

Muon flux unfolding: update on systematics

Pascal Gutjahr

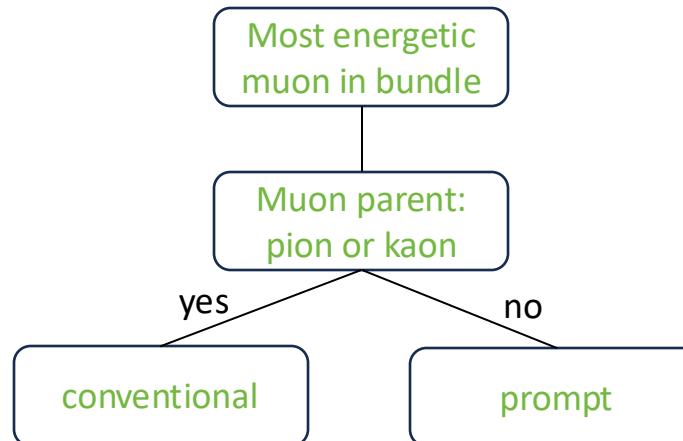
WG reviewer: Dennis Soldin
Technical reviewer: Karolin Hymon
Wiki: [prompt wiki](#)
Last update: [madison_talk](#)

CR-Call

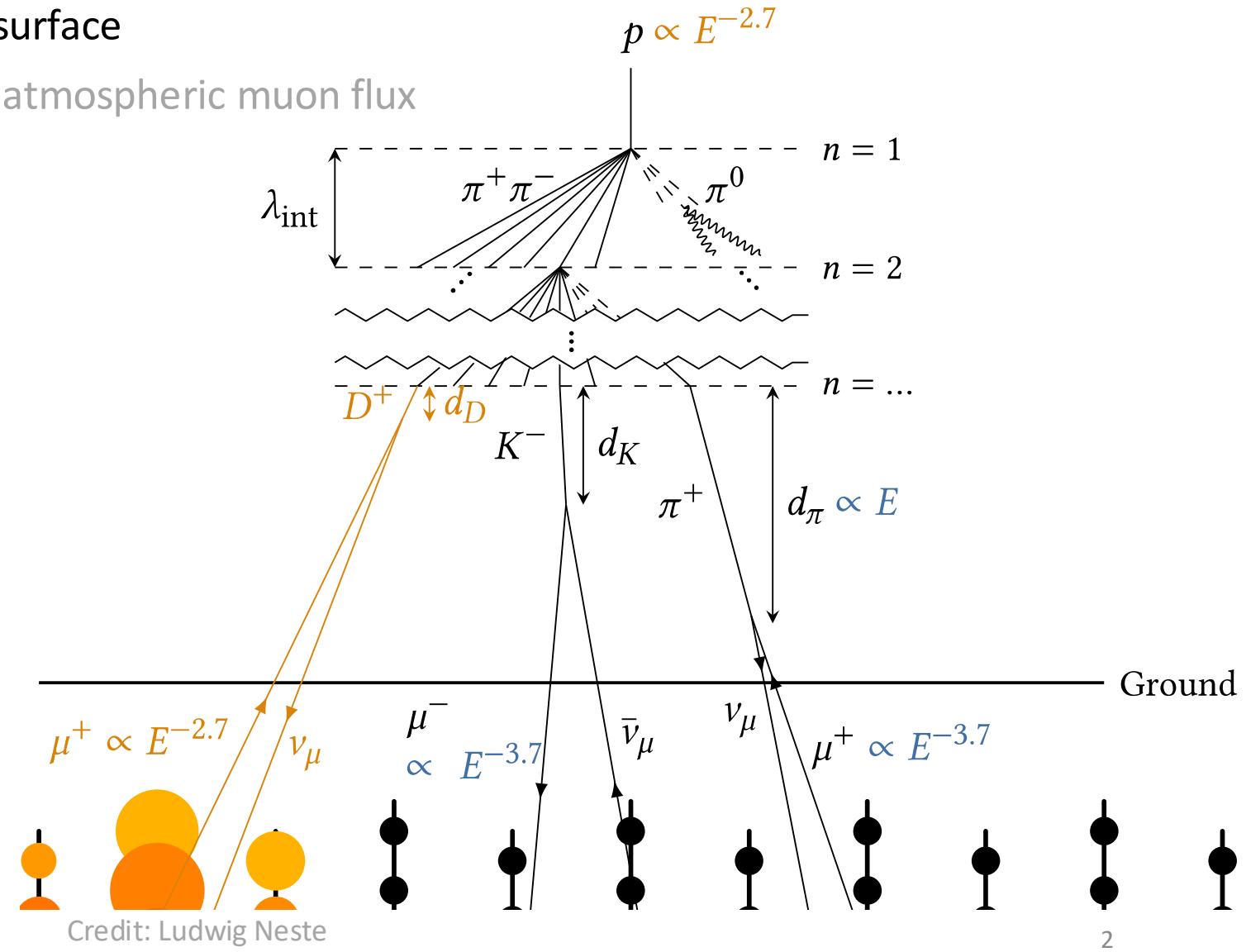
February 7, 2025

Analysis Goals: Detect Prompt Muons

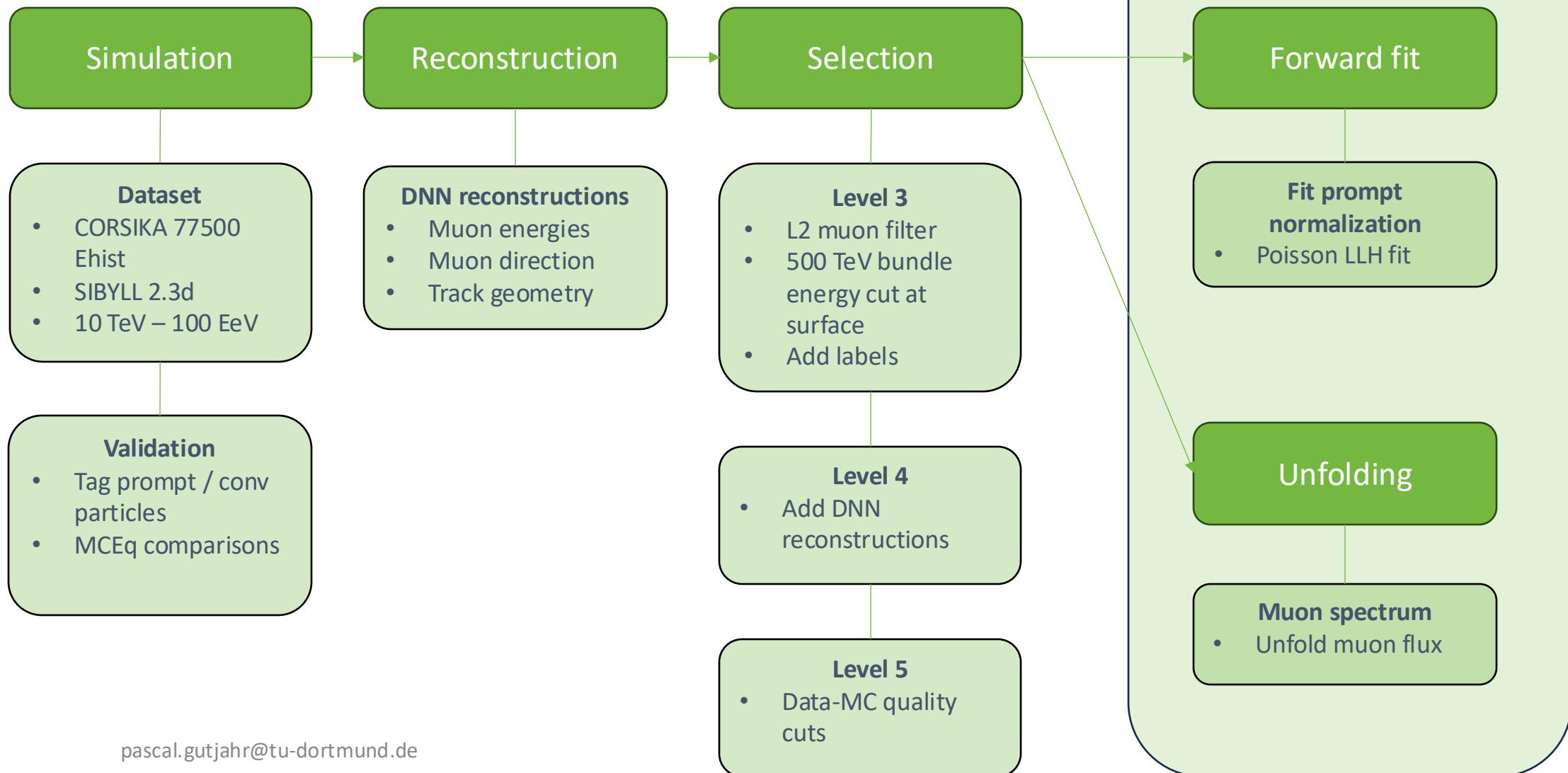
- 1) Unfold a muon energy spectrum at surface
- 2) Measure prompt component of the atmospheric muon flux



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Overview



Unfolding

Unfolding in a nutshell

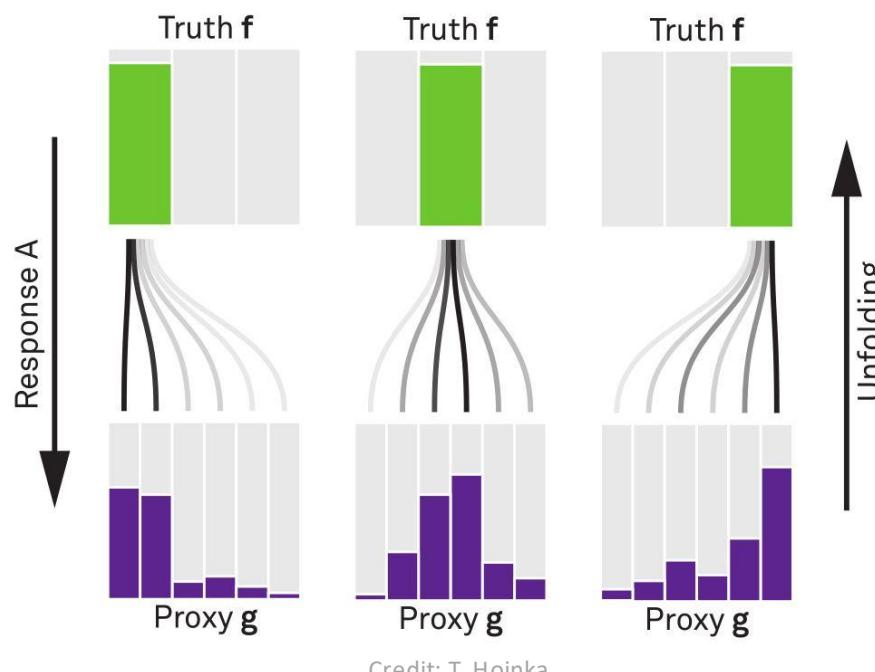
measured proxy

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

detector response

background

true energy distribution



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

2. maximum likelihood method:

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

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

3. Tikhonov regularization:

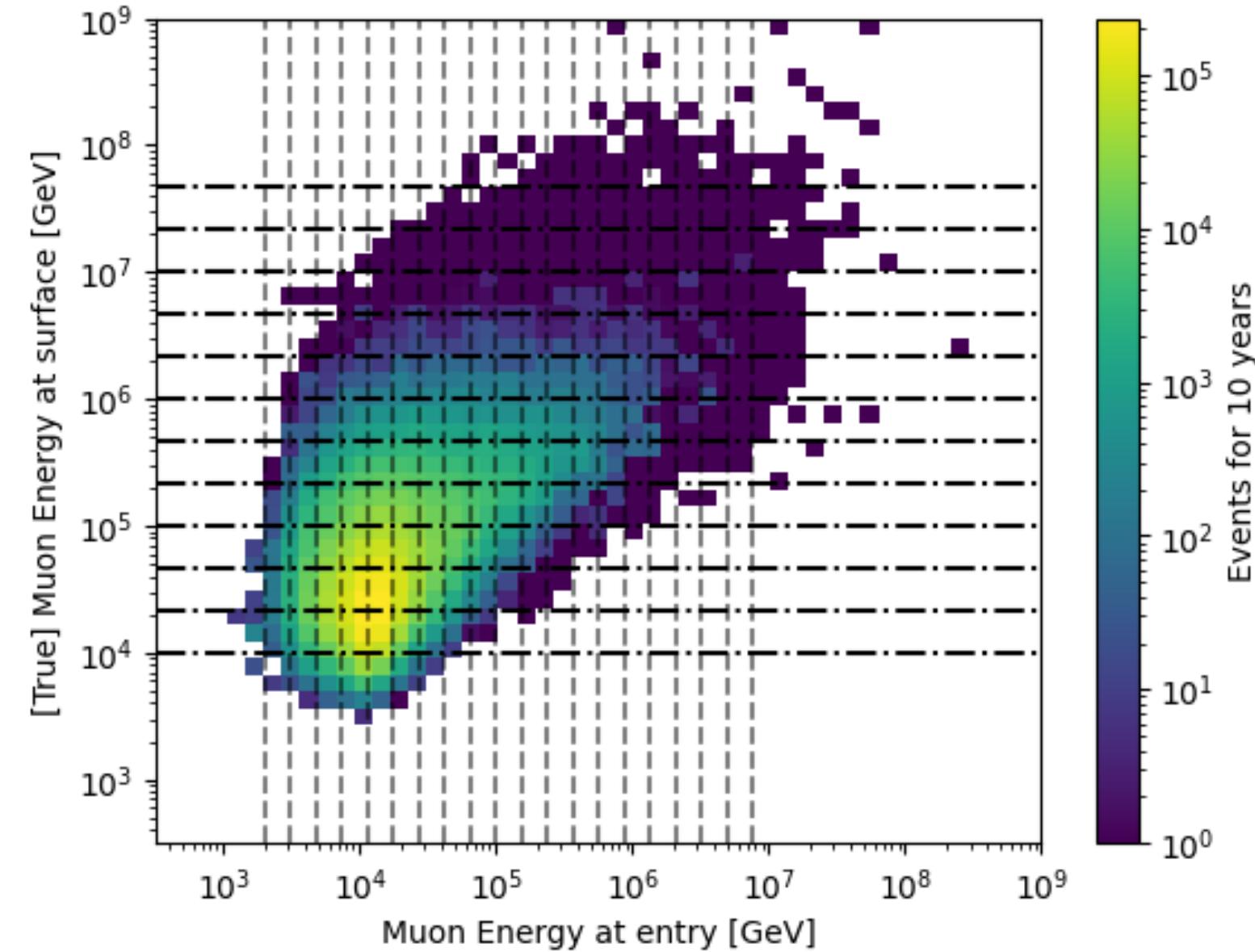
$$t(\vec{f}) = -\frac{1}{2} (\vec{C}\vec{f})^T (\tau I)^{-1} (\vec{C}\vec{f})$$

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



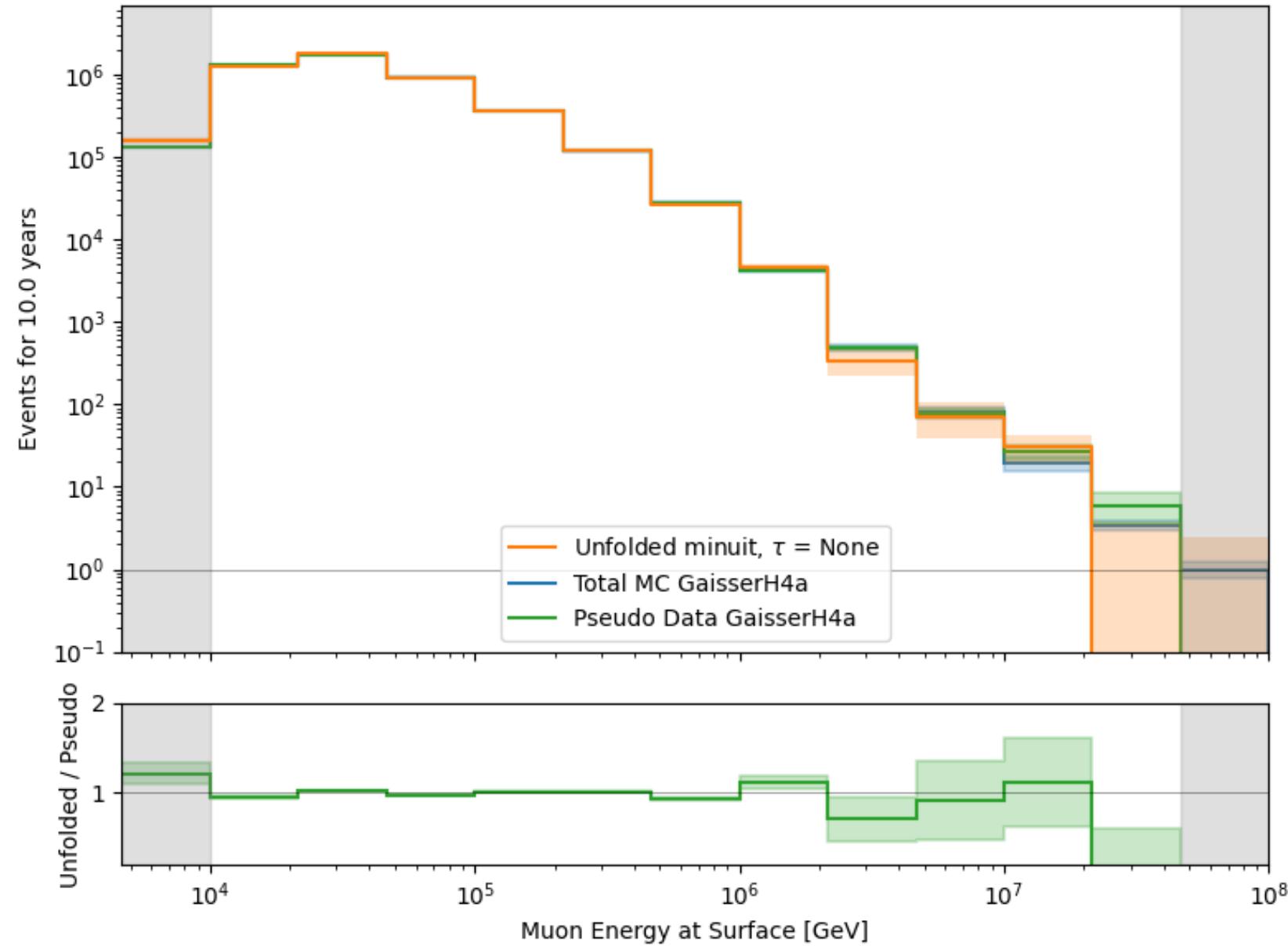
funfolding
by M. Börner

Proxy vs Target



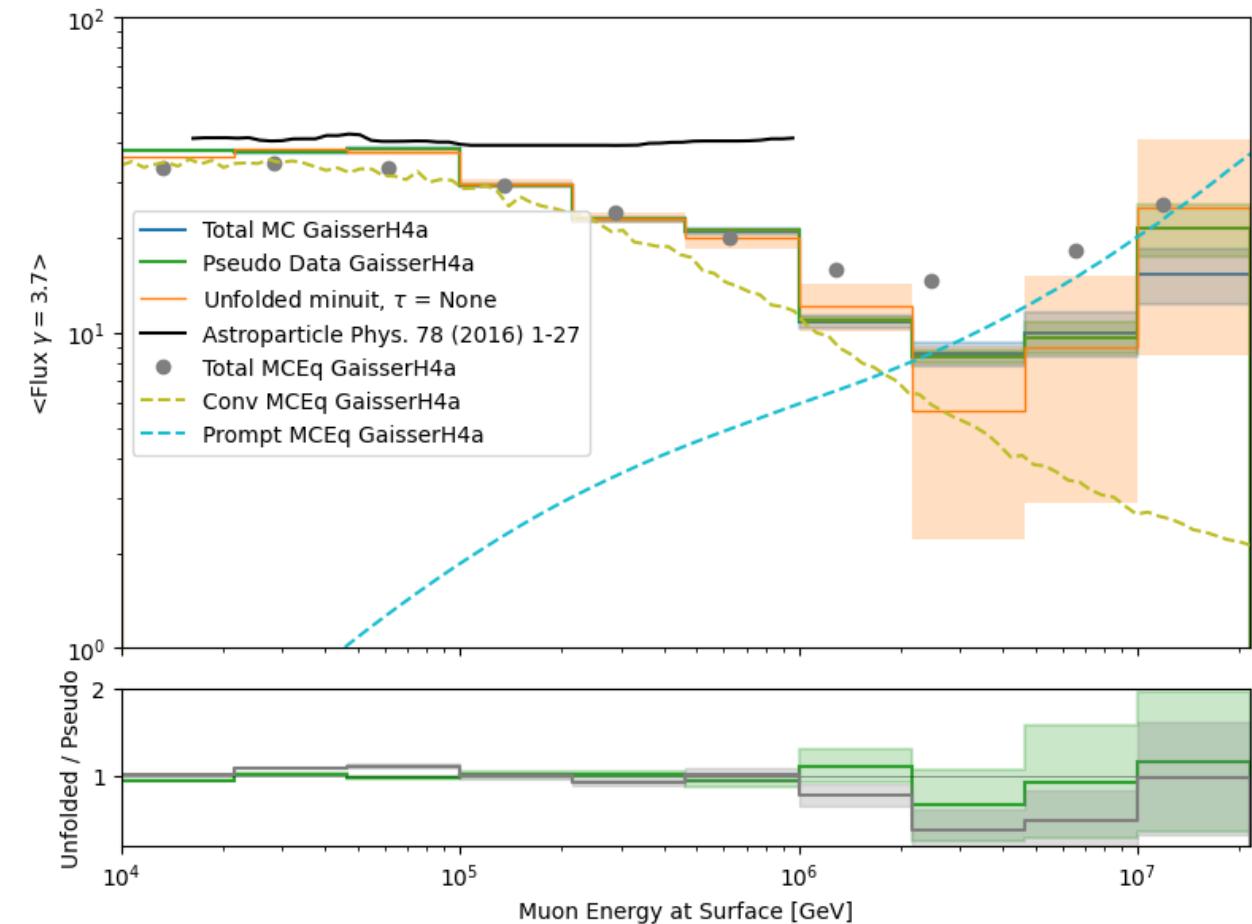
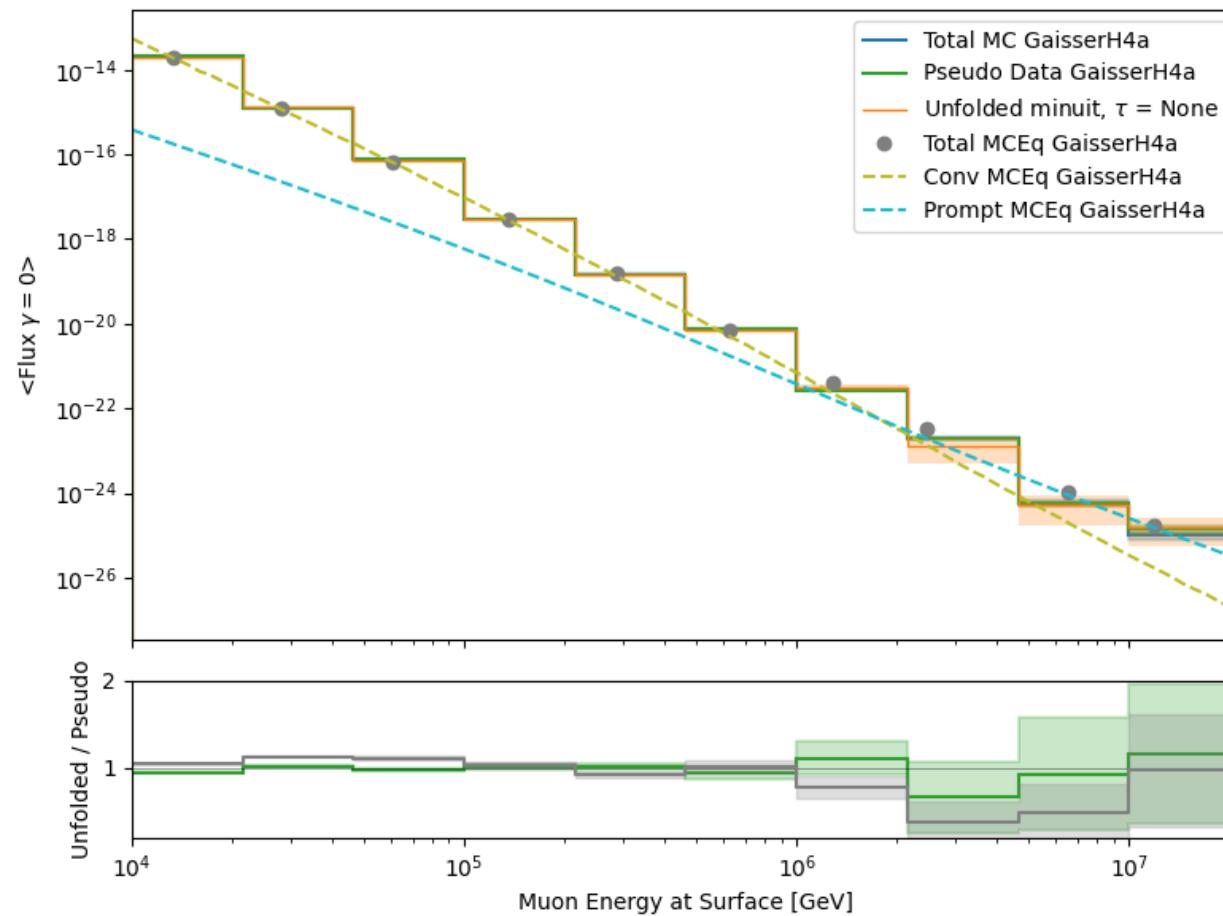
Unfold Event Rate

Event Rate



Unfold Muon Flux

Muon Flux at Surface

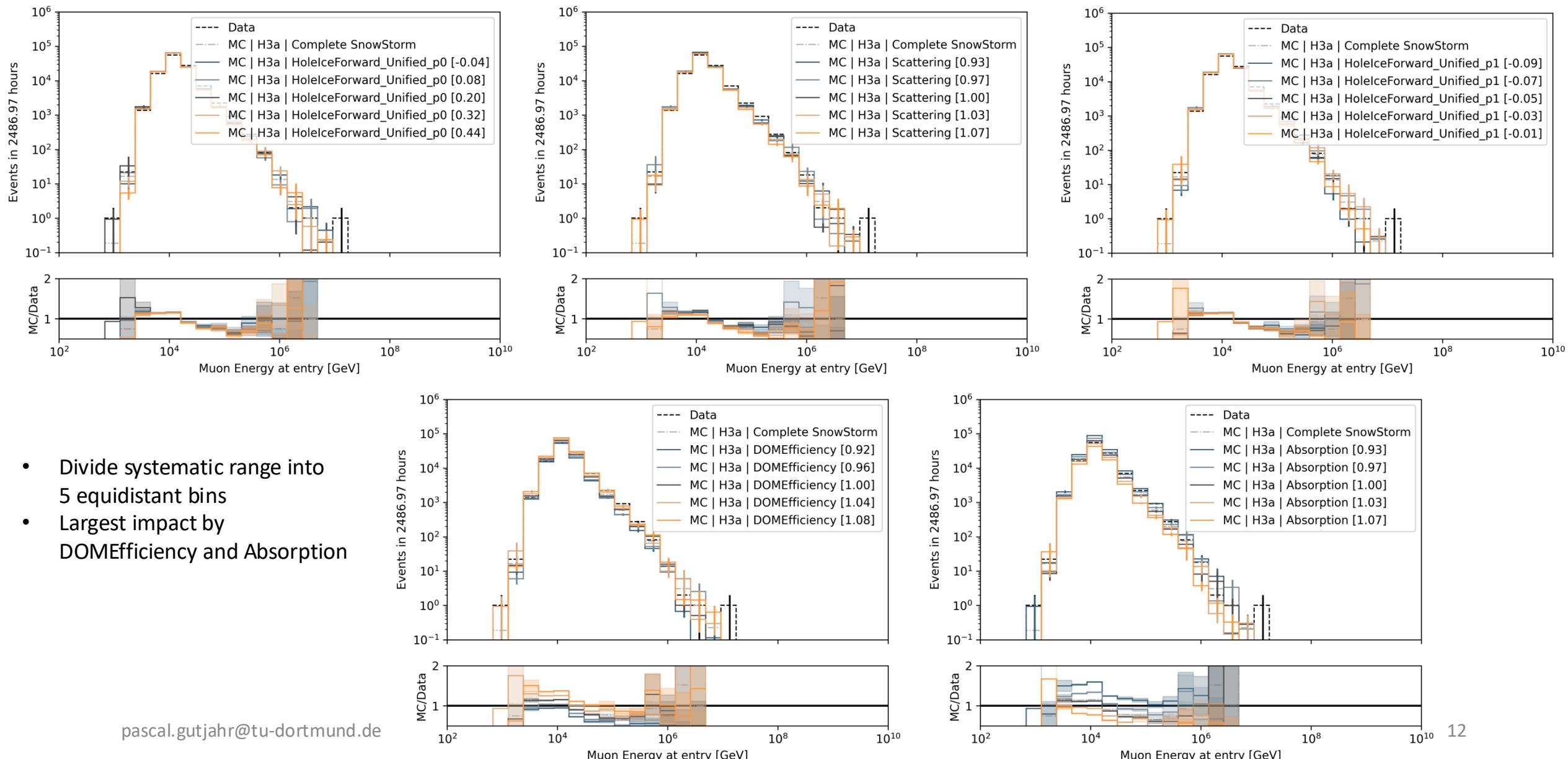


Ice Systematics

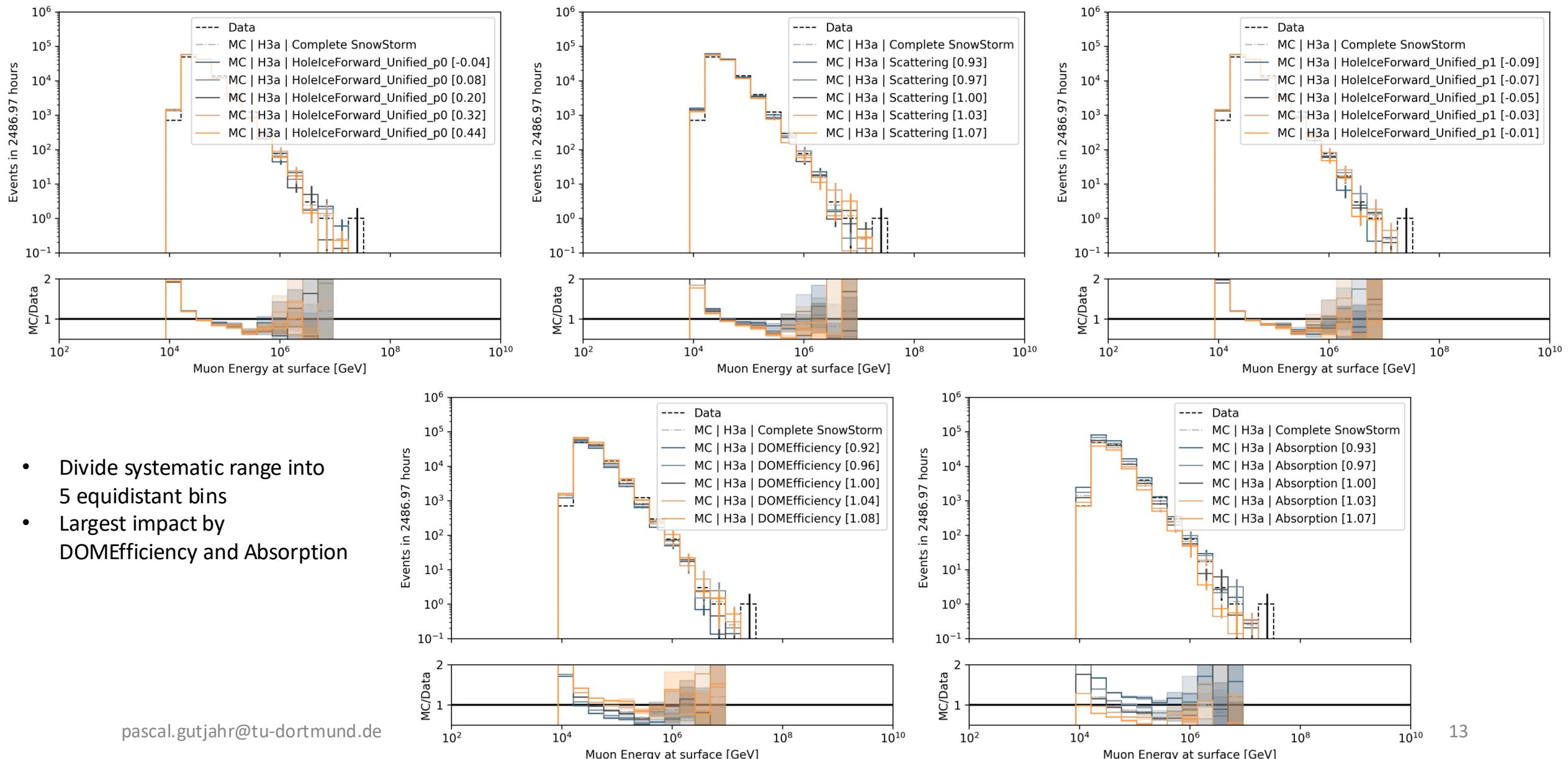
Snowstorm

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

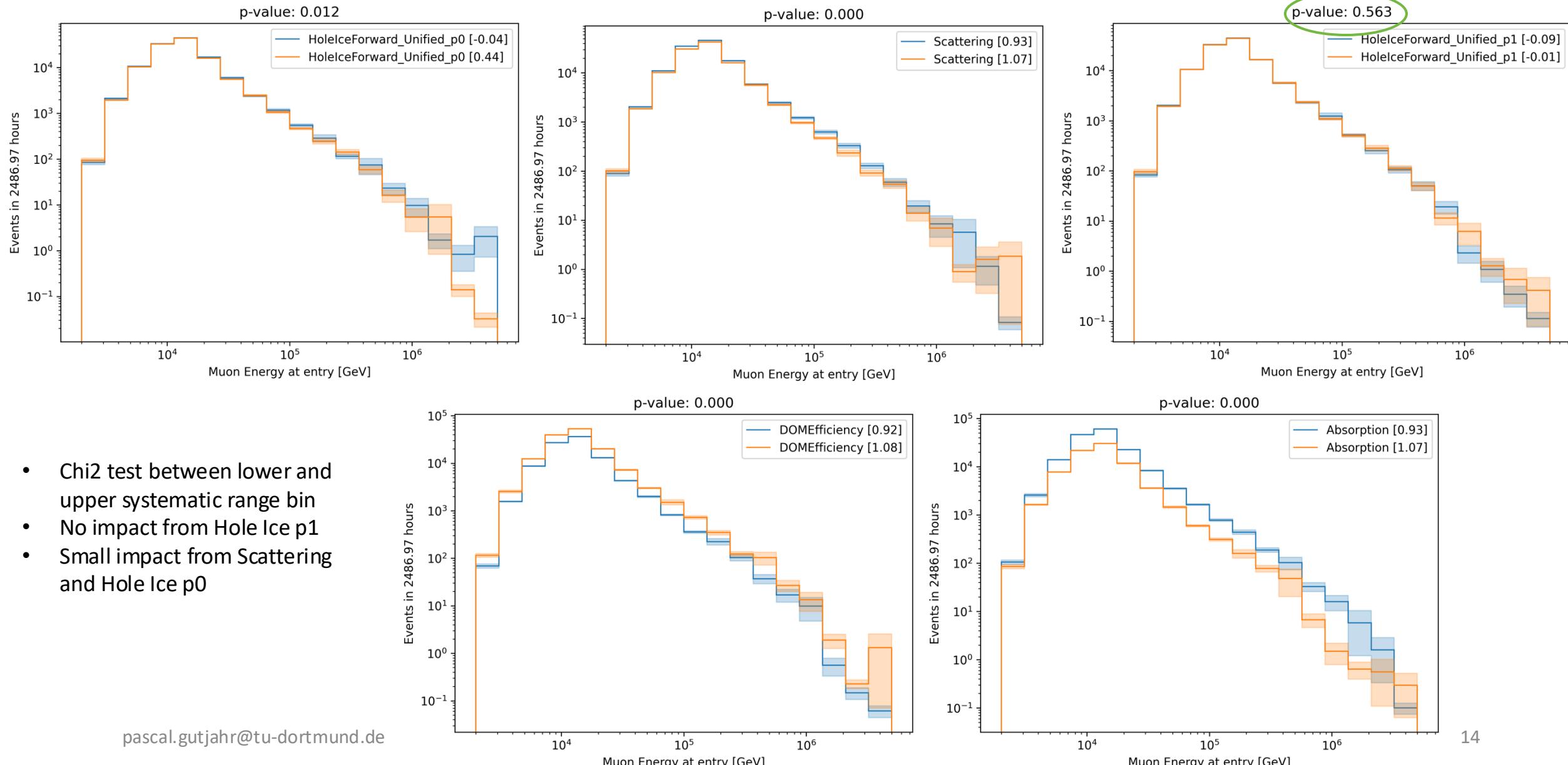
Systematics Impact on Muon Energy at Entry (Proxy)



Systematics Impact on Muon Energy at Surface (Target)



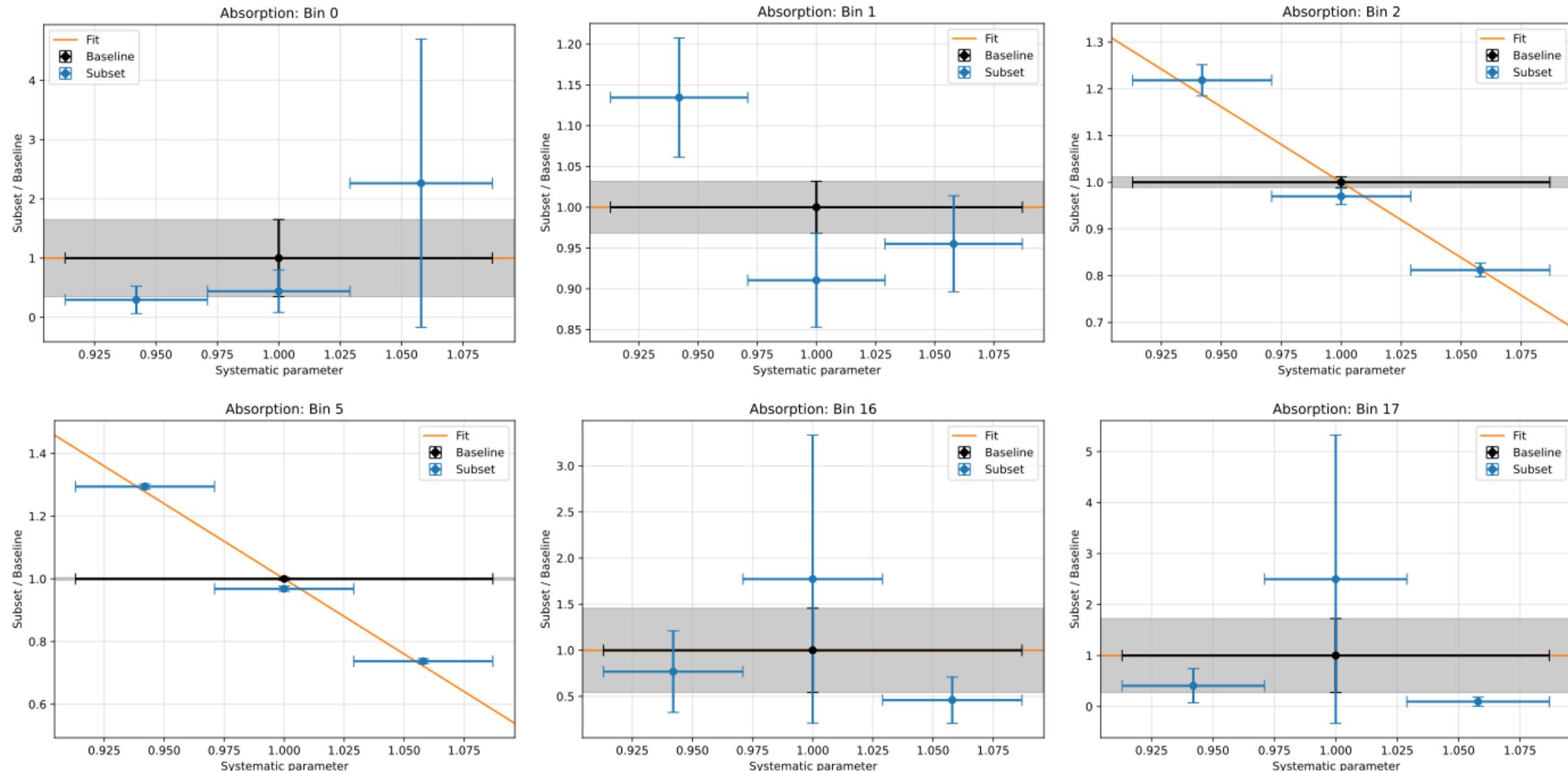
Chi2 Test: Muon Energy at Entry (Proxy)



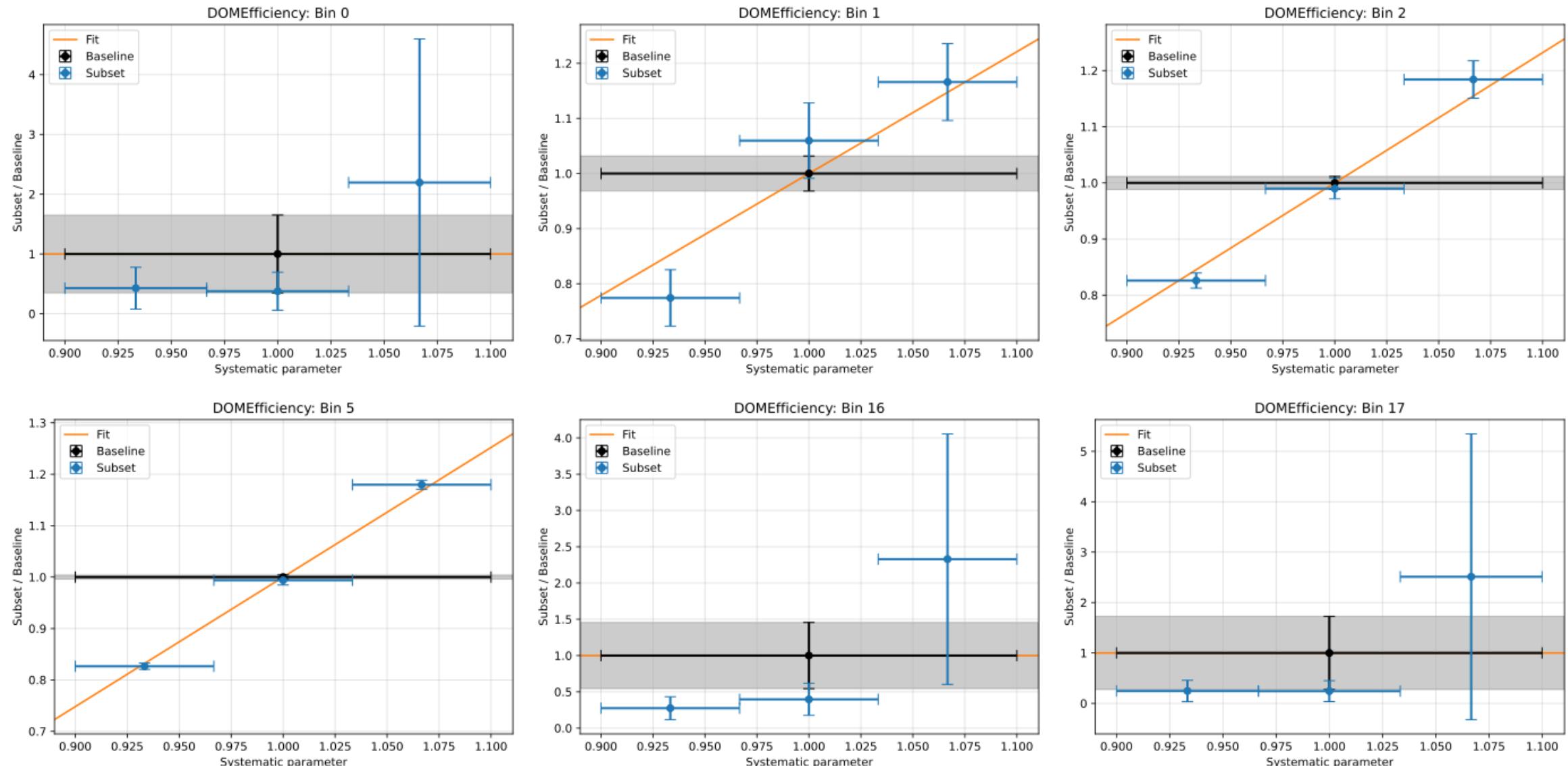
Parameterize Systematics

- 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)

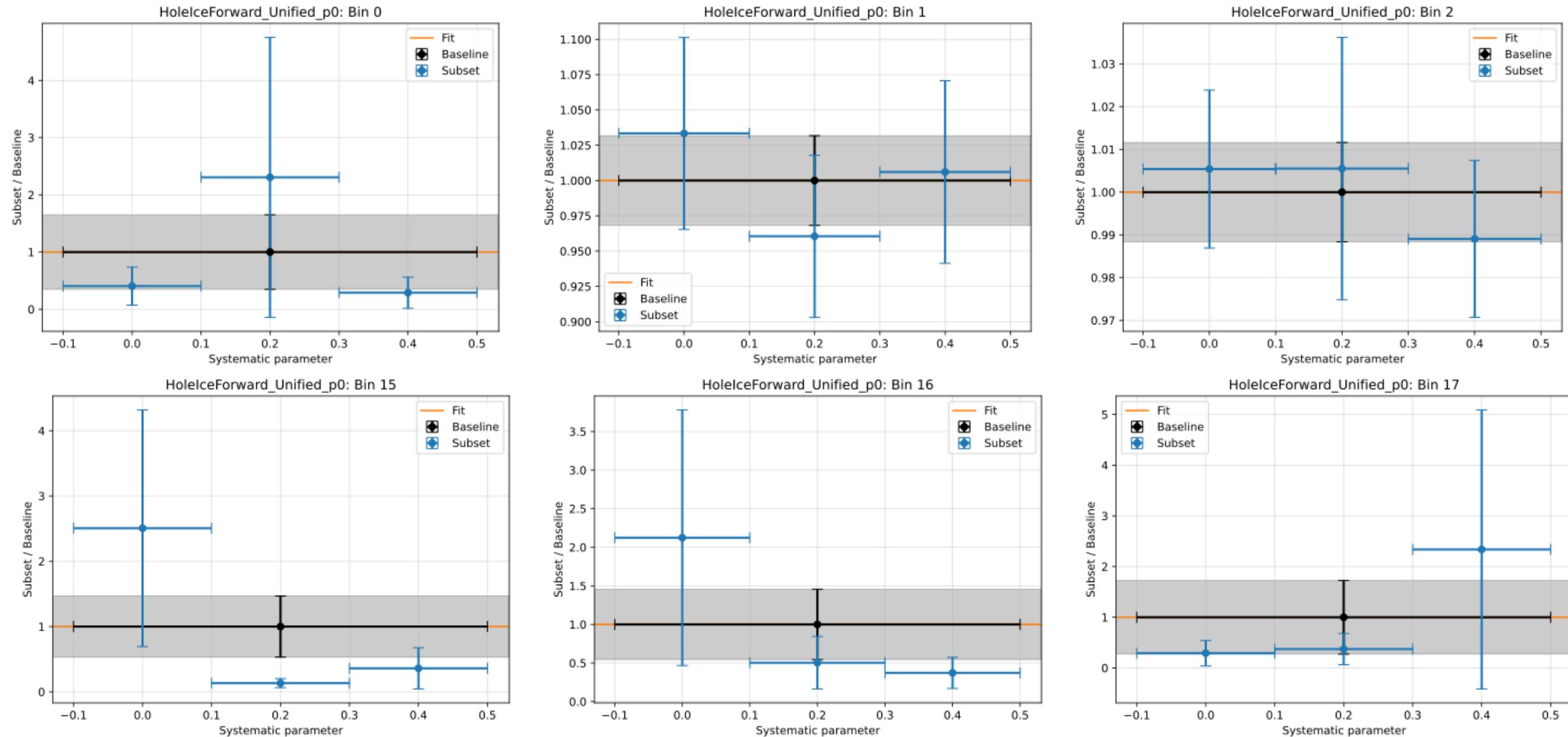
Absorption



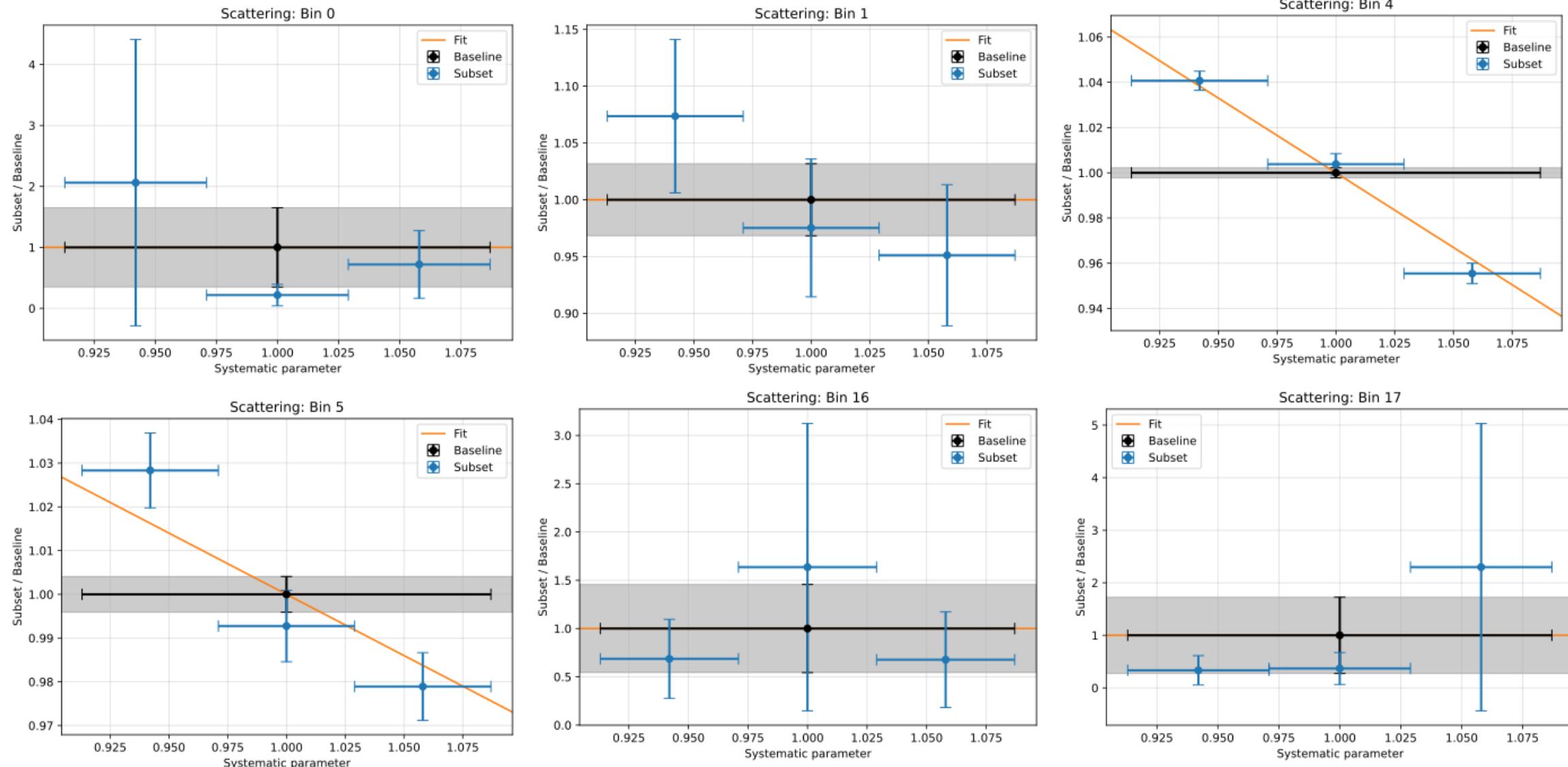
DOMEfficiency



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



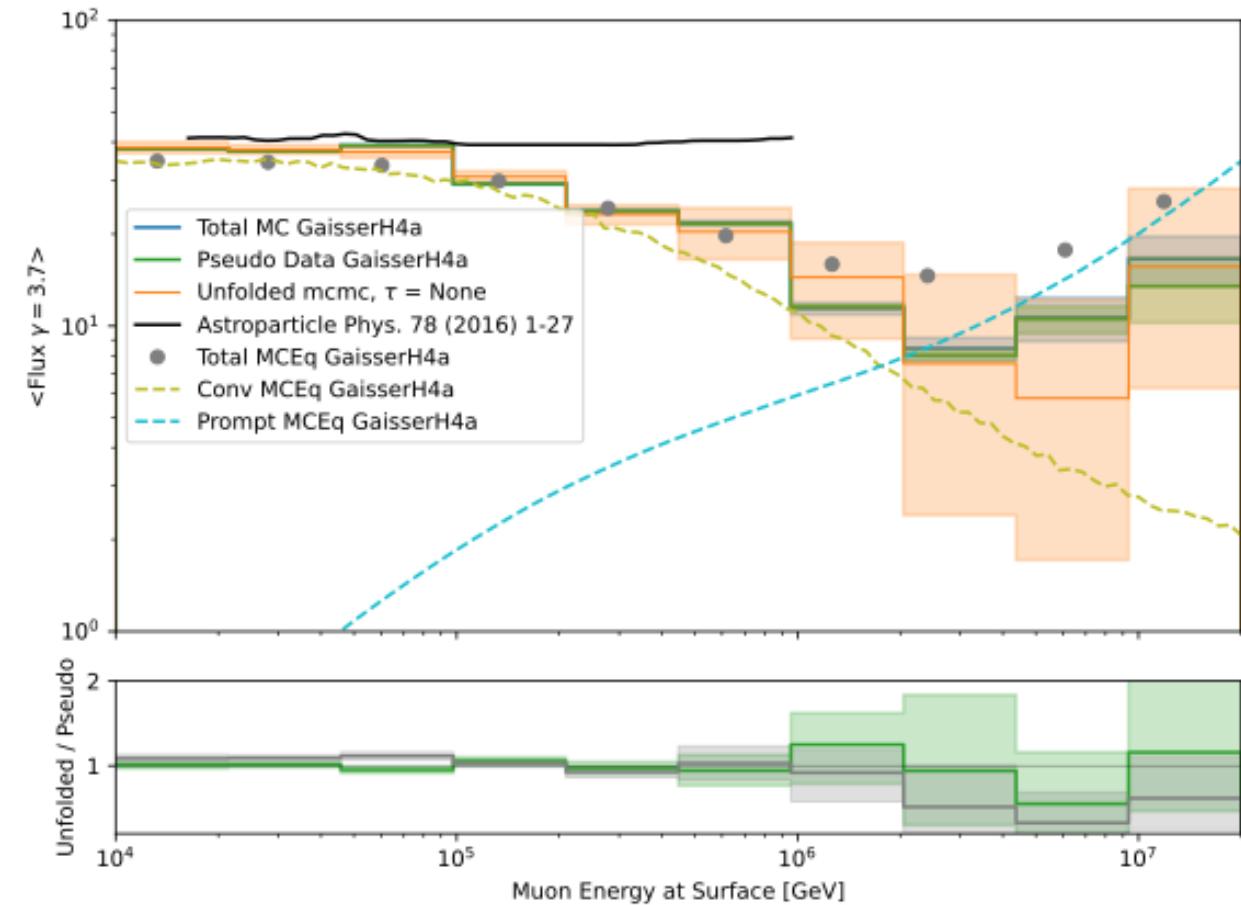
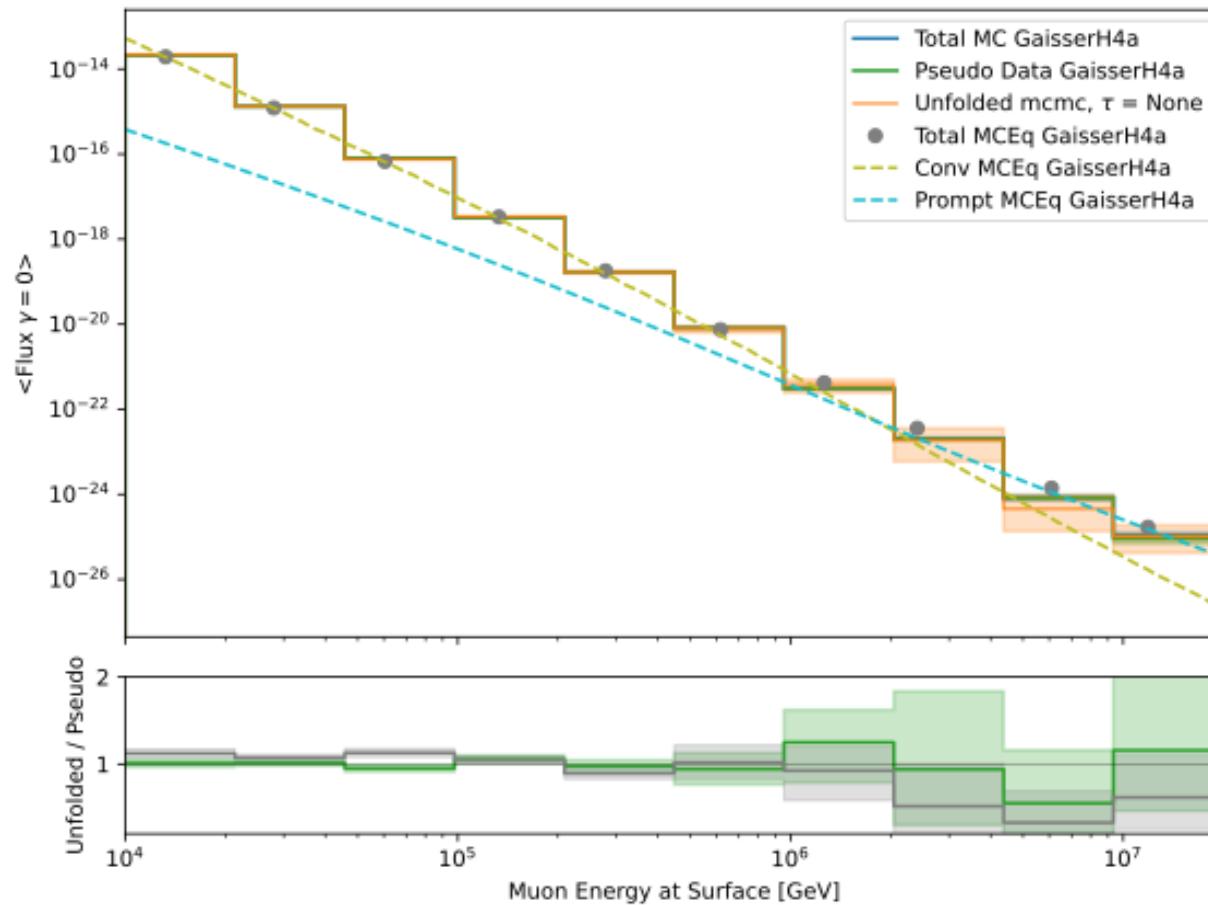
Scattering



Unfold Muon Flux with Systematics

No regularization

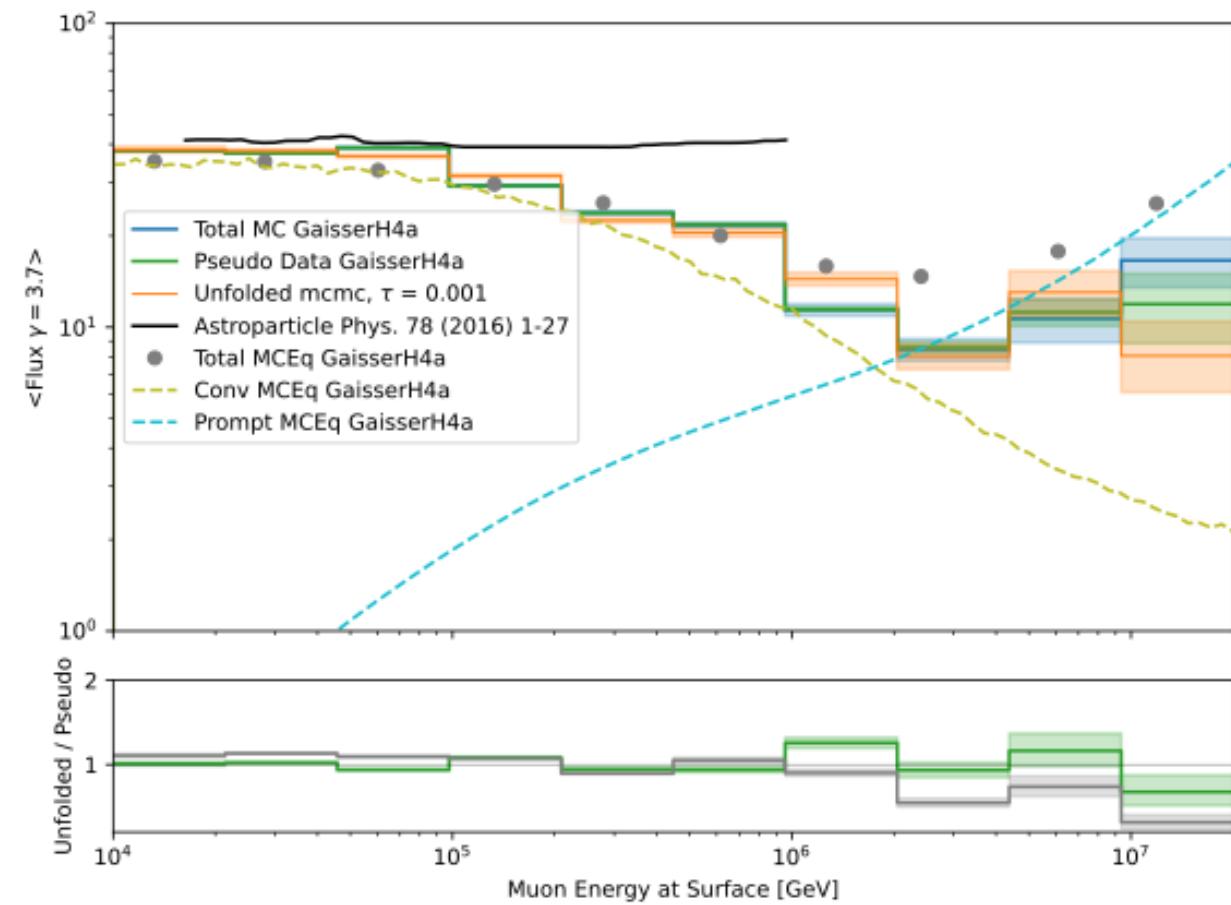
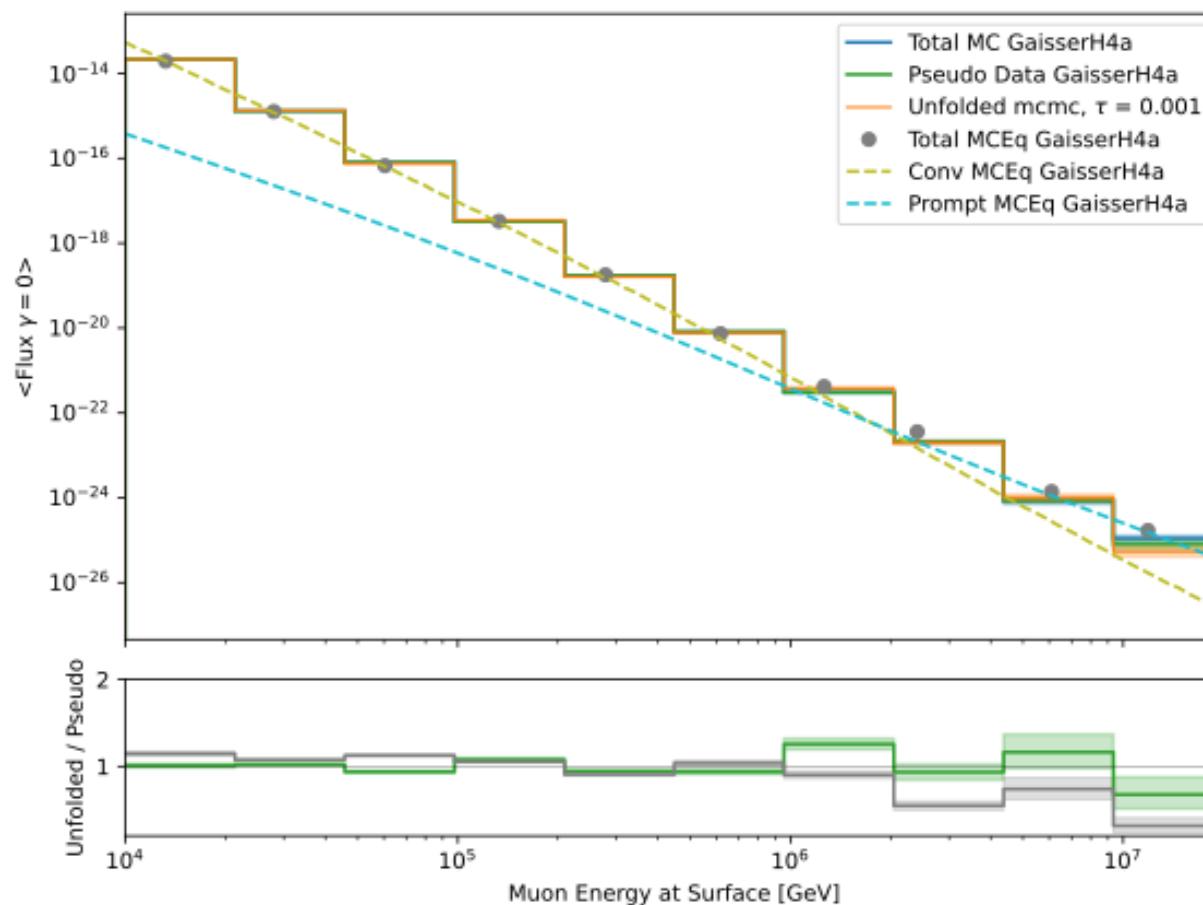
Muon Flux at Surface (no regularization)

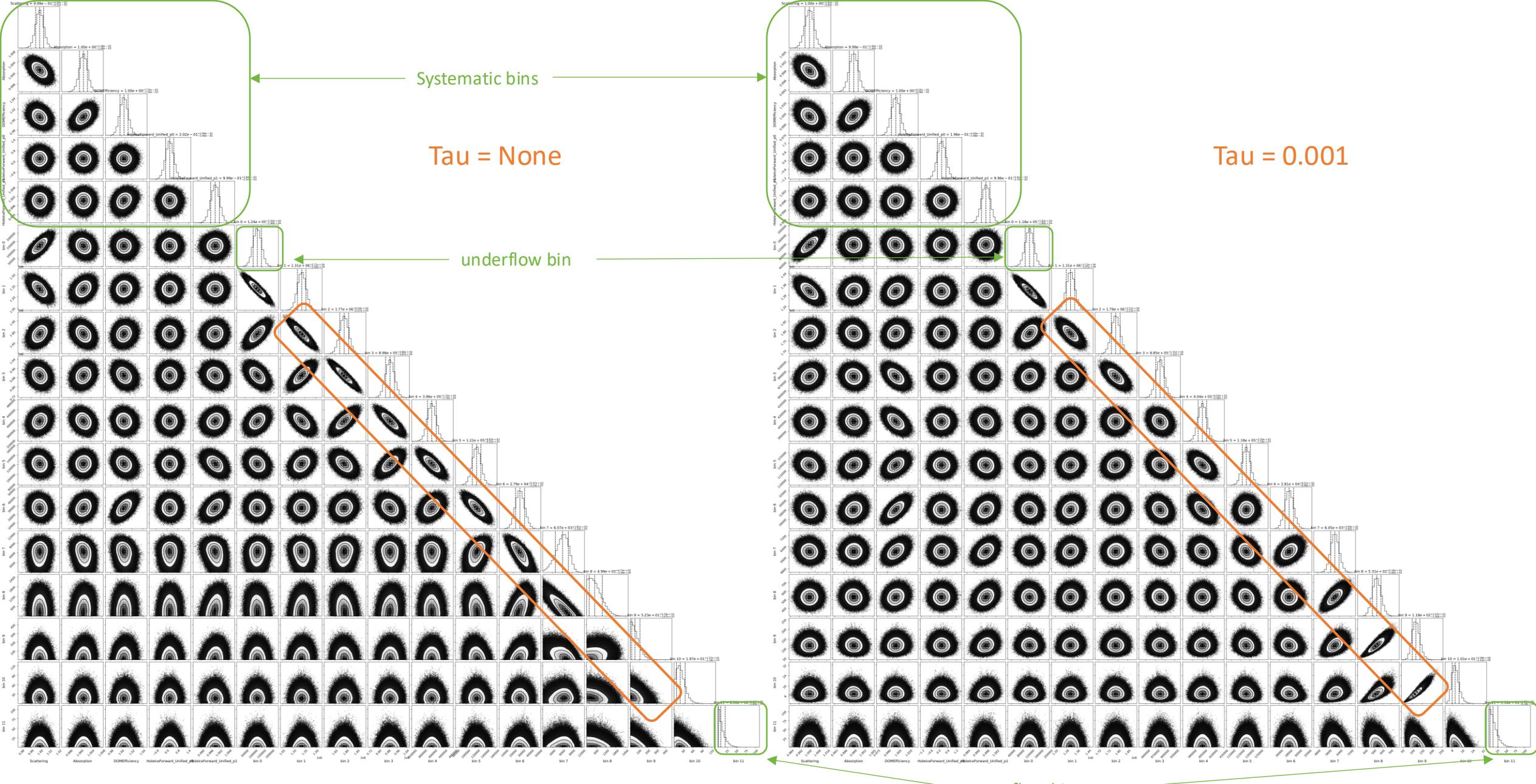


Unfold Muon Flux with Systematics

With regularization

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





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

Conclusion

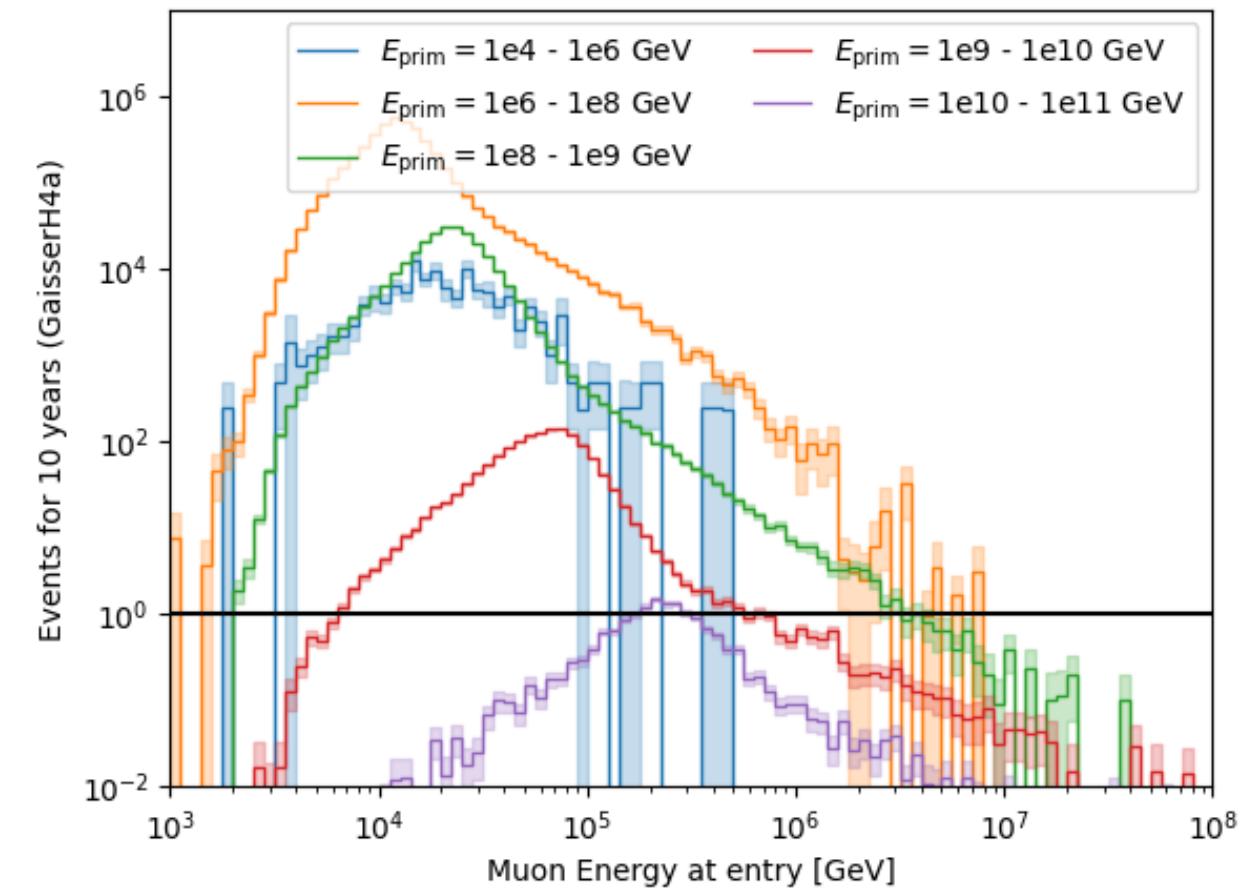
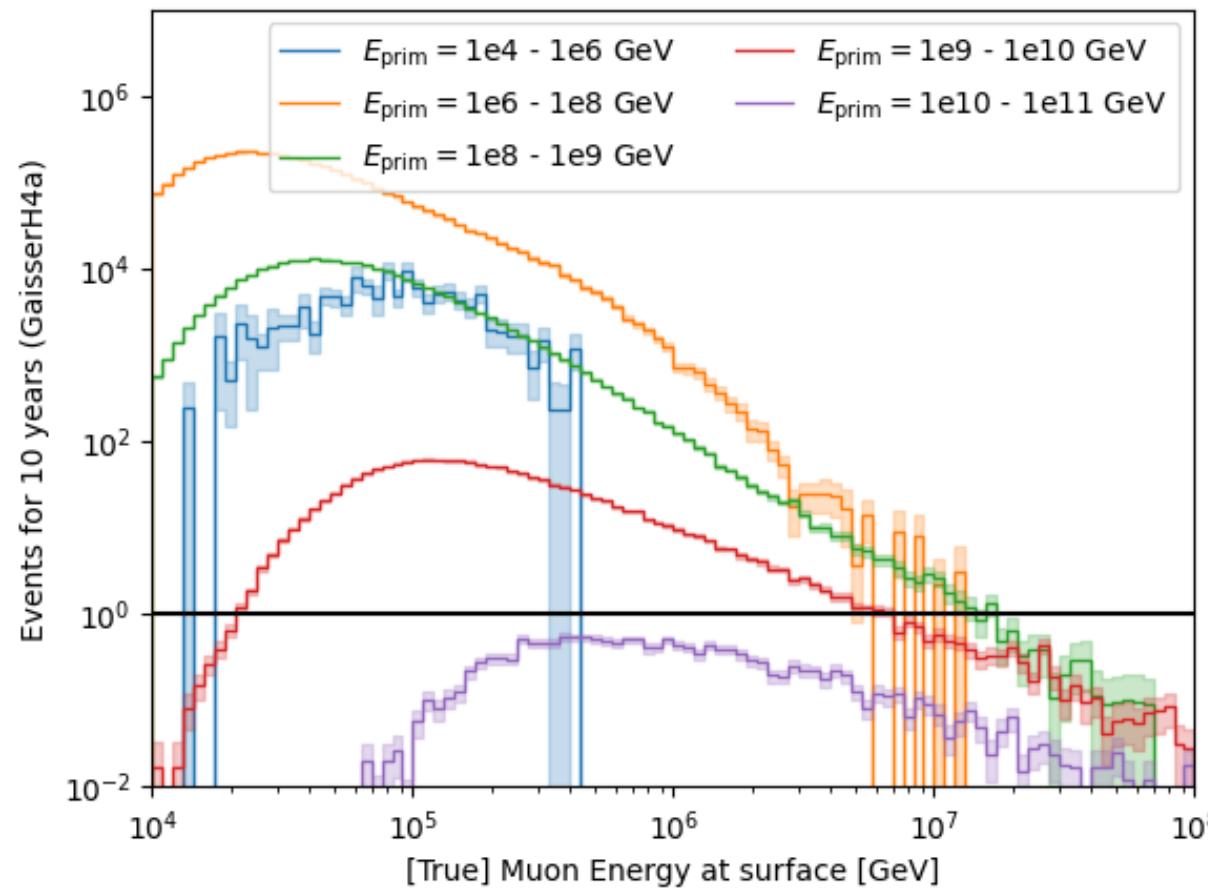
- Unfold muon event rate 
- Unfold muon flux at surface 
- Parameterize ice systematics 
 - Small impact from Scattering, Hole Ice p0 , and Hole Ice p1
 - Linear parameterization of Absorption and DOMEfficiency
- Unfold muon flux with systematics 

Next steps

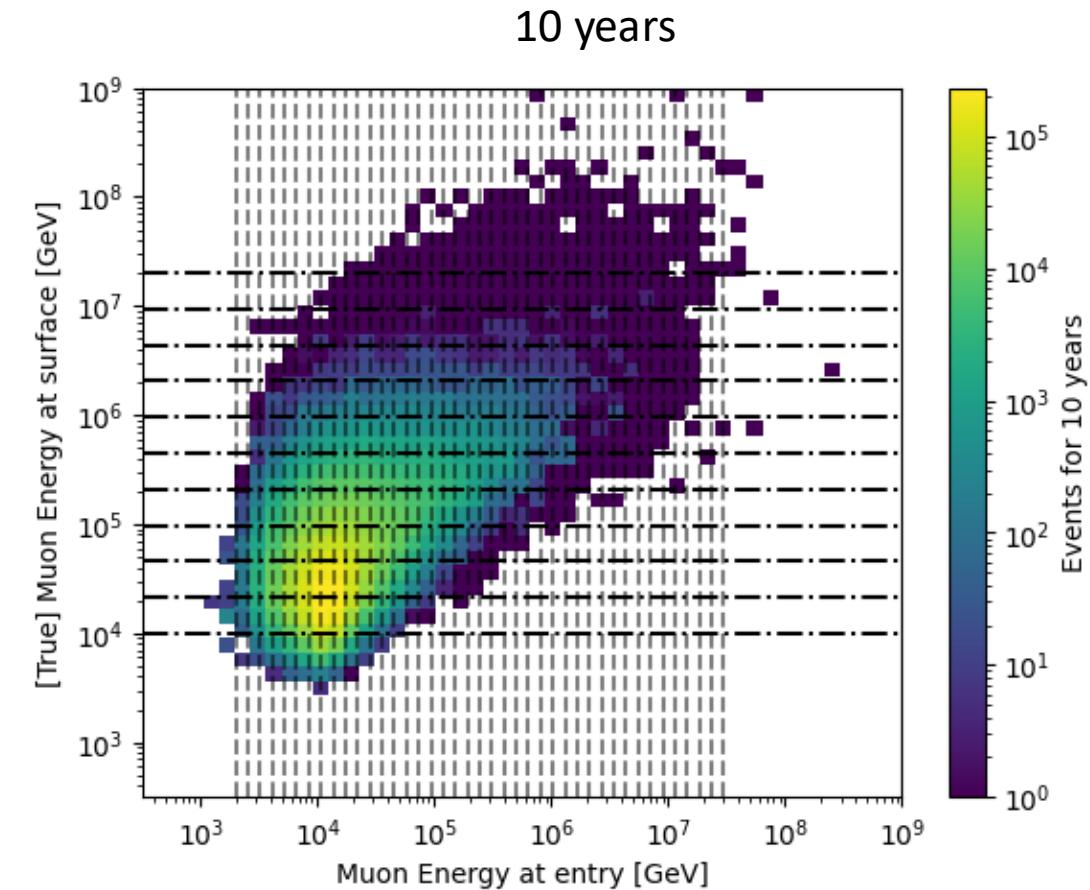
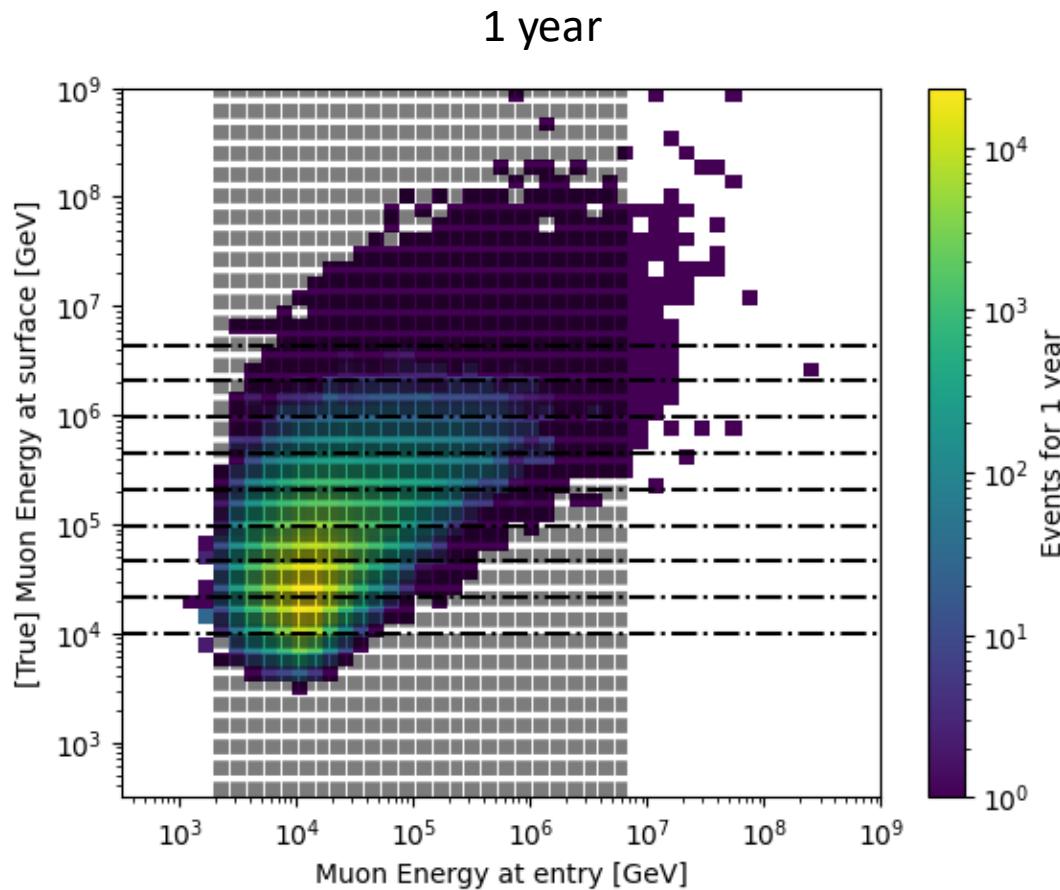
- Impact of primary flux
- Choose optimal regularization

Backup

Relation between primary energy and muon energy at surface and entry

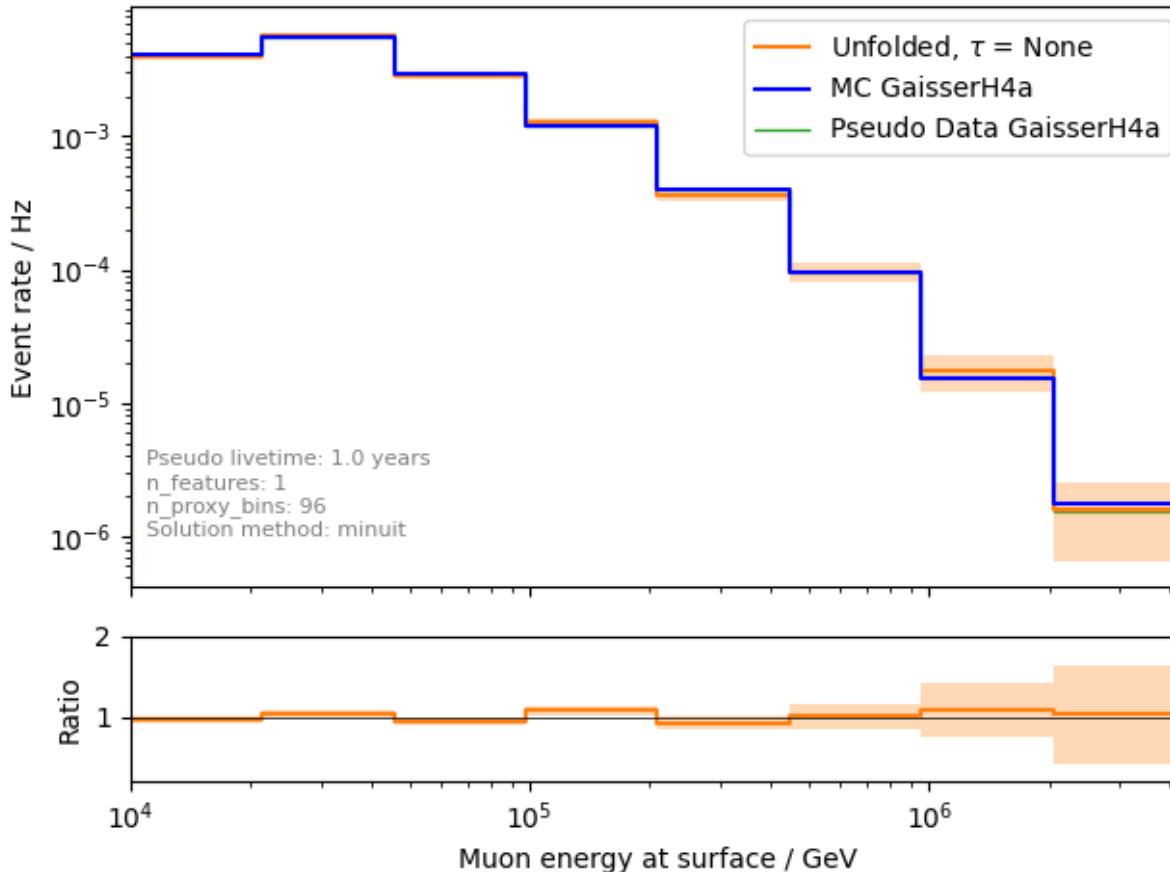


Proxy vs. target

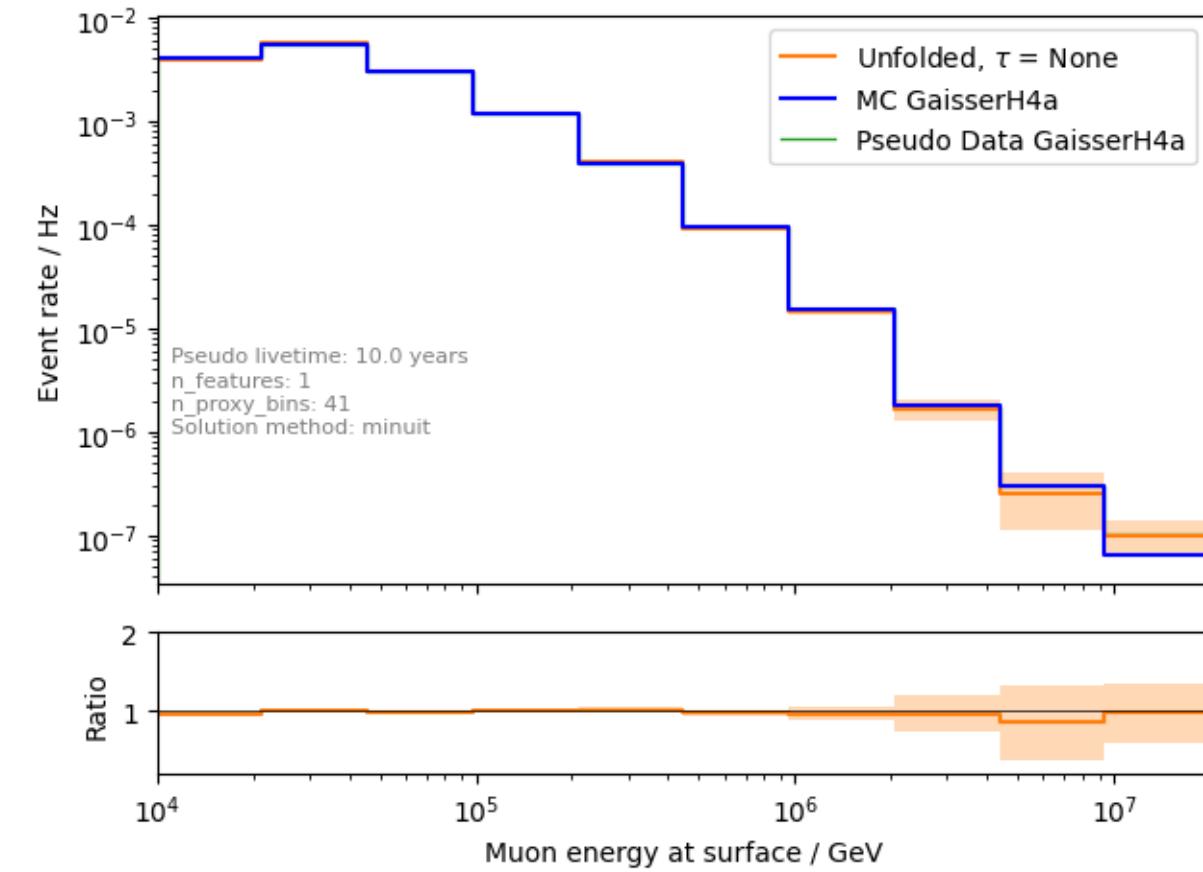


Unfolding event rate

1 year

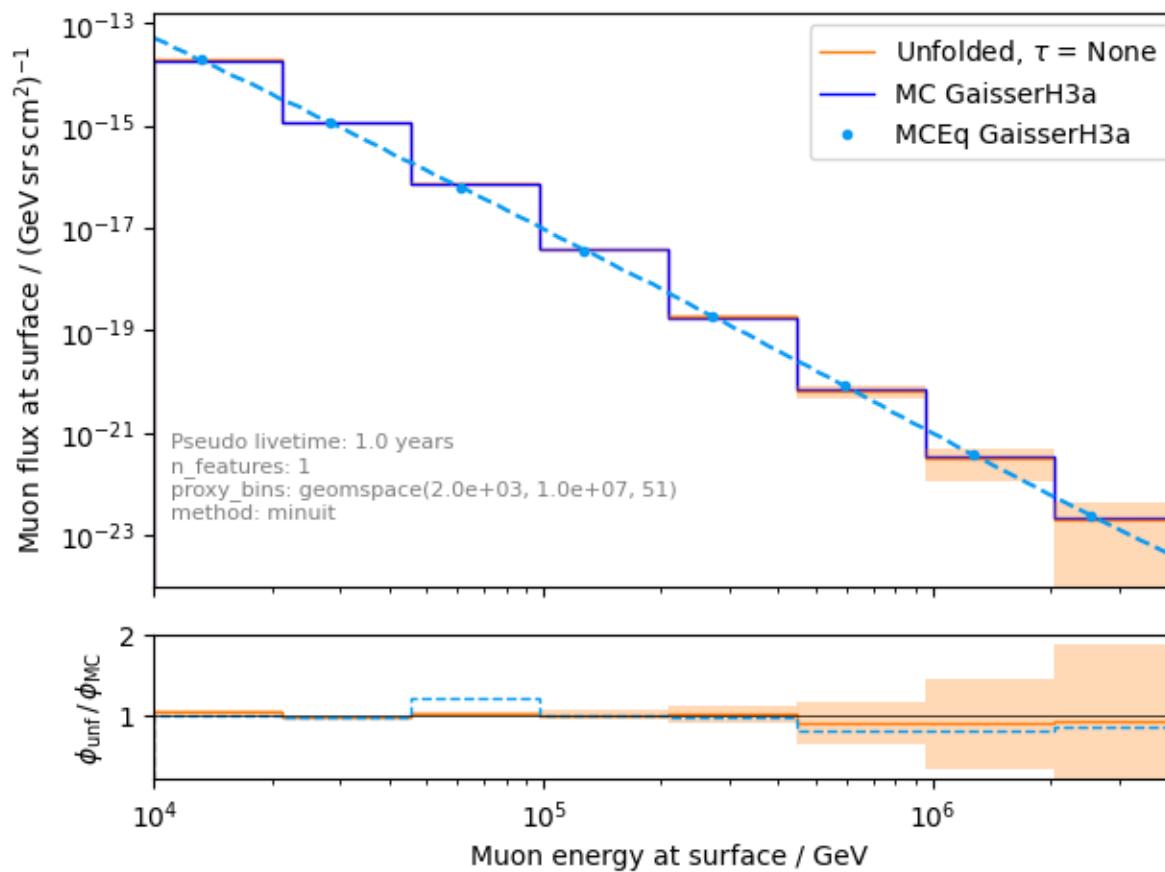


10 years

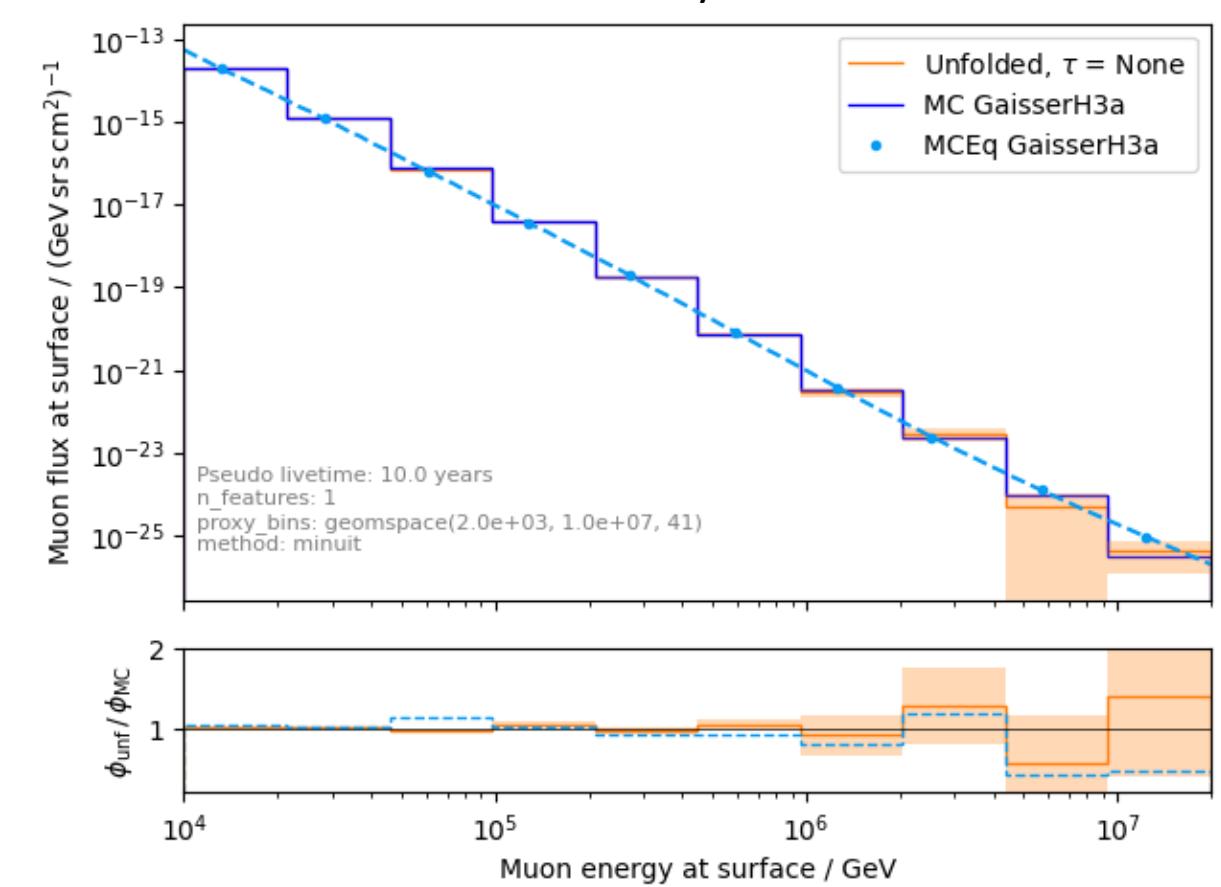


unfolding of muon flux at surface

1 year



10 years



Ice systematics

Snowstorm

Absorption

Scattering

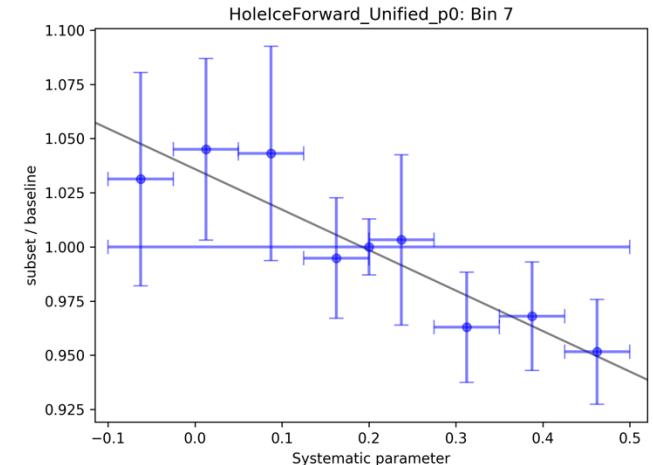
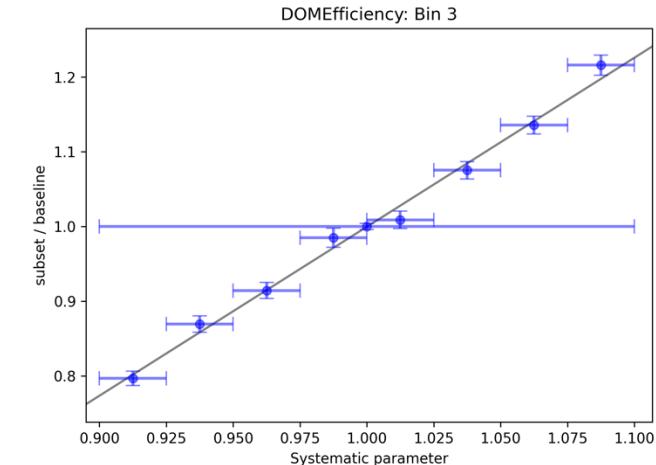
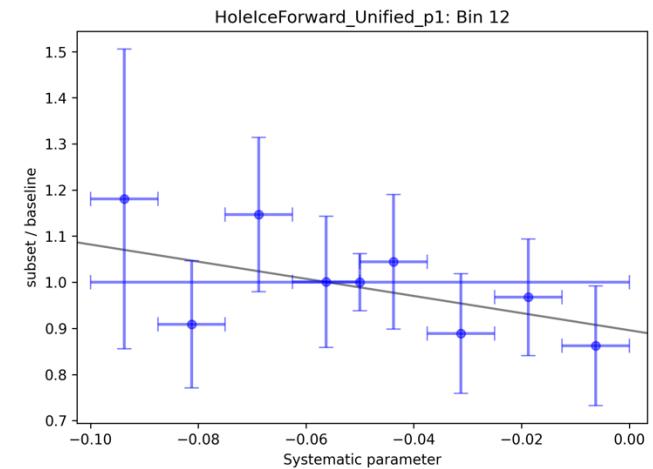
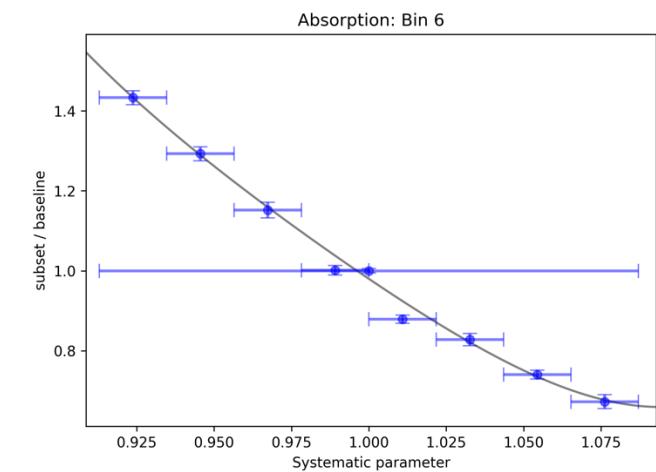
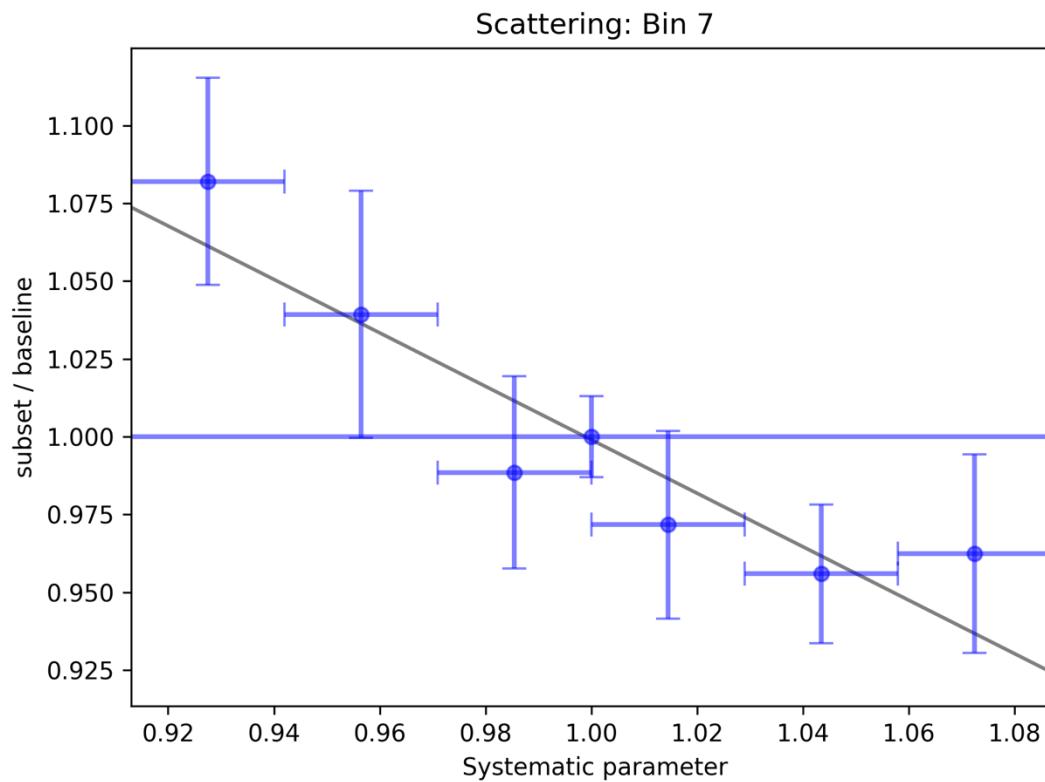
DOMEfficiency

HoleIce 0

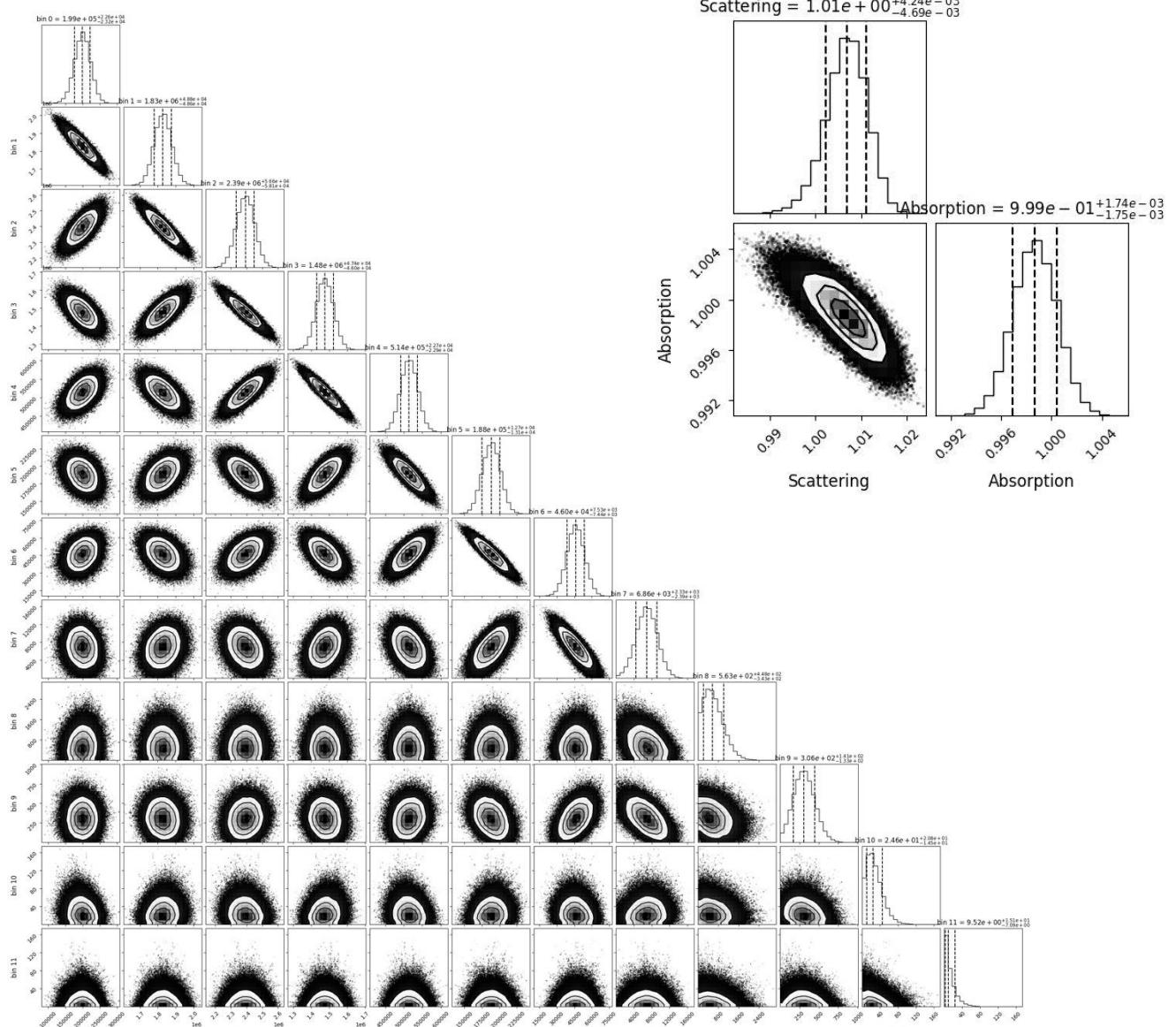
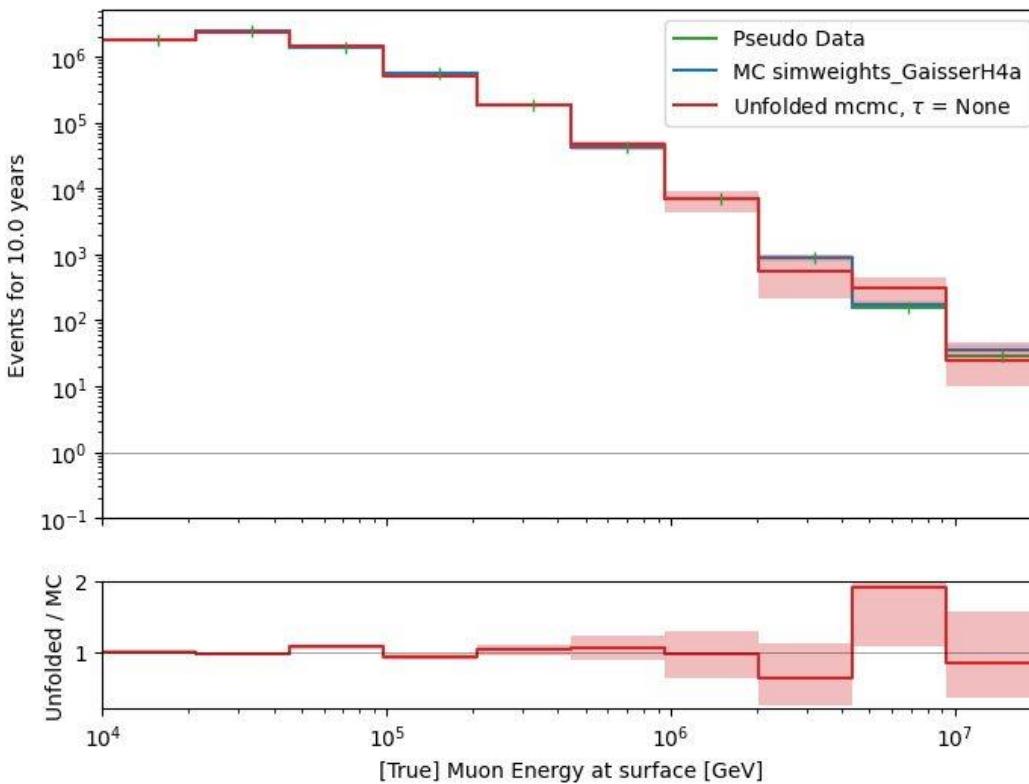
HoleIce 1

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

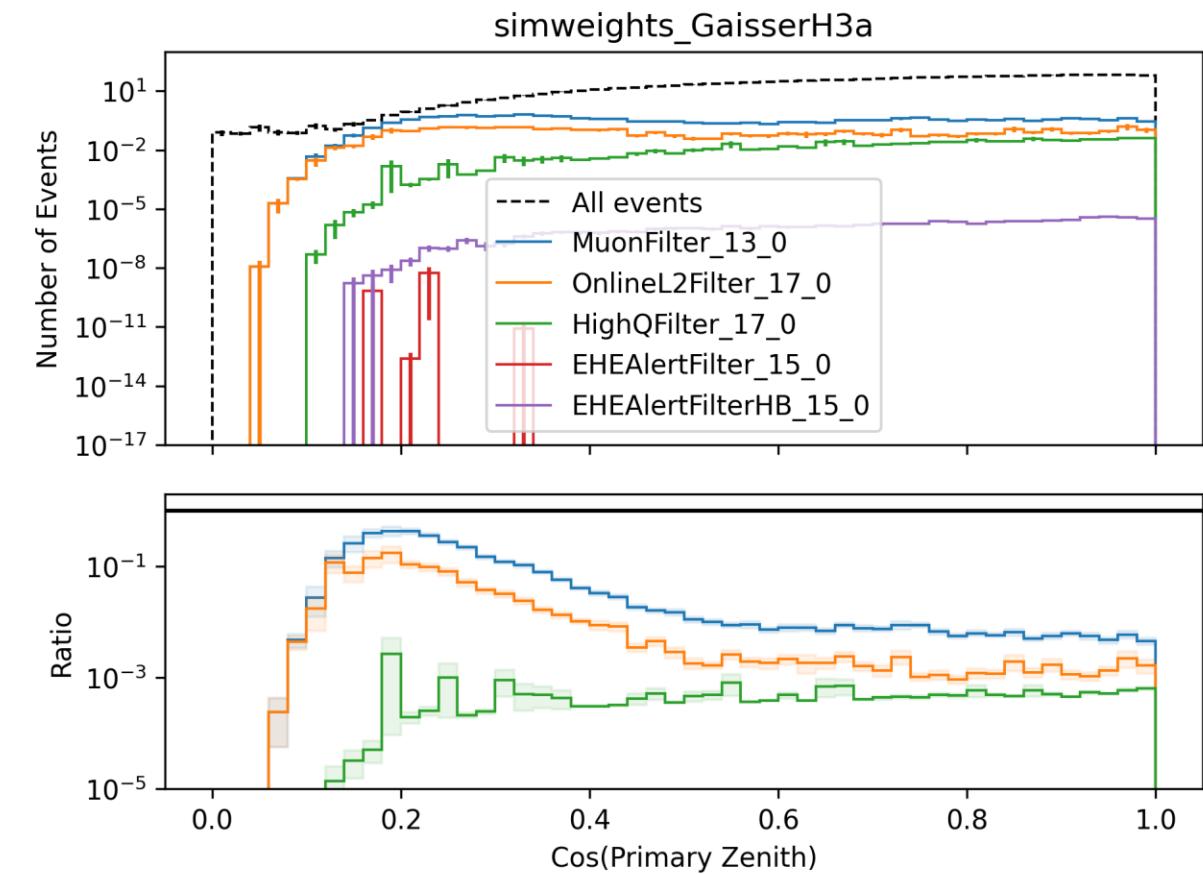
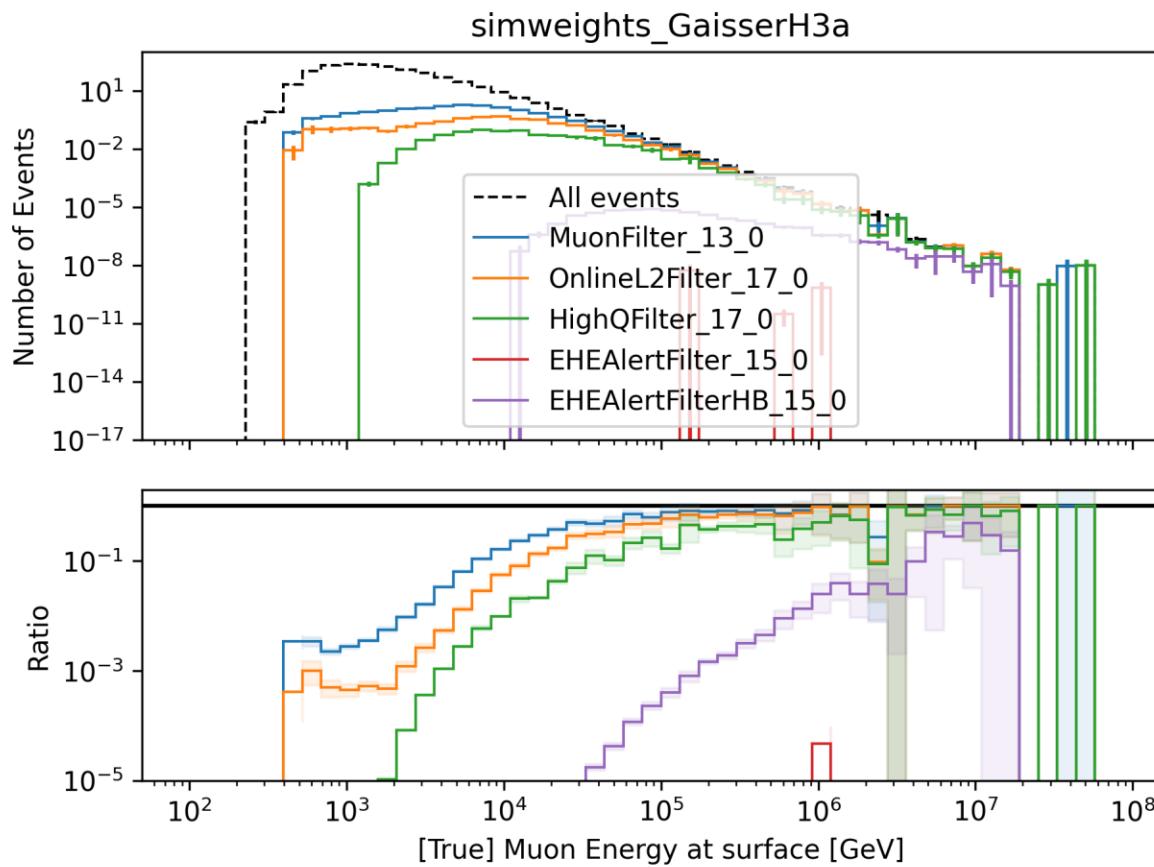
- New CORSIKA simulations with parent information
 - tag prompt and conventional muons
 - validation: agreement with MC Eq
- Add DNN-based reconstructions
- Good data-MC agreement
 - quality cuts defined
 - good agreement in $\cos(\text{zenith})$ distributions
 - mismatch in z—position → re-weight distributions
- 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.

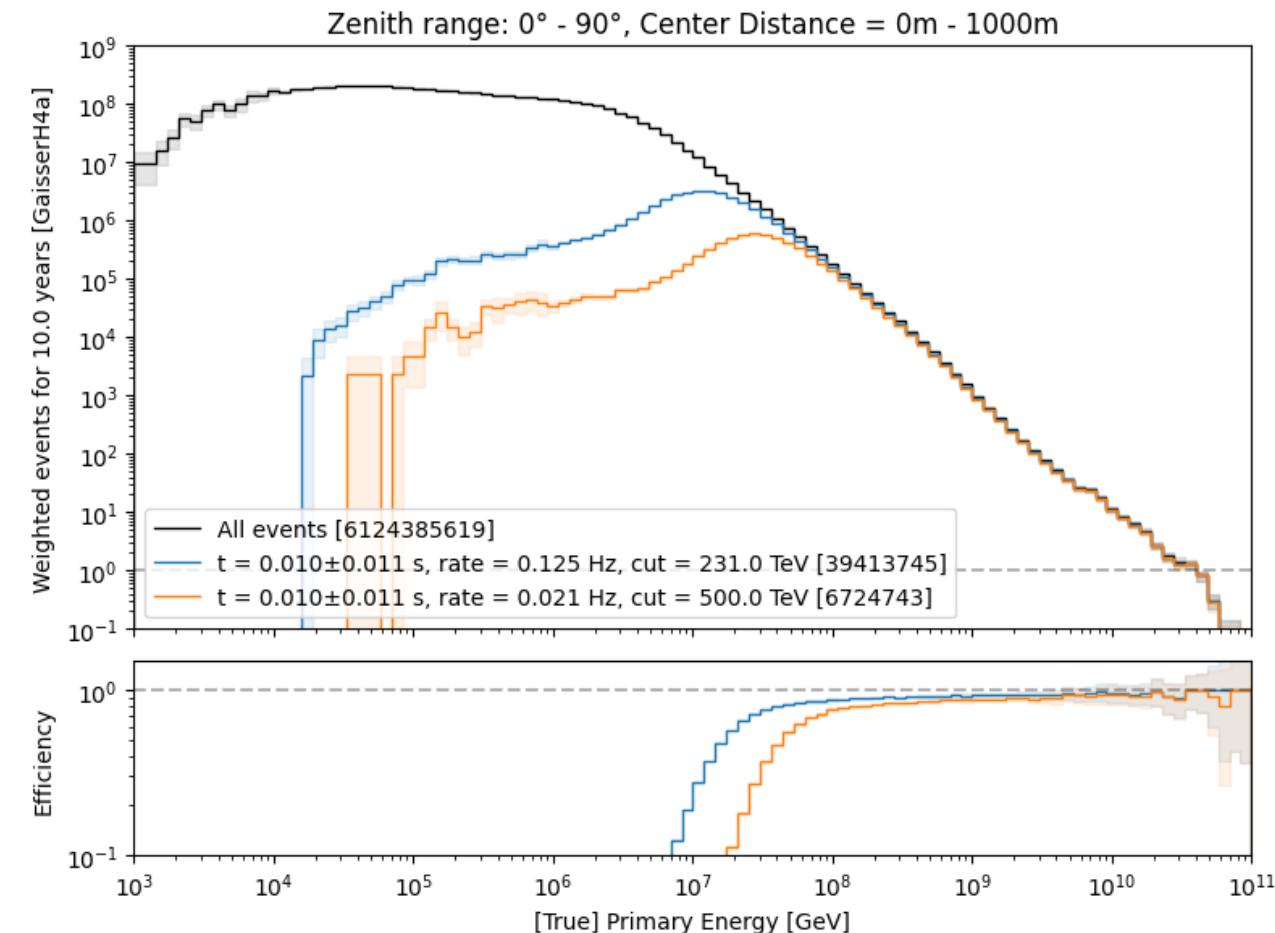
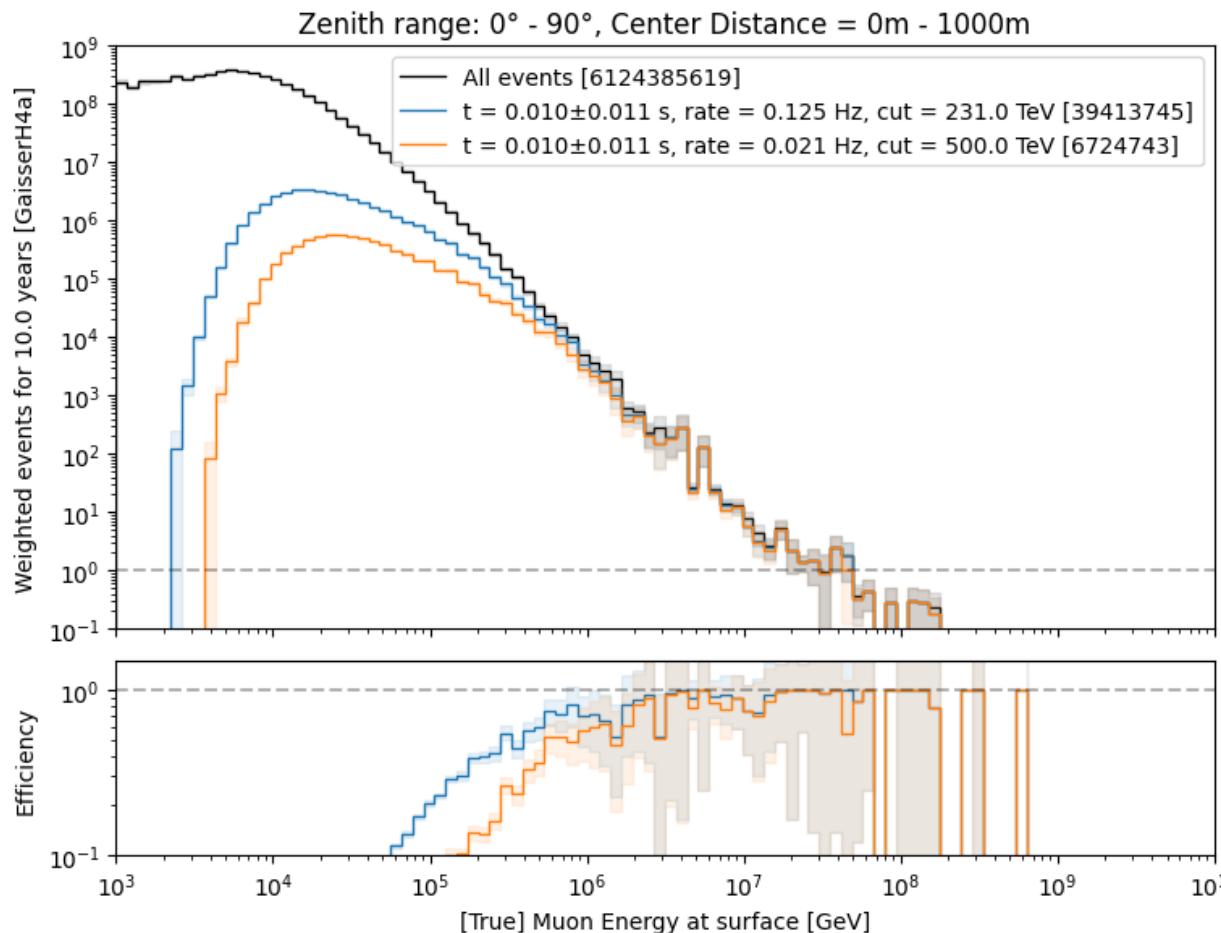
Selection

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

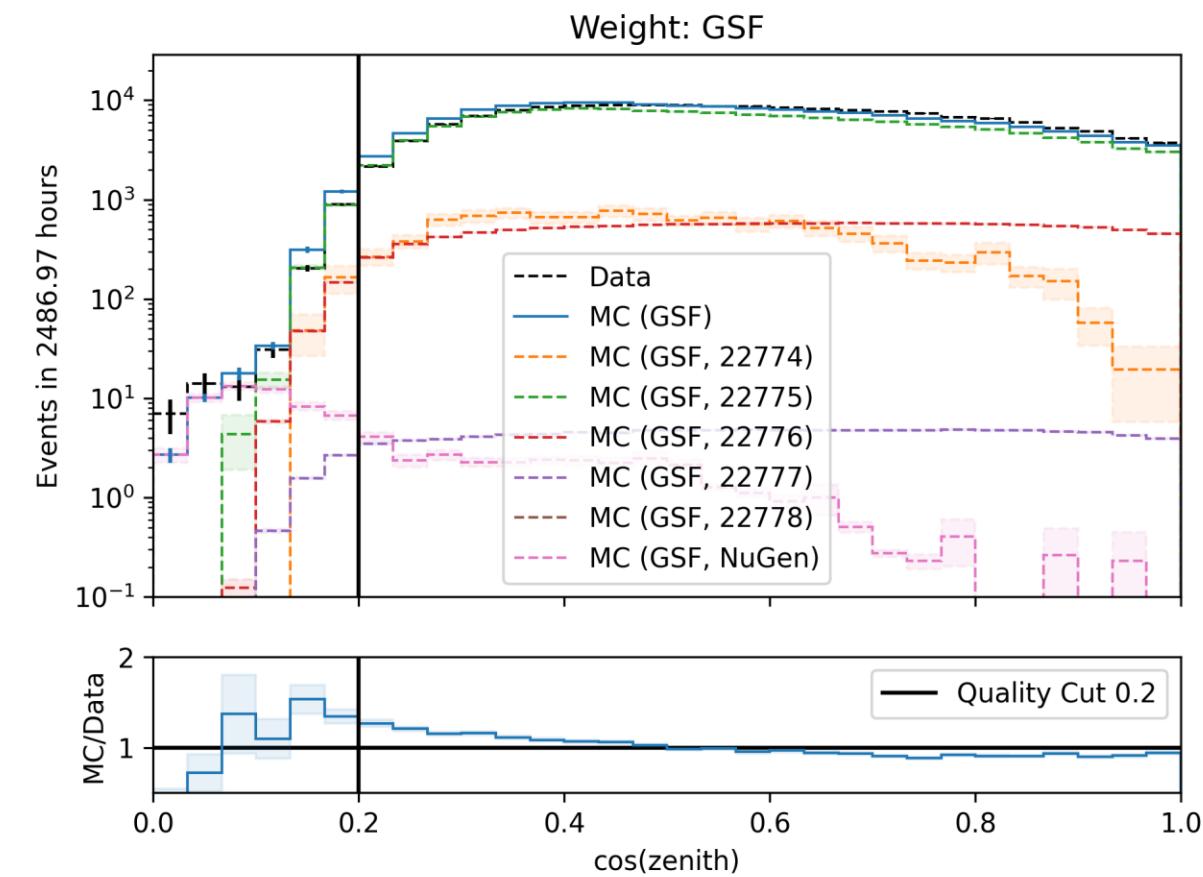
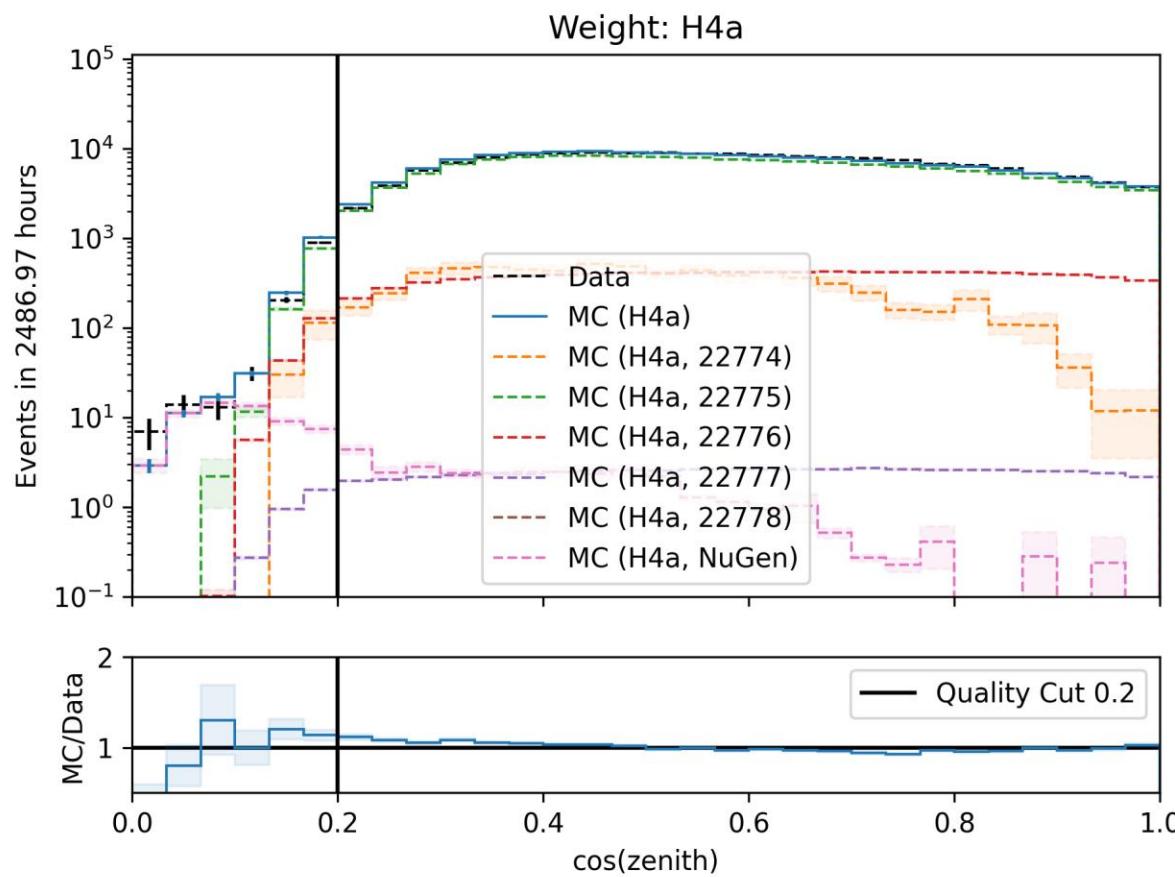
level3: 500 TeV bundle cut at surface



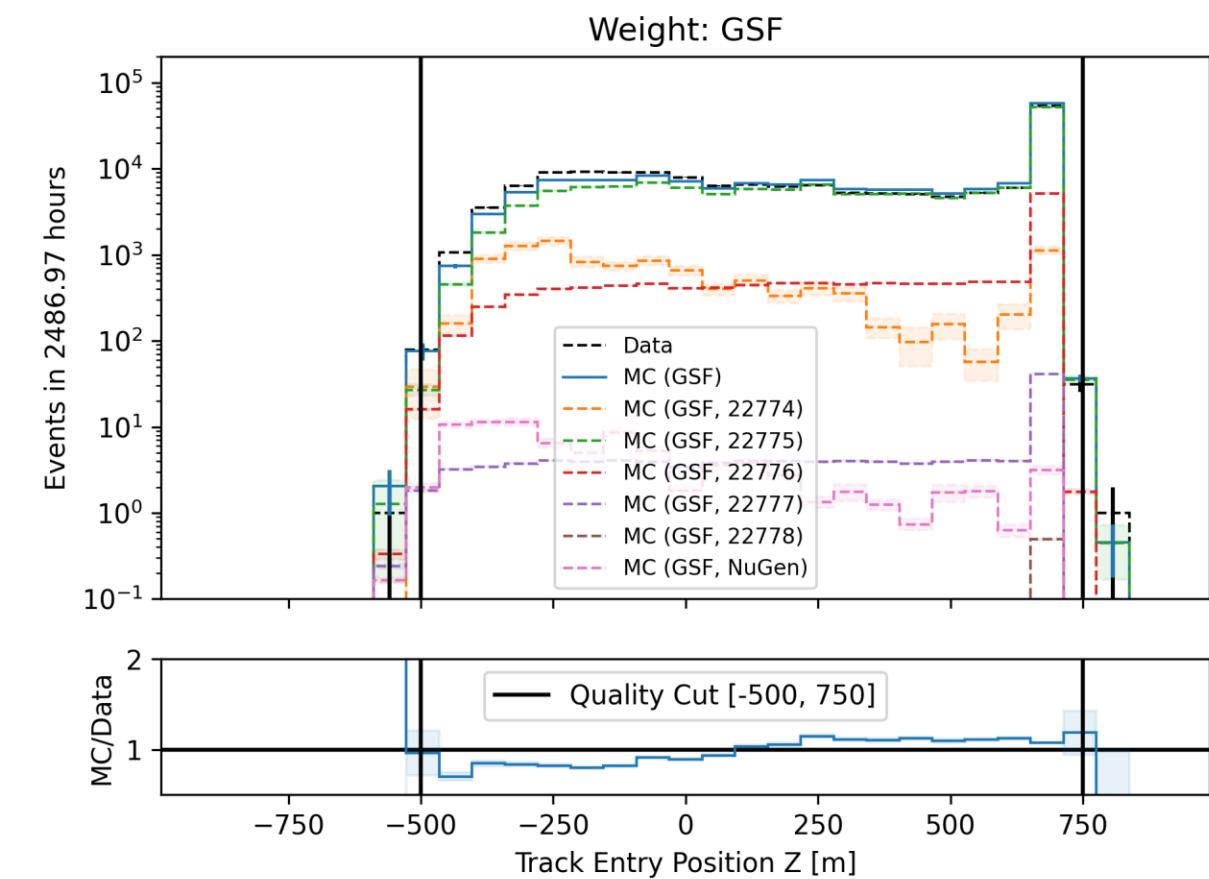
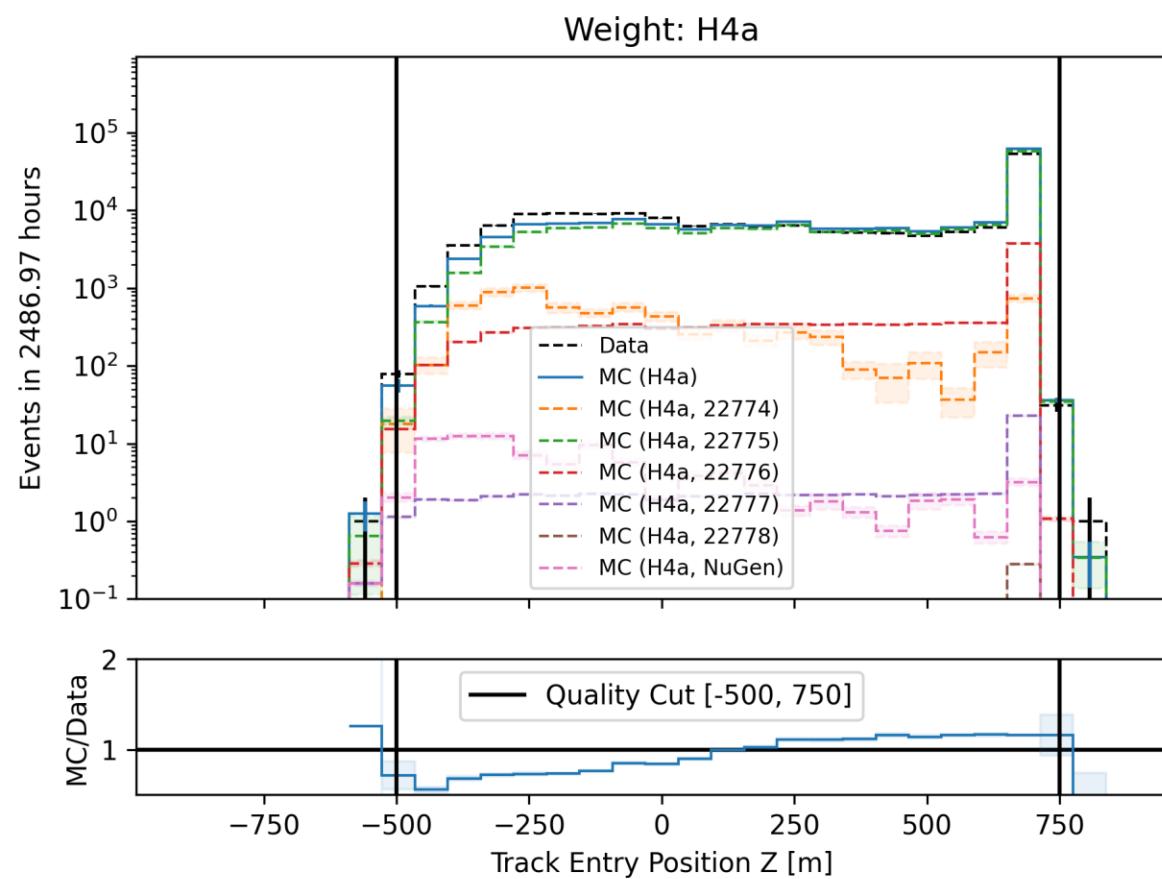
- 6 billion events expected: computationally not feasible → focus on high-energetic events
 - 500 TeV cut: 6.7 Mio events left

Data-MC

Cos(zenith)

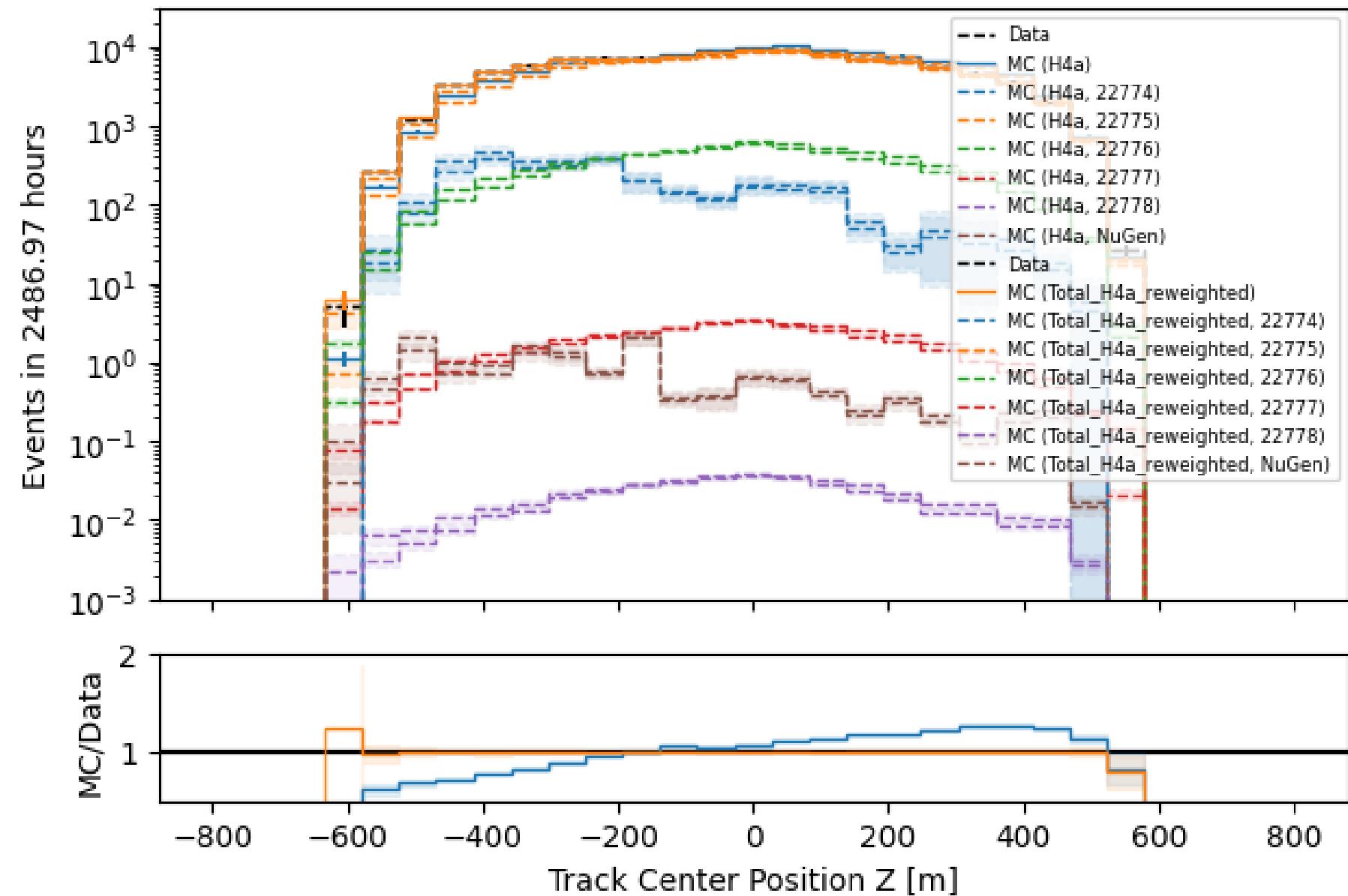


Entry position z—vertex

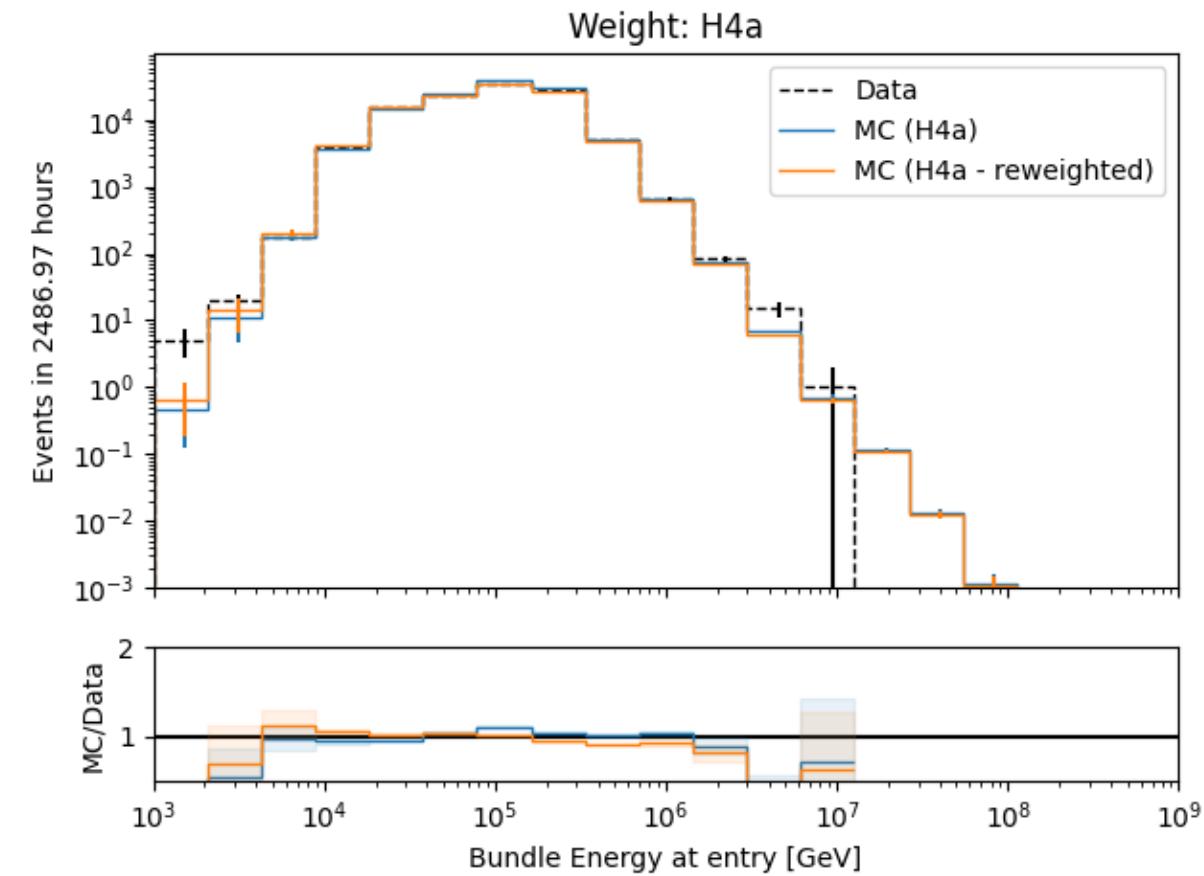
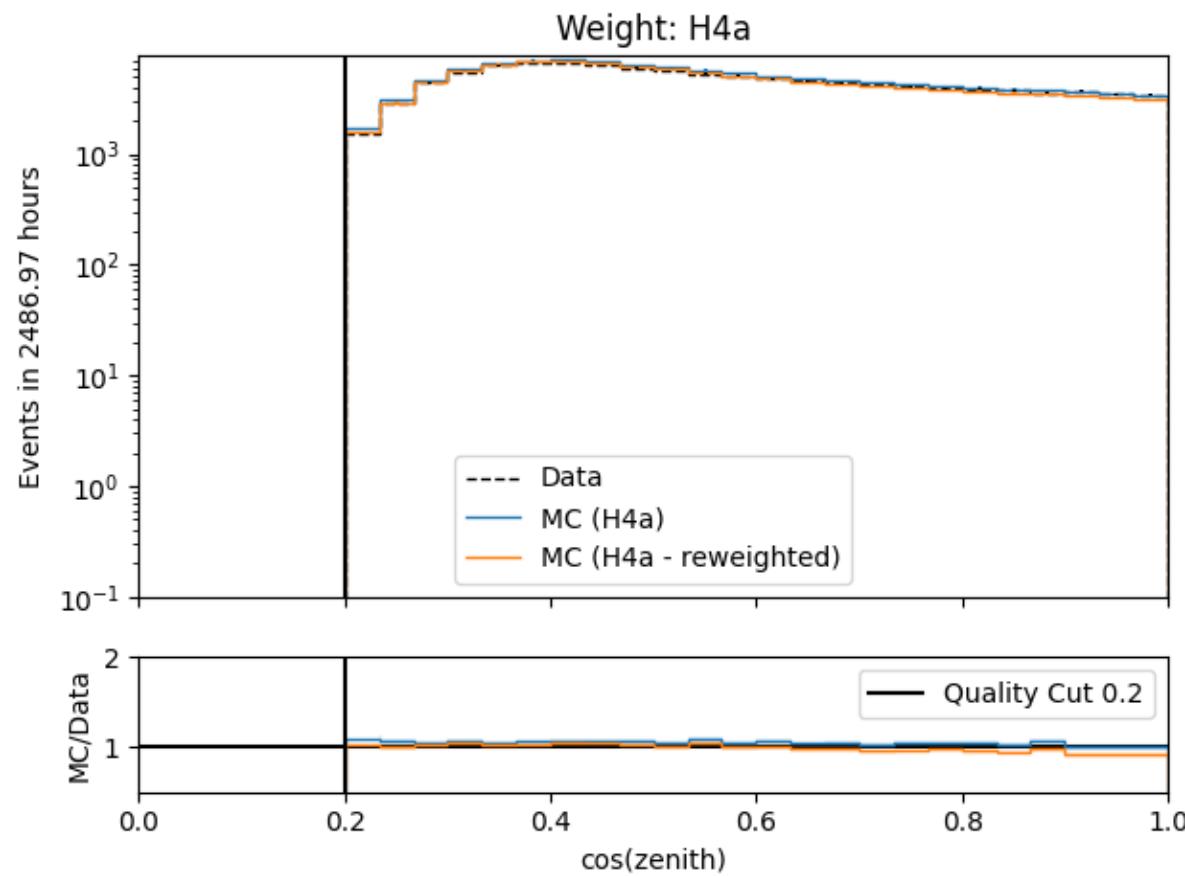


z—reweighting

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



Check z—reweighting



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

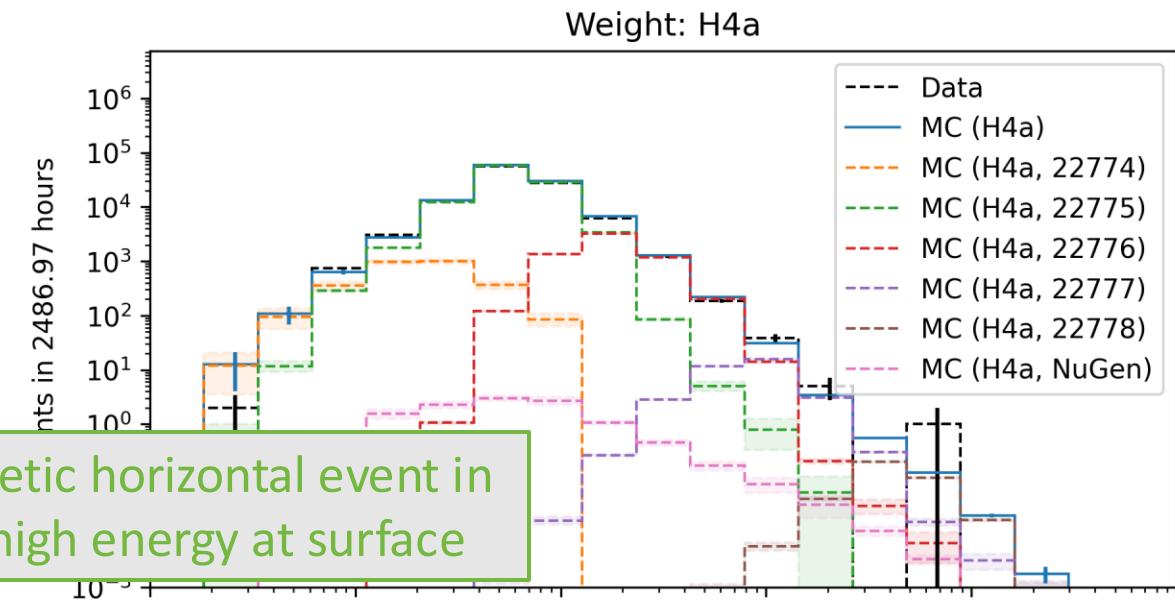
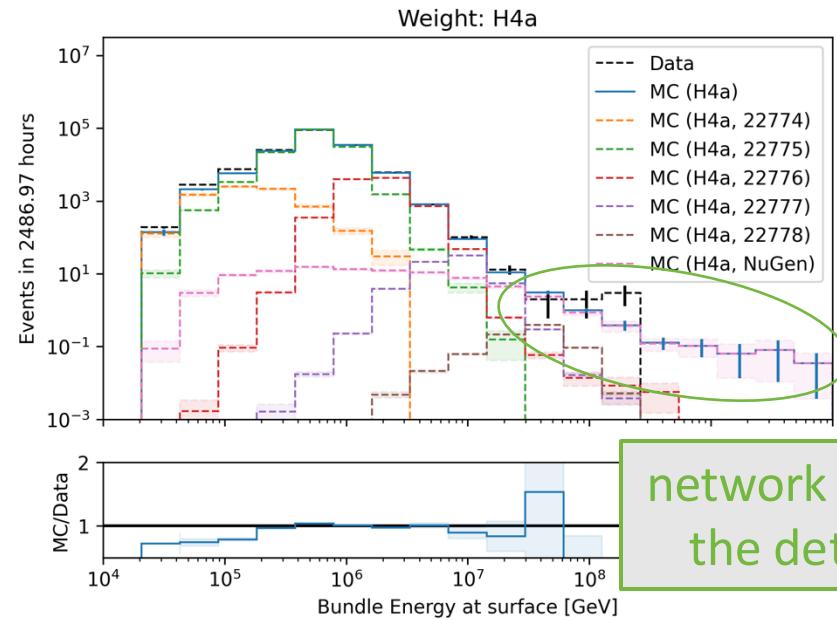
Level5: quality cuts

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

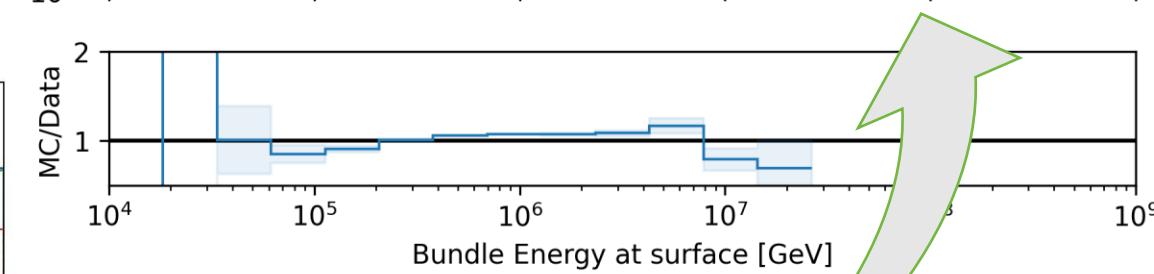
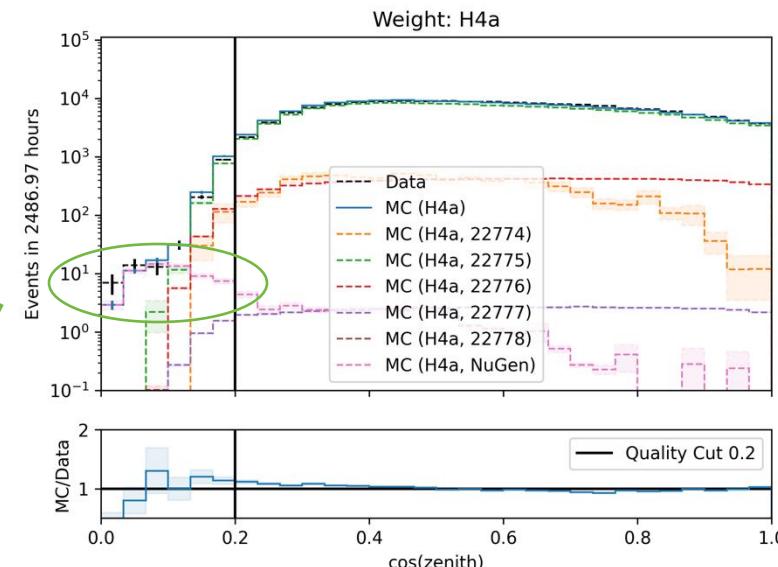
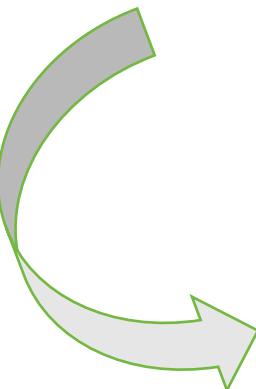
neutrino cuts	>	<
$\cos(\text{zenith})$	0.2	
length	5000 m	15000 m

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

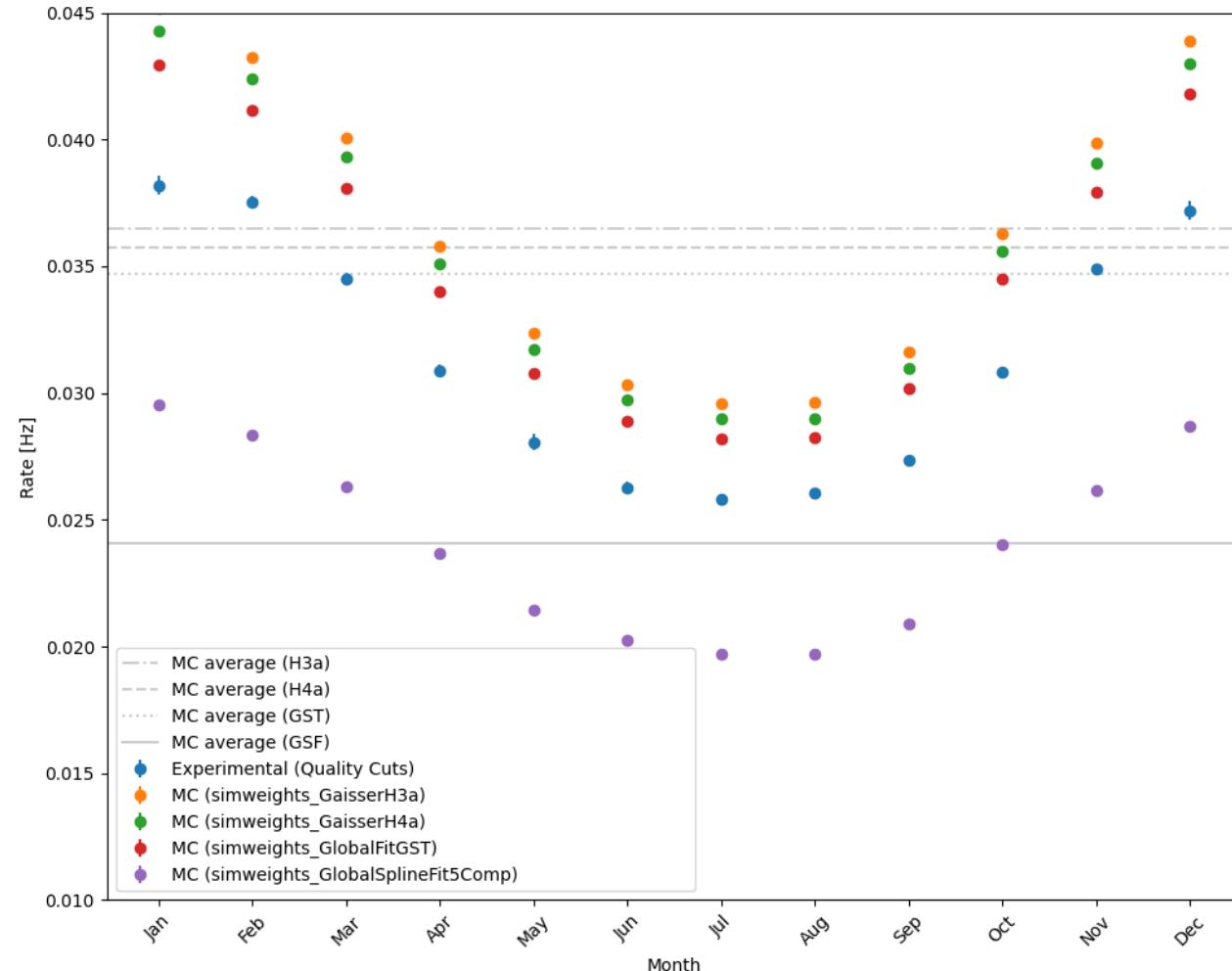


Rates per month

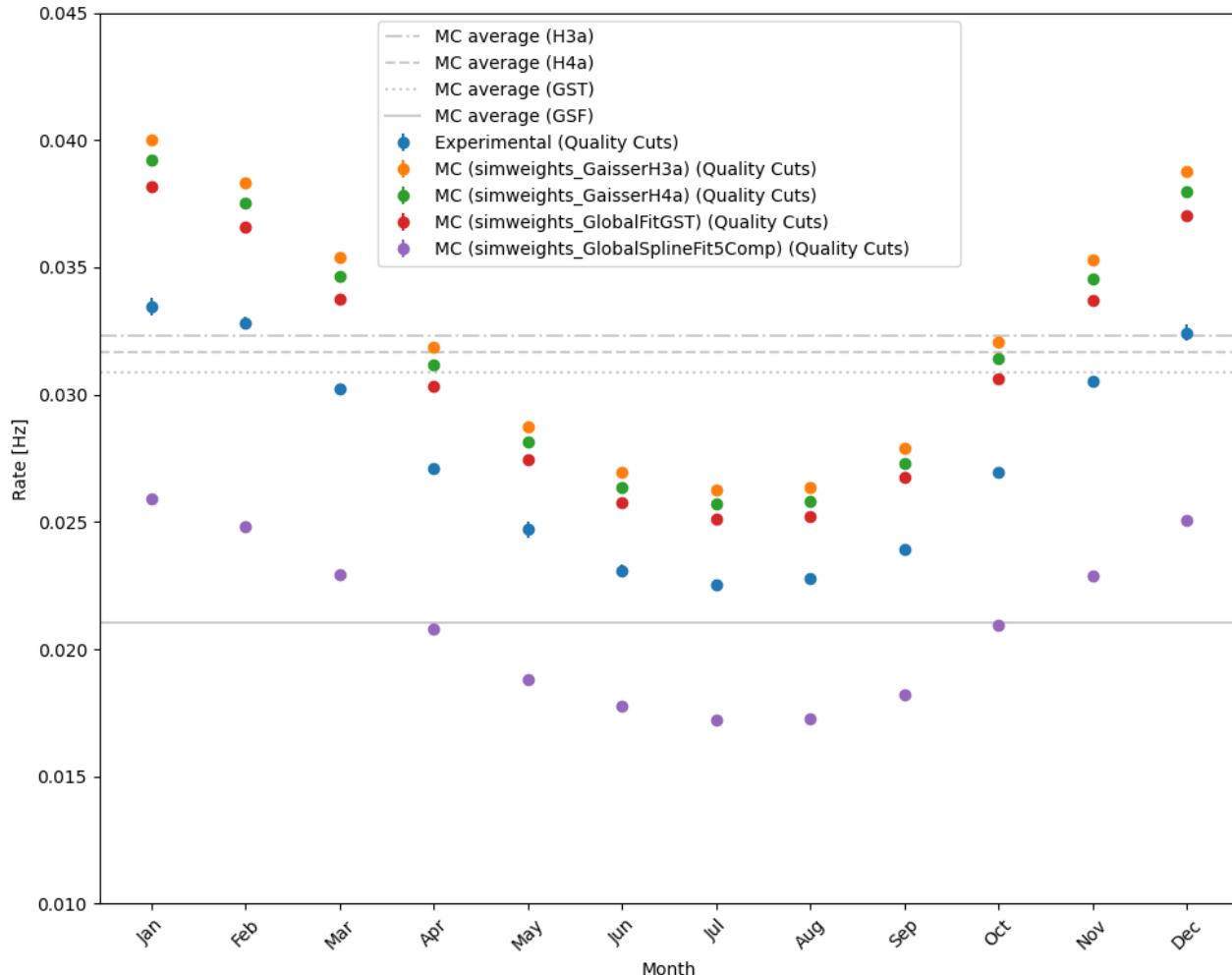
Data-MC

Rates per month

before quality cuts

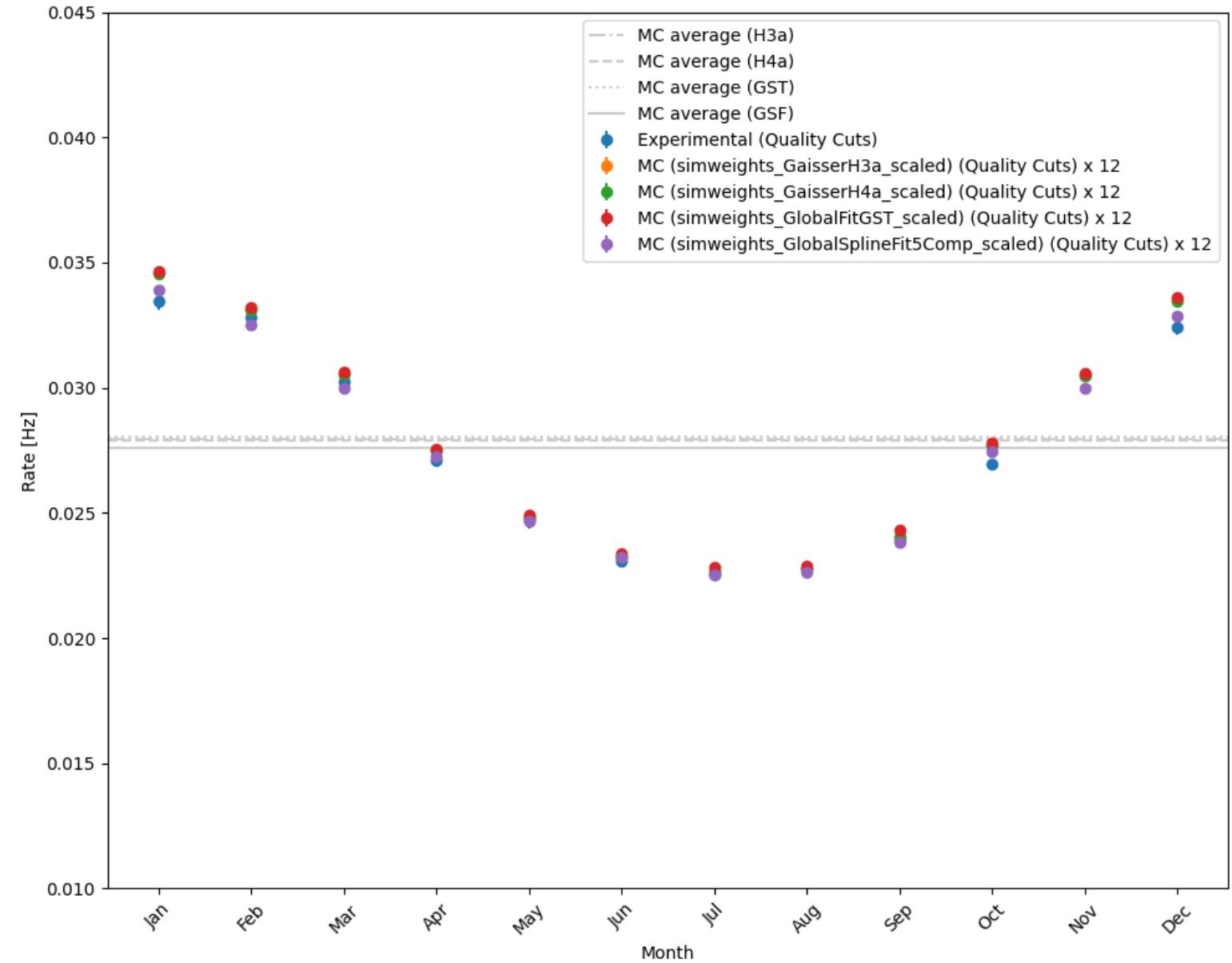


after quality cuts



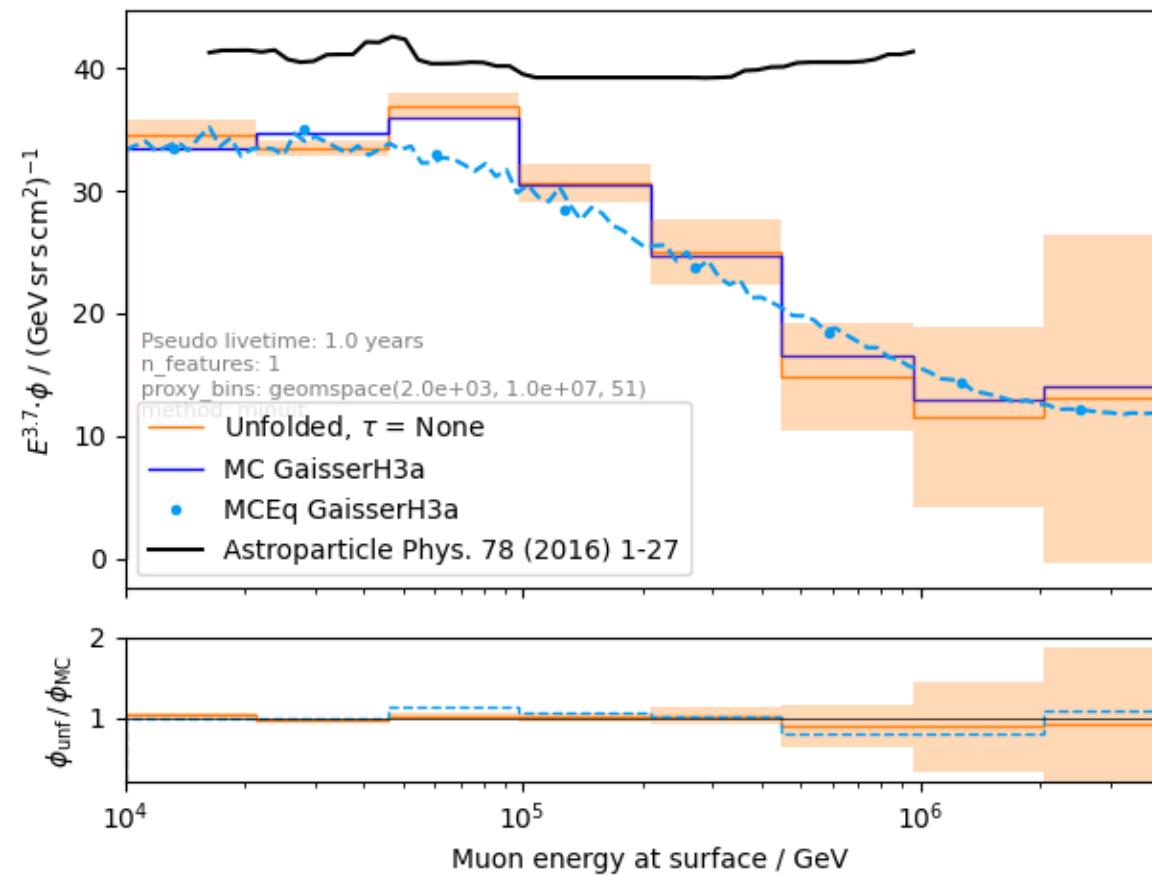
Rates per month: scaled

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

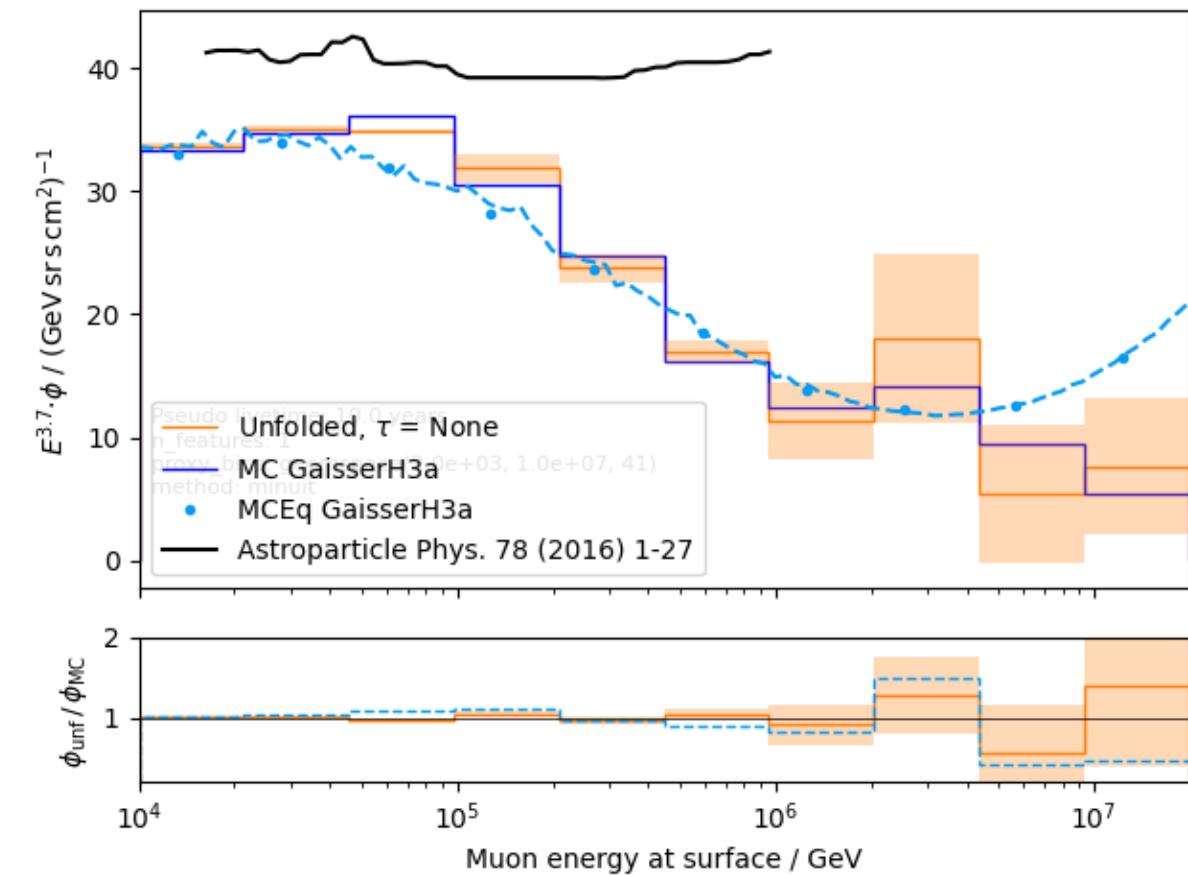


unfolding of muon flux at surface – weighted to $E^{3.7}$

1 year



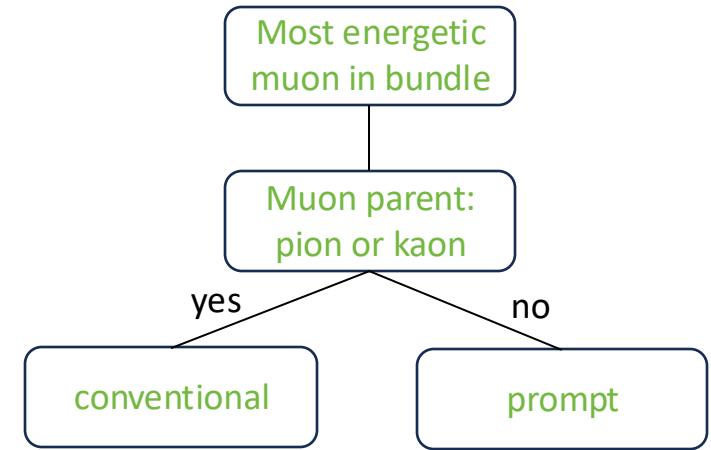
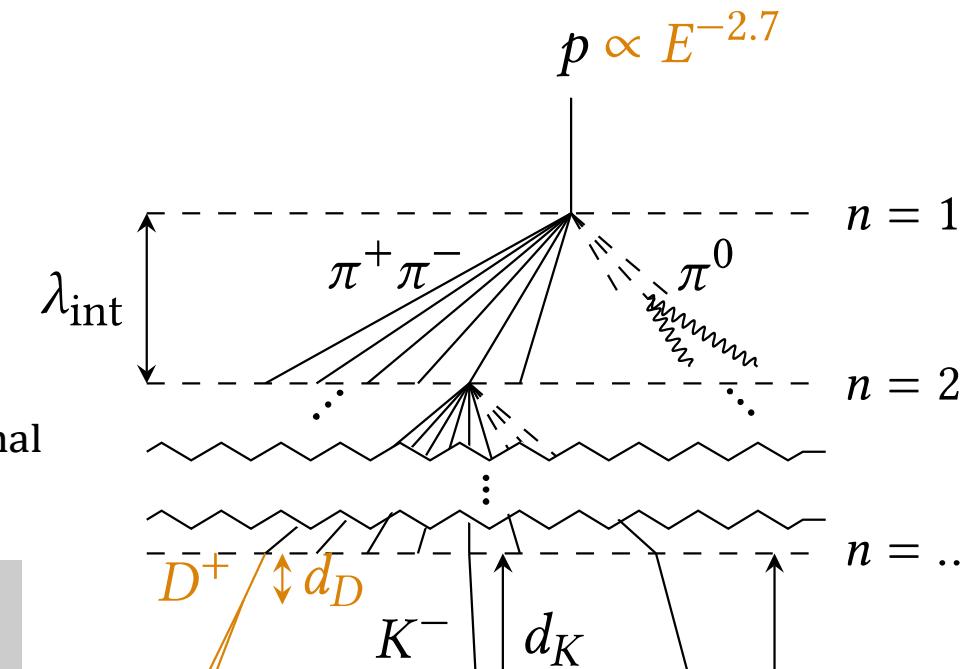
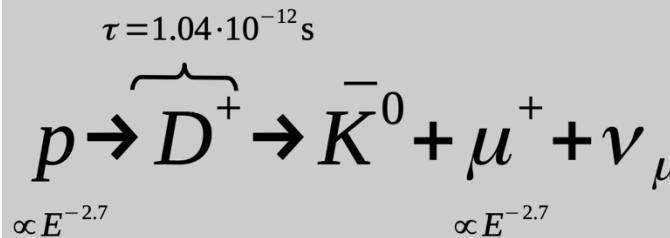
10 years



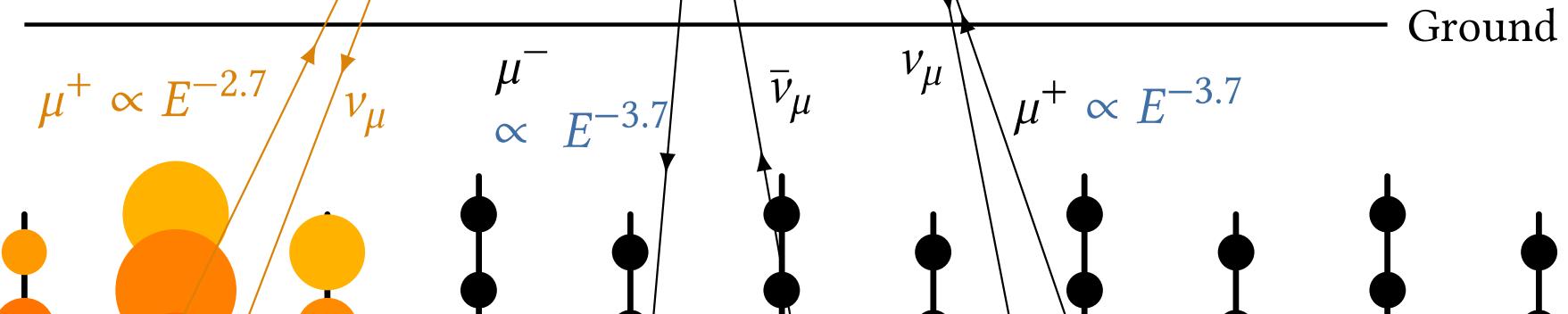
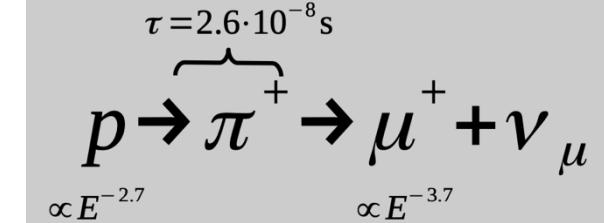
Muon flux

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

prompt component:

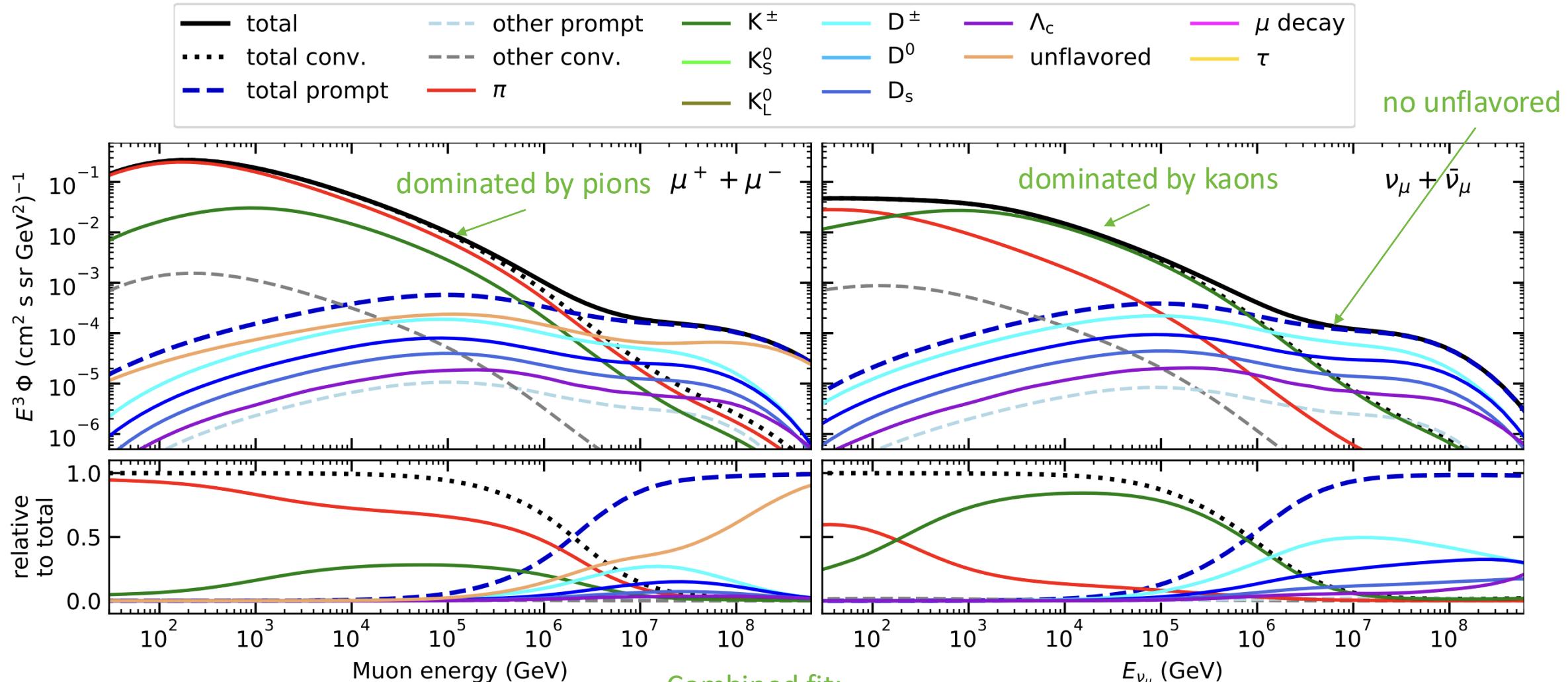


Conventional component:



Prompt atmospheric muons and neutrinos

10.1103/PhysRevD.100.103018

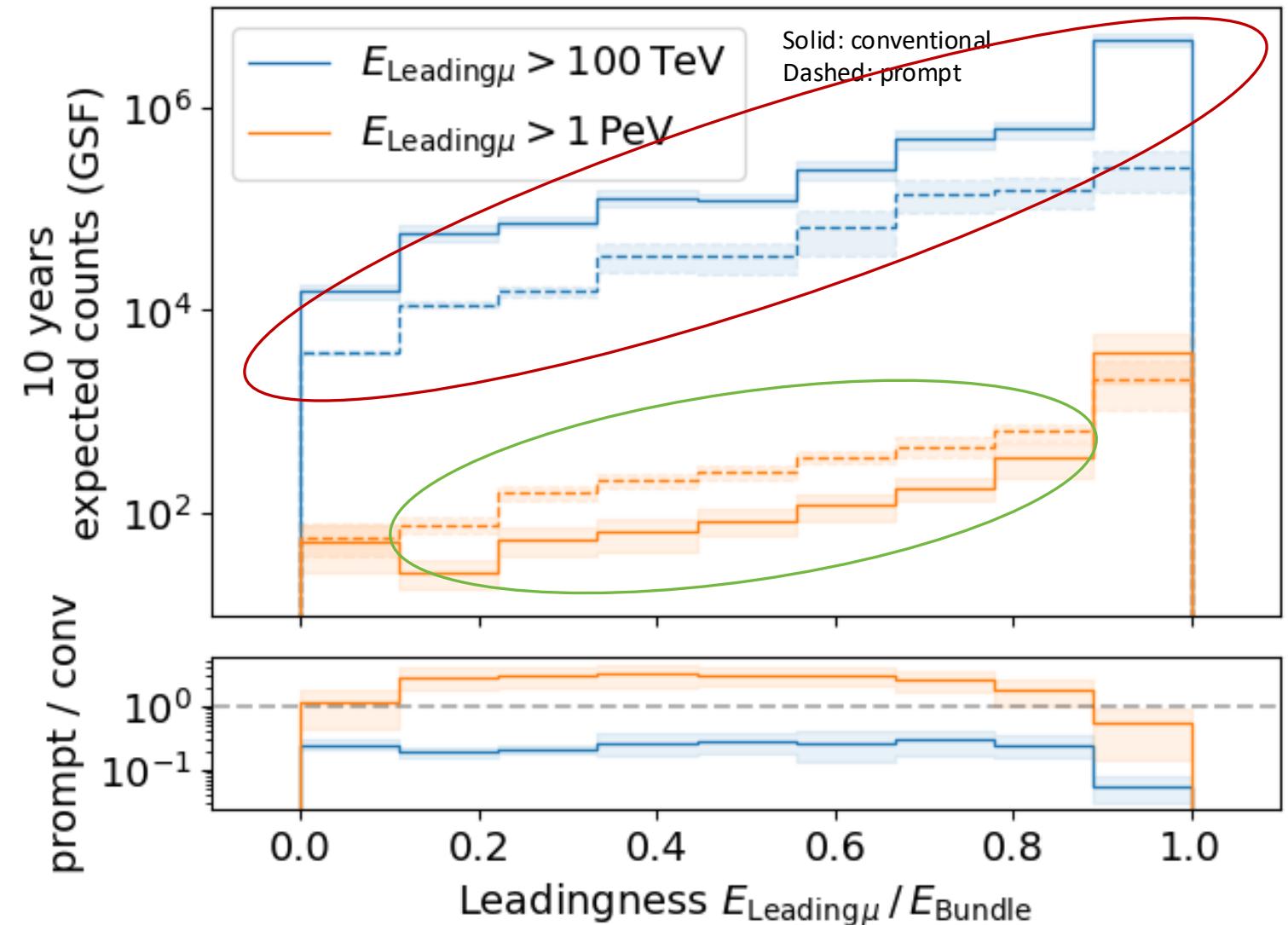


Combined fit:

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

Leading muon energy fraction

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



Leading muon contribution

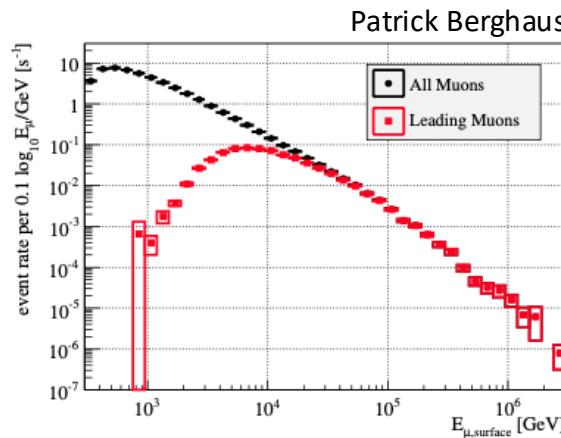
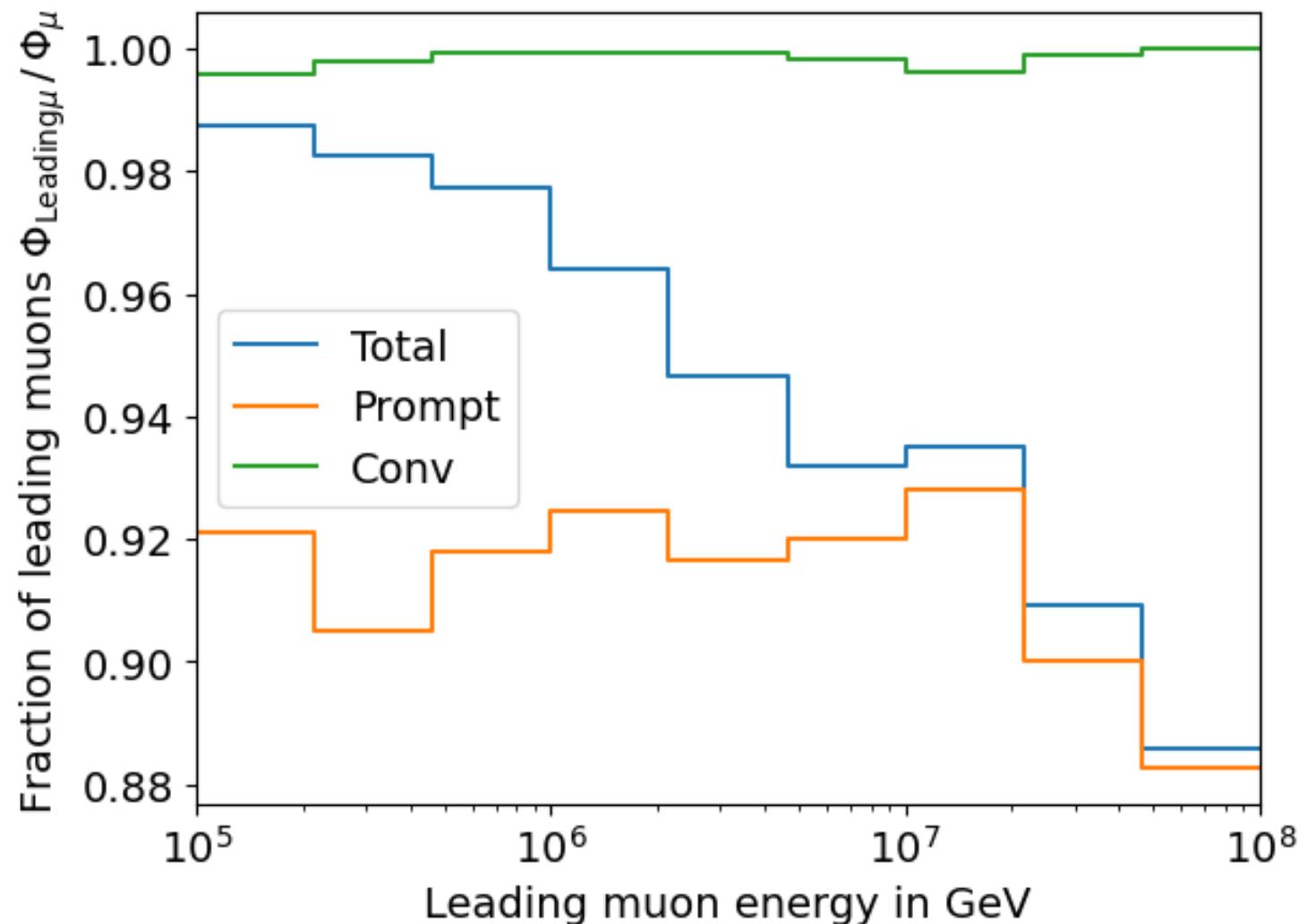


Figure 10: Surface energy distribution for all and most energetic (“leading”) muons in simulated events with a total of more than 1,000 registered photo-electrons in IceCube.

- 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

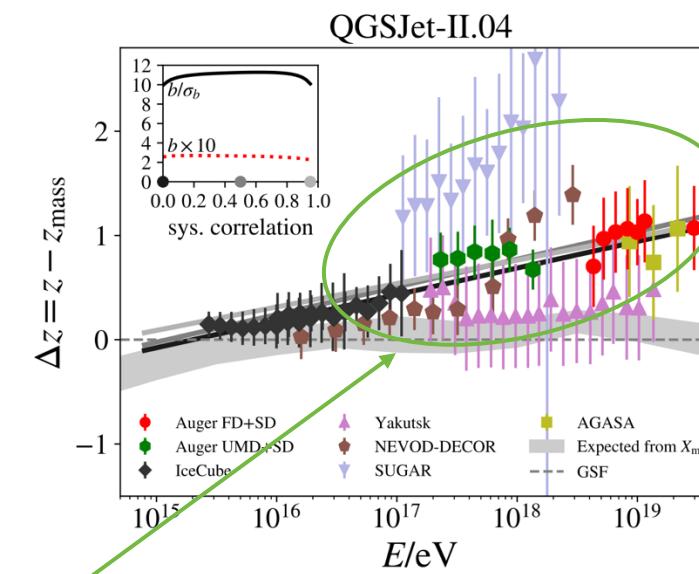
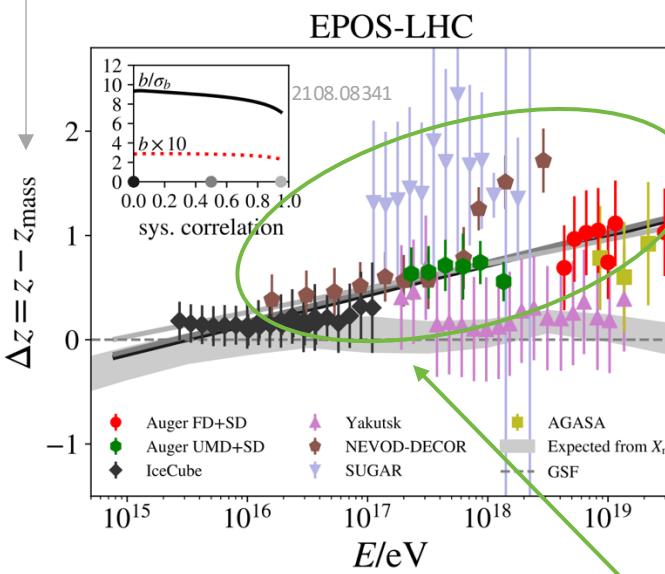


Muon puzzle and hadronic uncertainties

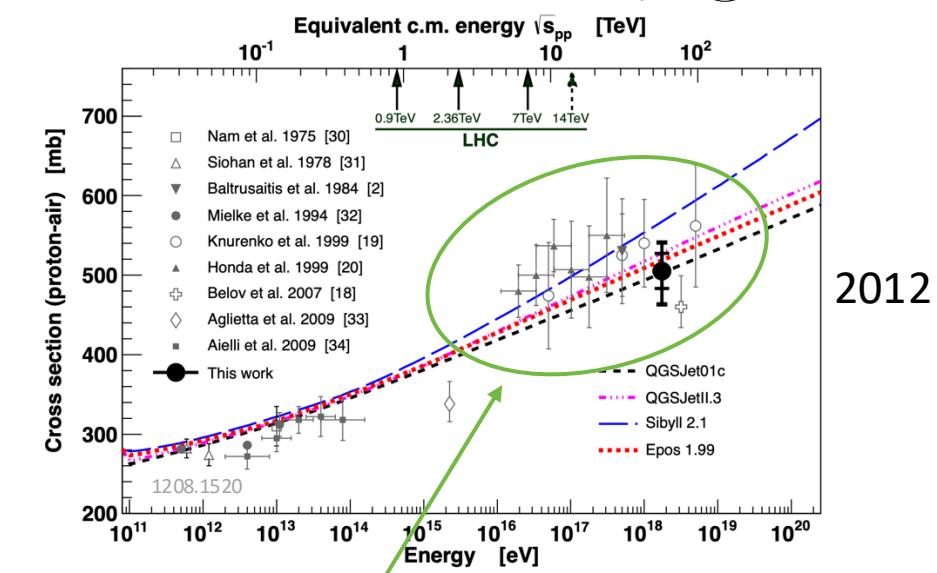
"muon number"

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

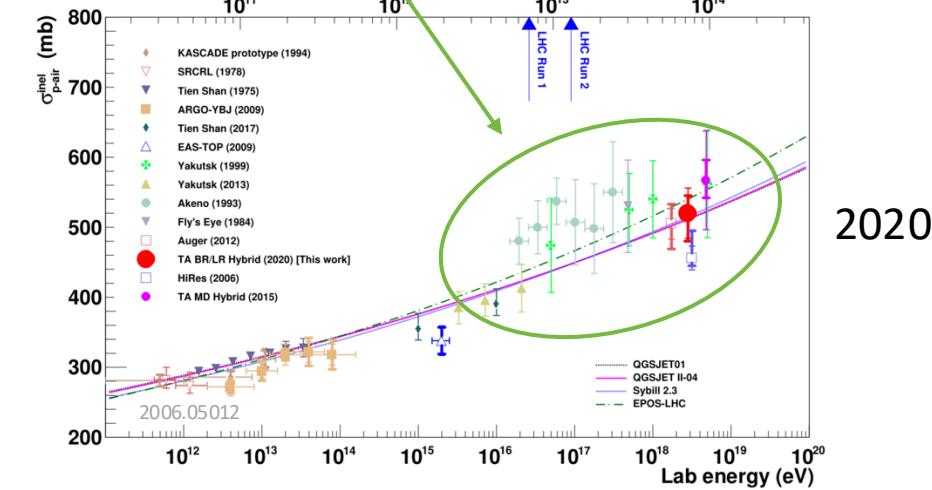
Expected z
("muon number")



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



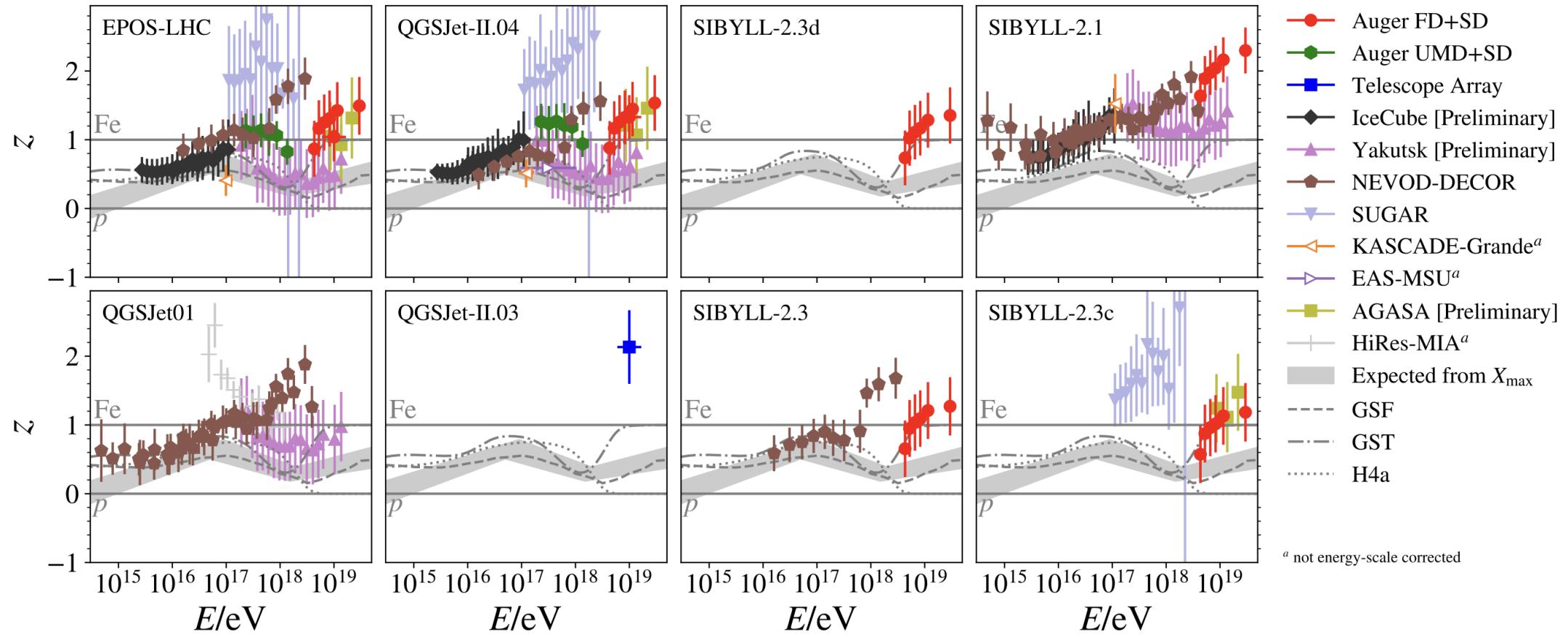
➤ Uncertainties at $E > 10 \text{ PeV}$



The Muon Puzzle

"muon number"

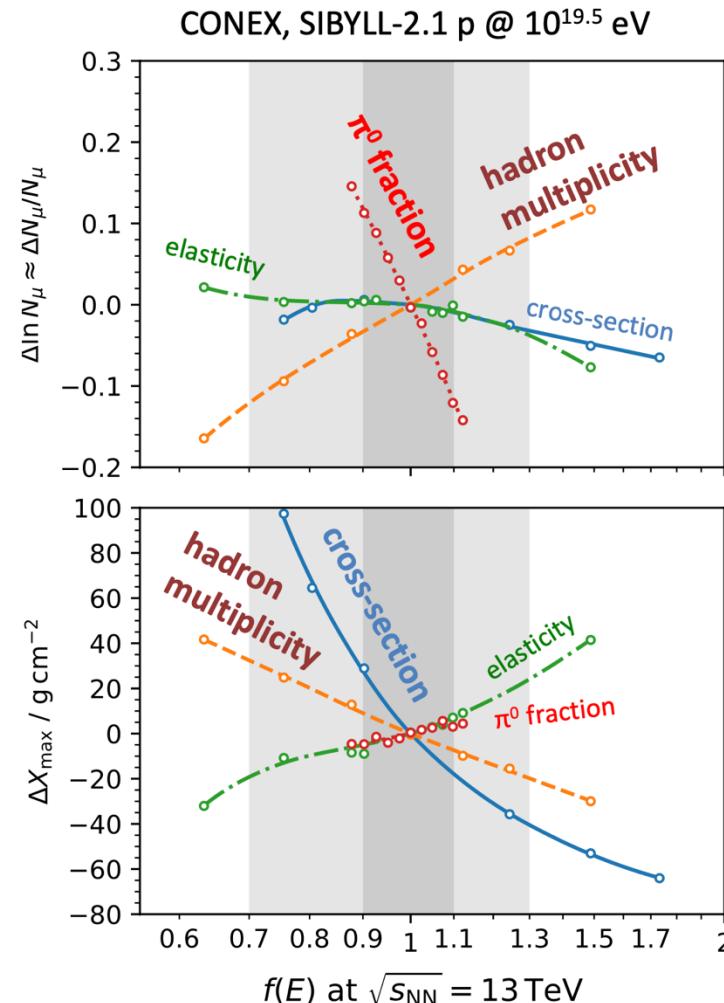
$$z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_p}{\ln\langle N_\mu \rangle_{\text{Fe}} - \ln\langle N_\mu \rangle_p}$$



2108.08341

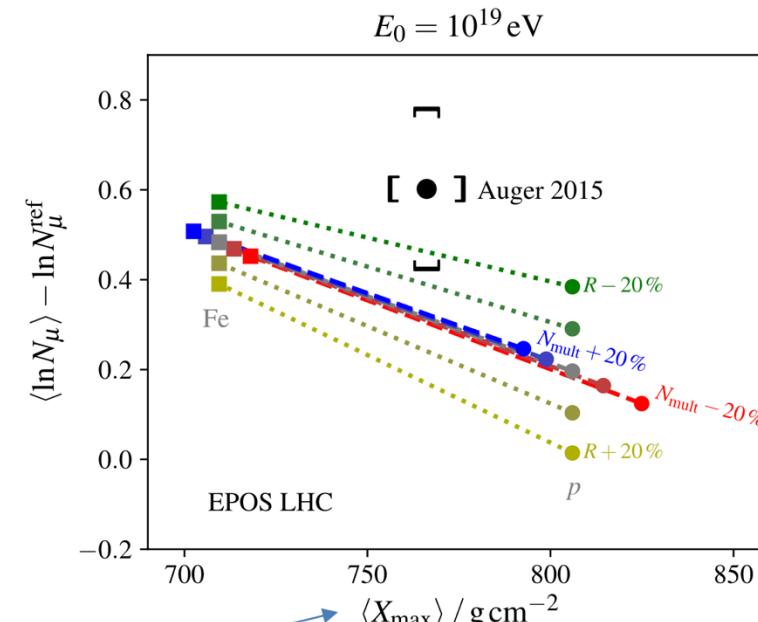
Possible Solutions

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



06.10.23 | P. Gutjahr

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

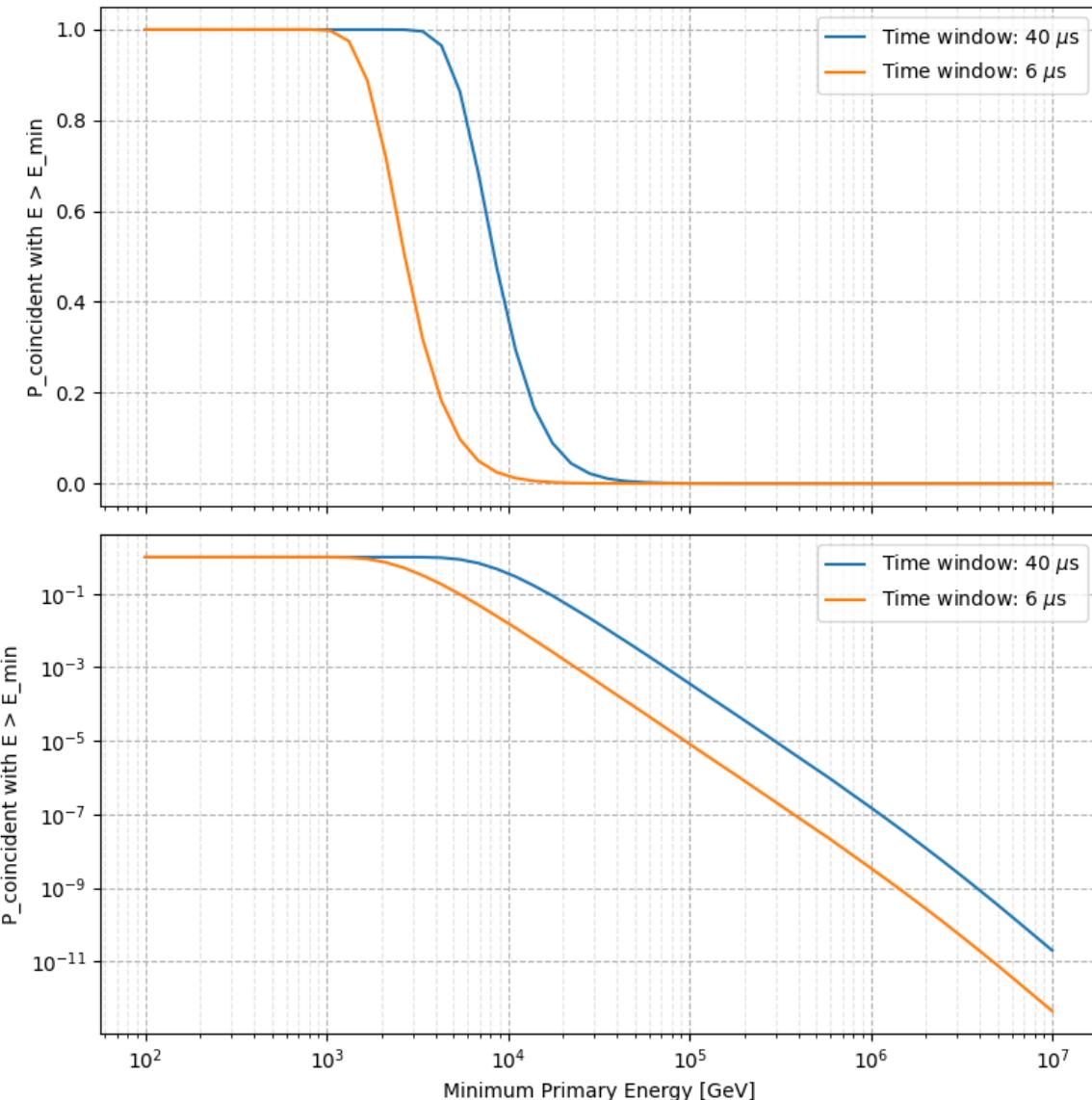


$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

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

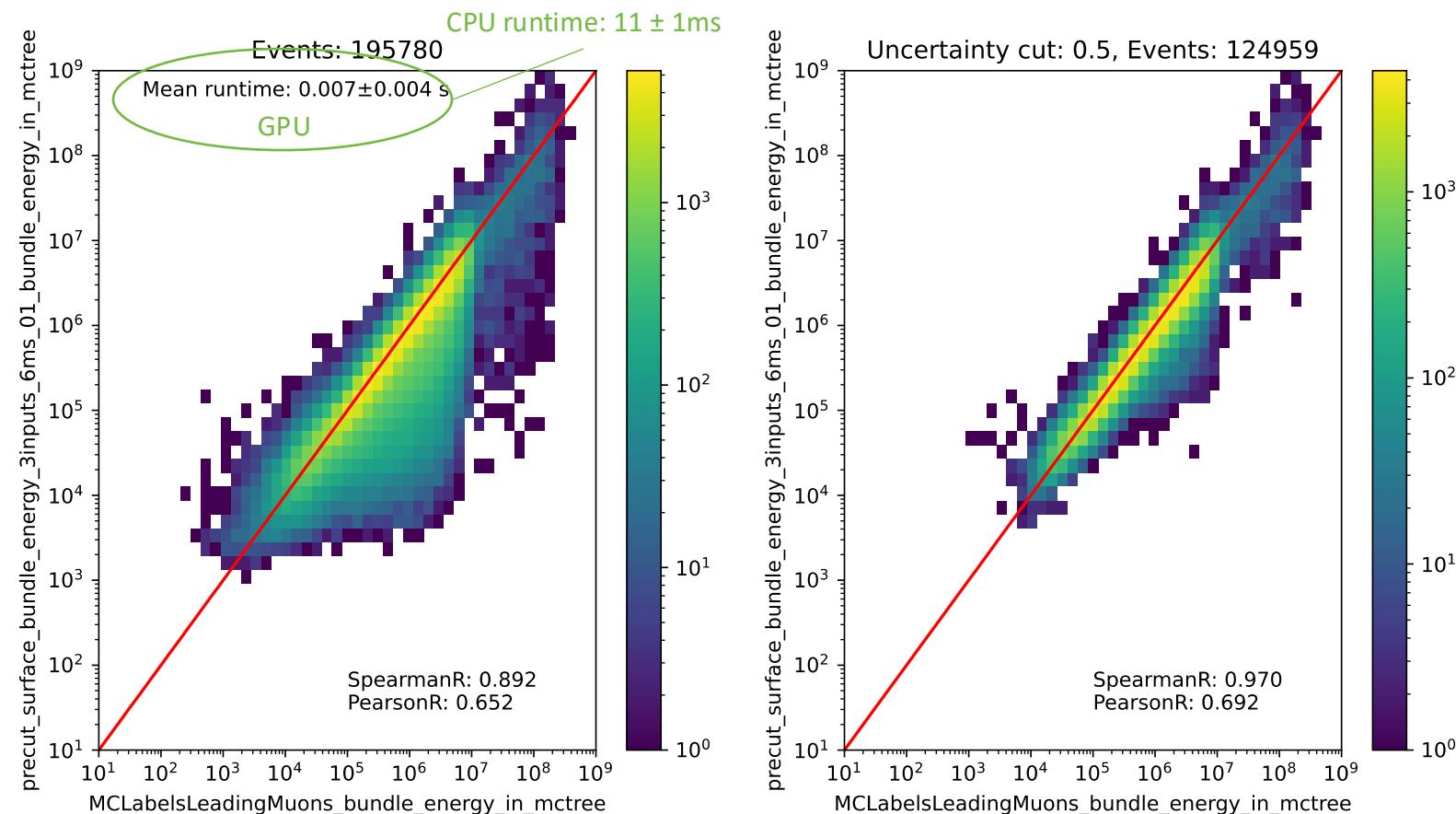
Simulation w/o coincident events

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



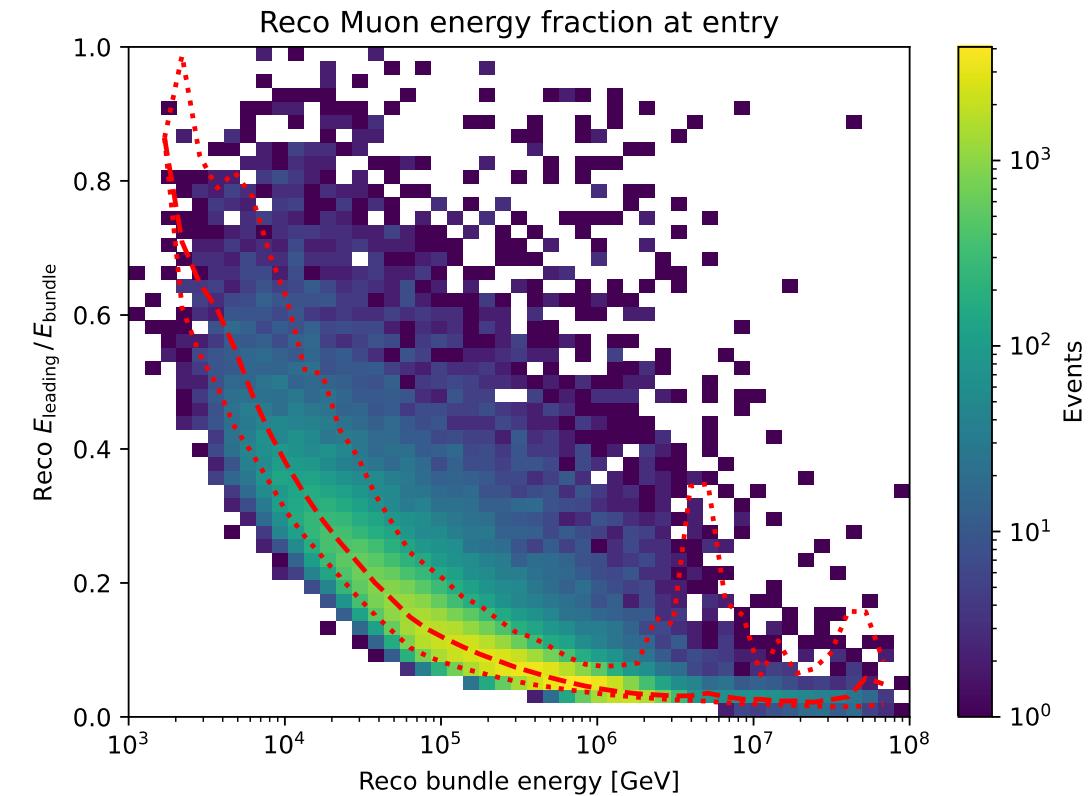
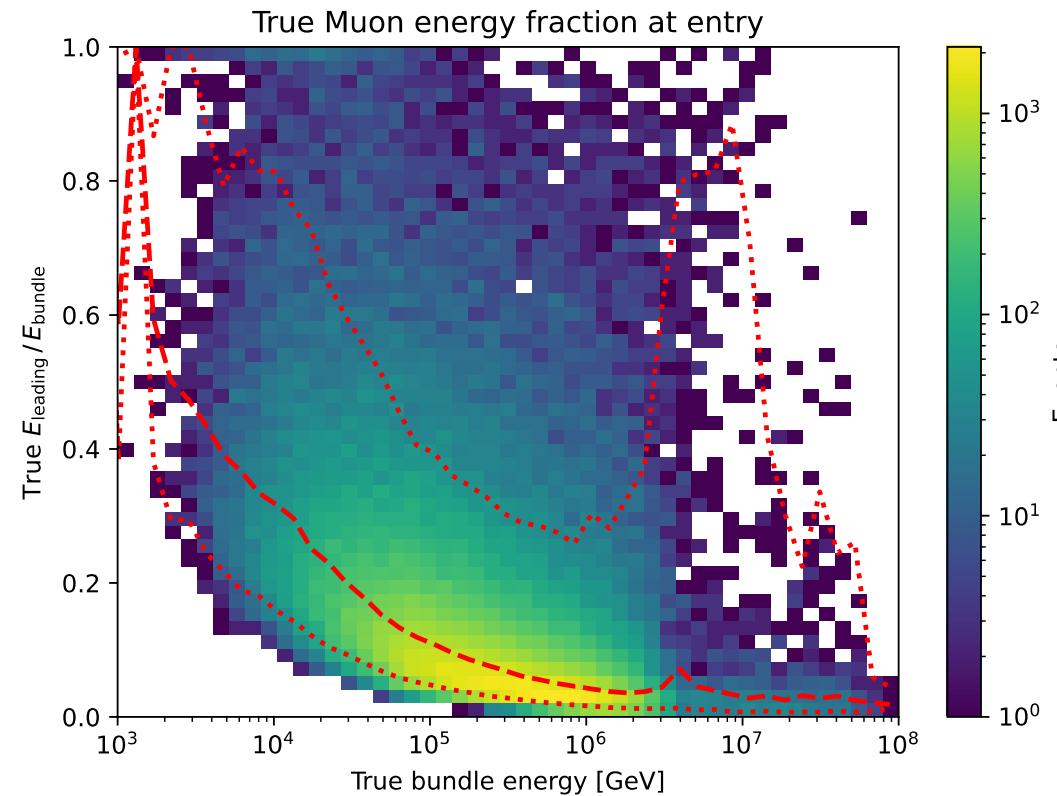
Bundle energy cut

- 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

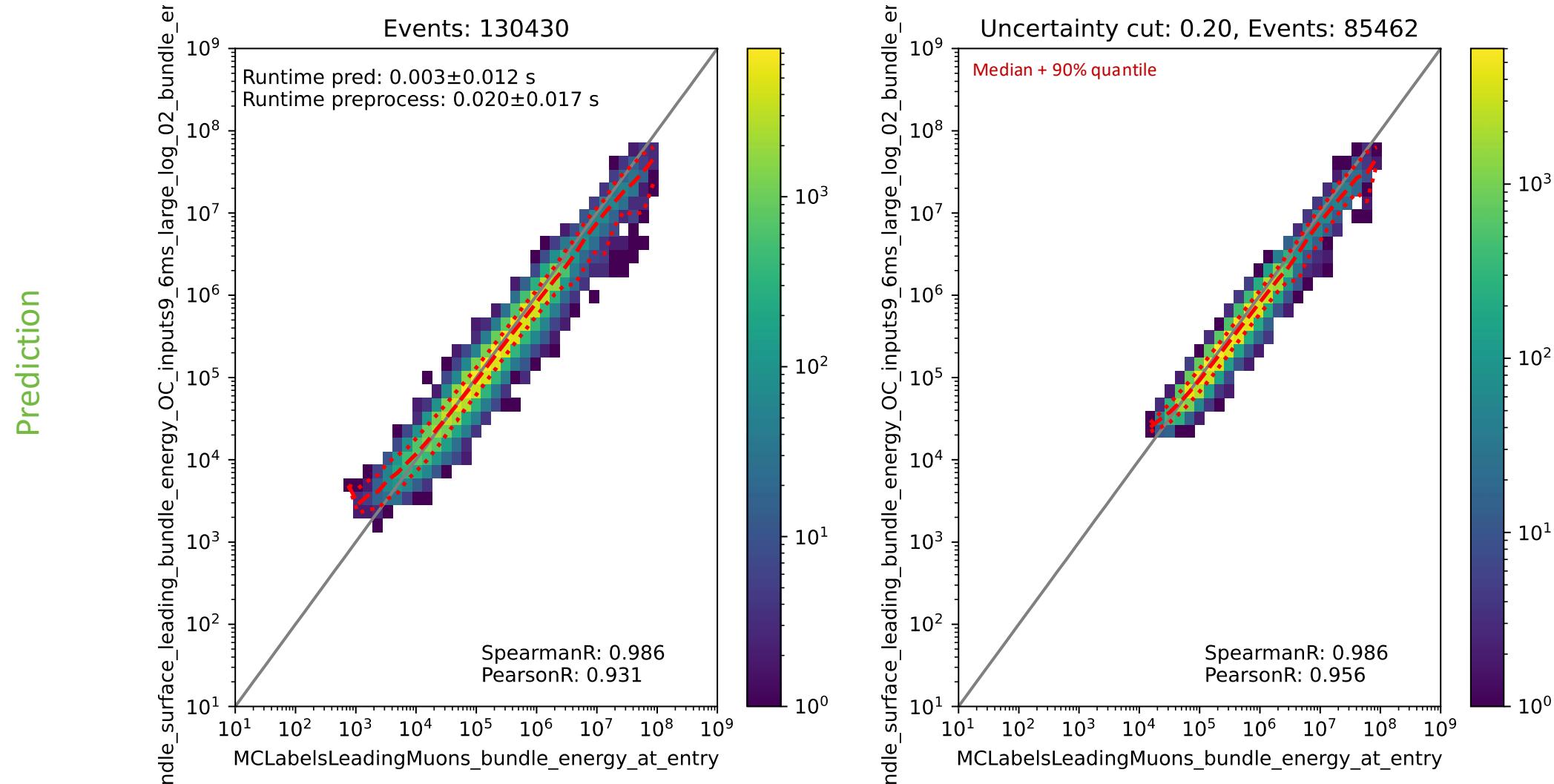


Leading muon energy fraction - leadingness

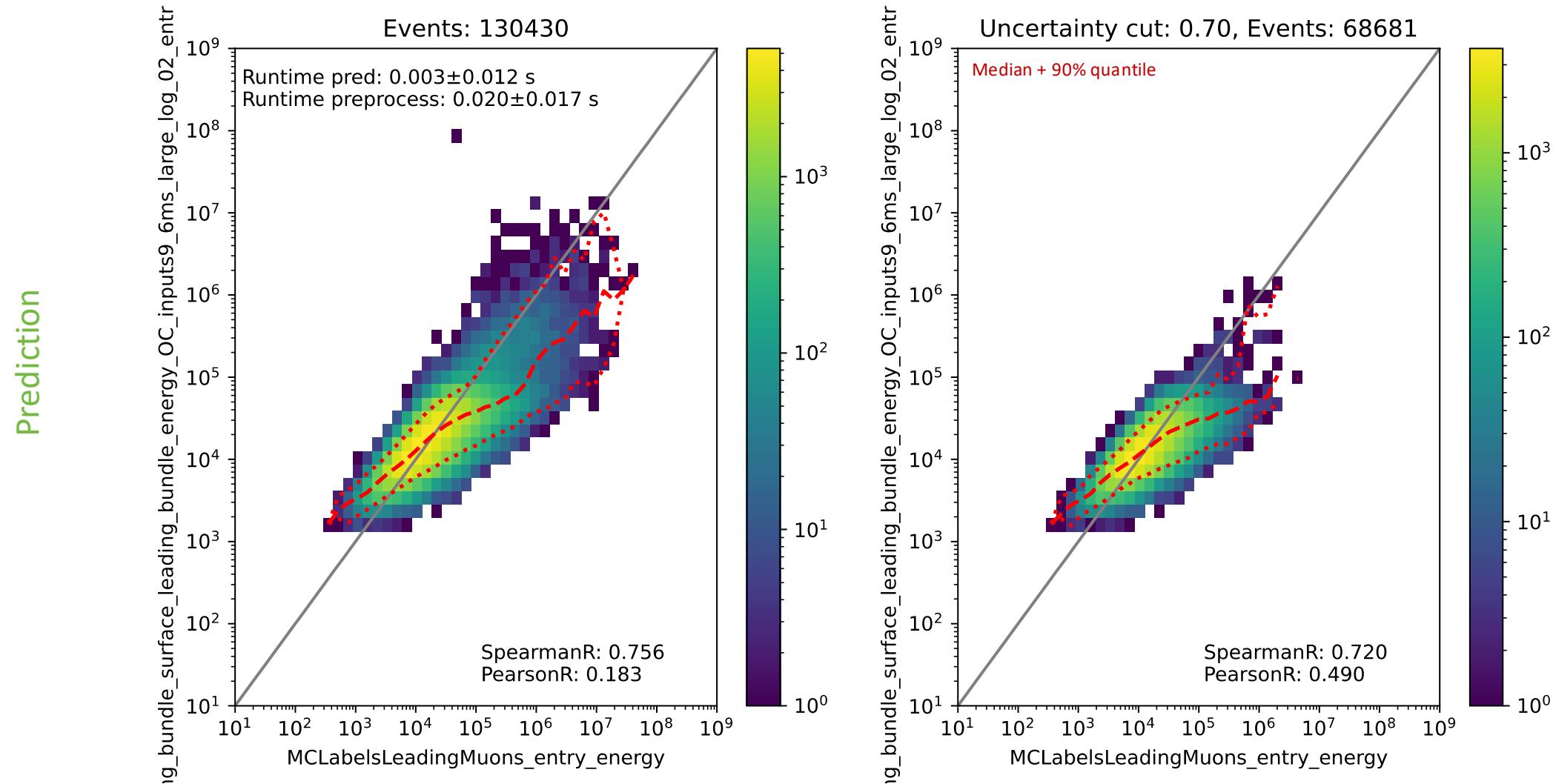
- True muon energy fraction is smeared
- Network tries to predict the median of the distribution



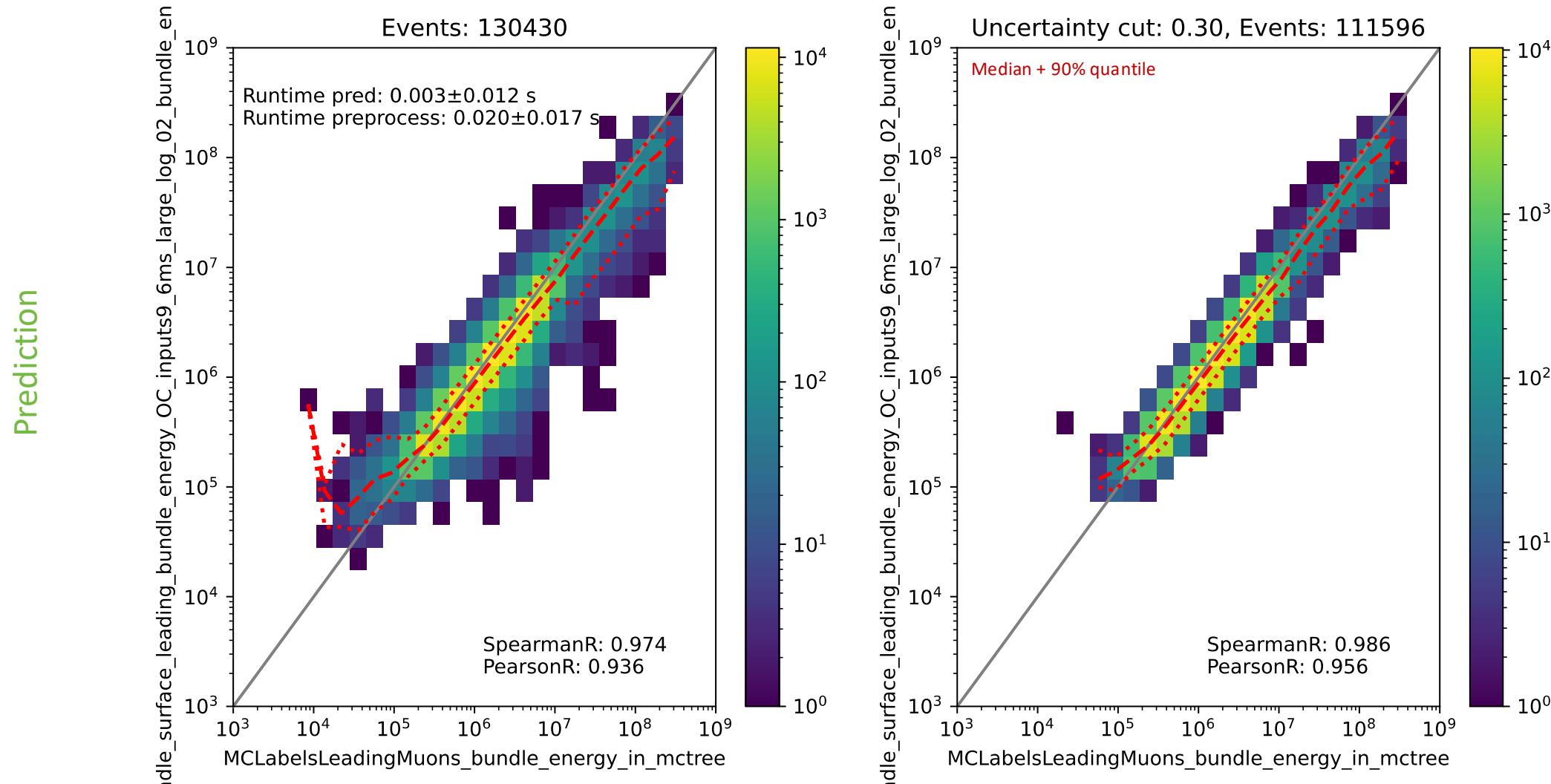
Bundle energy at entry – 6 μ s cleaned pulses



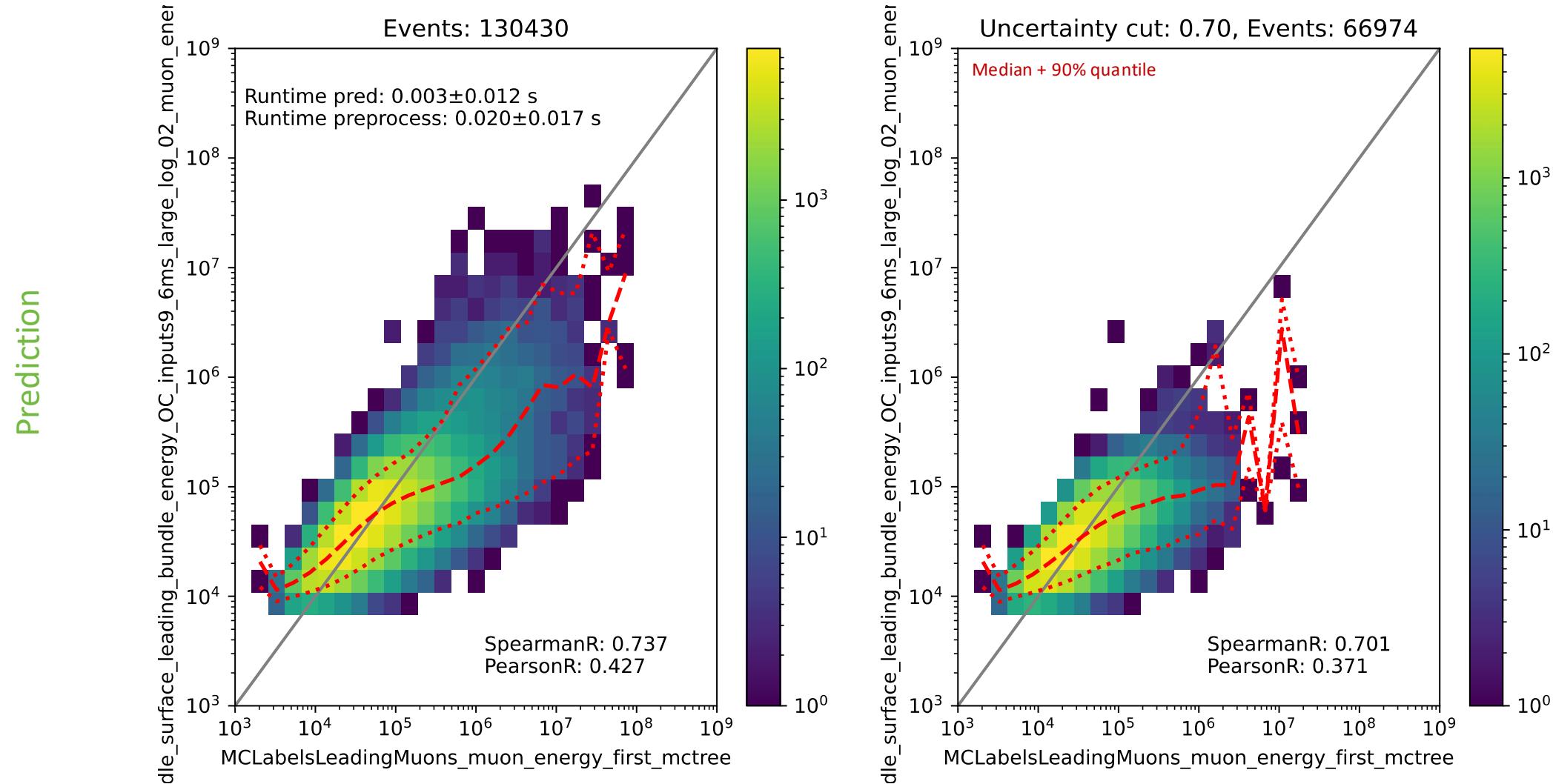
Leading muon energy at entry – 6 μ s cleaned pulses



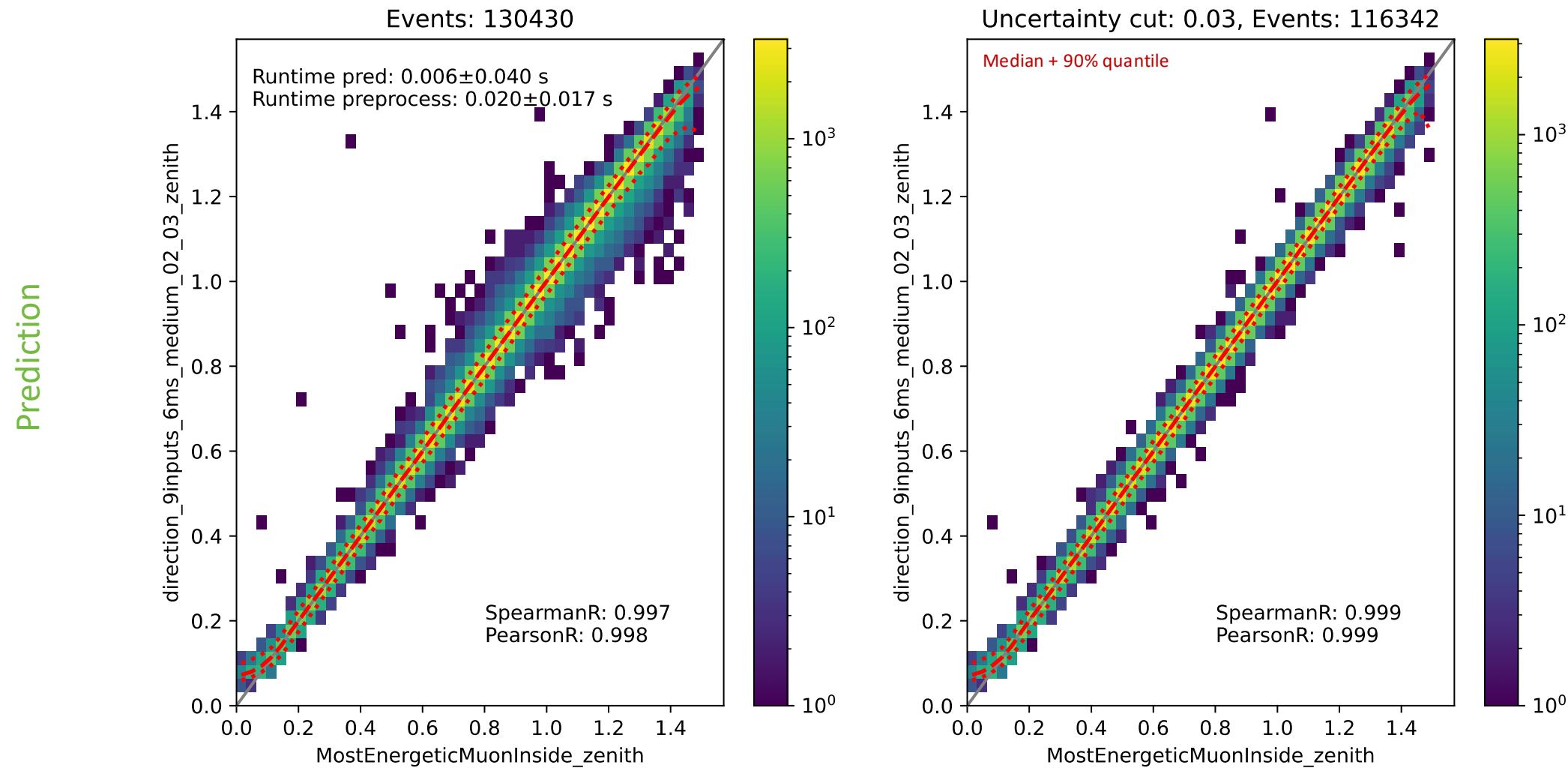
Bundle energy at surface – 6 μ s cleaned pulses



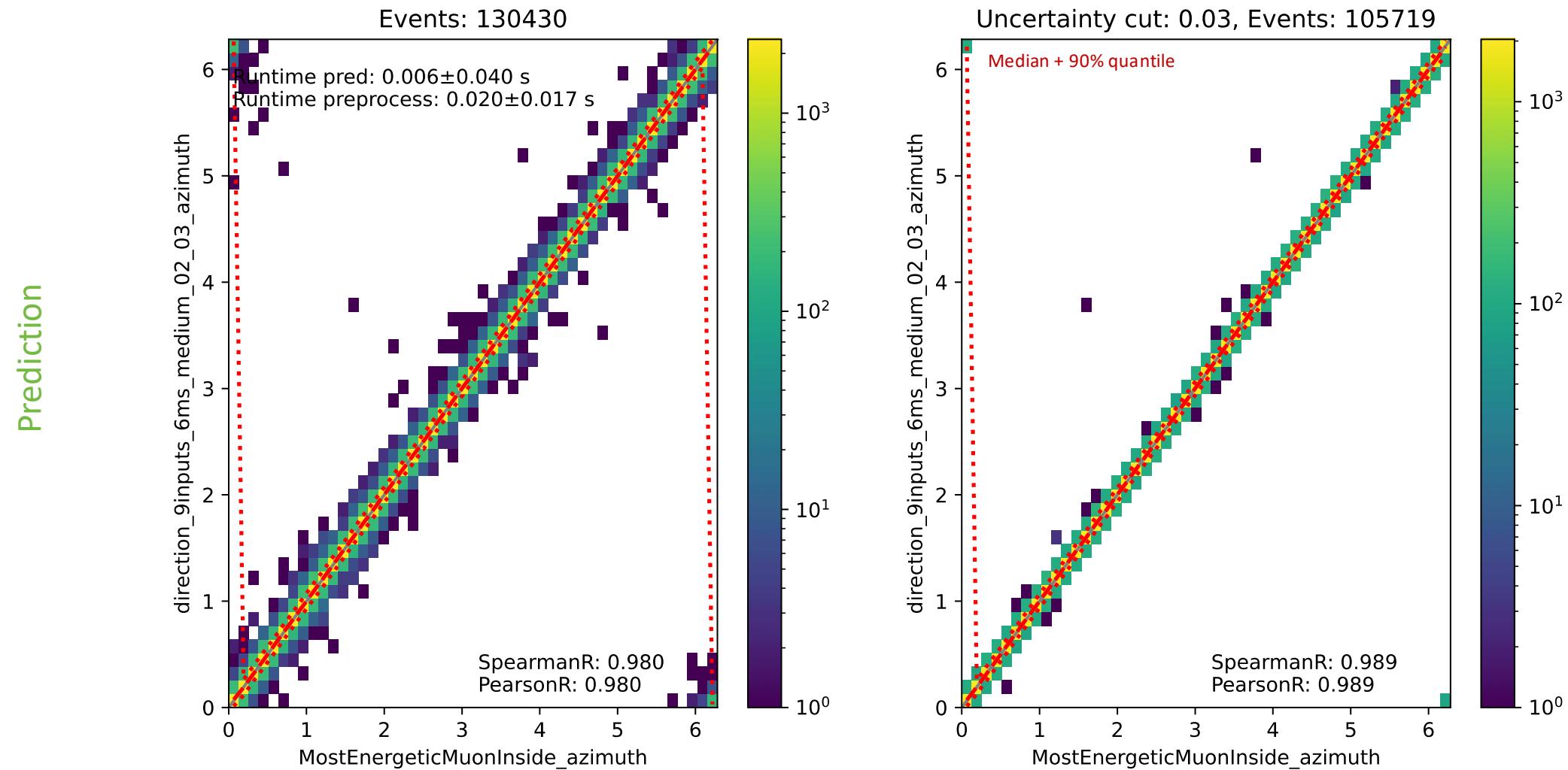
Leading muon energy at surface – 6 μ s cleaned pulses



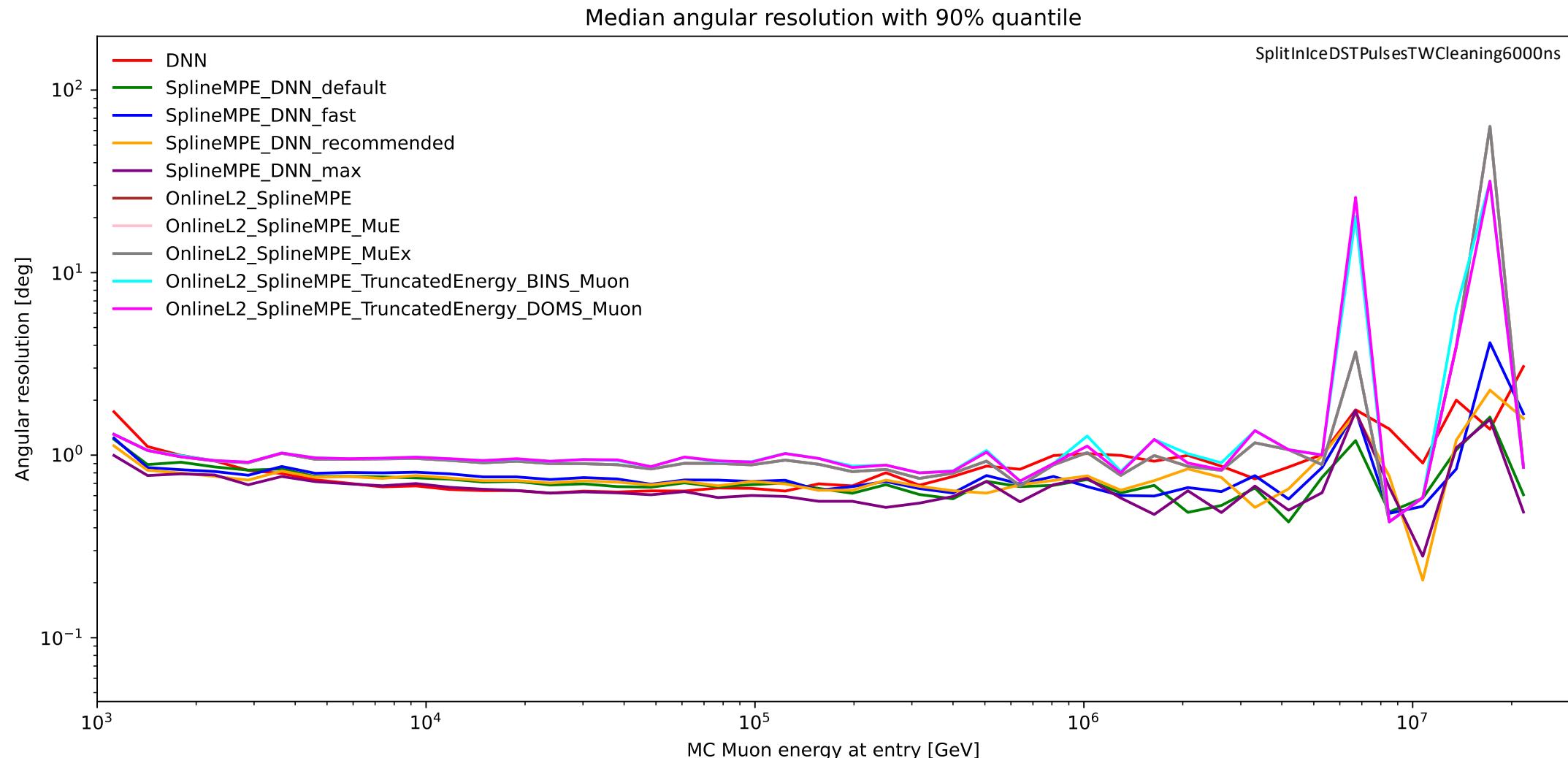
Zenith – 6 ms cleaned pulses



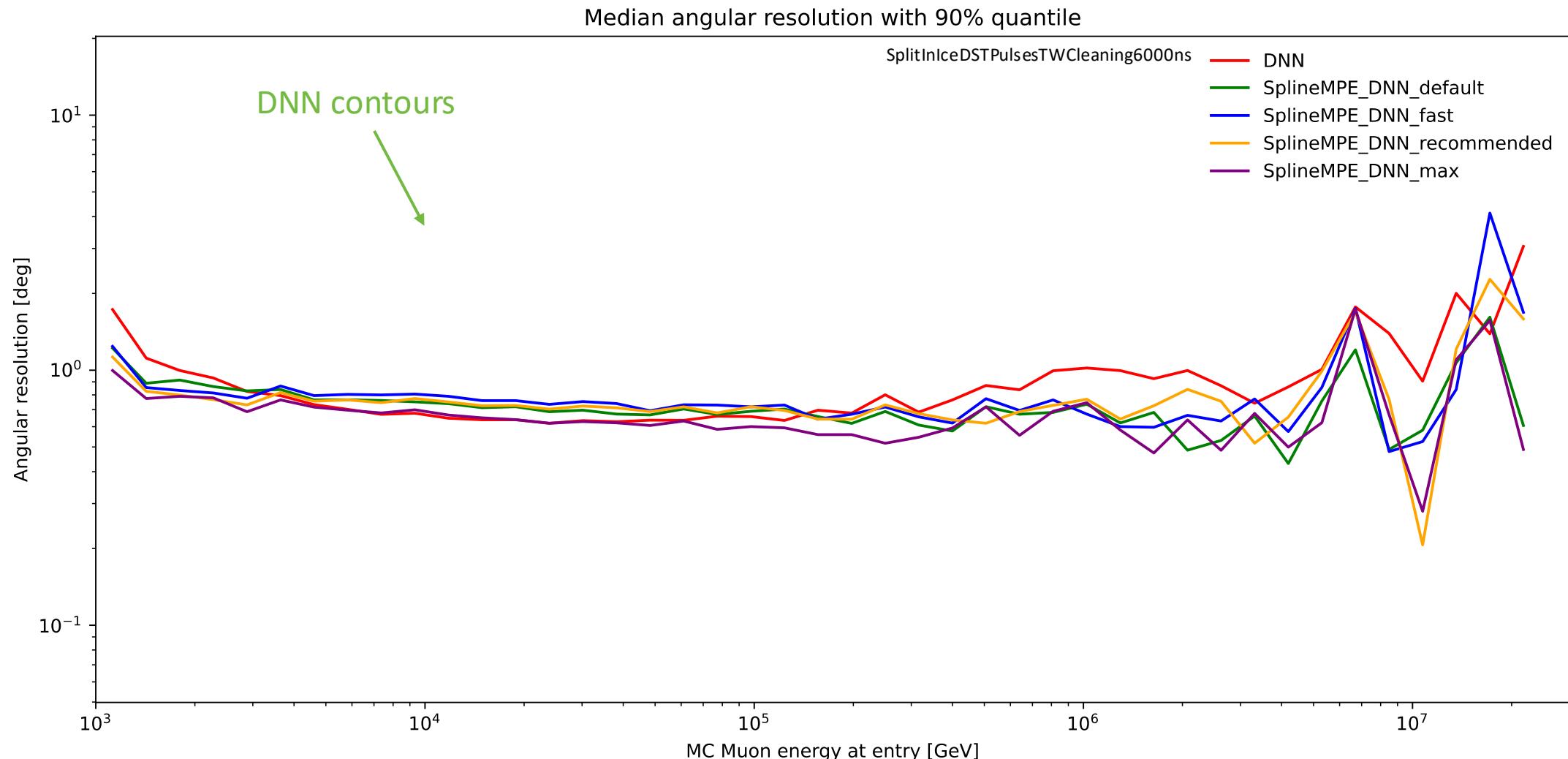
Azimuth – 6 ms cleaned pulses

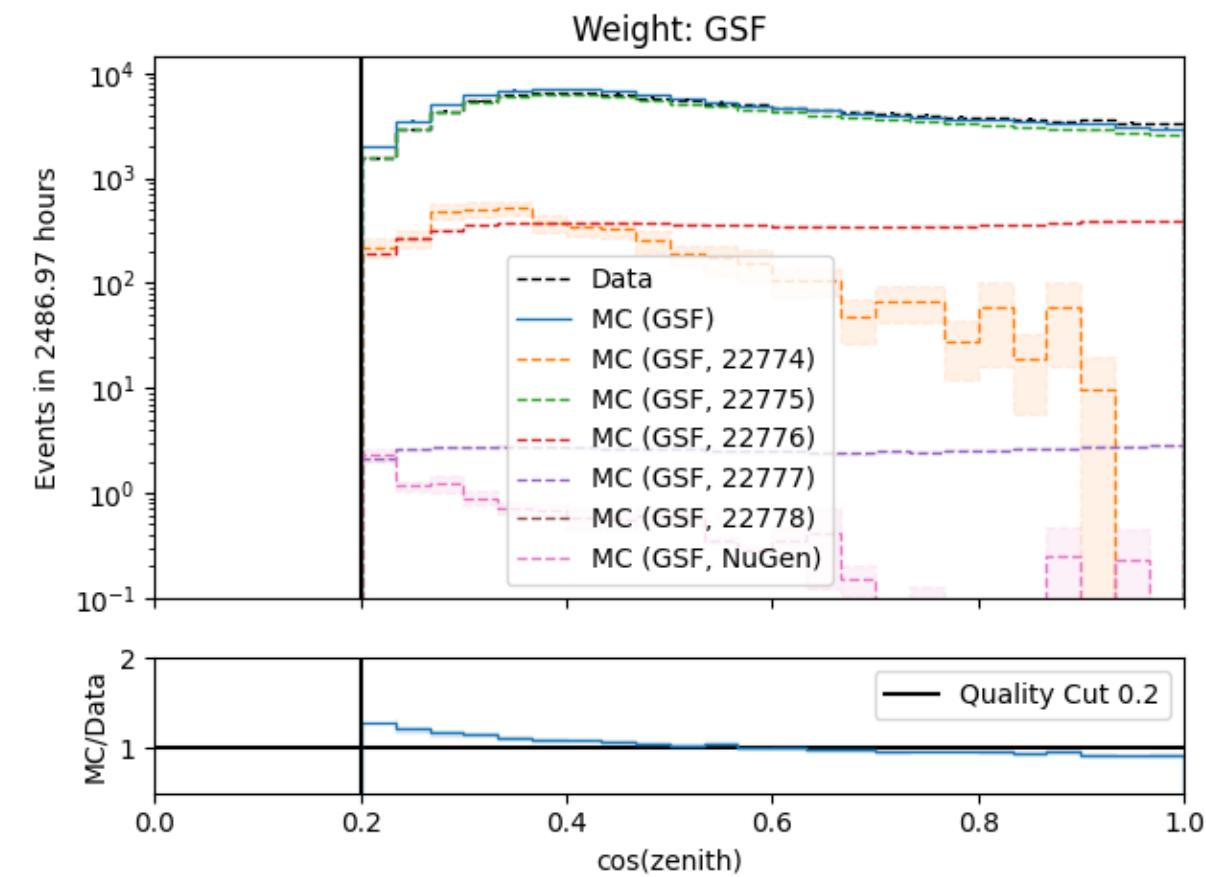
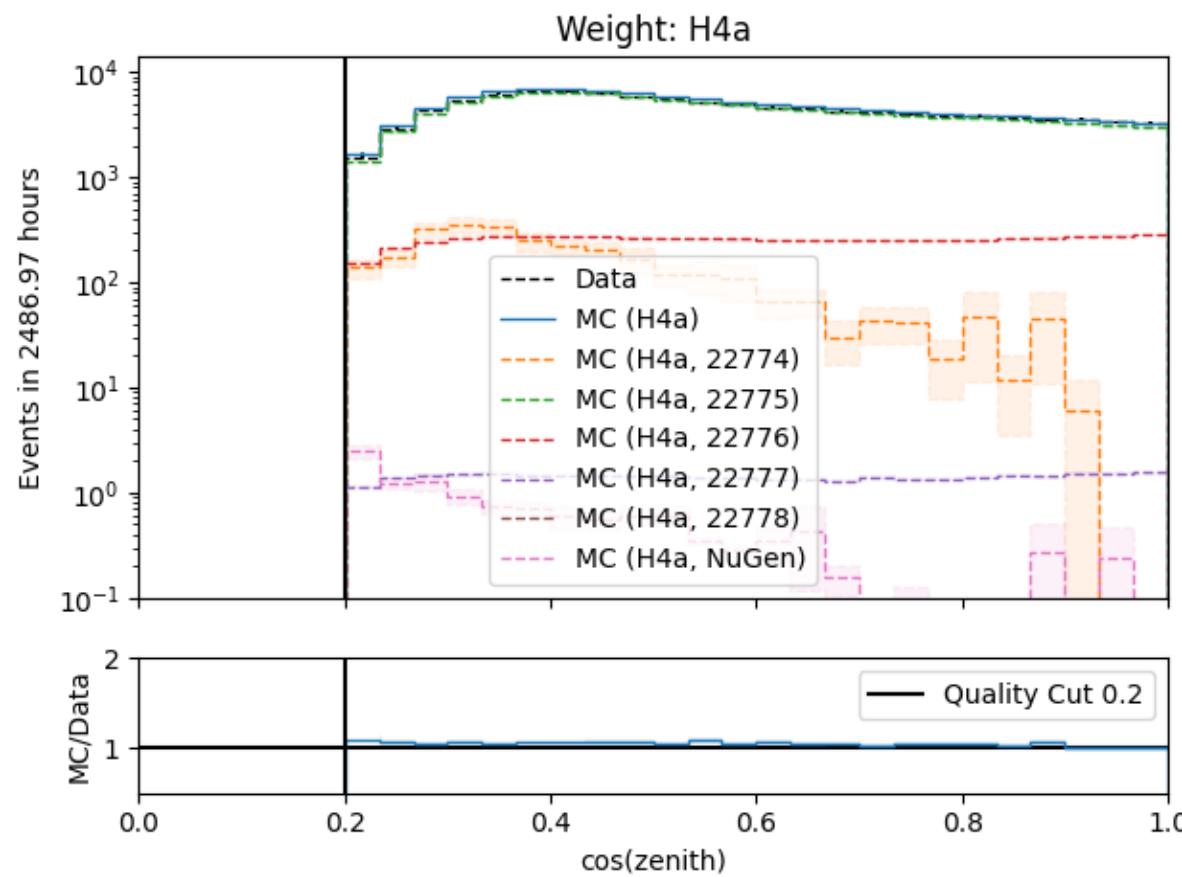


SplineMPE – DNN and conventional seeds

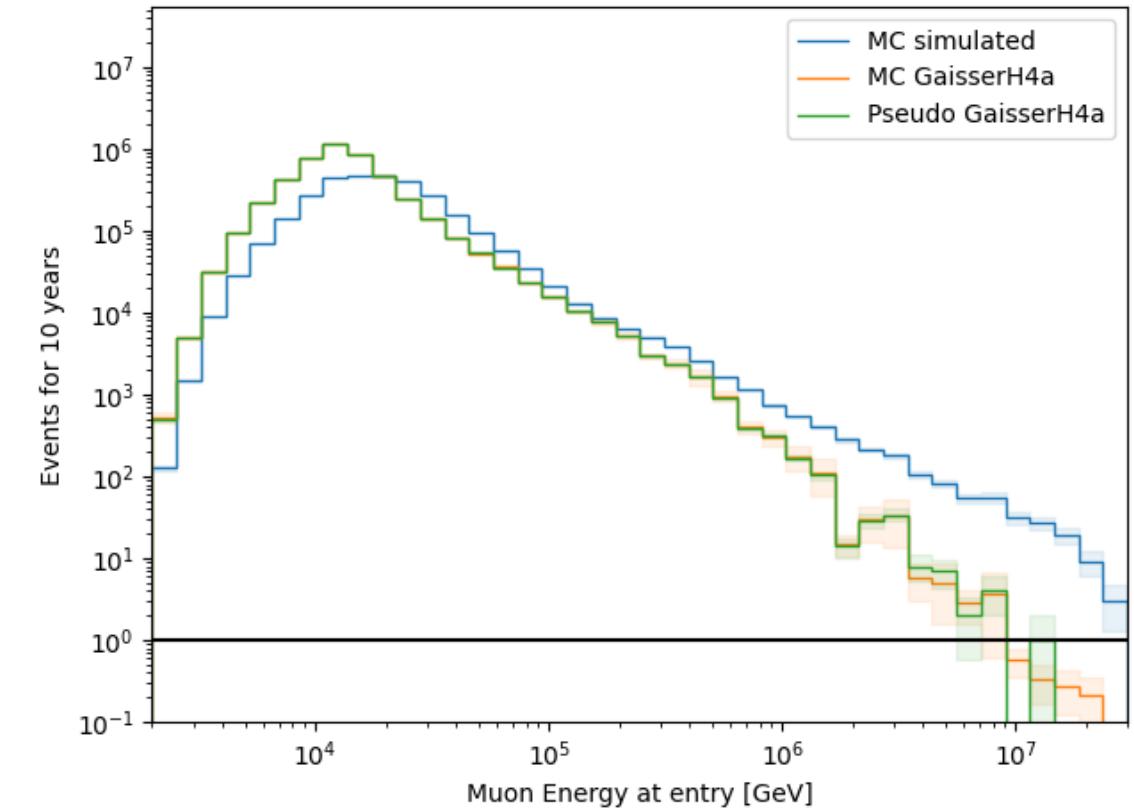
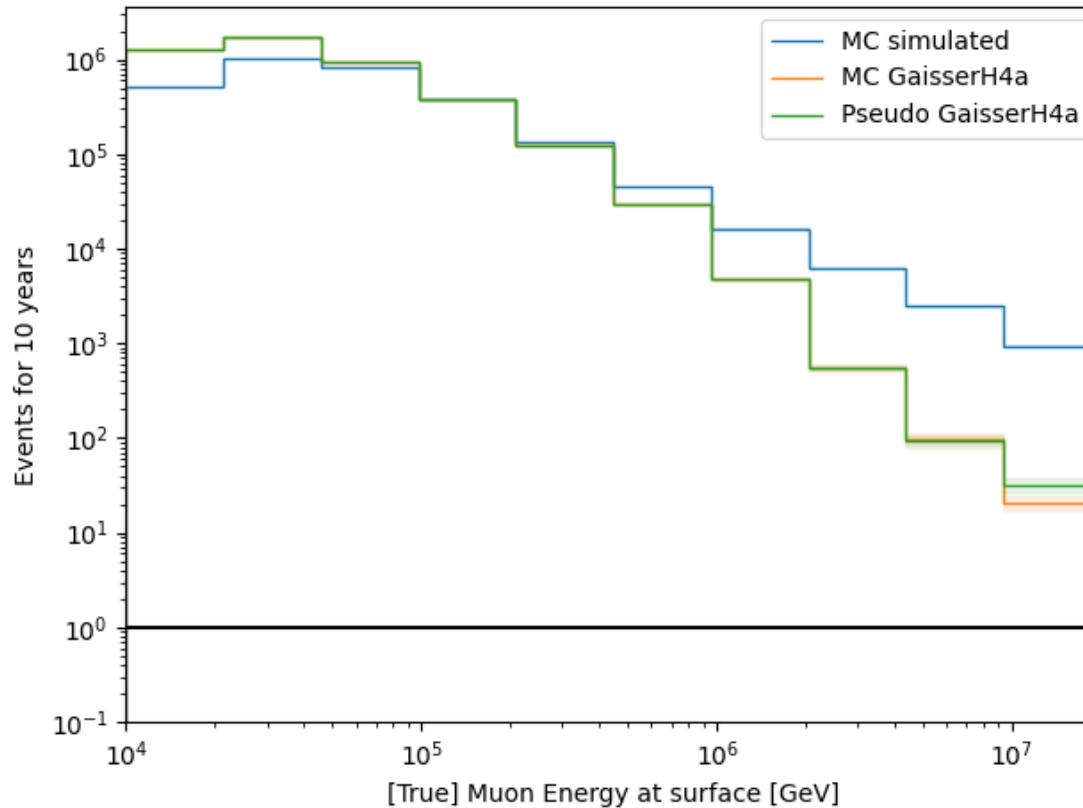


SplineMPE – DNN seeds

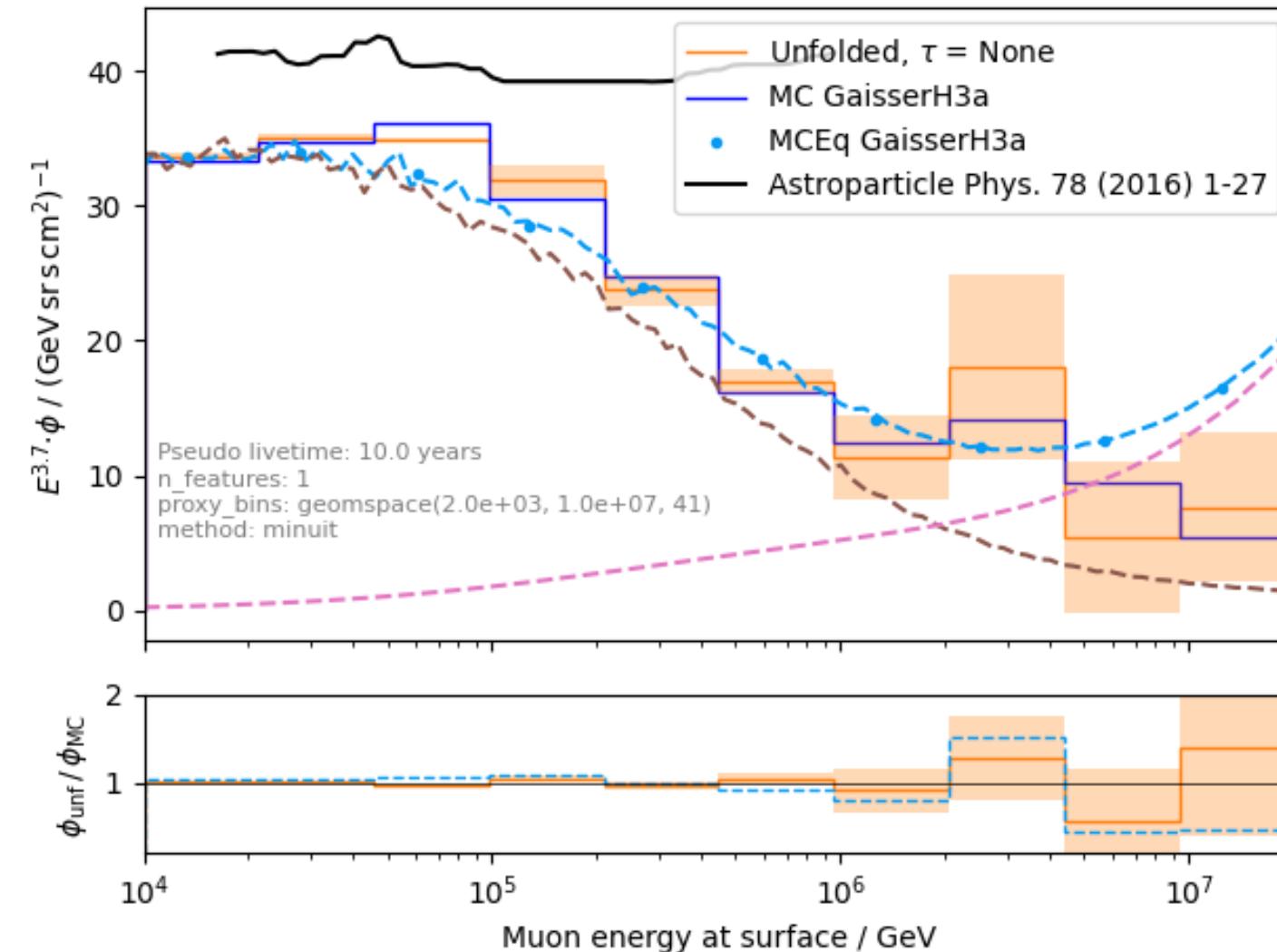


Level5: $\cos(\text{zenith})$ 

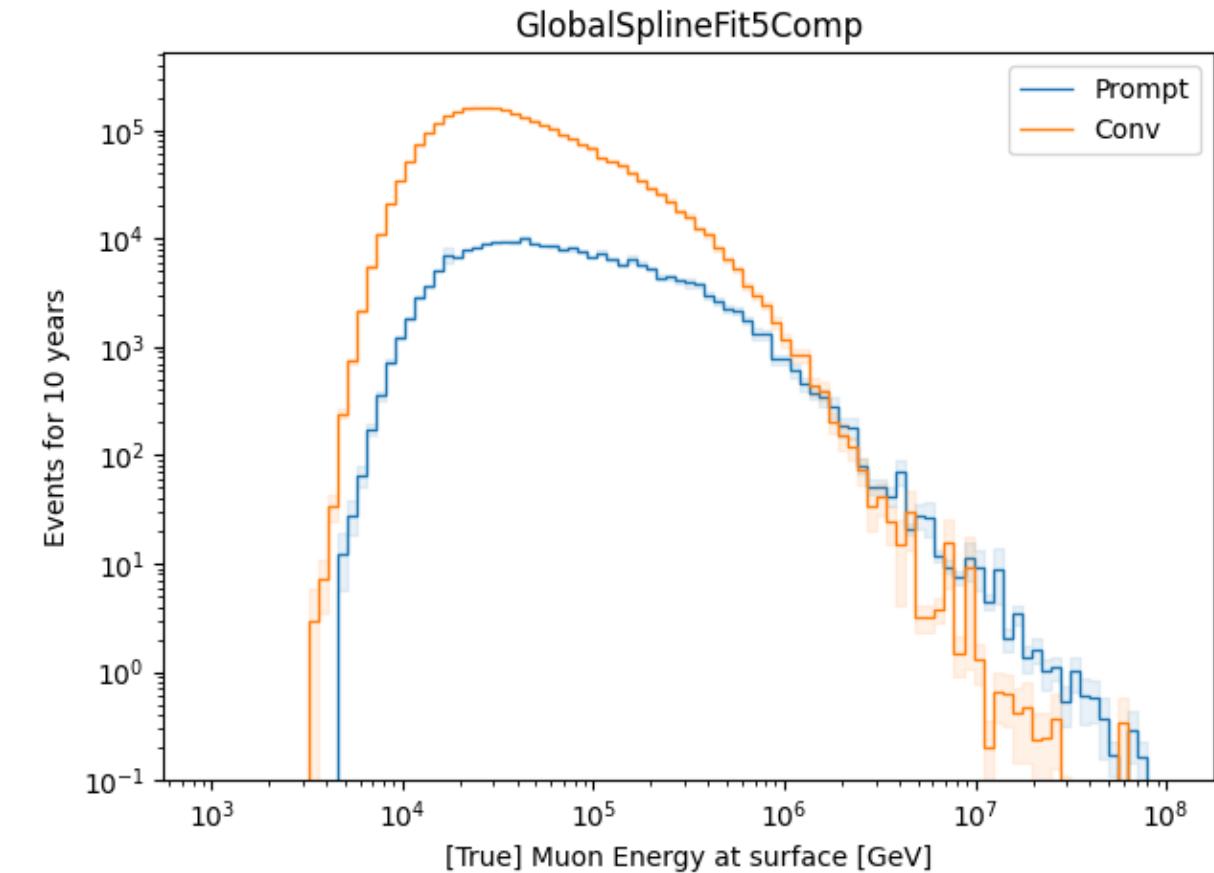
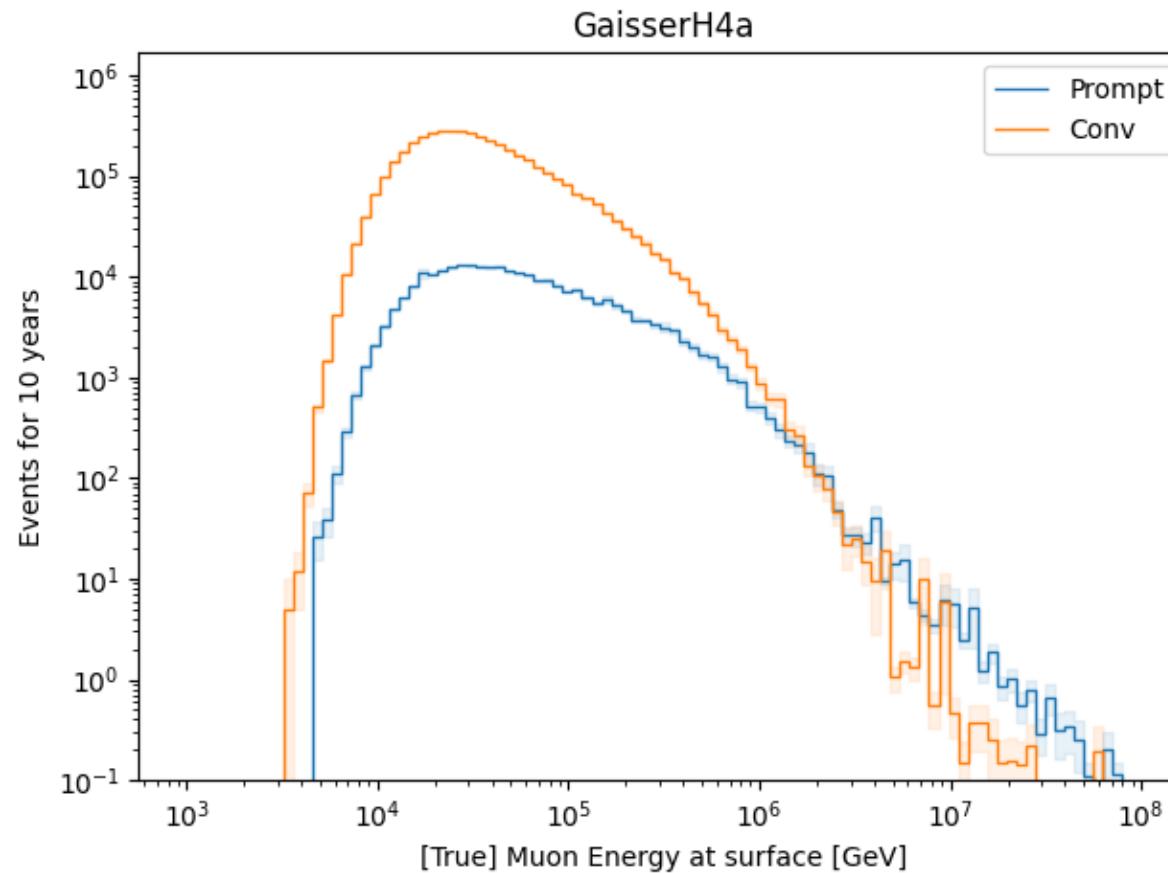
Proxy and target variable for unfolding – 10 years [H4a]



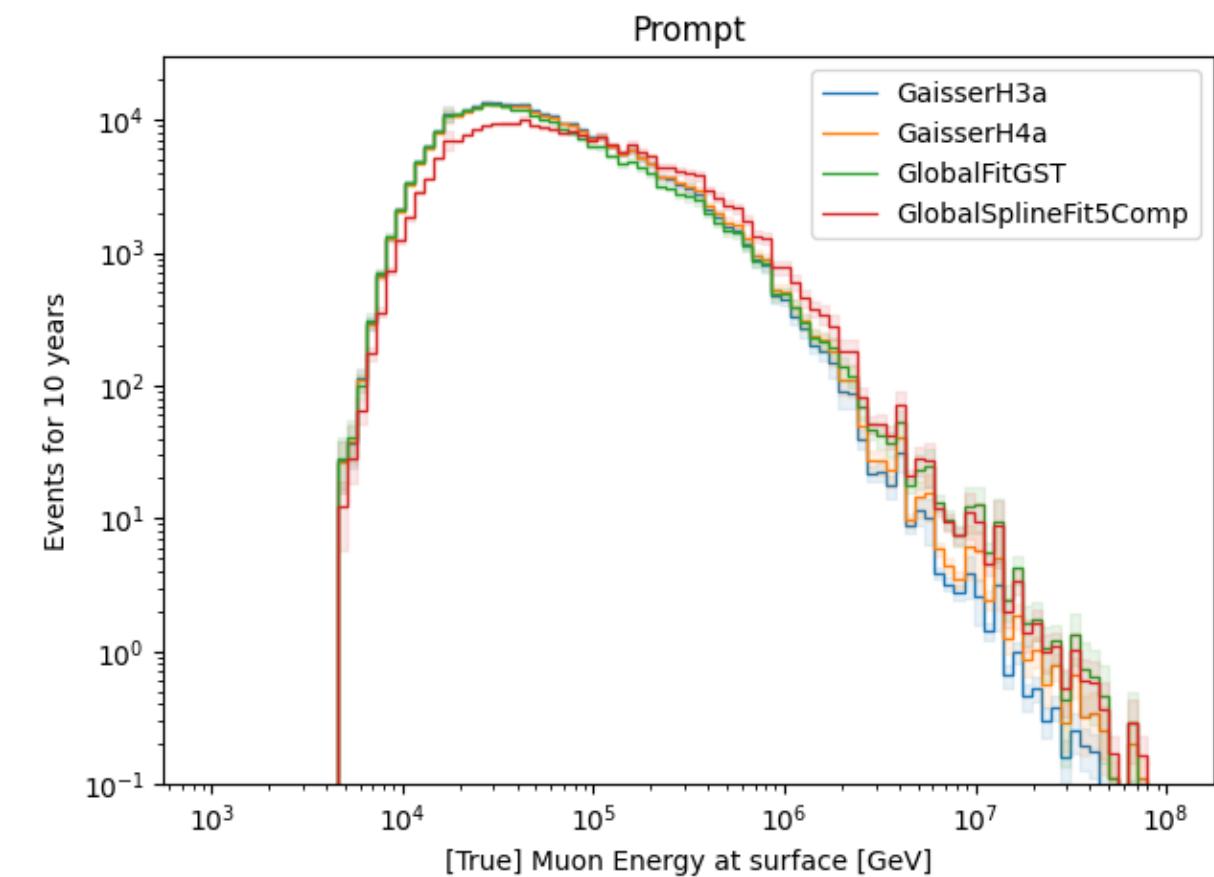
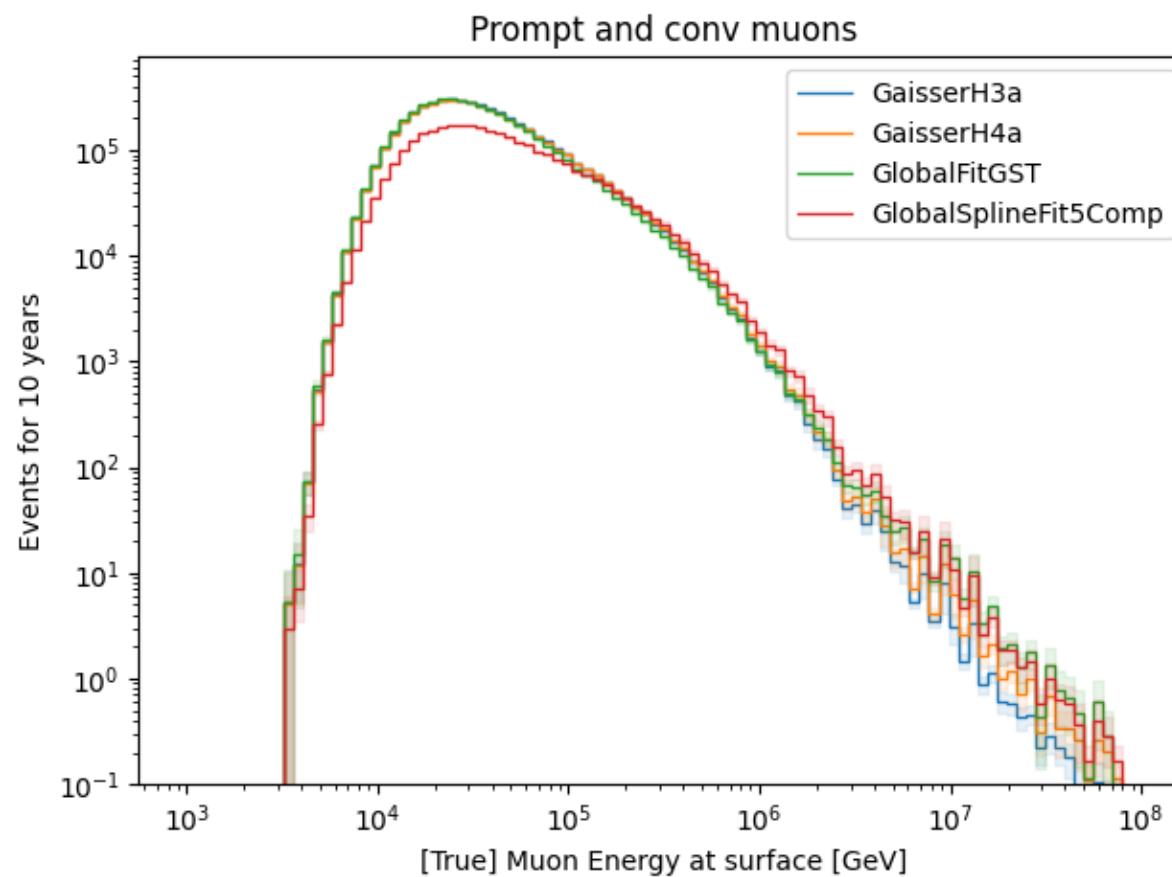
Unfolding with prompt and conv MCEq



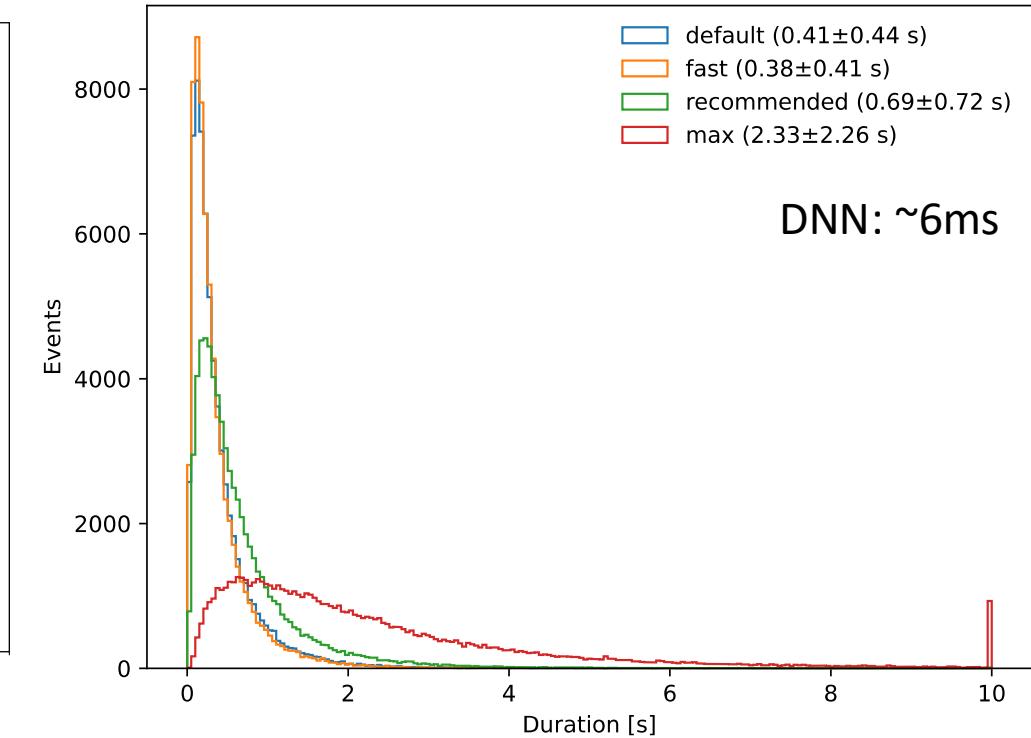
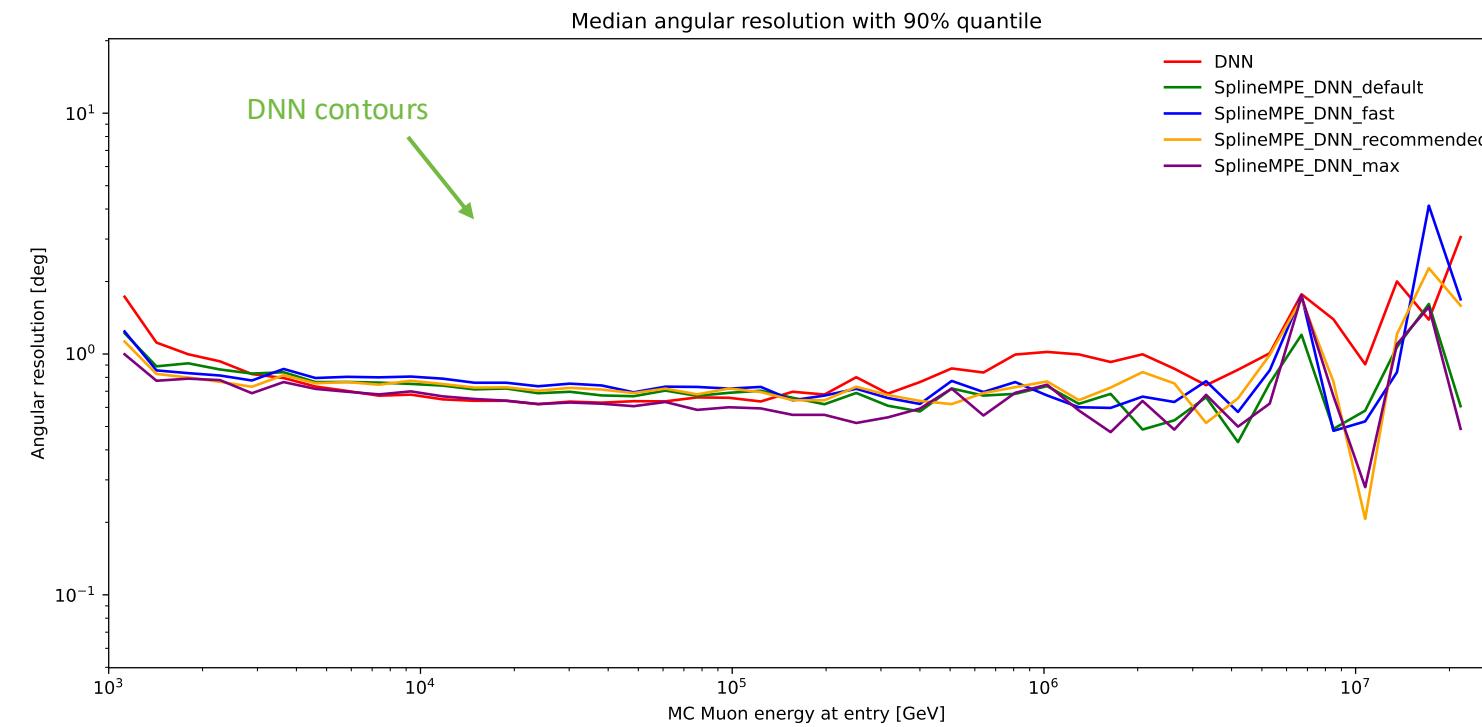
Prompt and conv: muon energy at surface for 10 years



Compare all primary fluxes



Angular reconstructions: DNN vs. SplineMPE

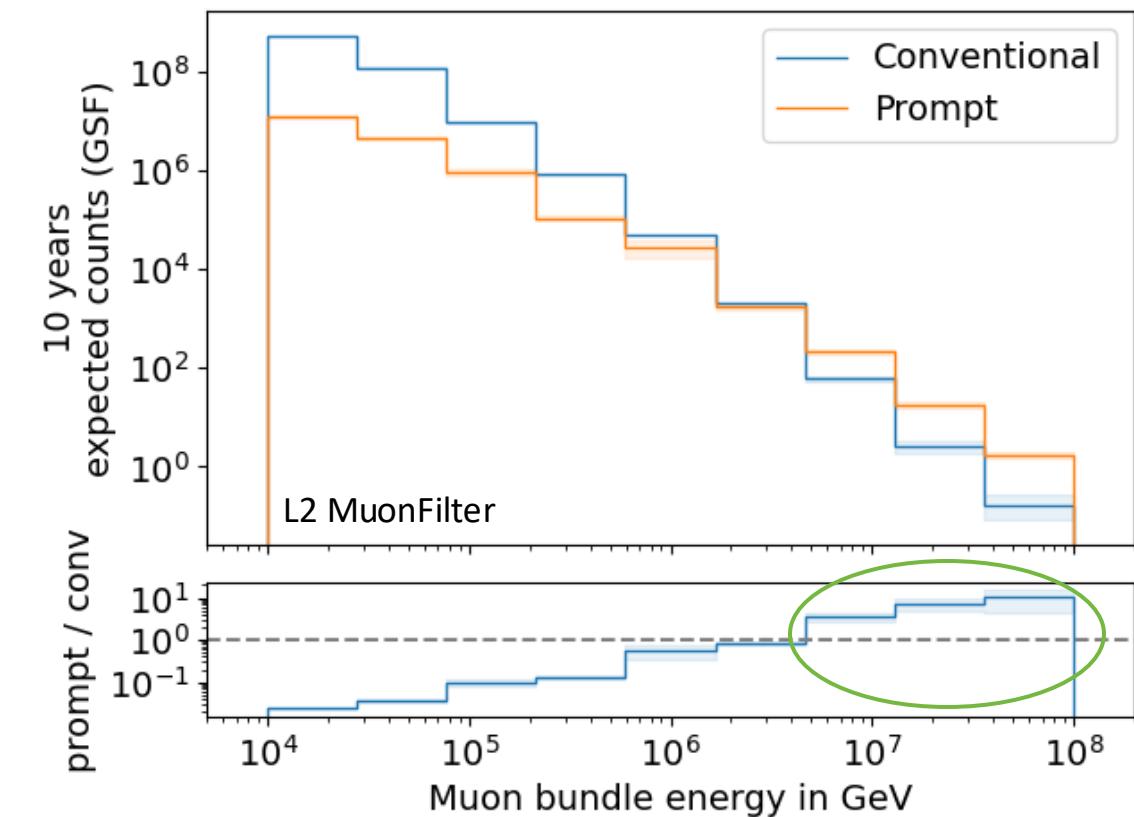
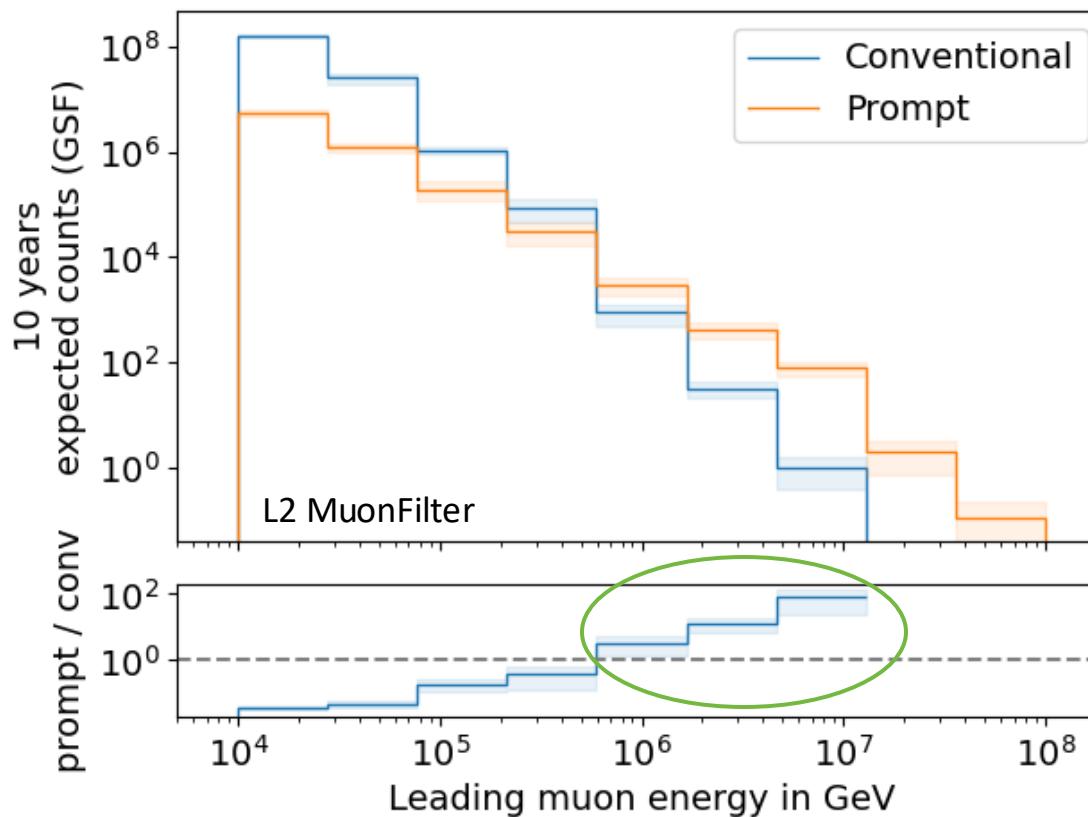


- Only small improvement at energies around 1 PeV
 - Contours are larger
 - Additional runtime
- > Use only DNN reconstruction, since we do not need the best angular resolution

Forward fit

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

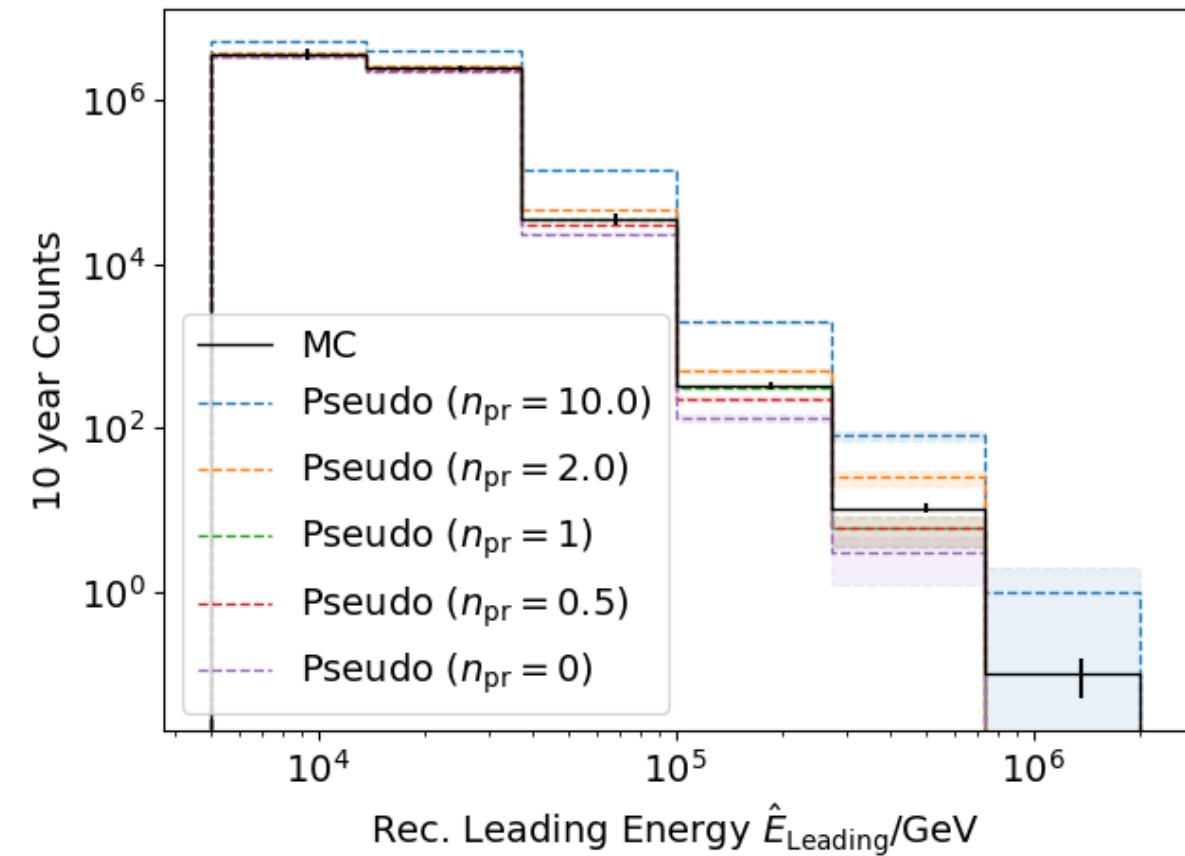
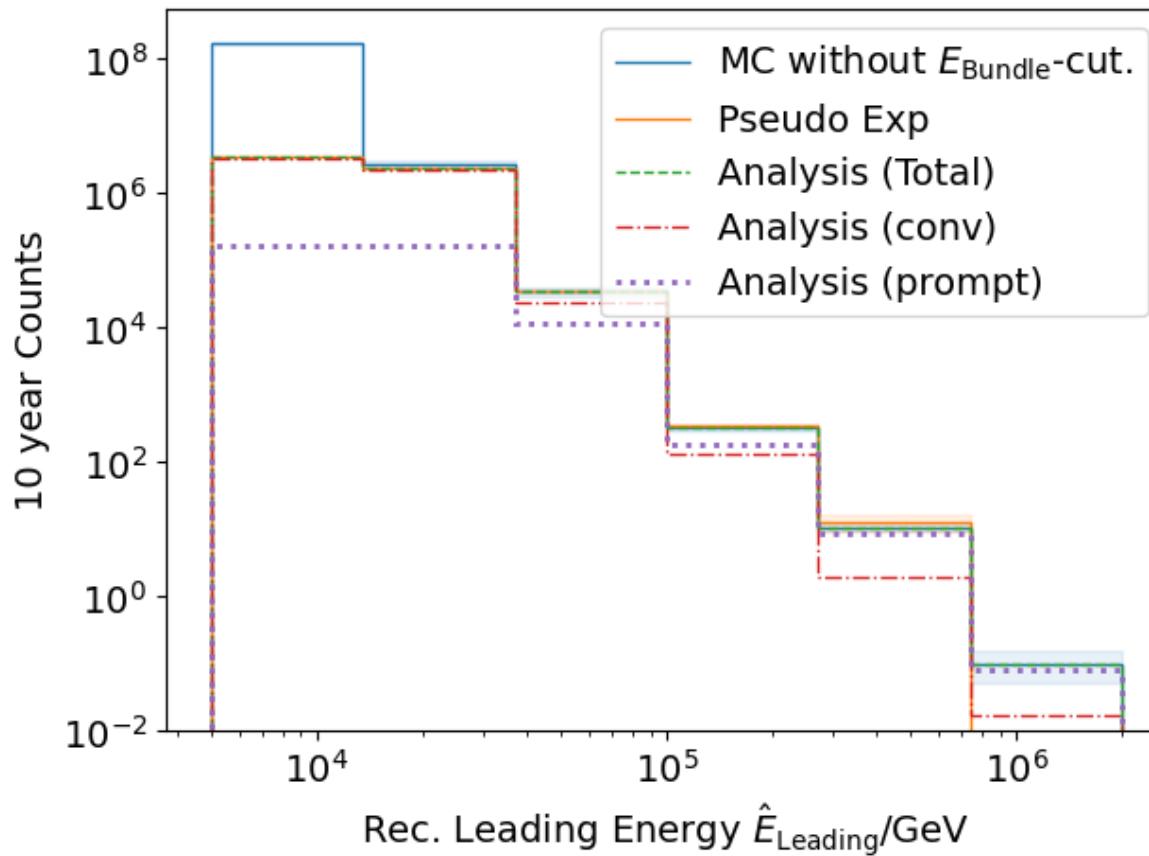
- leading: energy of most energetic muon in a muon bundle
- bundle: sum of energies of all muons of the bundle



- 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_{pr}

Poisson likelihood fit performed in leading muon energy

Cuts:
 L2 MuonFilter
 Bundle energy at entry > 100 TeV

Prompt scaling/normalization

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

MC counts per bin i

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

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

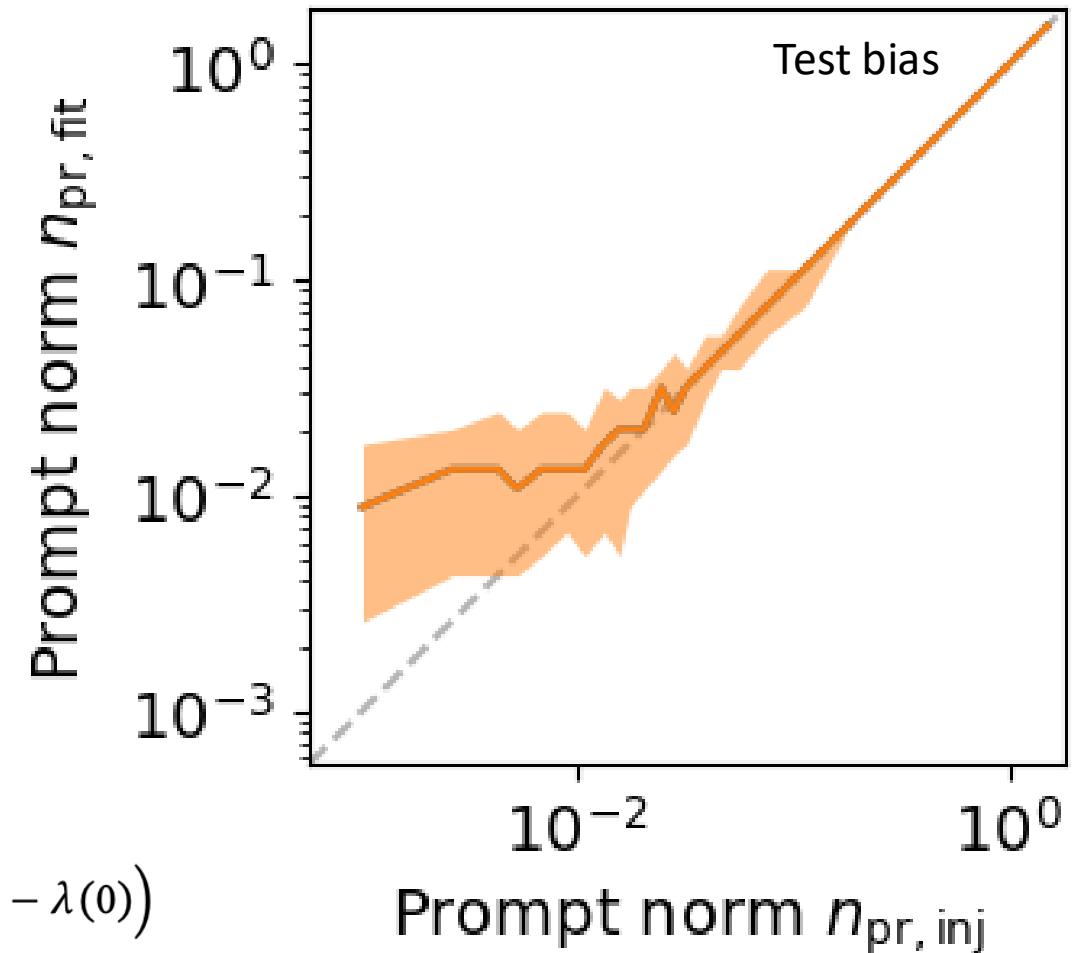
With a constant conv norm:
 bin counts depend only on prompt norm
 = expectation value per bin

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

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:

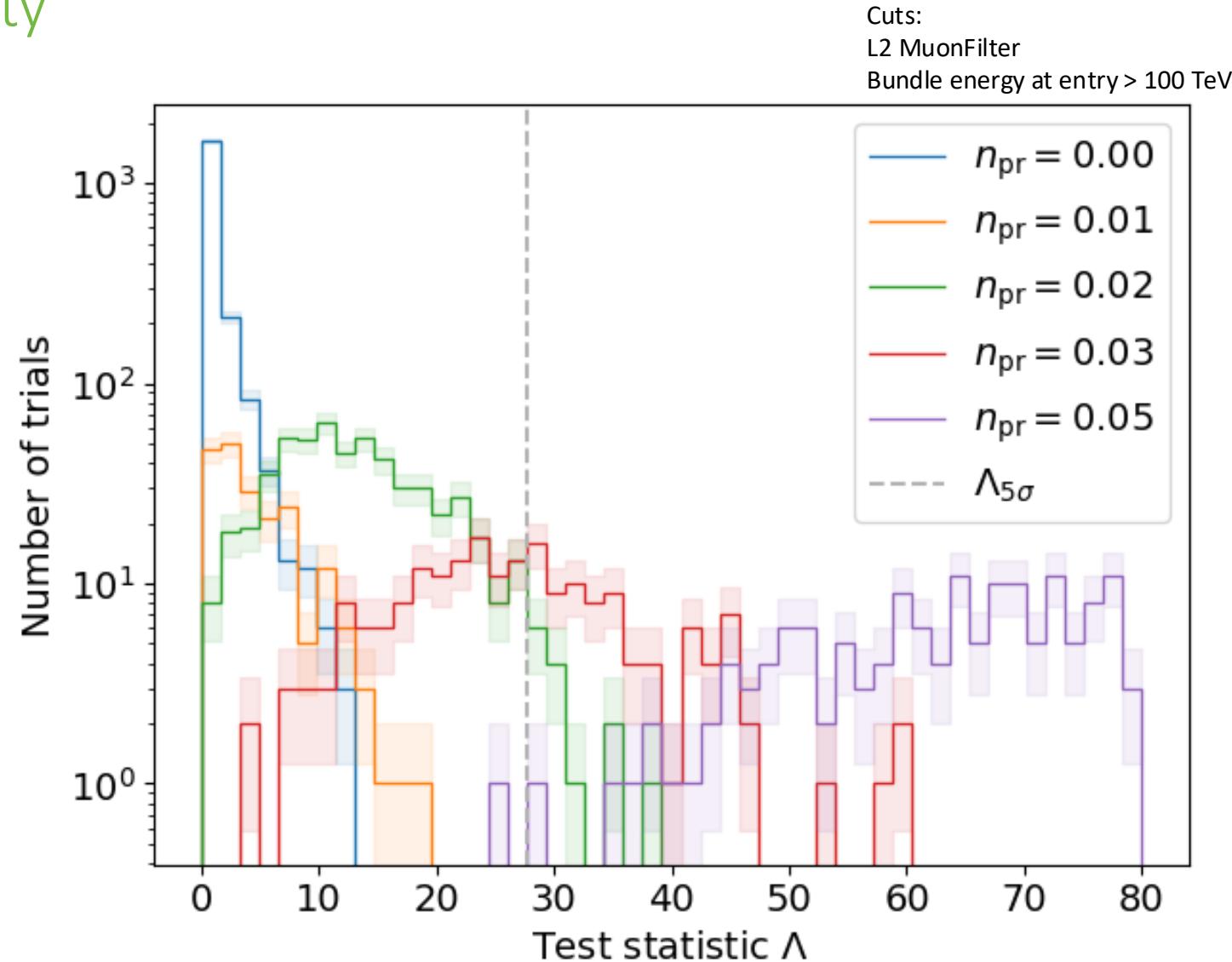
- 5 sigma discovery potential: 0.102 ± 0.005
- Sensitivity: 0.024 ± 0.001

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

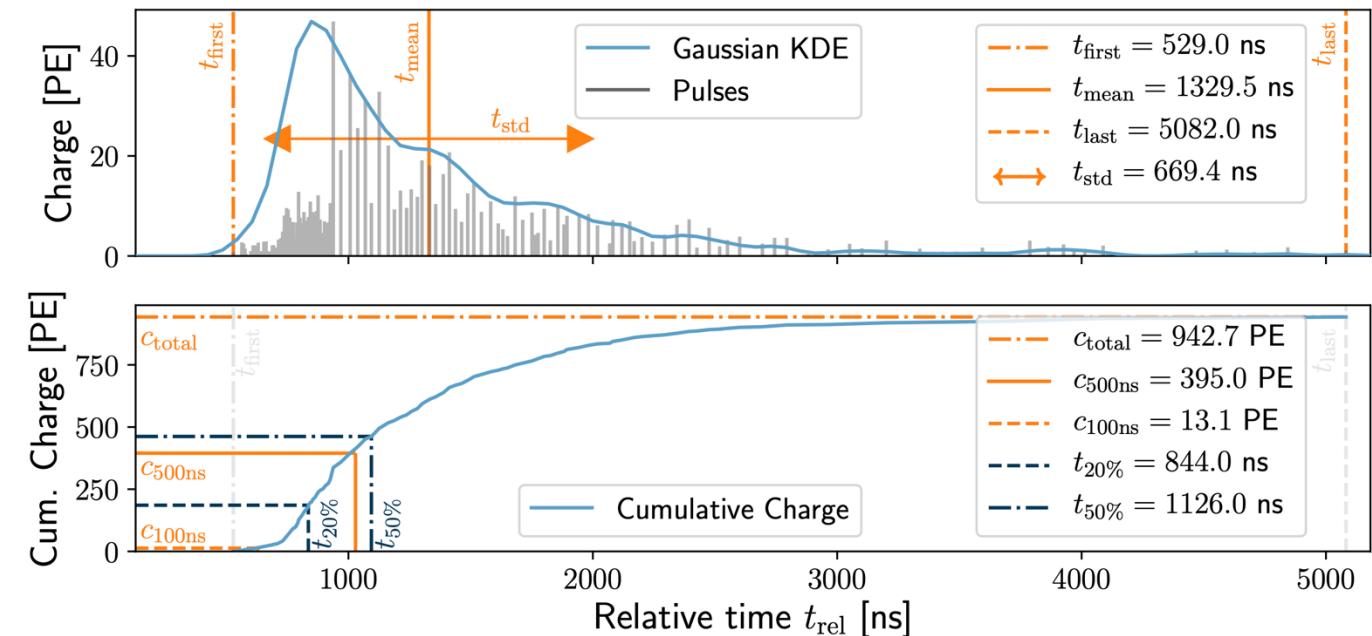
10.1088/1748-0221/16/07/P07041

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
- $c_{500\text{ns}}$: Charge at 500ns
 - Sum of charge after 500ns
- $c_{100\text{ns}}$: Charge at 100ns
 - Sum of charge after 100ns



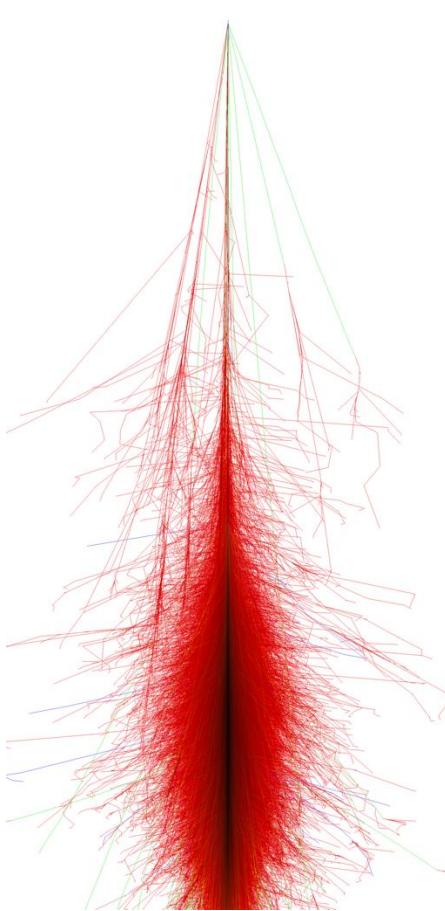
Input pulses

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

Training datasets

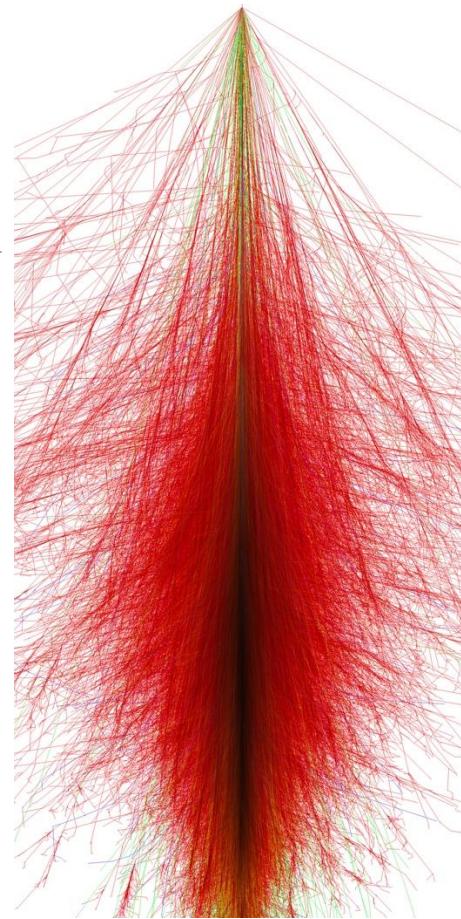
- 20904
- 21962
- 22020
- 22187

Air shower – 10 TeV

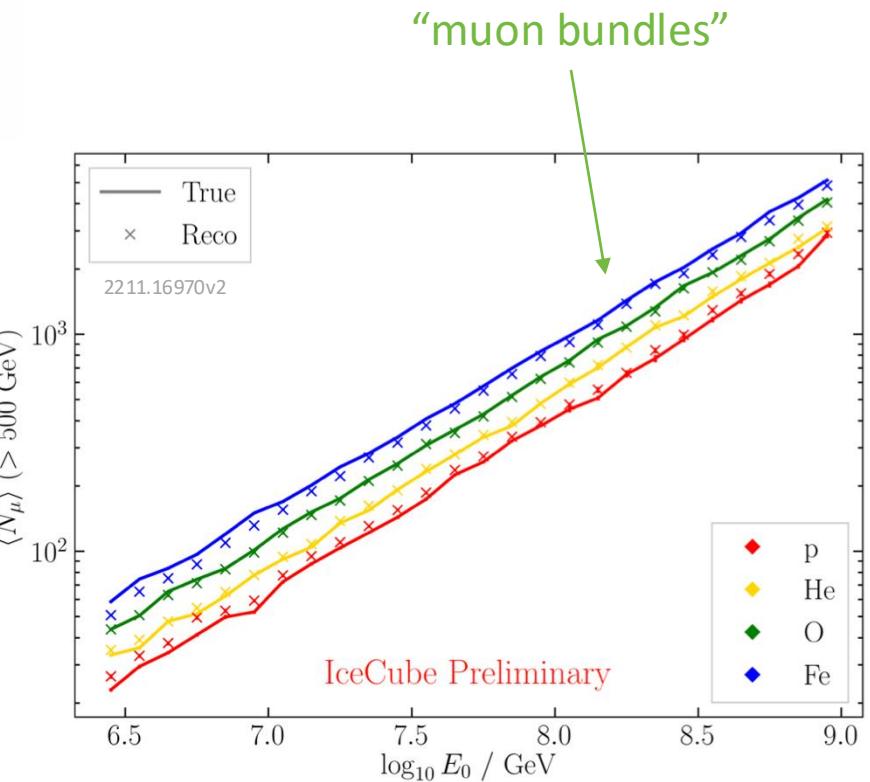
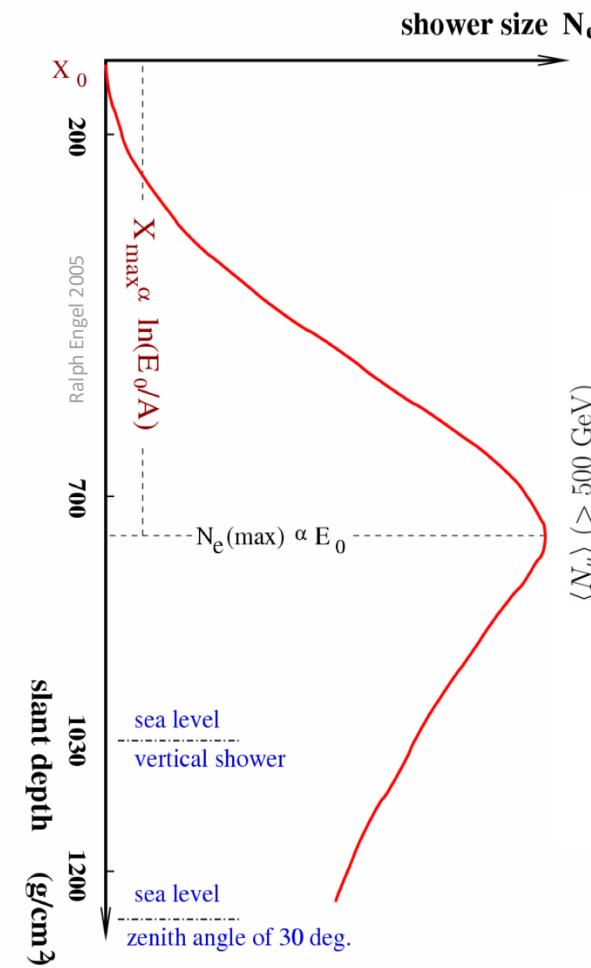


Proton

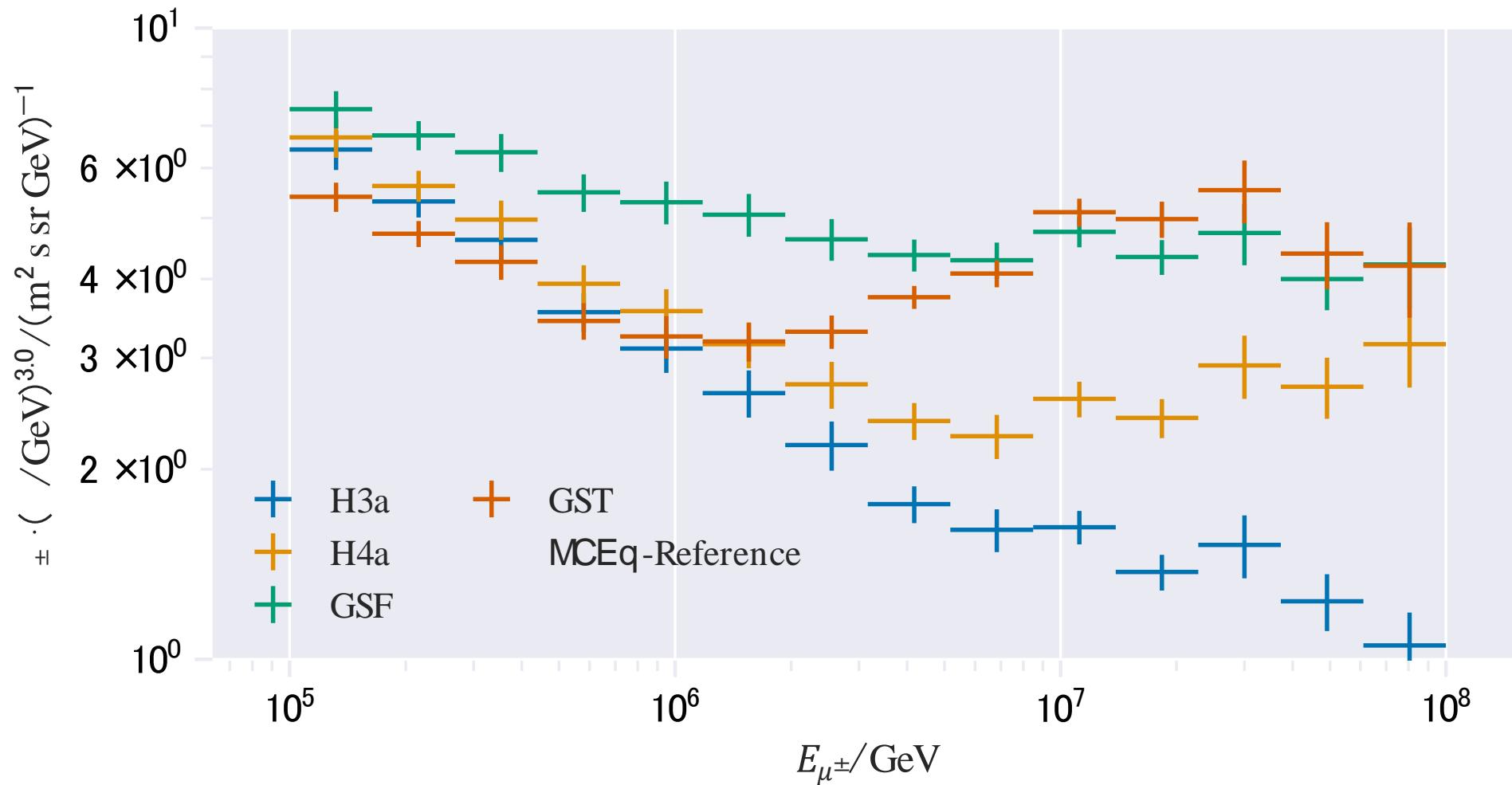
zeuthen.desy.de



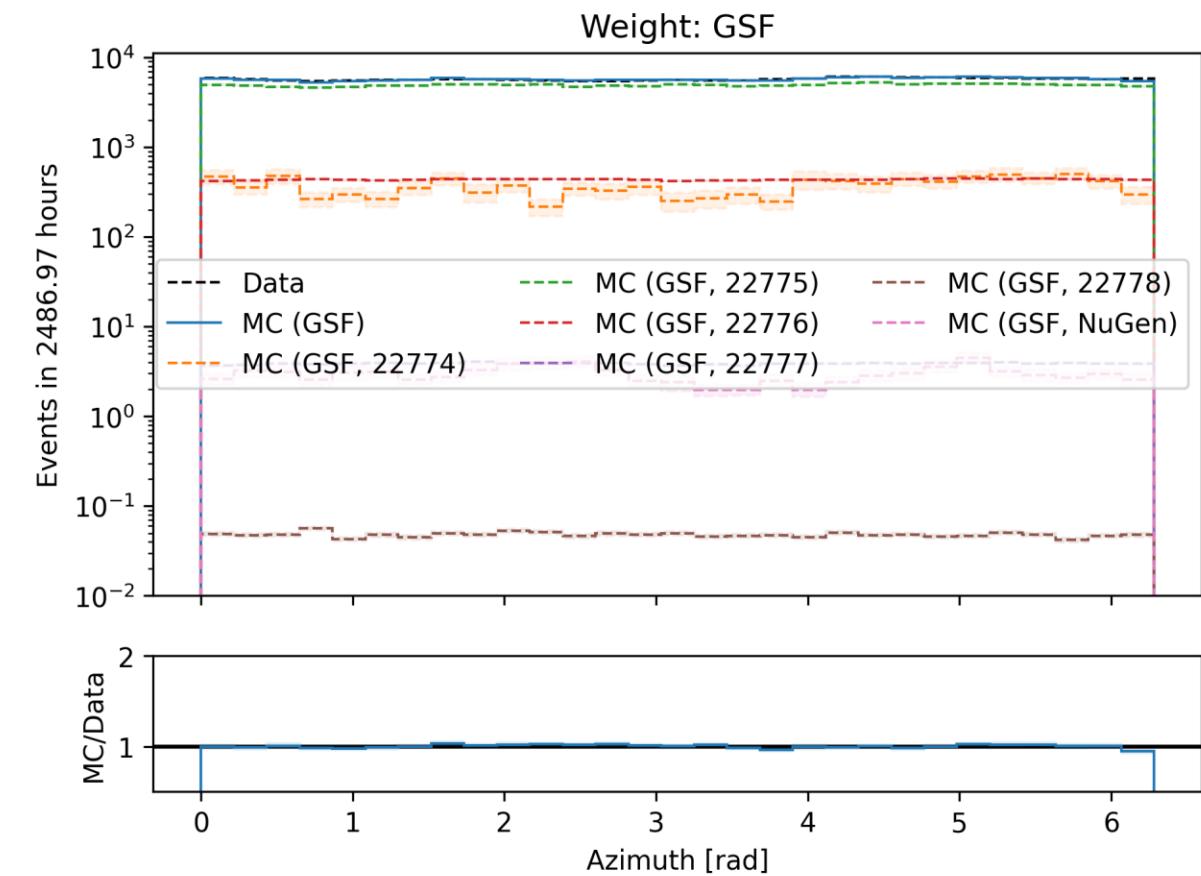
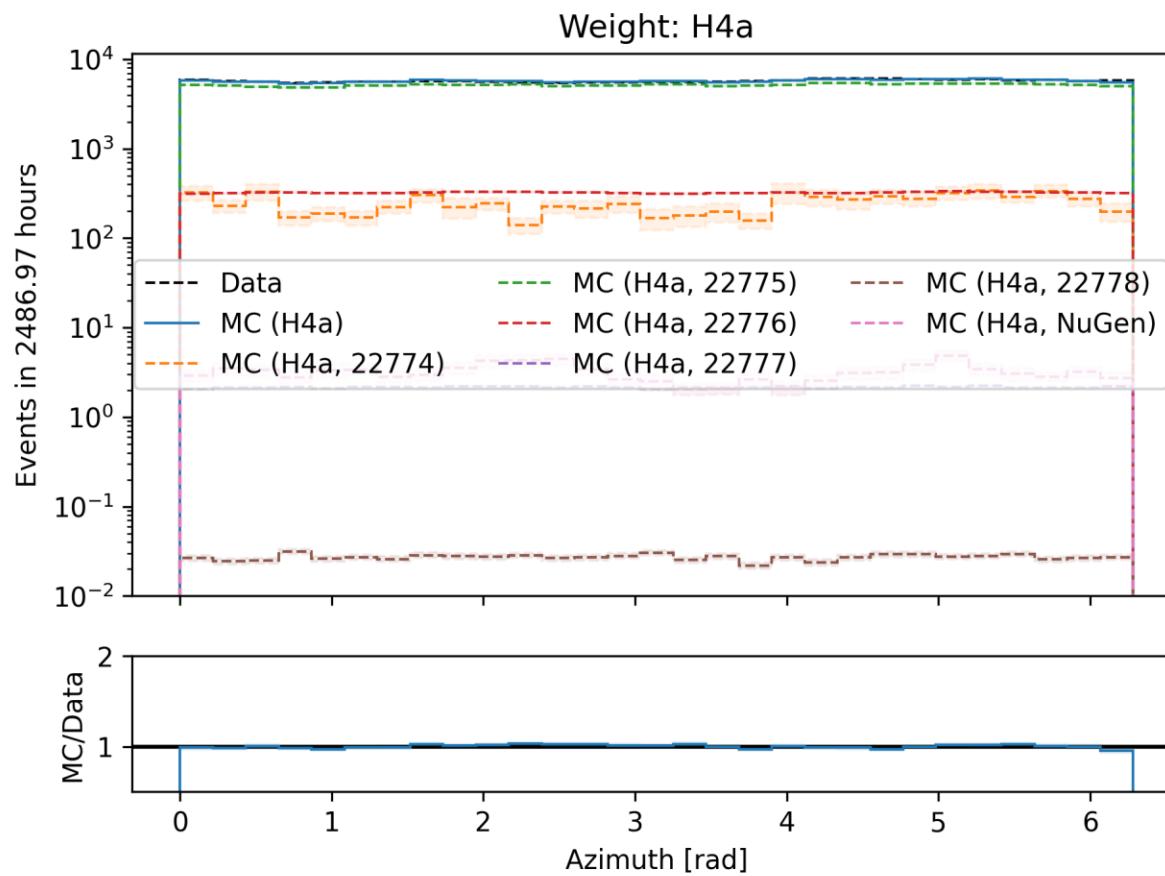
Iron



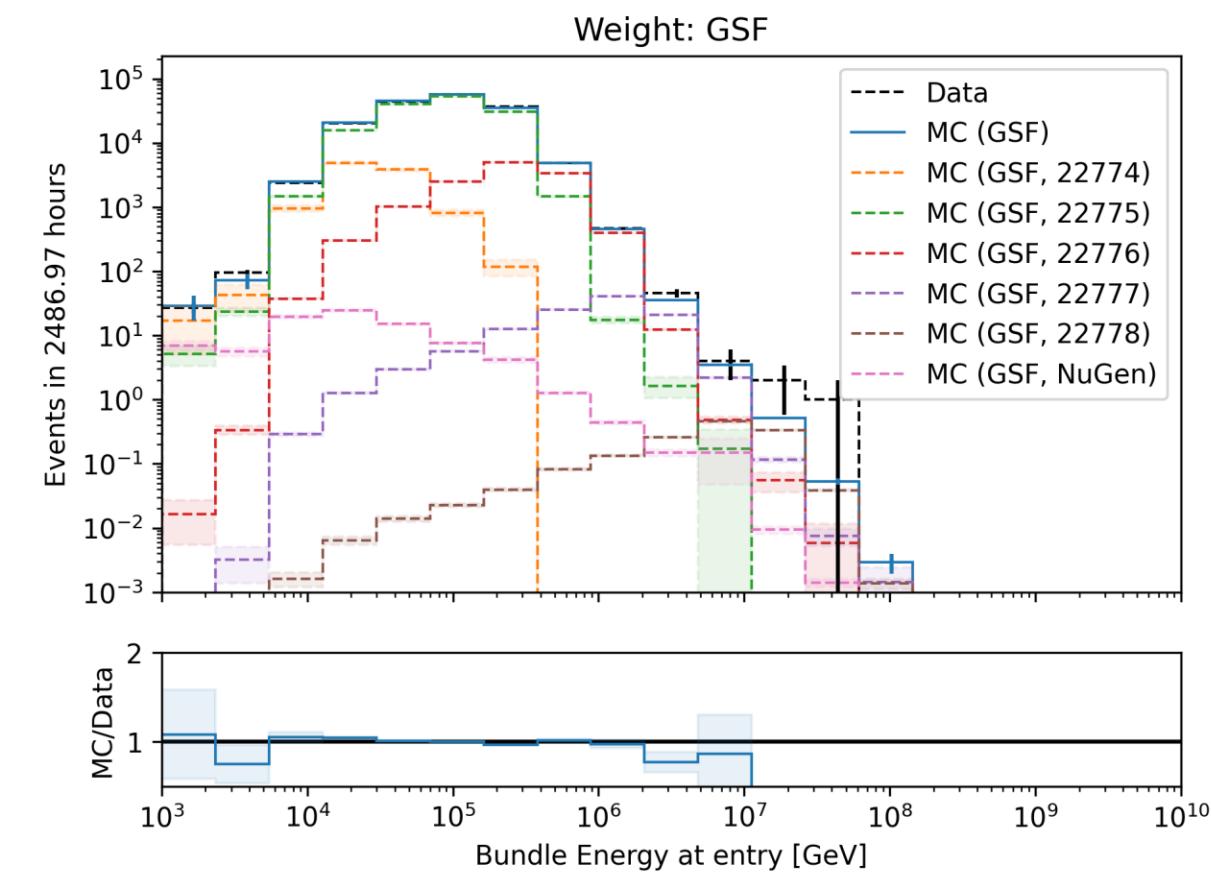
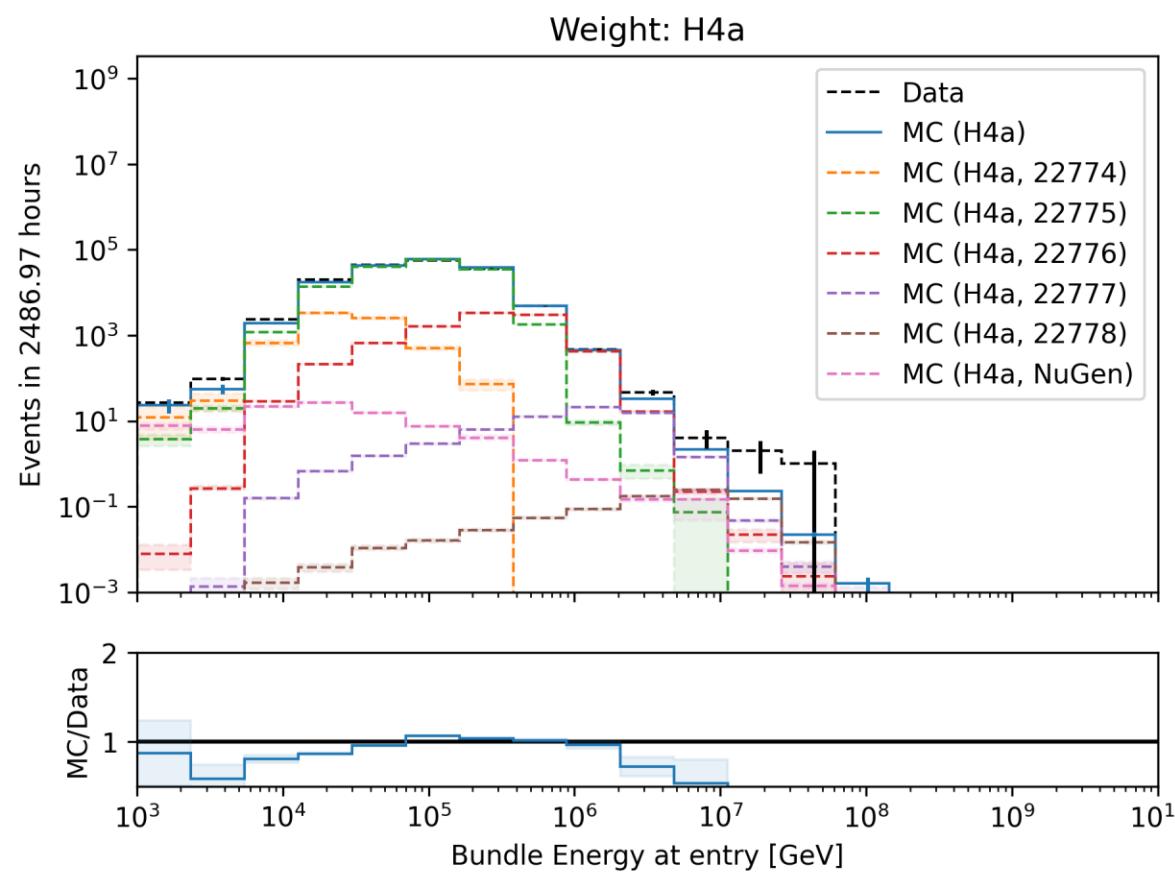
Agreement for different primary models



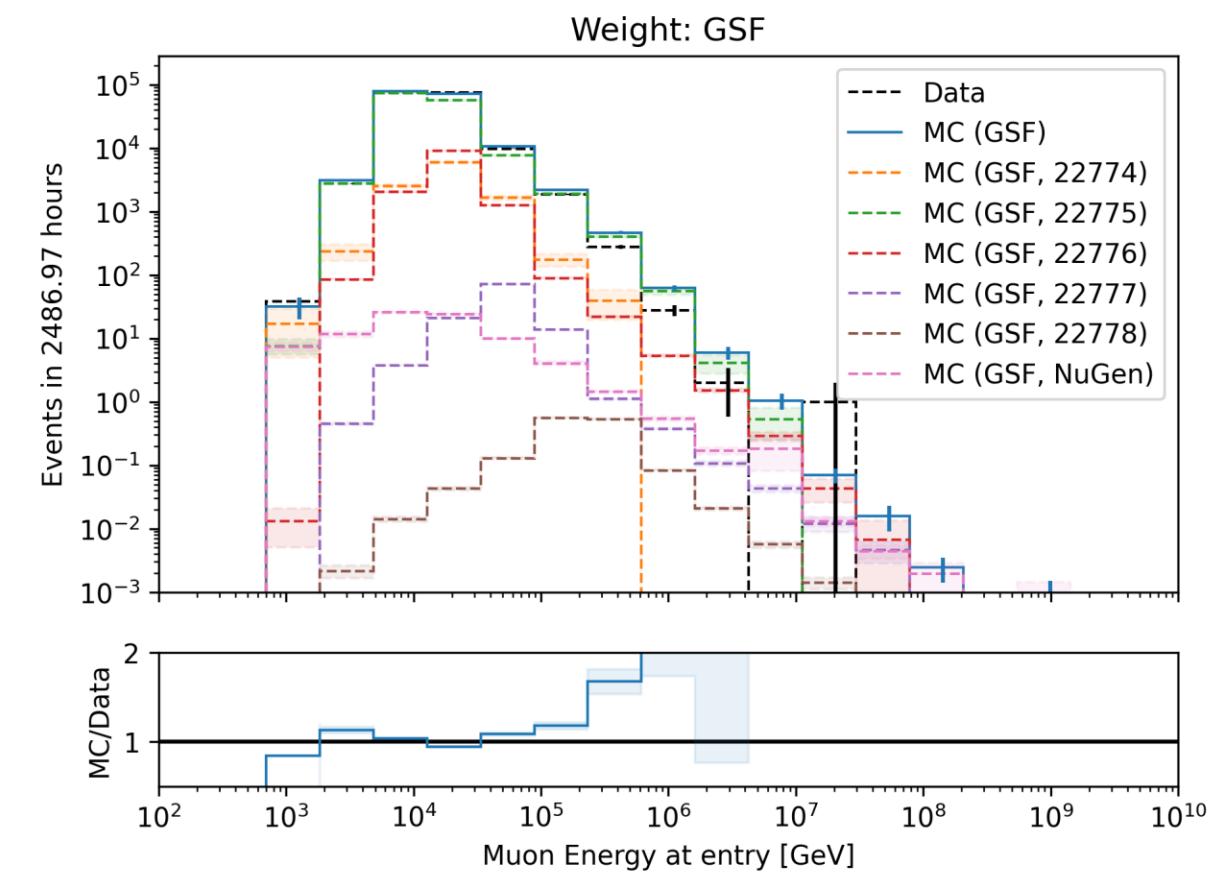
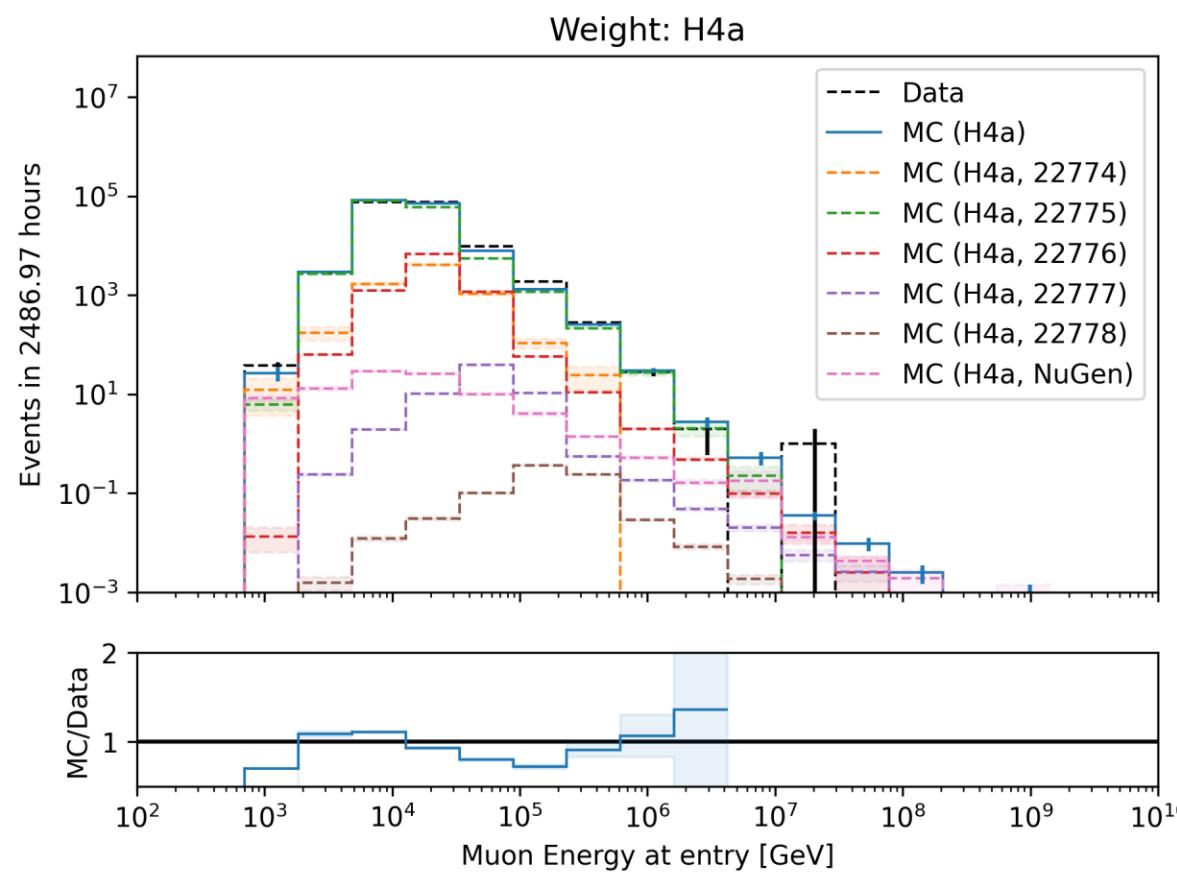
Azimuth



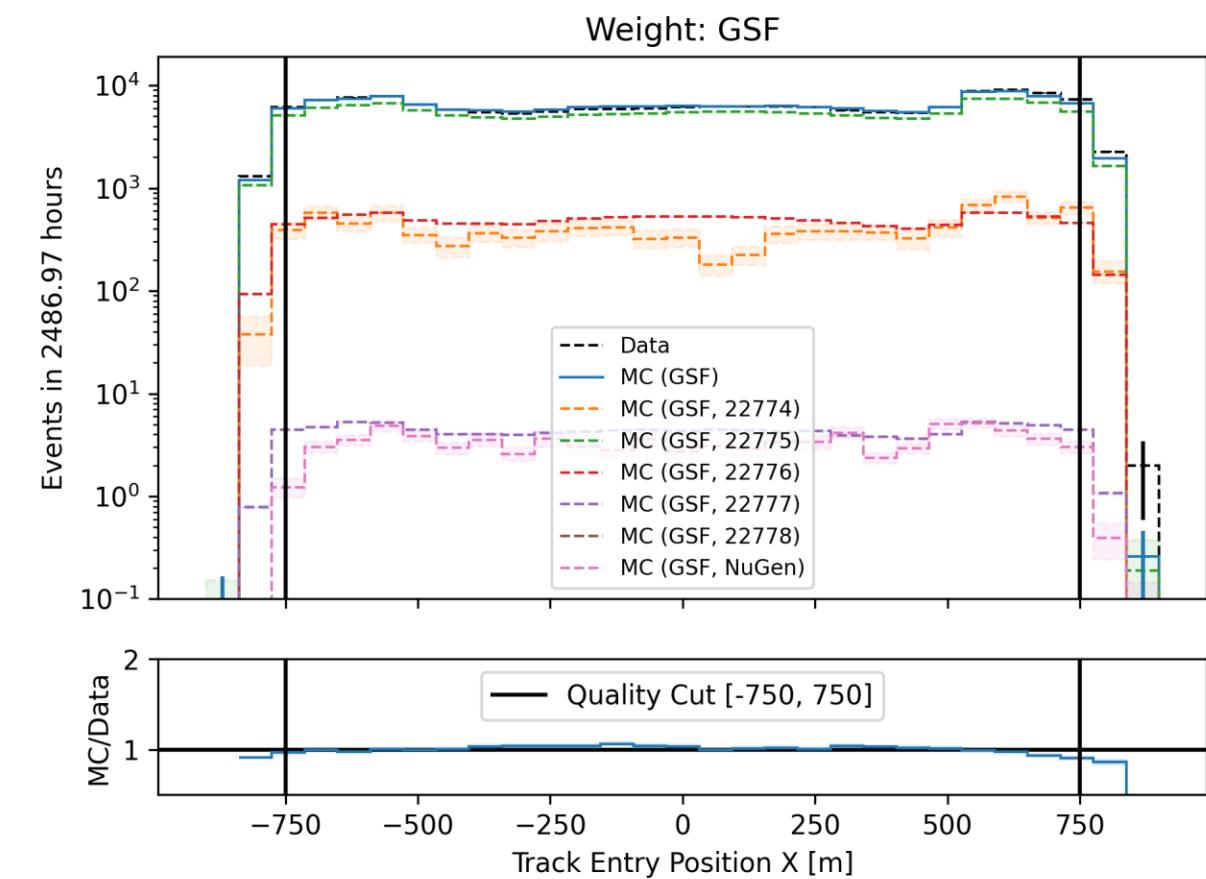
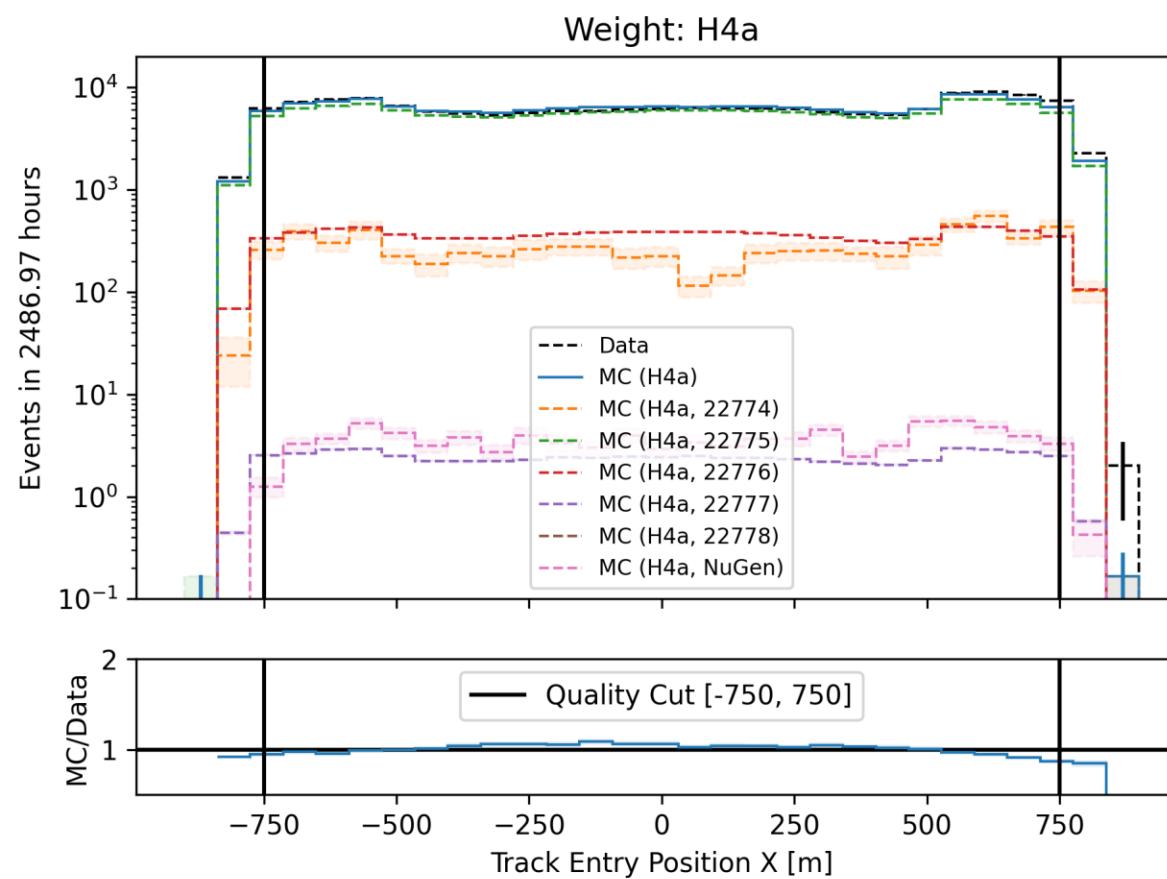
Bundle energy at entry



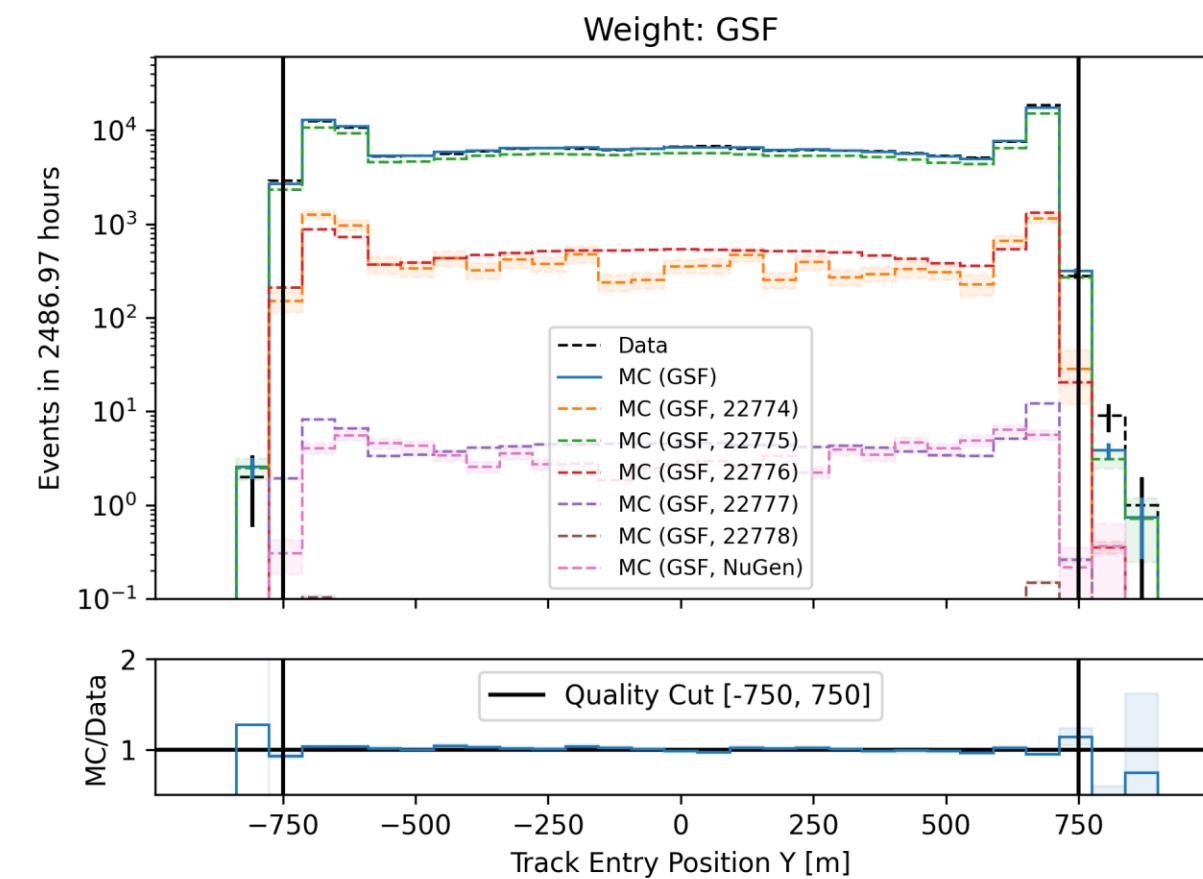
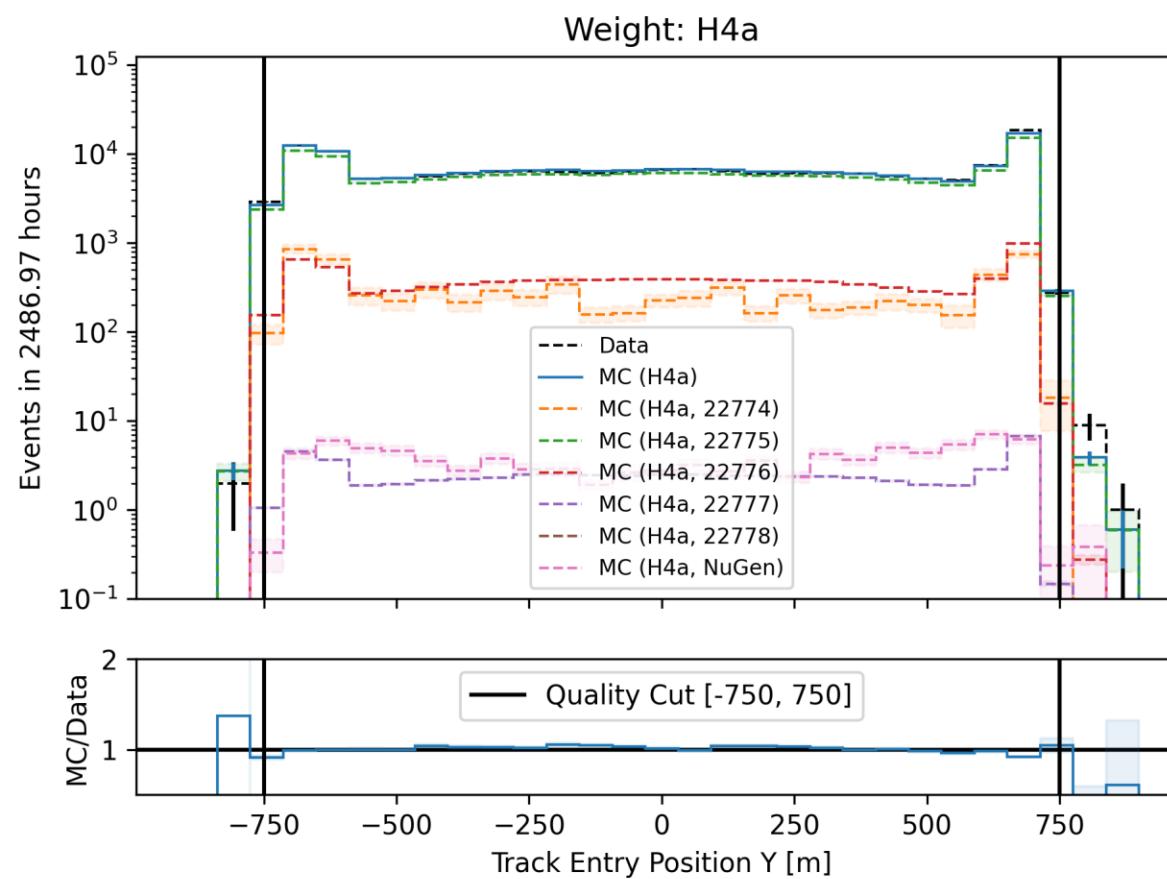
Leading muon energy at entry



Entry position x–vertex



Entry position y-vertex



DNN reconstructions

Reconstructed properties

Energy

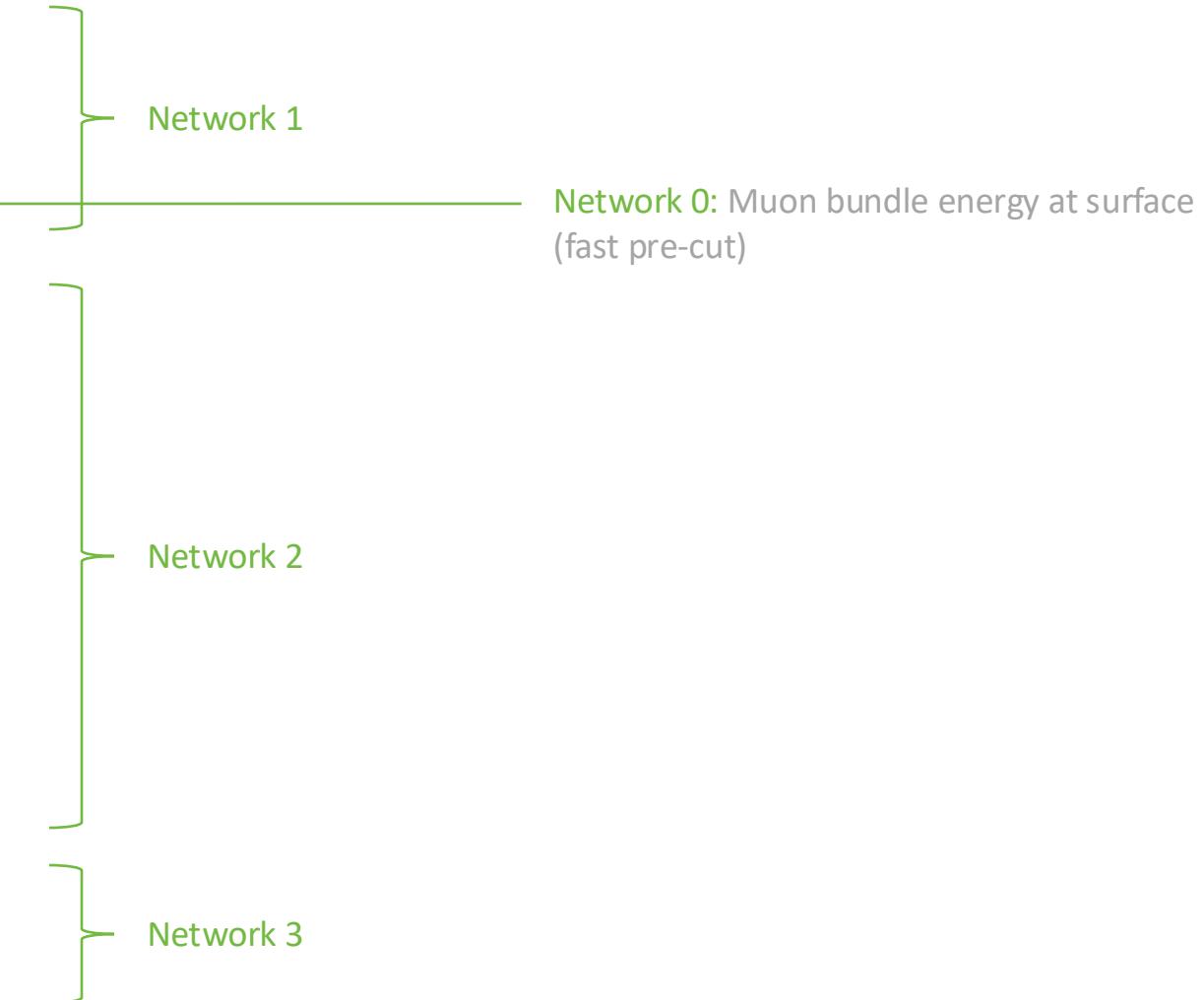
- `entry_energy`: Leading muon energy at the detector entry
- `bundle_energy_at_entry`: Muon bundle energy at the detector entry
- `muon_energy_first_mctree`: Leading muon energy at surface
- `bundle_energy_in_mctree`: Muon bundle energy at surface

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

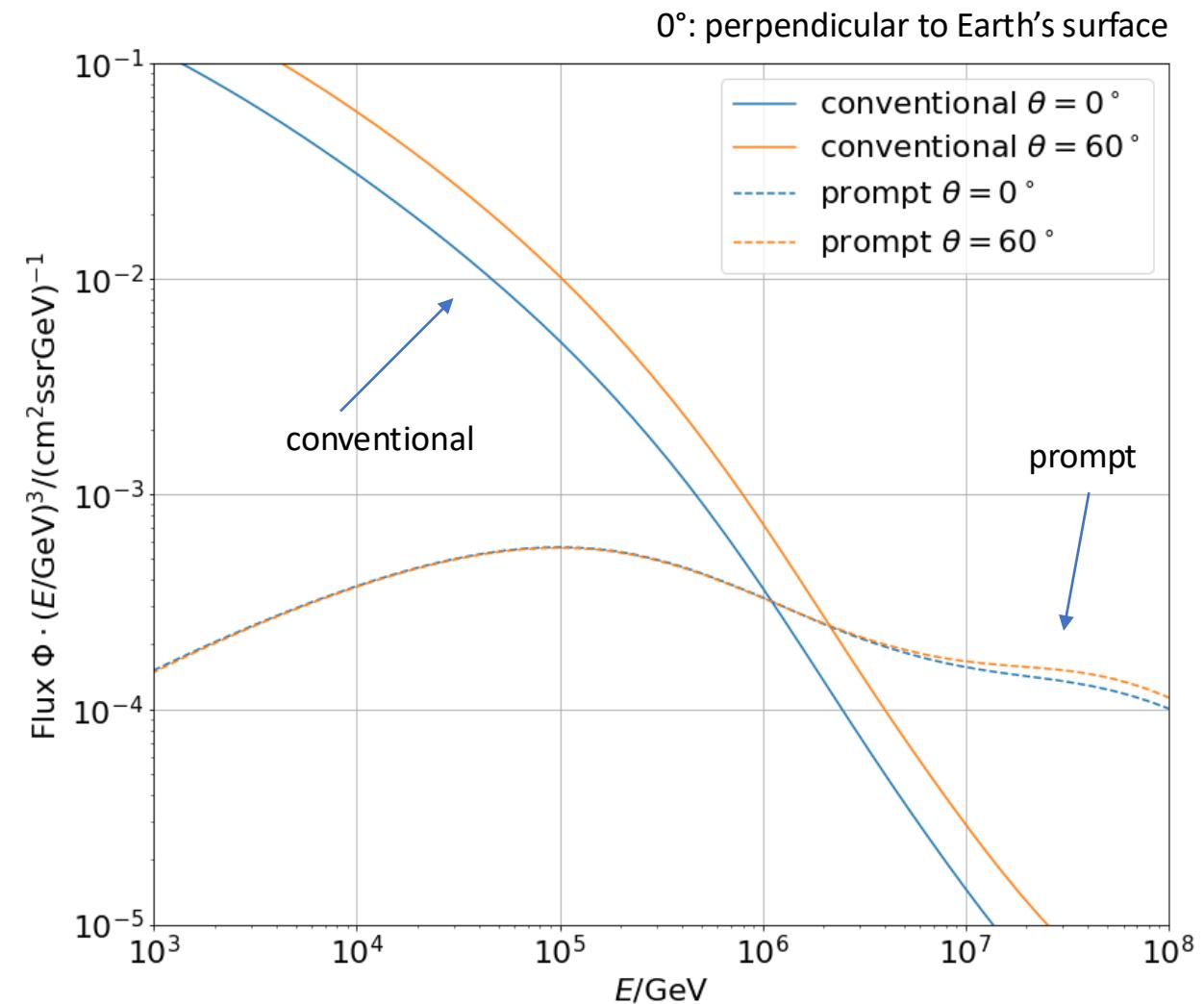
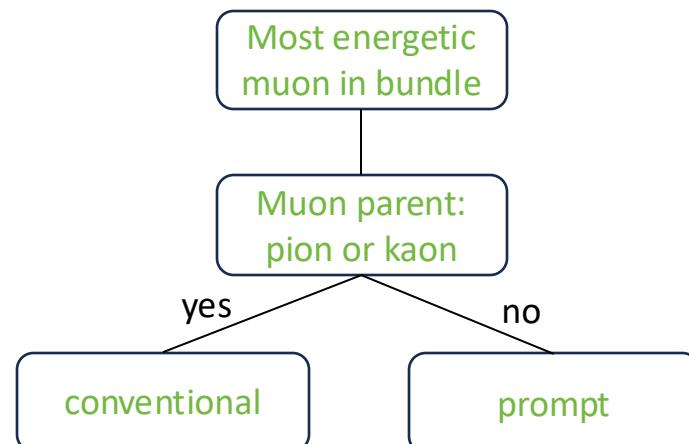
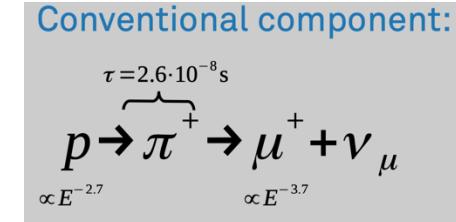
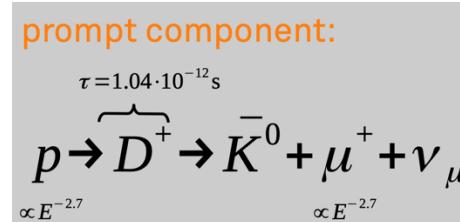
Direction

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



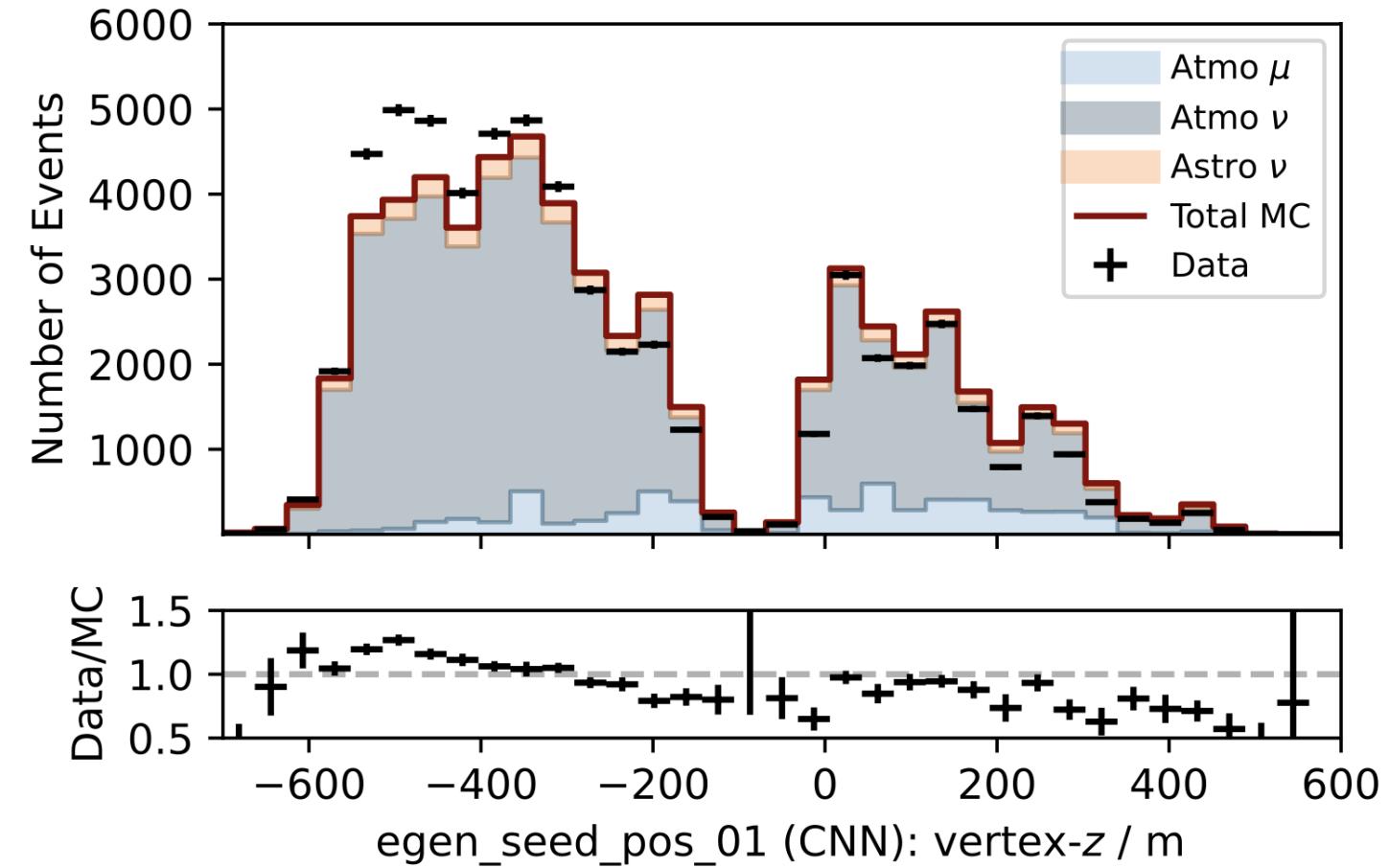
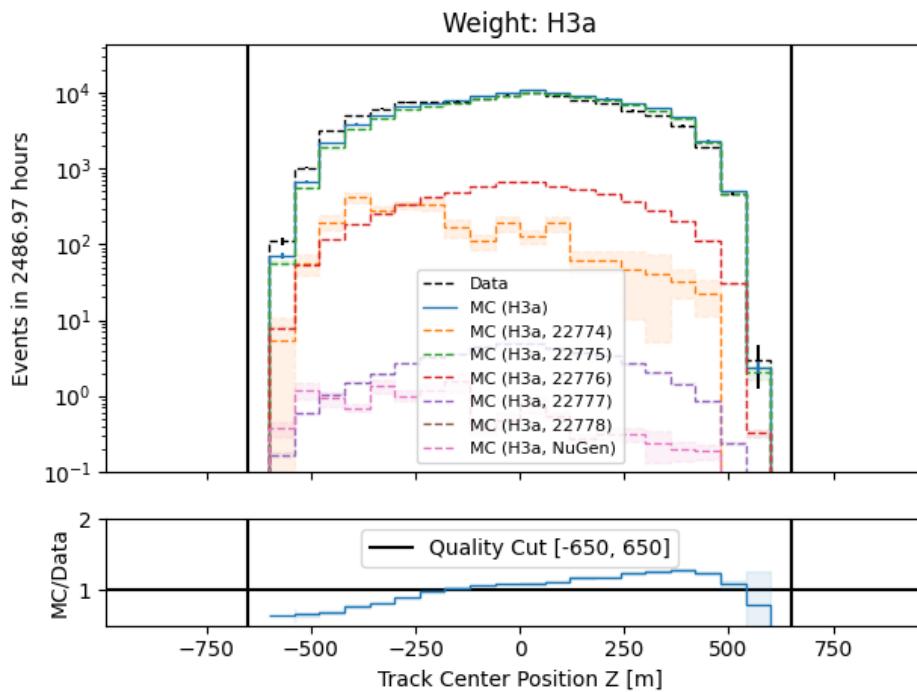
Muon flux: Prompt spectrum

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

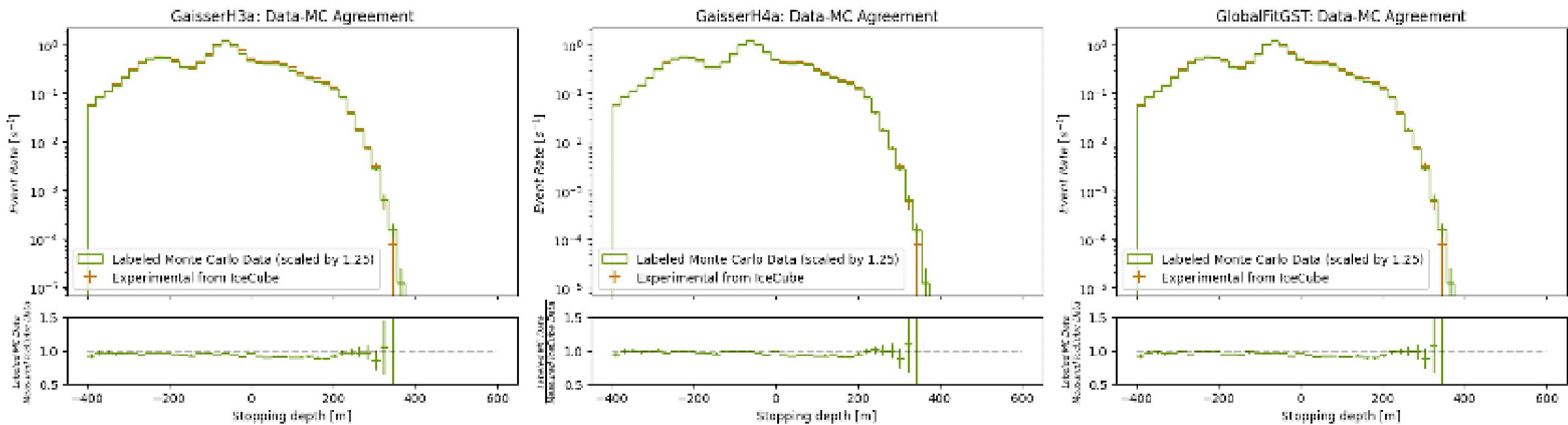


Neutrino: z-vertex

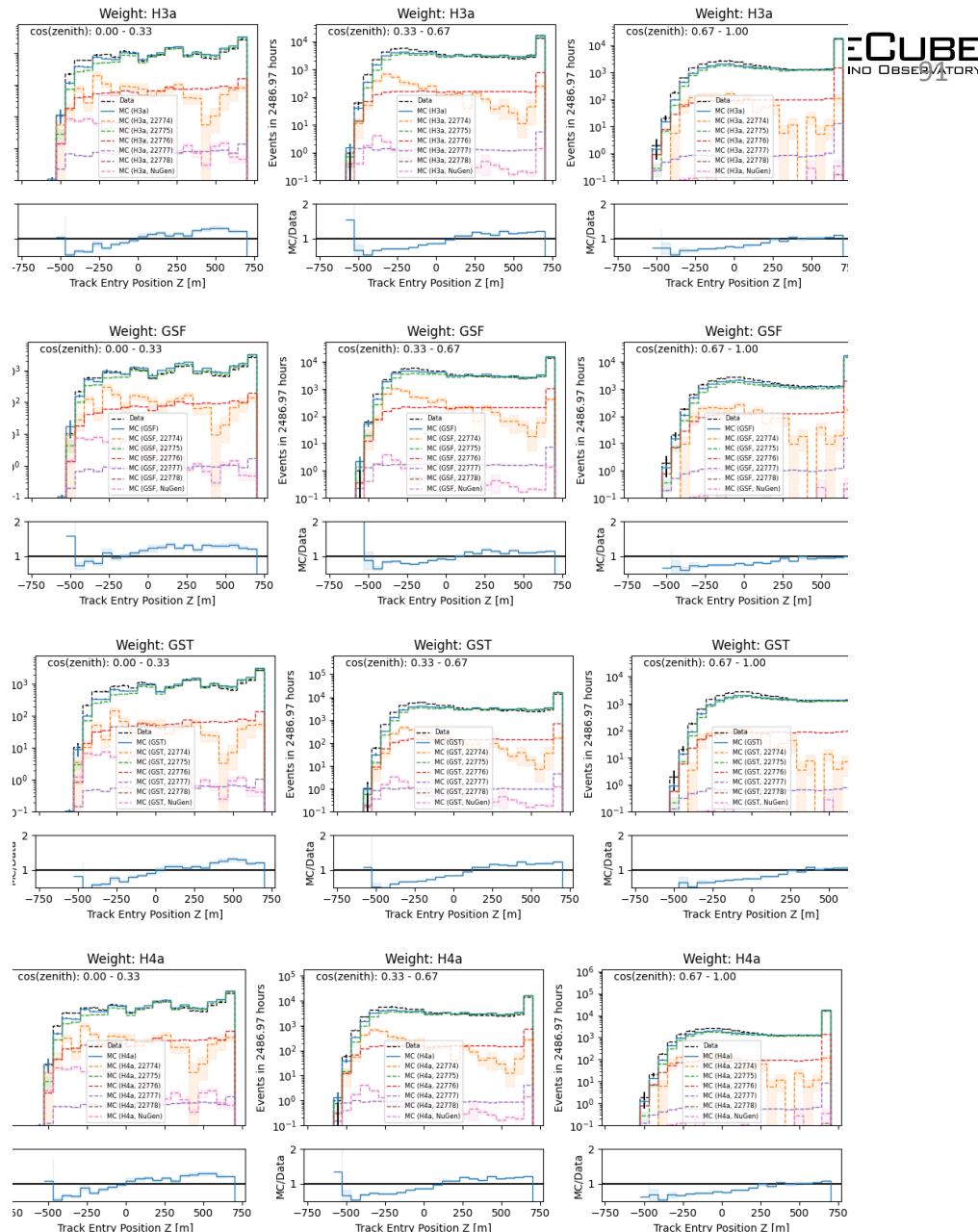
- Dissertation Mirco
- Same shape mismatch for neutrinos as for muons



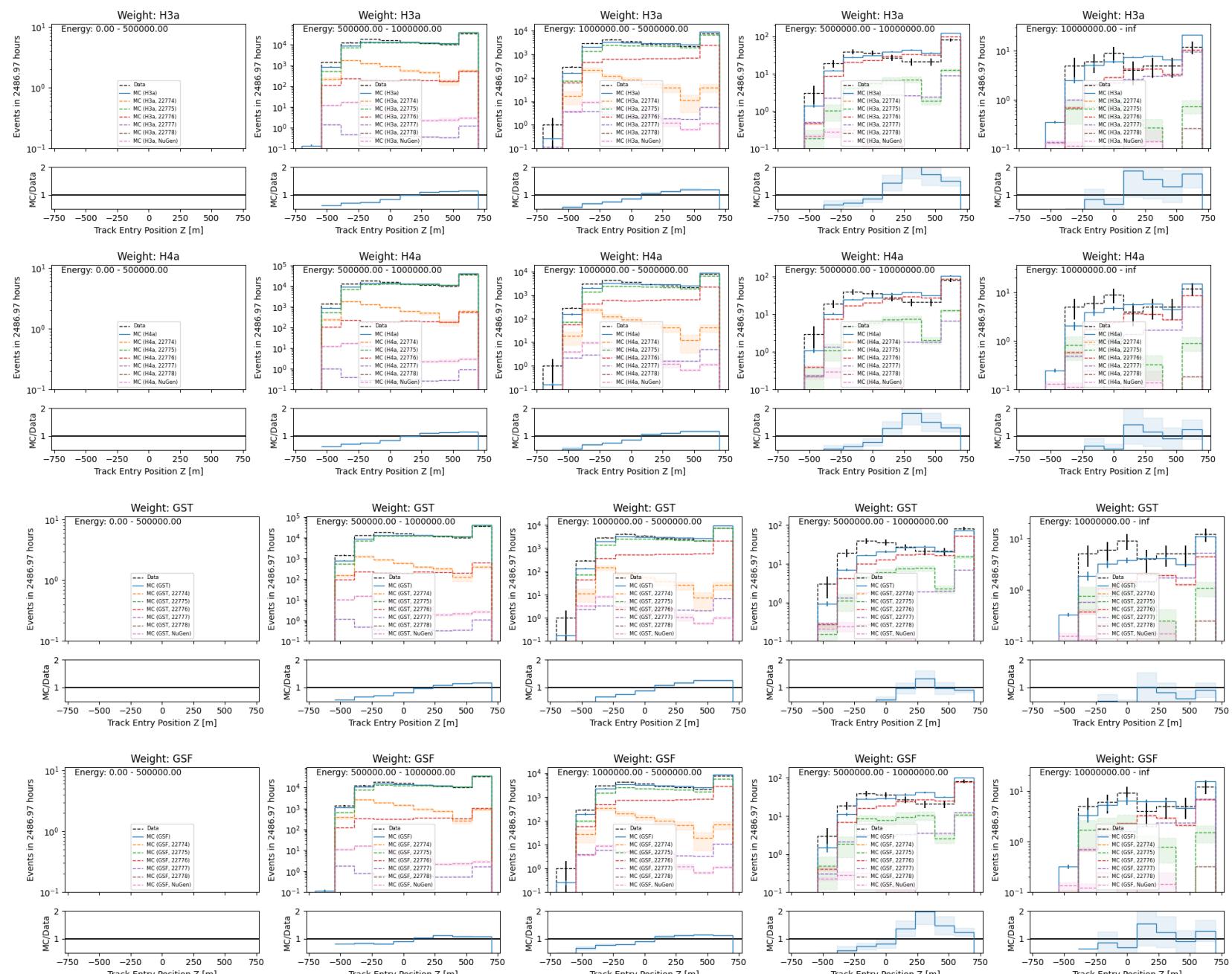
Stopping muons



Entry position z - different cos(zenith)



Entry position z
- different cuts on
bundle energy at
surface

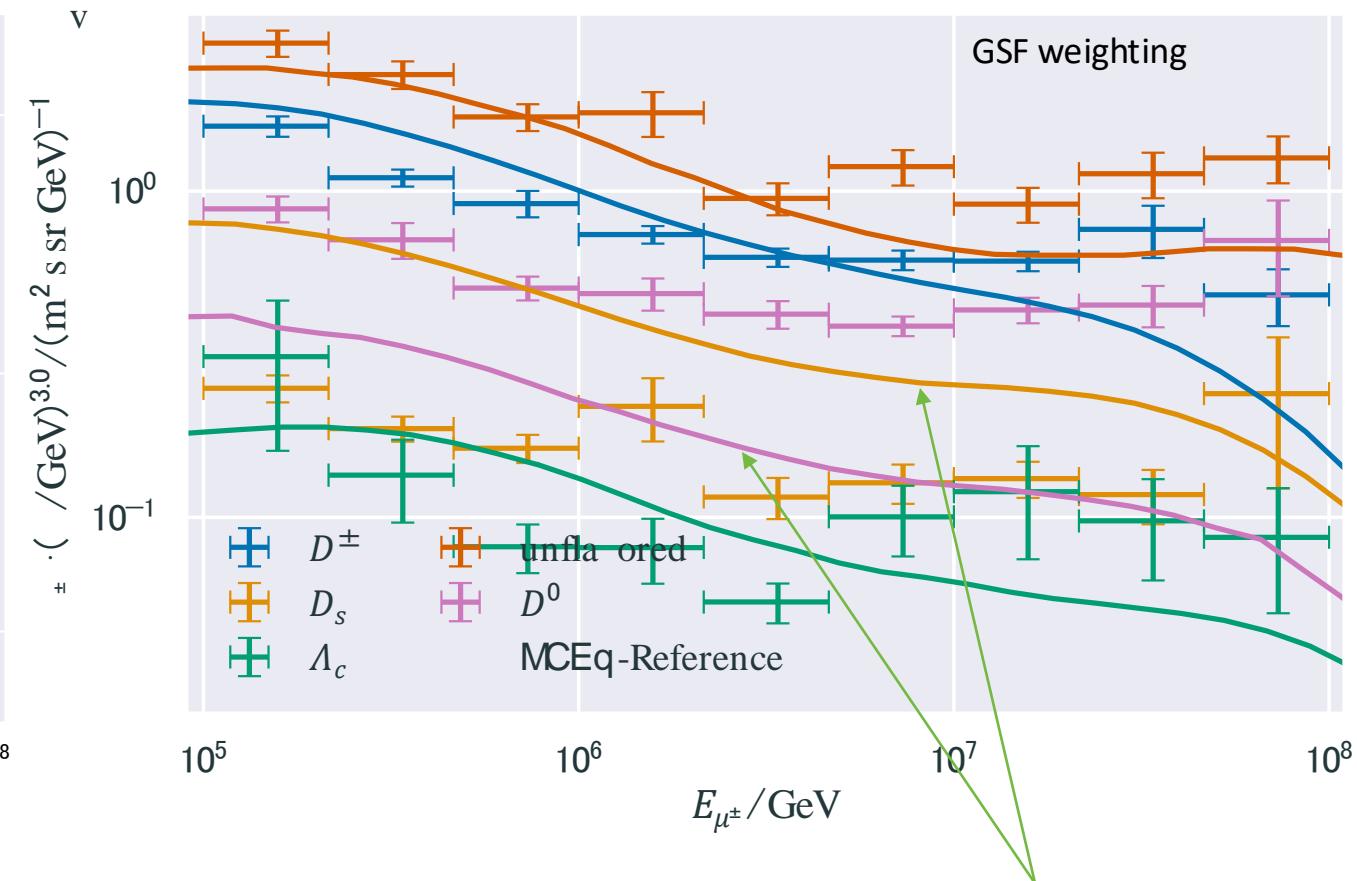
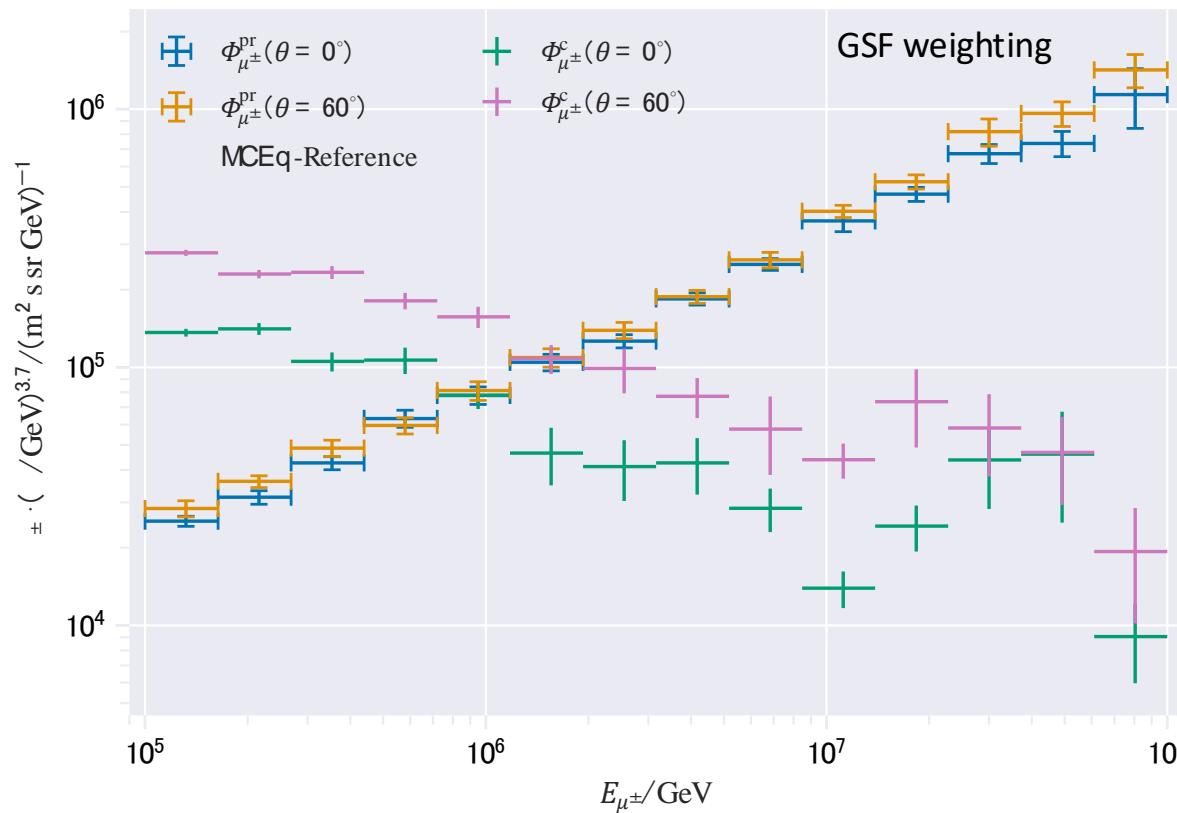


New CORSIKA simulation

with extended history option for information about the parent particles

CORSIKA 7 tagging and MCEq comparison

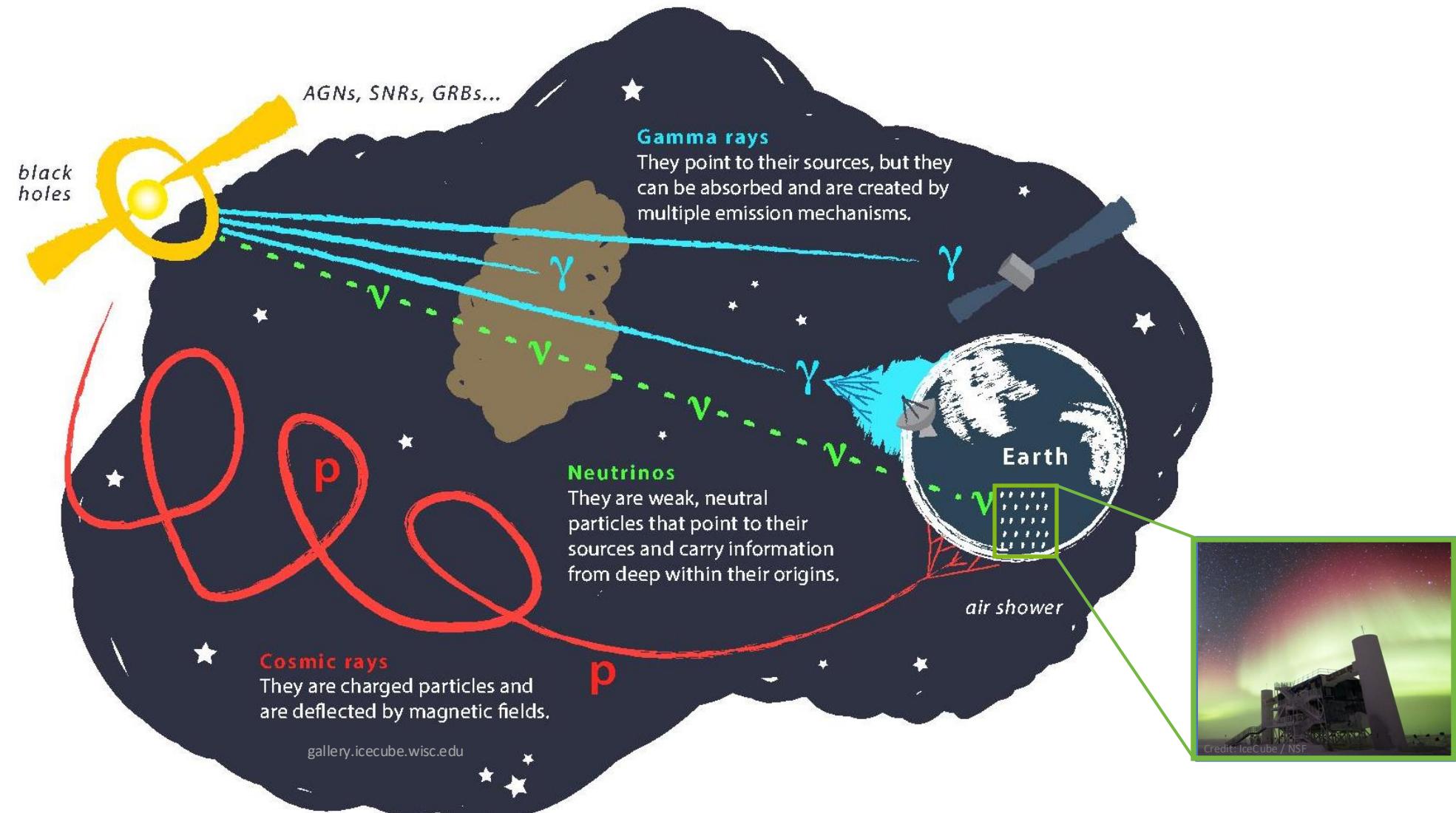
MCEq: tool to numerically solve the cascade equations that describes the evolution of particle densities as they propagate through a gaseous, dense medium
<https://github.com/mceq-project/MCEq>



➤ 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

