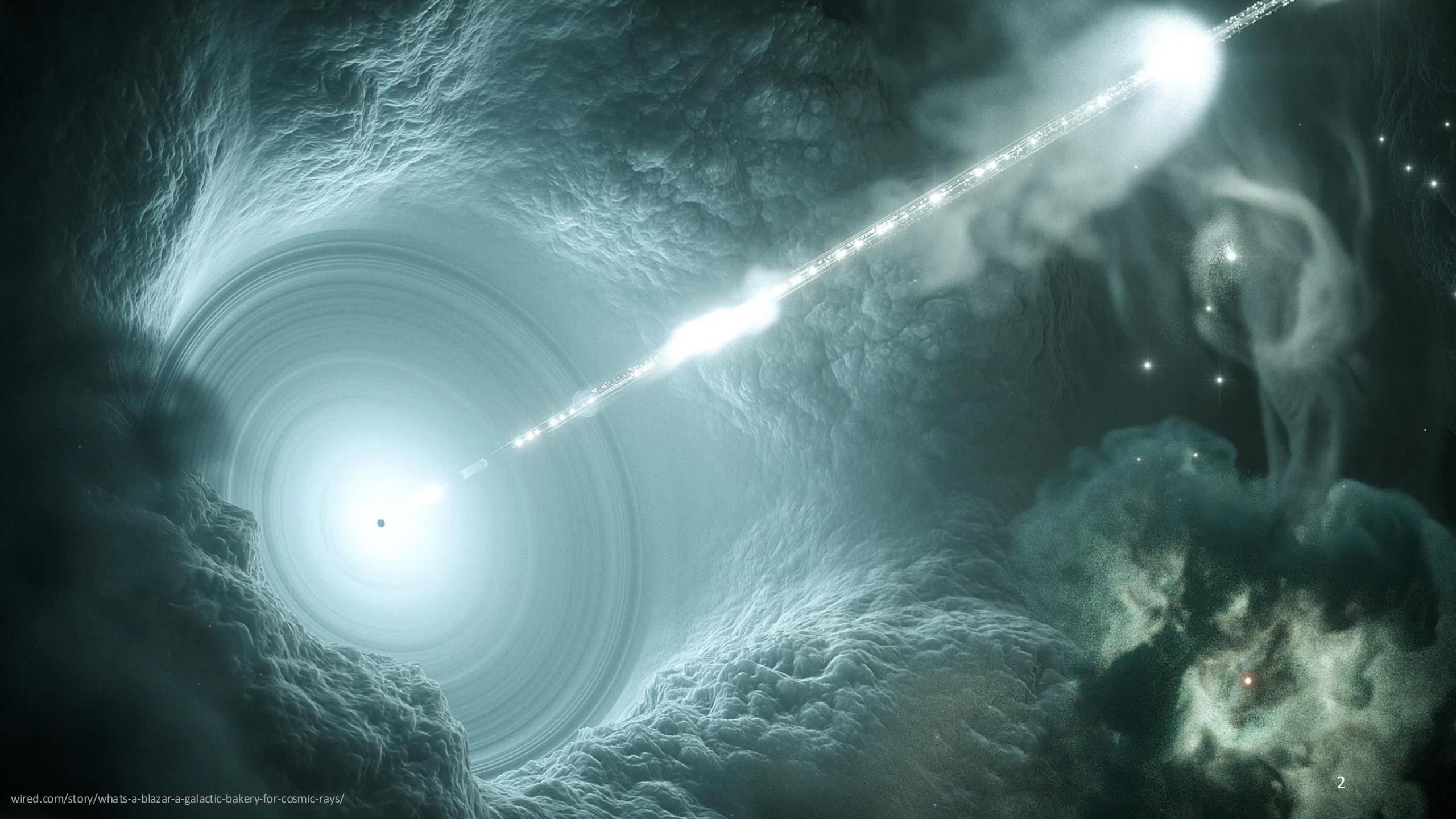
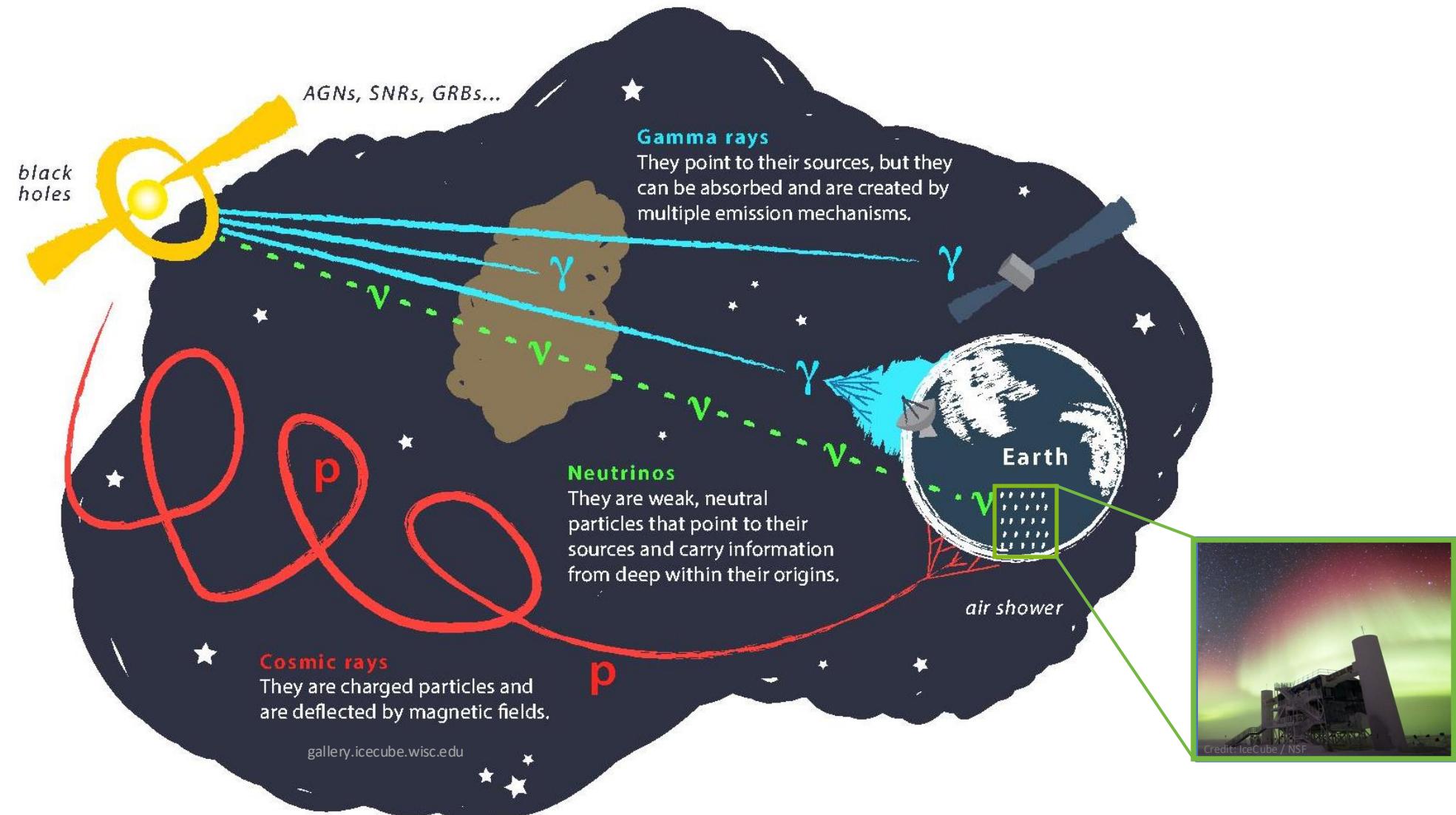


From IceCube to Sky: A Deep Dive into Prompt Muon Mysteries

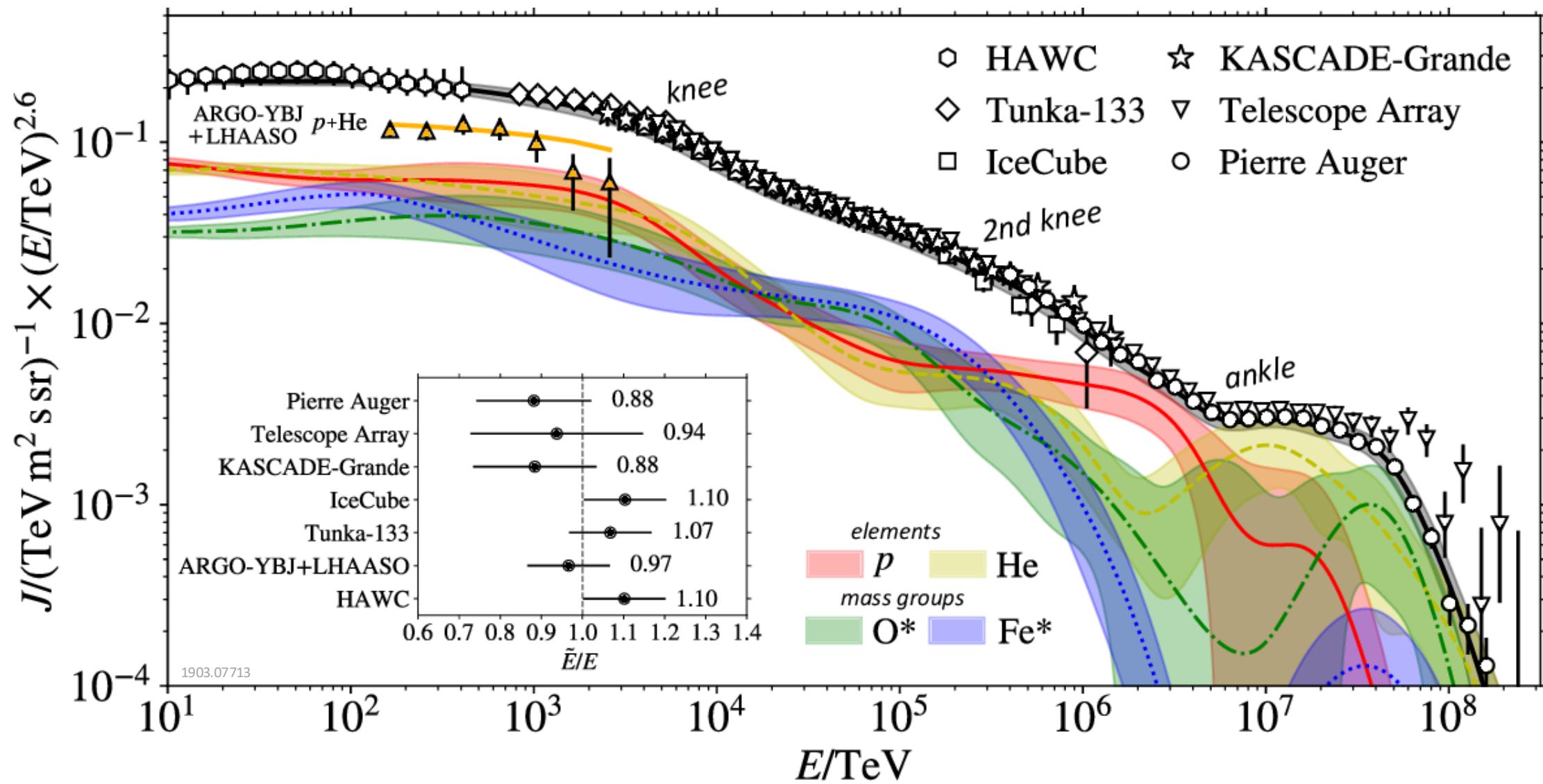
Pascal Gutjahr



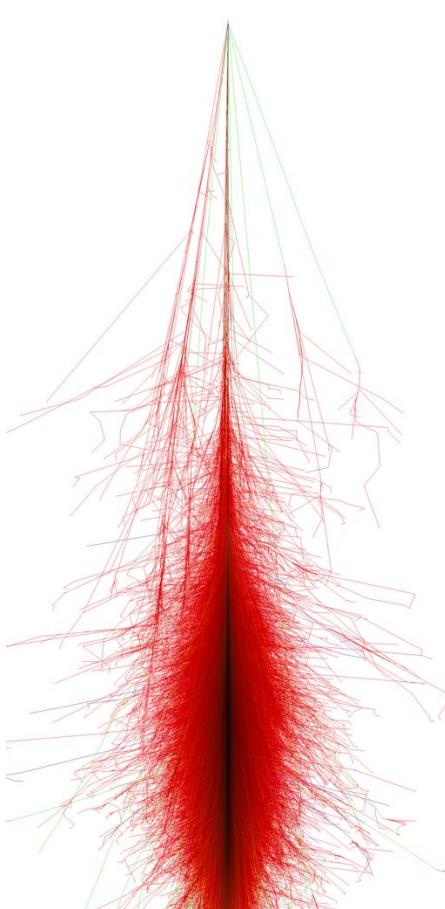
Astroparticle physics



Cosmic ray flux

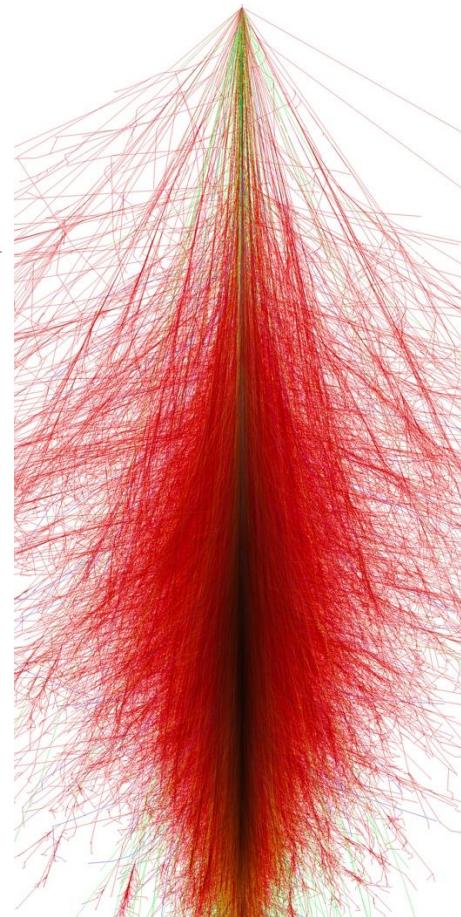


Air shower – 10 TeV

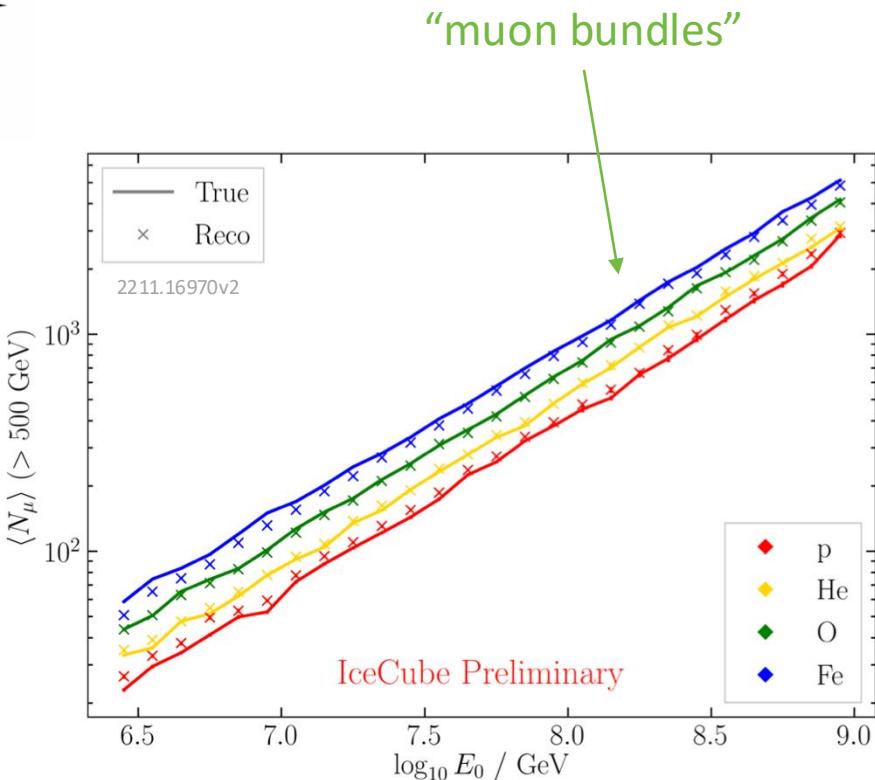
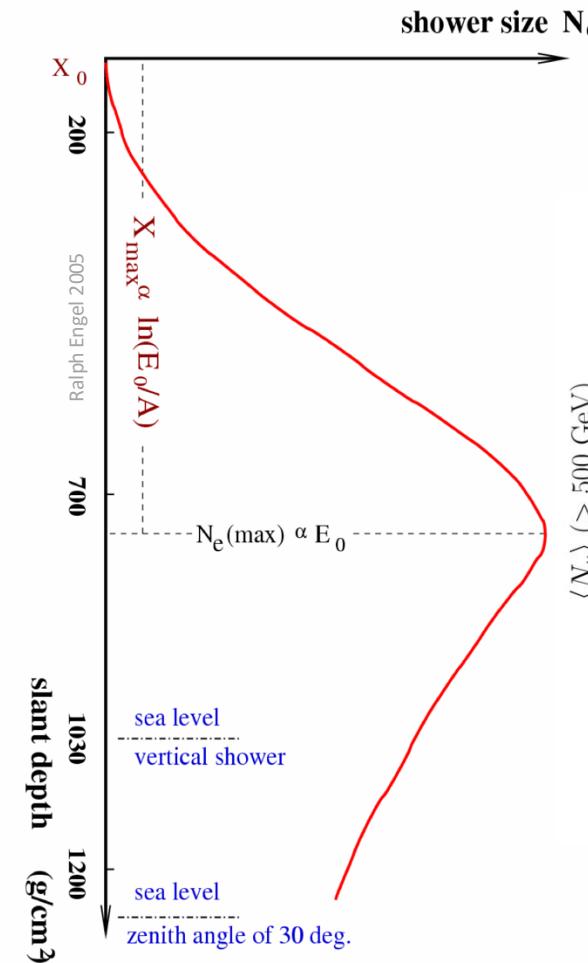


Proton

zeuthen.desy.de



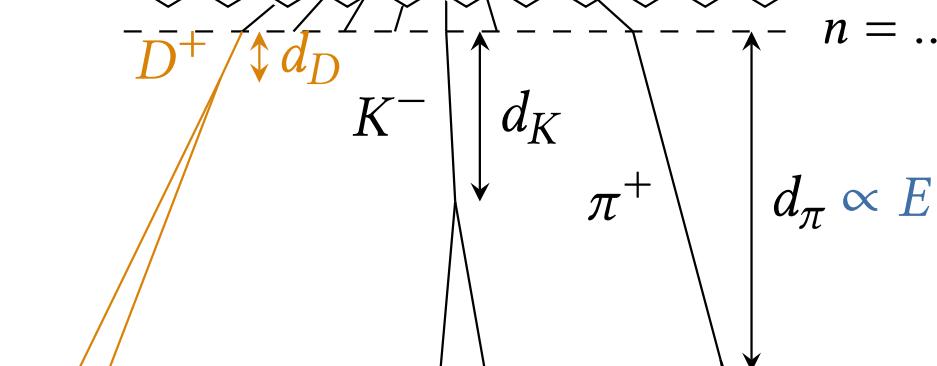
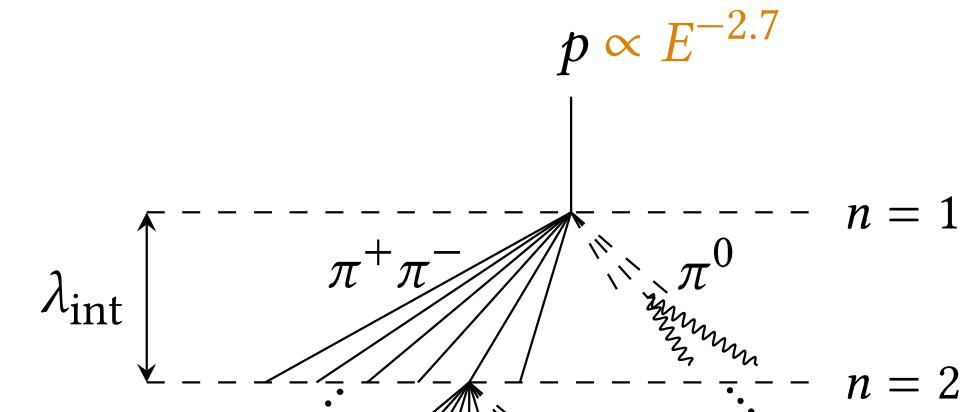
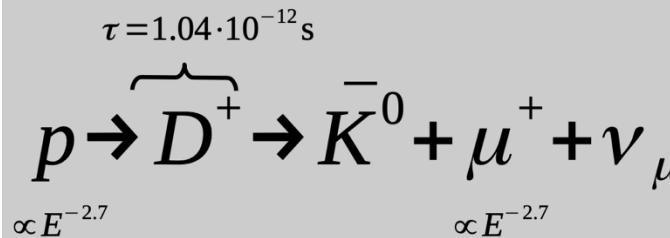
Iron



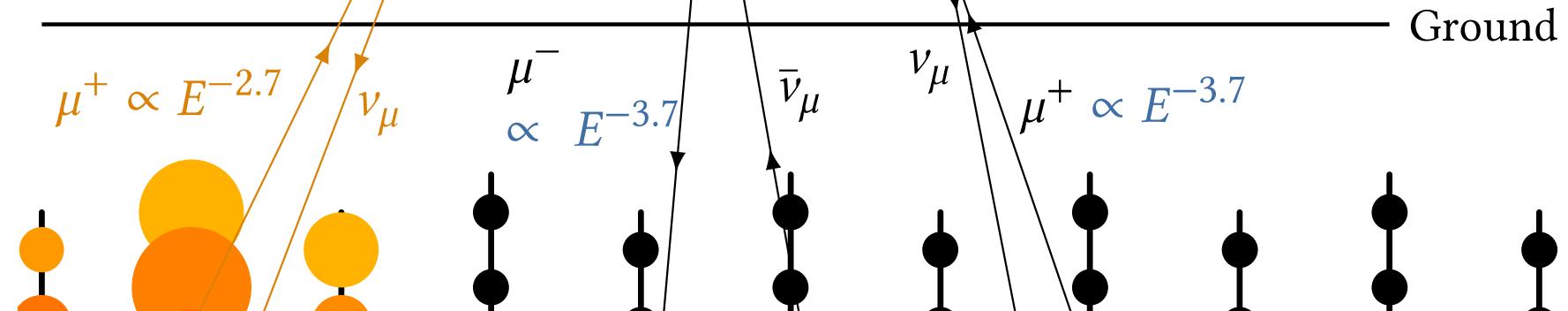
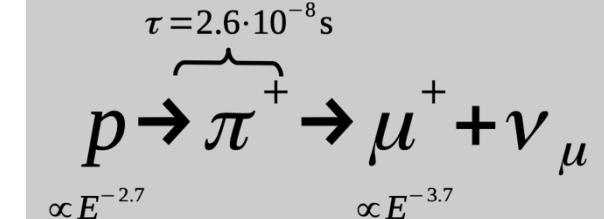
Muon flux

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

prompt component:

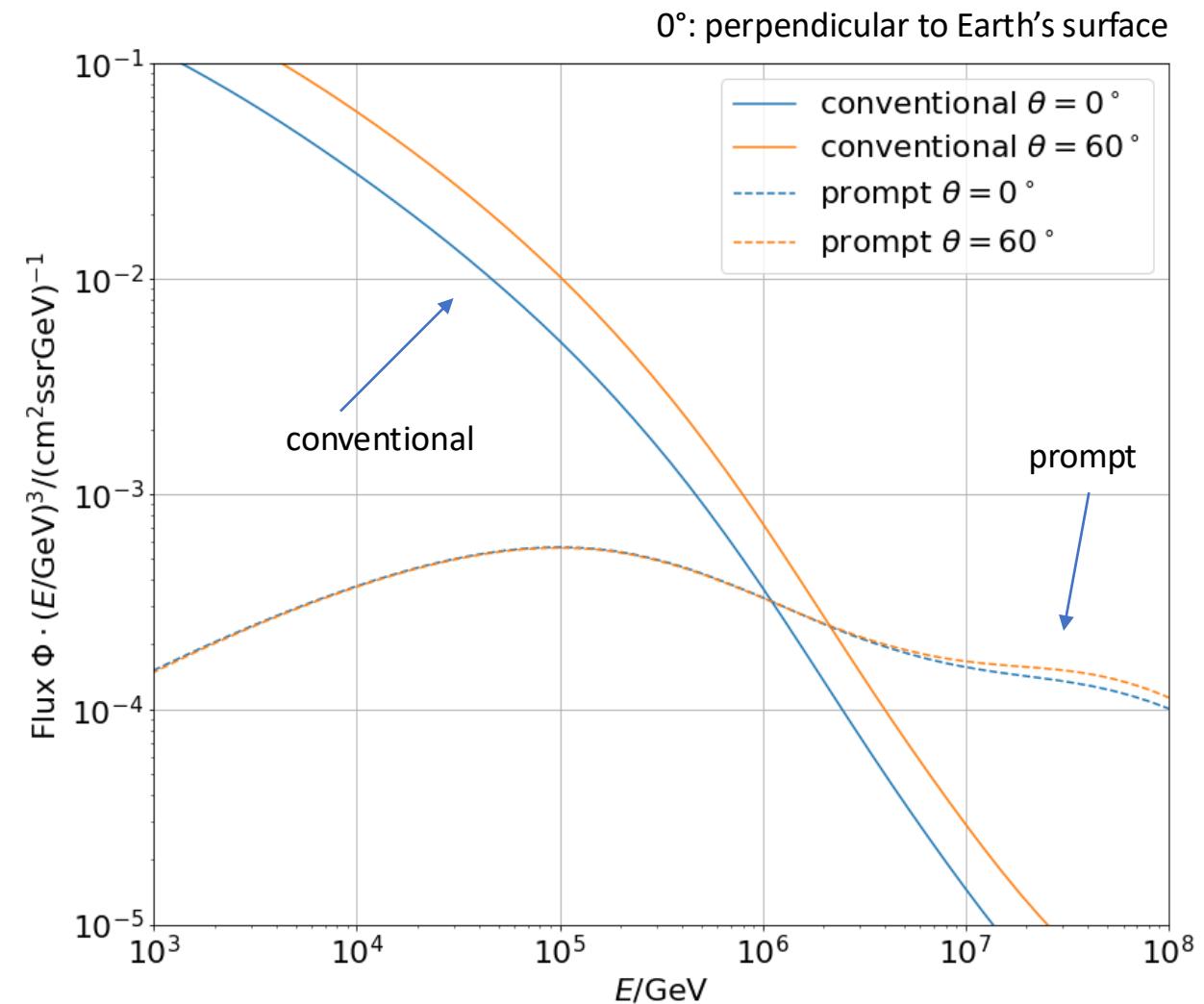
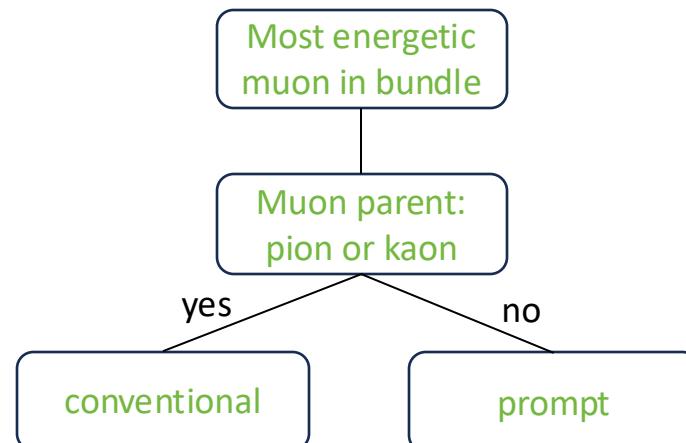
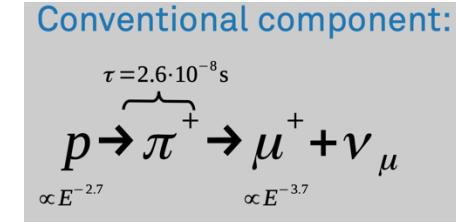
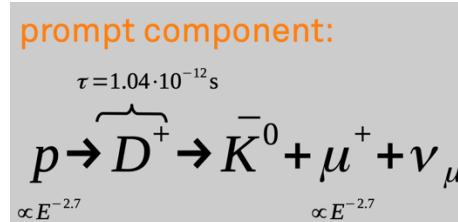


Conventional component:



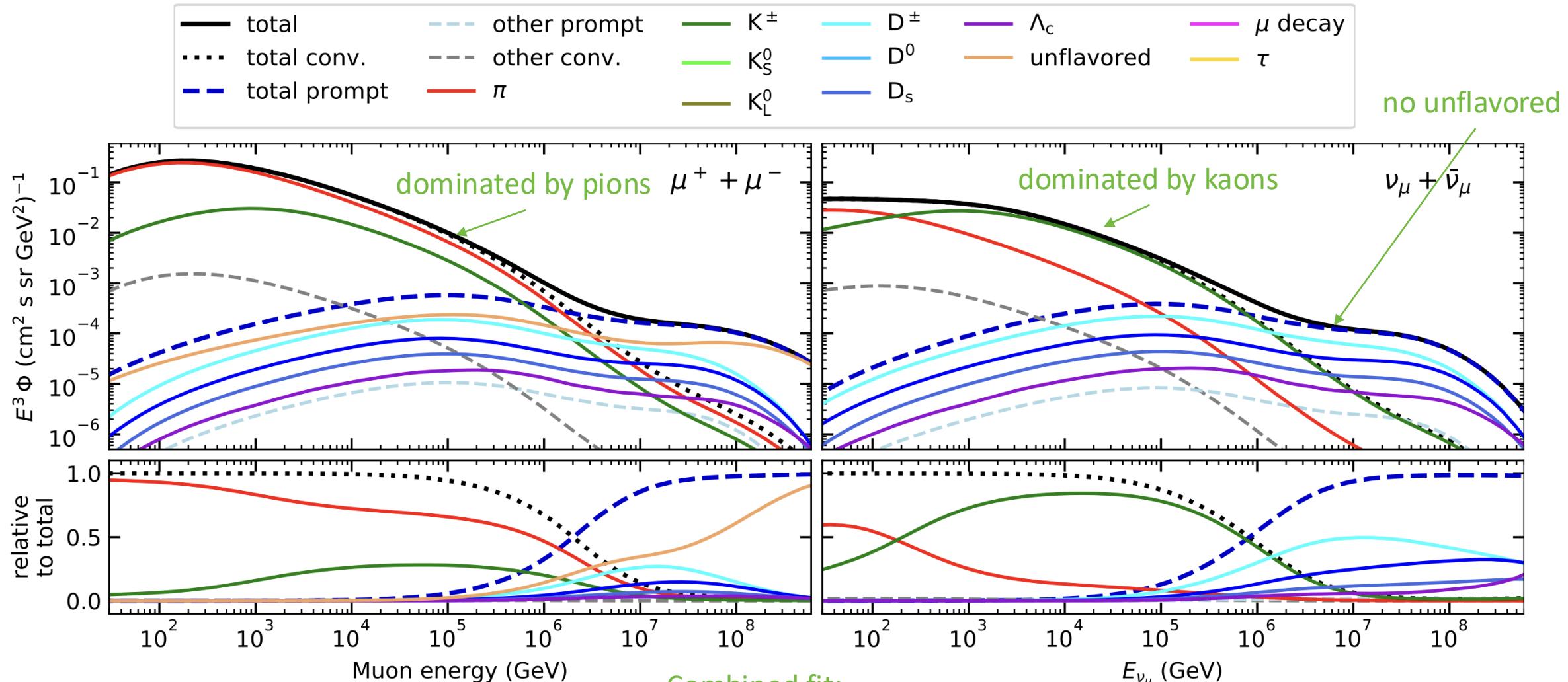
Muon flux: Prompt spectrum

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



Prompt atmospheric muons and neutrinos

10.1103/PhysRevD.100.103018



Combined fit:

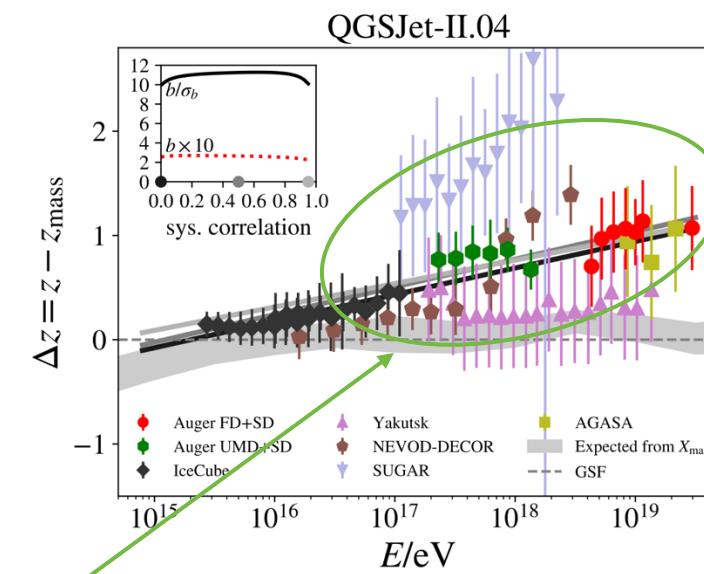
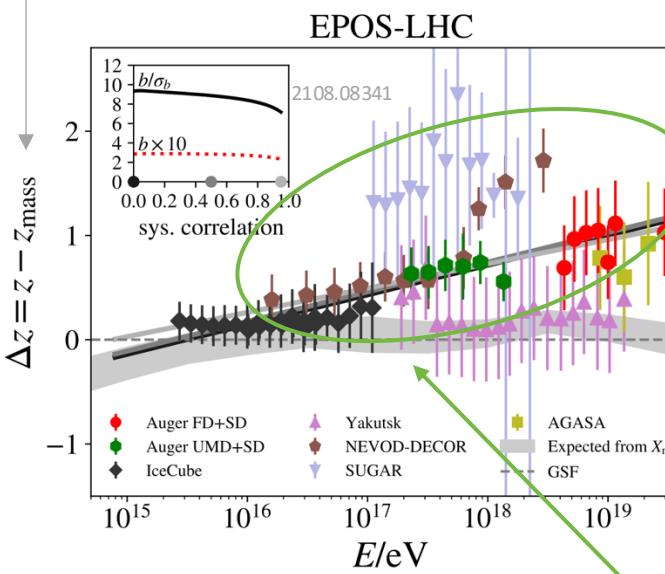
- handle on pion/kaon ratio
- handle on charmed mesons

Muon puzzle and model uncertainties

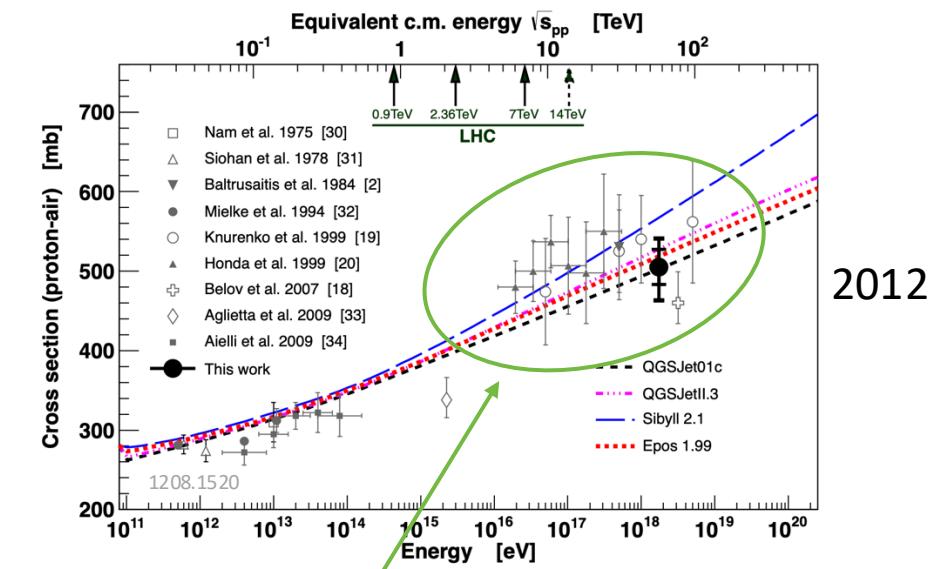
"muon number"

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

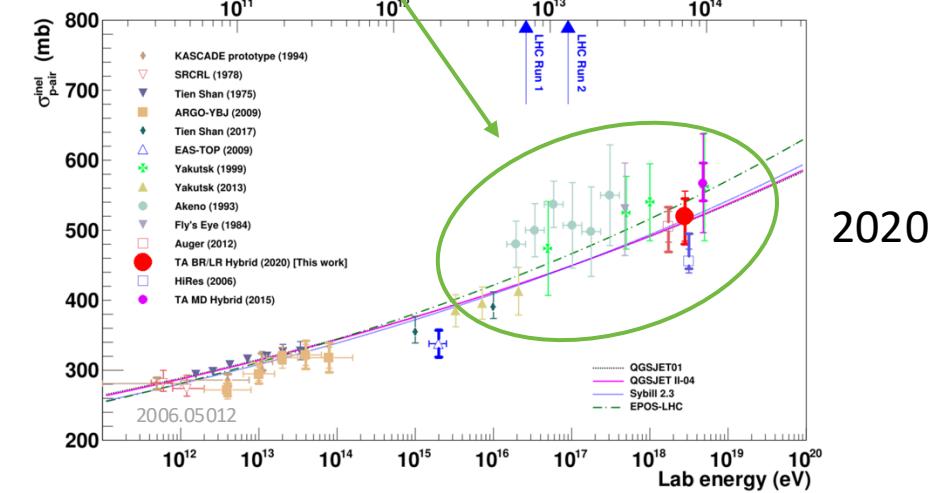
Expected z
("muon number")



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



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



Analysis goals

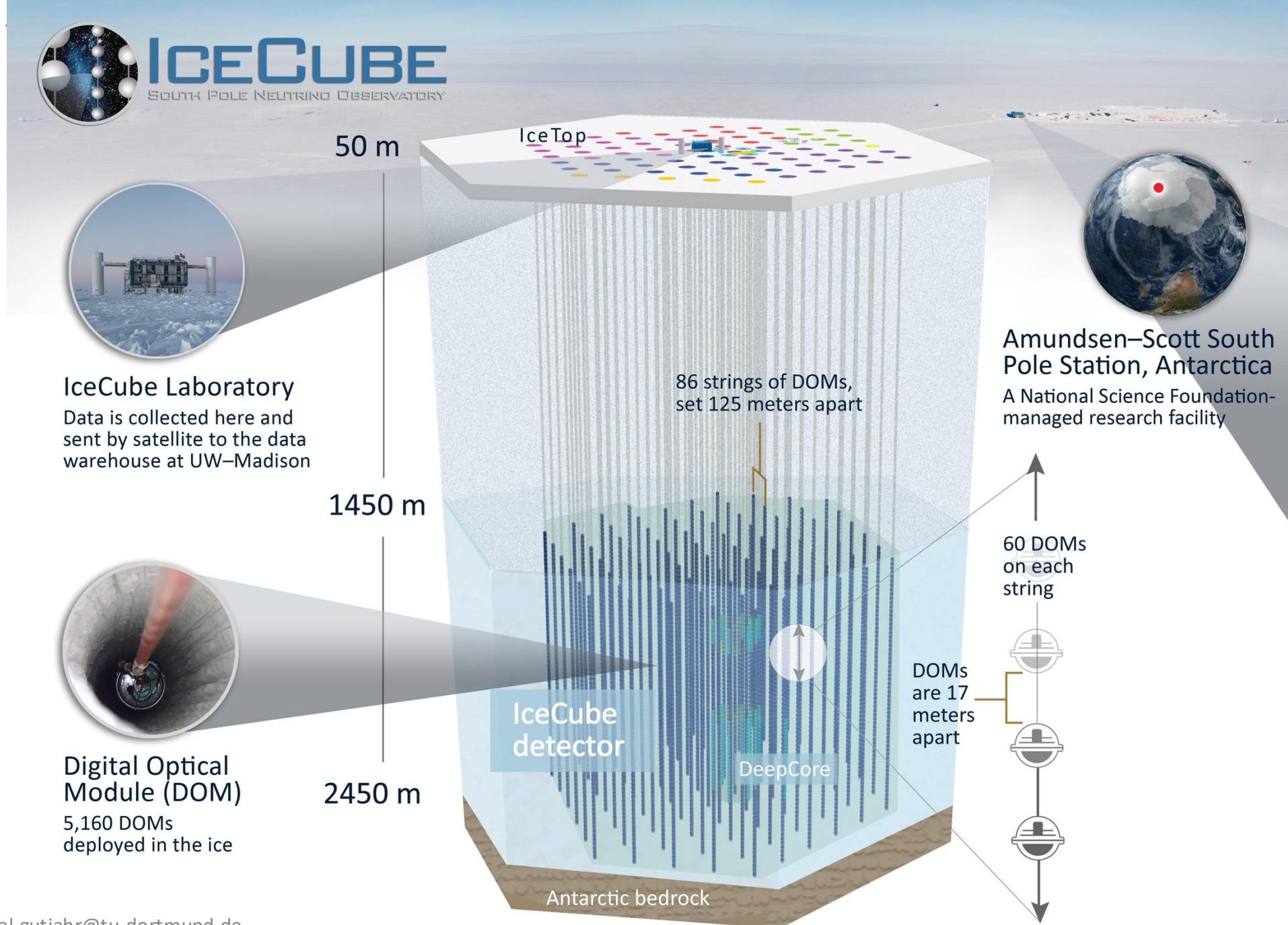
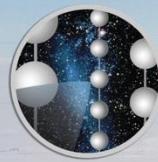
- 1) Detect prompt component of the atmospheric muon flux
 - Measure the normalization
 - Get handle on hadronic interaction models
- 2) Unfold a muon energy spectrum

Idea:

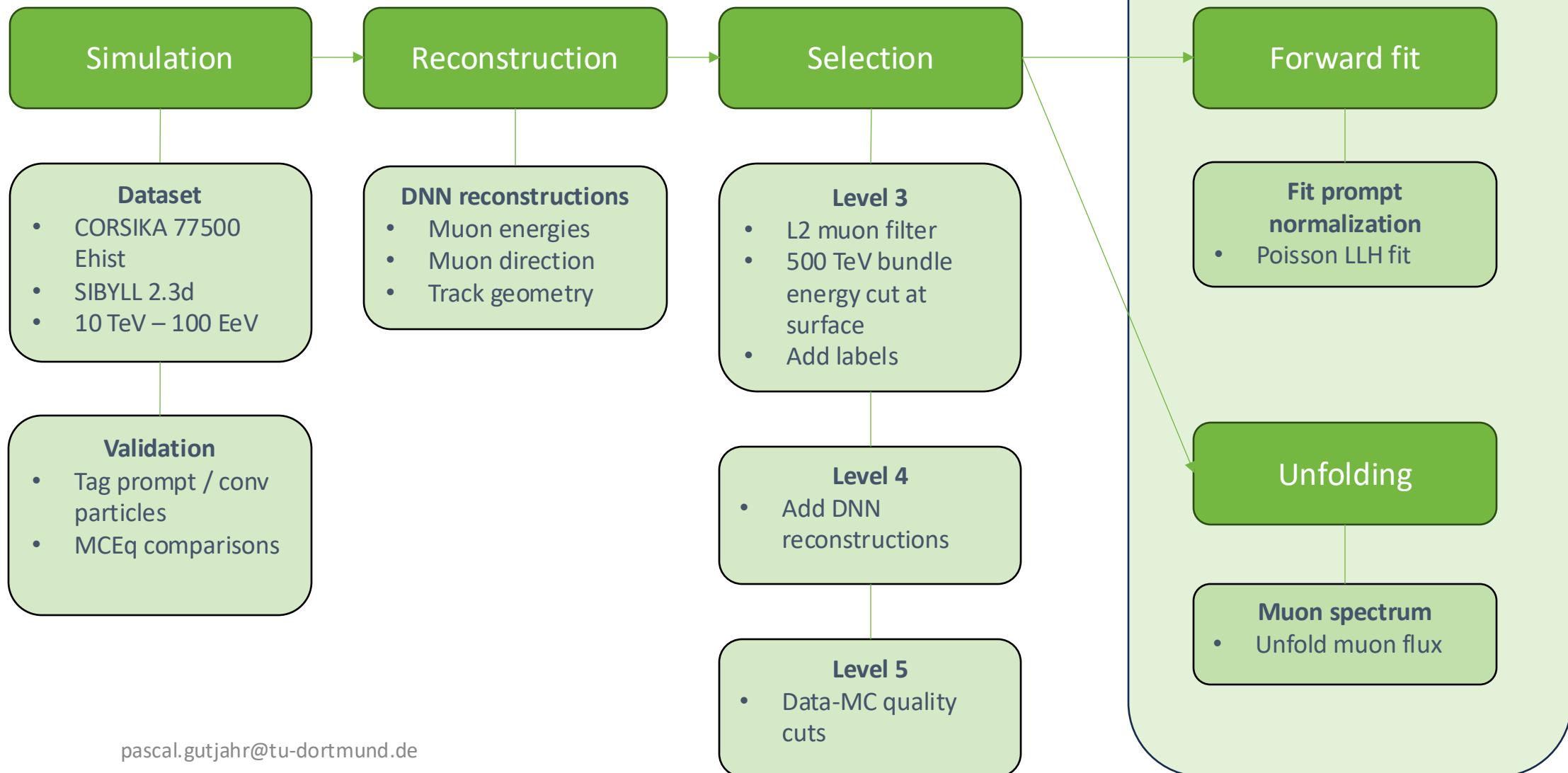
- New CORSIKA simulations with extended history
- Tag muons by parent → prompt or conventional
- Scale amount of prompt particles
 - Scaling saves time and resources instead of doing multiple simulations with different interaction models
 - Perform forward fit of the prompt normalization

Future:

- Measure prompt neutrinos
- Combined muon and neutrino fit → pion/kaon ratio



Overview

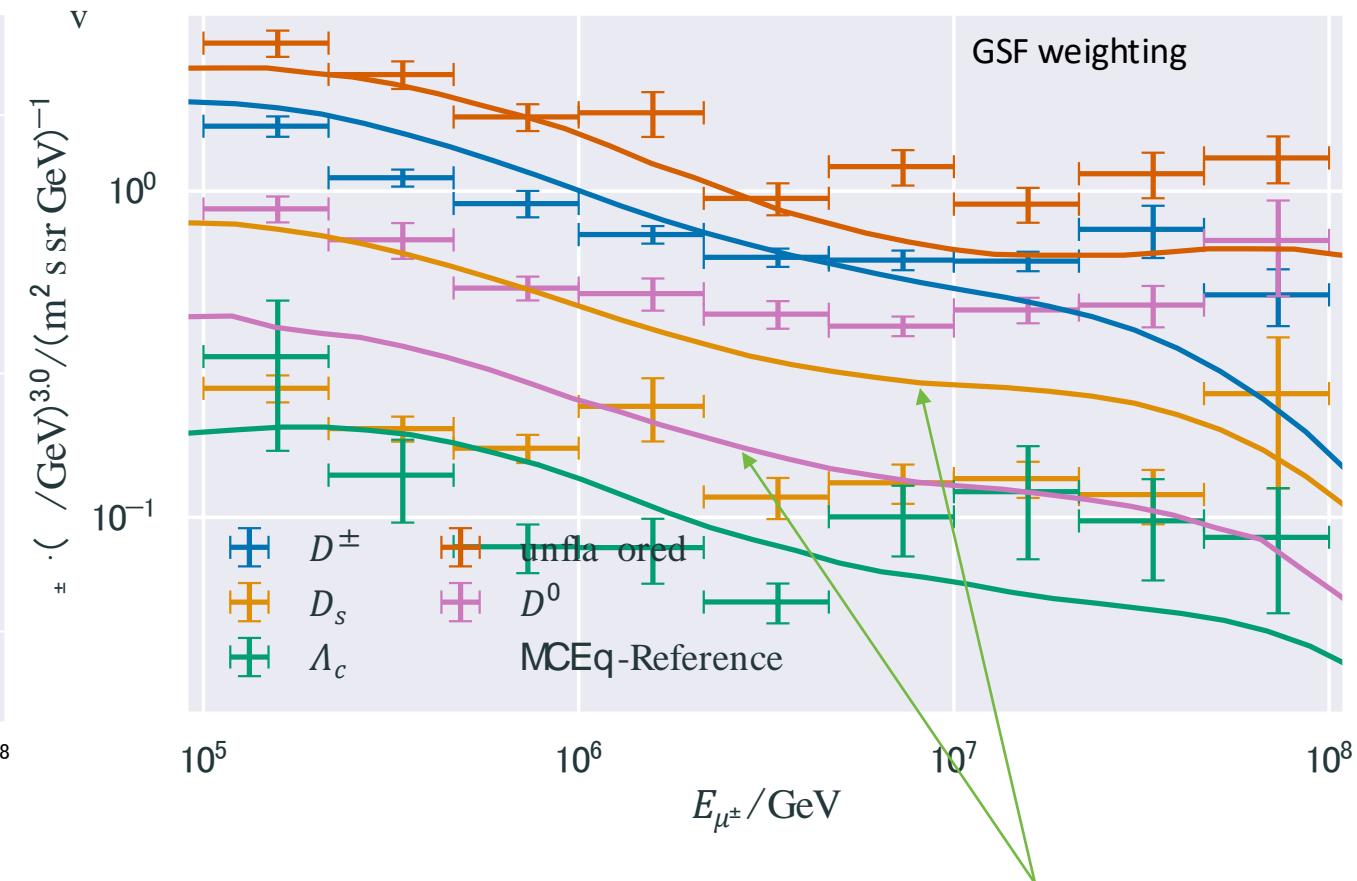
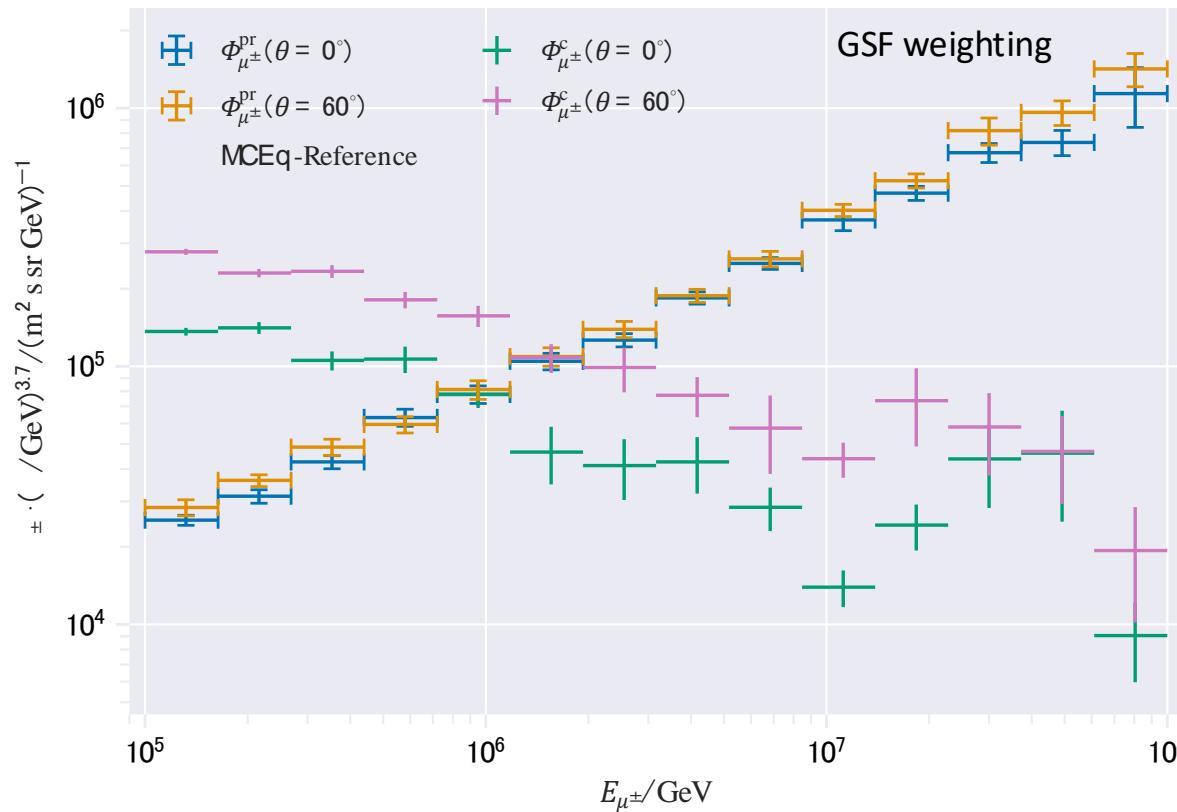


New CORSIKA simulation

with extended history option for information about the parent particles

CORSIKA 7 tagging and MCEq comparison

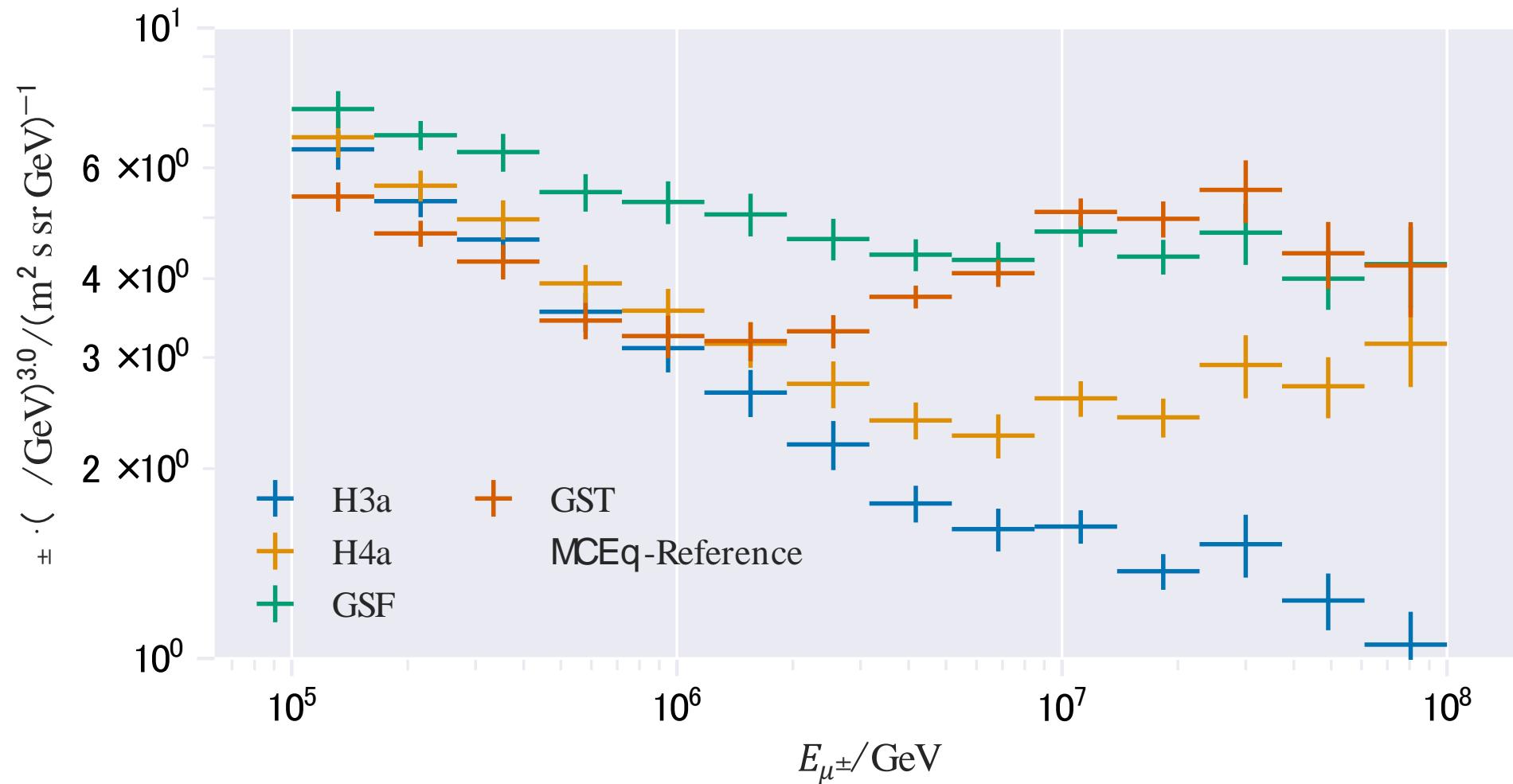
MCEq: tool to numerically solve the cascade equations that describes the evolution of particle densities as they propagate through a gaseous, dense medium
<https://github.com/mceq-project/MCEq>



➤ Good agreement in total prompt and conv muon flux

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

Agreement for different primary models

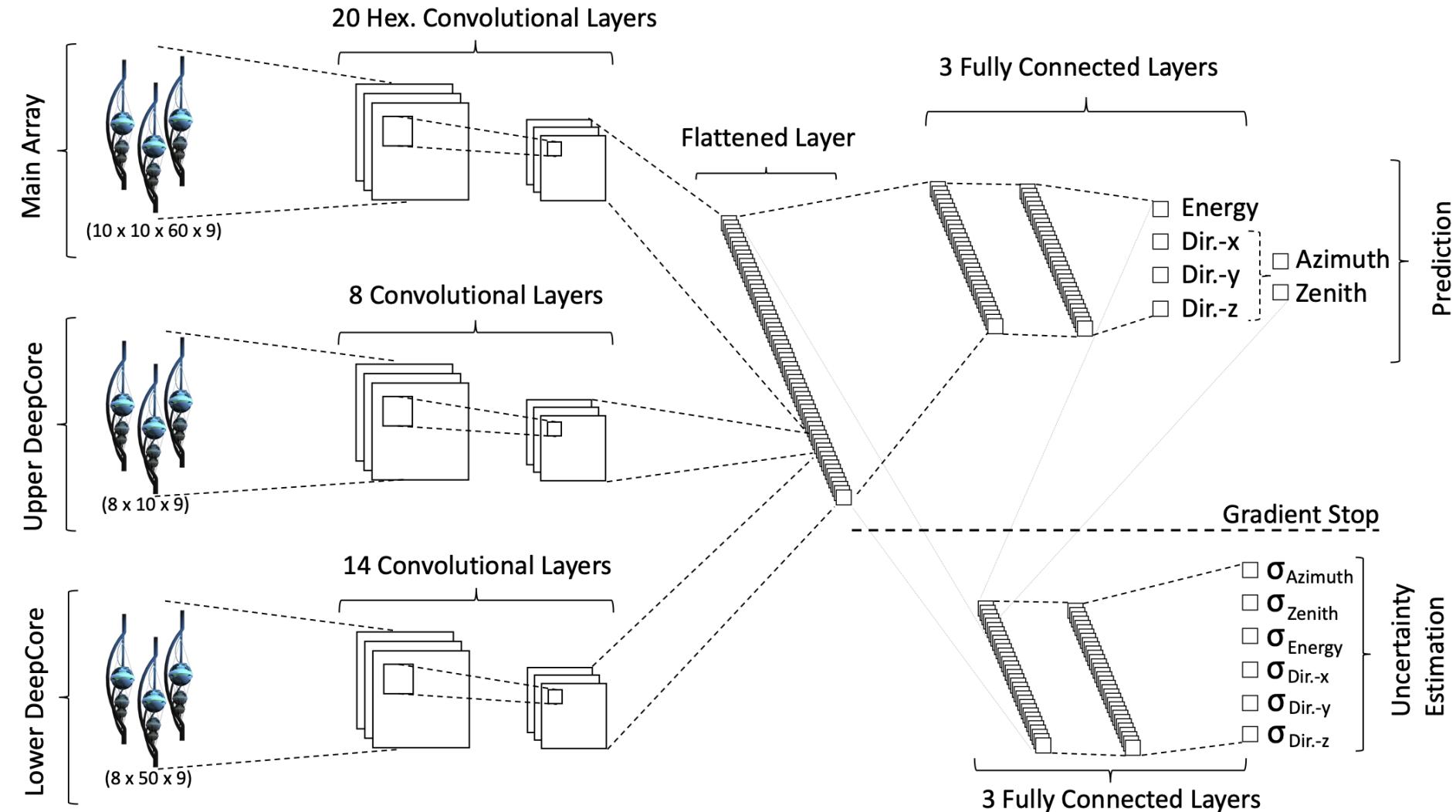


DNN reconstructions

Convolutional Neural Network (CNN)

Machine learning approach:

- fast
- identifying spatial patterns
- better event reconstruction and classification



Input data per DOM

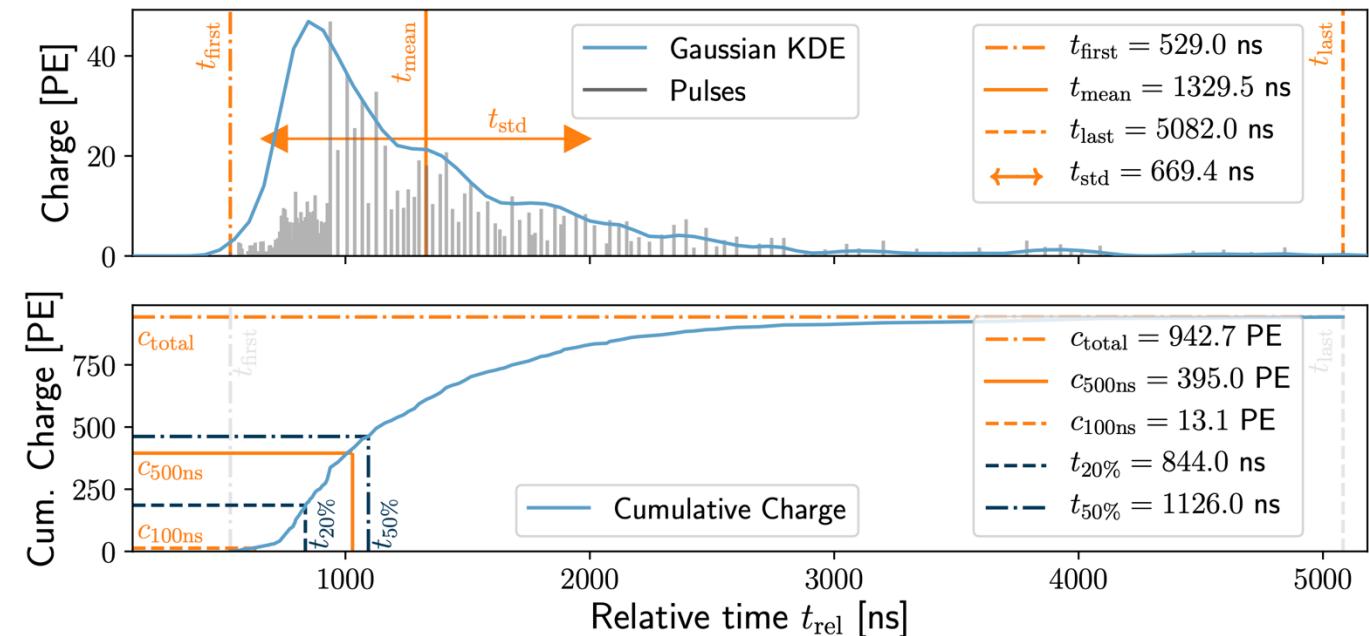
10.1088/1748-0221/16/07/P07041

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

Reconstructed properties

Energy

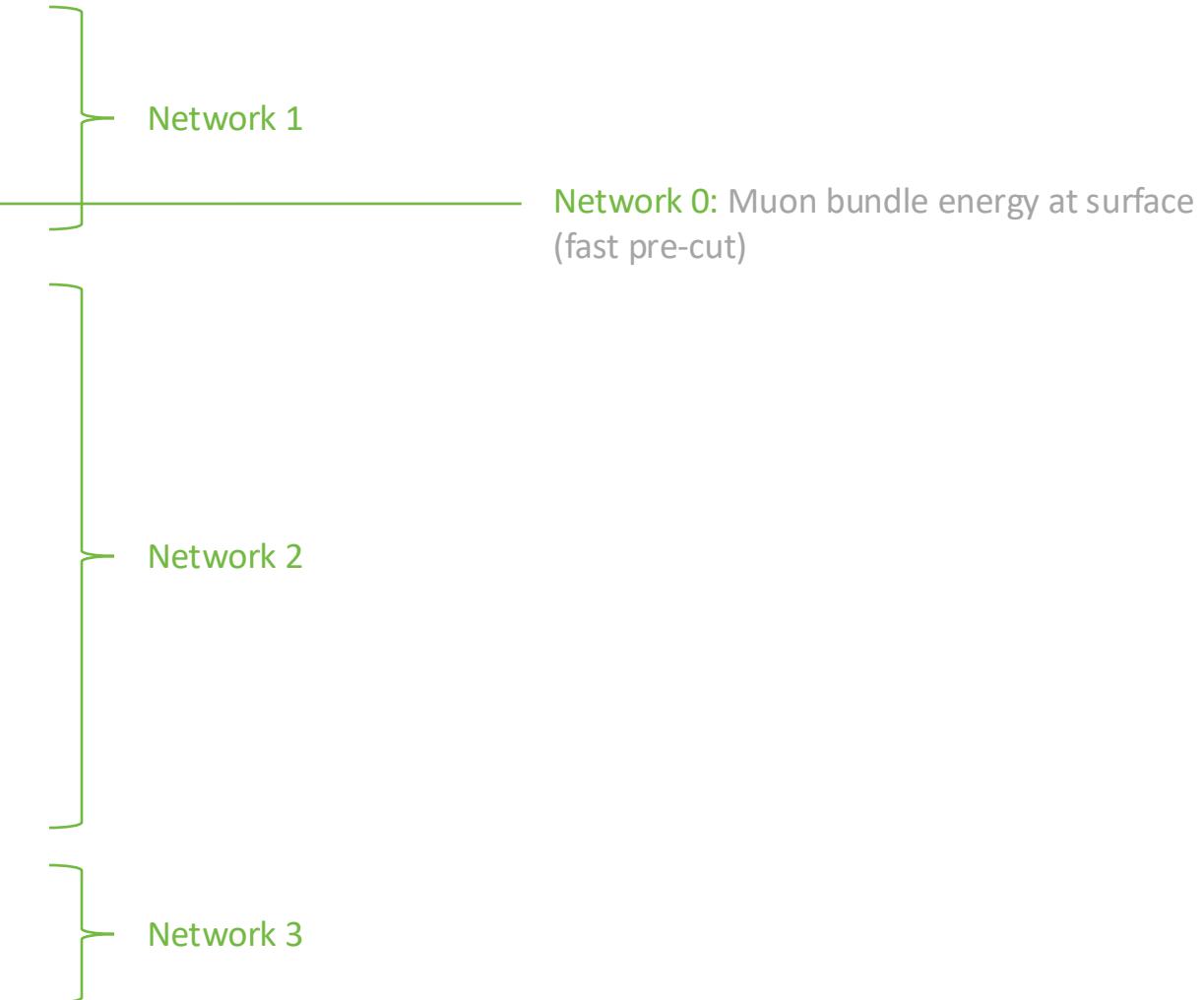
- `entry_energy`: Leading muon energy at the detector entry
- `bundle_energy_at_entry`: Muon bundle energy at the detector entry
- `muon_energy_first_mctree`: Leading muon energy at surface
- `bundle_energy_in_mctree`: Muon bundle energy at surface

Track geometry

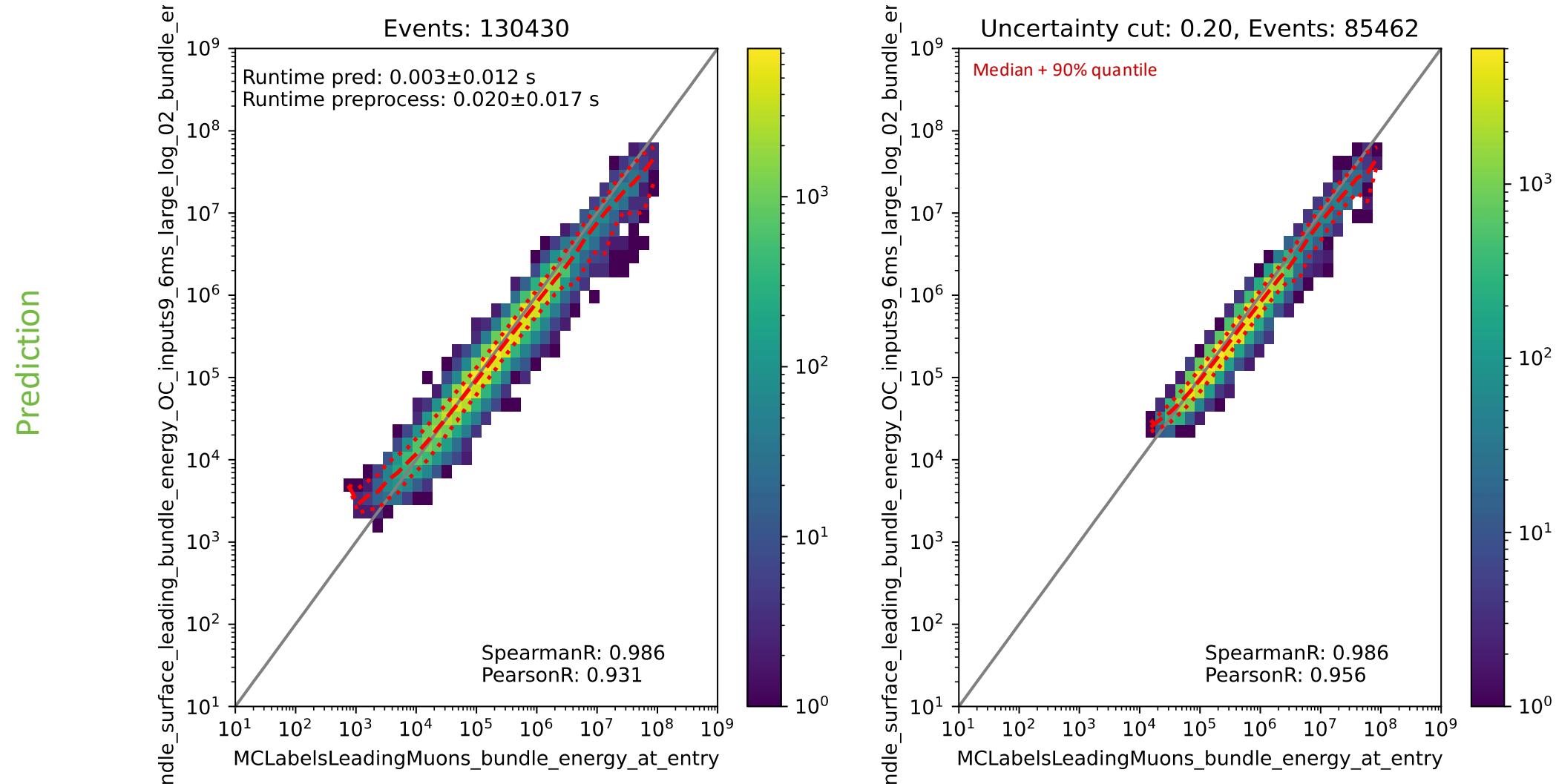
- `Length`: Propagation length of muon in the ice
- `LengthInDetector`: Propagation length of muon in the detector
- `center_pos_x`: Closest x position of muon to center of the detector
- `center_pos_y`: Closest y position of muon to center of the detector
- `center_pos_z`: Closest z position of muon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

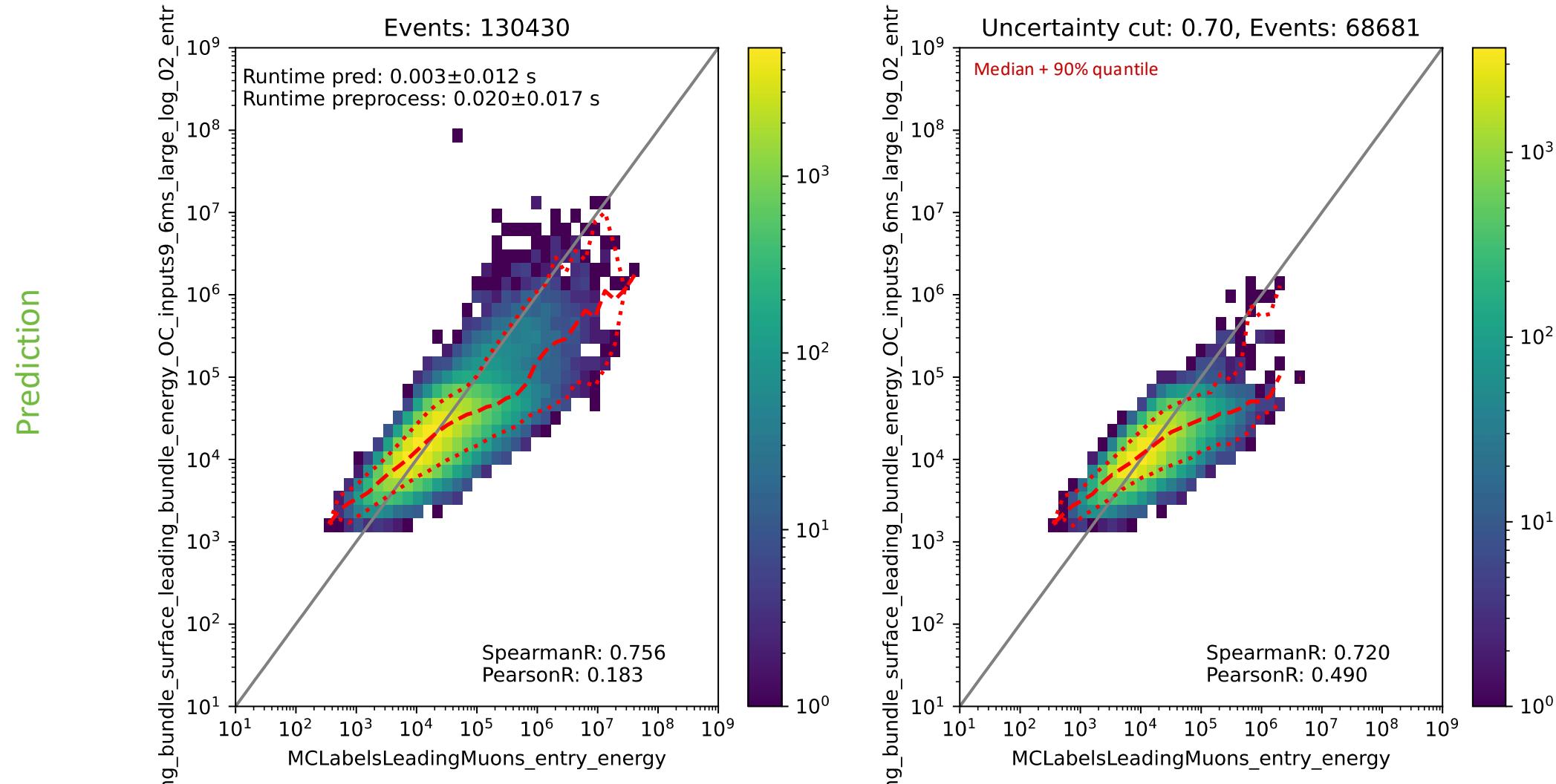
- `zenith`: Zenith angle of muon
- `azimuth`: Azimuth angle of muon



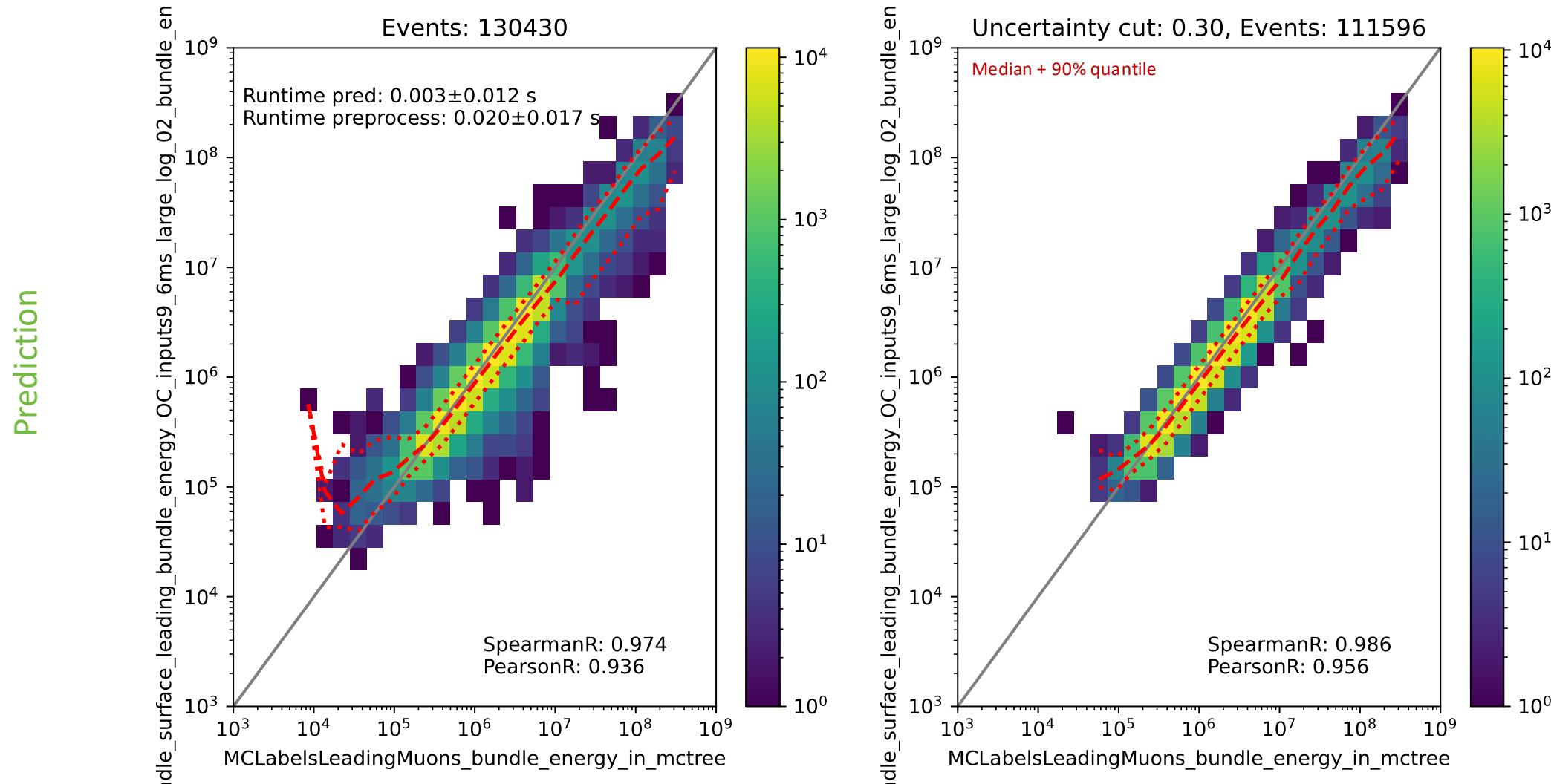
Bundle energy at entry – 6 μ s cleaned pulses



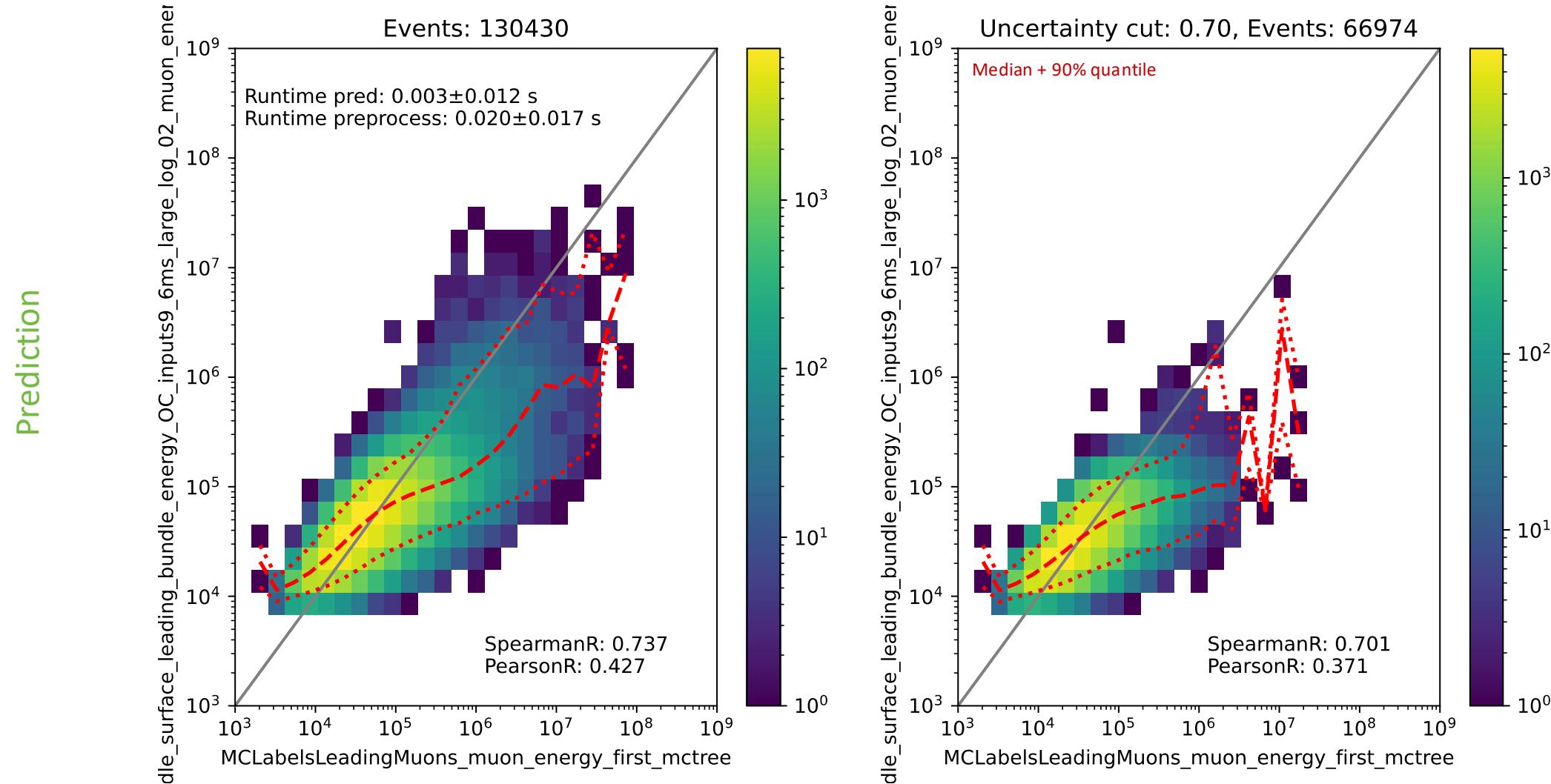
Leading muon energy at entry – 6 μ s cleaned pulses



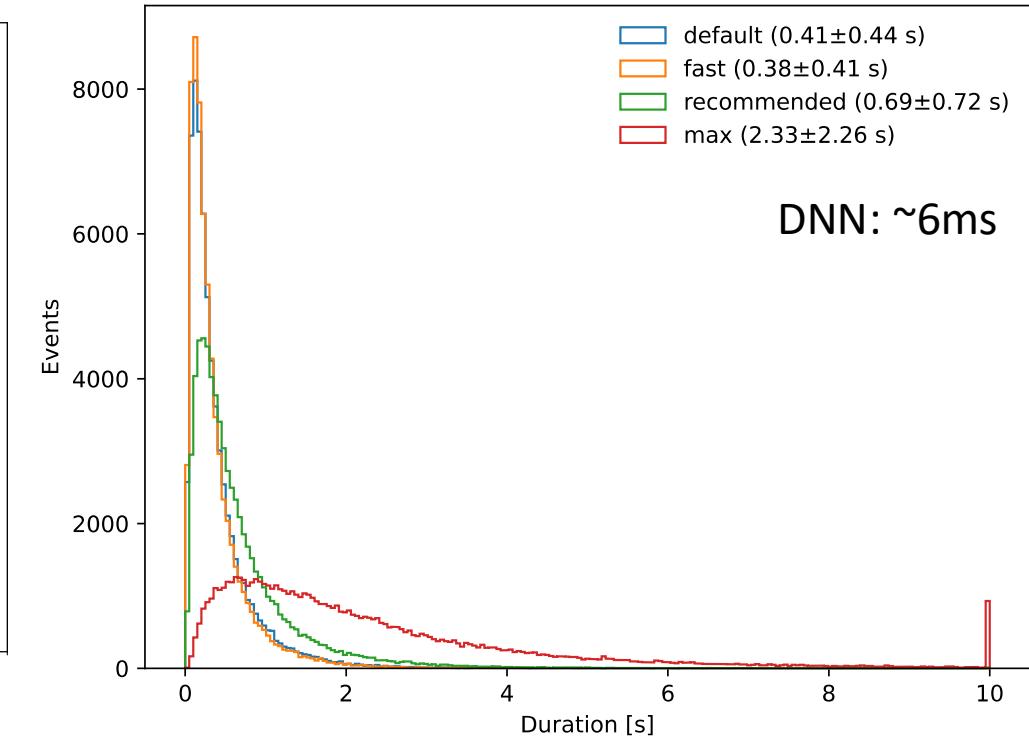
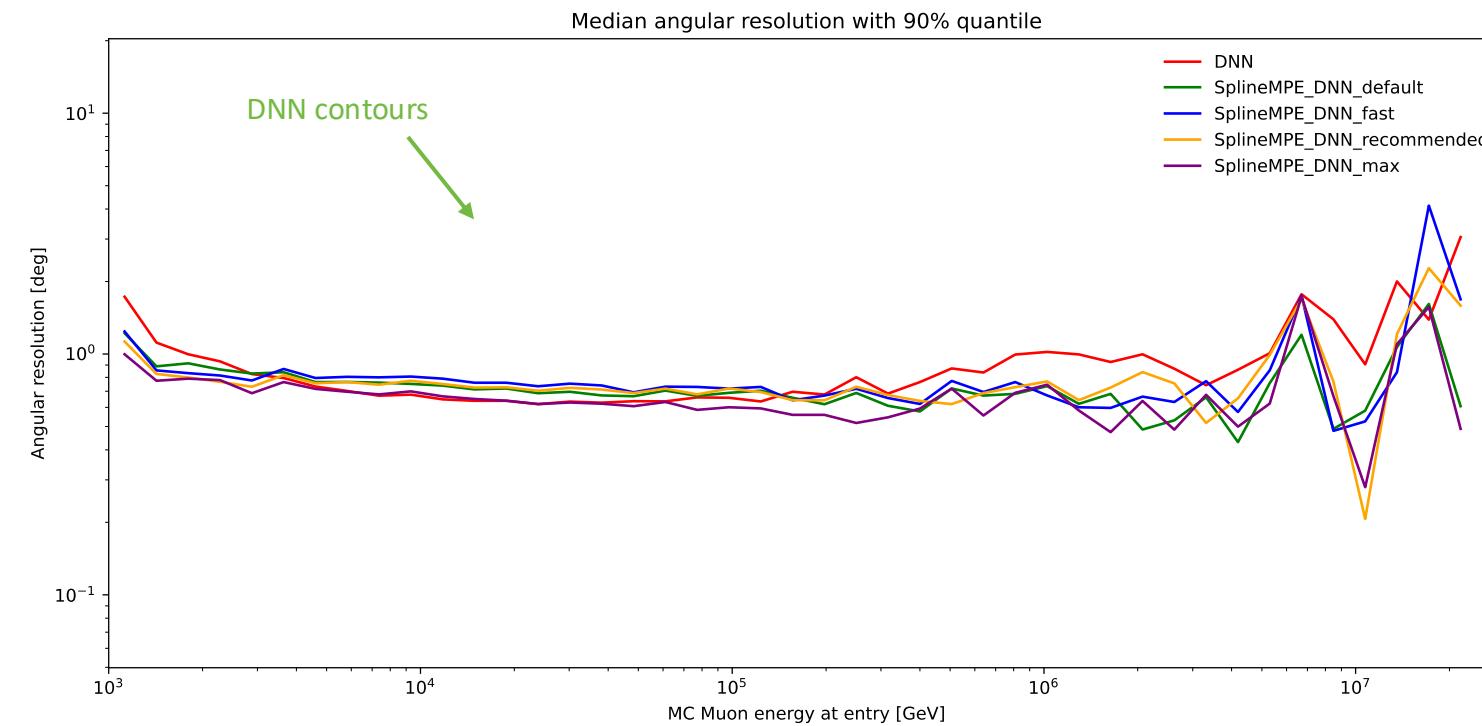
Bundle energy at surface – 6 μ s cleaned pulses



Leading muon energy at surface – 6 μ s cleaned pulses



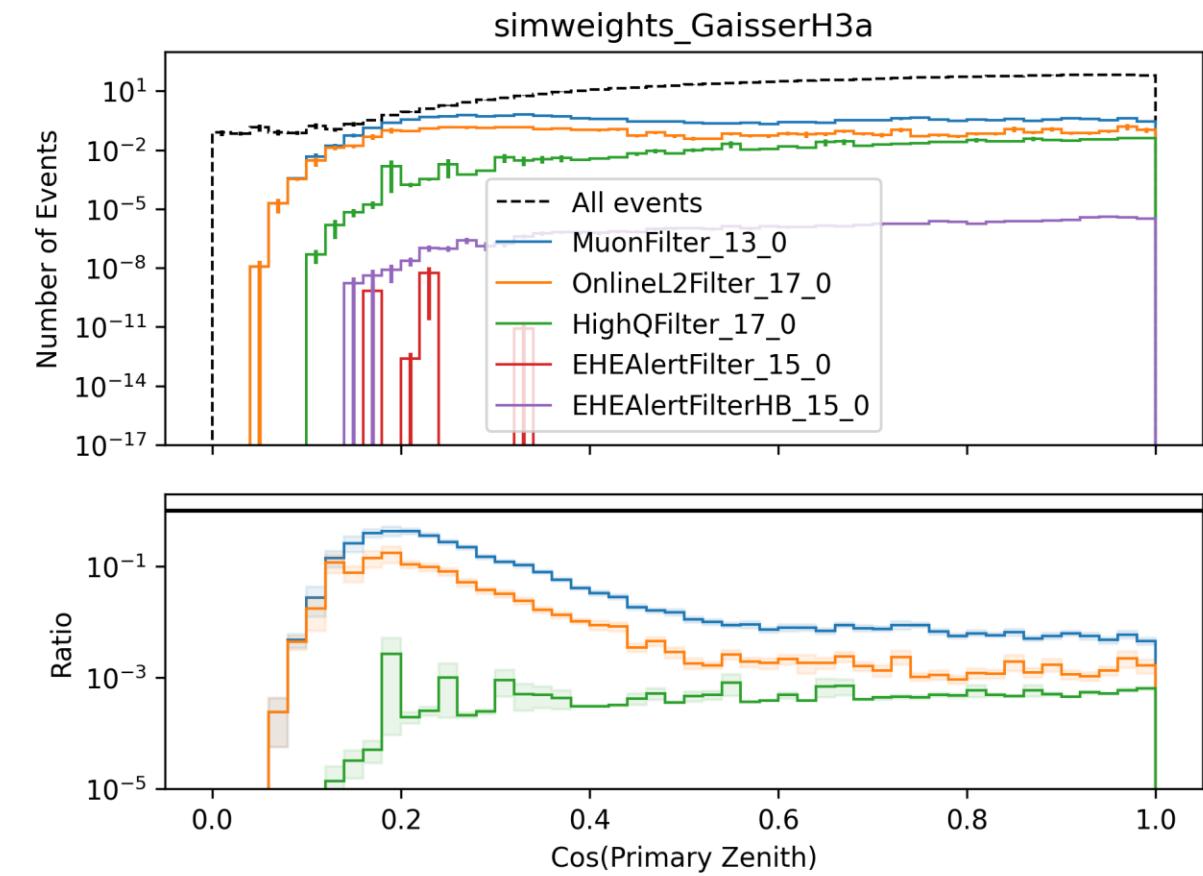
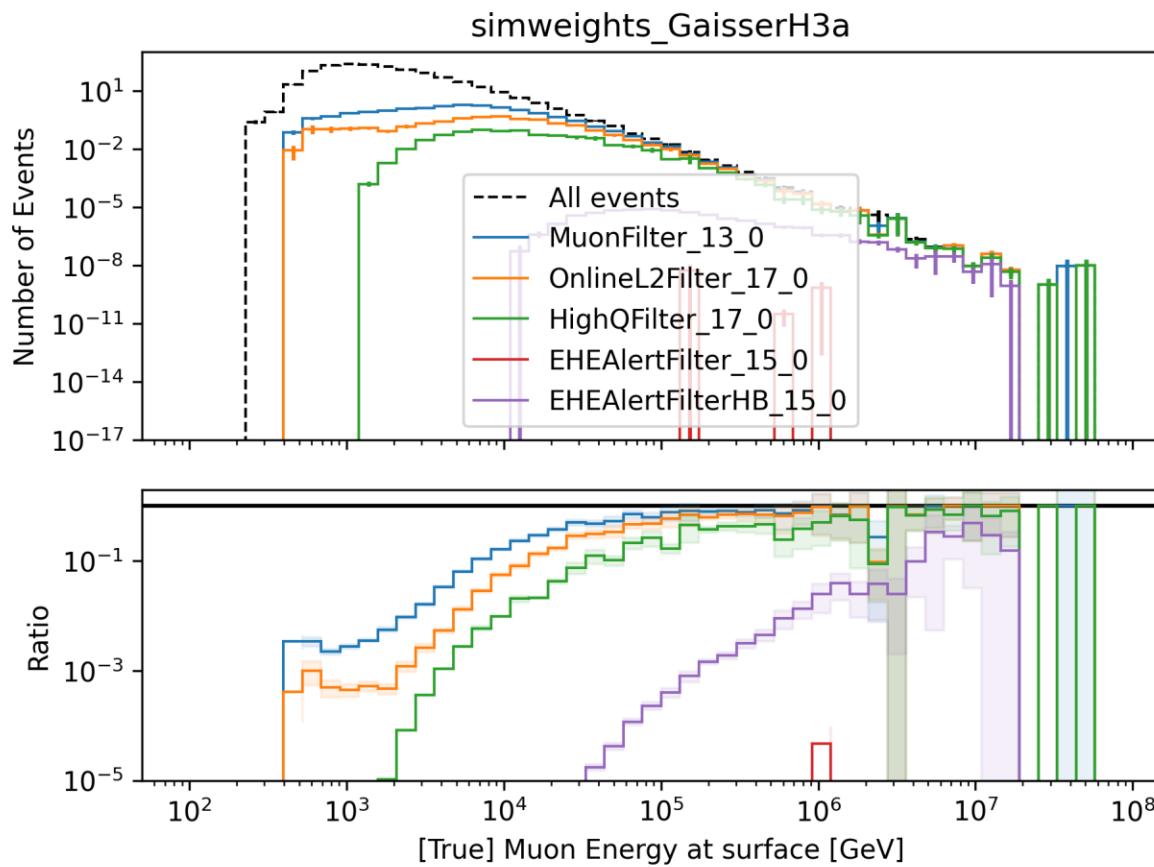
Angular reconstructions: DNN vs. SplineMPE



- 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

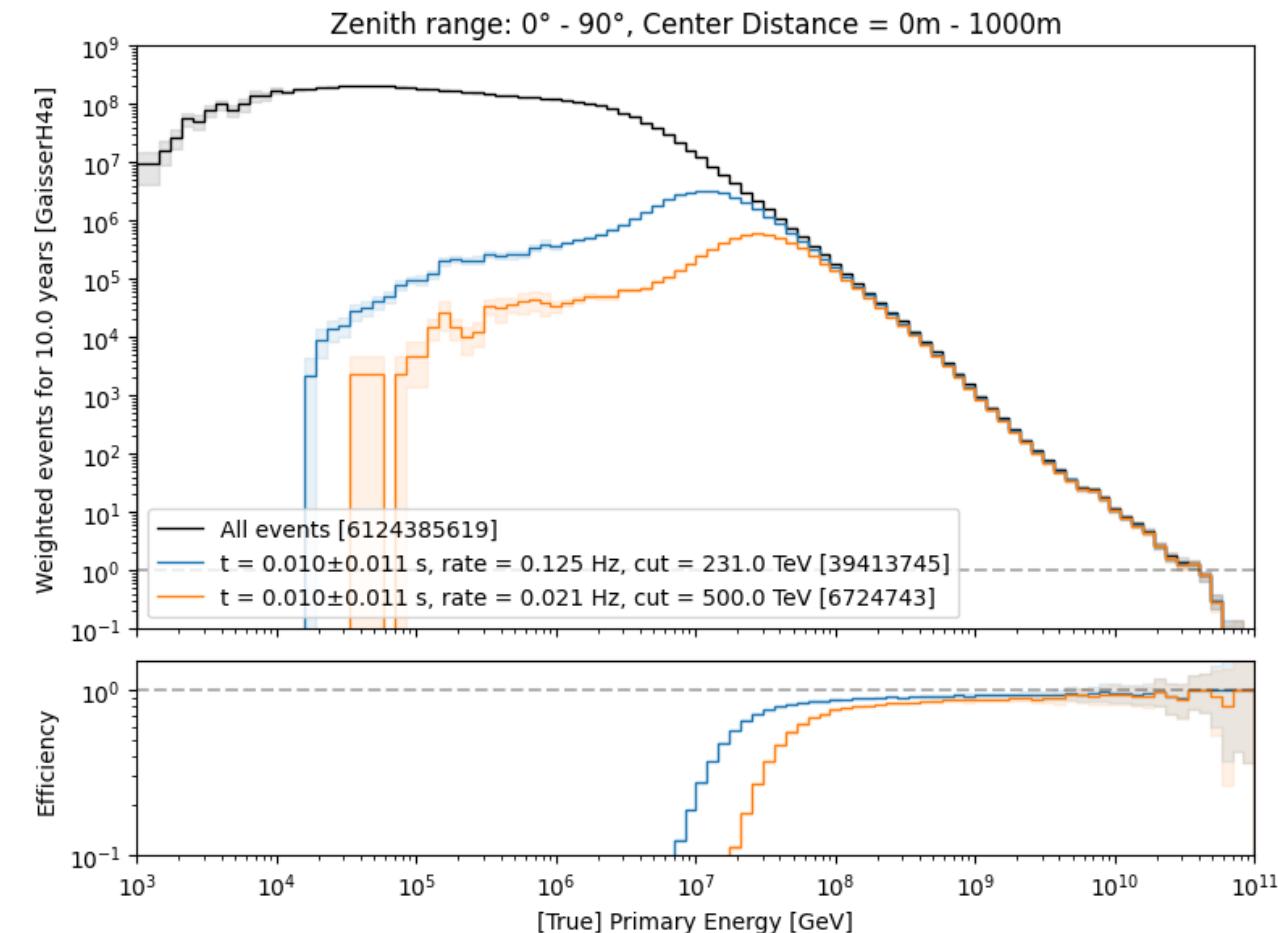
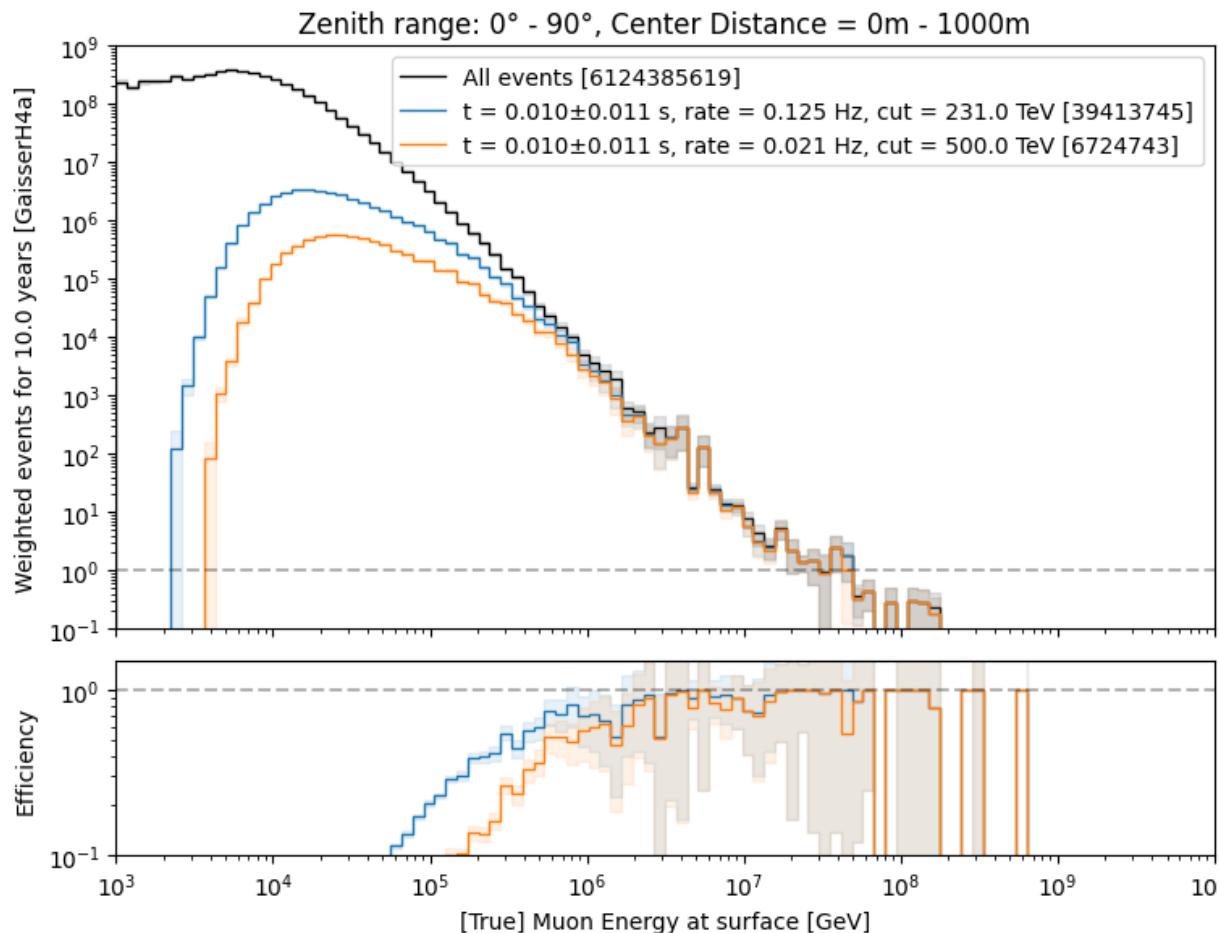
Selection

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



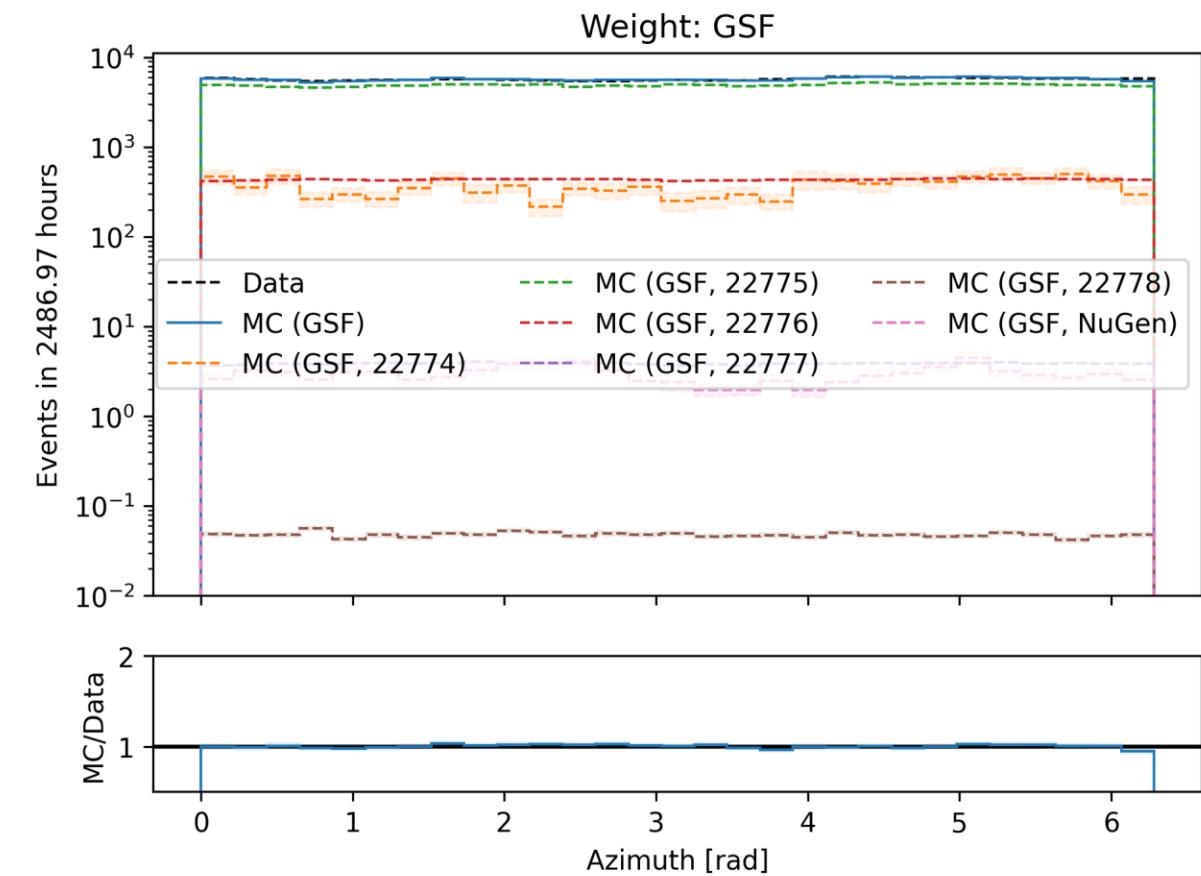
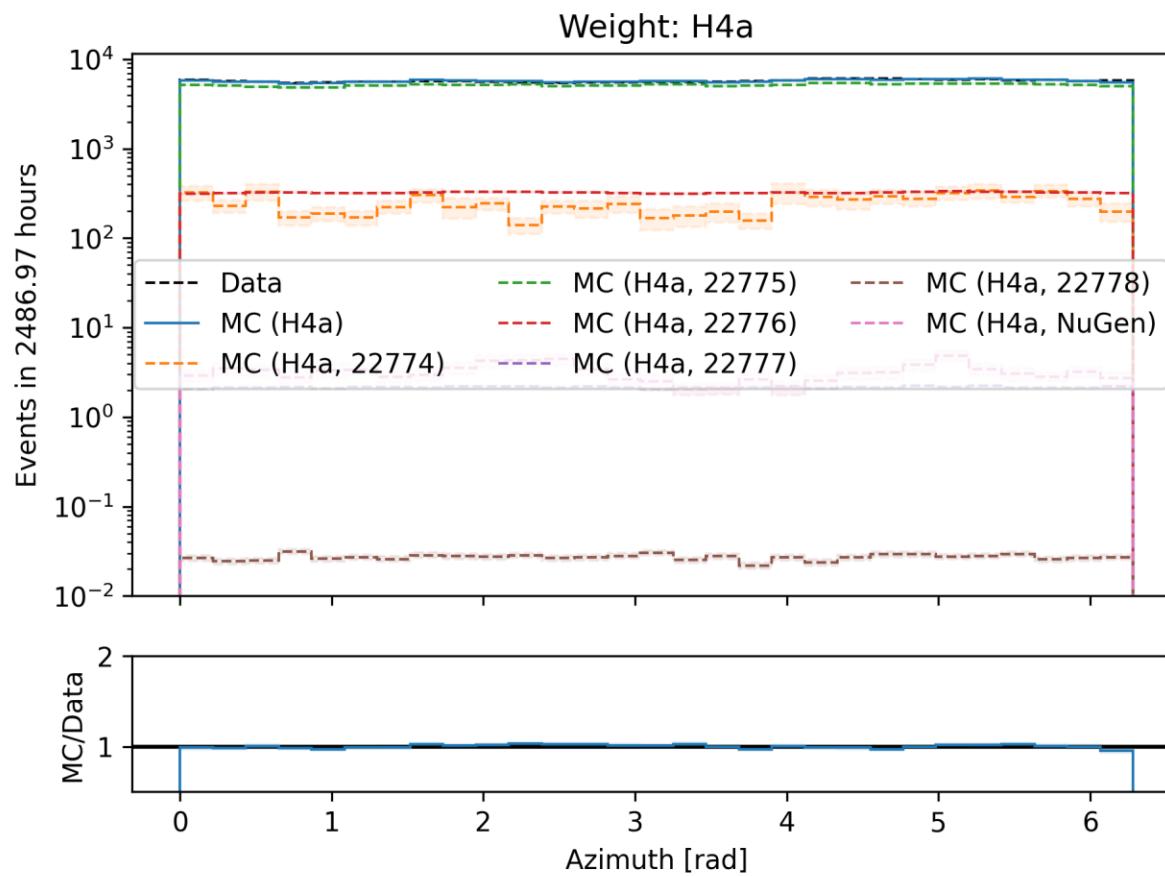
- 6 billion events expected: computationally not feasible → focus on high-energetic events
 - 500 TeV cut: 6.7 Mio events left

level4: add dnn reconstructions

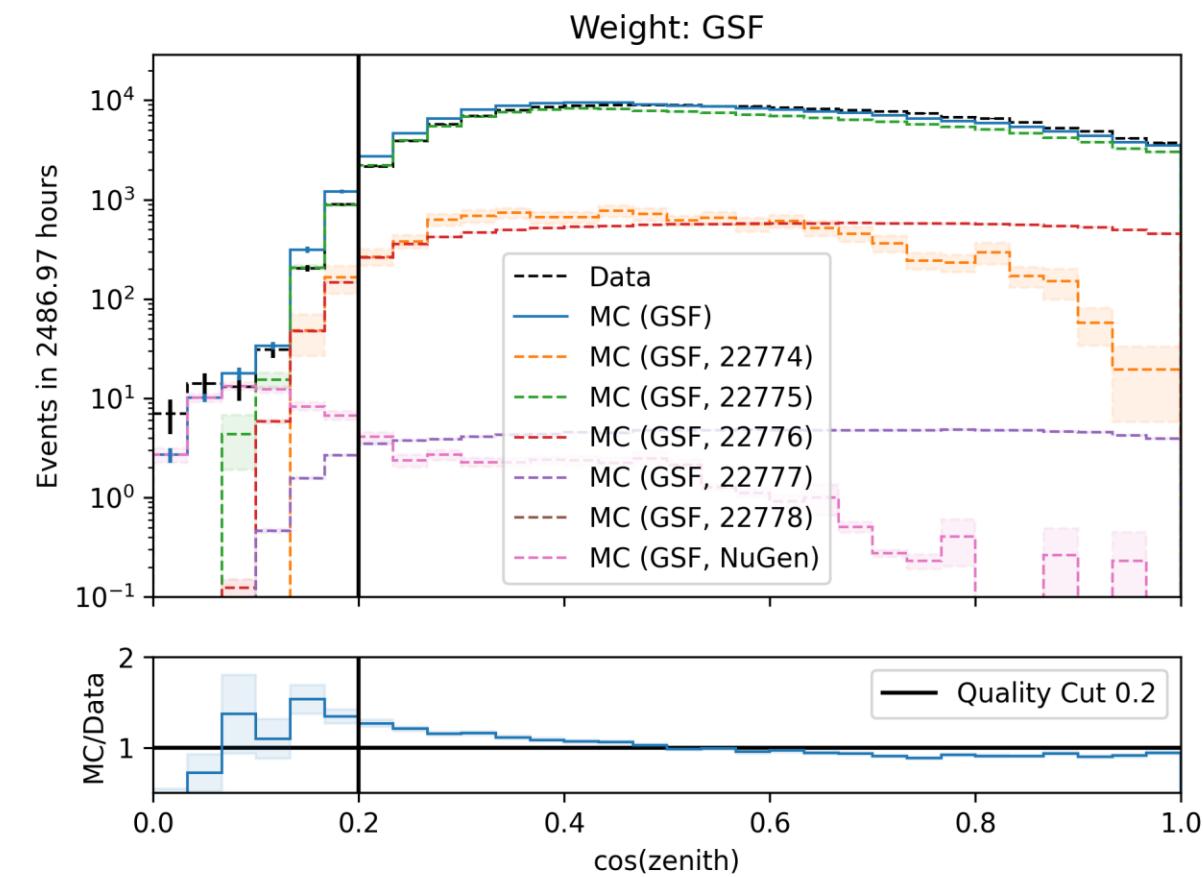
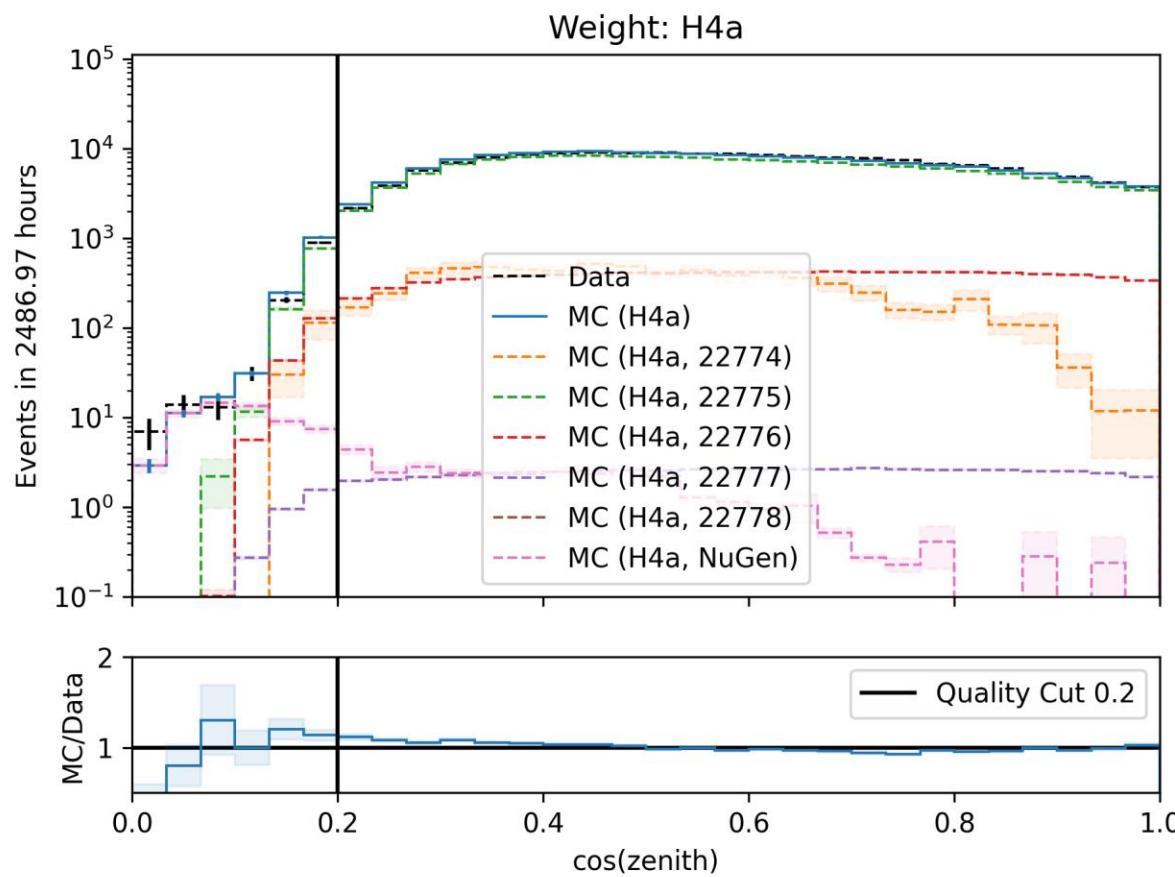
- Network 1: Energy
- Network 2: Track geometry
- Network 3: Direction

Data-MC

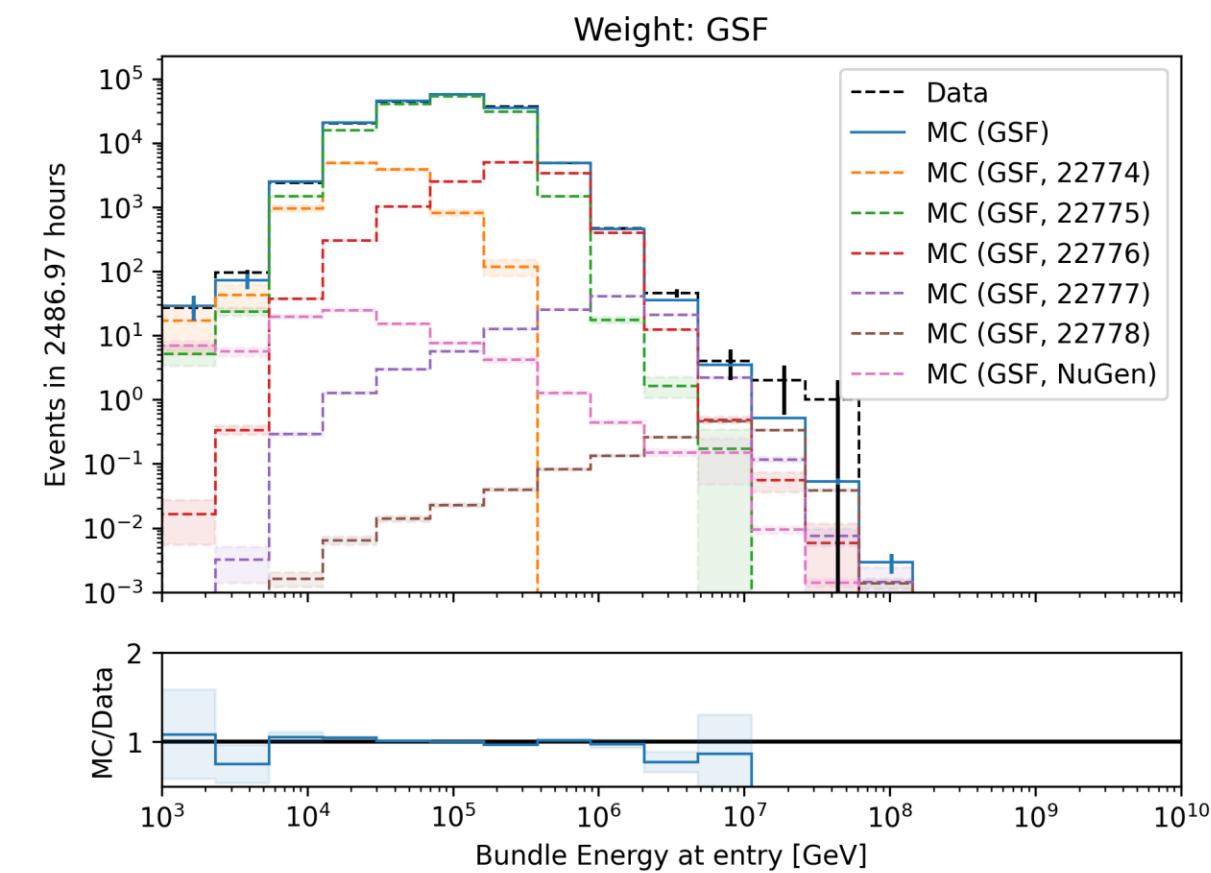
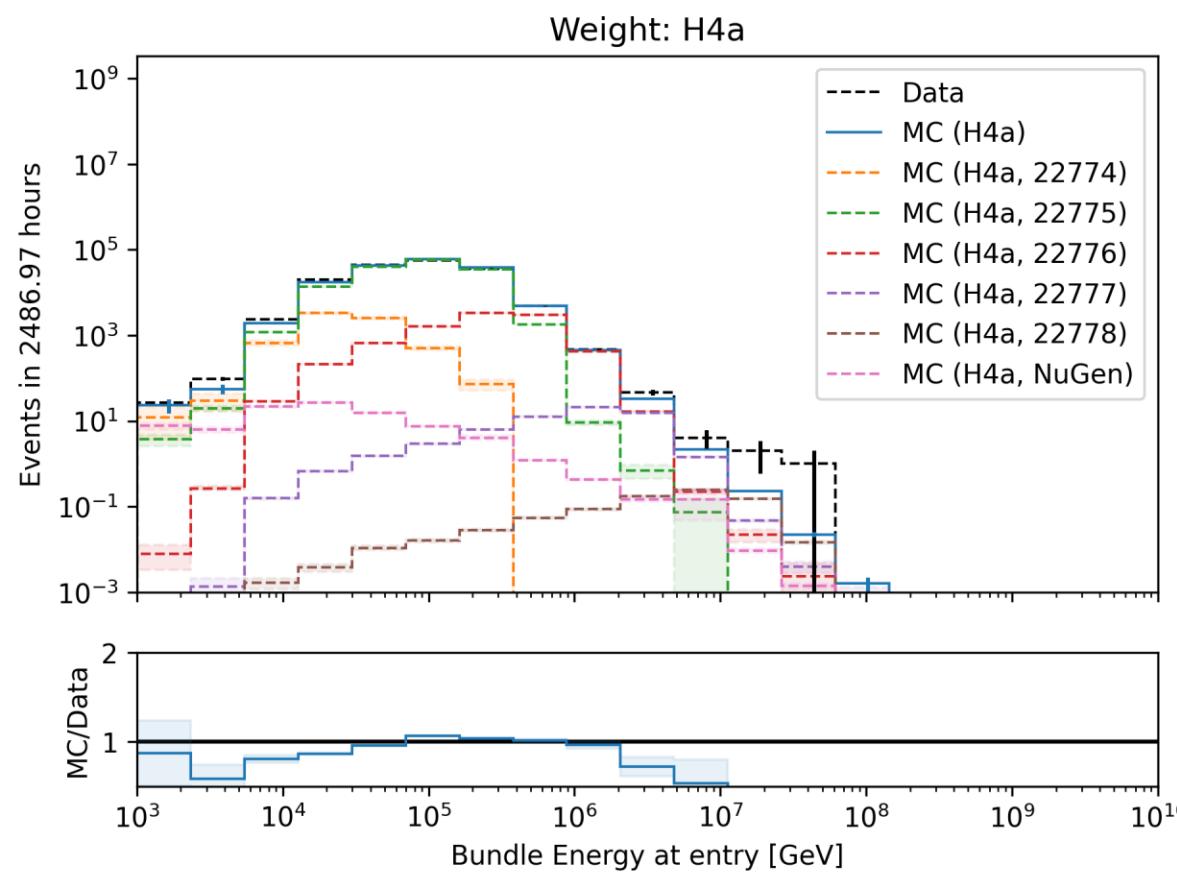
Azimuth



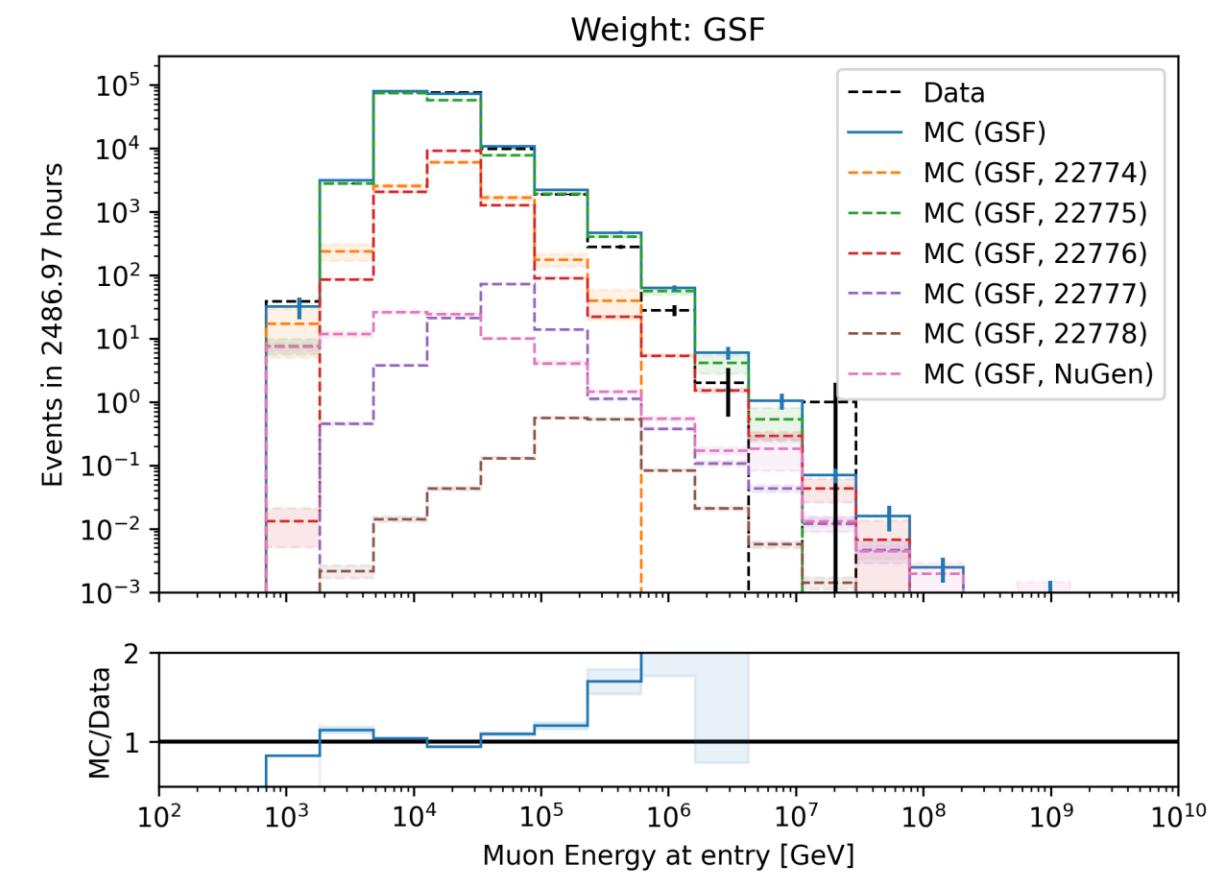
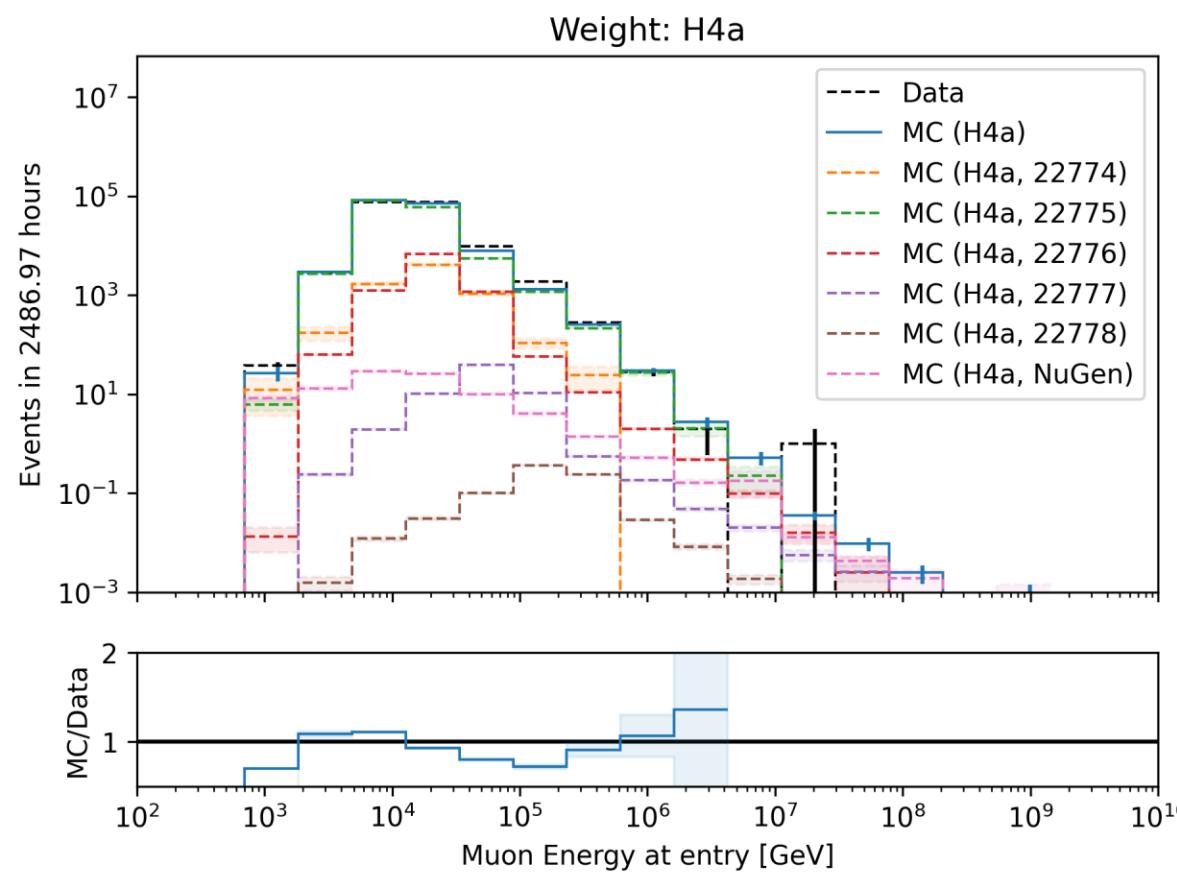
Cos(zenith)



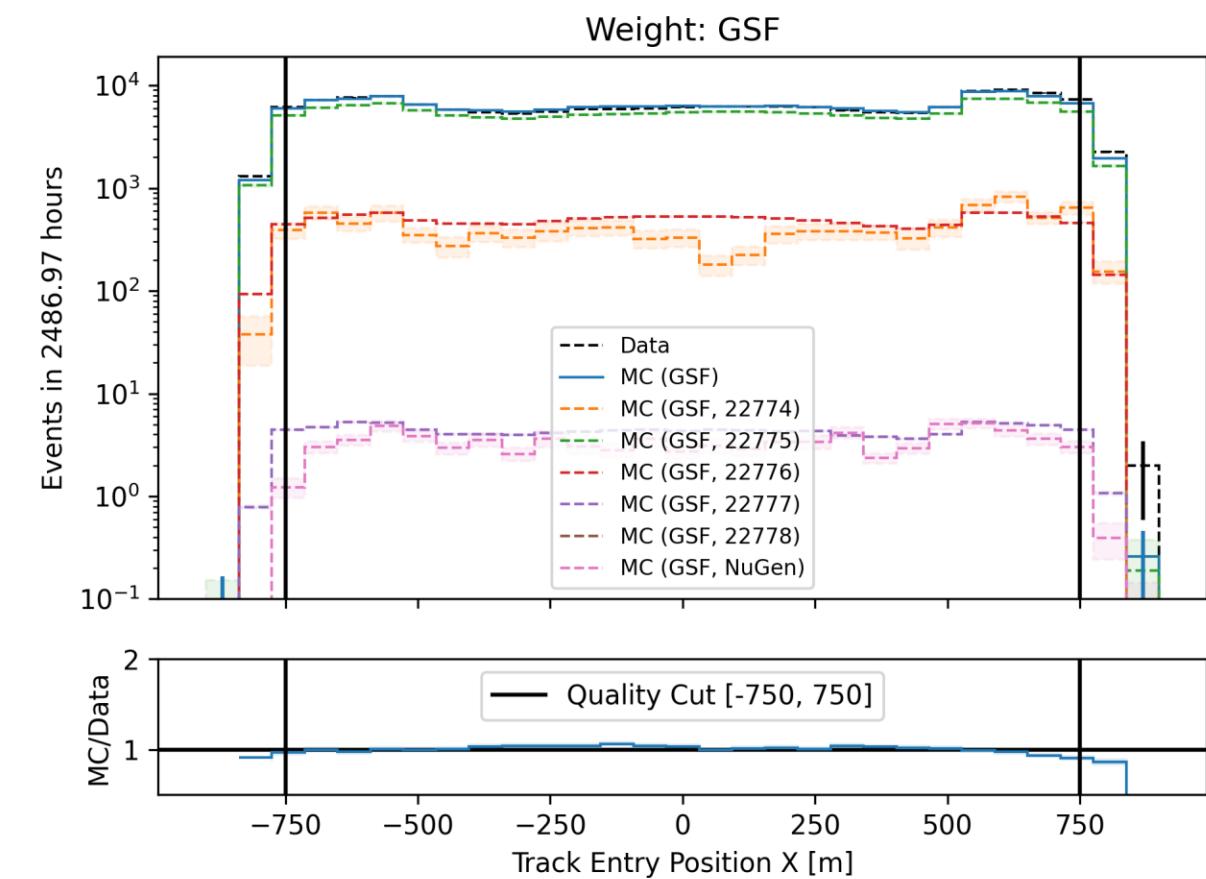
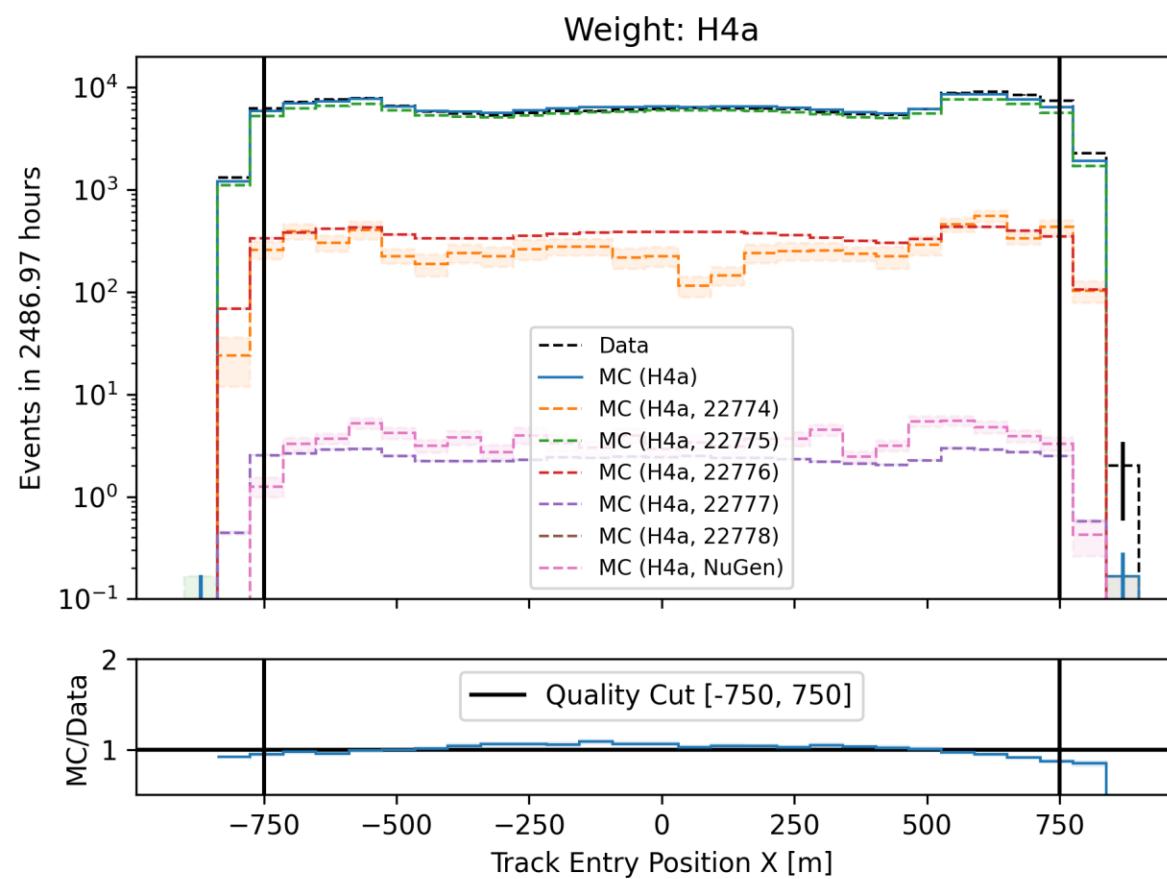
Bundle energy at entry



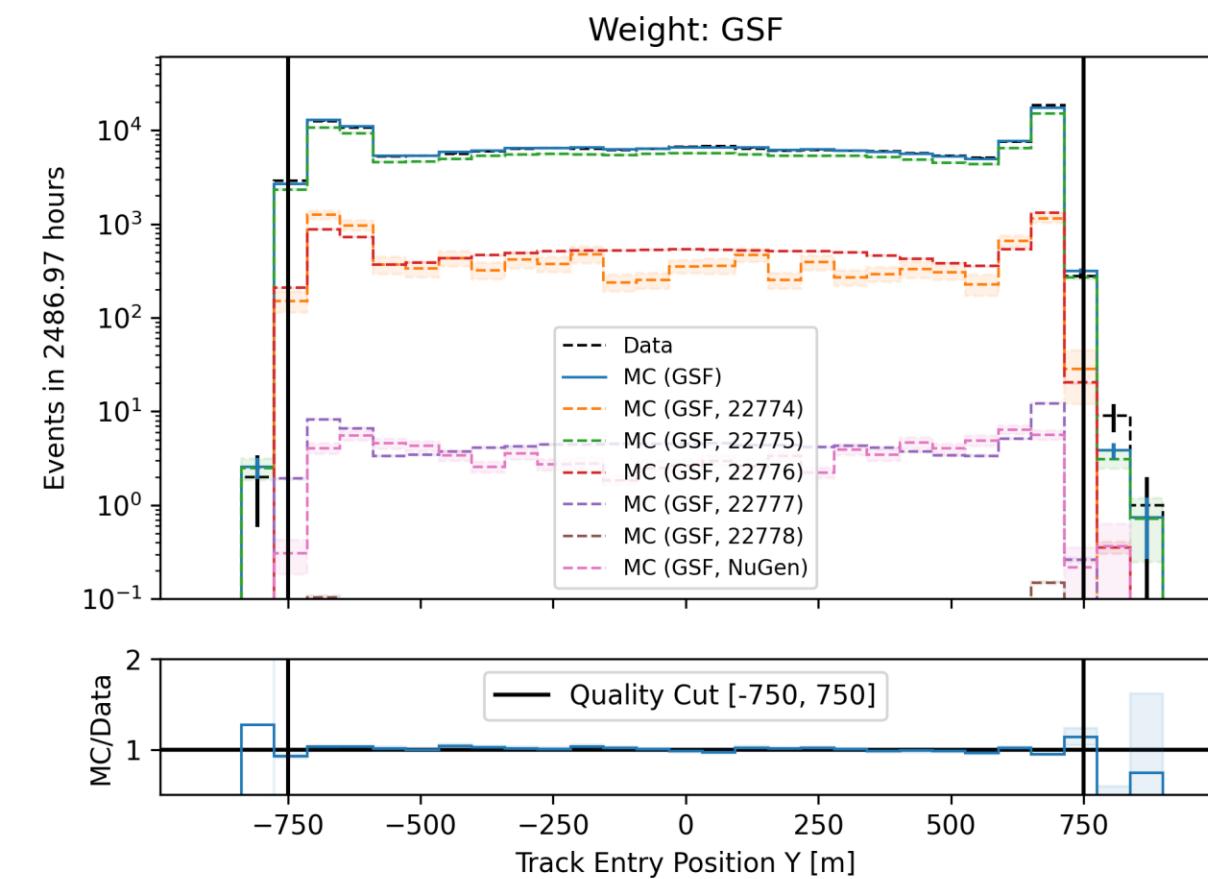
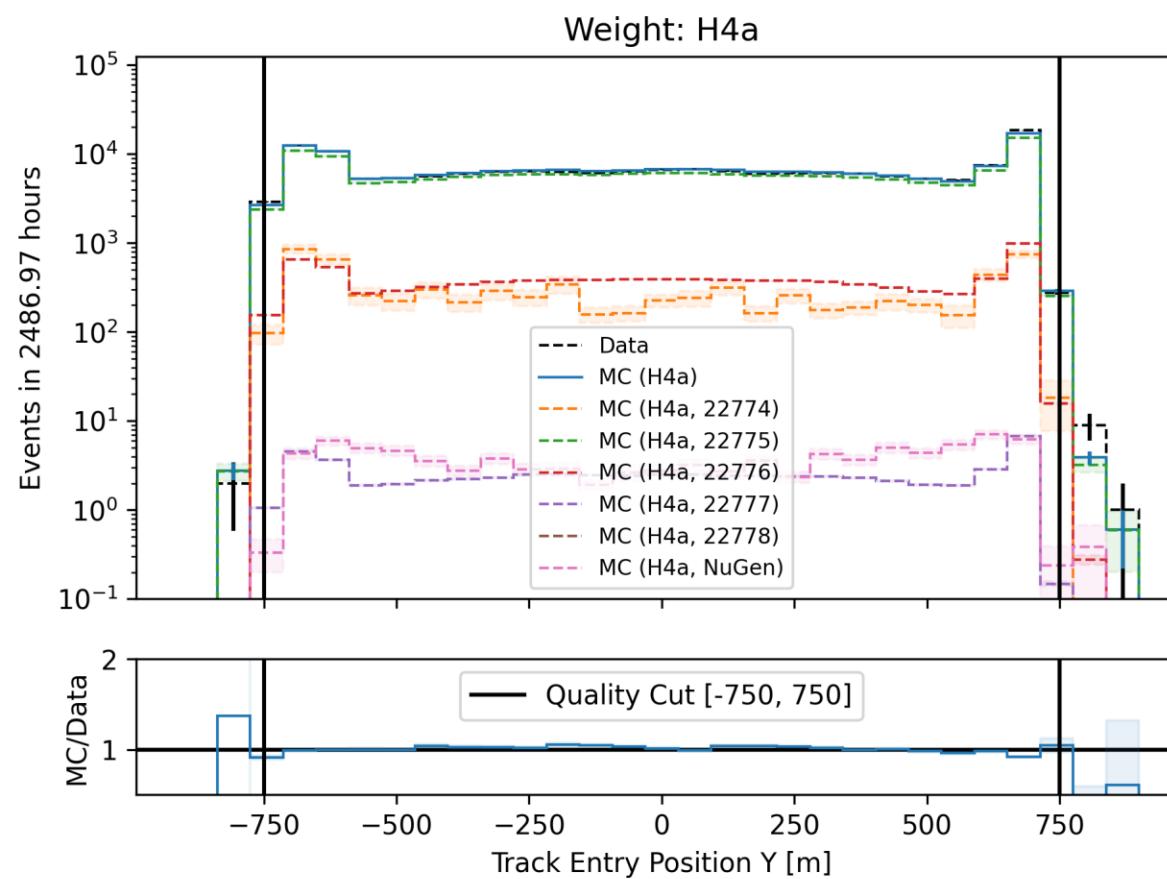
Leading muon energy at entry



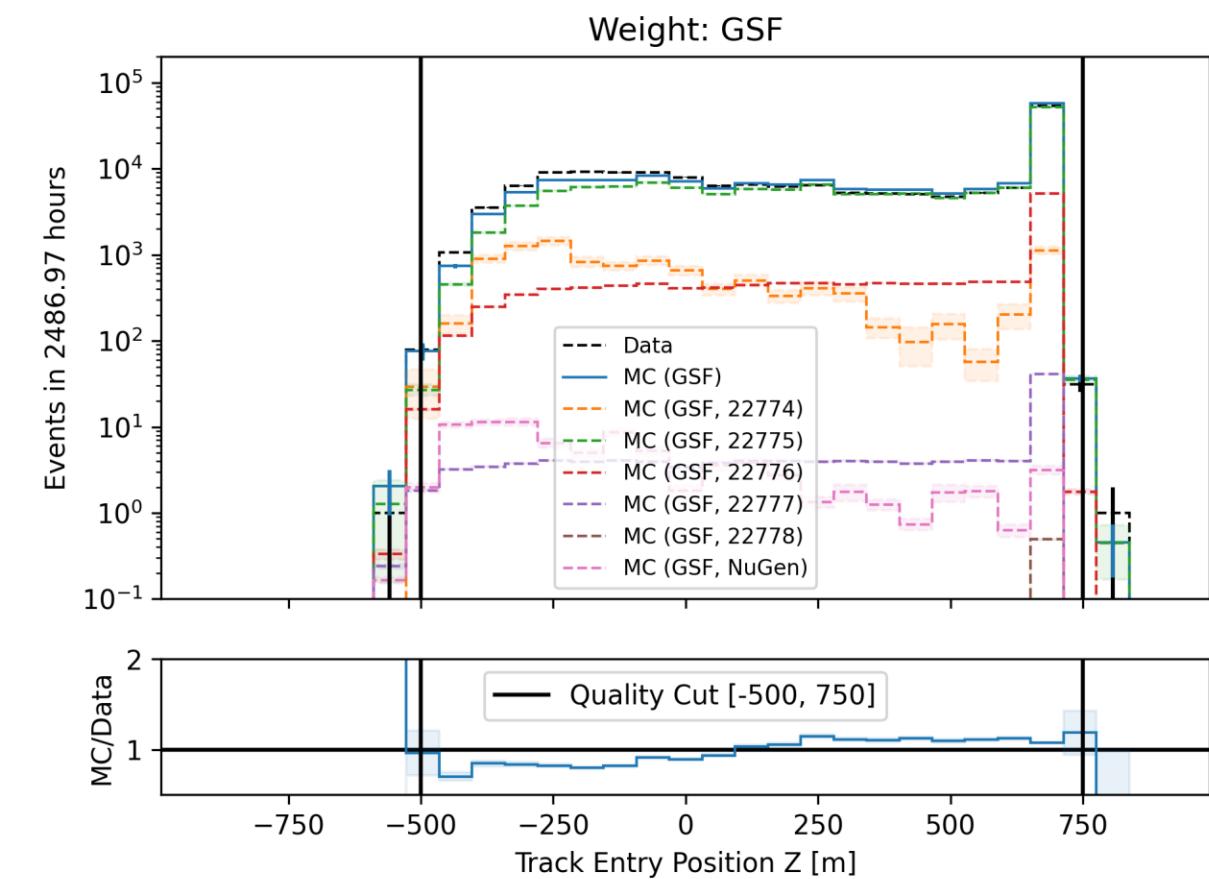
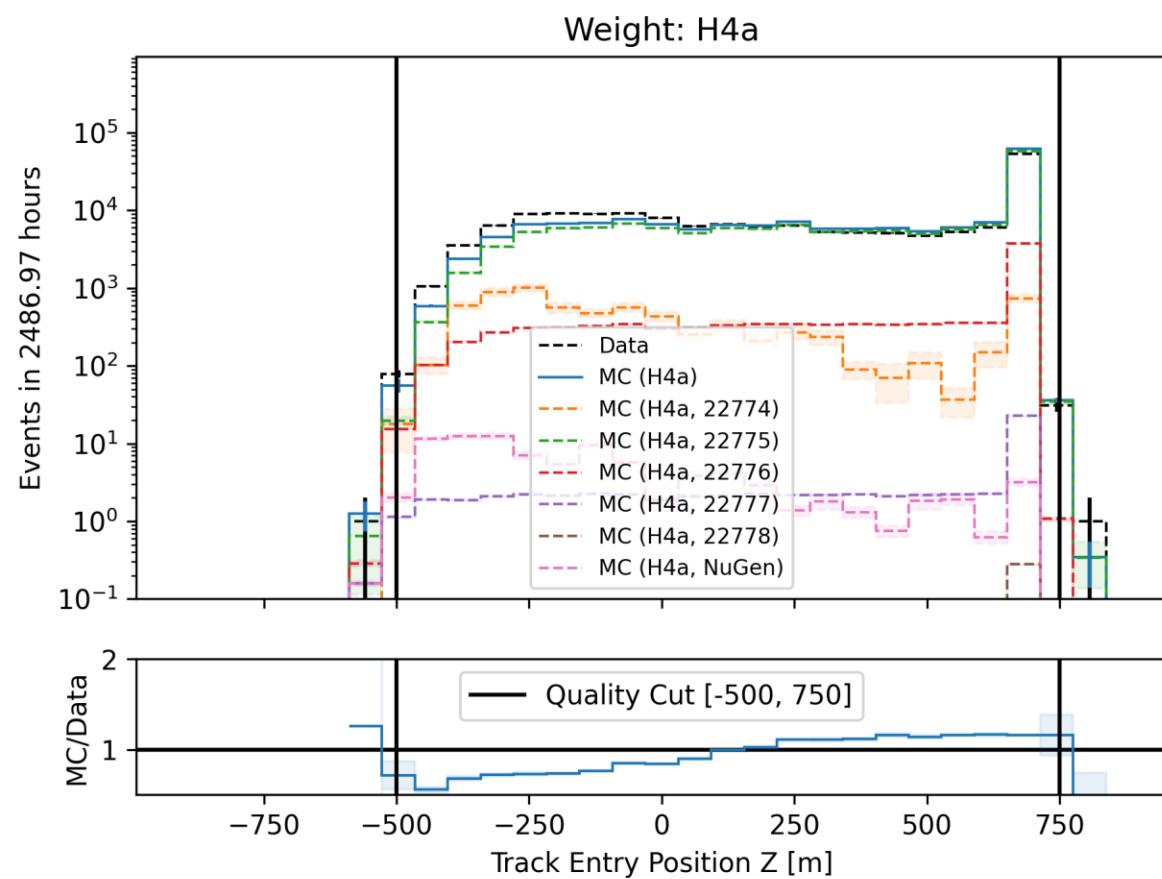
Entry position x–vertex



Entry position y–vertex

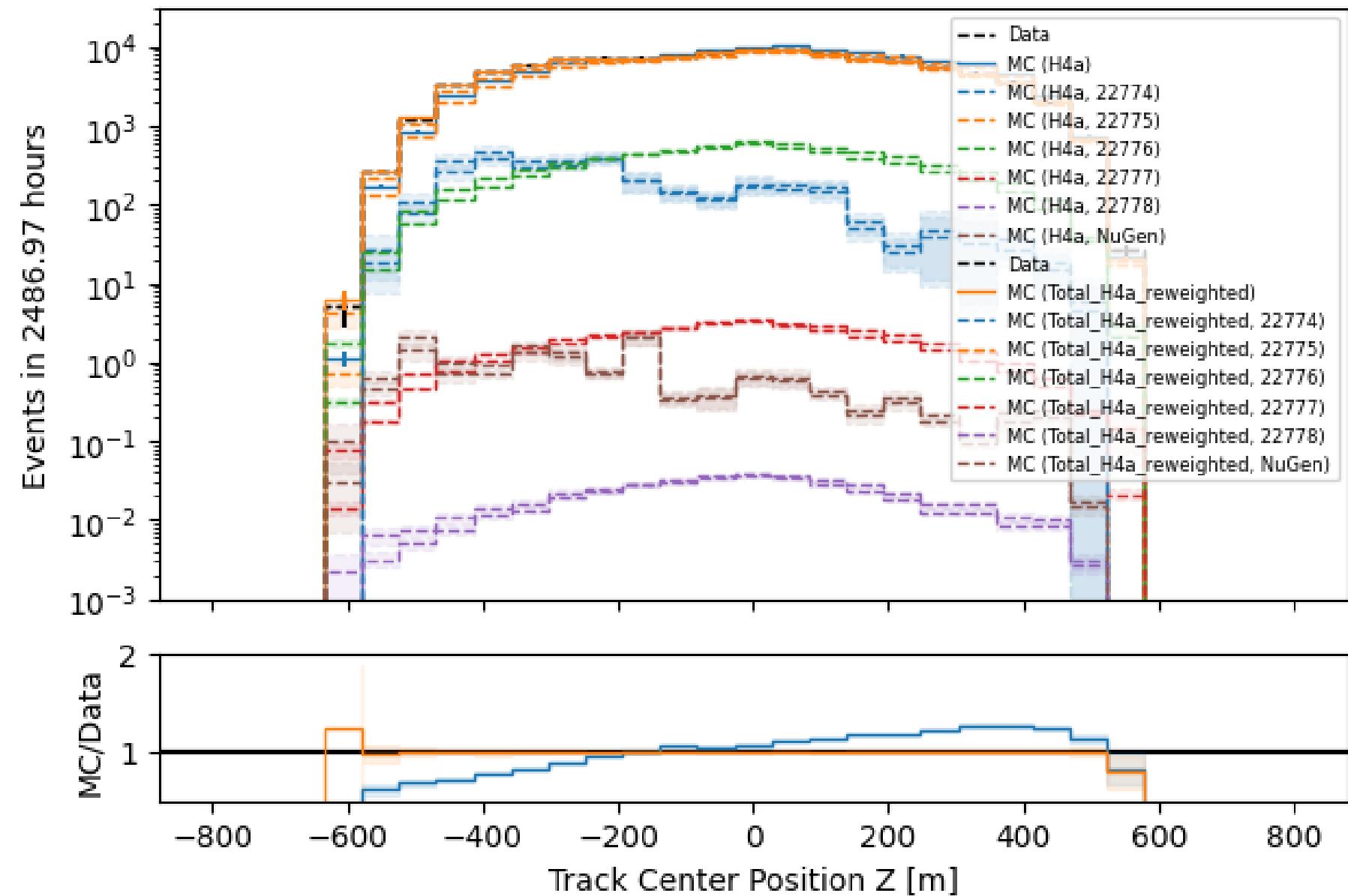


Entry position z—vertex

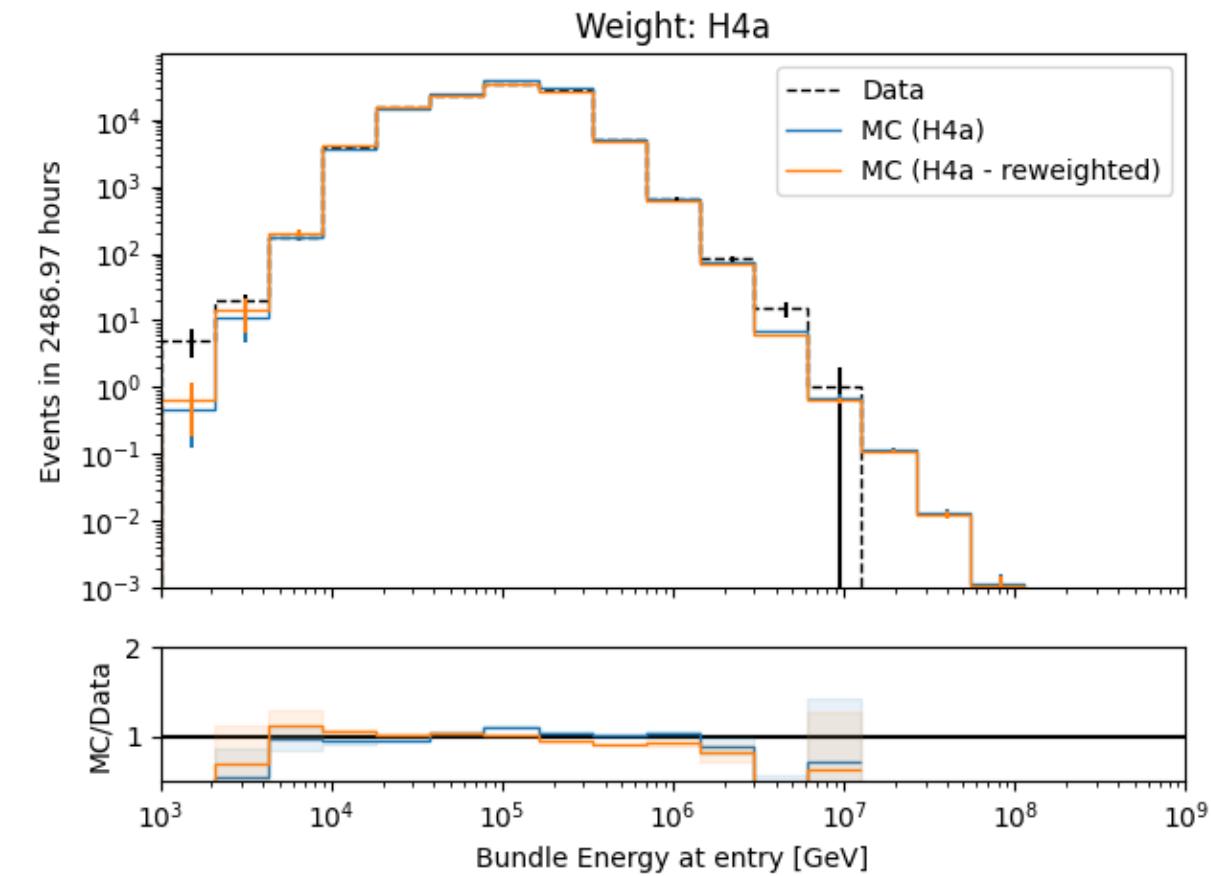
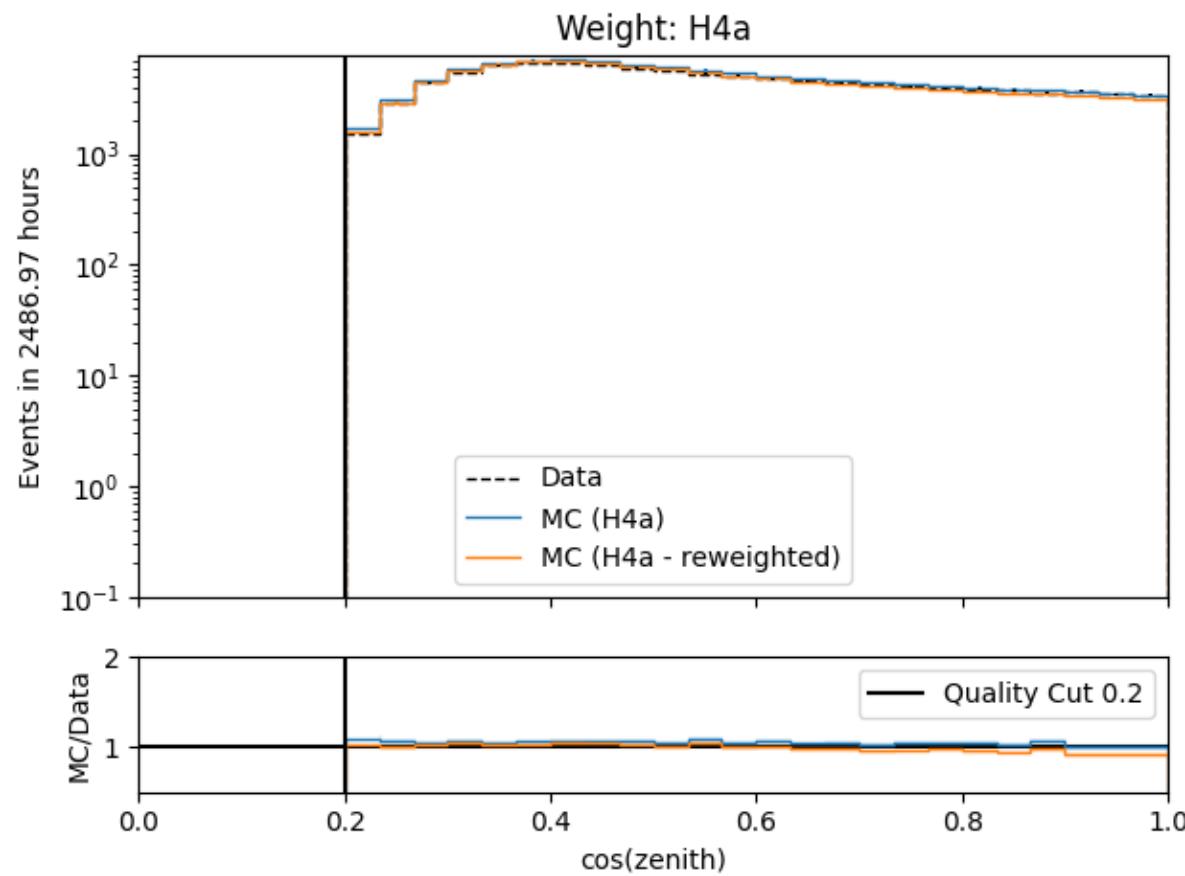


z—reweighting

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



Check z—reweighting



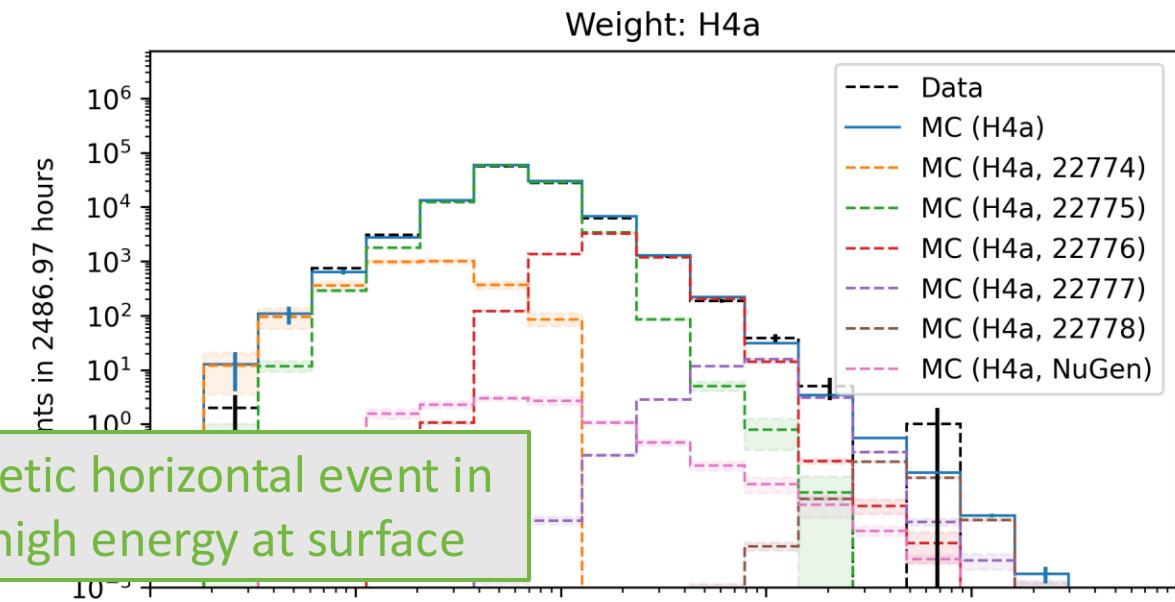
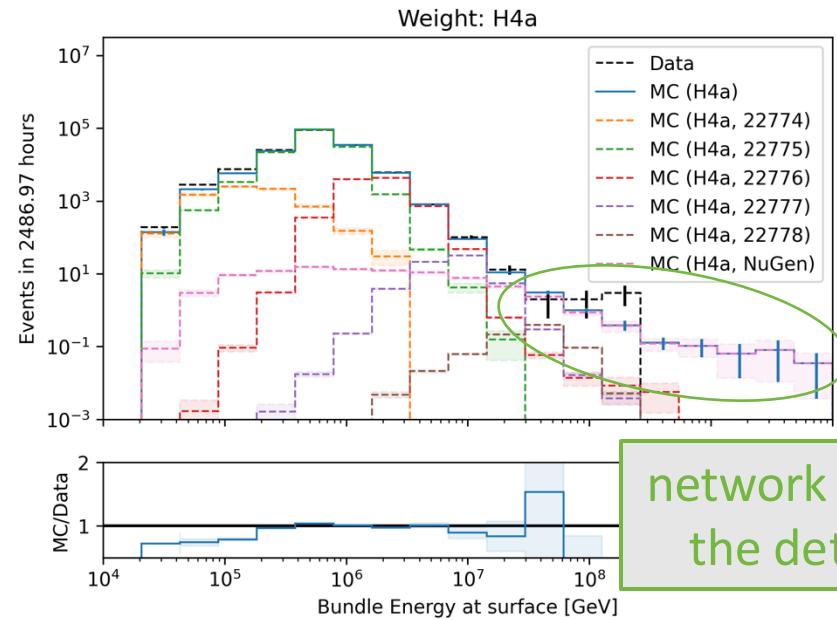
Level5: quality cuts

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

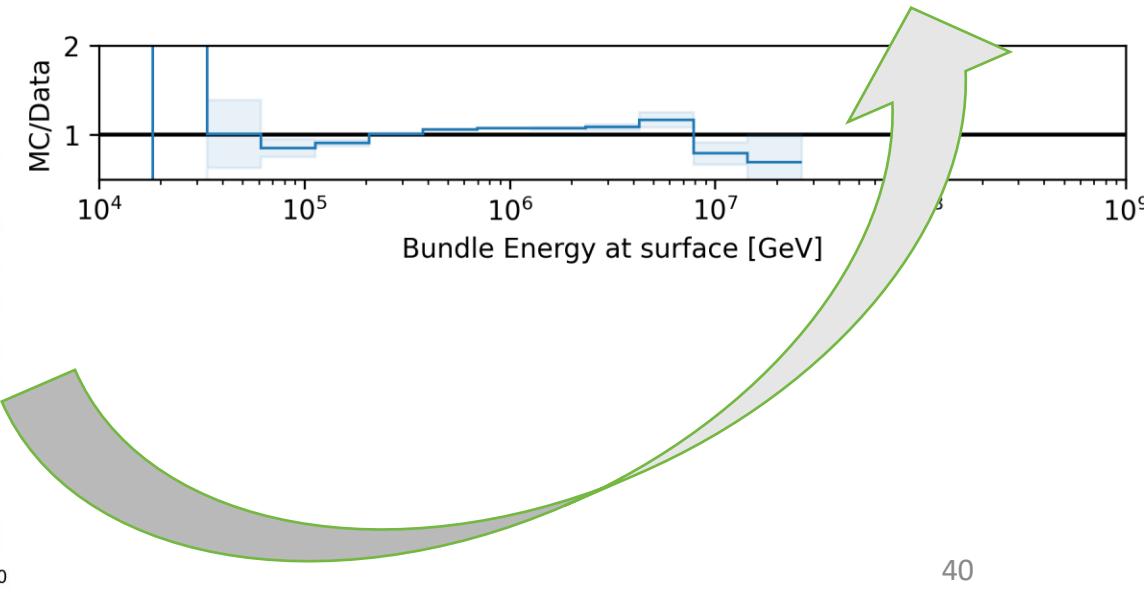
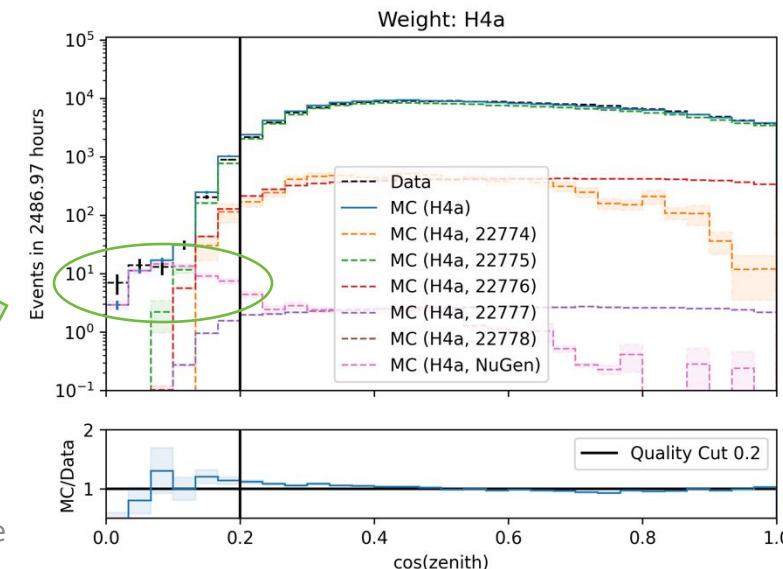
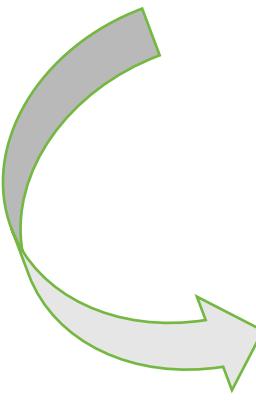
neutrino cuts	>	<
$\cos(\text{zenith})$	0.2	
length	5000 m	15000 m

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



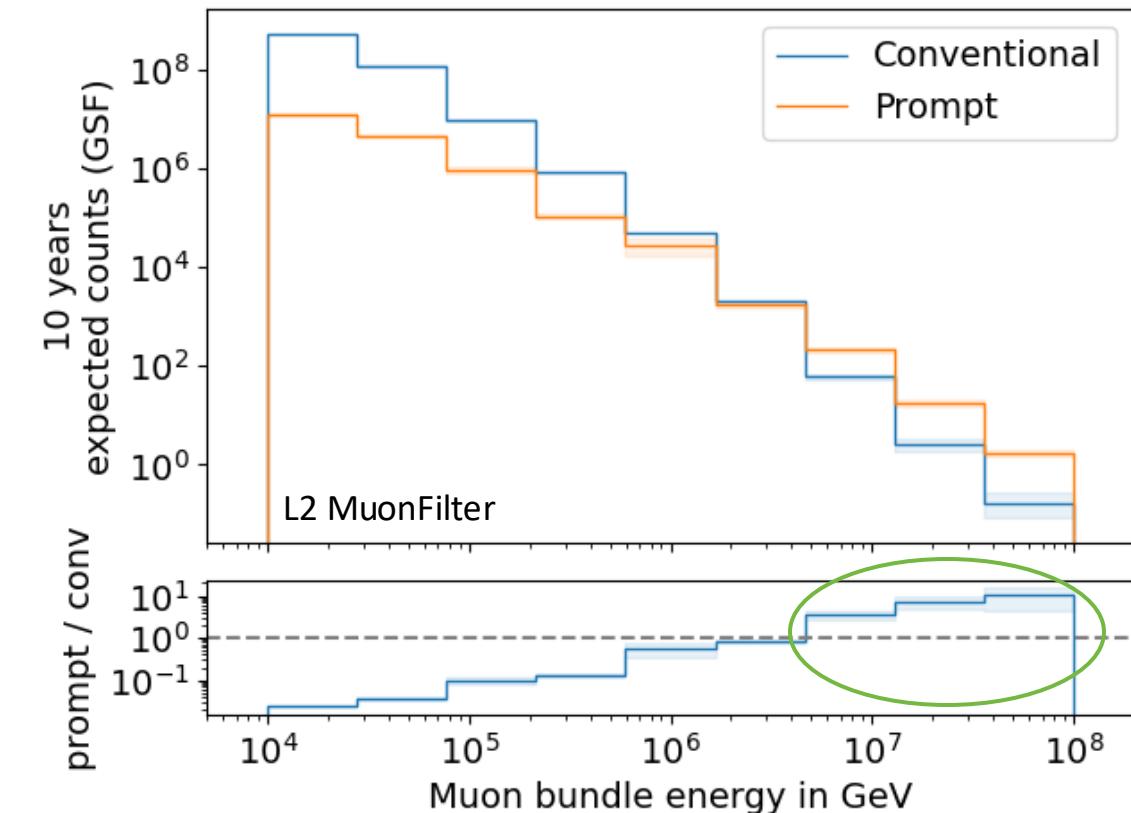
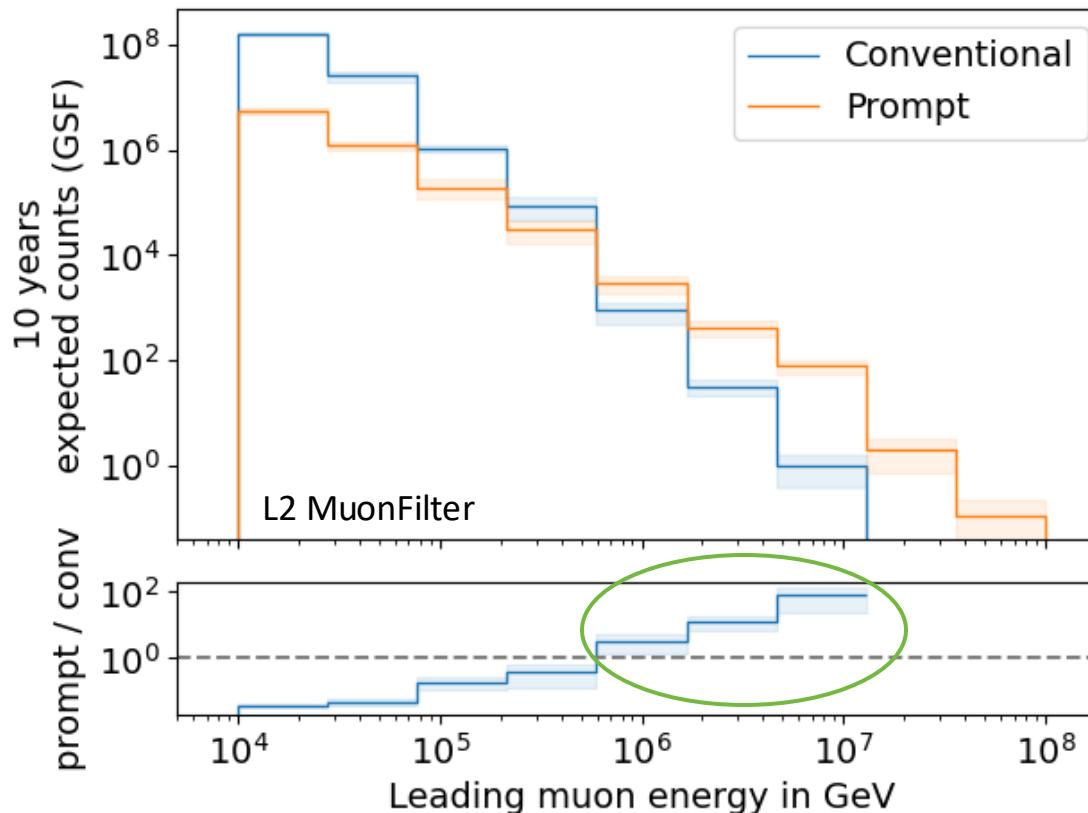
network learns: a high-energetic horizontal event in
the detector needs a very high energy at surface



Forward fit

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

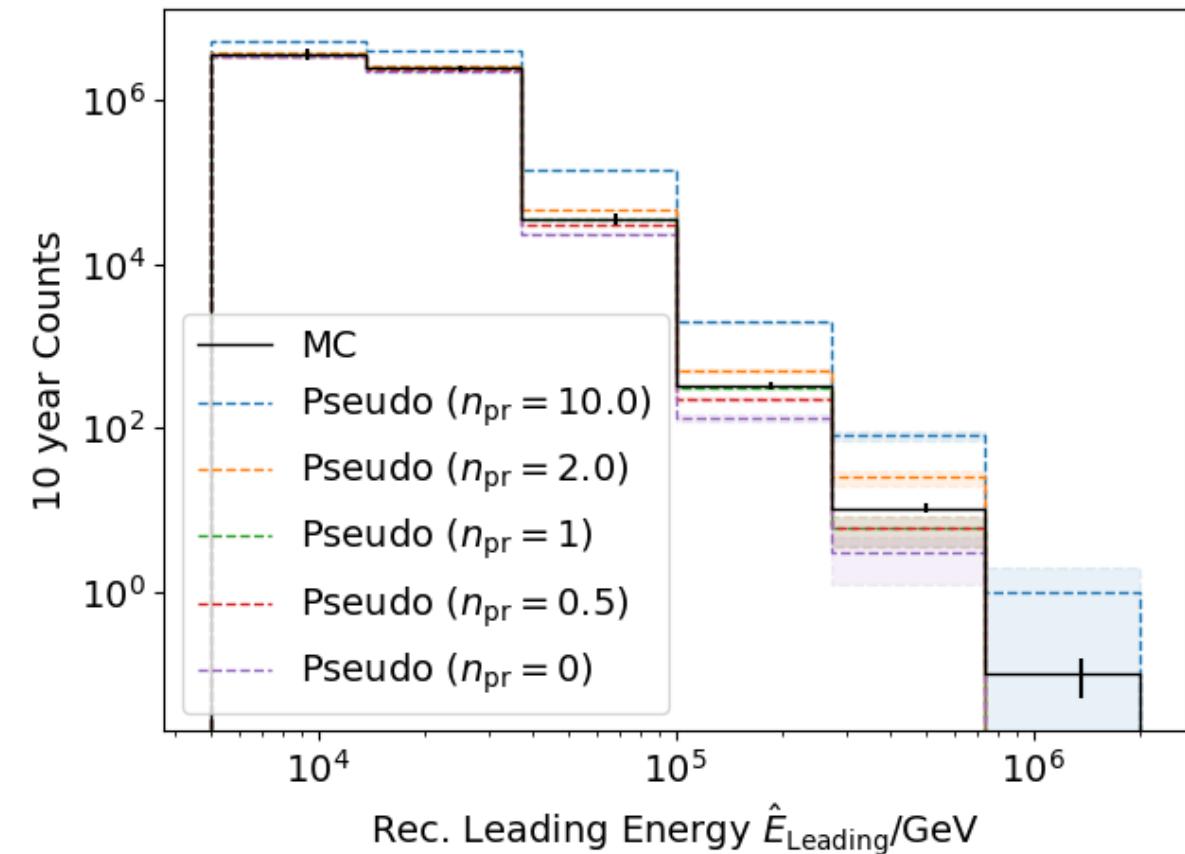
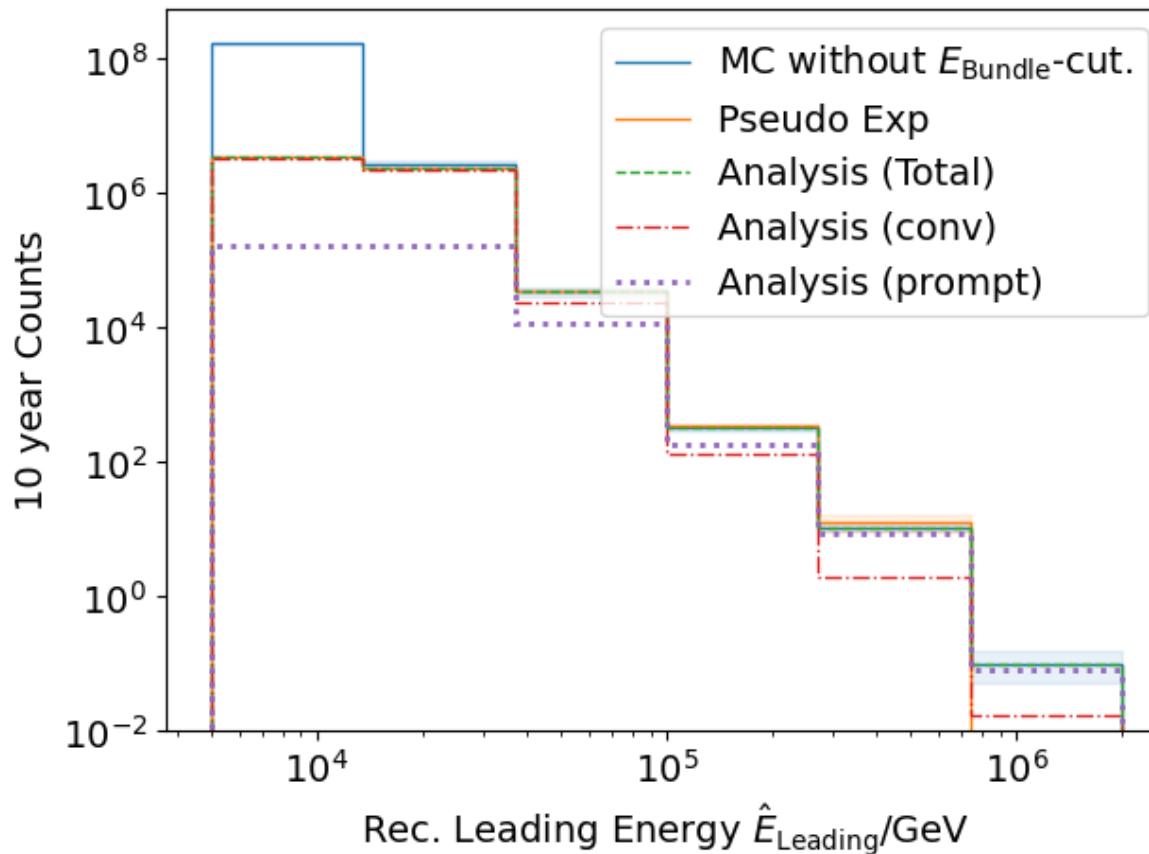
- leading: energy of most energetic muon in a muon bundle
- bundle: sum of energies of all muons of the bundle



- 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

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

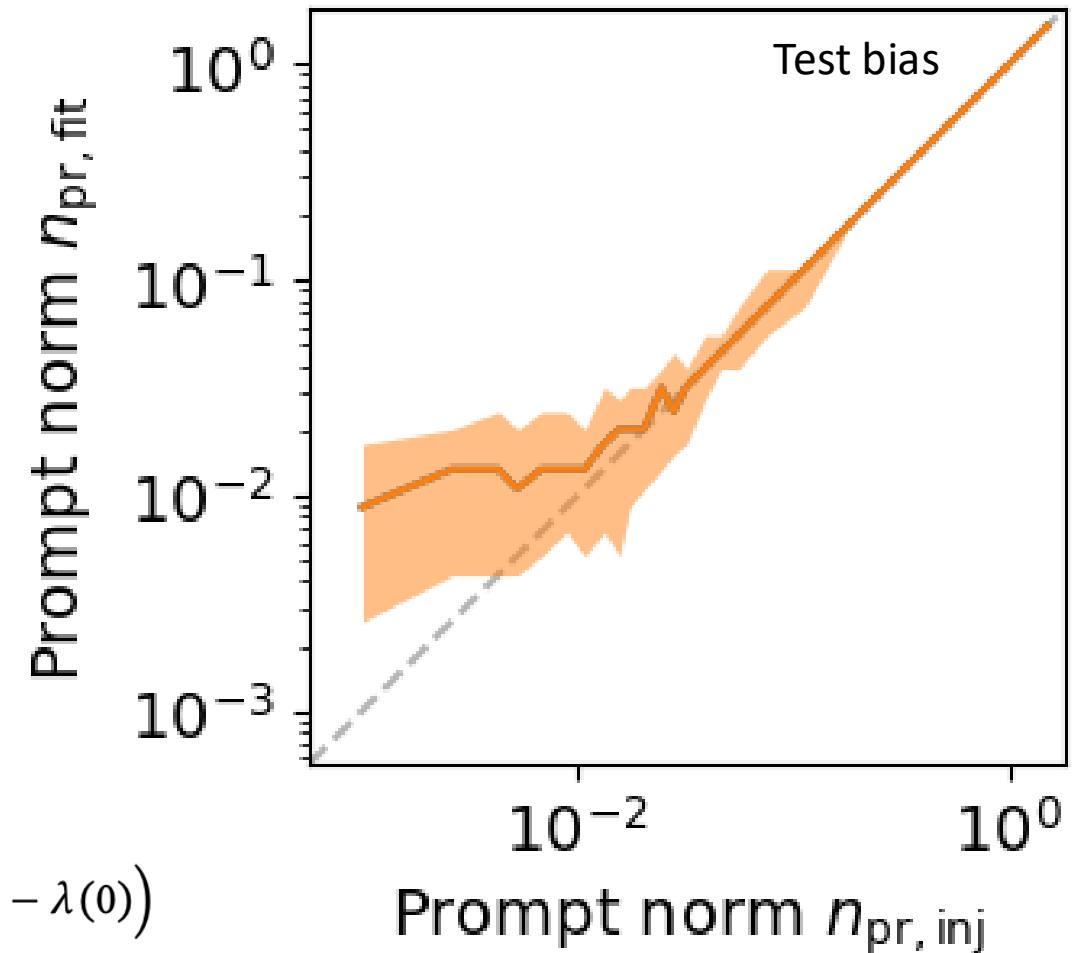
With a constant conv norm:
 bin counts depend only on prompt norm
 = expectation value per bin

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

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:

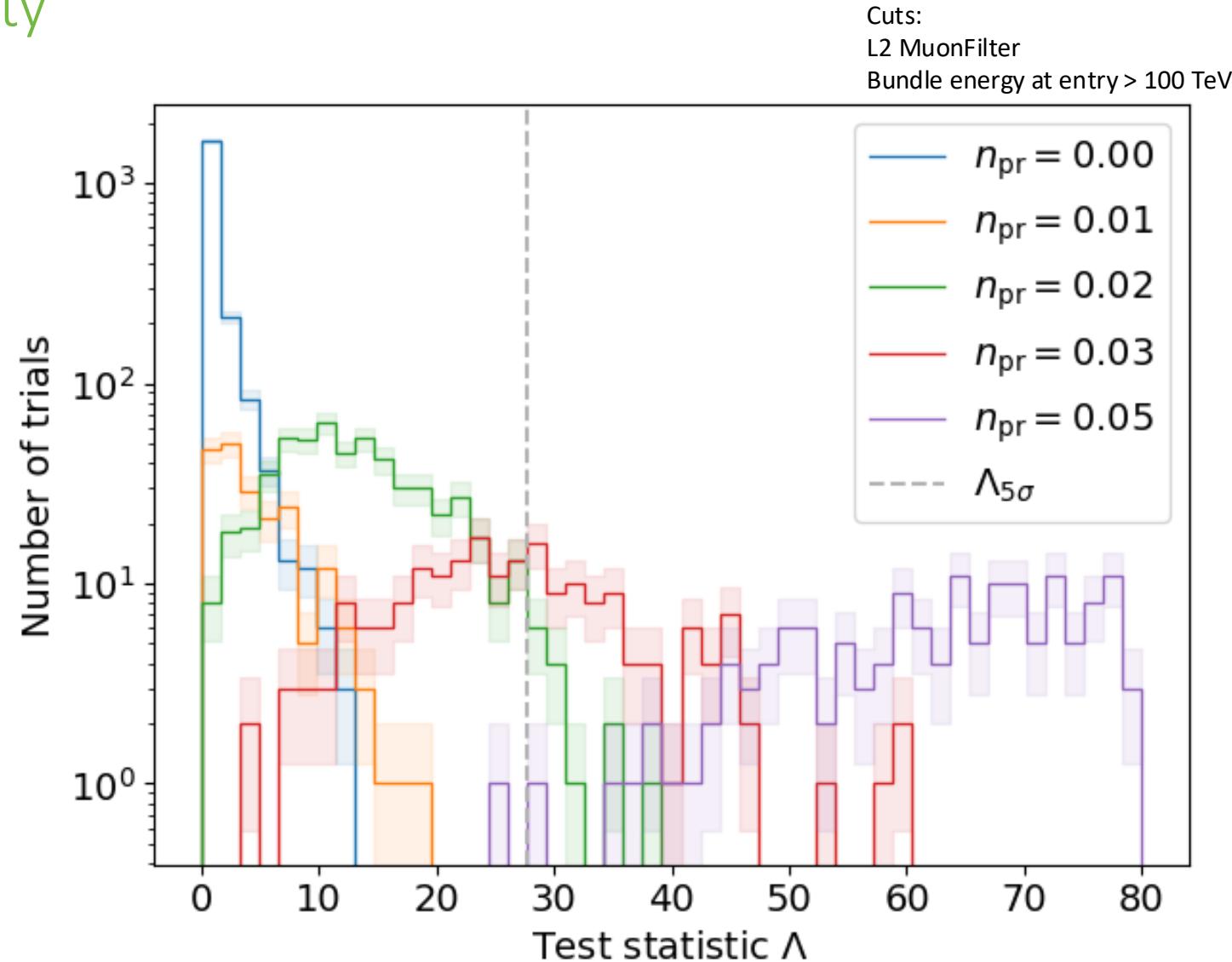
- 5 sigma discovery potential: 0.102 ± 0.005
- Sensitivity: 0.024 ± 0.001

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



Unfolding

Unfolding in a nutshell

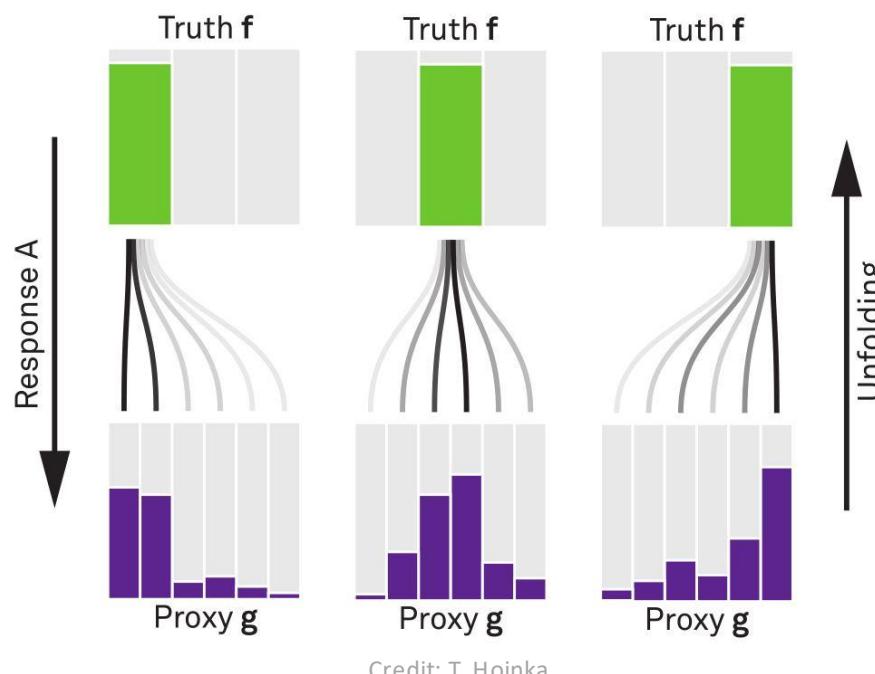
measured proxy

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

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:

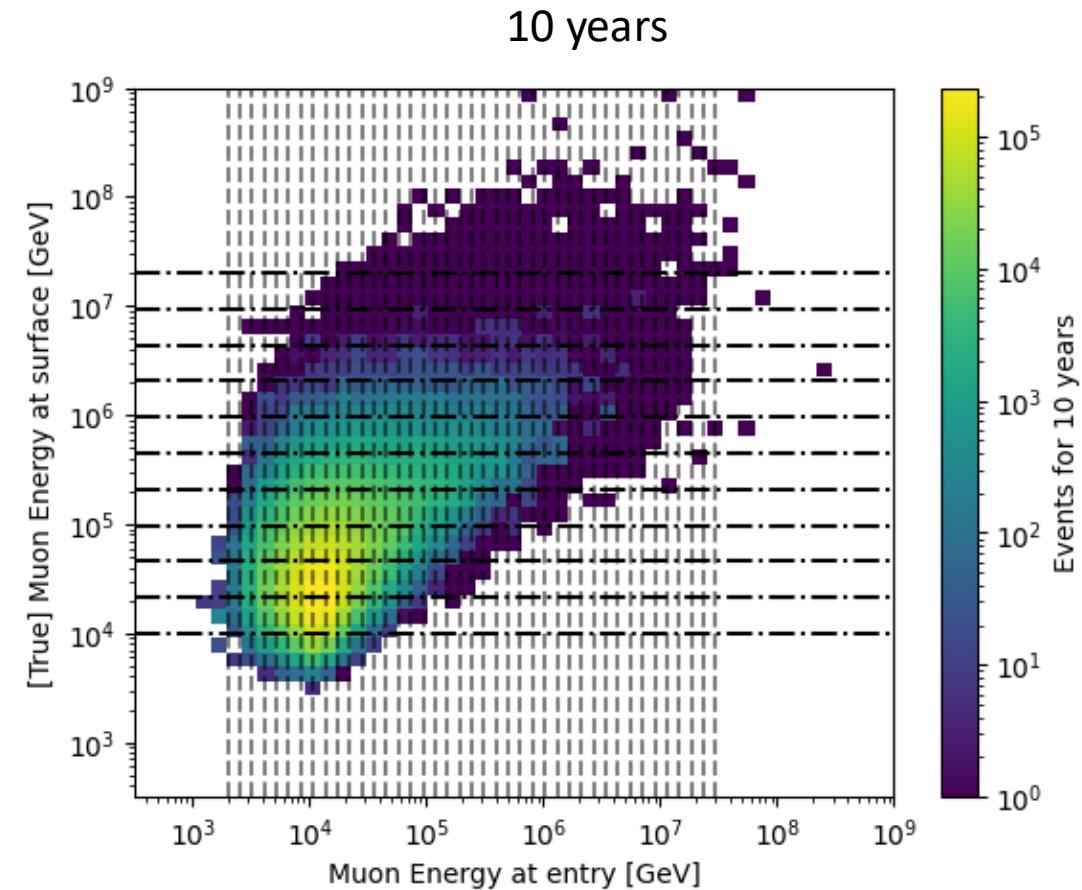
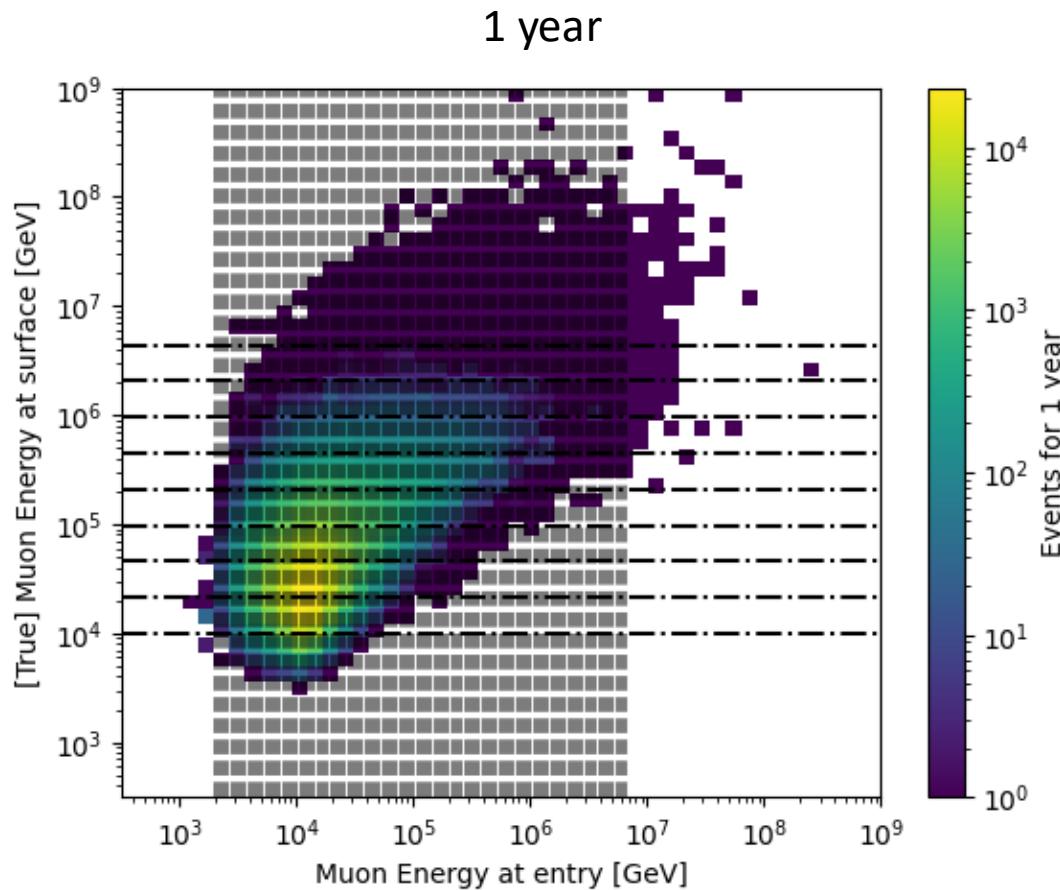
$$t(\vec{f}) = -\frac{1}{2} (\vec{C}\vec{f})^T (\tau I)^{-1} (\vec{C}\vec{f})$$

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



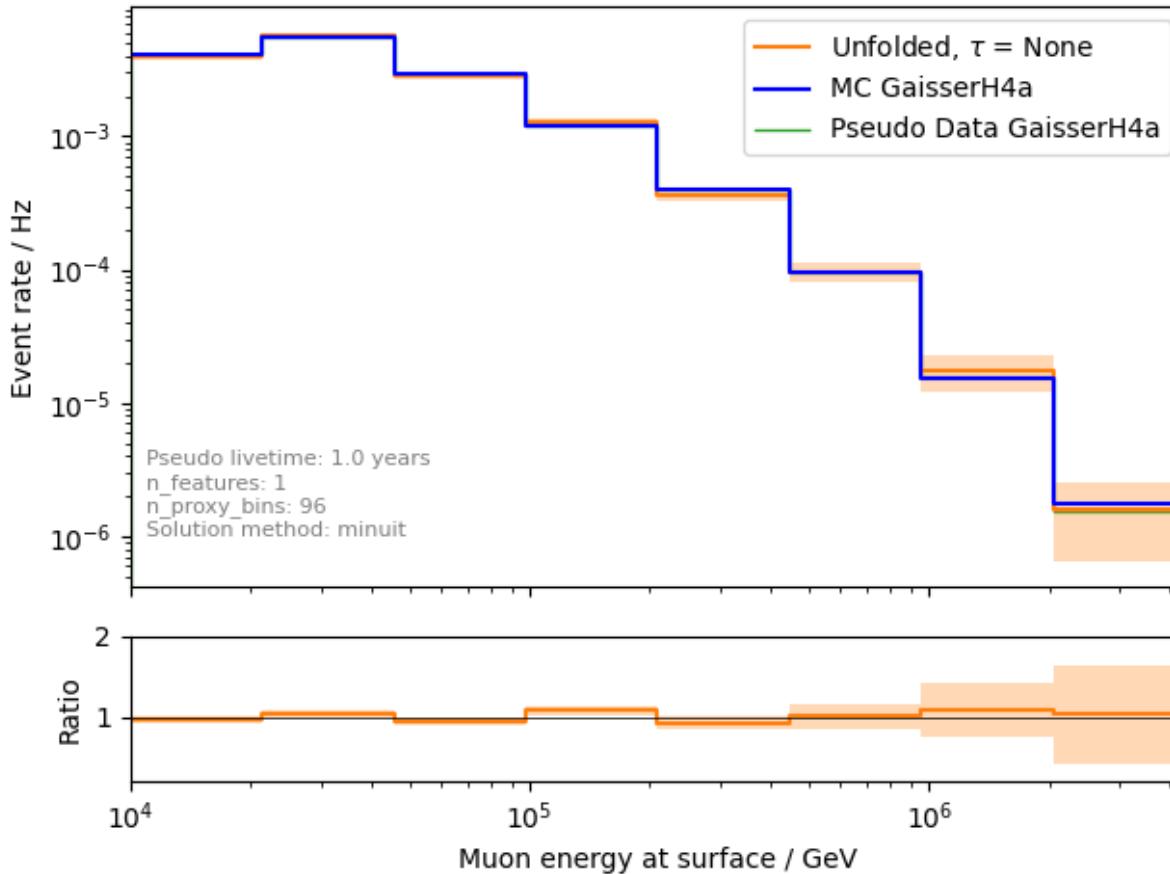
[funfolding](#)
by M. Börner

Proxy vs. target

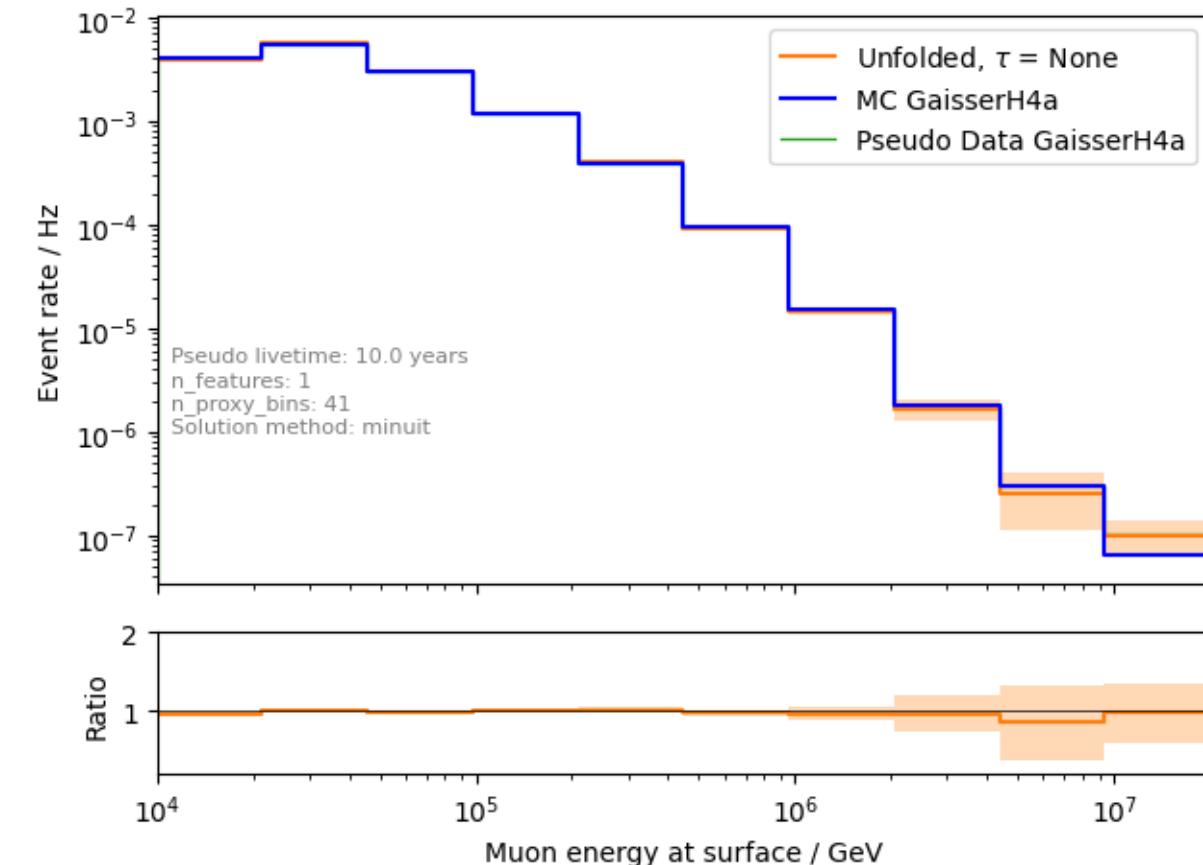


Unfolding event rate

1 year

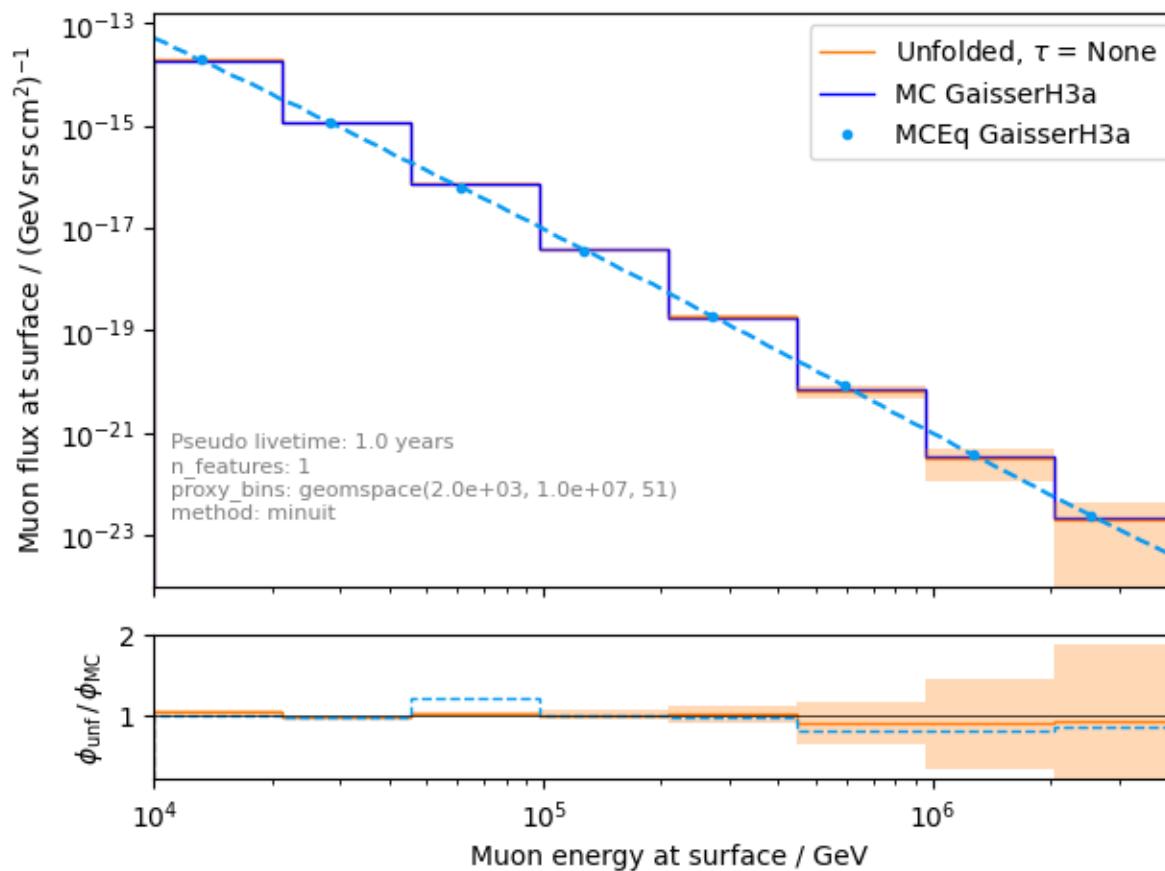


10 years

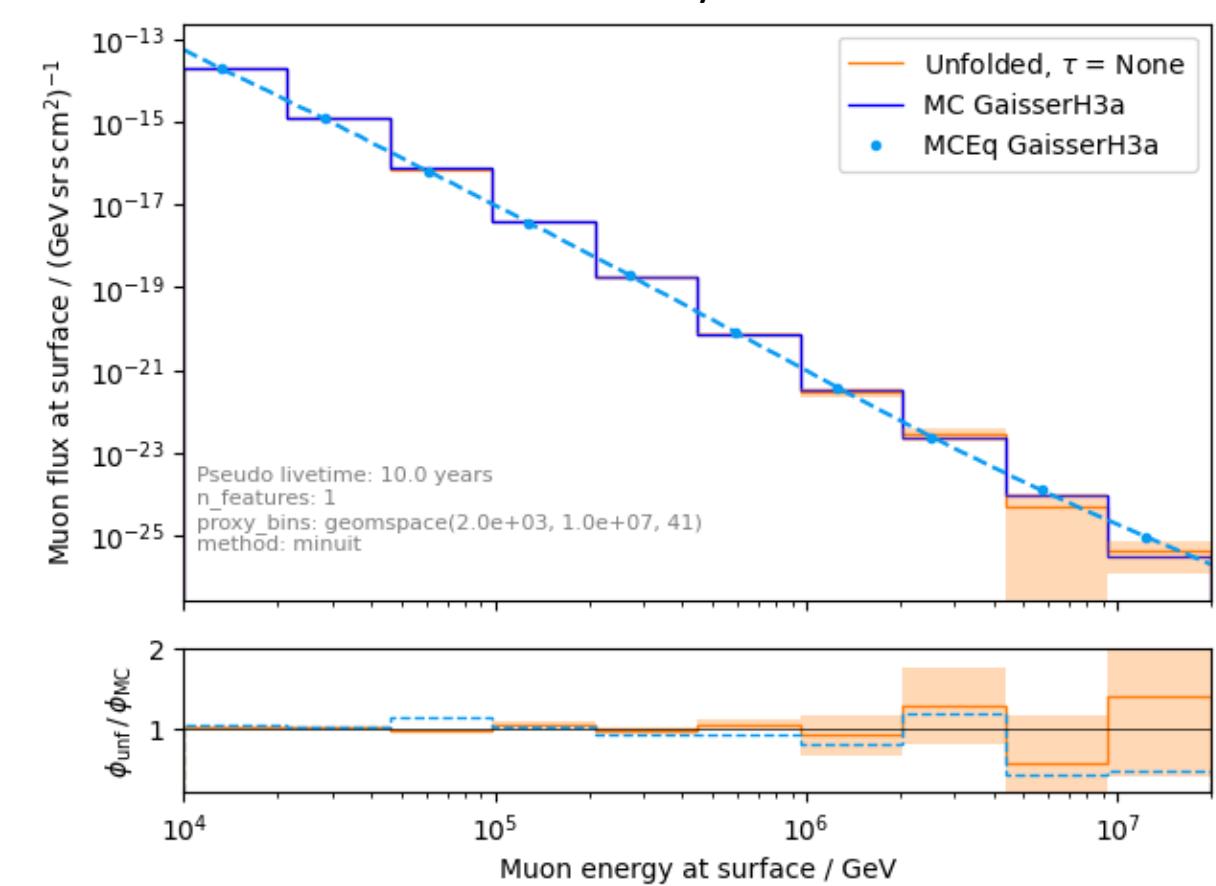


unfolding of muon flux at surface

1 year

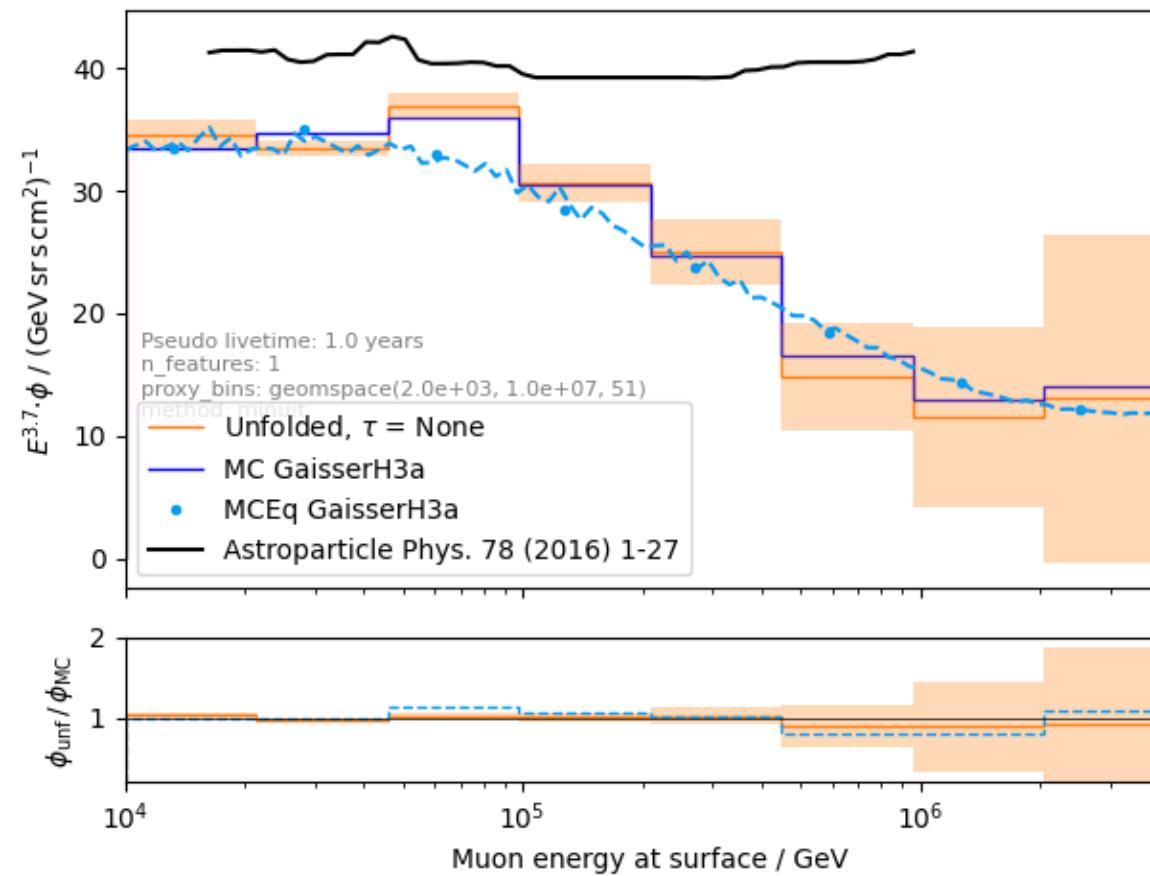


10 years

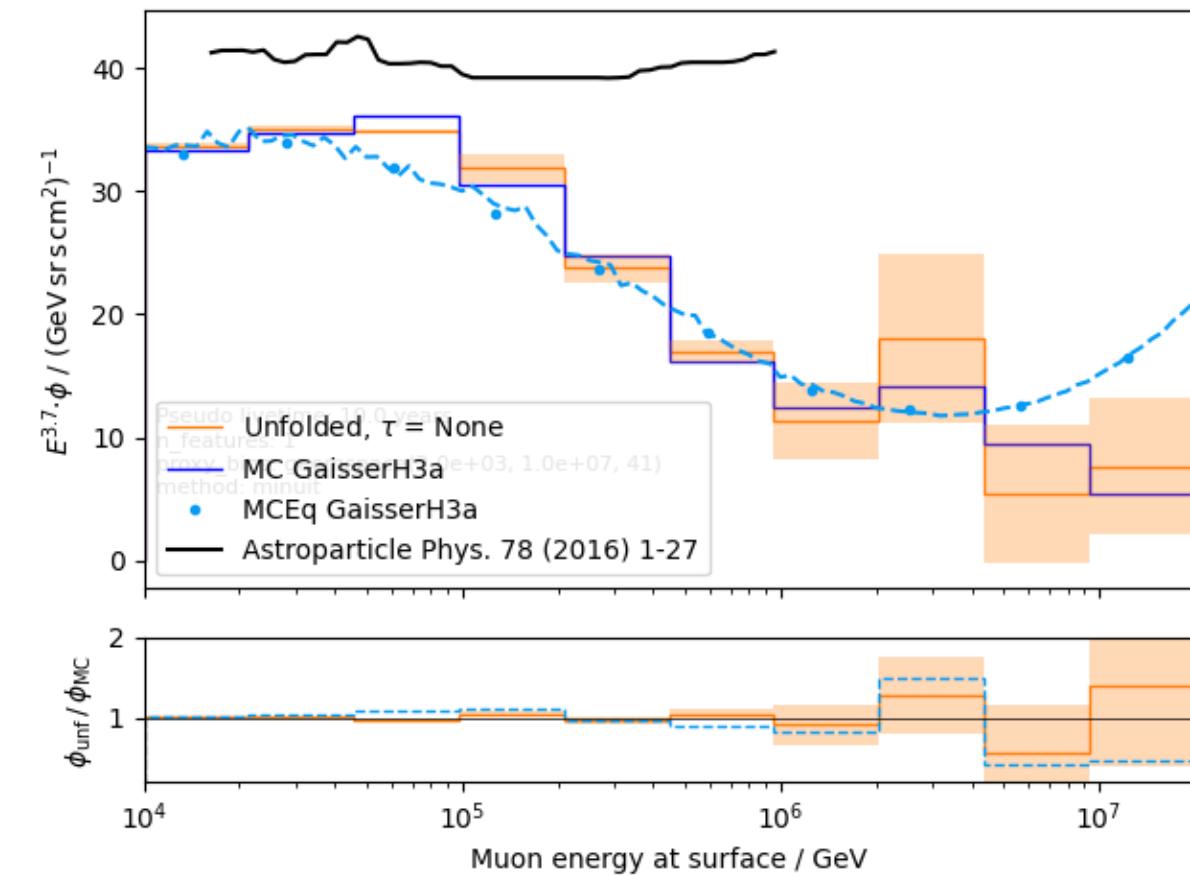


unfolding of muon flux at surface – weighted to $E^{3.7}$

1 year



10 years



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
- Fit of prompt normalization is promising
 - systematics need to be included
- Unfolding is set up
 - systematics can be included, minor investigations needed

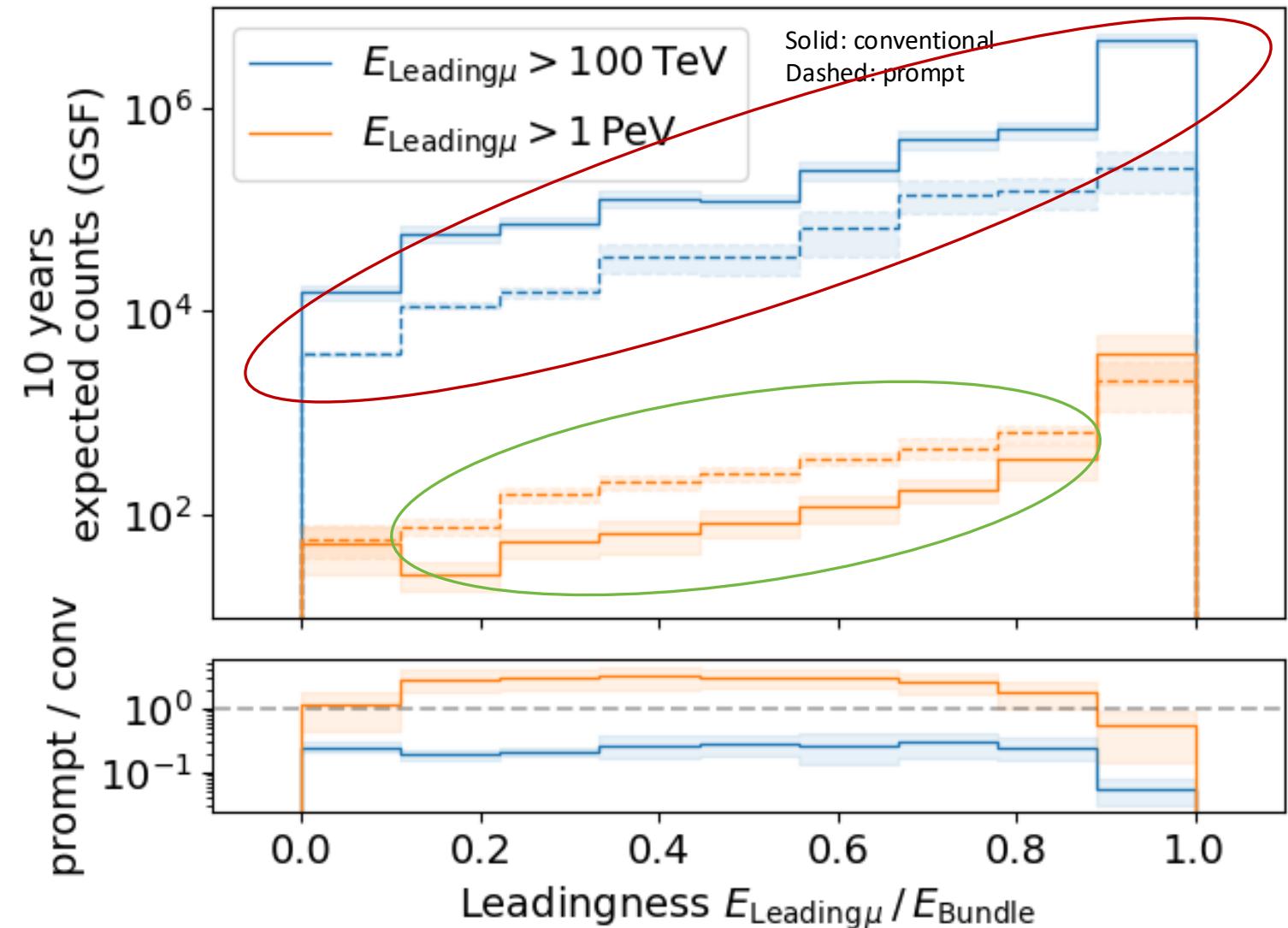


How ChatGPT illustrates the detection of a prompt muon with IceCube.

Backup

Leading muon energy fraction

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



Leading muon contribution

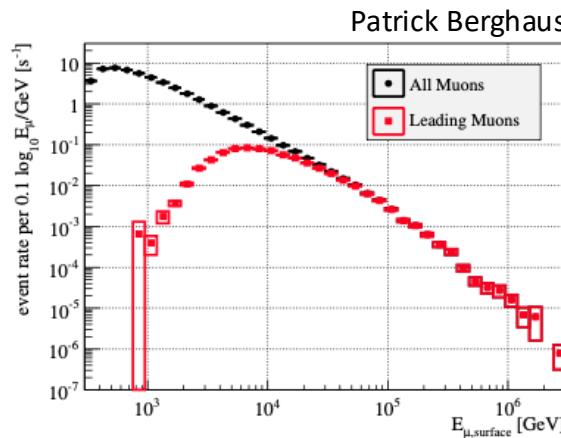
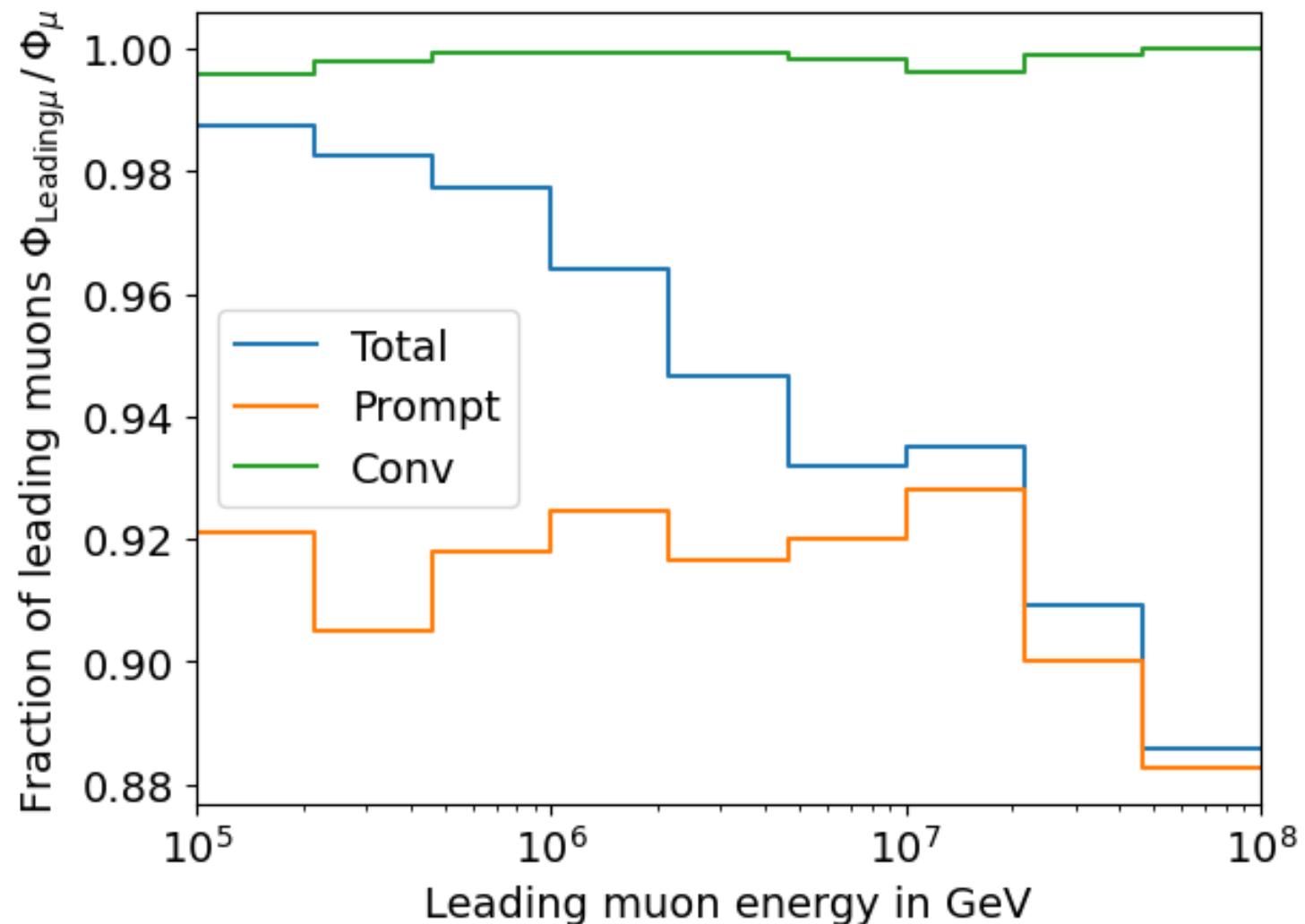


Figure 10: Surface energy distribution for all and most energetic (“leading”) muons in simulated events with a total of more than 1,000 registered photo-electrons in IceCube.

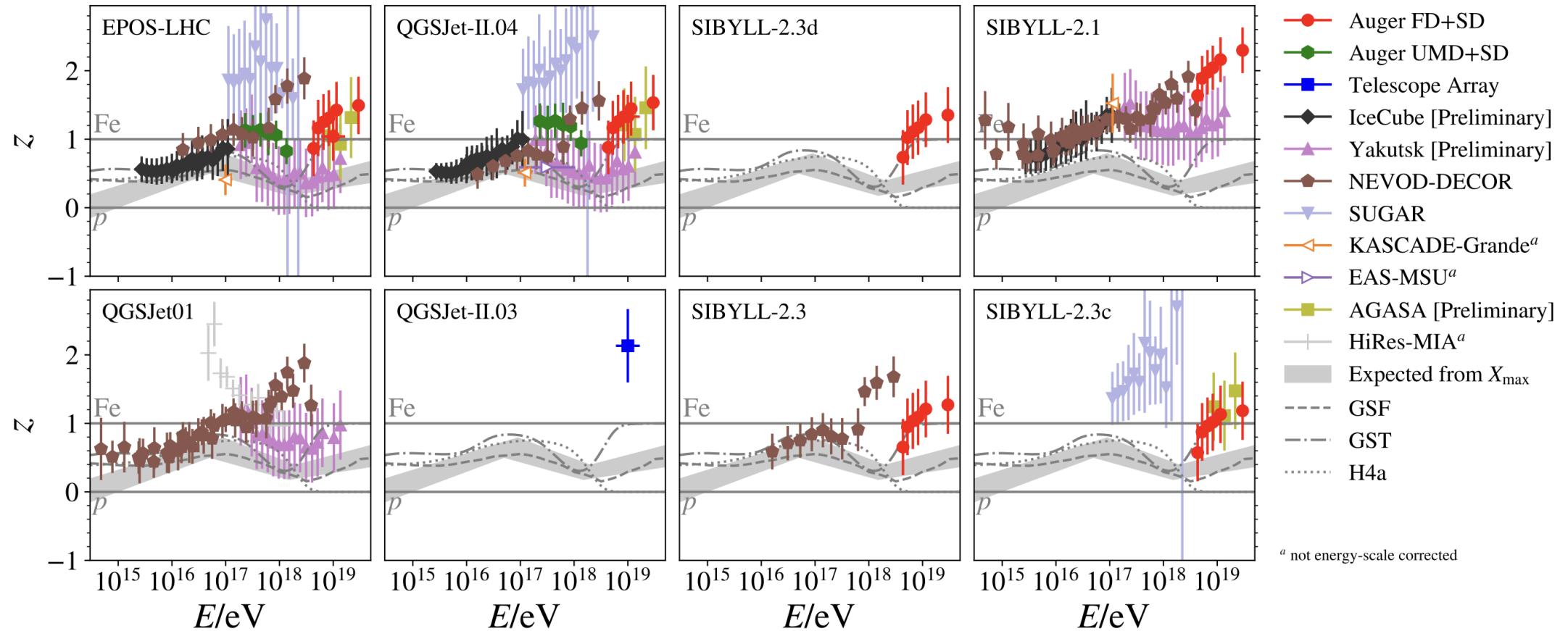
- Muons with energies between 100 TeV and 50 PeV dominate the bundle by more than 90%
 - In average conventional muons are more dominant than prompt
 - But: at high energies, there are more prompt than conventional events
- High leading energy fraction does not lead to more sensitivity to detect prompt



The Muon Puzzle

"muon number"

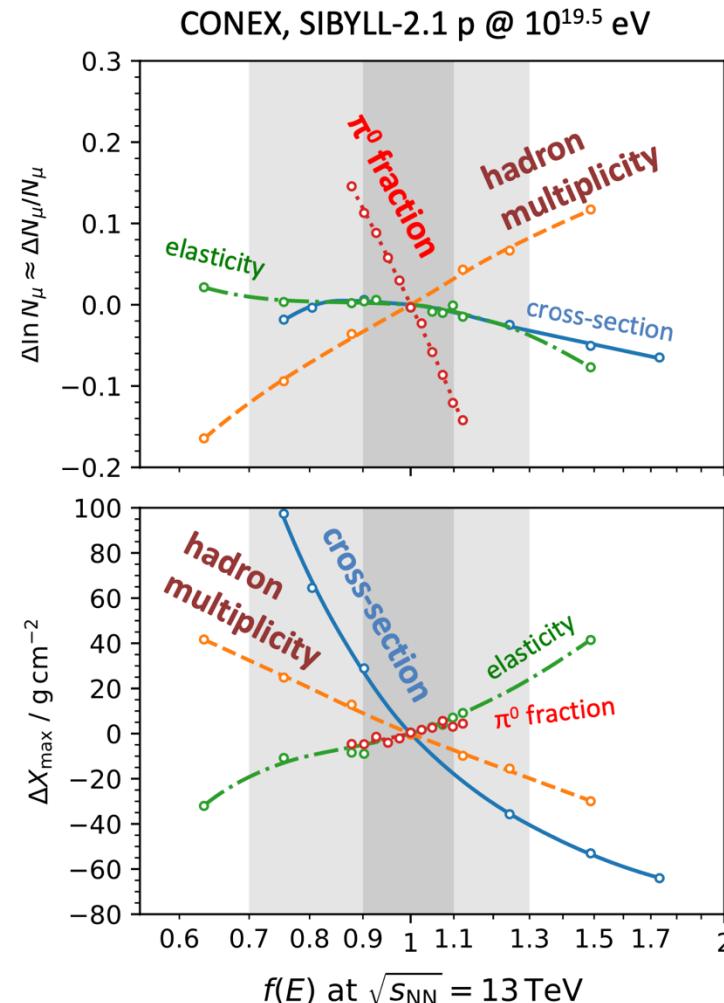
$$z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_p}{\ln\langle N_\mu \rangle_{\text{Fe}} - \ln\langle N_\mu \rangle_p}$$



2108.08341

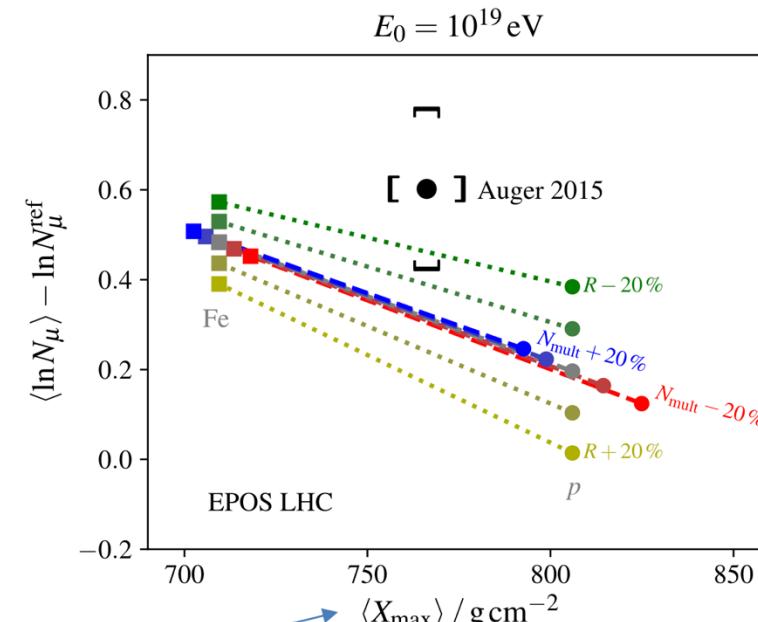
Possible Solutions

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

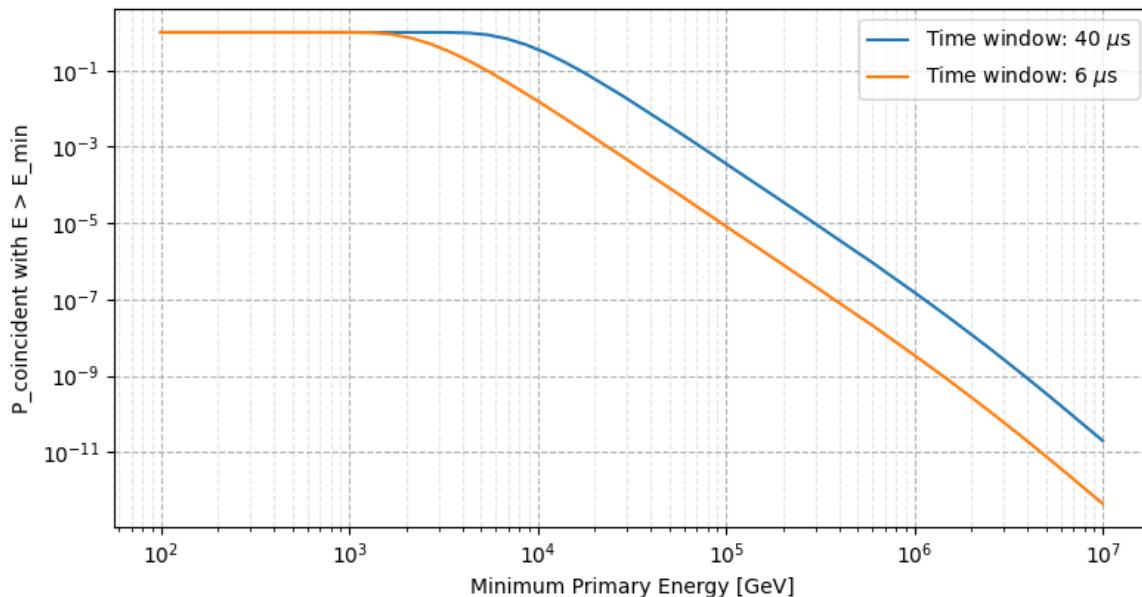
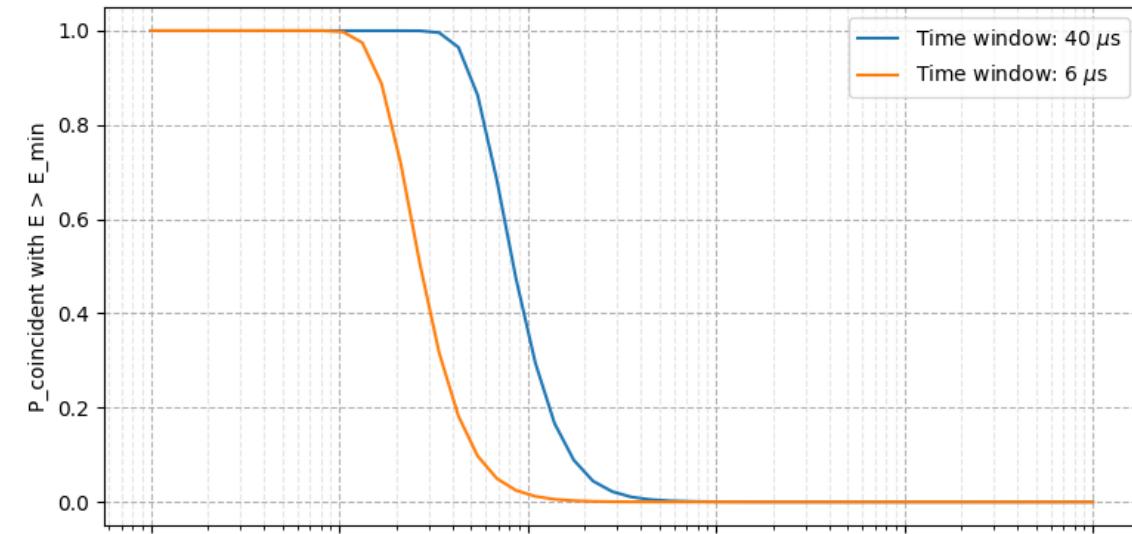


$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

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

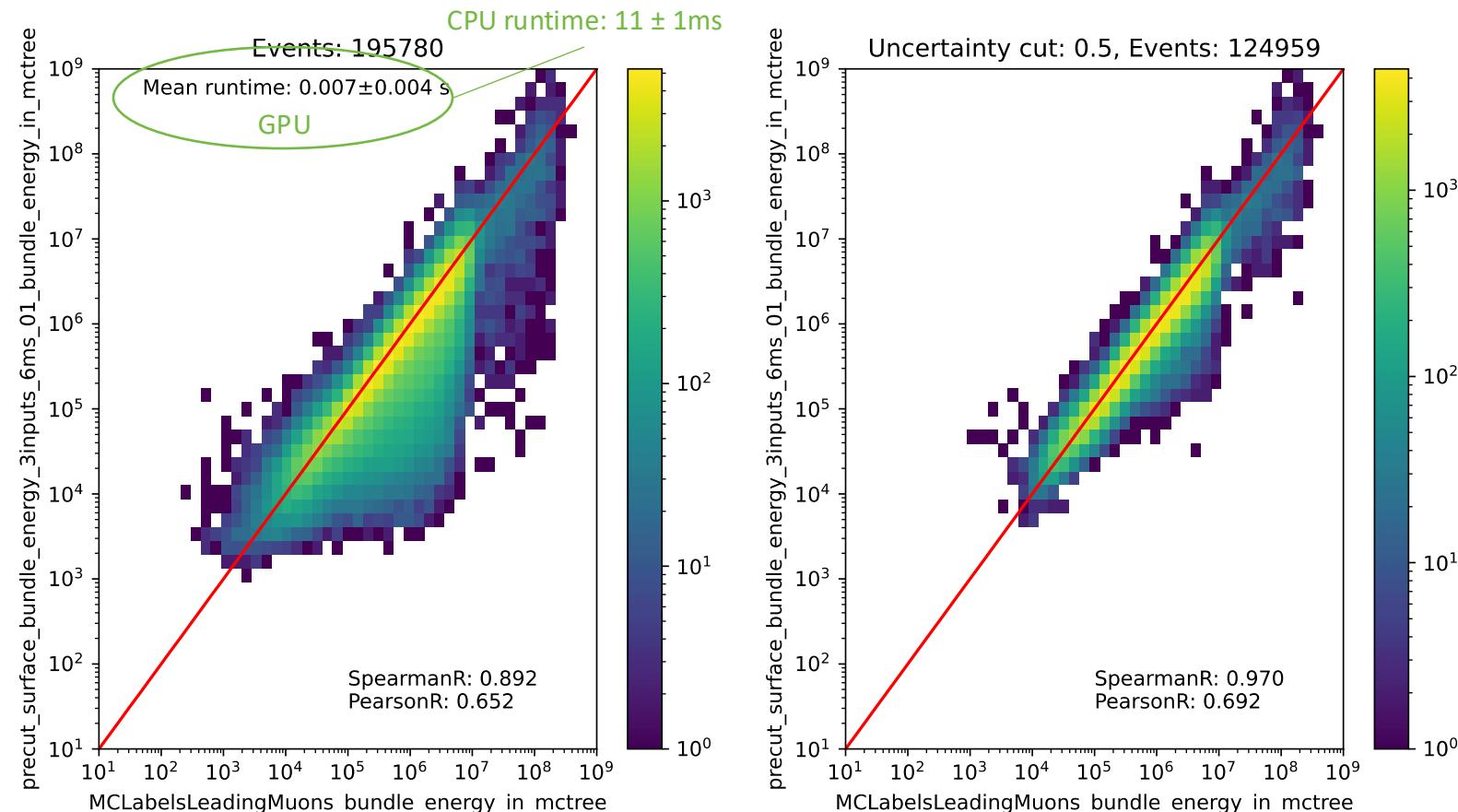
Simulation w/o coincident events

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



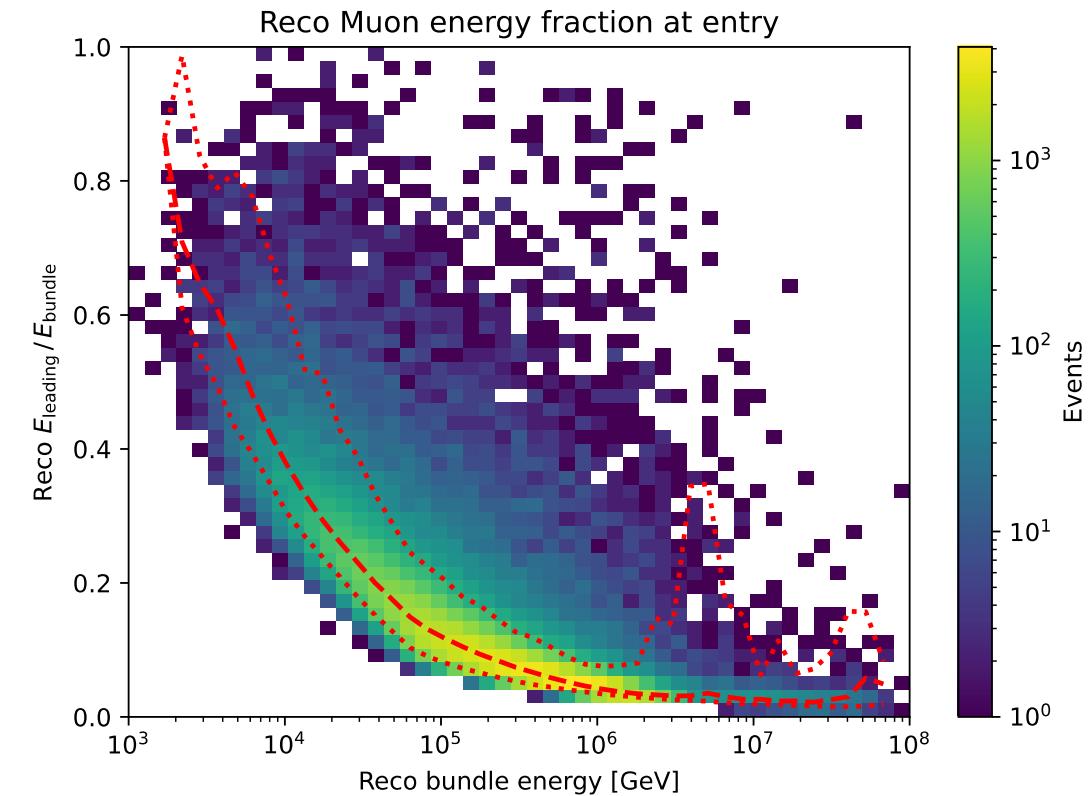
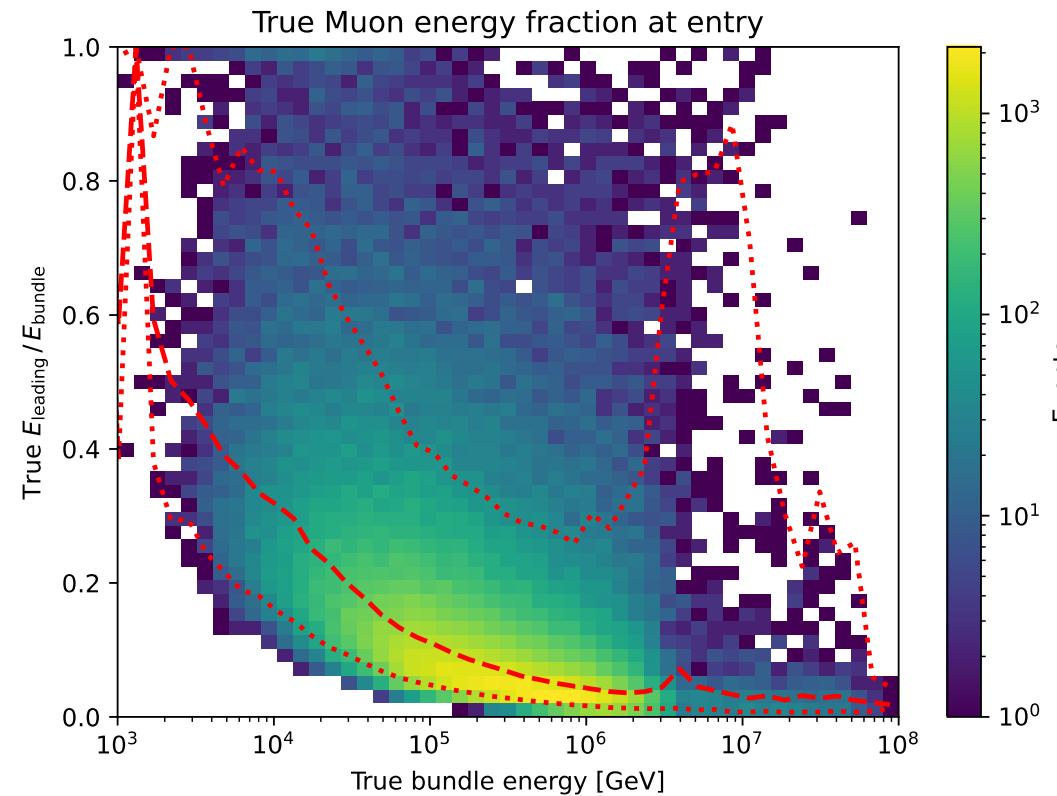
Bundle energy cut

- 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

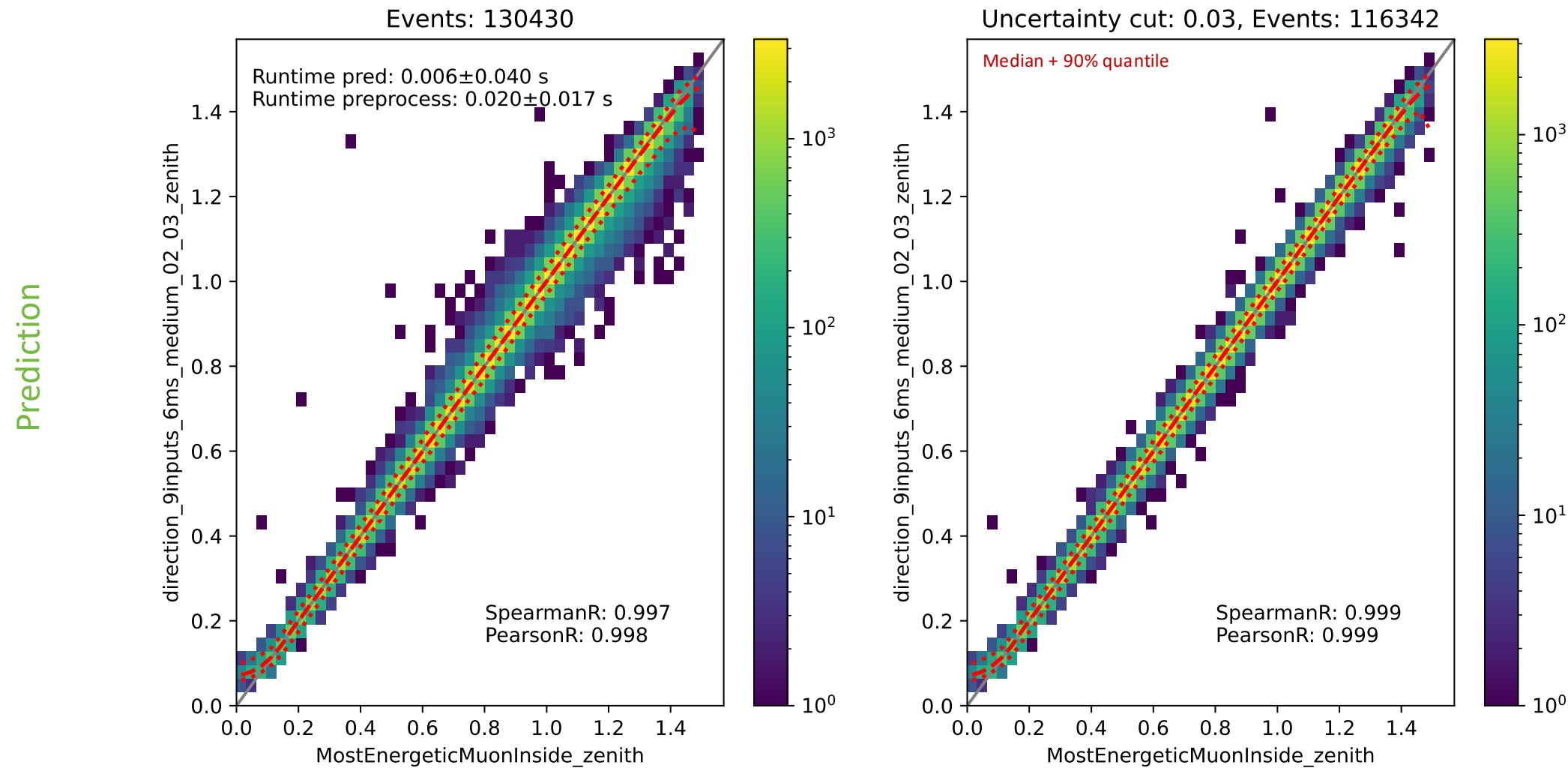


Leading muon energy fraction - leadingness

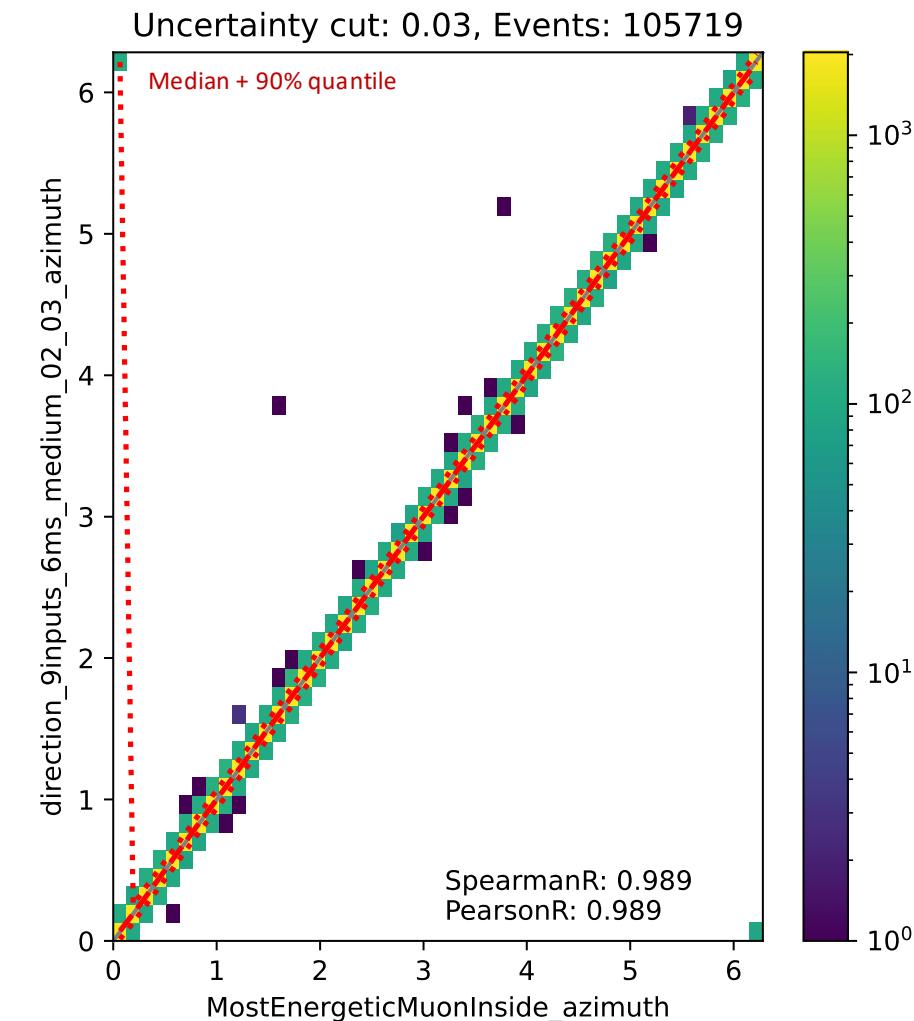
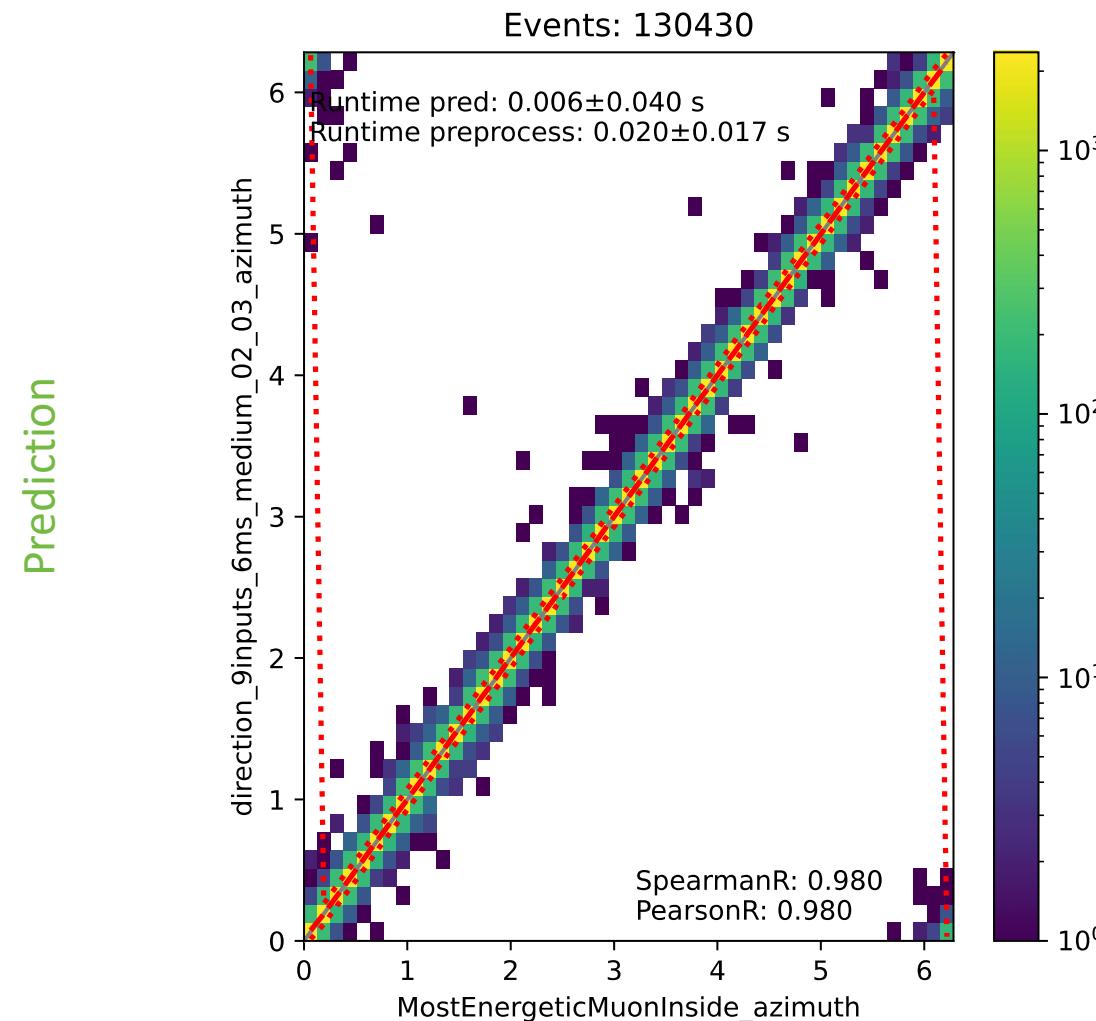
- True muon energy fraction is smeared
- Network tries to predict the median of the distribution



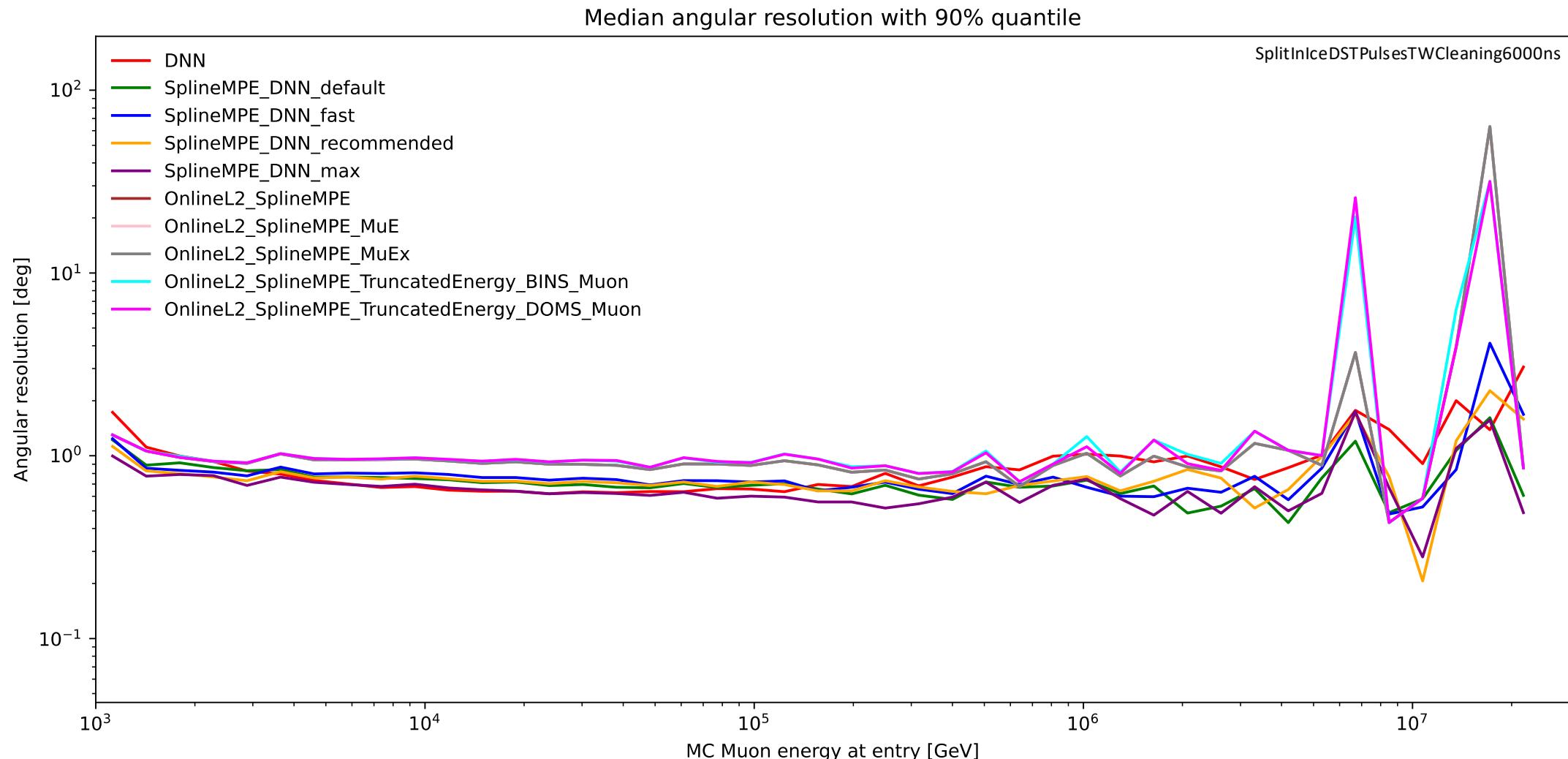
Zenith – 6 ms cleaned pulses



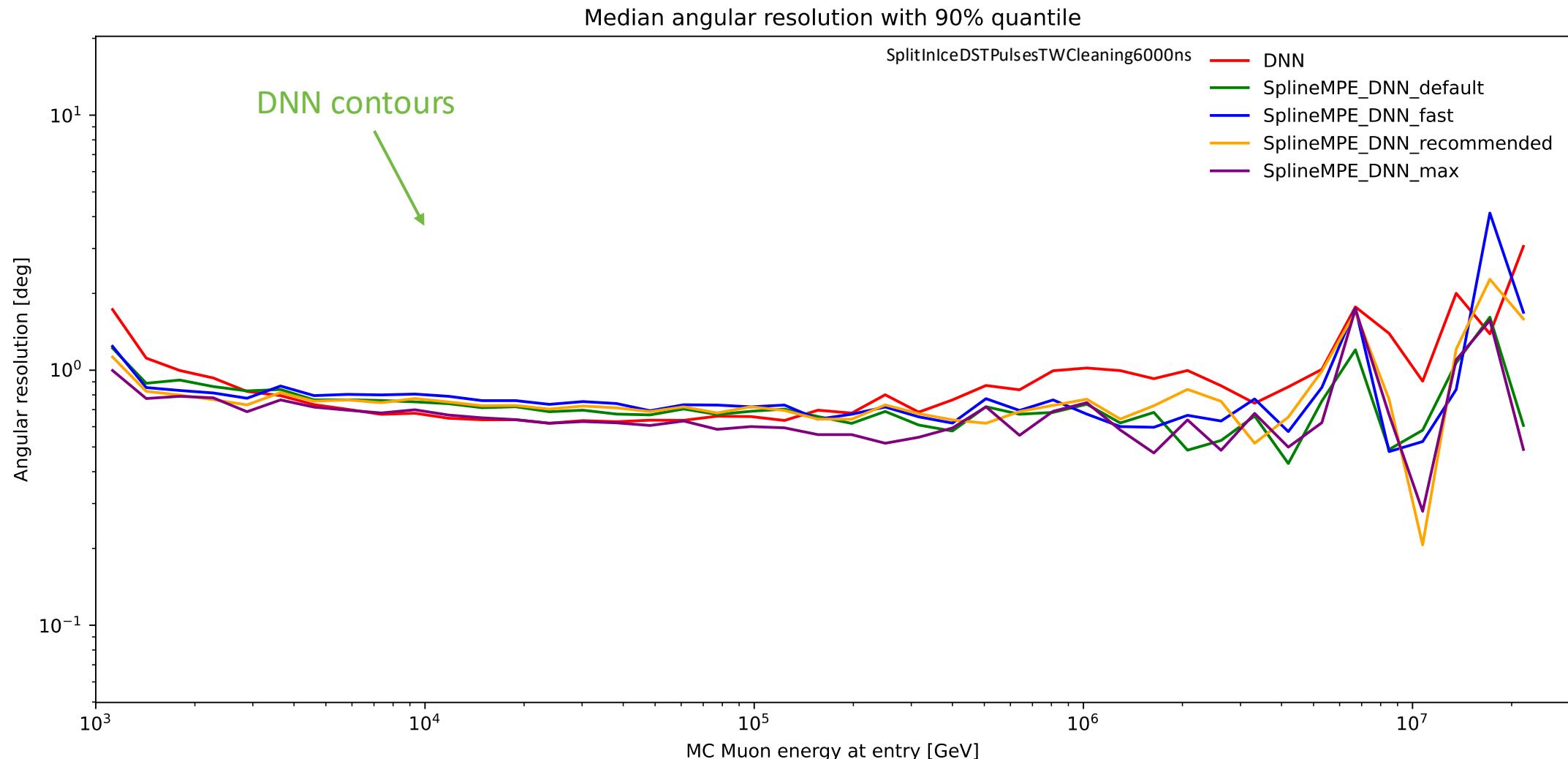
Azimuth – 6 ms cleaned pulses

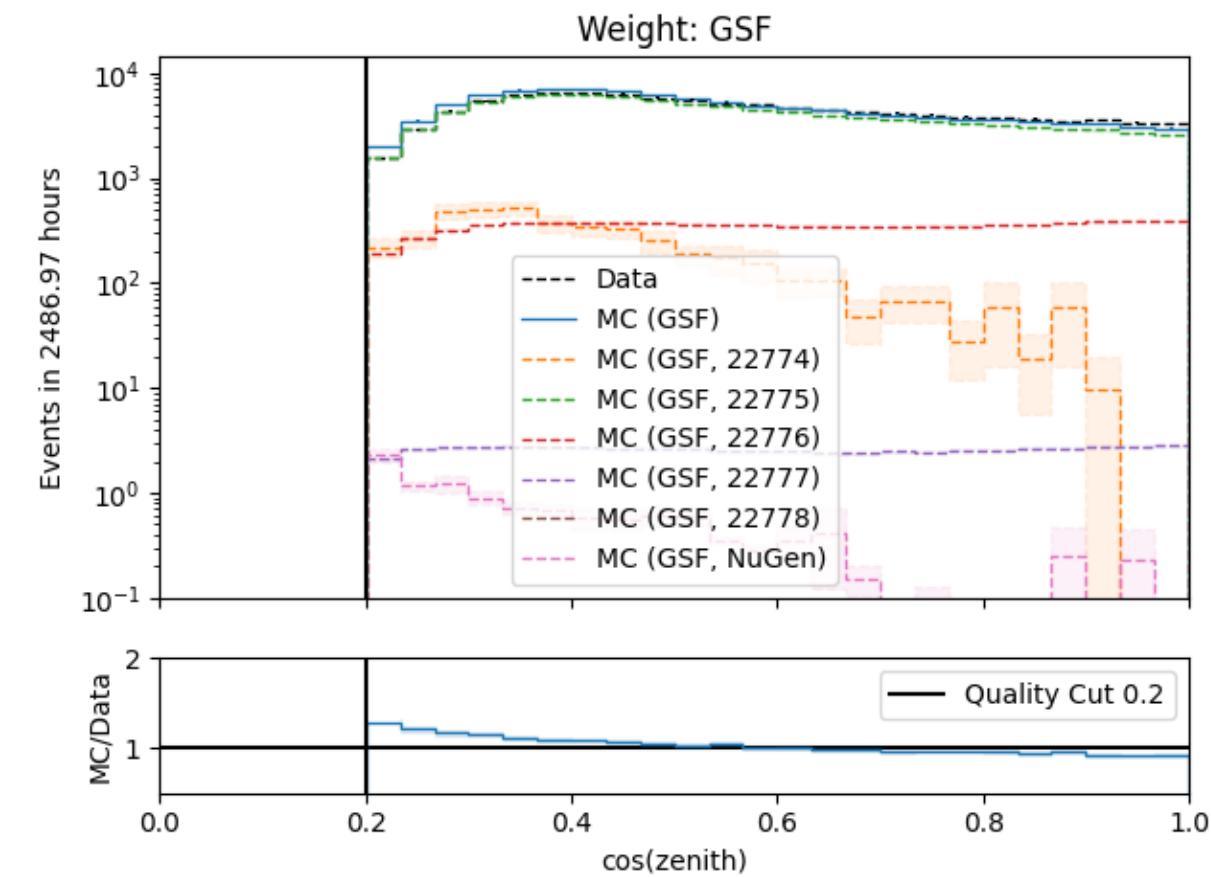
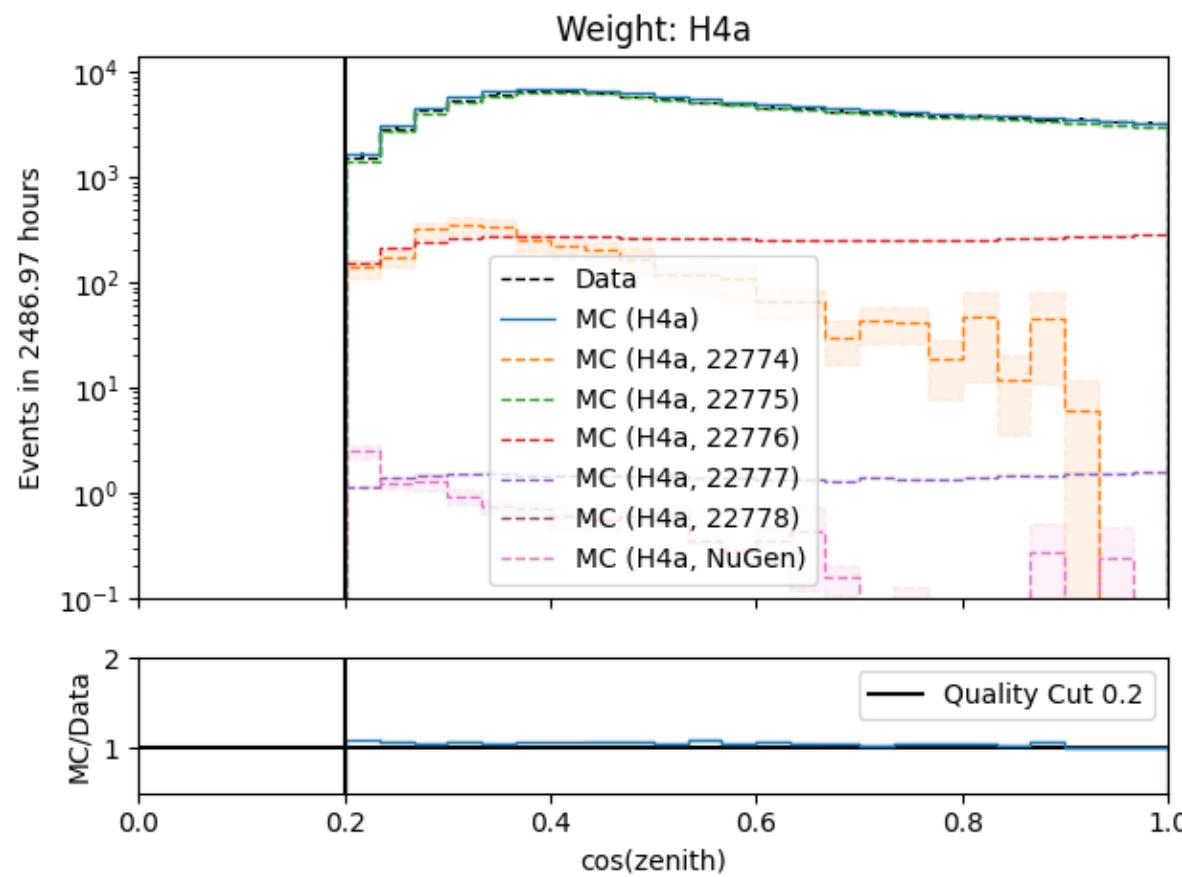


SplineMPE – DNN and conventional seeds

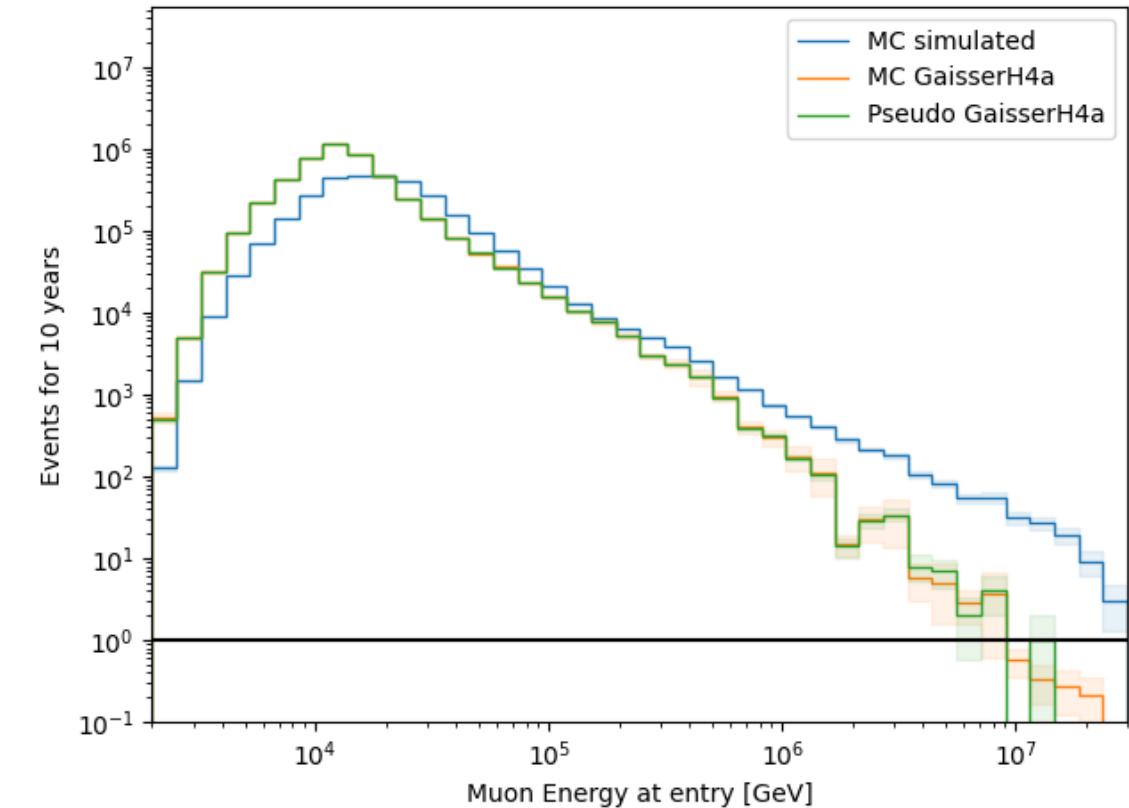
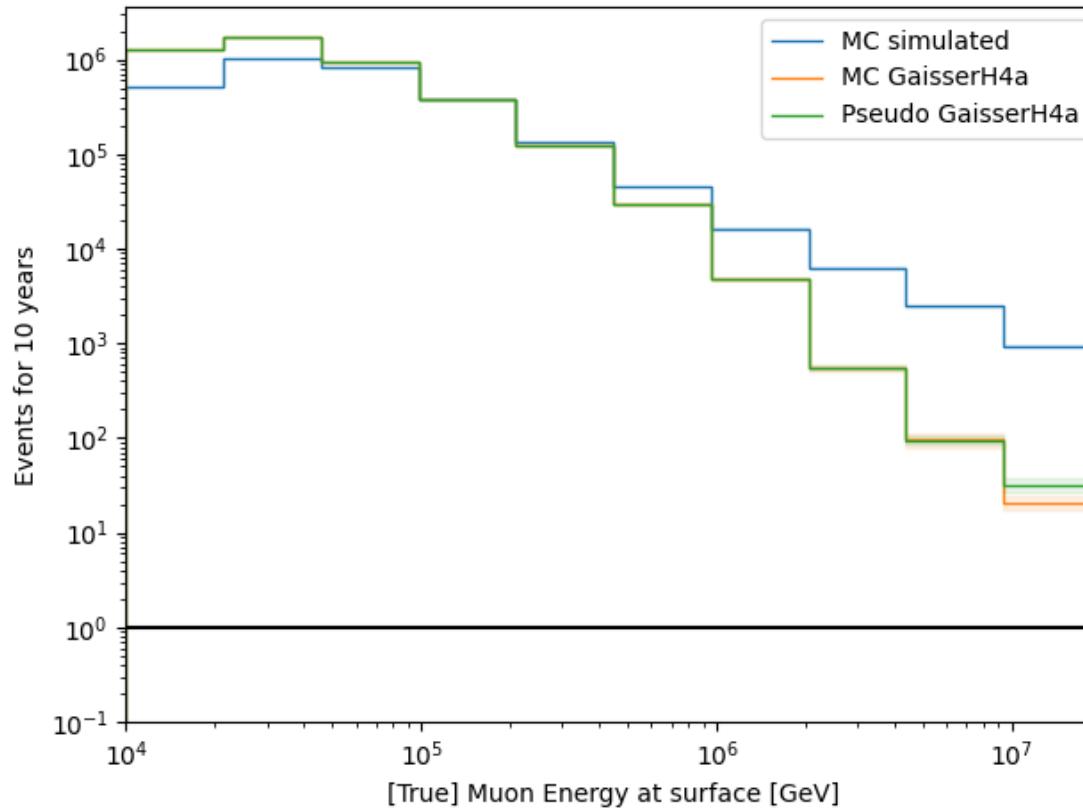


SplineMPE – DNN seeds

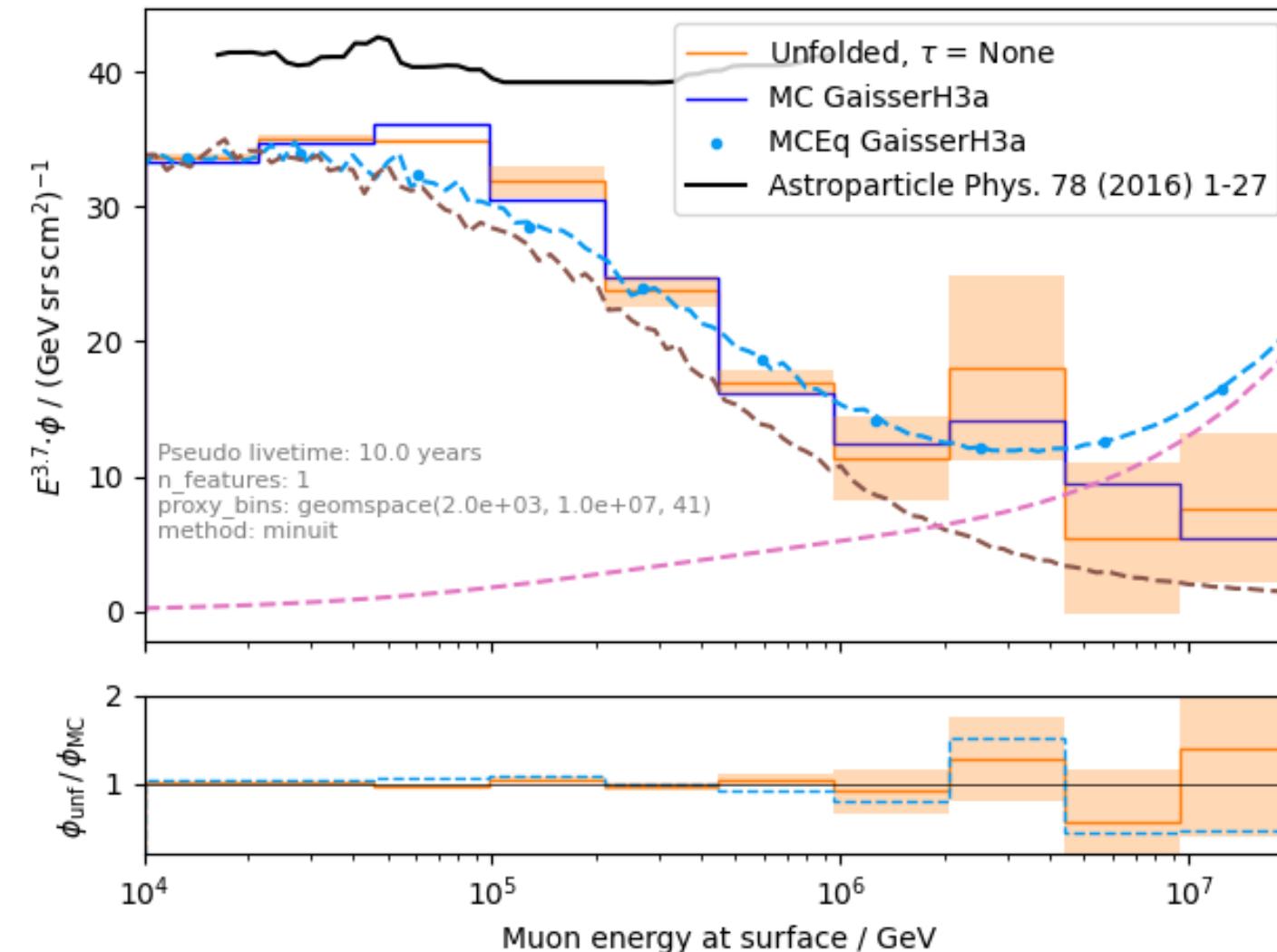


Level5: $\cos(\text{zenith})$ 

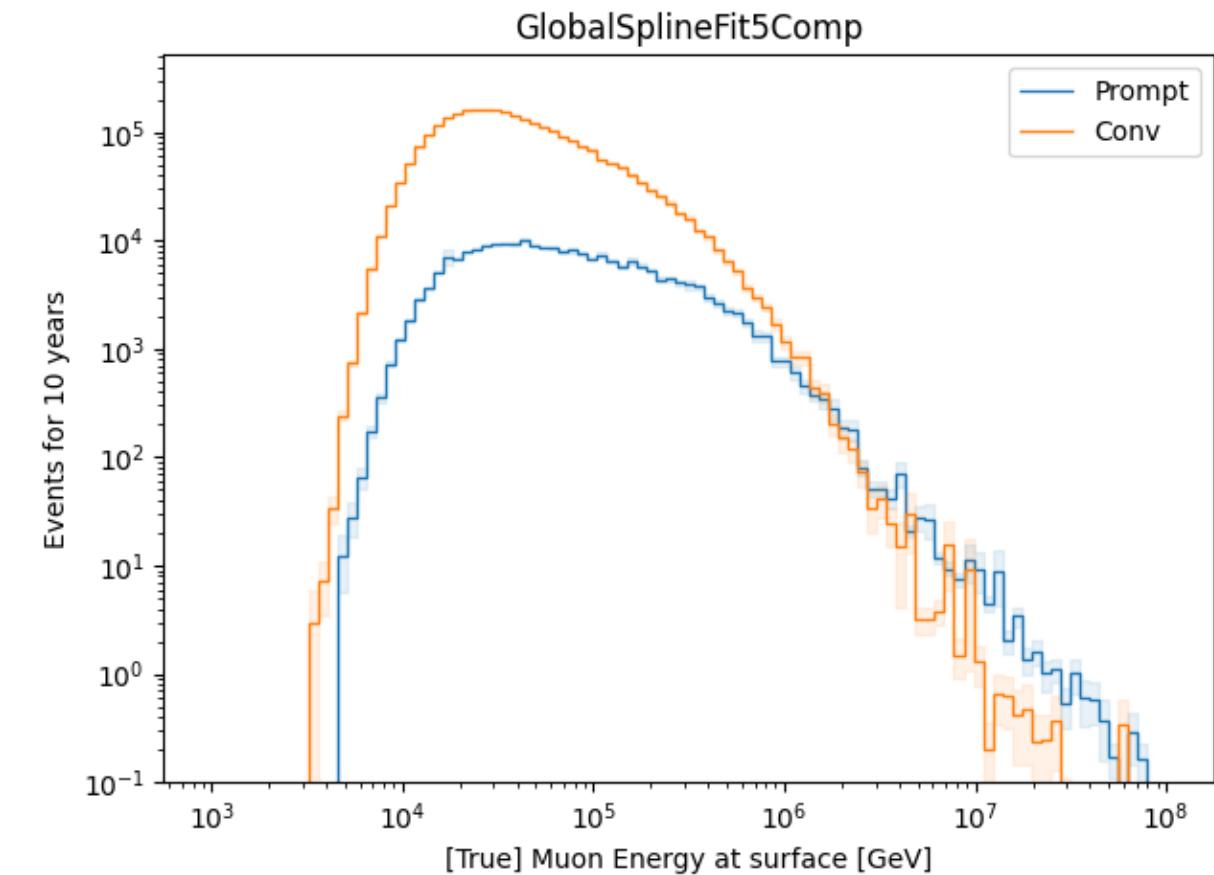
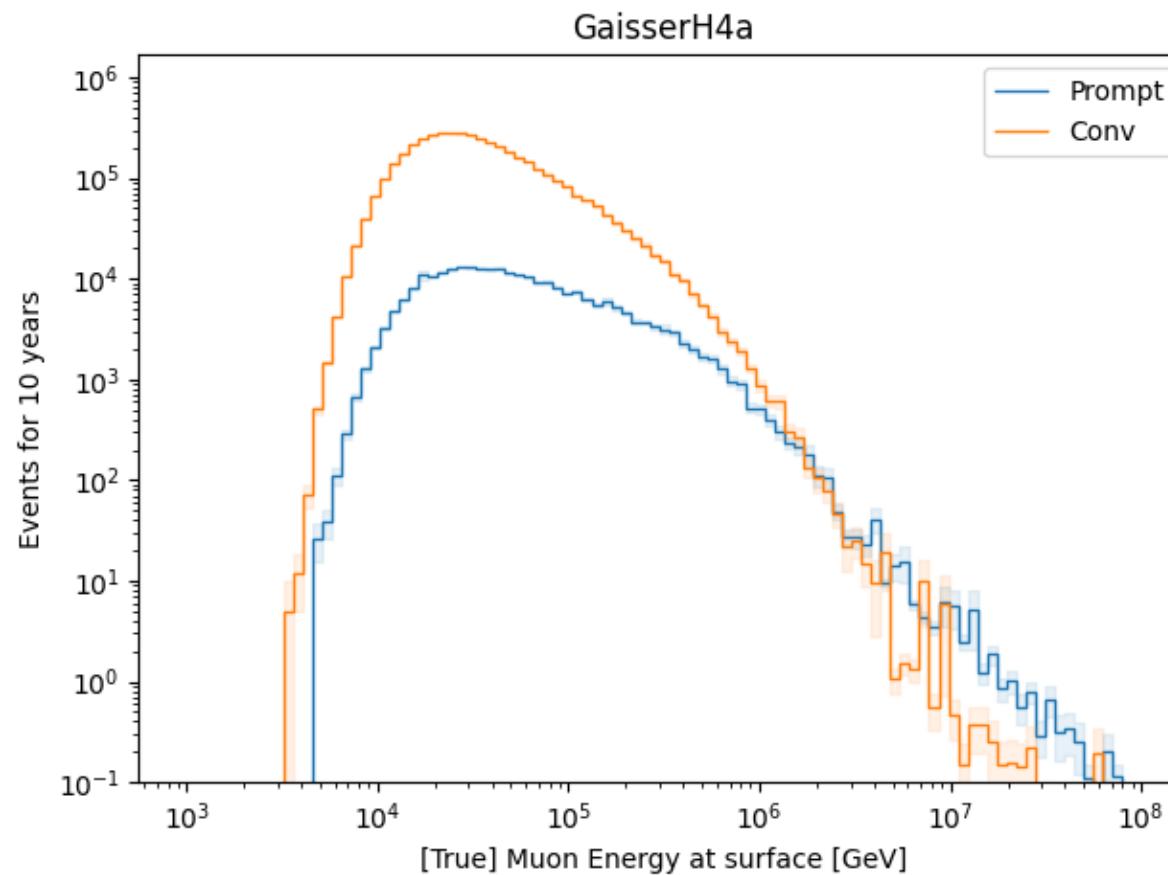
Proxy and target variable for unfolding – 10 years [H4a]



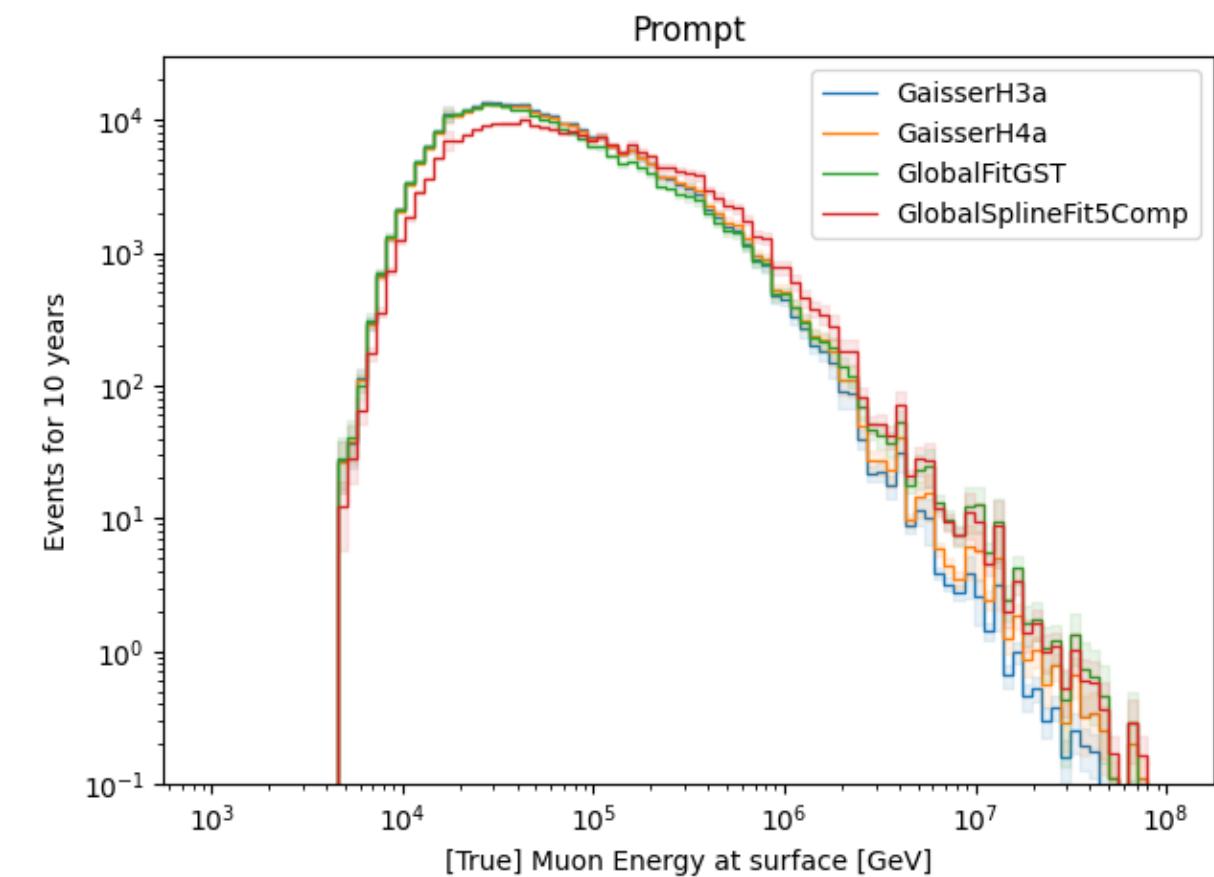
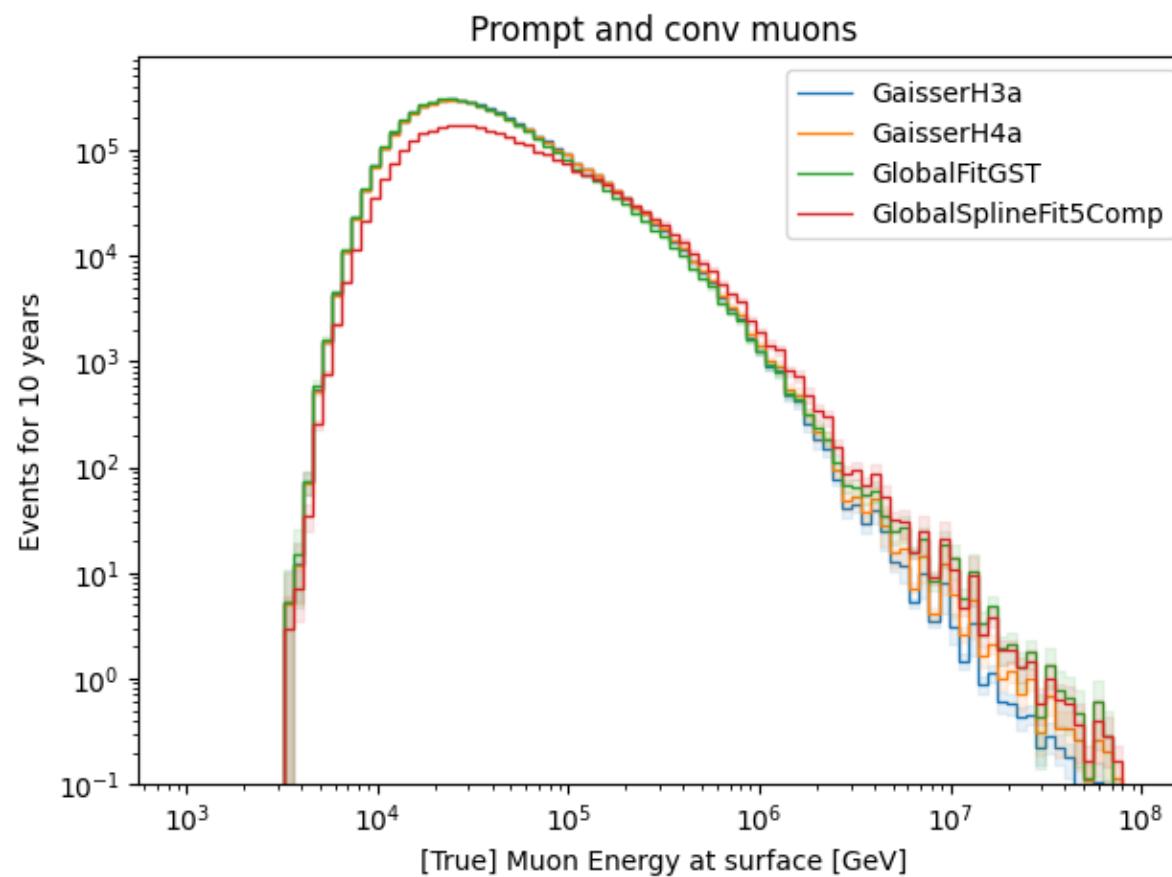
Unfolding with prompt and conv MCEq



Prompt and conv: muon energy at surface for 10 years

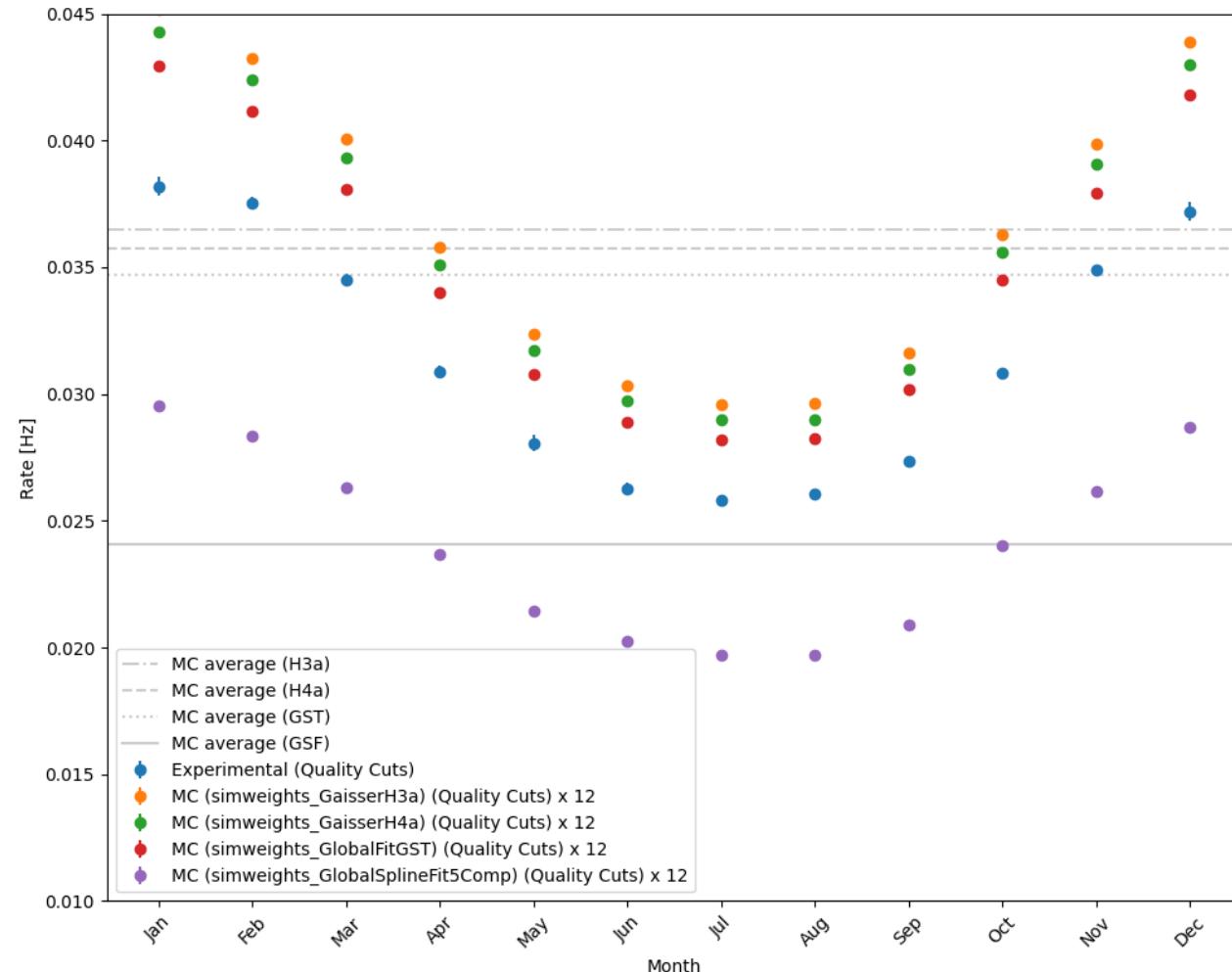


Compare all primary fluxes

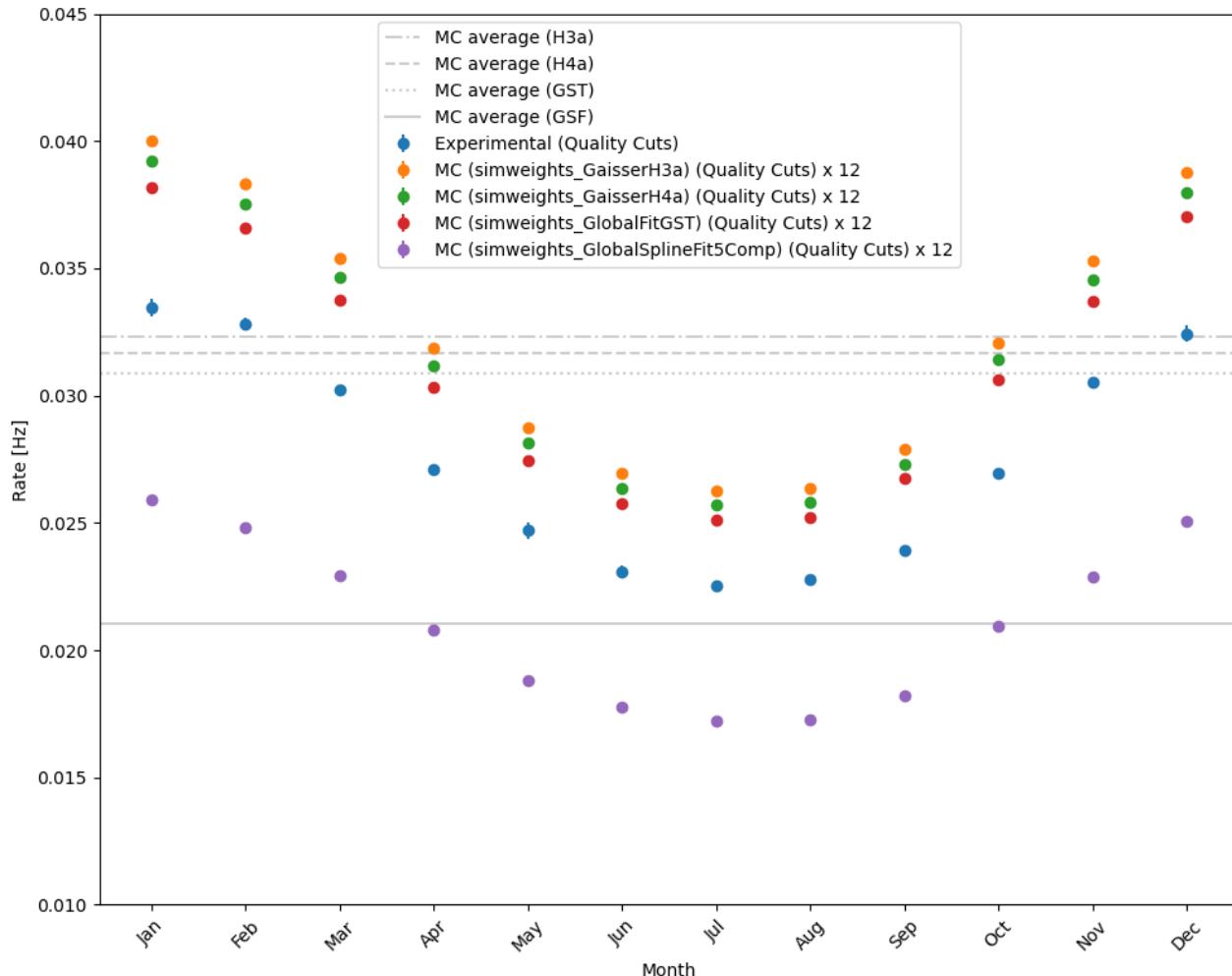


Rates per month

before quality cuts



after quality cuts



Rates per month: scaled

