

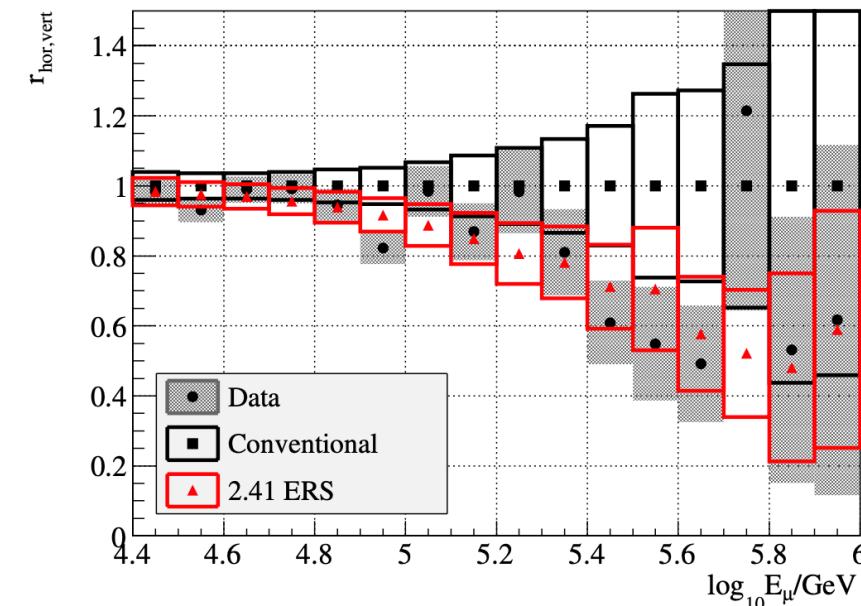
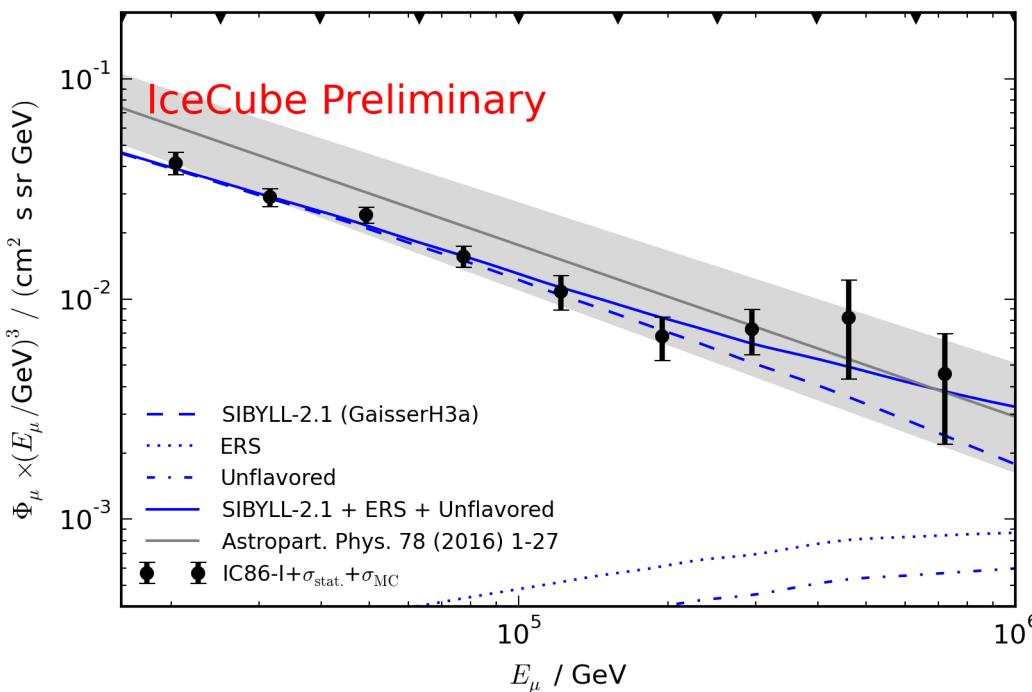
## Updates on prompt atmospheric muon analysis

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CR-Call September 29, 2023

# Motivation

- Prompt atmospheric muons have never been significantly measured
- Old analyses:
  - Leading muon analysis: limited MC statistics (by Tomasz Fuchs, [https://wiki.icecube.wisc.edu/index.php/Analysis\\_of\\_Leading\\_Muons](https://wiki.icecube.wisc.edu/index.php/Analysis_of_Leading_Muons))
  - Characterization of the muon flux: zenith problem (by Patrick Berghaus, <https://arxiv.org/abs/1506.07981>)



Sample	Best Fit (ERS)	$1\sigma$ Interval (90% CL)	$\sigma(\Phi_{\text{prompt}} > 0)$
Uncorrected	4.93	4.05-5.87 (3.55-6.56)	9.43
Marginalized Ang. Corr.	3.19	1.64-5.48 (0.98-7.26)	3.46

# Intention

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

## Idea:

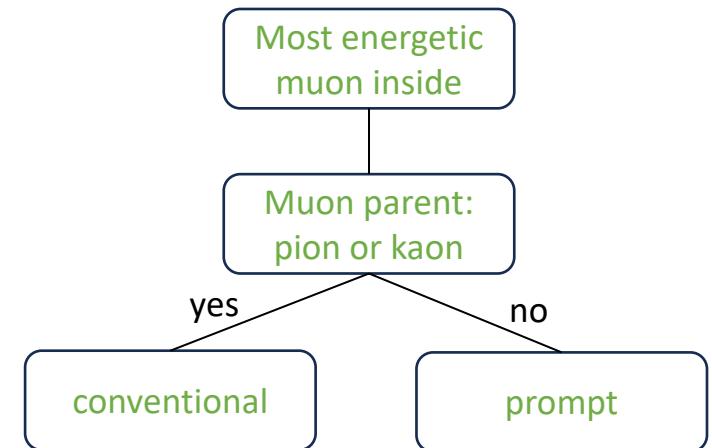
- New CORSIKA simulations with extended history
- Tag muons by parent → prompt or conventional
- Scale amount of prompt particles
  - Scaling saves time and resources instead of doing multiple simulations with different interaction models
  - Perform forward fit of the prompt normalization

# Some definitions and wording...

- **Leading muon**
  - The most energetic muon inside a bundle (no minimum fraction required)
- **Single muon**
  - Except for stopping and very low energetic muons, there are never any single muons (almost every event is muon bundle)
- **Prompt muon**
  - Muon parent is not pion or kaon

## Suggestion:

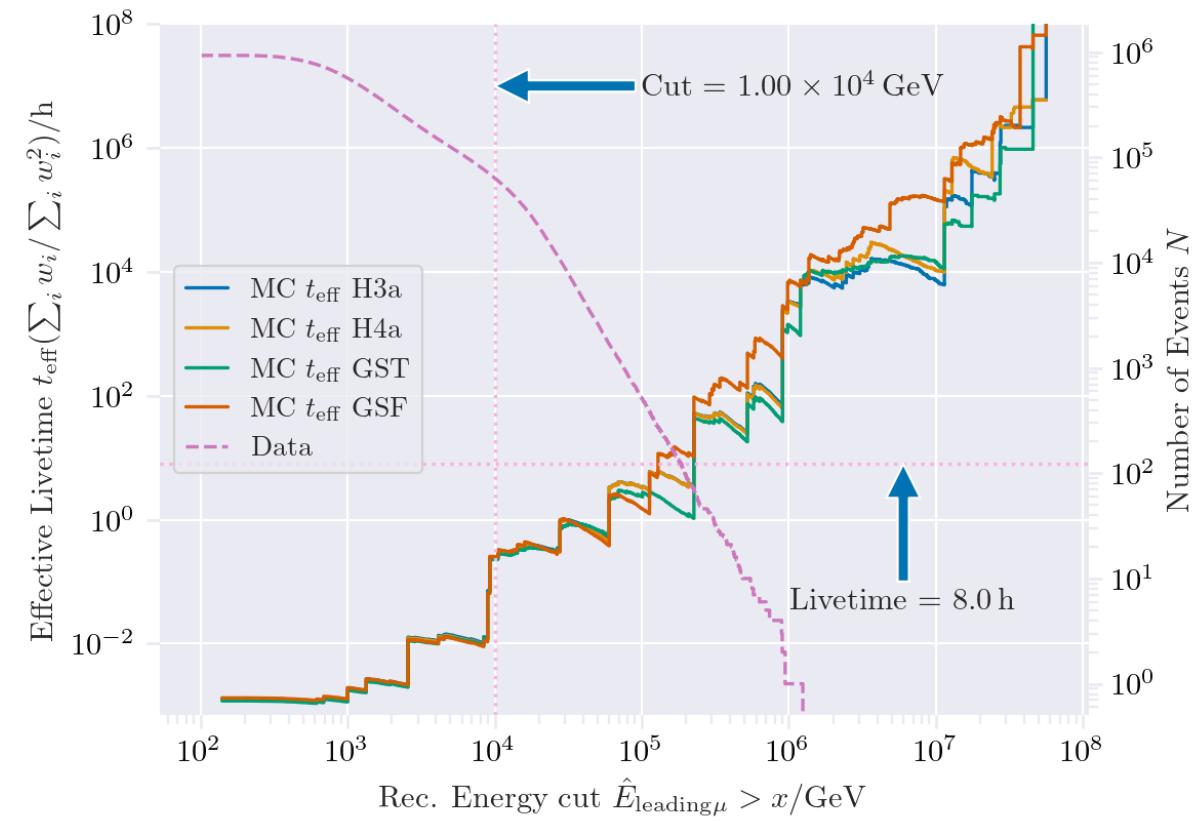
To avoid confusion regarding different leading muon definitions we can introduce a “leadingness”  
(For example: Tomasz used a leadingness of 50%, ...)



# New CORSIKA extended history simulations

- CORSIKA 77420
- SIBYLL 2.3d
- Icetray 1.5.1
- 5 components (p, He, N, Al, Fe)
- Polyplopia: True
- Trimshower: True
- Ecuts1: 273 GeV (hadron min energy)
- Ecuts2: 273 GeV (muon min energy)
- Ecuts3:  $10^{20}$  GeV (electron min energy)
- Ecuts4:  $10^{20}$  GeV (photon min energy)
- 4 datasets:
  - 30010: 600 GeV – 1 PeV
  - 30011: 1 PeV – 100 PeV
  - 30012: 100 PeV – 1 EeV
  - 30013: 1 EeV – 50 EeV
- [/data/sim/IceCube/2023/generated/CORSIKA\\_EHISTORY/](#)

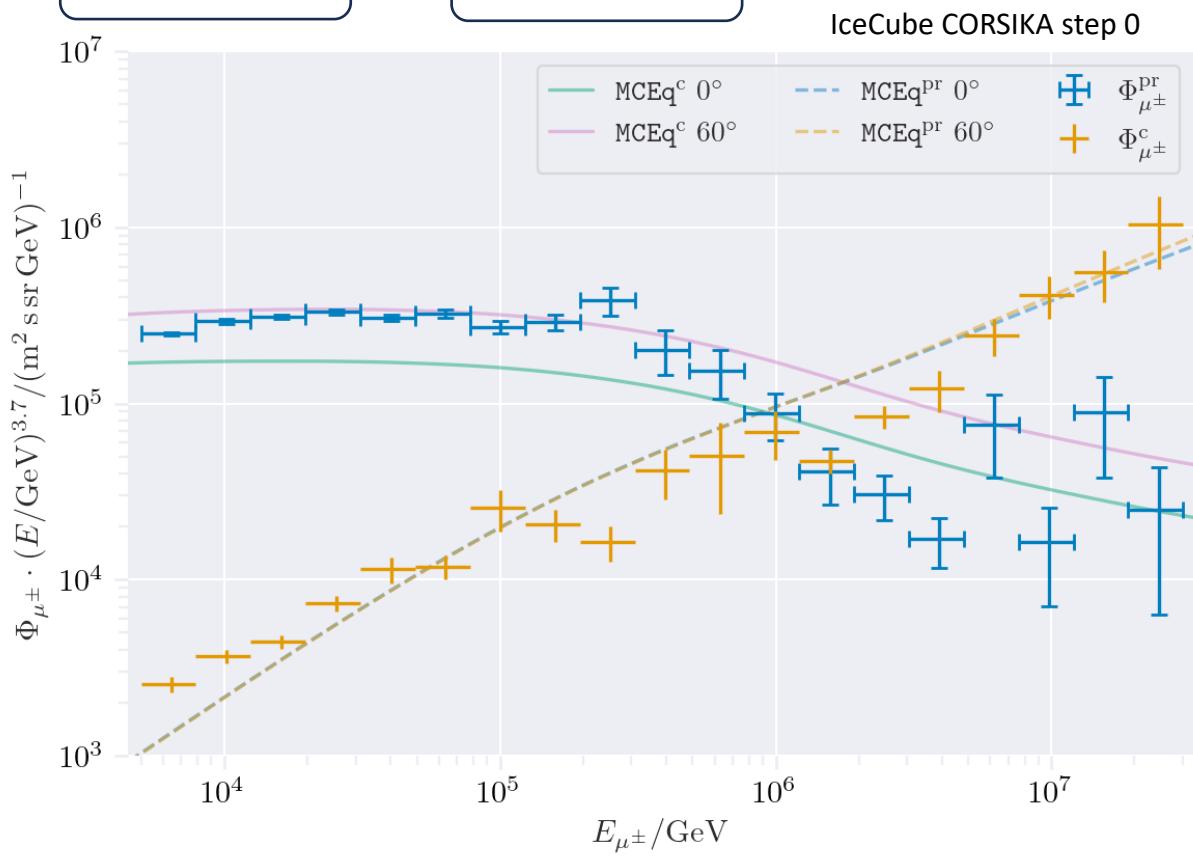
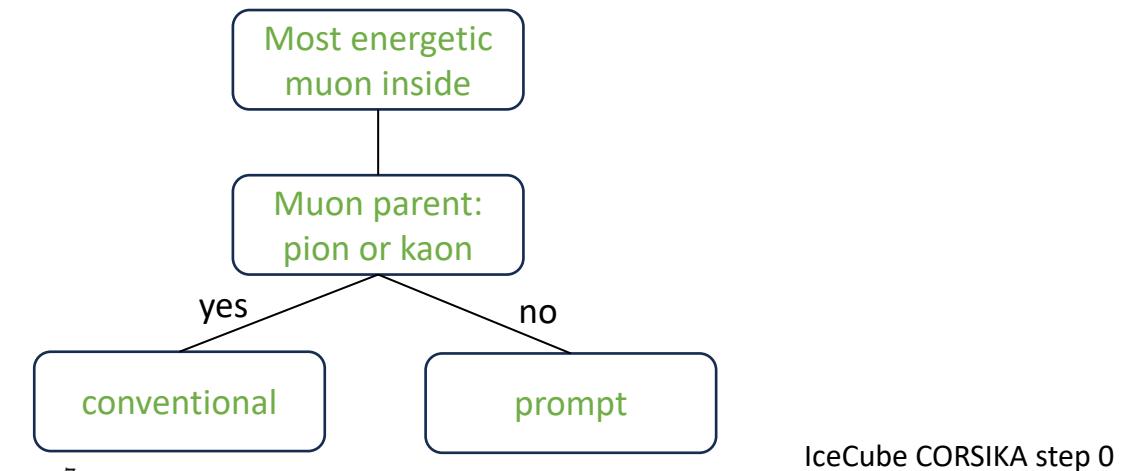
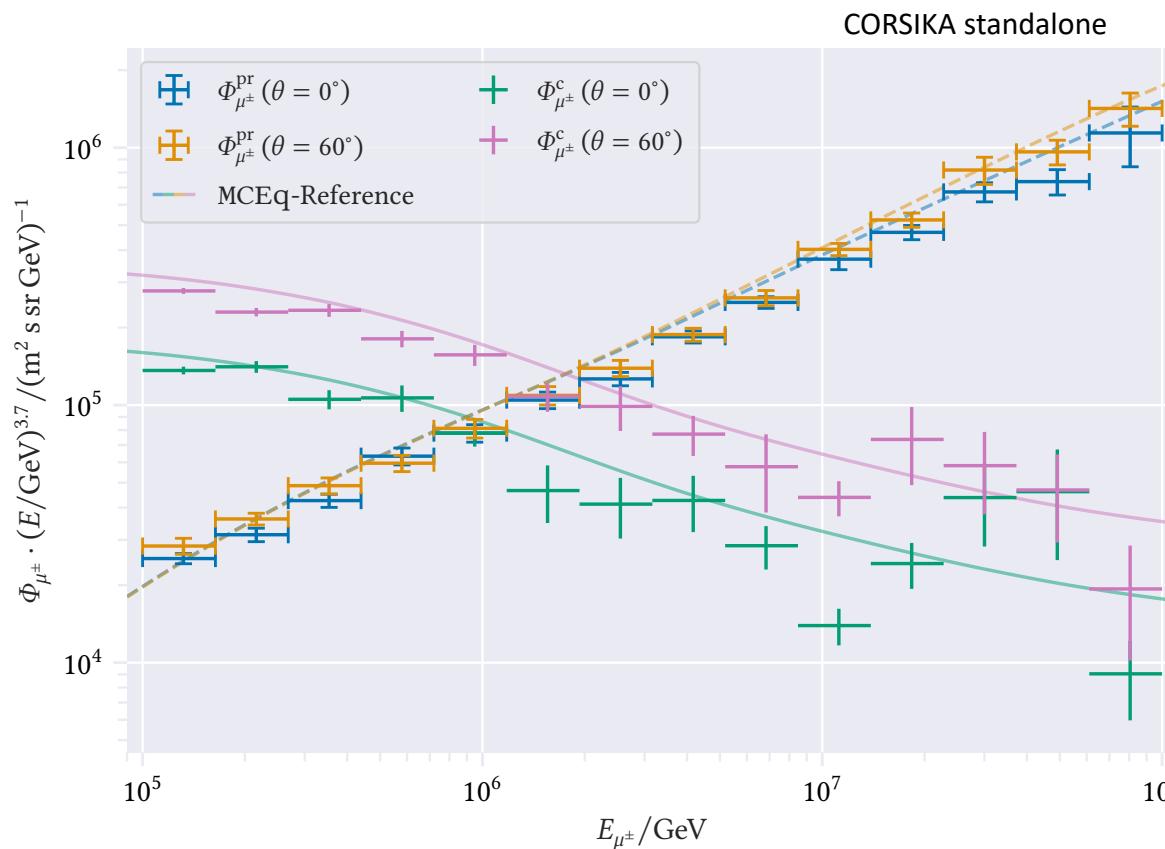
Please go ahead and test the datasets



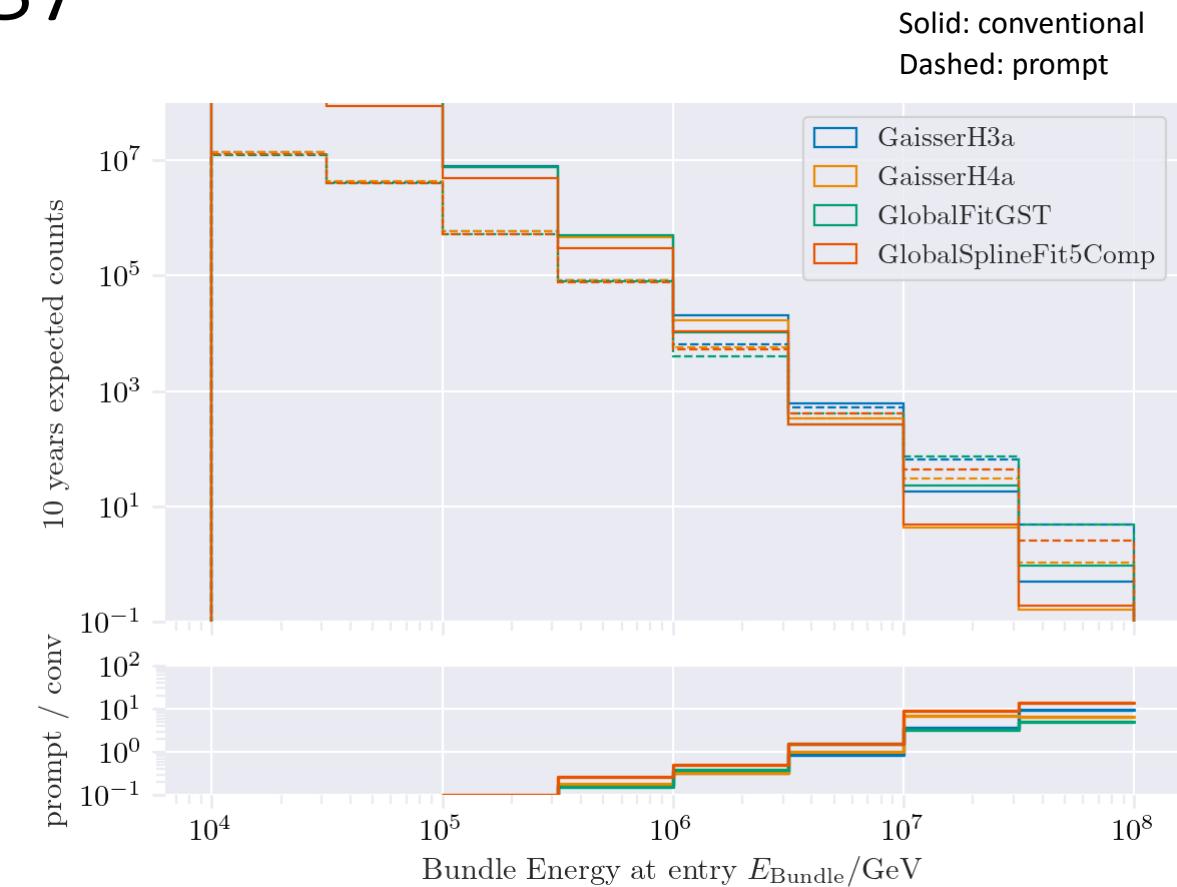
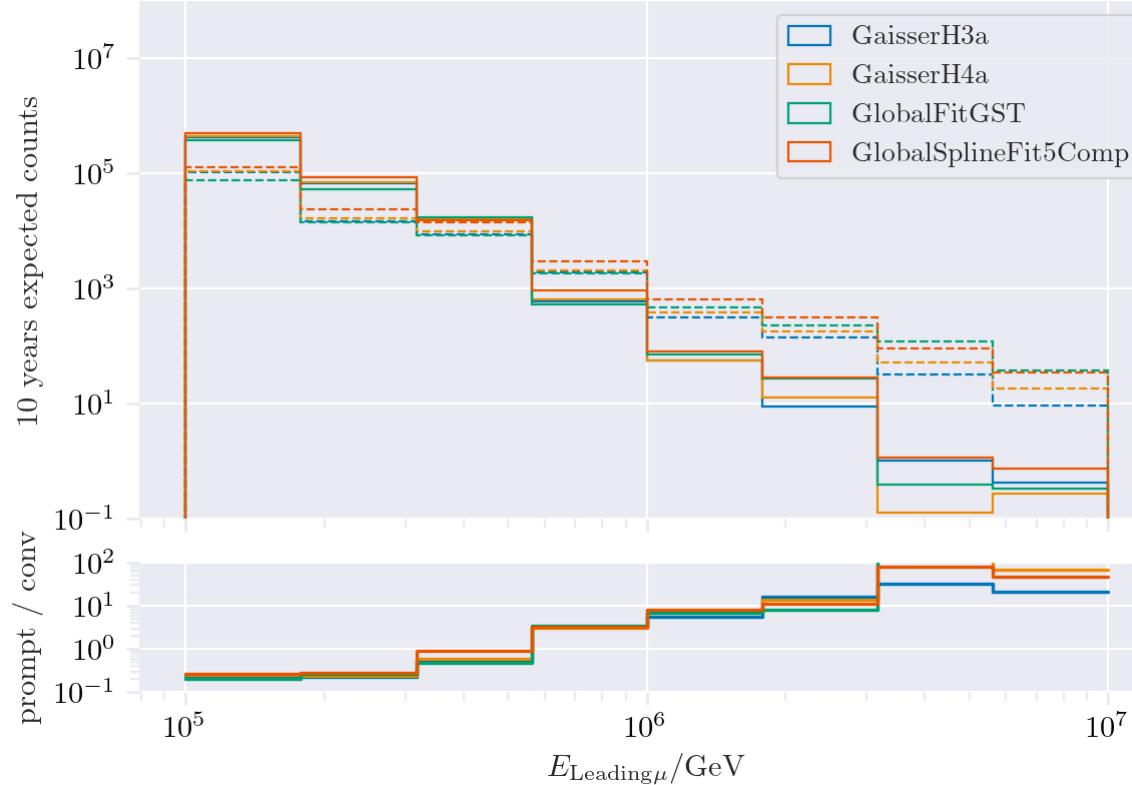
- Sufficient statistics above 1 PeV
- Too few statistics at lower energies

# CORSIKA vs. MC Eq

➤ Good agreement

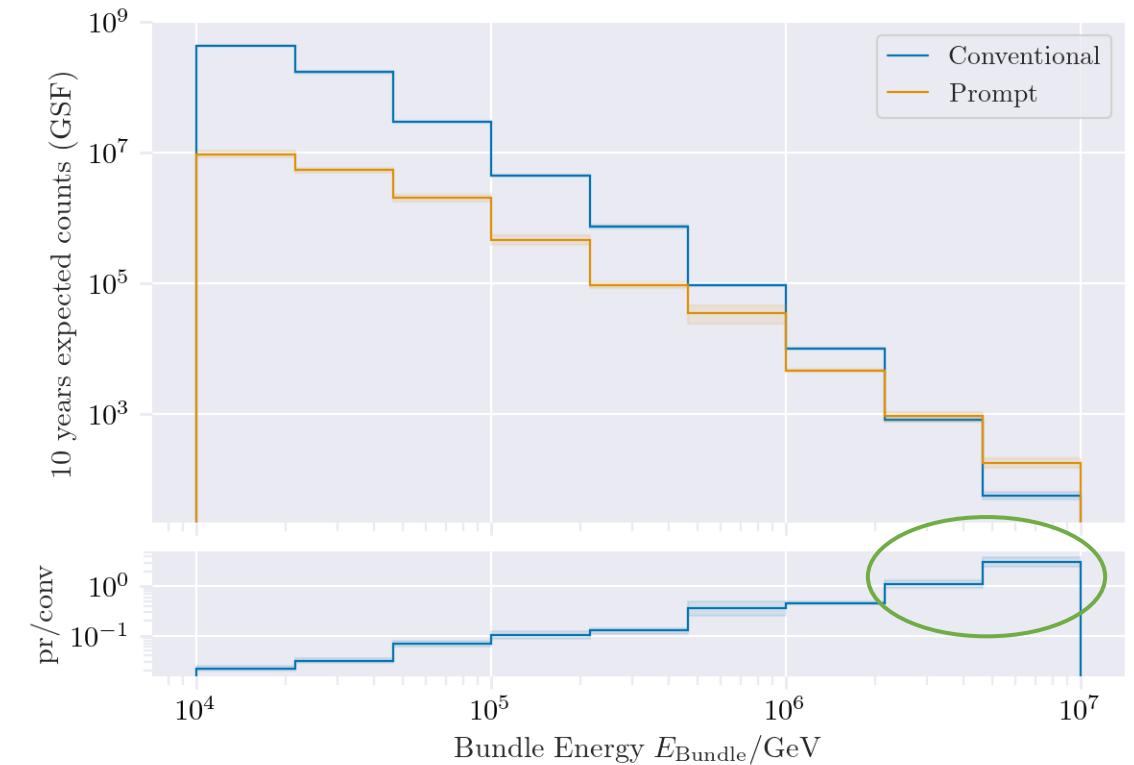
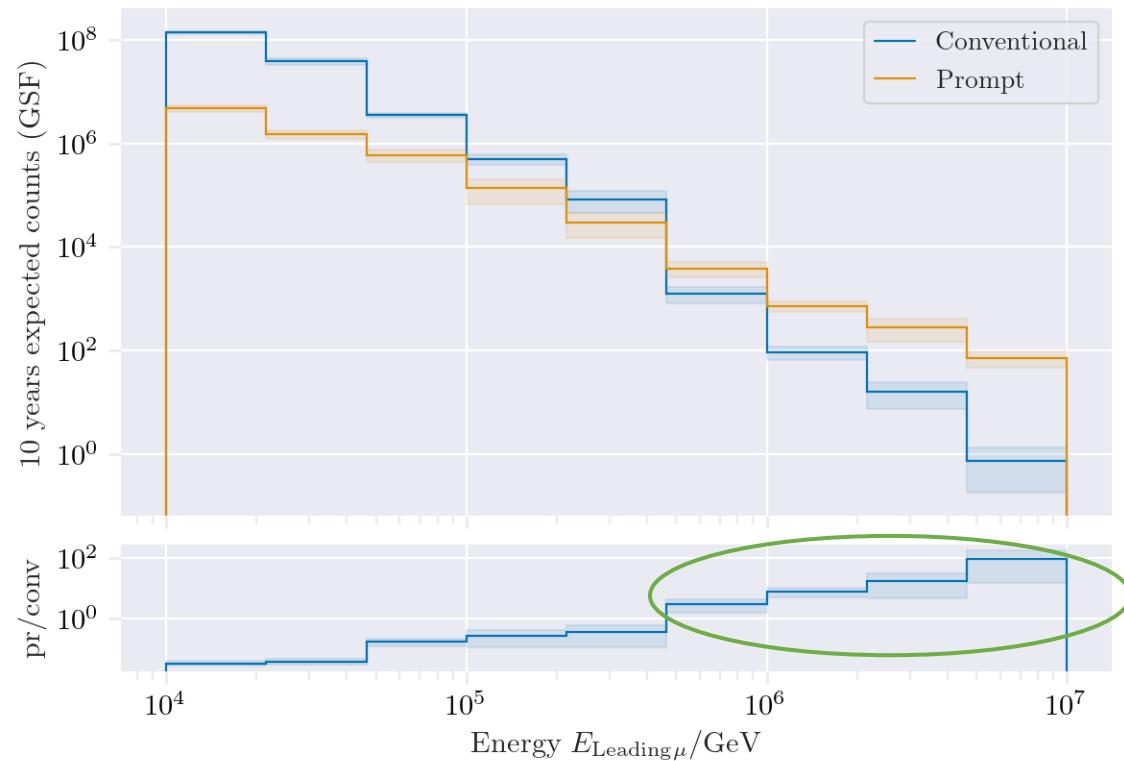


# Expected muons for 10 years: leading vs. bundle energy



- Different primary fluxes lead to different prompt fluxes
- Bundle energy extends to higher energies

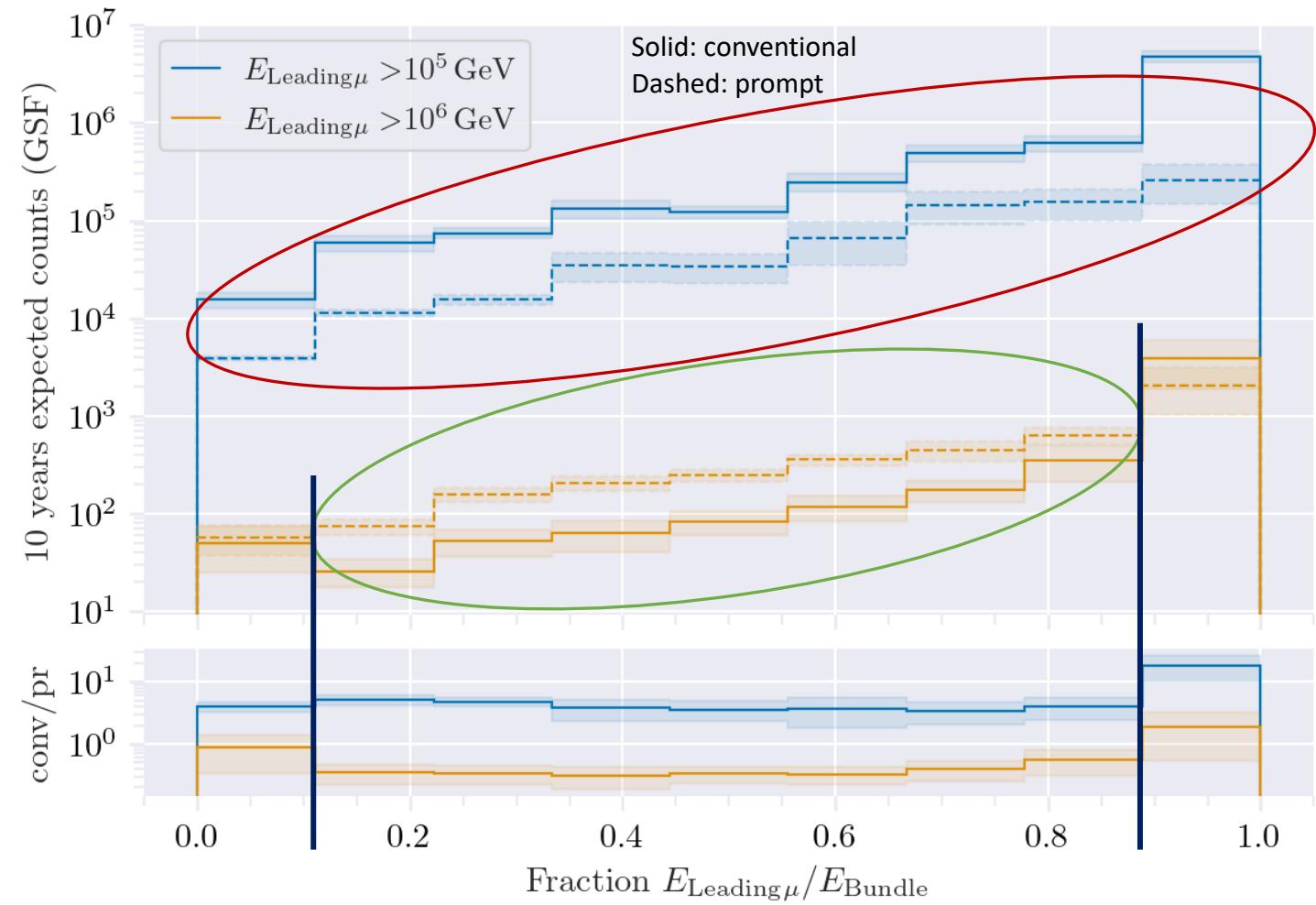
# Expected muons for 10 years: leading vs. bundle energy (GSF)



➤ Leading muon energy is more sensitive to detect prompt

# Leading muon energy fraction

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



# Leading muon contribution

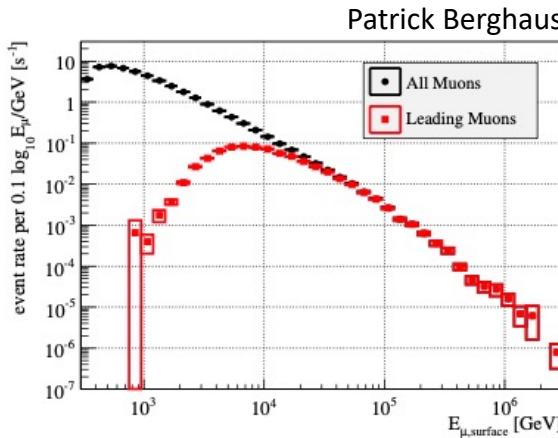
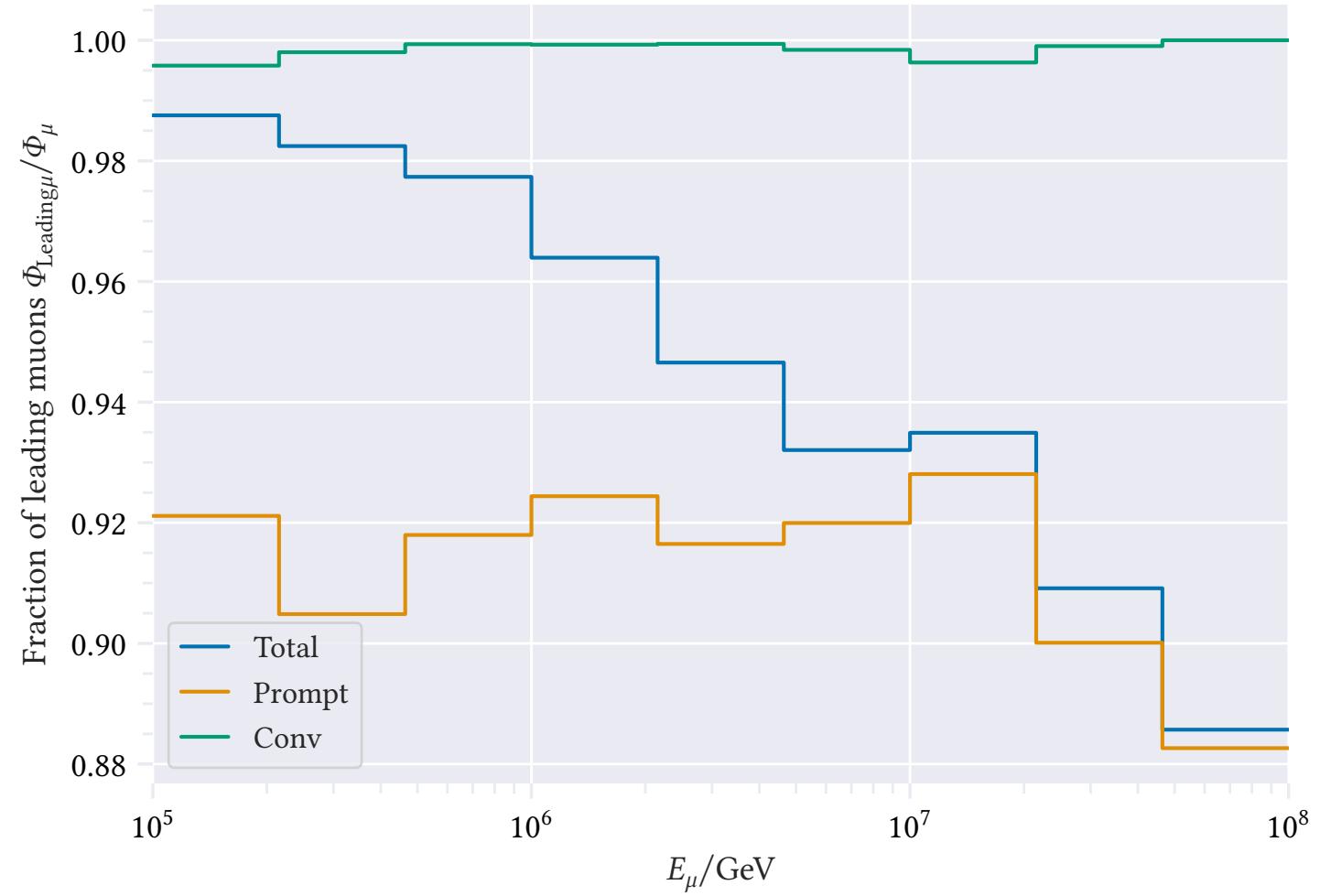


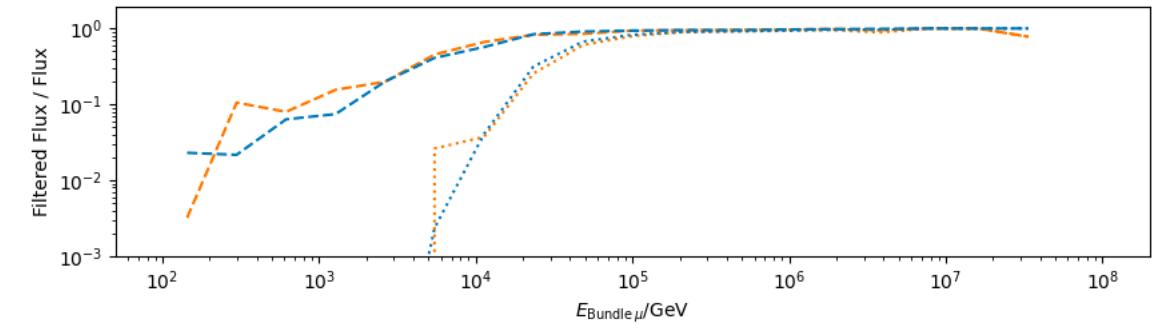
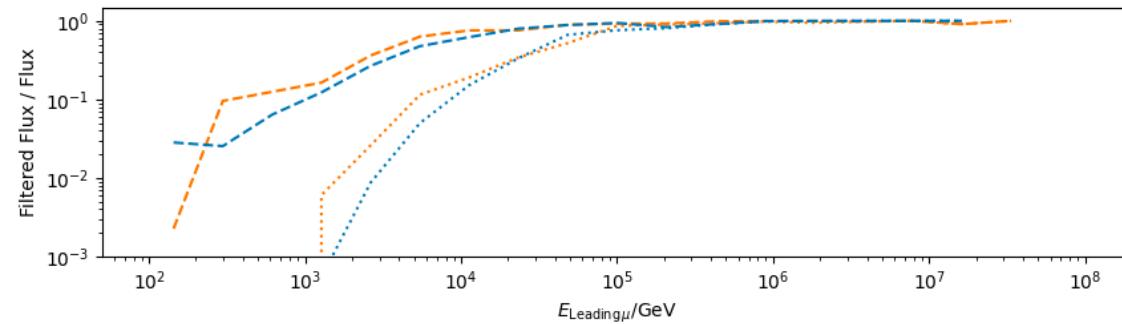
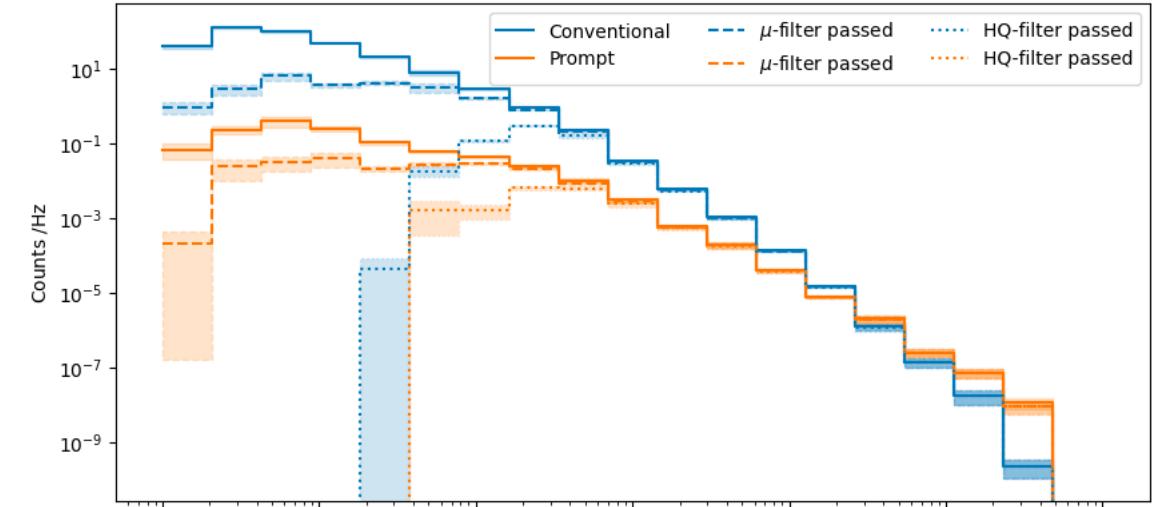
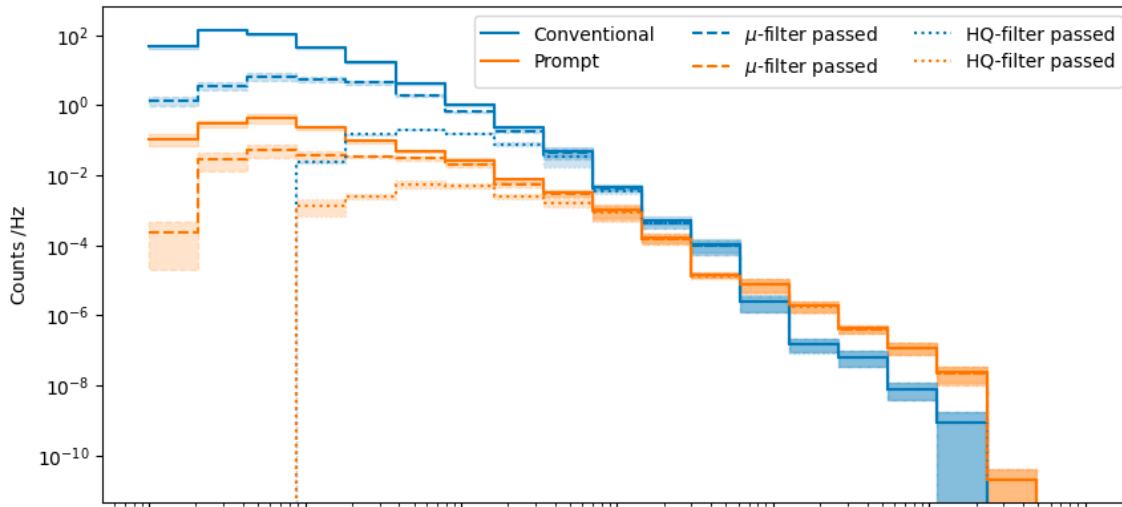
Figure 10: Surface energy distribution for all and most energetic (“leading”) muons in simulated events with a total of more than 1,000 registered photo-electrons in IceCube.

- 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



# L2 Filters

Fraction events rejected	All energies	Leading energy > 10 TeV	Leading energy > 100 TeV
MuonFilter	0.93	0.28	0.06
HQFilter	0.99	0.74	0.18



➤ Choose muon filter to remove large amount of statistics at low energies

# Data-MC agreements

- Two bachelor students worked on reconstructions using the dnn\_reco framework (thesis available in english):
  - Leander Flottau
  - Benjamin Brandt

Reconstructions:

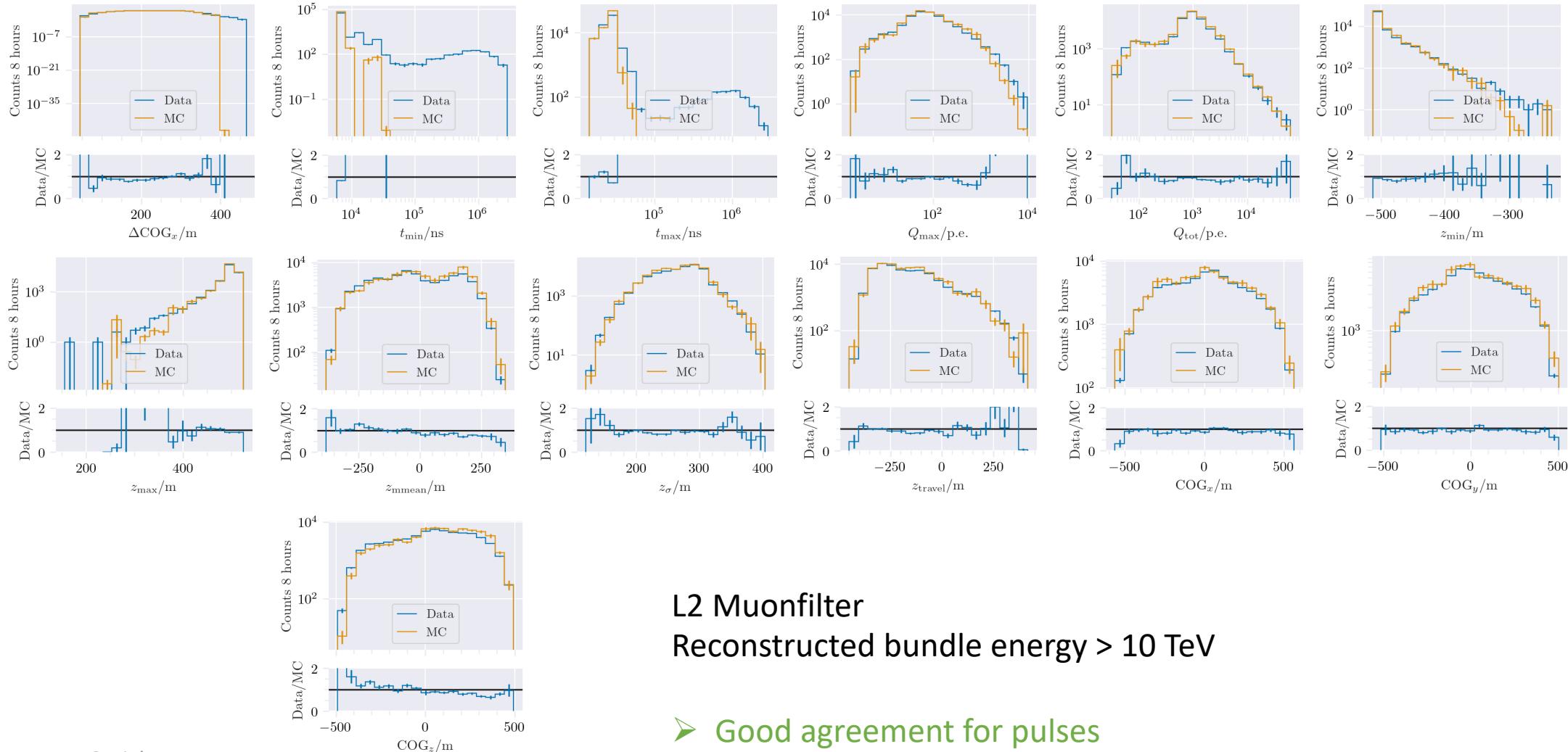
- Leading energy
- Leading fraction
- Bundle energy
- Multiplicity
- Azimuth
- Zenith

*Work in progress*

General:

- Trained on uncleaned and 6 $\mu$ s cleaned muon pulses
- Processed 1 day of experimental data (July 4th, 2020)

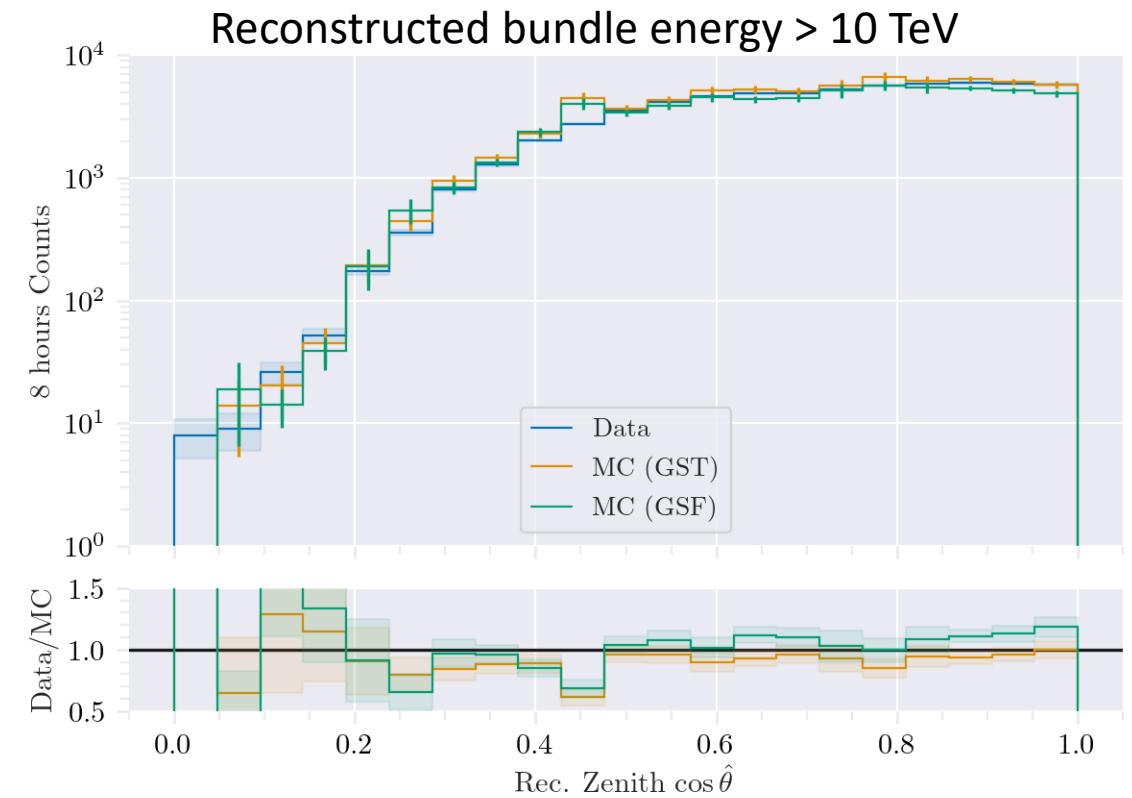
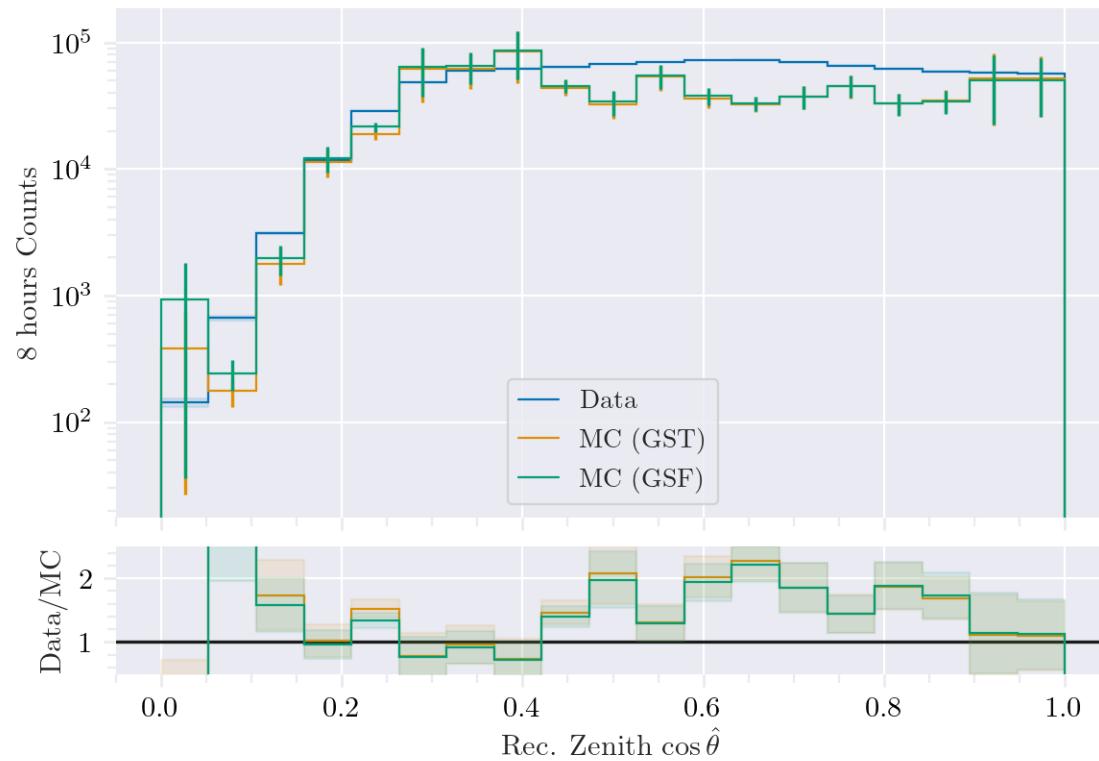
# Data-MC: HitStatistics - SplitInIceDSTPulses



L2 Muonfilter  
Reconstructed bundle energy > 10 TeV

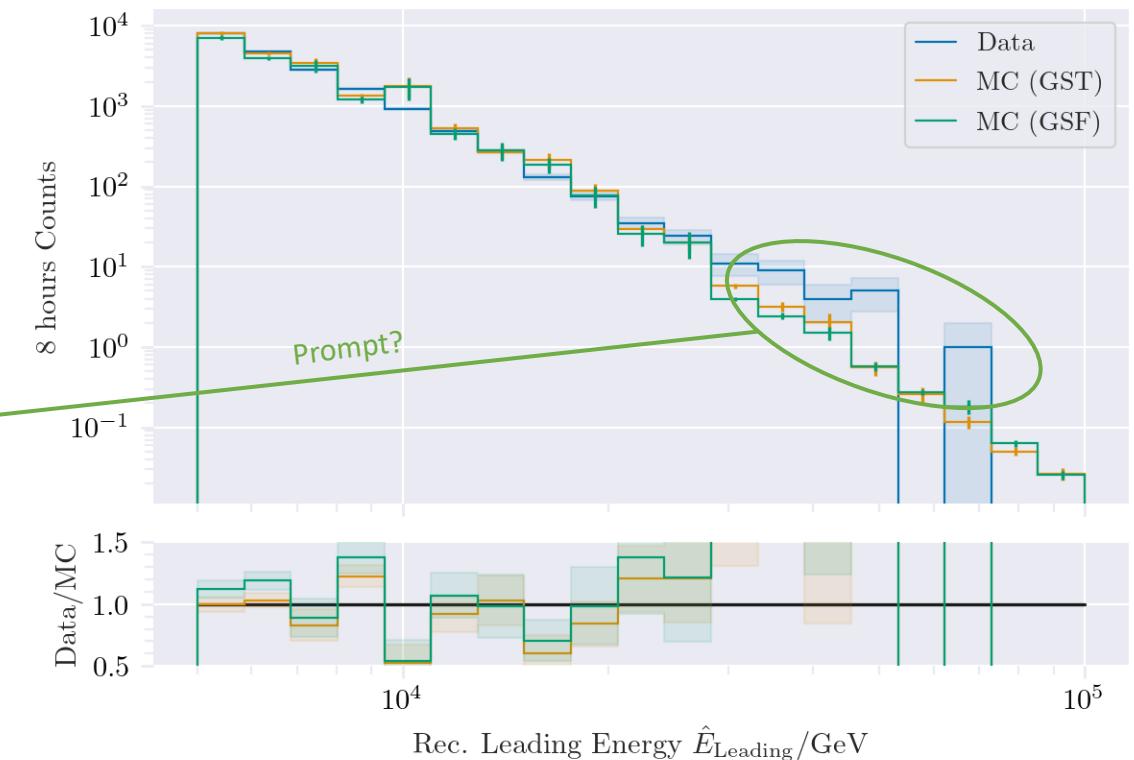
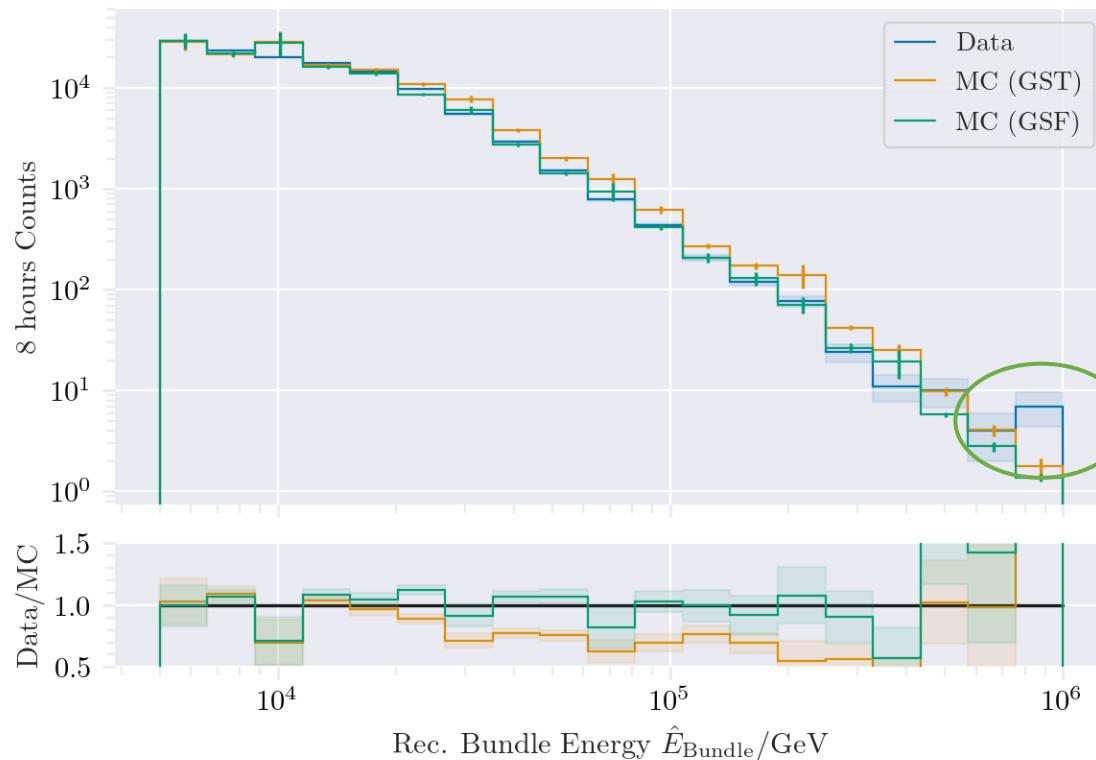
➤ Good agreement for pulses

# Data-MC: $\cos(\text{zenith})$



➤ Deviations at low  $\cos(\text{zenith})$ , but very small statistics

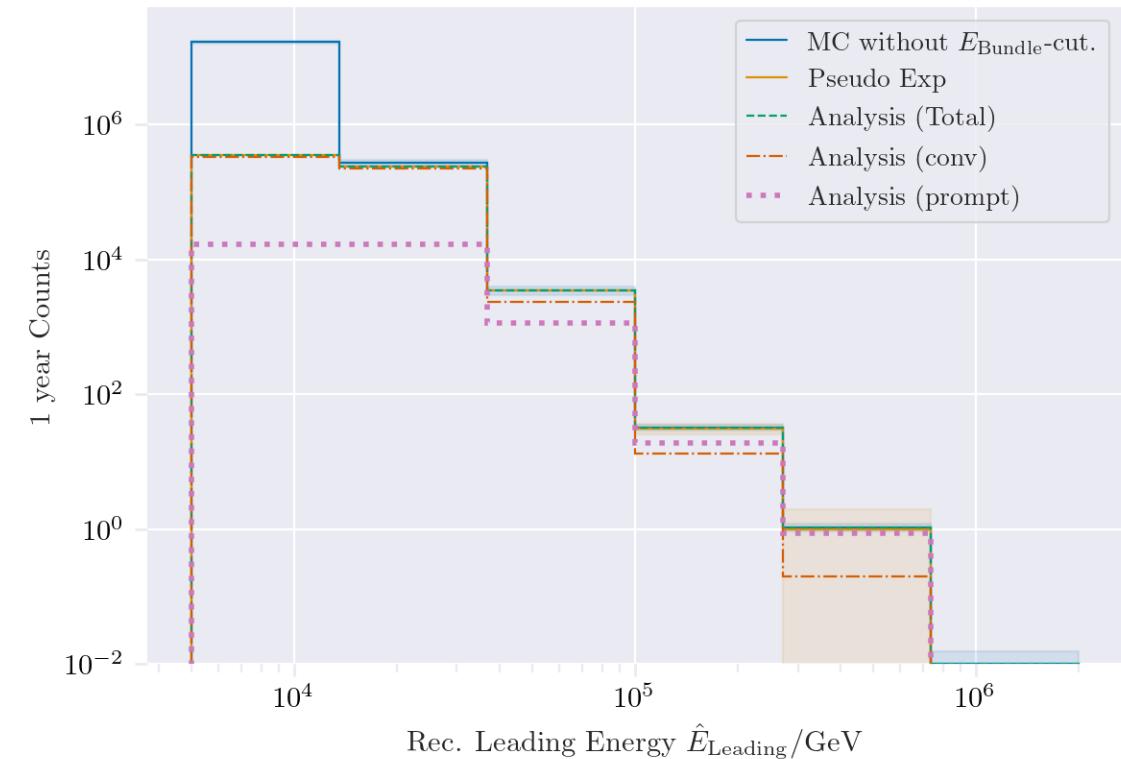
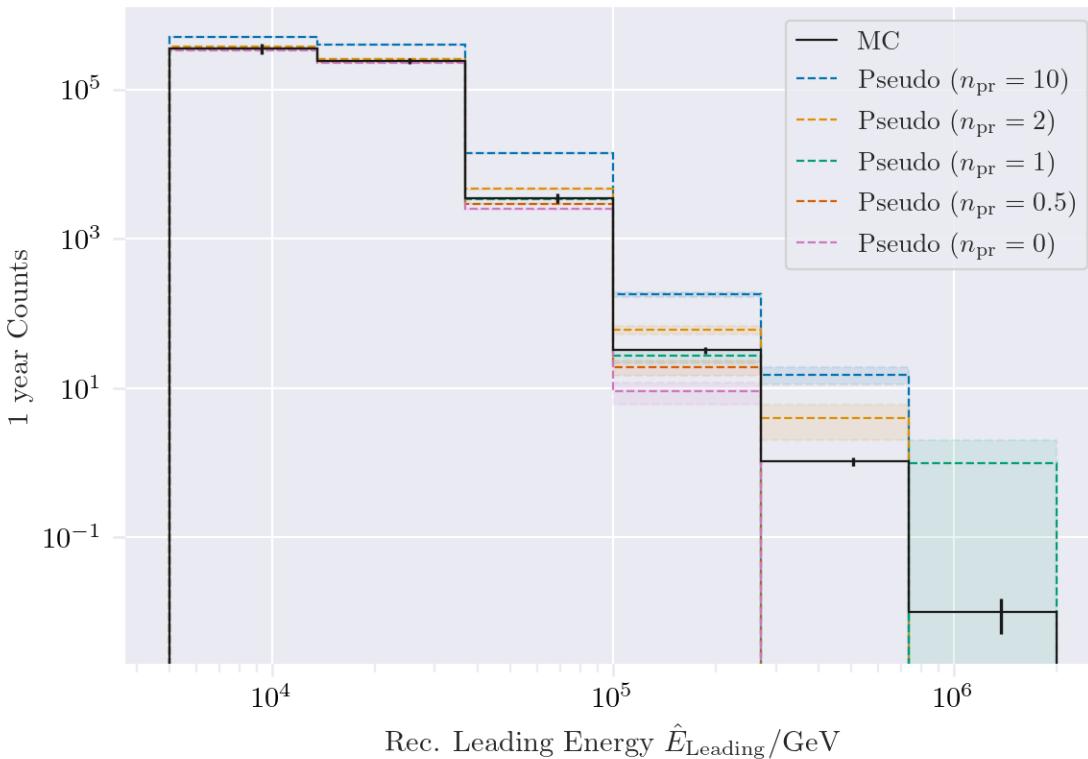
# Data-MC: energy spectrum



➤ Bundle energy: good agreement with GSF

# Pseudo analysis

# Pseudo data sampling



➤ Tagging allows scaling of prompt by factor  $n_{\text{pr}}$

# Poisson likelihood fit performed in leading muon energy

Prompt scaling/normalization

MC counts per bin i

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

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

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

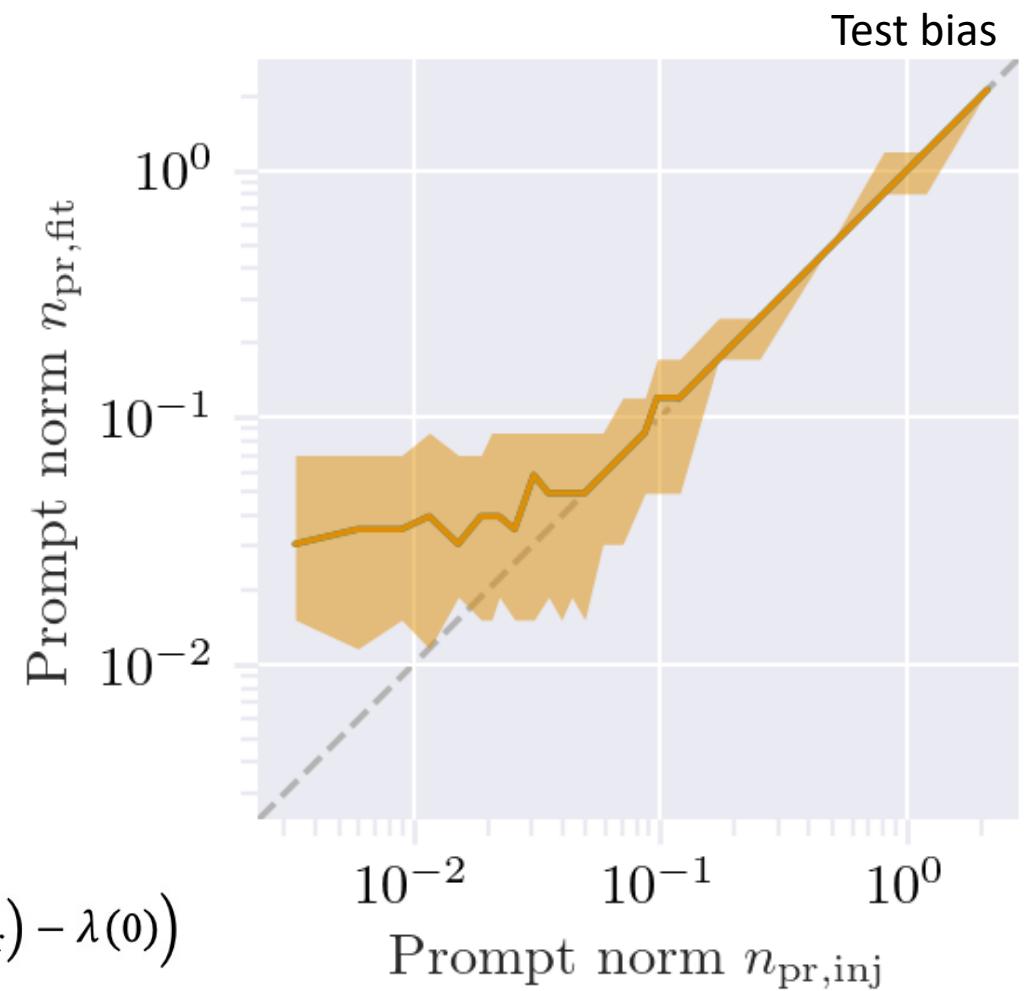
With a constant conv norm:  
bin counts depend only on prompt norm  
= expectation value per bin

Test statistic for Wilk's theorem

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

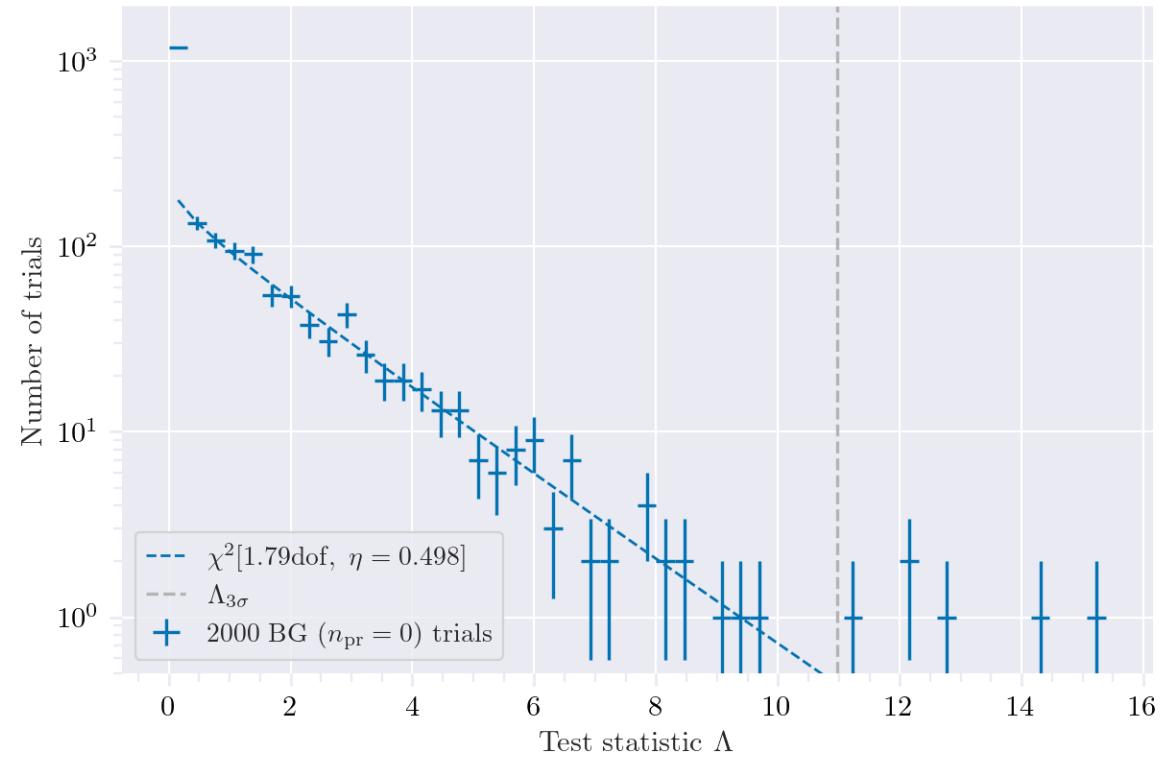
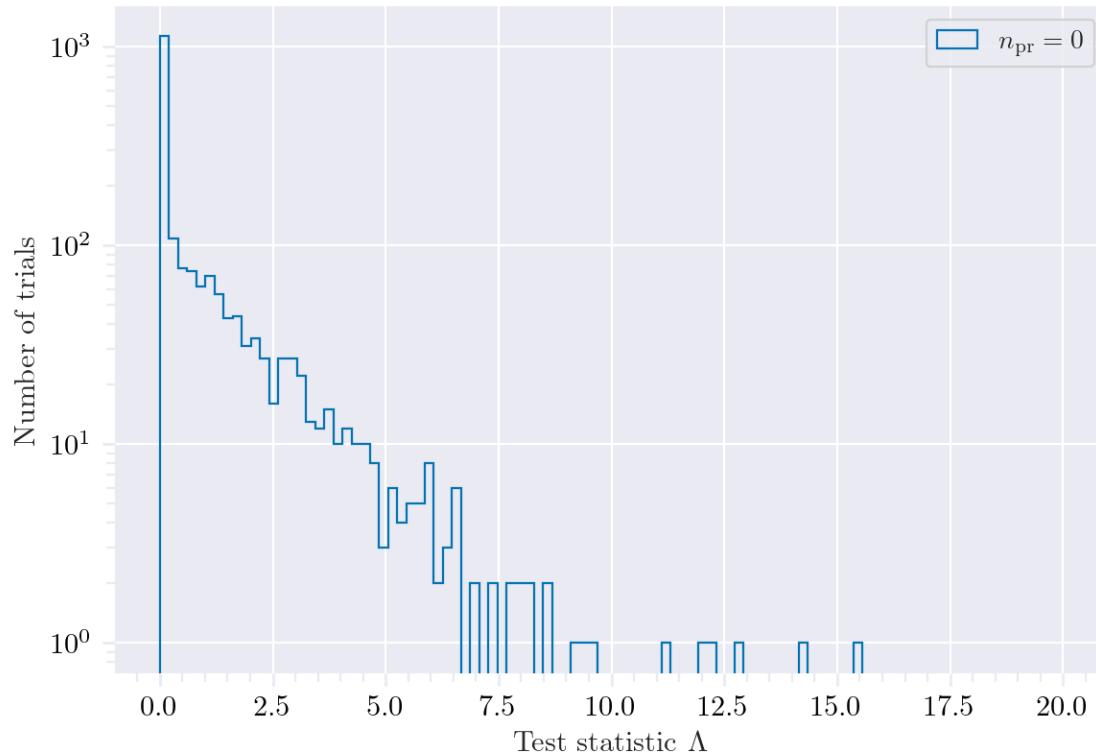
Null hypothesis: no prompt

P. Gutjahr



➤ Bias starts below a prompt  
normalization of 0.1

# Test background statistics



- Background statistic is  $\chi^2$  – distributed
- Assume Wilks' theorem for test statistics

# Discovery potential and sensitivity

Expectation for 1 year:

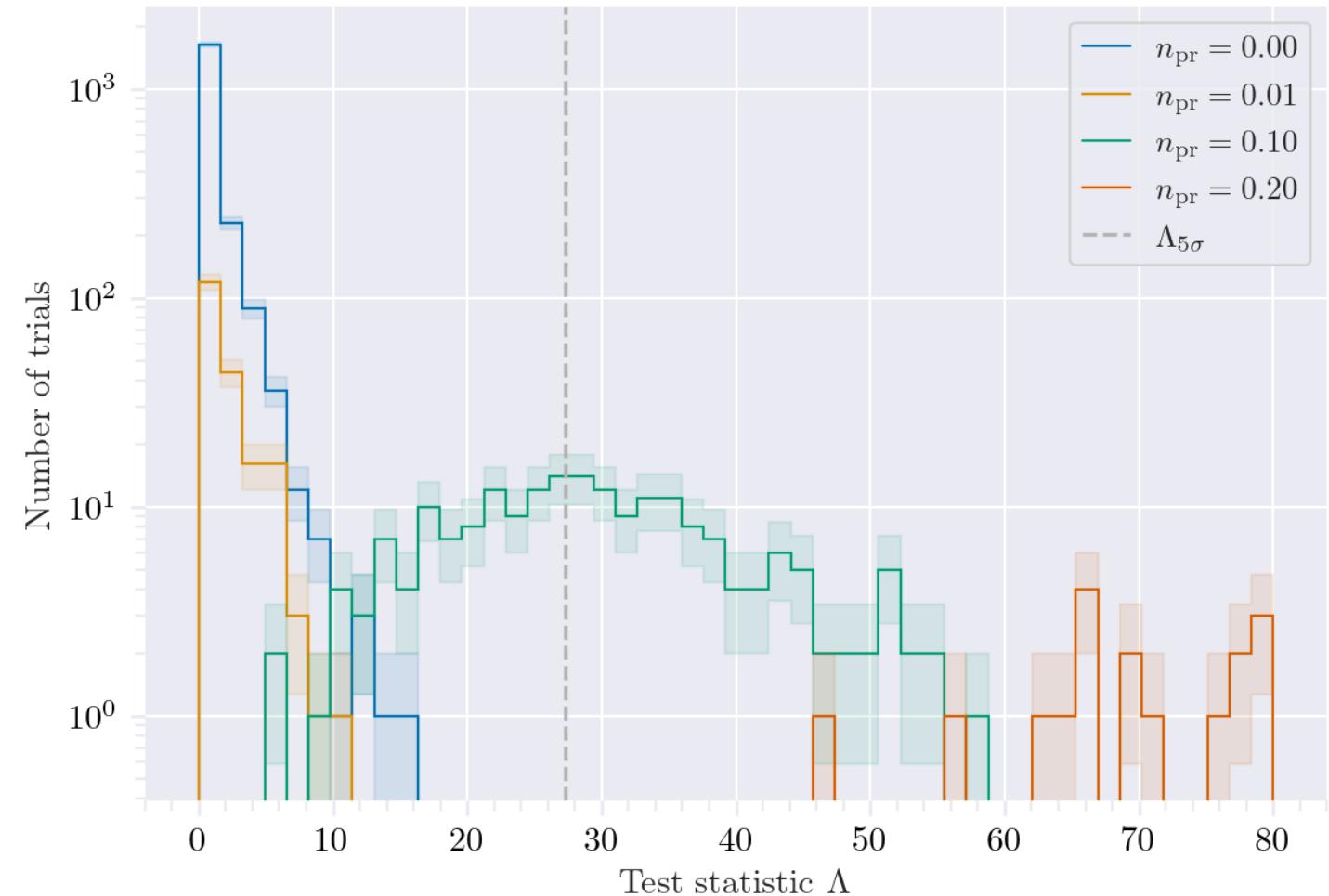
- 5 sigma discovery potential:  $0.102 \pm 0.005$
- Sensitivity:  $0.024 \pm 0.001$

Expectation for 10 years:

- 5 sigma discovery potential:  $0.032 \pm 0.001$
- Sensitivity:  $0.007 \pm 0.000$

Caution:

Limited MC statistics -> events are  
oversampled in pseudo dataset



# Conclusion

- New CORSIKA EHIST simulations
- CORSIKA vs. MC Eq agreement
- DNN angular and energy reconstructions
- First data-MC comparisons
- Pseudo analysis is set up

➤ Results are promising

# Outlook

- Wiki page
- Data-MC agreement of dnn input
- Optimize DNN reconstructions
- Include systematics (snowstorm)
  - Scattering
  - Absorption
  - Anisotropy
  - Hole ice 1
  - Hole ice 2
  - Dom efficiency
  - Conventional normalization
- ❖ We do not include systematics of the primary fluxes, instead we perform the analysis several times for different flux models
- ❖ Entire analysis is based on CORSIKA 7 and SIBYLL 2.3d, perform “minor” simulation with another hadronic model?

# Backup

# Definition of the muon flux

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

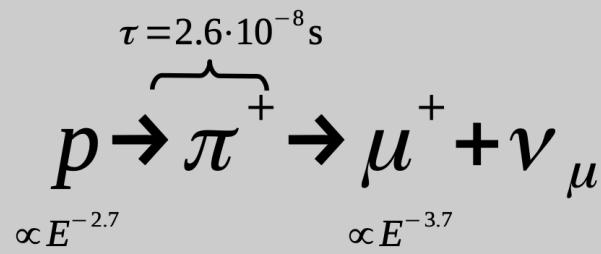


$$\pi, K \propto E^{-3.7}$$

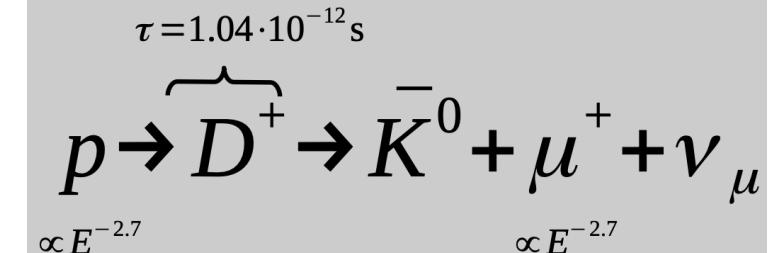


$$\text{"not"} \pi, K \propto E^{-2.7}$$

Conventional component:



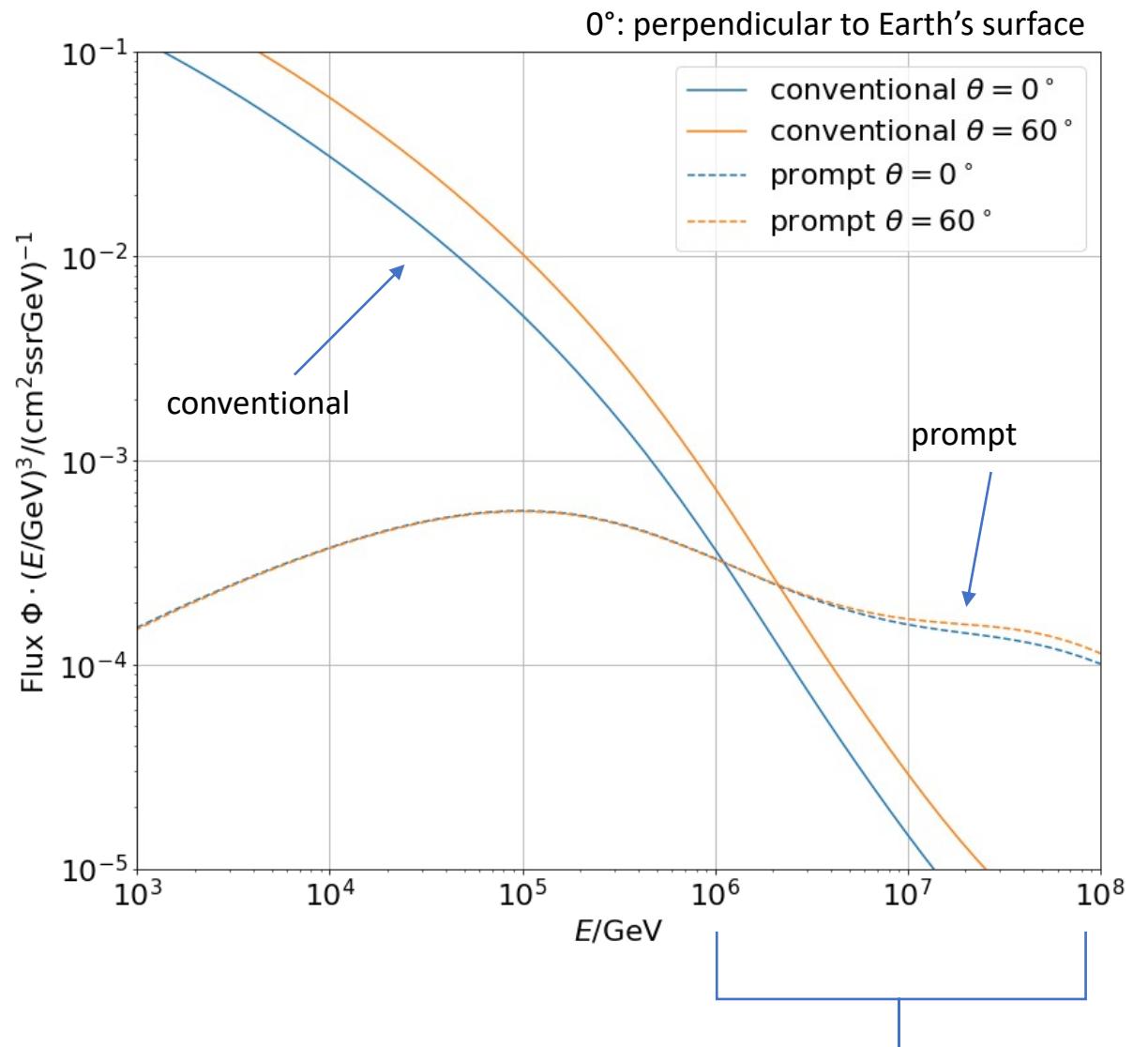
prompt component:



# Muon flux

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

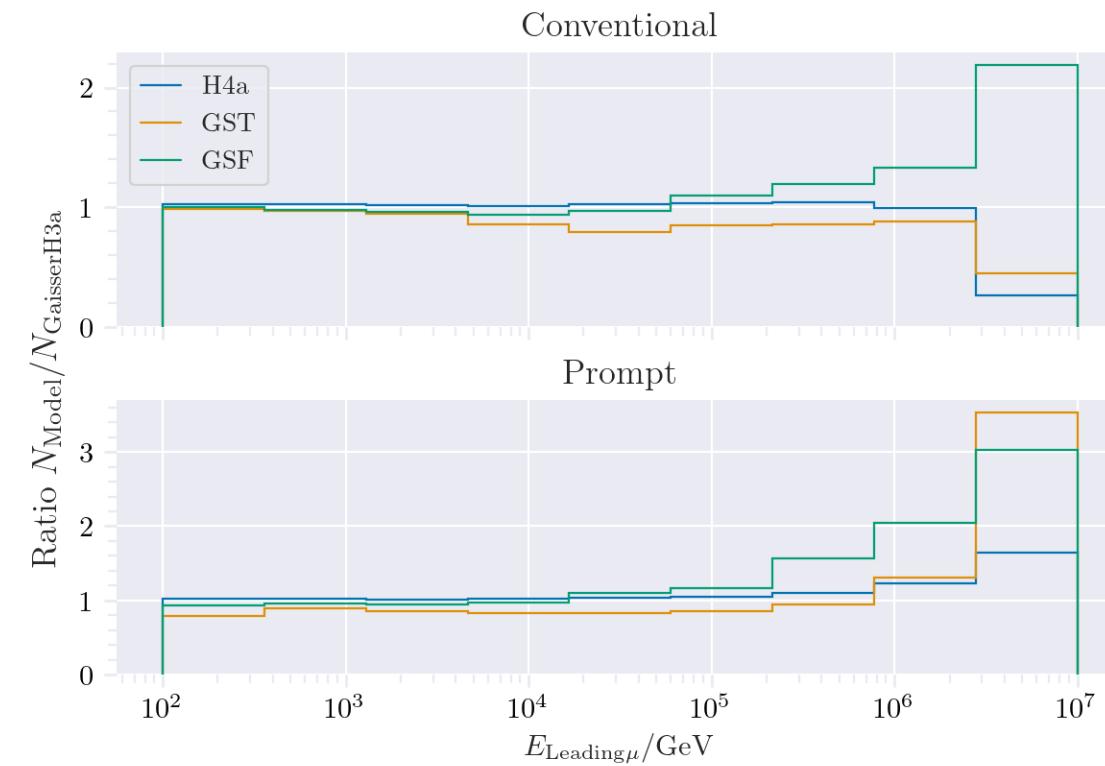
- Prompt dominates at energies larger than PeV
- Conventional particle flux depends on zenith angle



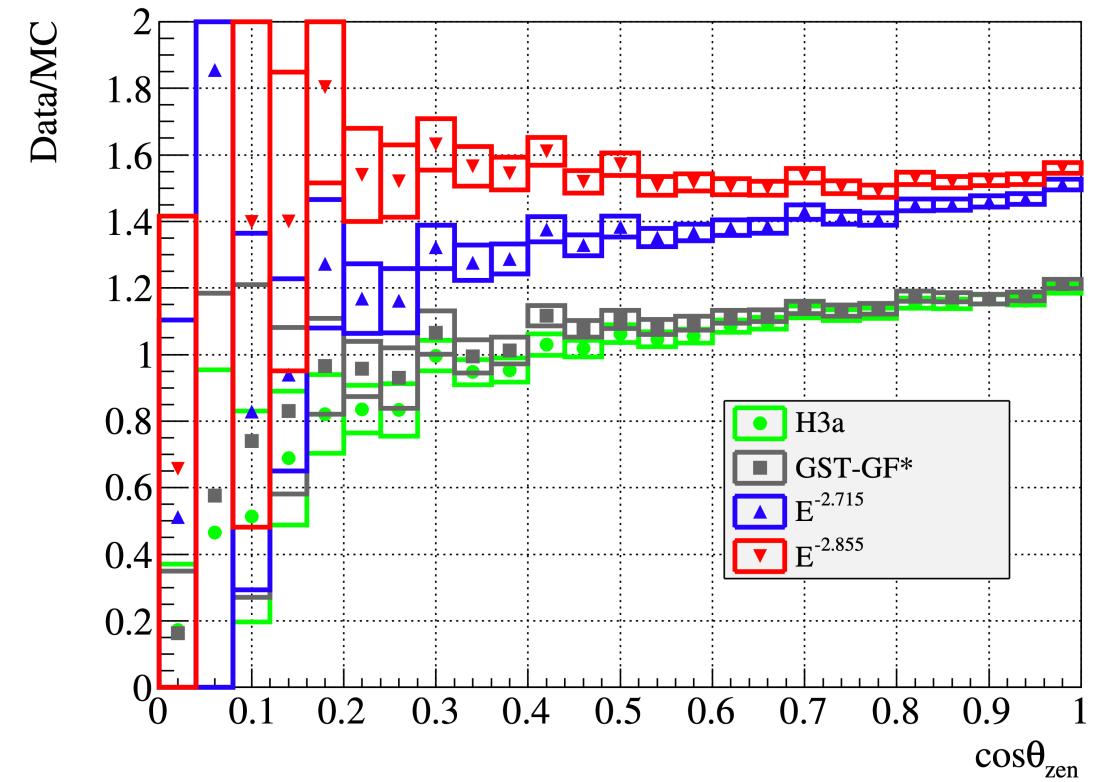
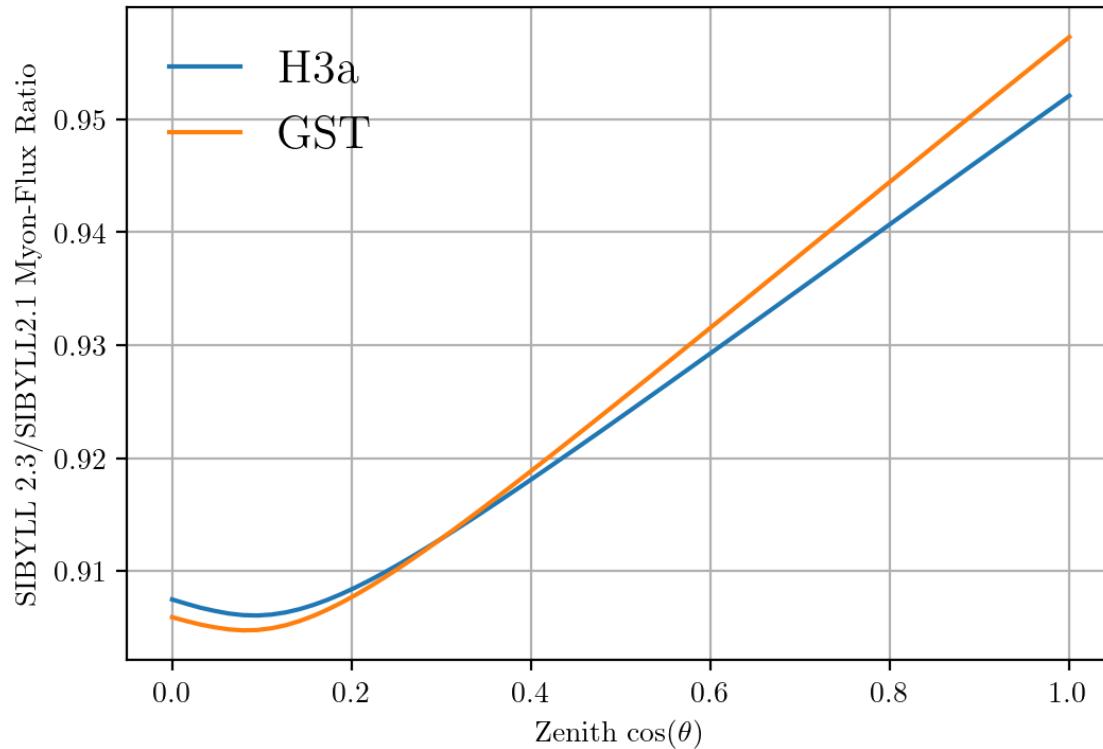
We can measure prompt muon energies from ~1 PeV to ~100 PeV

# Muon production – different weightings

GST predicts most prompt

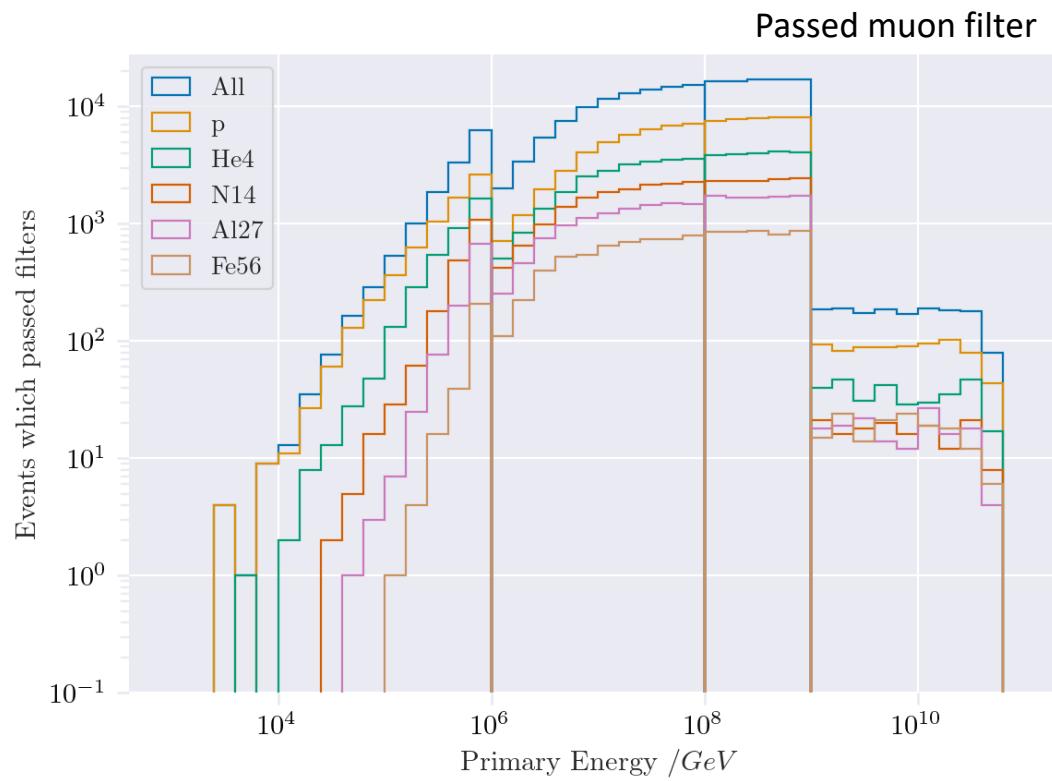


# Solution to zenith problem?



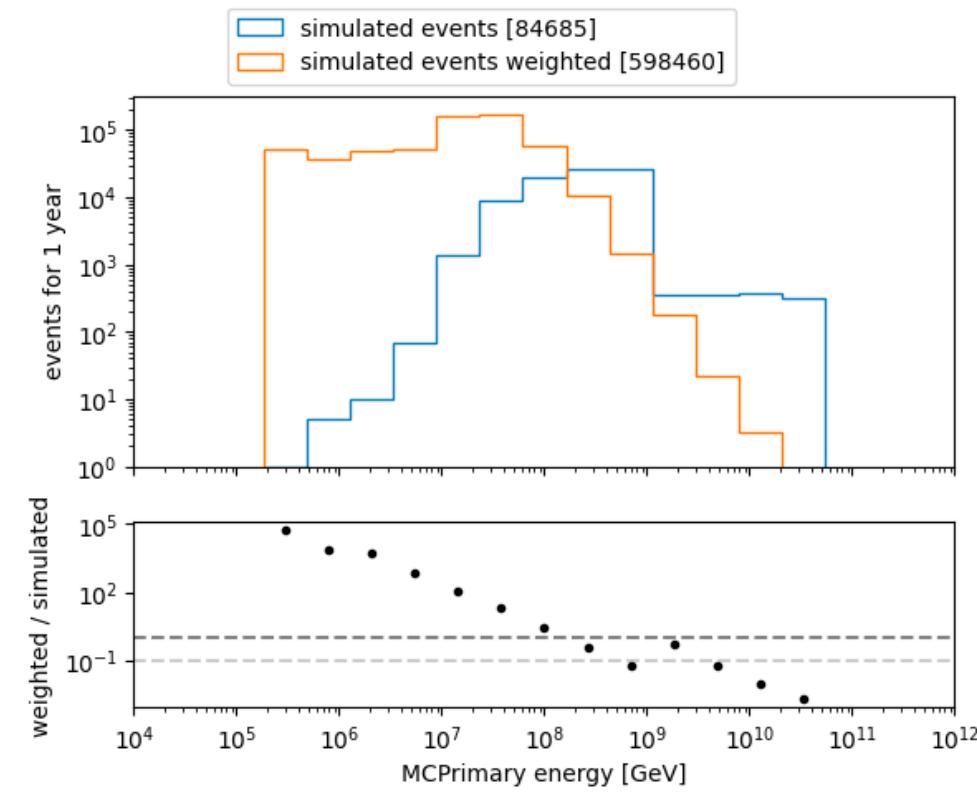
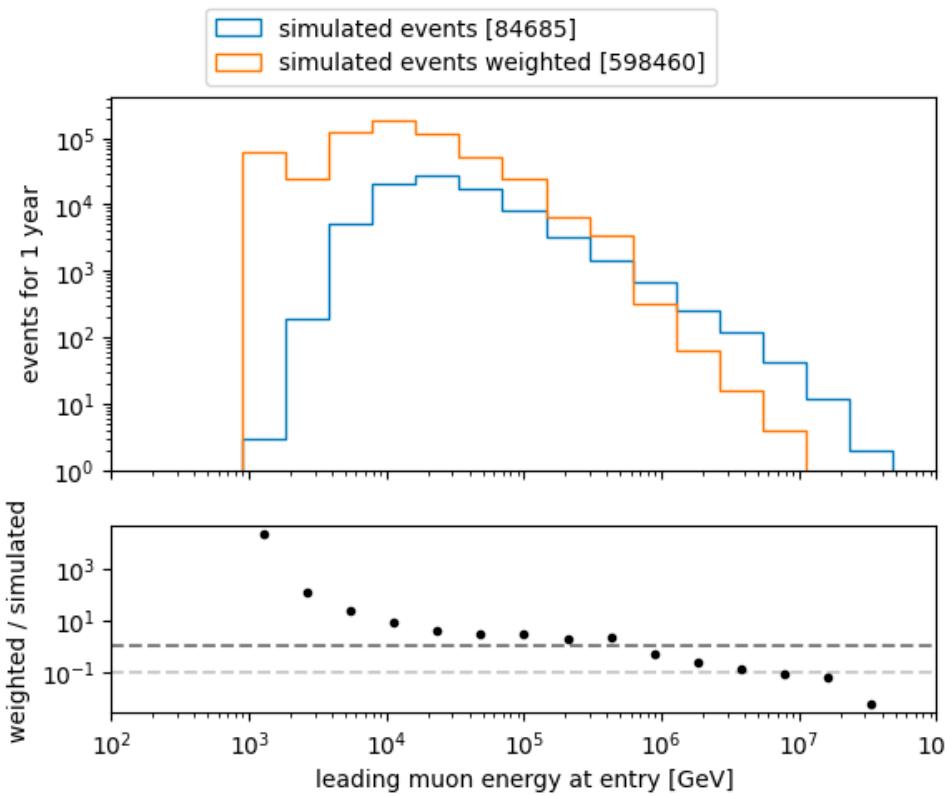
- No complete solution, but a step in the right direction

# Simulated events



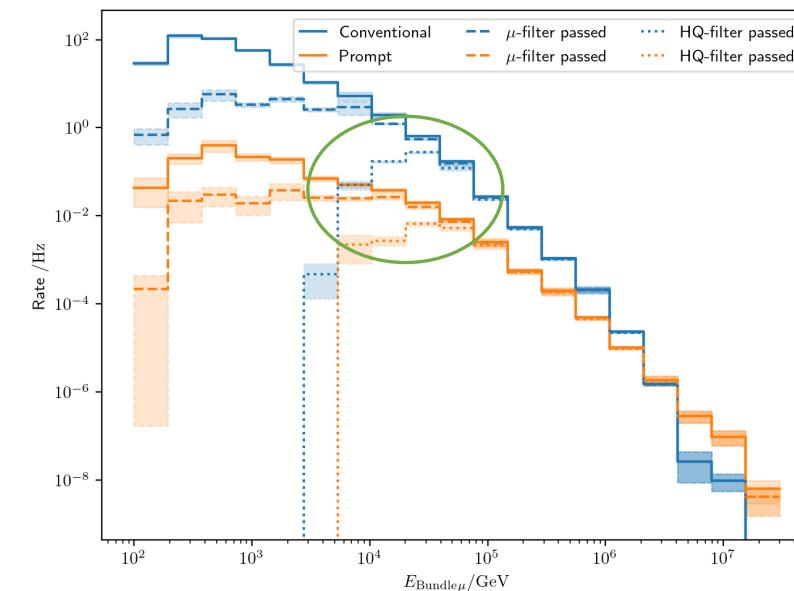
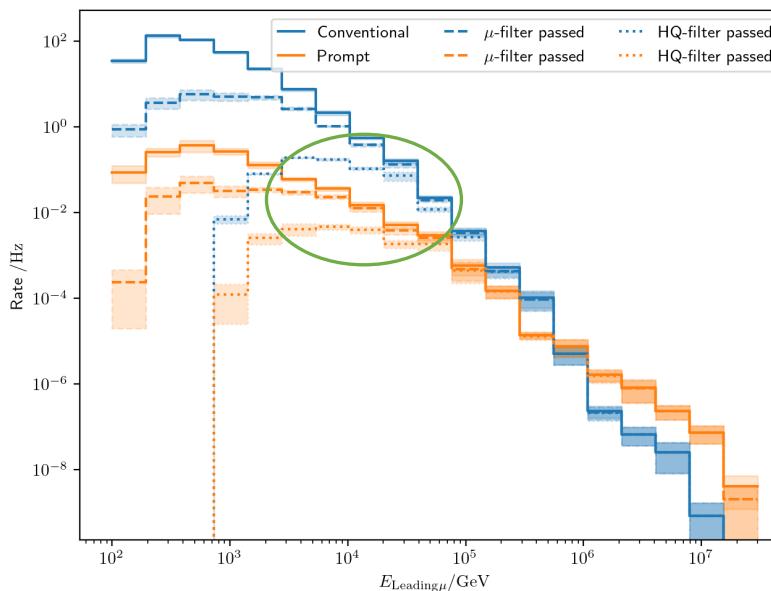
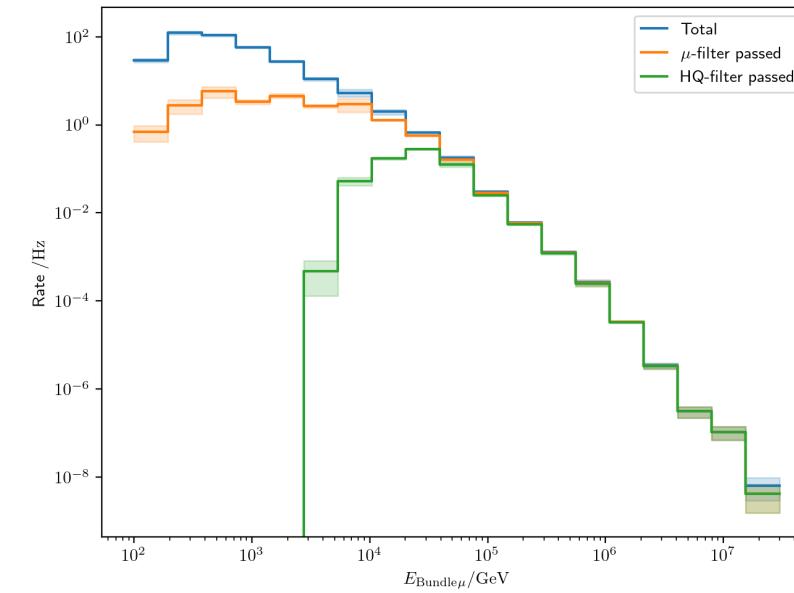
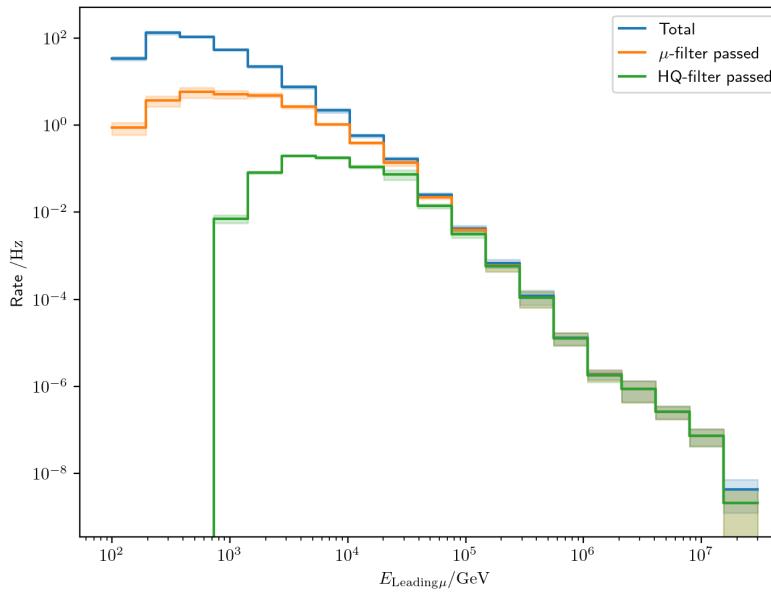
# Which energies to we need to simulate?

L2 MuonFilter  
Bundle energy > 100 TeV

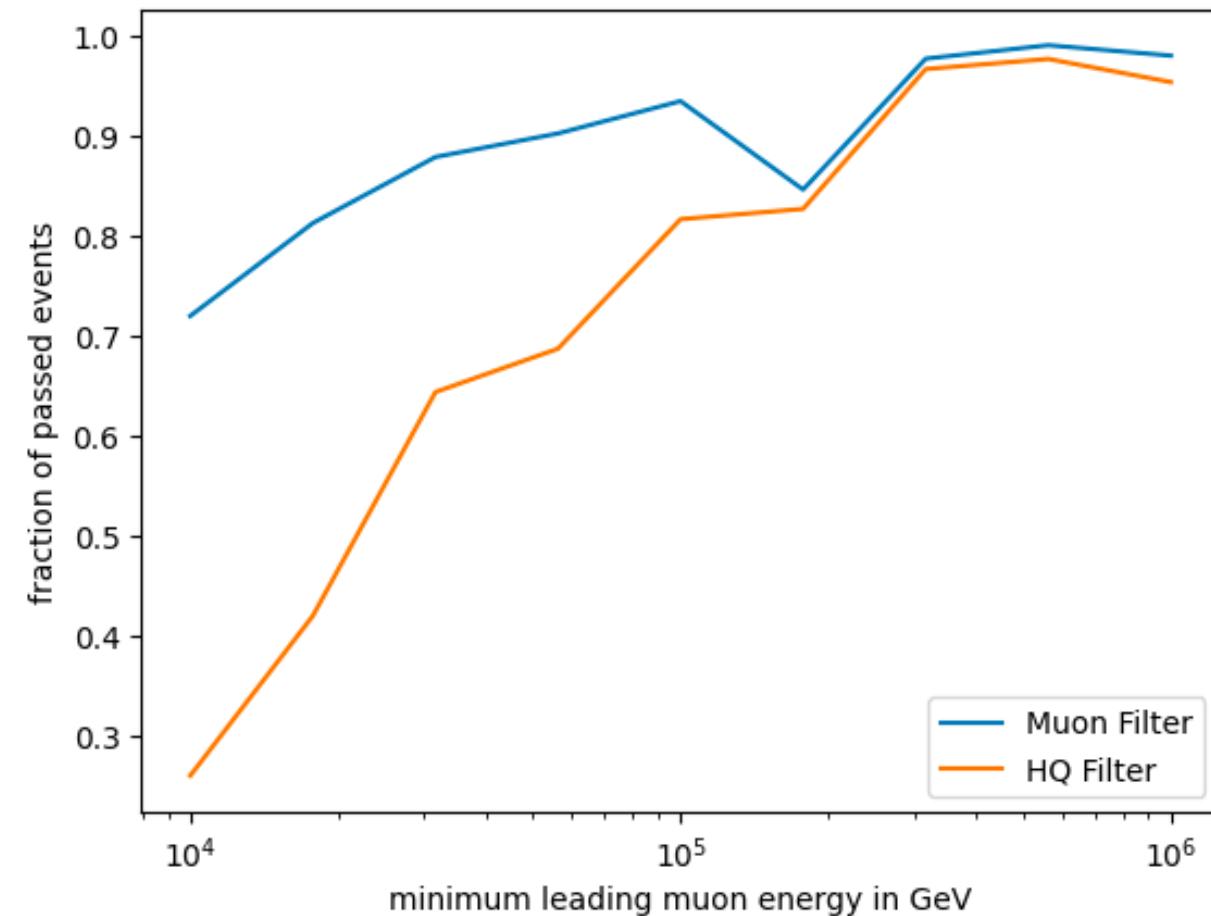


# Filters

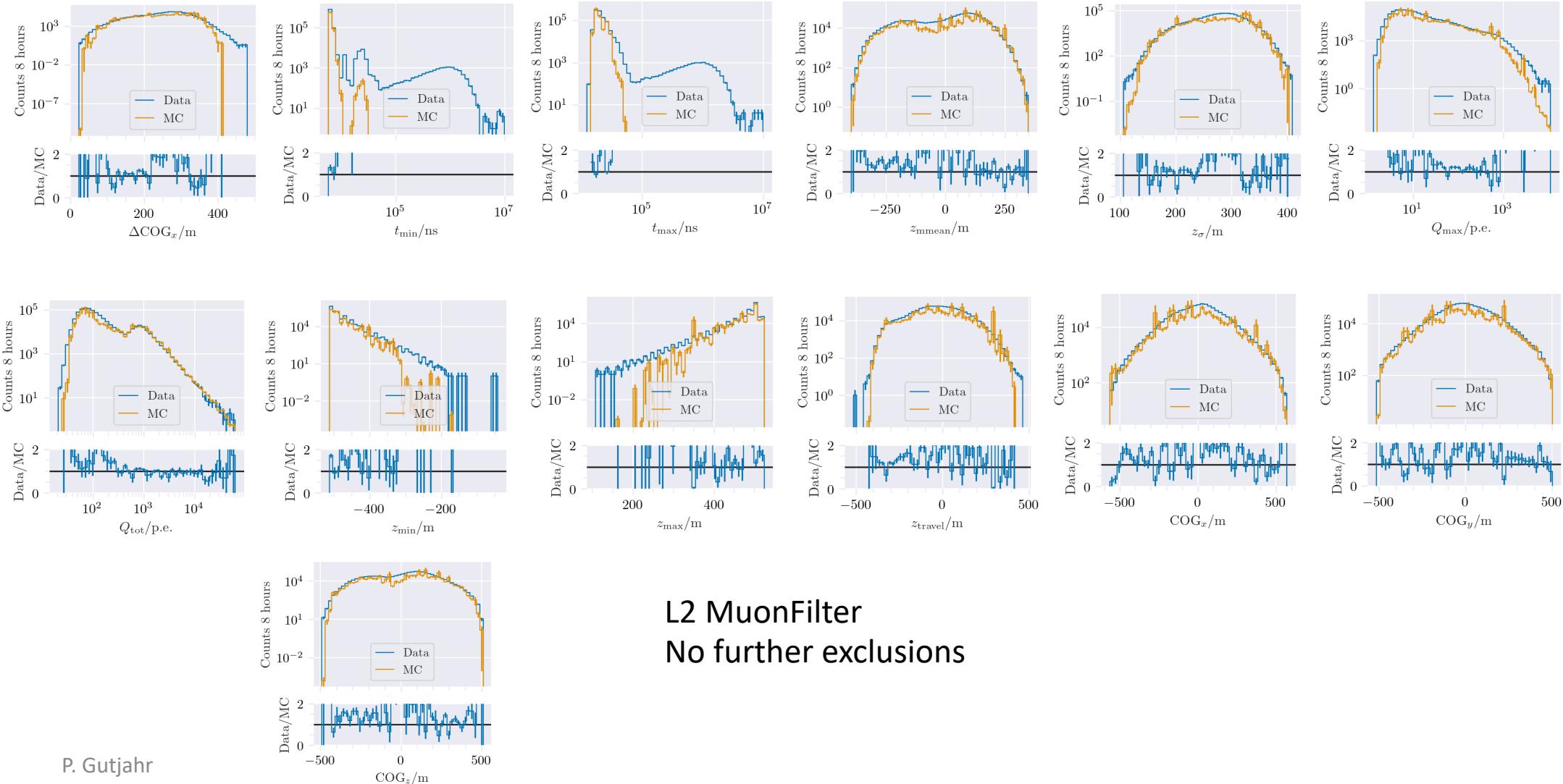
Choose muon filter,  
larger statistics at 10 TeV



# Filters – passed events per leading energy



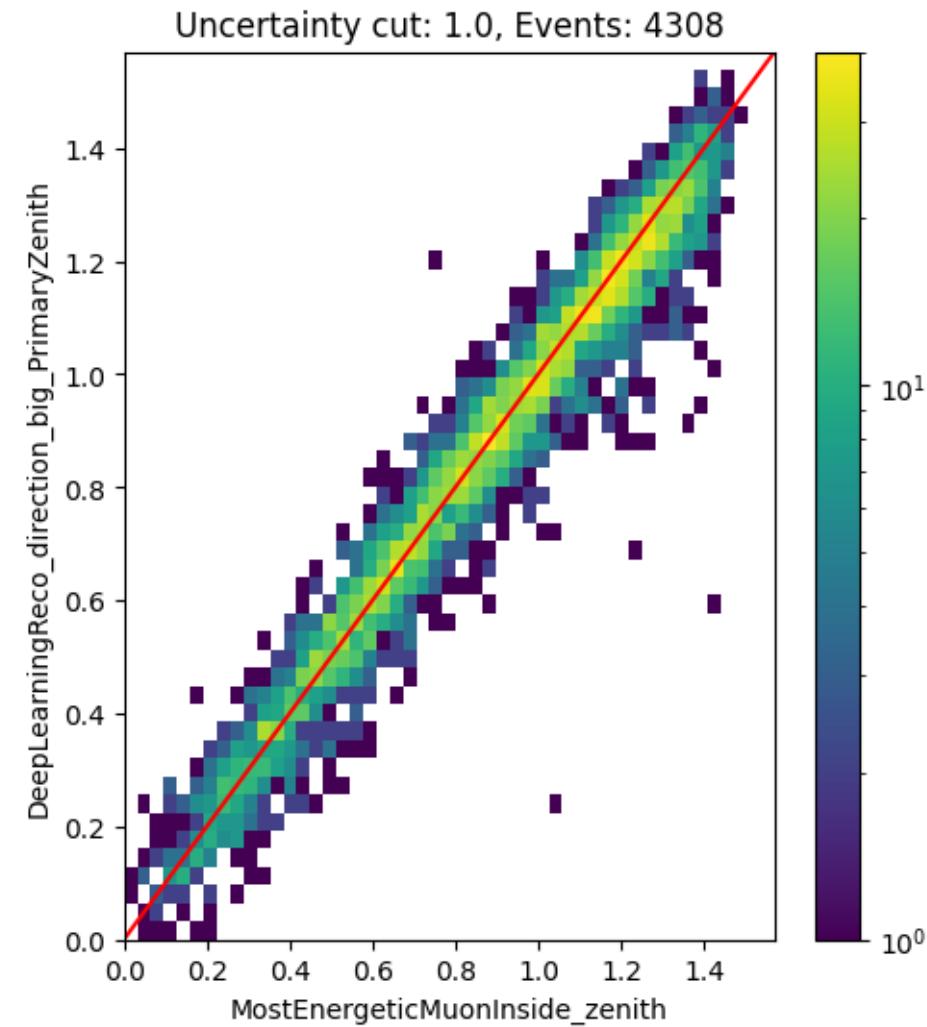
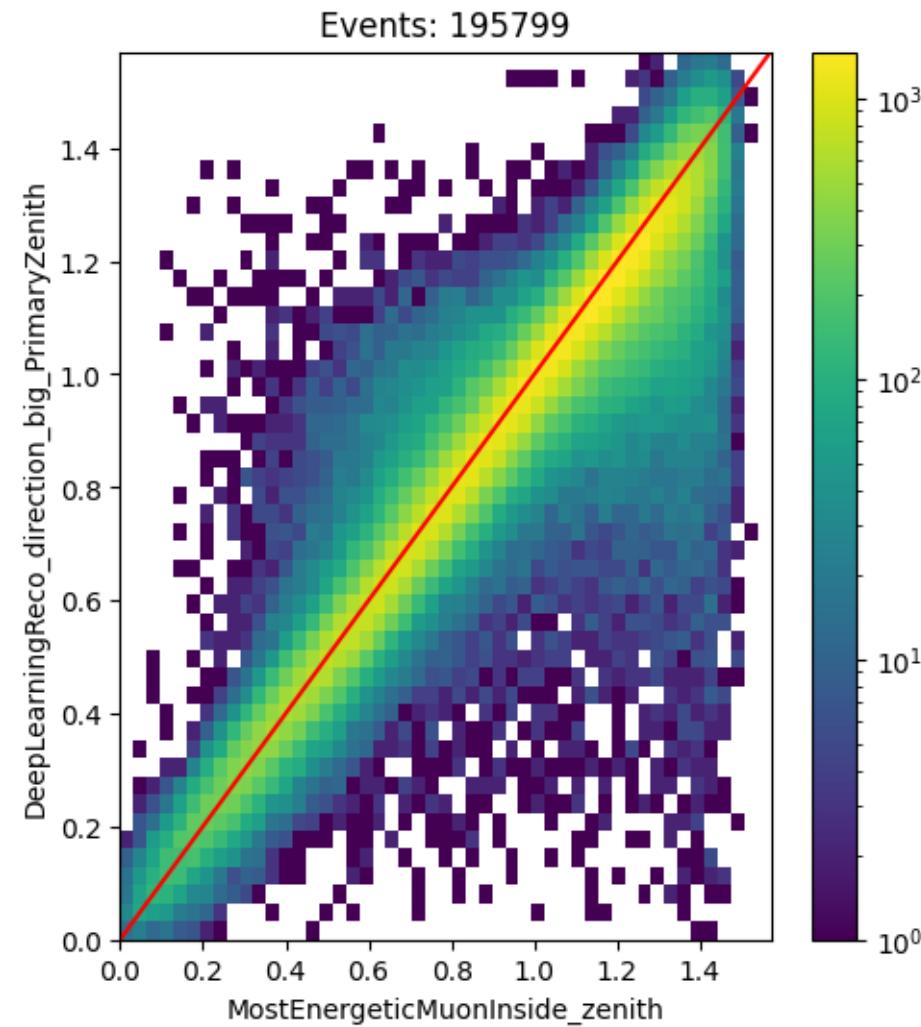
# Data-MC: HitStatistics - SplitInIceDSTPulses



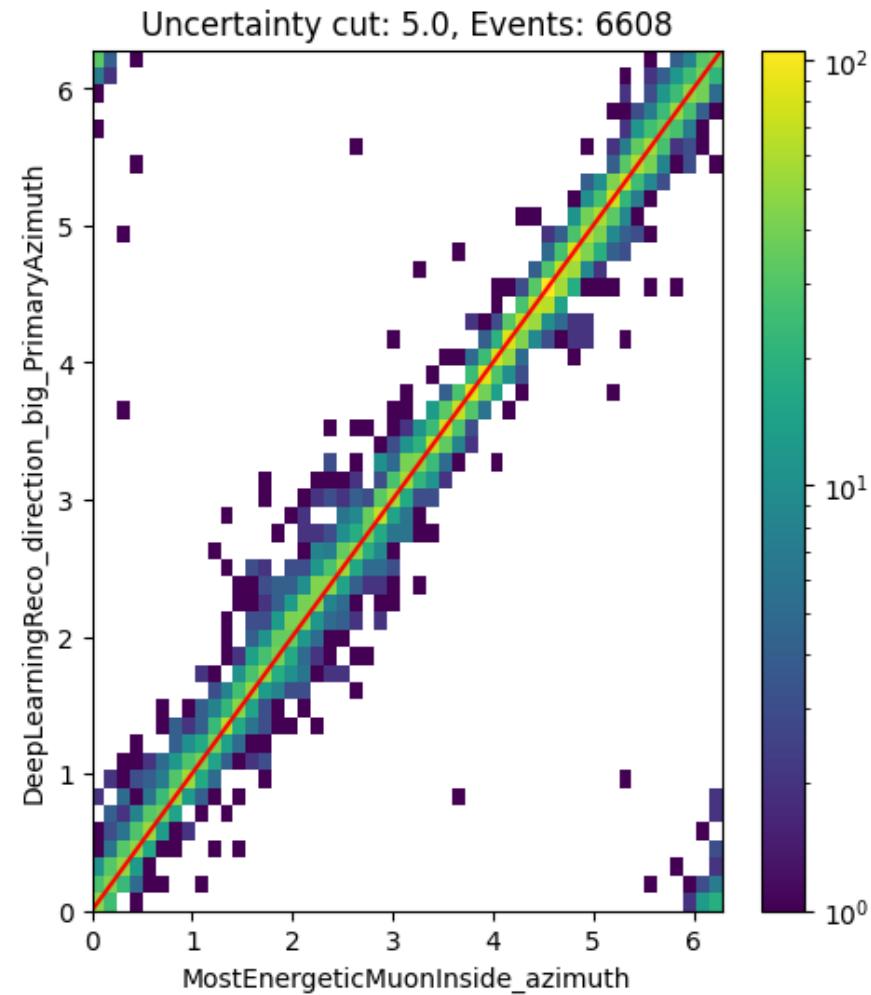
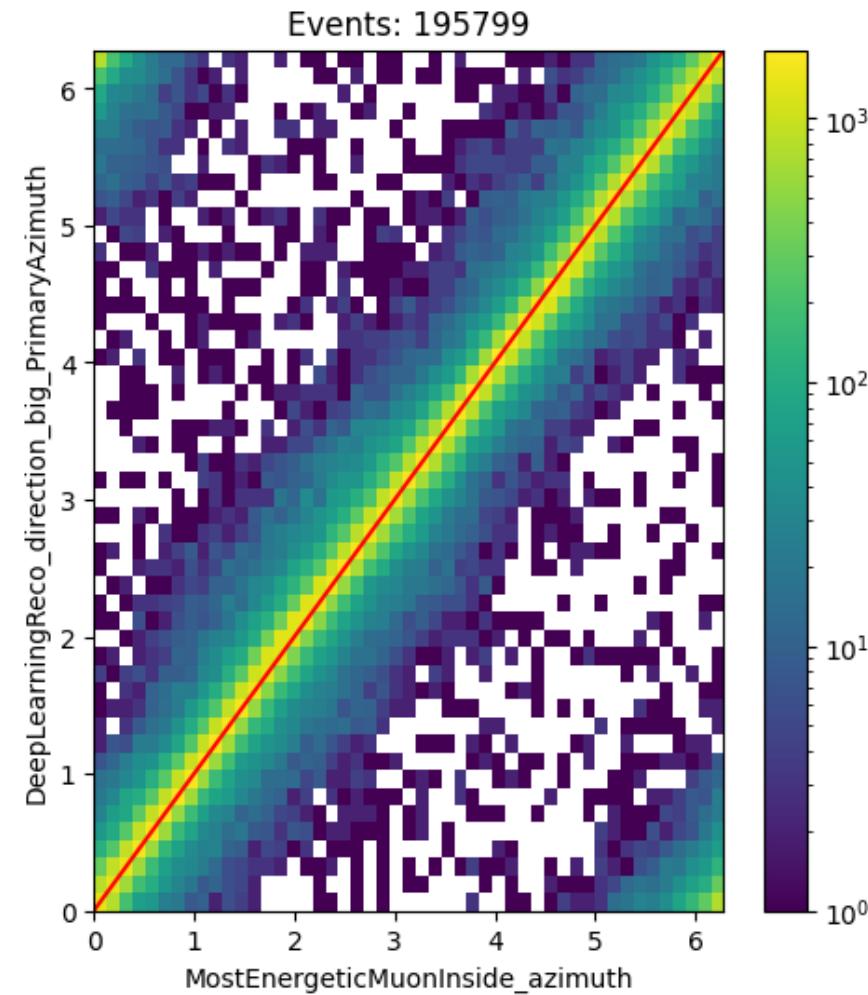
# Evaluation of models used in pseudo analysis

- Note: the DNN reconstruction models are still investigated! The models used here are in an early stage. So far, the two bachelor students have trained models with better performance.
- Updates on the models and reconstructions are provided in the near future

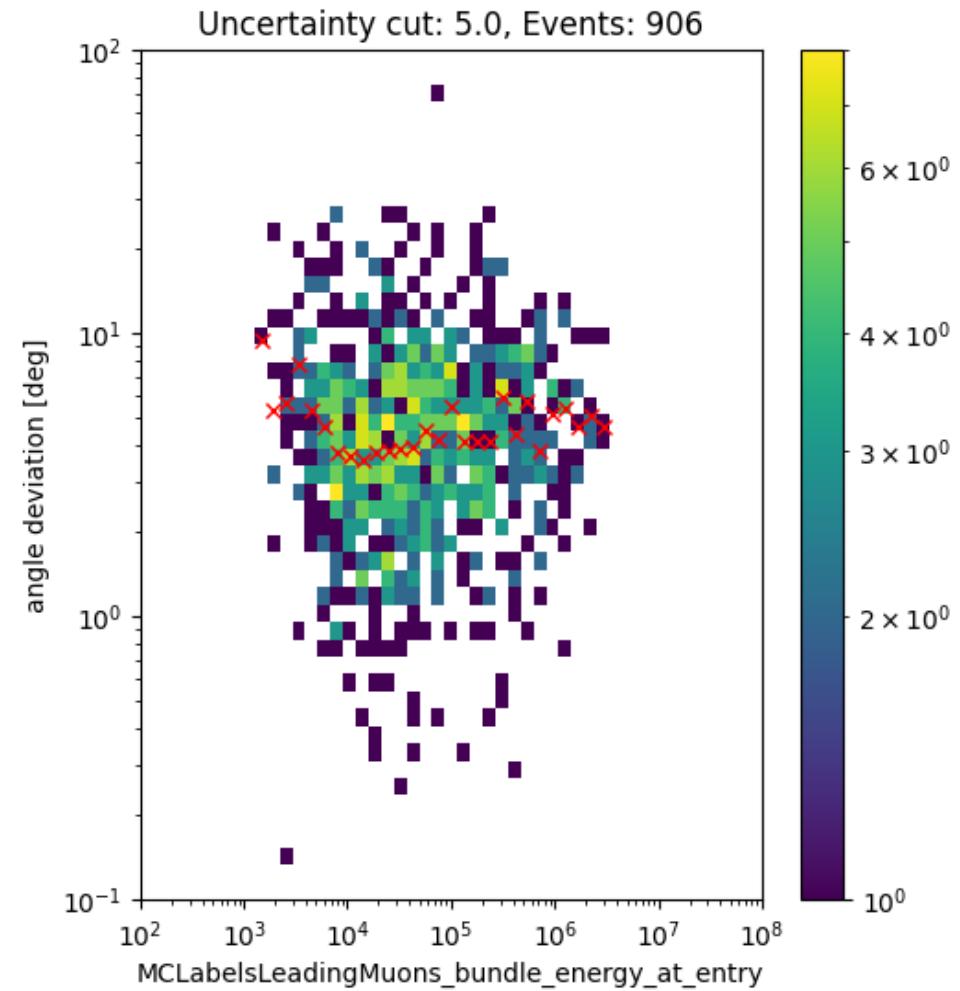
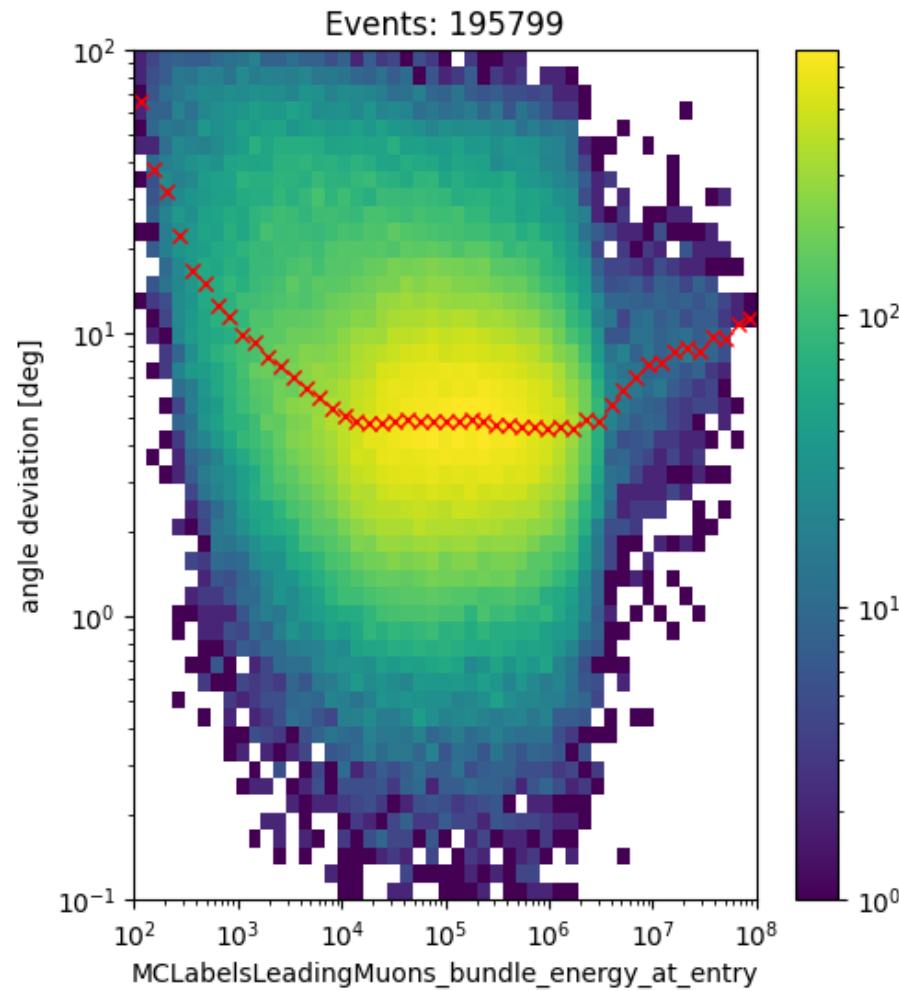
# Zenith reconstructions



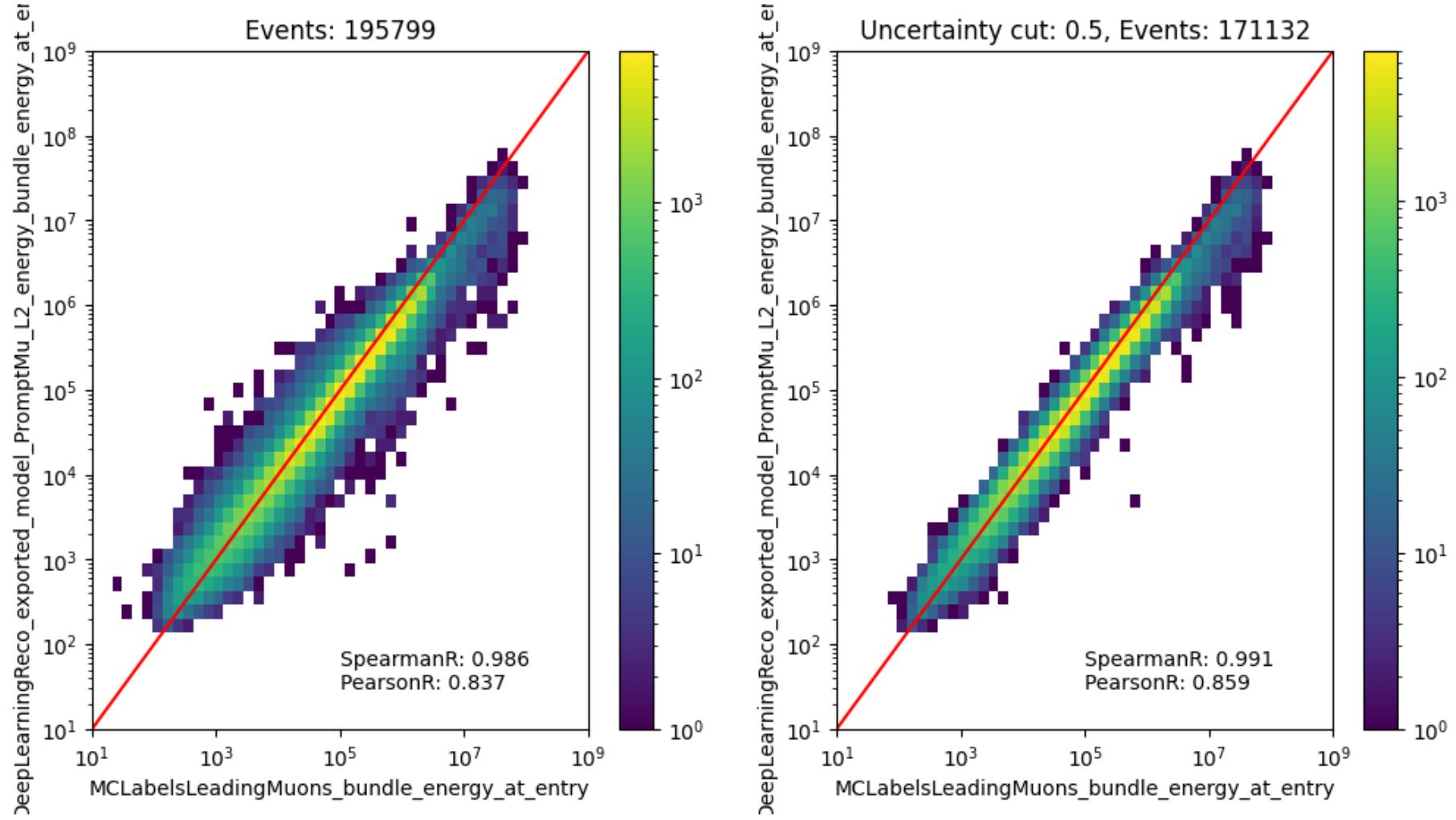
# Azimuth reconstructions



# Angular resolution



# Bundle energy reconstruction



# Leading energy reconstruction

