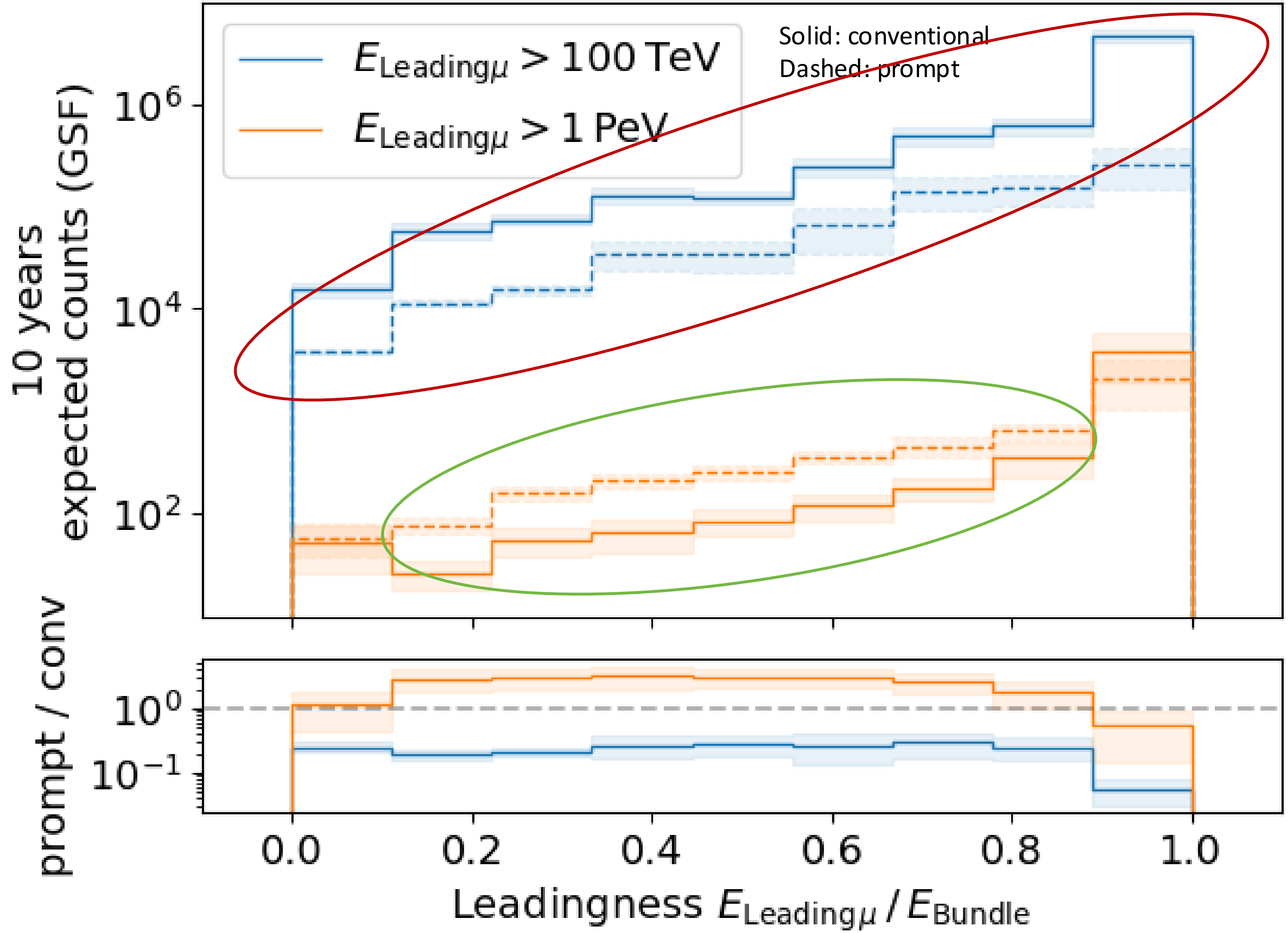
10.1103/PhysRevD.100.103018



Combined fit:

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

Leading muon energy fraction



- Prompt dominates for energies > 1 PeV
- Leading energy sweet spot: 0.1 – 0.9

Leading muon contribution

Patrick Berghaus

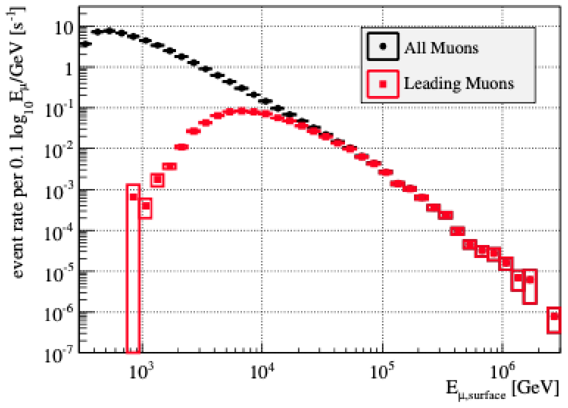
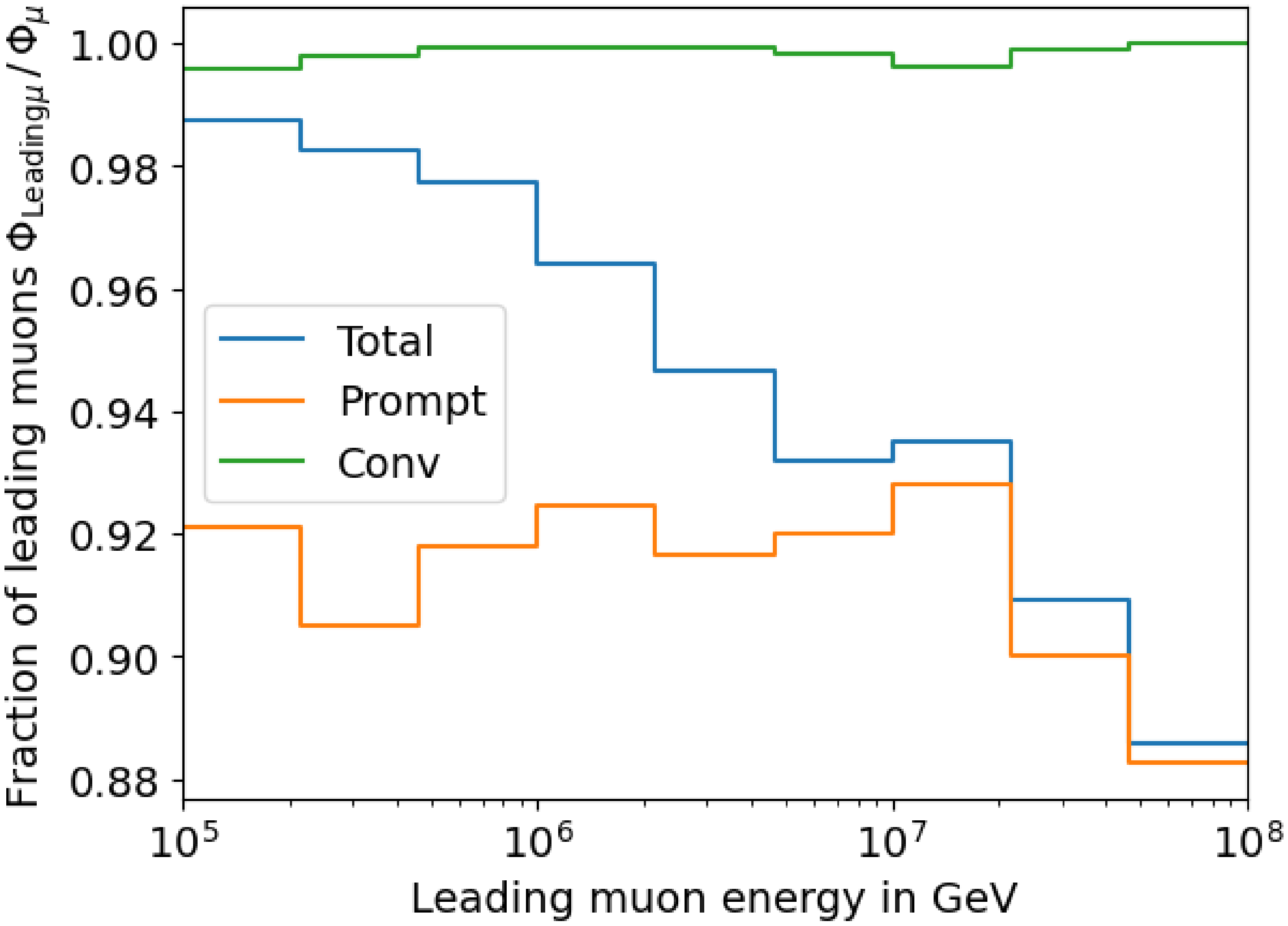


Figure 10: Surface energy distribution for all and most energetic ("leading") muons in simulated events with a total of more than 1,000 registered photo-electrons in IceCube.

- 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

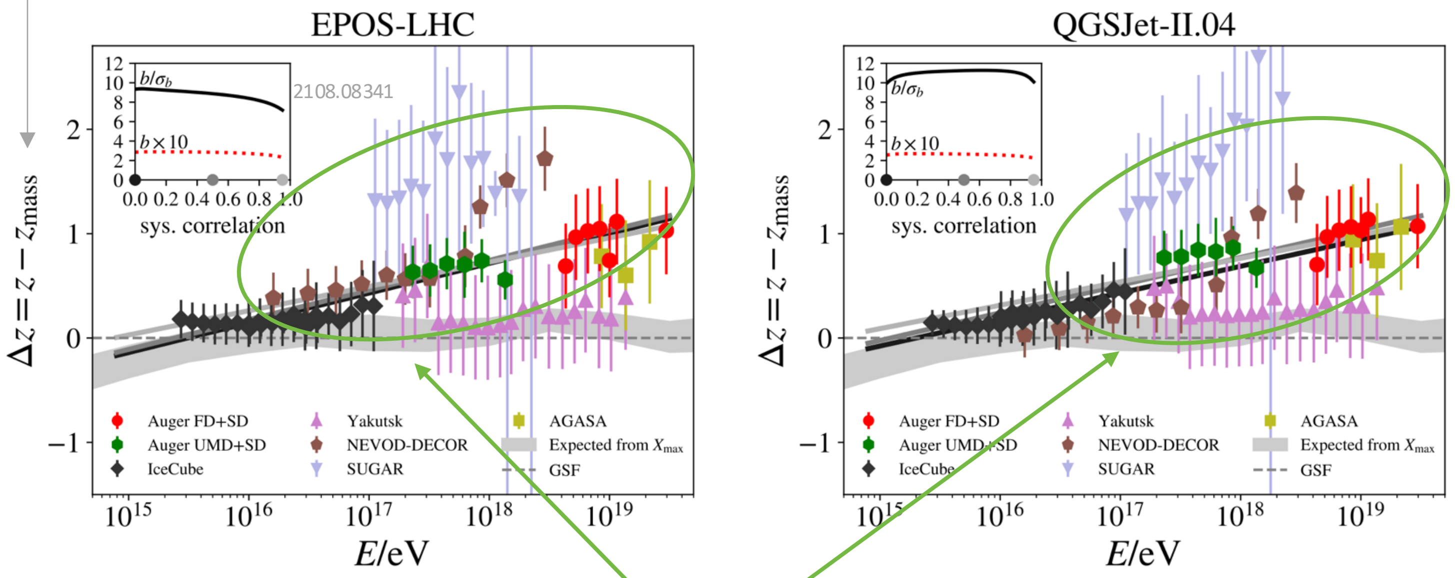


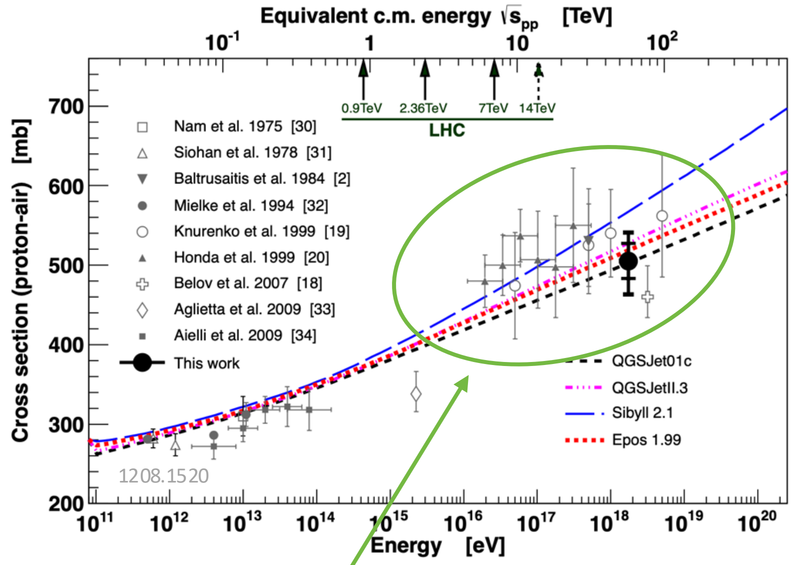
Muon puzzle and hadronic uncertainties

”muon number”

Expected z
(“muon number”)

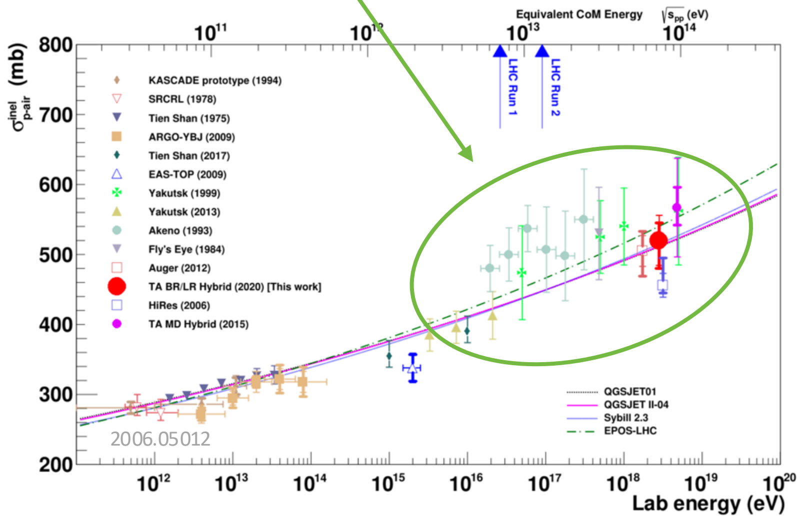
$$z = \frac{\ln\langle N_\mu\rangle - \ln\langle N_\mu\rangle_p}{\ln\langle N_\mu\rangle_{\mathrm{Fe}} - \ln\langle N_\mu\rangle_p}$$





2012

➢ Uncertainties at E > 10 PeV



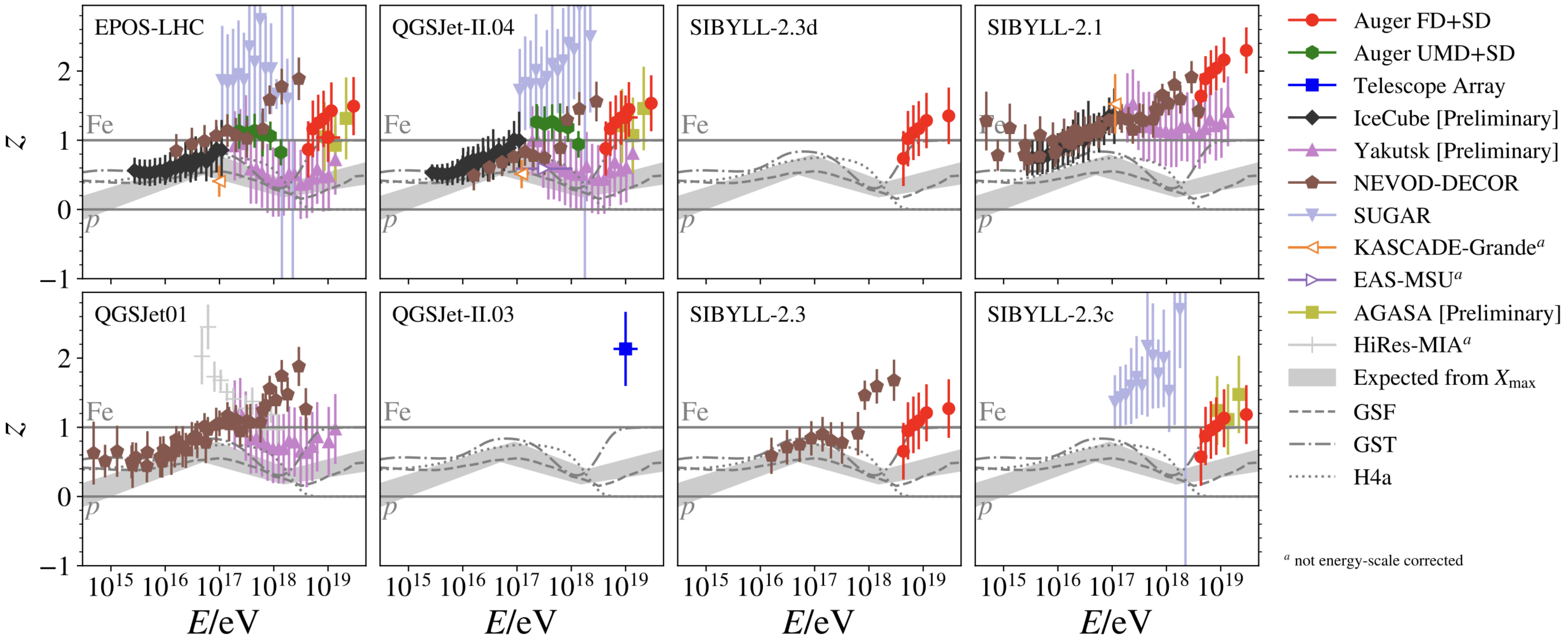
2020

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

The Muon Puzzle

"muon number"

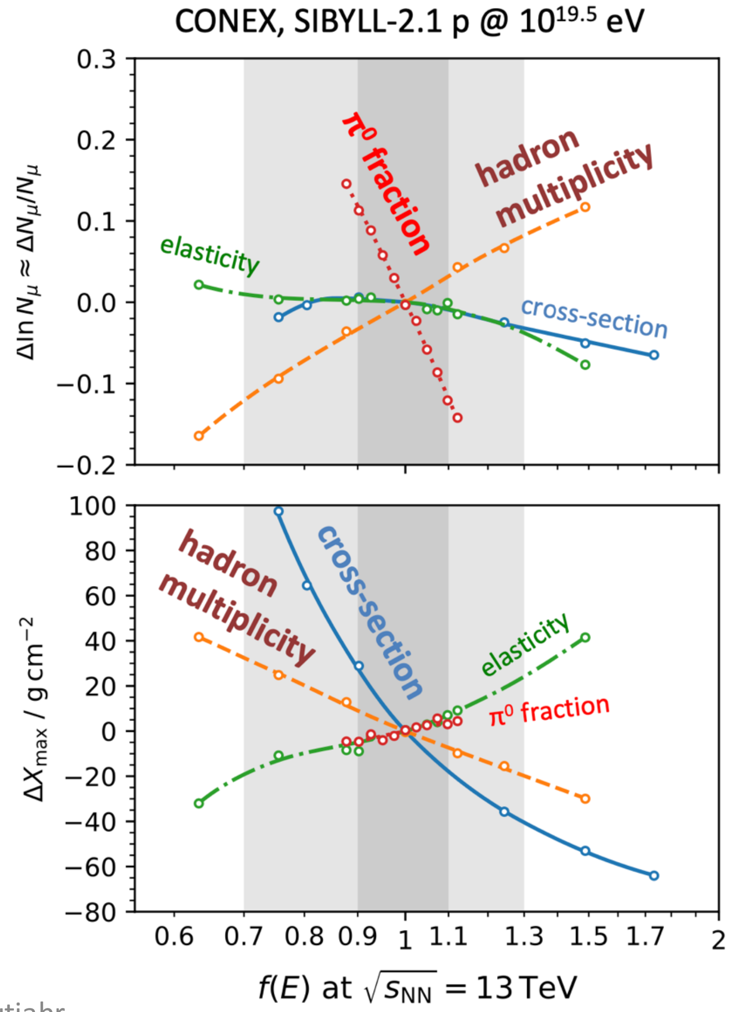
$$z = \frac{\ln\langle N_\mu\rangle - \ln\langle N_\mu\rangle_p}{\ln\langle N_\mu\rangle_{\mathrm{Fe}} - \ln\langle N_\mu\rangle_p}$$



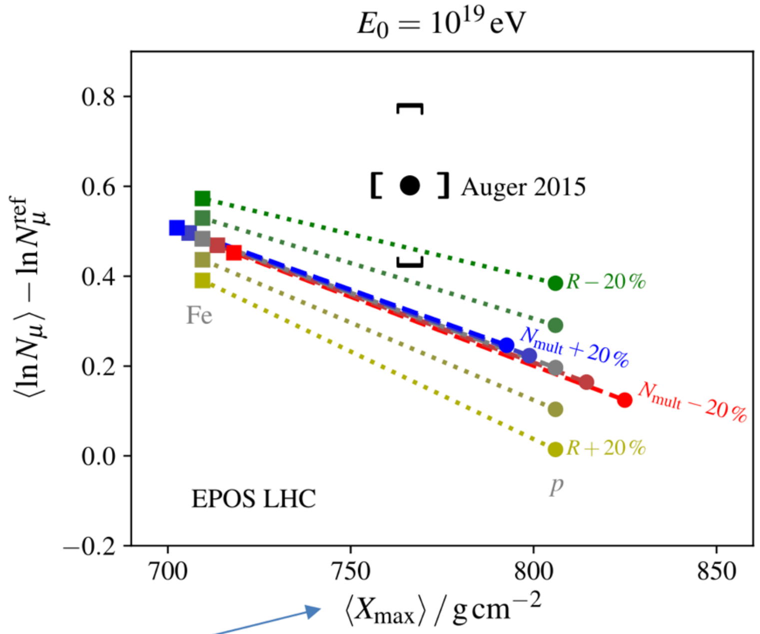
2108.08341

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



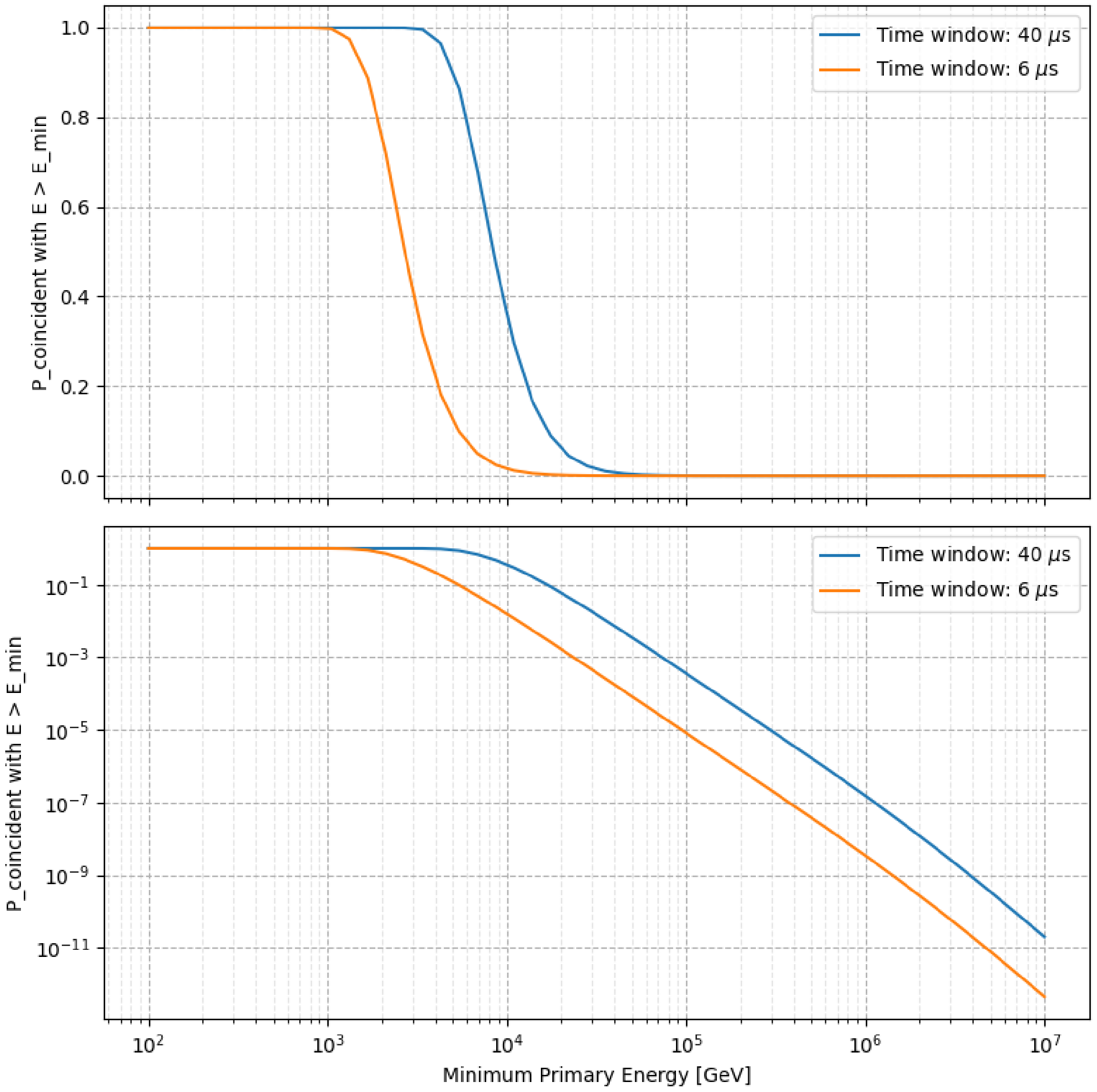
$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

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

Hans Dembinski

Simulation w/o coincident events

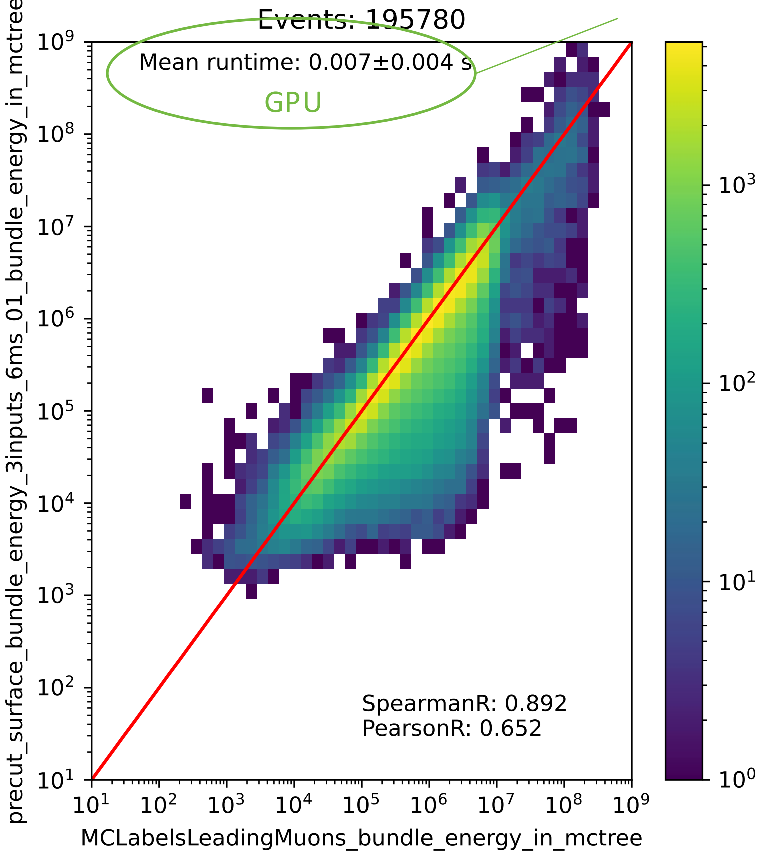
- for primary energies above 10 TeV, using a time window of 6 µs, the chance for a coincident event is ≤ 1 %

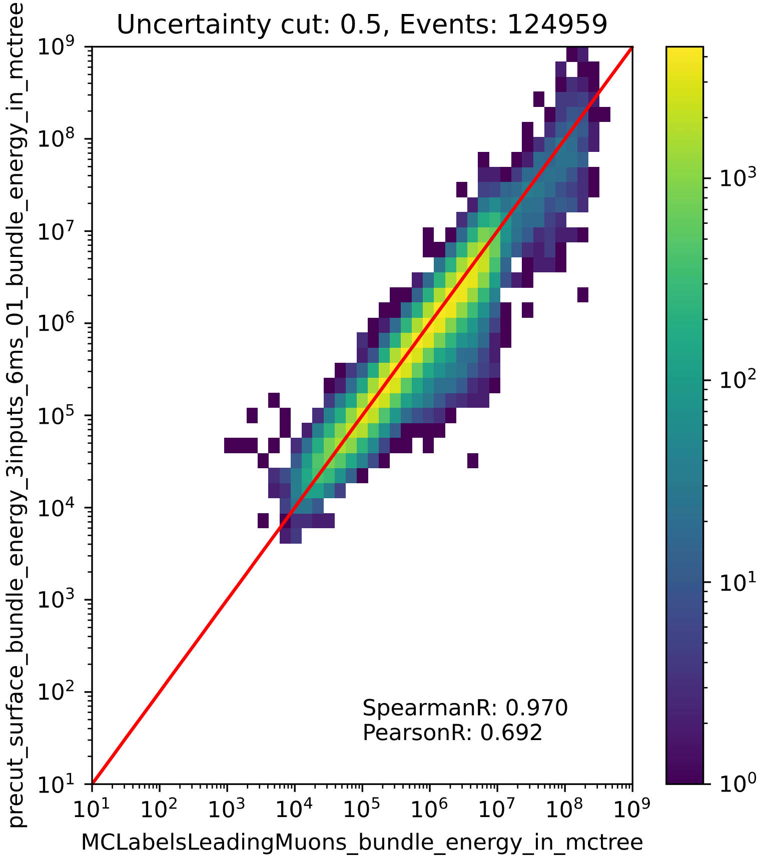


Bundle energy cut

- 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

CPU runtime: 11 ± 1ms

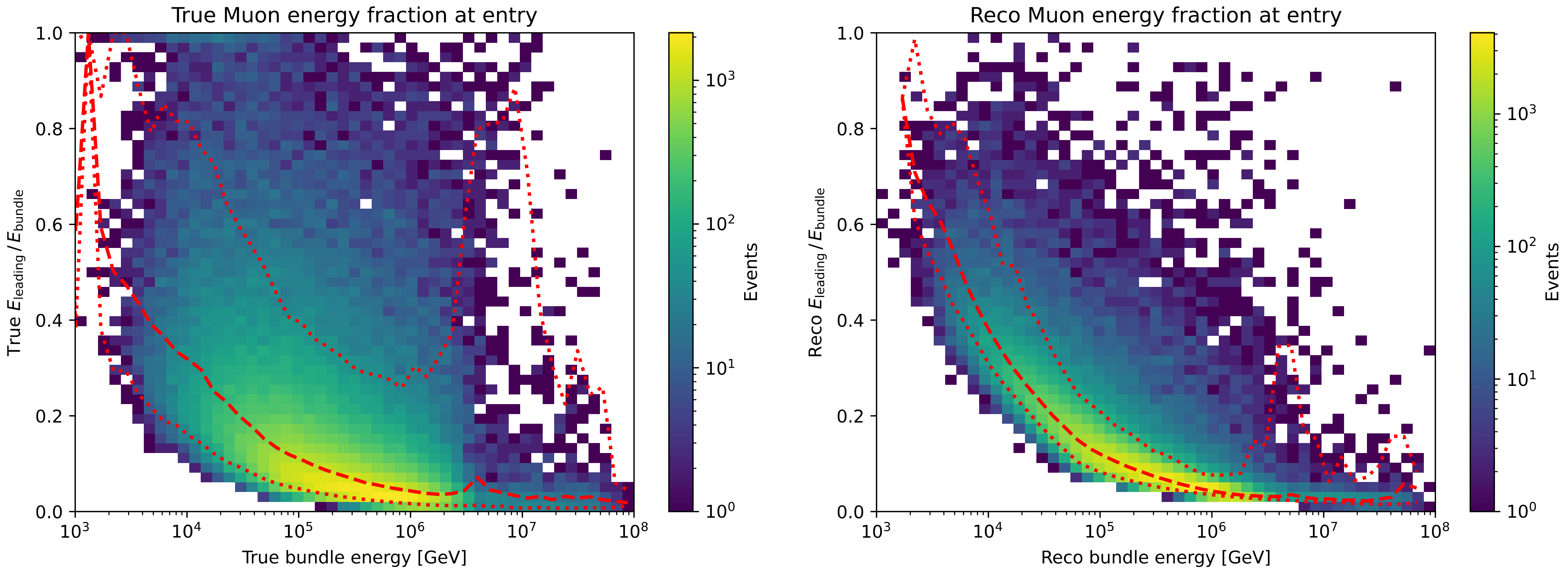




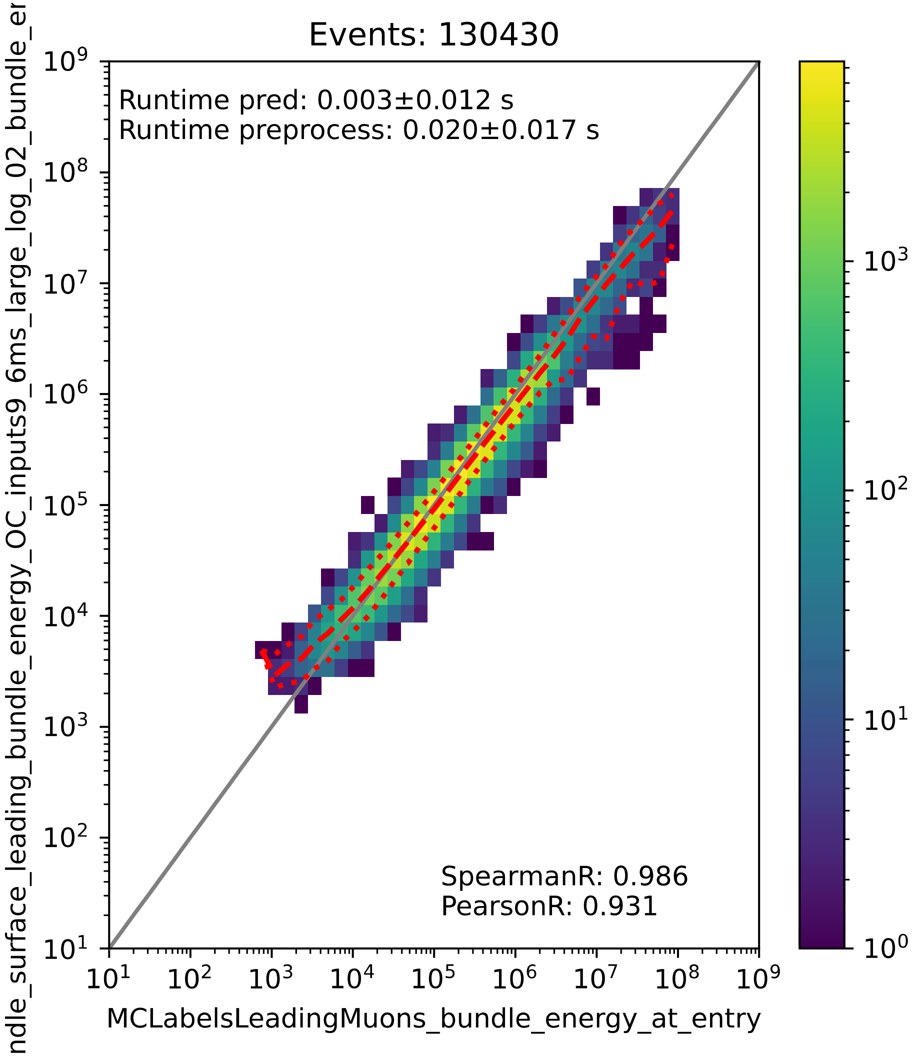
Network: precut_surface_bundle_energy_3inputs_6ms_01

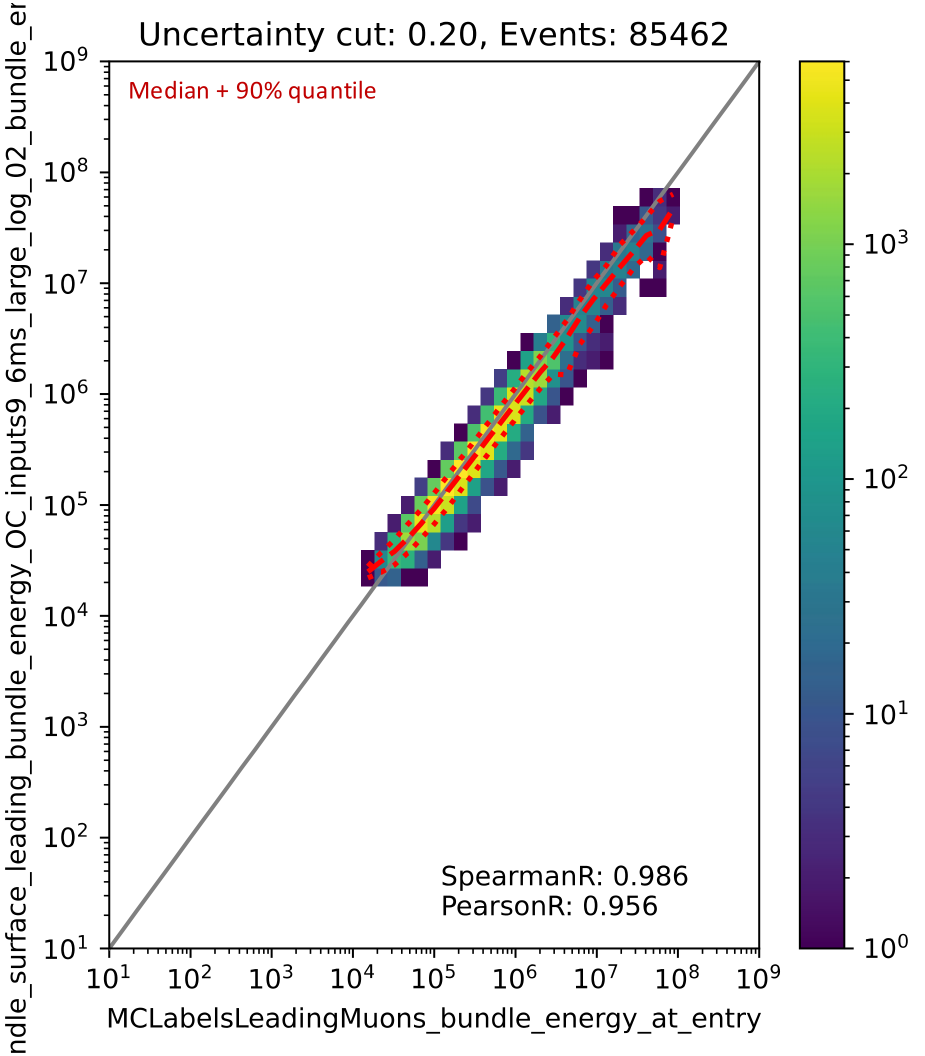
Leading muon energy fraction - leadingness

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



Bundle energy at entry – 6 µs cleaned pulses



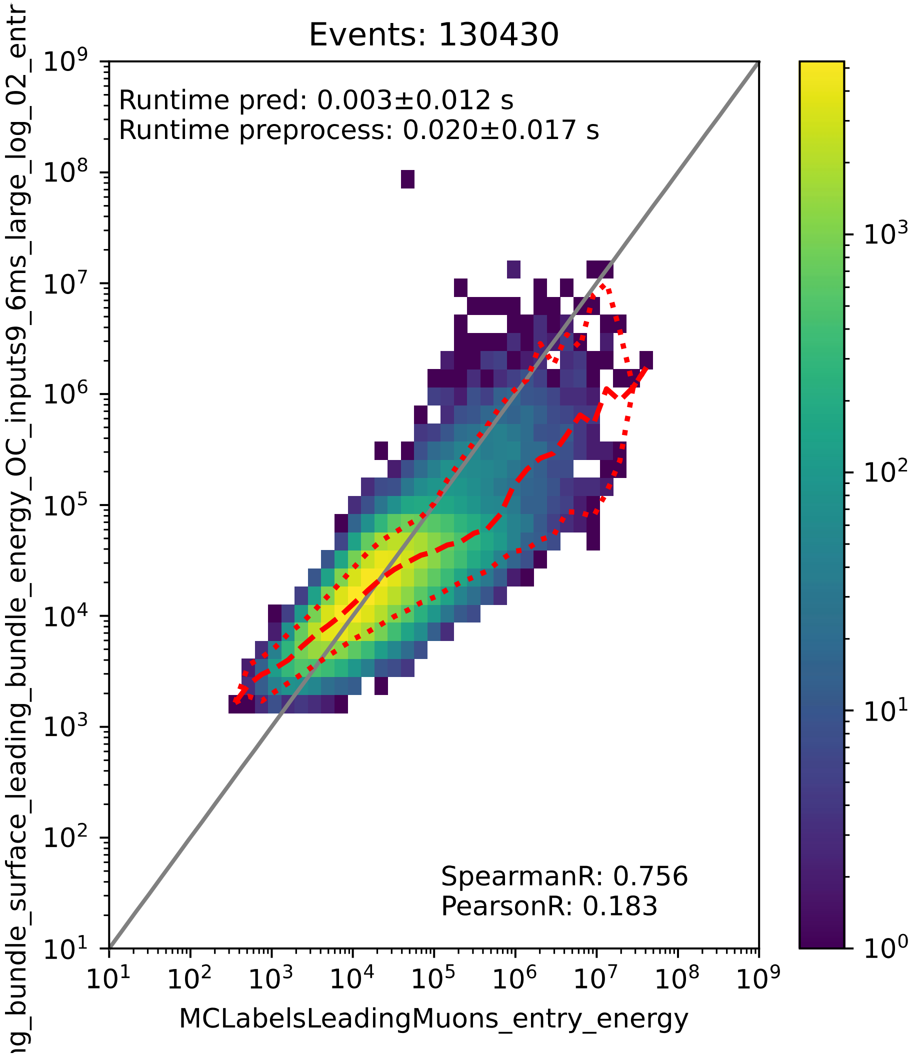


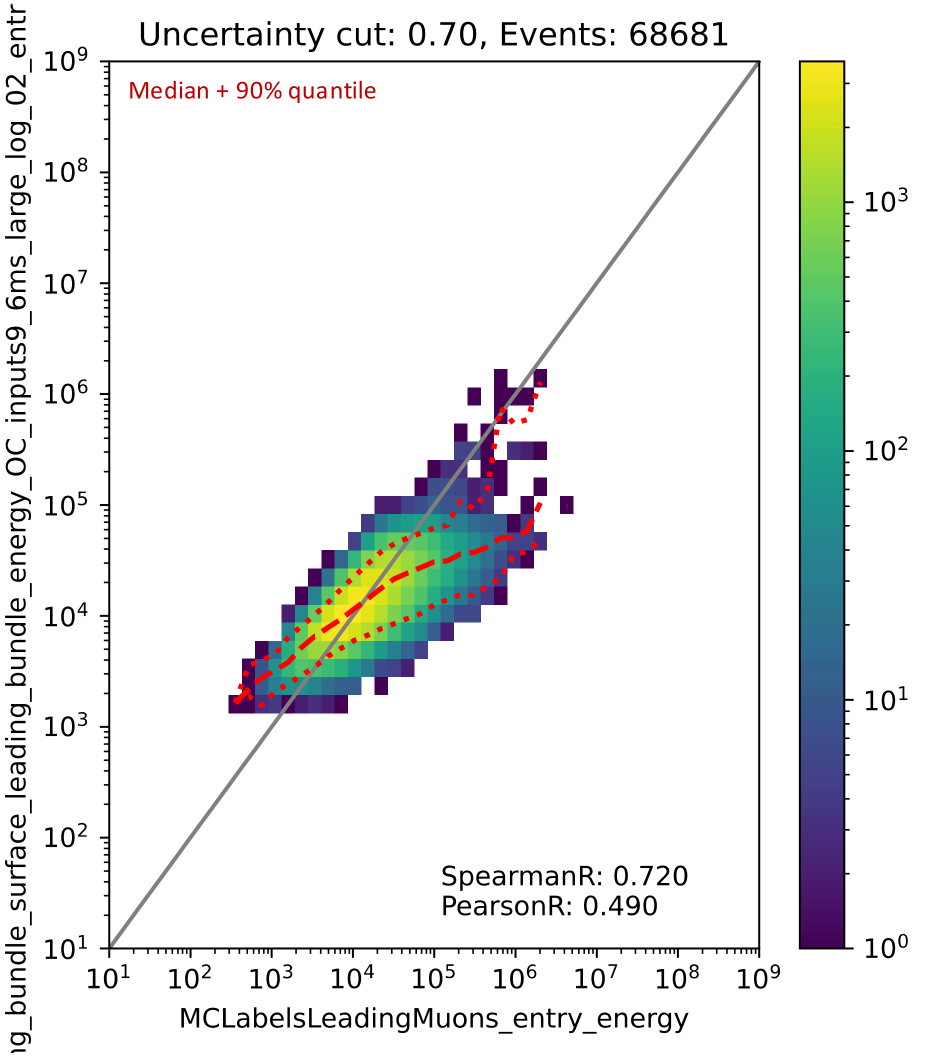
Prediction

True

Leading muon energy at entry – 6 µs cleaned pulses

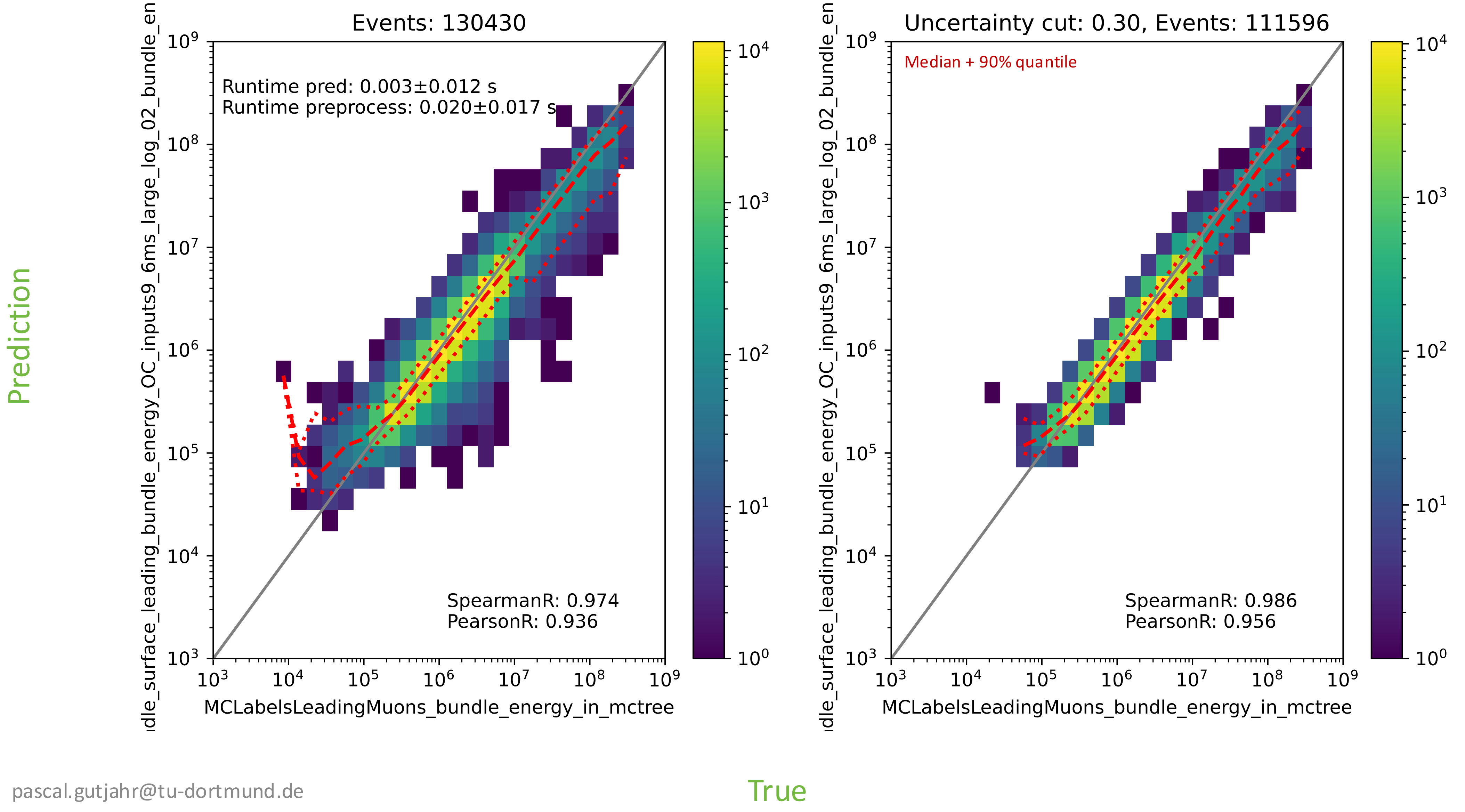
Prediction



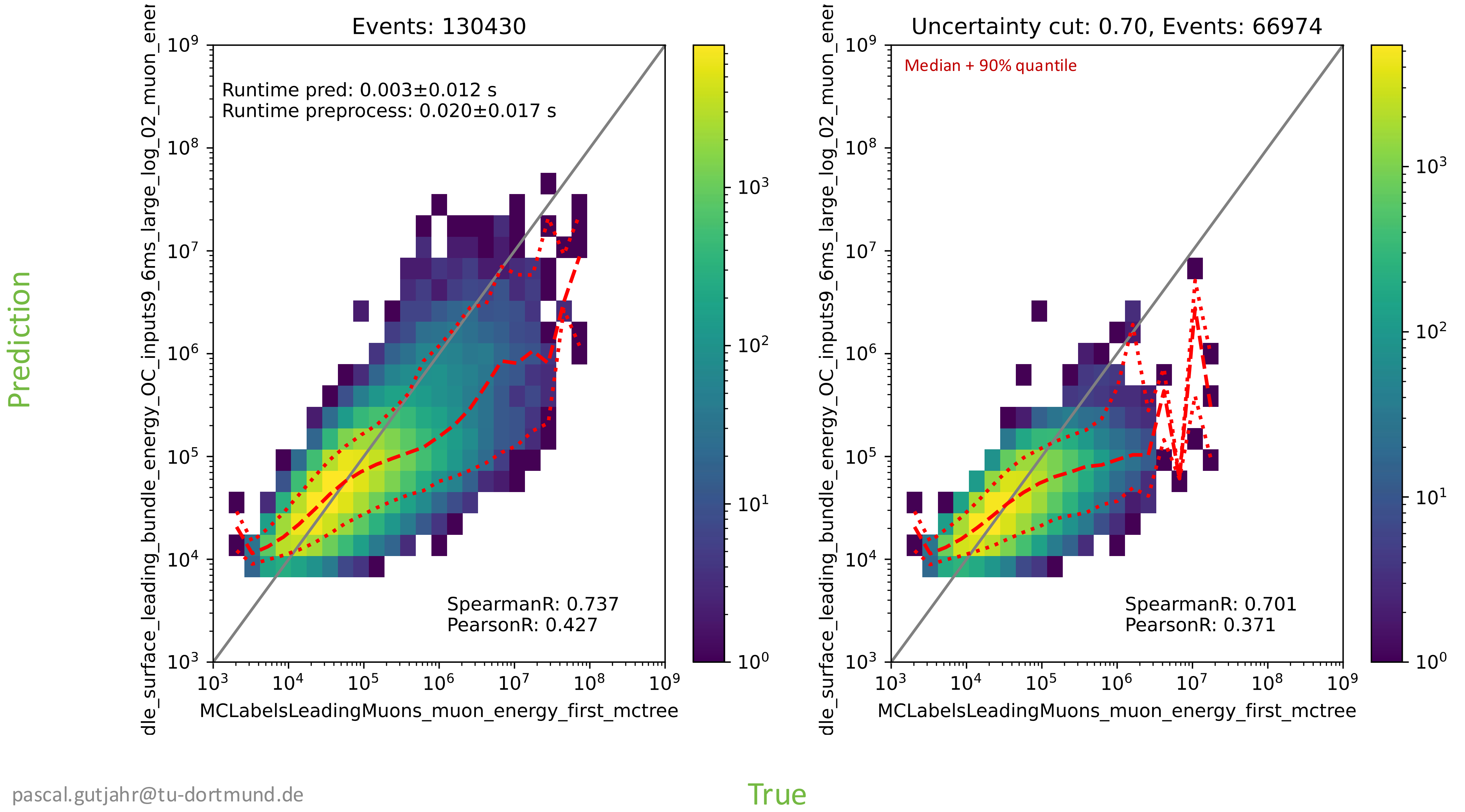


True

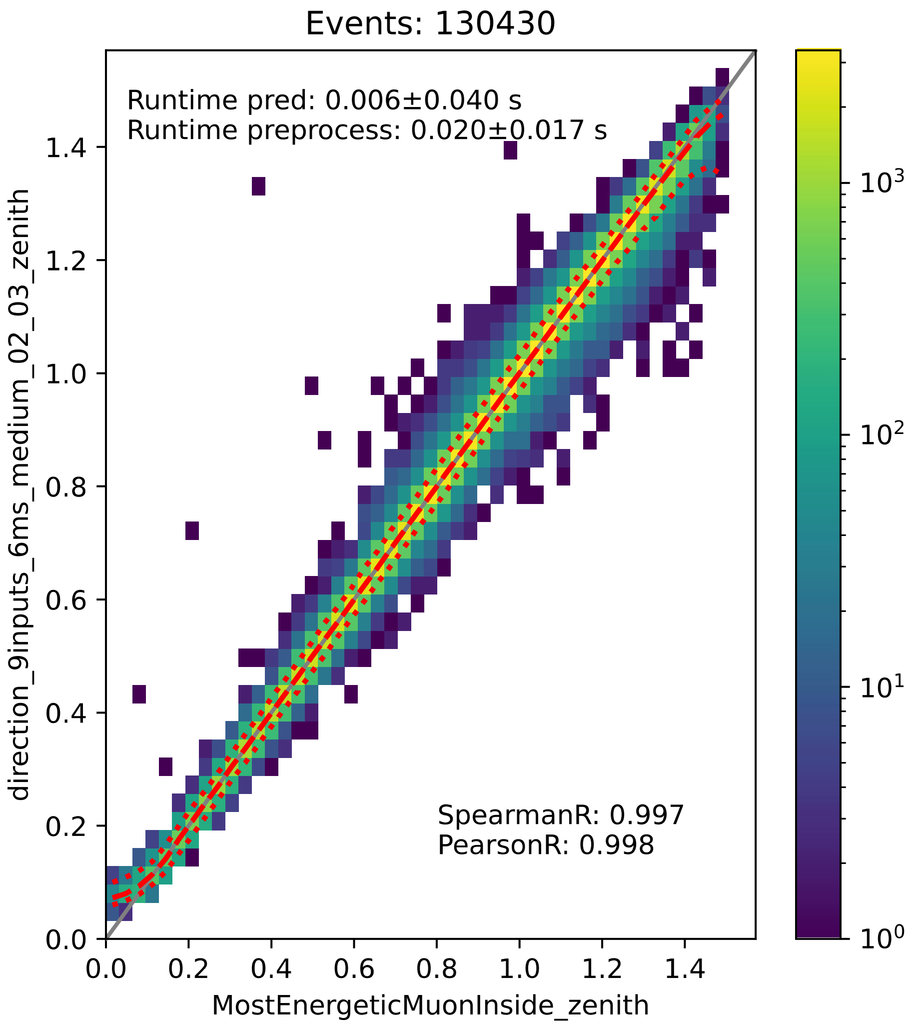
Bundle energy at surface – 6 µs cleaned pulses

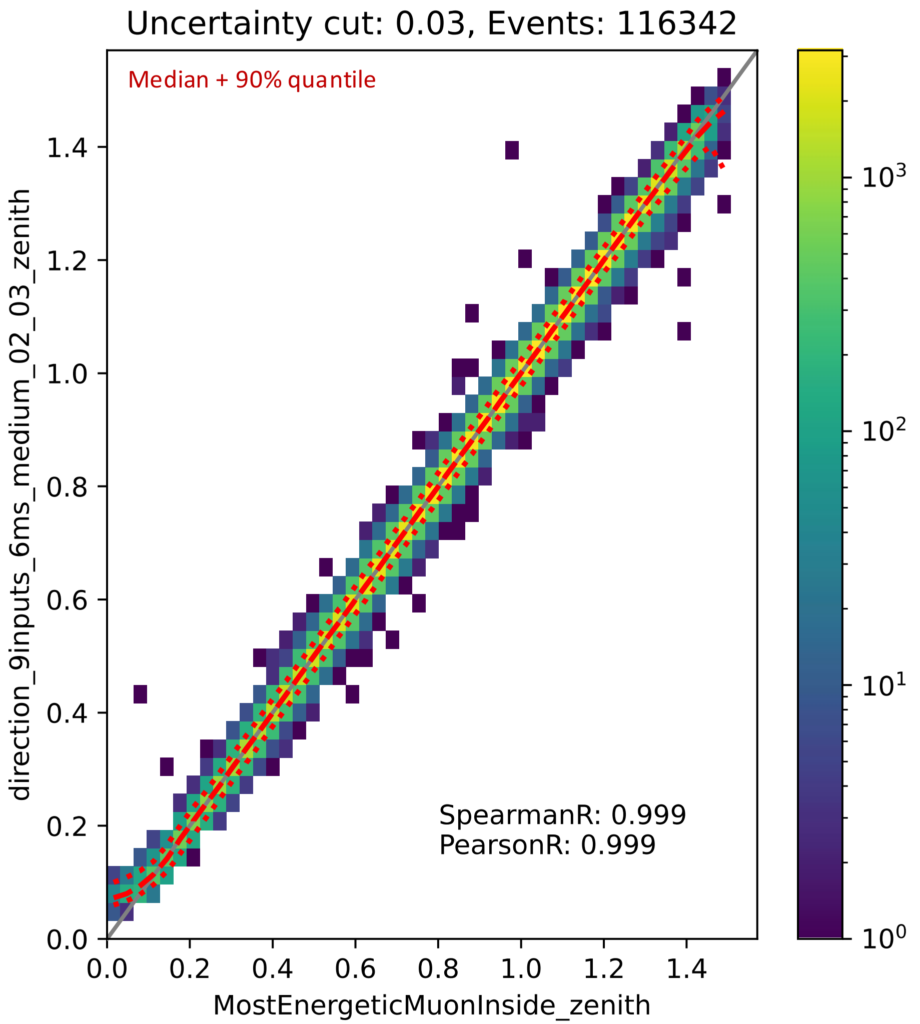


Leading muon energy at surface – 6 µs cleaned pulses



Zenith – 6 ms cleaned pulses





Prediction

True

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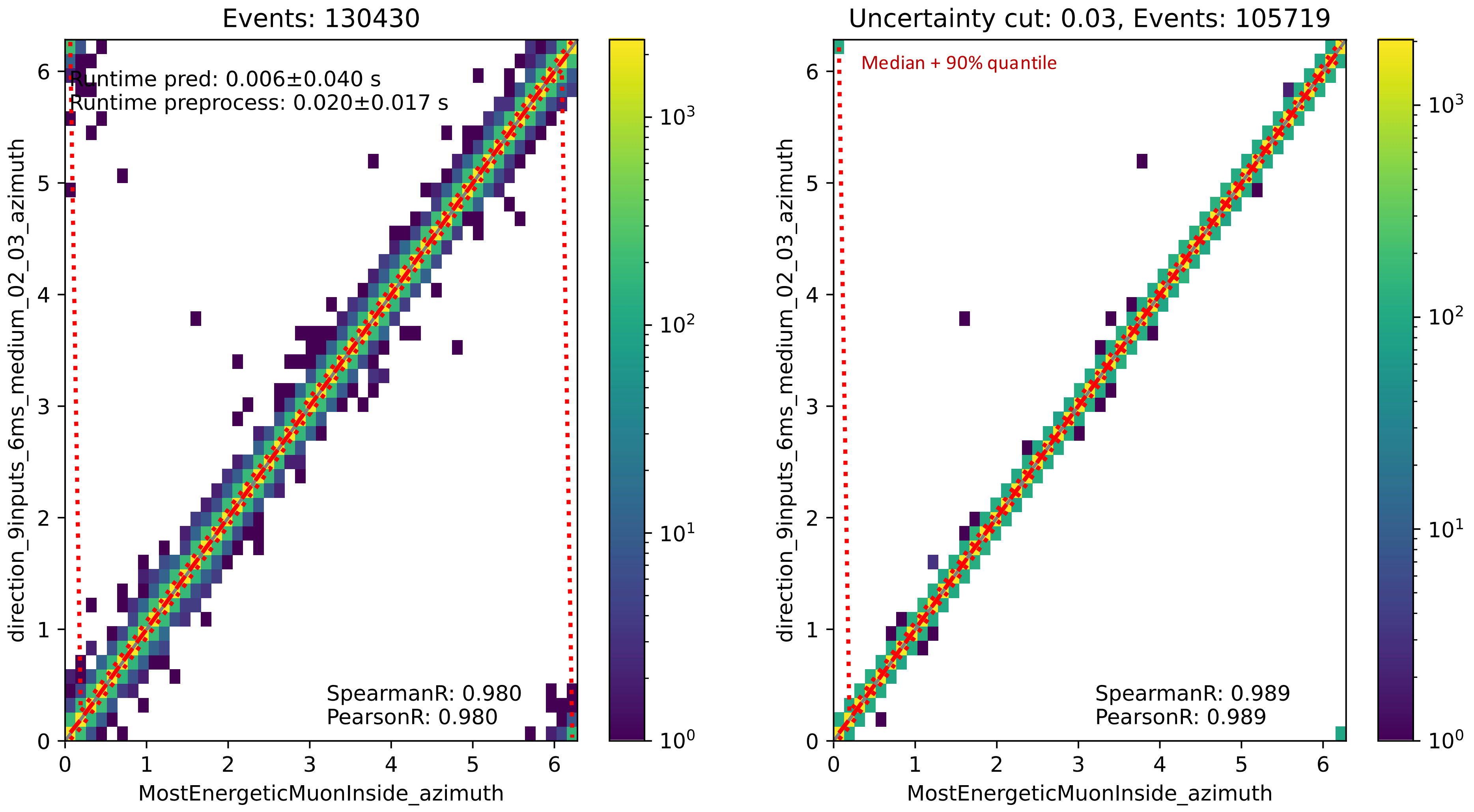
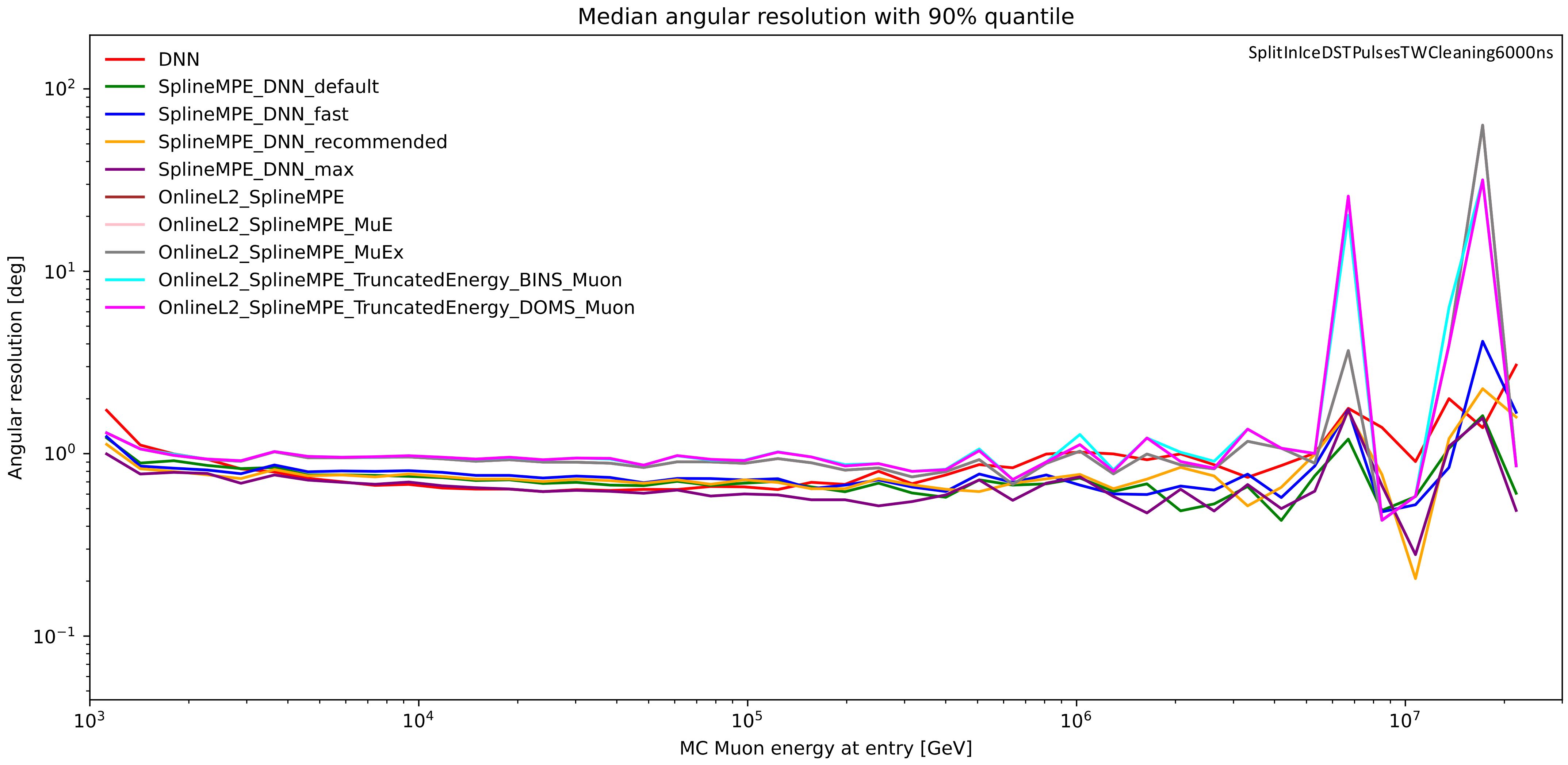
Azimuth – 6 ms cleaned pulses

Prediction

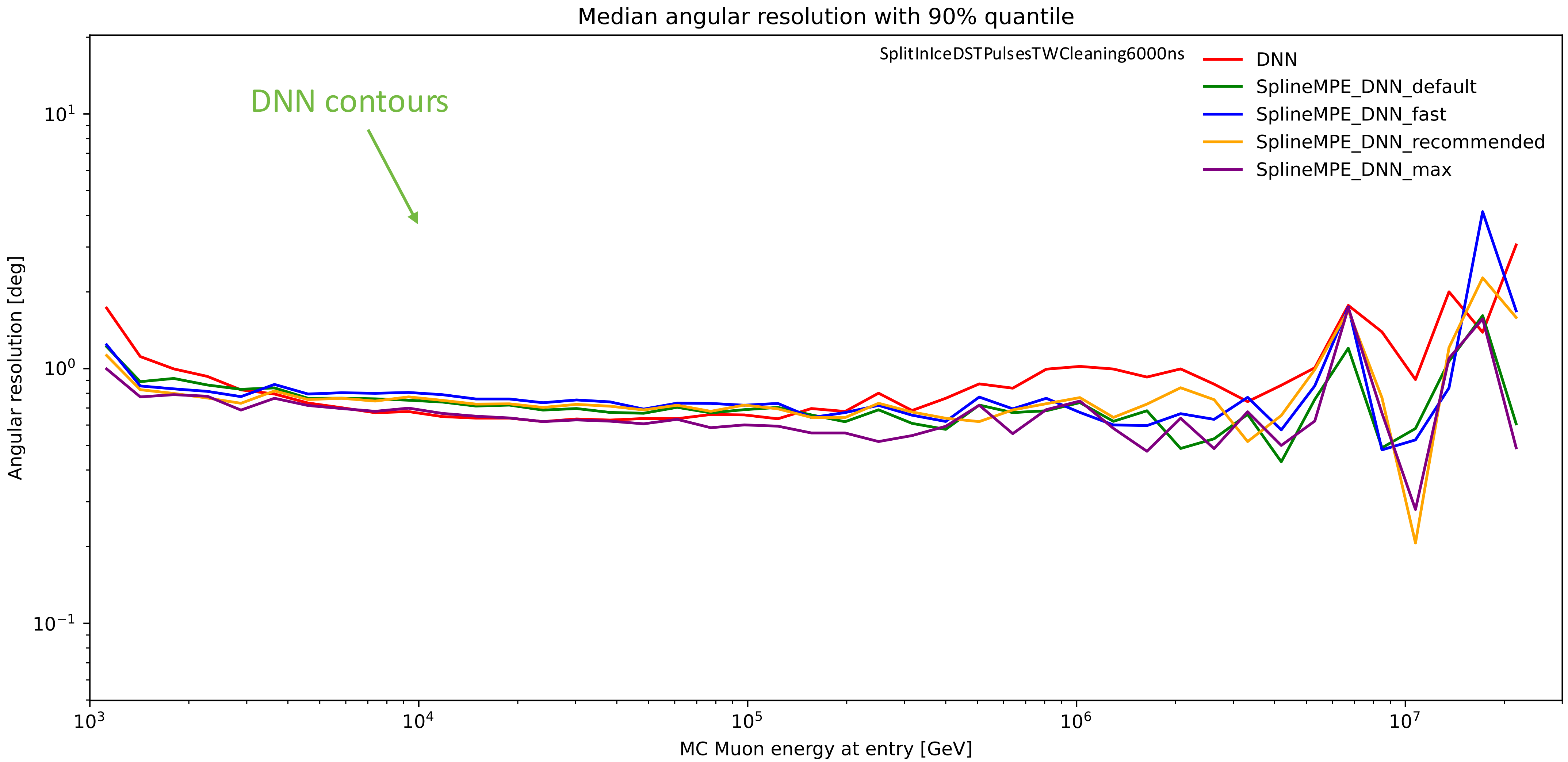


True

SplineMPE – DNN and conventional seeds

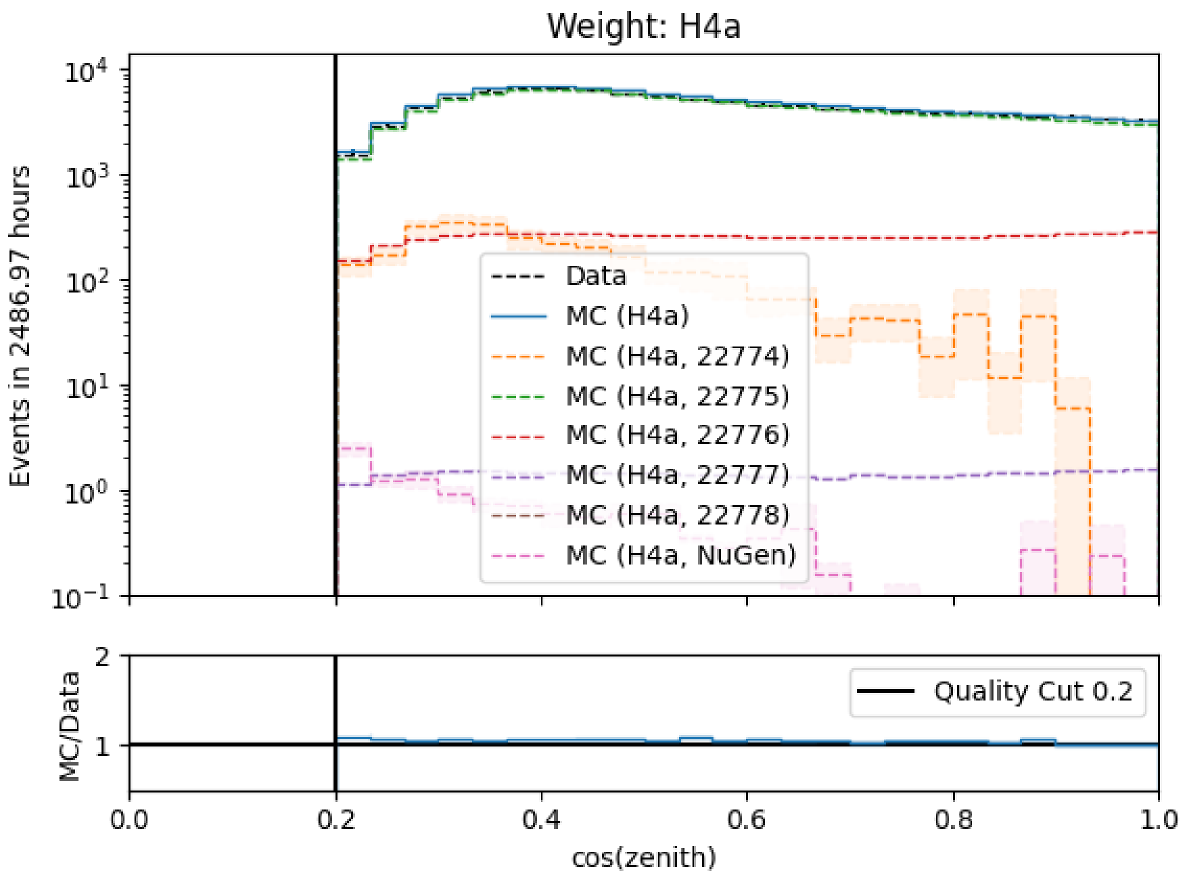


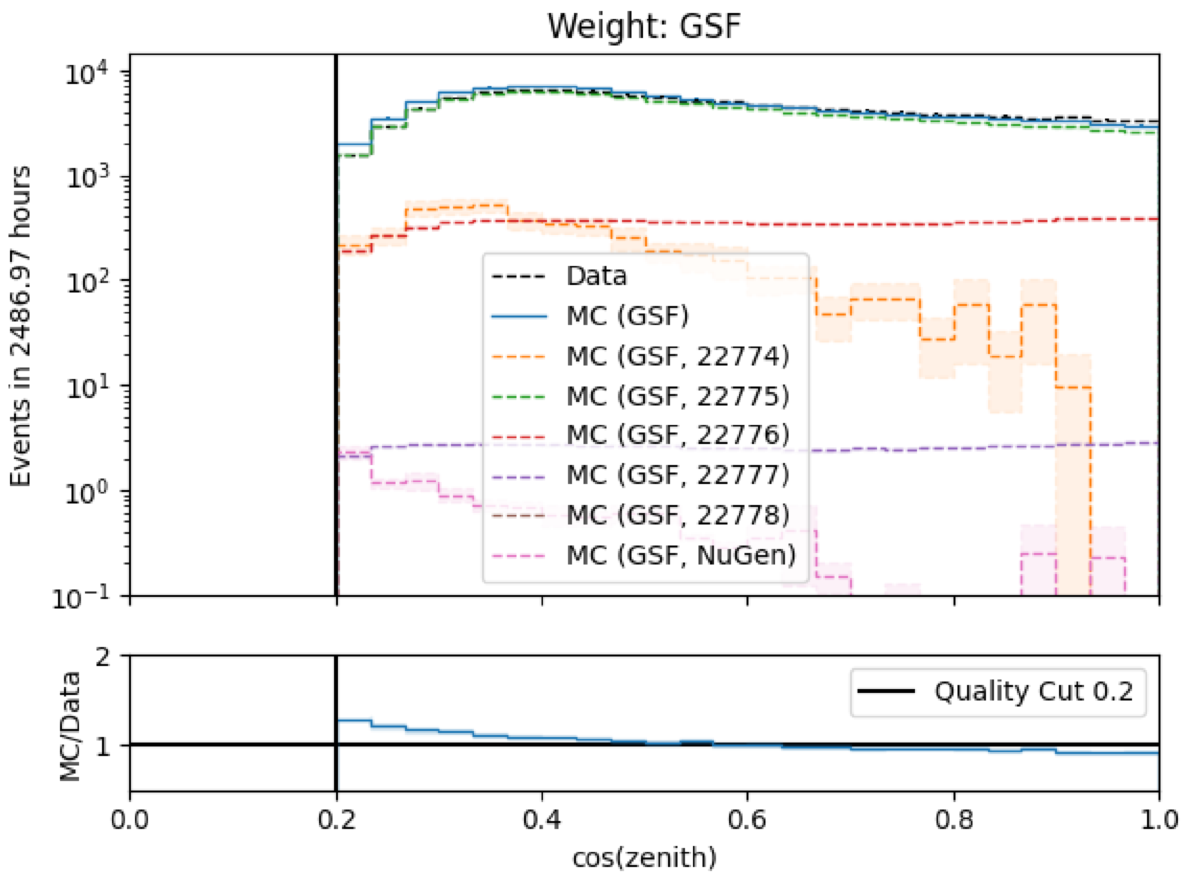
SplineMPE – DNN seeds



DNN contours

Level5: cos(zenith)





Caution:
weights are scaled

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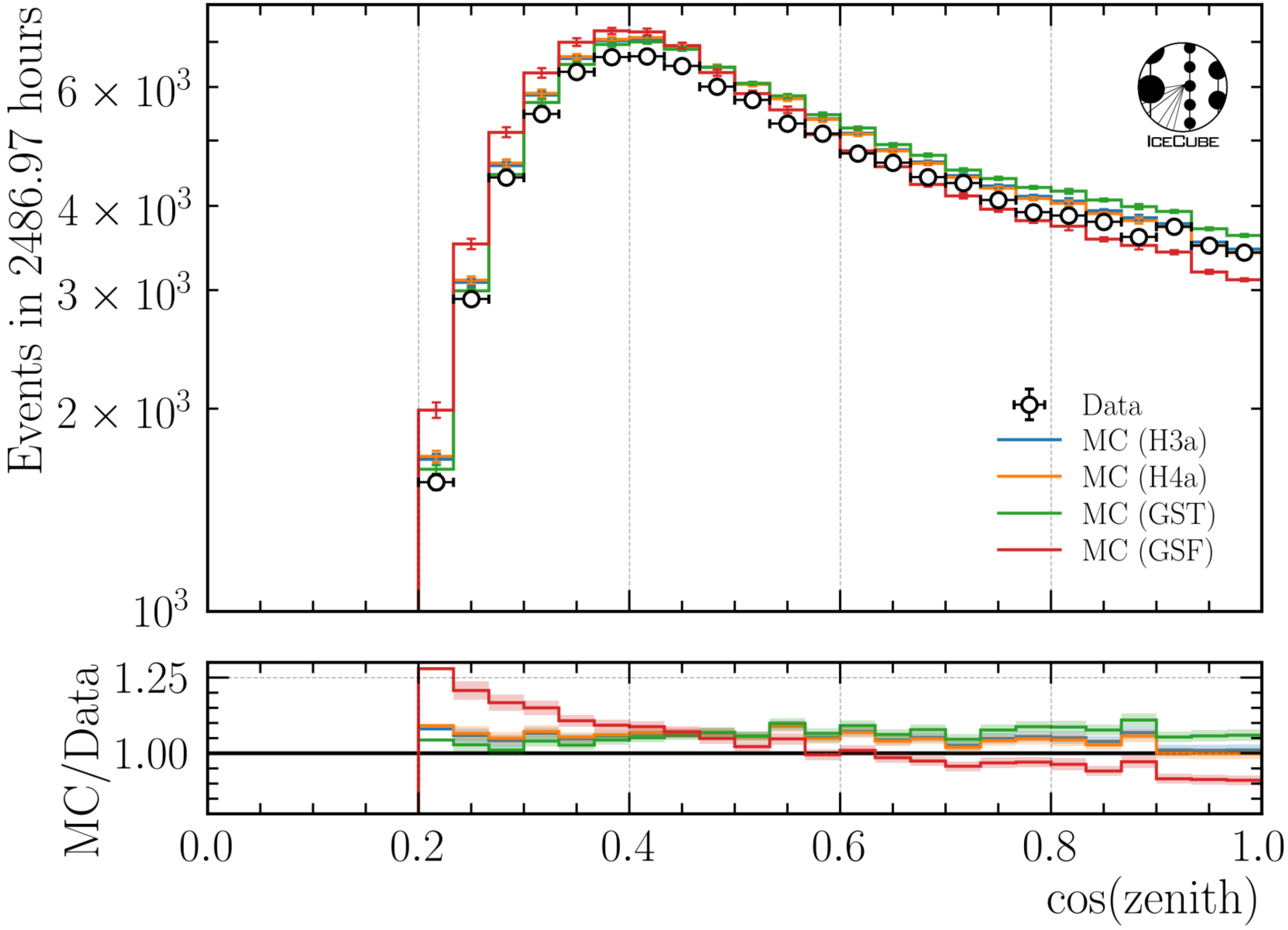
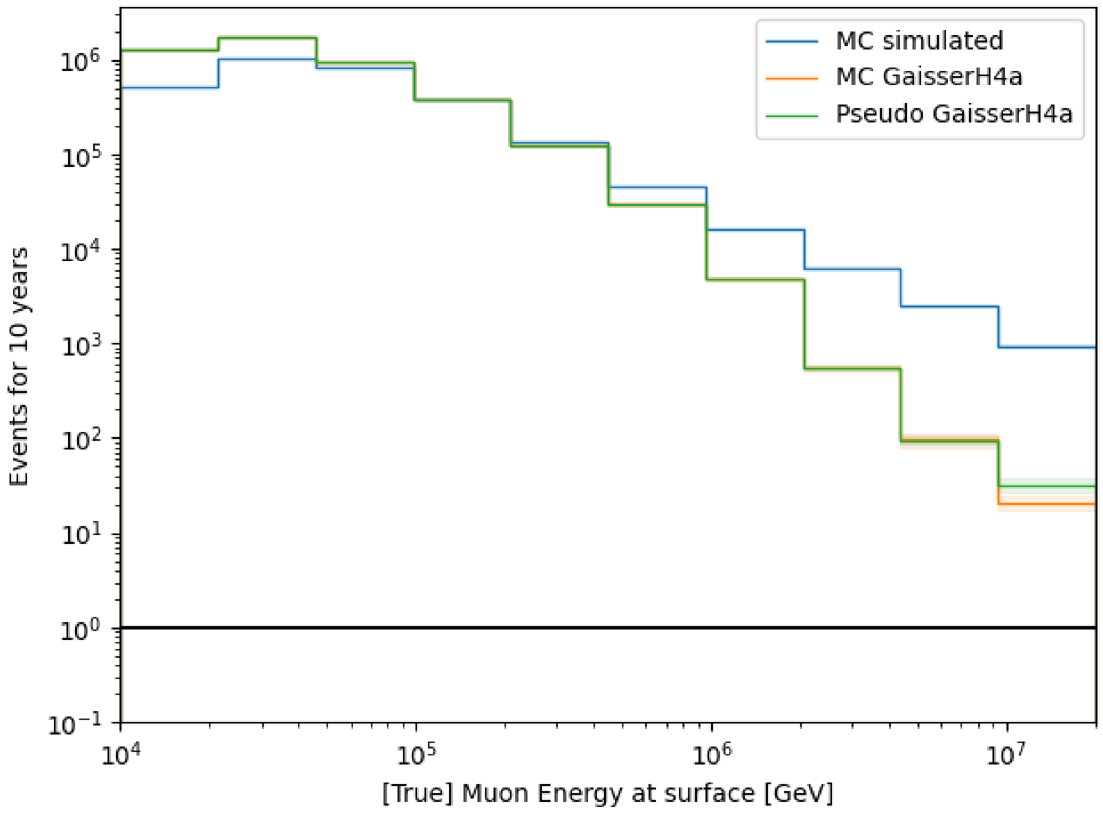
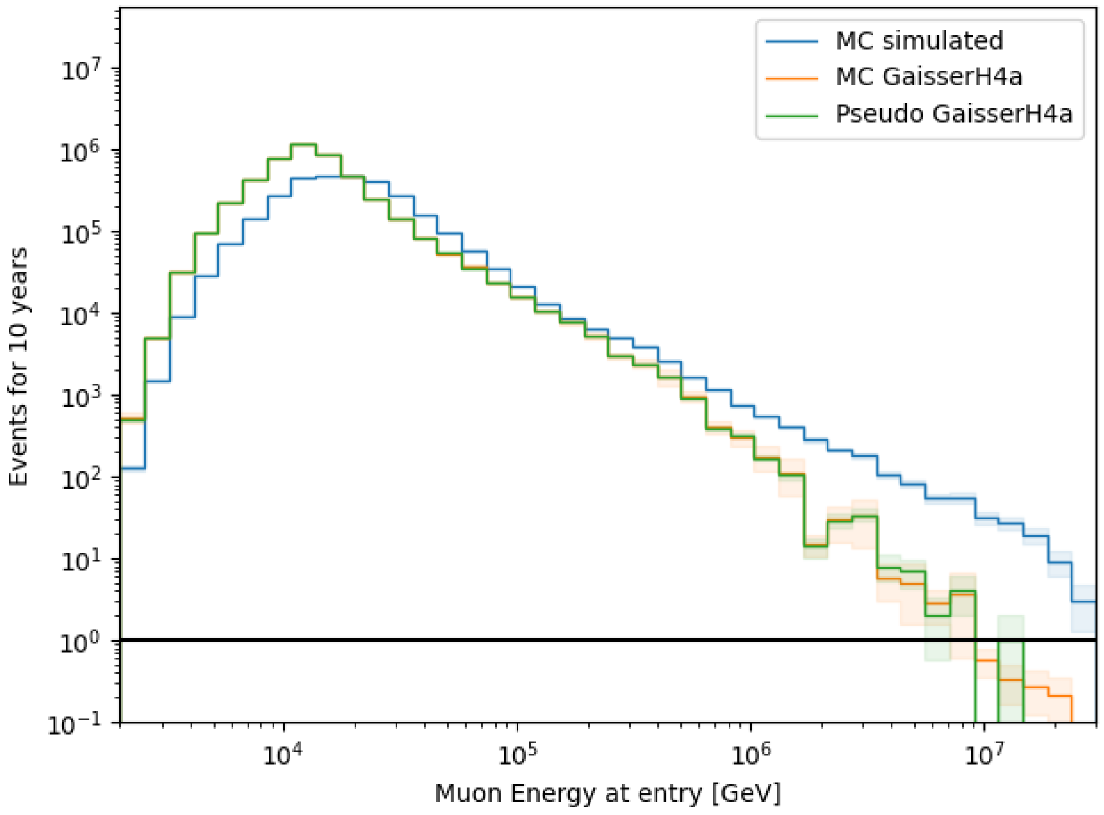
Level5: cos(zenith) – all primary models



Caution:
weights are scaled

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





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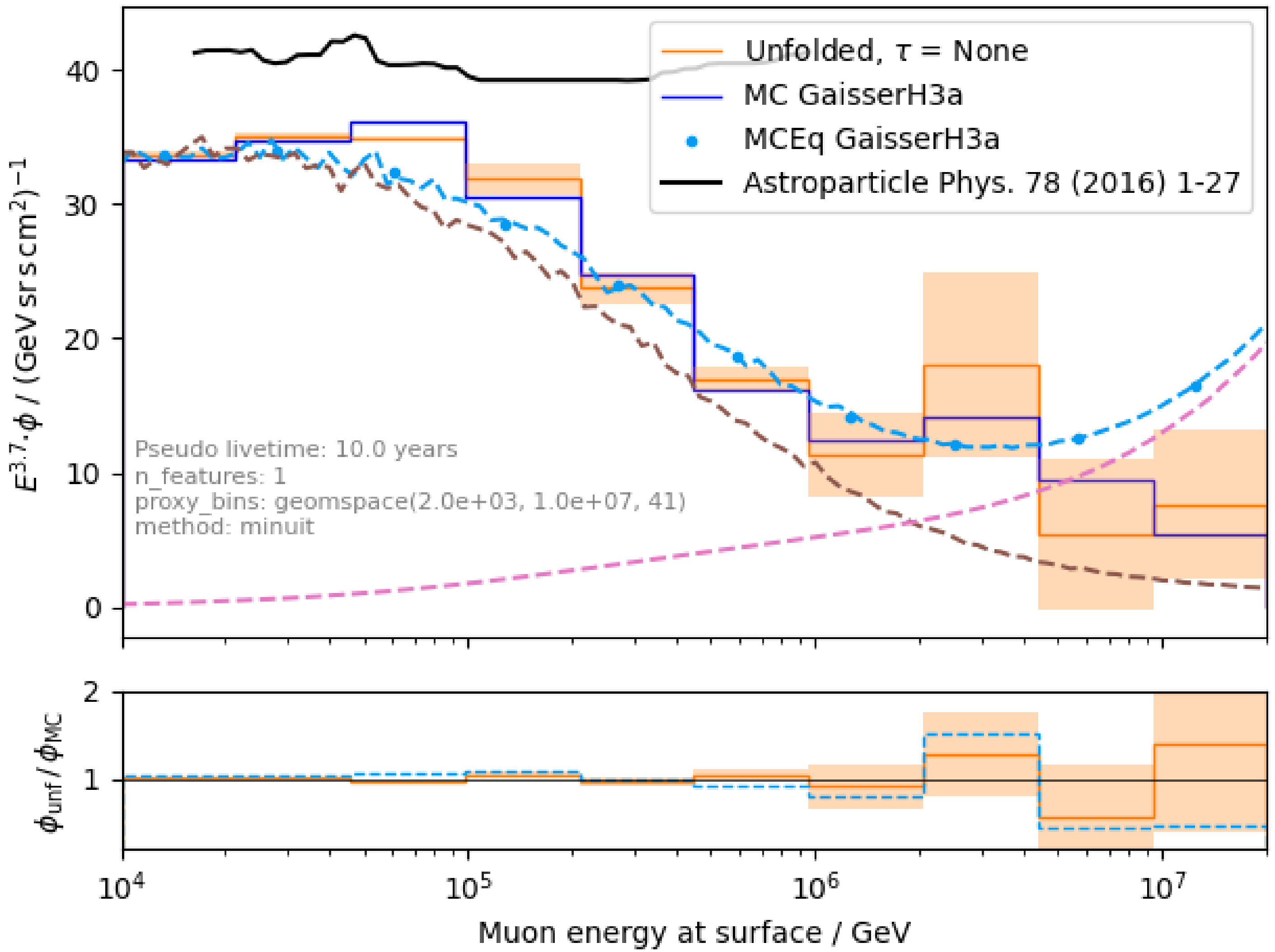
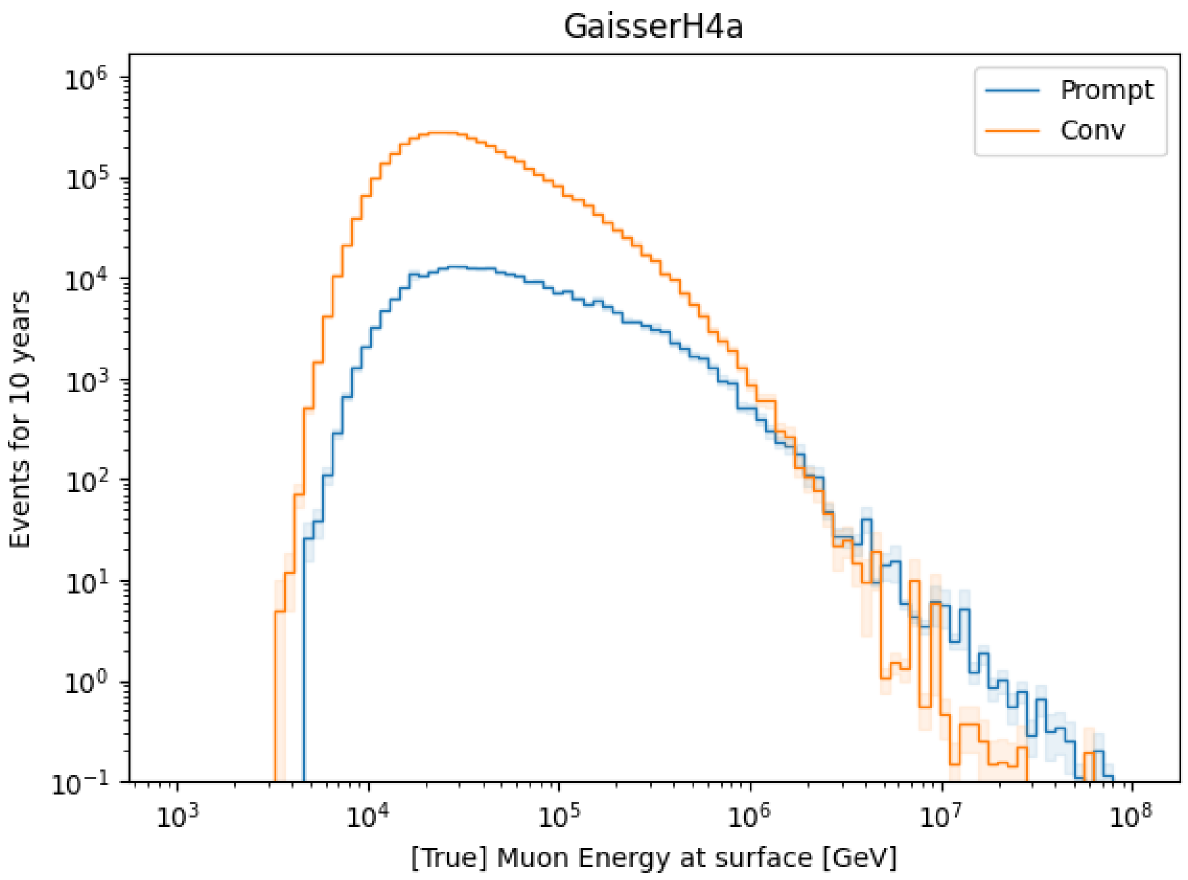
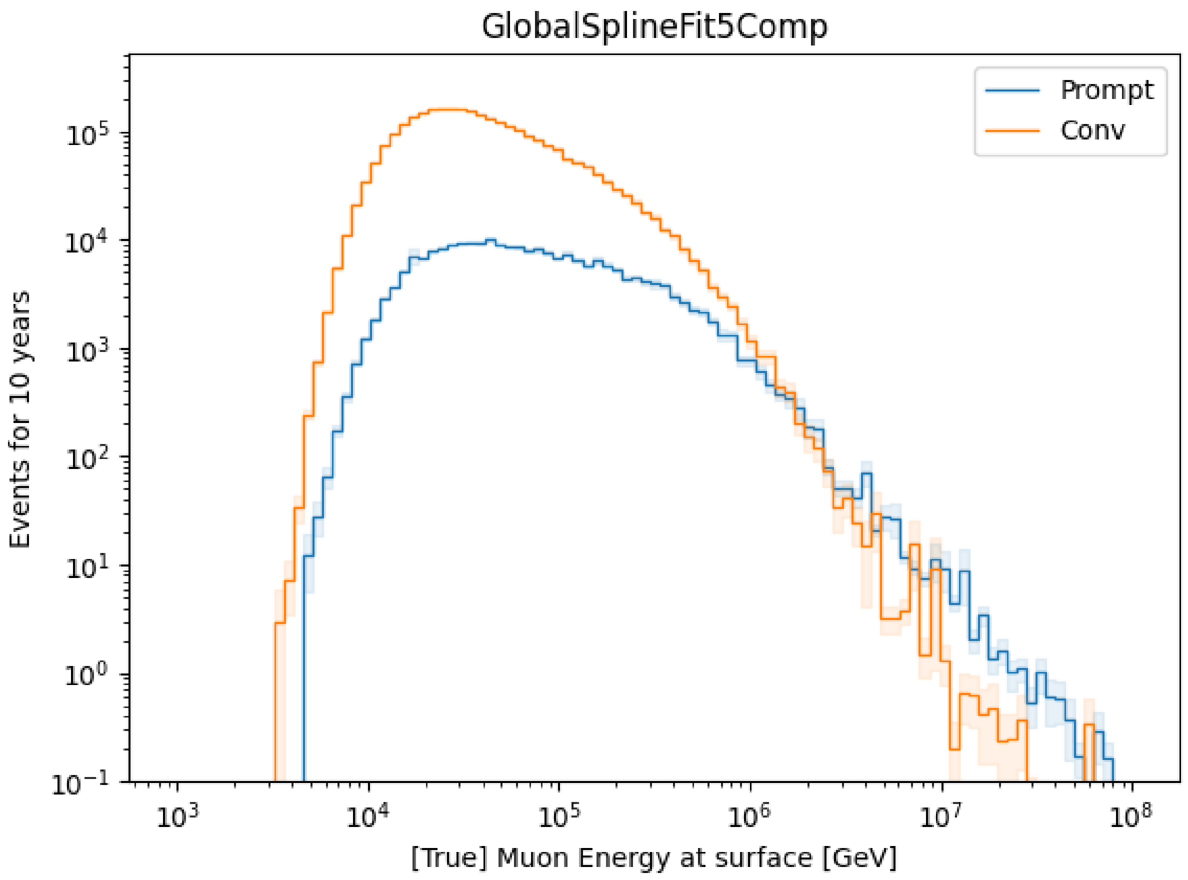
Unfolding with prompt and conv MCEq

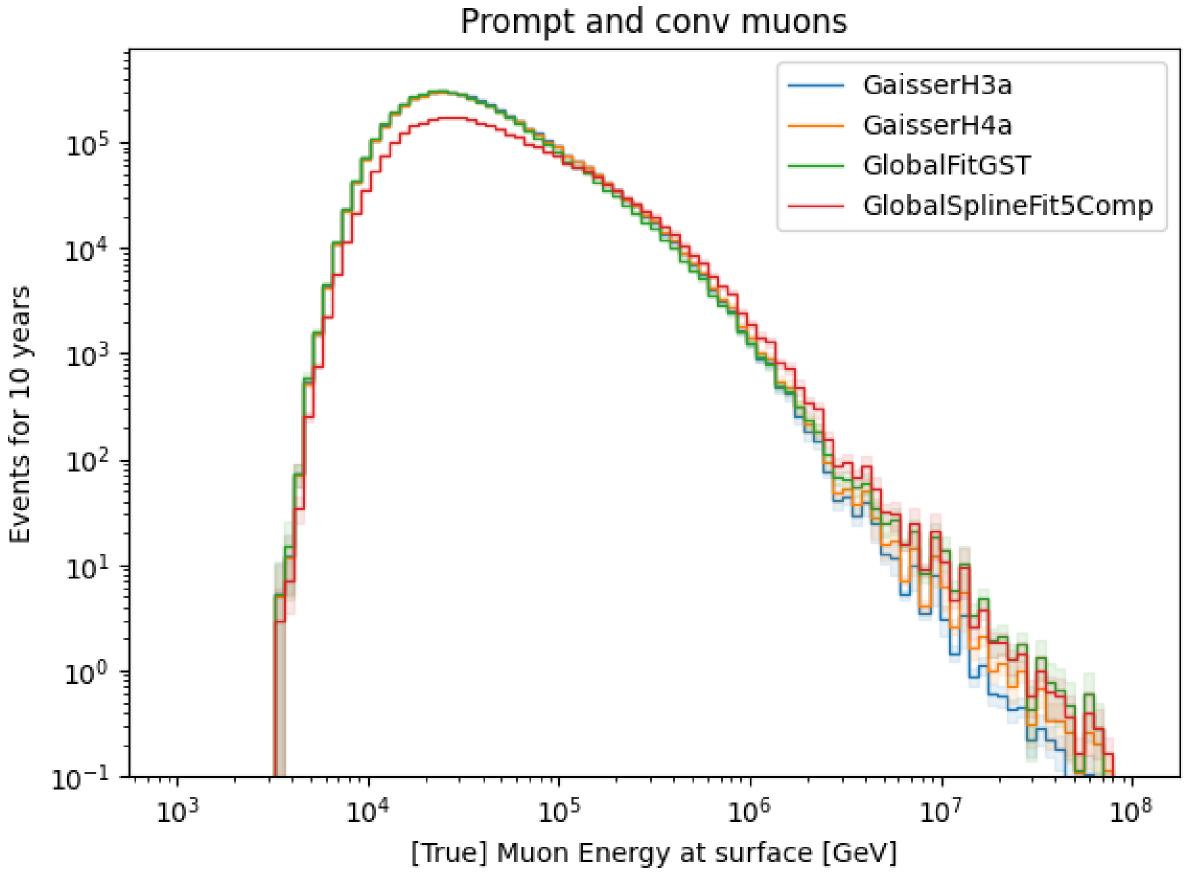


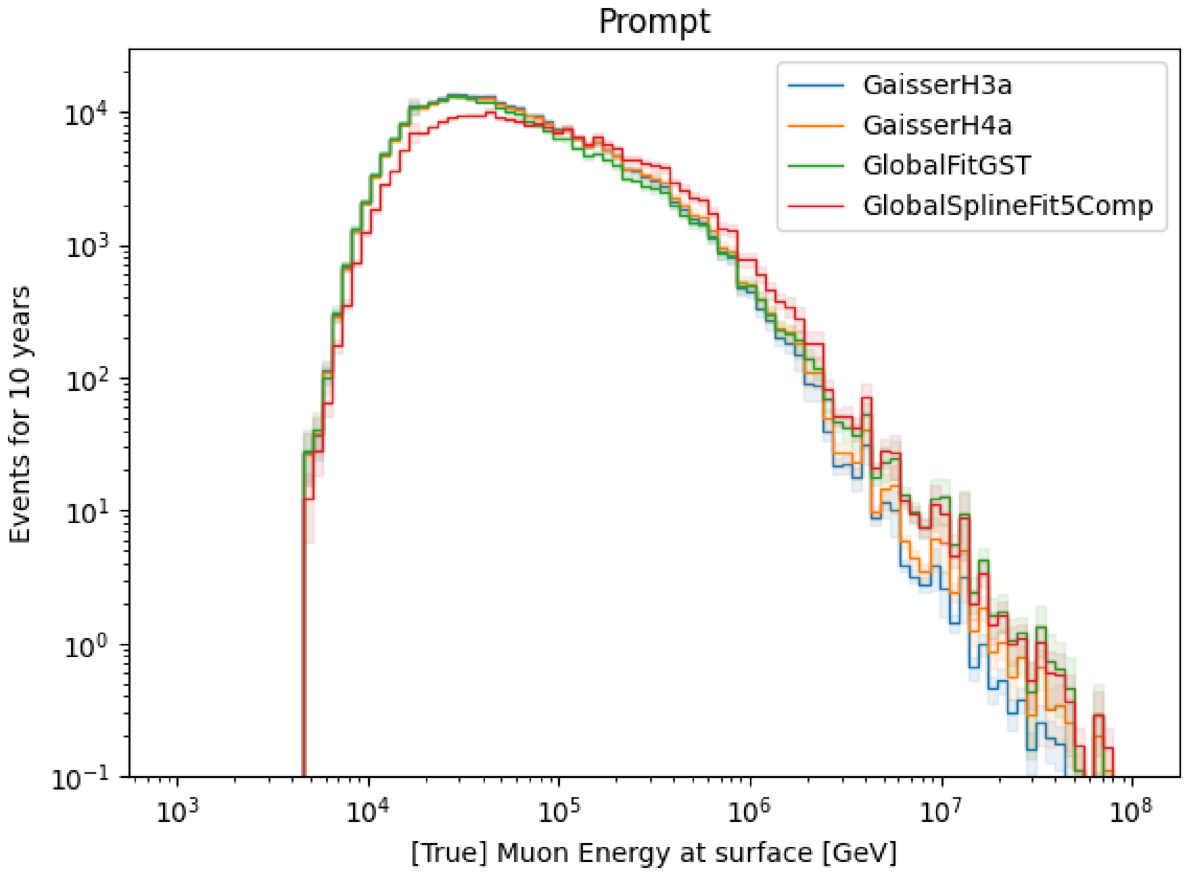
Prompt and conv: muon energy at surface for 10 years



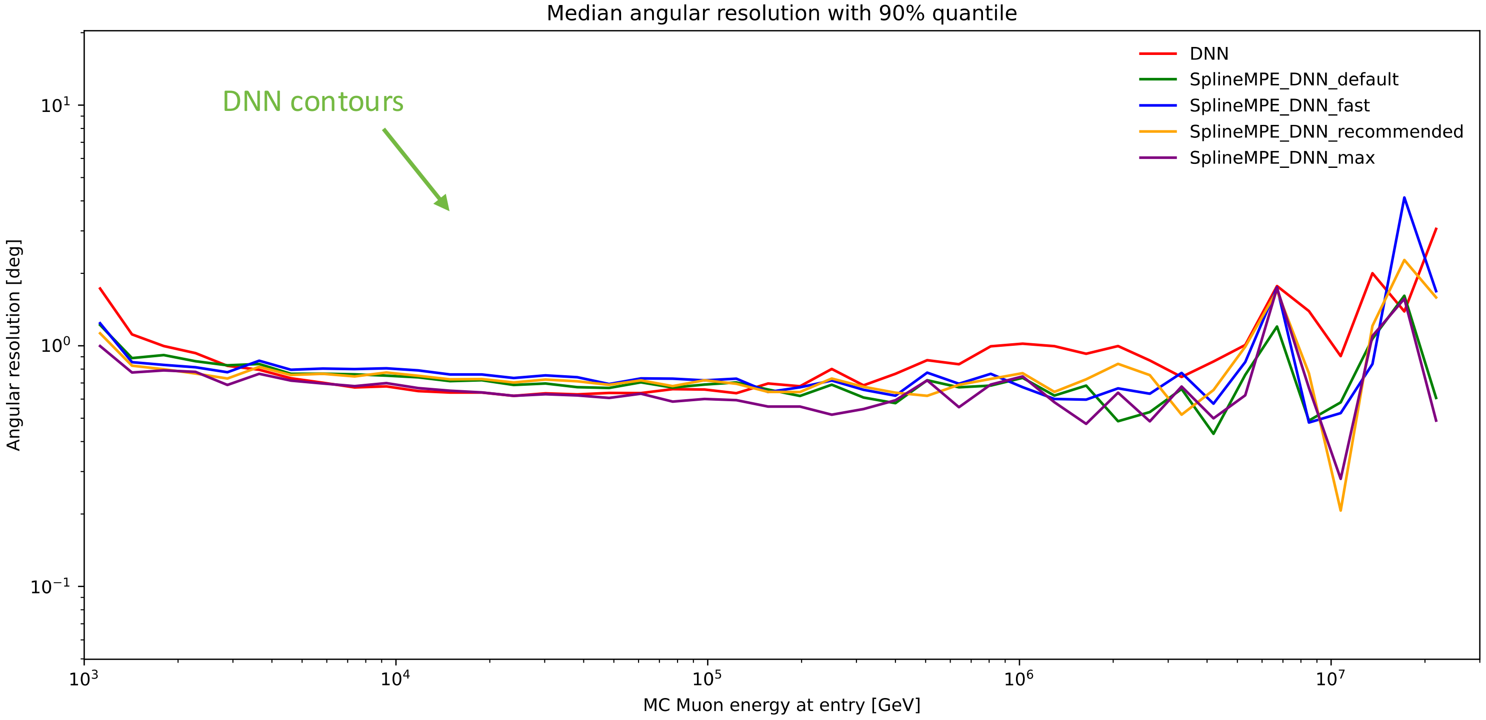


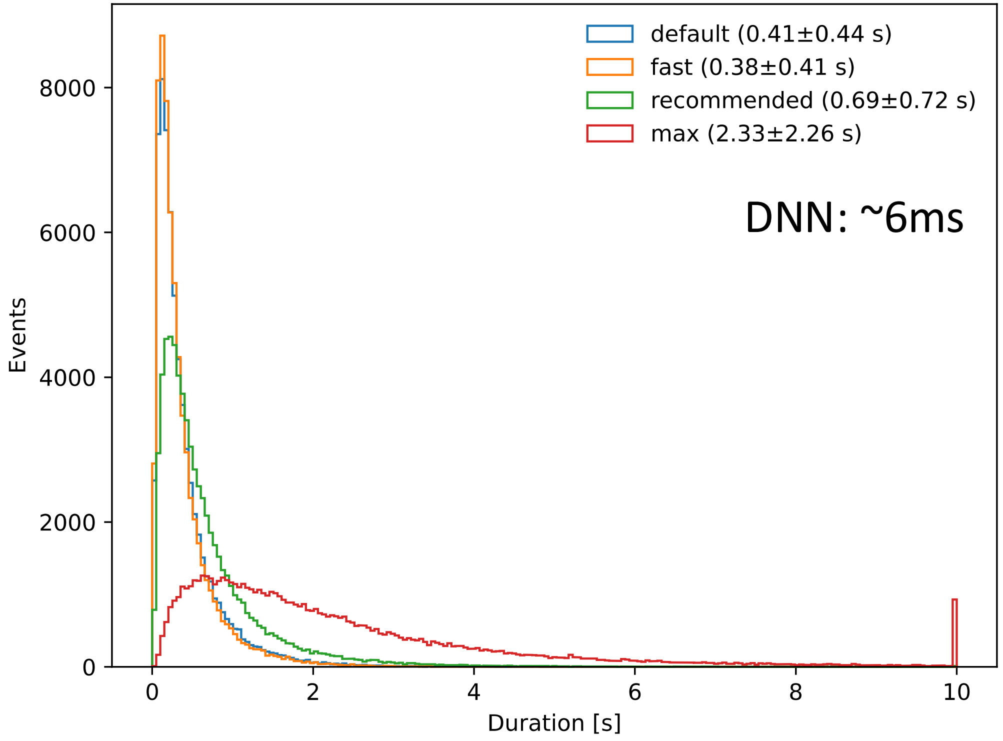
Compare all primary fluxes





Angular reconstructions: DNN vs. SplineMPE





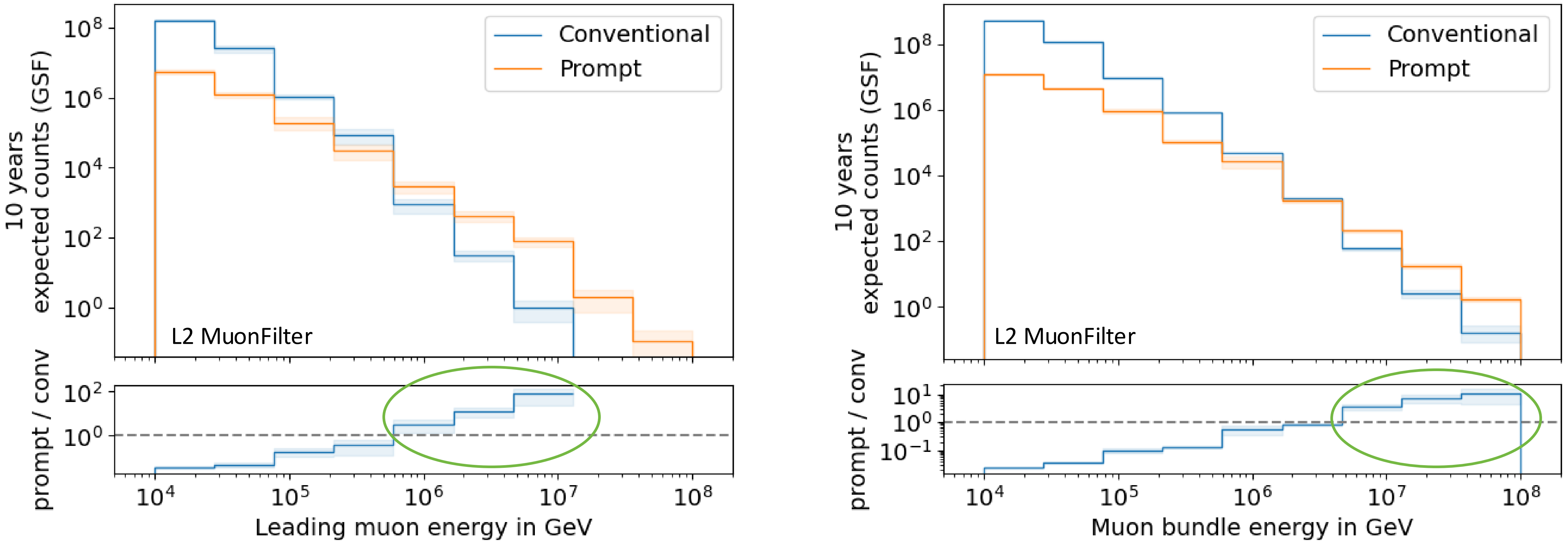
- Only small improvement at energies around 1 PeV
- Countours are larger
- Additional runtime

-> 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)

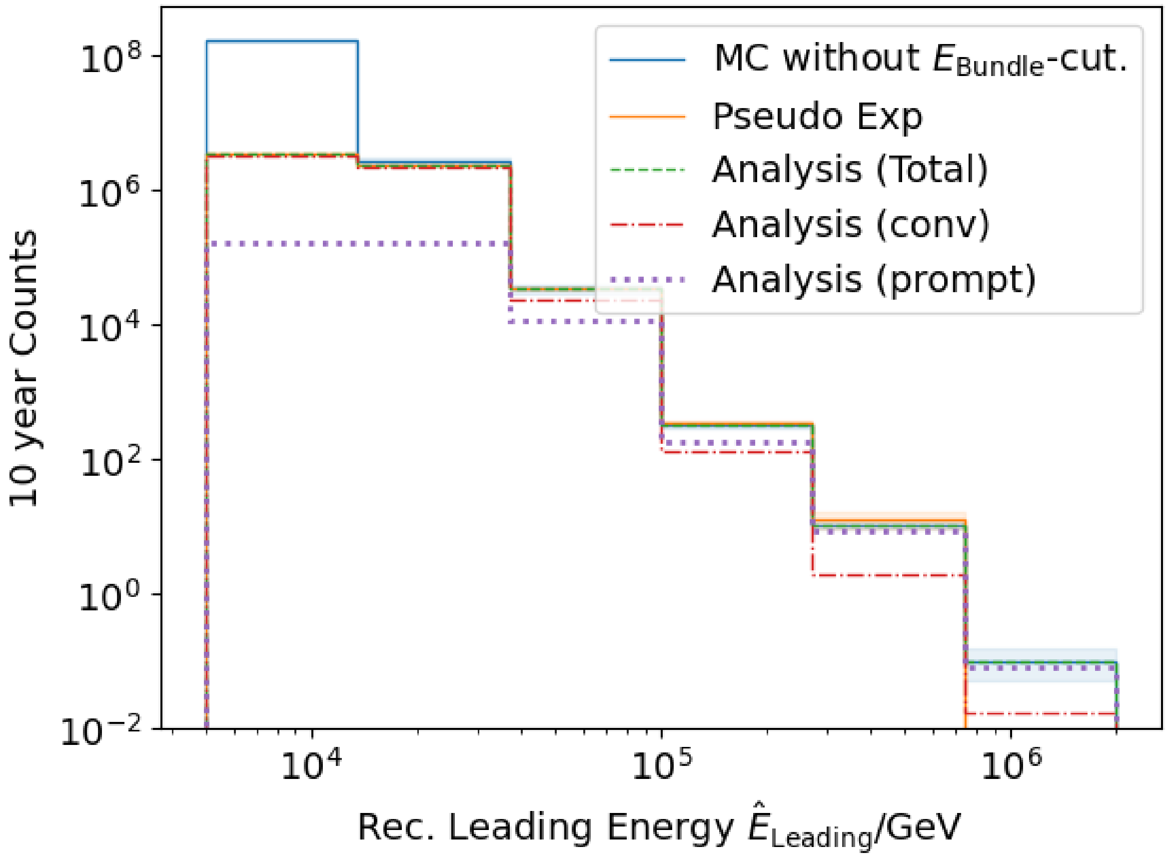
- leading: energy of most energetic muon in a muon bundle
- bundle: sum of energies of all muons of the bundle

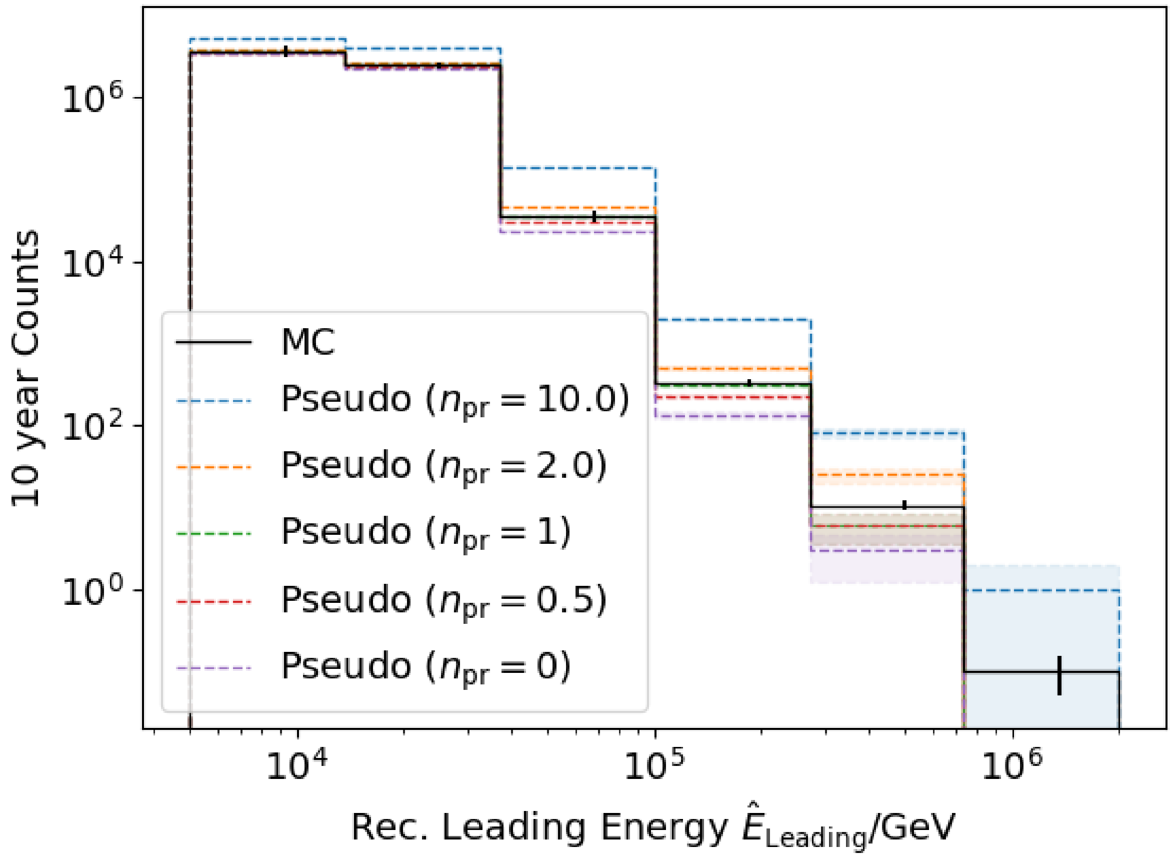


➢ Both leading and bundle energy are sensitive to detect prompt
➢ Leading muon energy is more sensitive

Pseudo data sampling

Cuts:
L2 MuonFilter
Bundle energy at entry > 100 TeV





- Tagging allows scaling of prompt by factor n_{pr}

Poisson likelihood fit performed in leading muon energy

Cuts:
L2 MuonFilter
Bundle energy at entry > 100 TeV

Prompt scaling/normalization

Conv norm = 1

MC counts per bin i

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

Experimental counts

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

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

Maximize likelihood

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

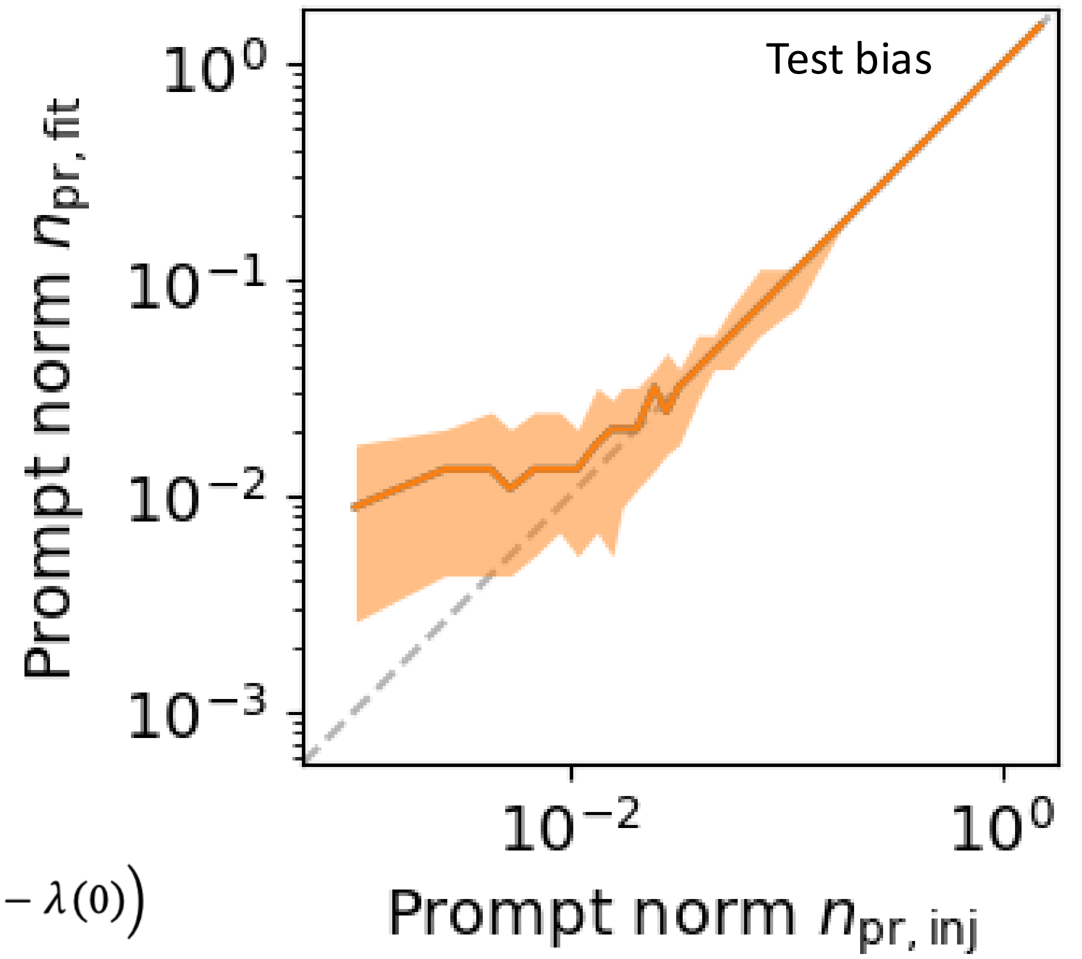
Easier:
minimize negative
log-likelihood

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

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

Test statistic for Wilks' theorem

Null hypothesis: no prompt



- Bias starts at a prompt normalization of ~0.1

Discovery potential and sensitivity

Cuts:
L2 MuonFilter
Bundle energy at entry > 100 TeV

Expectation for 1 year:

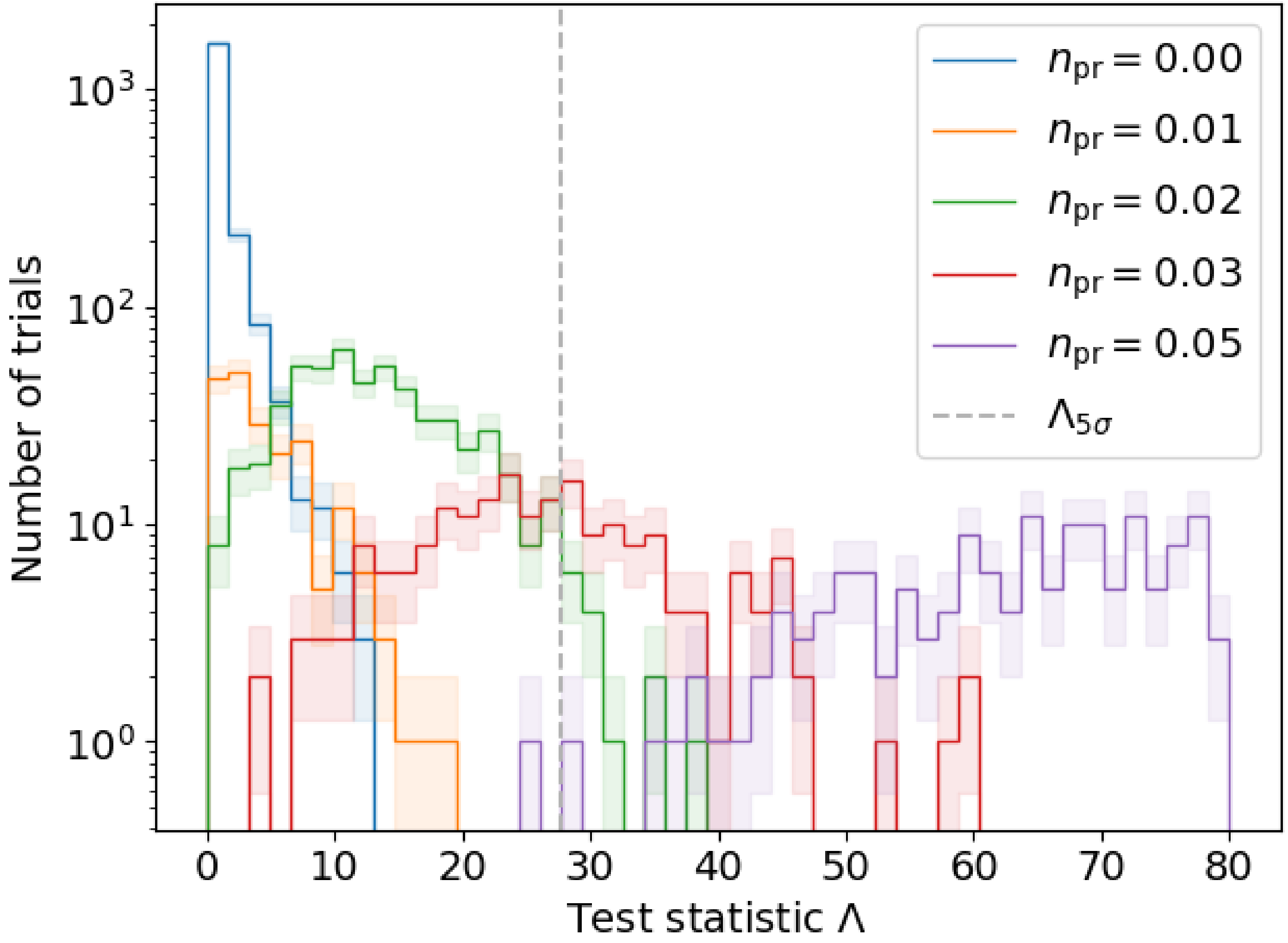
- 5 sigma discovery potential: 0.102 ± 0.005
- Sensitivity: 0.024 ± 0.001

Expectation for 10 years:

- 5 sigma discovery potential: 0.032 ± 0.001
- Sensitivity: 0.007 ± 0.000

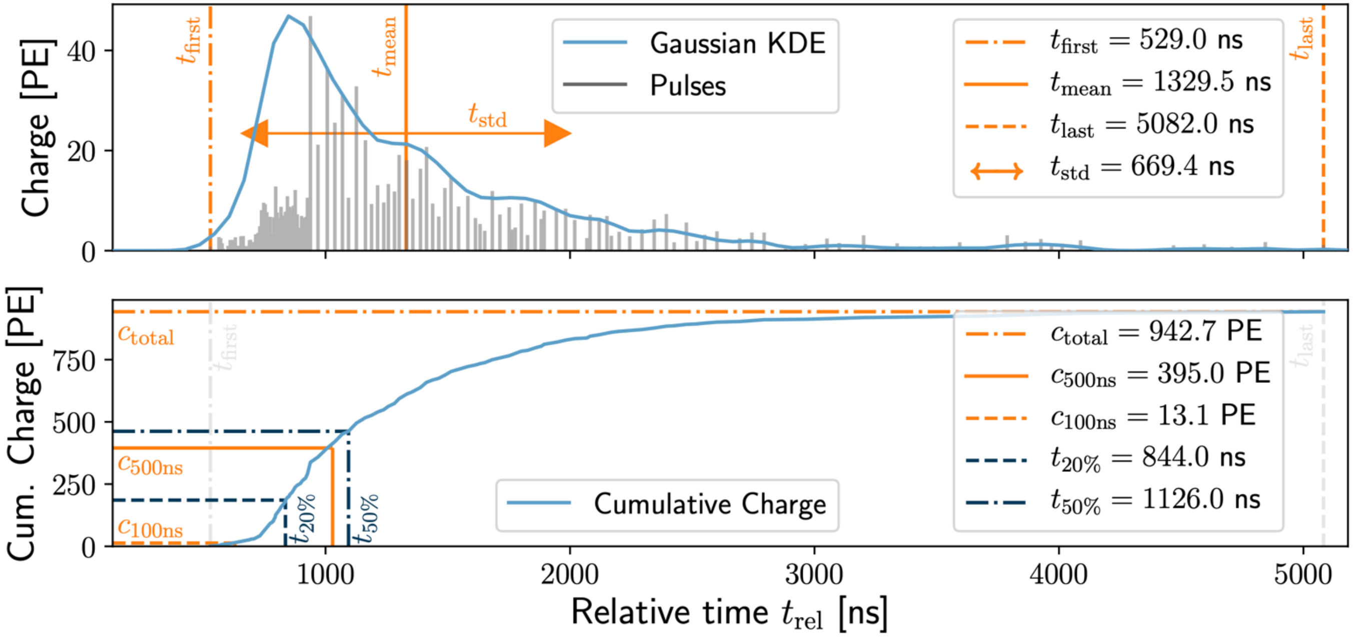
Caution:

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



Input data per DOM

10.1088/1748-0221/16/07/P07041



3 inputs

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

9 inputs

- t_{last}: Relative time of last pulse
  - Relative to total time offset, calculated as the charge weighted mean time of all pulses
- $t_{20\%}$: Relative time of 20% charge
  - Relative to total time offset, calculated as the charge weighted mean time of all pulses
- $t_{50\%}$: Relative time of 50% charge
  - Relative to total time offset, calculated as the charge weighted mean time of all pulses
- t_{mean}: Mean time
  - Charge weighted mean time of all pulses relative to total time offset
- c_{500ns}: Charge at 500ns
  - Sum of charge after 500ns
- c_{100ns}: Charge at 100ns
  - Sum of charge after 100ns

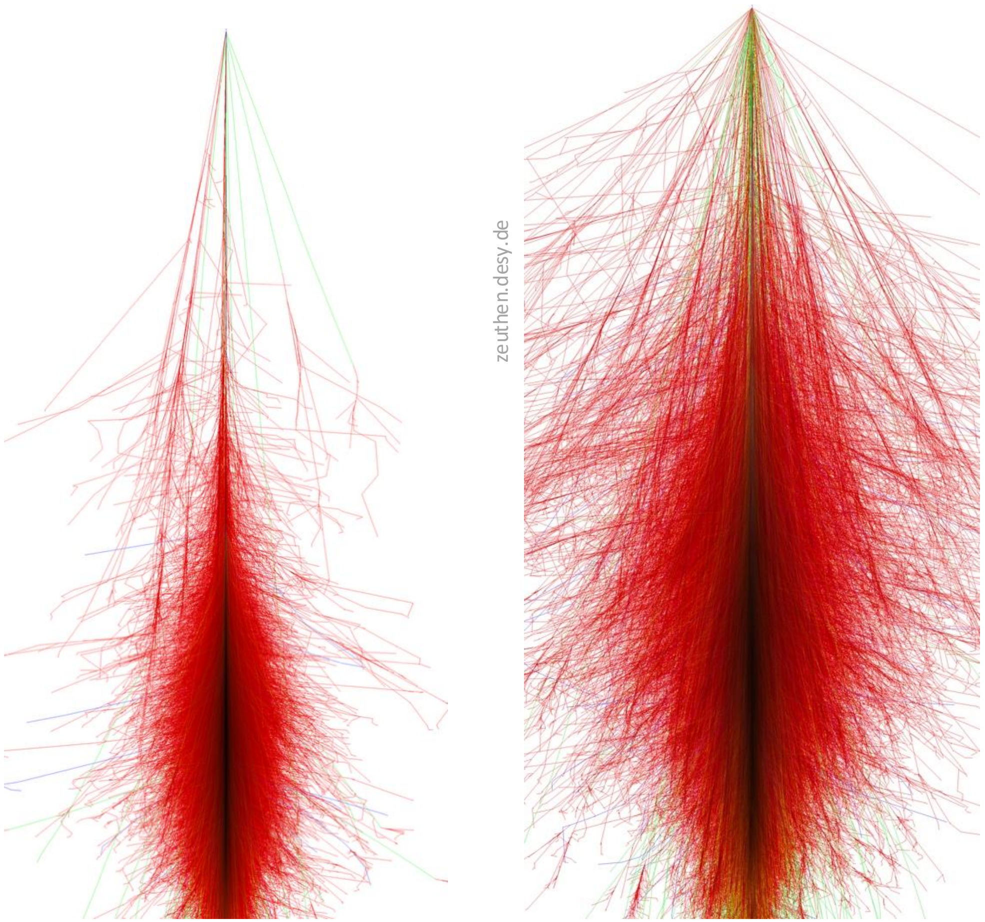
Input pulses

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

Training datasets

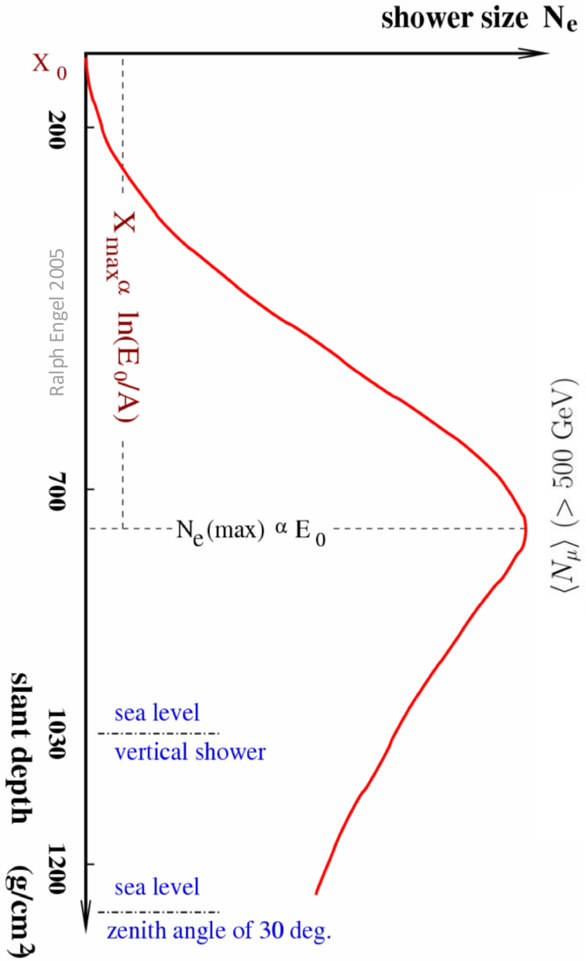
- 20904
- 21962
- 22020
- 22187

Air shower – 10 TeV

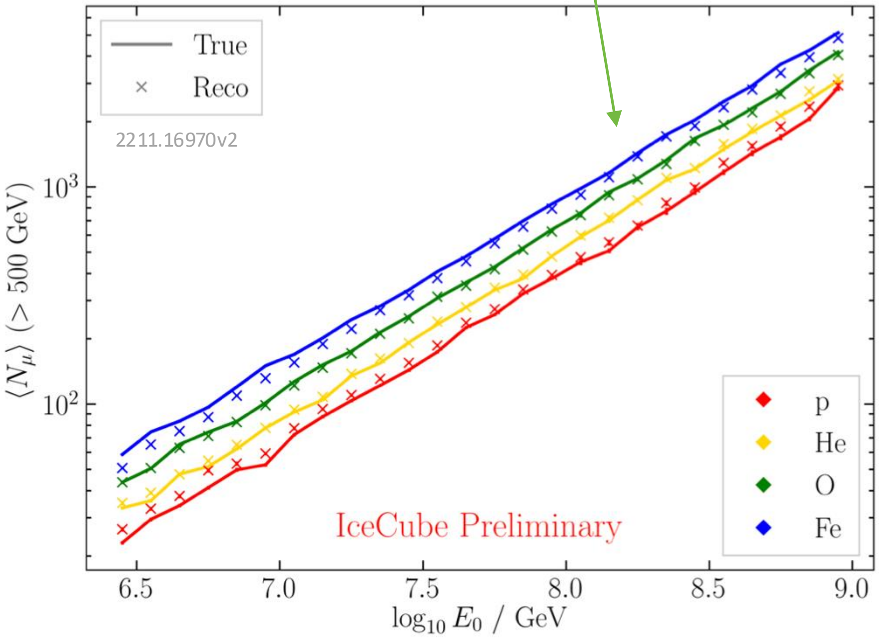


Proton

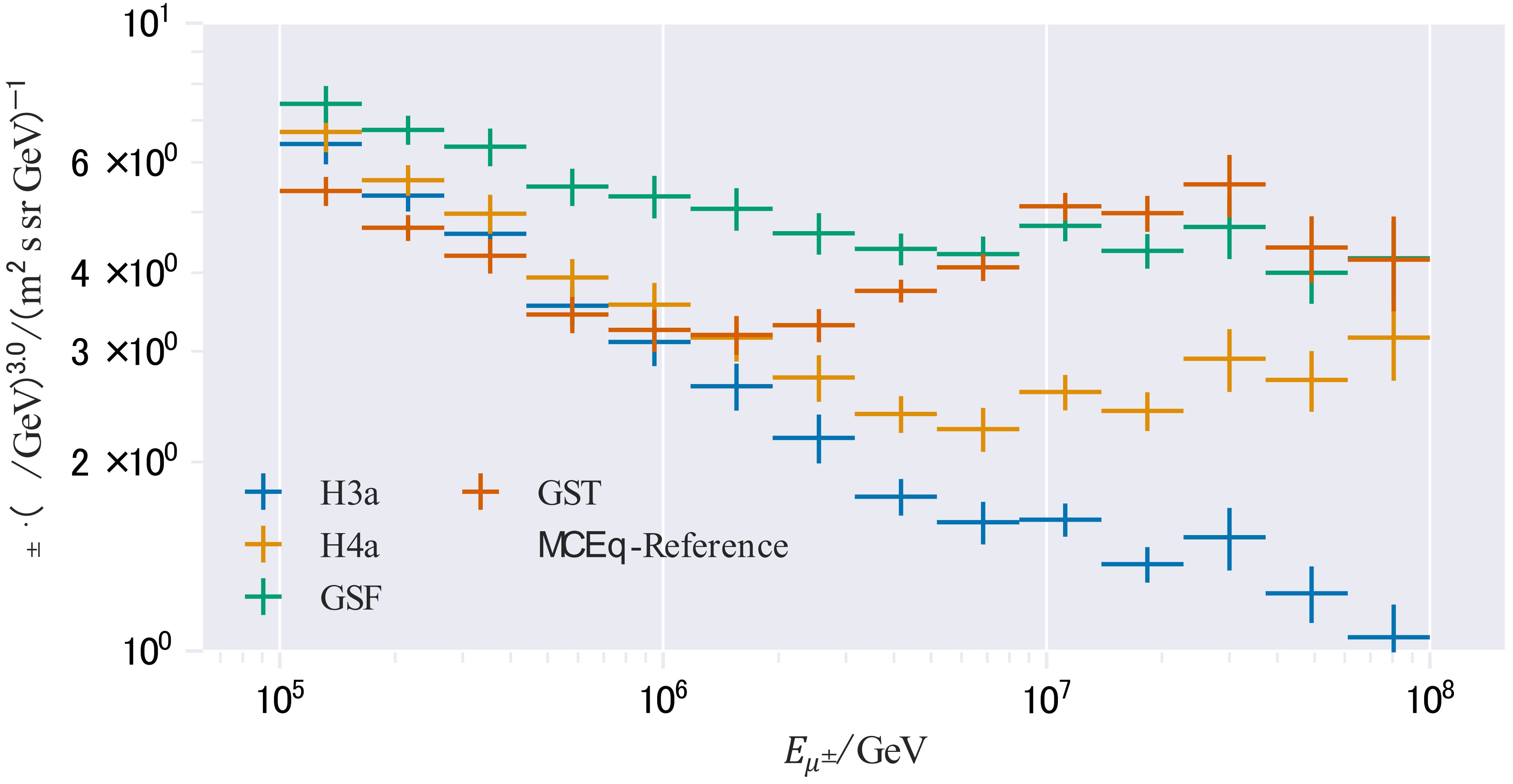
Iron



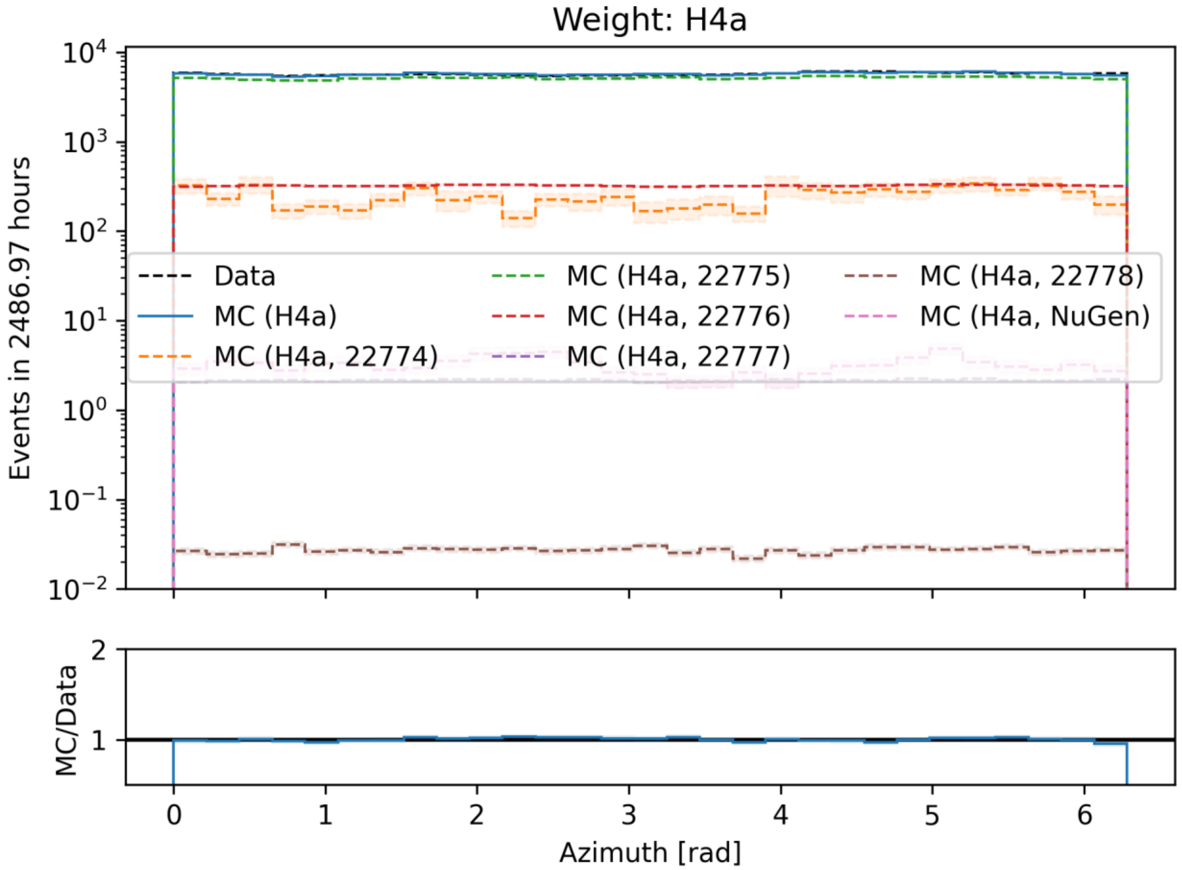
“muon bundles”



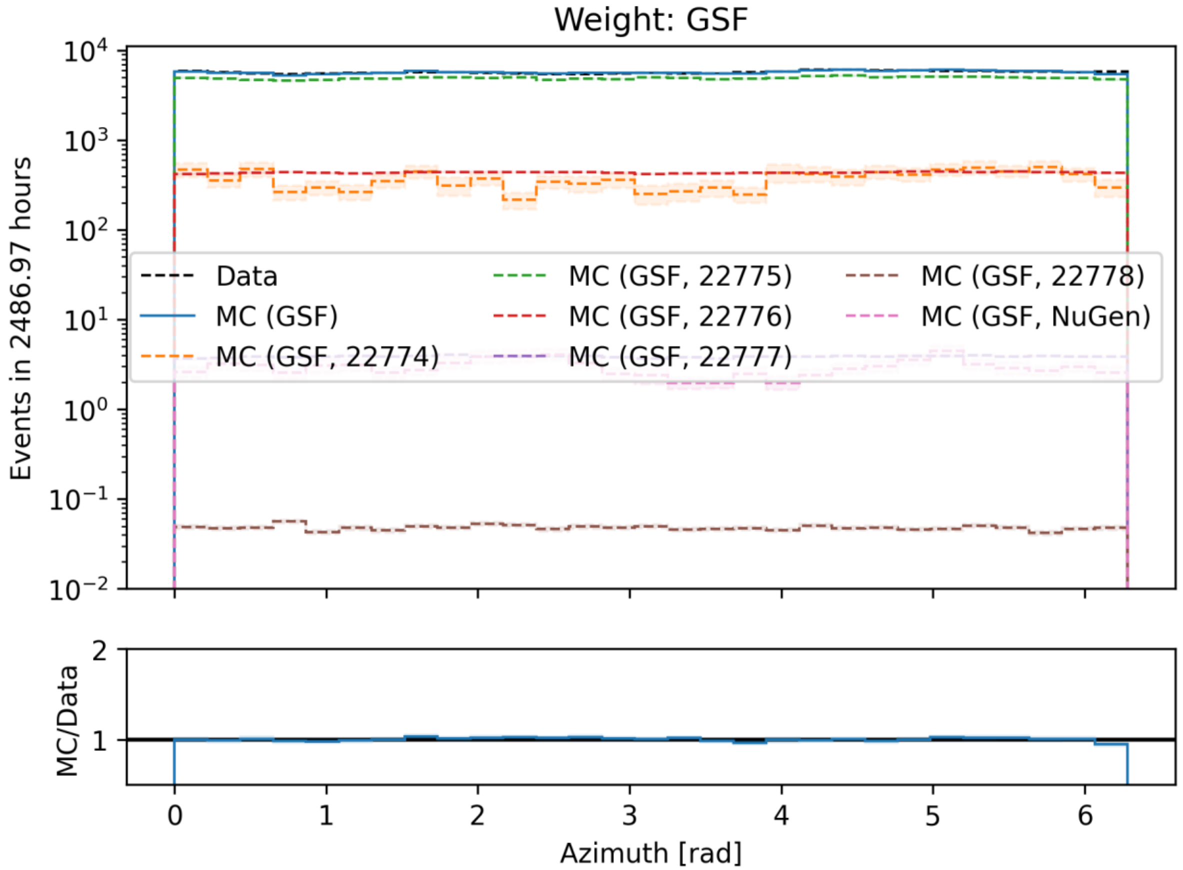
Agreement for different primary models



Azimuth

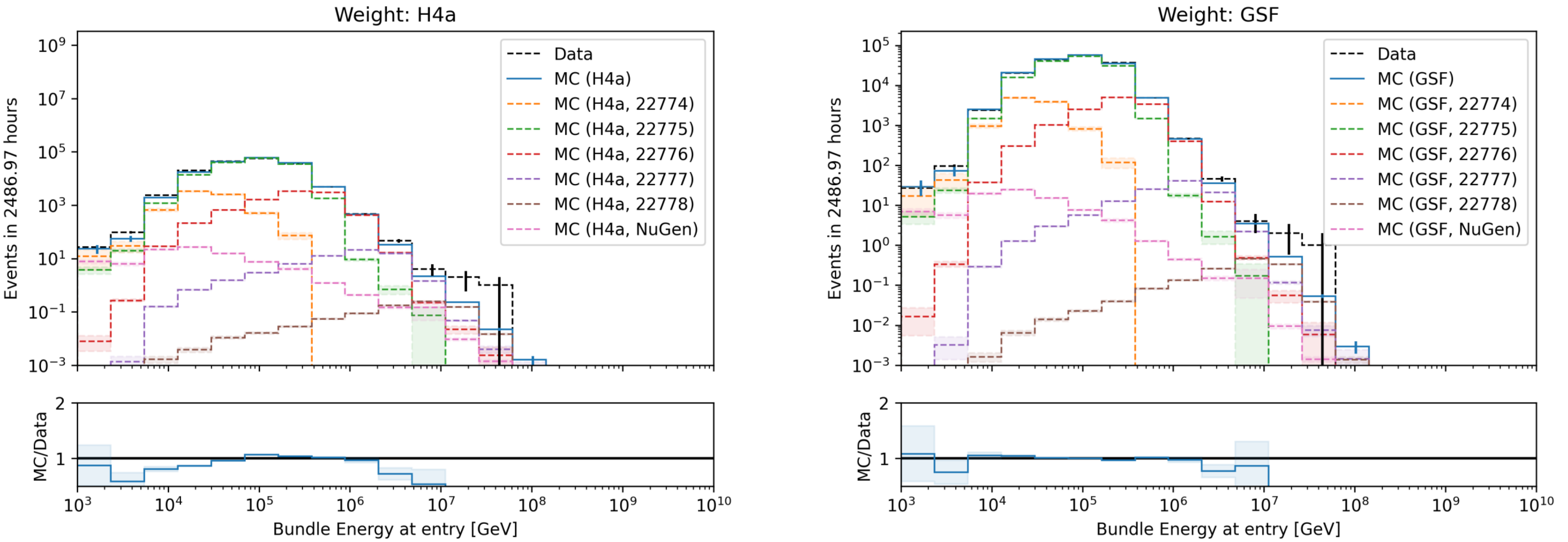


Weight: H4a
Events in 2486.97 hours
Data
MC (H4a)
MC (H4a, 22774)
MC (H4a, 22775)
MC (H4a, 22776)
MC (H4a, 22777)
MC (H4a, 22778)
MC (H4a, NuGen)
MC/Data
Azimuth [rad]

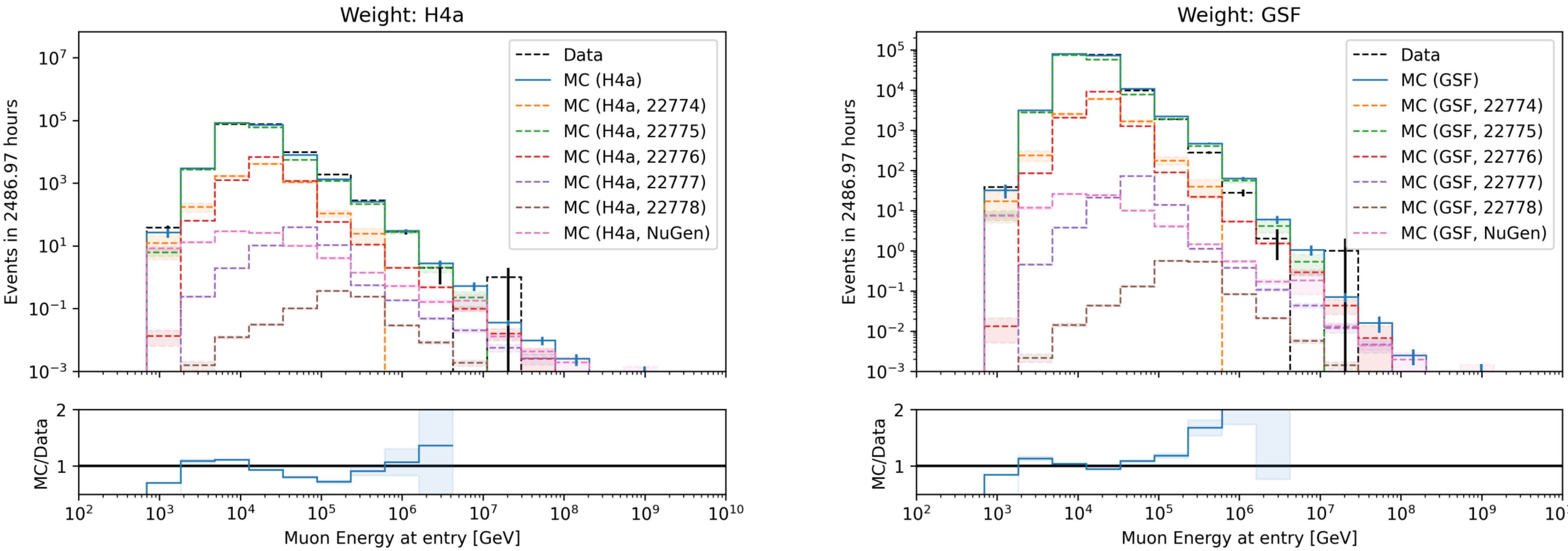


Weight: GSF
Events in 2486.97 hours
Data
MC (GSF)
MC (GSF, 22774)
MC (GSF, 22775)
MC (GSF, 22776)
MC (GSF, 22777)
MC (GSF, 22778)
MC (GSF, NuGen)
MC/Data
Azimuth [rad]

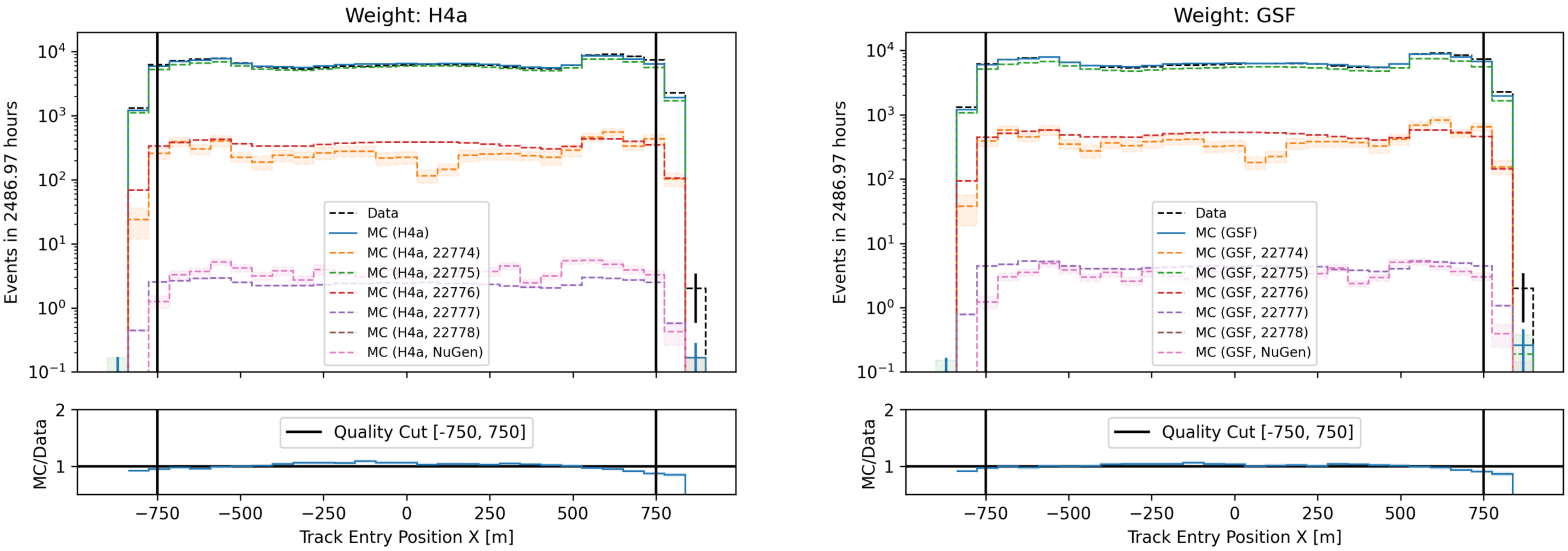
Bundle energy at entry



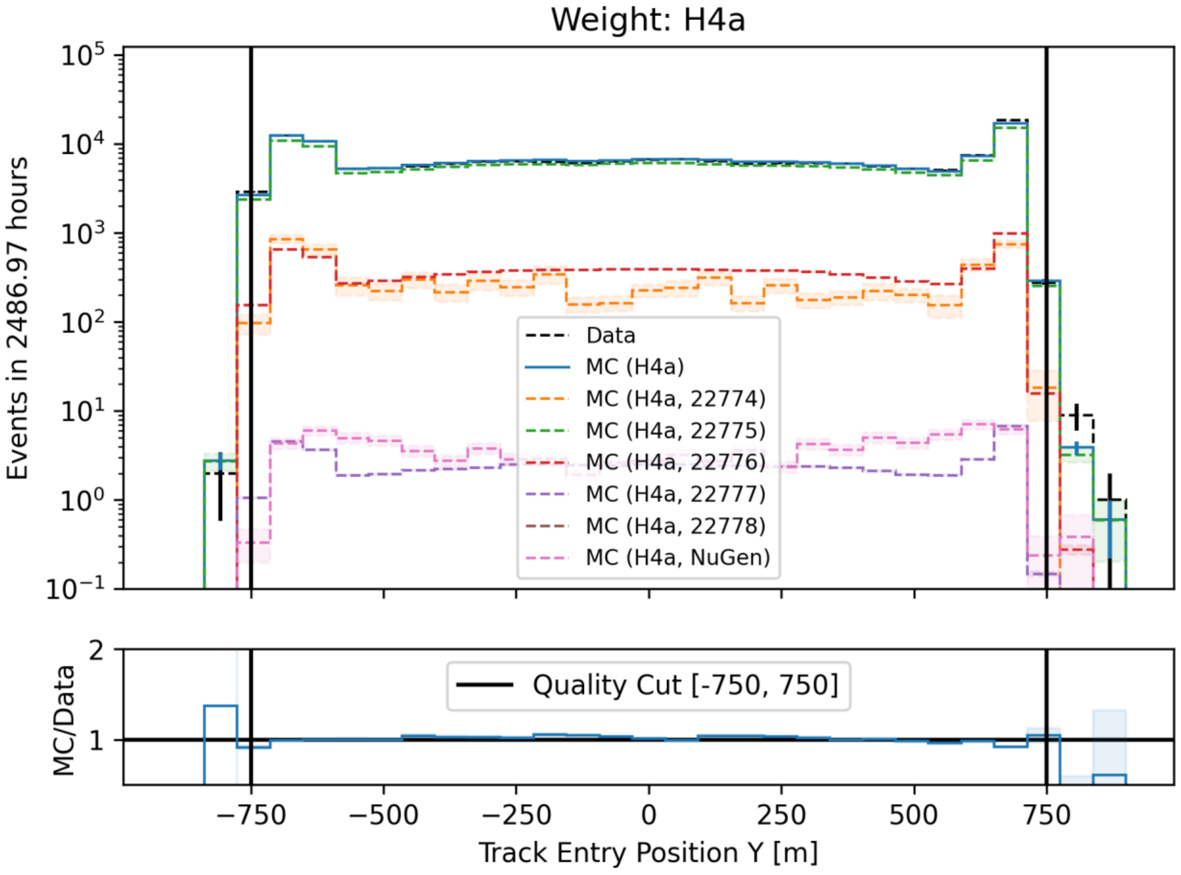
Leading muon energy at entry

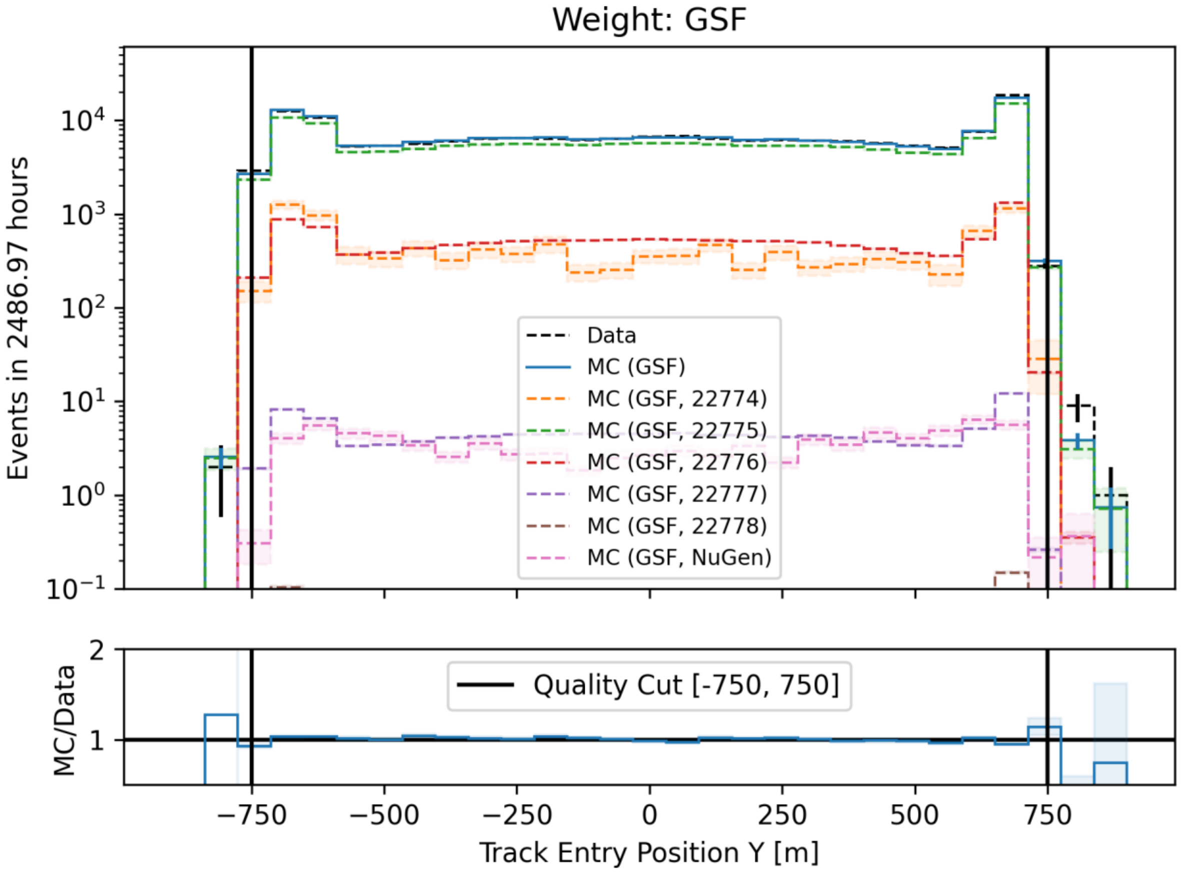


Entry position x–vertex



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

Network 1

Network 0: Muon bundle energy at surface (fast pre-cut)

Track geometry

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

Network 2

Direction

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

Network 3

Muon flux: Prompt spectrum

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

prompt component:

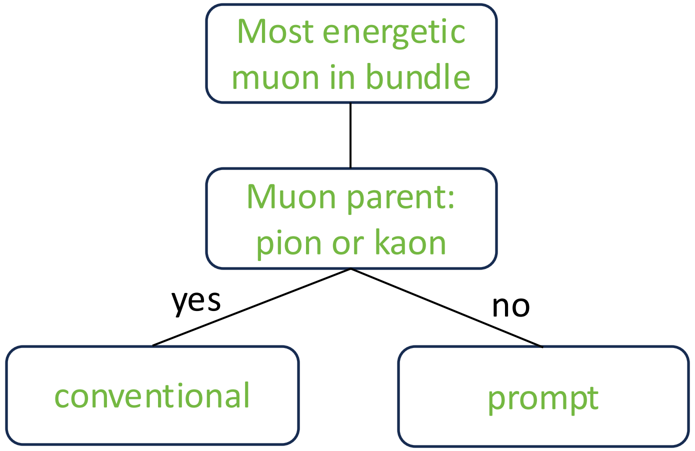
$$p \to \overbrace{D^+}^{\tau=1.04\cdot 10^{-12}\,\mathrm{s}} \to \bar{K}^0 + \mu^+ + \nu_\mu$$

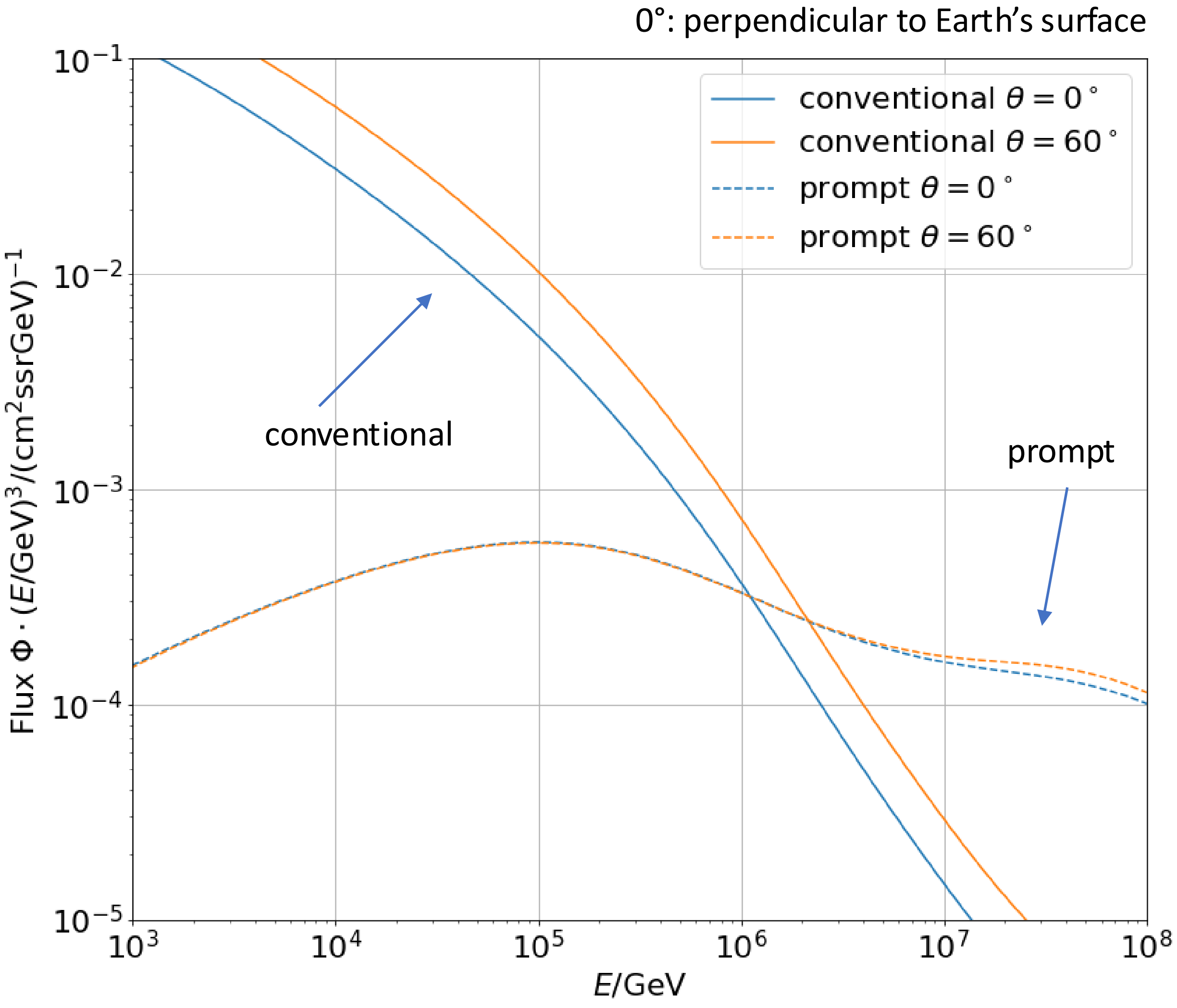
$\propto E^{-2.7}$ $\propto E^{-2.7}$

Conventional component:

$$p \to \overbrace{\pi^+}^{\tau=2.6\cdot 10^{-8}\,\mathrm{s}} \to \mu^+ + \nu_\mu$$

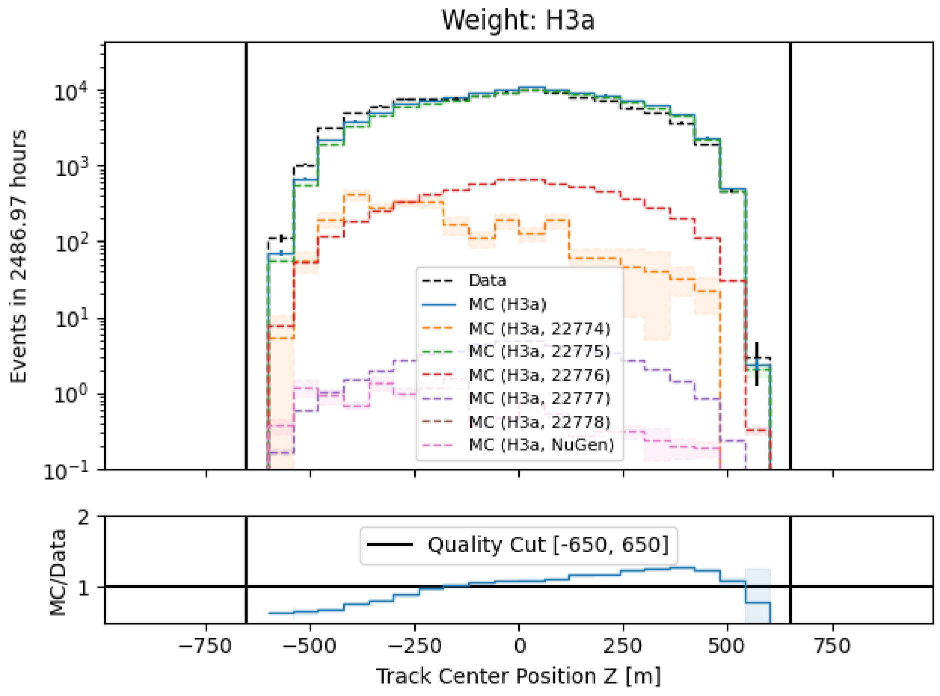
$\propto E^{-2.7}$ $\propto E^{-3.7}$

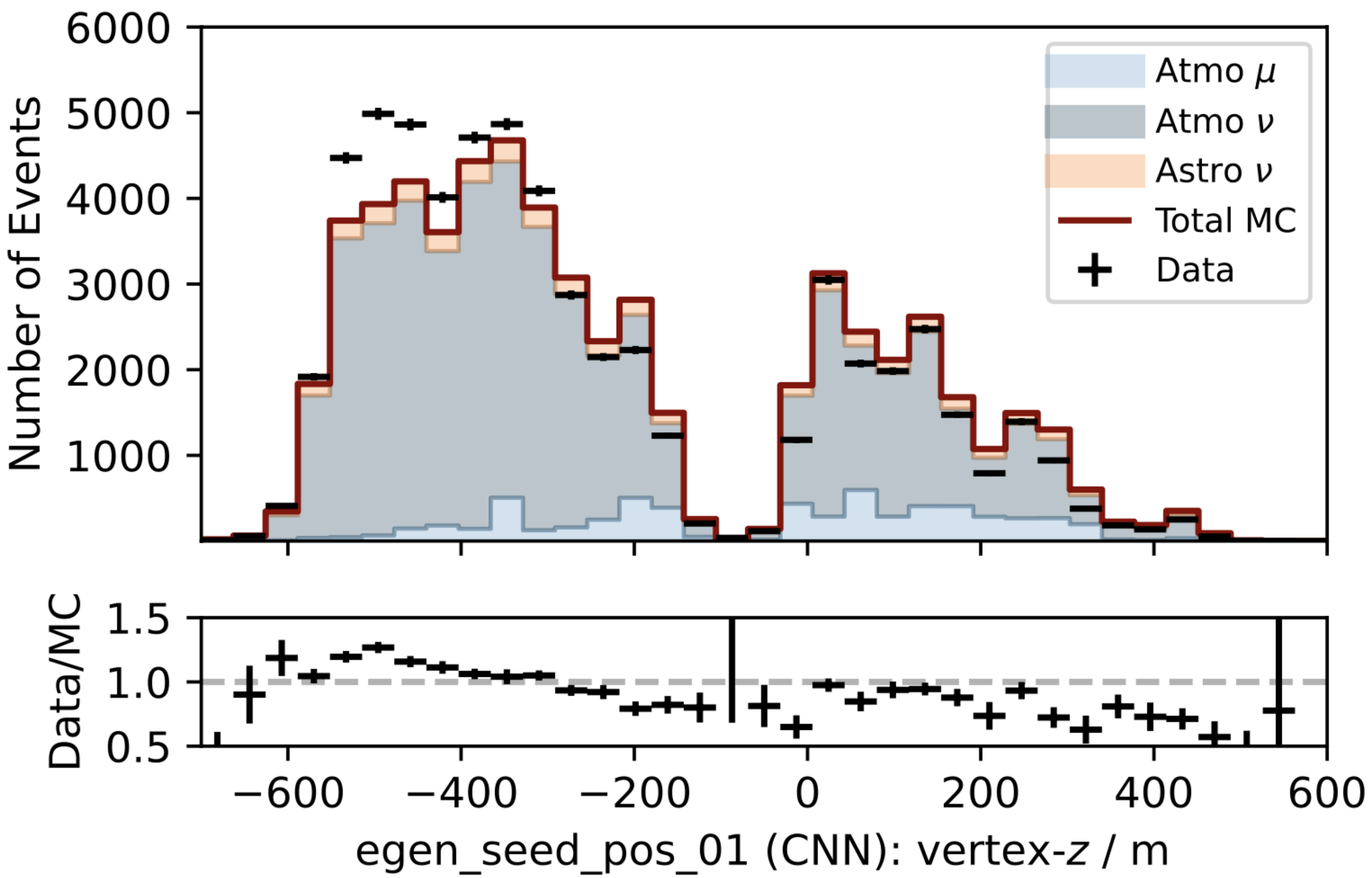




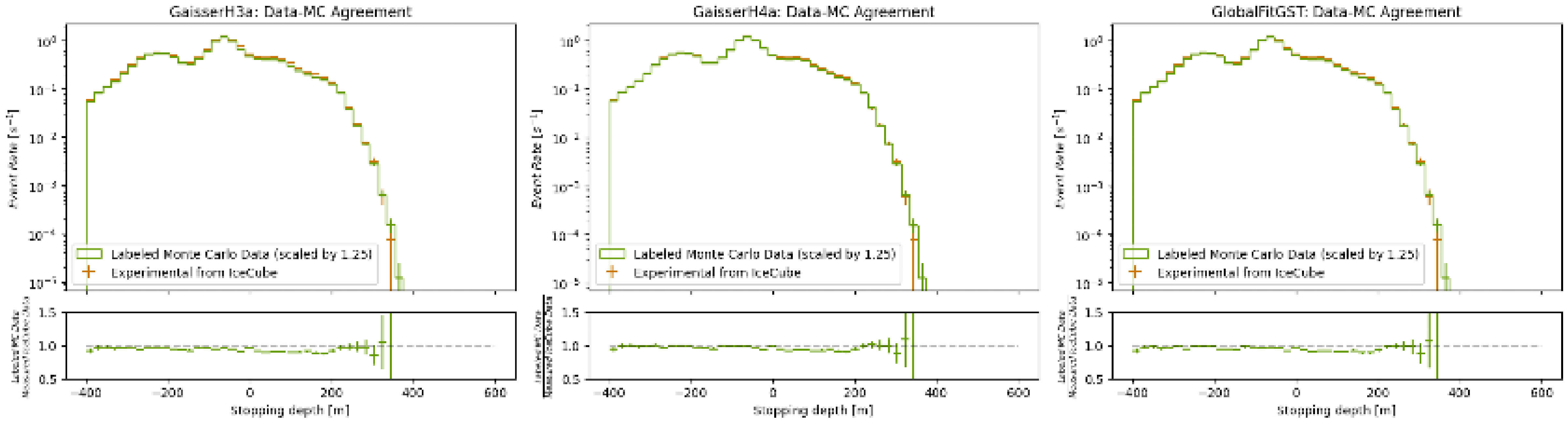
Neutrino: z-vertex

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

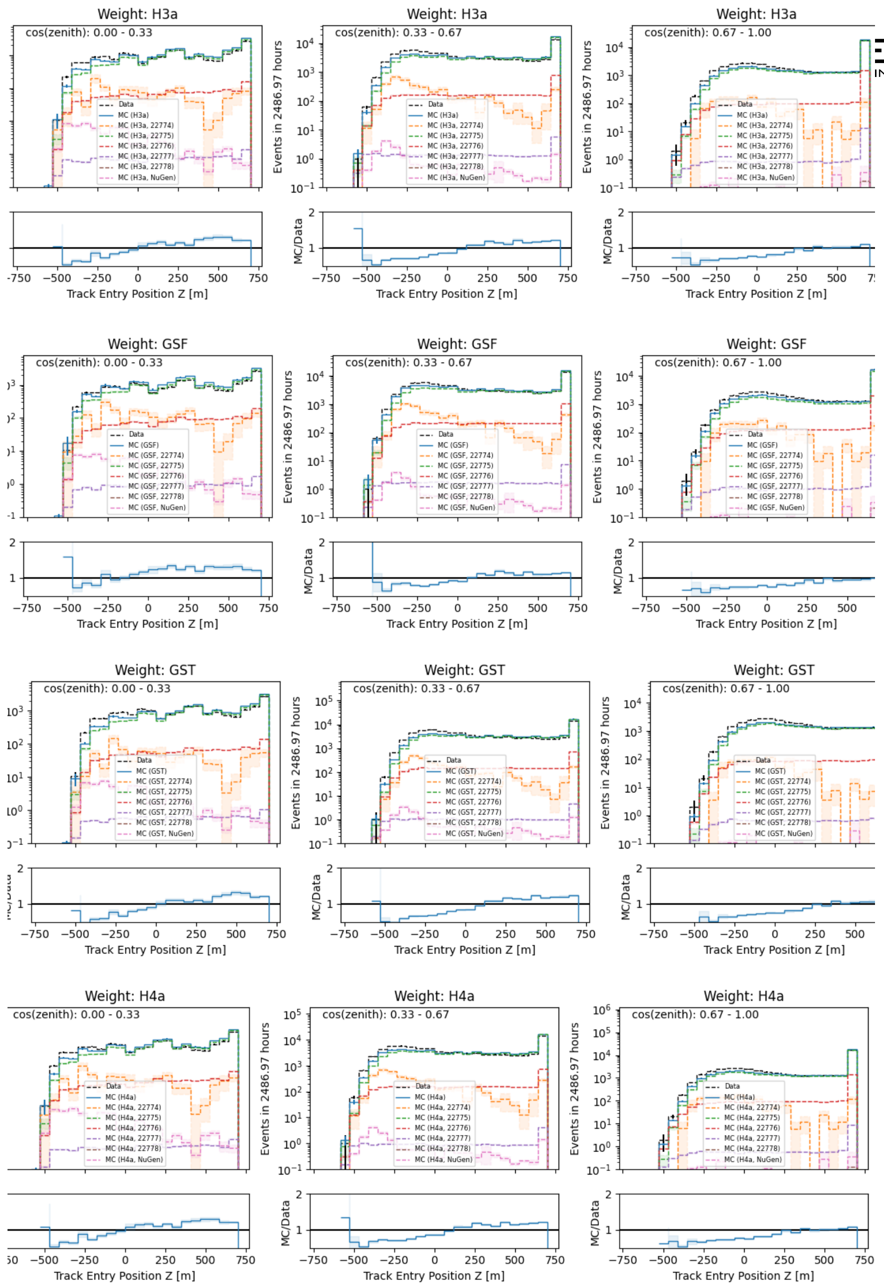




Stopping muons

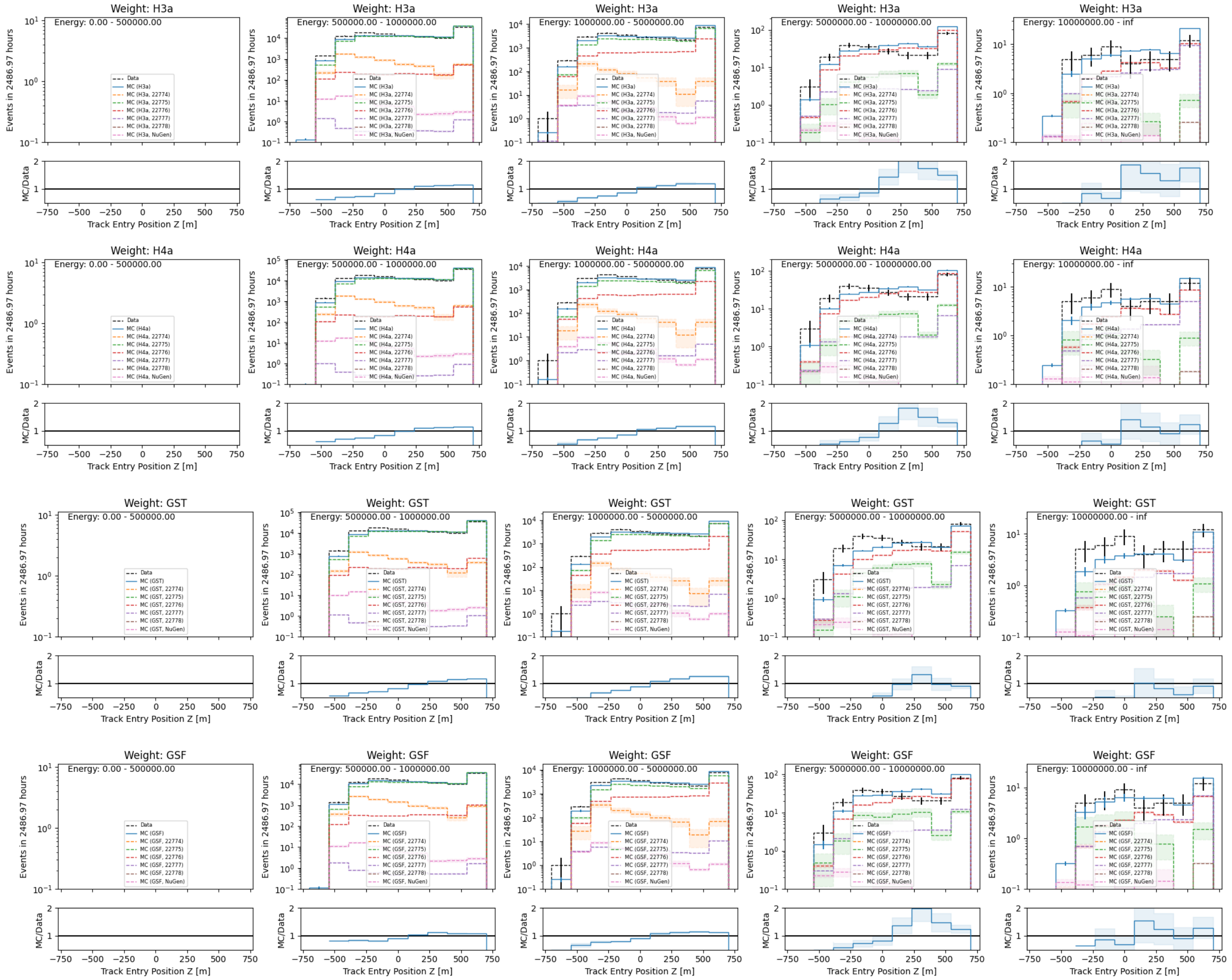


Entry position z - different cos(zenith)



pascal.gutjahr@tu-dortmund.de

Entry position z - different cuts on bundle energy at surface



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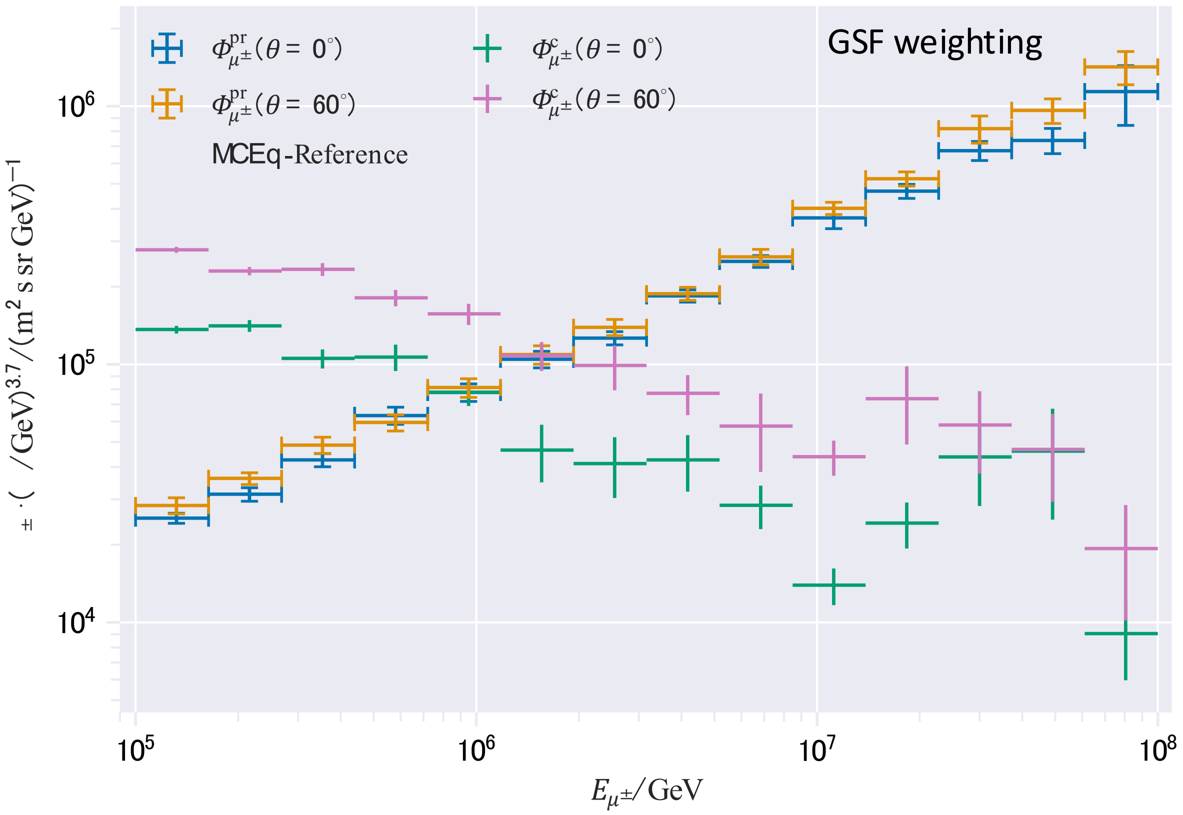
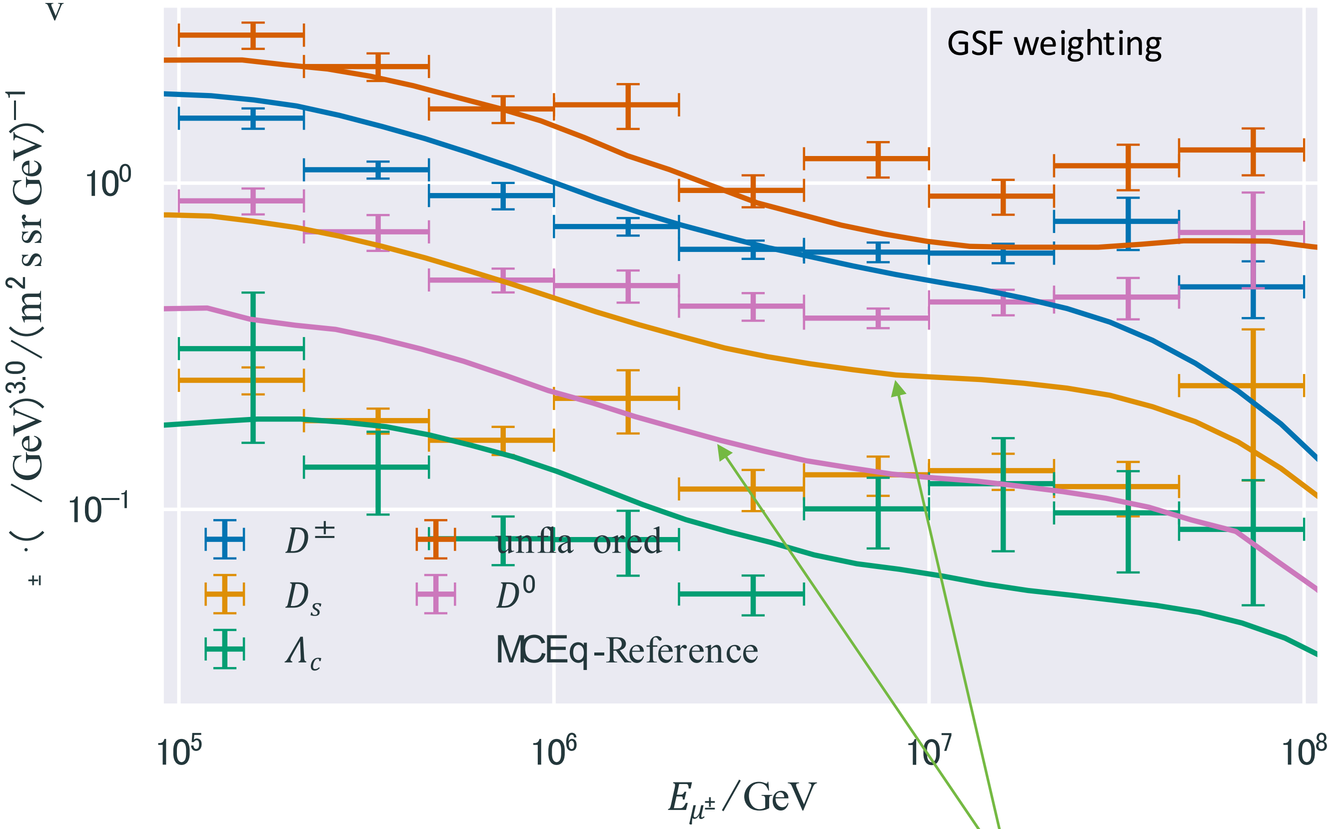
New CORSIKA simulation

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

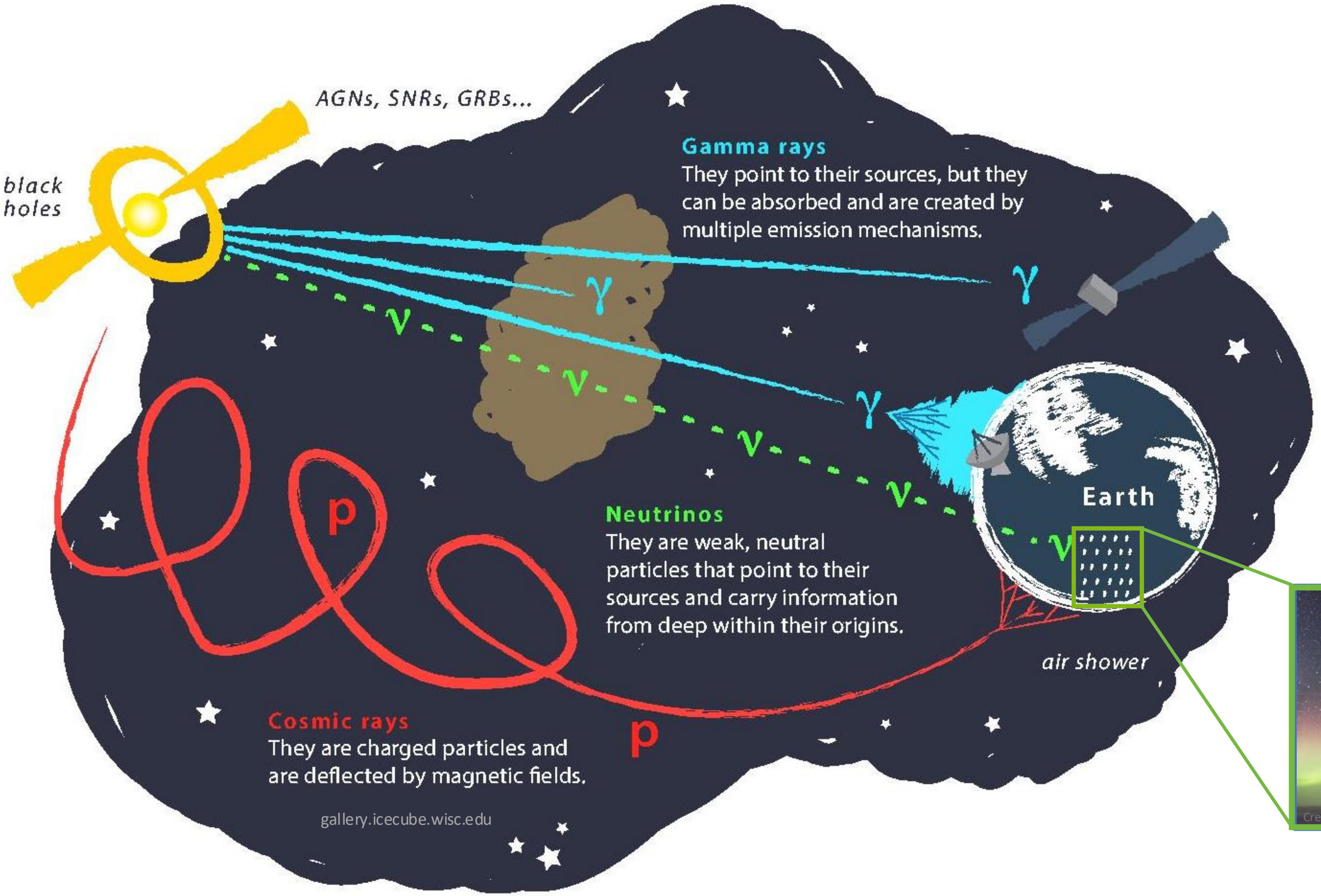




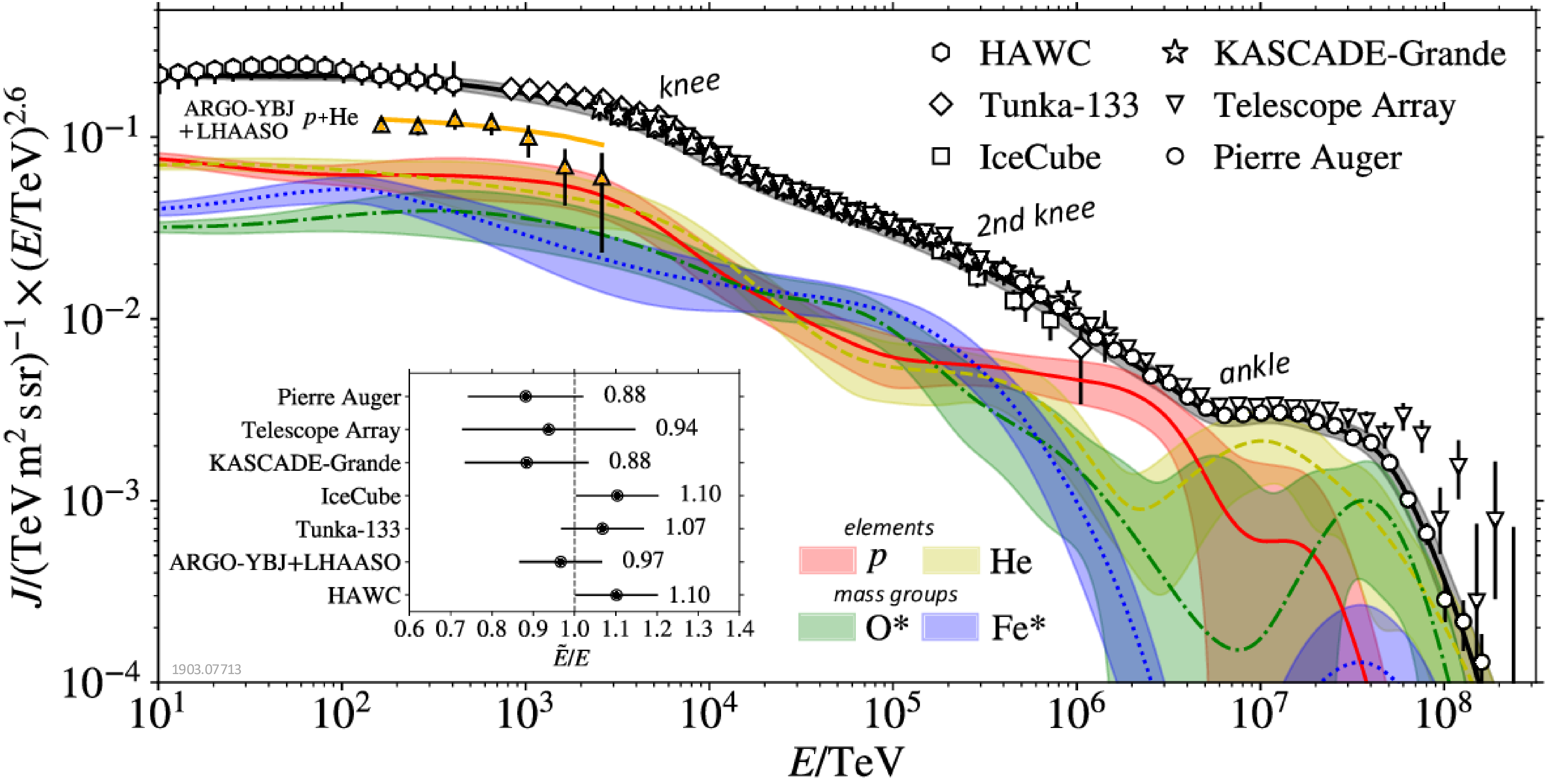
- Good agreement in total prompt and conv muon flux

- 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)