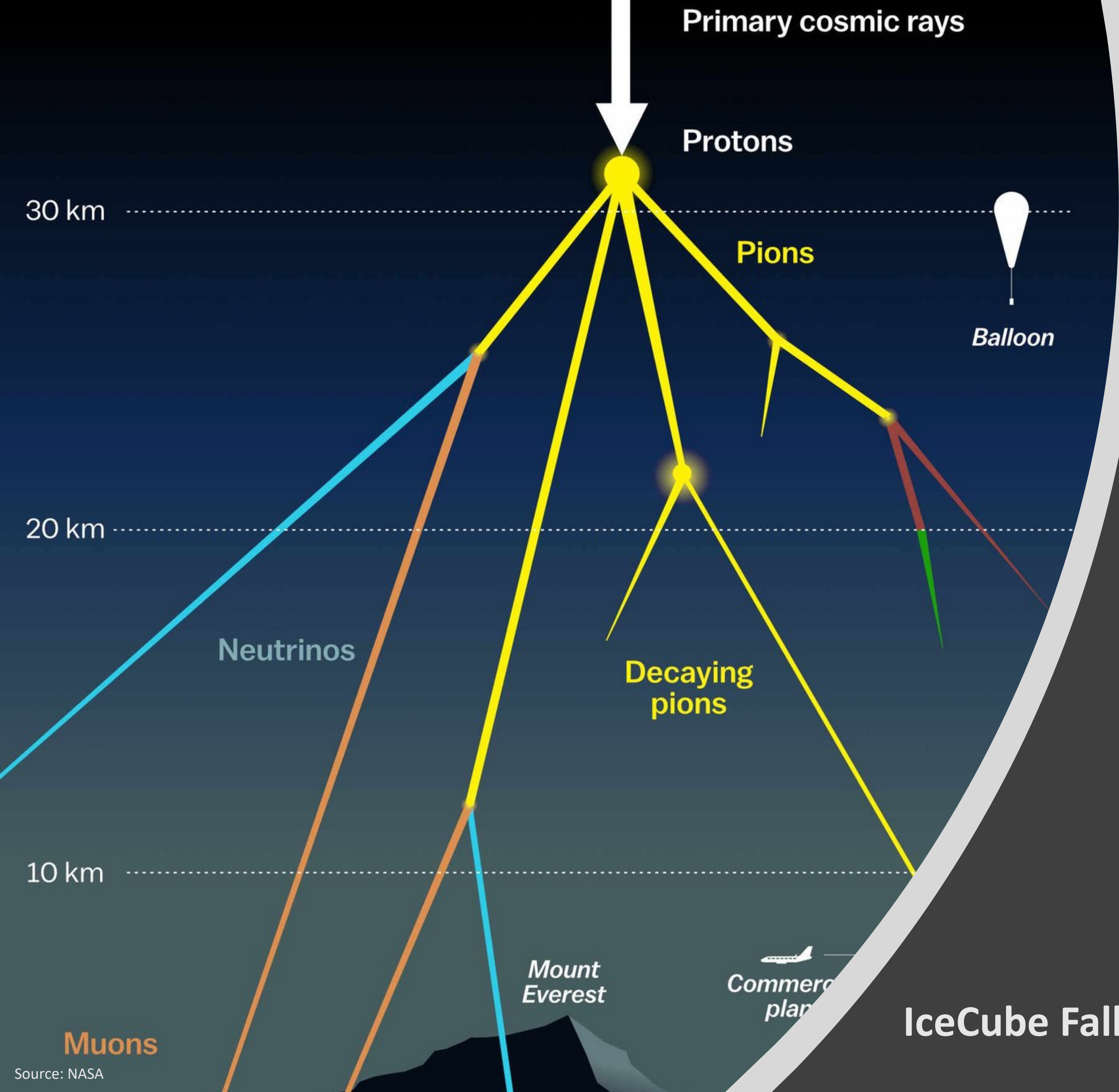



Source: NASA

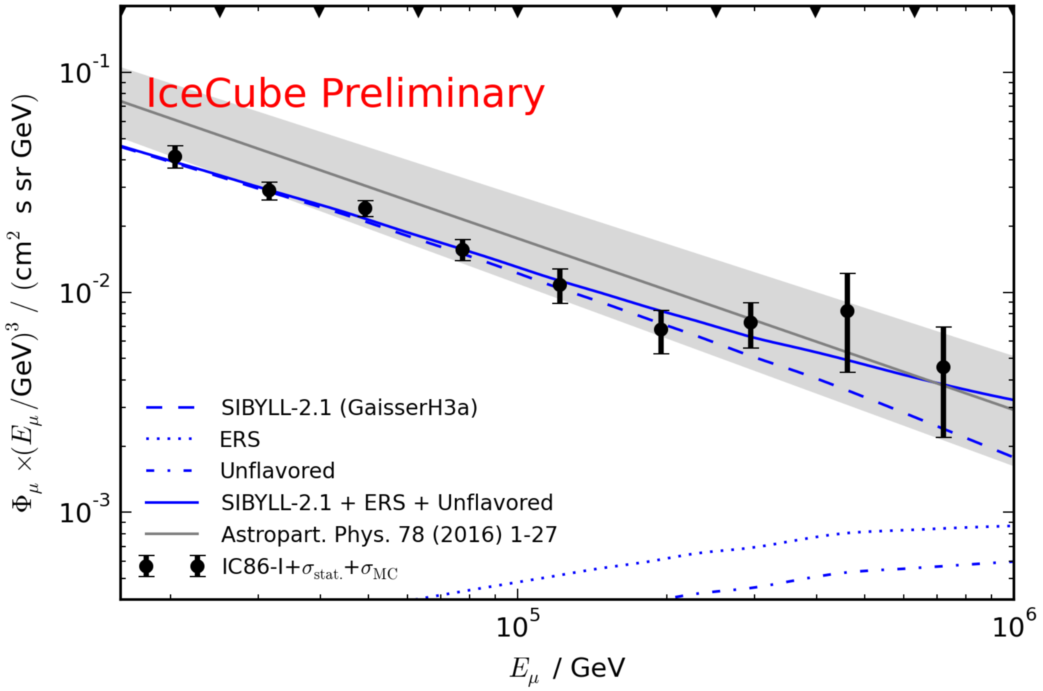
# Measurement of the prompt component of the atmospheric muon flux

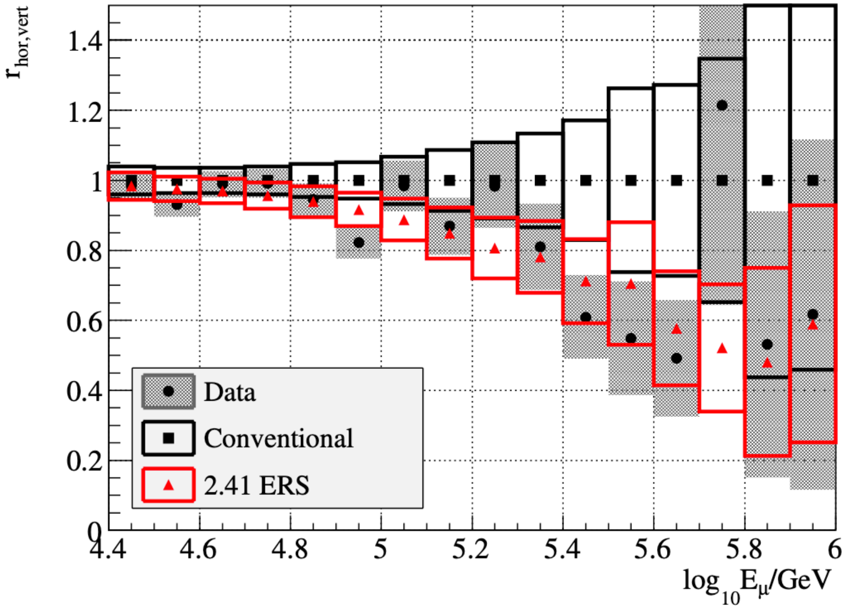
Ludwig Neste and Pascal Gutjahr

IceCube Fall Collaboration Meeting Grand Rapids 2023

# Motivation

- Detect and measure normalization of prompt component of atmospheric muon flux
- Constrain uncertainties on hadronic interaction models at very high energies
- Old analyses:
  - Leading muon analysis: limited MC statistics (by Tomasz Fuchs, 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)

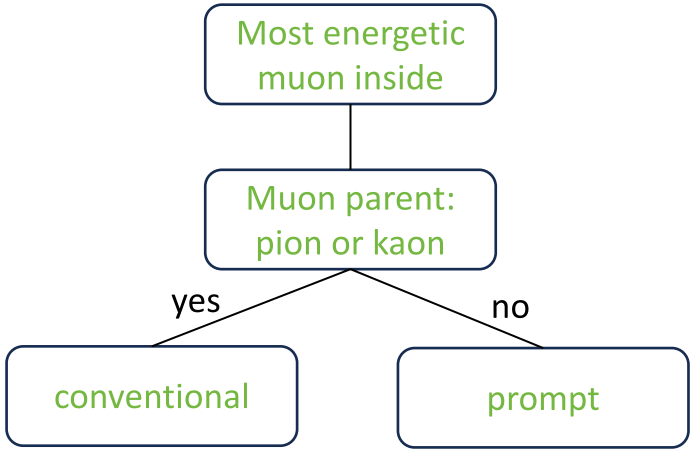



| Sample | Best Fit (ERS) | 1$\sigma$ Interval (90% CL) | $\sigma(\Phi_{\mathrm{prompt}} > 0)$ |
|---|---|---|---|
| Uncorrected | 4.93 | 4.05-5.87 (3.55-6.56) | 9.43 |
| Marginalized Ang. Corr. | 3.19 | 1.64-5.48 (0.98-7.26) | 3.46 |

- Good analyses with some challenges
- Prompt MC truth not available -> new CORSIKA simulations

# Overview




## Final goals

❑ Measure normalization of the atmospheric prompt muon flux

❑ Unfold muon energy spectrum

## Steps for normalization measurement

❑ Verify CORSIKA extended history simulations

❑ Tag prompt muons

❑ Comparisons to MCEq

❑ Set up preliminary analysis chain

❑ Reconstruct muon energy and direction

❑ Data/MC comparisons

❑ Include systematics

❑ Run full statistics simulation

## Additional steps for unfolding

❑ Effective area

## Terminology

- Muon bundle: all muons in a bundle
- Leading muon: most energetic muon in a muon bundle
- Single muon: no single muons at high energies
- Prompt muon: parent is pion or kaon

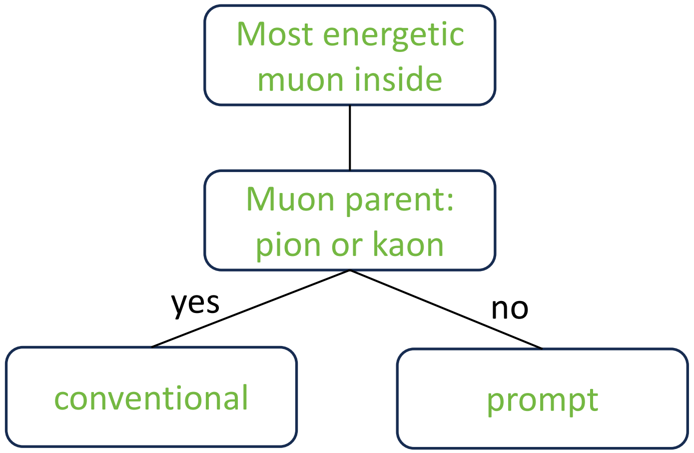
## New (preliminary) CORSIKA Ehist simulation

- CORSIKA 77420
- SIBYLL 2.3d
- 600 GeV – 50 EeV
- /data/sim/IceCube/2023/generated/CORSIKA_EHISTORY/

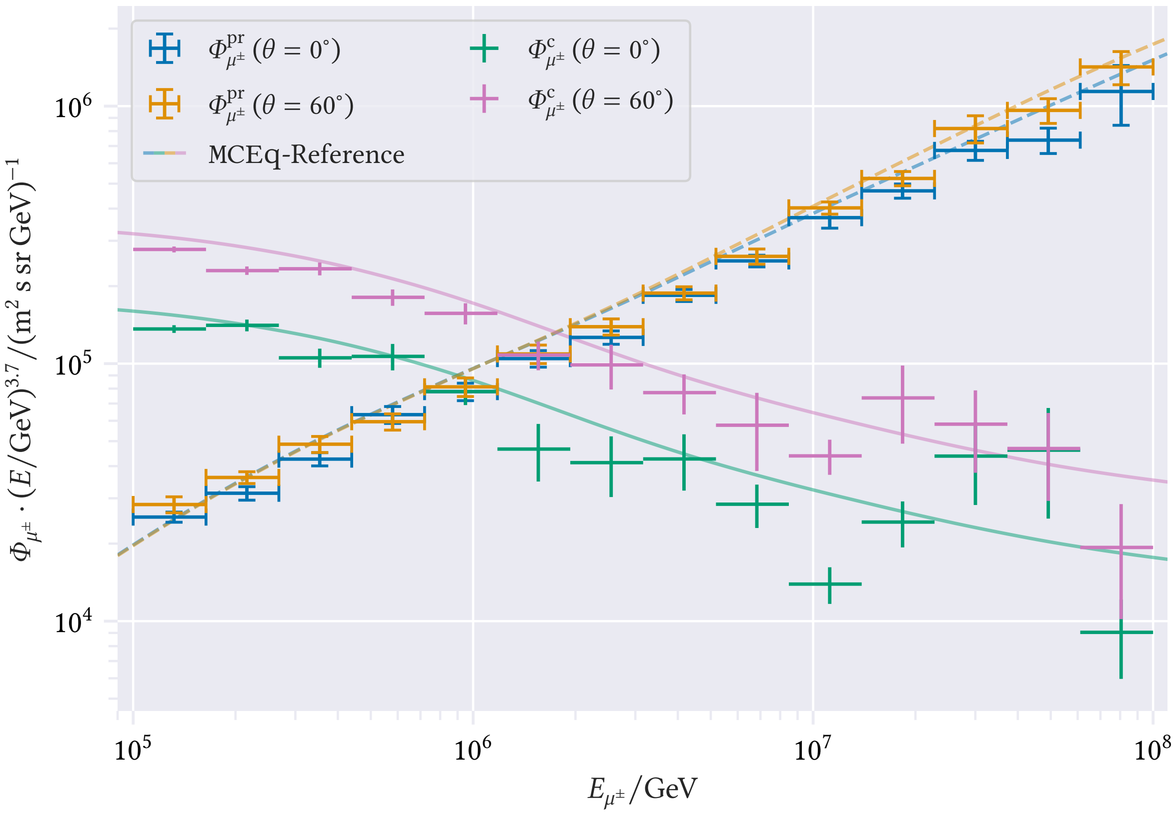
# CORSIKA vs. MCEq

- Presented by Ludwig Neste

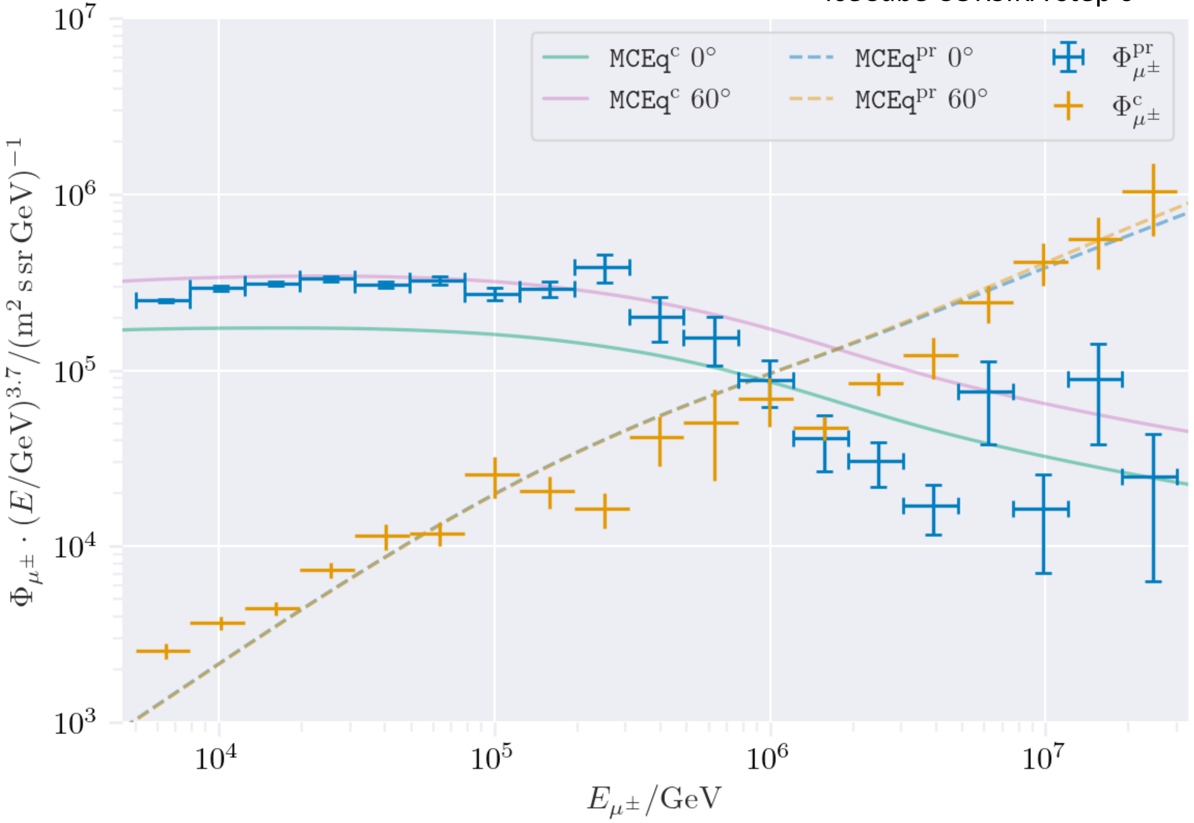
- Good agreement




CORSIKA standalone

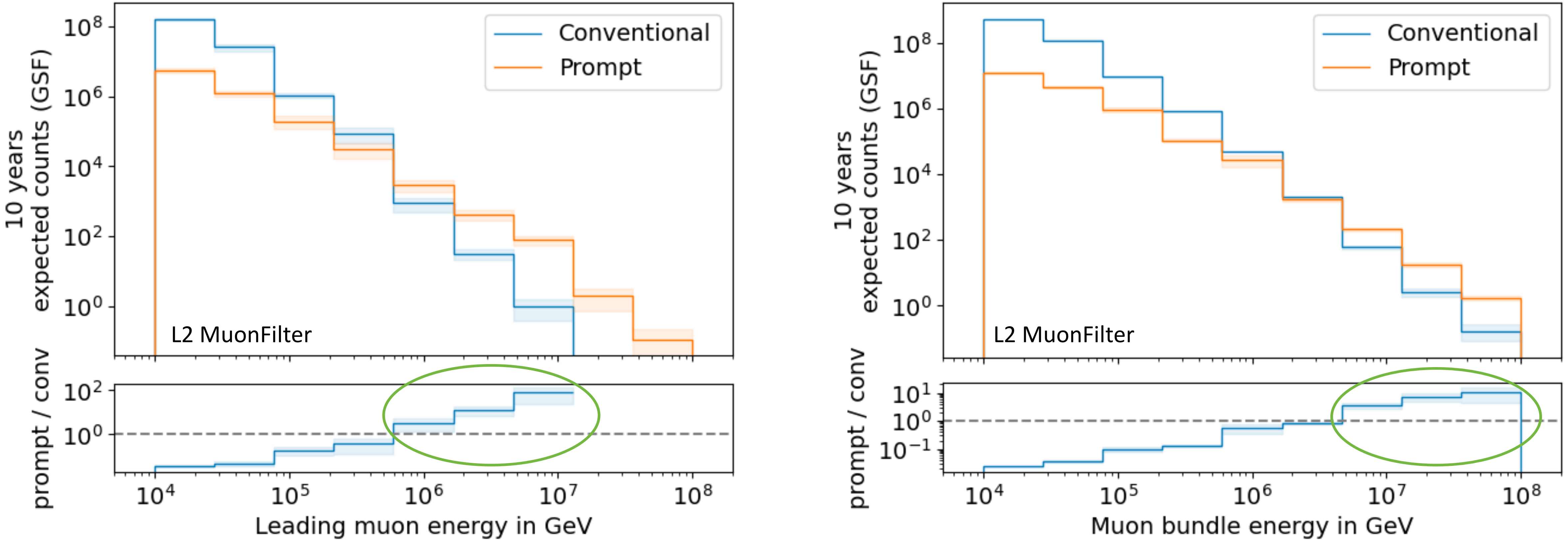



IceCube CORSIKA step 0



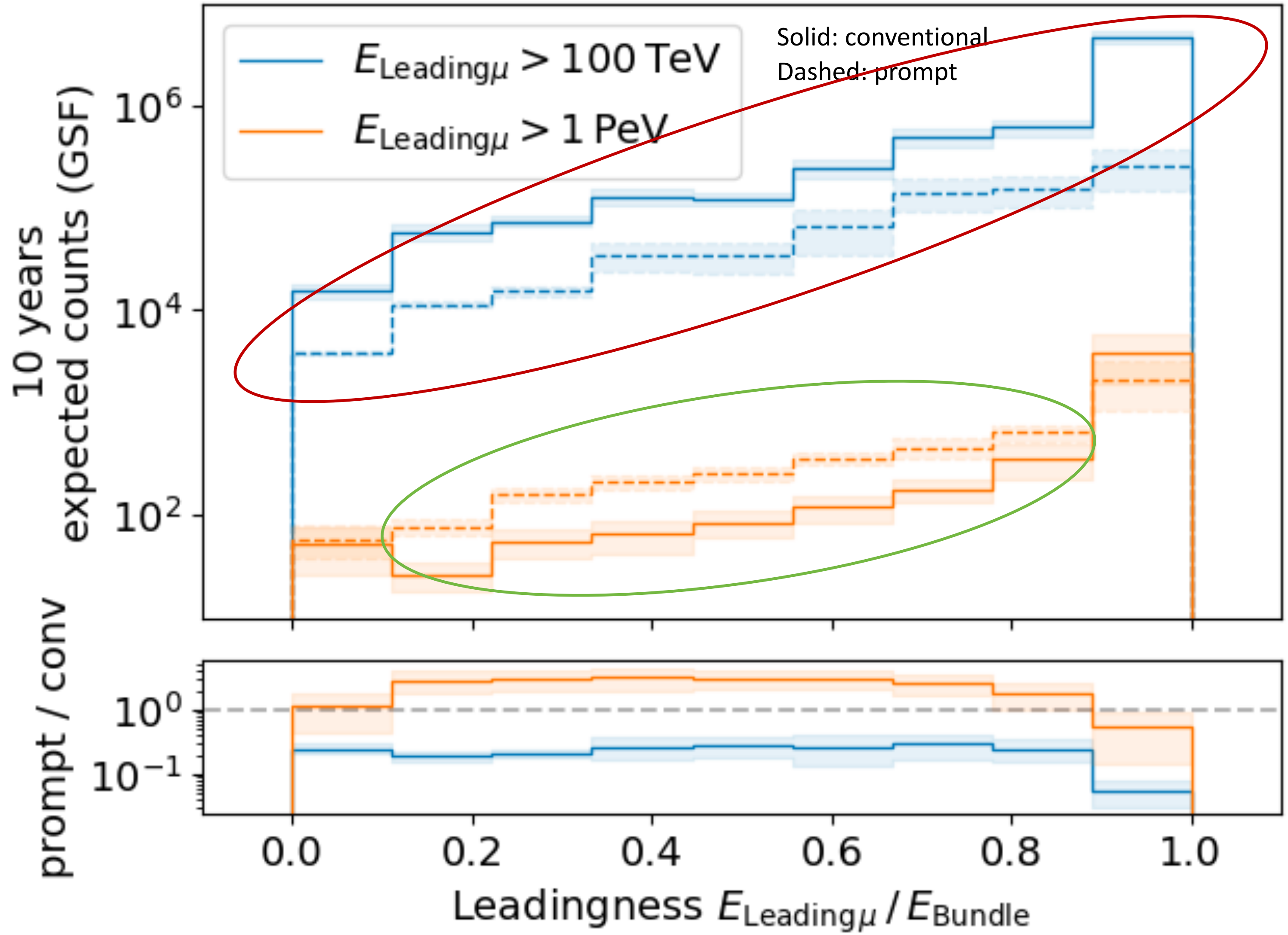
# MC data exploration

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




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

# Leading muon energy fraction




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

# Leading muon contribution

Patrick Berghaus

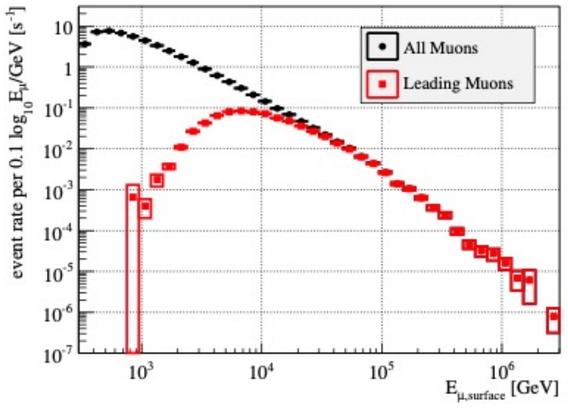
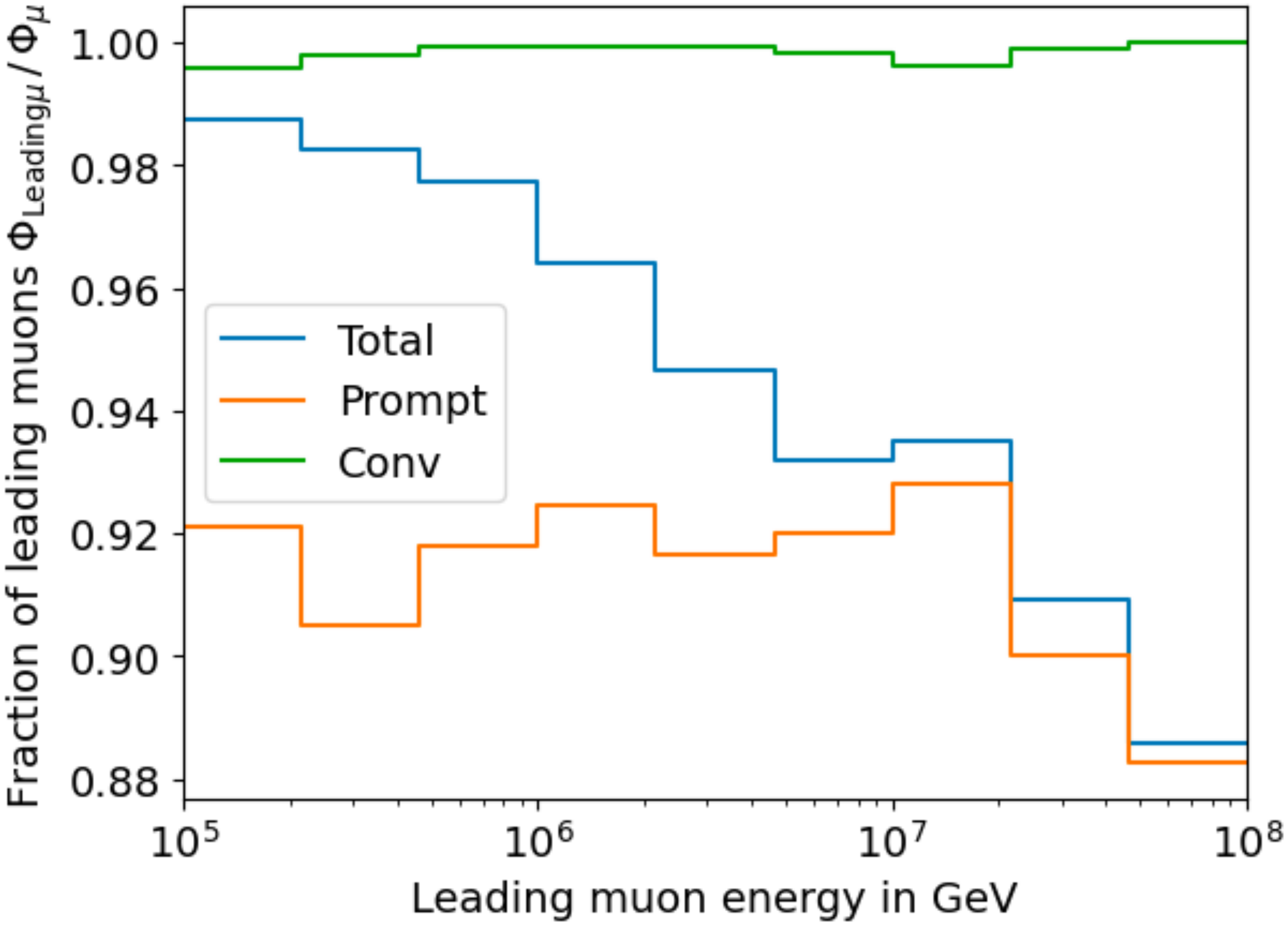



Figure 10: Surface energy distribution for all and most energetic ("leading") muons in simulated events with a total of more than 1,000 registered photo-electrons in IceCube.

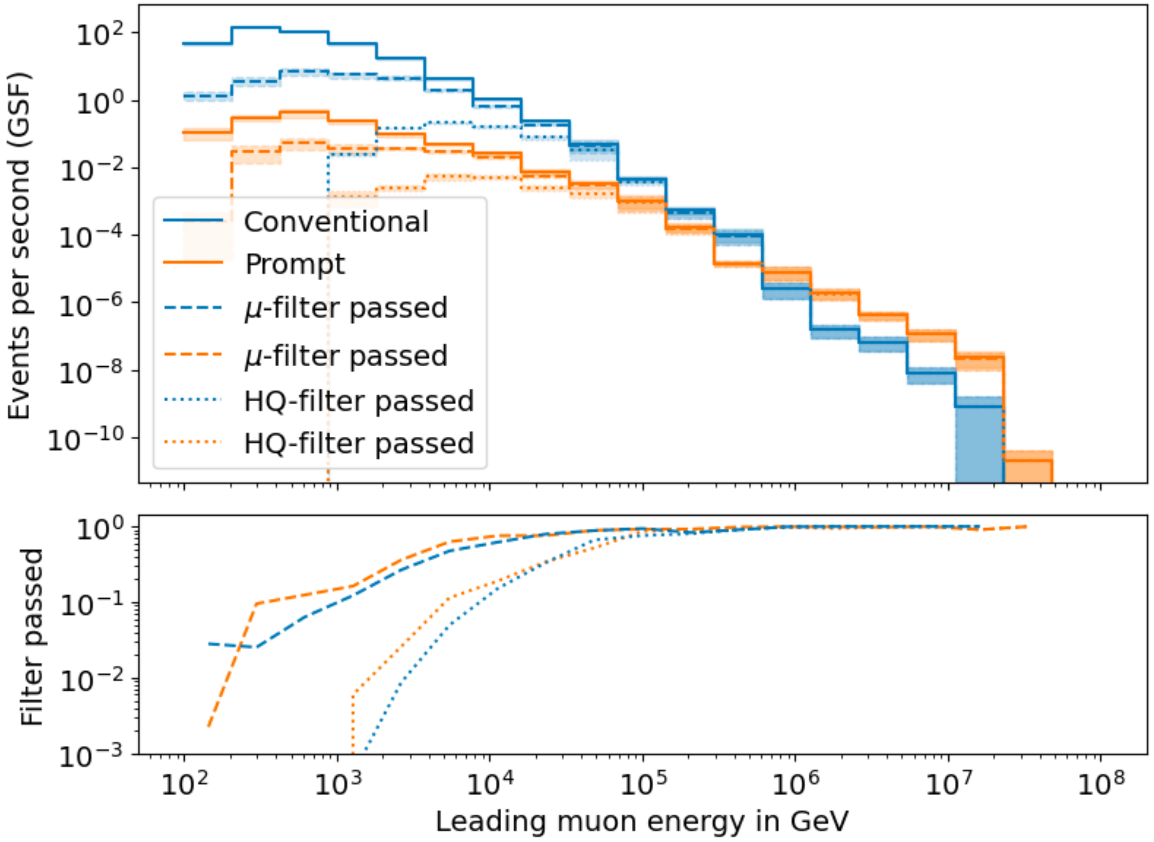


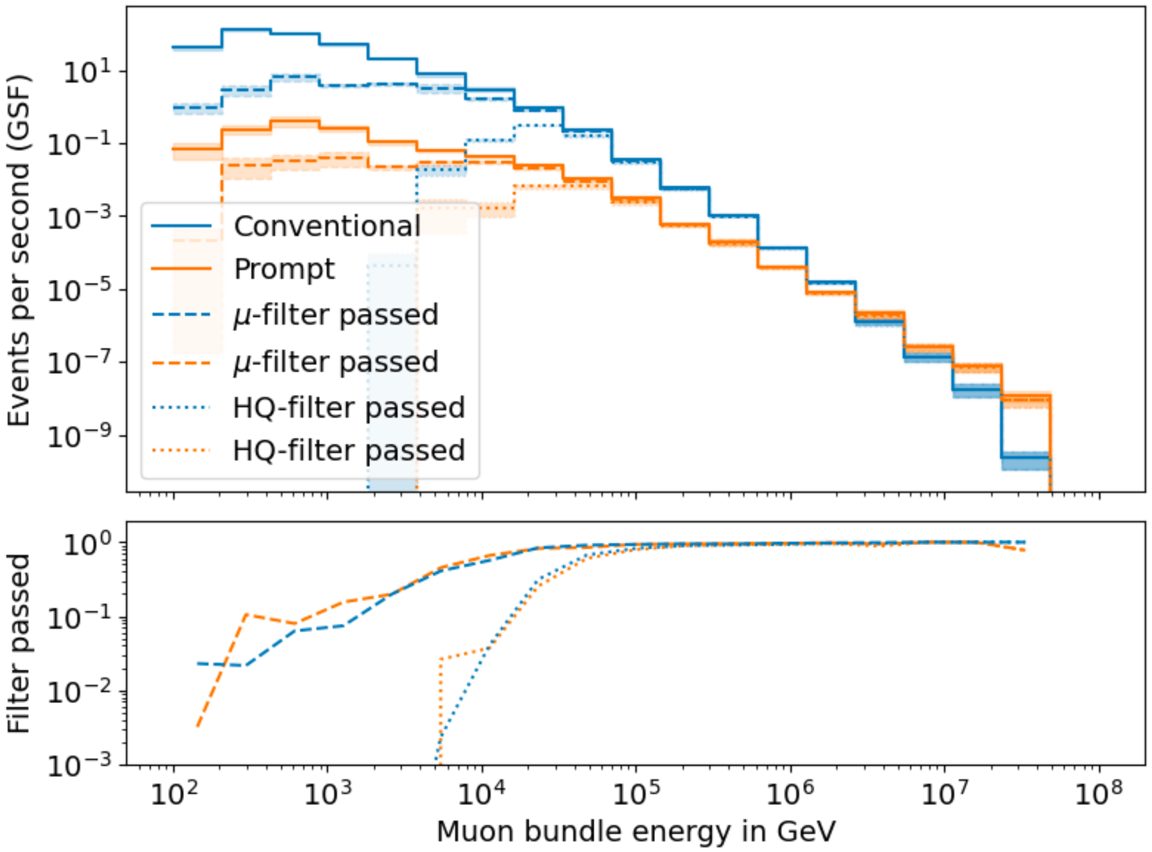

- Muons with energies between 100 TeV and 50 PeV dominate the bundle by more than 90%
- In average conventional muons are more dominant than prompt
- But: at high energies, there are more prompt than conventional events

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

# 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

dortmund
university

# DNN reconstructions

# DNN Reconstructions

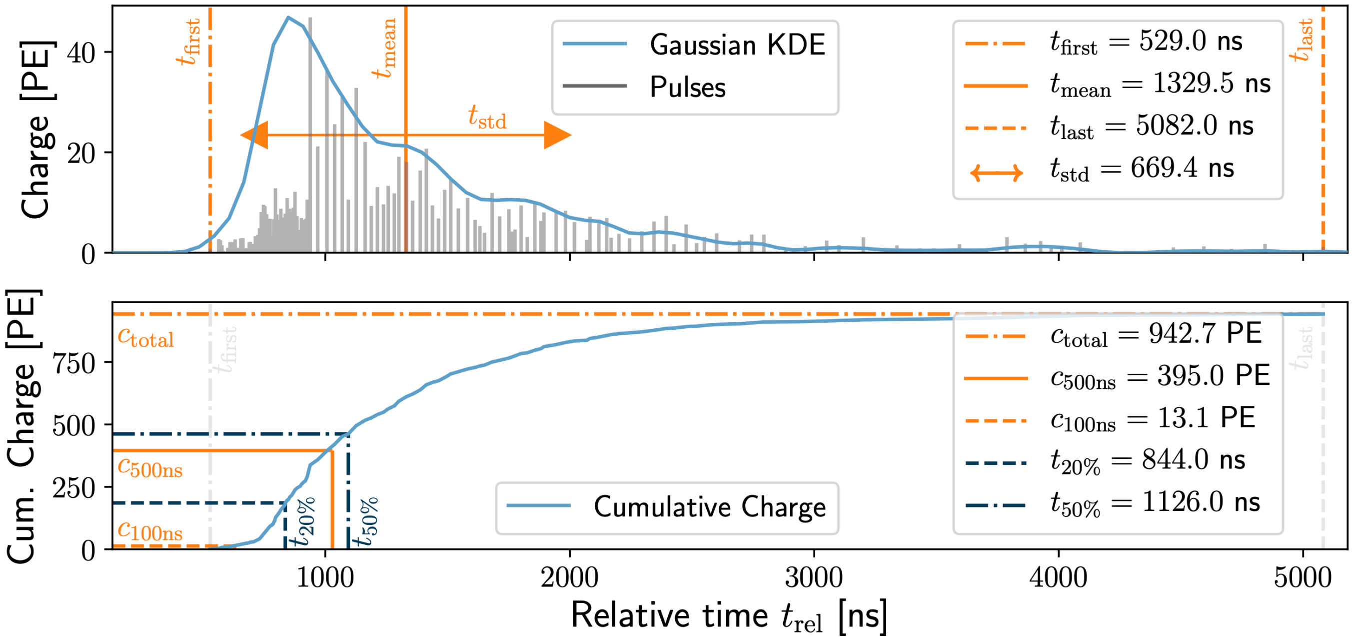
## Reconstruct

- ❑ Muon bundle energy
- ❑ Leading muon energy
- ❑ Direction (zenith/azimuth)

## Physics motivation

- Muons lose energy stochastically
  - High leadingness: energy depositions are dominated by large stochastic losses
  - Low leadingness: stochastic losses sum up and appear continuously
- High energies: forward production
  - High leadingness: small bundle radius
  - Low leadingness: larger bundle radius

10.1088/1748-0221/16/07/P07041

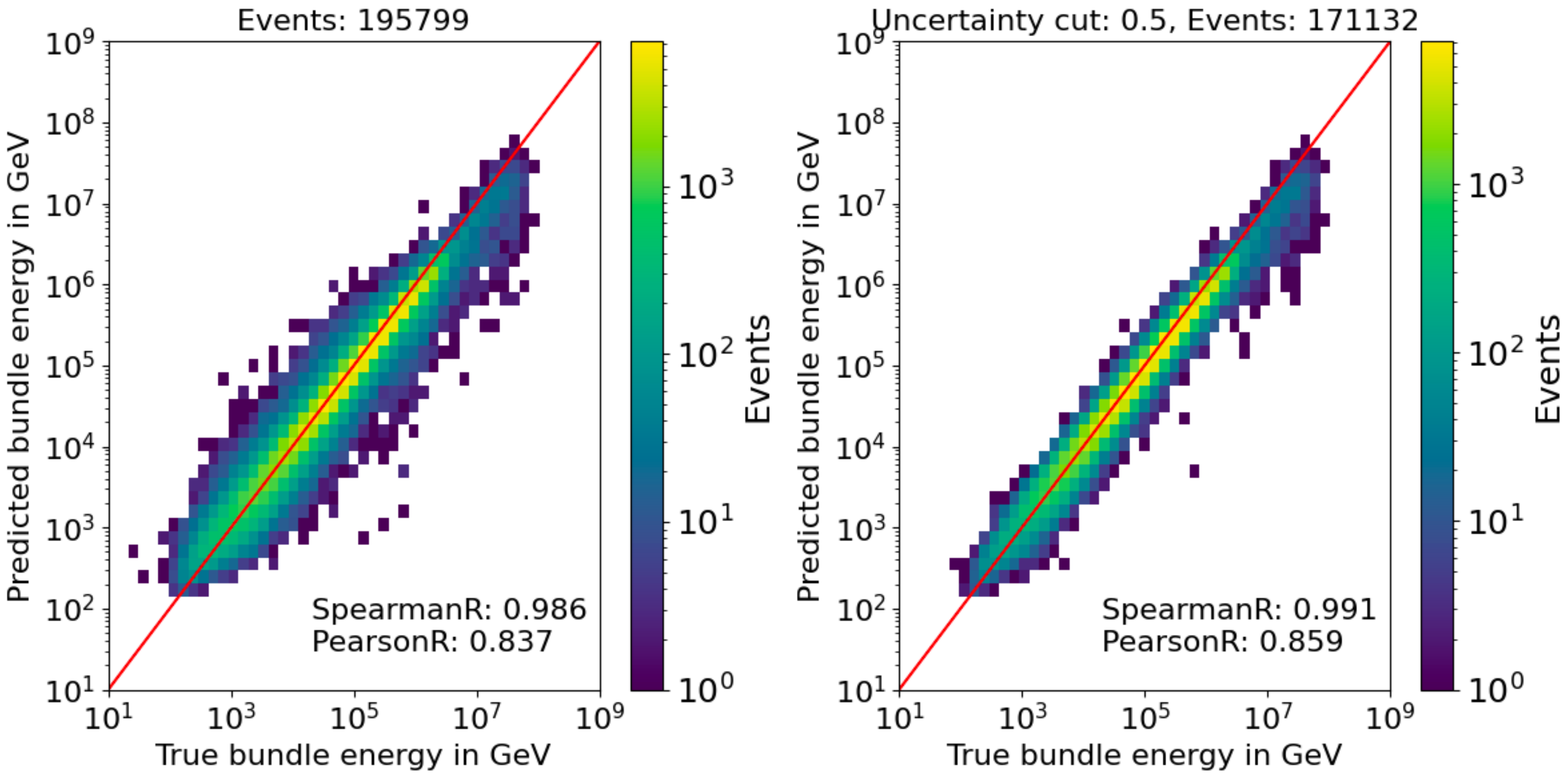



## Input data per DOM

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

SplitInIceDSTPulsesTWCleaning6000ns

# Bundle energy reconstruction

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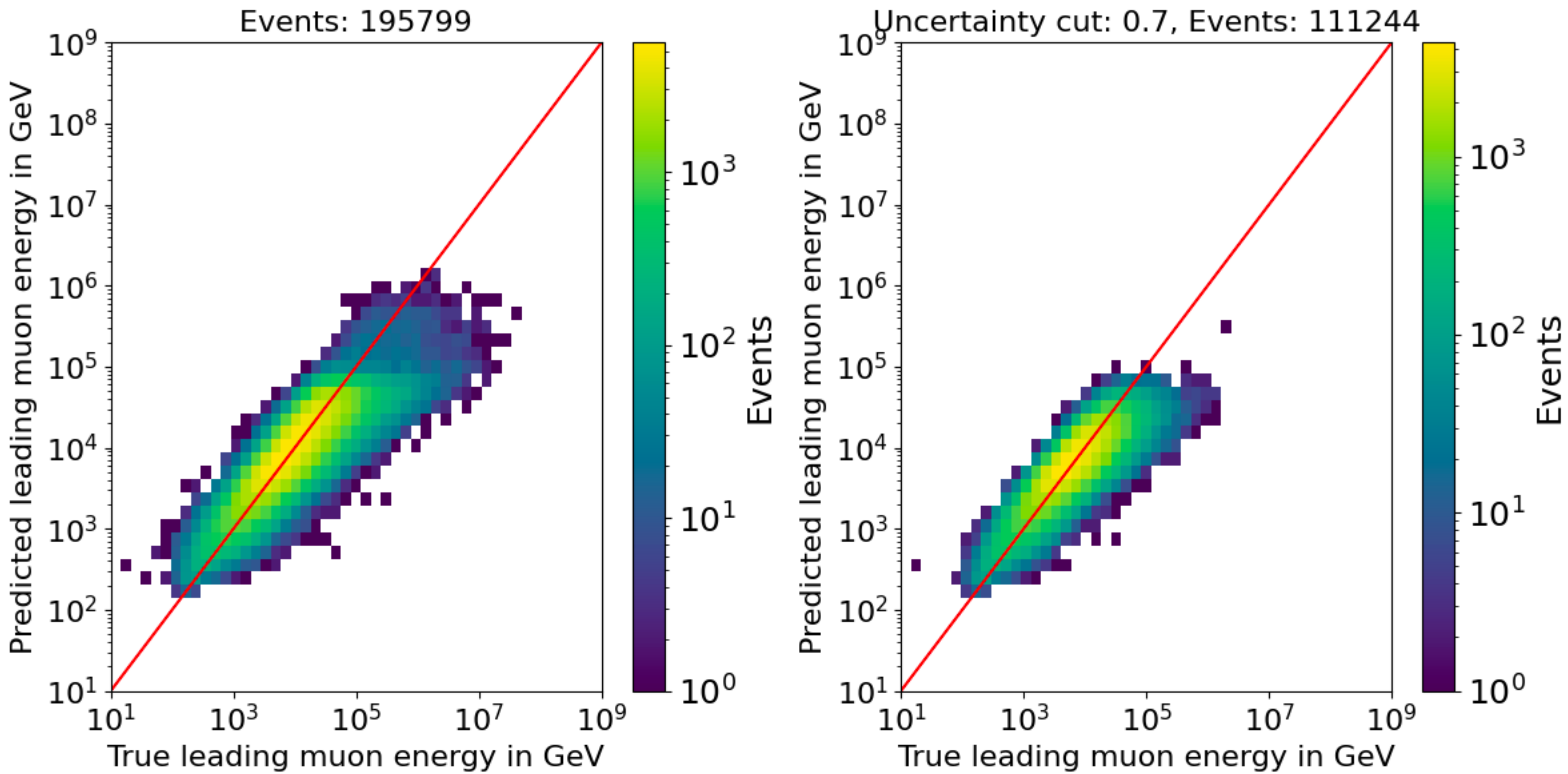
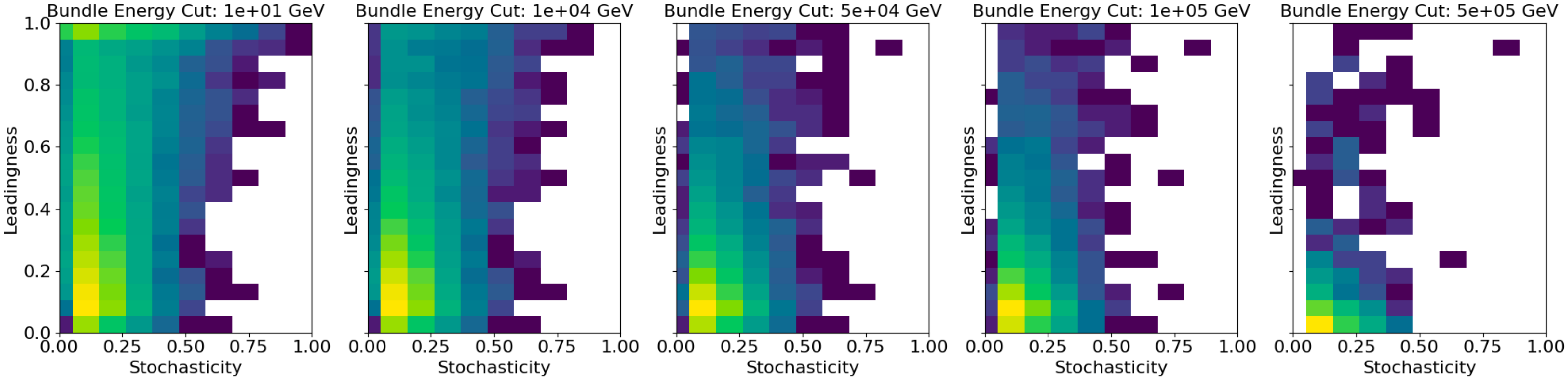
# Leading energy reconstruction

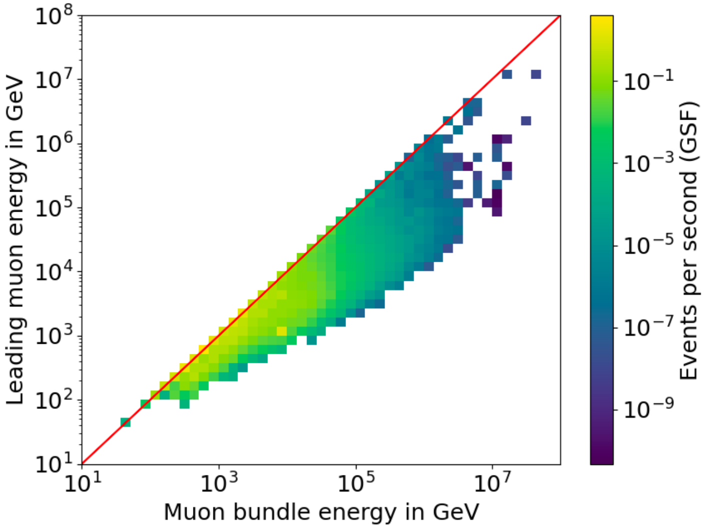


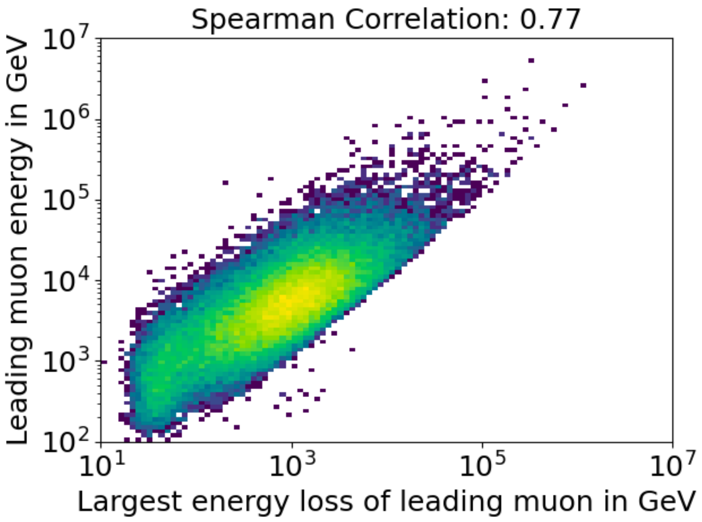
tu dortmund university

Bundle energy cut

# Stochasticity



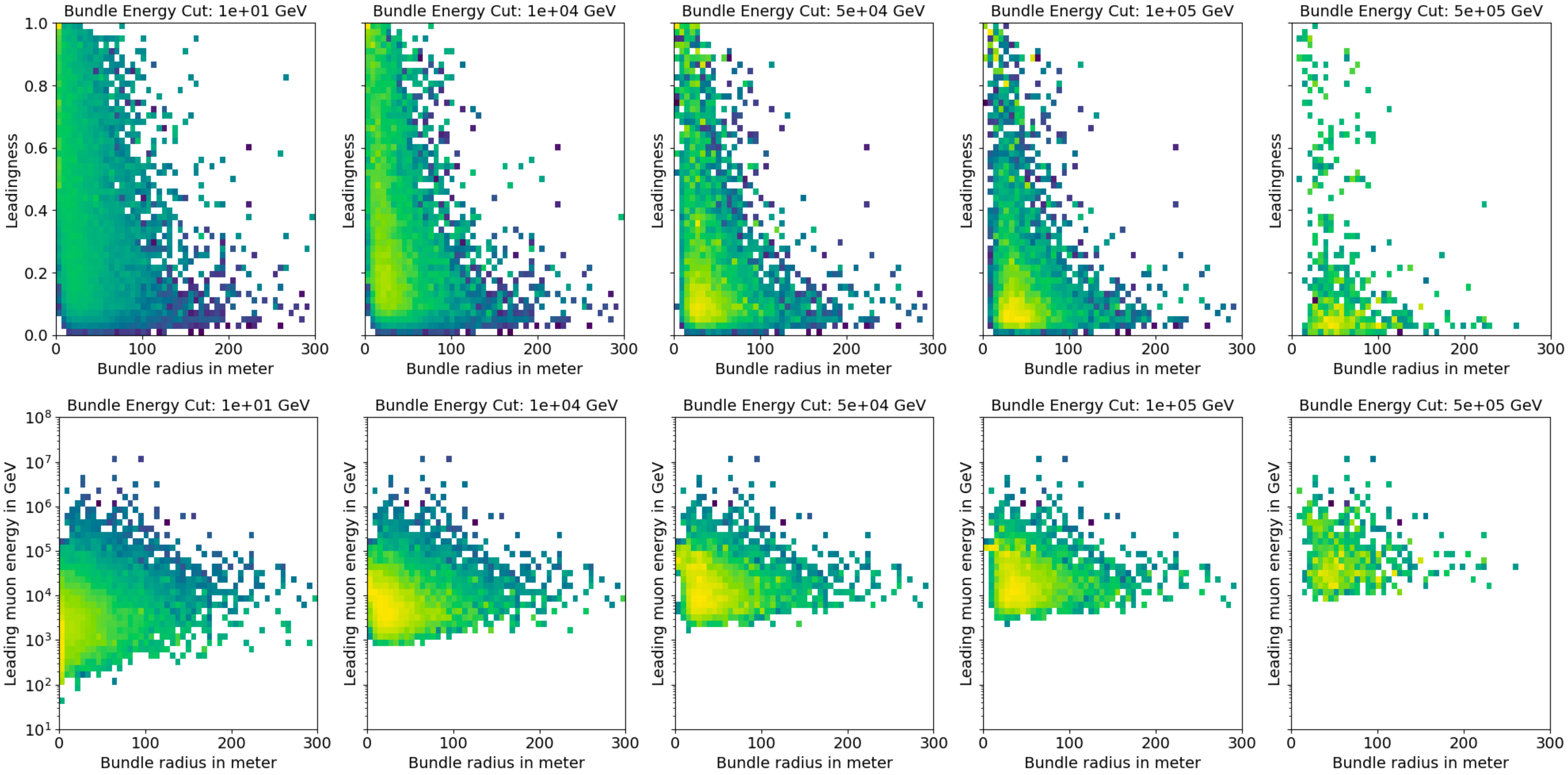




- High stochasticity leads to high leadingness, but only for a small number of events
- Leading muon energy smears out at large bundle energies
- Largest energy loss of the leading muon correlates with the leading muon energy

Bundle energy cut

# Bundle radius




➢ Large bundle radius leads to low leadingness

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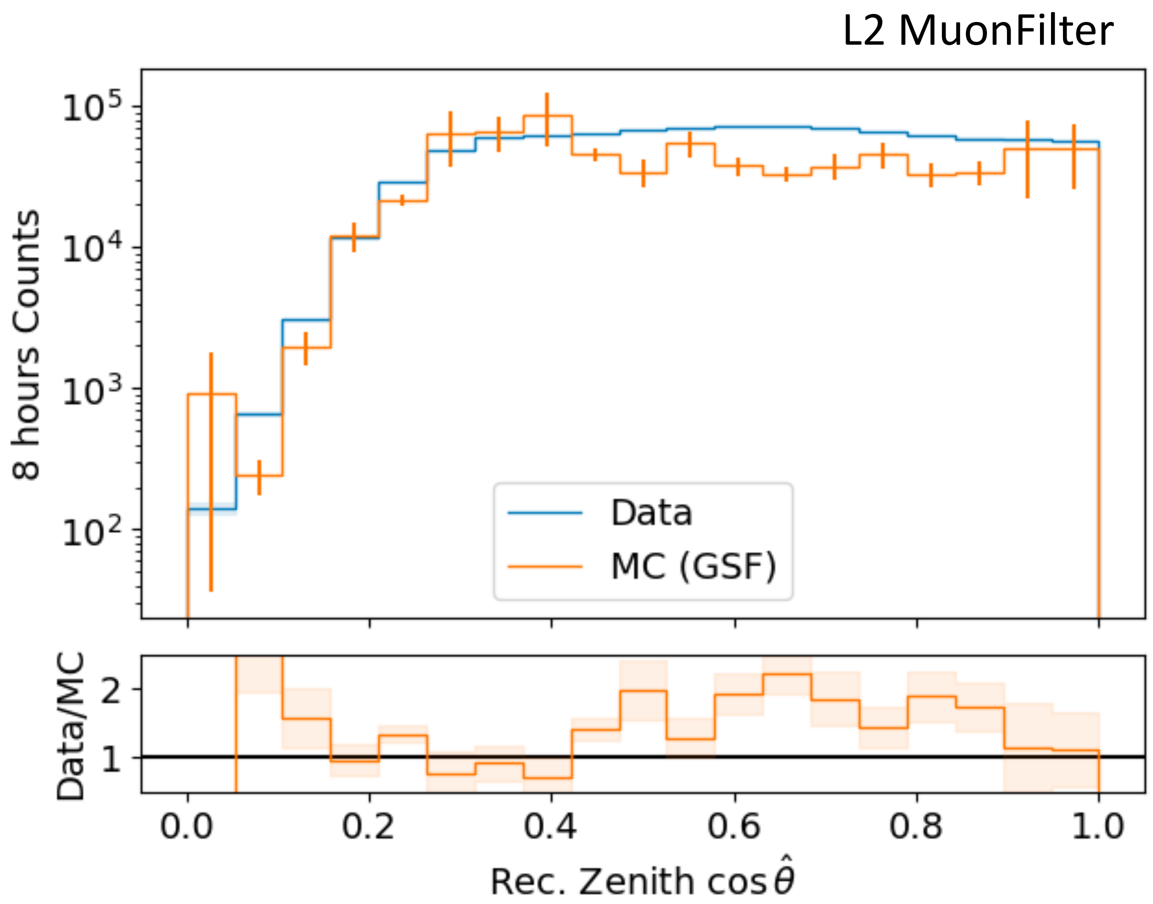
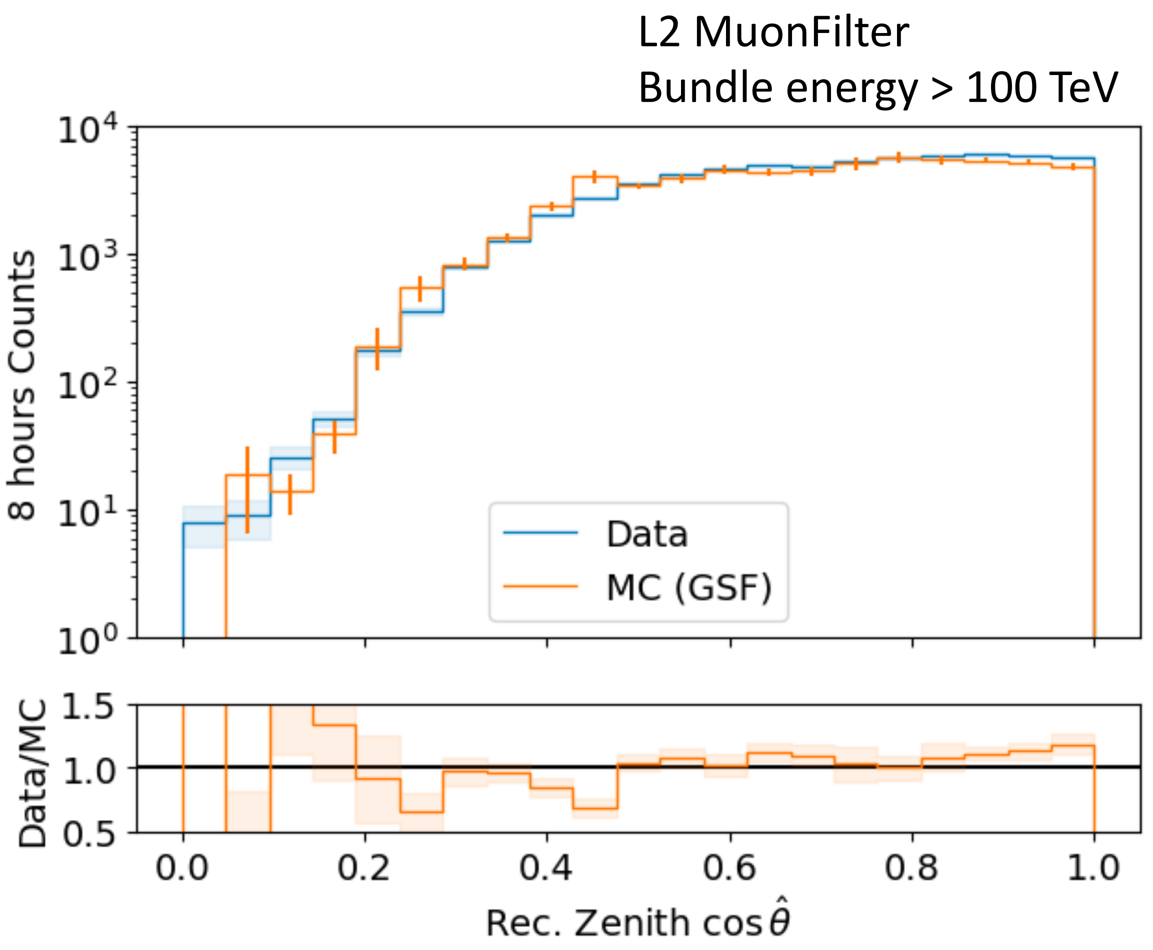
# Data/MC

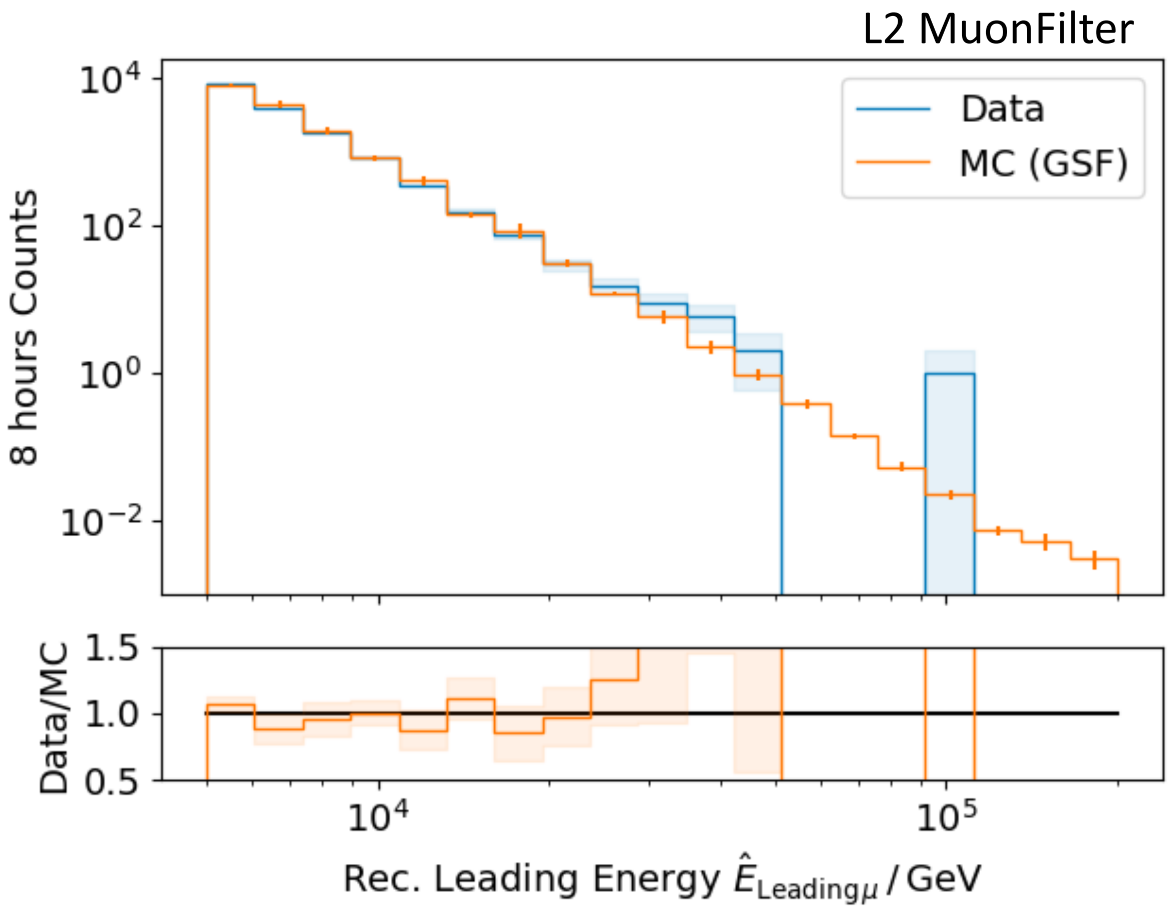
# Data-MC: cos(zenith)

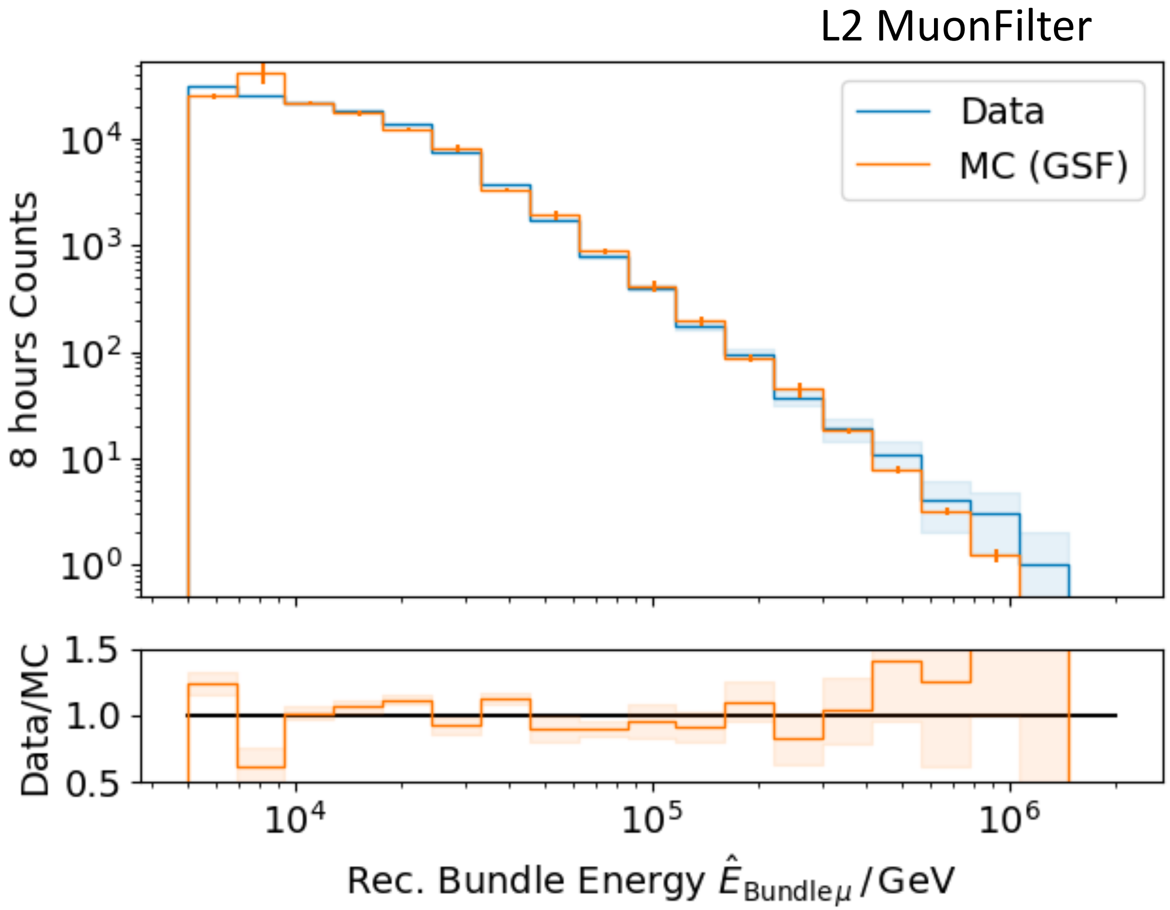



- Deviations at low cos(zenith), but very small statistics
- More data at cos(zenith) > 0.5
- Less data at cos(zenith) ~ 0.3

# Data-MC: energy spectrum



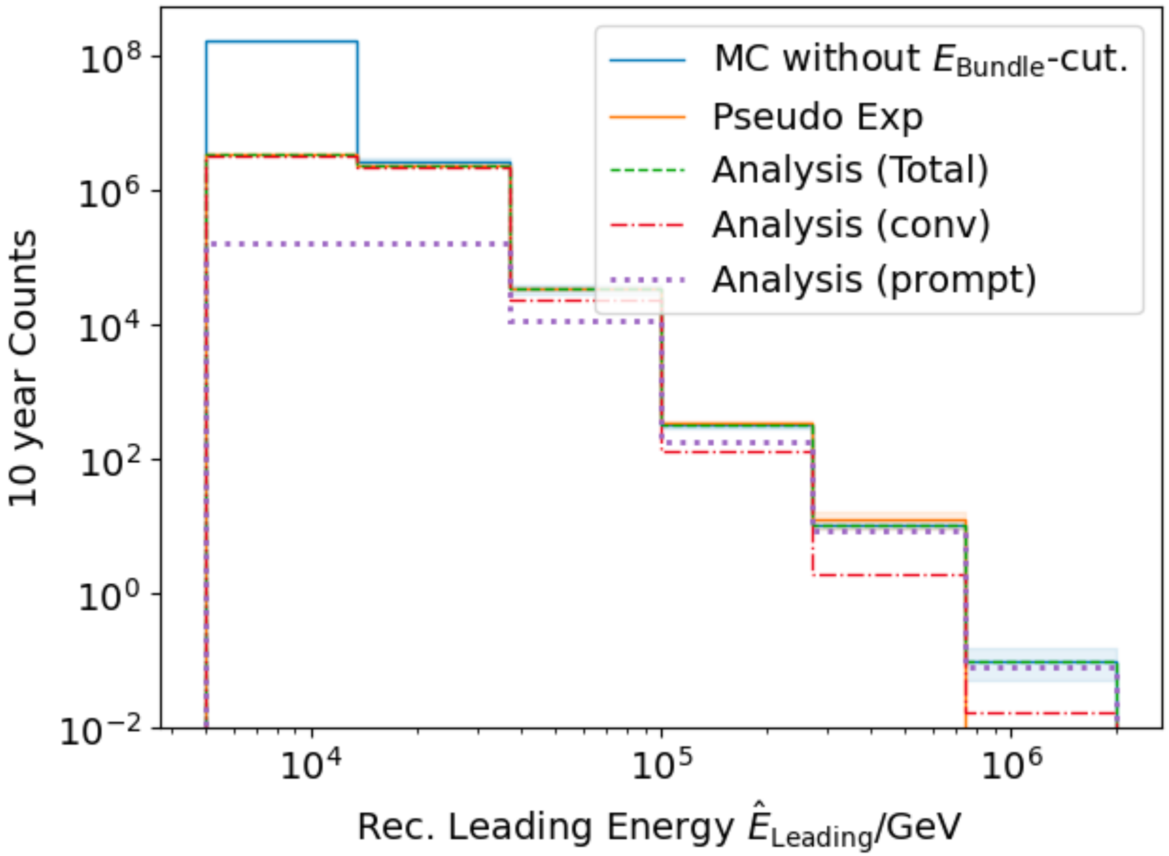



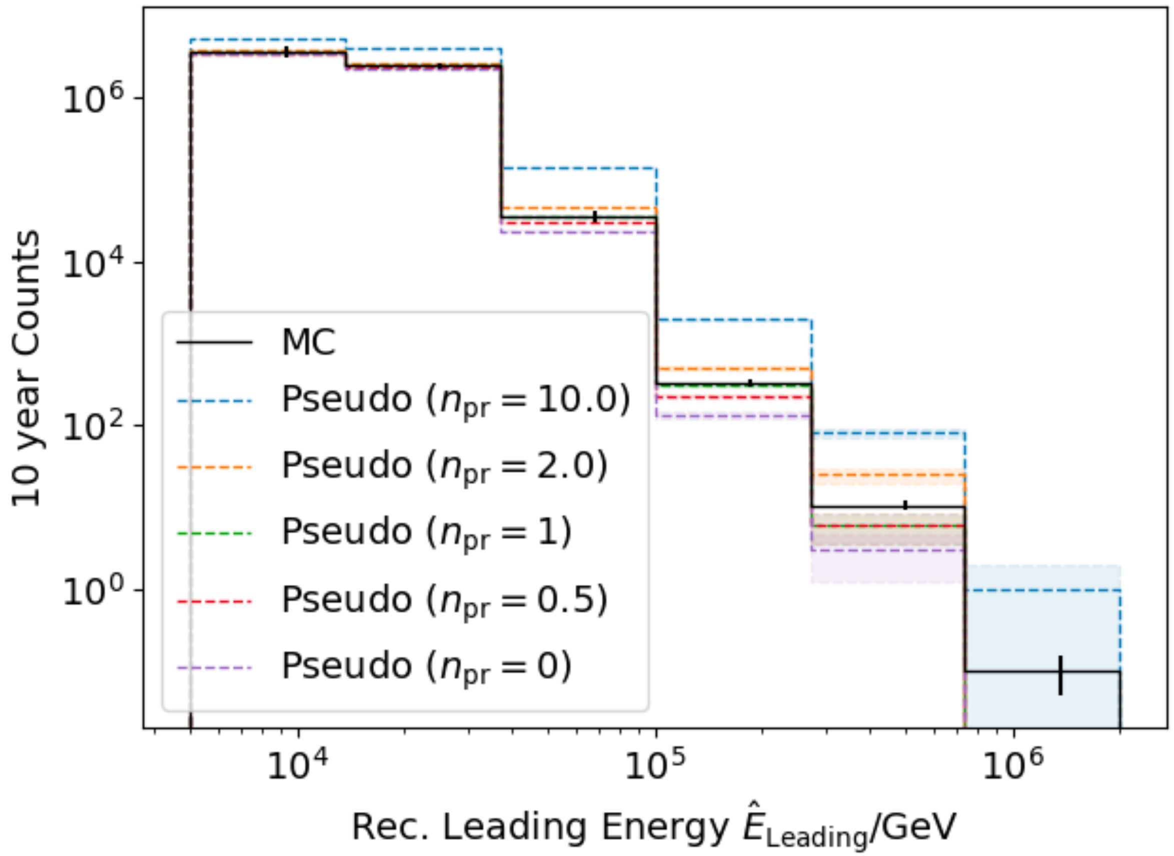

- Bundle energy: good agreement with GSF up to 300 TeV
- But insufficient statistics

# Pseudo analysis

# Pseudo data sampling

Cuts:
L2 MuonFilter
Bundle energy > 100 TeV




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

# Poisson likelihood fit performed in leading muon energy

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

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

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

Maximize likelihood

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

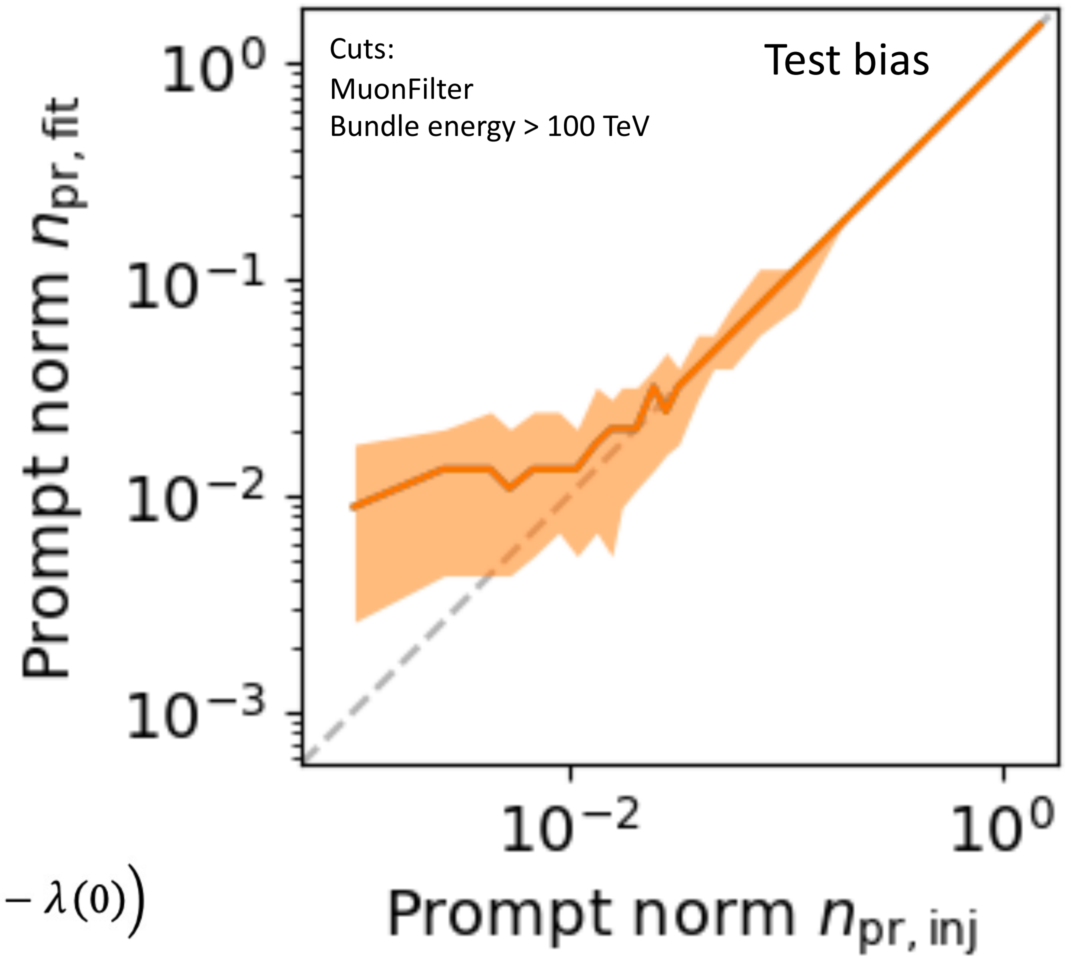
Easier: minimize negative log-likelihood

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

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

Test statistic for Wilks' theorem

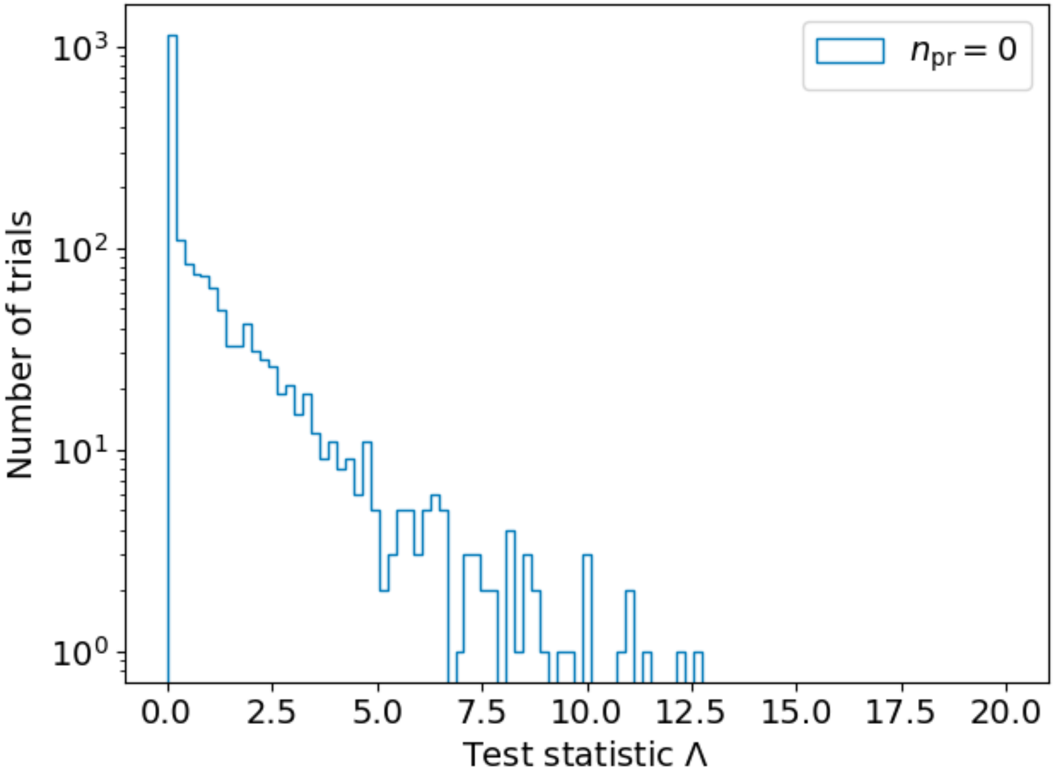
Null hypothesis: no prompt

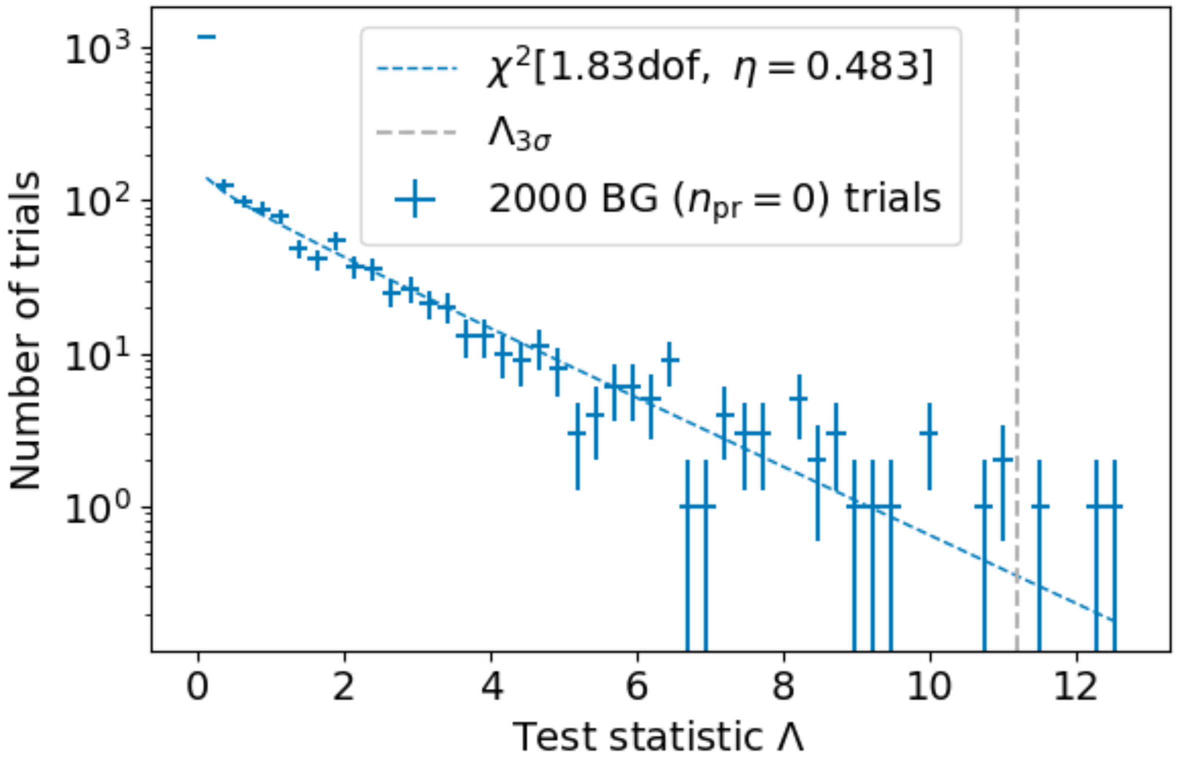



- Bias starts at a prompt normalization of 0.1

# Test background statistics

Cuts:
L2 MuonFilter
Bundle energy > 100 TeV




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

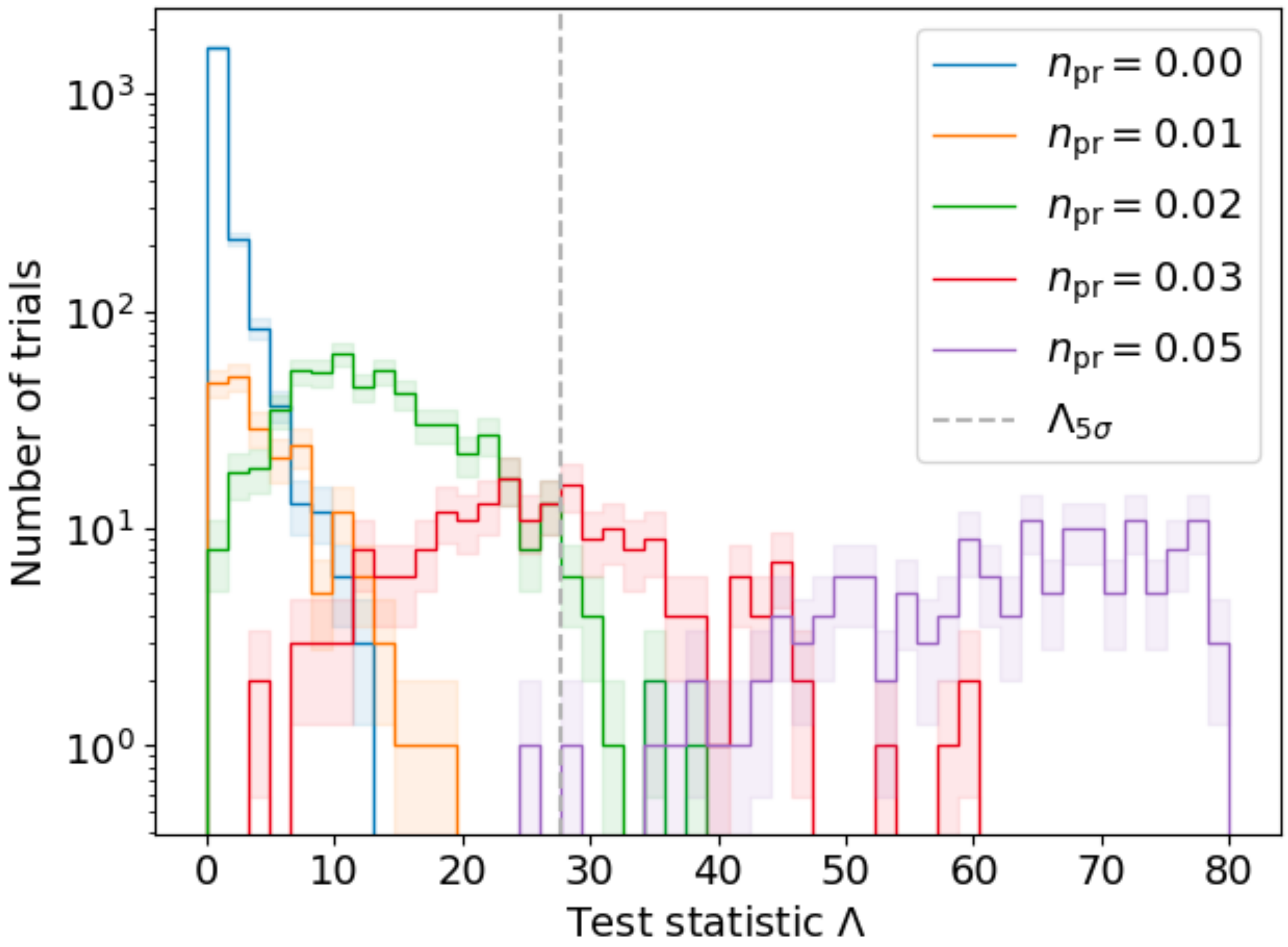
# Discovery potential and sensitivity

Cuts:
L2 MuonFilter
Bundle energy > 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



# Conclusion and outlook

## Next goal

- ❑ Measure normalization of the atmospheric prompt muon flux

## Steps for normalization

- ☑ Verify CORSIKA extended history simulations
- ☑ Tag prompt muons (see talk by Ludwig Neste)
- ☑ Comparisons to MCEq (see talk by Ludwig Neste)
- ☑ Set up preliminary analysis chain
- ★ Reconstruct muon energy and direction
- ★ Data/MC comparisons
- ❑ Include systematics
- ❑ Run full statistics simulation



Thank you for your attention ☺

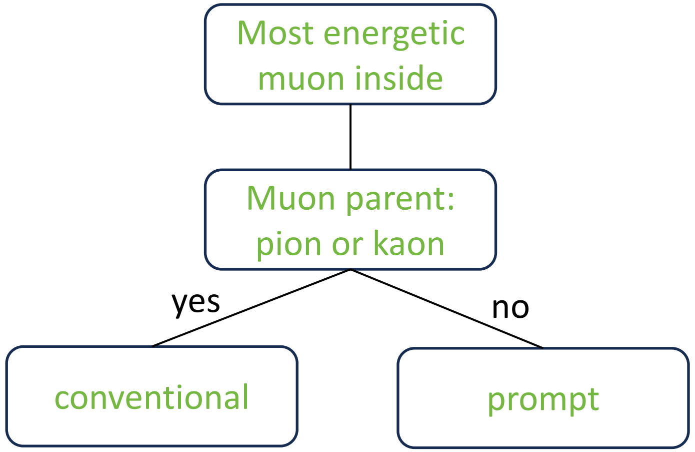
# Backup

# 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%, …)



# 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

# Definition of the muon flux

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

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

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

**Conventional component:**

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

**prompt component:**

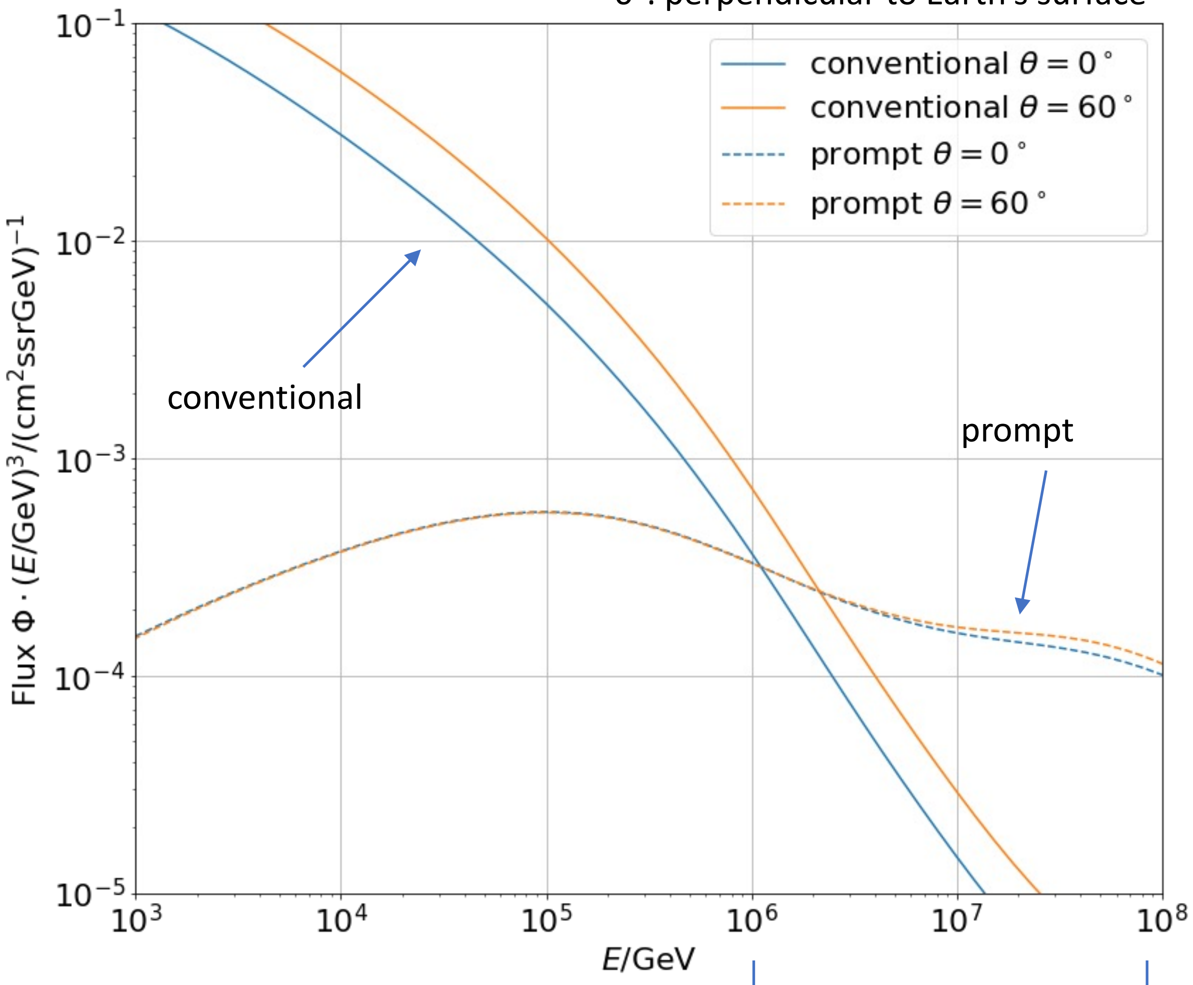
$$\underset{\propto E^{-2.7}}{p} \rightarrow \overbrace{D^{+}}^{\tau = 1.04 \cdot 10^{-12}\,\text{s}} \rightarrow \bar{K}^{0} + \underset{\propto E^{-2.7}}{\mu^{+}} + \nu_{\mu}$$

# 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

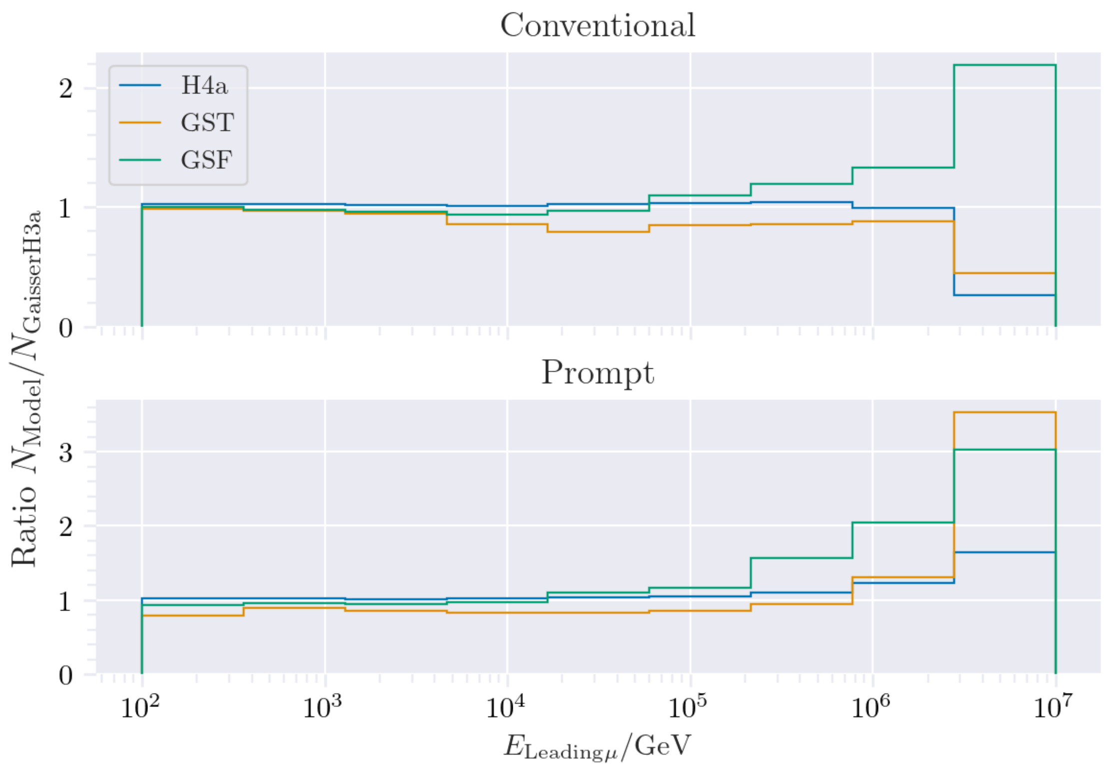
0°: perpendicular to Earth's surface




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

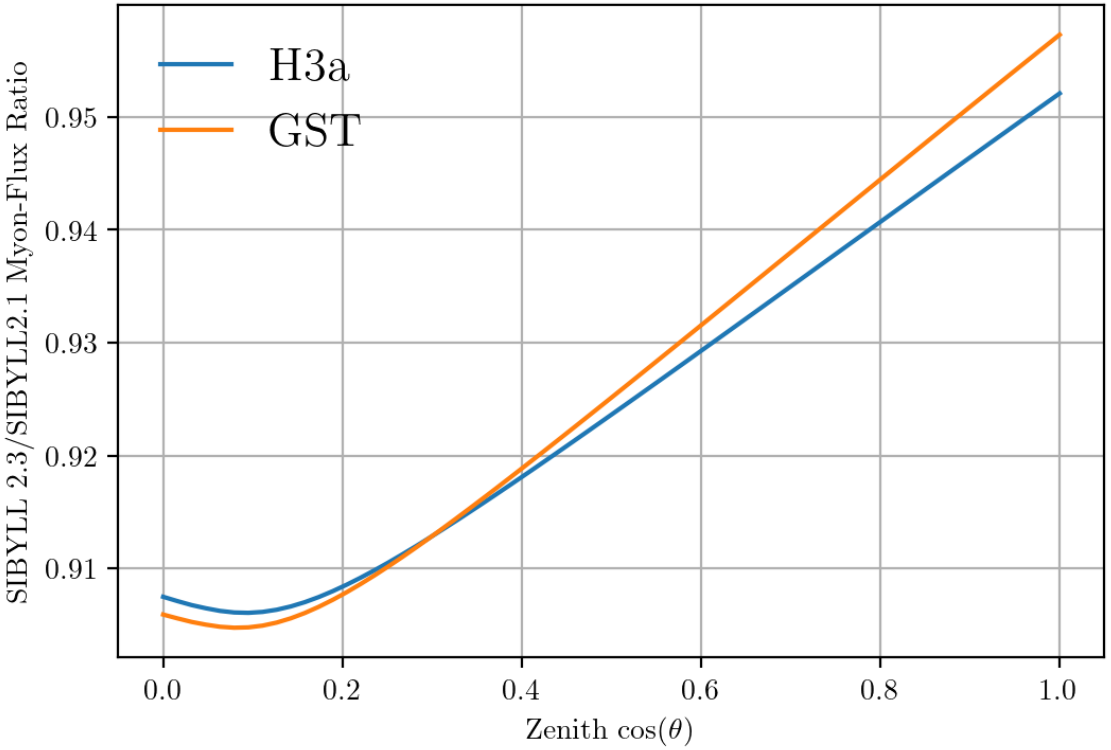
# Muon production – different weightings

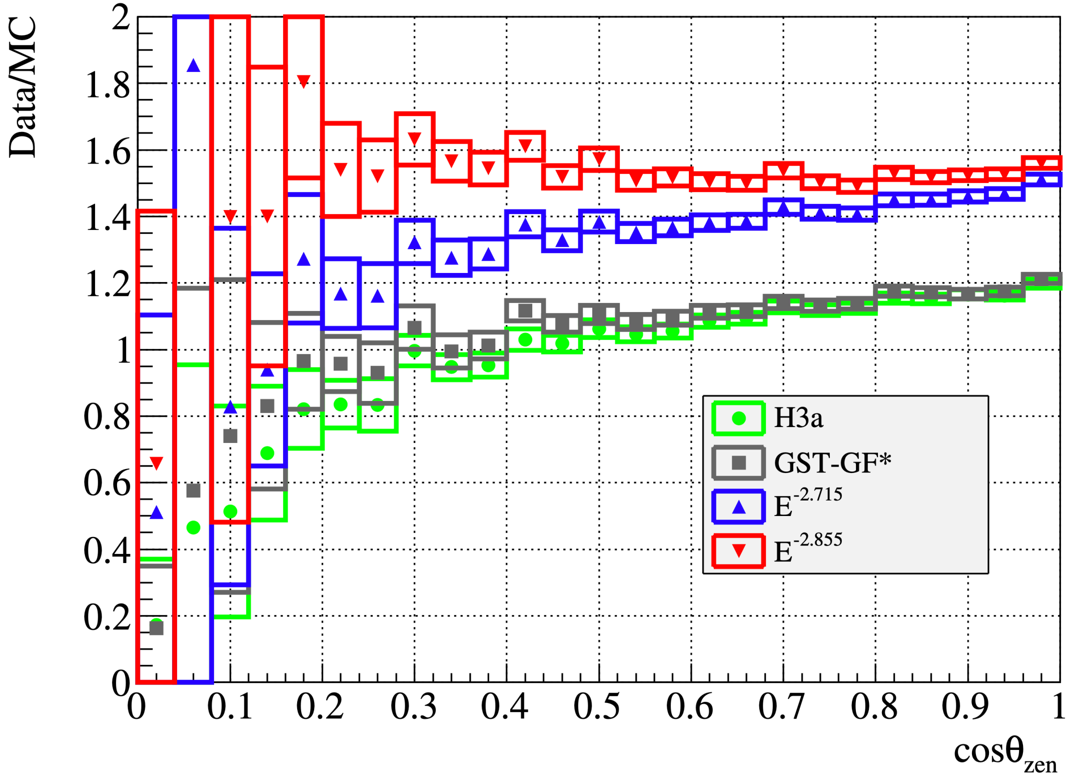
GST predicts most prompt




MCLabelsLeadingMuons_entry_energy

# Solution to zenith problem?

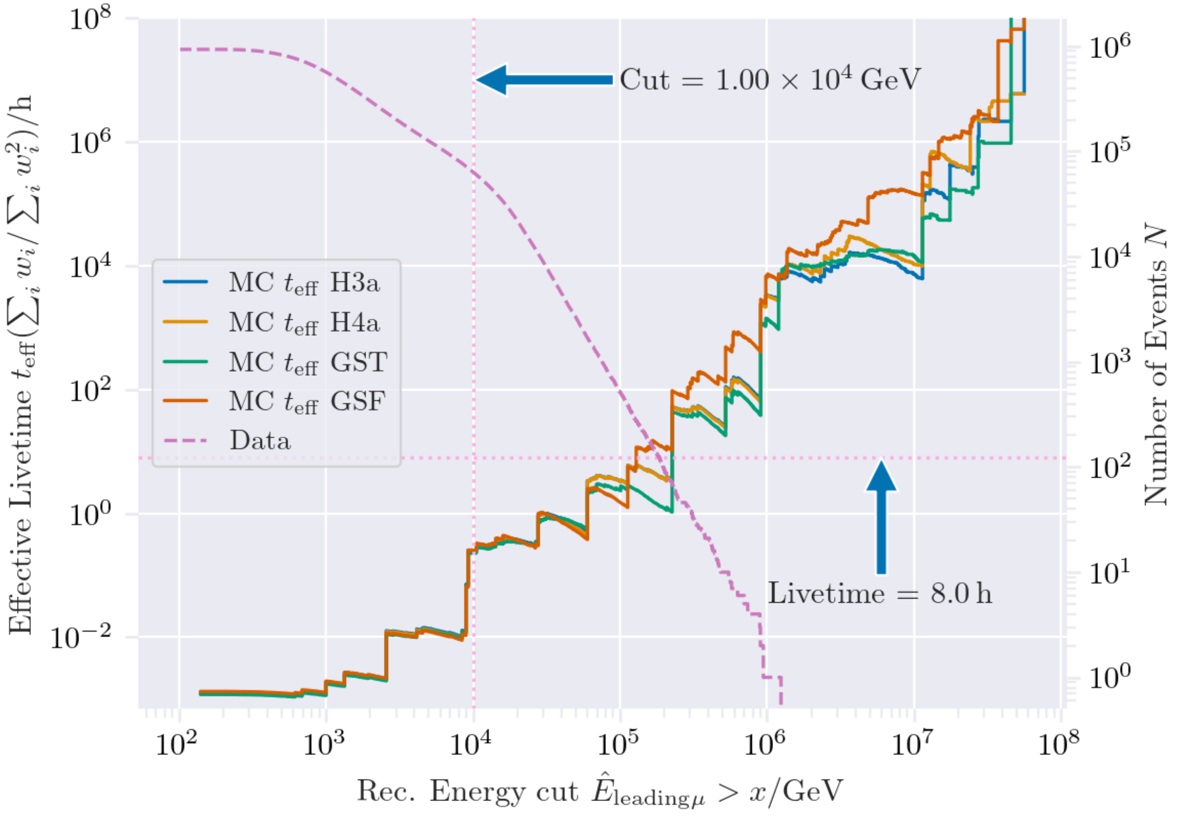



➢ No complete solution, but a step in the right direction

# 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/

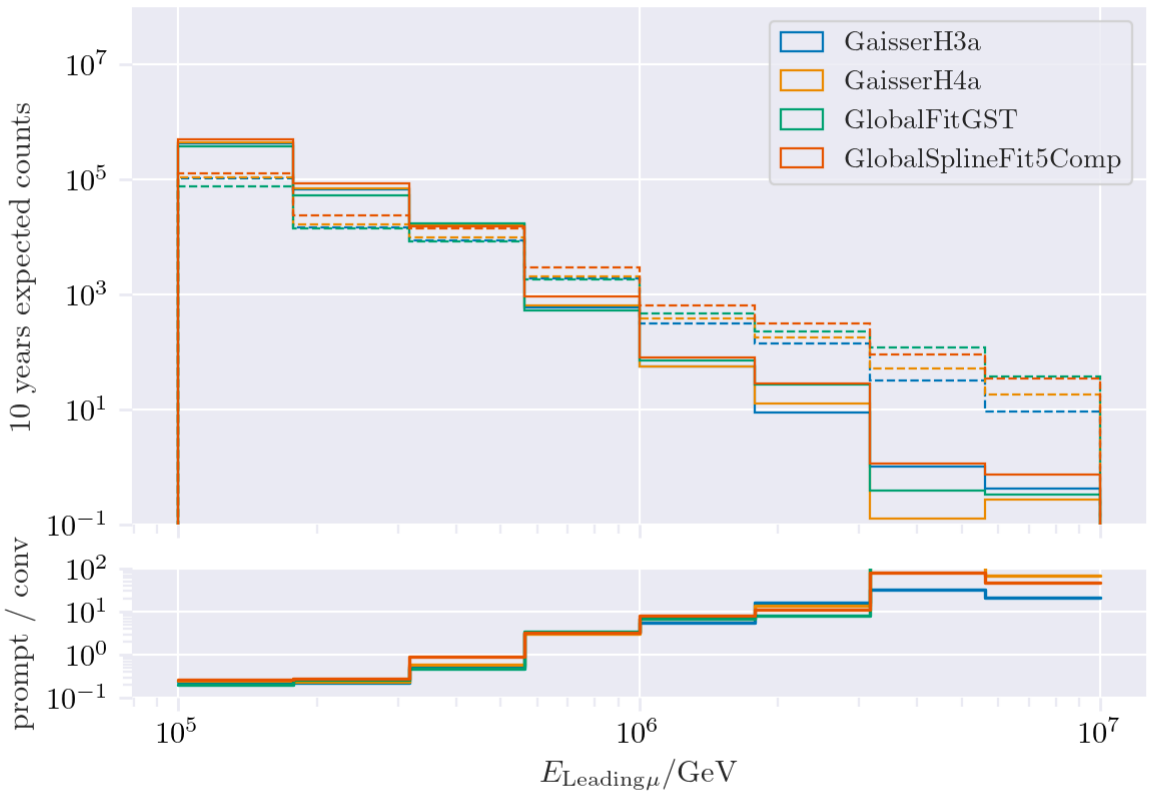


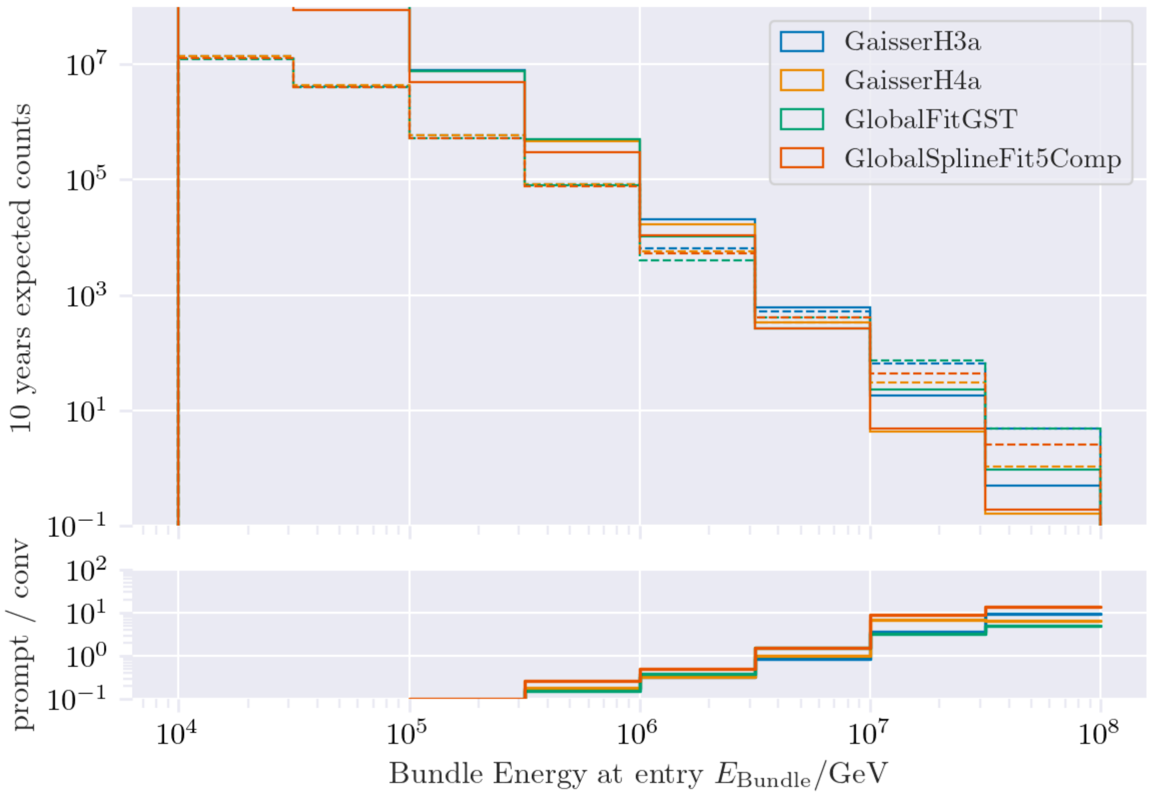

Please go ahead and test the datasets

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

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

Solid: conventional
Dashed: prompt

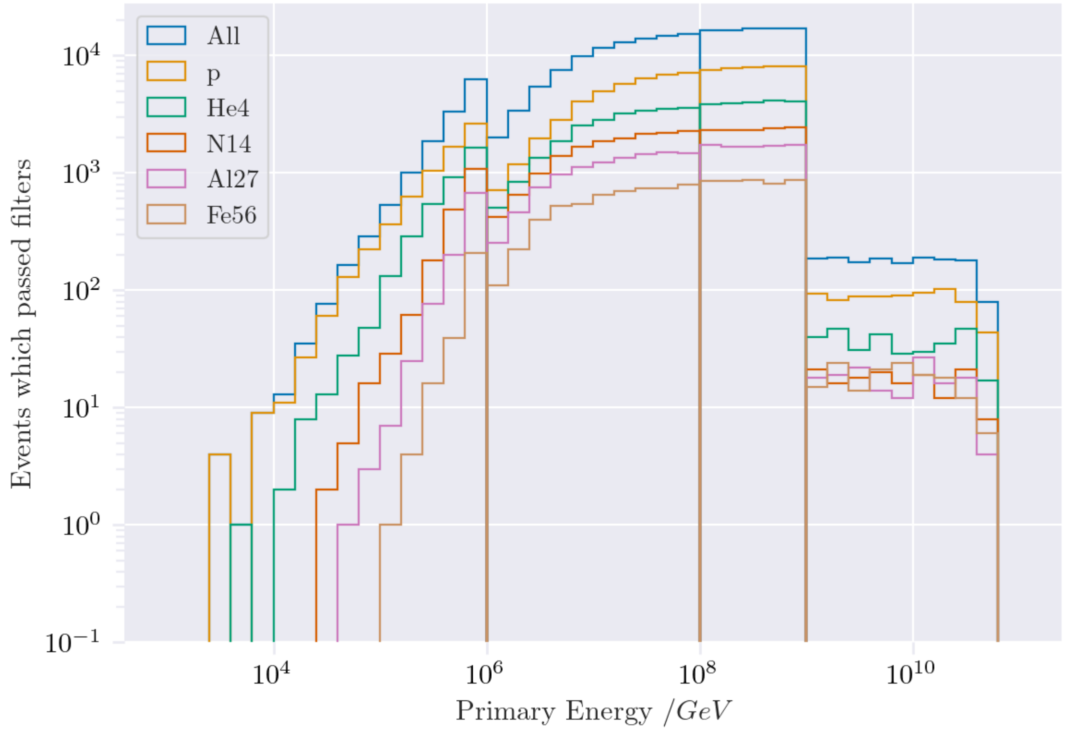



- Different primary fluxes lead to different prompt fluxes
- Bundle energy extends to higher energies

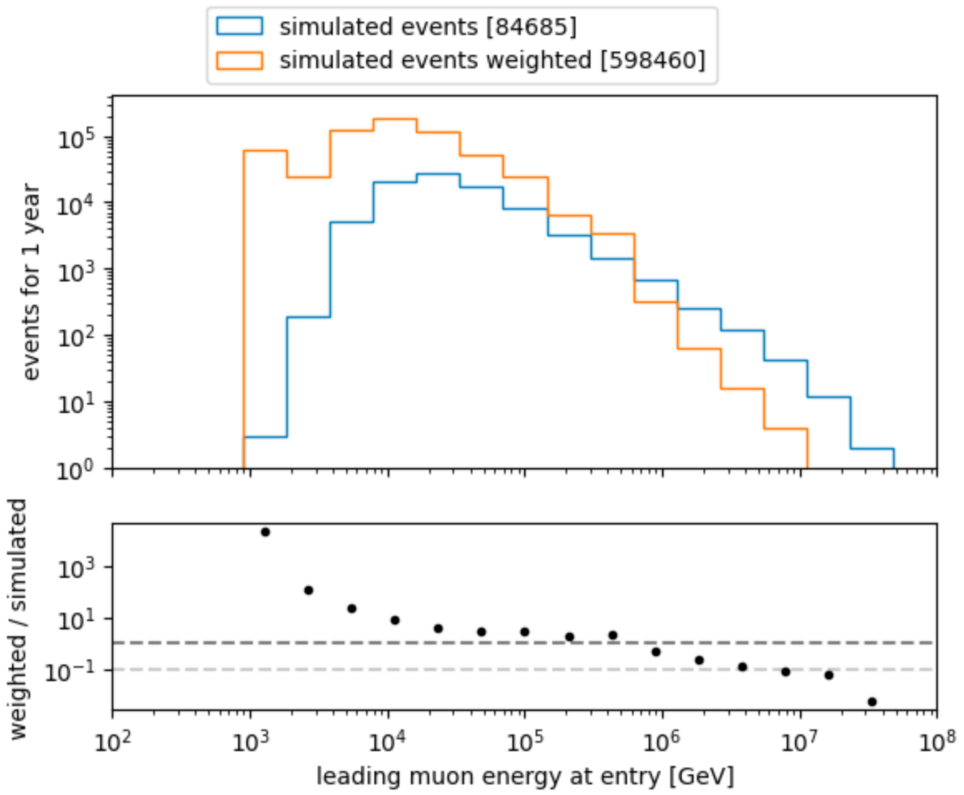
# Simulated events

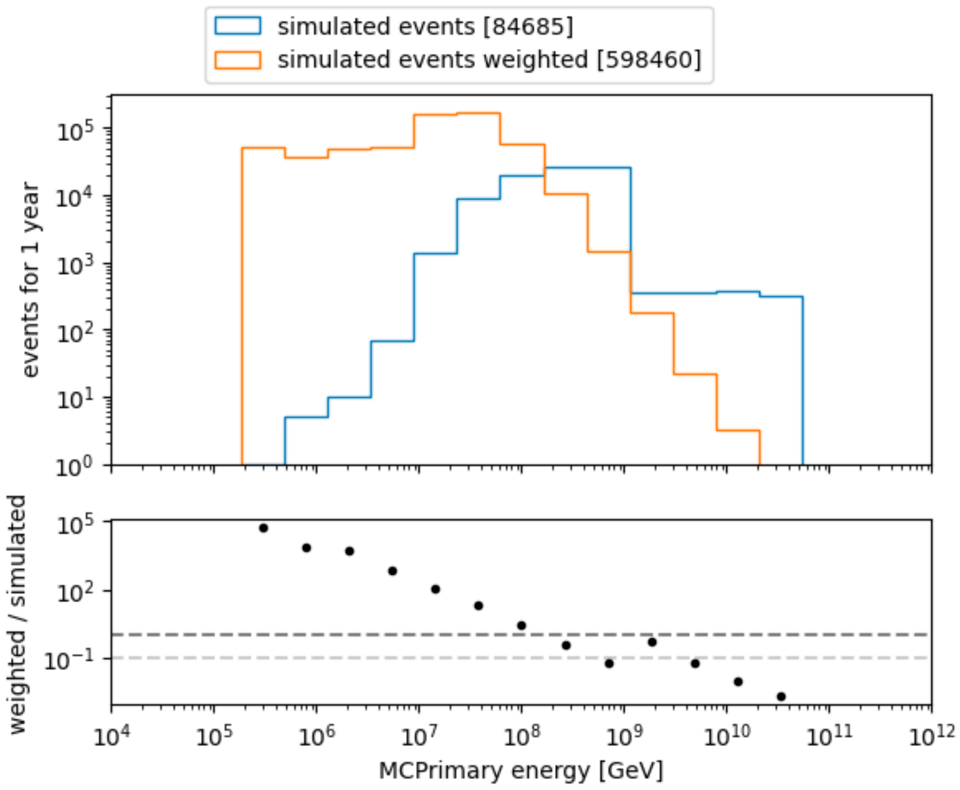
Passed muon filter



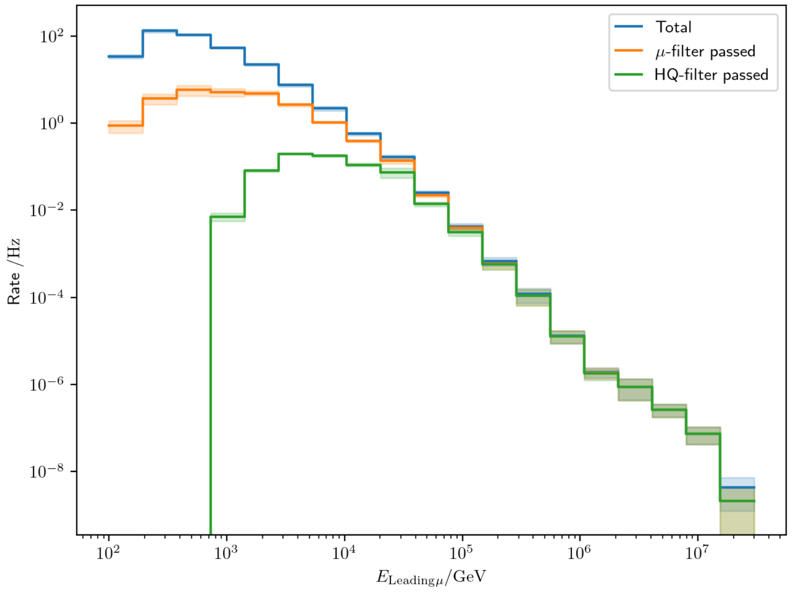
# Which energies do we need to simulate?

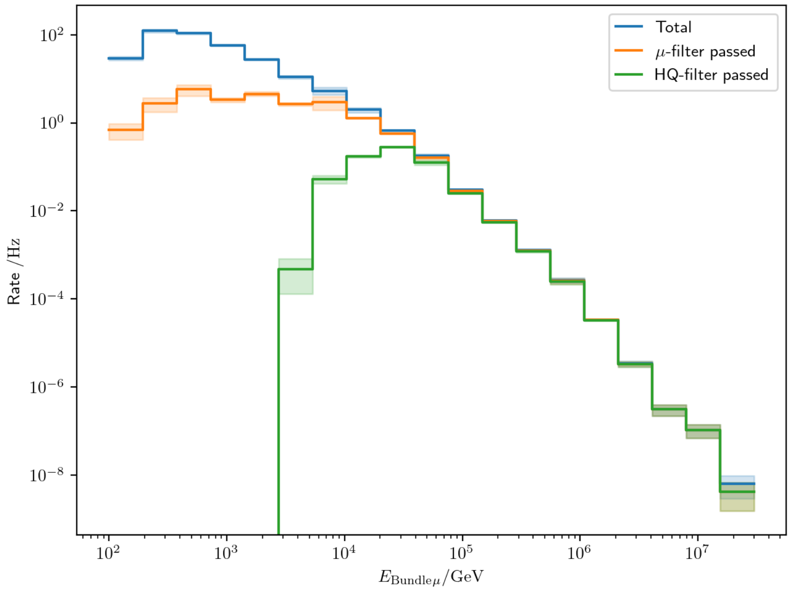
L2 MuonFilter
Bundle energy > 100 TeV



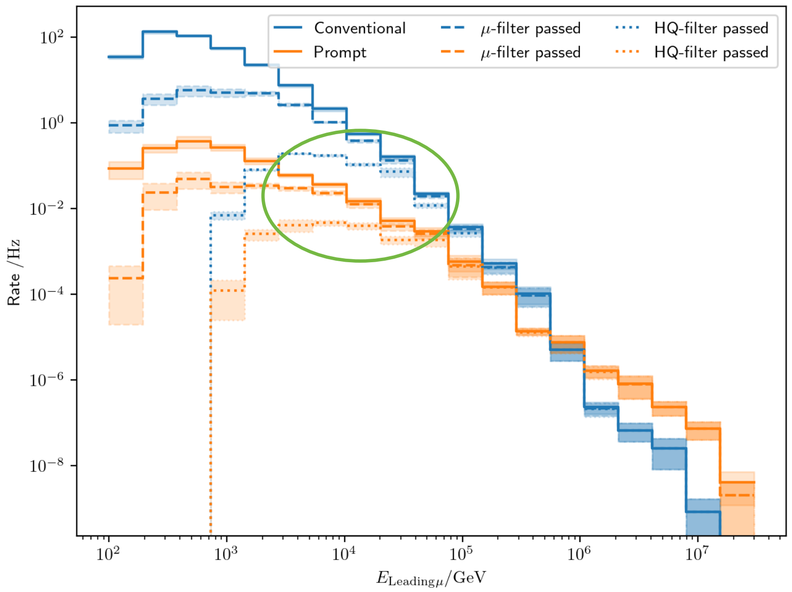



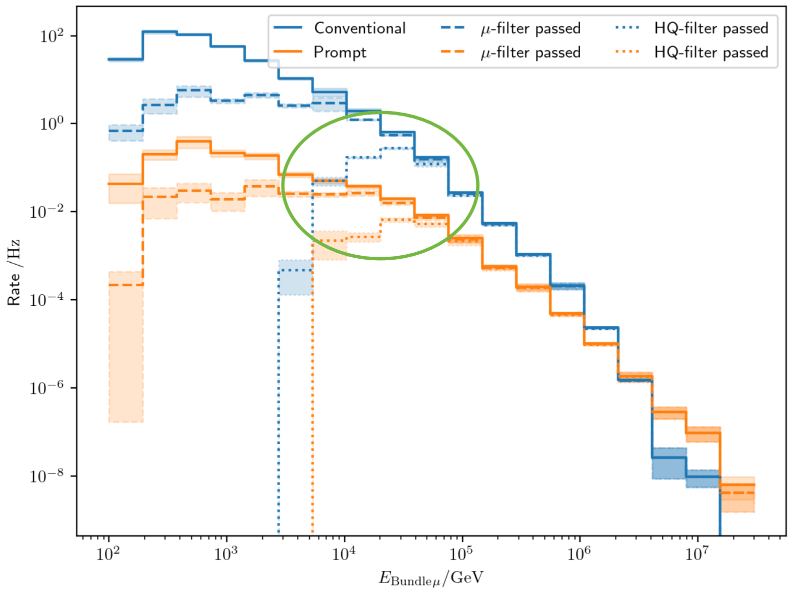
# Filters



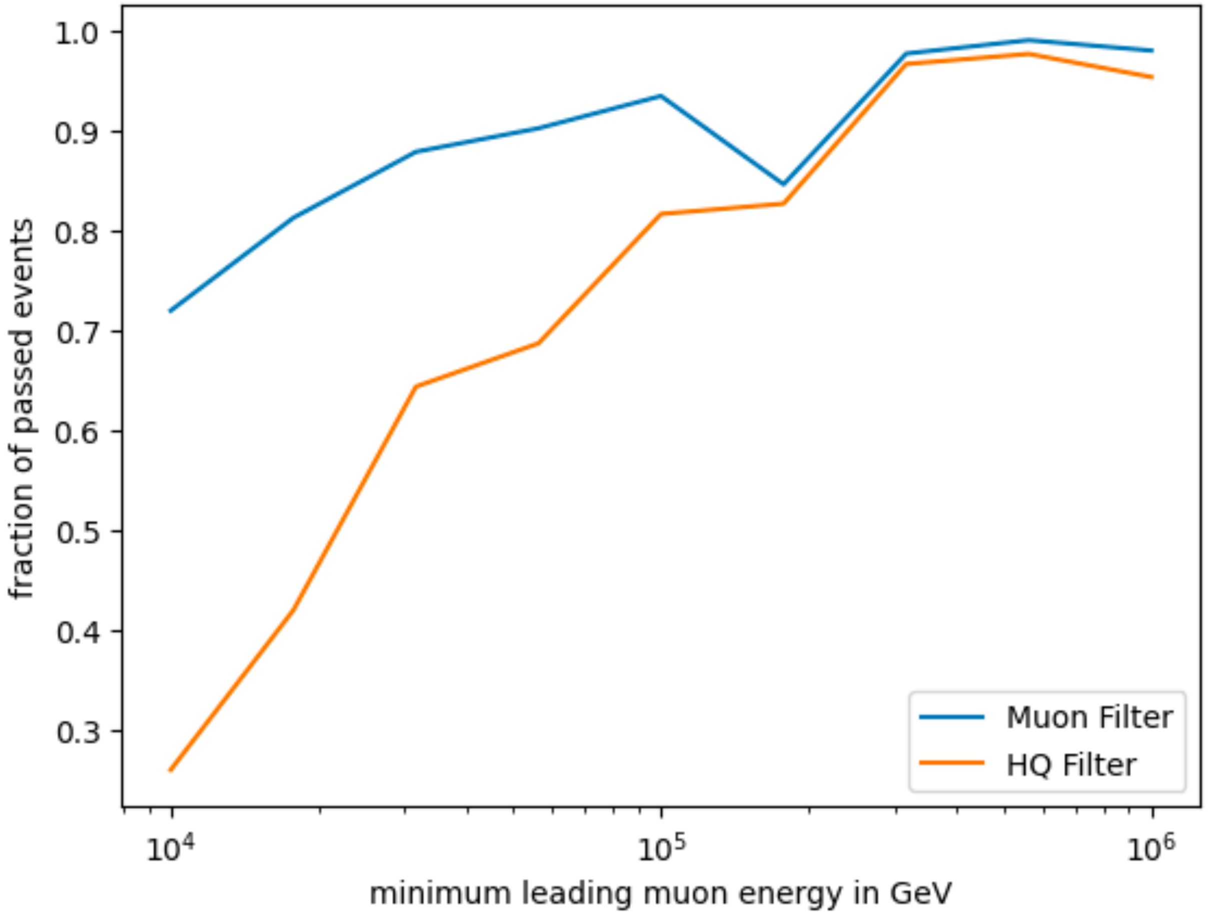




Choose muon filter,
larger statistics at 10 TeV

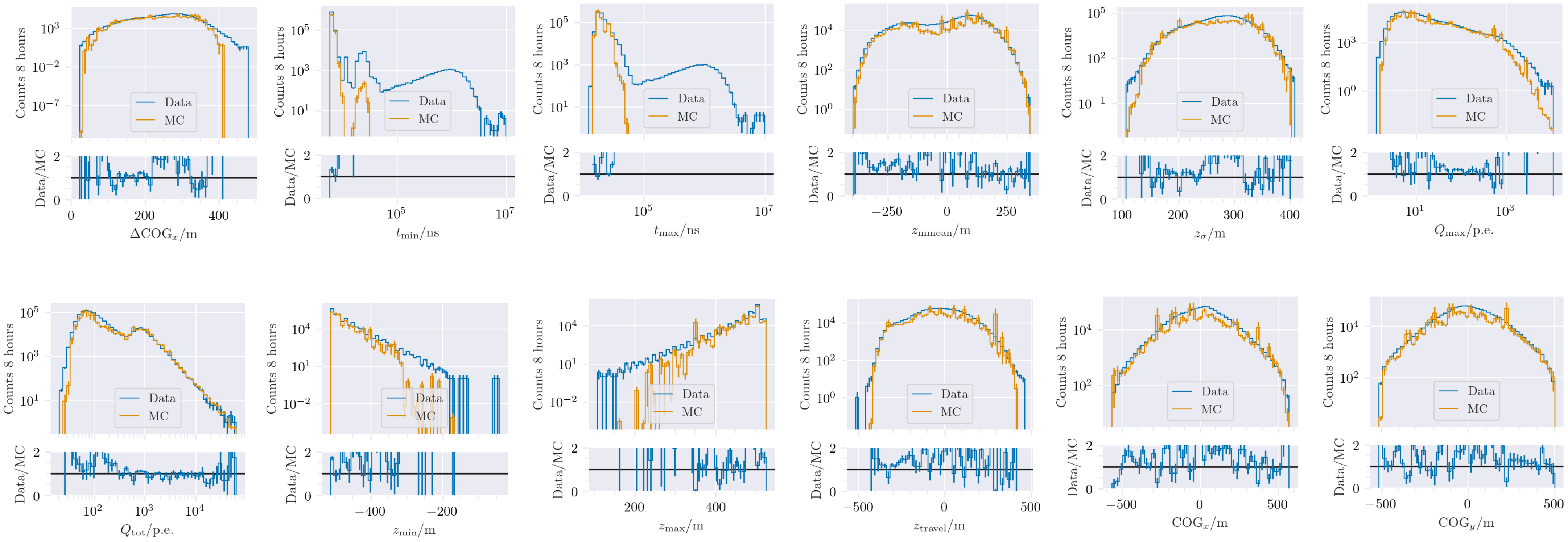


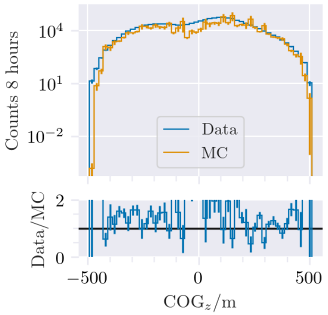



# Filters – passed events per leading energy



# Data-MC: HitStatistics - SplitInIceDSTPulses




L2 MuonFilter
No further exclusions

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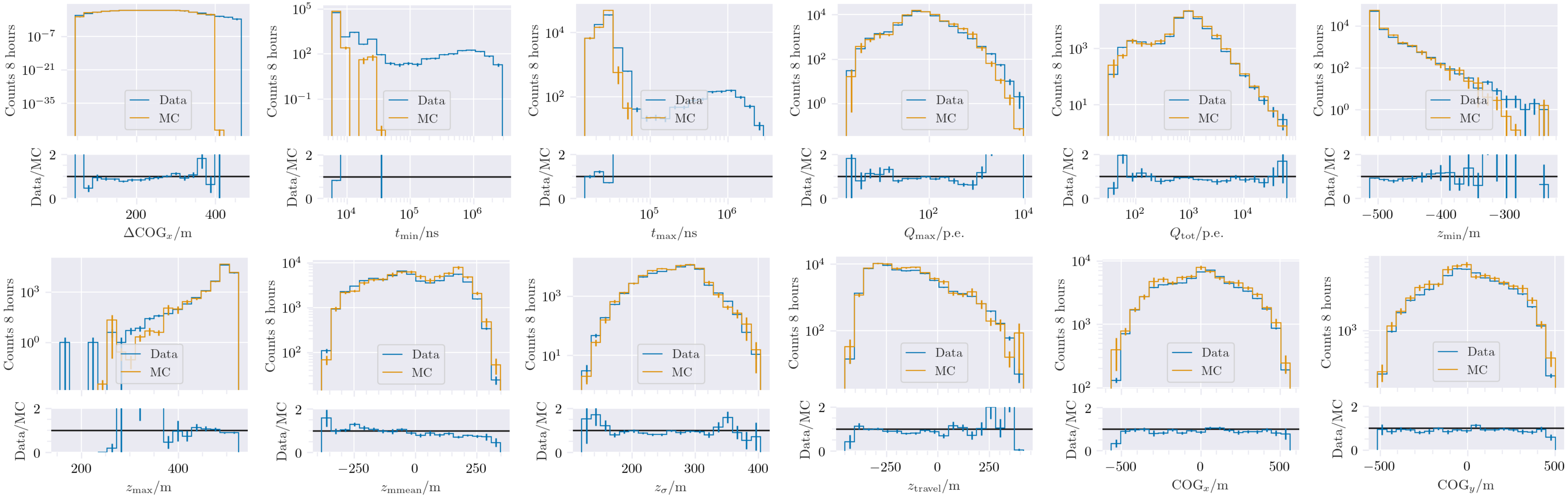
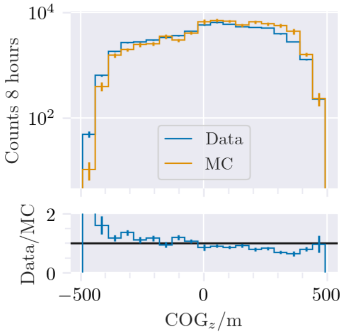



L2 Muonfilter
Reconstructed bundle energy > 10 TeV

➢ Good agreement for pulses

# 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

# Data-MC agreements

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

Reconstructions:

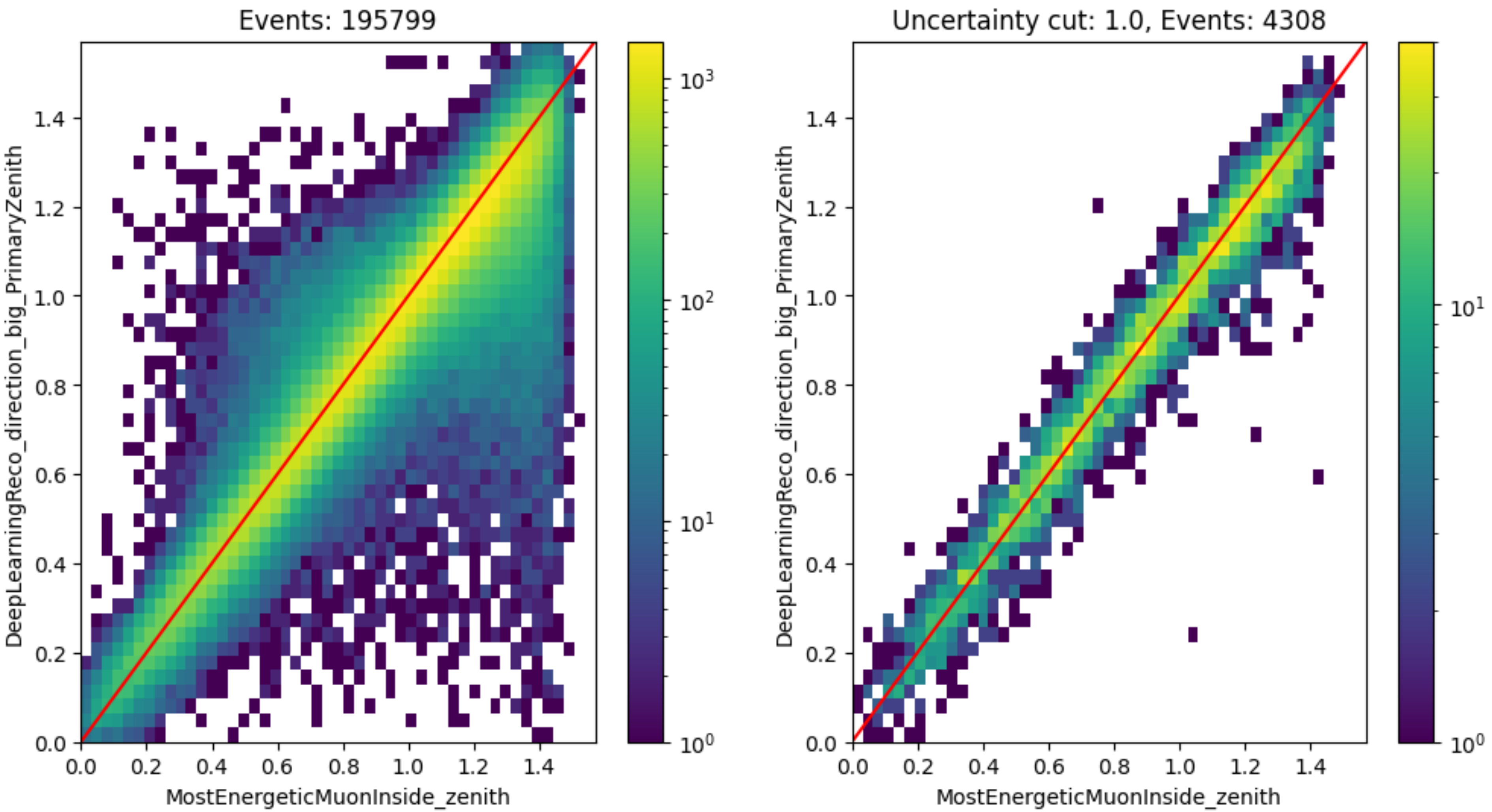
- Leading energy
- Leading fraction
- Bundle energy
- Multiplicity
- Azimuth
- Zenith

Work in progress

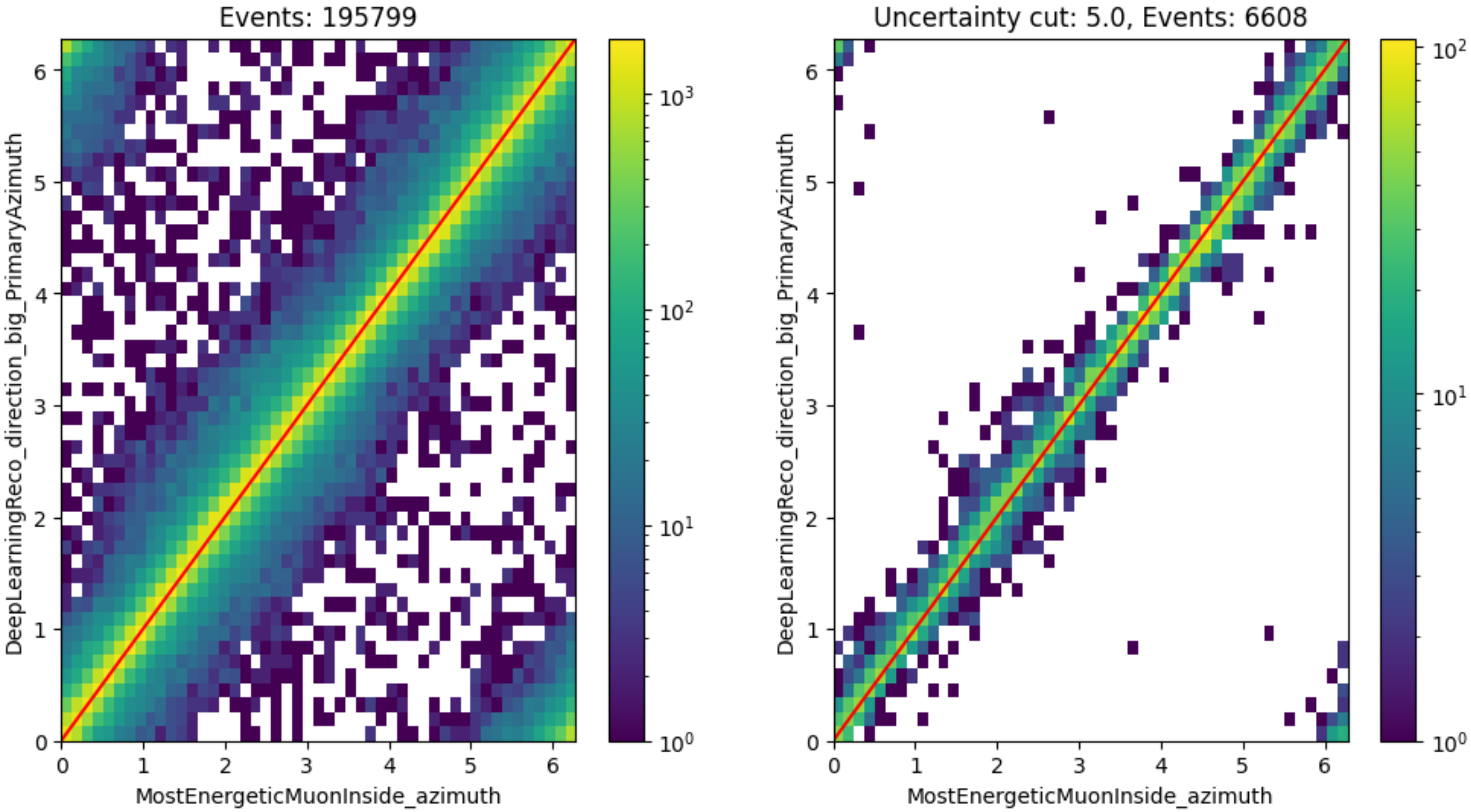
General:

- Trained on uncleaned and 6µs cleaned muon pulses
- Processed 8h of experimental data (June 4th, 2020)

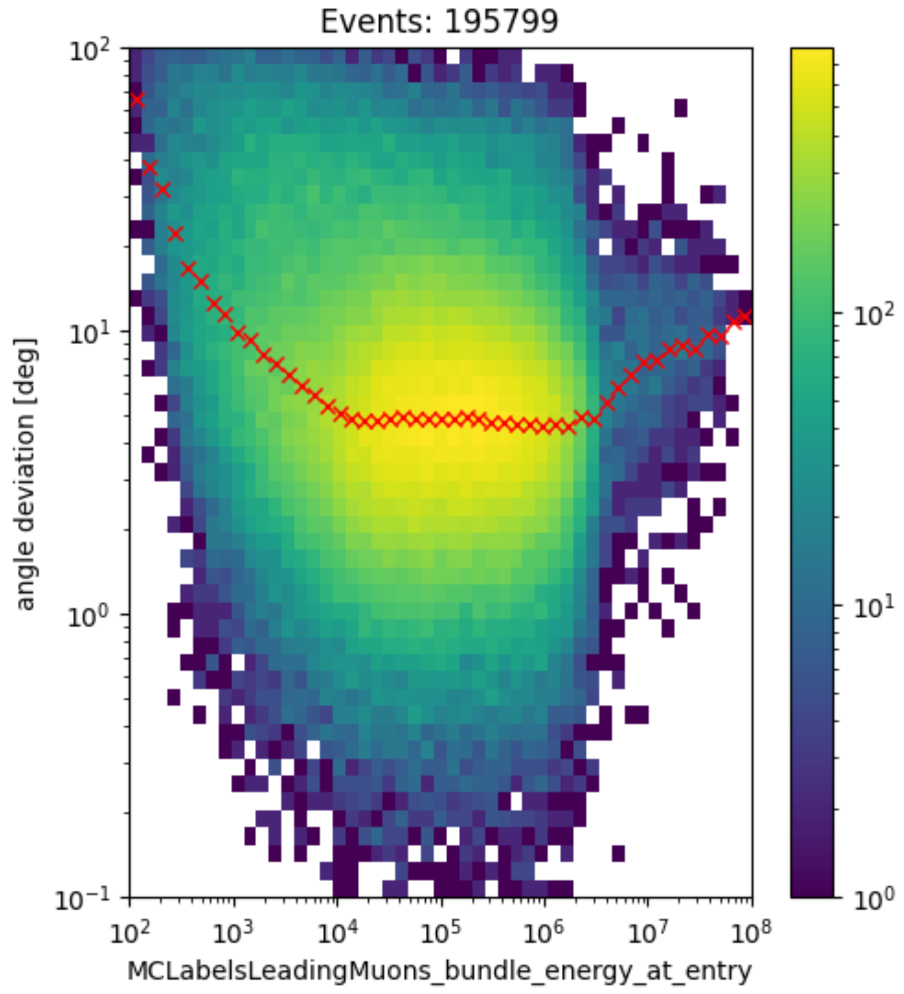
# Zenith reconstructions

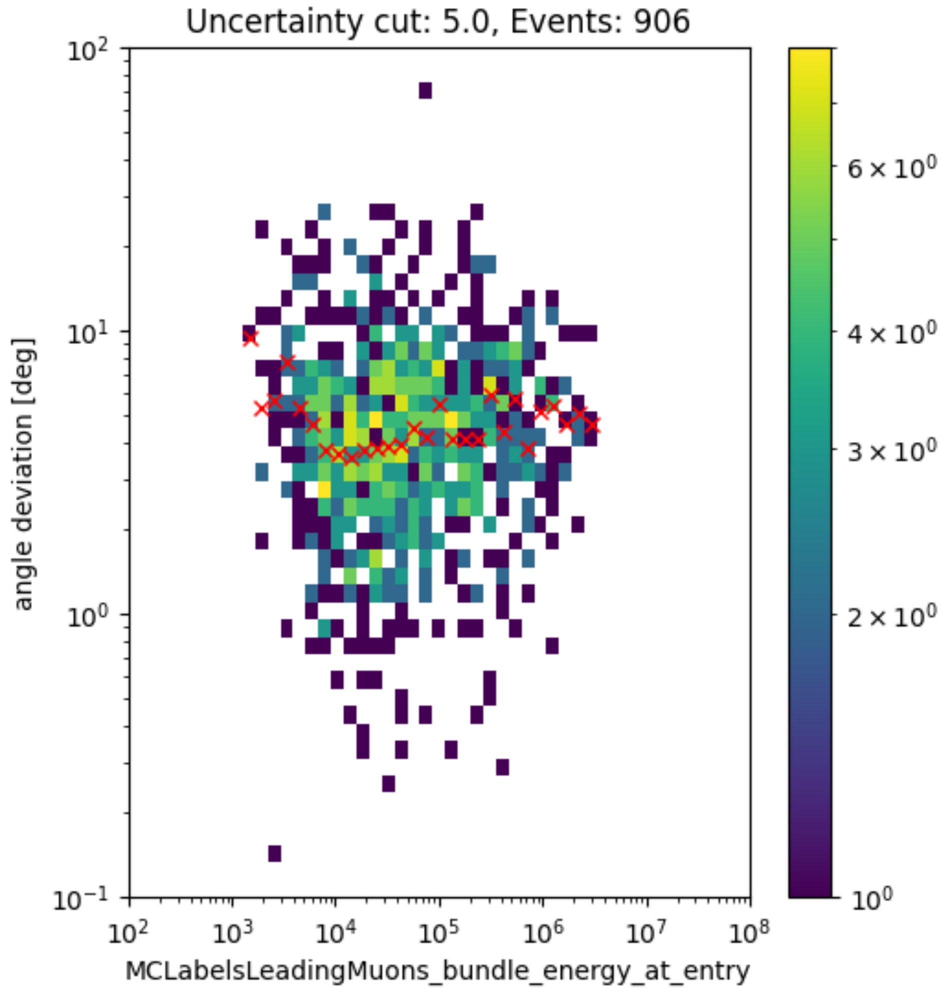


# Azimuth reconstructions



# Angular resolution

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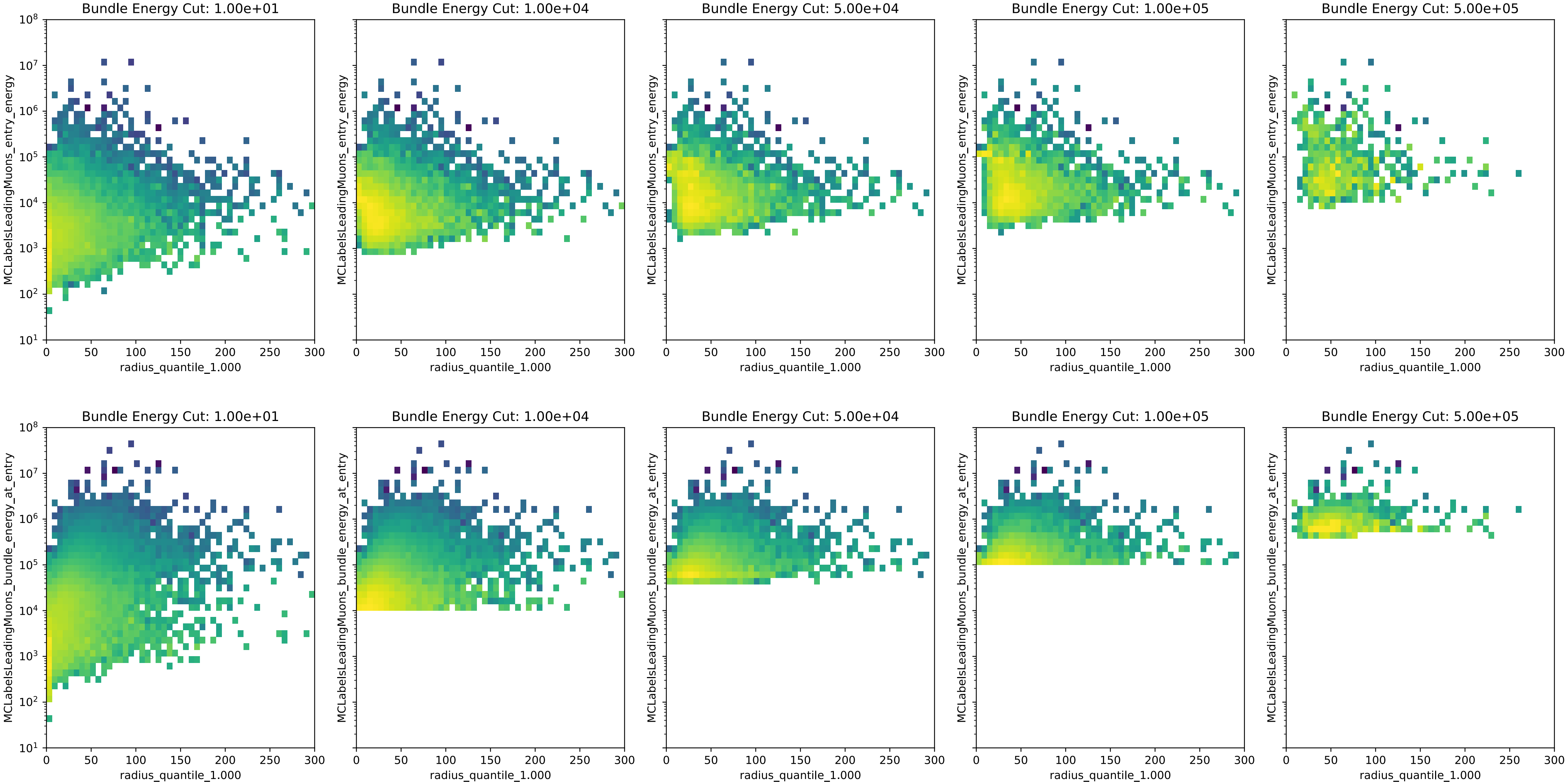
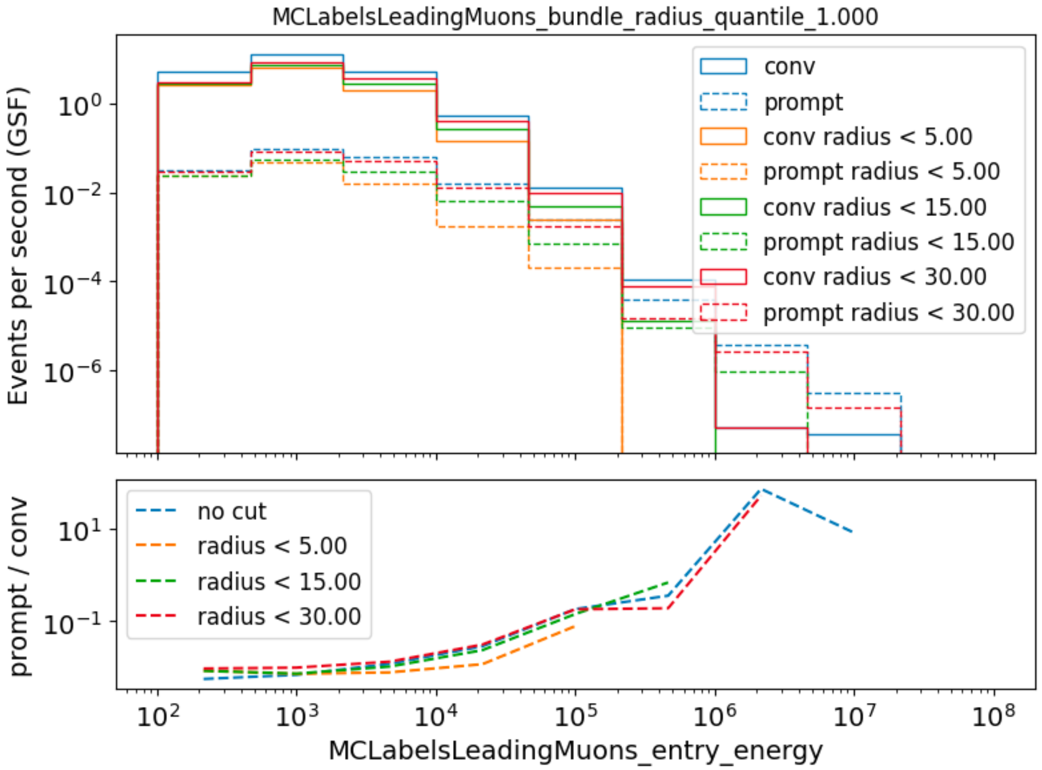
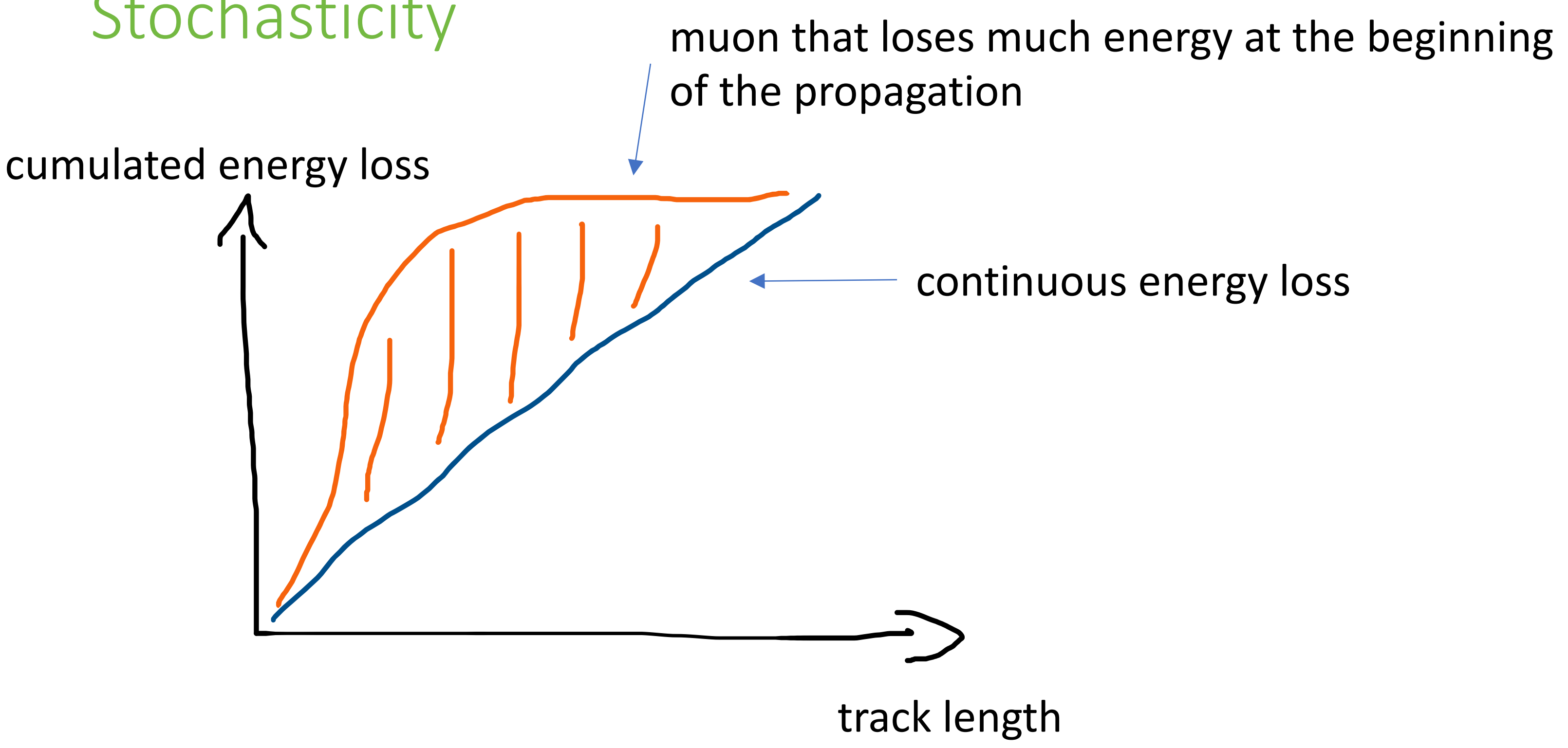
# Bundle radius - energy



# Muon flux – bundle radius



# Stochasticity




- calculate the area between the “continuous muon energy loss” and the accumulated muon energy losses and normalize it
- high stochasticity: area = 1
- no stochasticity: area = 0

# Bundle radius

- calculate perpendicular distance between leading muon and closest point to detector center
  - reference point
- calculate the distance between the leading muon and all the other muons at the reference point
- analyze the distances weighted by their energy (100%, 99%, 95%,... energy containment)