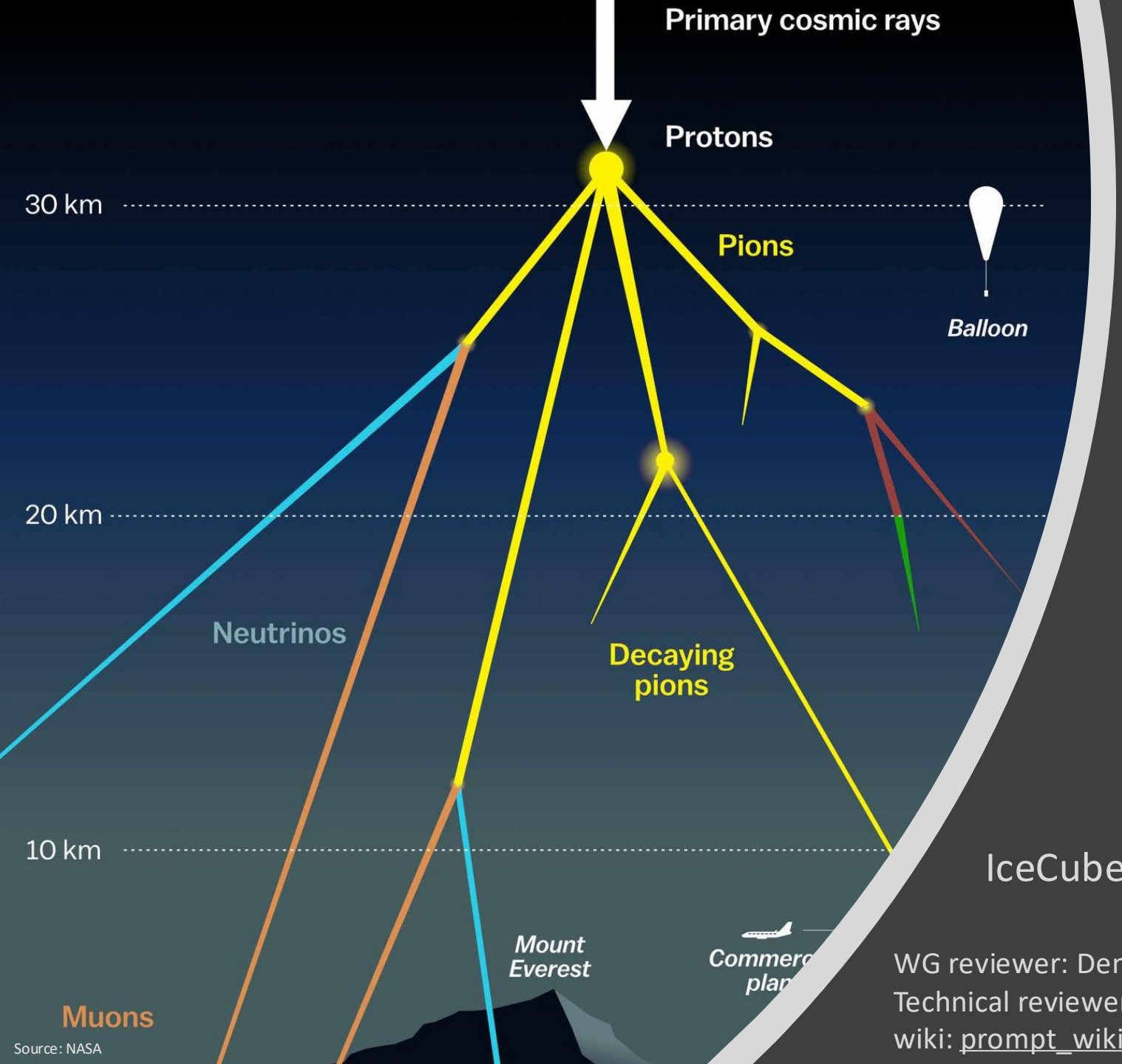


Measuring the prompt component of the atmospheric muon flux

Pascal Gutjahr

IceCube Collaboration Meeting Fall 2024, Madison

WG reviewer: Dennis Soldin
Technical reviewer: Karolin Hymon
wiki: prompt_wiki

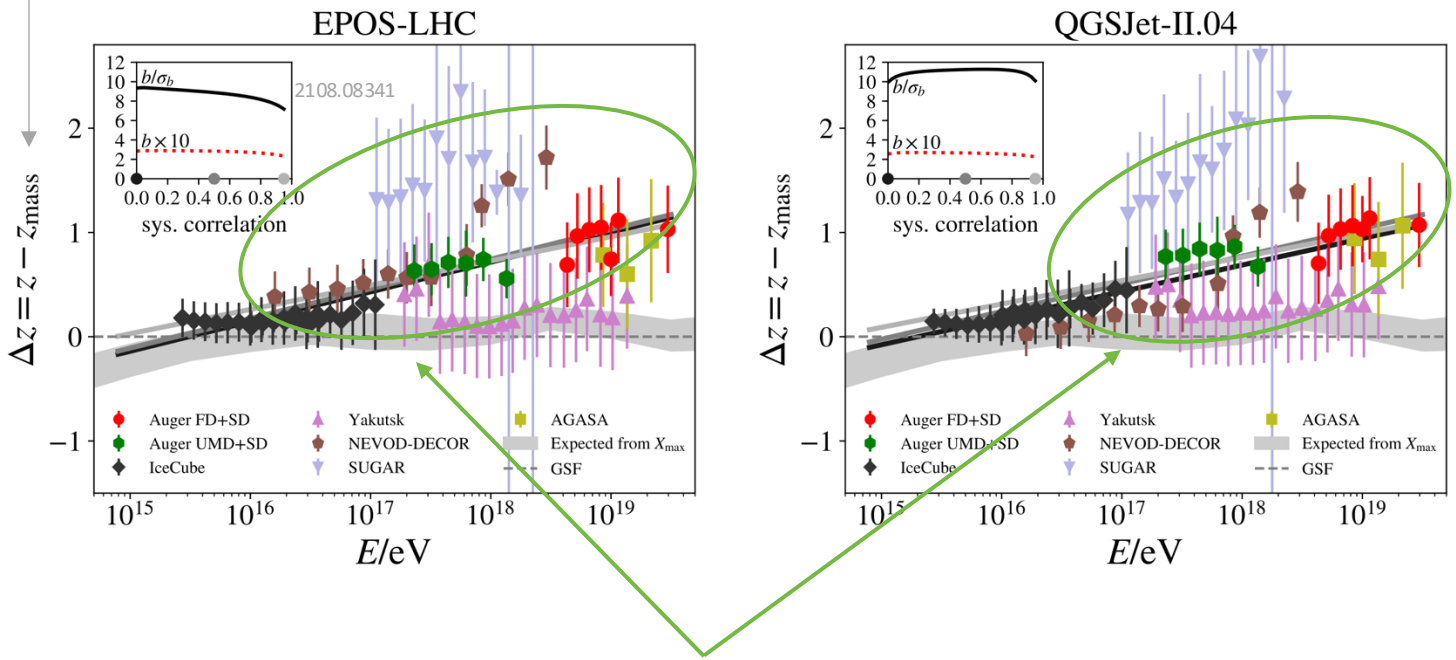
September 25, 2024

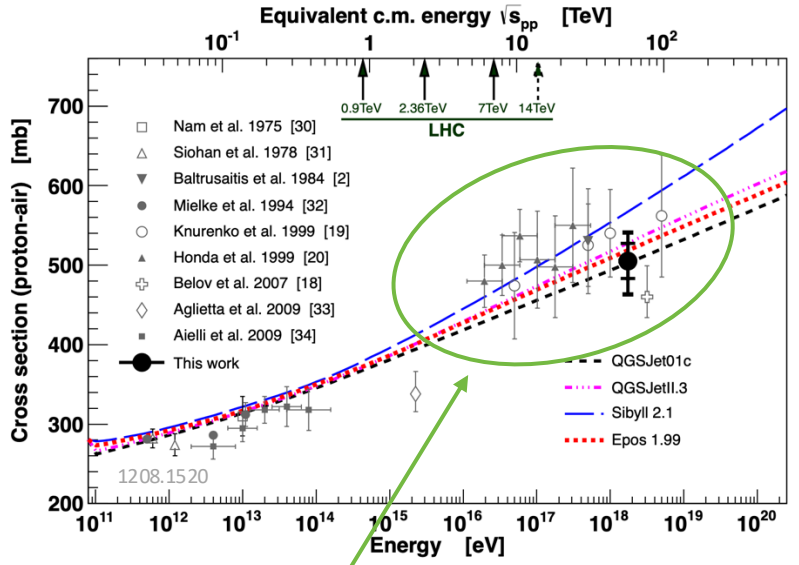
Muon puzzle and hadronic uncertainties

”muon number”

Expected z
(“muon number”)

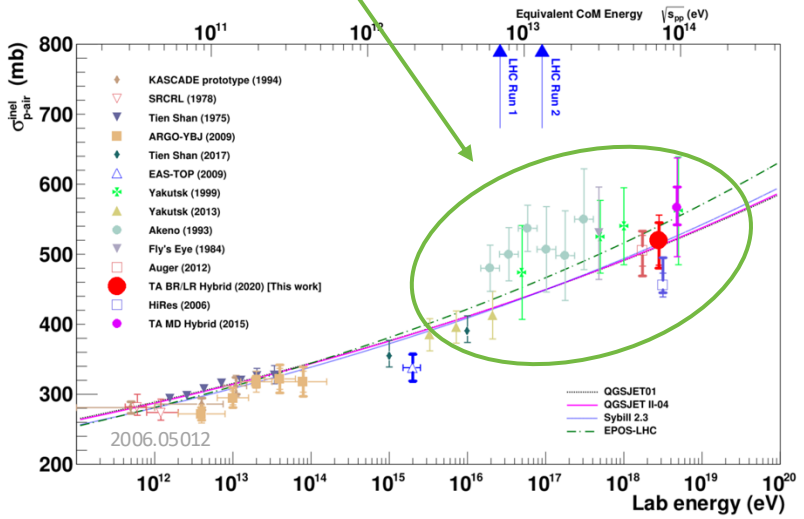
$$z = \frac{\ln\langle N_\mu\rangle - \ln\langle N_\mu\rangle_p}{\ln\langle N_\mu\rangle_{\mathrm{Fe}} - \ln\langle N_\mu\rangle_p}$$





2012

➢ Uncertainties at E > 10 PeV



2020

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

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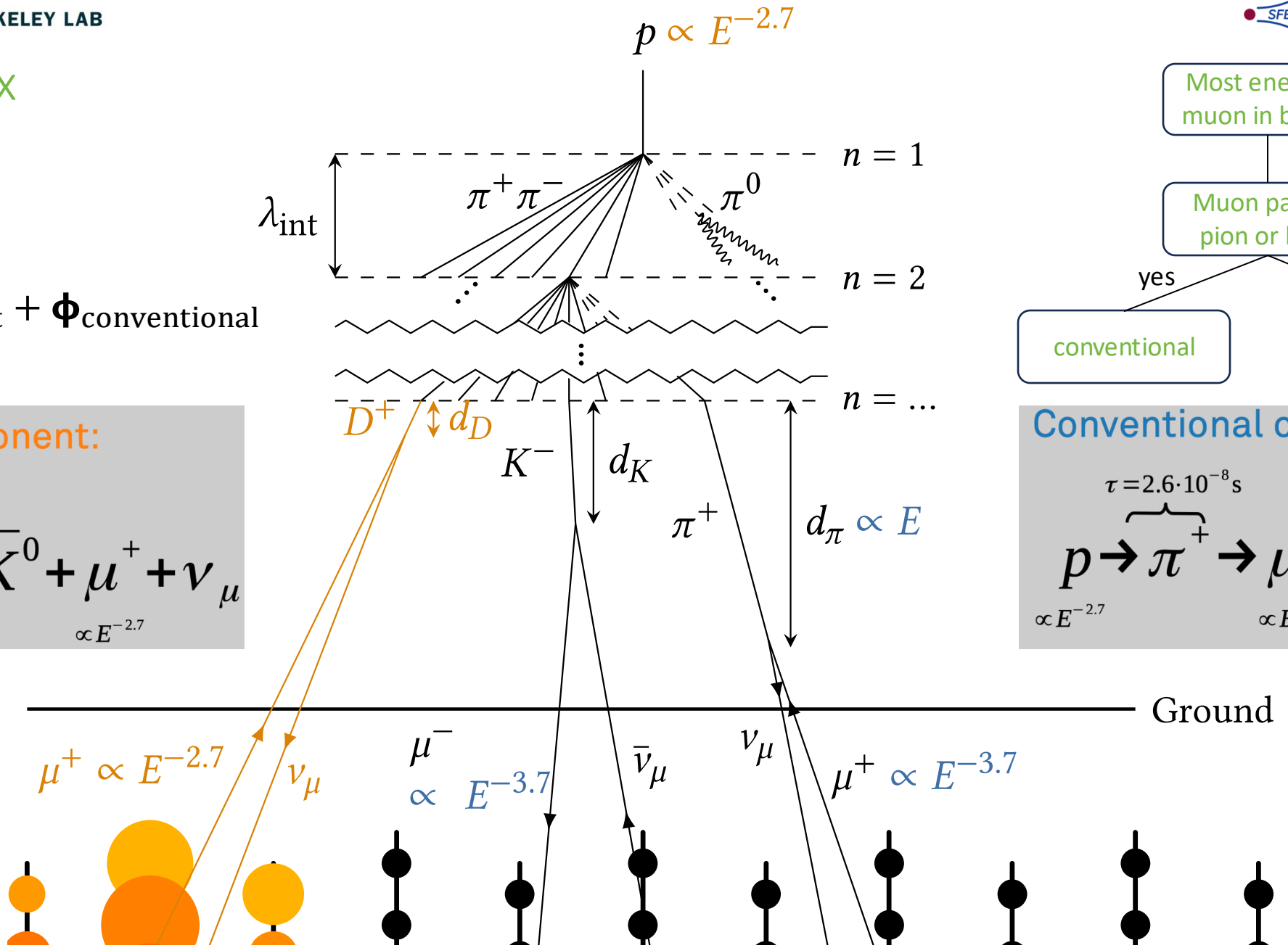
Muon flux

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



prompt component:

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

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

Conventional component:

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

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

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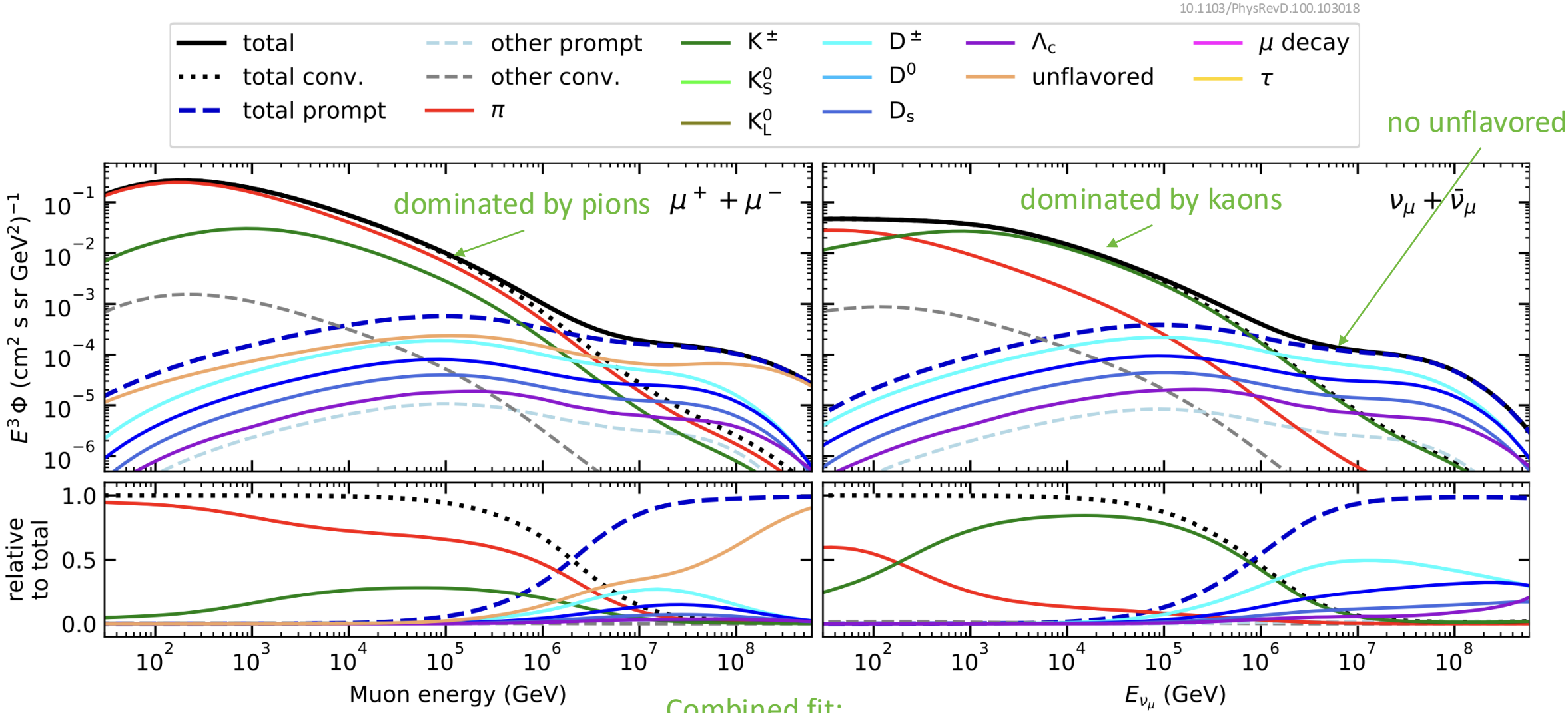
Credit: Ludwig Neste

Prompt atmospheric muons and neutrinos

10.1103/PhysRevD.100.103018



Combined fit:

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

Analysis goals

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

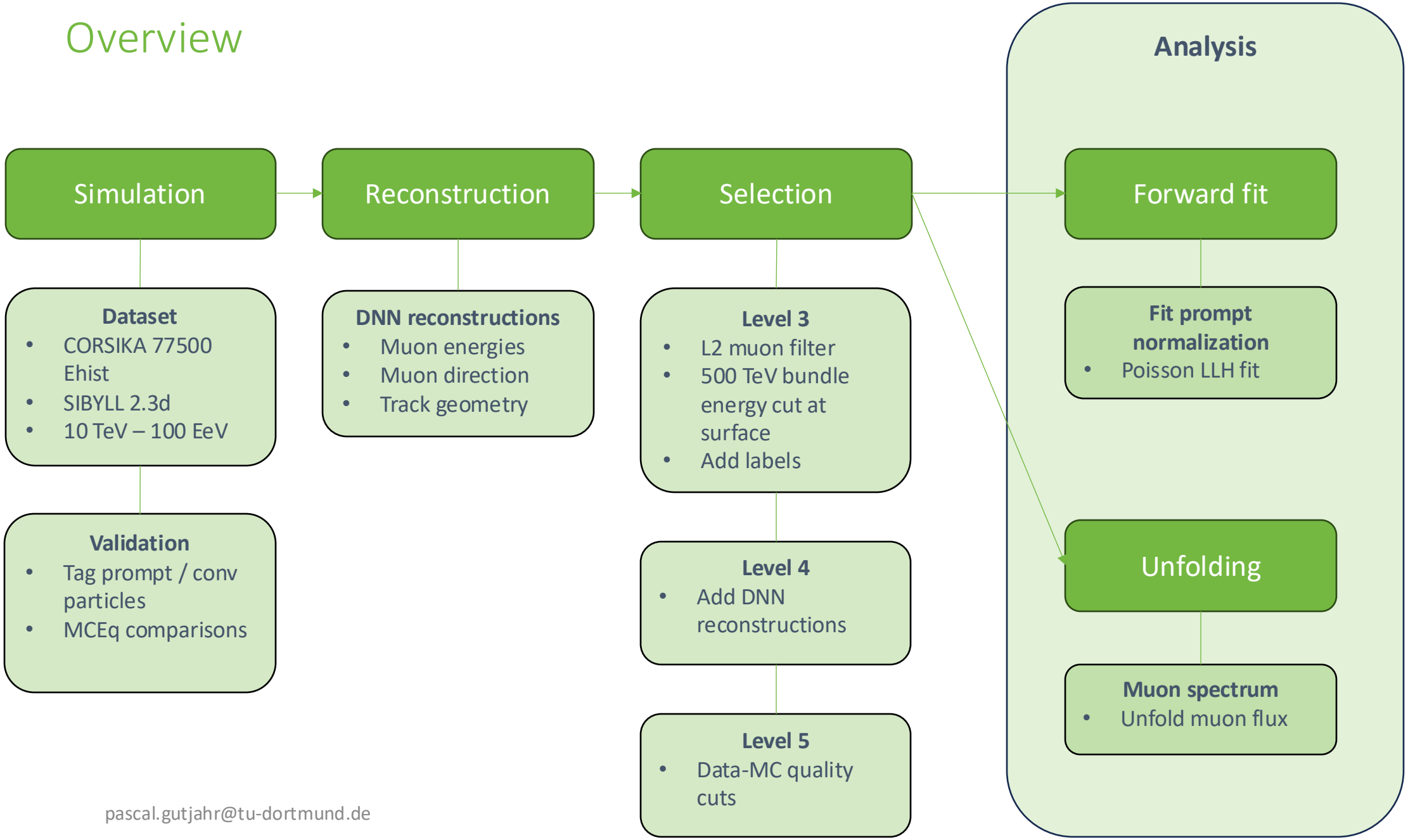
Idea:

- 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:

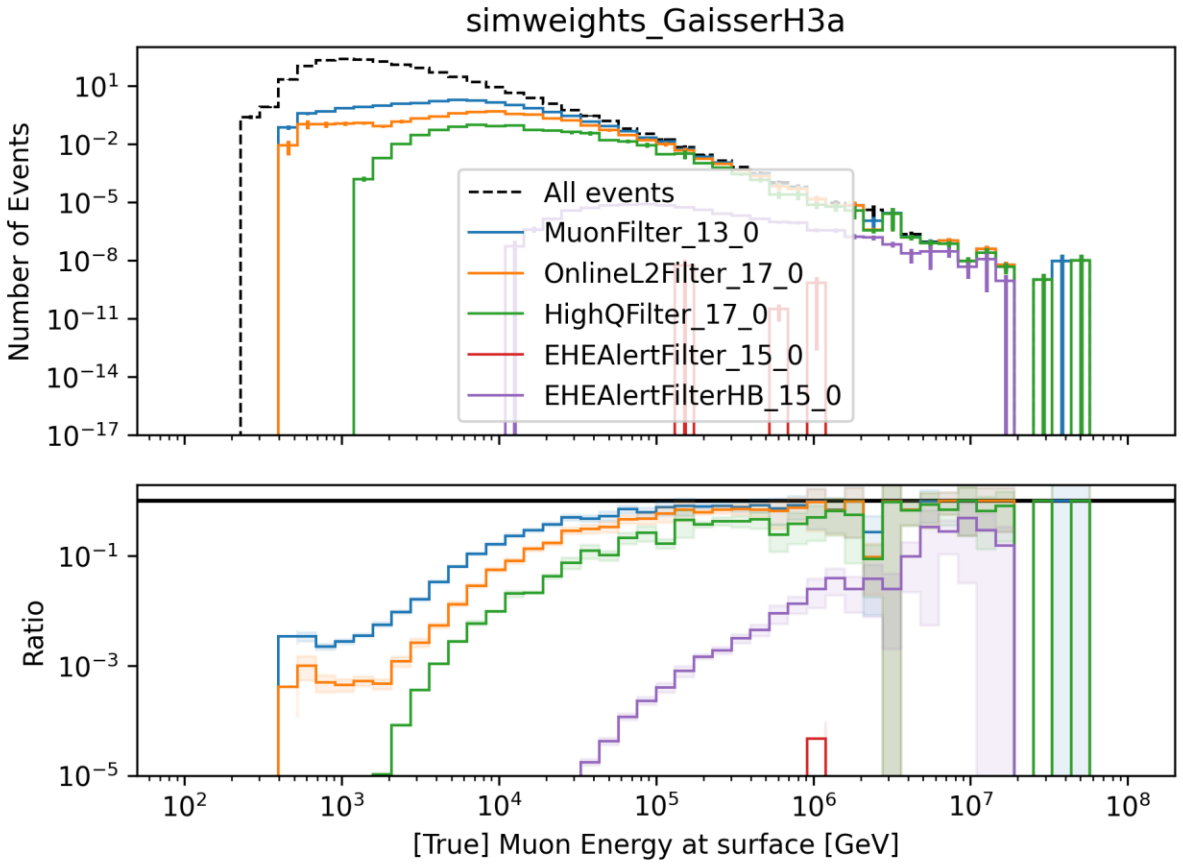
- Measure prompt neutrinos
- Combined muon and neutrino fit → pion/kaon ratio

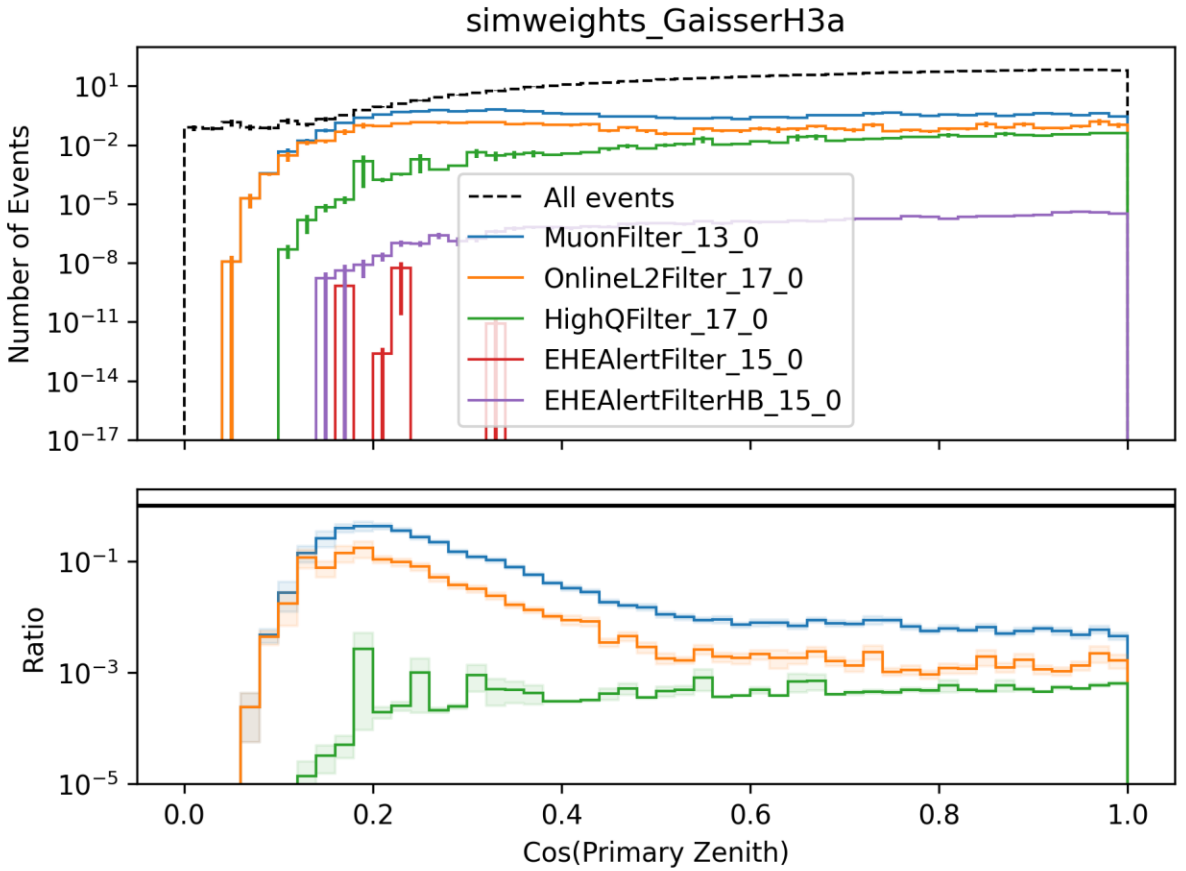
Overview


Simulation
Reconstruction
Selection
Analysis
Forward fit
Unfolding
Dataset
• CORSIKA 77500 Ehist
• SIBYLL 2.3d
• 10 TeV – 100 EeV
Validation
• Tag prompt / conv particles
• MCEq comparisons
DNN reconstructions
• Muon energies
• Muon direction
• Track geometry
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
Fit prompt normalization
• Poisson LLH fit
Muon spectrum
• Unfold muon flux

Selection

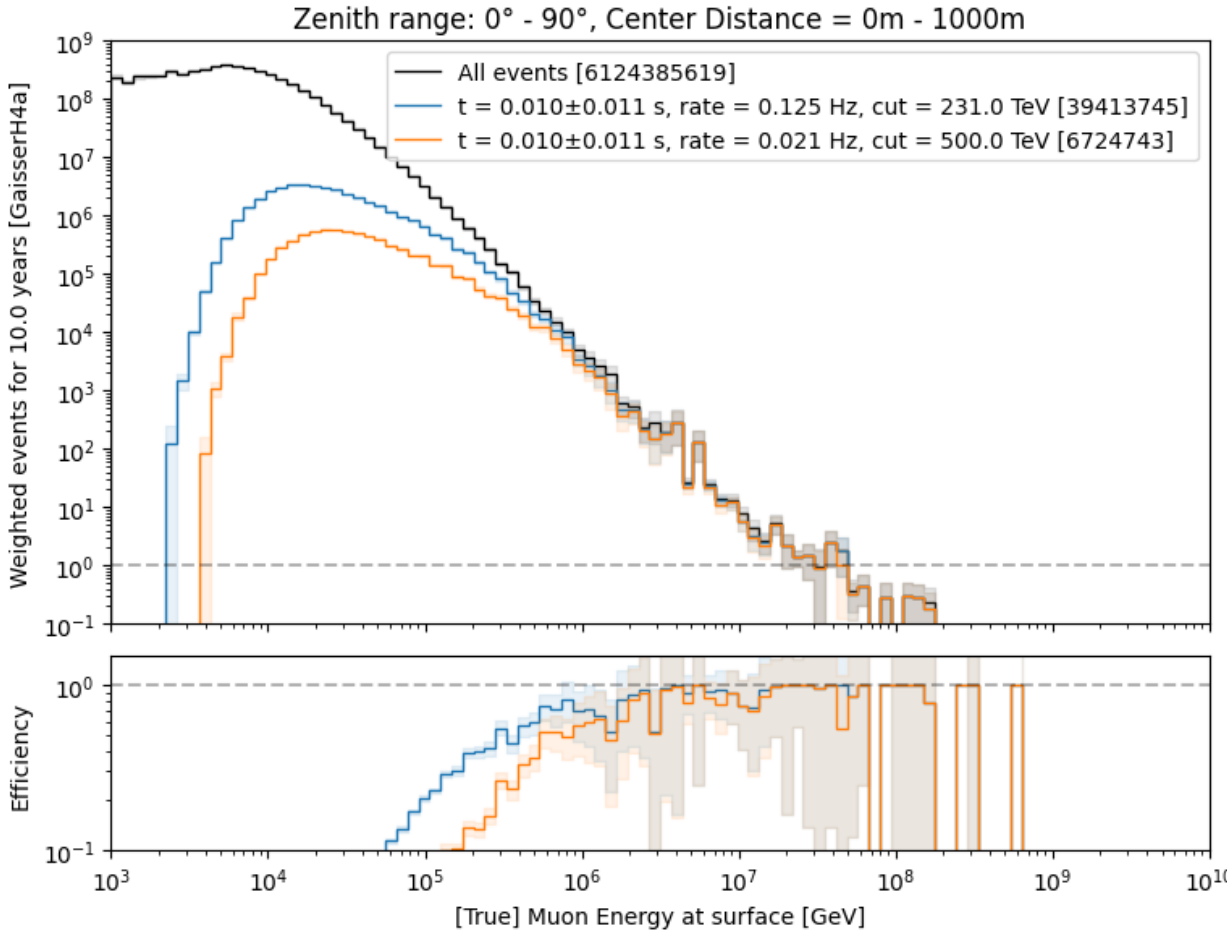
level3: muon filter

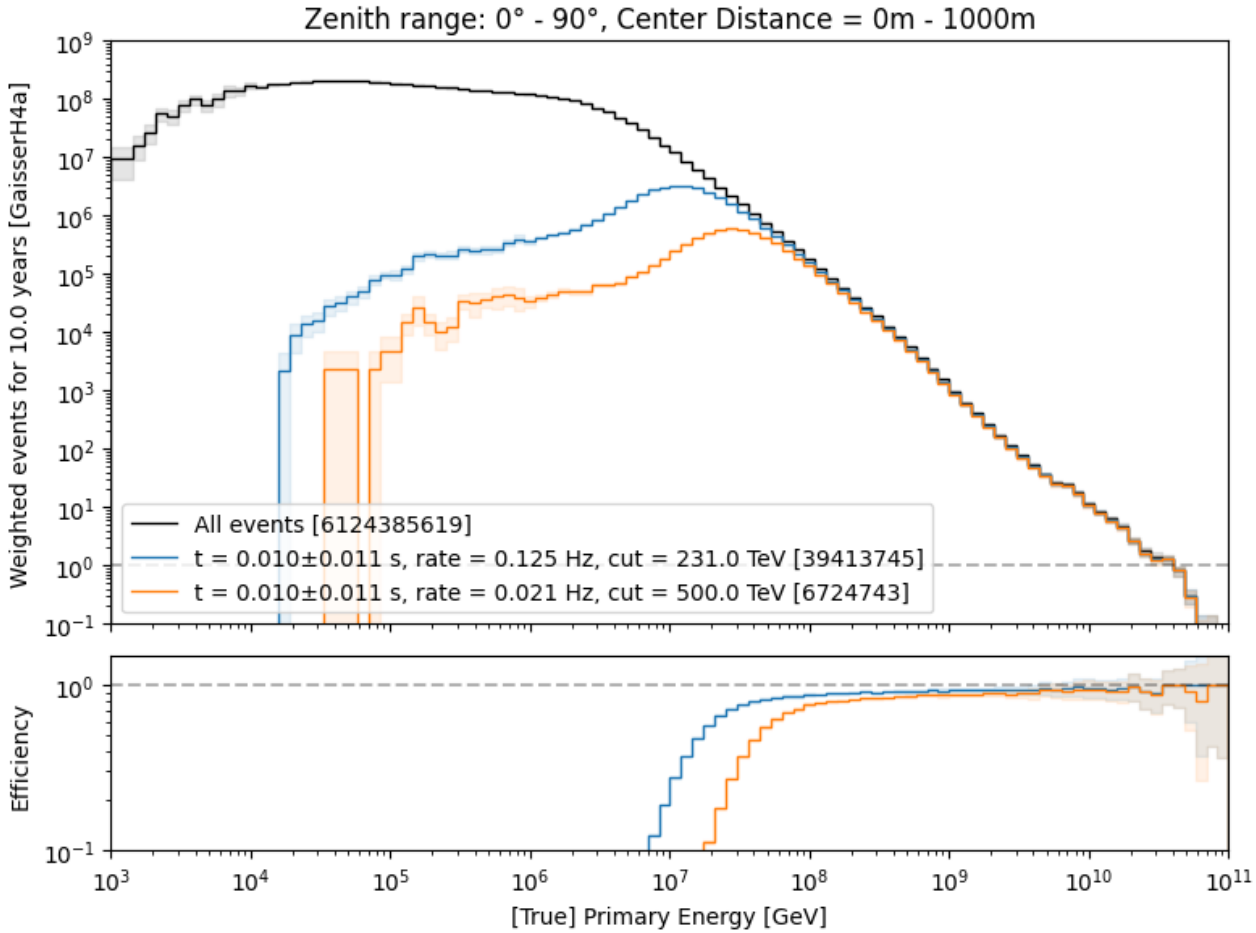




- HighQFilter: removes more horizontal events → muons travel large distances, not enough energy left to pass high-charge filter
- Goal: keep AMAP high-energy events at surface → muon filter

level3: 500 TeV bundle cut at surface

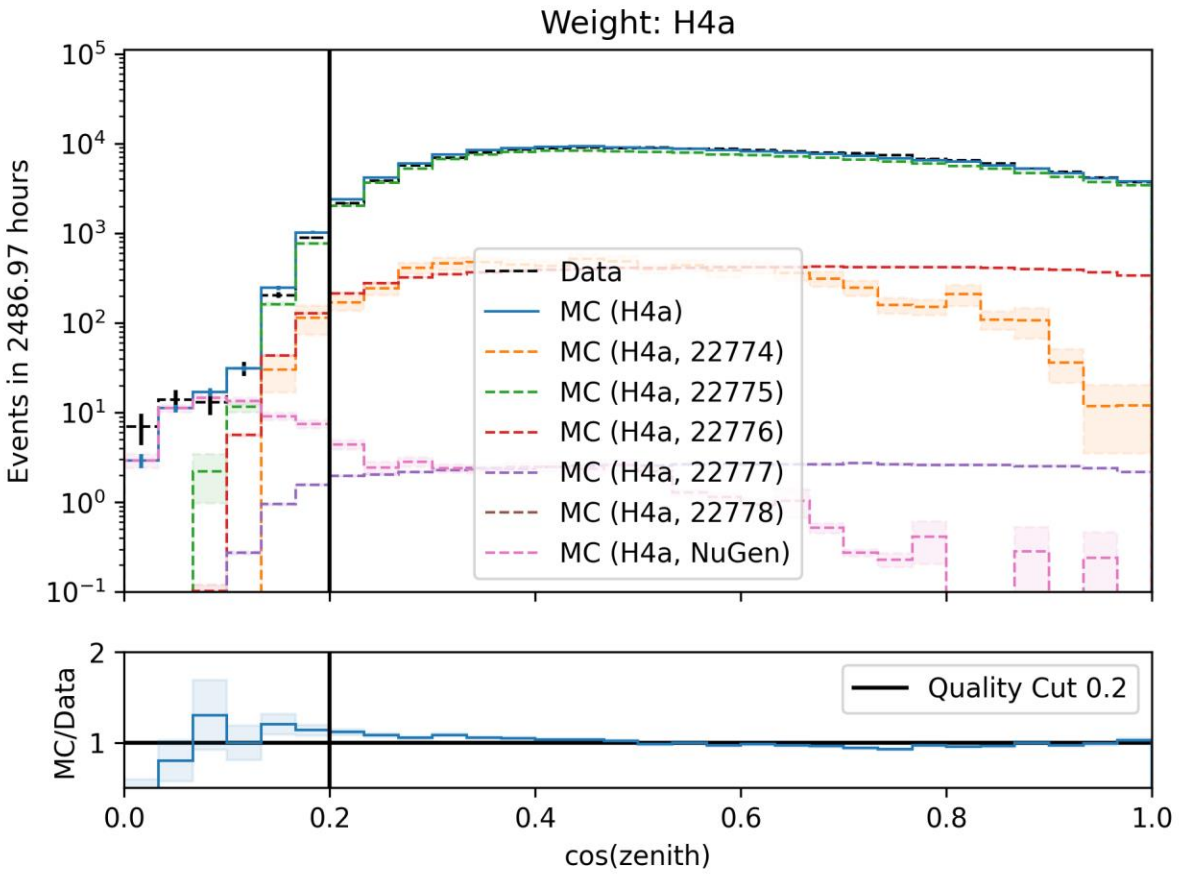


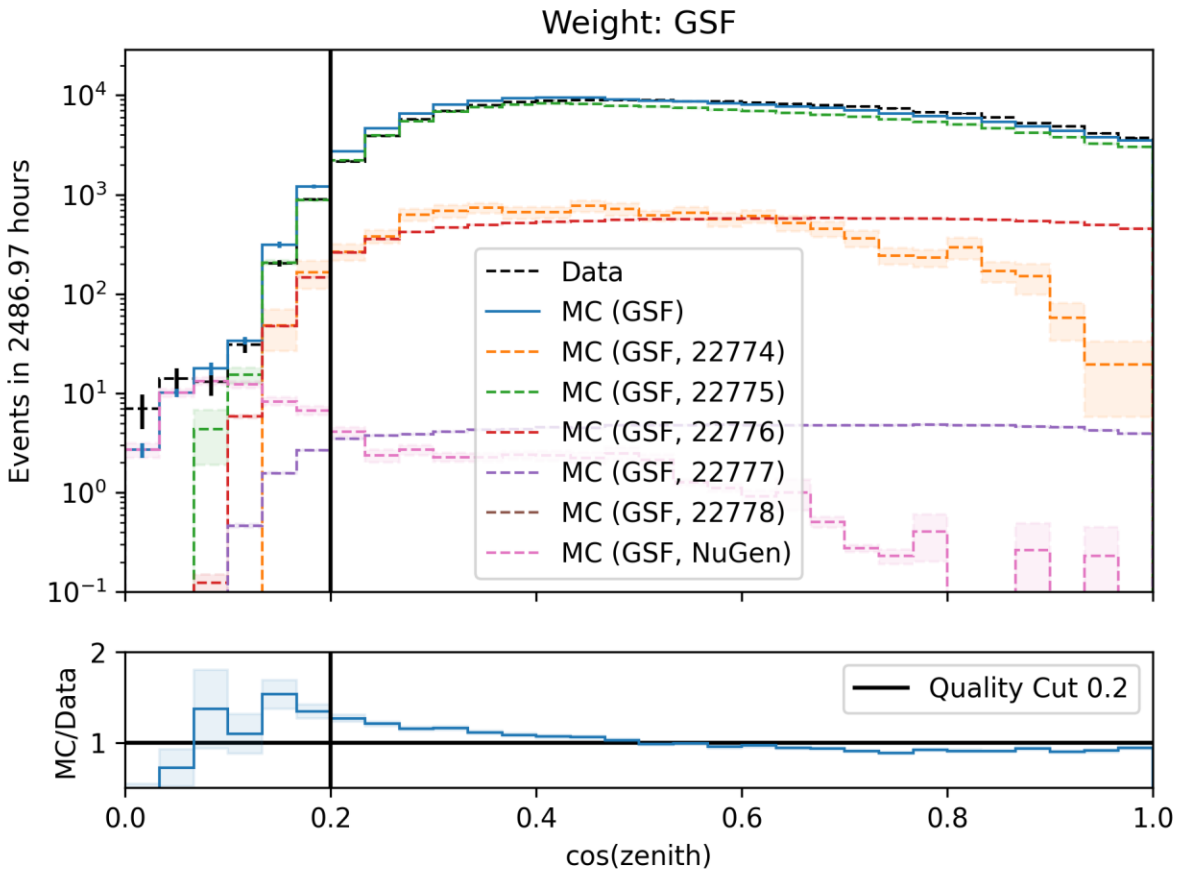


- 6 billion events expected: computationally not feasible → focus on high-energetic events
- ➢ 500 TeV cut: 6.7 Mio events left

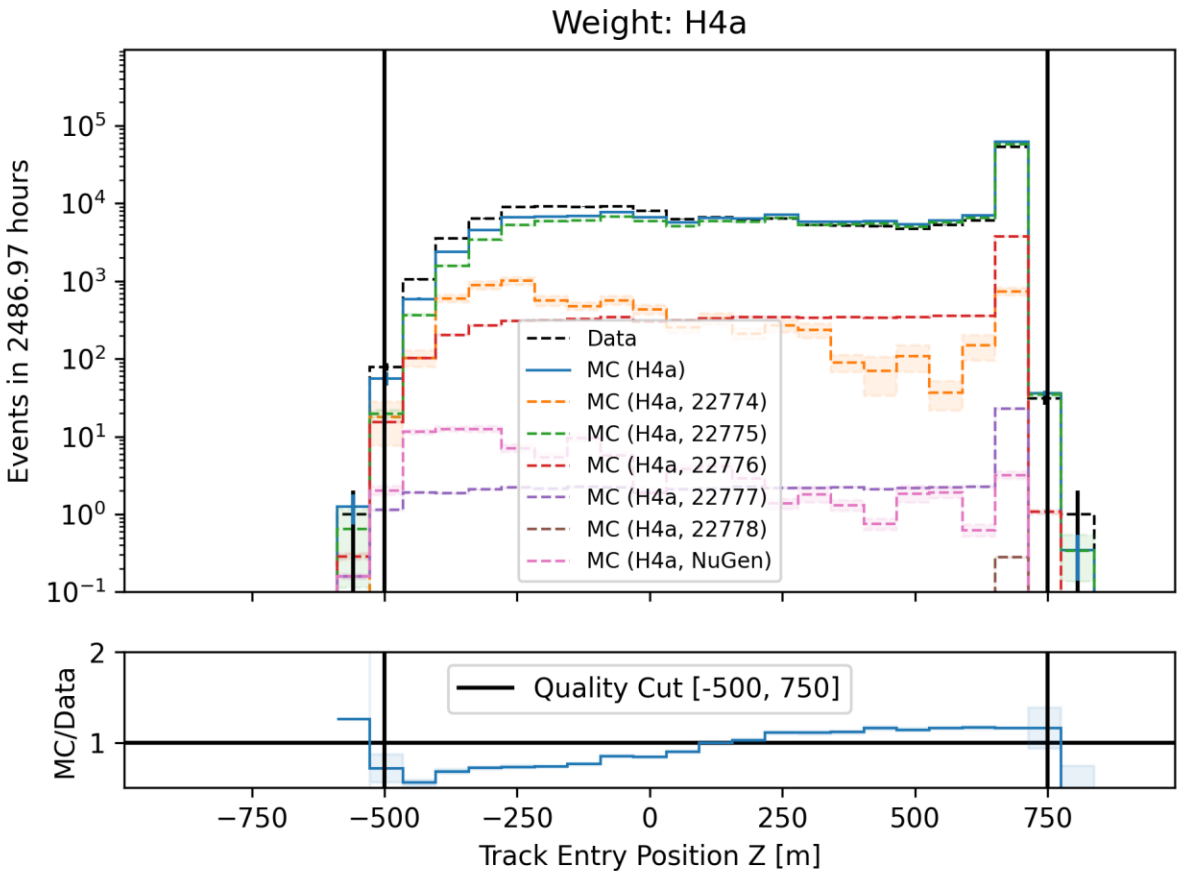
Data-MC

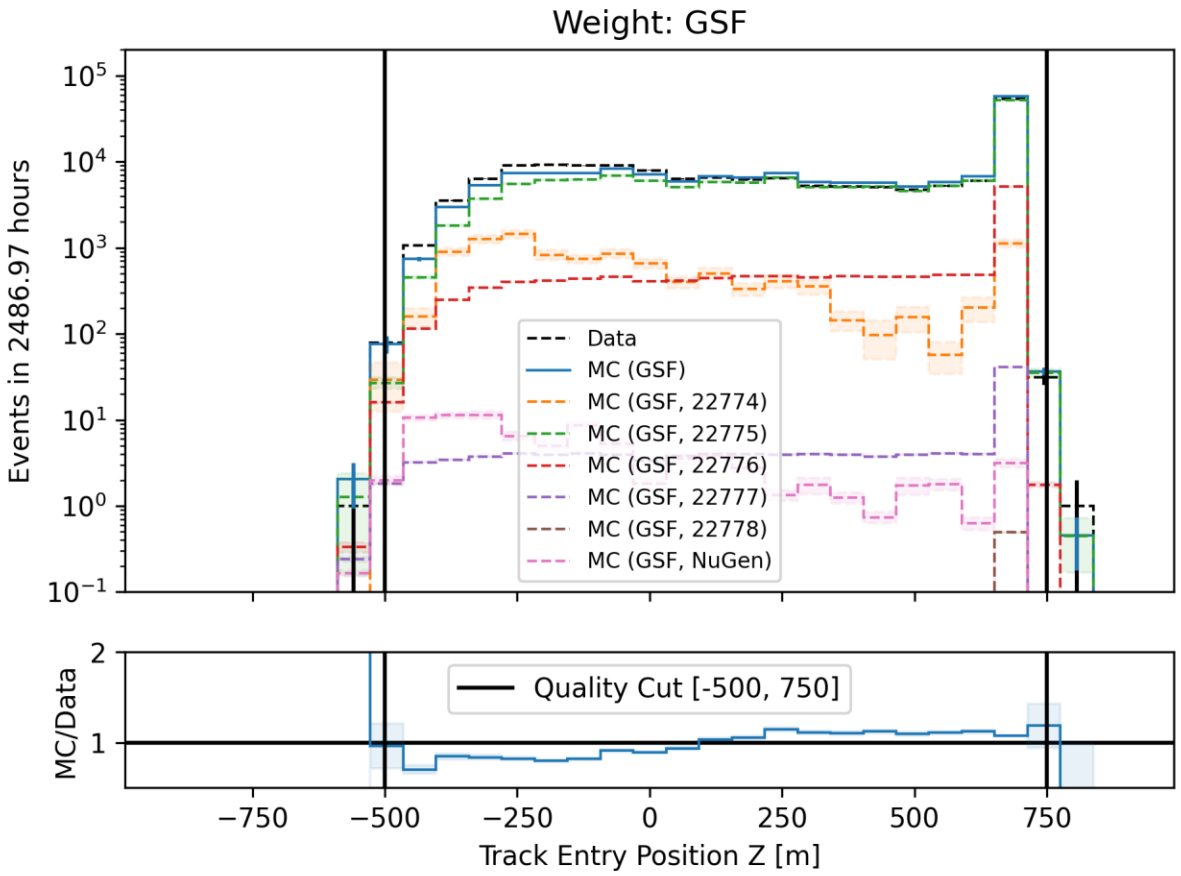
Cos(zenith)


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
Quality Cut 0.2
cos(zenith)


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
Quality Cut 0.2
cos(zenith)

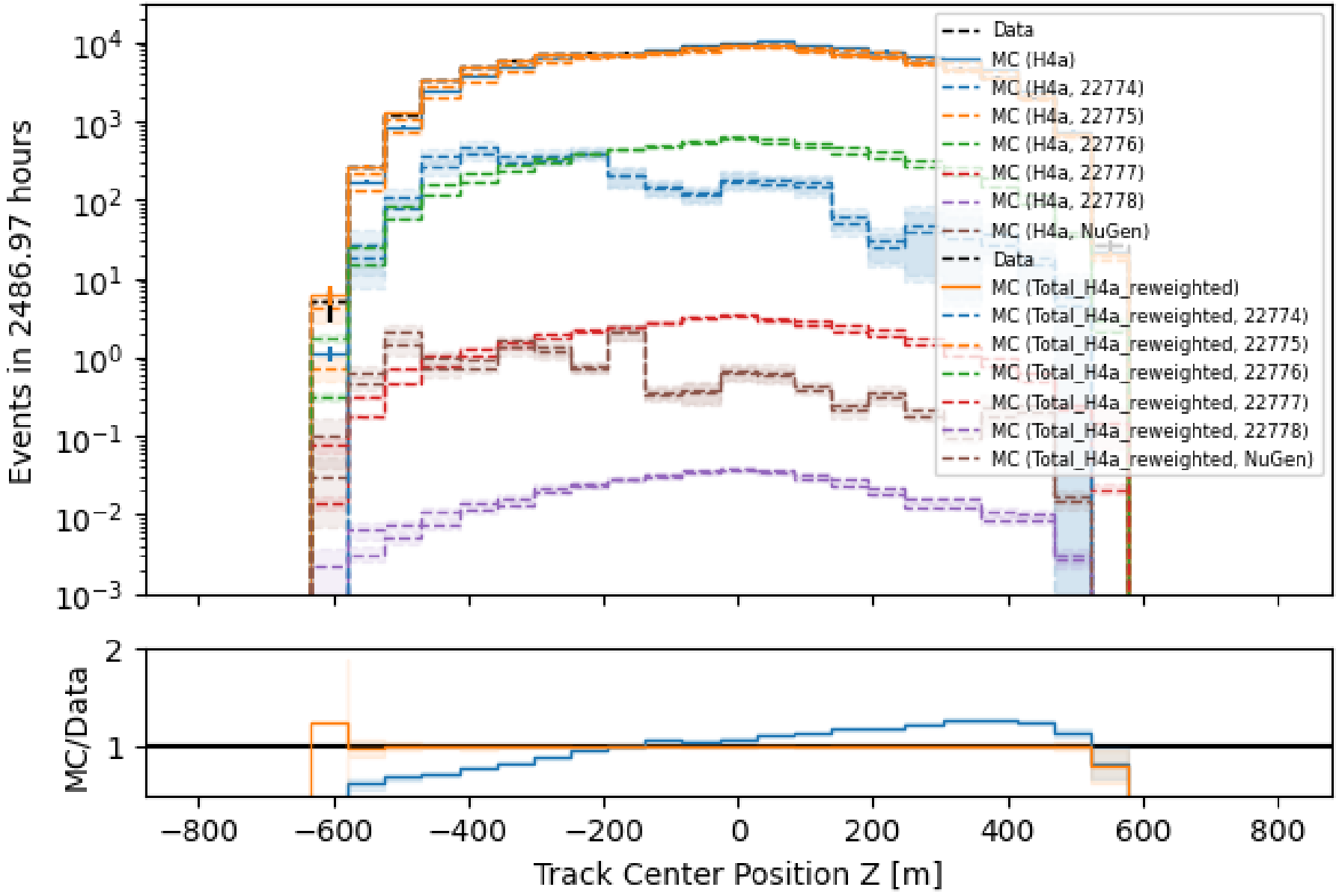
Entry position z—vertex



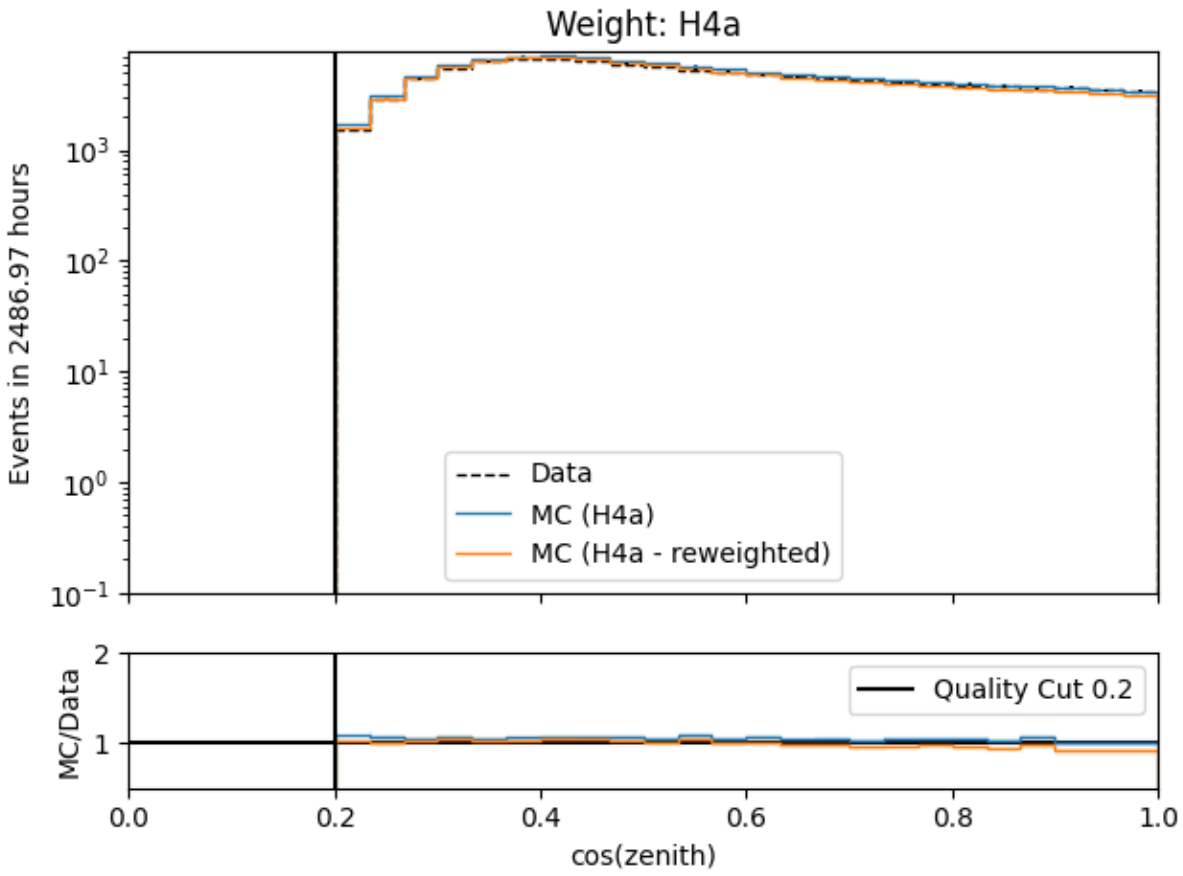


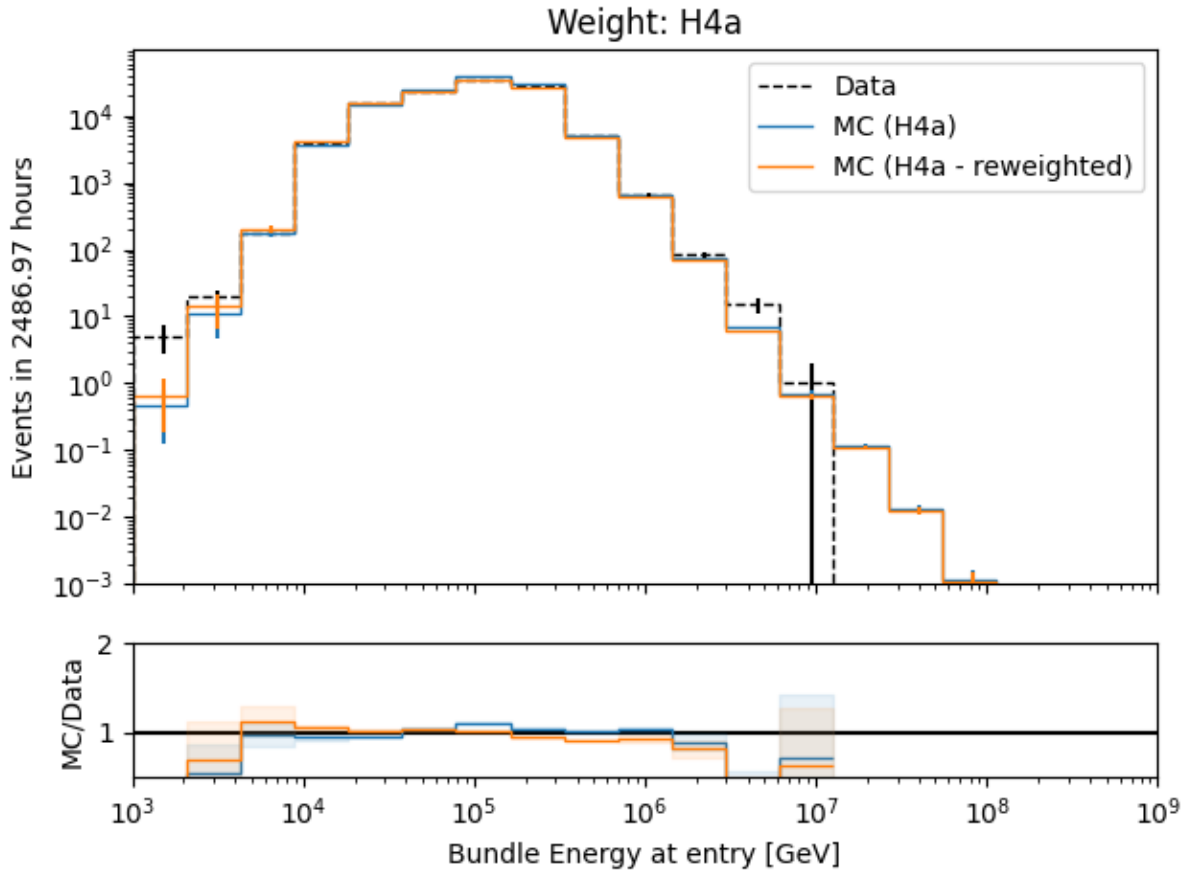
z—reweighting

- 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

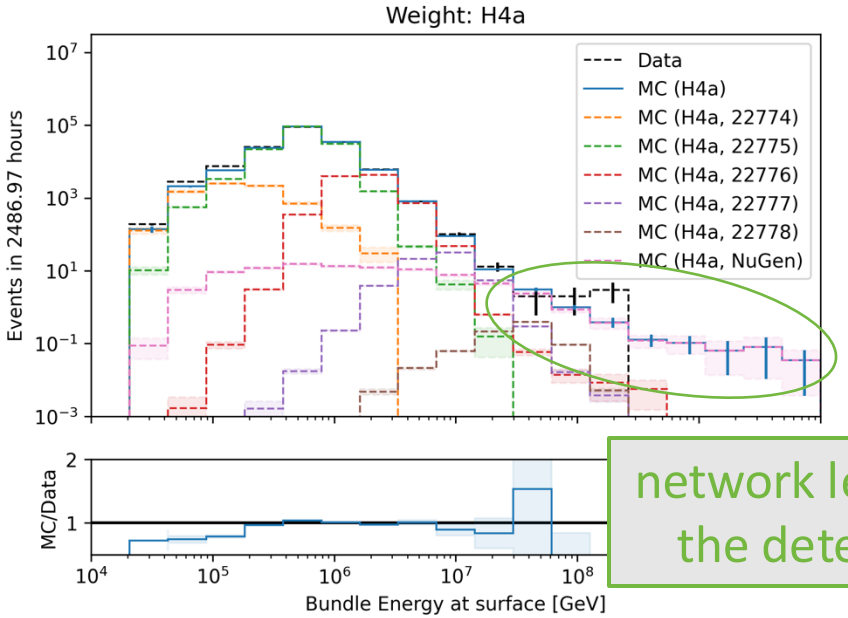
Level5: quality cuts

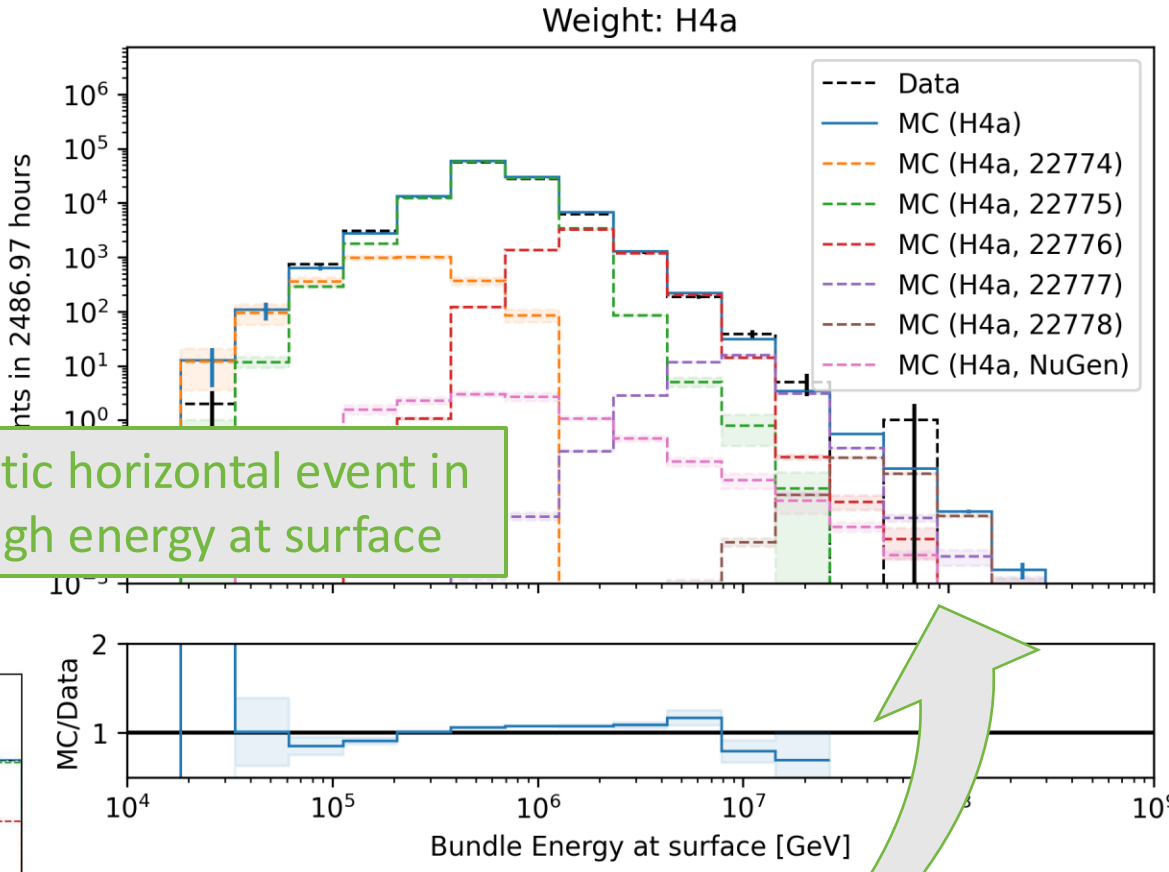
containment cuts	>	<
length in detector	1000 m	2000 m
entry pos x, y	-750 m	750 m
entry pos z	-500 m	750 m
center pos x, y	-550 m	550 m
center pos z	-650 m	650 m

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

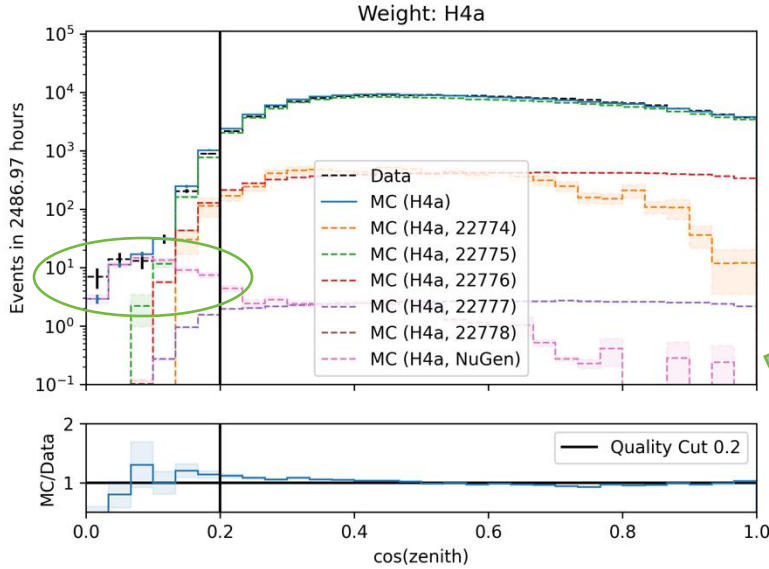
uncertainty cuts	<
bundle energy at entry	0.9 log10(GeV)
bundle energy at surface	2.0 log10(GeV)
zenith	0.1 rad
azimuth	0.2 rad
entry pos x , y, z	42 m
center pos x, y, z	50 m
entry pos time	200 ns
center pos time	600 ns
length in detector	160 m
length	2000 m

Level5: quality cuts → removes neutrinos





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

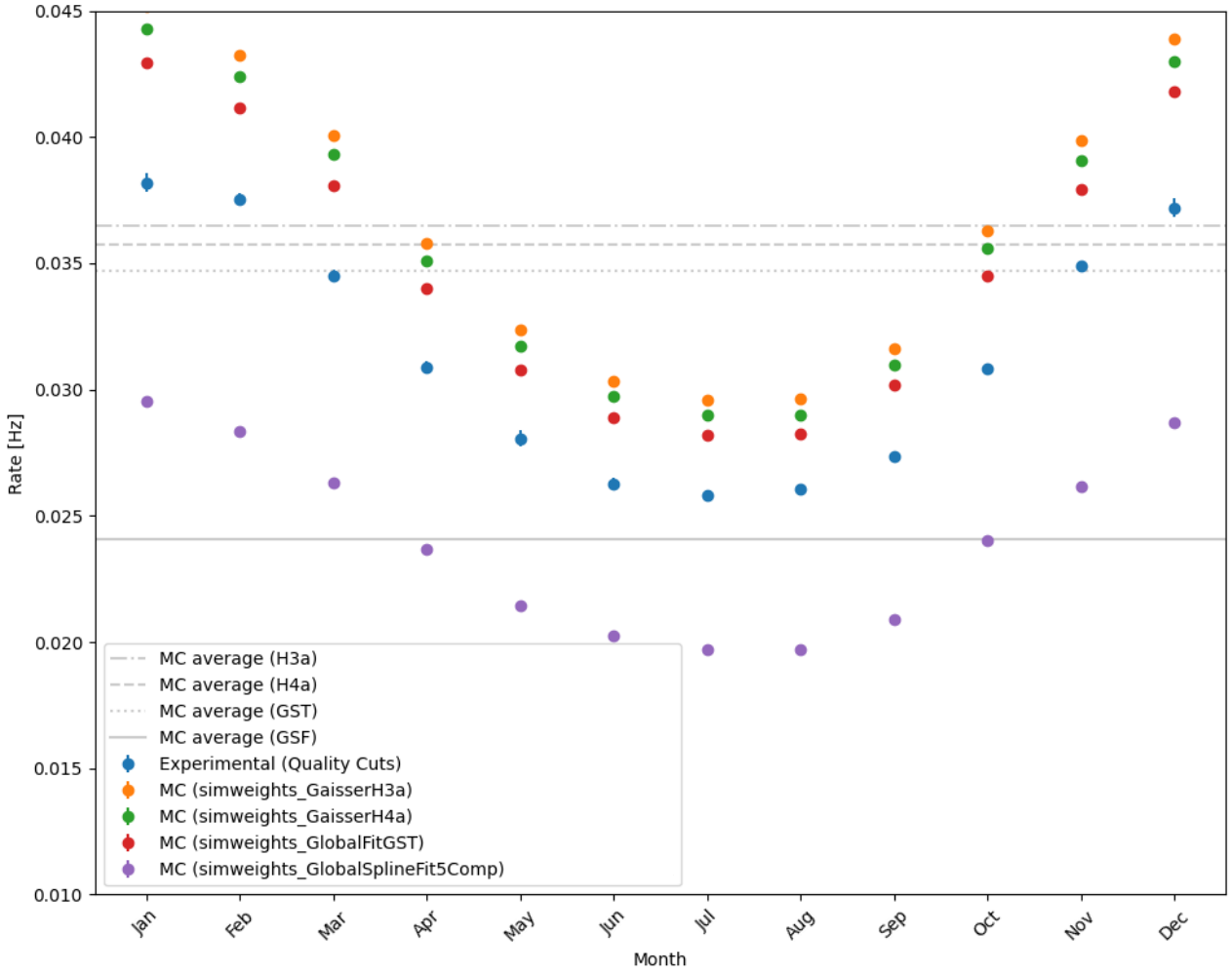


Rates per month

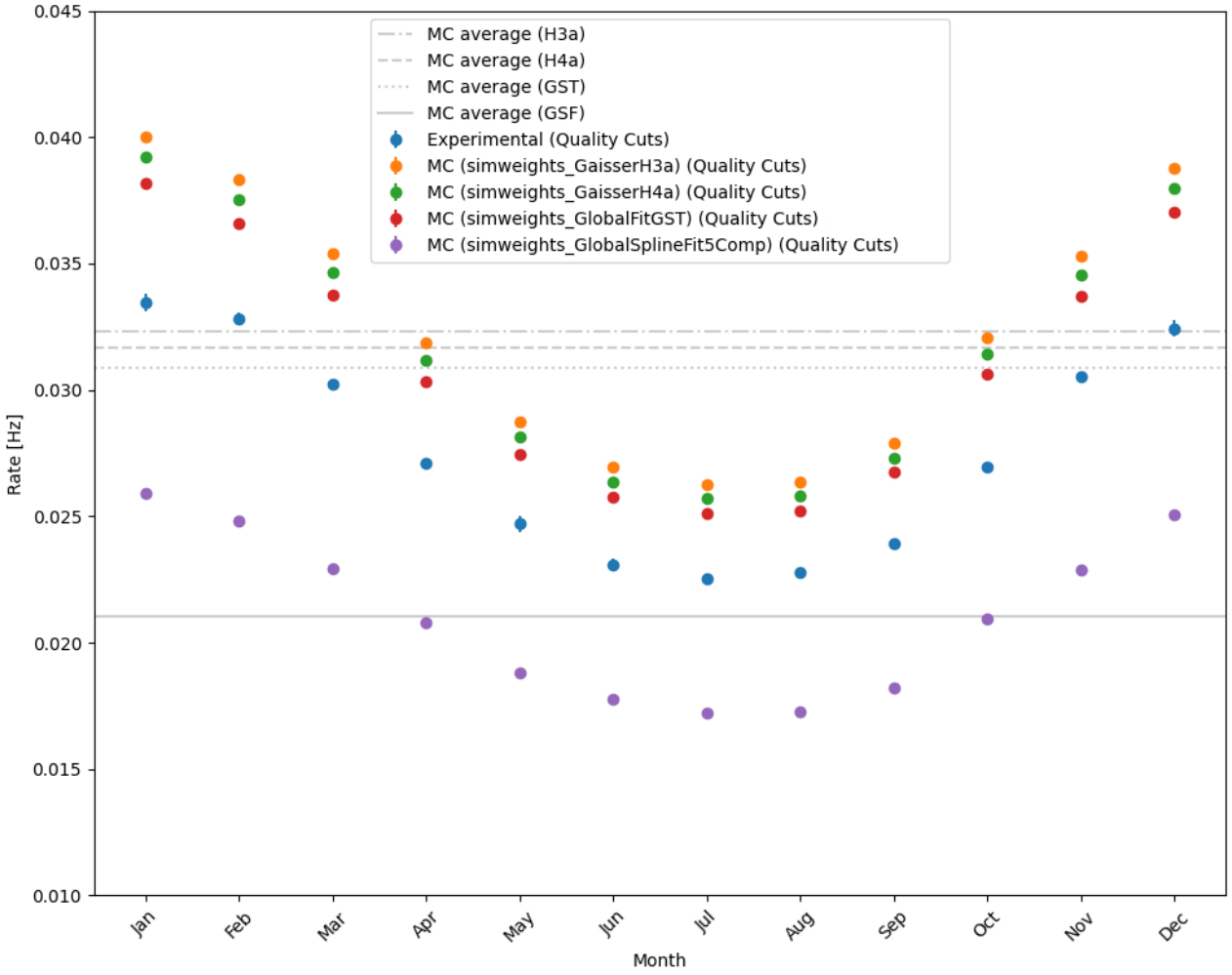
Data-MC

Rates per month

before quality cuts



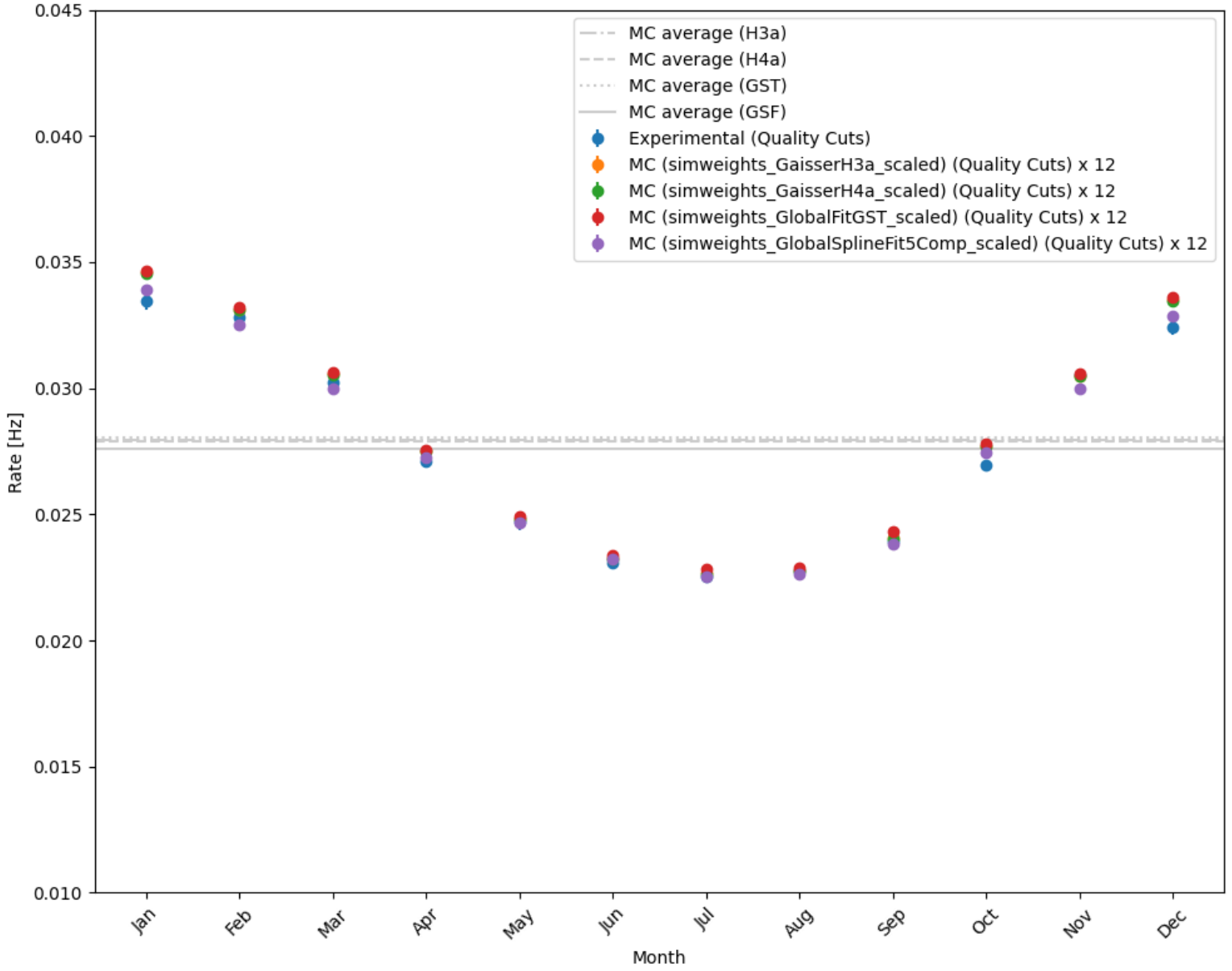
after quality cuts



➢ 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

Unfolding in a nutshell

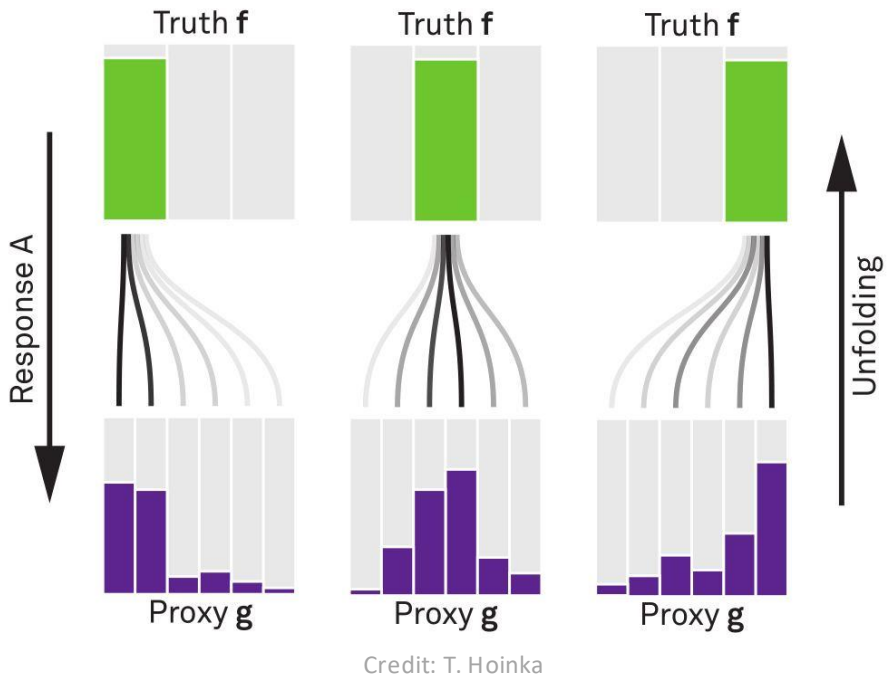
measured proxy — detector response — background

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

$f(E_\mu)$: true energy distribution

folding — unfolding

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



Credit: T. Hoinka

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:

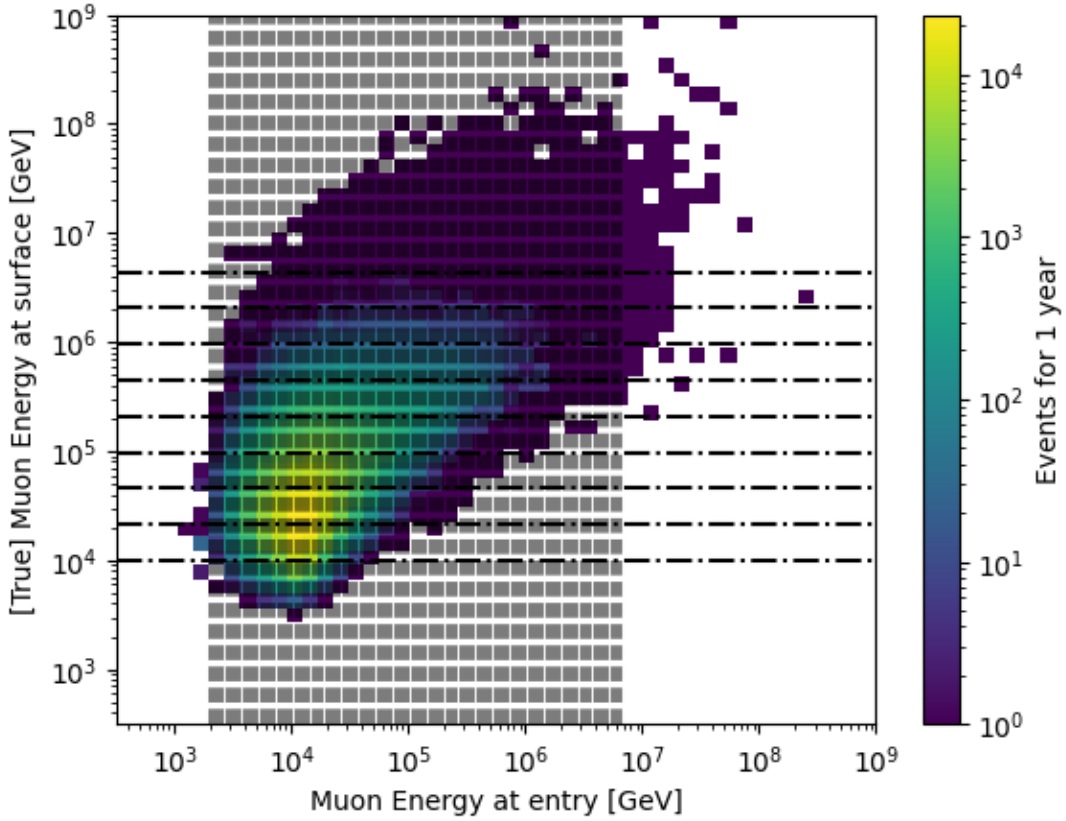
$$t(\vec{f}) = -\frac{1}{2}(C\vec{f})^T(\tau 1)^{-1}(C\vec{f})$$

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

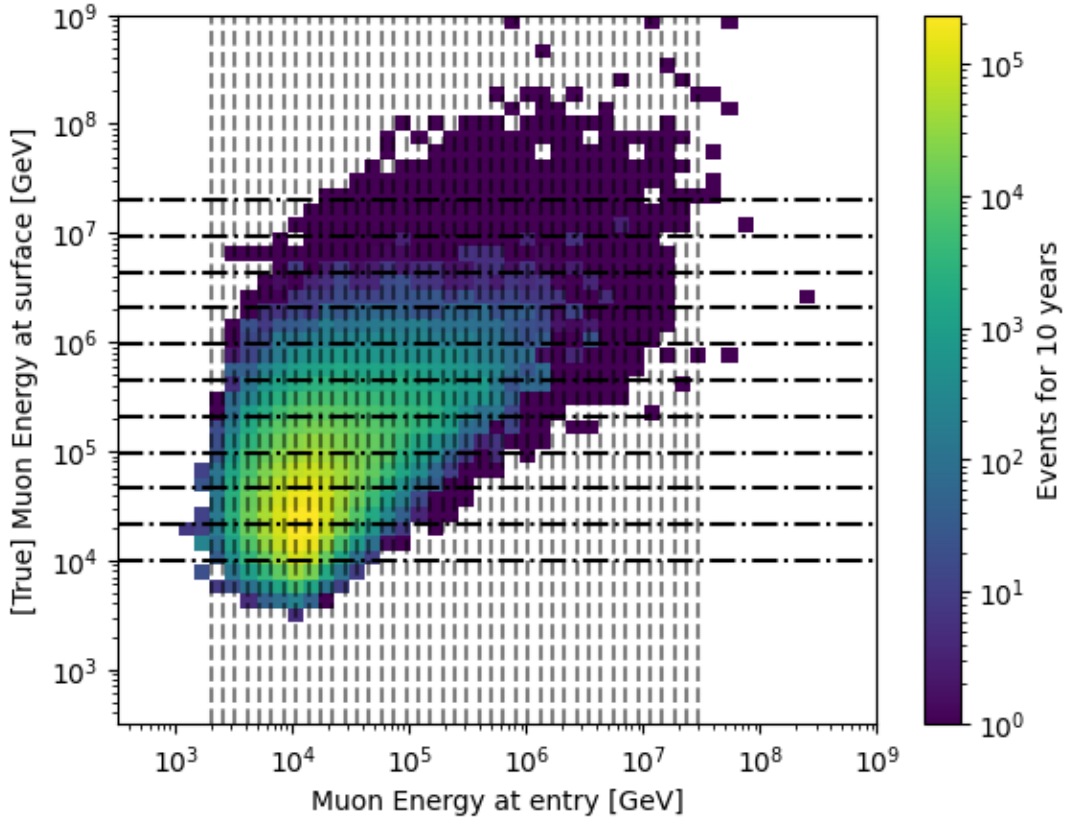
GitHub **funfolding** by M. Börner

Proxy vs. target

1 year

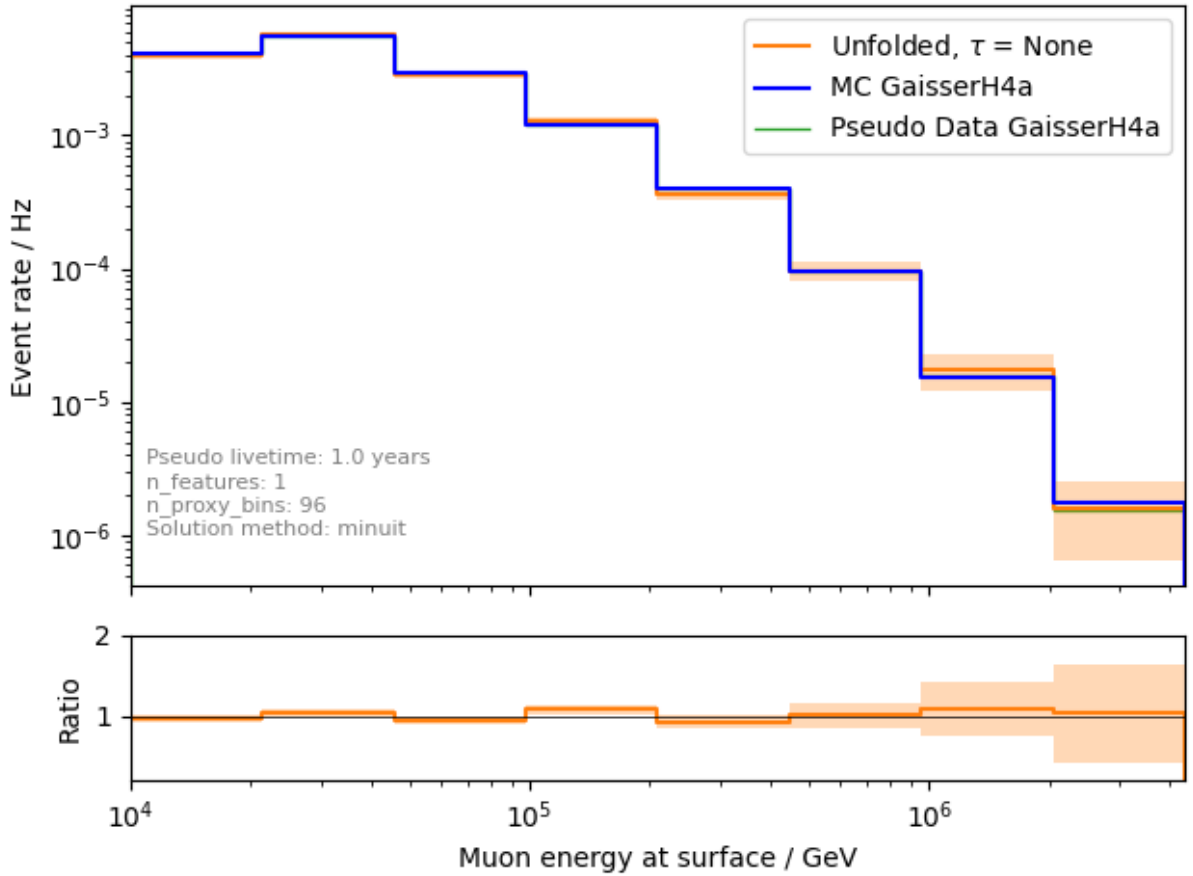


10 years

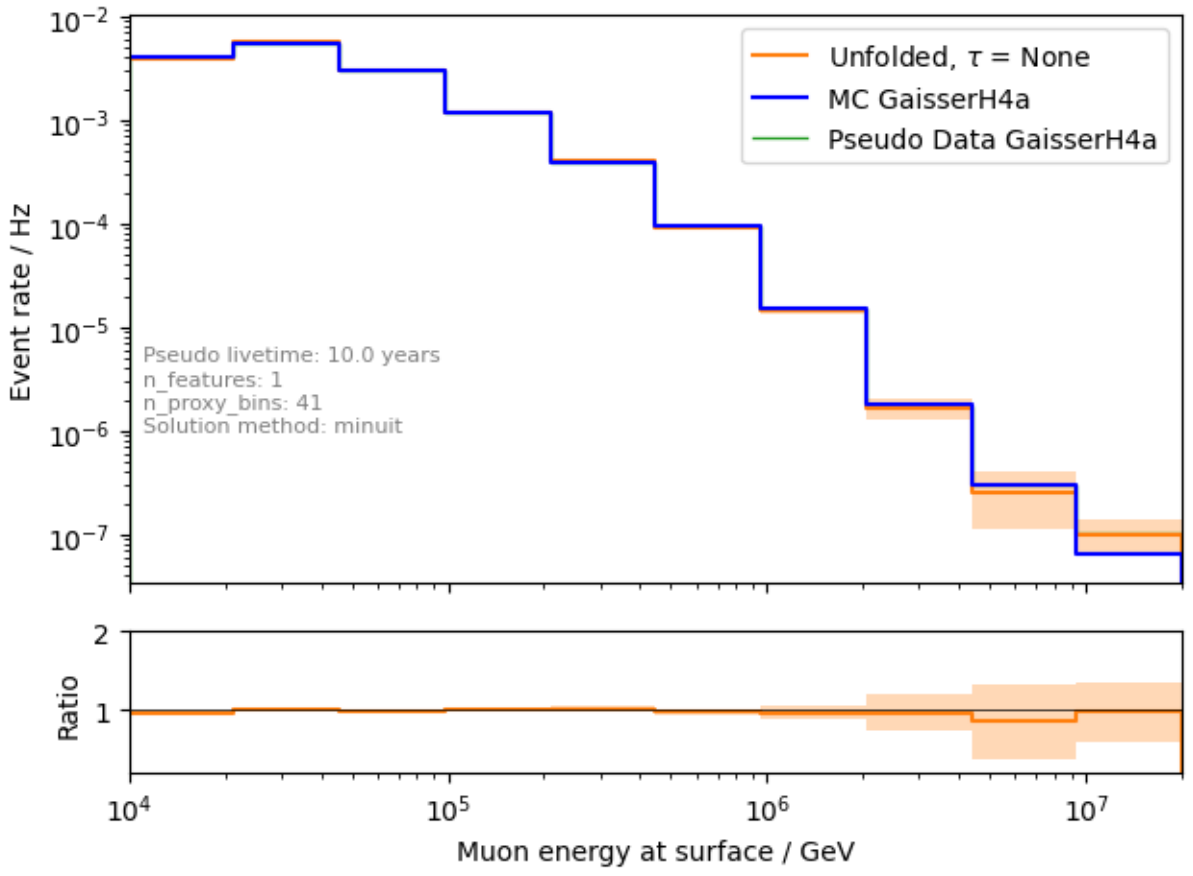


Unfolding event rate

1 year

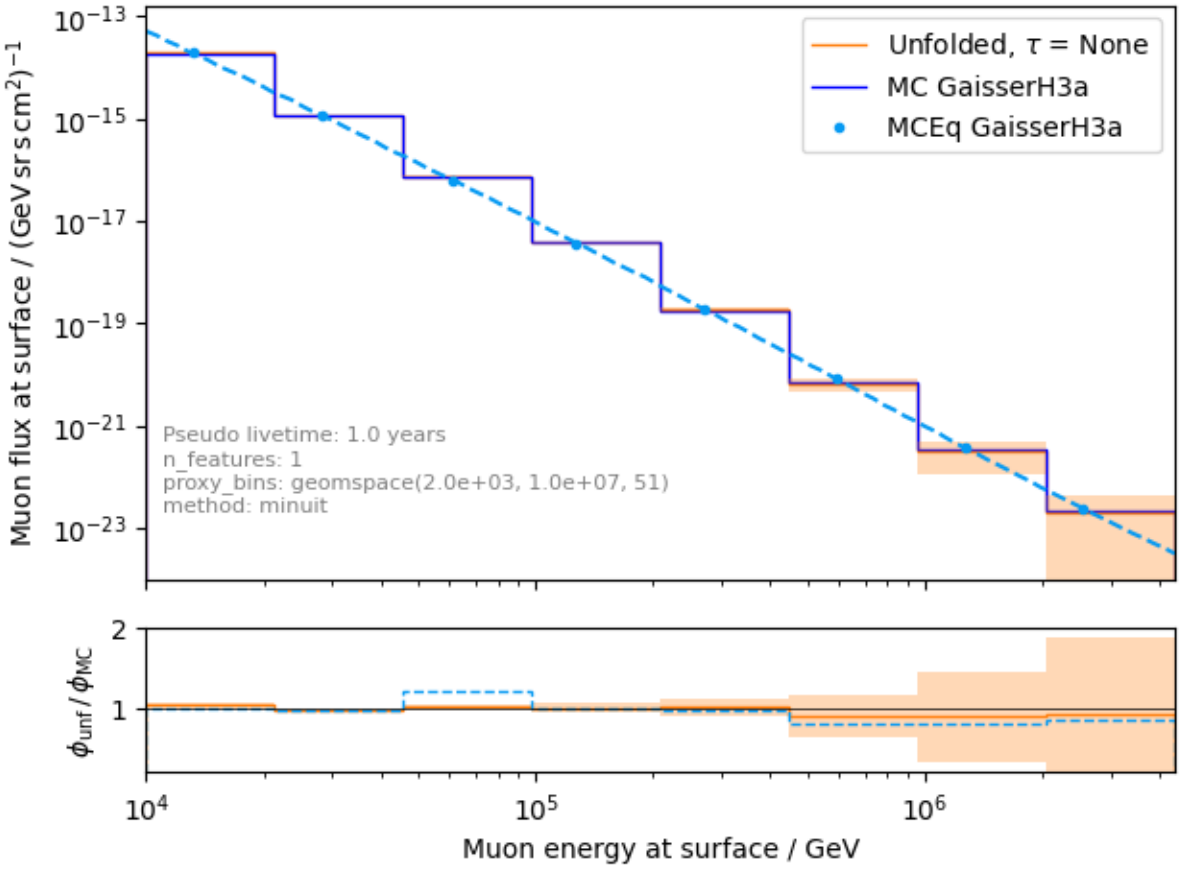


10 years

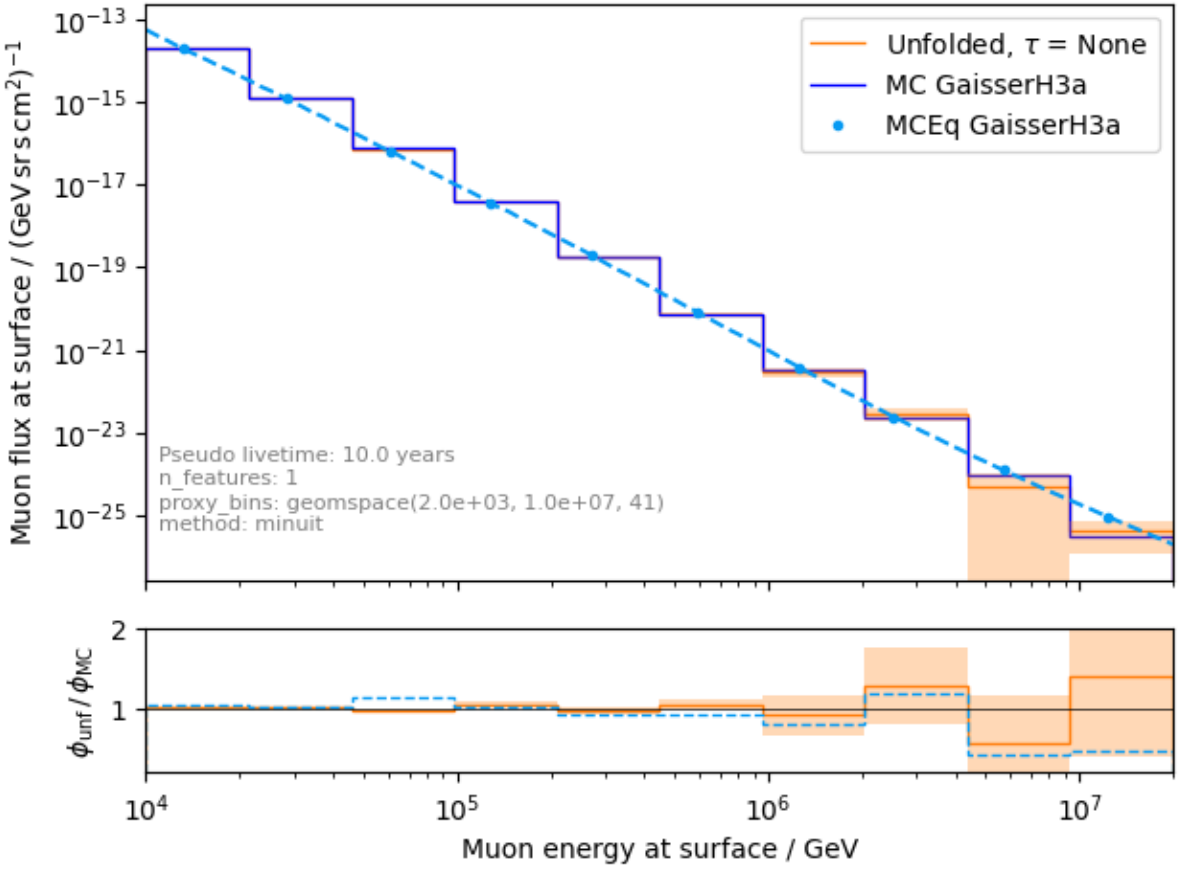


unfolding of muon flux at surface

1 year



10 years



Ice systematics

Snowstorm

Absorption

Scattering

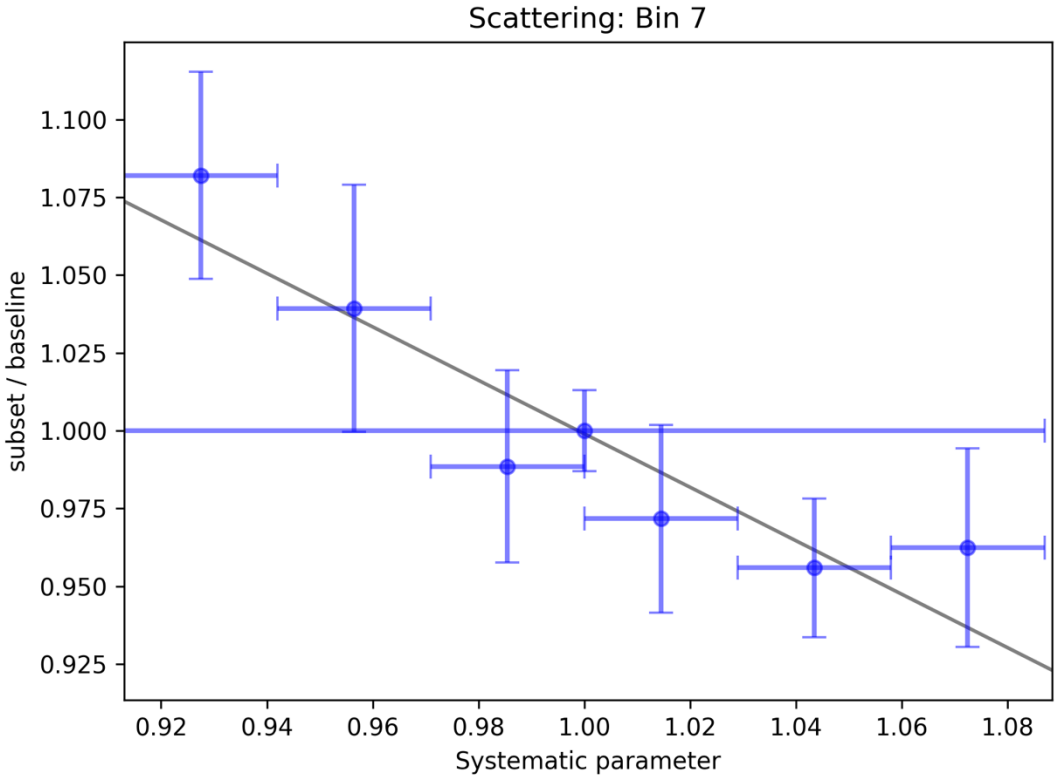
DOMEfficiency

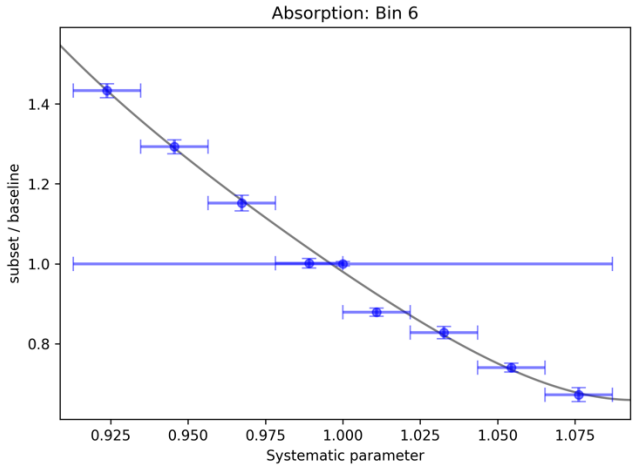
HoleIce 0

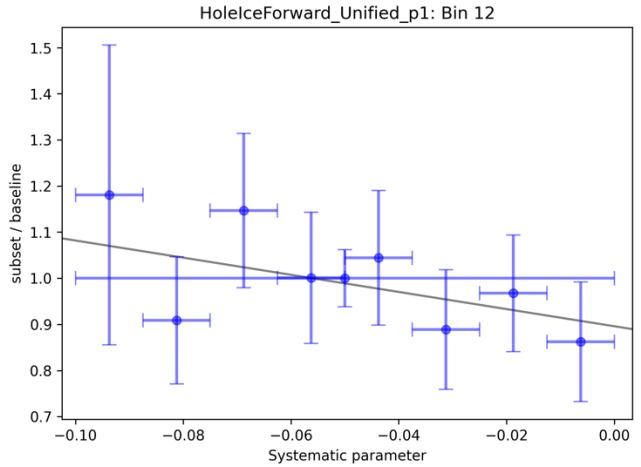
HoleIce 1

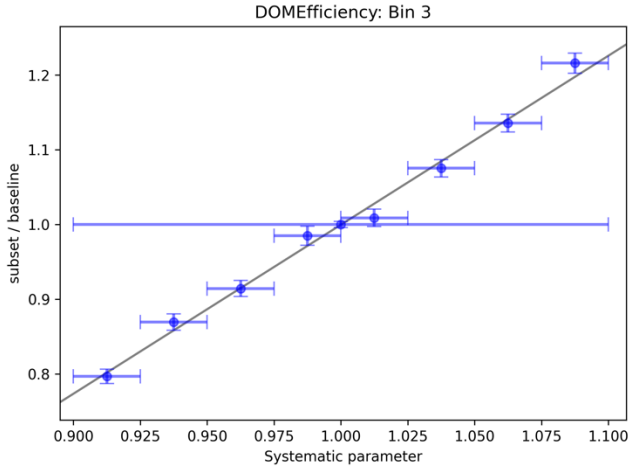
Fit ice systematics:

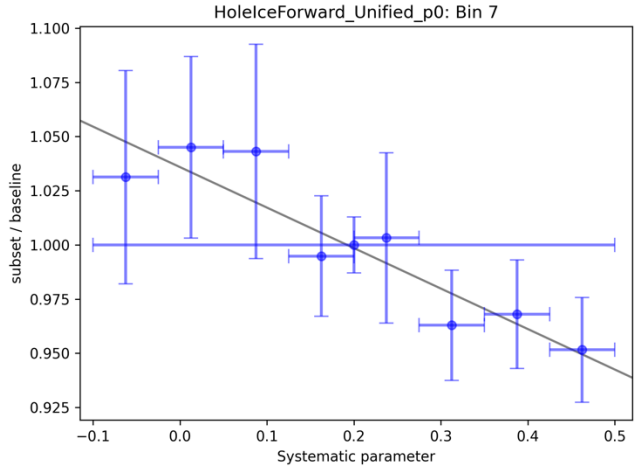
- Parametrization for systematics in each proxy bin
- Proxy: leading muon energy at entry











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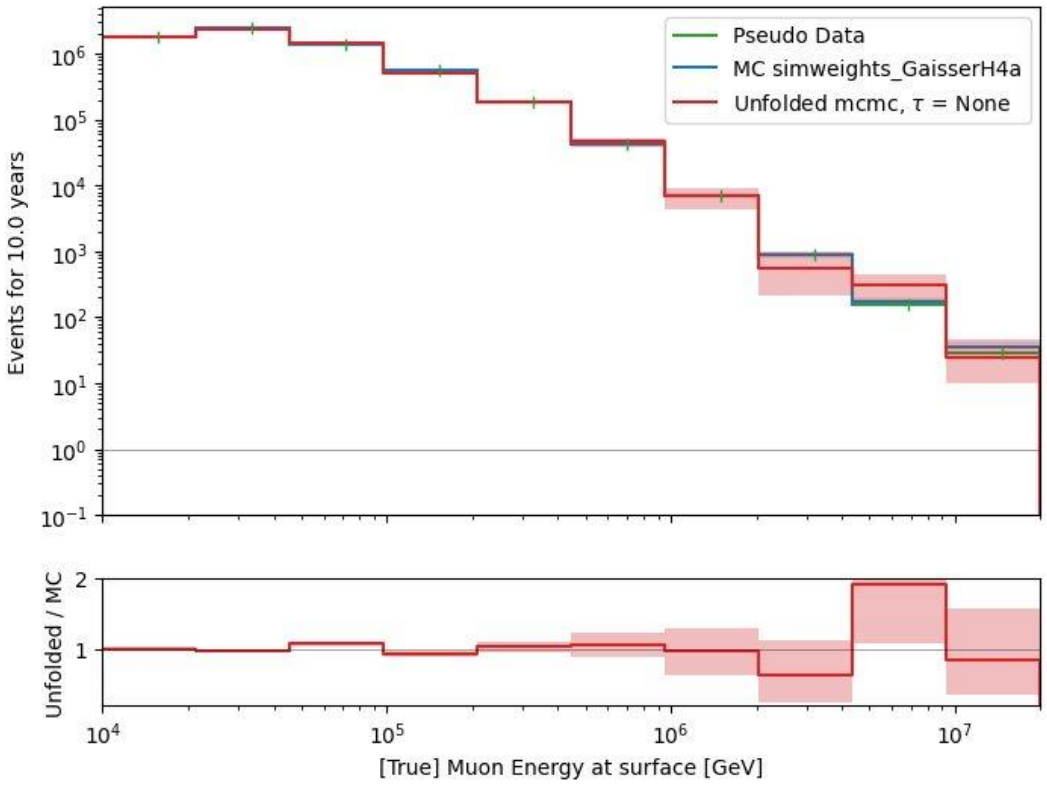
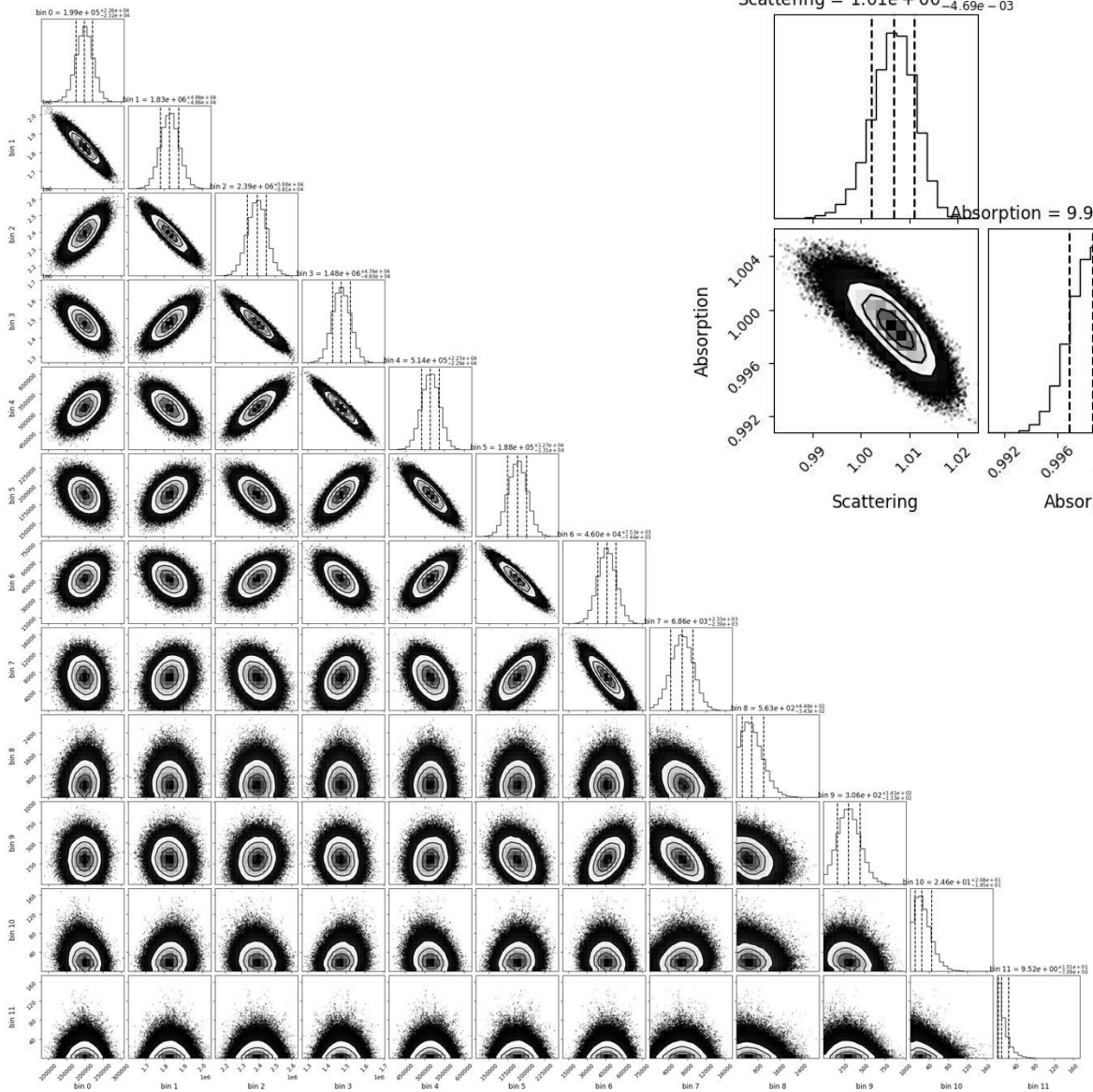
➢ This is done for each systematic and every proxy bin

Unfolded event rate with systematics

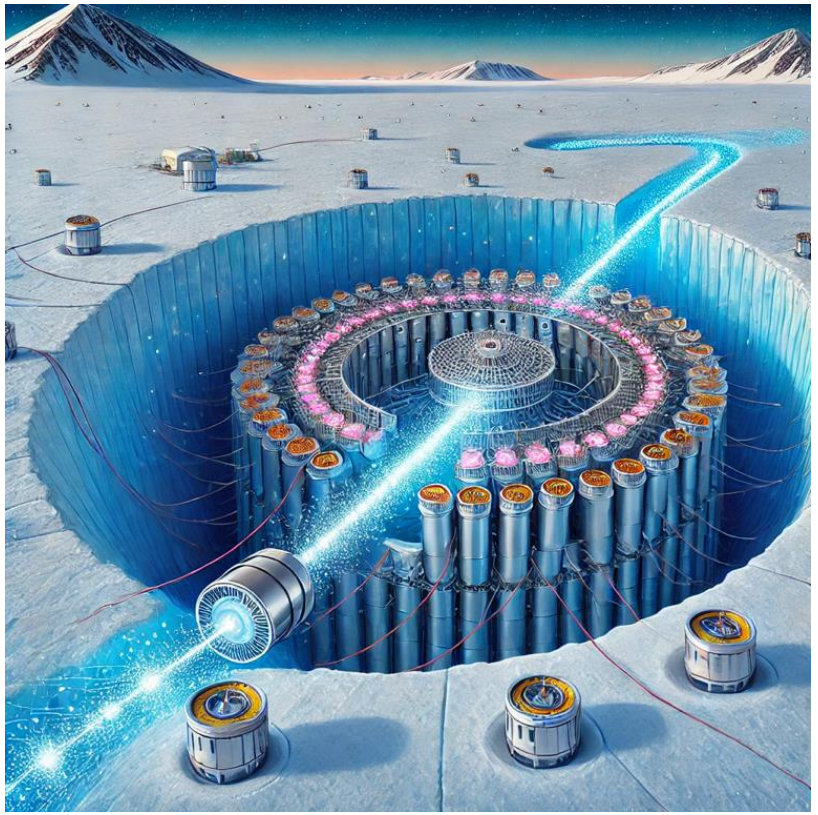




- Use regularization to reduce unphyiscal oscillations

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.

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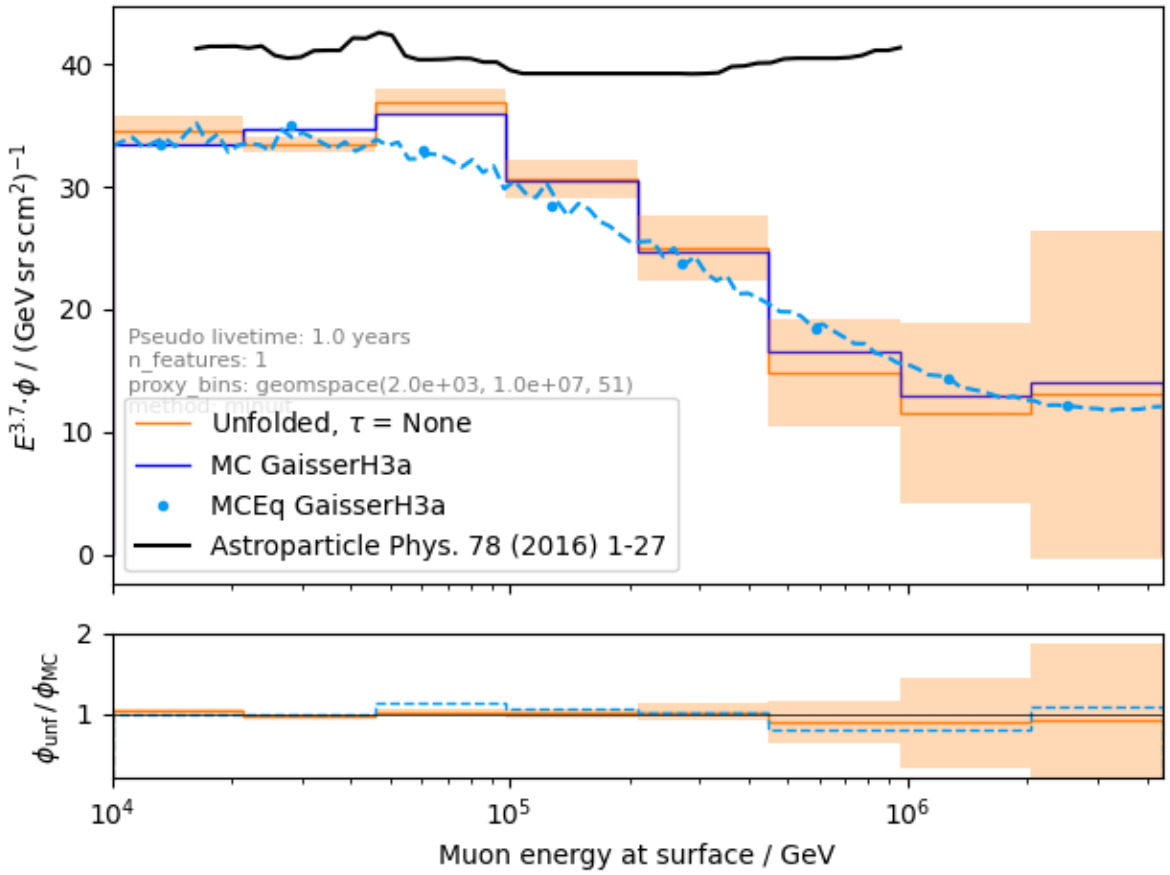
Thank you for your attention!

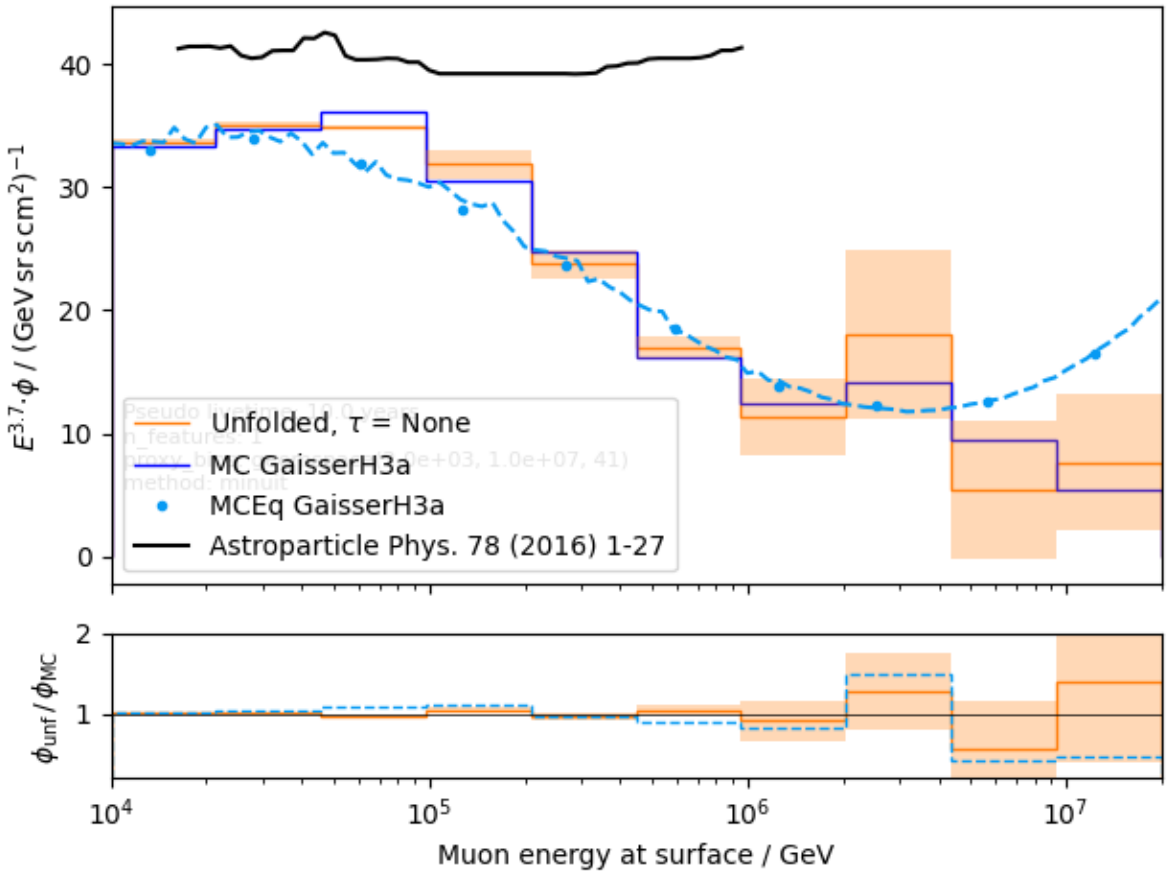
Backup

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

1 year

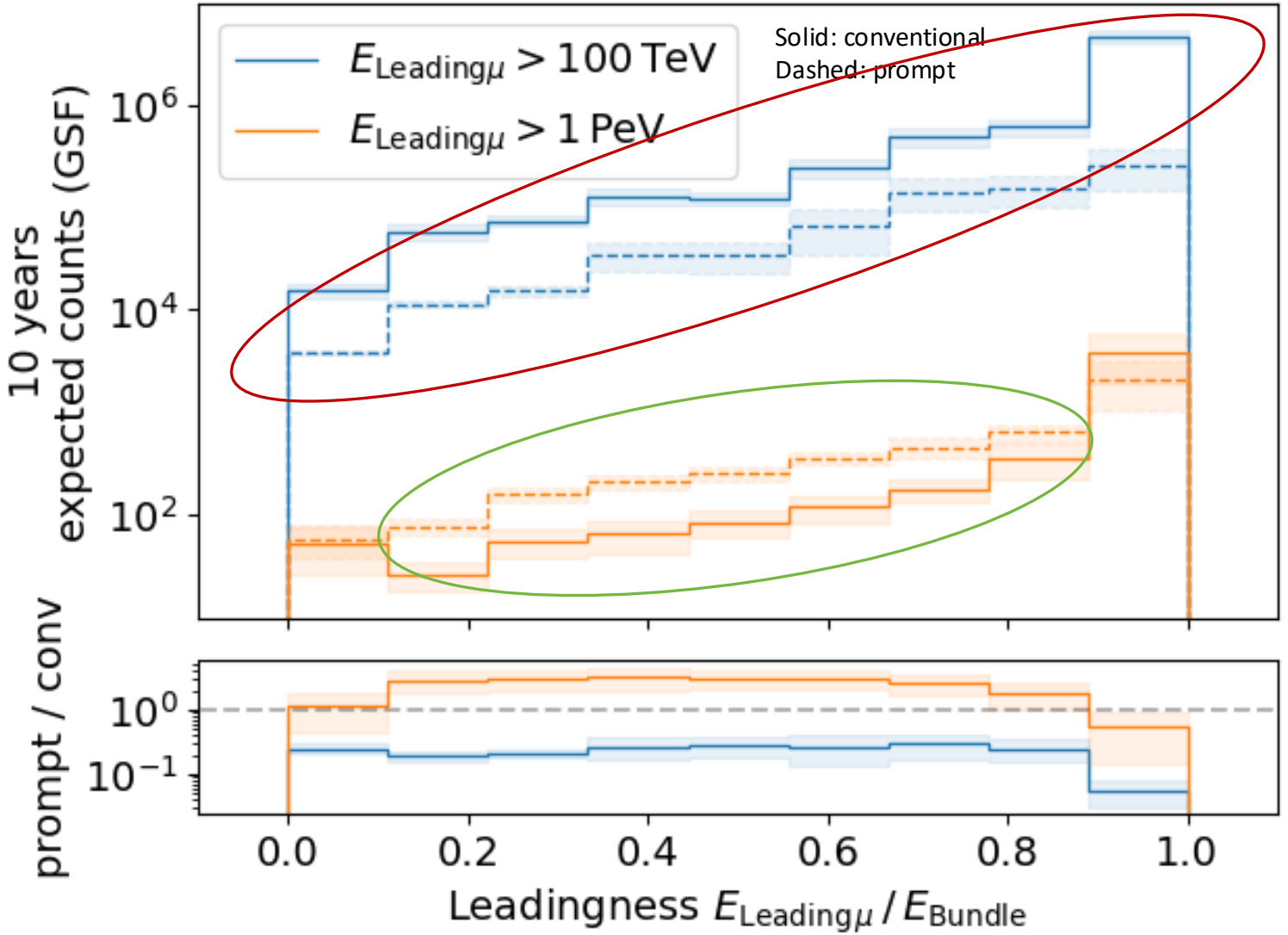


10 years



Leading muon energy fraction

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



Leading muon contribution

Patrick Berghaus

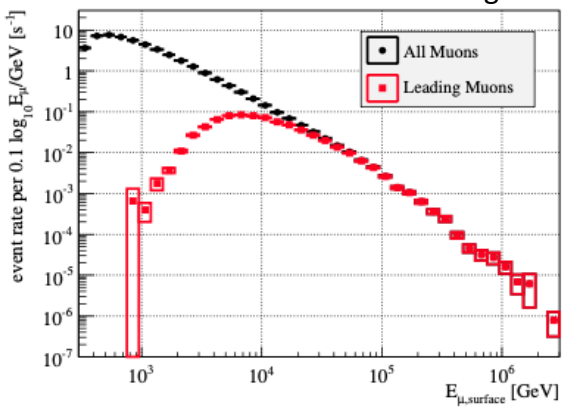
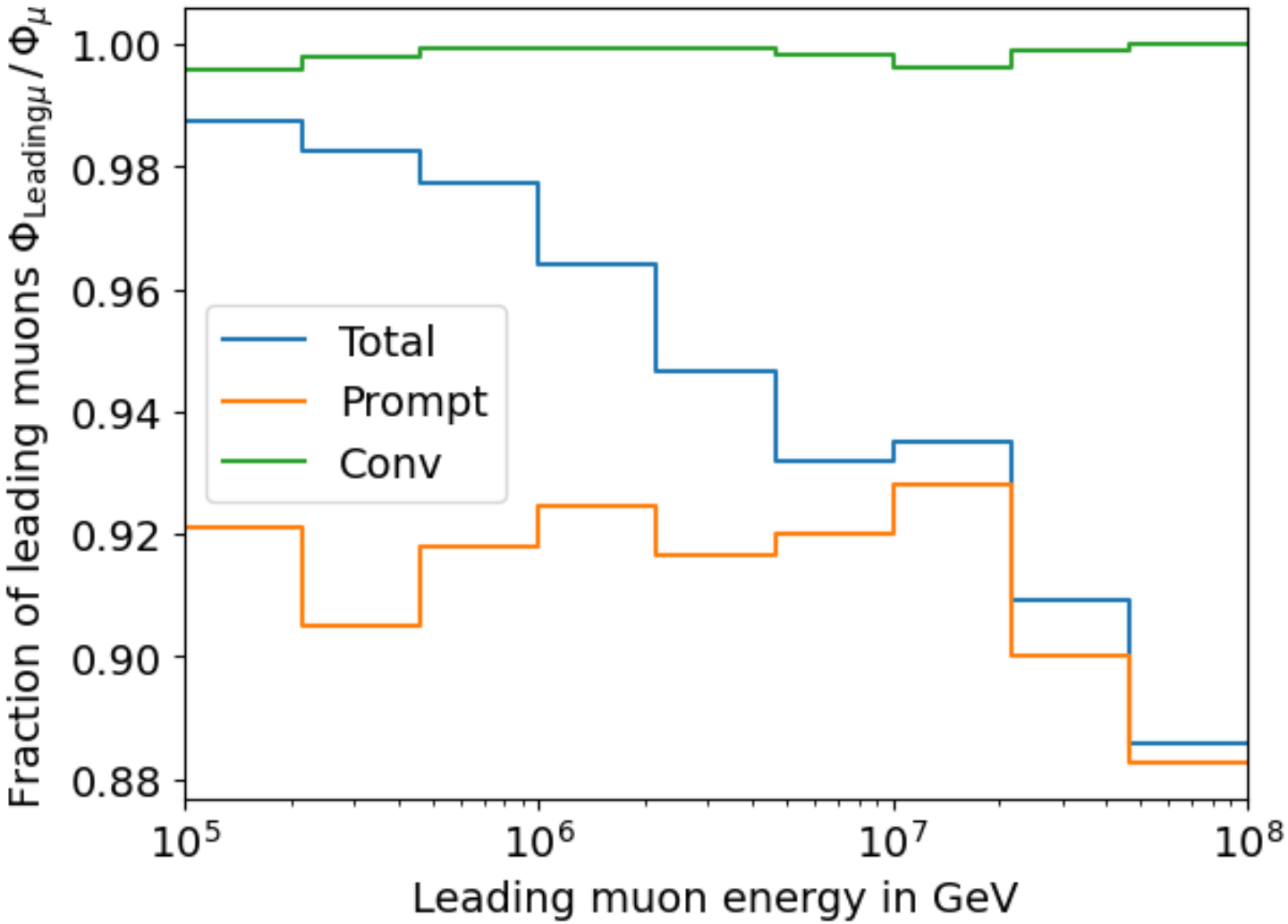


Figure 10: Surface energy distribution for all and most energetic ("leading") muons in simulated events with a total of more than 1,000 registered photo-electrons in IceCube.

- 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

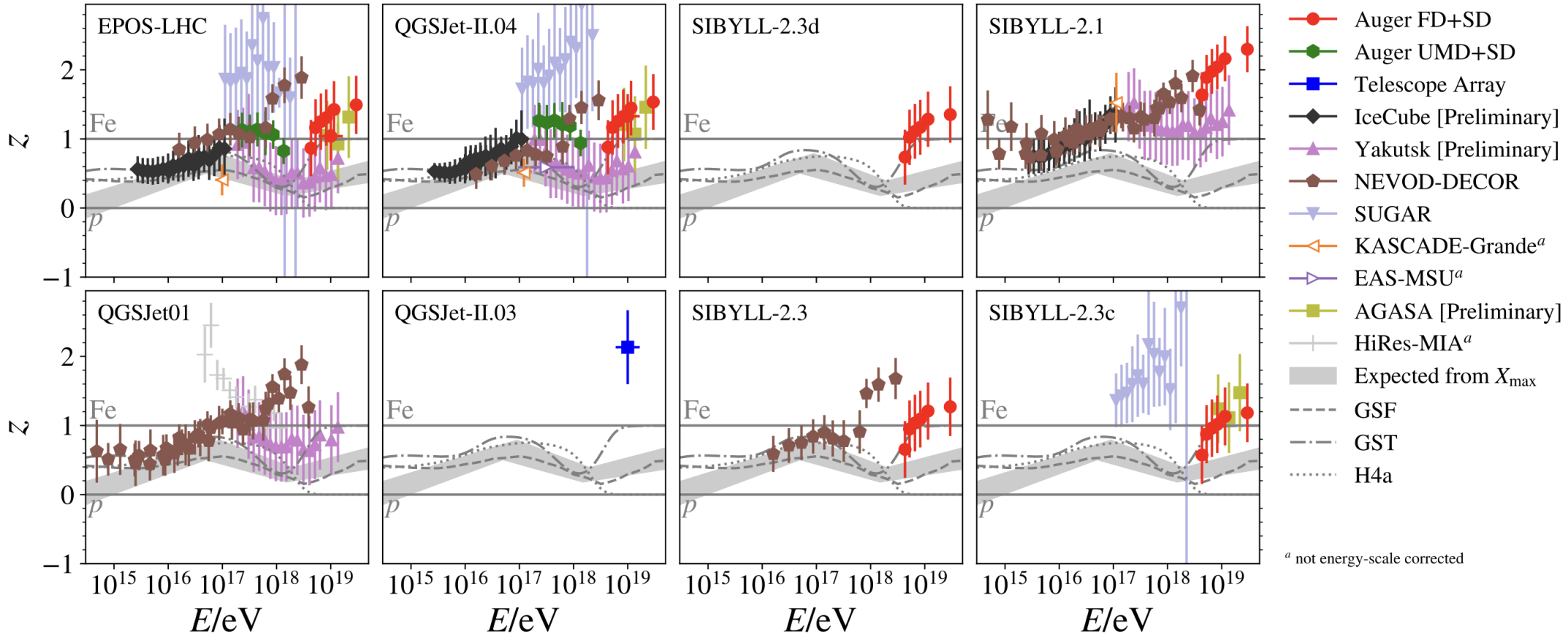
➢ High leading energy fraction does not lead to more sensitivity to detect prompt



The Muon Puzzle

"muon number"

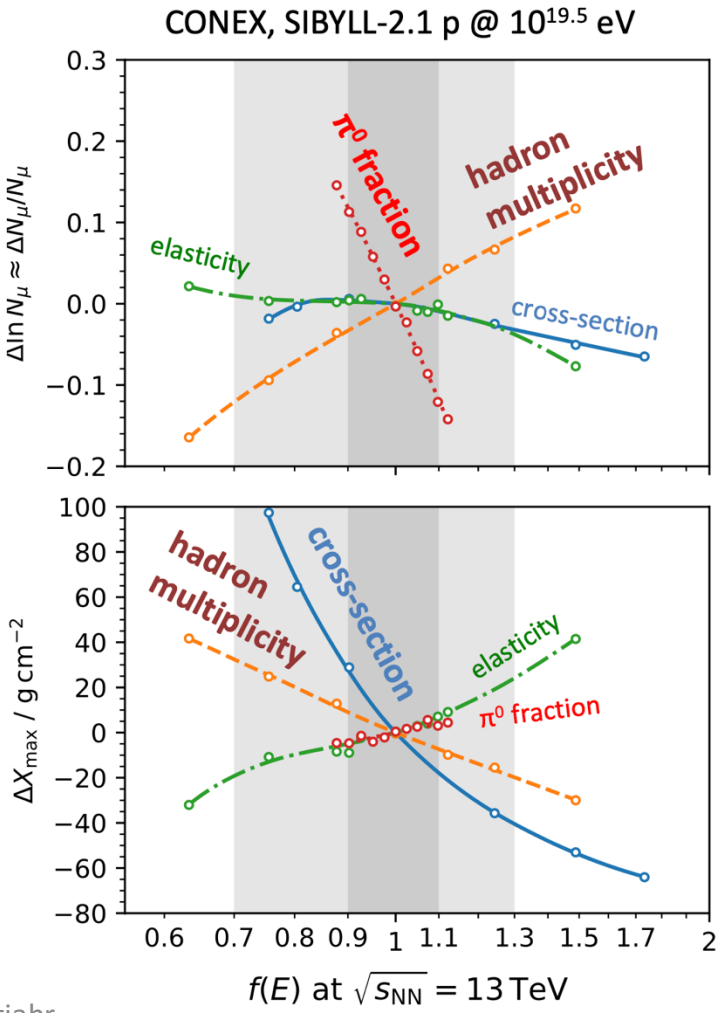
$$z = \frac{\ln\langle N_\mu\rangle - \ln\langle N_\mu\rangle_p}{\ln\langle N_\mu\rangle_{\mathrm{Fe}} - \ln\langle N_\mu\rangle_p}$$



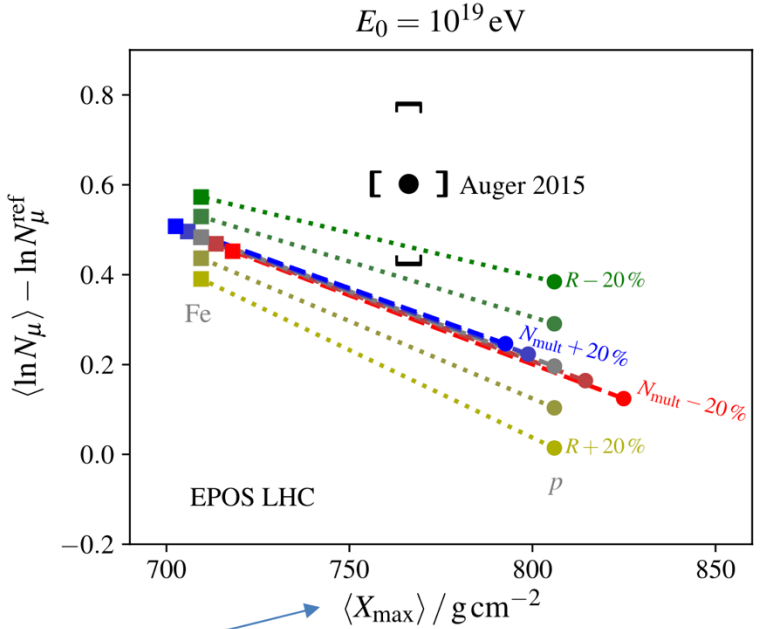
2108.08341

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



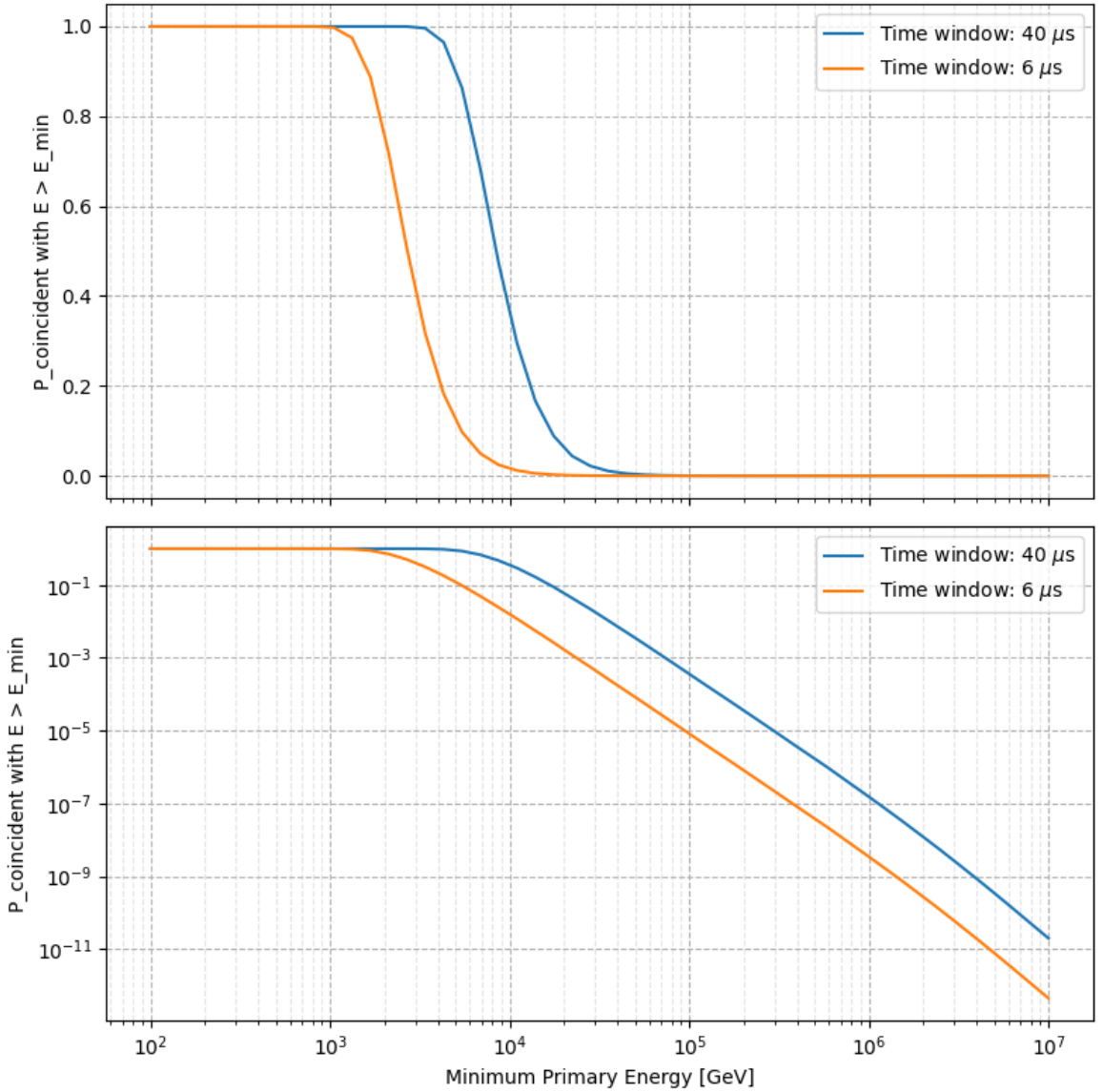
$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

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

Hans Dembinski

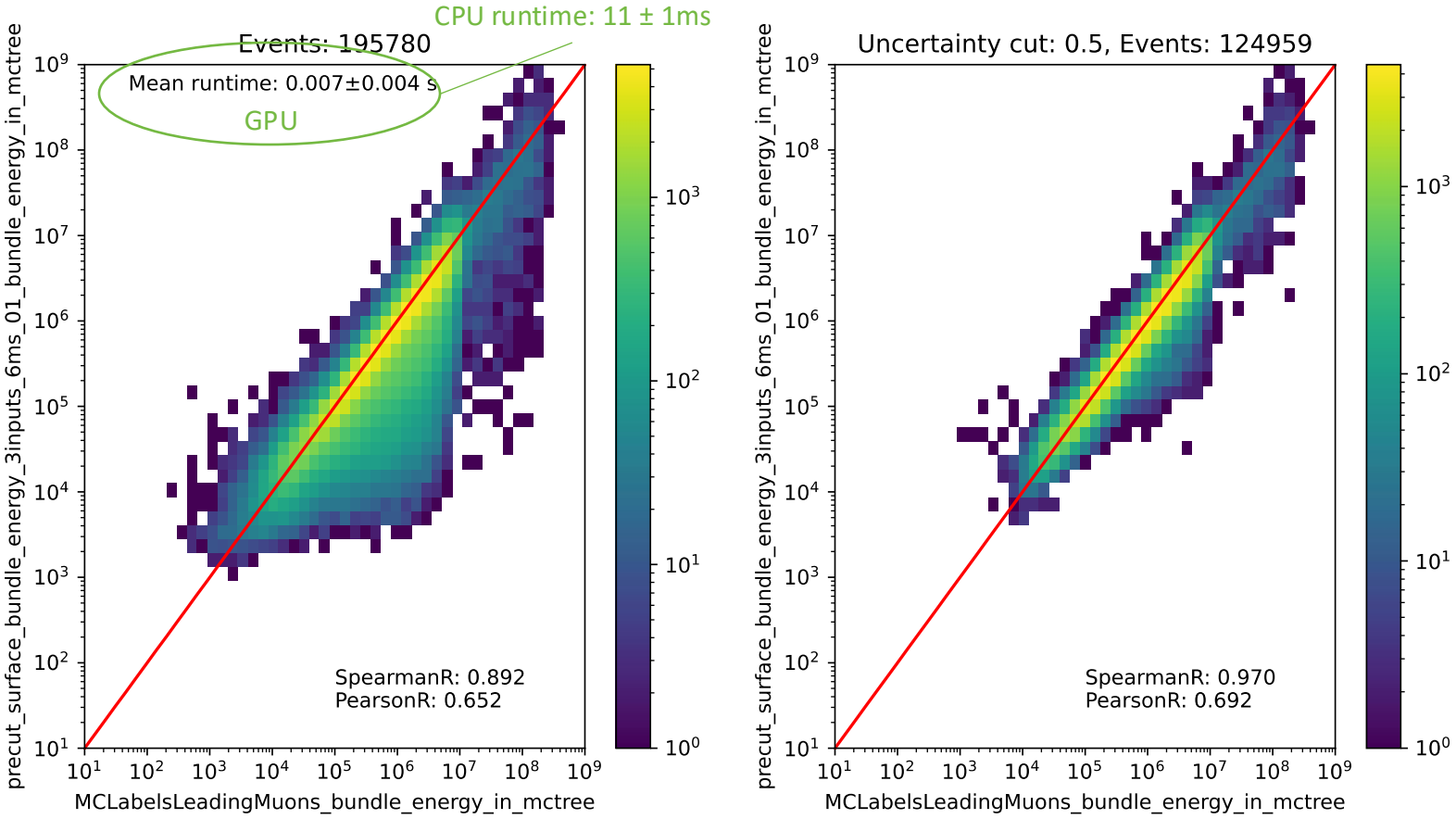
Simulation w/o coincident events

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



Bundle energy cut

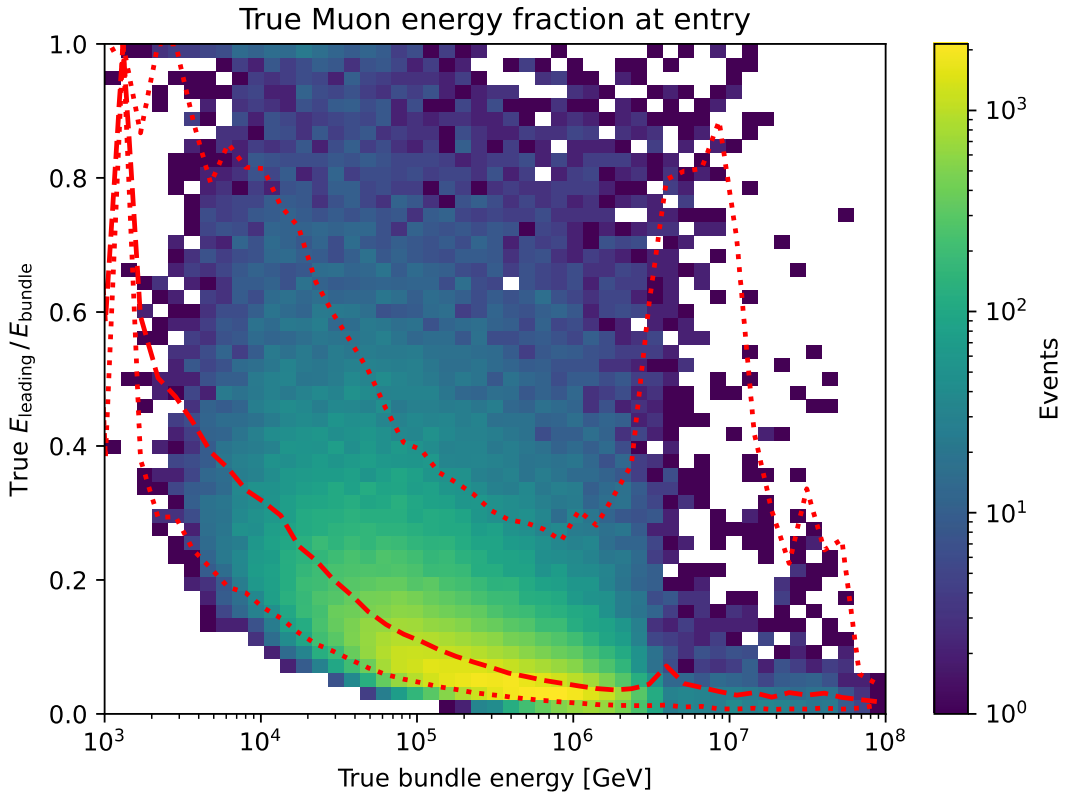
- Rate after muon filter: 24.62 Hz
- If the process of 1 event needs 1 second, 8h run takes 200h -> needs to be reduced!
- Use small, fast network to remove low energy events -> target rate 125 mHz

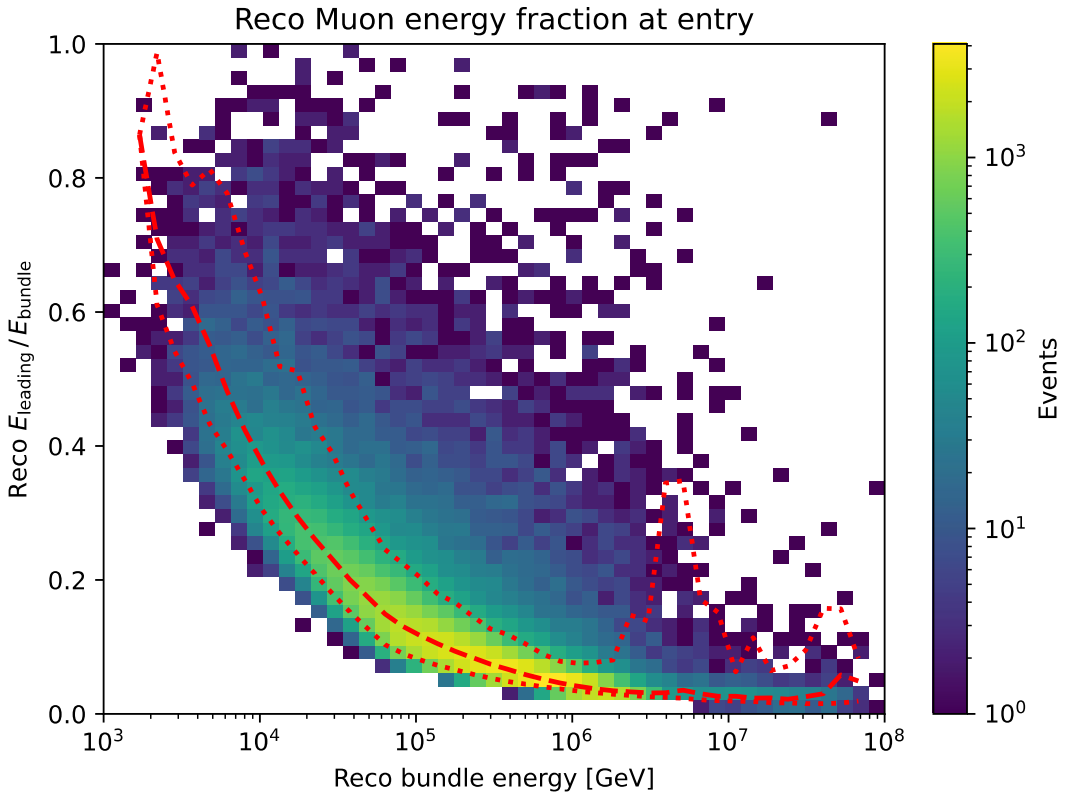


Network: precut_surface_bundle_energy_3inputs_6ms_01

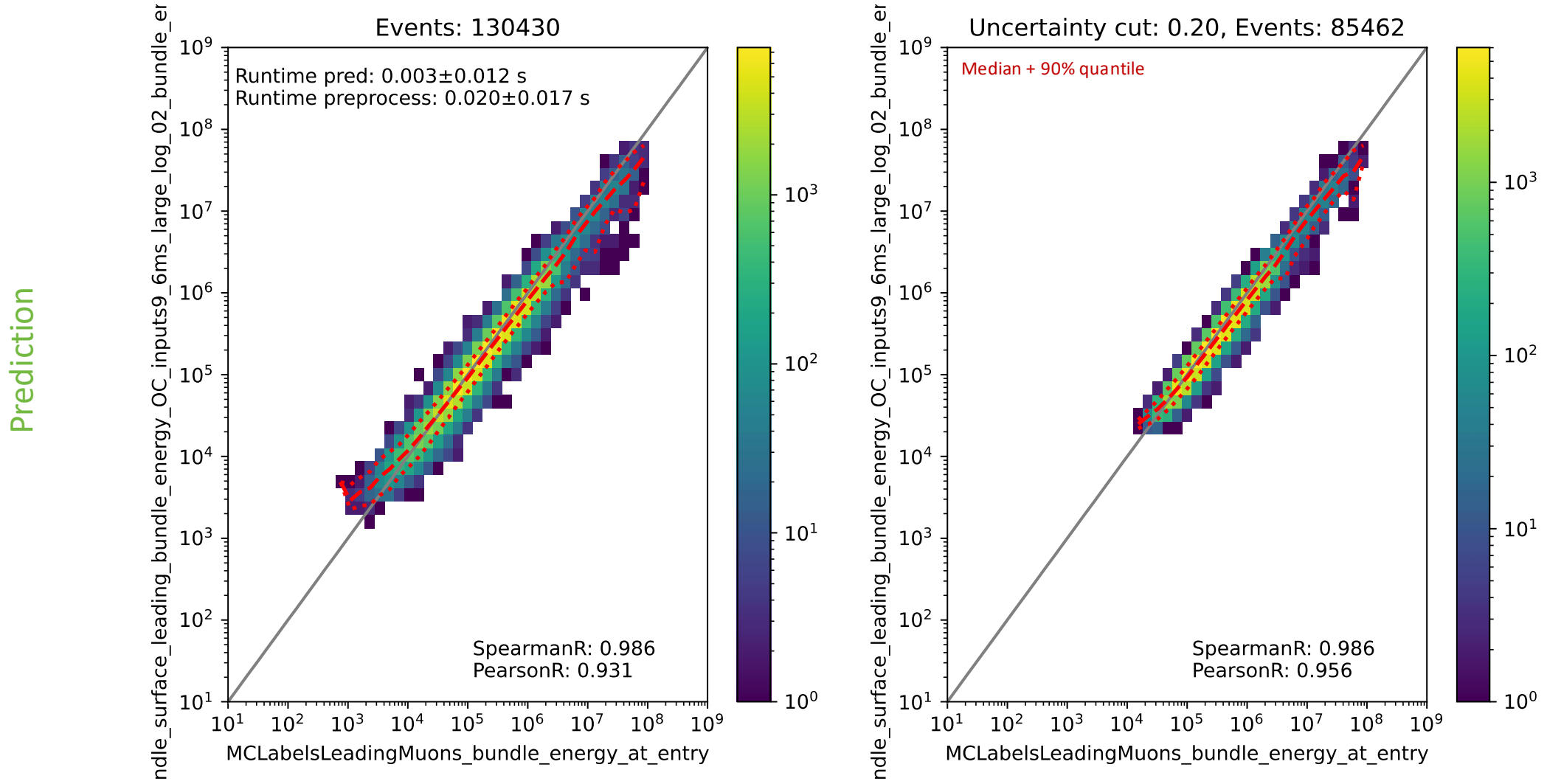
Leading muon energy fraction - leadingness

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

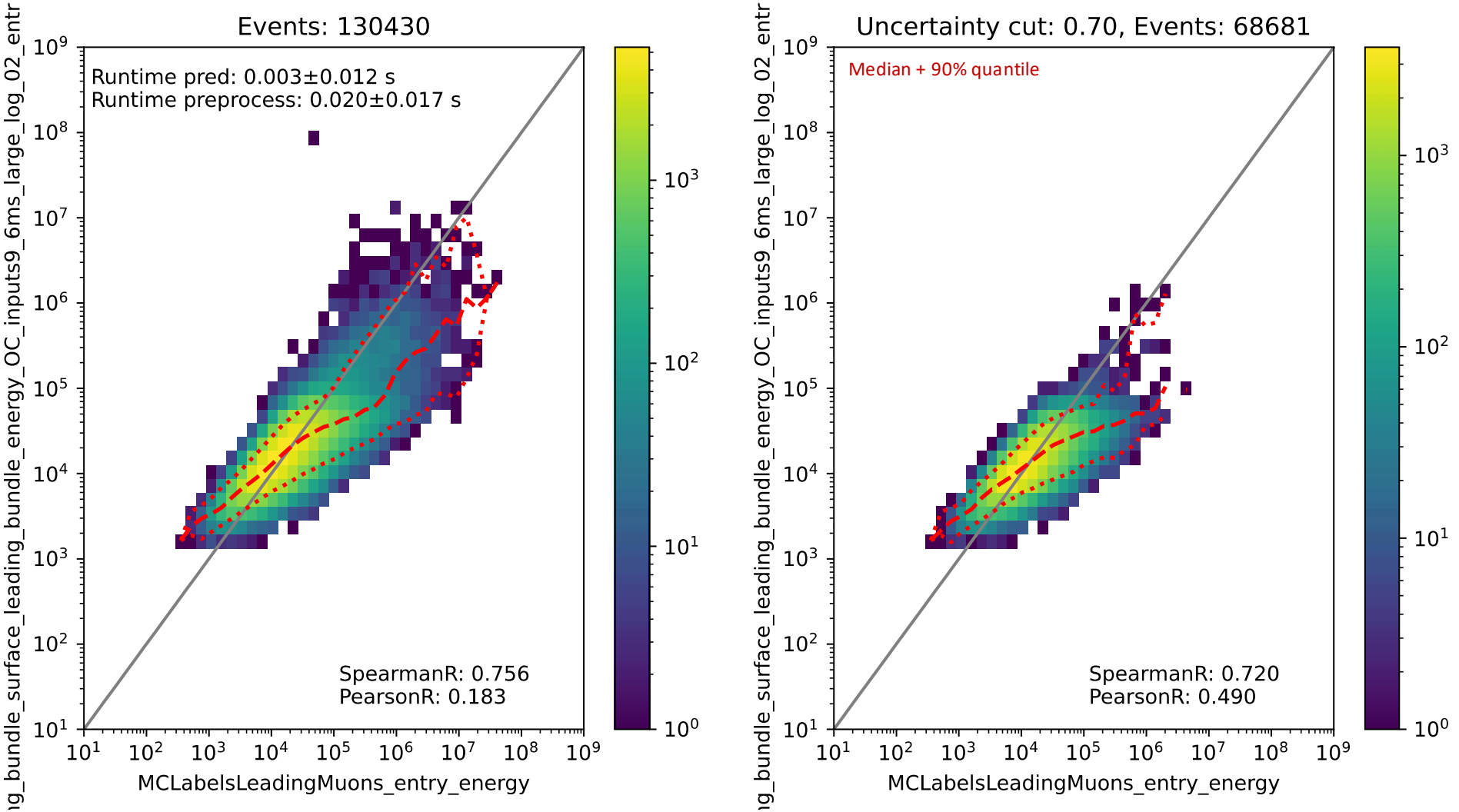




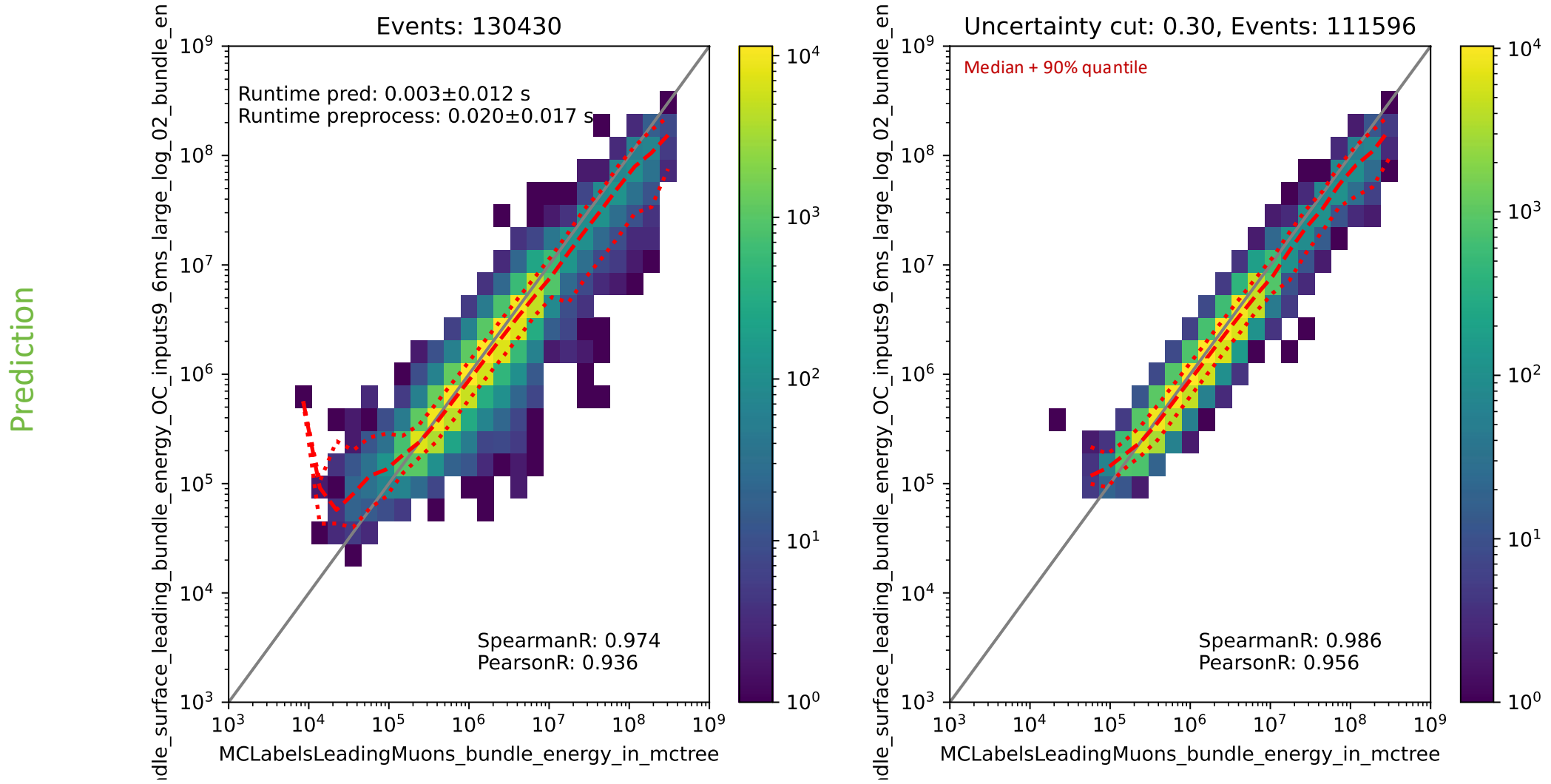
Bundle energy at entry – 6 µs cleaned pulses



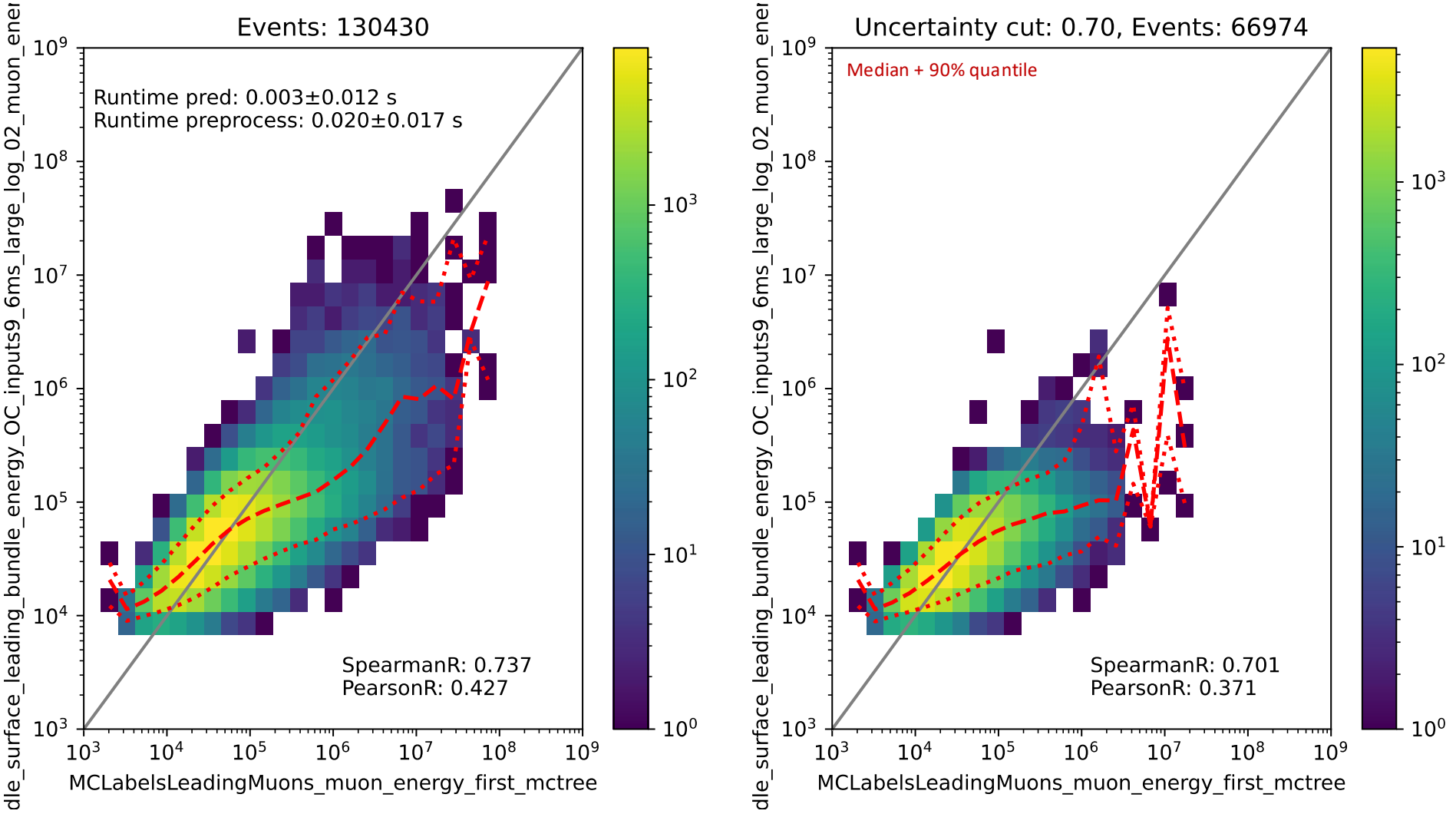
Leading muon energy at entry – 6 µs cleaned pulses



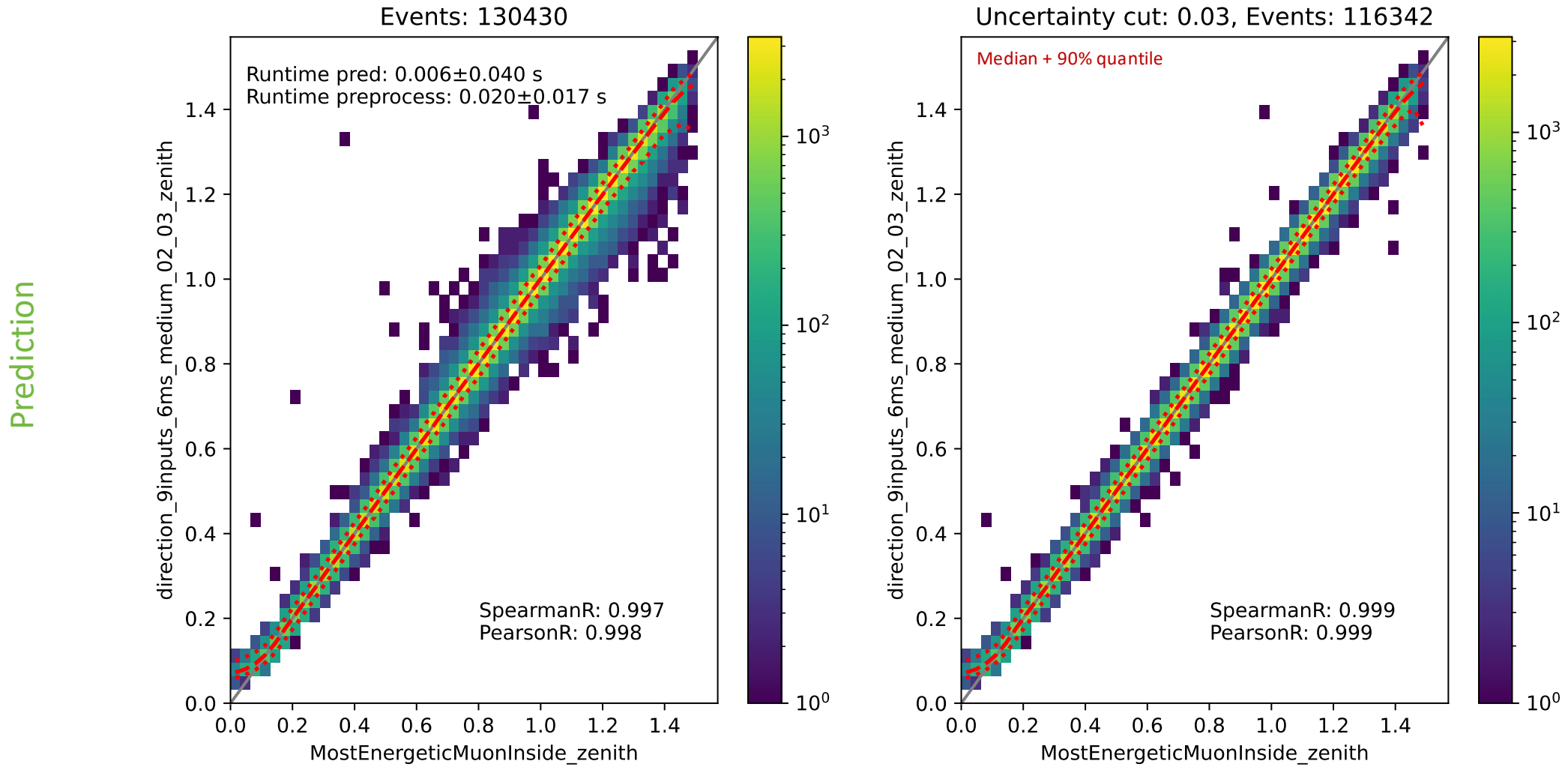
Bundle energy at surface – 6 µs cleaned pulses



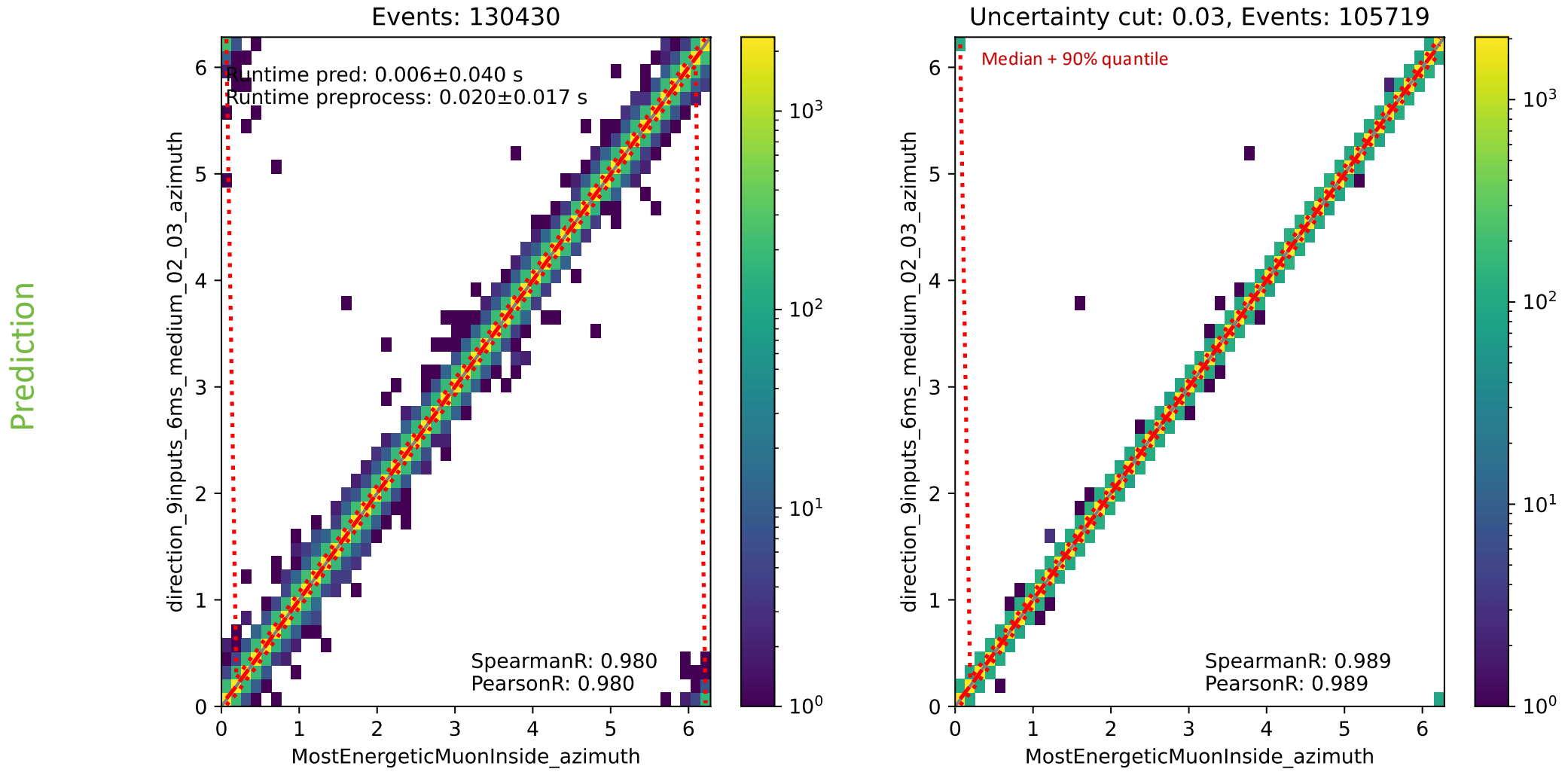
Leading muon energy at surface – 6 µs cleaned pulses



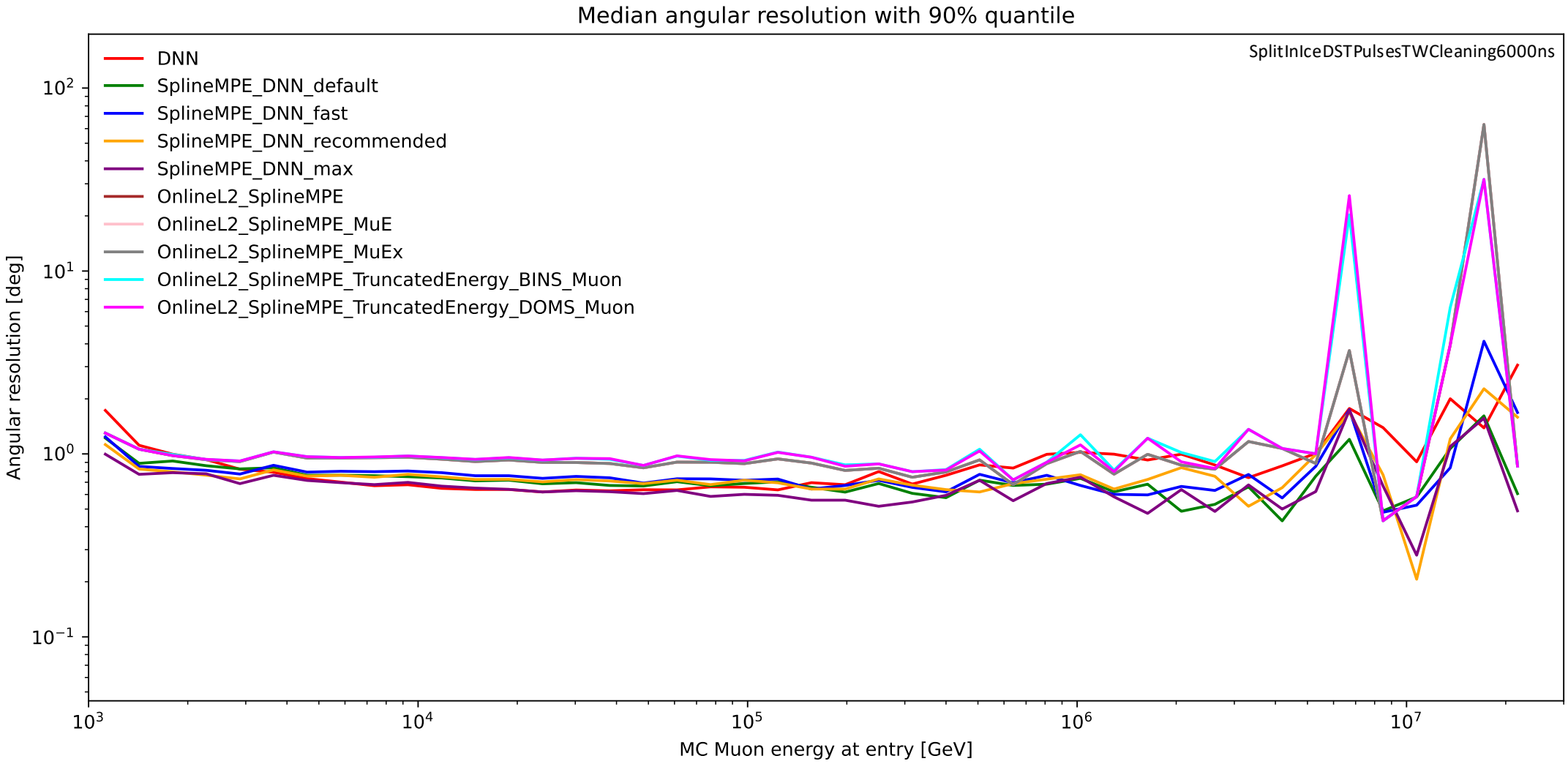
Zenith – 6 ms cleaned pulses



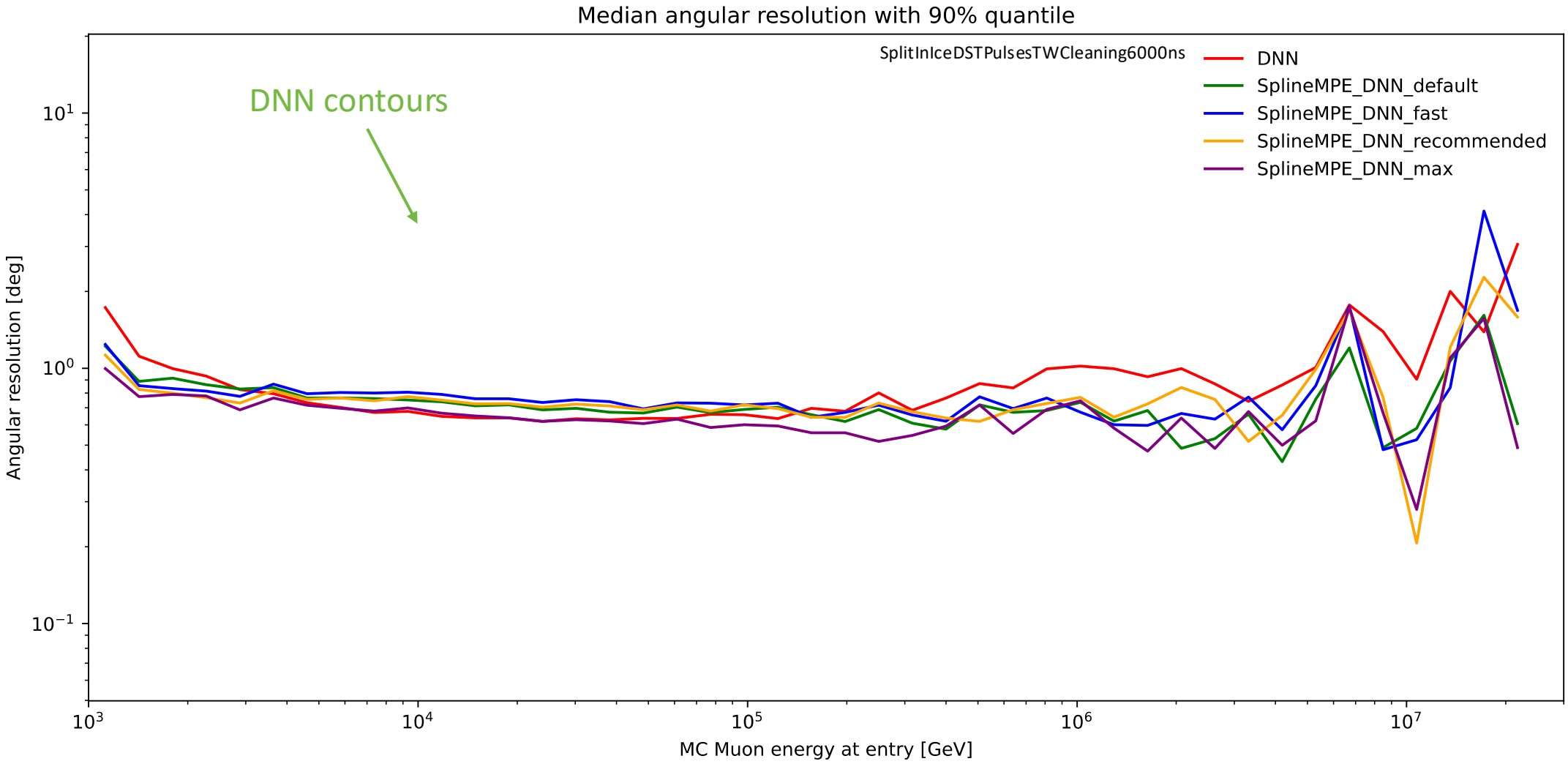
Azimuth – 6 ms cleaned pulses



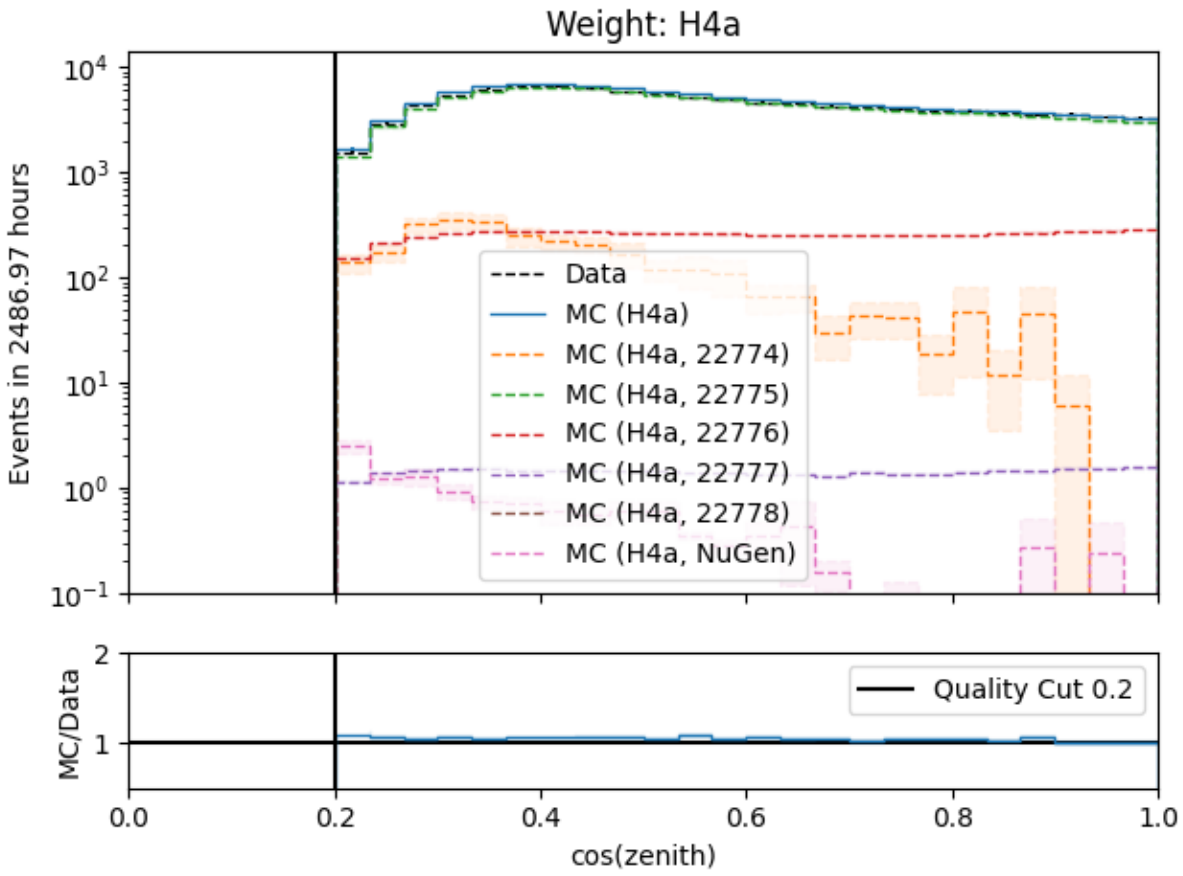
SplineMPE – DNN and conventional seeds

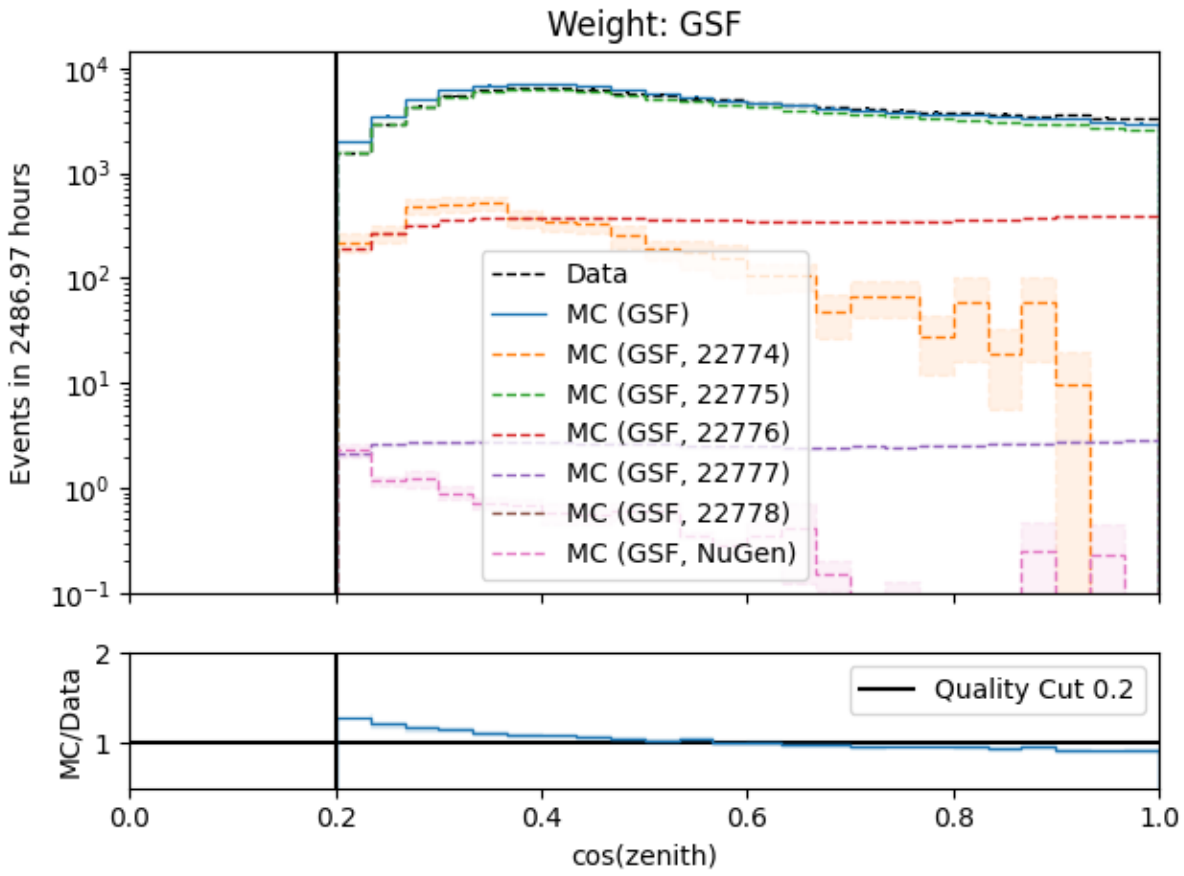


SplineMPE – DNN seeds

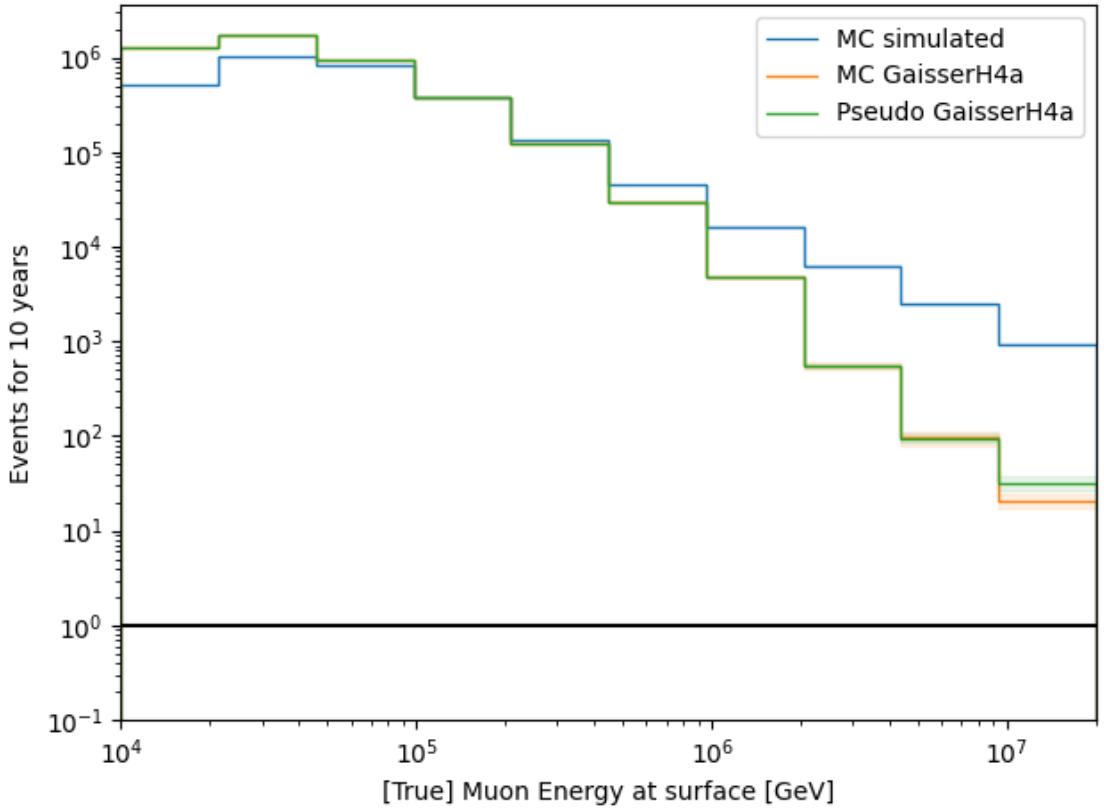


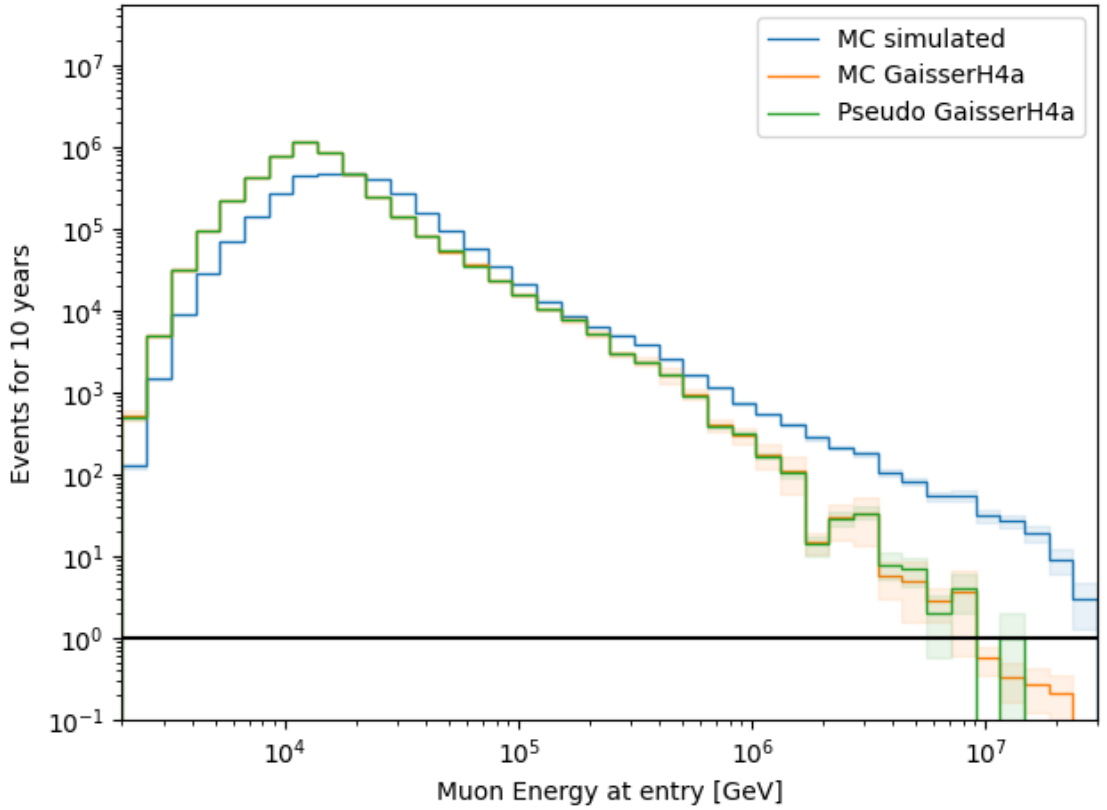
Level5: cos(zenith)



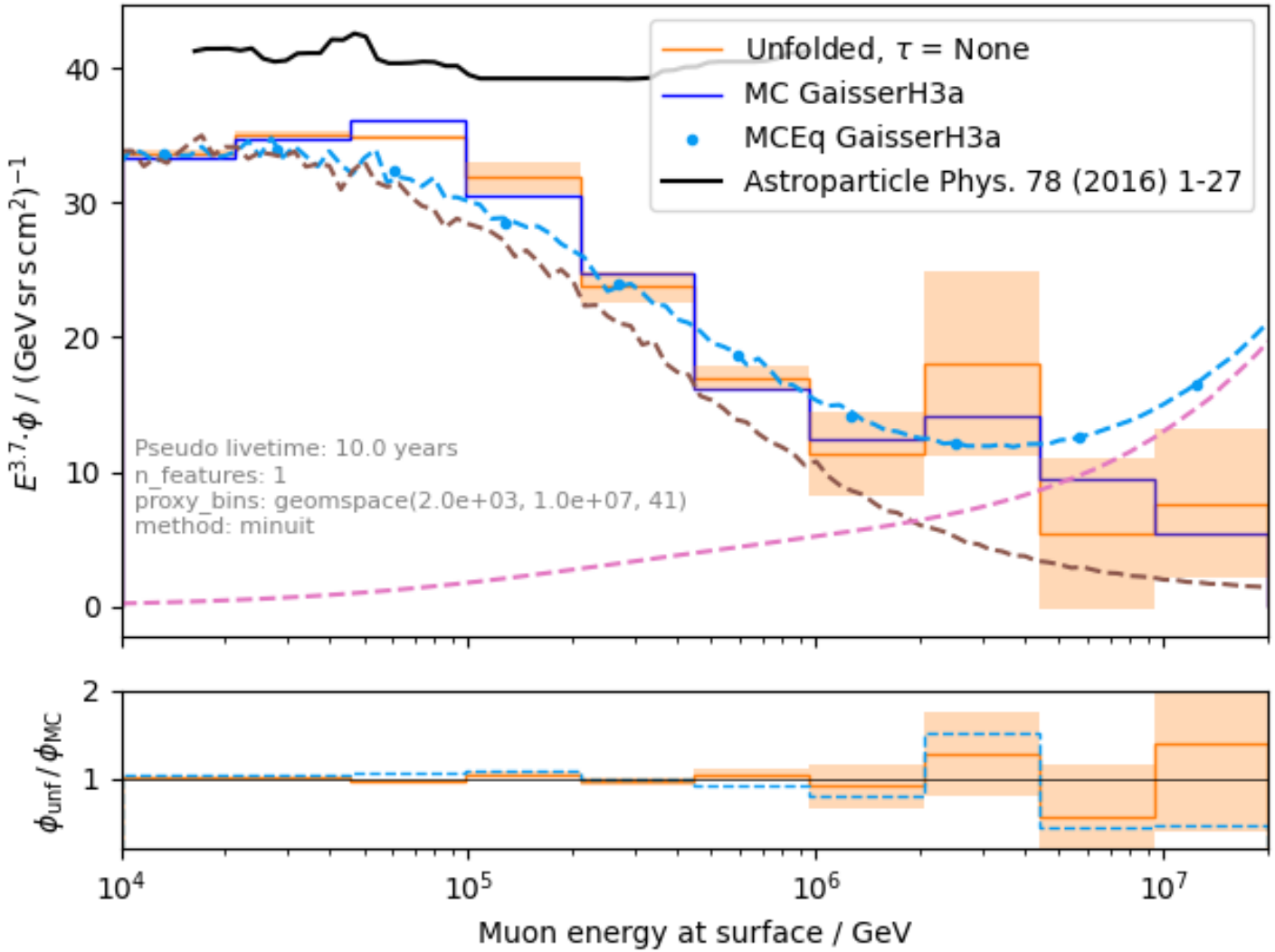


Proxy and target variable for unfolding – 10 years [H4a]

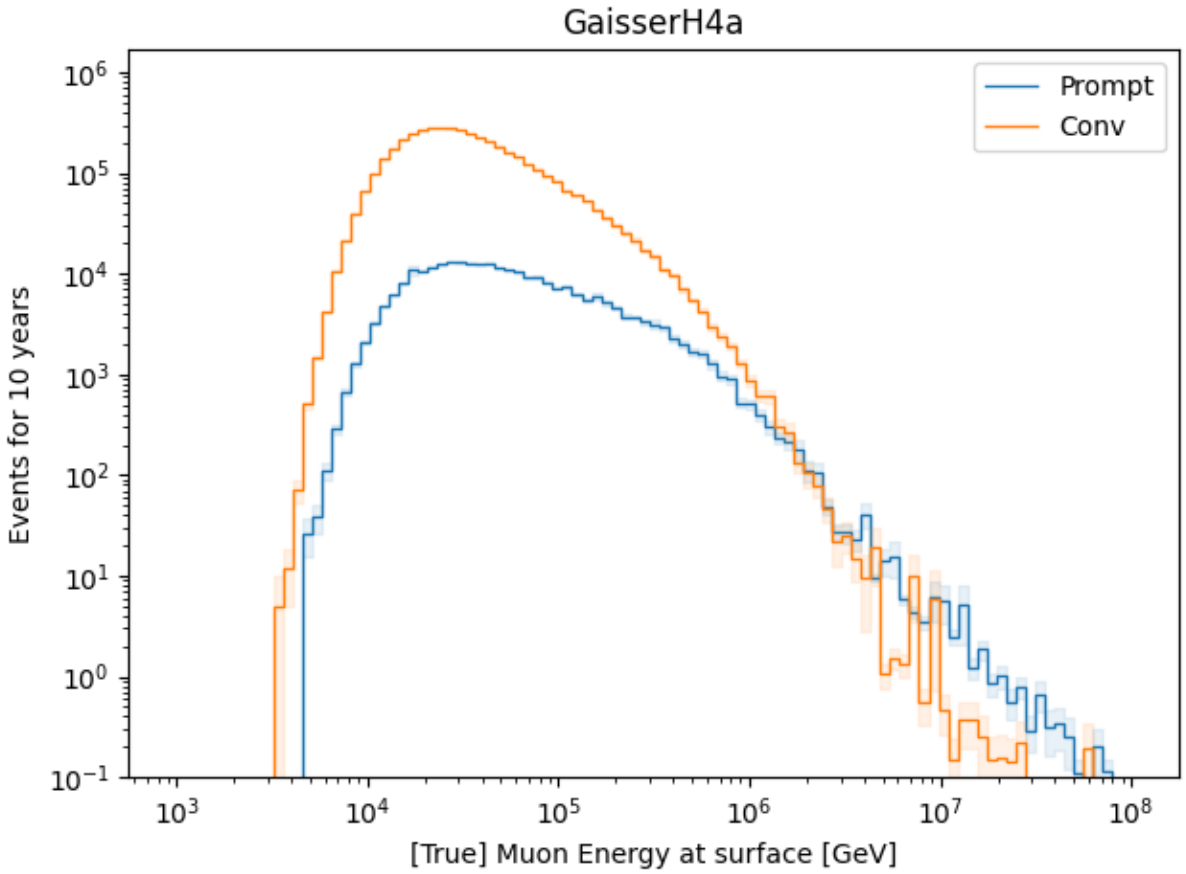


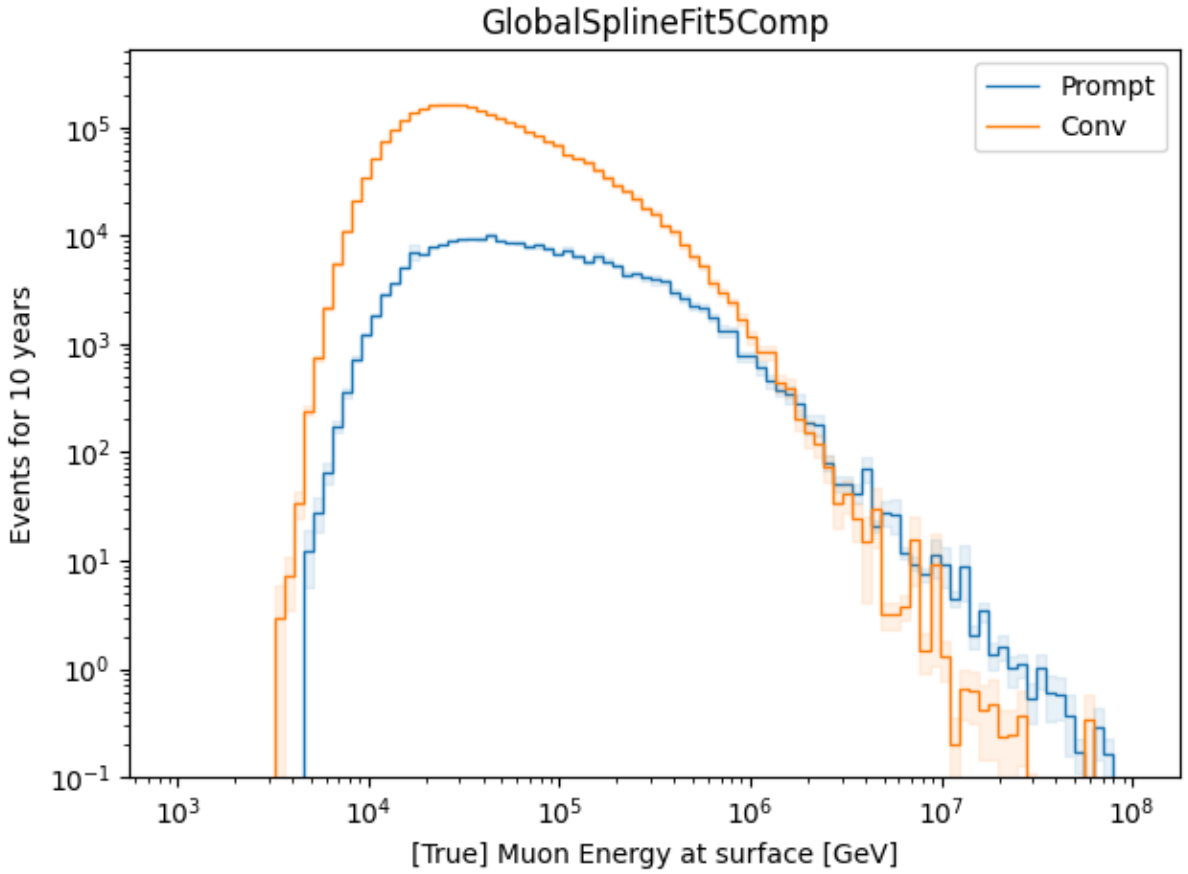


Unfolding with prompt and conv MCEq

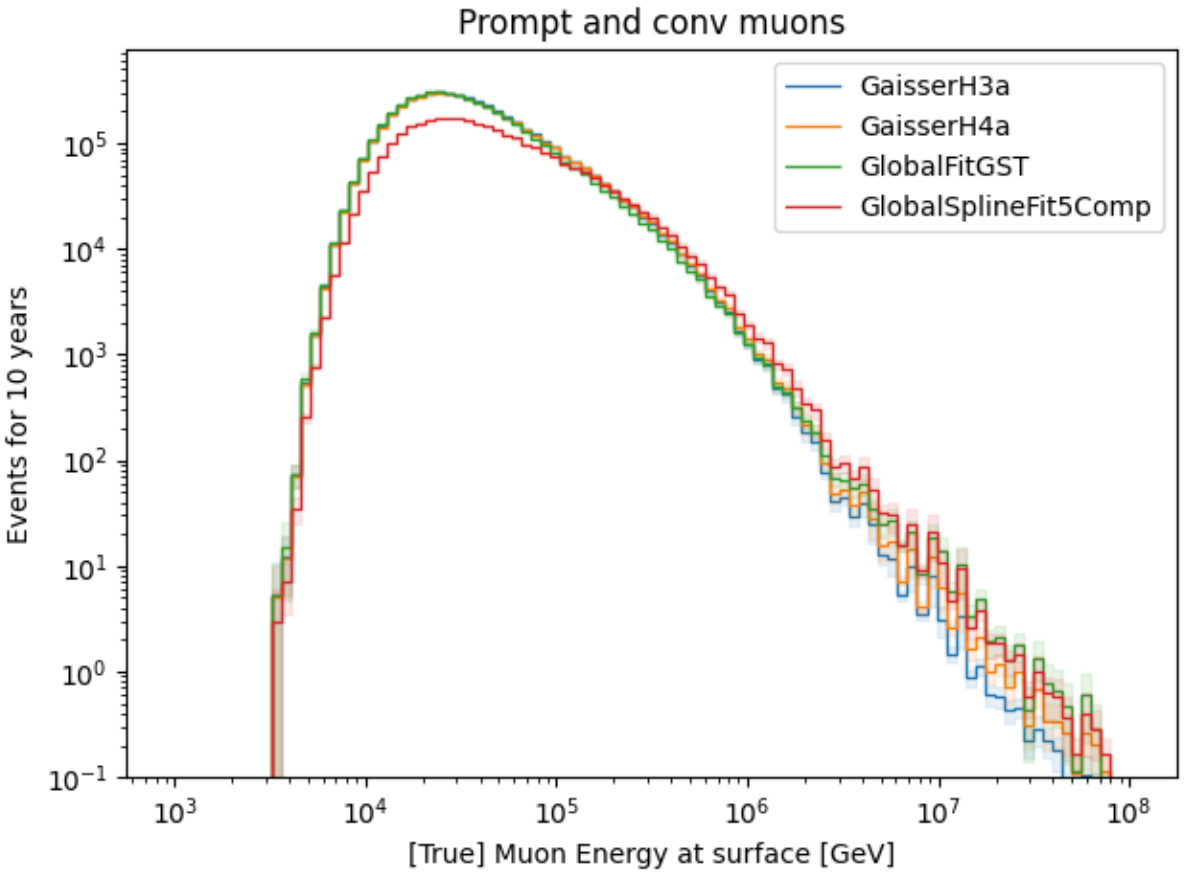


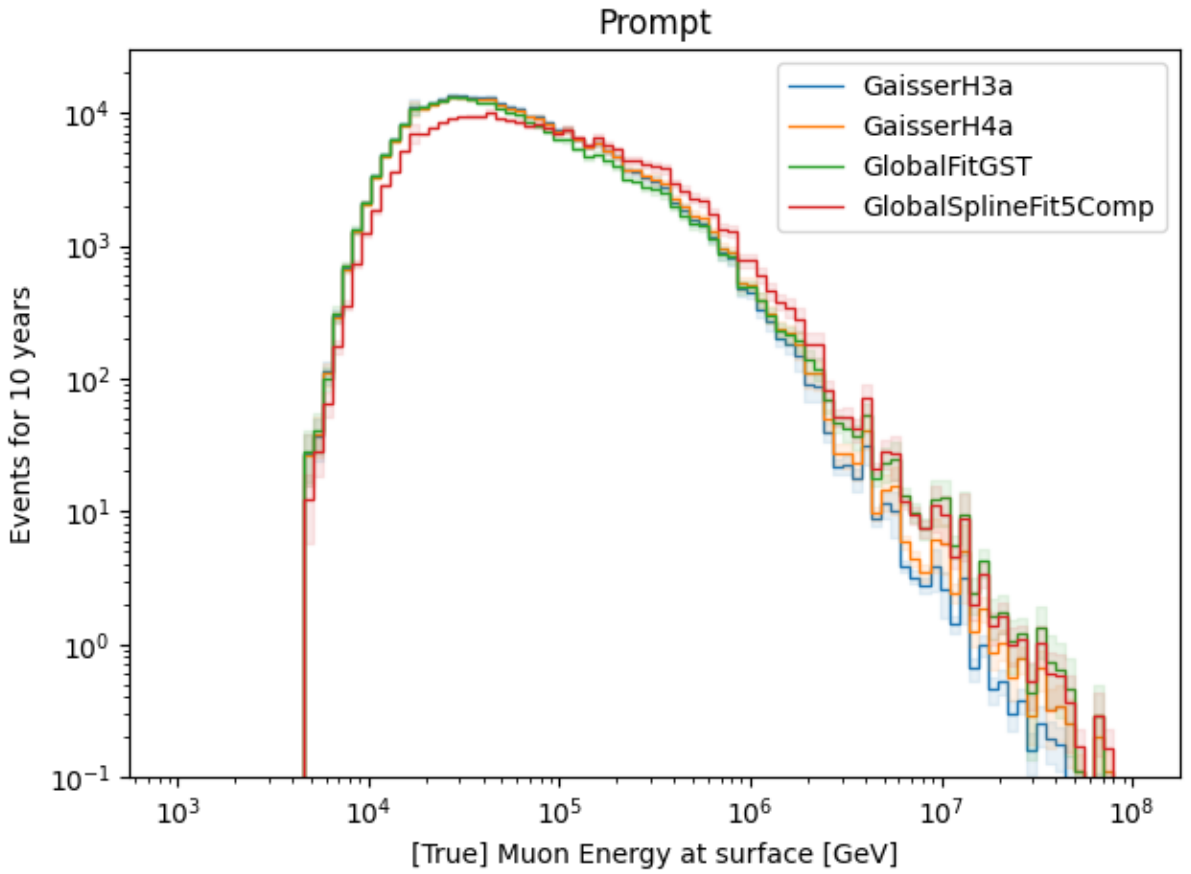
Prompt and conv: muon energy at surface for 10 years



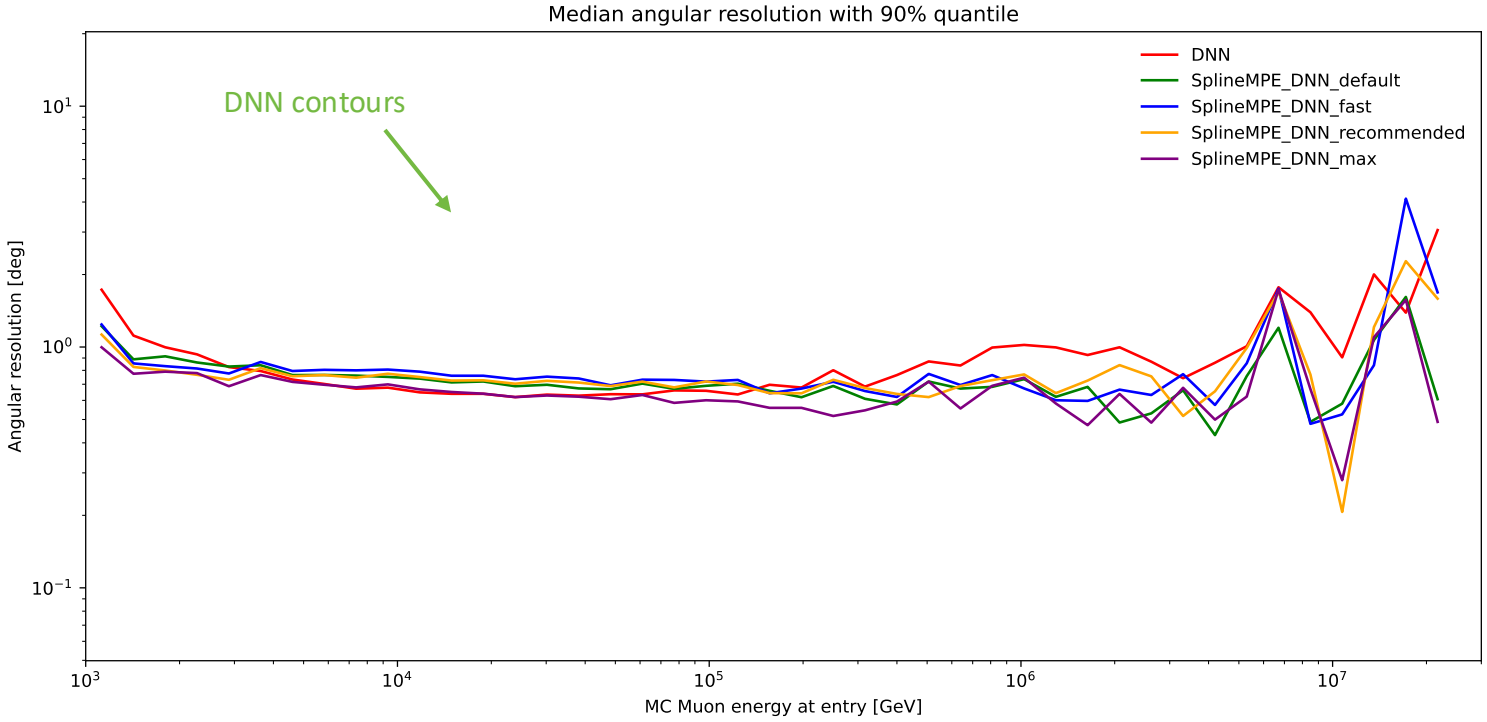


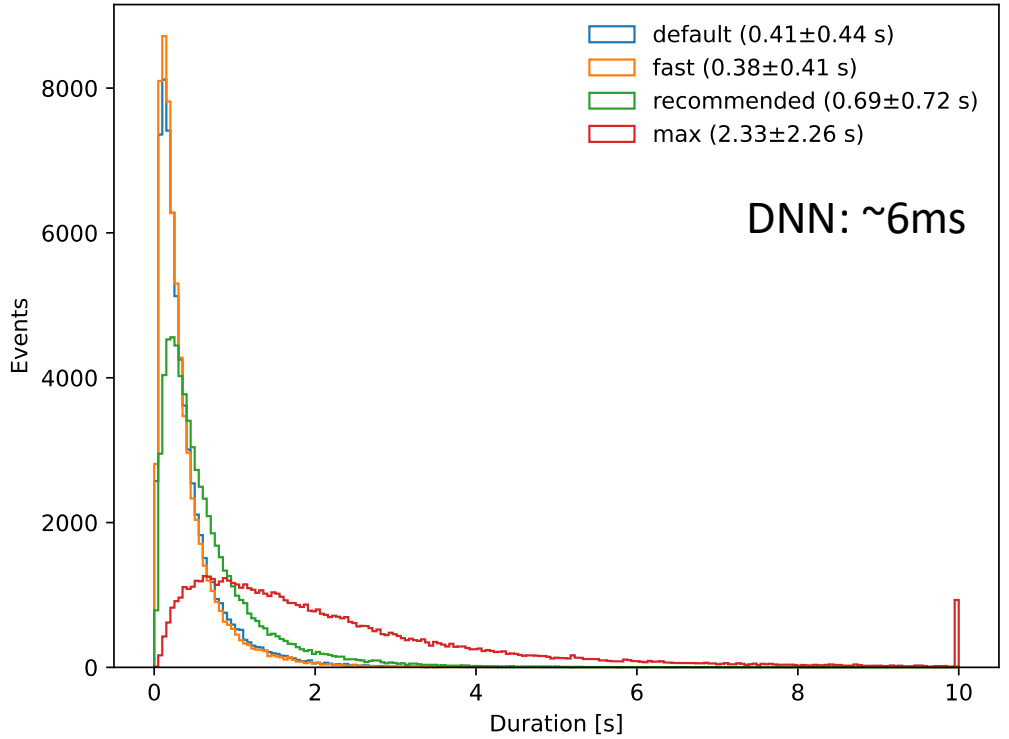
Compare all primary fluxes





Angular reconstructions: DNN vs. SplineMPE





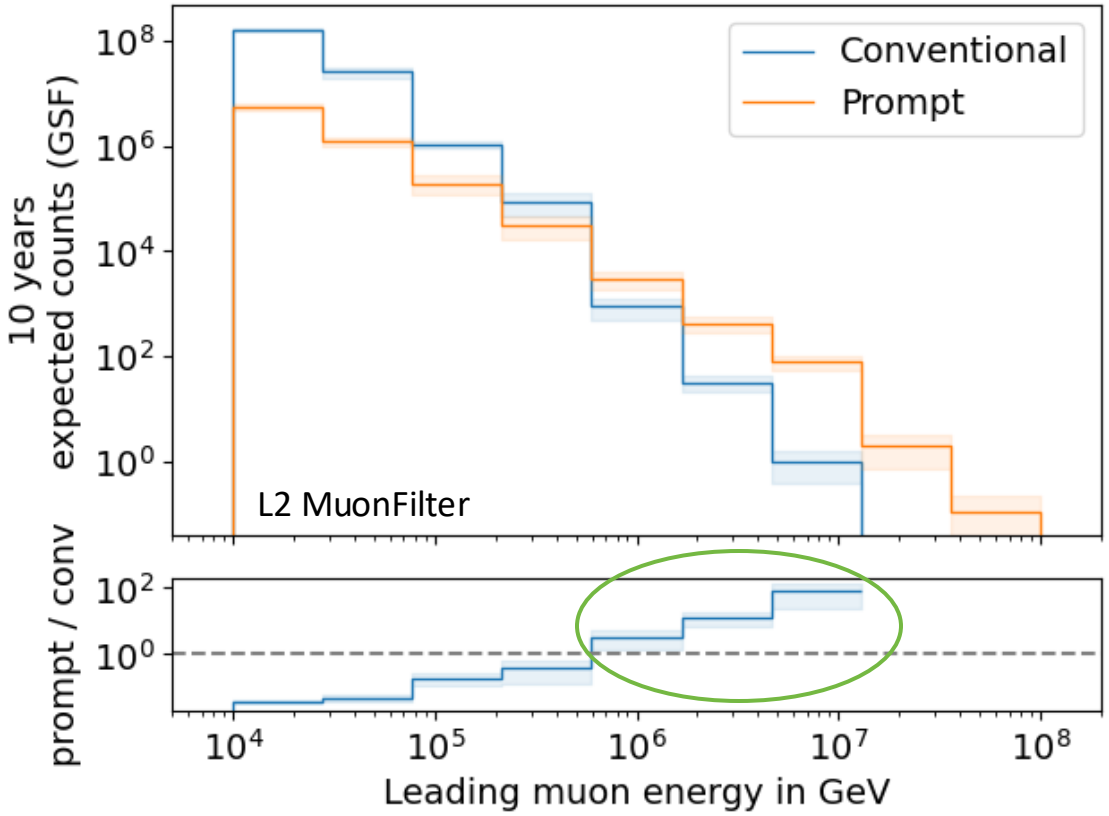
- Only small improvement at energies around 1 PeV
- Countours are larger
- Additional runtime

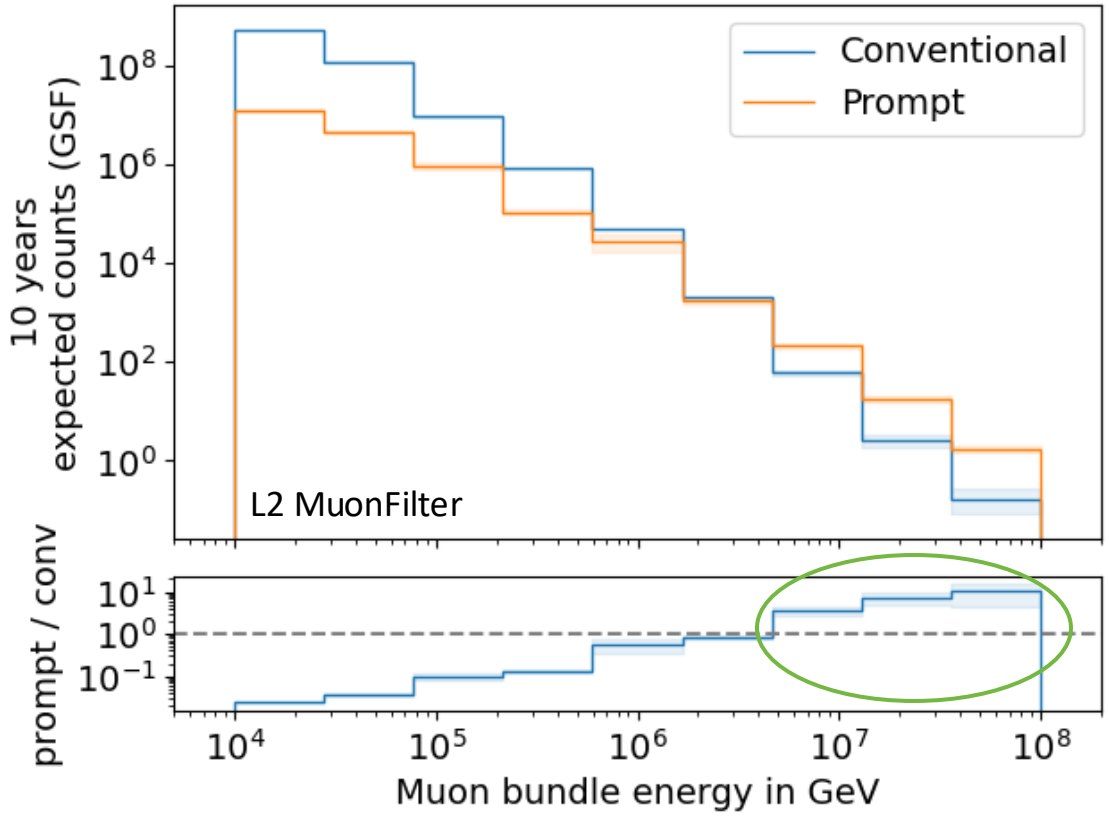
-> Use only DNN reconstruction, since we do not need the best angular resolution

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

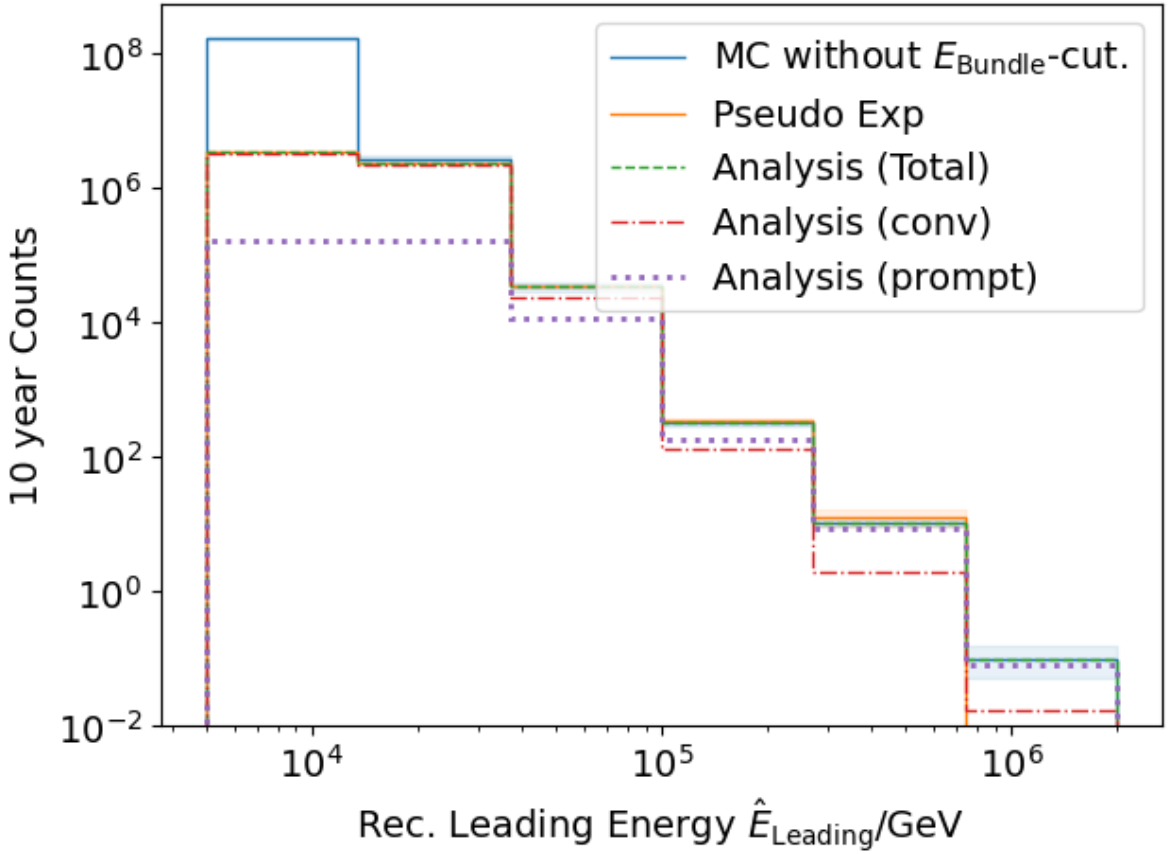


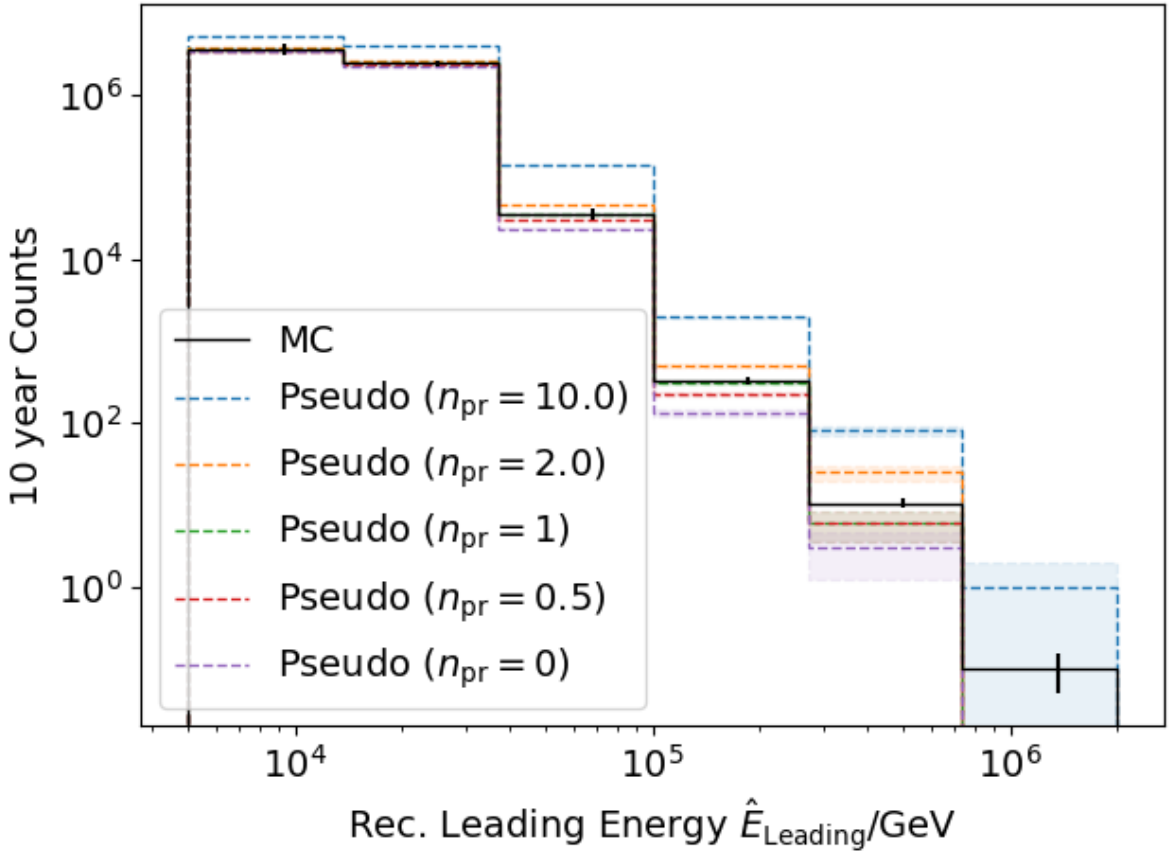


- Both leading and bundle energy are sensitive to detect prompt
- Leading muon energy is more sensitive

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

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

Experimental counts

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

Maximize likelihood

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

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

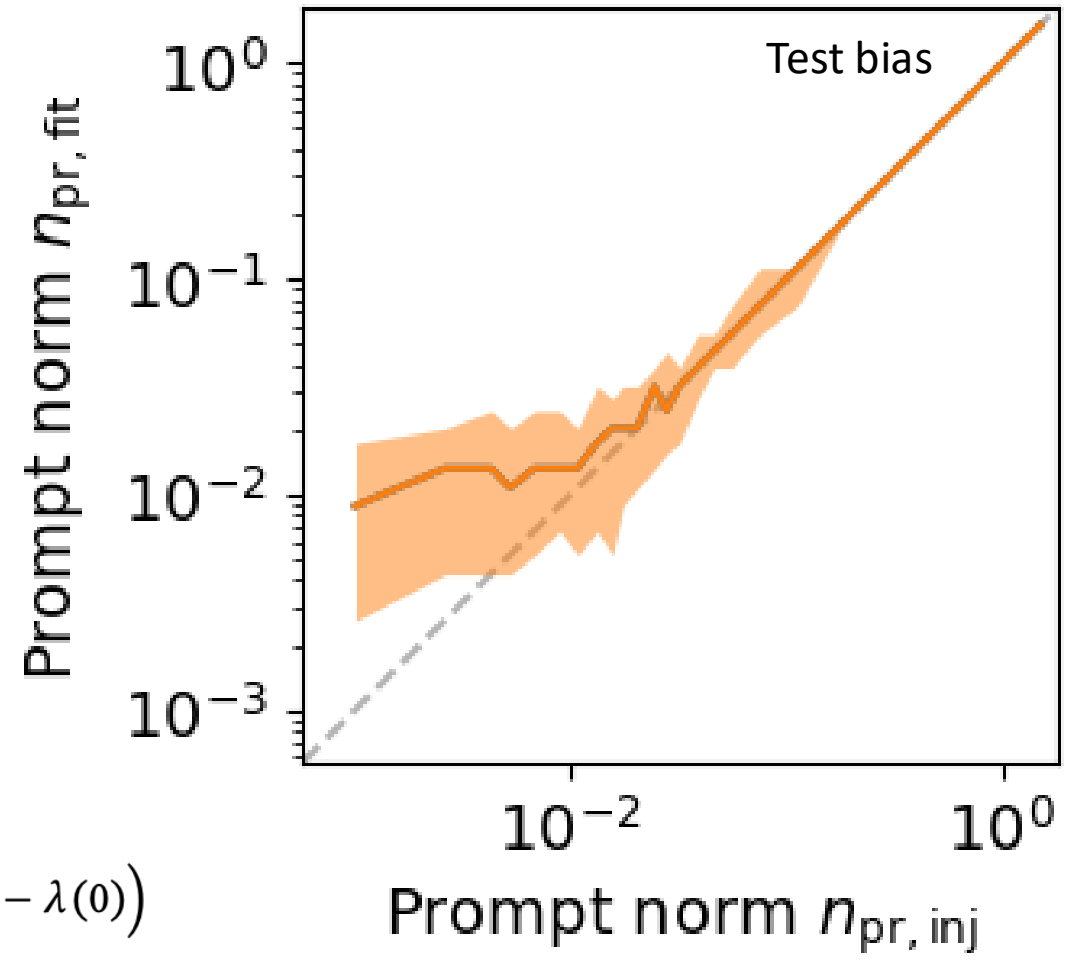
Easier:
minimize negative
log-likelihood

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

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

Test statistic for Wilks' theorem

Null hypothesis: no prompt



- Bias starts at a prompt normalization of ~0.1

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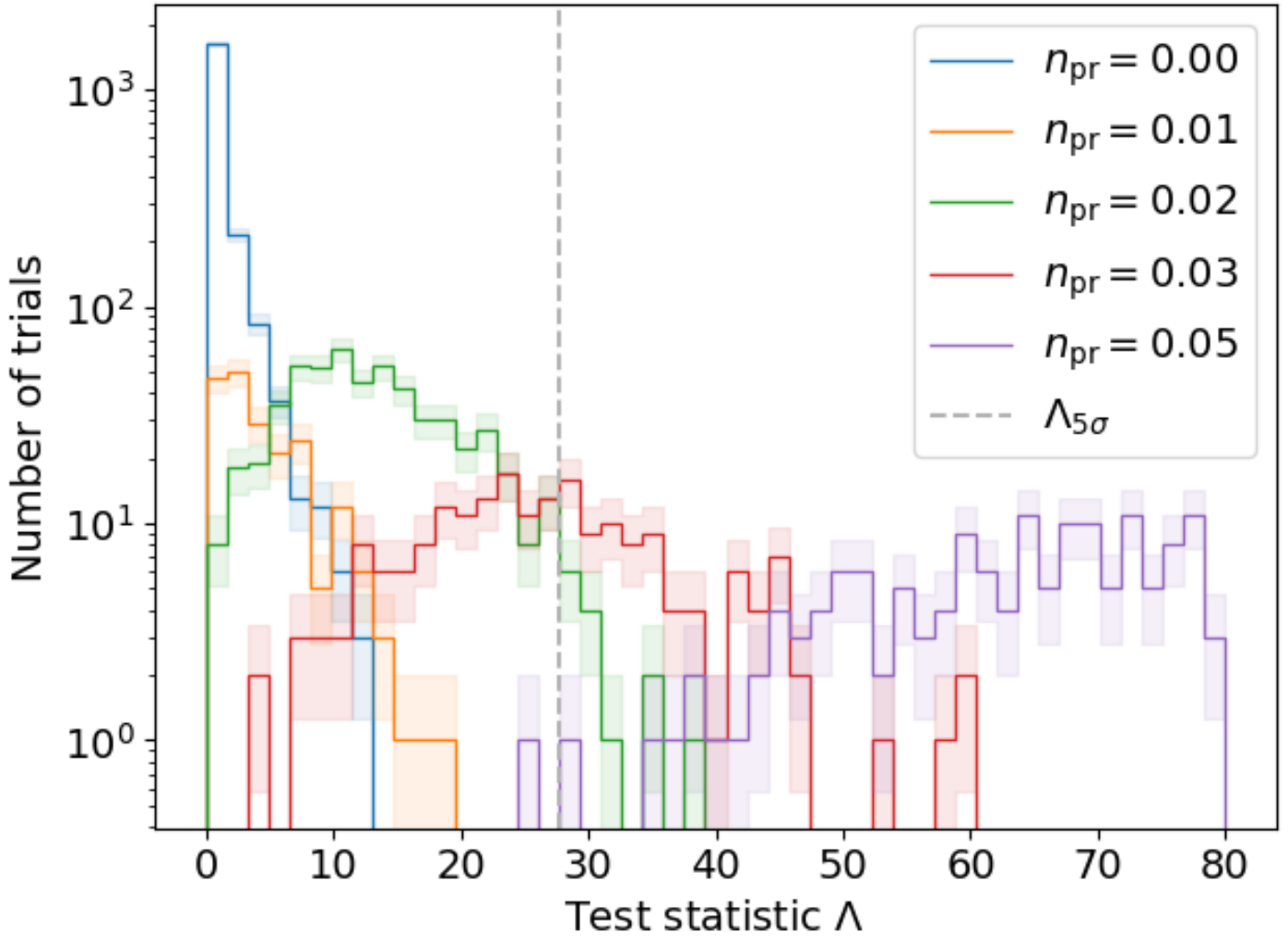
Discovery potential and sensitivity

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

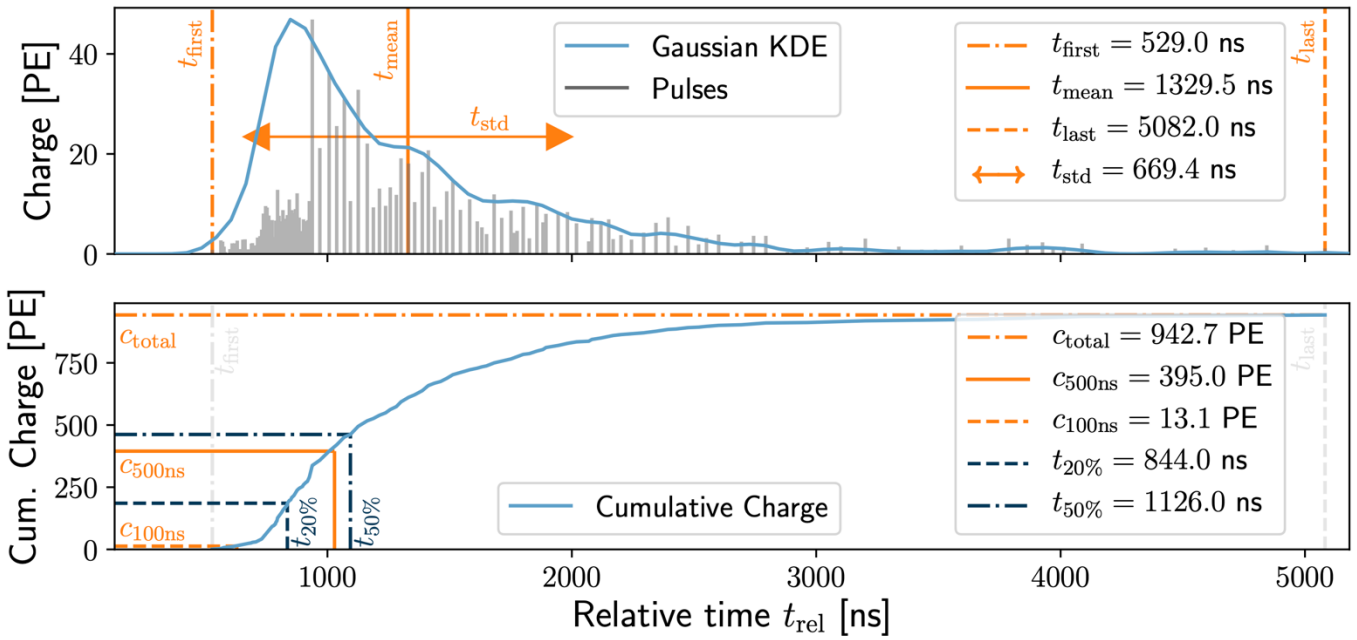
Expectation for 10 years:
- 5 sigma discovery potential: 0.032 ± 0.001
- Sensitivity: 0.007 ± 0.000

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

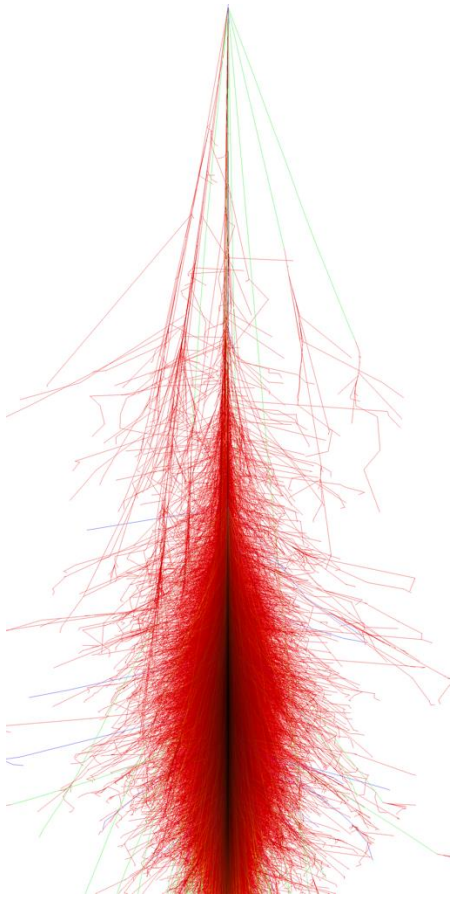
Input pulses

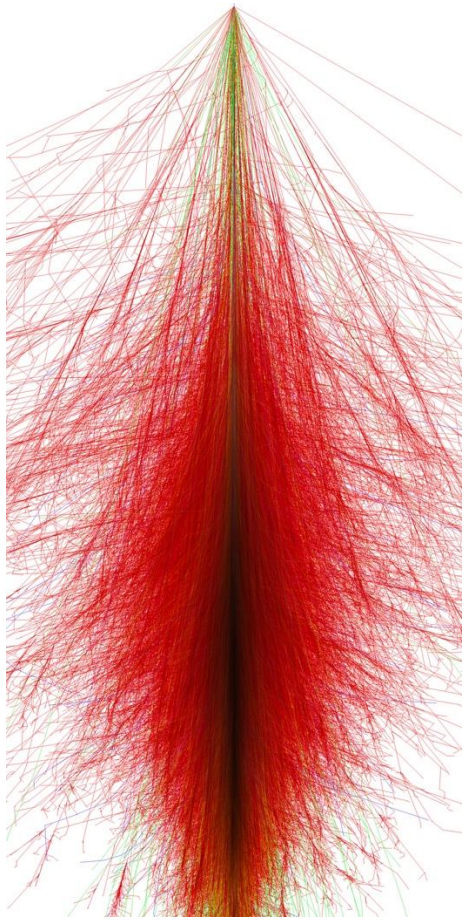
- SplitInIceDSTPulses
- SplitInIceDSTPulsesTWCleaning6000ns
- (DNN framework performs an internal cleaning)

Training datasets

- 20904
- 21962
- 22020
- 22187

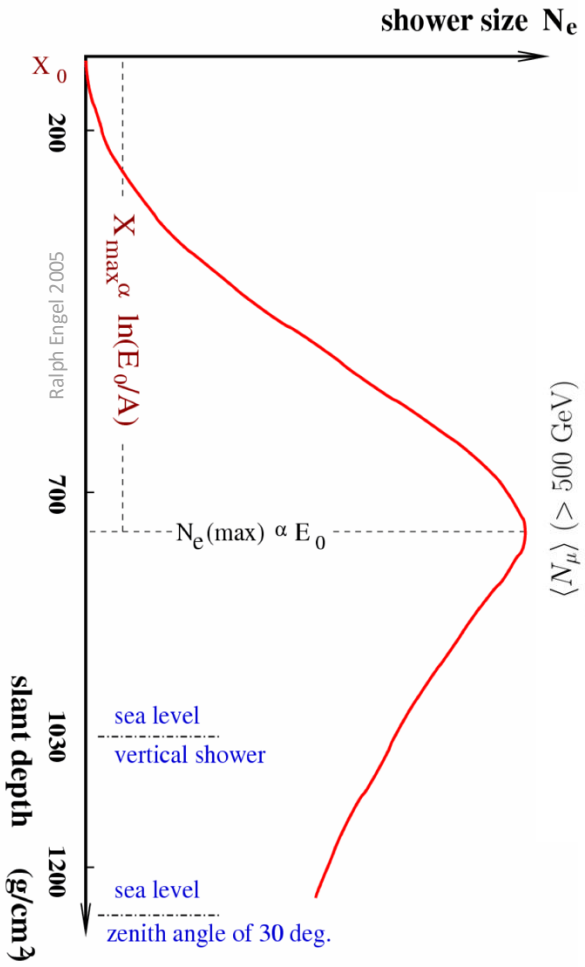
Air shower – 10 TeV



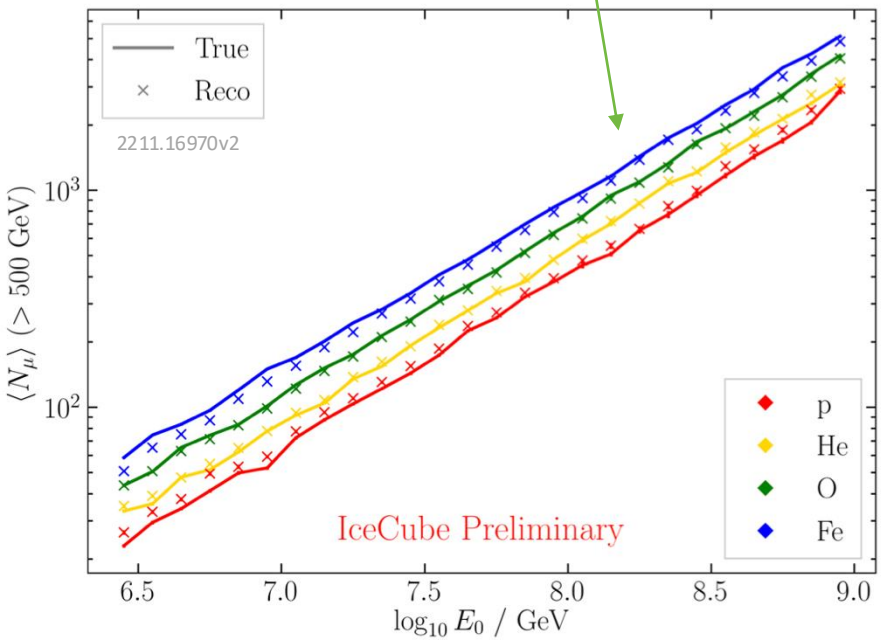


Proton

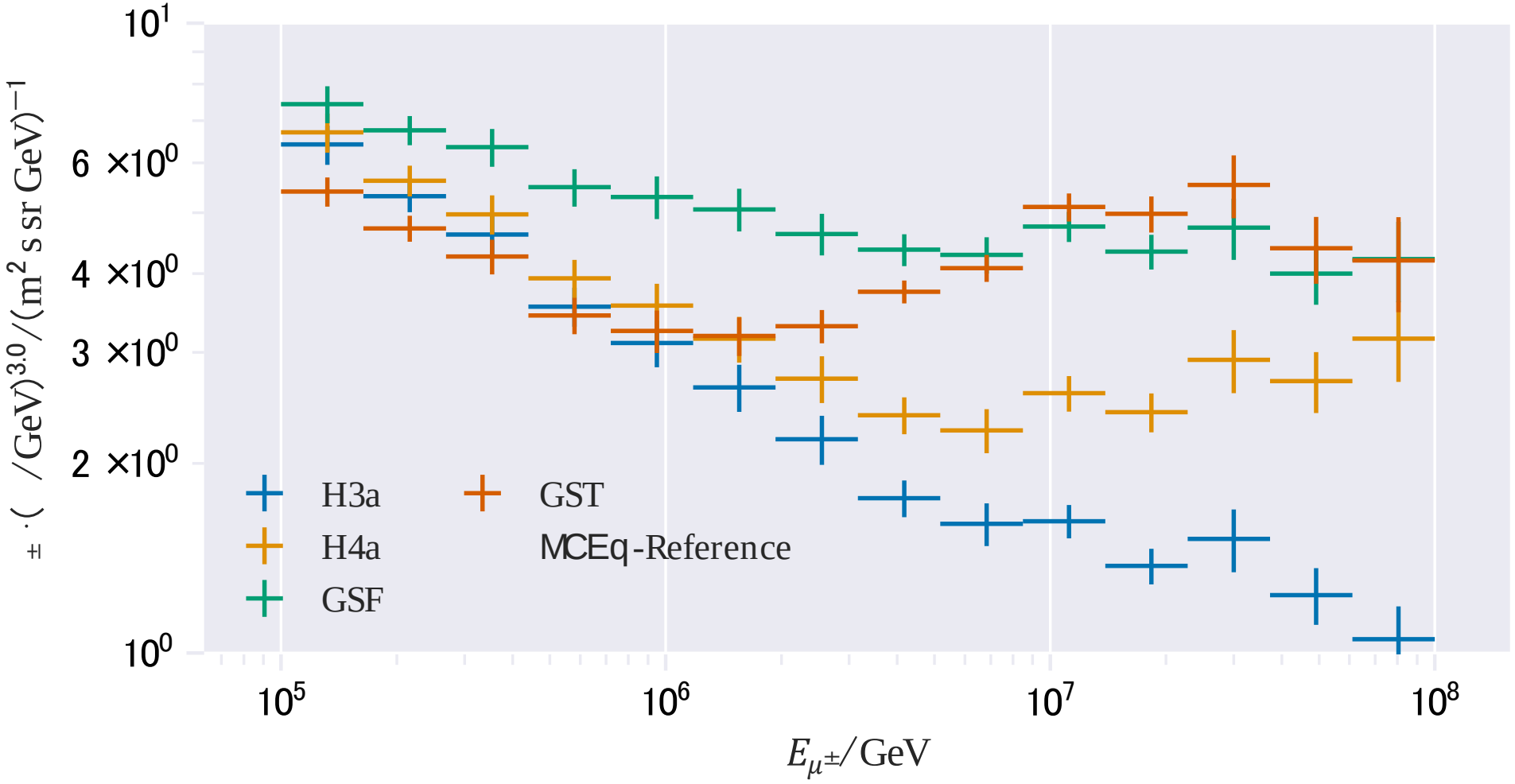
Iron



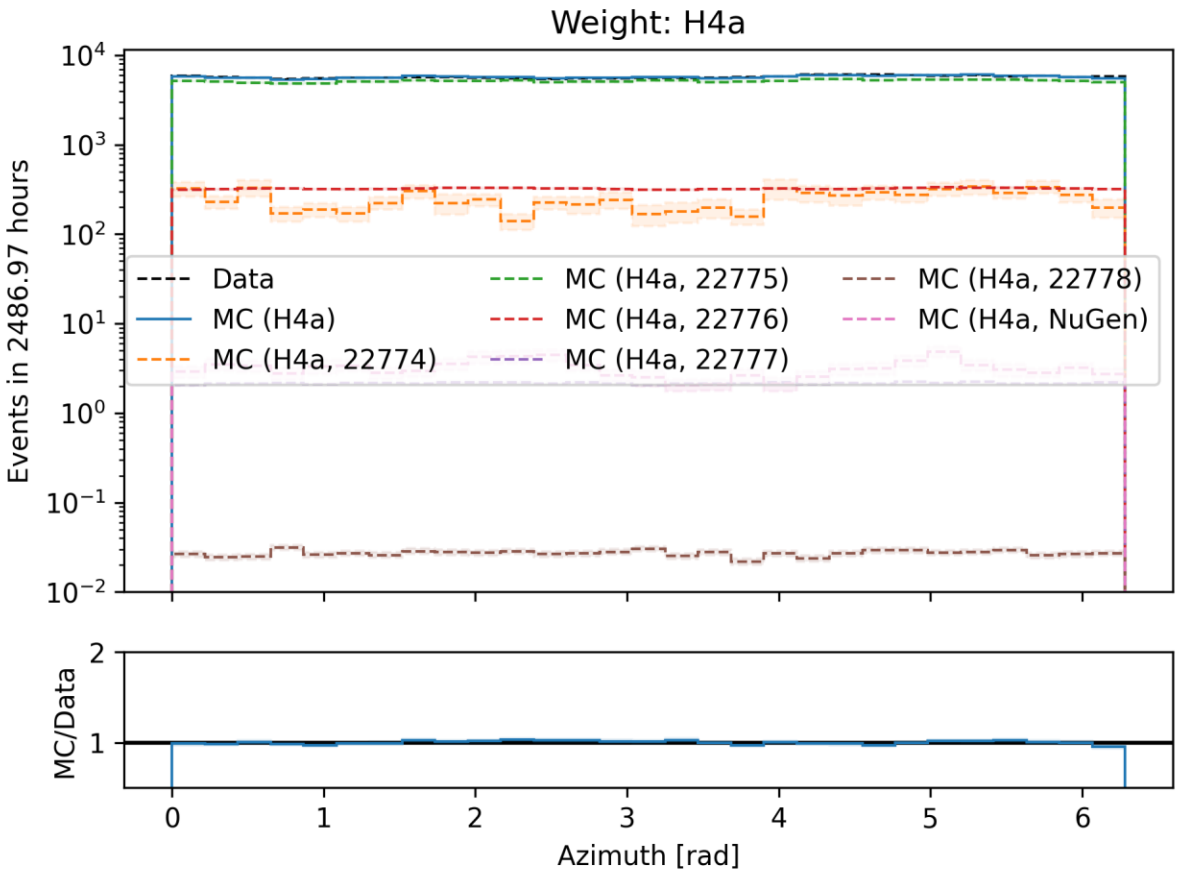
“muon bundles”

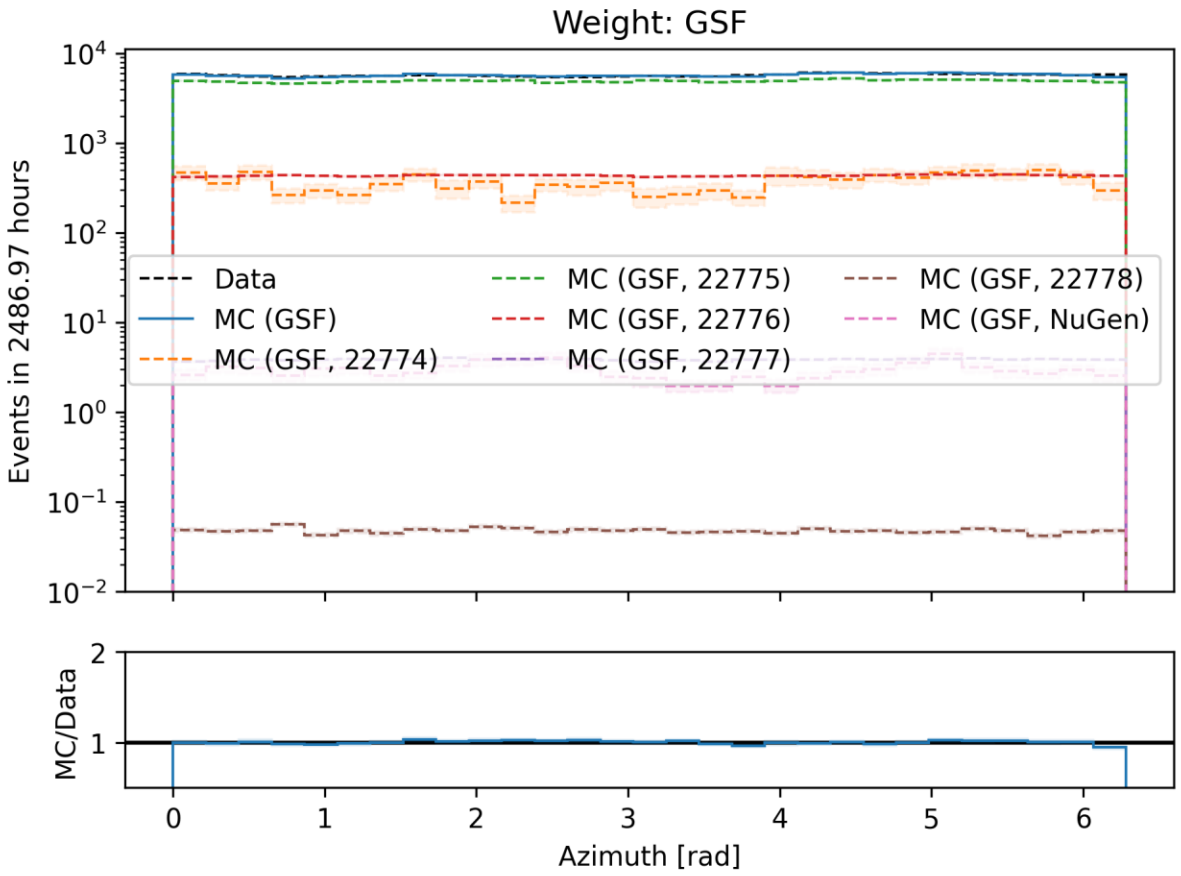


Agreement for different primary models

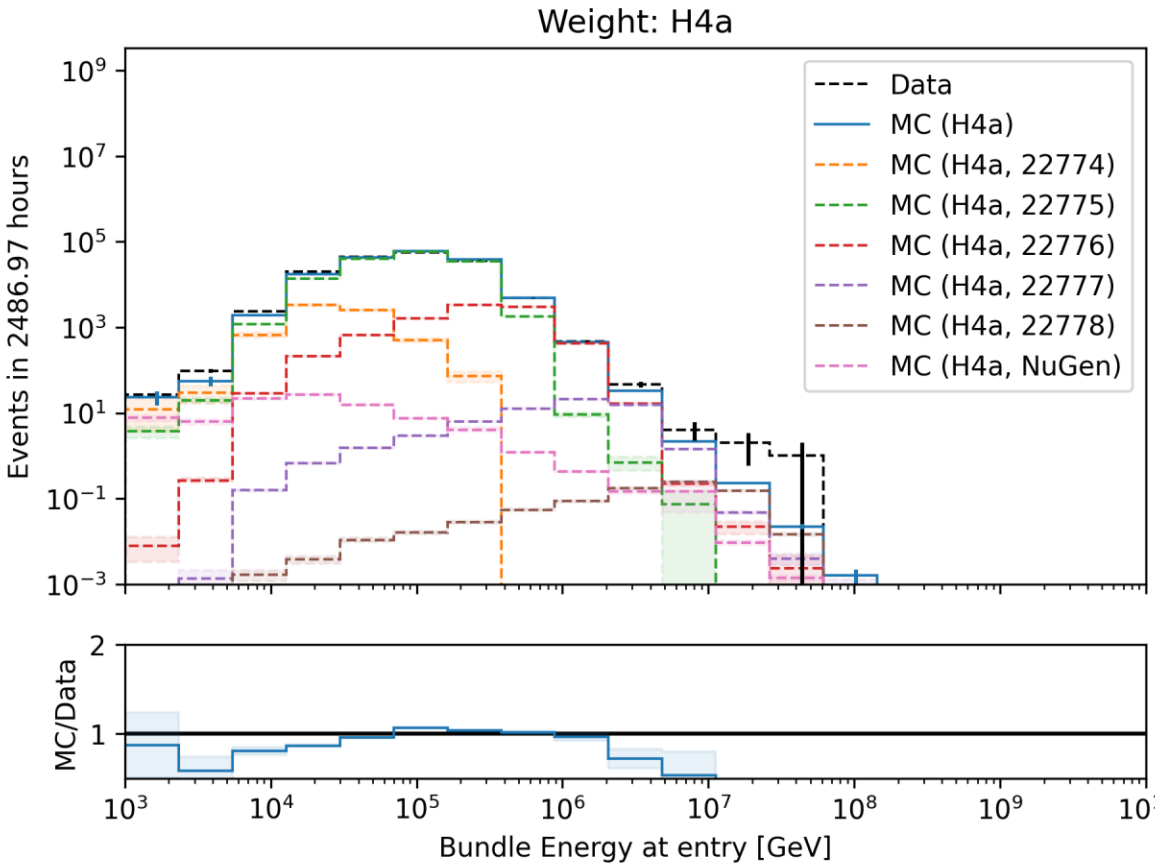


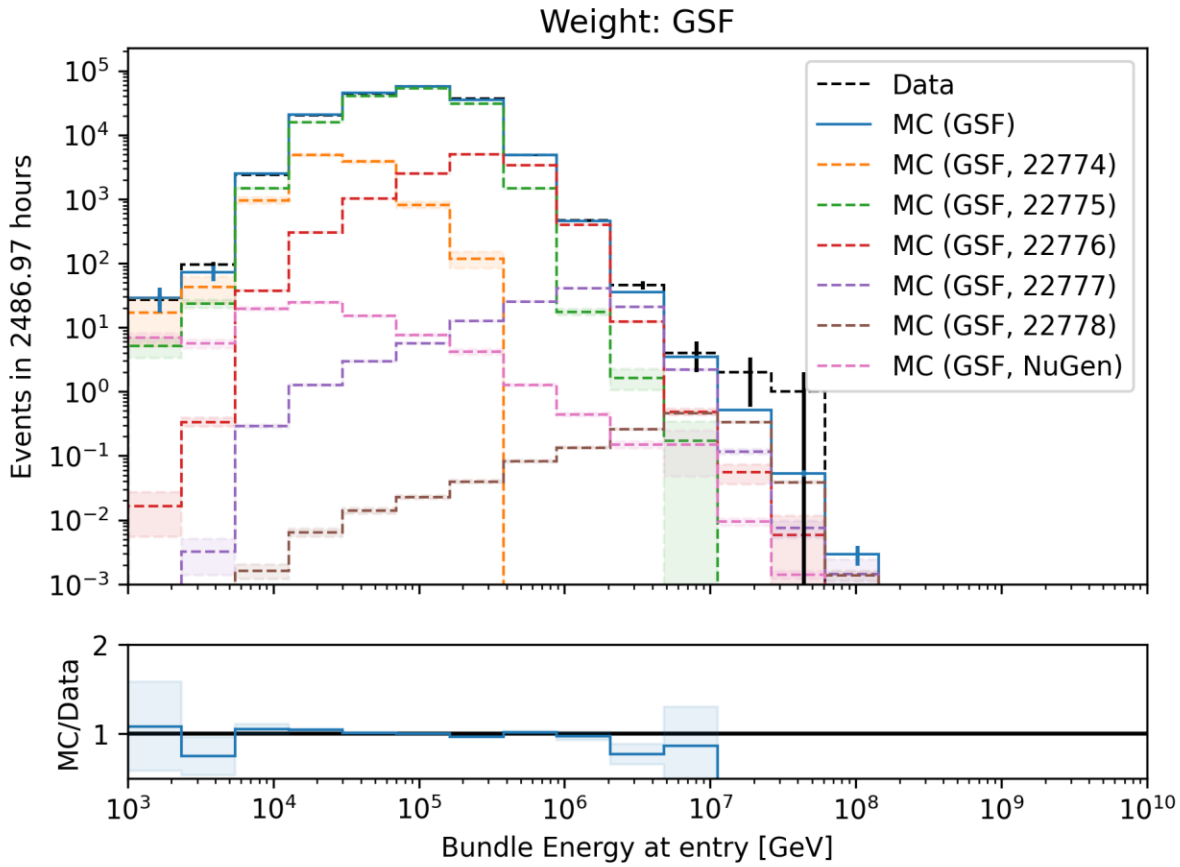
Azimuth


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]

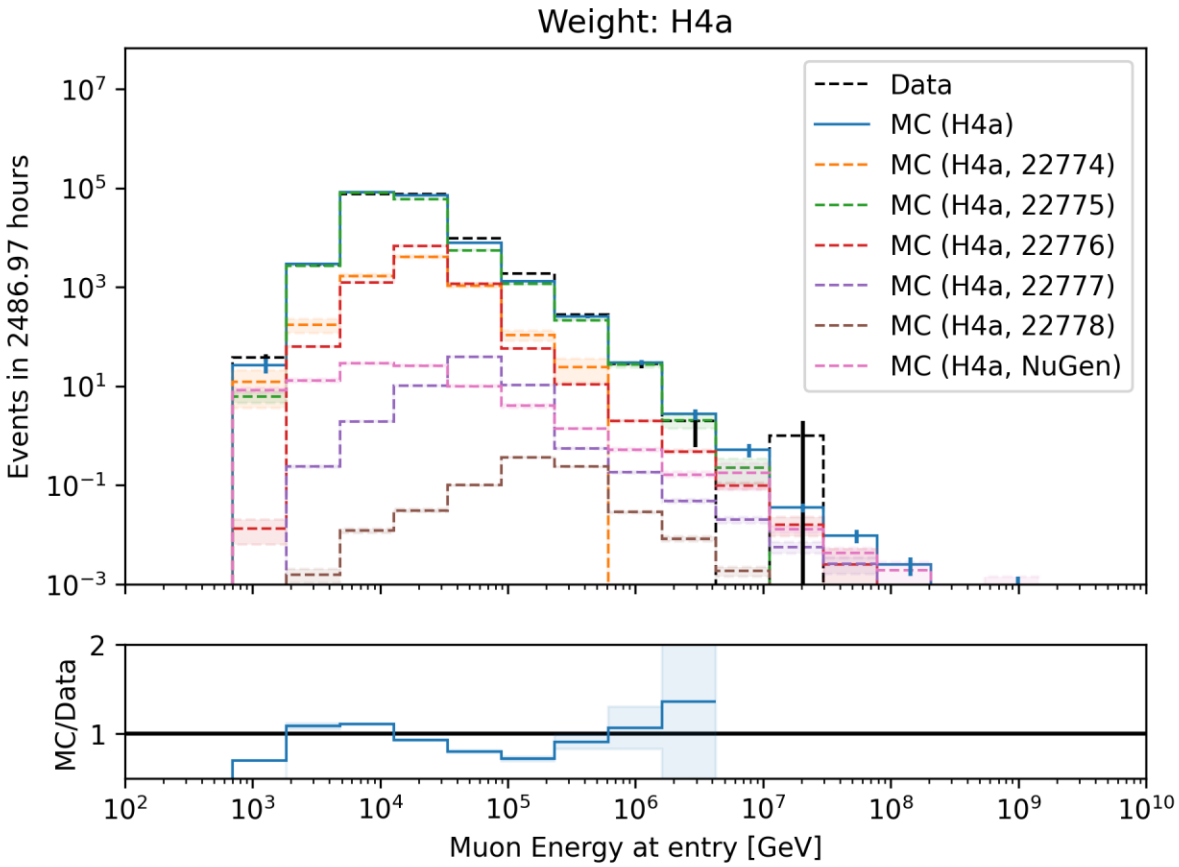

Weight: GSF
Events in 2486.97 hours
Data
MC (GSF)
MC (GSF, 22774)
MC (GSF, 22775)
MC (GSF, 22776)
MC (GSF, 22777)
MC (GSF, 22778)
MC (GSF, NuGen)
MC/Data
Azimuth [rad]

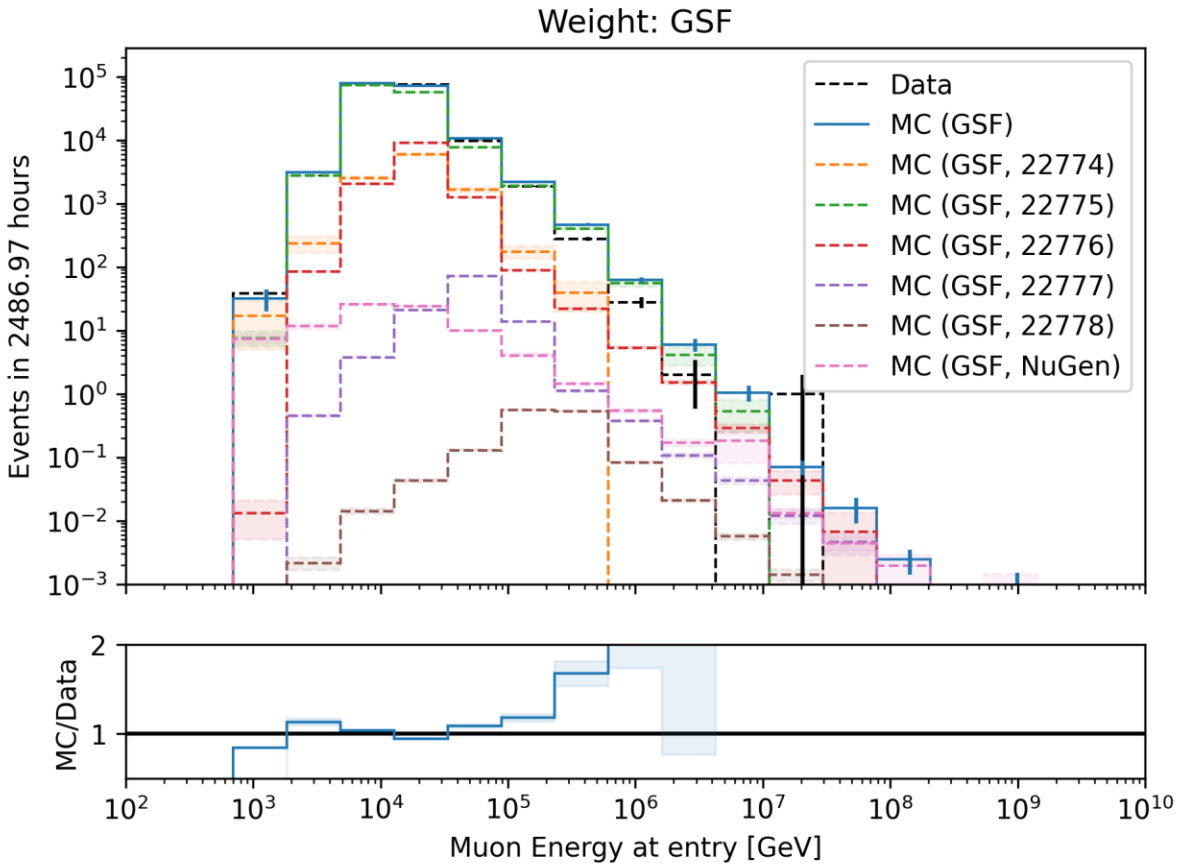
Bundle energy at entry



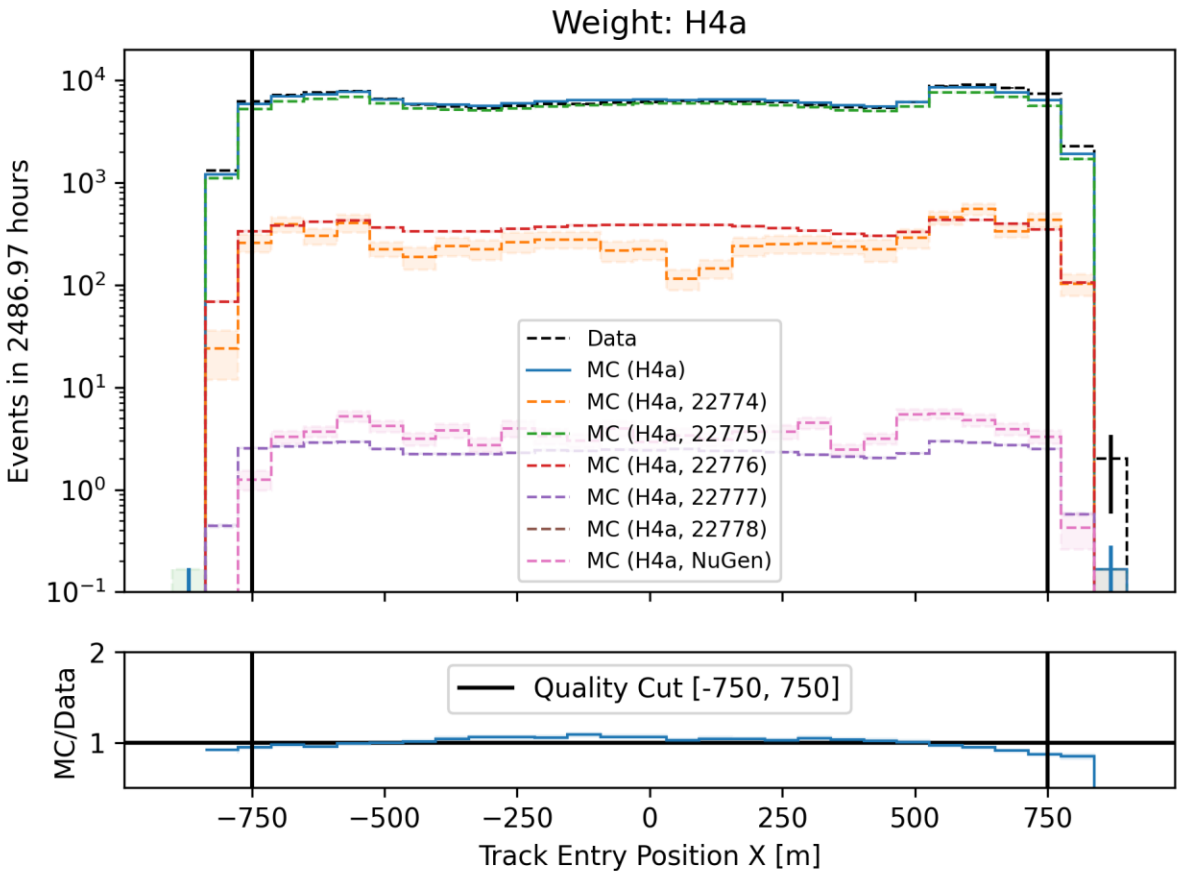


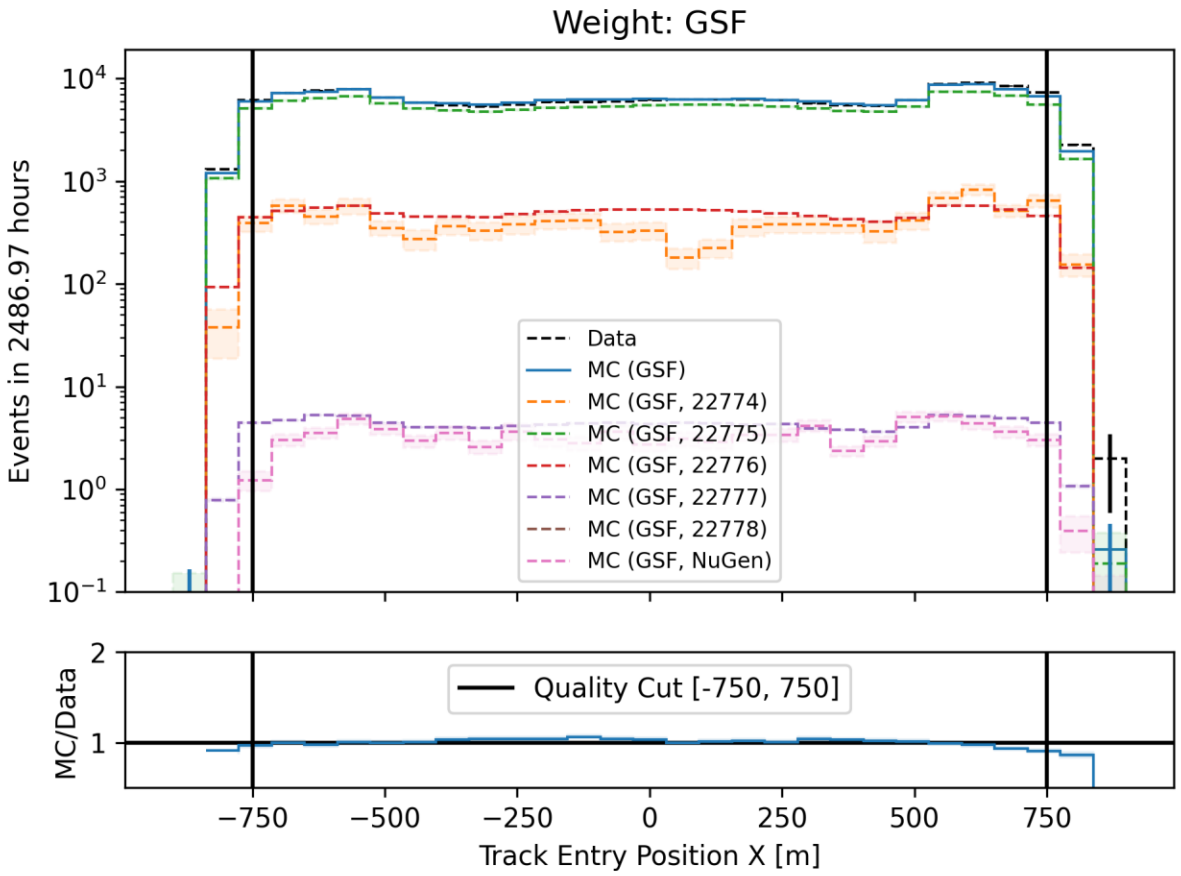
Leading muon energy at entry



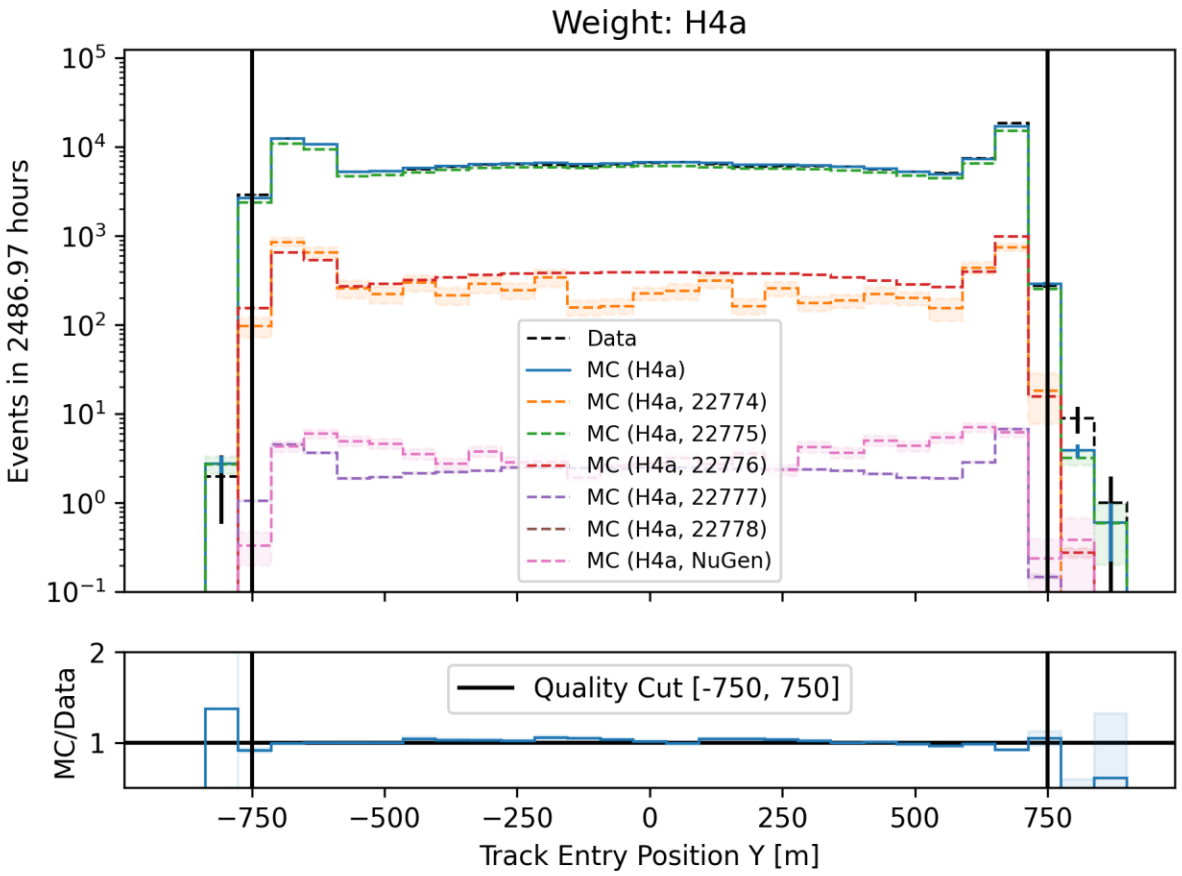


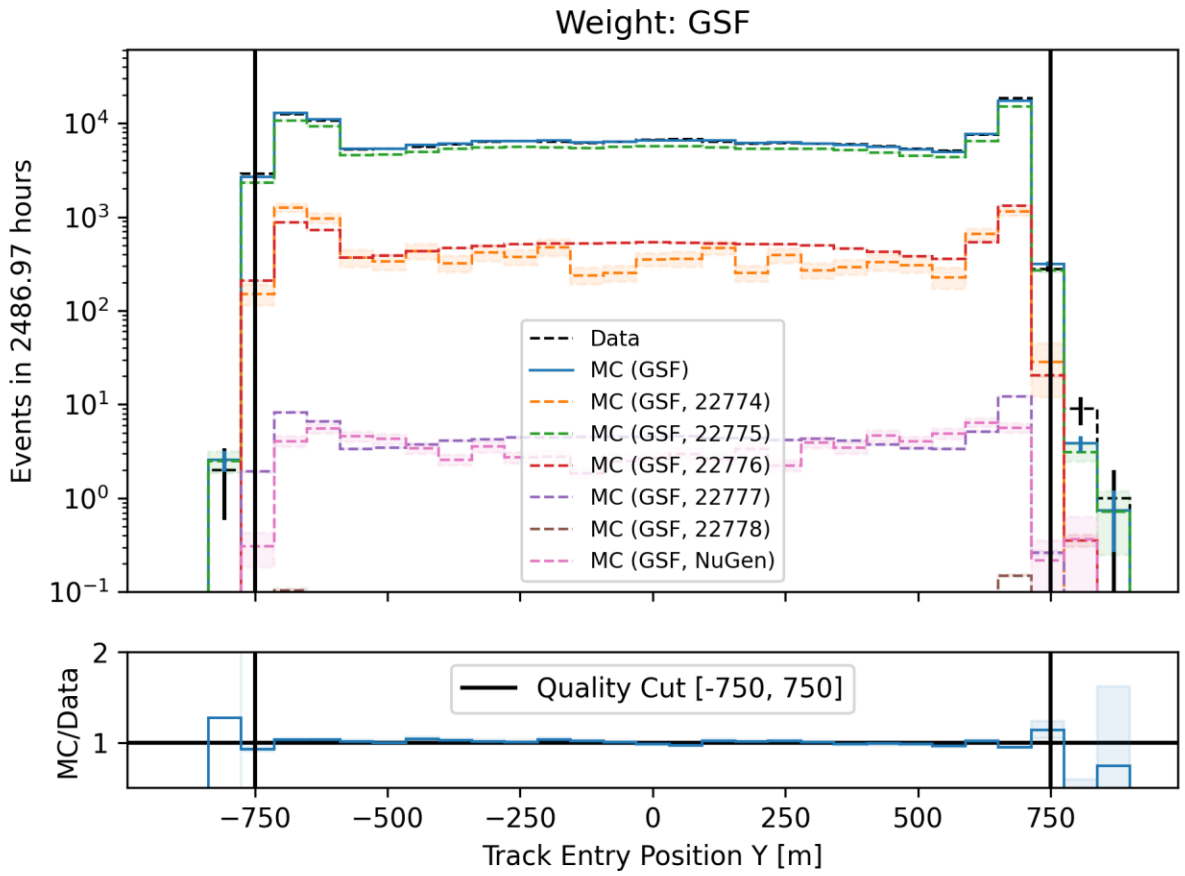
Entry position x–vertex





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

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

Network 1

Network 2

Network 3

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

Muon flux: Prompt spectrum

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

prompt component:

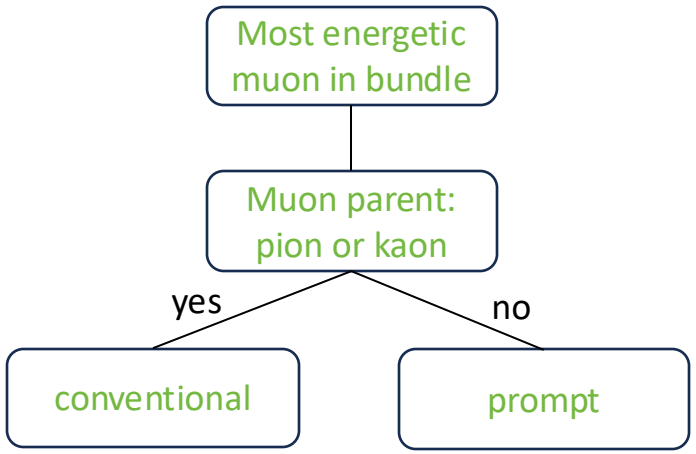
$$p \rightarrow \overbrace{D^{+}}^{\tau = 1.04 \cdot 10^{-12}\,\text{s}} \rightarrow \bar{K}^{0} + \mu^{+} + \nu_{\mu}$$

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

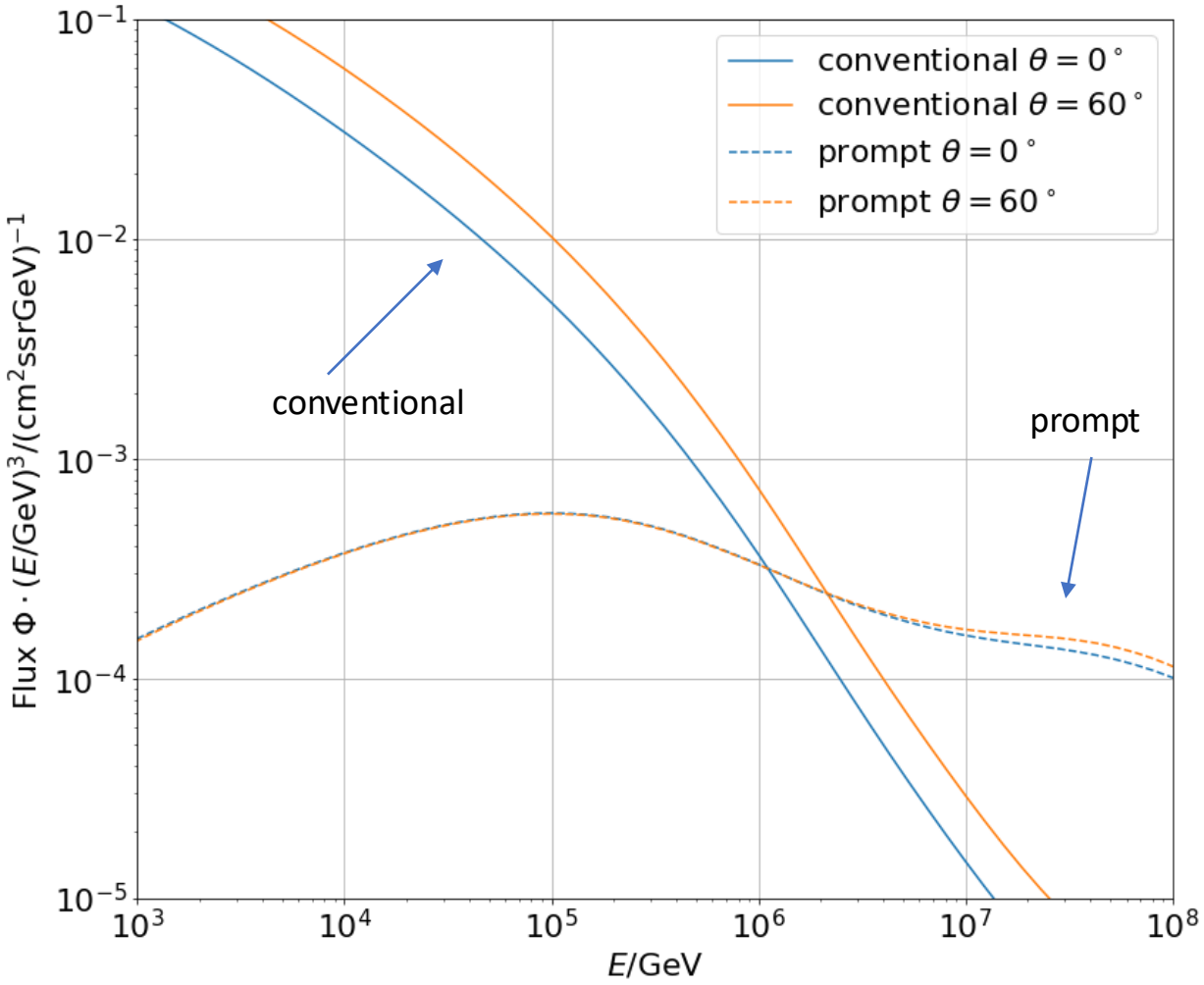
Conventional component:

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

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

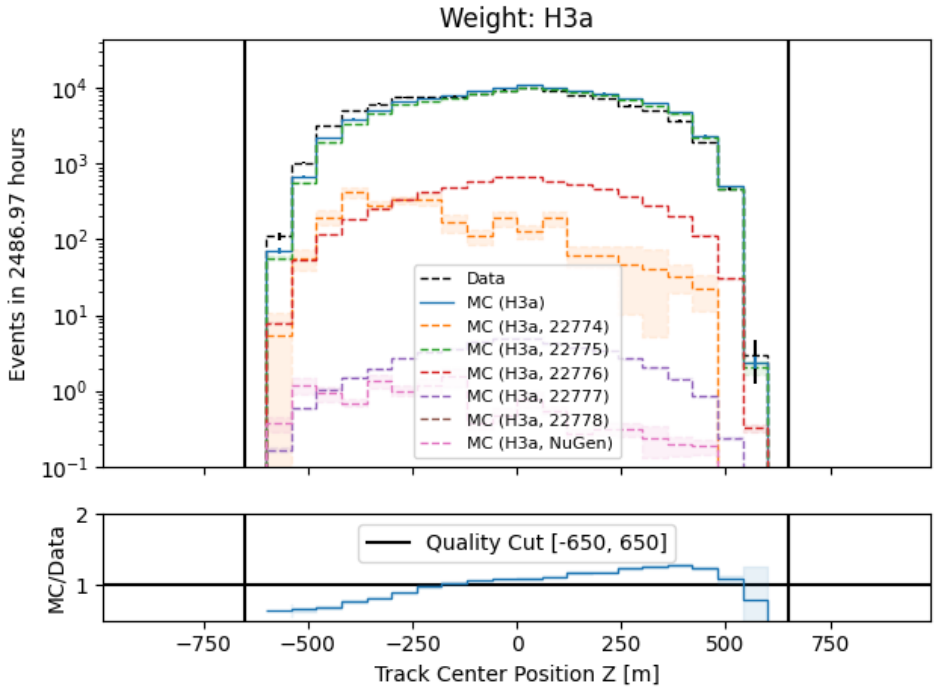


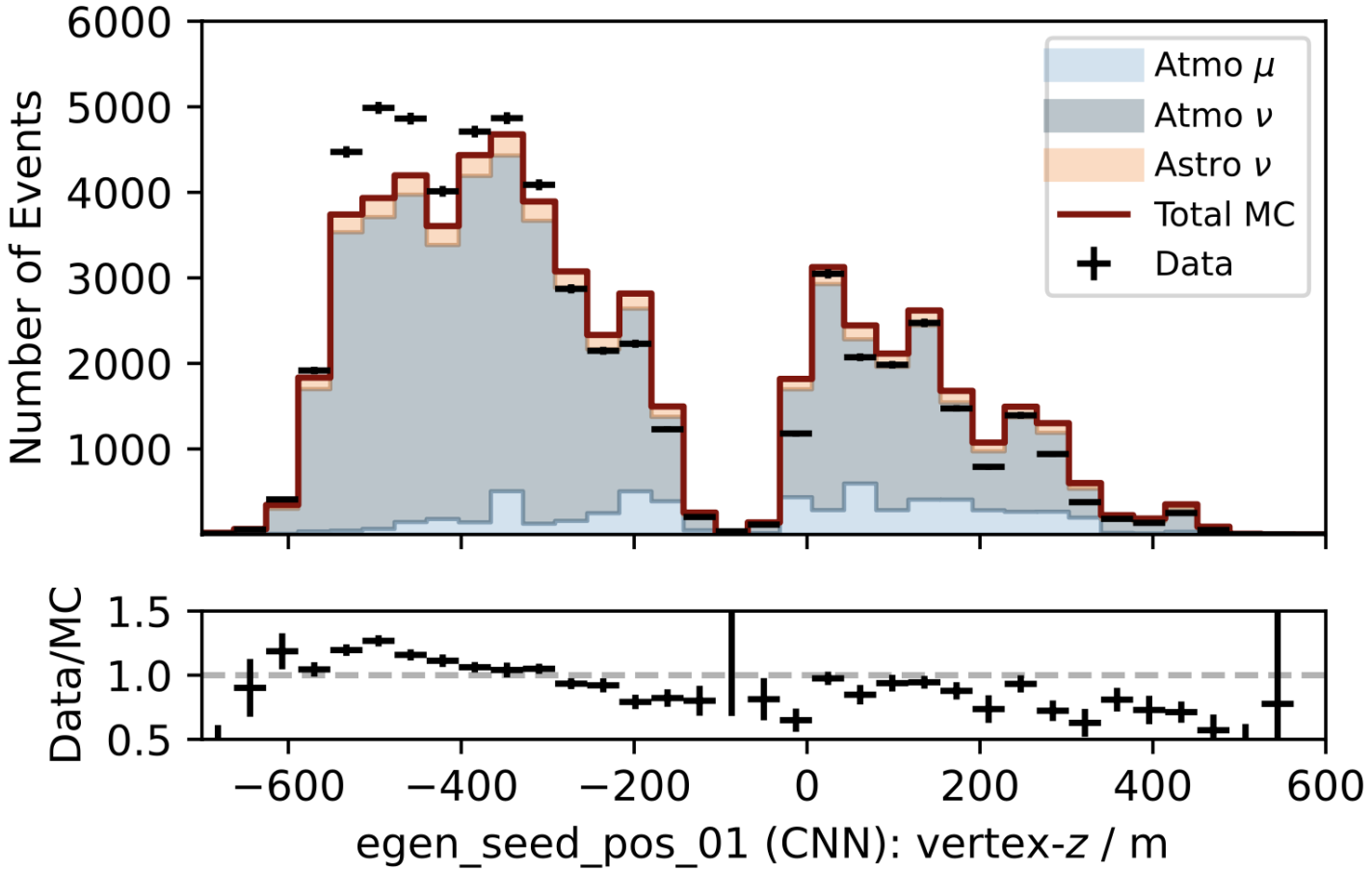
0°: perpendicular to Earth's surface



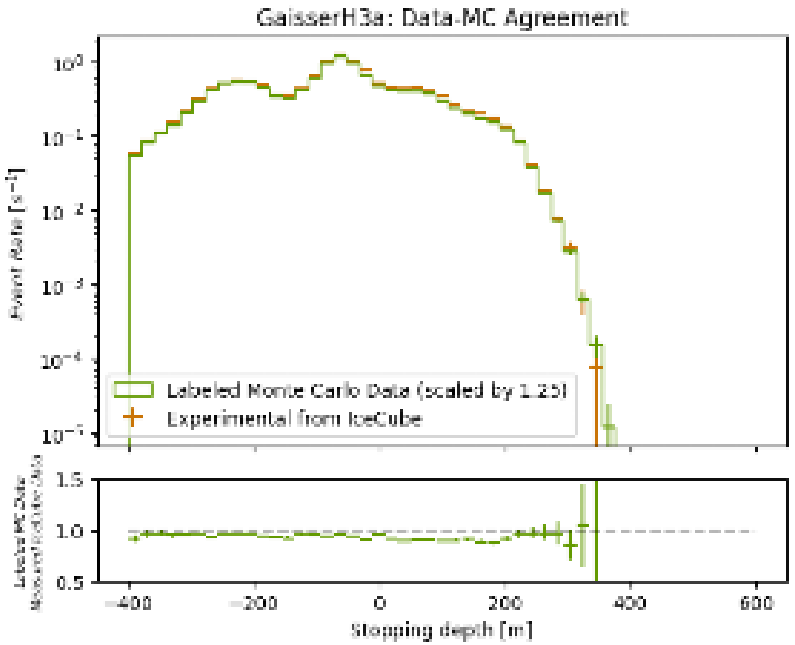
Neutrino: z-vertex

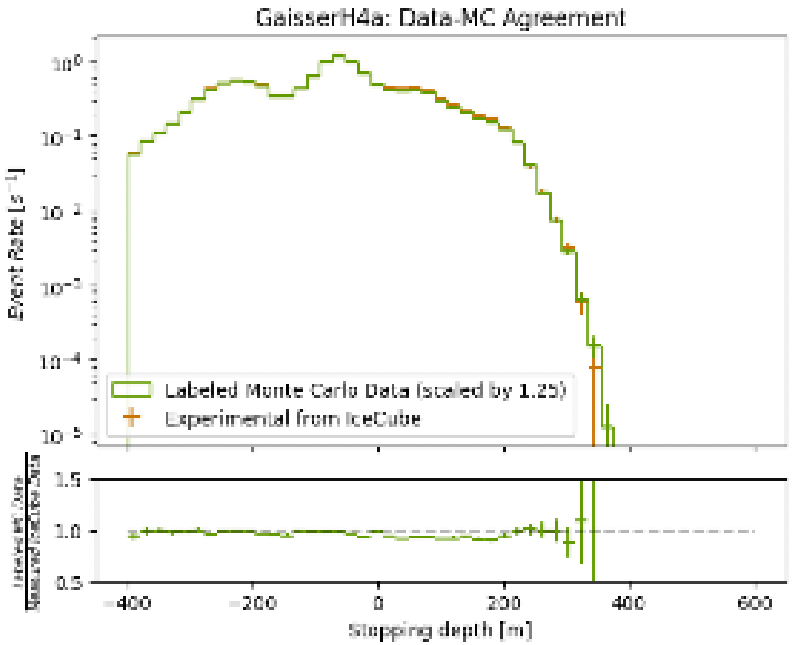
- Dissertation Mirco
- Same shape mismatch for neutrinos as for muons

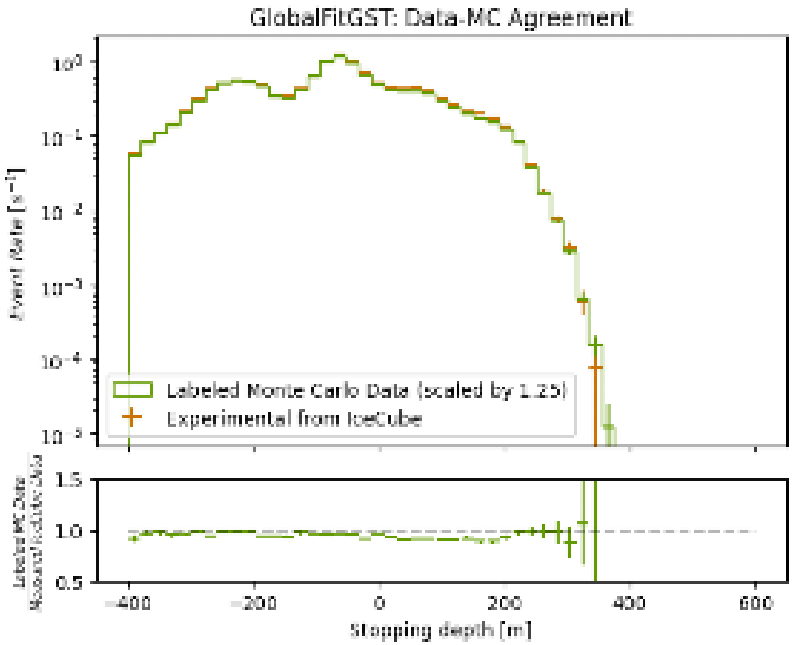




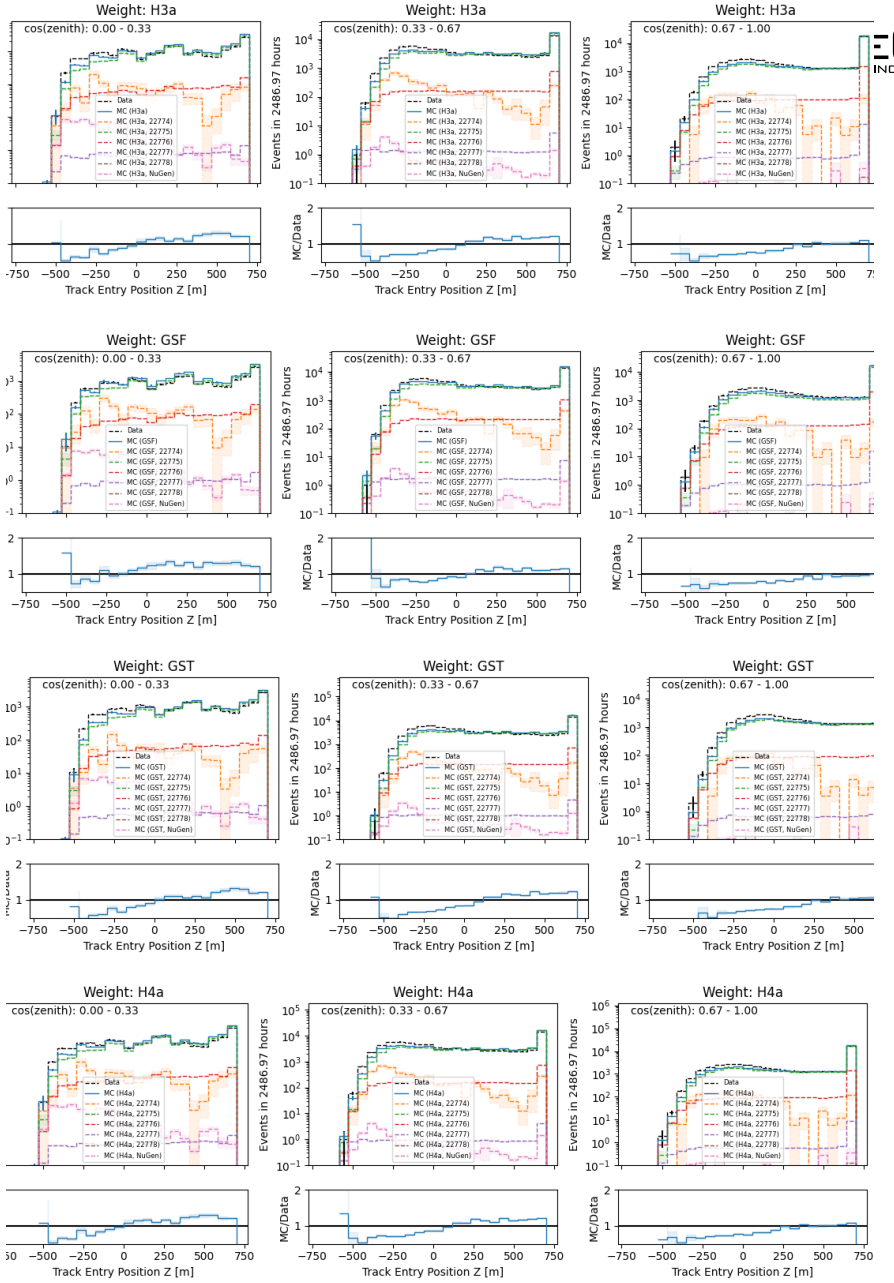
Stopping muons







Entry position z - different cos(zenith)



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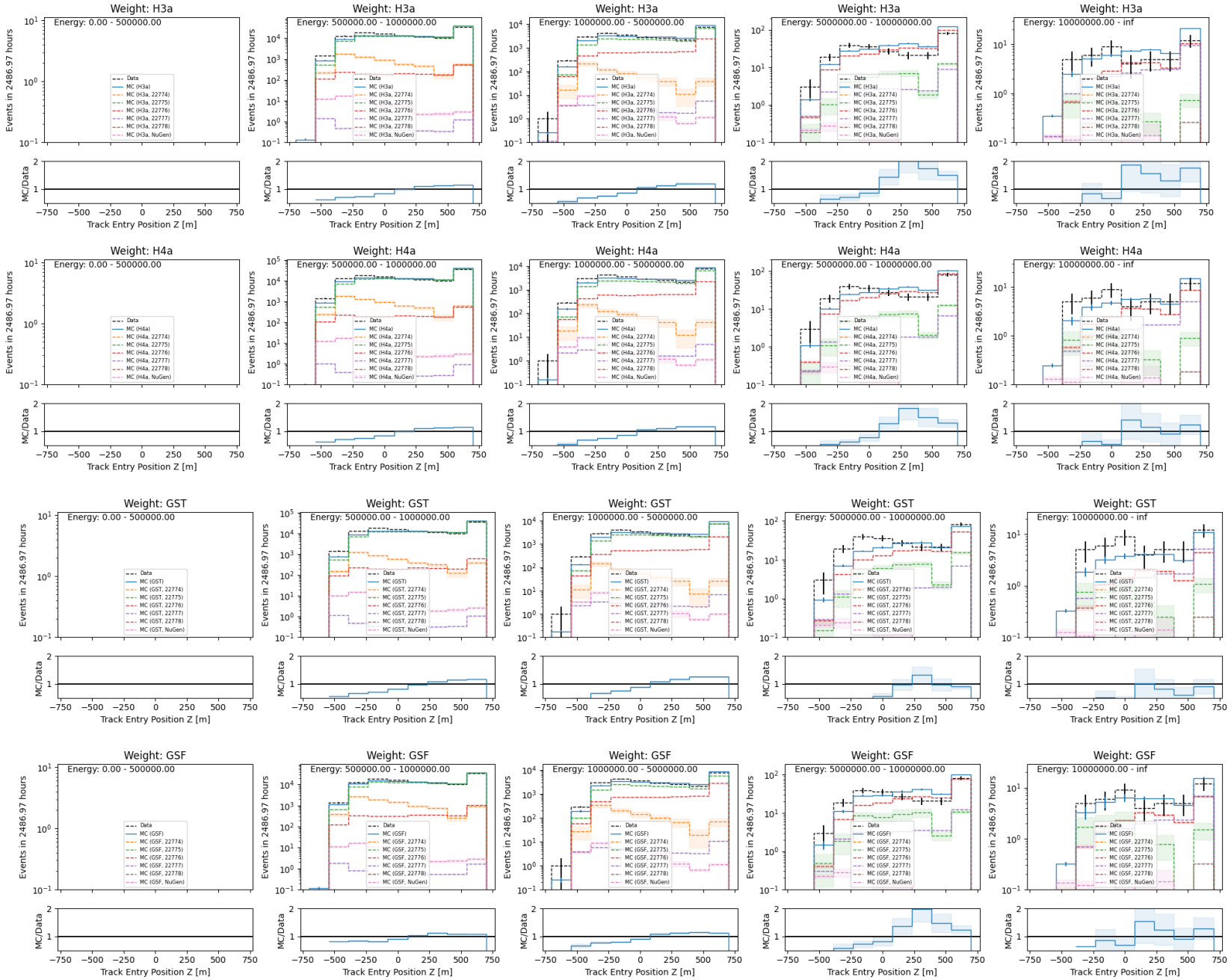
Entry position z - different cuts on bundle energy at surface



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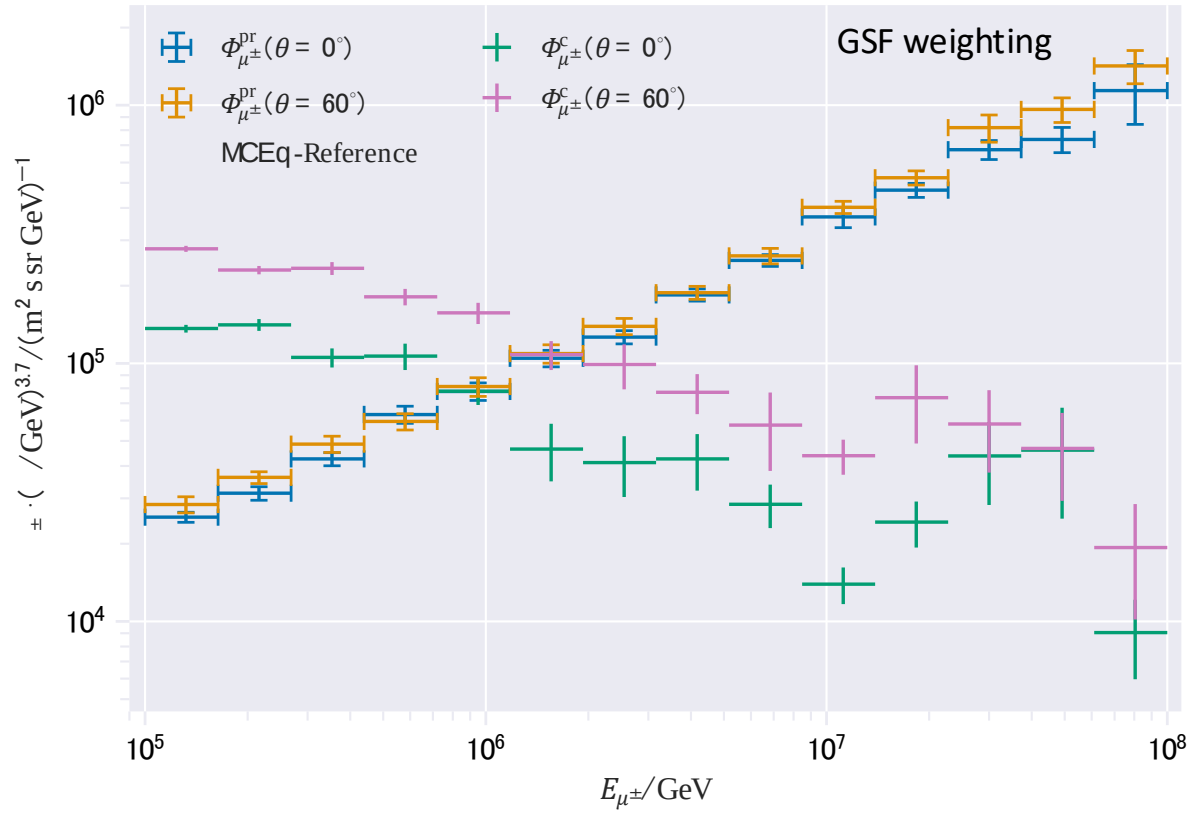
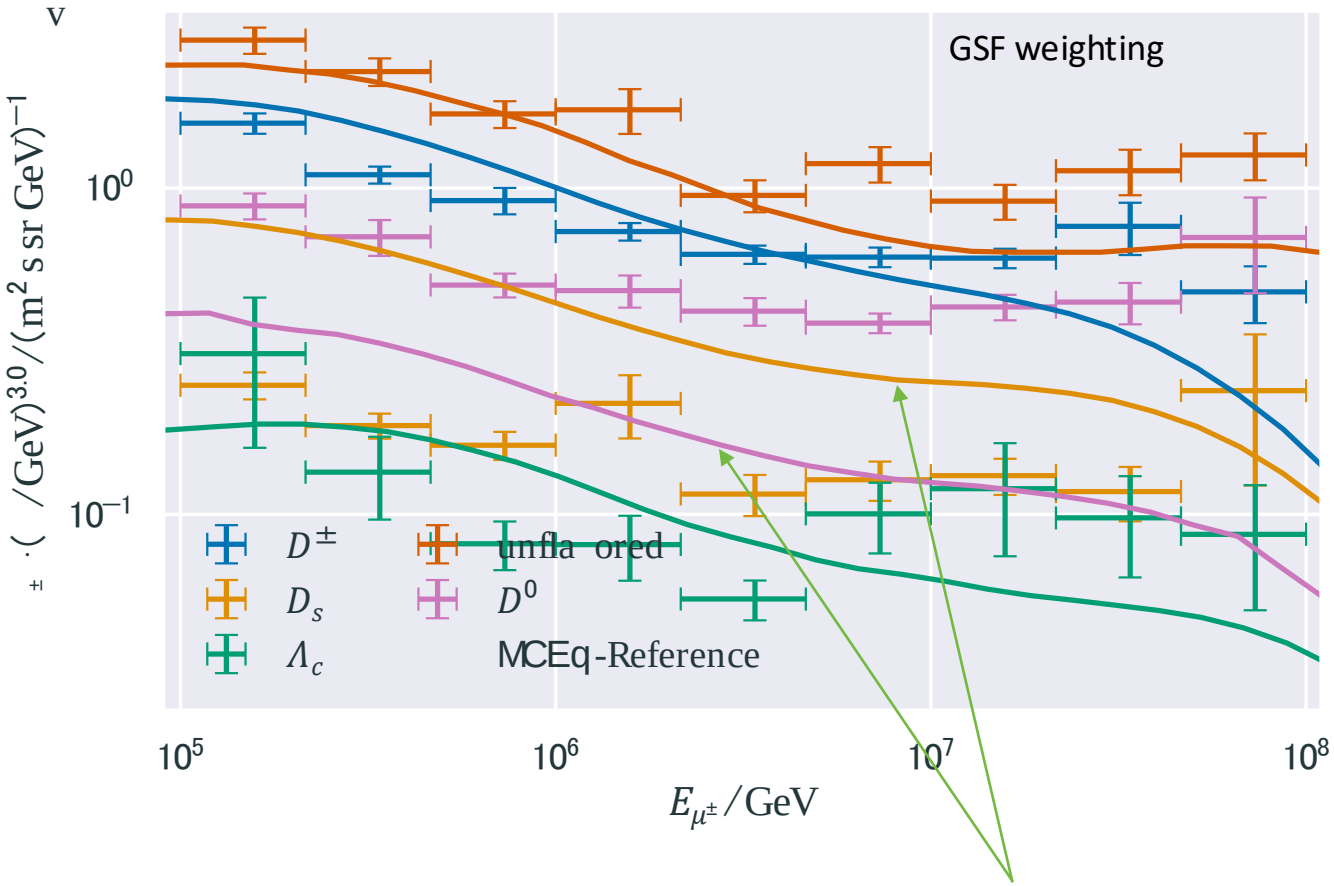
New CORSIKA simulation

with extended history option for information about the parent particles

CORSIKA 7 tagging and MCEq comparison

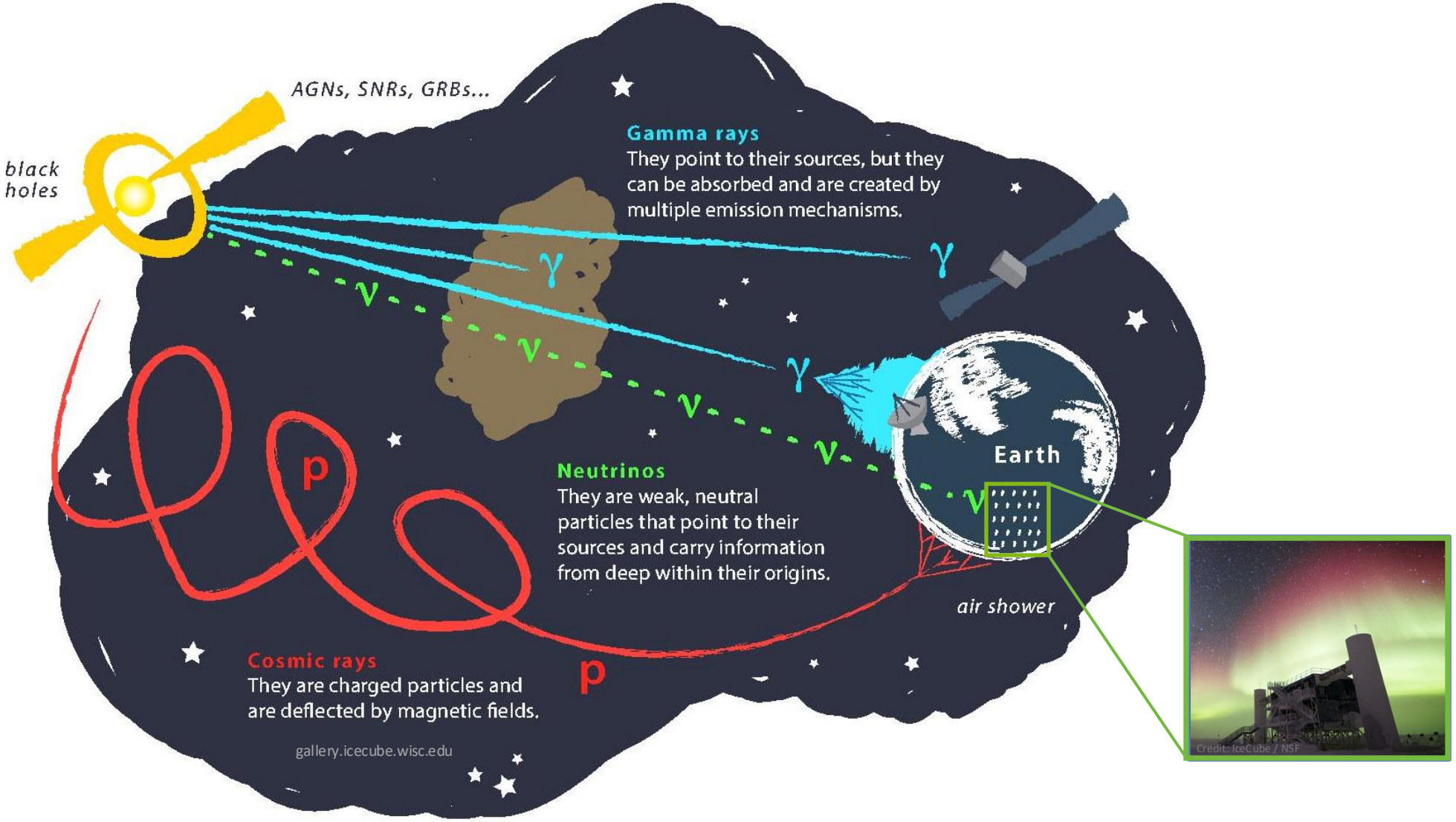
MCEq: tool to numerically solve the cascade equations that describes the evolution of particle densities as they propagate through a gaseous, dense medium
https://github.com/mceq-project/MCEq





- 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