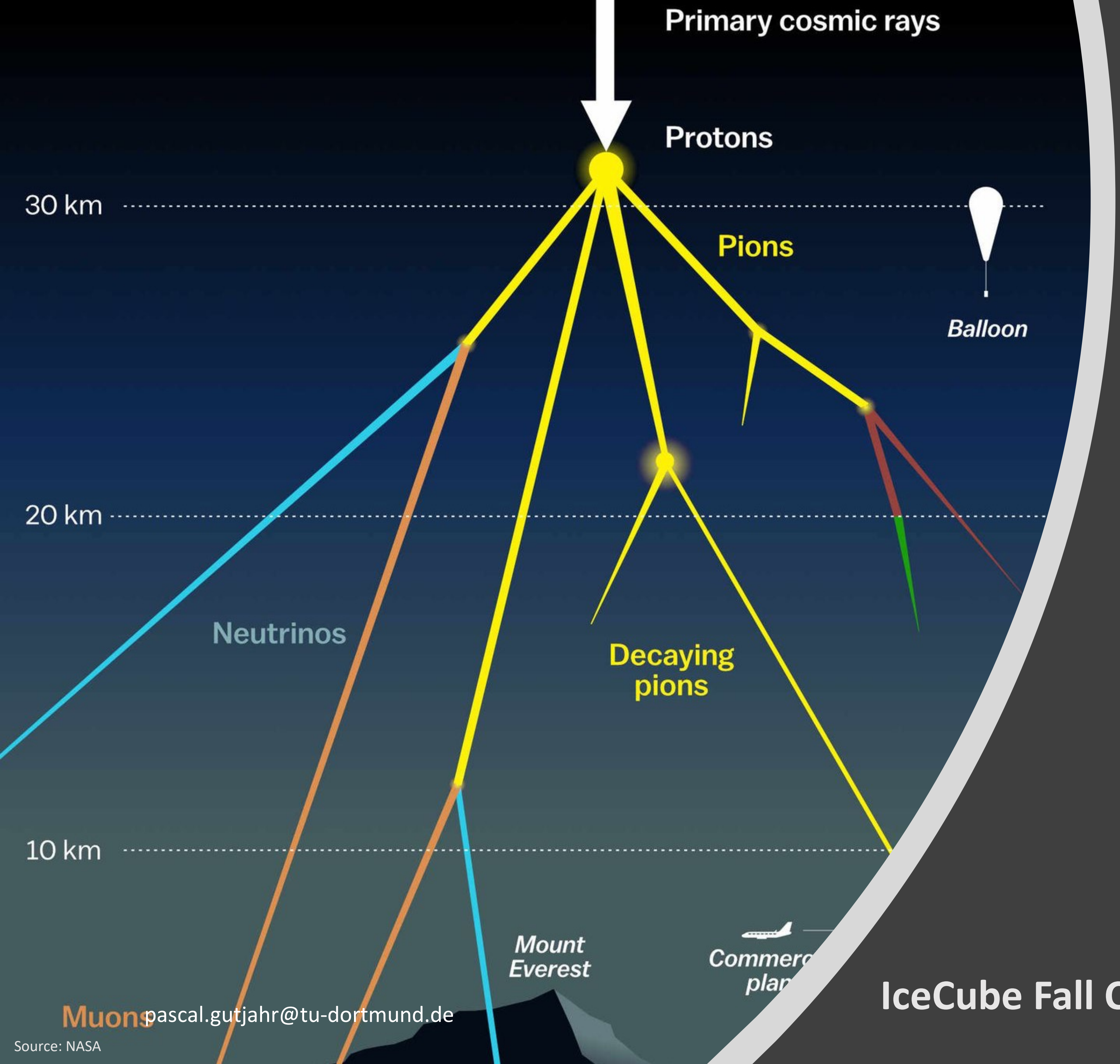


Source: NASA

Measurement of the prompt component of the atmospheric muon flux

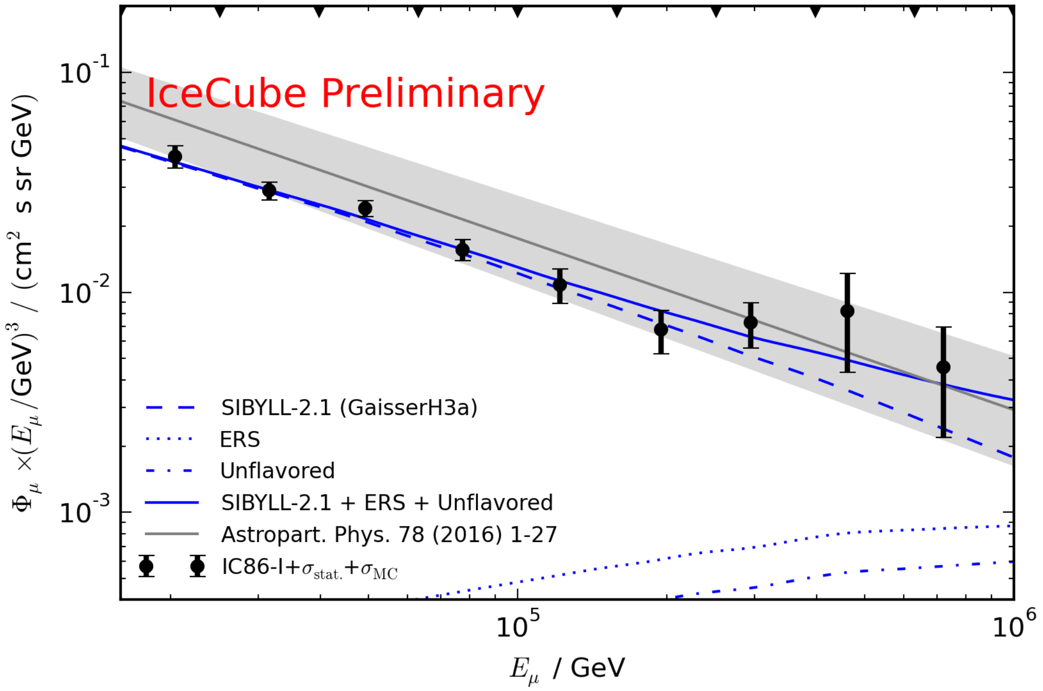
Ludwig Neste and Pascal Gutjahr

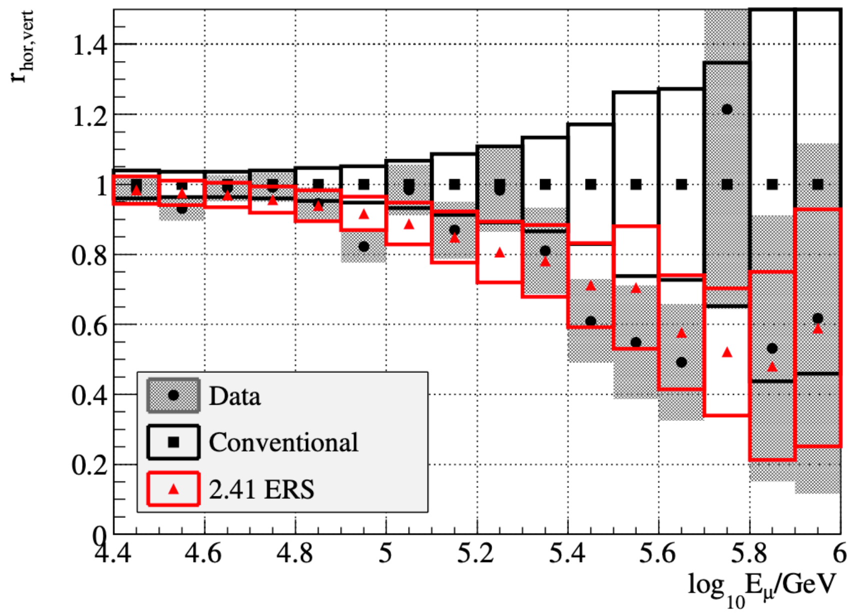
pascal.gutjahr@tu-dortmund.de

IceCube Fall Collaboration Meeting Grand Rapids 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)
  - Characterization of the muon flux: zenith problem (by Patrick Berghaus, https://arxiv.org/abs/1506.07981)





Sample	Best Fit (ERS)	1σ 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 issues

Overview

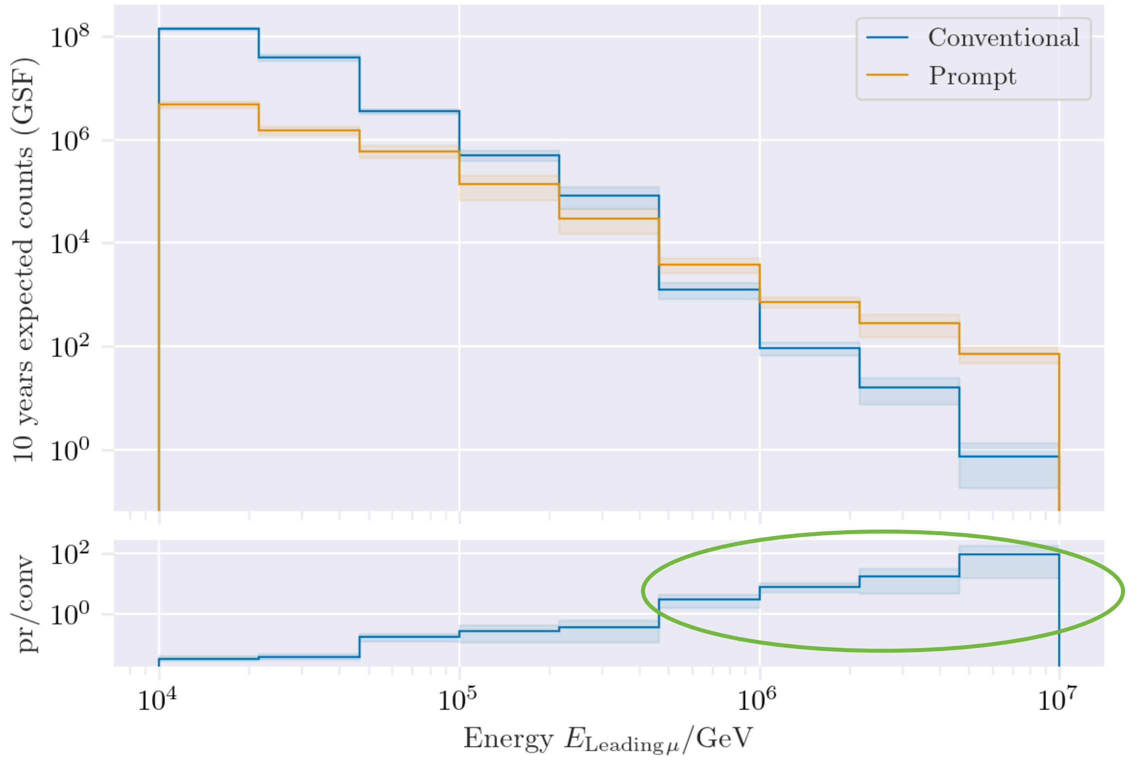
- mention our intention, our goals, what we have reached so far, what we will look into in the near future

Introduction

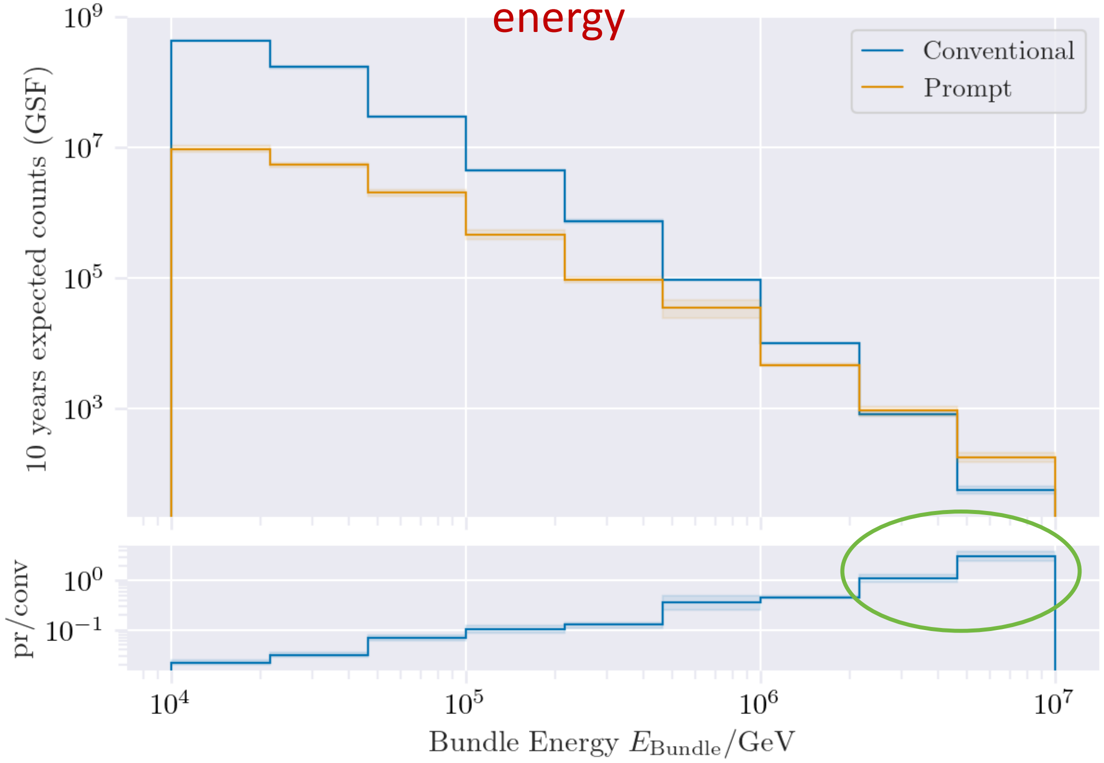
- mention new simulation, prompt definition, wording,

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

adjust xlim, bundle extends to higher energies



add definition of leading and bundle energy

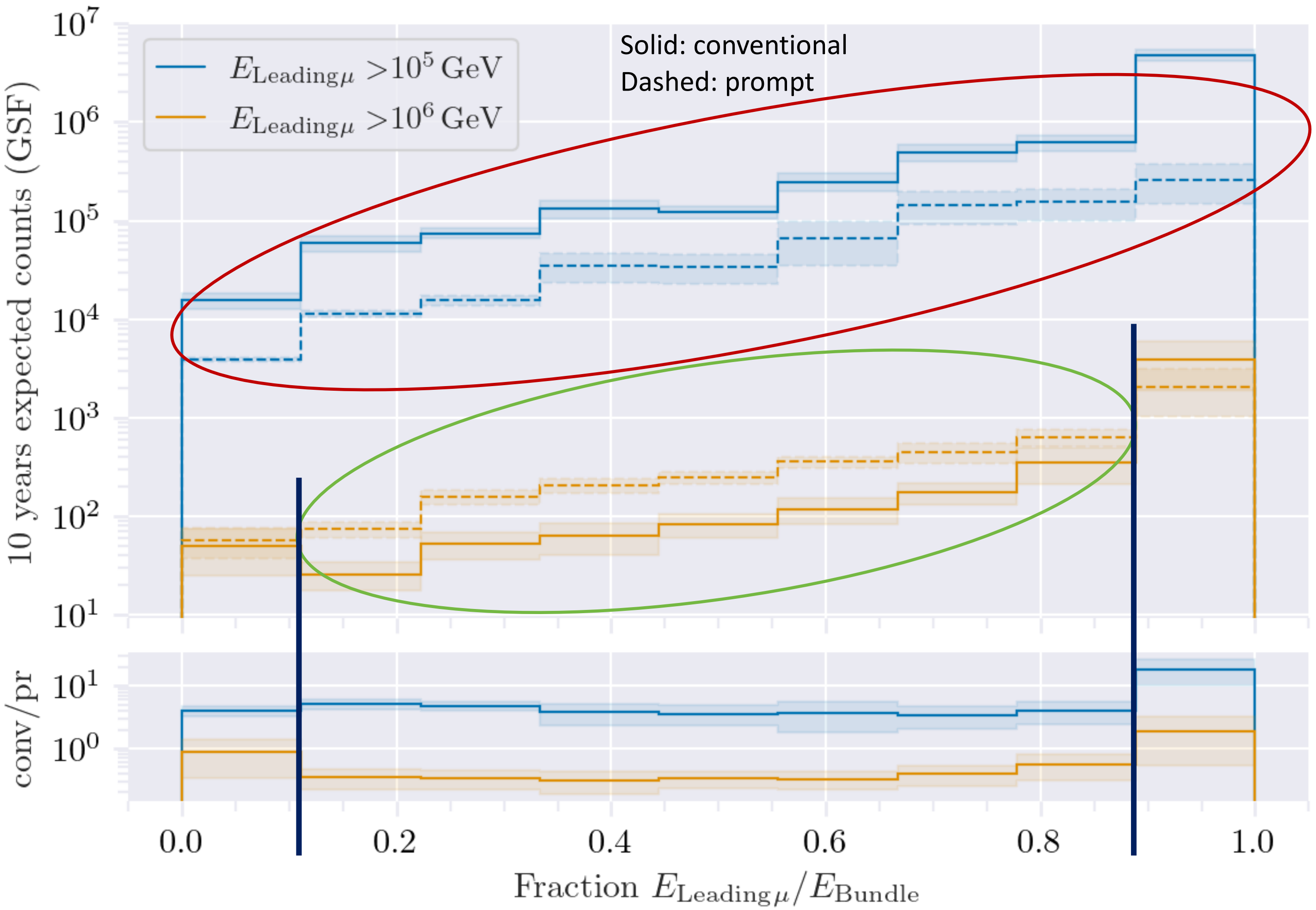


- ➢ Leading muon energy is more sensitive to detect prompt dortmund university

ICECUBE NEUTRINO OBSERVATORY

Leading muon energy fraction

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



Leading muon contribution

Patrick Berghaus

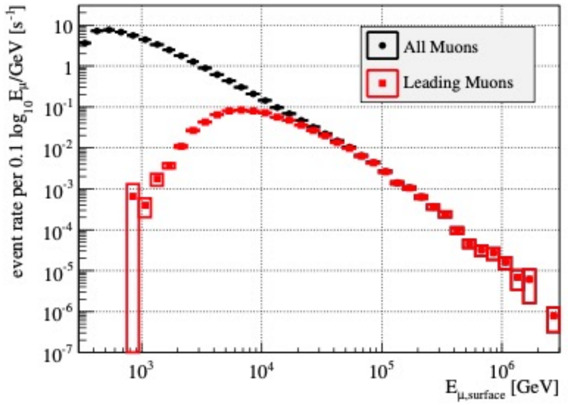
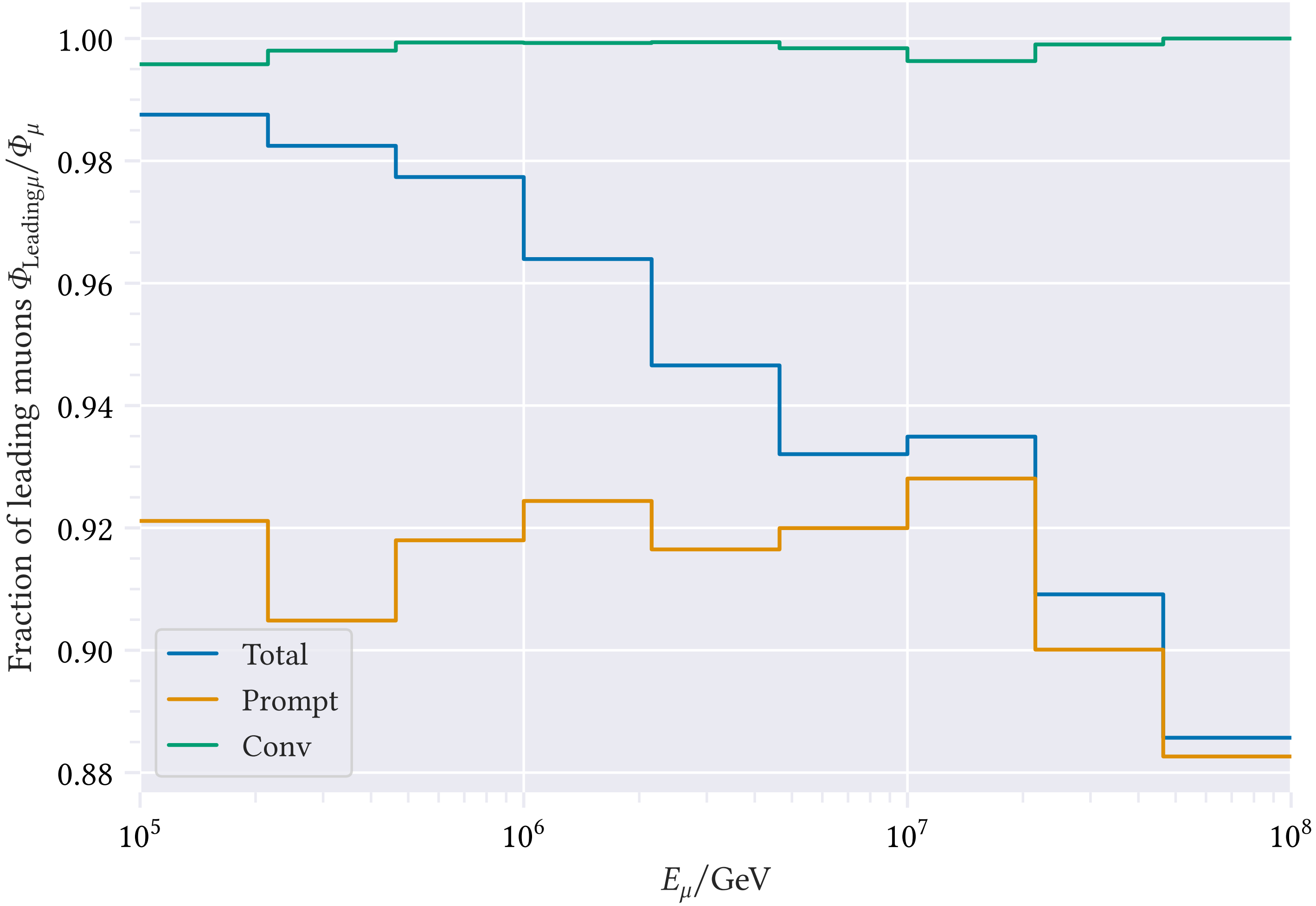


Figure 10: Surface energy distribution for all and most energetic ("leading") muons in simulated events with a total of more than 1,000 registered photo-electrons in IceCube.

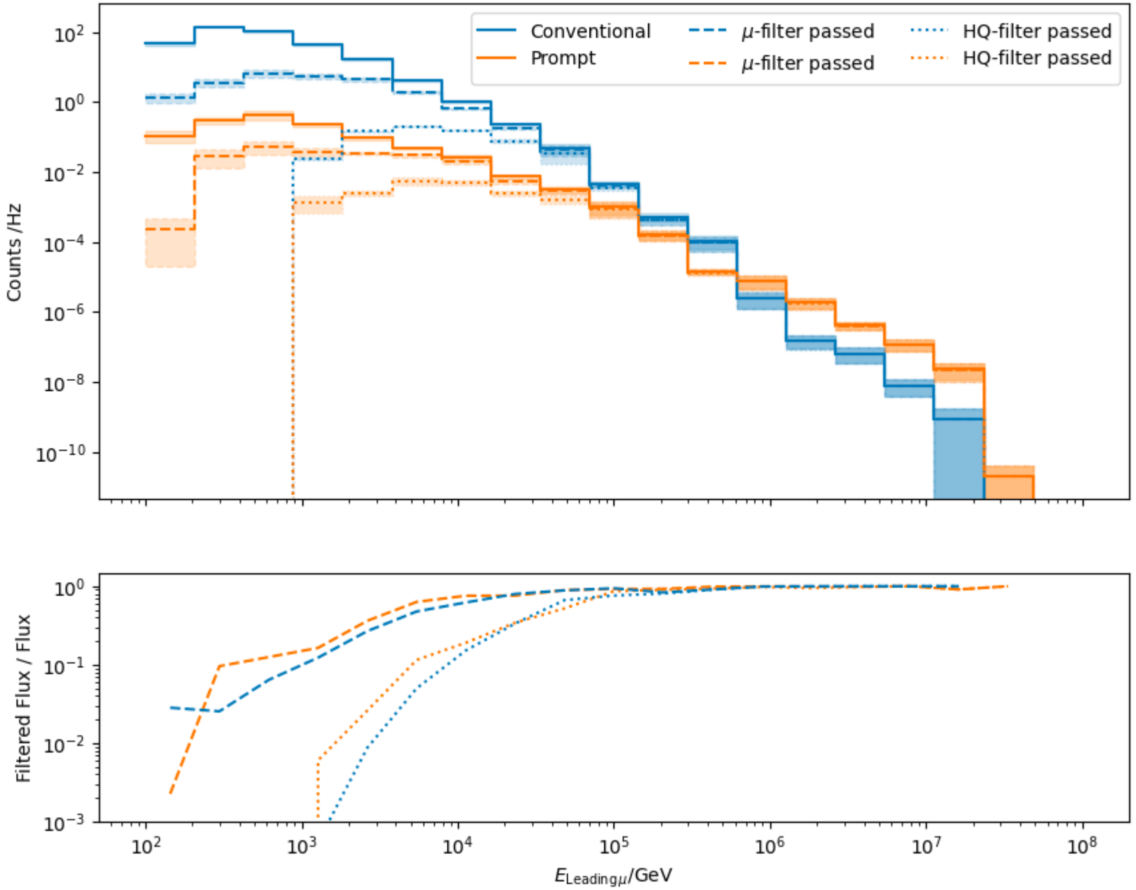


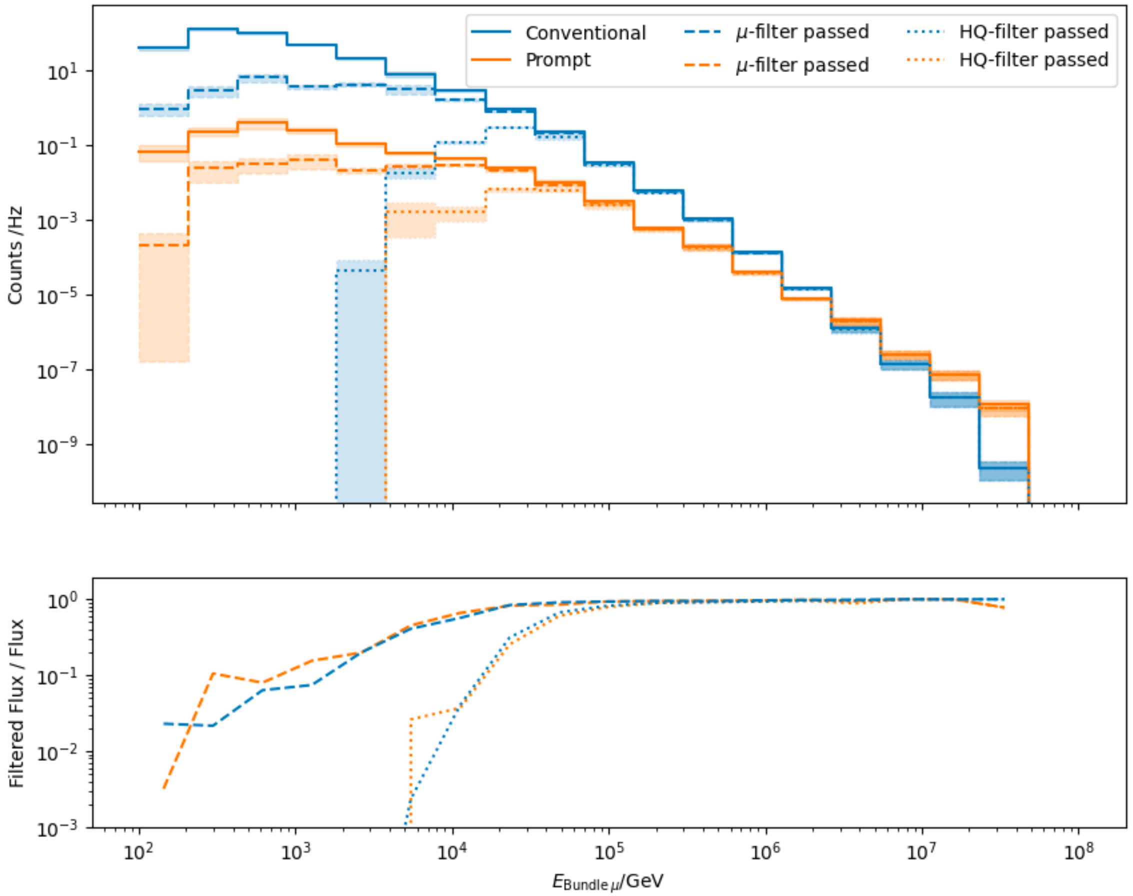
- Muons with energies between 100 TeV and 50 PeV dominate the bundle by more than 90%
- In average conventional muons are more dominant than prompt
- But: at high energies, there are more prompt than conventional events

➢ 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





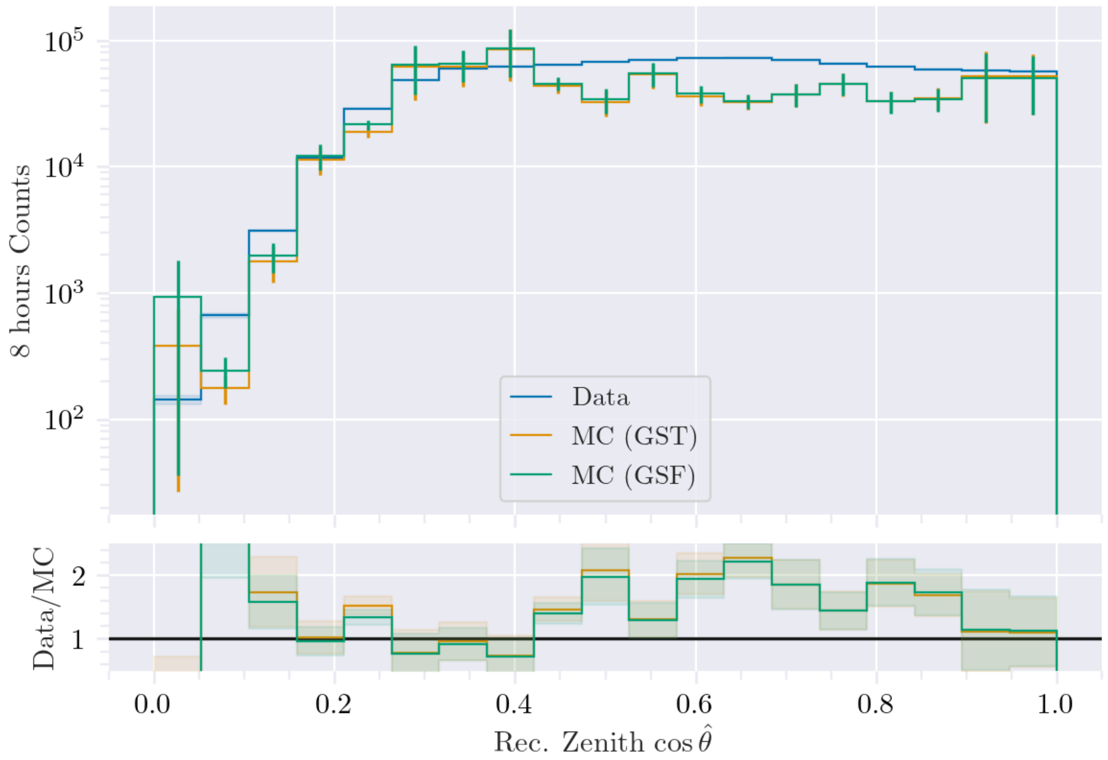
➢ Choose muon filter to remove large amount of statistics at low energies

DNN Reconstructions

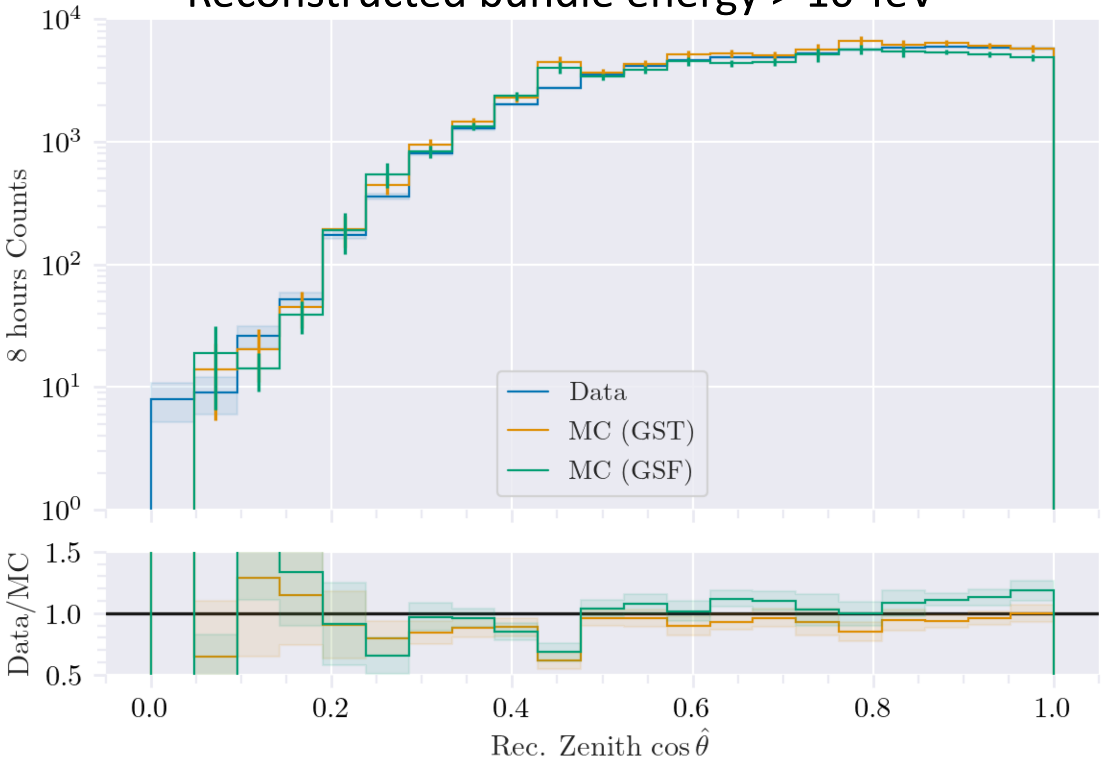
- mention, what we have done so far
- what we will further do
- mention stochasticity investigation
- mention bundle radius investigation

Data-MC: cos(zenith)

remove GST

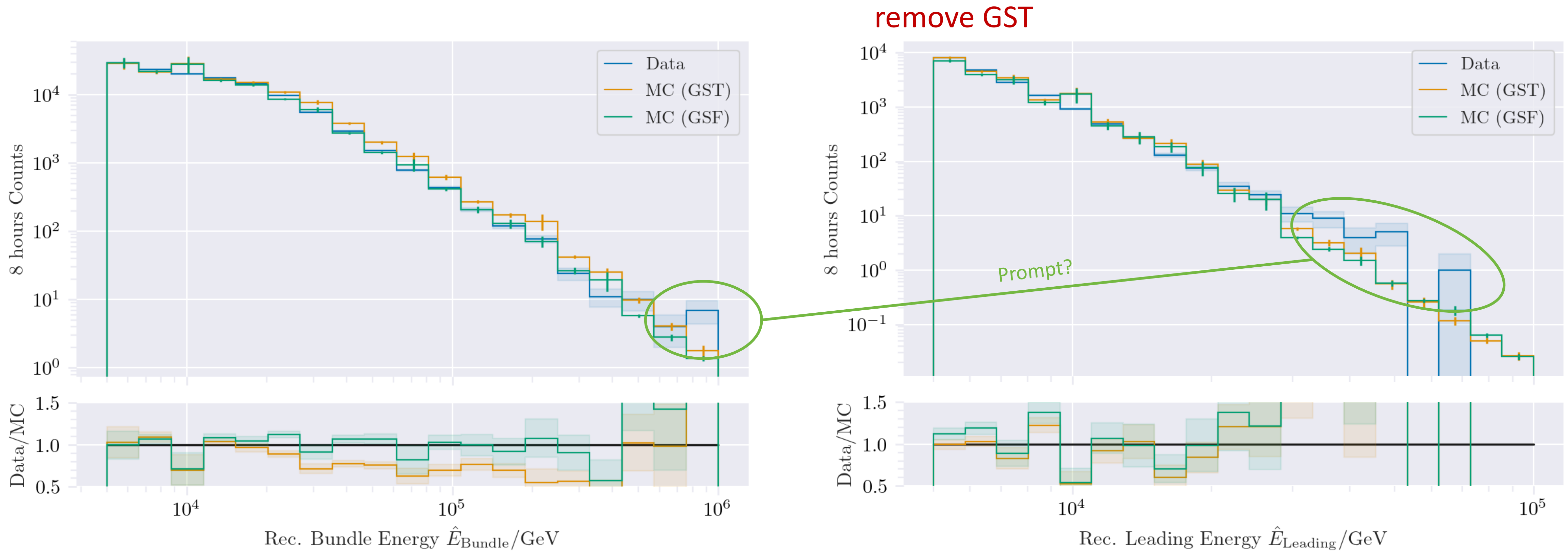


Reconstructed bundle energy > 10 TeV



➢ Deviations at low cos(zenith), but very small statistics processed 8h of experimental data (June 4th, 2020)

Data-MC: energy spectrum



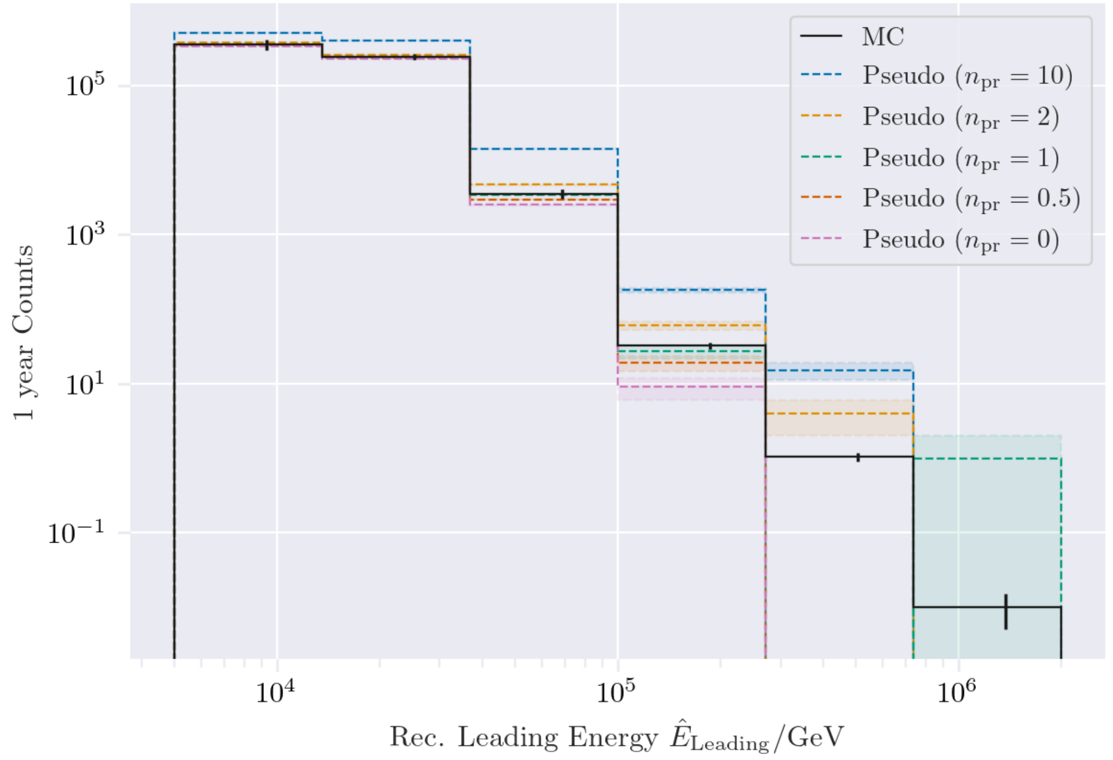
➢ Bundle energy: good agreement with GSF

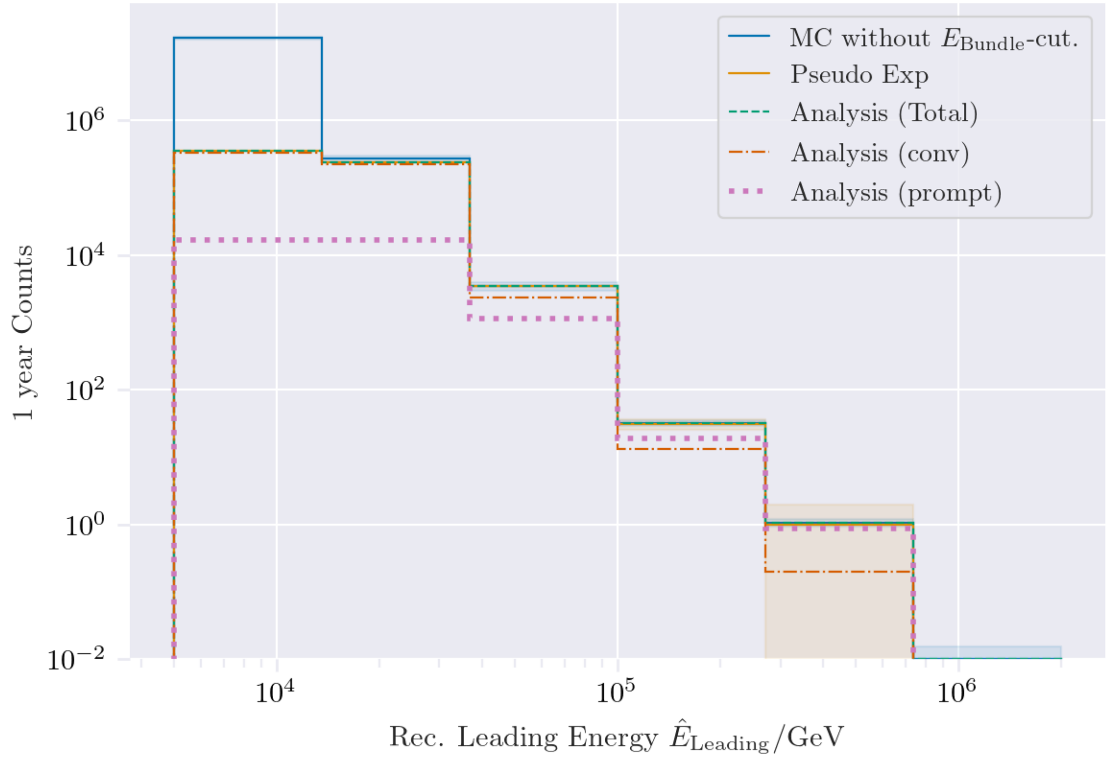
pascal.gutjahr@tu-dortmund.de

Pseudo analysis

Pseudo data sampling

Cuts:
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

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

Experimental counts

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

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

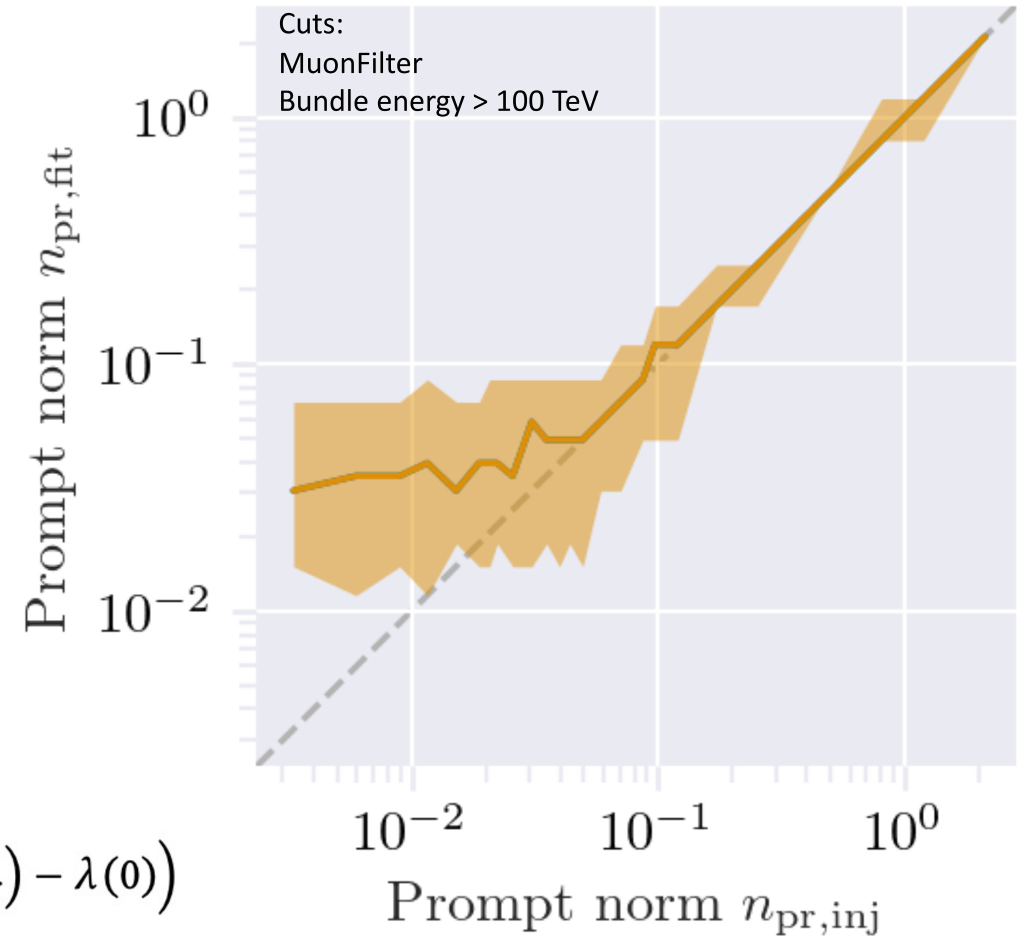
$$-\ln \mathscr{L} = -\sum_{i=1}^{M} C_i \ln \lambda\left(n_{\mathrm{pr}}\right) - \lambda\left(n_{\mathrm{pr}}\right) - \ln C_i!$$

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

Test statistic for Wilk's theorem

Null hypothesis: no prompt

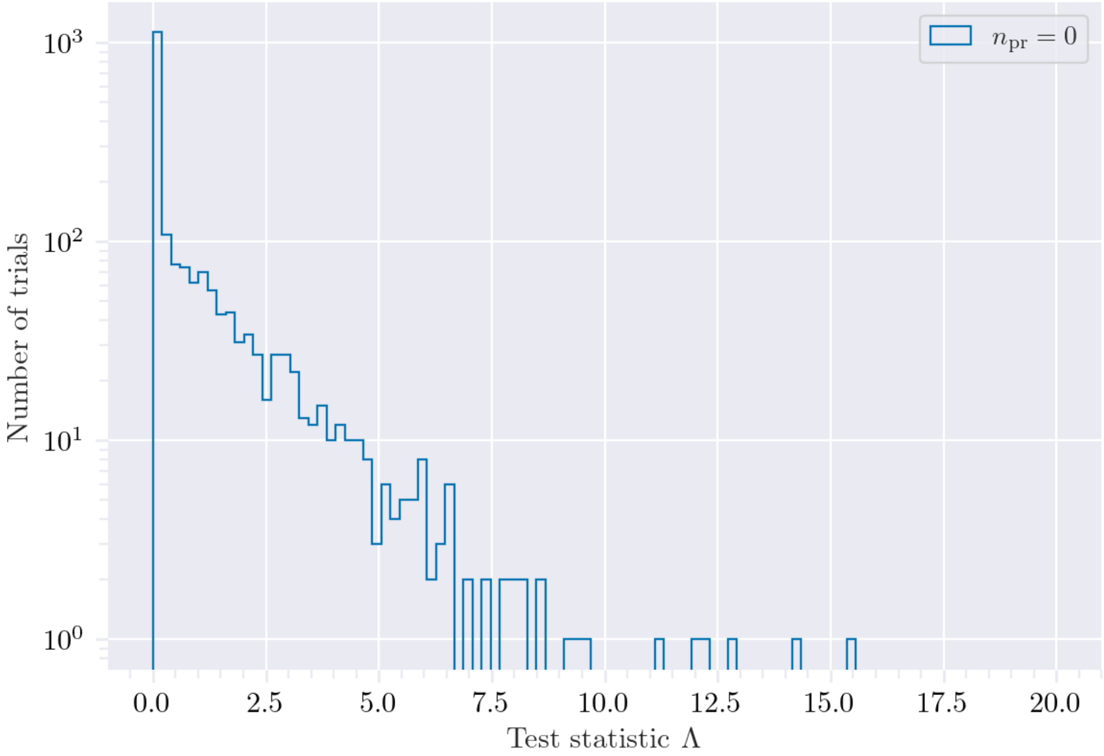
Test bias

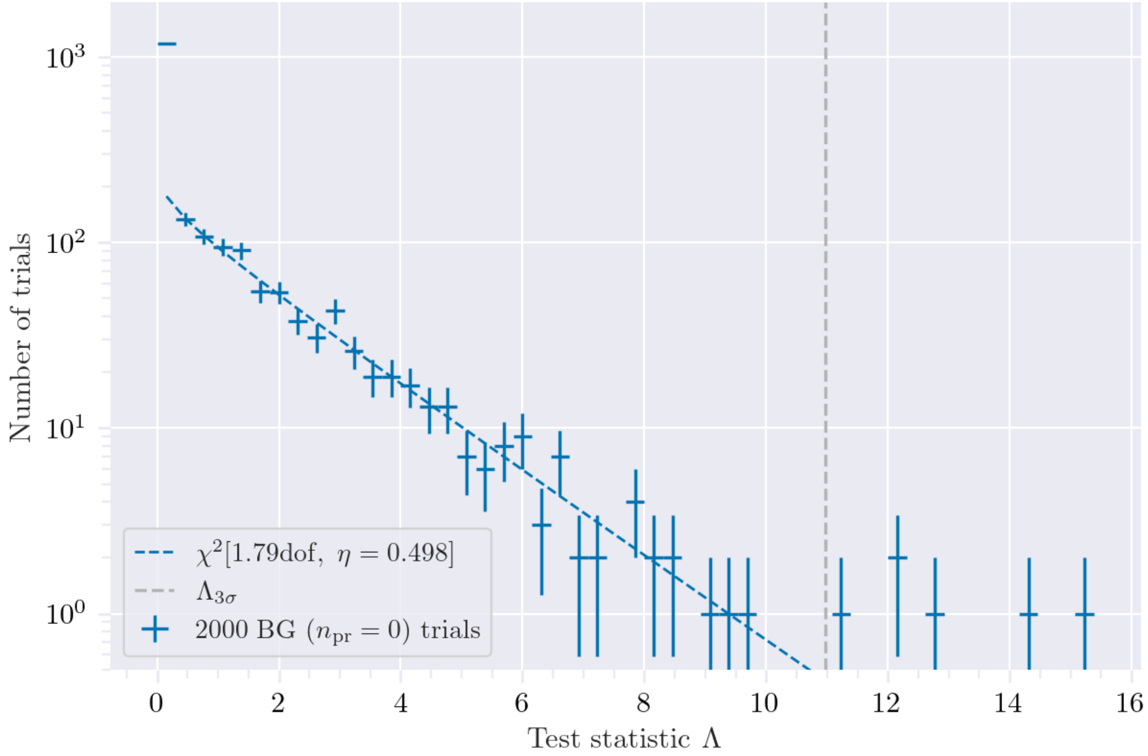


➢ Bias starts below a prompt normalization of 0.1

Cuts:
MuonFilter
Bundle energy > 100 TeV

Test background statistics





- Background statistic is χ^2 – distributed
- Assume Wilks' theorem for test statistics

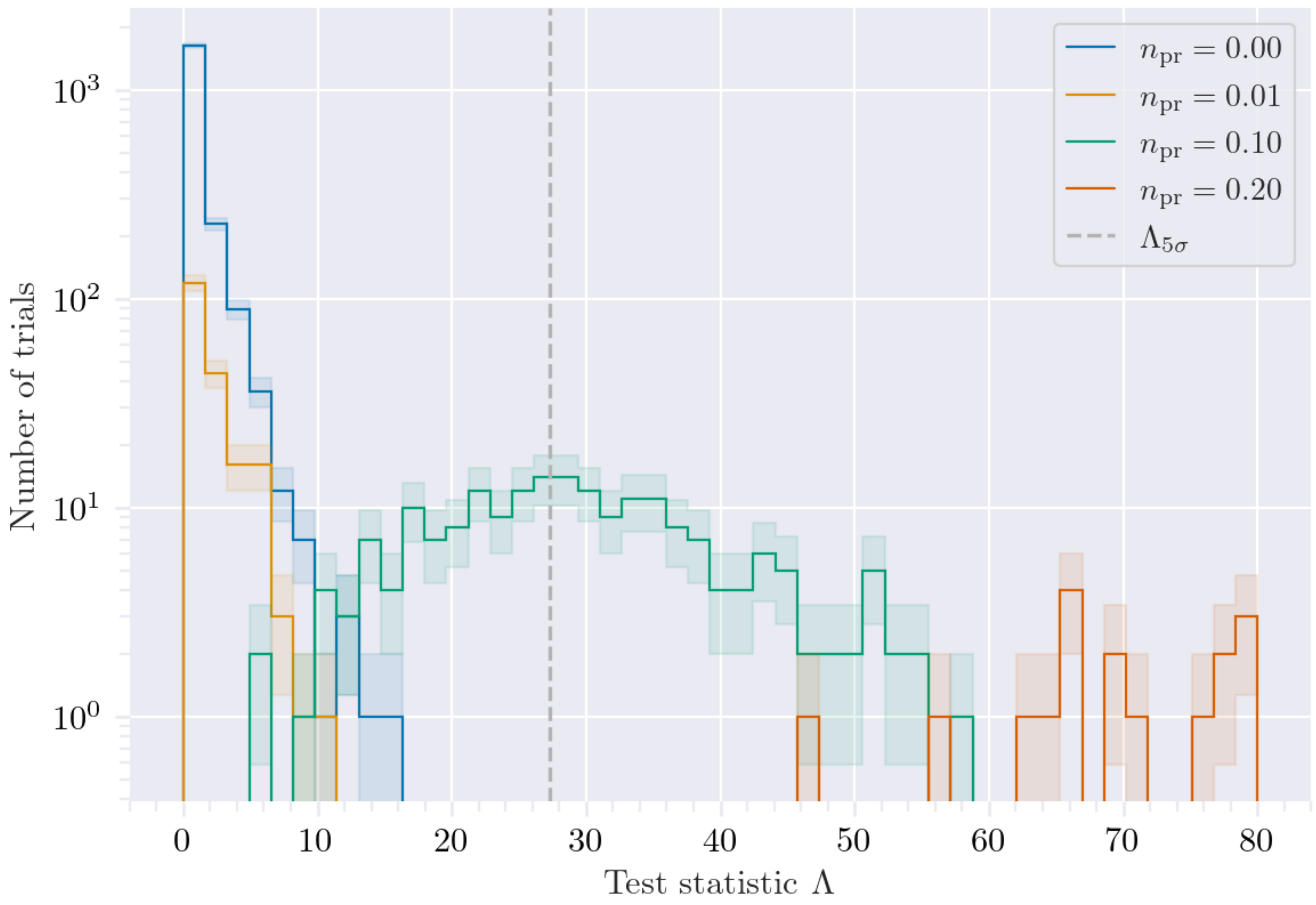
Cuts:
MuonFilter
Bundle energy > 100 TeV

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



Conclusion

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

➢ Results are promising

Outlook

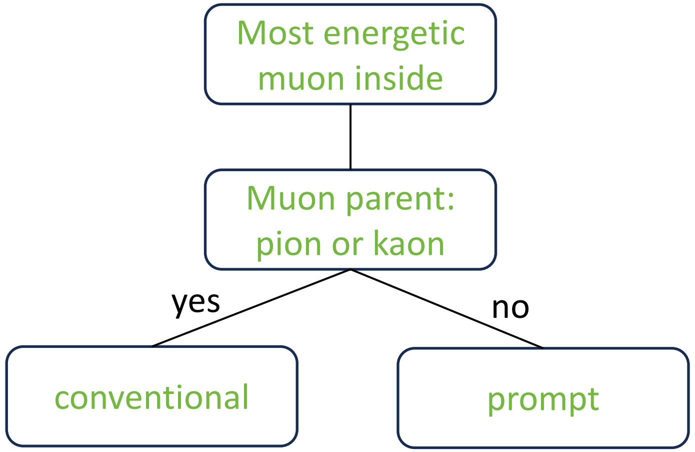
- Wiki page
- Data-MC agreement of dnn input
- Optimize DNN reconstructions
- Include systematics (snowstorm)
  - Scattering
  - Absorption
  - Anisotropy
  - Hole ice 1
  - Hole ice 2
  - Dom efficiency
  - Conventional normalization
  - ❖ We do not include systematics of the primary fluxes, instead 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?

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:

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

prompt component:

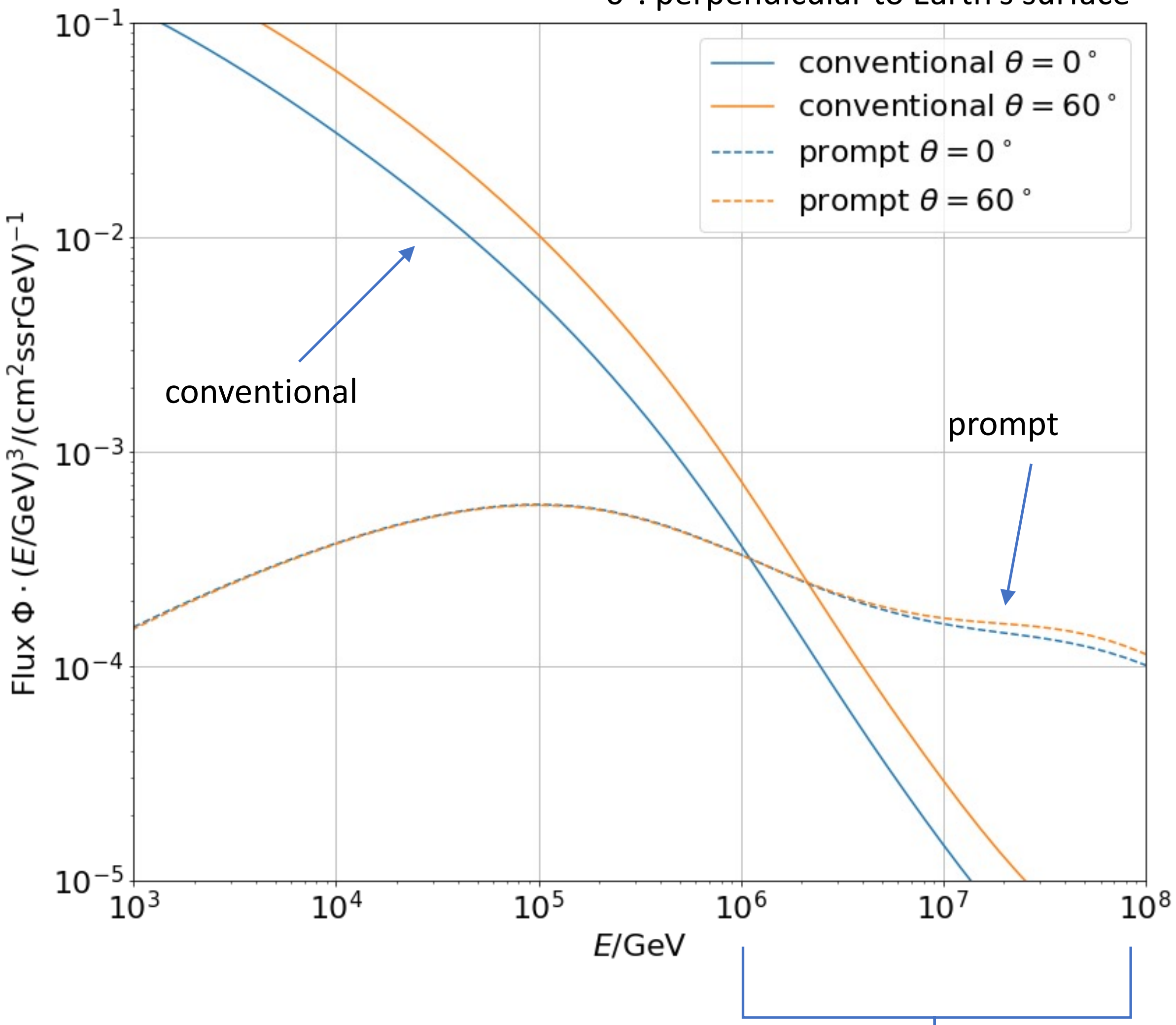
$$\underset{\propto E^{-2.7}}{p} \rightarrow \overbrace{D^{+}}^{\tau = 1.04\cdot 10^{-12}\,\mathrm{s}} \rightarrow \bar{K}^{0} + \underset{\propto E^{-2.7}}{\mu^{+}} + \nu_{\mu}$$

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

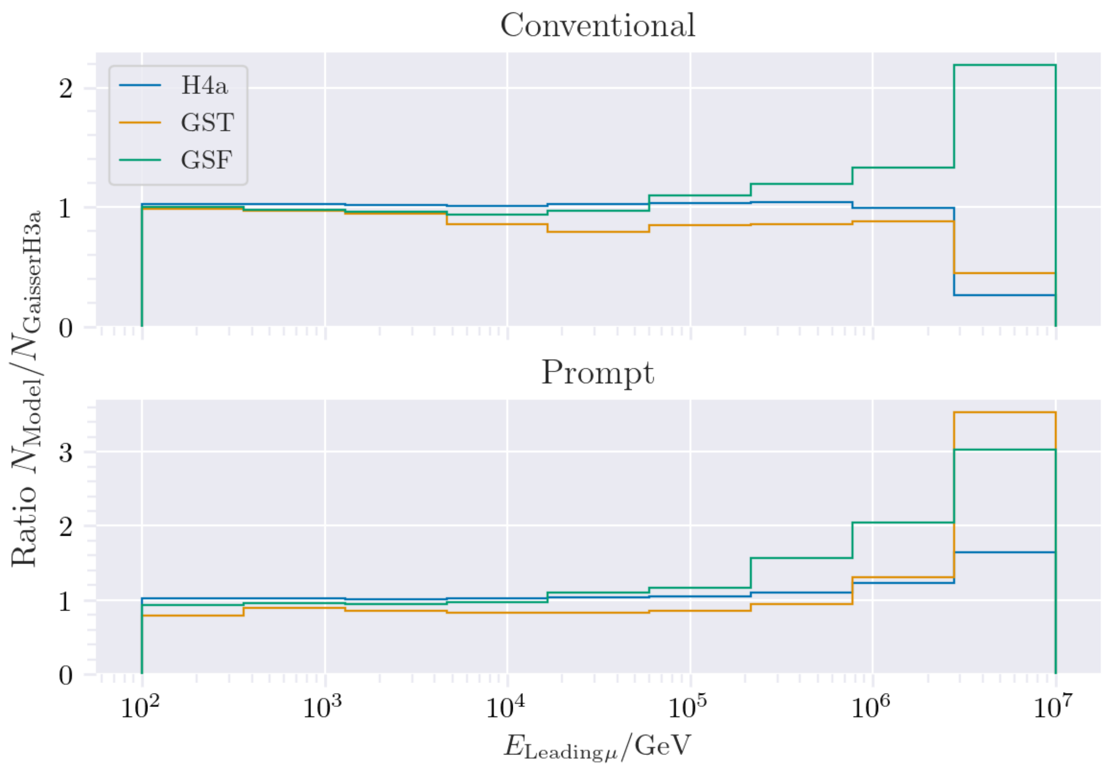
0°: perpendicular to Earth's surface



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

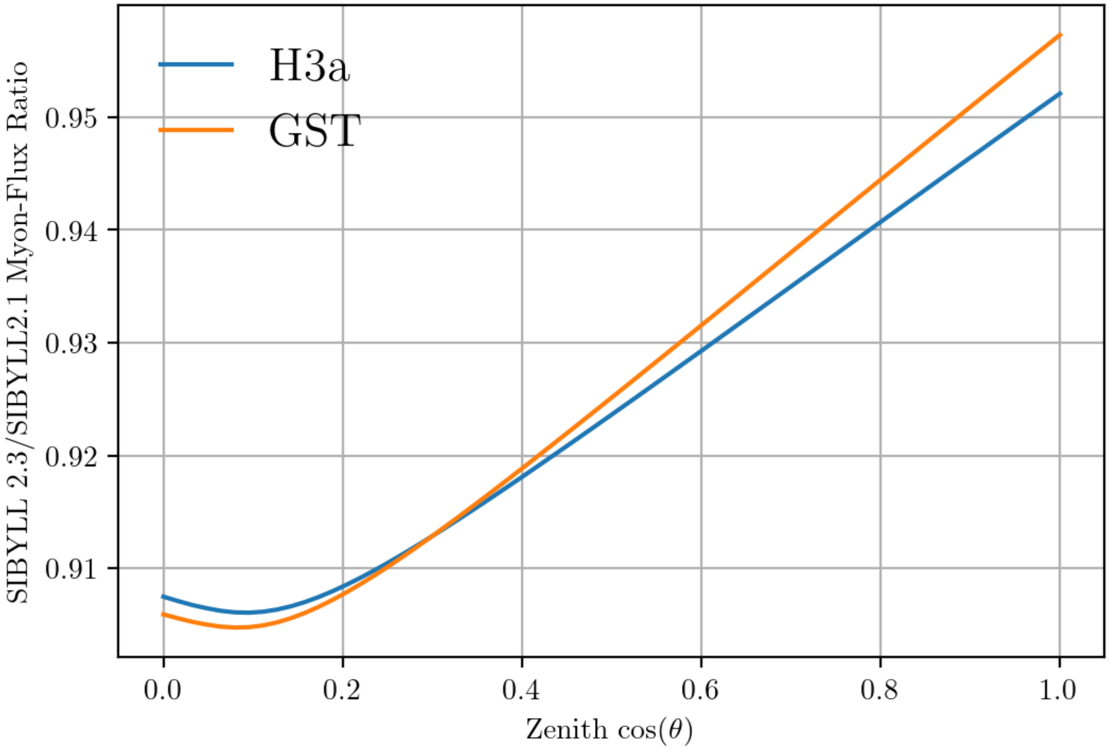
Muon production – different weightings

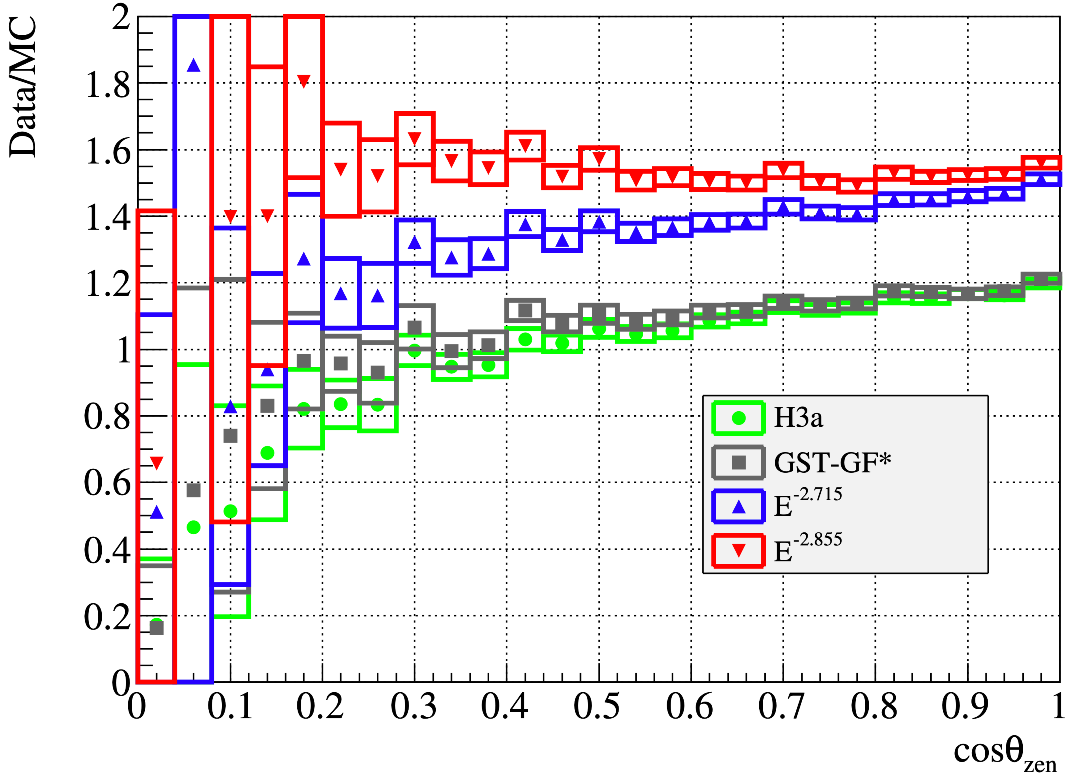
GST predicts most prompt



MCLabelsLeadingMuons_entry_energy

Solution to zenith problem?



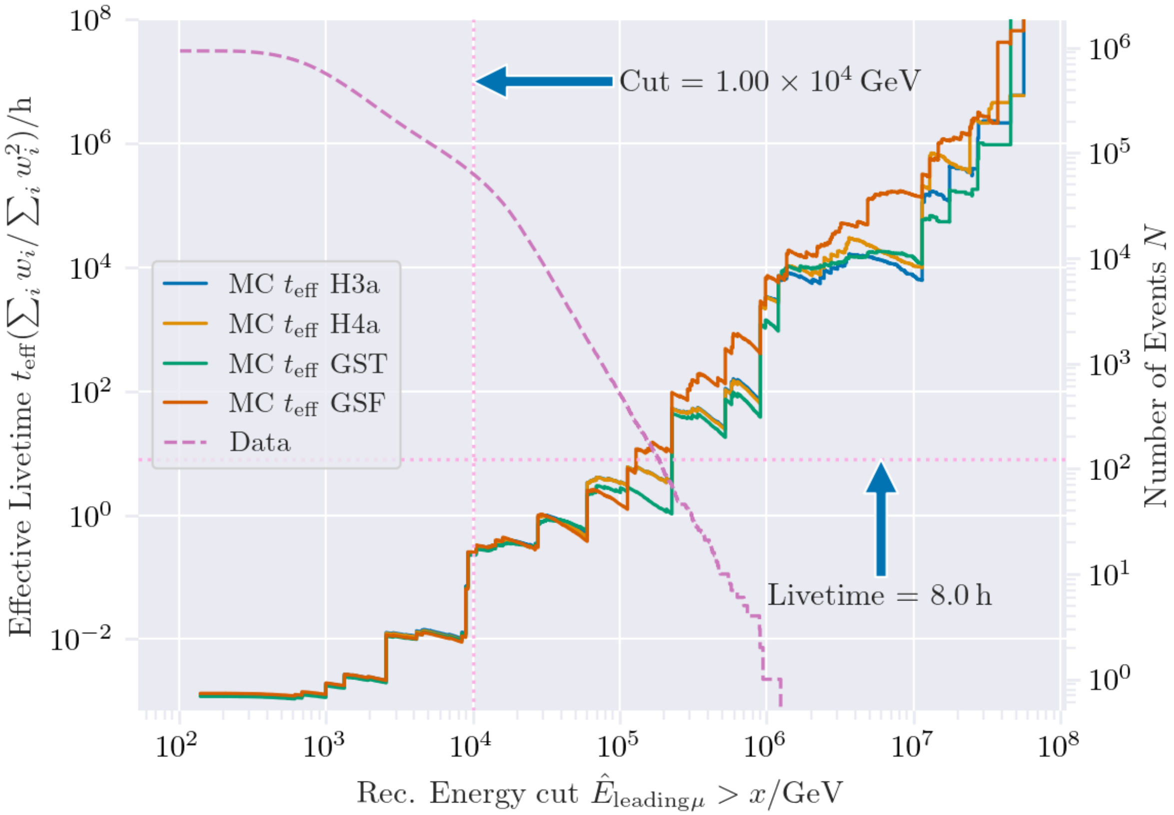


➢ No complete solution, but a step in the right direction

New CORSIKA extended history simulations

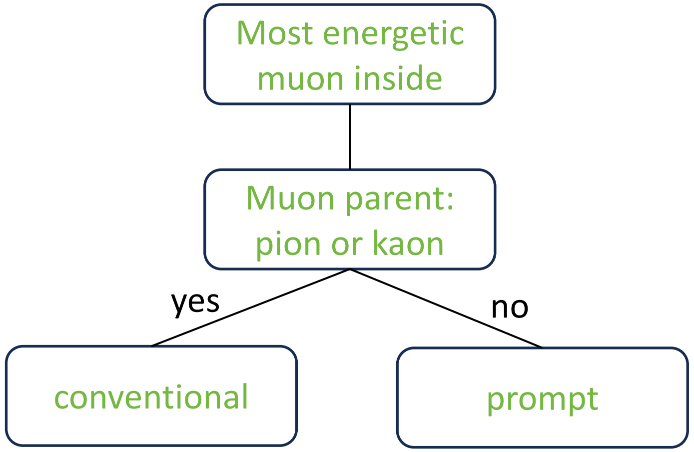
- CORSIKA 77420
- SIBYLL 2.3d
- Icetray 1.5.1
- 5 components (p, He, N, Al, Fe)
- Polyplopia: True
- Trimshower: True
- Ecuts1: 273 GeV (hadron min energy)
- Ecuts2: 273 GeV (muon min energy)
- Ecuts3: 10^{20} GeV (electron min energy)
- Ecuts4: 10^{20} GeV (photon min energy)
- 4 datasets:
  - 30010: 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



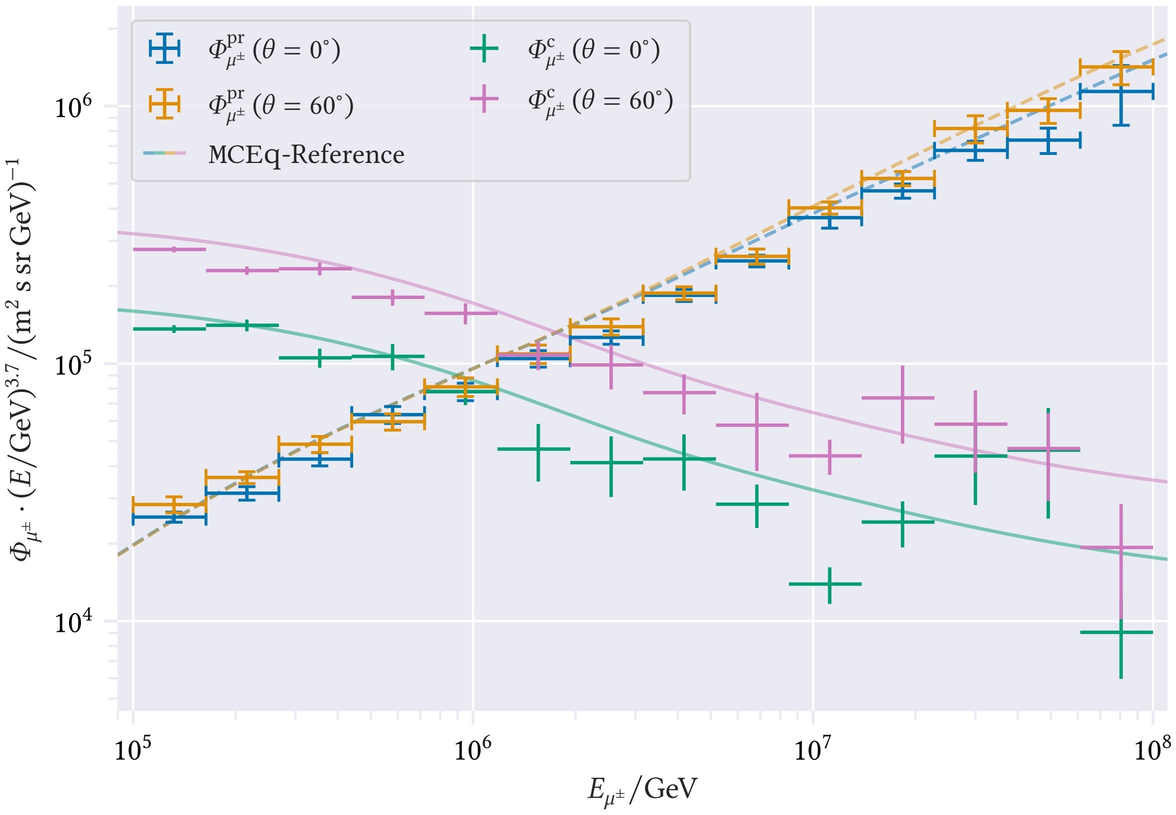
- ➢ Sufficient statistics above 1 PeV
- ➢ Too few statistics at lower energies

CORSIKA vs. MCEq

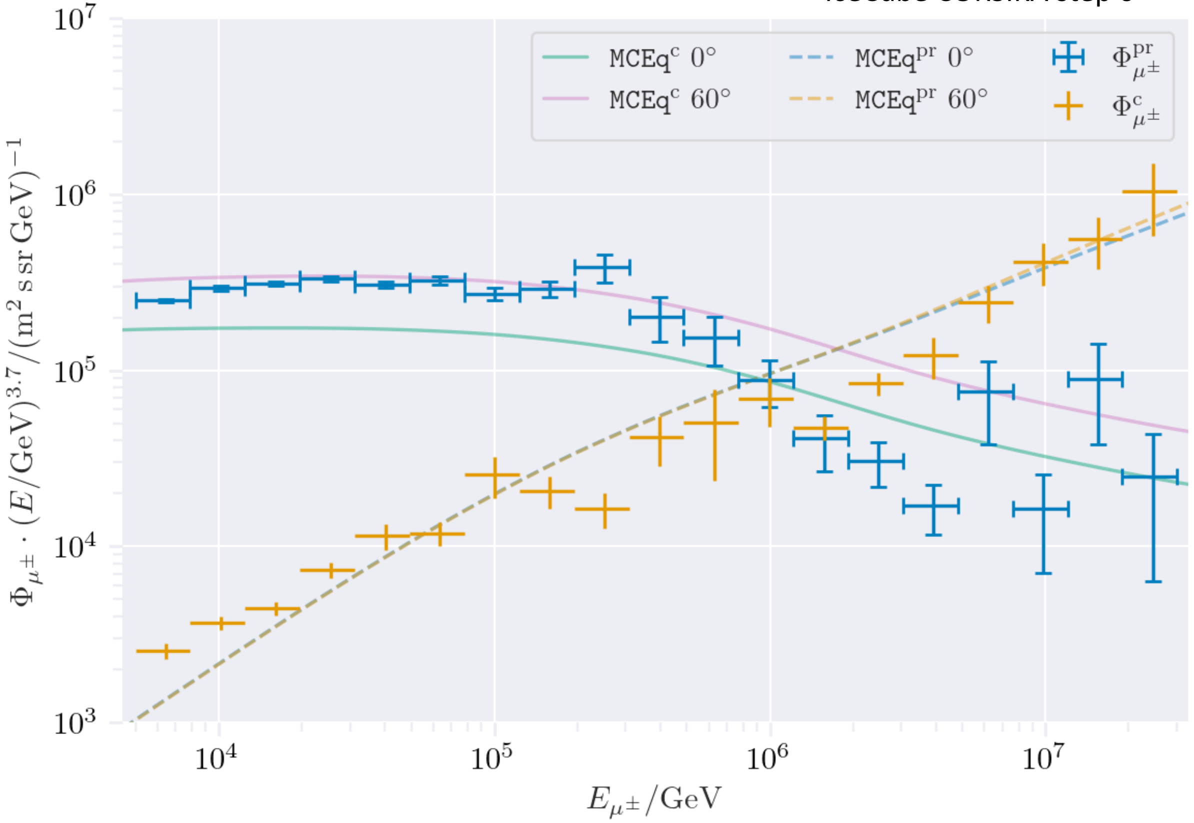


- Good agreement

CORSIKA standalone



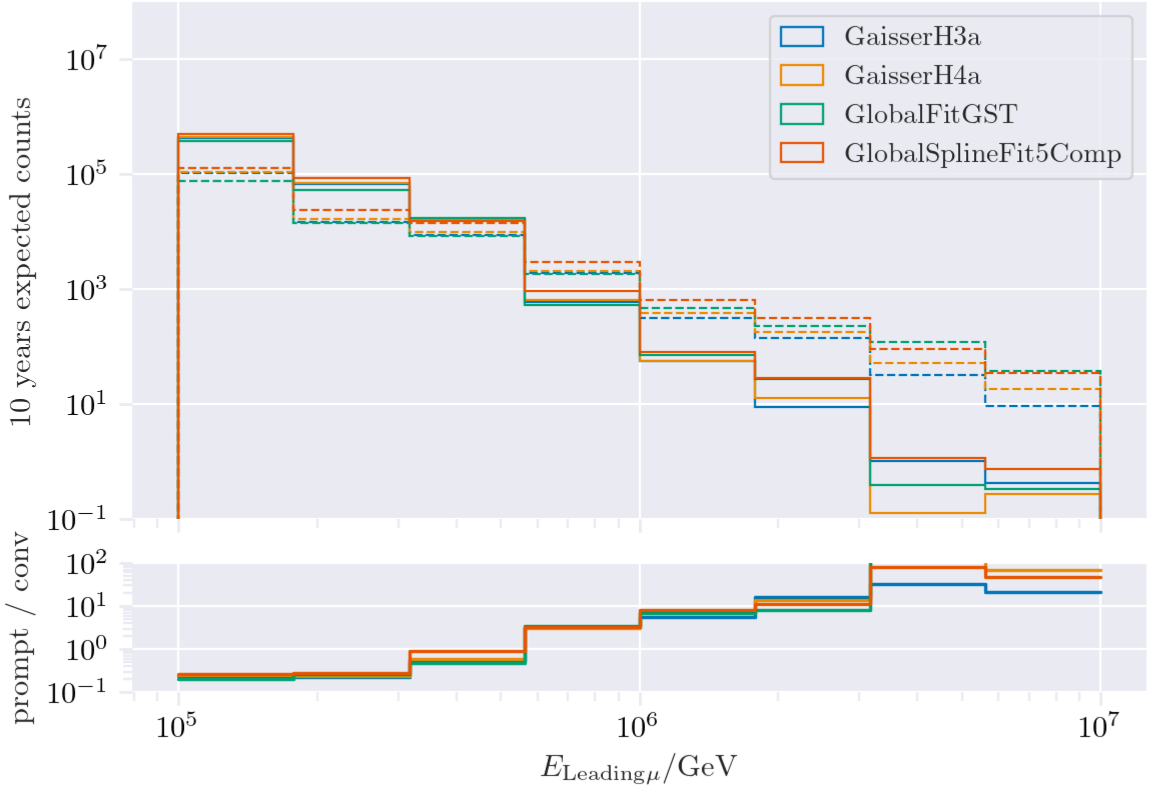
IceCube CORSIKA step 0

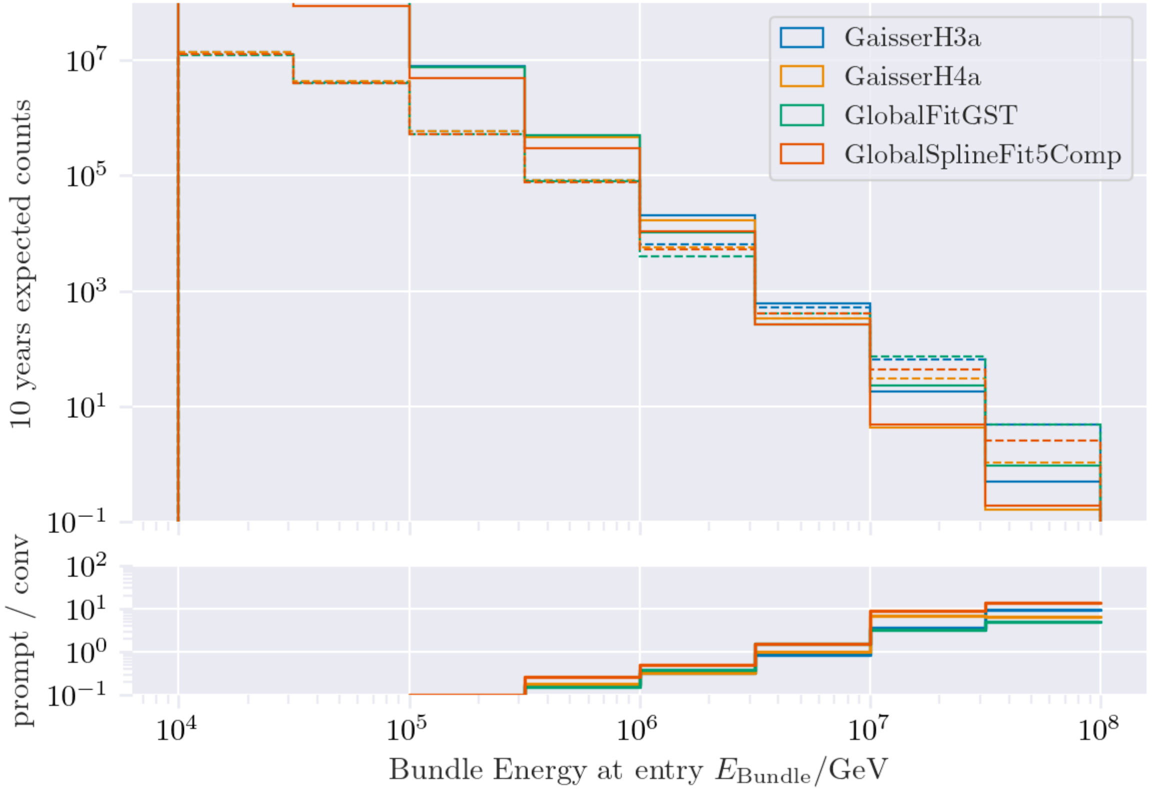


- For detailed information, see the talk by Ludwig Neste at the upcoming collaboration meeting

Expected muons for 10 years: leading vs. bundle energy

Solid: conventional
Dashed: prompt

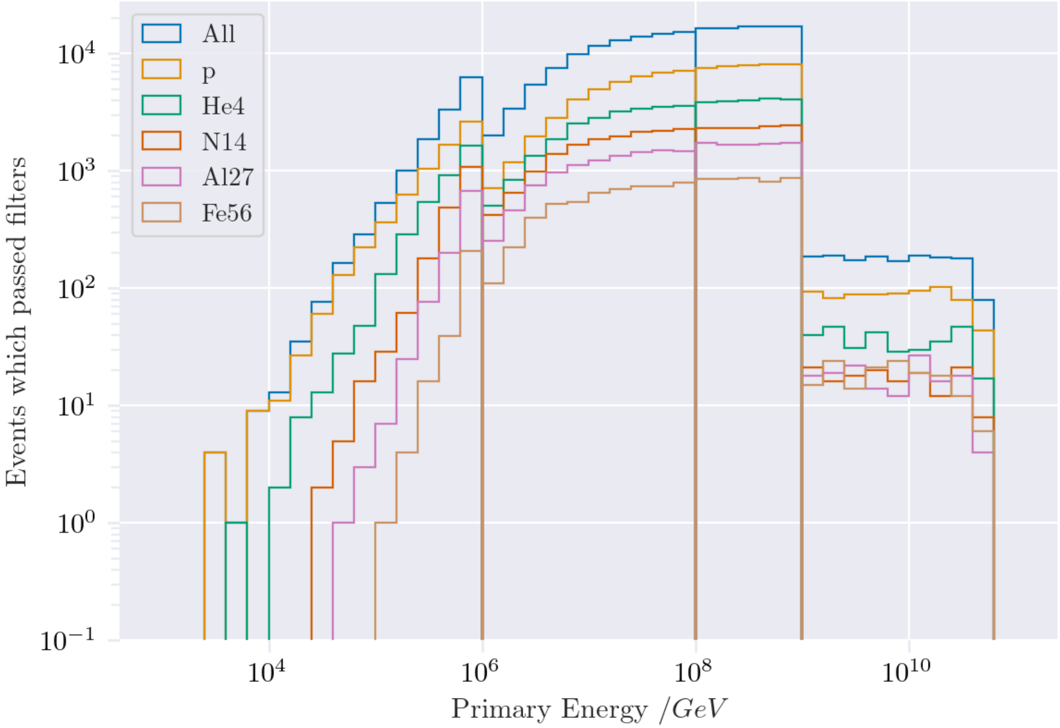




- Different primary fluxes lead to different prompt fluxes
- Bundle energy extends to higher energies

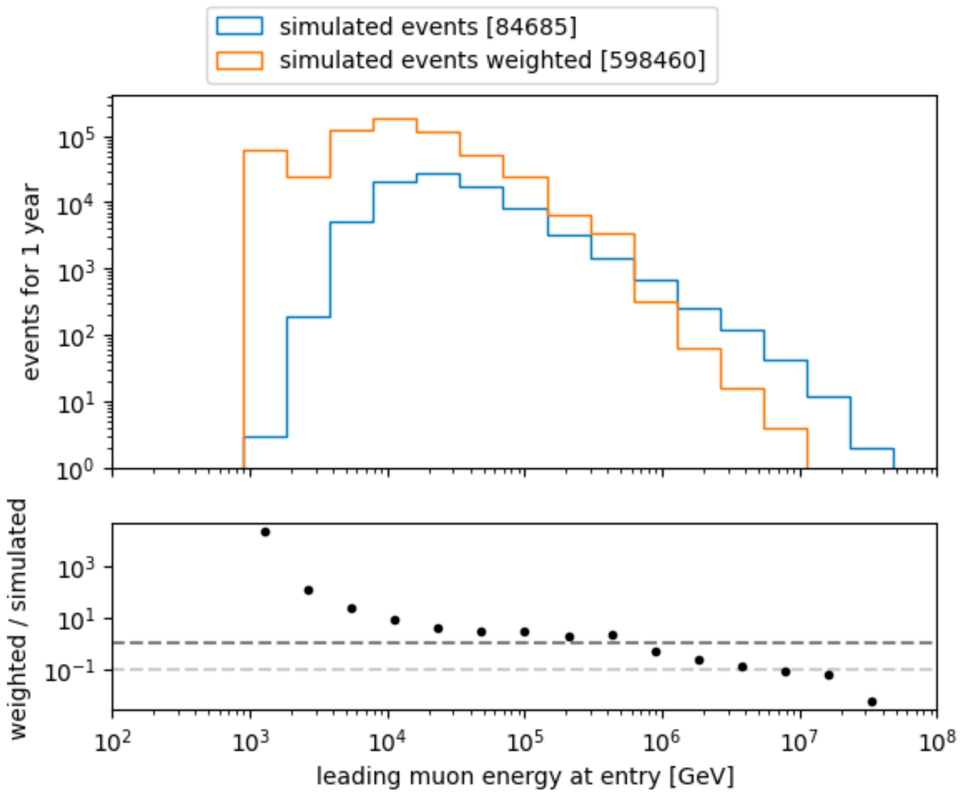
Simulated events

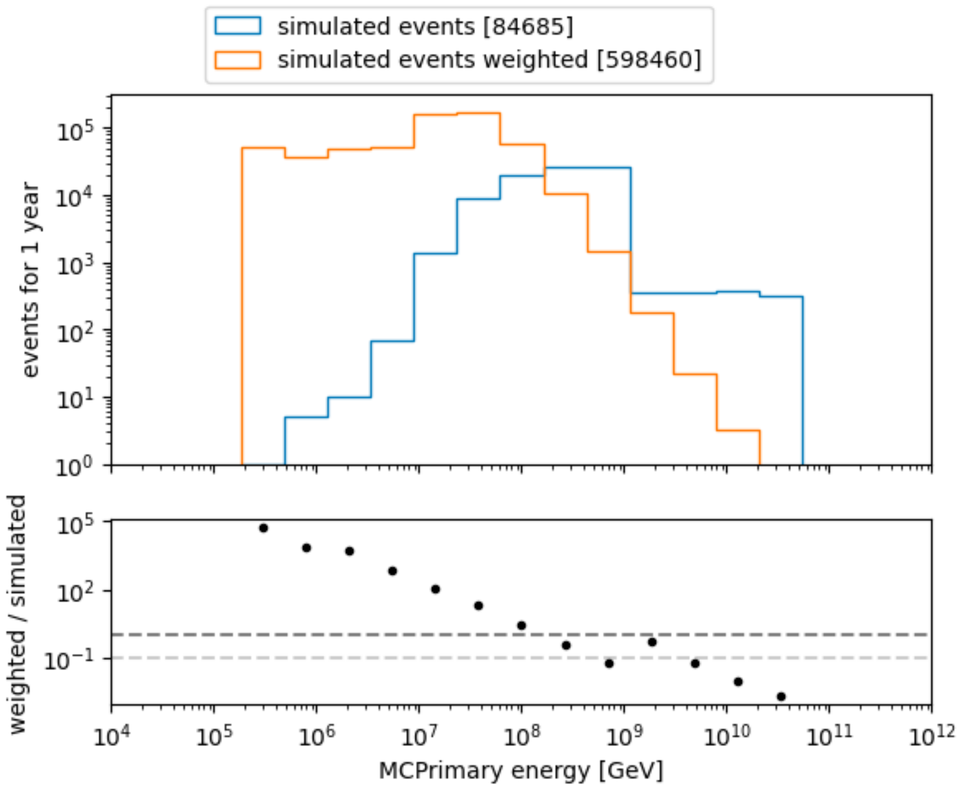
Passed muon filter



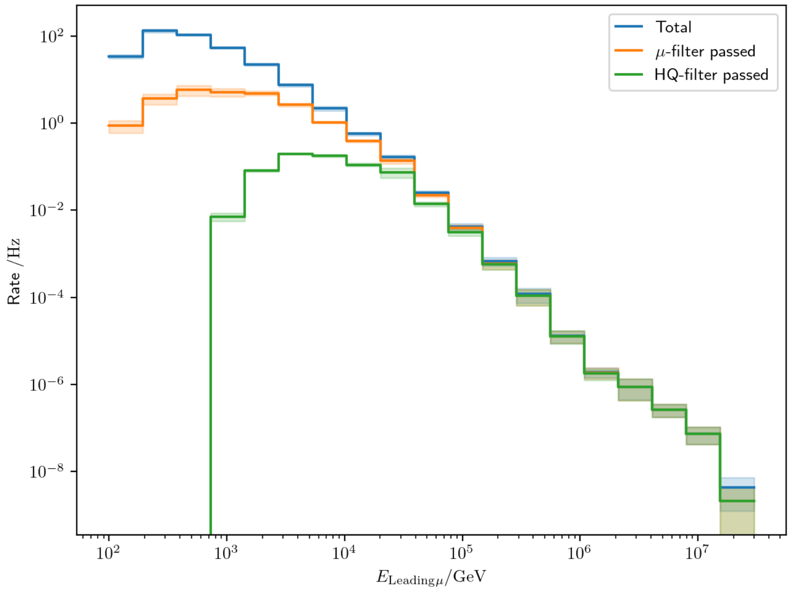
Which energies to we need to simulate?

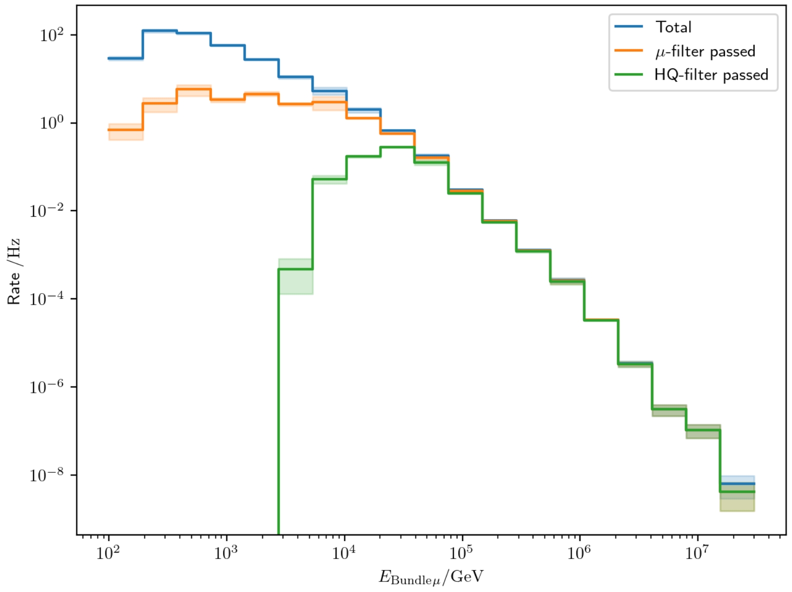
L2 MuonFilter
Bundle energy > 100 TeV



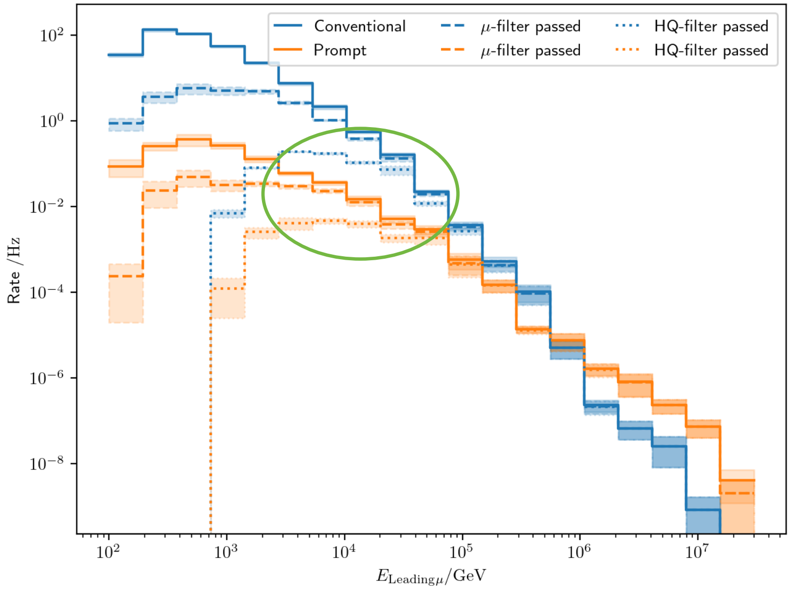


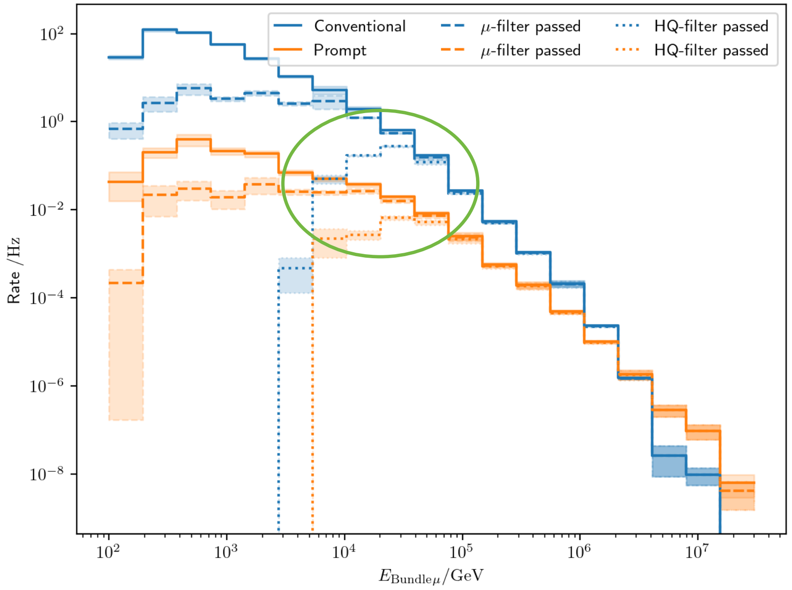
Filters



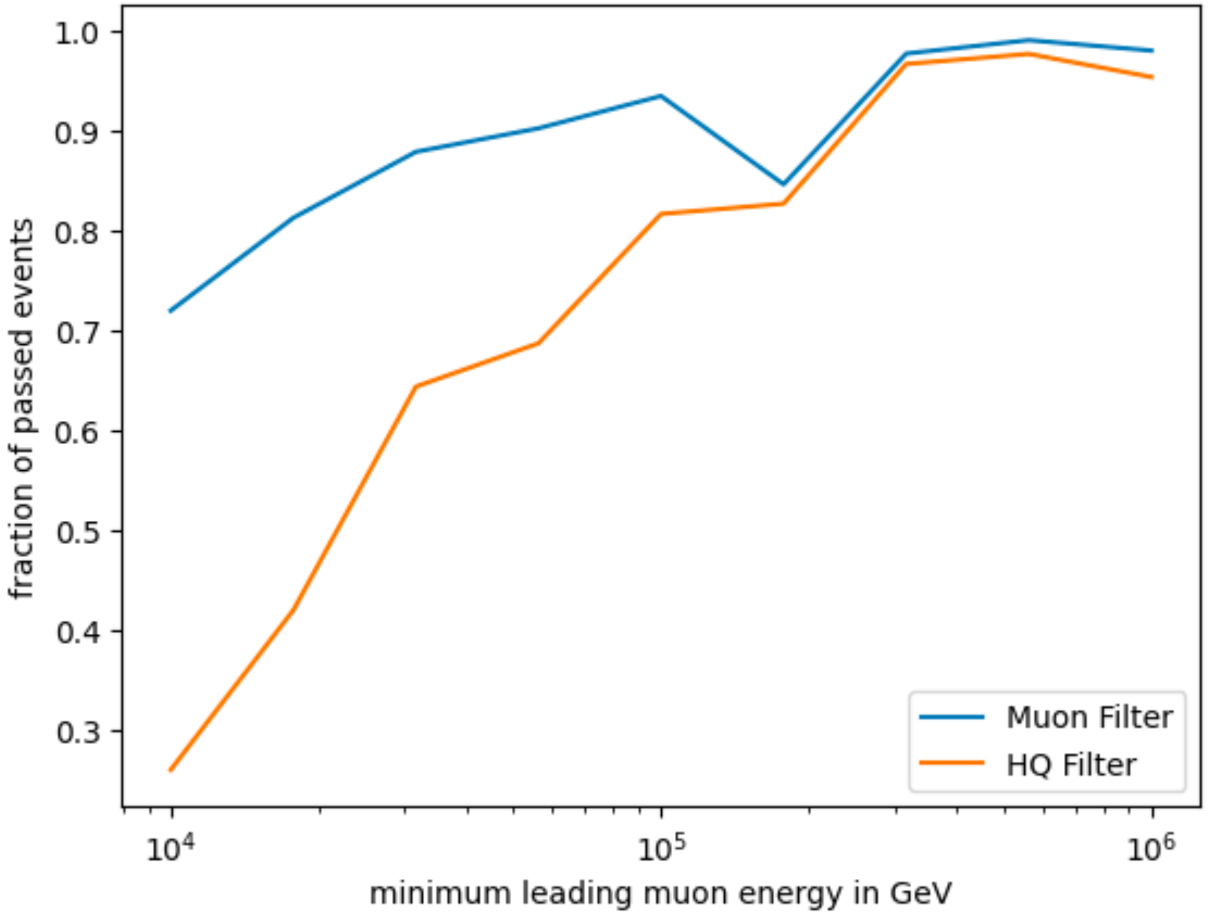


Choose muon filter,
larger statistics at 10 TeV

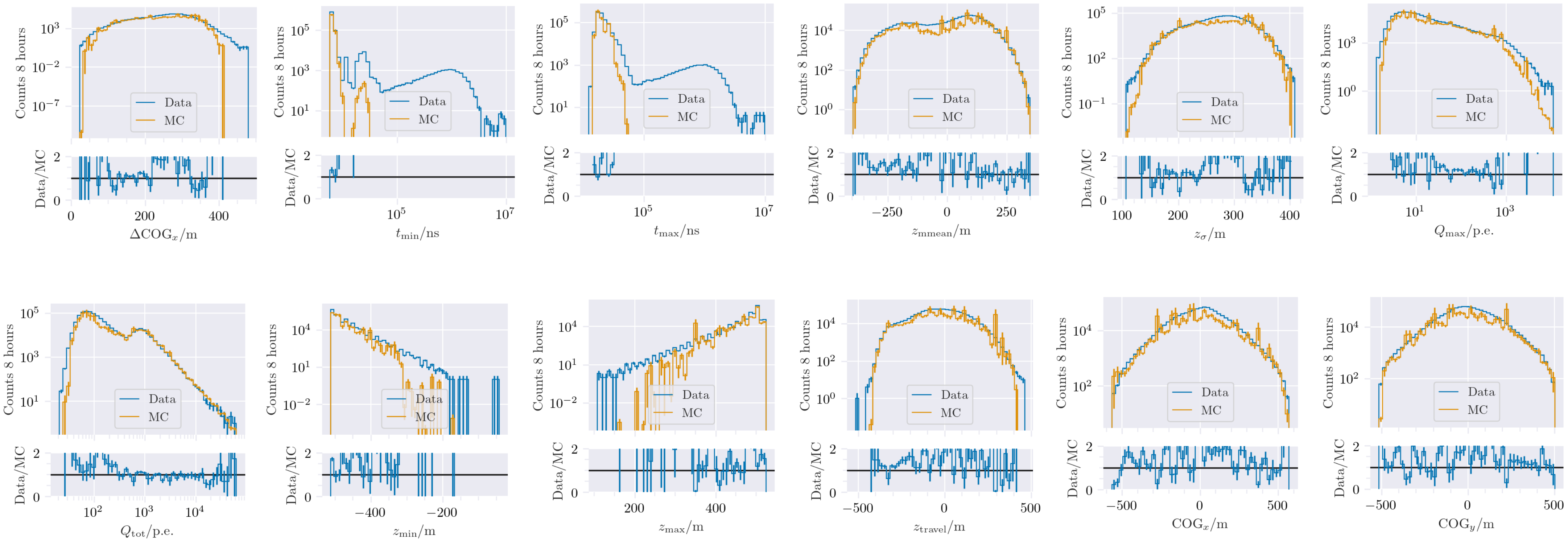


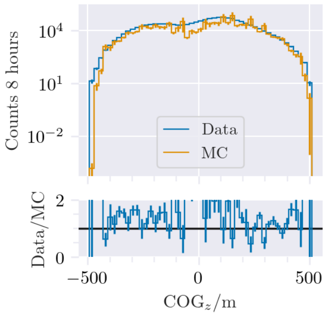


Filters – passed events per leading energy



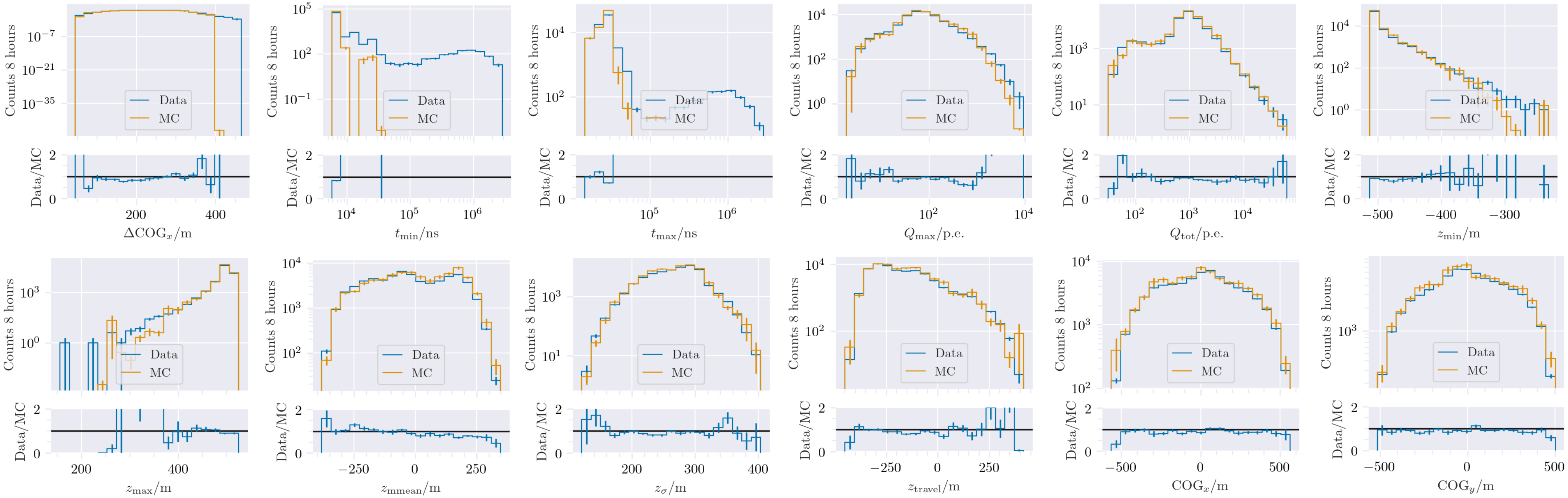
Data-MC: HitStatistics - SplitInIceDSTPulses

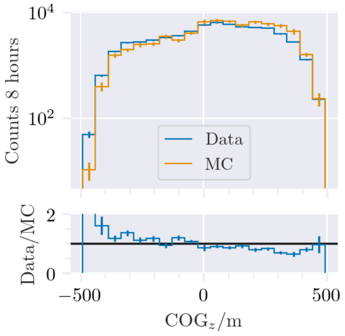




L2 MuonFilter
No further exclusions

Data-MC: HitStatistics - SplitInIceDSTPulses





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:

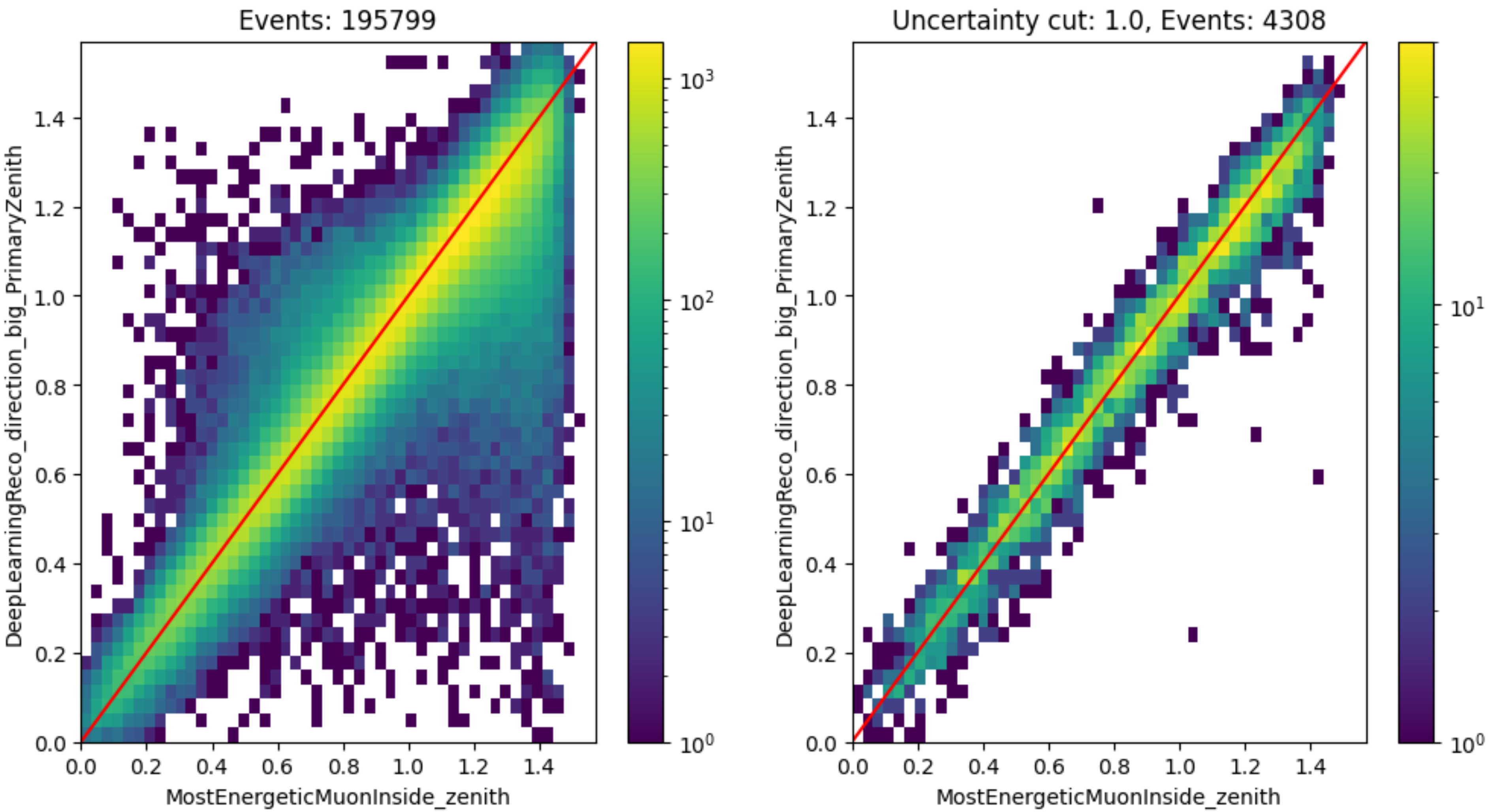
- Leading energy
- Leading fraction
- Bundle energy
- Multiplicity
- Azimuth
- Zenith

Work in progress

General:

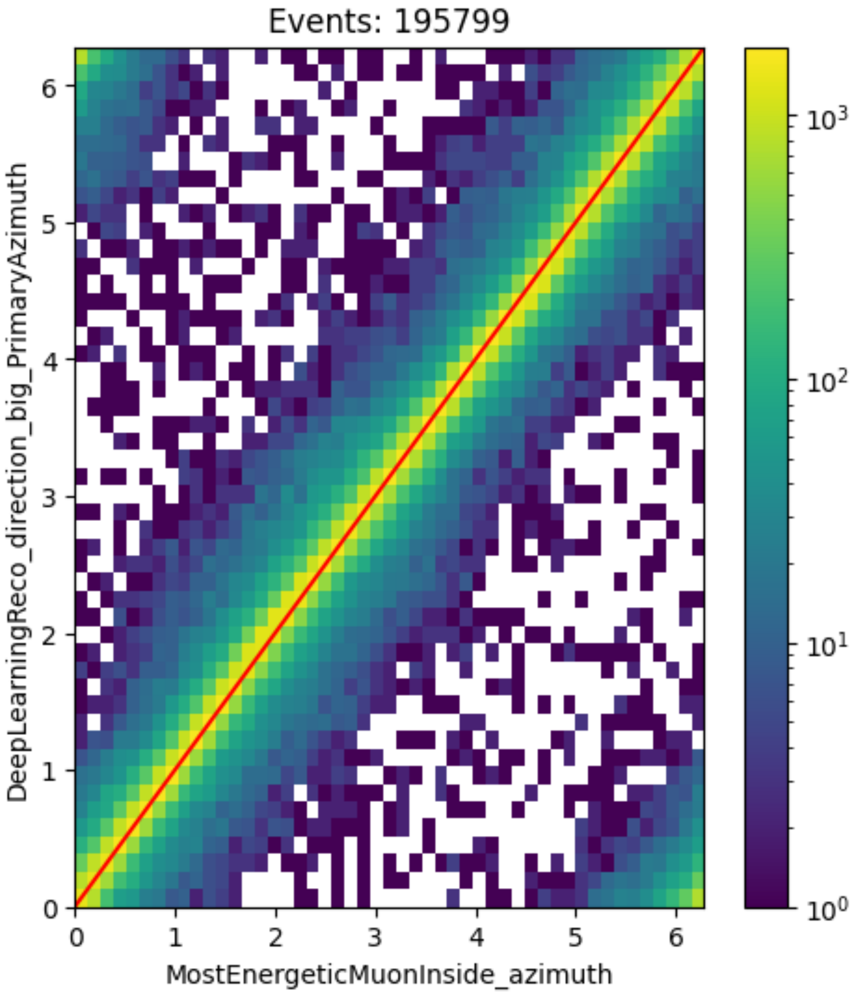
- Trained on uncleaned and 6µs cleaned muon pulses
- Processed 8h of experimental data (June 4th, 2020)

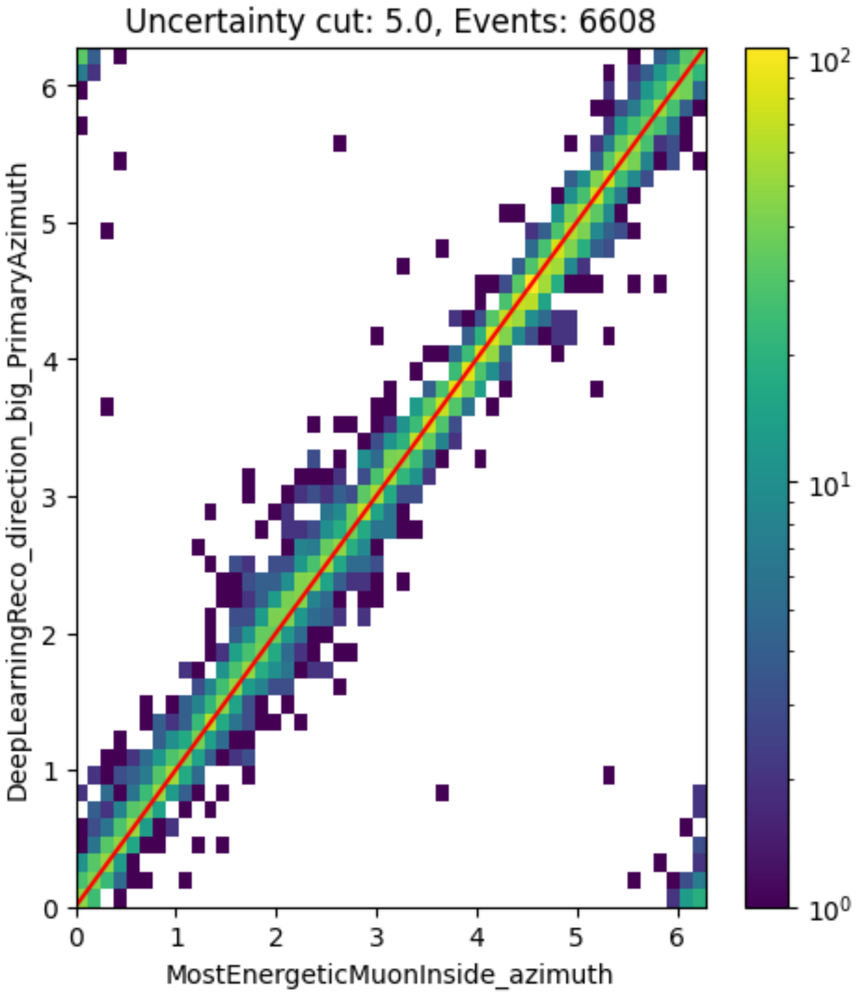
Zenith reconstructions



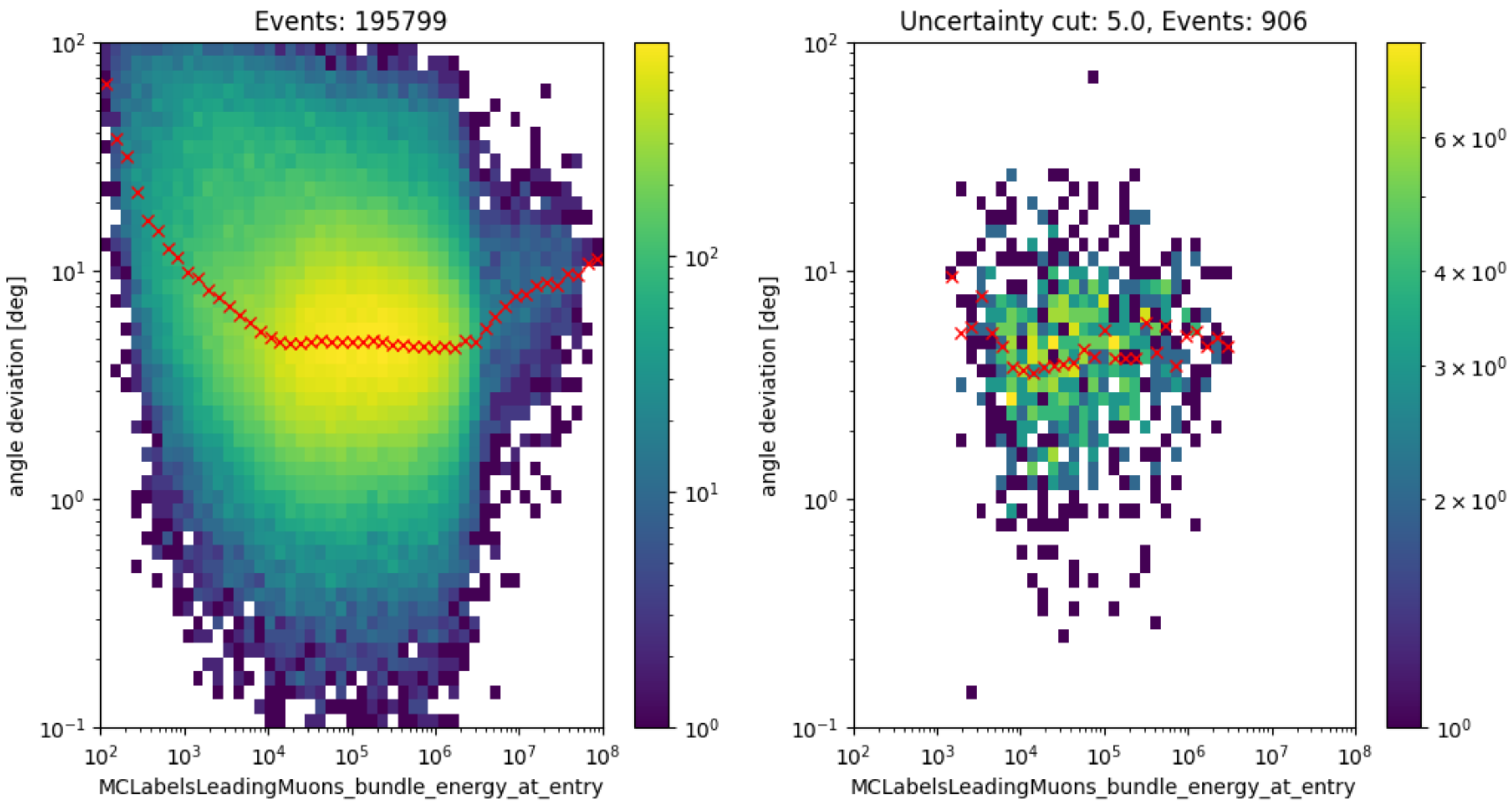
tu dortmund university

Azimuth reconstructions





Angular resolution



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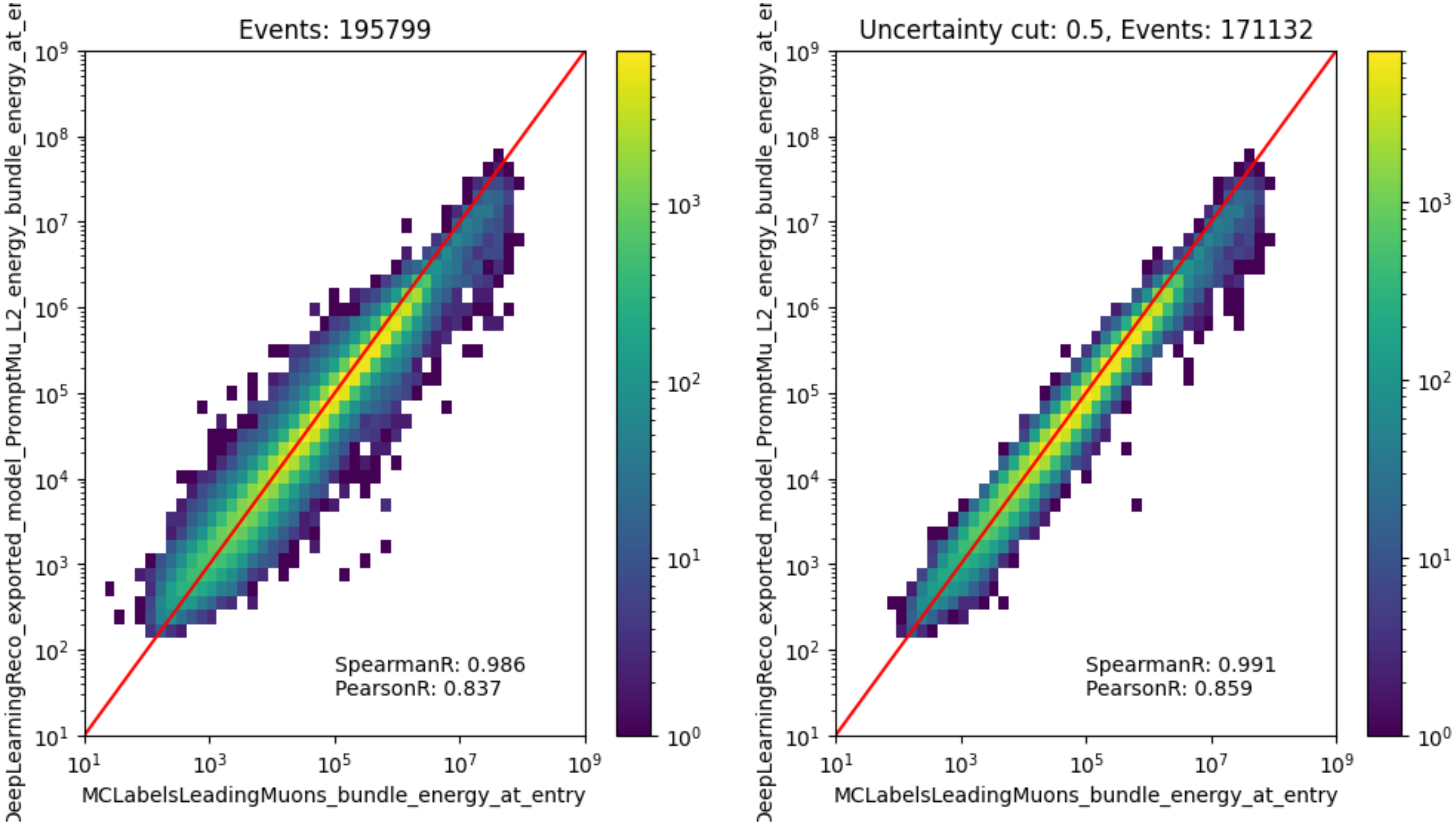
Bundle energy reconstruction



Leading energy reconstruction