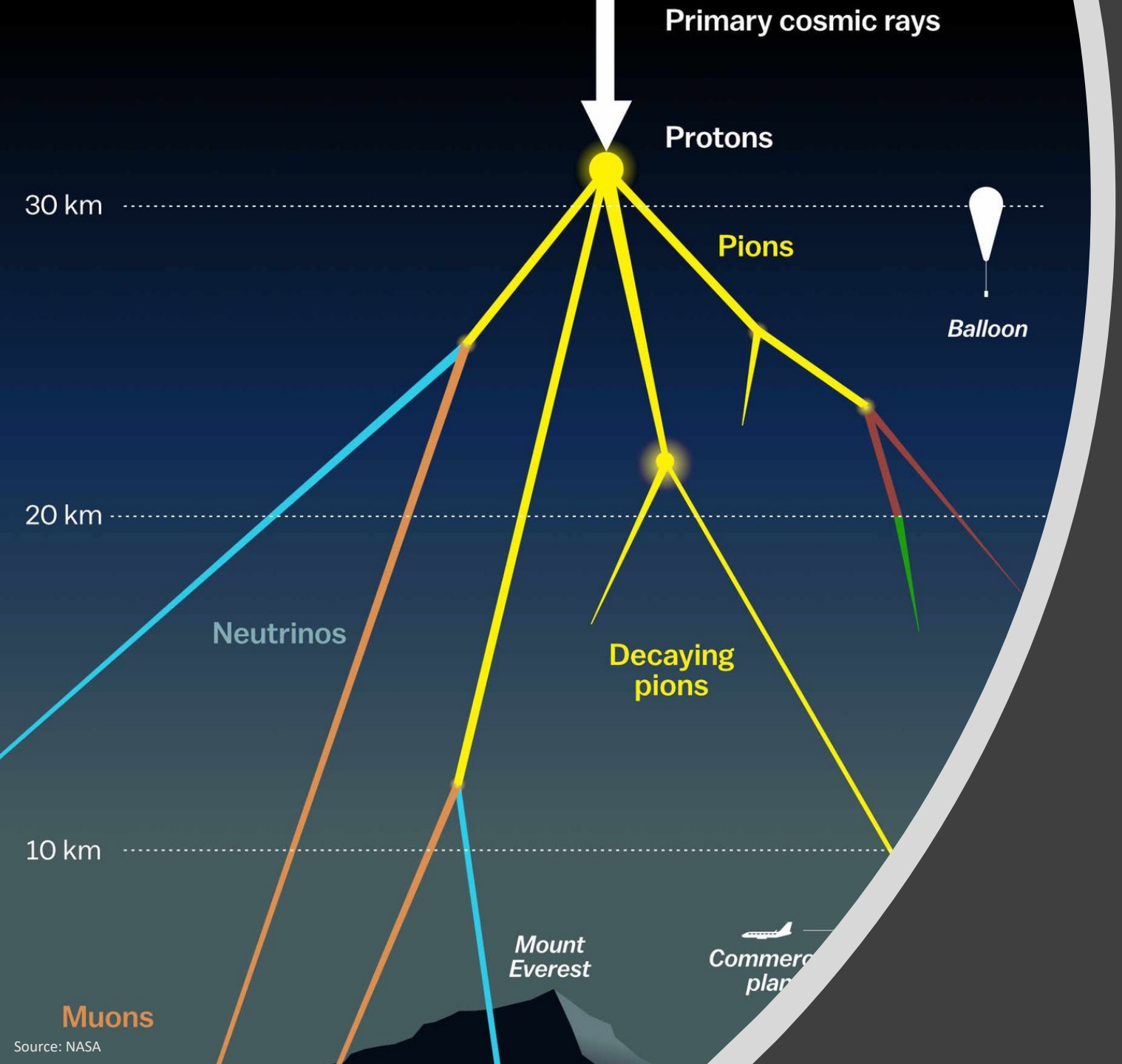
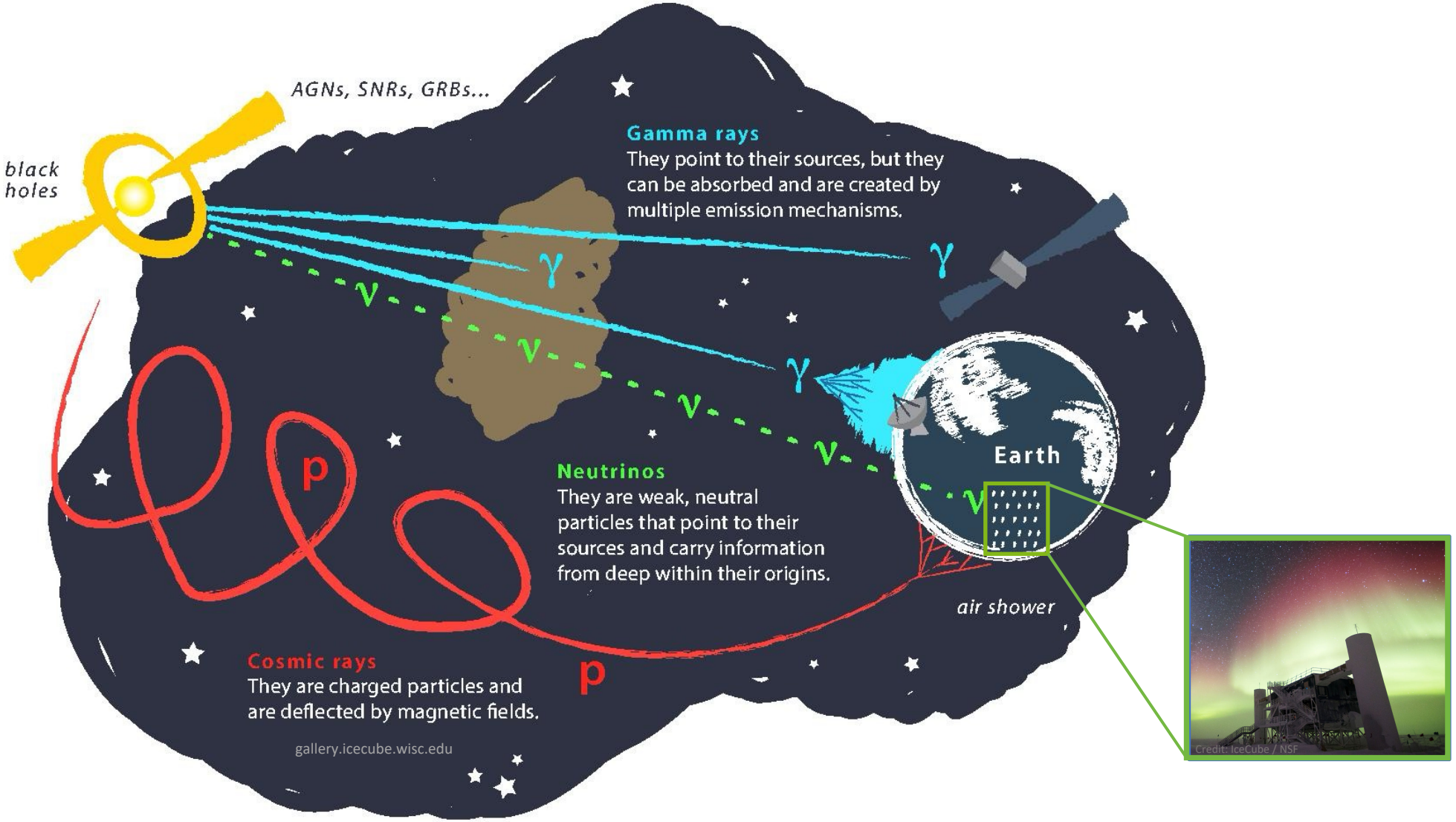


An analysis concept to measure atmospheric prompt muons with IceCube

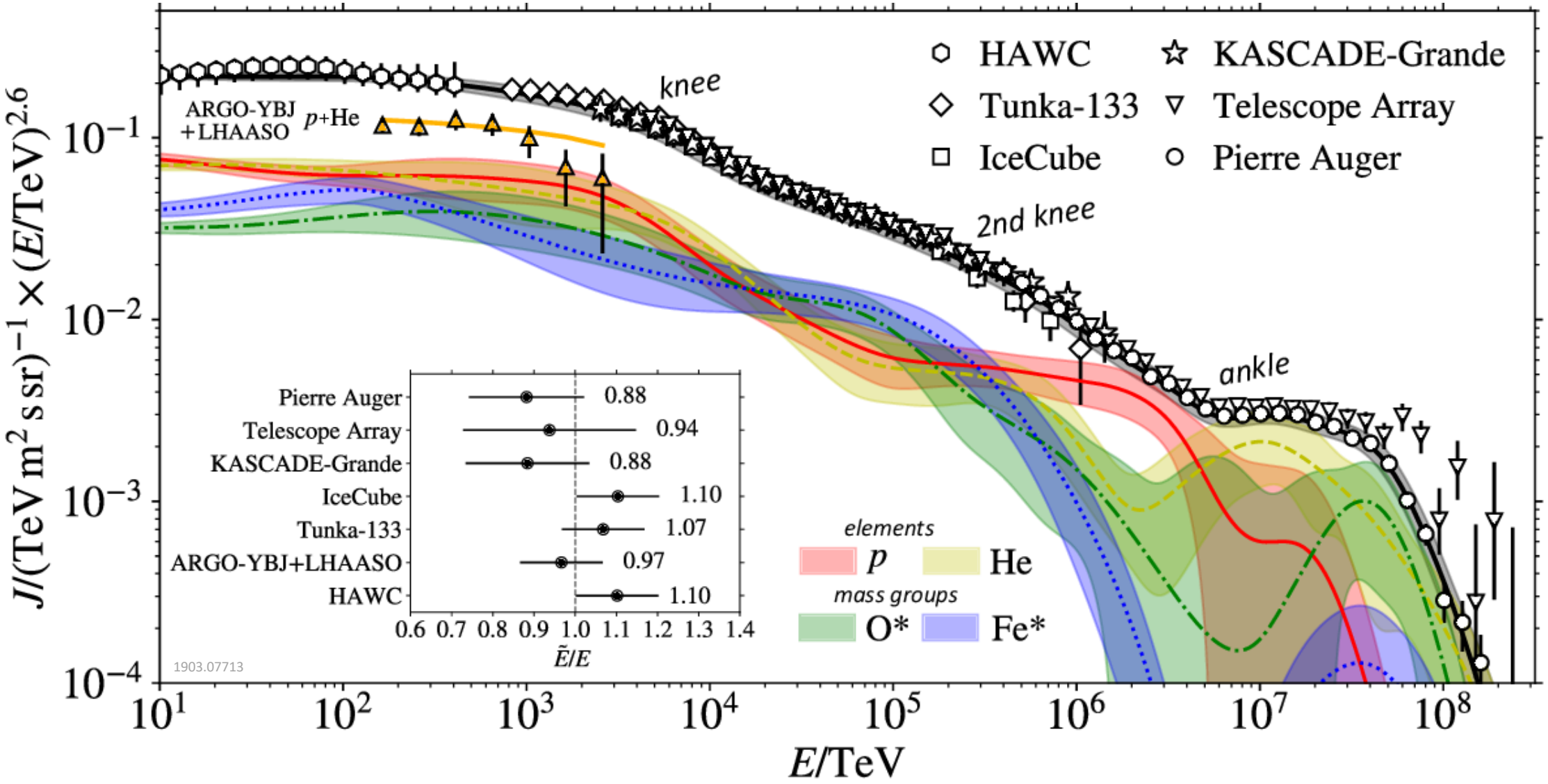
Pascal Gutjahr and Mirco Hünnefeld

DPG-Frühjahrstagung, Karlsruhe 2024

Astroparticle physics

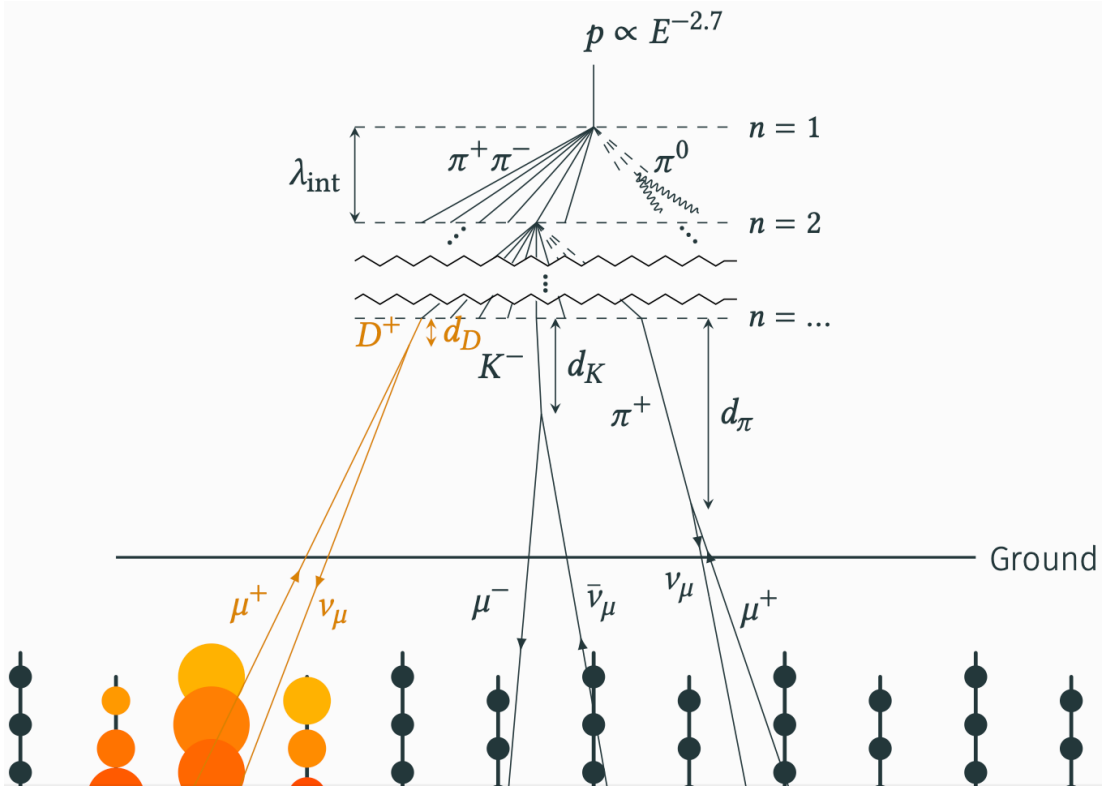


Cosmic ray flux



Muon flux: Definition of prompt

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

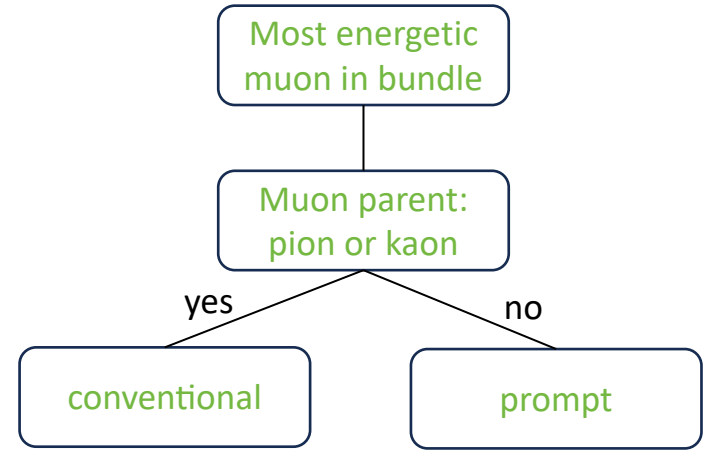


prompt component:

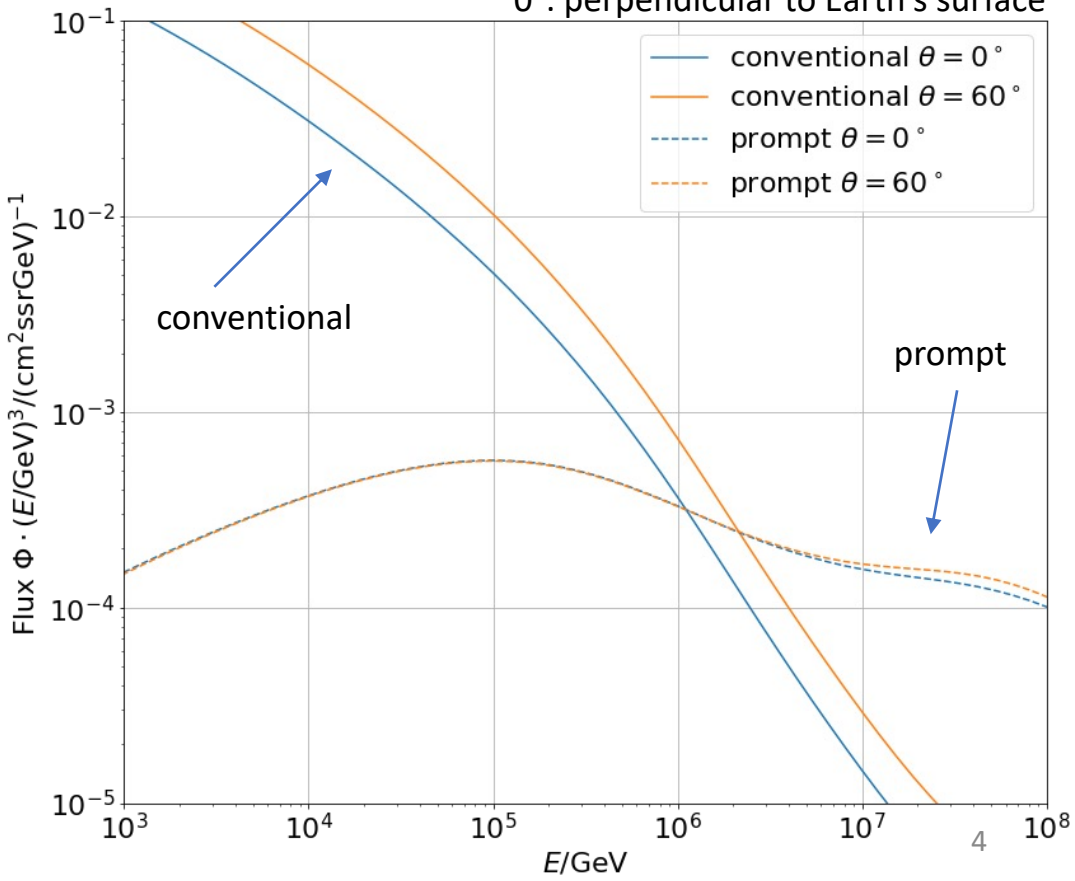
$$p \xrightarrow[\propto E^{-2.7}]{\tau = 1.04 \cdot 10^{-12}\,\text{s}} D^+ \xrightarrow[\propto E^{-2.7}]{} \bar{K}^0 + \mu^+ + \nu_\mu$$

Conventional component:

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



0°: perpendicular to Earth's surface



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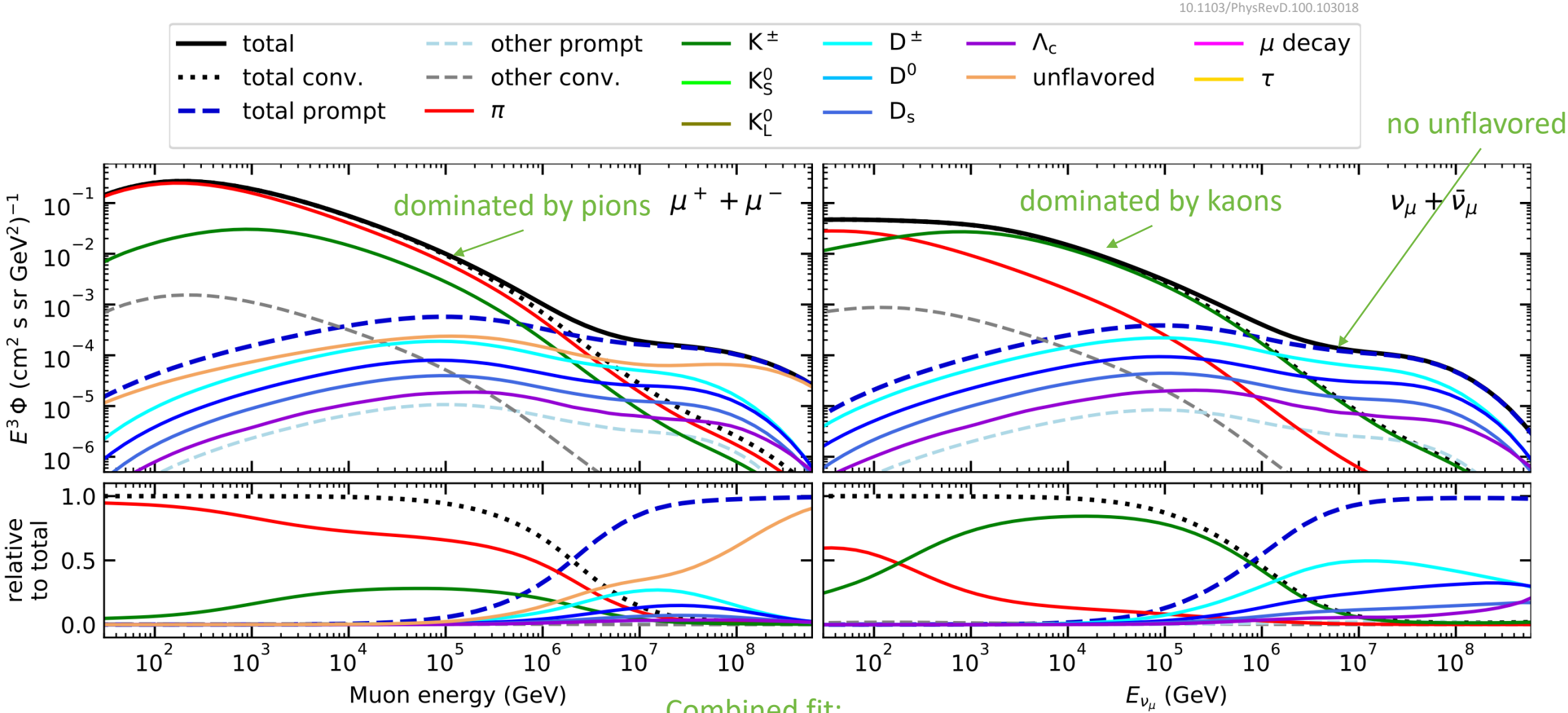
Prompt atmospheric muons and neutrinos

10.1103/PhysRevD.100.103018



Combined fit:

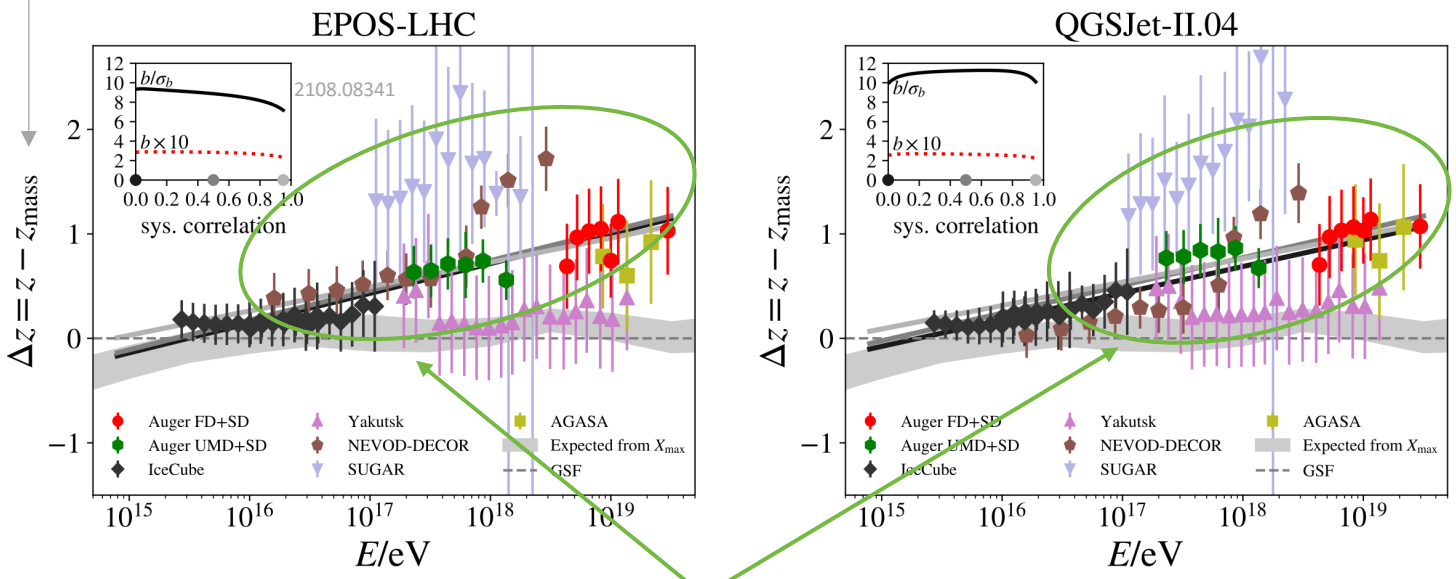
- handle on pion/kaon ratio
- handle on charmed mesons

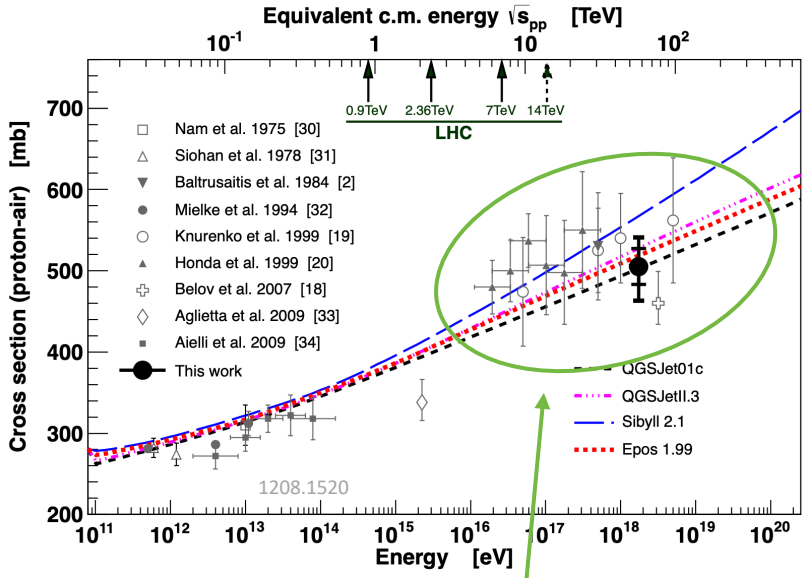
Muon Puzzle and model uncertainties

”muon number”

Expected z
(“muon number”)

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





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

➢ Large uncertainties at E > 10 PeV

Intention

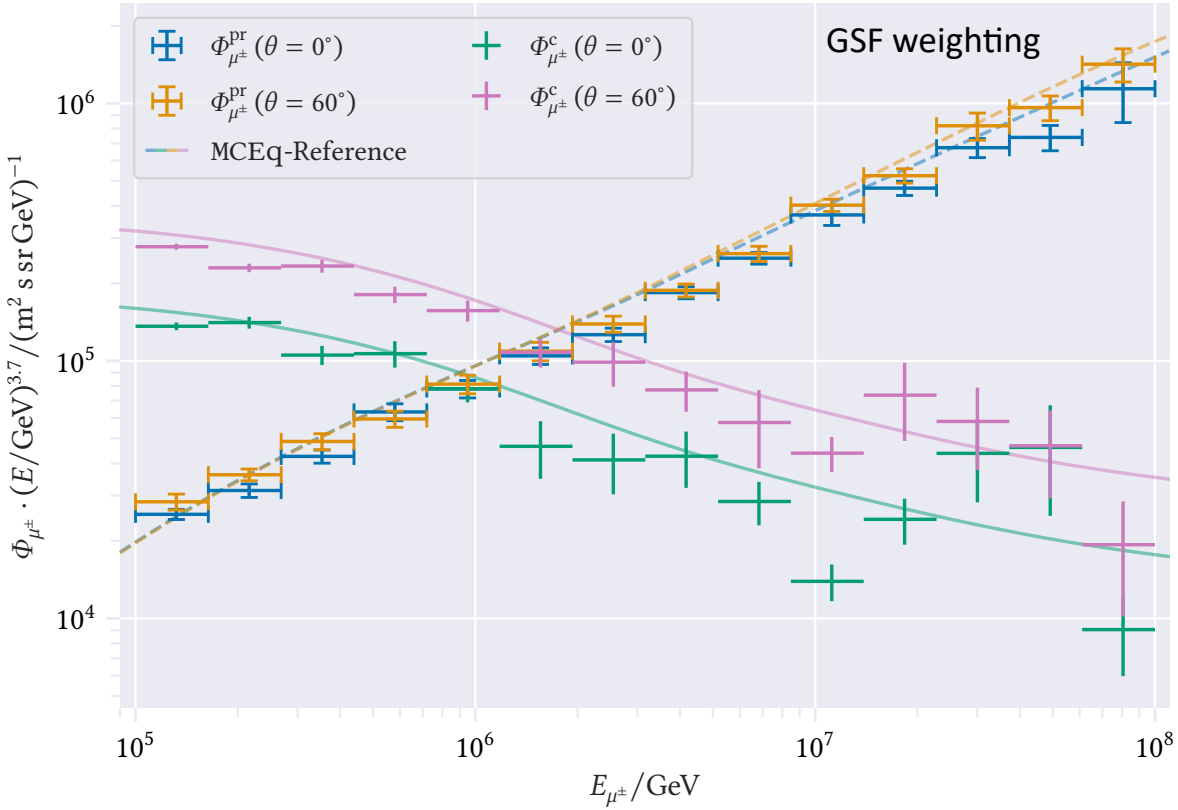
- Detect prompt component of the atmospheric muon flux
  - Measure the normalization
  - Get handle on hadronic interaction models

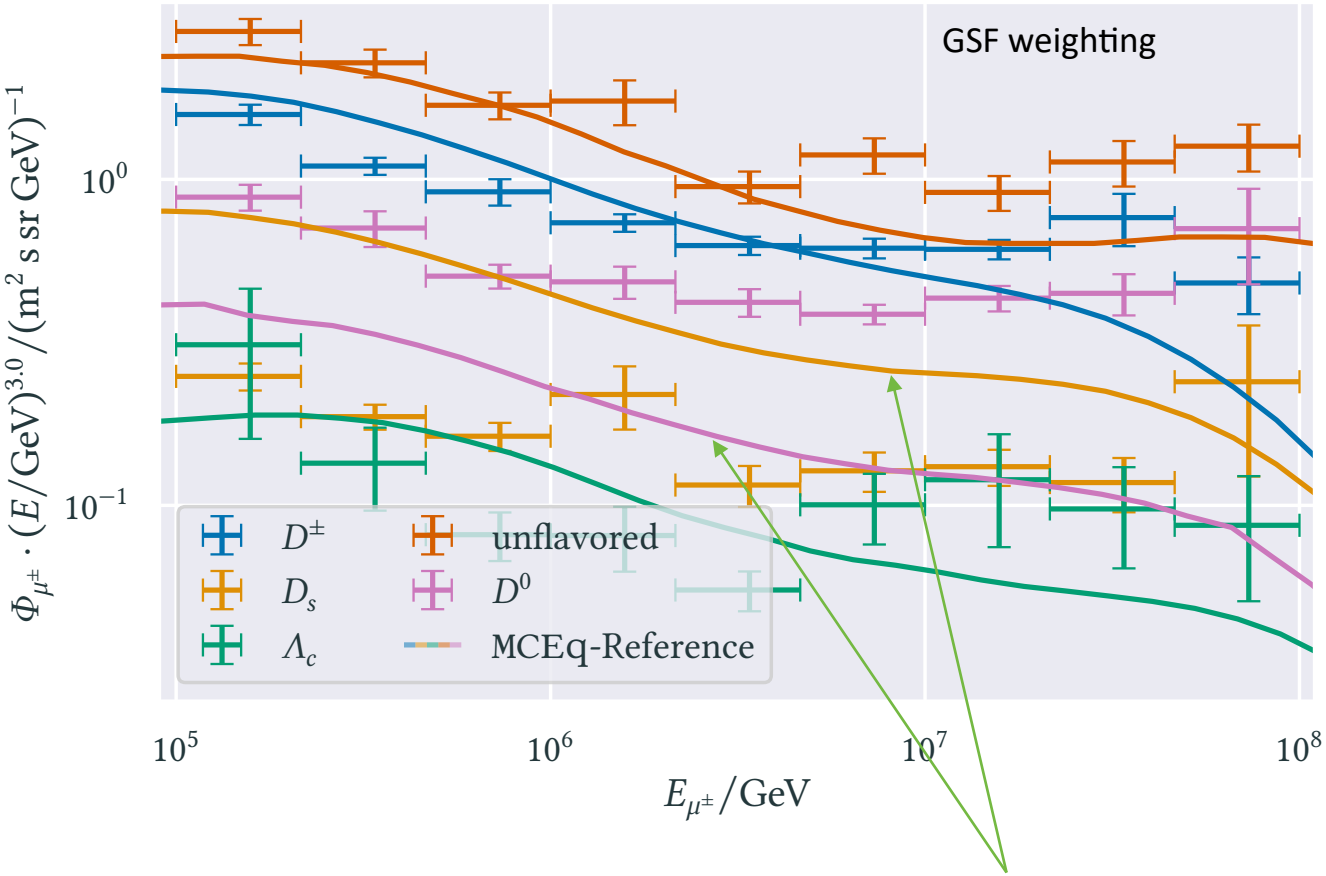
Idea:

- 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

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



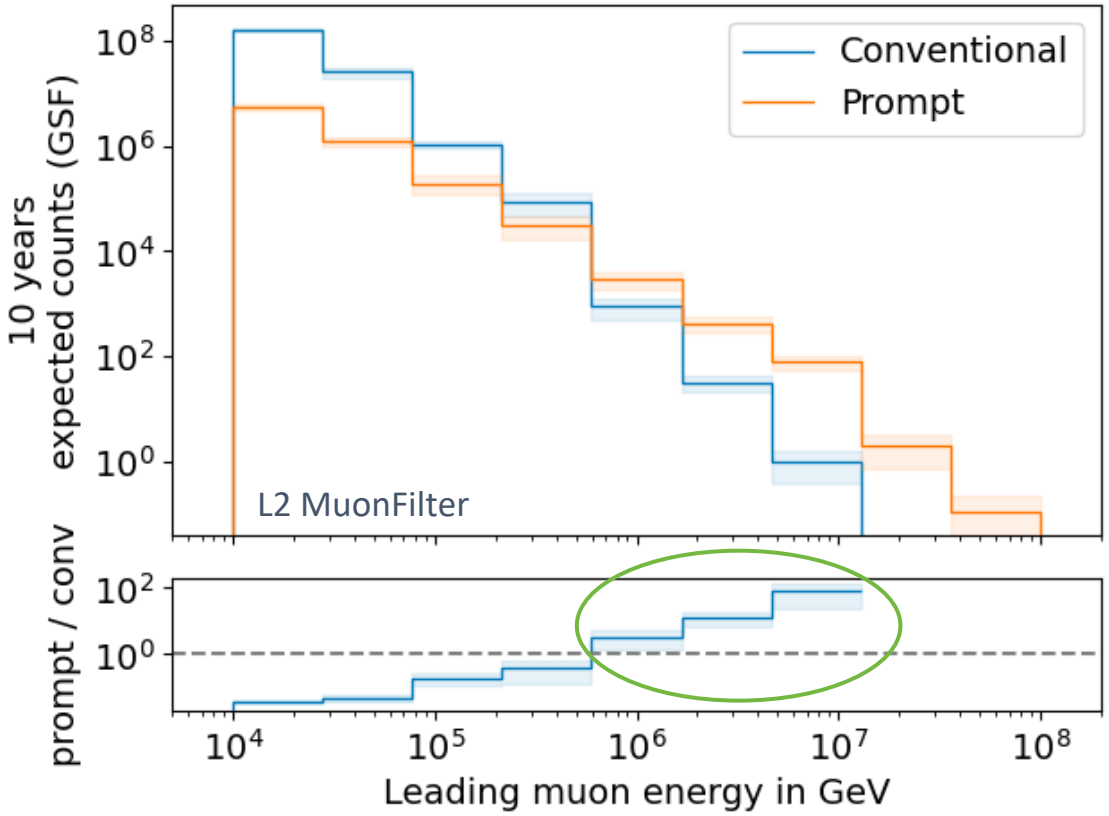


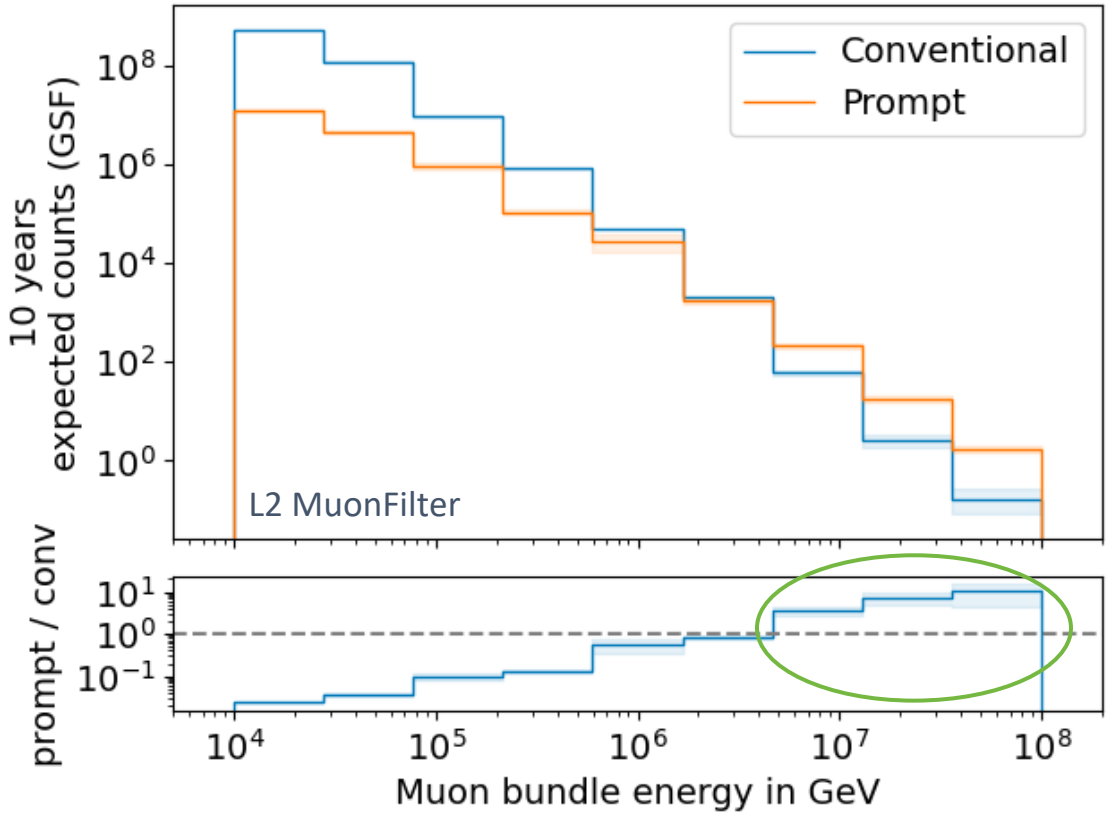
- Good agreement in total prompt and conventional muon flux
- D^0 and D_s are swapped here but this is fixed in MCEq

Pseudo analysis

Expected muons for 10 years: leading vs. bundle energy

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

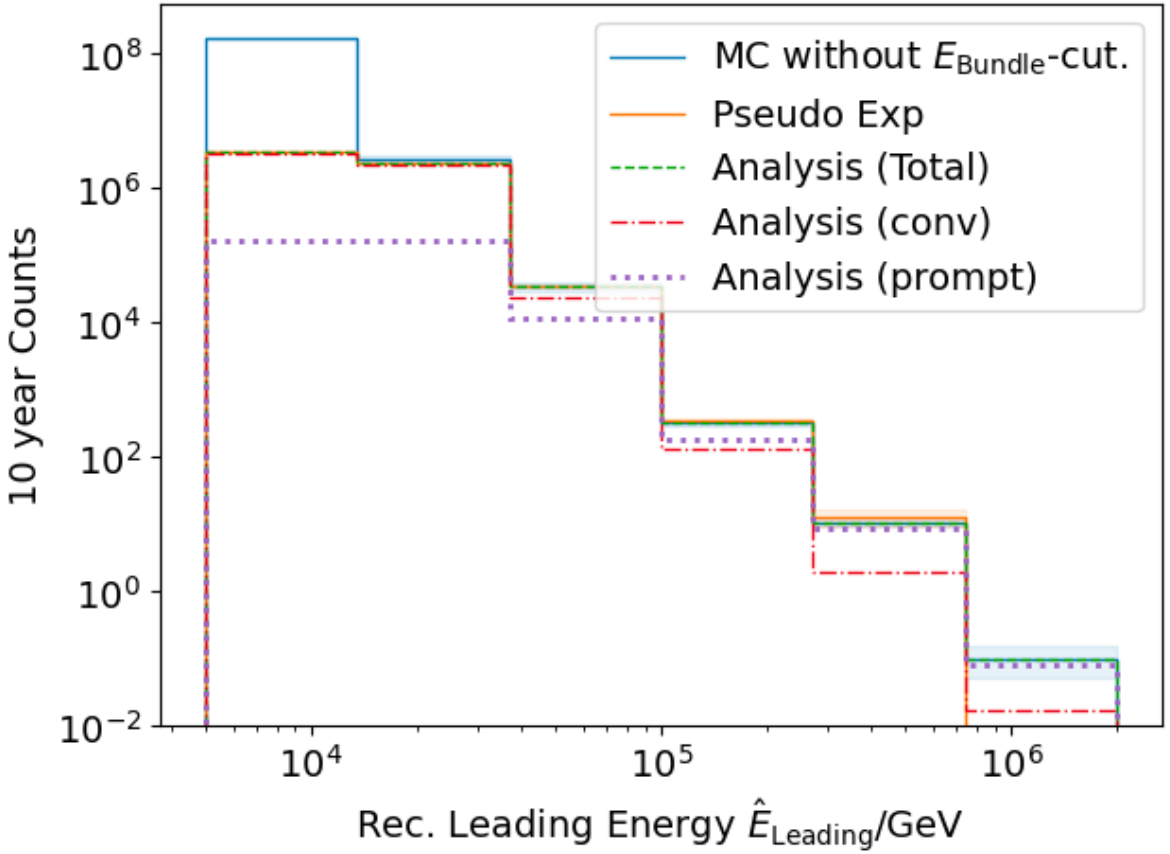


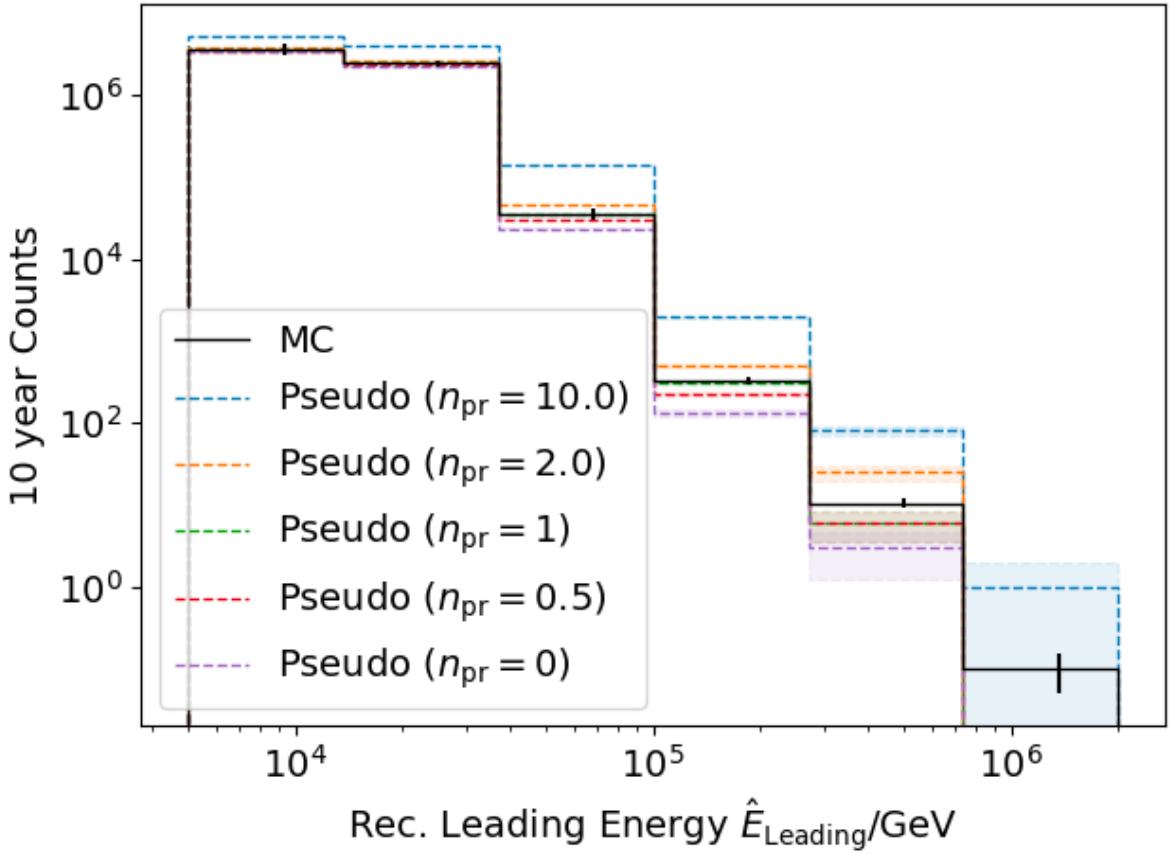


- Both leading and bundle energy are sensitive to detect prompt
- Leading muon energy is more sensitive

Pseudo data sampling

Cuts:
L2 MuonFilter
Bundle energy > 100 TeV





➢ Tagging allows scaling of prompt by factor n_{pr}

Poisson likelihood fit performed in leading muon energy

Cuts:
L2 MuonFilter
Bundle energy > 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

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

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

Maximize likelihood

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

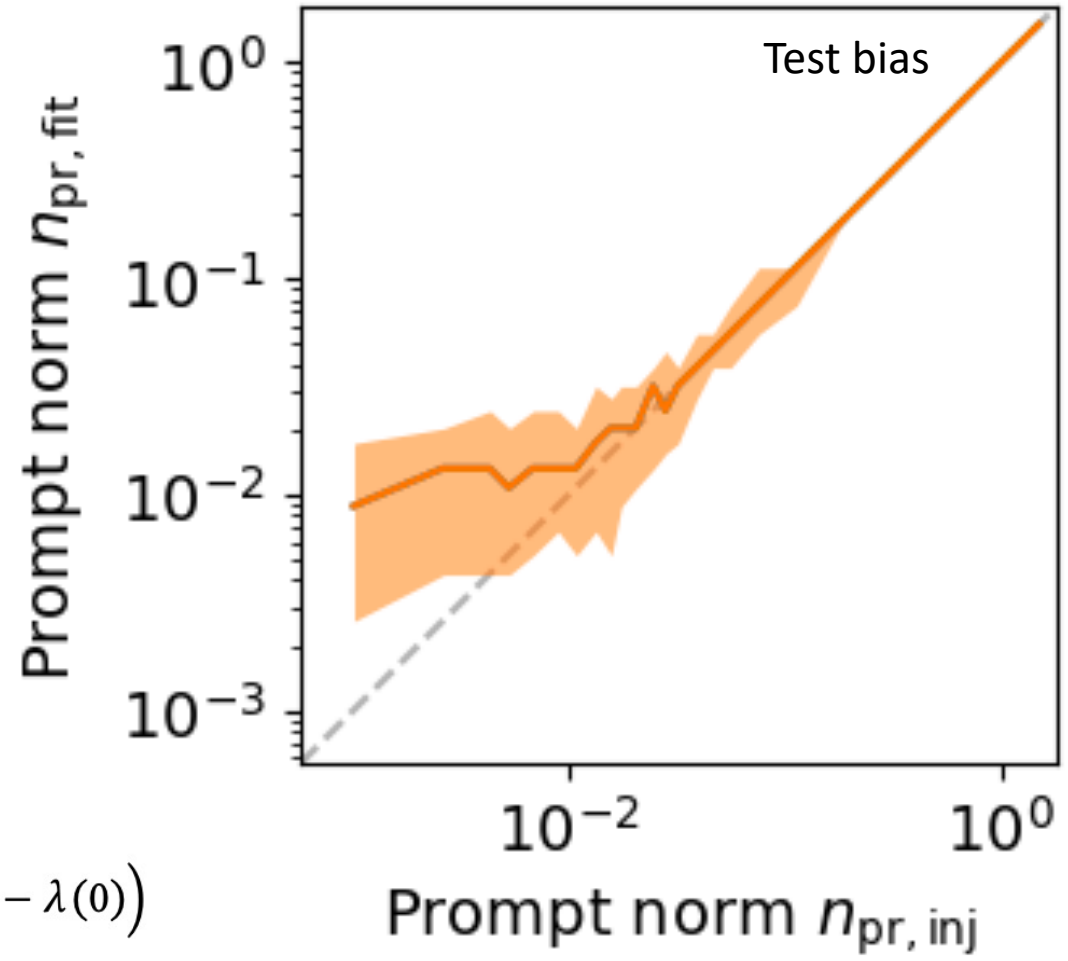
Easier:
minimize negative
log-likelihood

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

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

Test statistic for Wilks' theorem

Null hypothesis: no prompt



- Bias starts at a prompt normalization of 0.1

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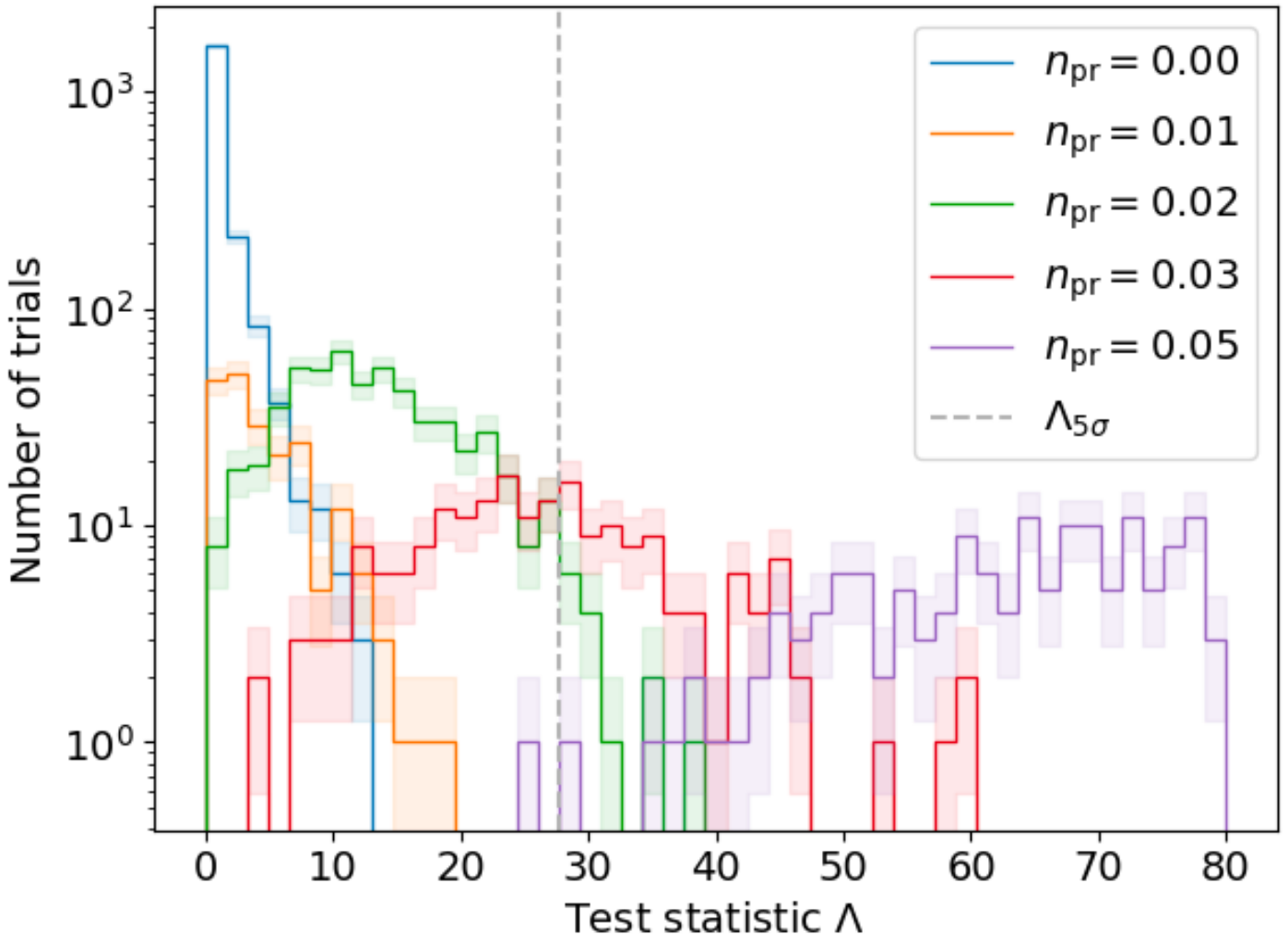
Discovery potential and sensitivity

Cuts:
L2 MuonFilter
Bundle energy > 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

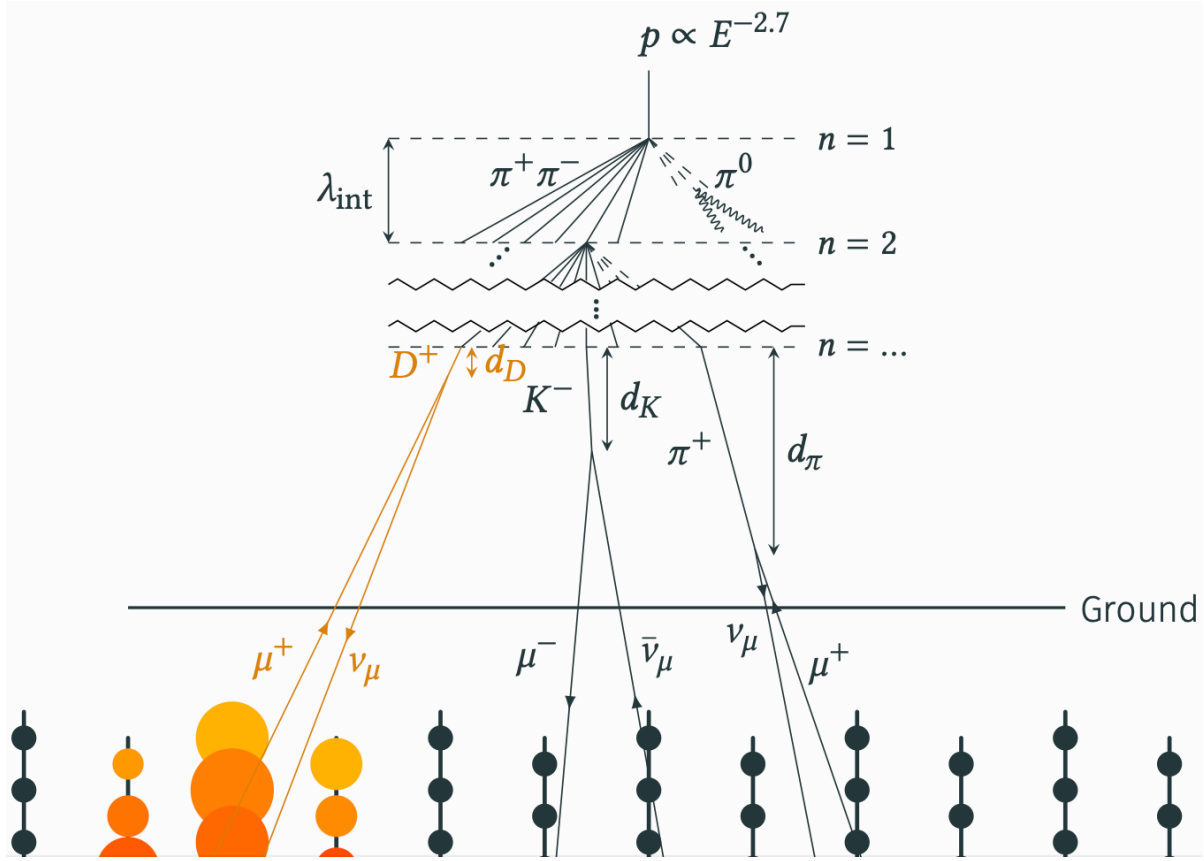


Conclusion and outlook

- ☑ CORSIKA 7 test simulations
  - ☑ Prompt identification
  - ☑ MCEq comparison
  - ☐ Few-author paper in progress (publish in 2024)
- ☑ First analysis chain for prompt muon normalization
- ☐ Proceed analysis…(systematics etc.)
- ☐ Unfold muon spectrum

Future plan

- ☐ Combined fit (prompt muons + neutrinos)
  - ☐ Measure pion/kaon ratio -> muon puzzle

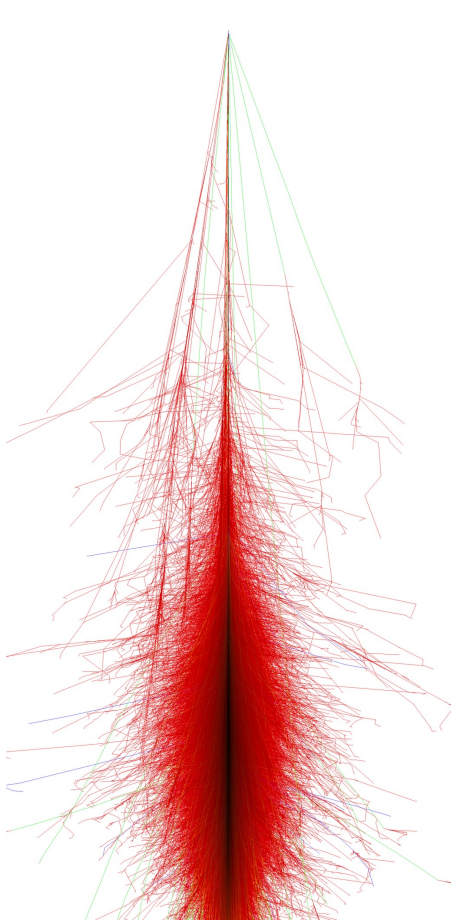


➢ Prompt neutrino analysis
(Lars Bollmann Tue 16:45, T 42.4)

Thank you for your attention ☺

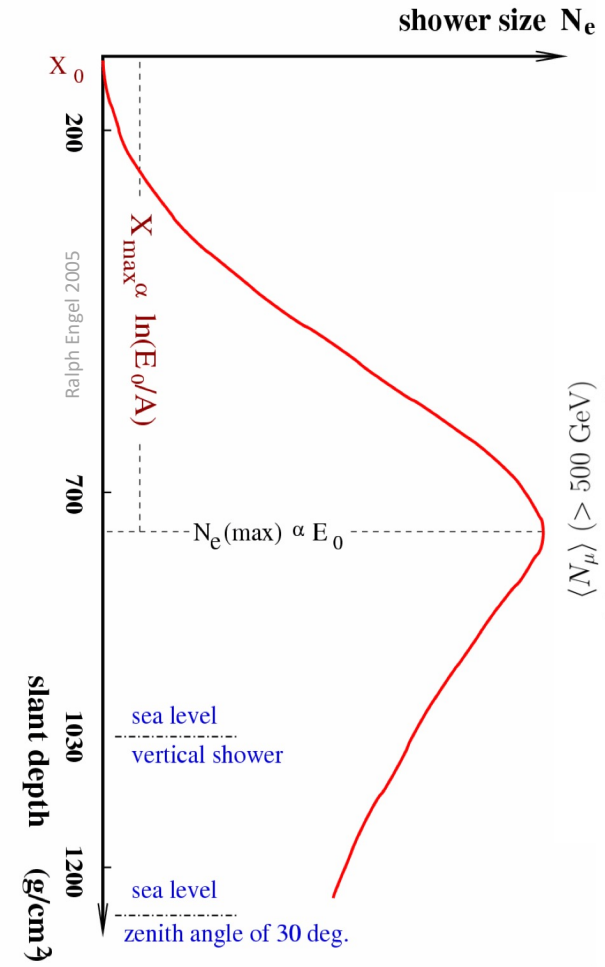
Backup

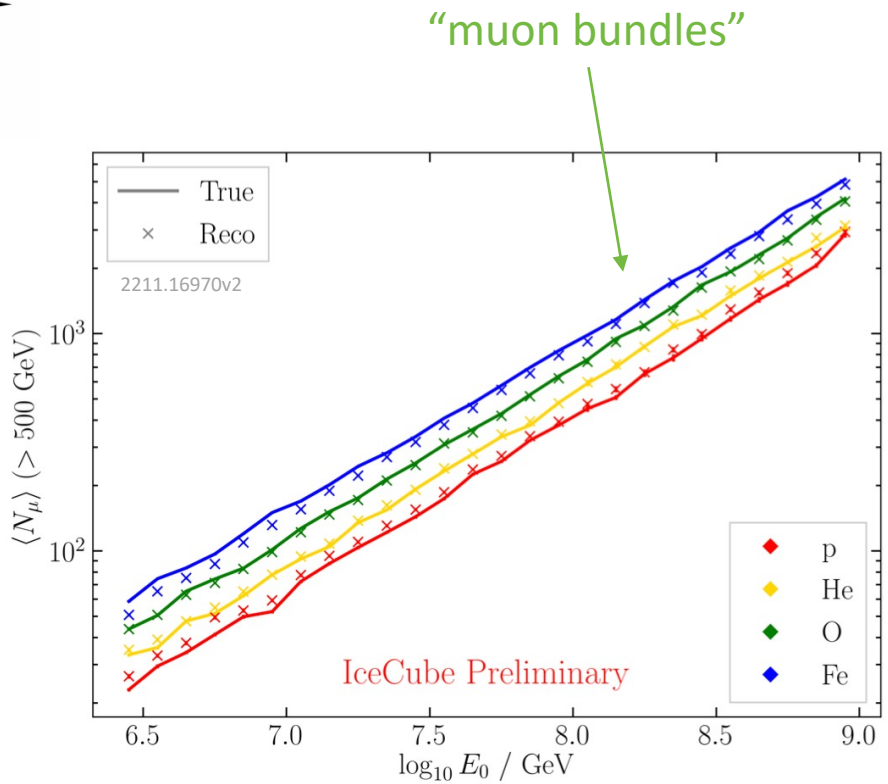
Air shower – 10 TeV



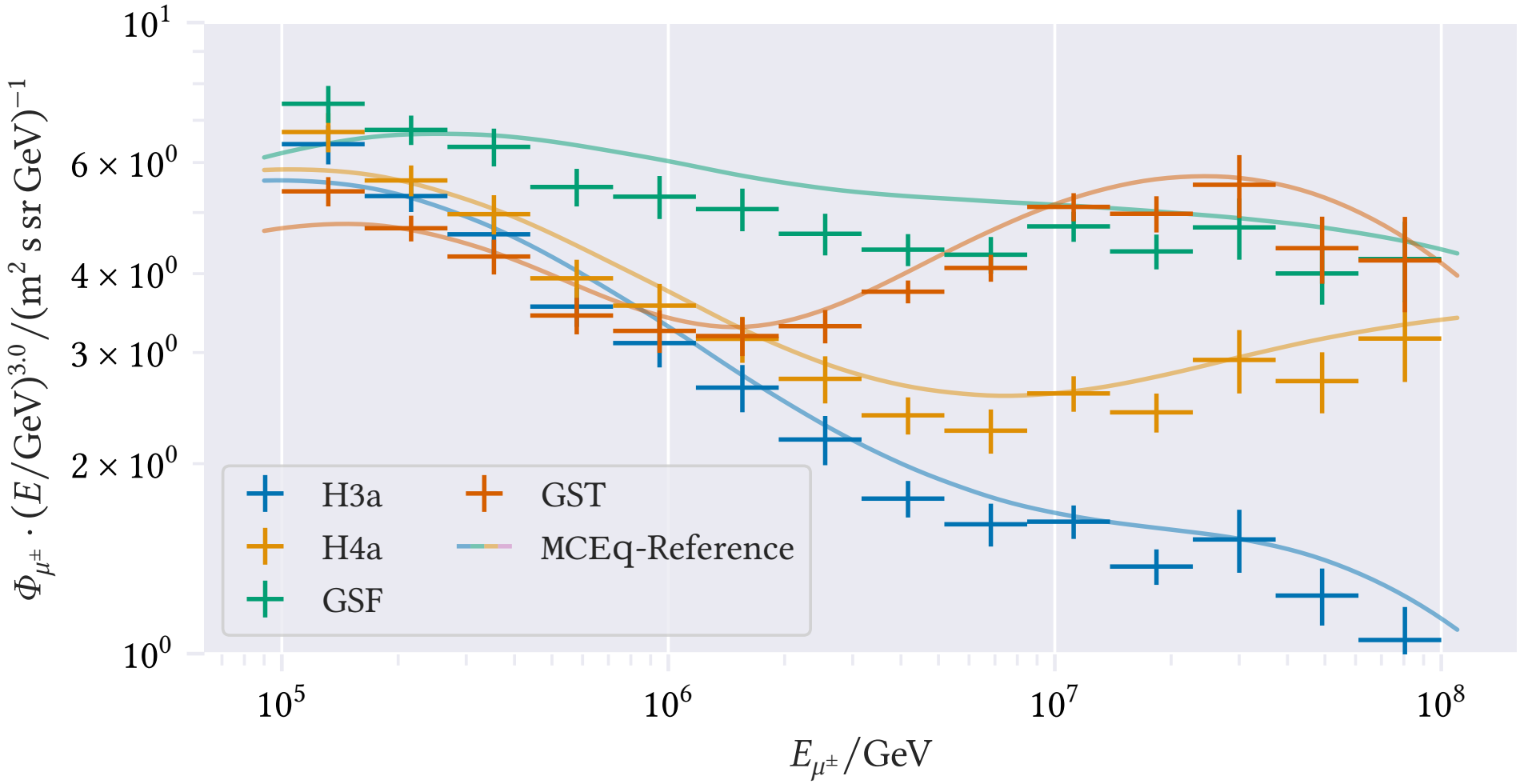
Proton

Iron





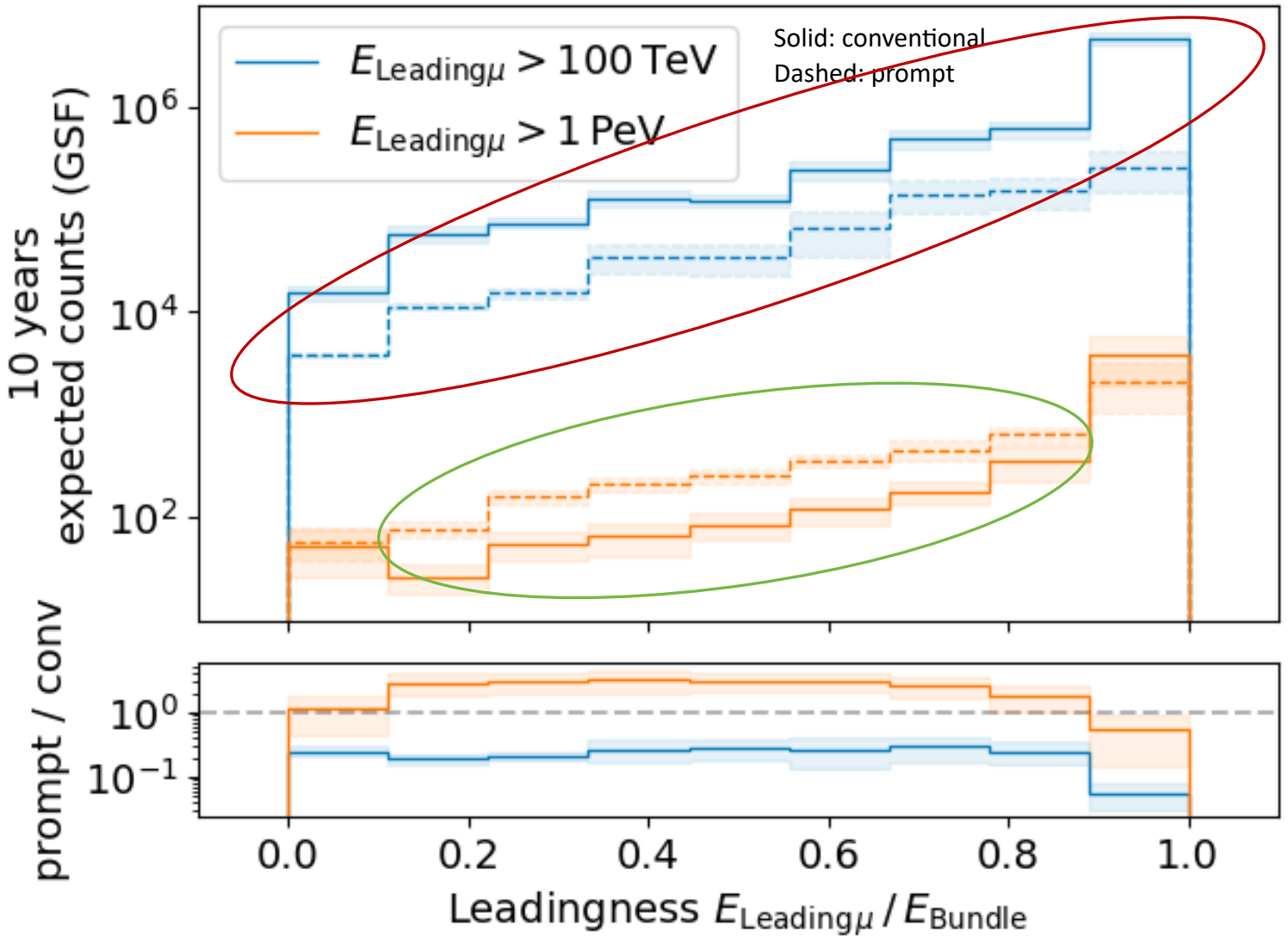
Agreement for different primary models



MC data exploration

Leading muon energy fraction

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



Leading muon contribution

Patrick Berghaus

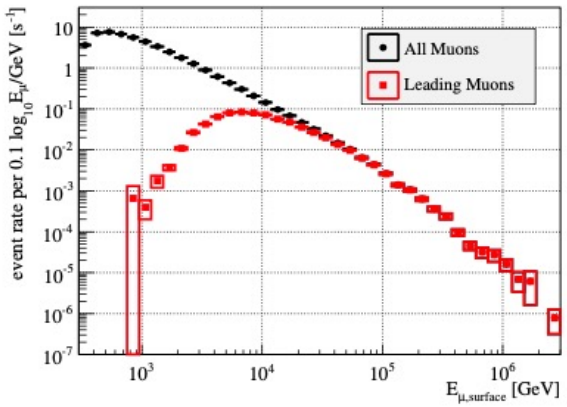
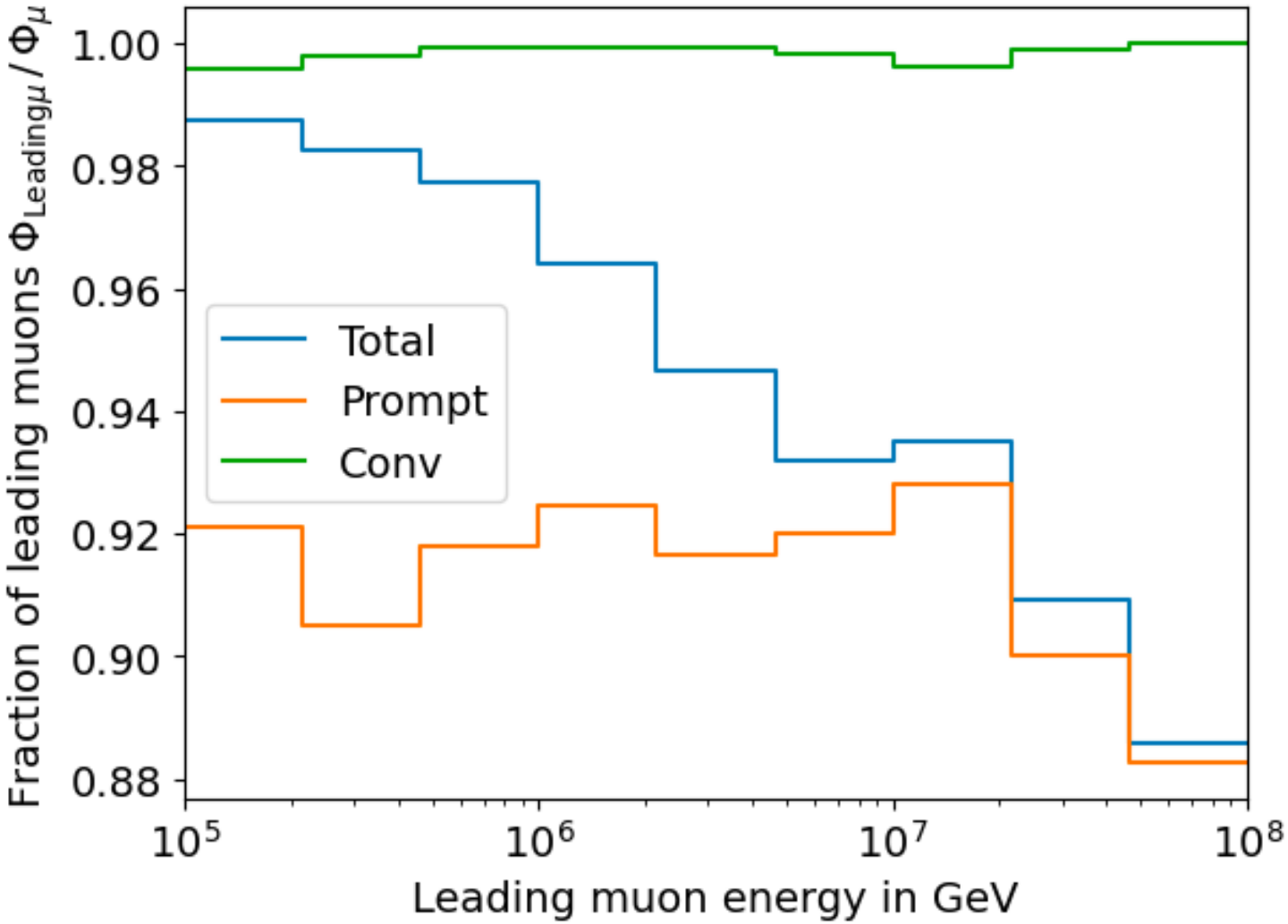


Figure 10: Surface energy distribution for all and most energetic ("leading") muons in simulated events with a total of more than 1,000 registered photo-electrons in IceCube.

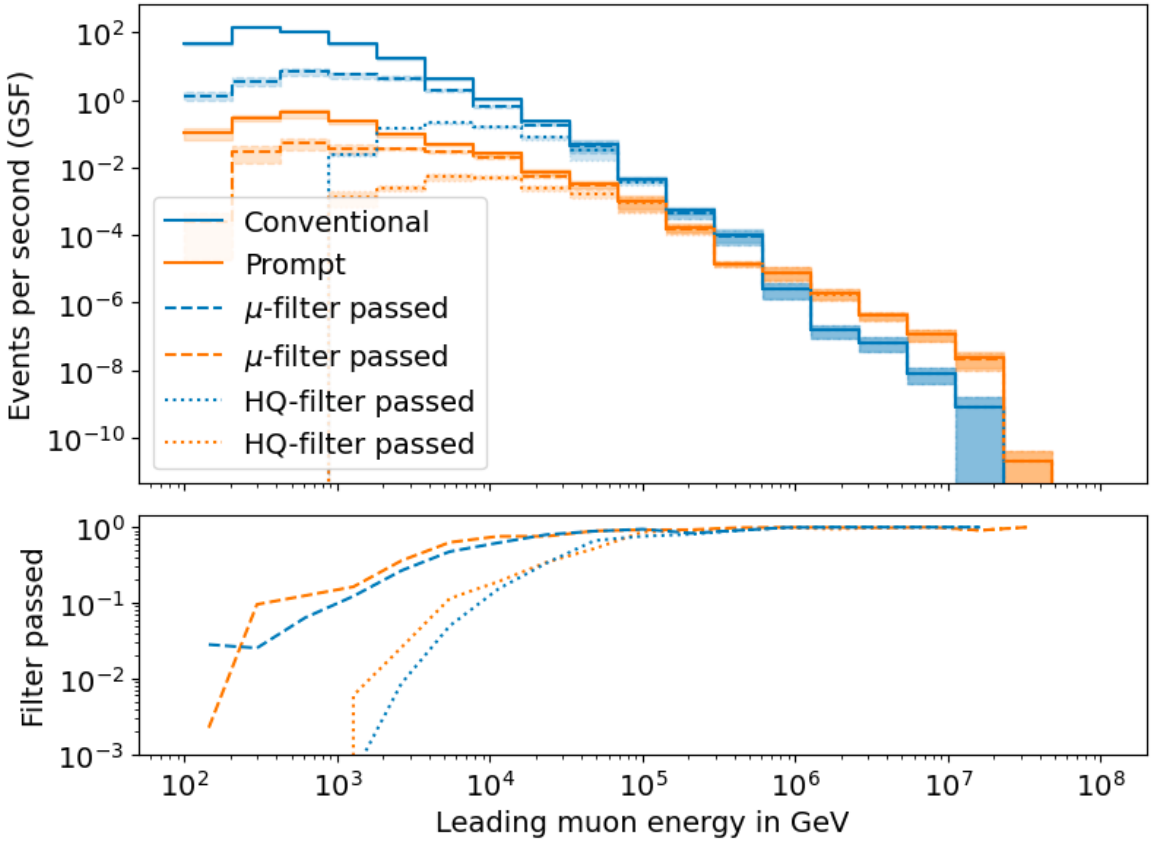
- Muons with energies between 100 TeV and 50 PeV dominate the bundle by more than 90%
- In average conventional muons are more dominant than prompt
- But: at high energies, there are more prompt than conventional events

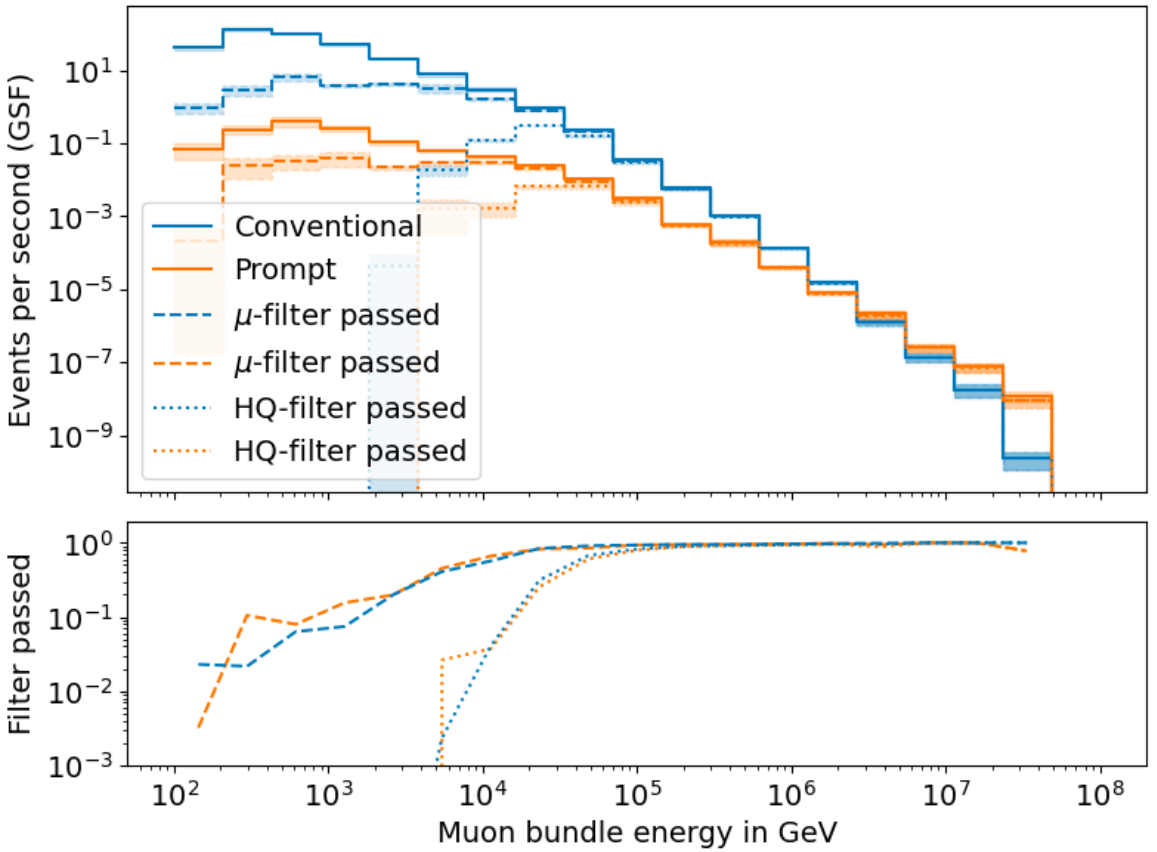
➢ High leading energy fraction does not lead to more sensitivity to detect prompt



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

DNN Reconstructions

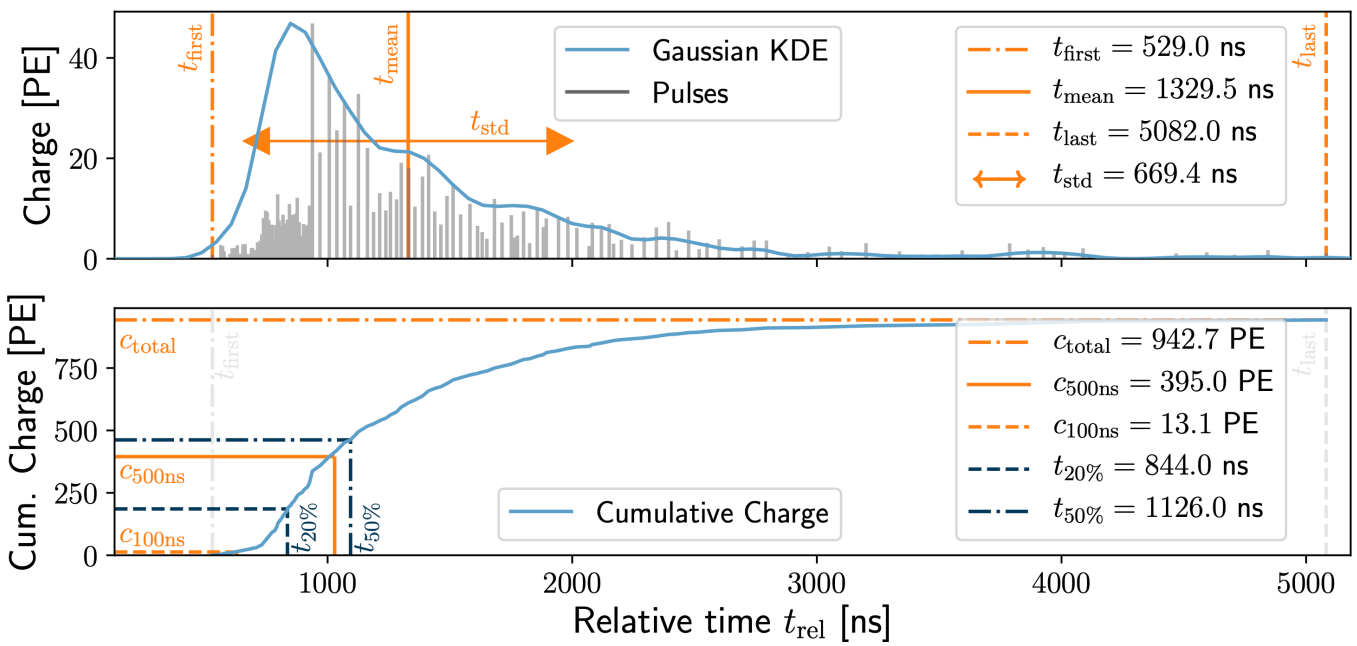
Reconstruct

- ❑ 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

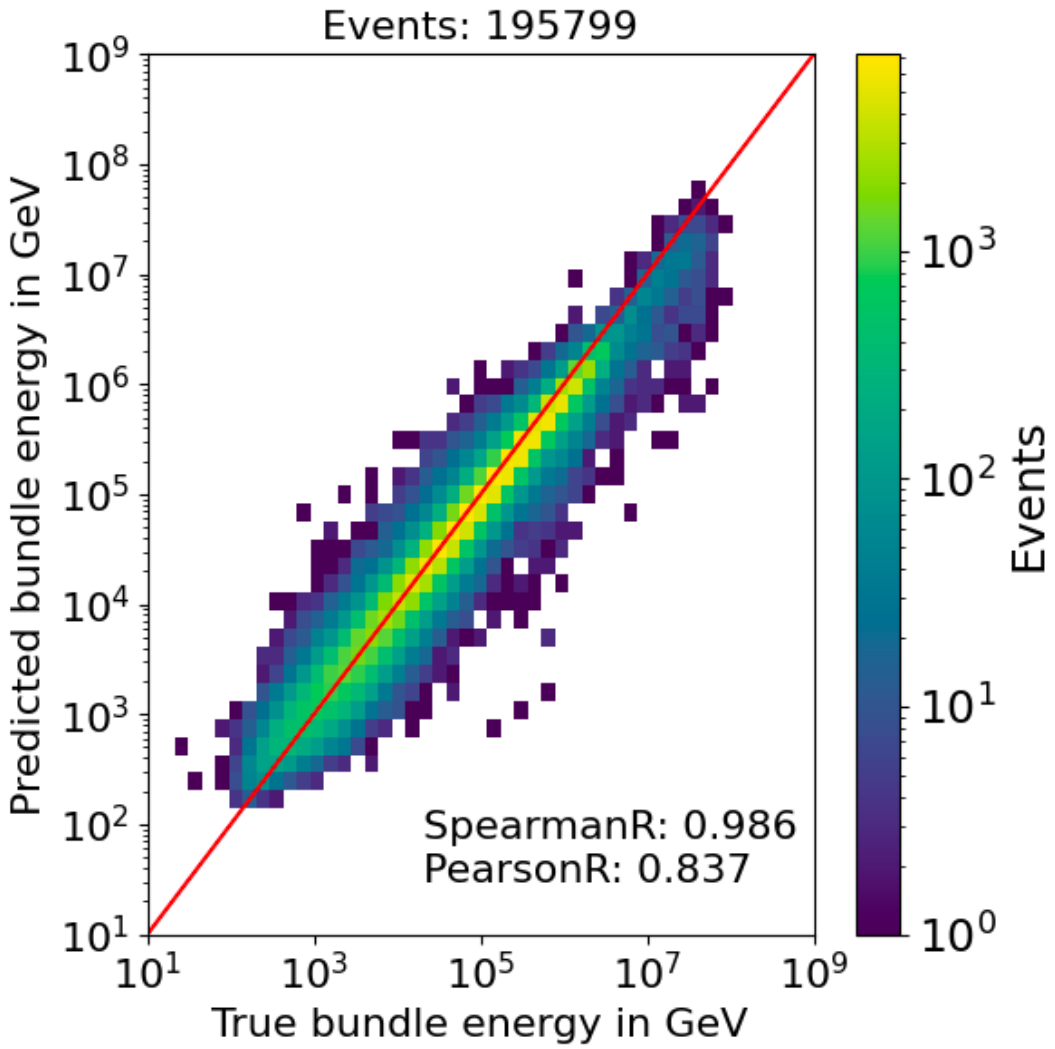


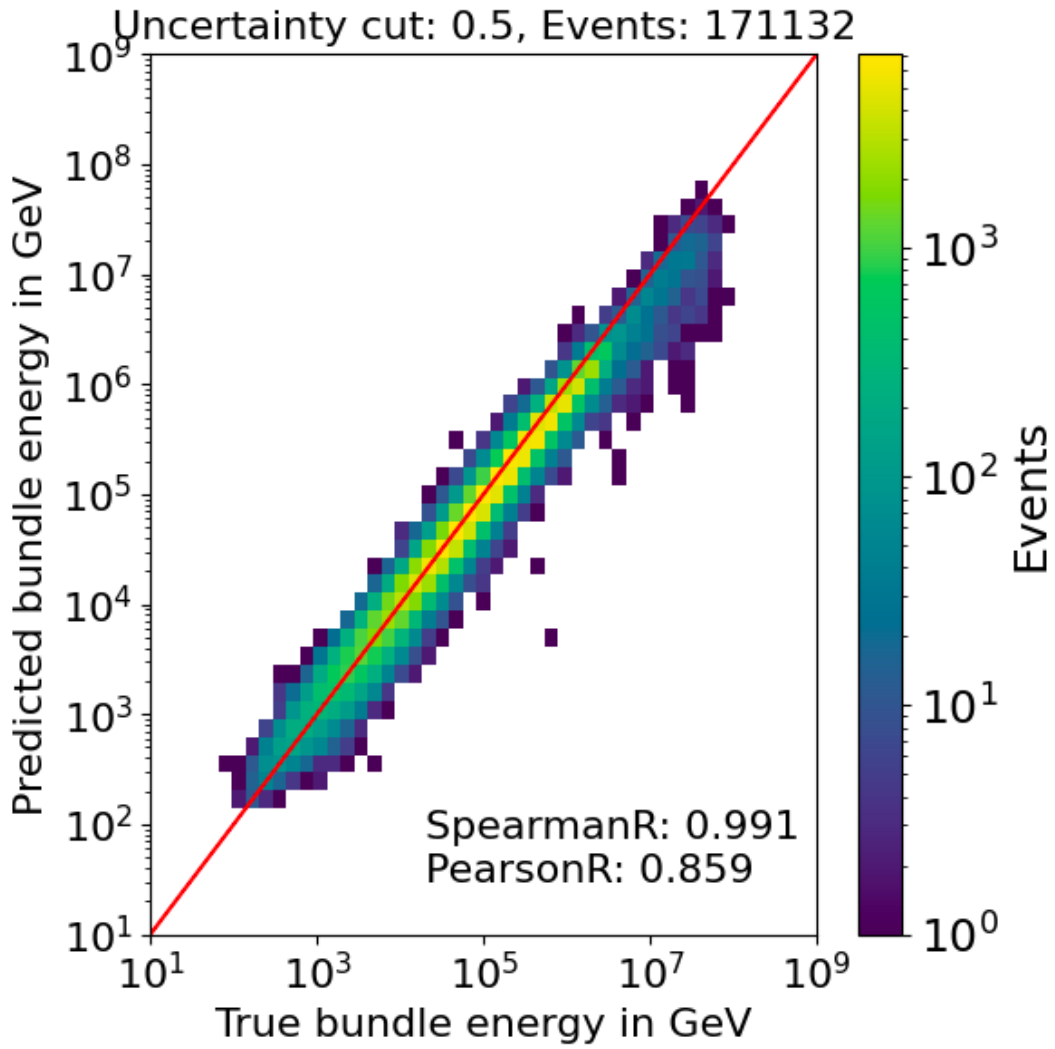
Input data per DOM

- 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

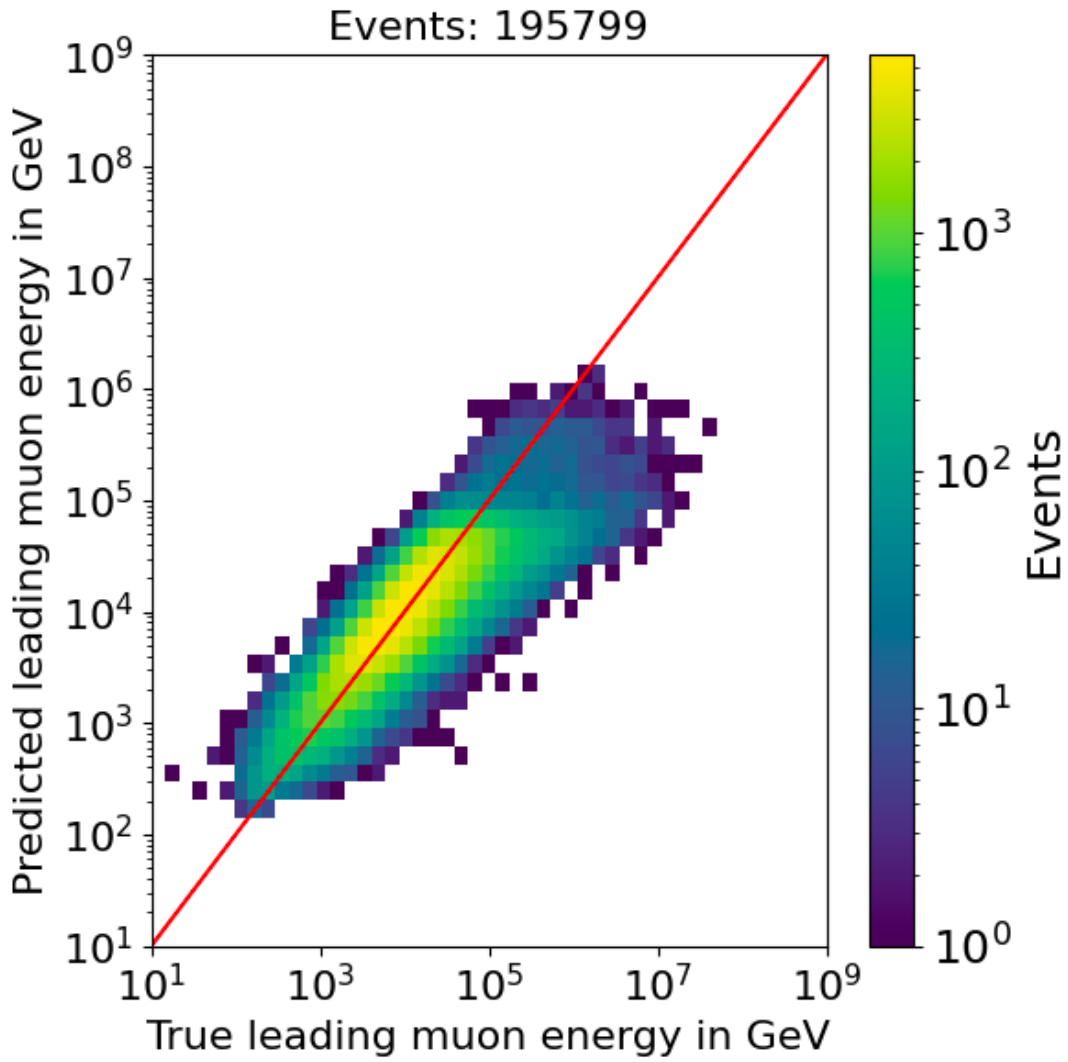
SplitInIceDSTPulsesTWCleaning6000ns

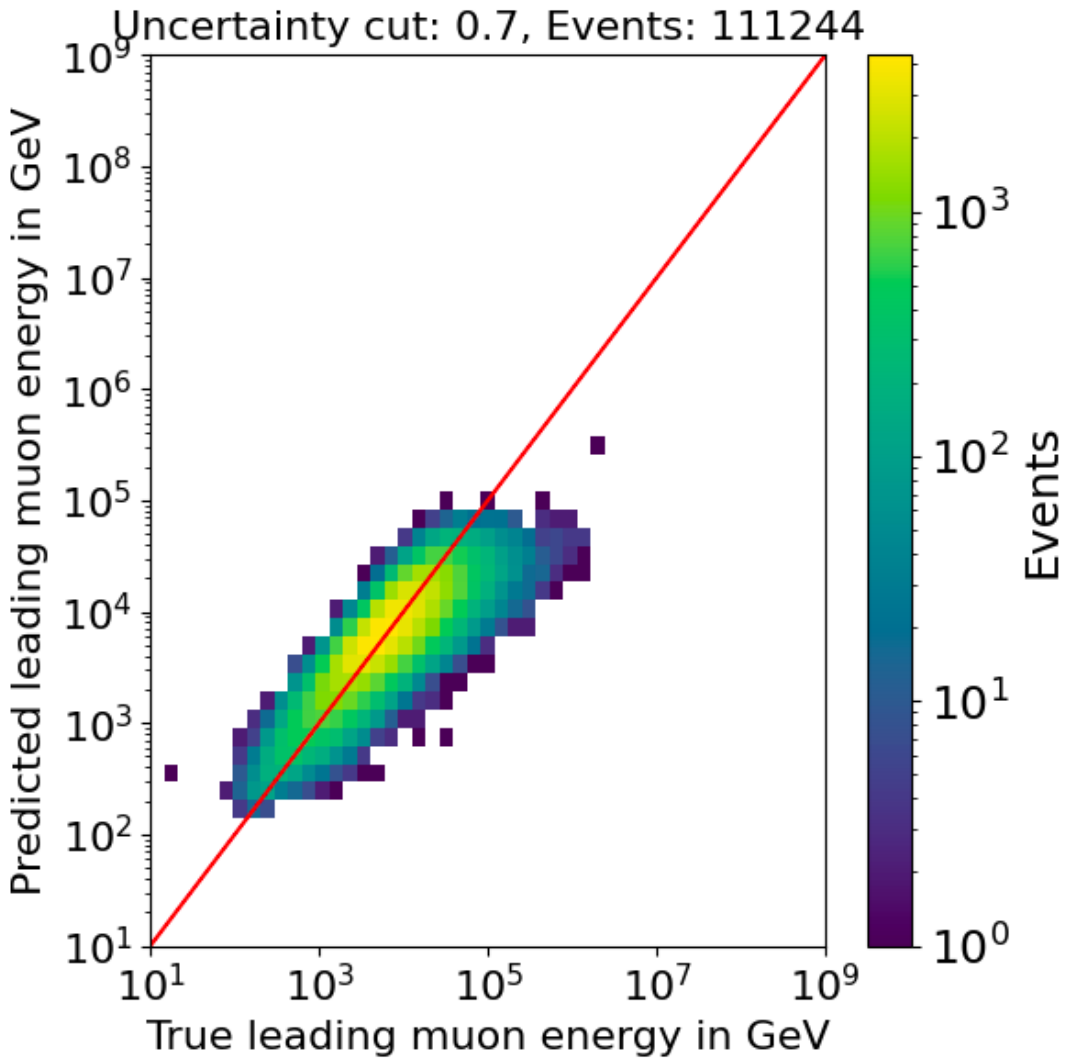
Bundle energy reconstruction





Leading energy reconstruction

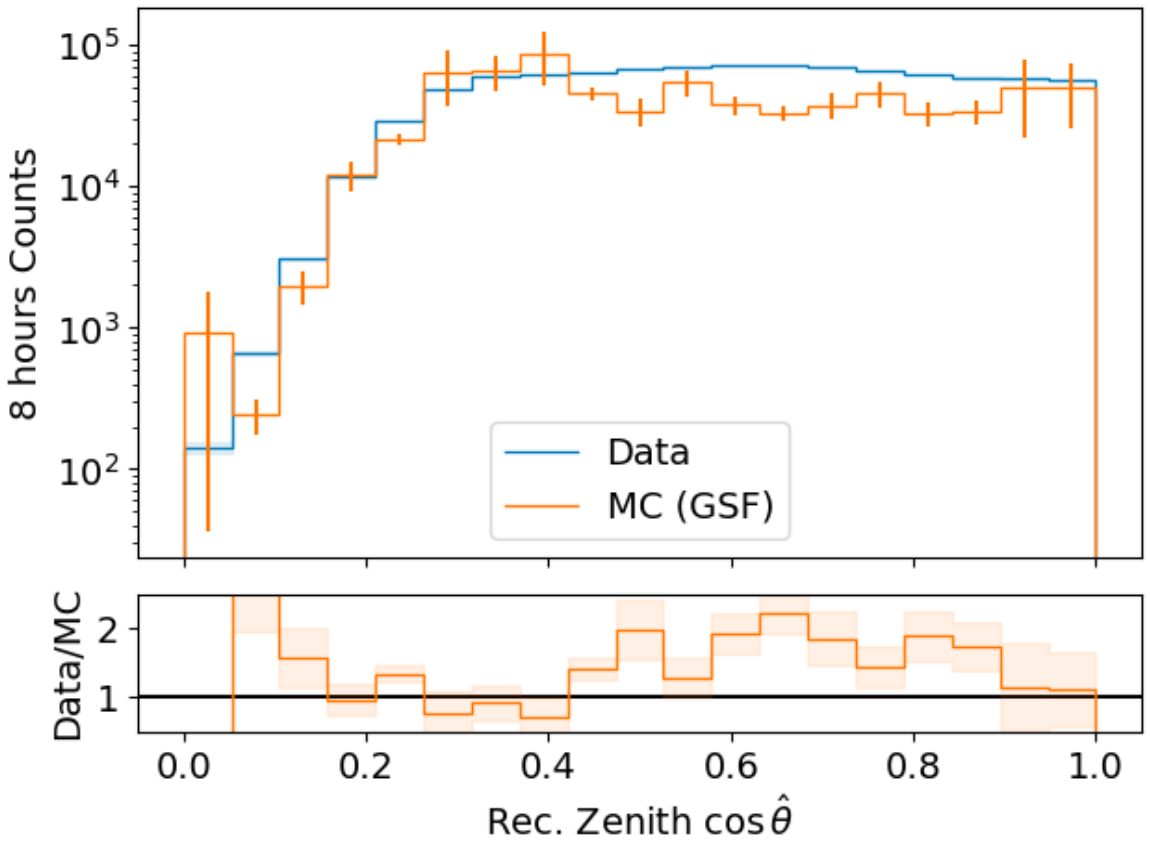




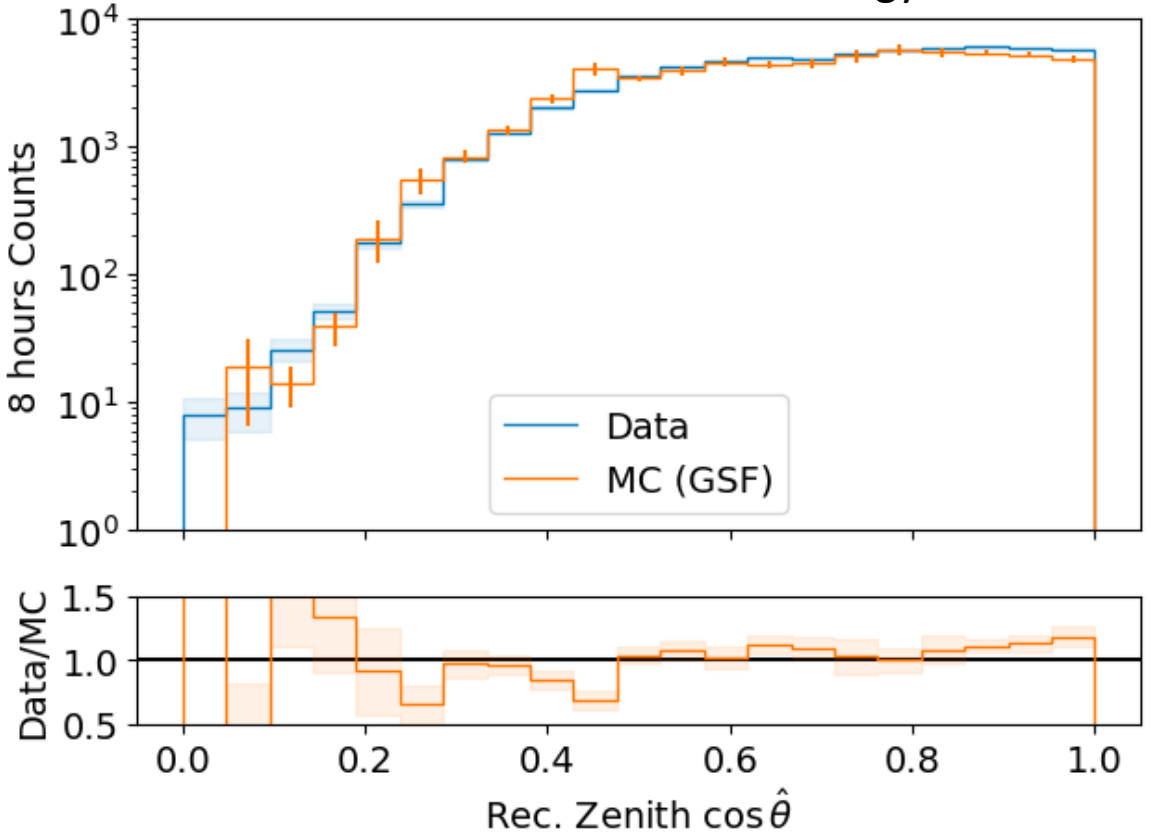
Data/MC

Data-MC: cos(zenith)

L2 MuonFilter

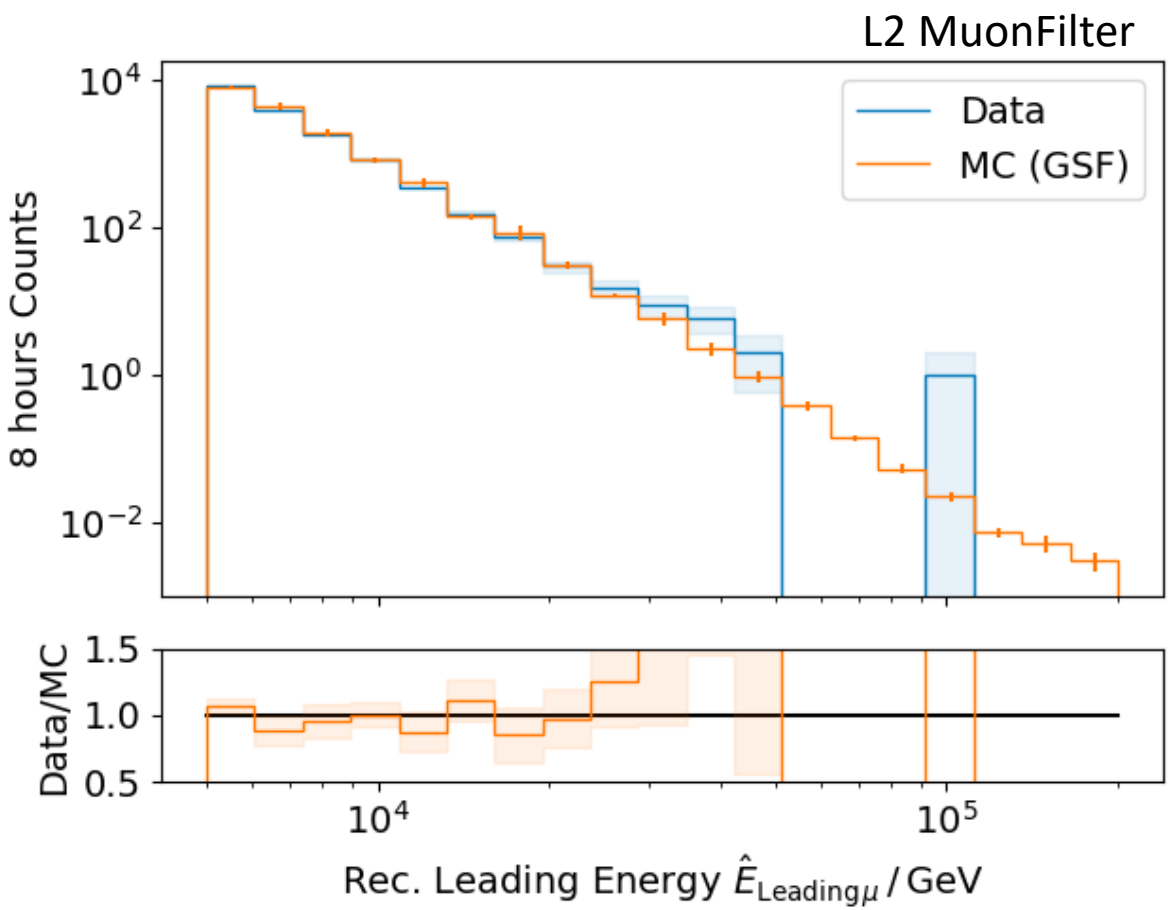


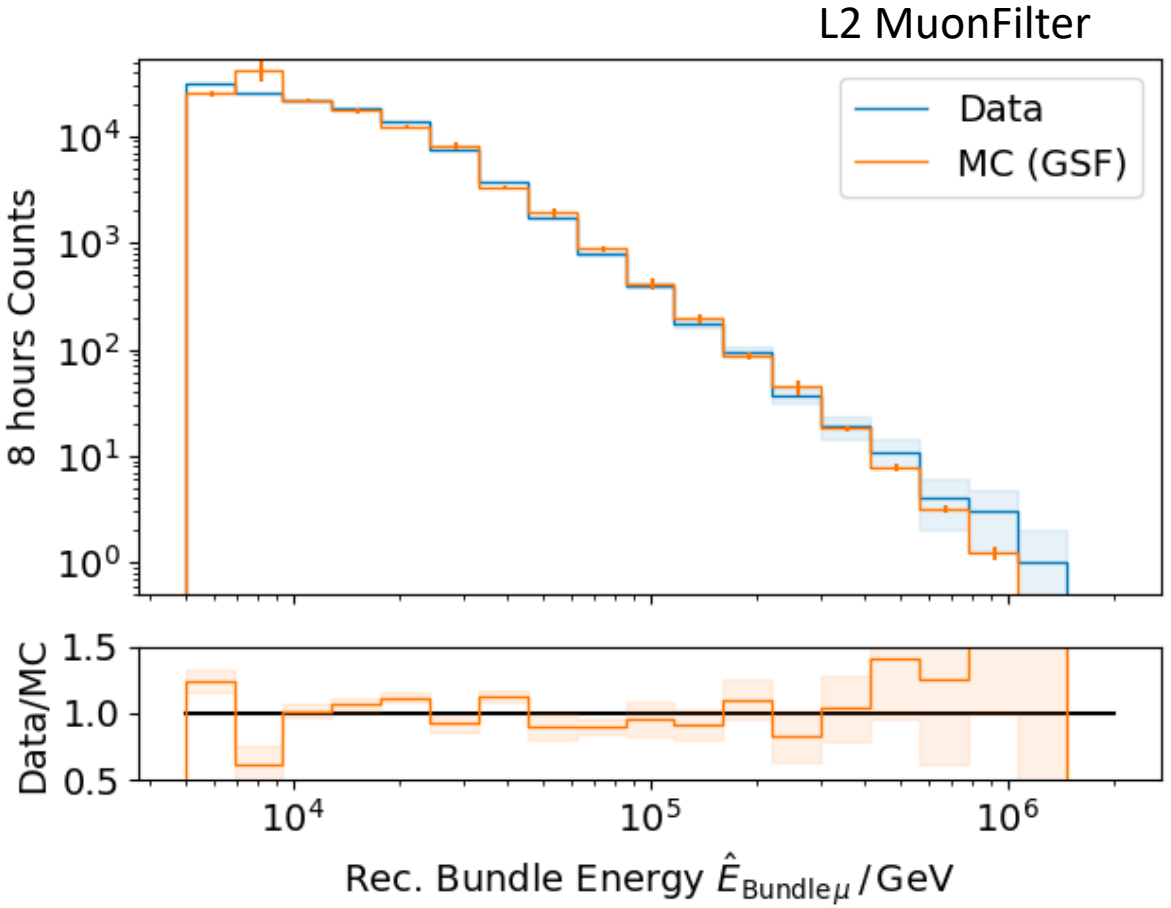
L2 MuonFilter
Bundle energy > 100 TeV



- 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

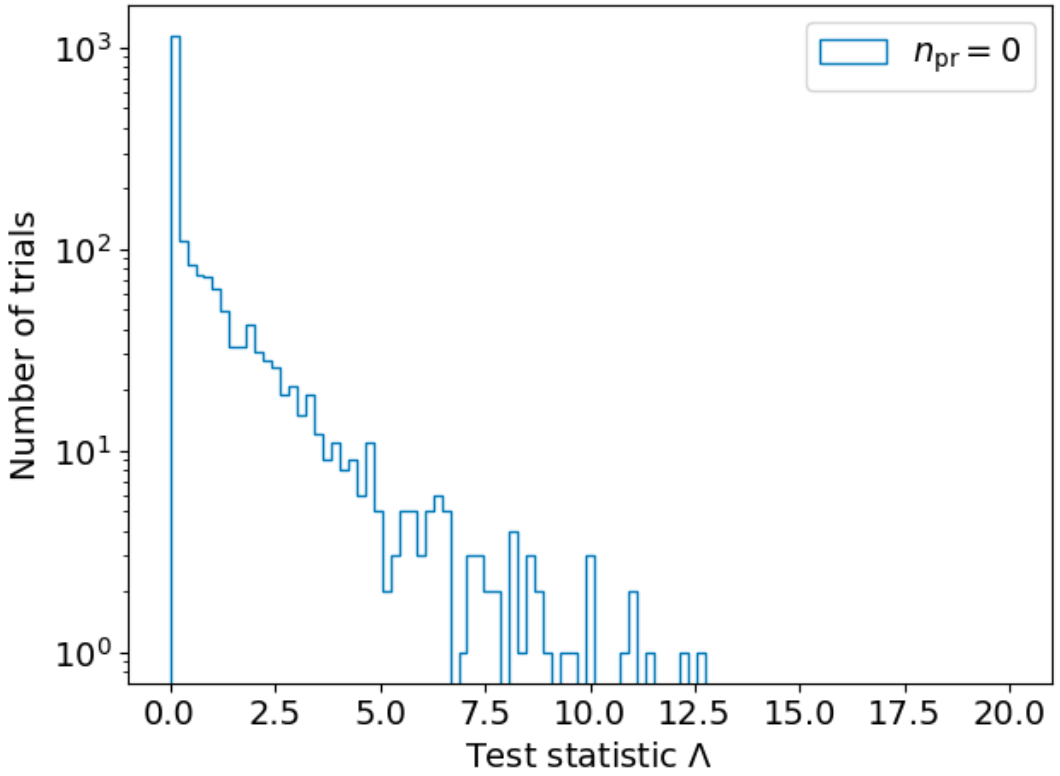


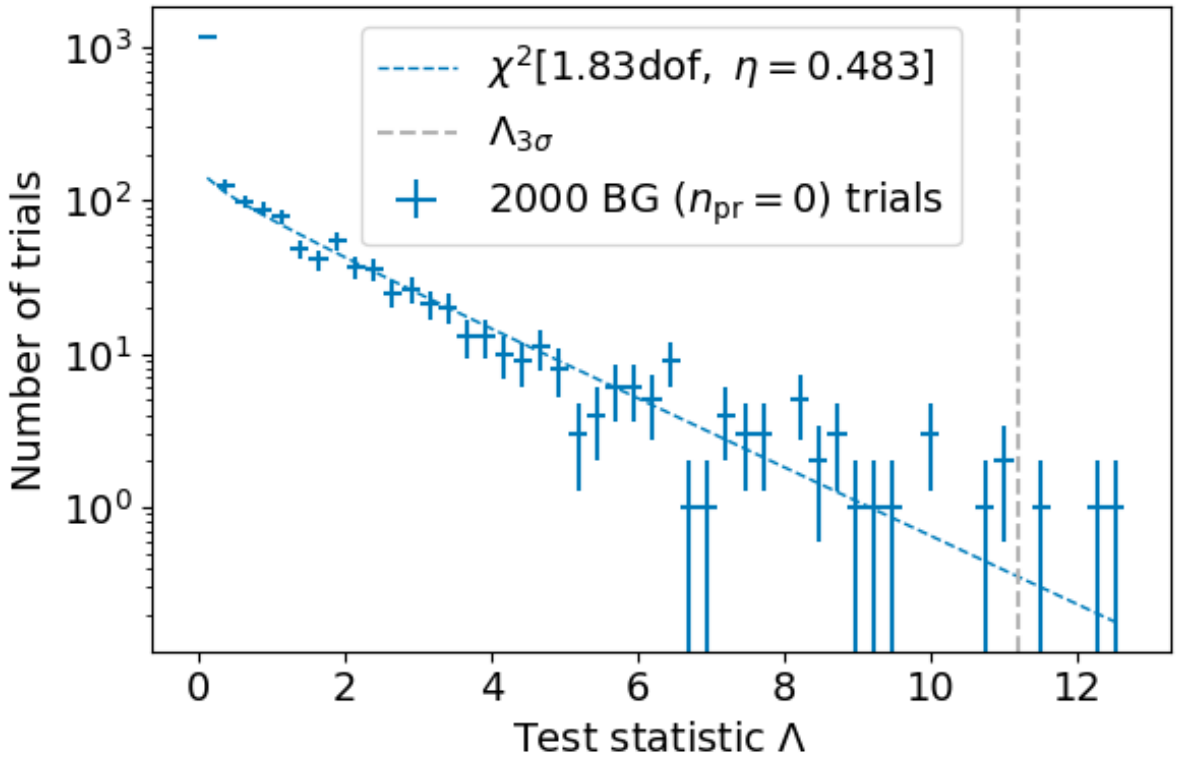


- Bundle energy: good agreement with GSF up to 300 TeV
- But insufficient statistics

Test background statistics

Cuts:
L2 MuonFilter
Bundle energy > 100 TeV

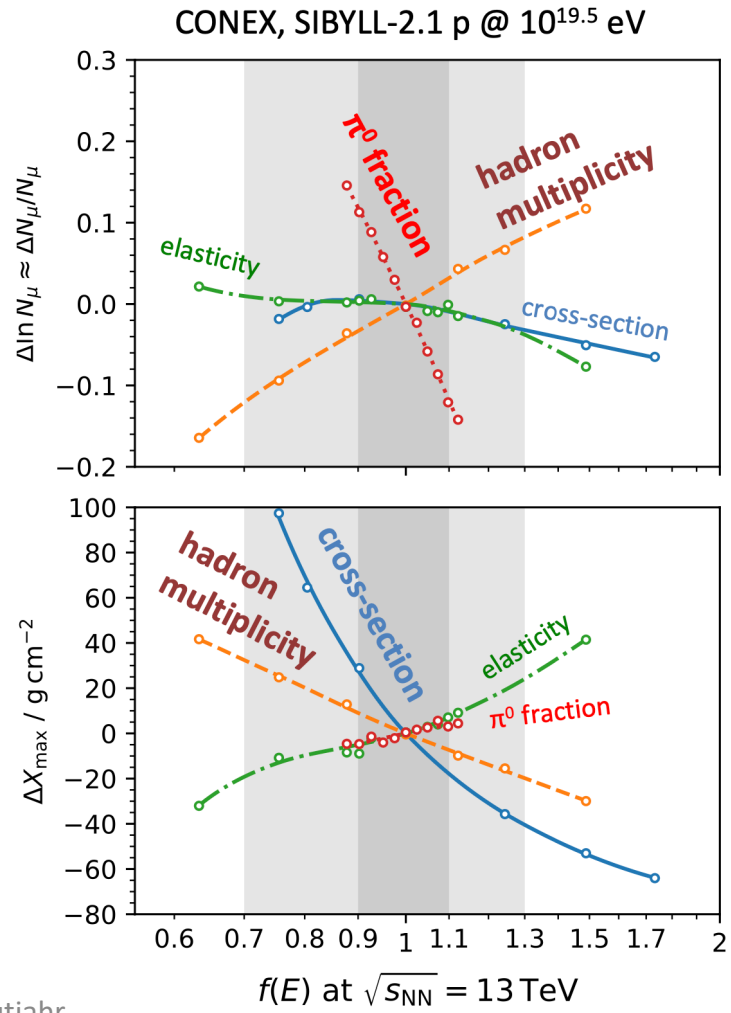




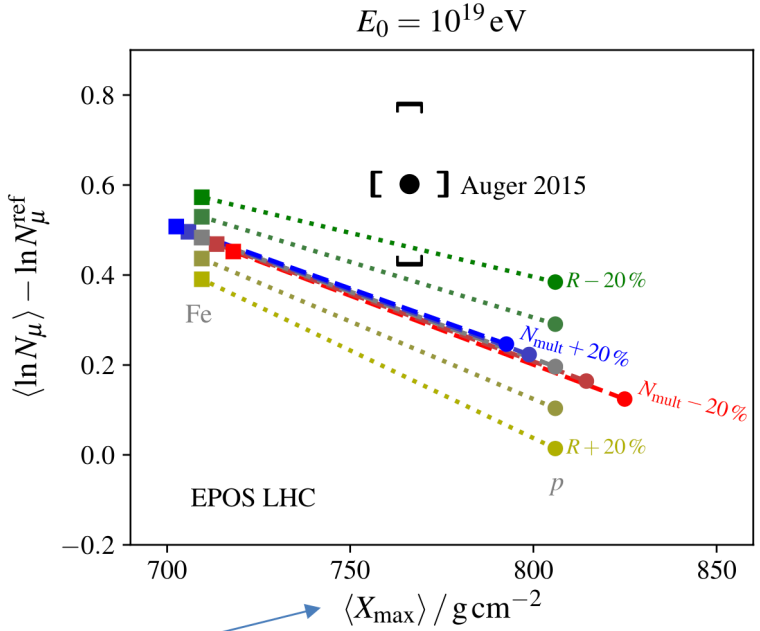
- Background statistic is χ^2 – distributed
- Assume Wilks' theorem for test statistics

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



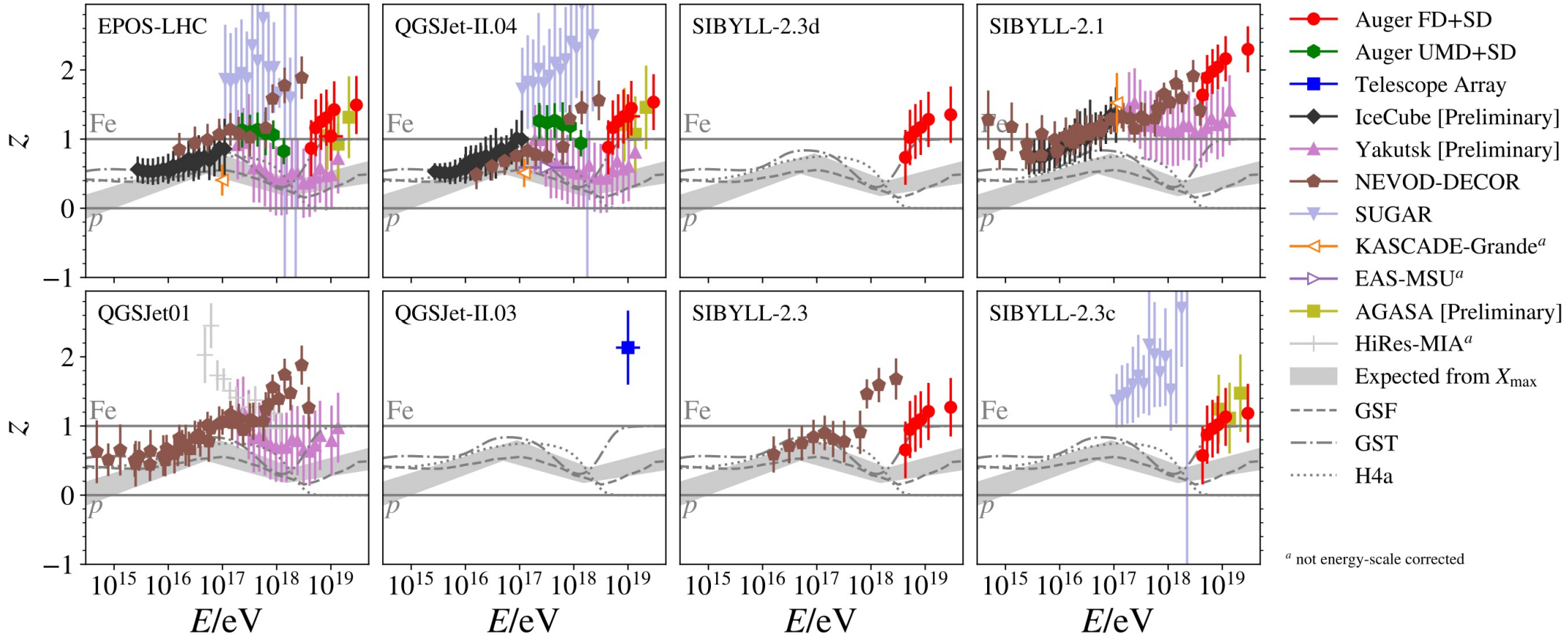
$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

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

The Muon Puzzle

"muon number"

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



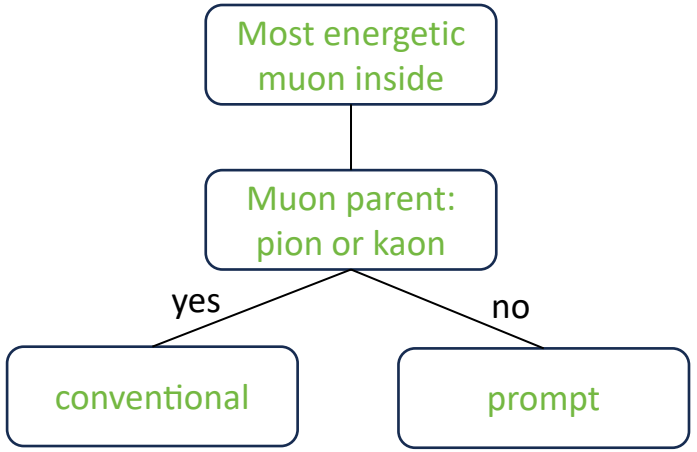
2108.08341

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

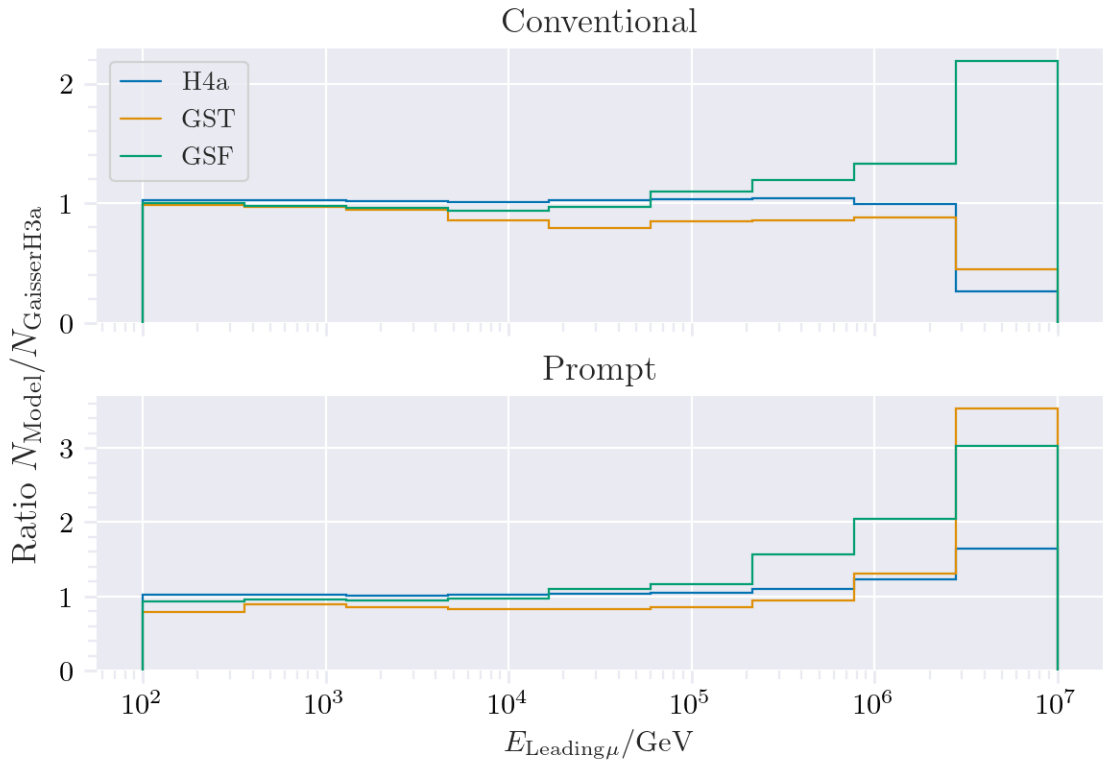
Suggestion:

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



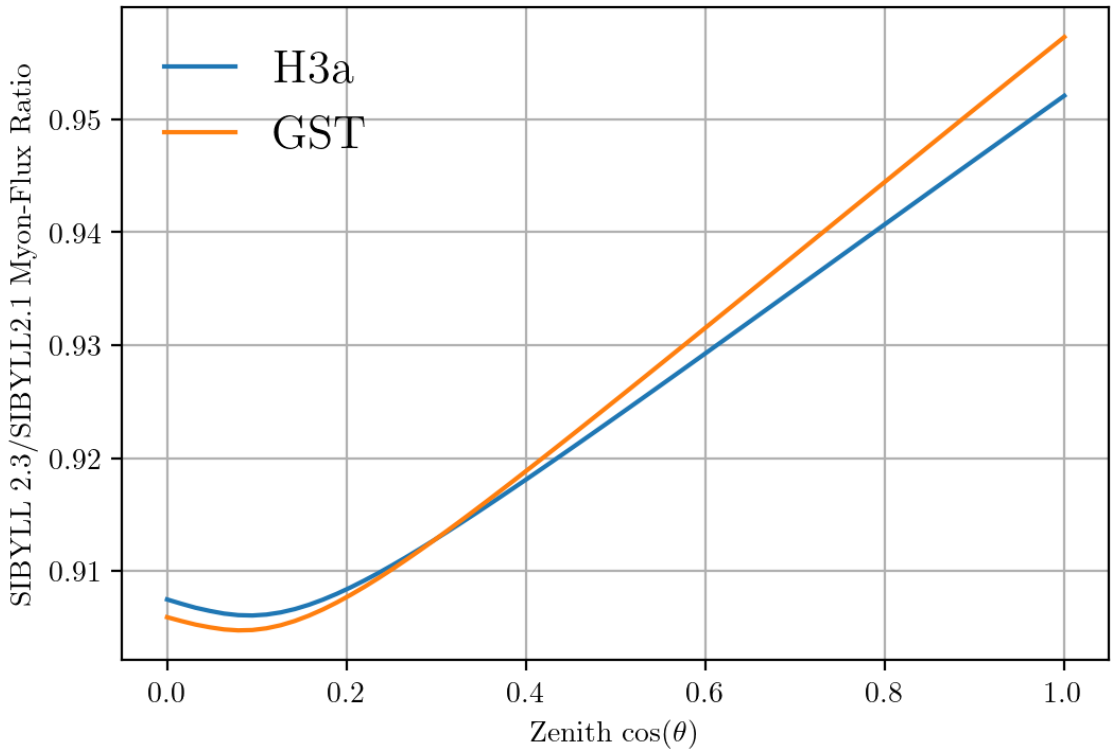
Muon production – different weightings

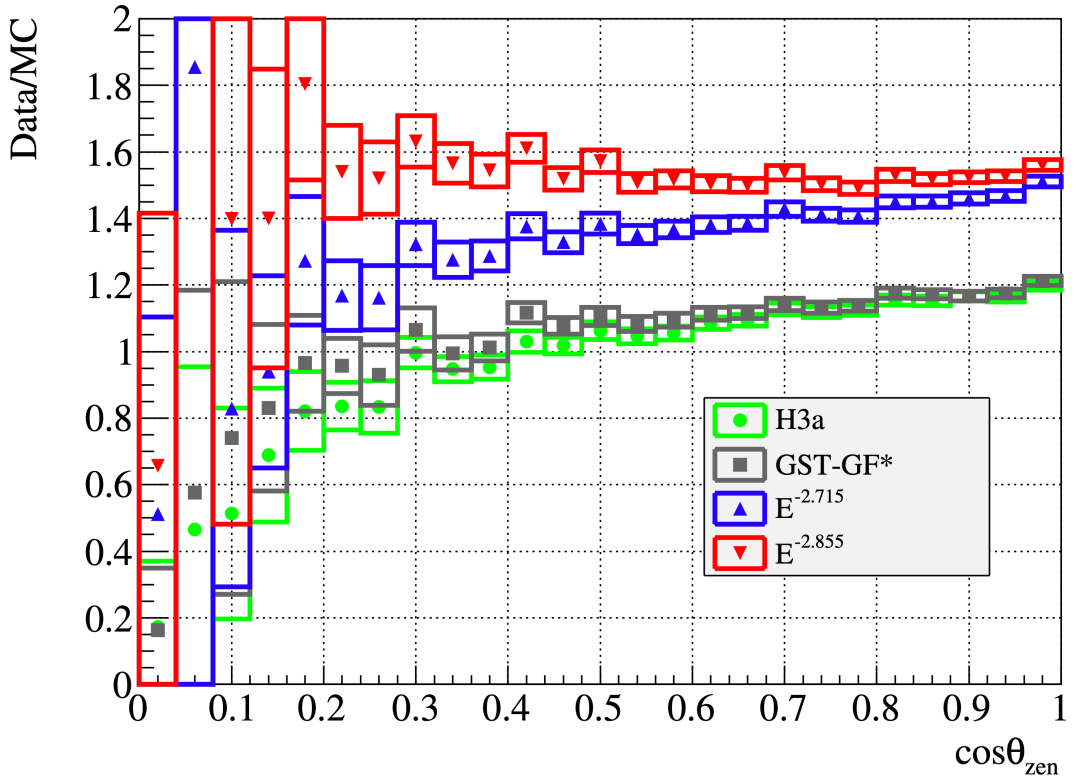
GST predicts most prompt



MCLabelsLeadingMuons_entry_energy

Solution to zenith problem?

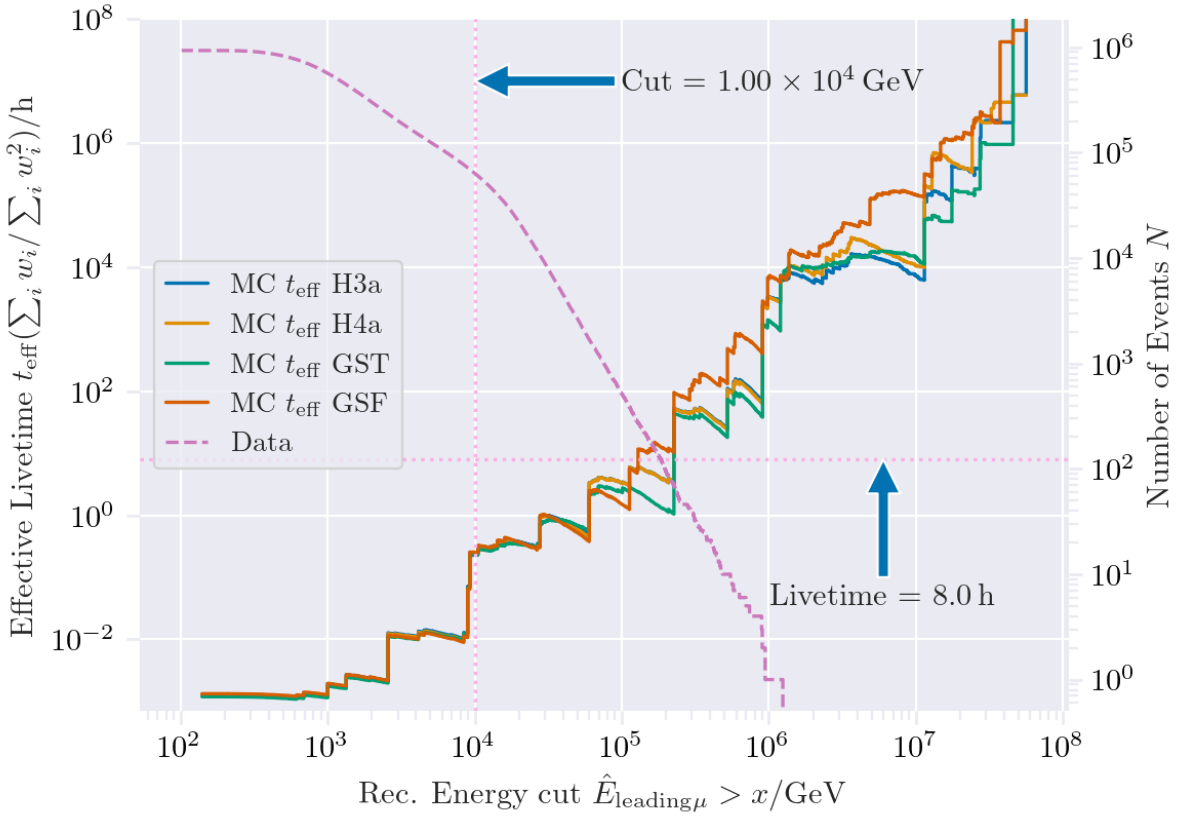




- No complete solution, but a step in the right direction

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/

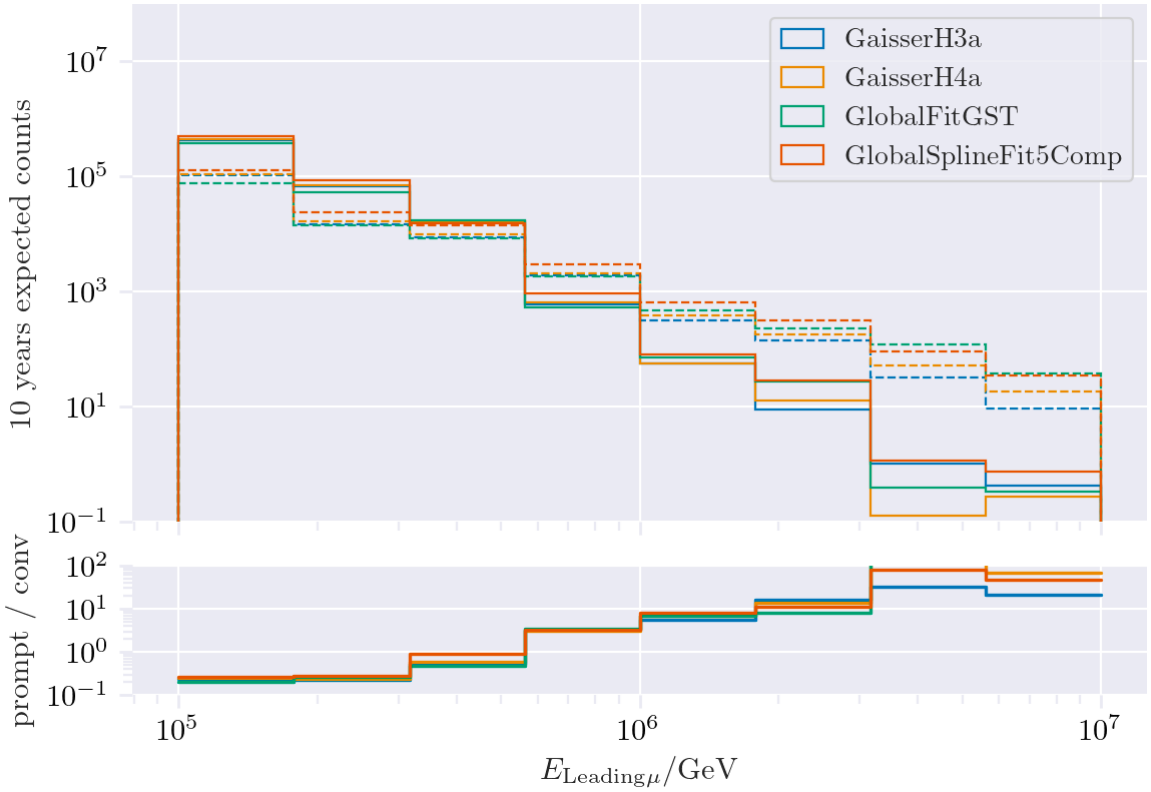


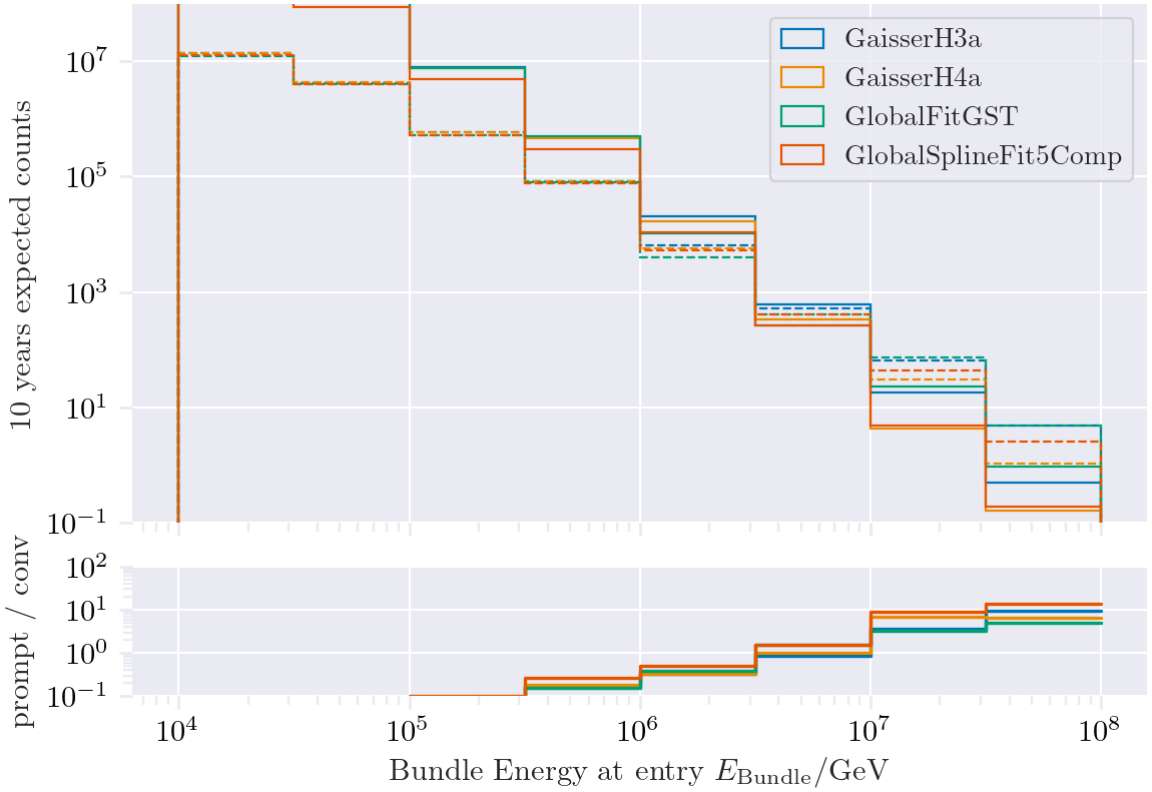
Please go ahead and test the datasets

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

Expected muons for 10 years: leading vs. bundle energy

Solid: conventional
Dashed: prompt

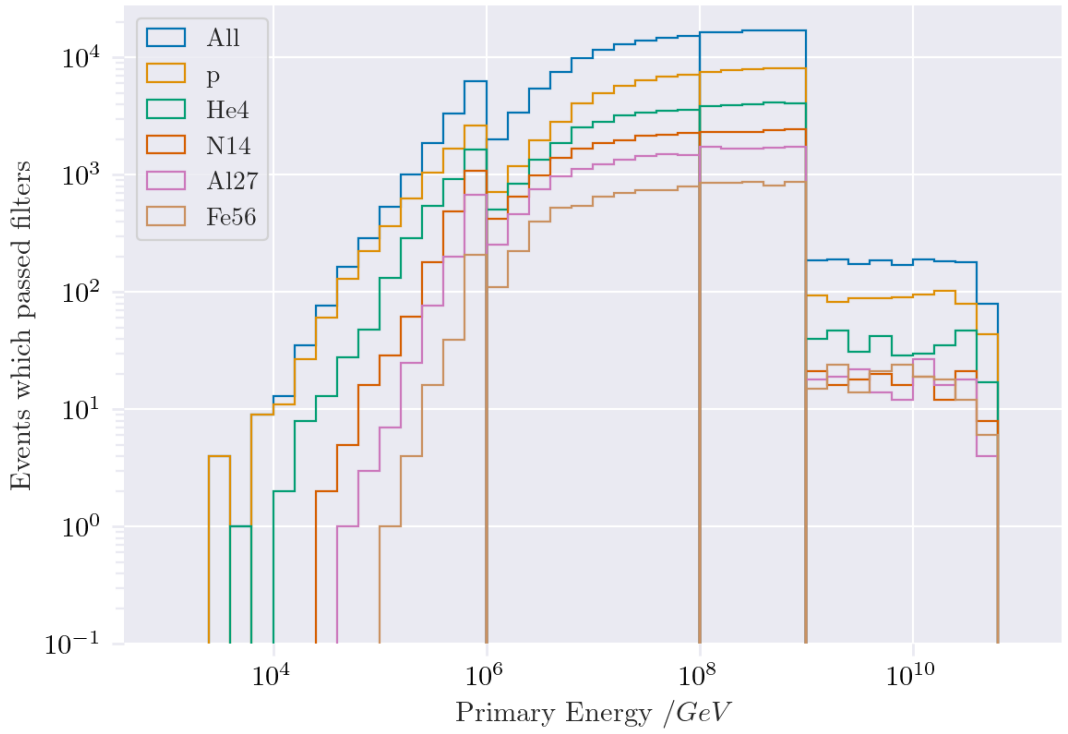




- Different primary fluxes lead to different prompt fluxes
- Bundle energy extends to higher energies

Simulated events

Passed muon filter



Which energies do we need to simulate?

L2 MuonFilter
Bundle energy > 100 TeV