

Ideas to measure the prompt component of the atmospheric muon flux

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Muons

<https://www.vox.com/the-highlight/2019/7/16/17690740/cosmic-rays-universe-theory-science>

Definition of the muon flux

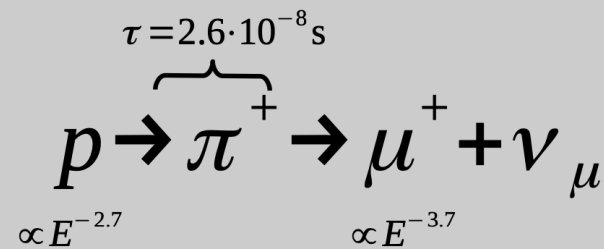
$$\Phi_{\text{tot}} = \Phi_{\text{conv}} + \Phi_{\text{prompt}}$$

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

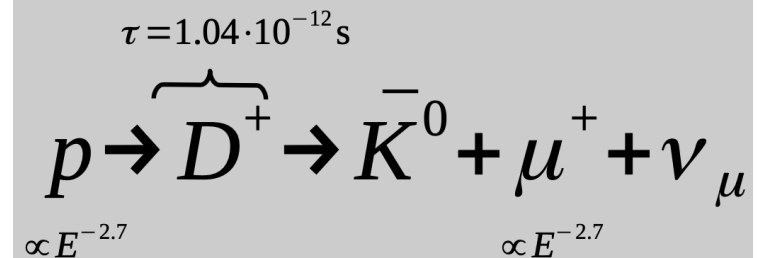
“not” $\pi, K \propto E^{-2.7}$

(all particles with a decay length lower than 0.123 cm = MCEq definition)

Conventional component:



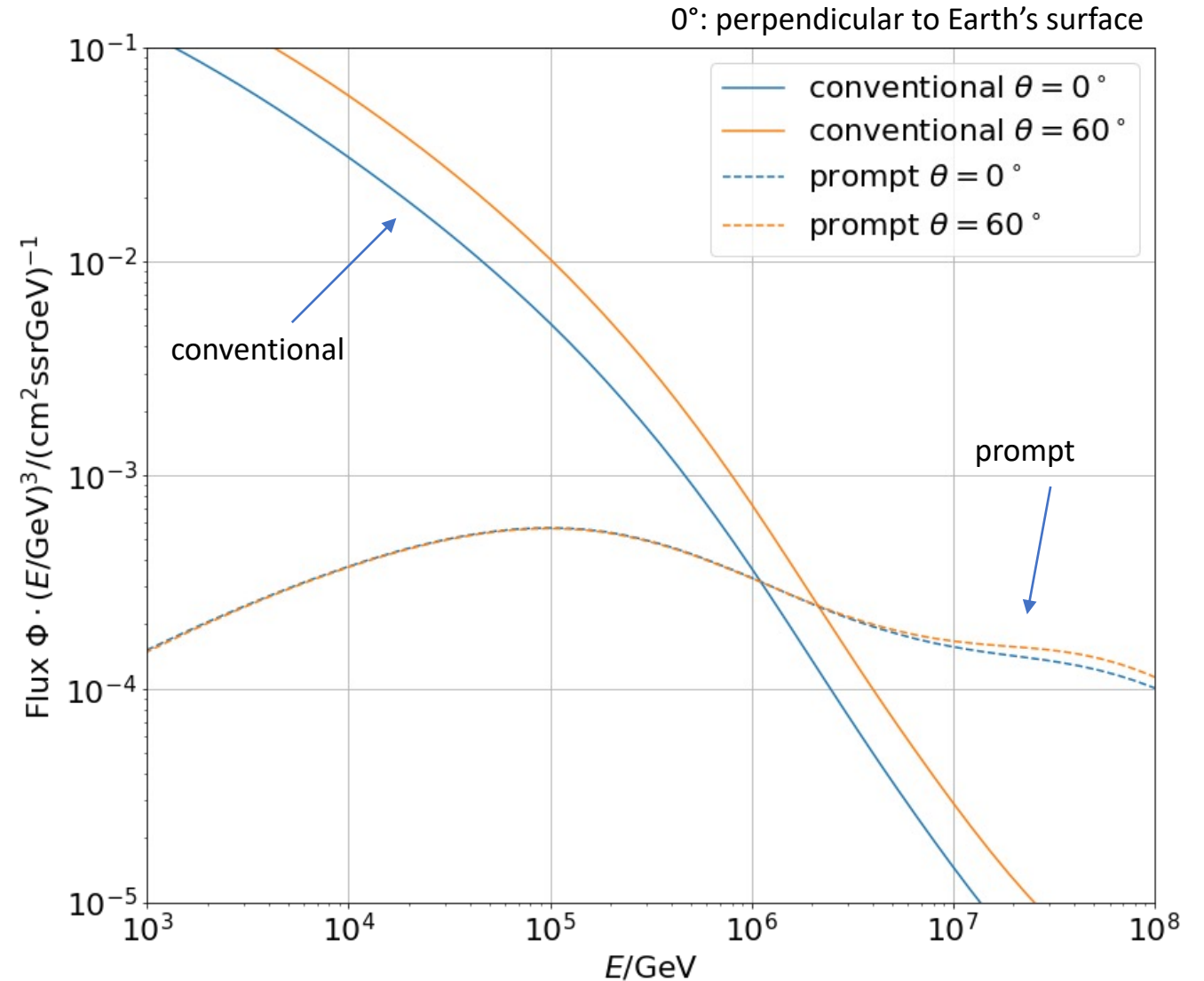
prompt component:



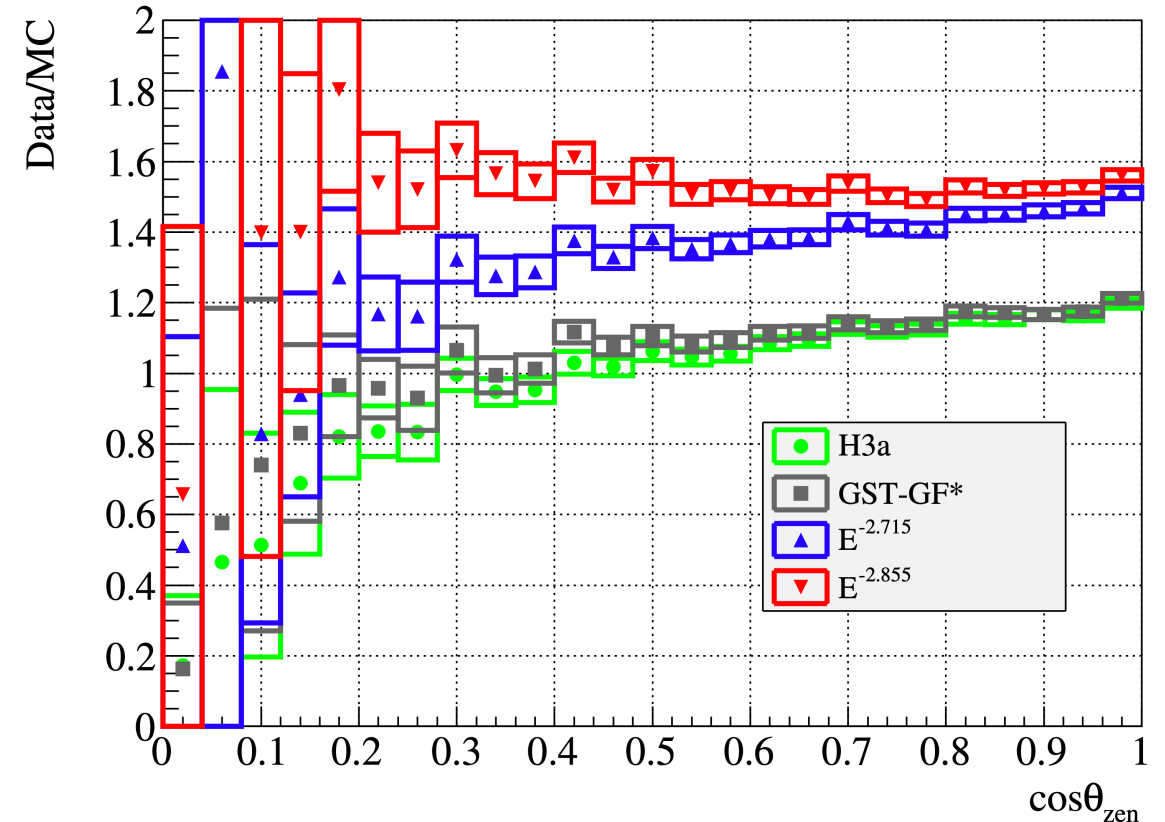
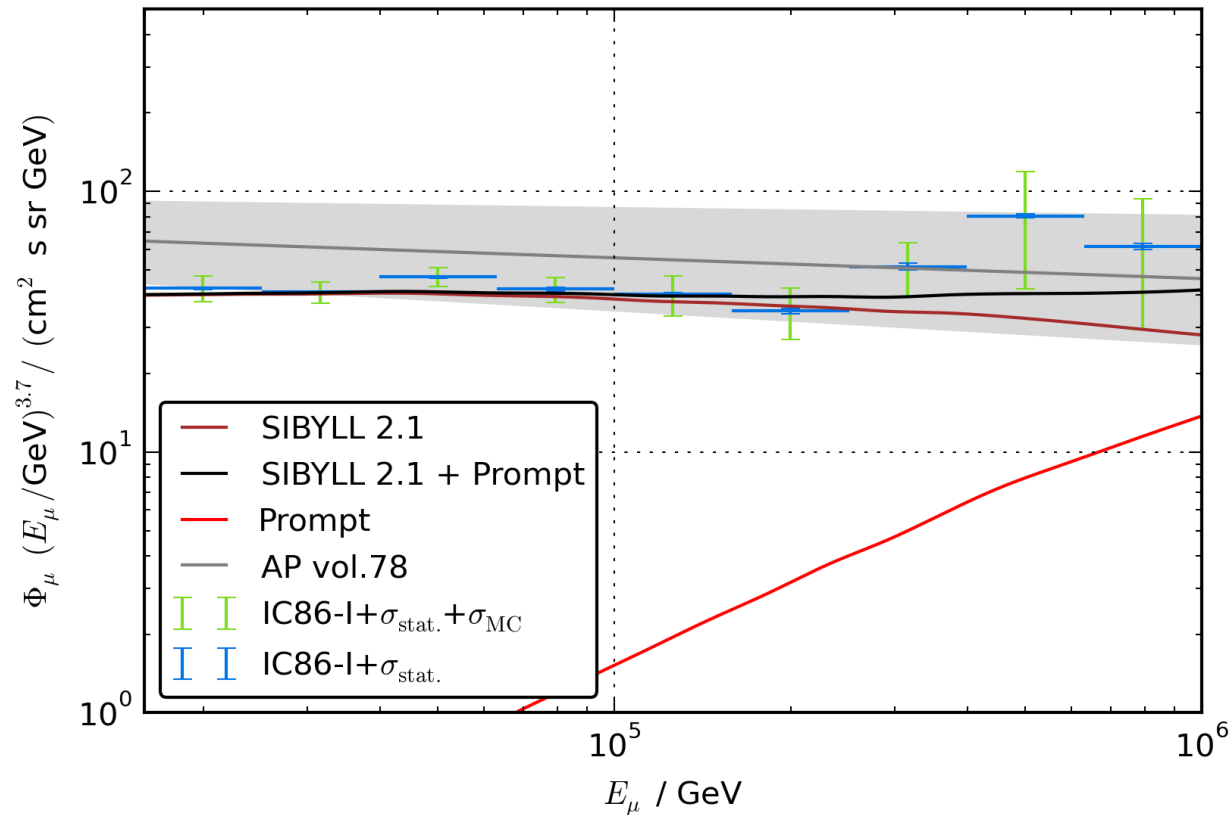
Muon flux

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

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



Previous analyses



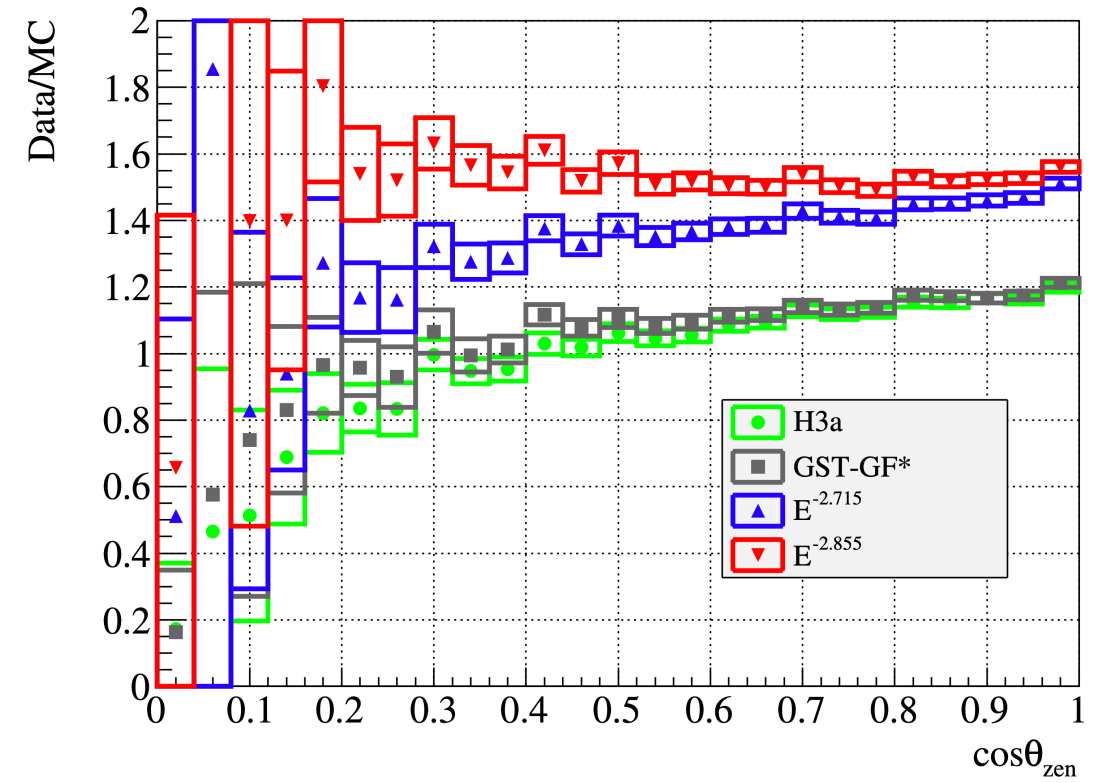
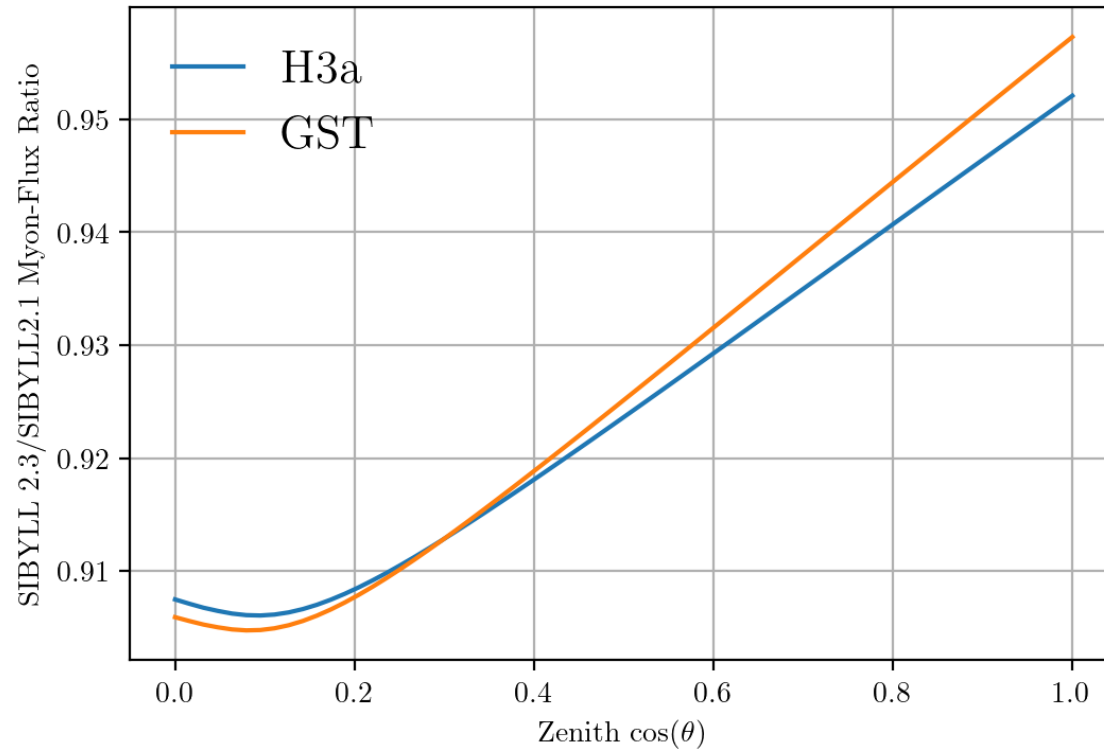
- Fit compatible with zero
- MC uncertainties too large

- Results promising, but zenith problem

[T. Fuchs, PhD Thesis, 10.17877/DE290R-17241]

[IceCube Collaboration, Astroparticle Physics, 10.1016/j.astropartphys.2016.01.006]

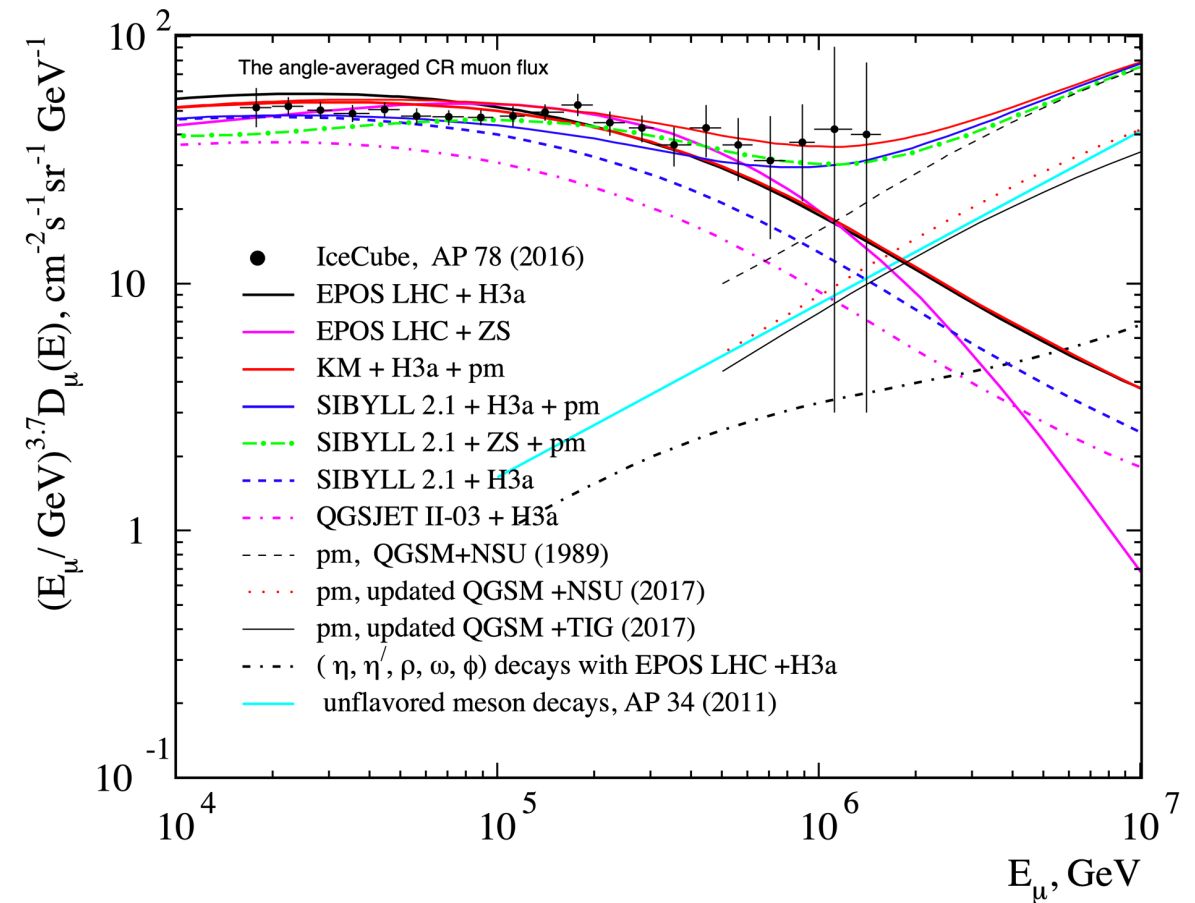
Solution to zenith problem?



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

Observations

- Mismatch between data and hadronic interaction models
 - No charm included in the past
 - Prompt was neglected
 - Fits better by adding prompt model
- New simulations including charm



[Journal of Physics: Conf. Series. 2019. V. 1181, 012054]

New ideas to measure the prompt component

- Latest software CORSIKA 77420 and PROPOSAL
- SIBYLL 2.3d → charm included
- Use extended history option in CORSIKA → parent information
 - Tag muon parent particles in MC (prompt/conv)
- Scale amount of prompt particles to create several datasets
 - Fit of prompt flux normalization
 - Get handle on hadronic interaction models
 - Scaling saves time and resources instead of doing multiple simulations with different interaction models
- Analyze:
 - Muon energy
 - Zenith angle
 - Time (seasonal variations)
 - Conventional flux depends on the season

```
I3MCTree:
3001 PPlus (-162238m, 157642m, 108123m) (64.4051deg, 135.708deg) -819815ns 214166GeV 220335m
3002 PiPlus (nanm, nanm, nanm) (64.1885deg, 135.701deg) nanns 2077.16GeV nanm
3008 KPlus (-21004m, 19853.1m, 1884.56m) (64.1846deg, 135.7deg) nanns 1210.41GeV nanm
3009 NuMu (-3593.81m, 2844.39m, 1948.43m) (64.402deg, 135.662deg) -10.3179ns 409.741GeV nanm
3010 MuPlus (-3582.39m, 2855.52m, 1948.43m) (64.403deg, 135.7deg) -9.81788ns 795.696GeV nanm
3003 PiPlus (nanm, nanm, nanm) (64.2276deg, 135.706deg) nanns 1992.84GeV nanm
3011 Rho7700 (-17868.8m, 16795.2m, 1902.91m) (64.229deg, 135.719deg) nanns 1729.8GeV nanm
3012 unknown (nanm, nanm, nanm) (nandeg, nandeg) nanns nanGeV nanm
3013 NuMuBar (-3555.5m, 2848.75m, 1948.45m) (64.4281deg, 135.744deg) 63.2446ns 304.713GeV nanm
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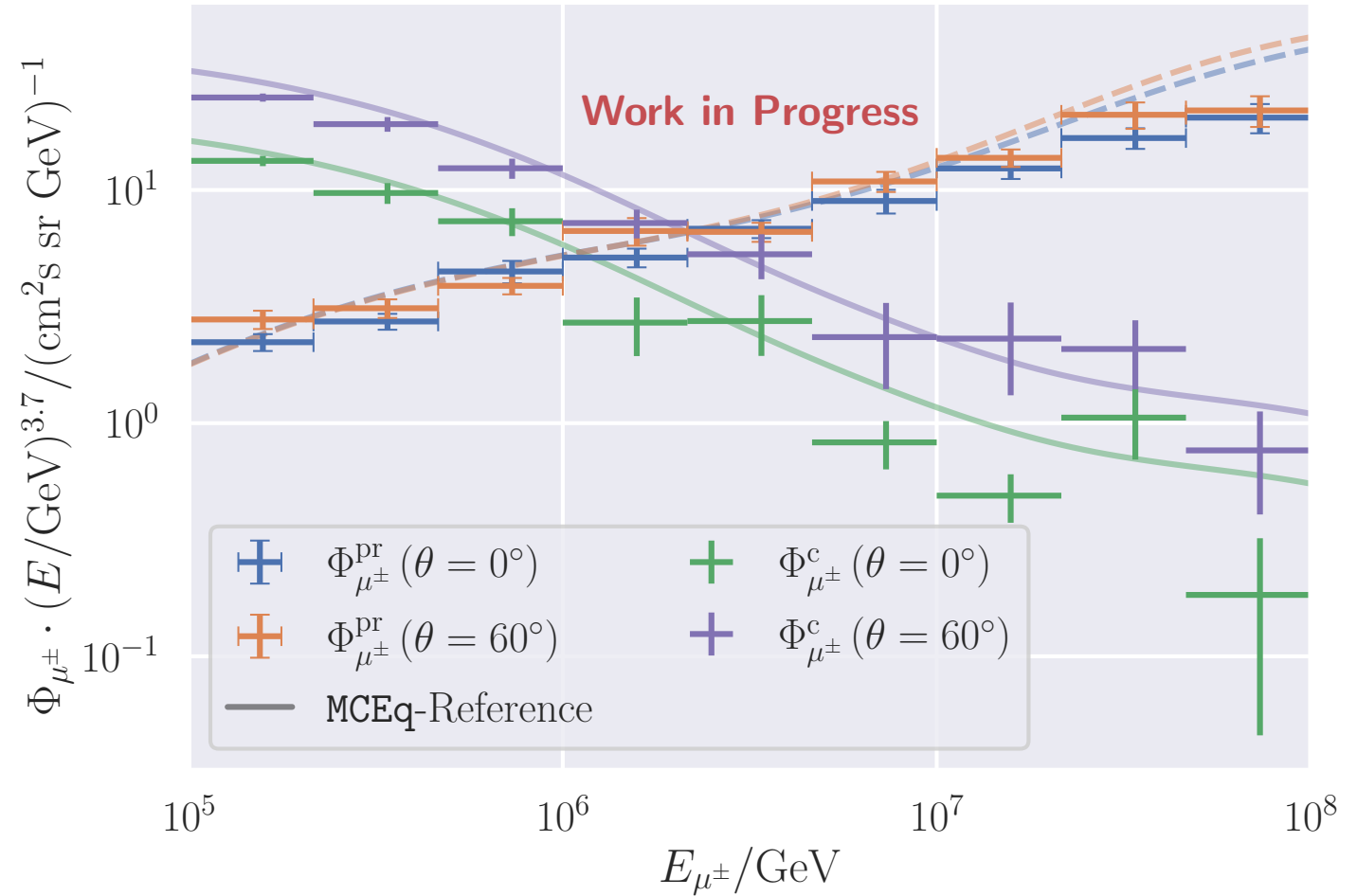
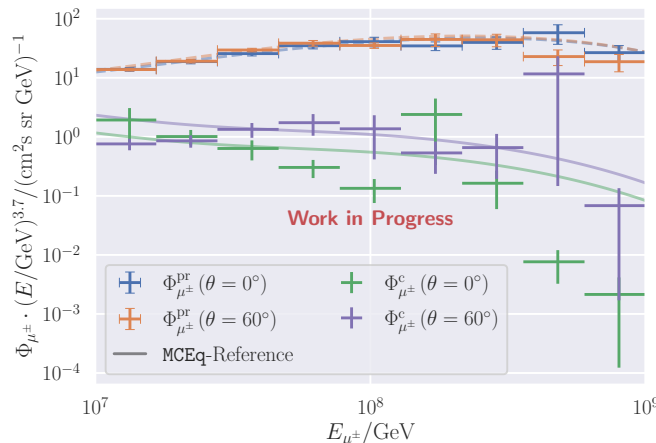
- ✓ CORSIKA reader adopted
- ✓ First simulations running
- ✓ /data/sim/IceCube/2023/generated/
CORSIKA_EHISTORY/

Identify prompt particles in air shower

- CORSIKA 7
- 10 Mio. air showers (primary: proton)
- Initial energy: $10^5 - 10^9$ GeV
- Two different injection angles θ
- SIBYLL 2.3d
- Sampled from E^{-1} , reweighted to Gaisser H3a
- Extended history option to identify and tag the prompt particles manually

Deviations at energies $> 10^7$ GeV

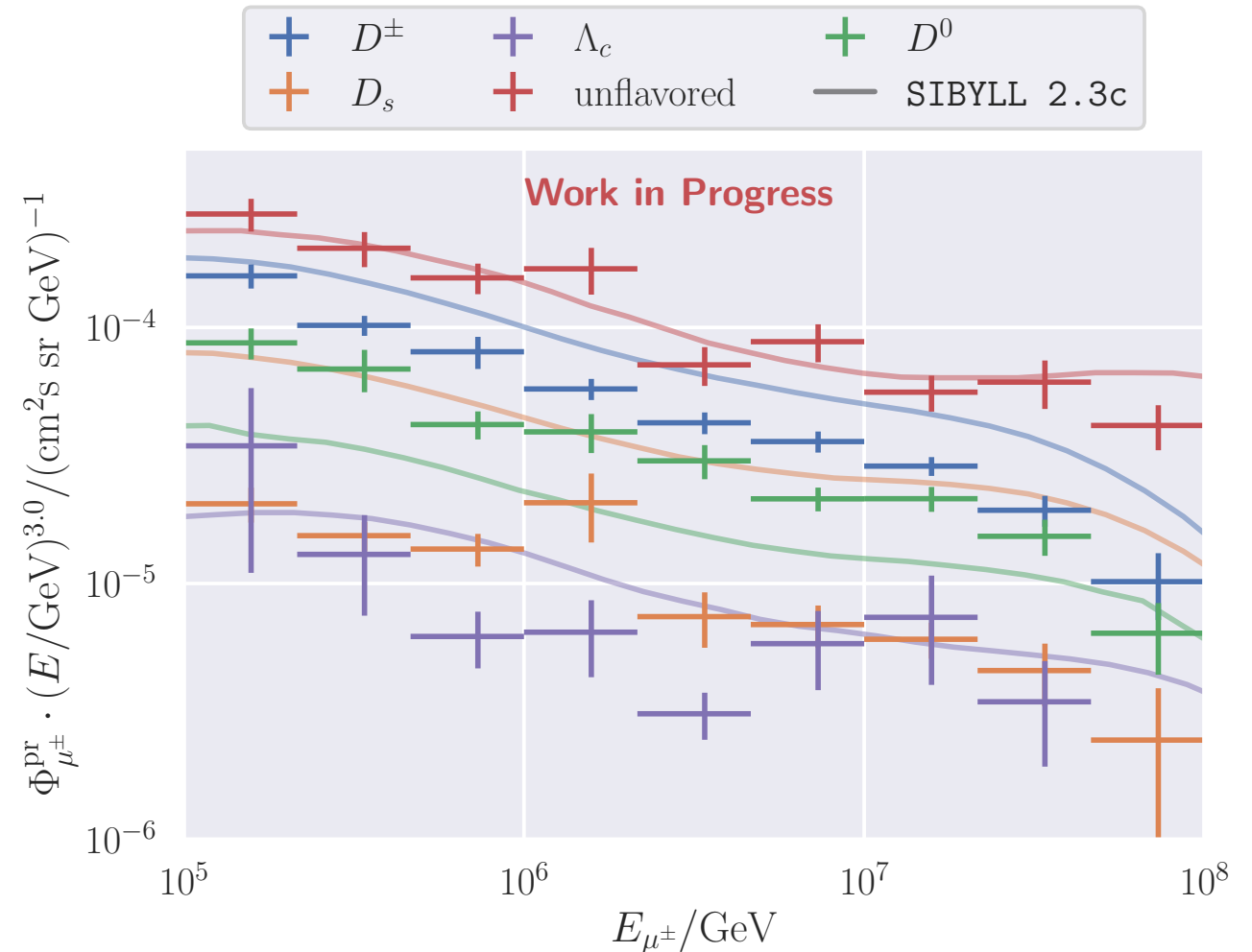
- Maximum injected energy lower than the maximum possible energy (GZK cutoff at $\sim 5 \cdot 10^{10}$ GeV)
- MCEq: SIBYLL 2.3c



✓ Good agreement between CORSIKA and MCEq

Specific parent particle identification

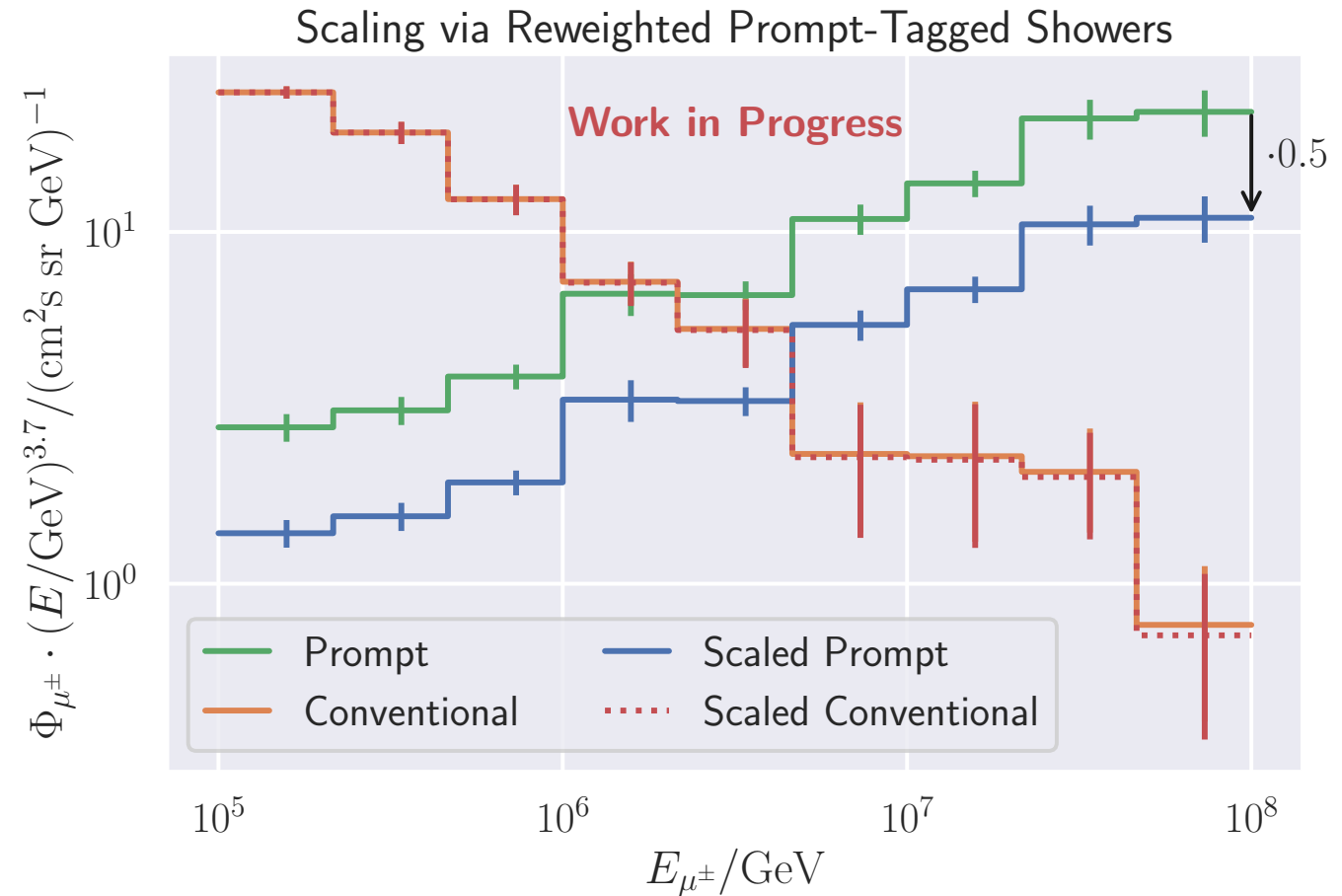
- CORSIKA 7 using SIBYLL 2.3d vs. SIBYLL 2.3c¹
- Good agreement with unflavored particles
- Mismatches occur for all the D-mesons
 - Issue not yet solved
 - Only protons simulated with CORSIKA



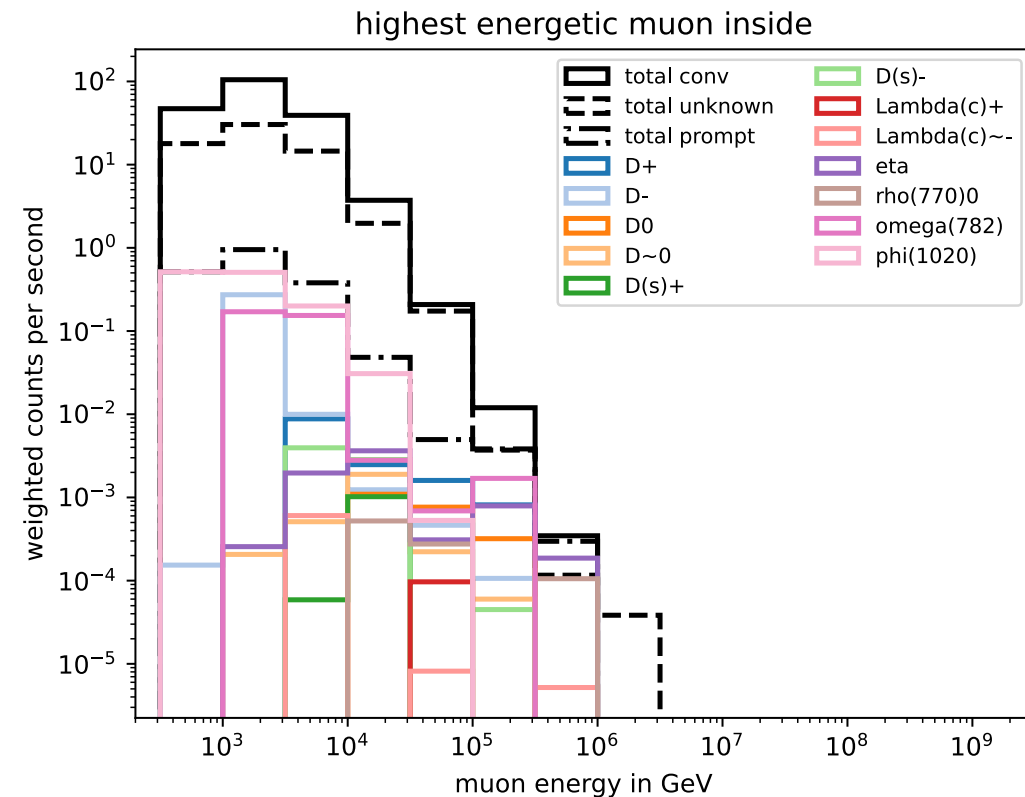
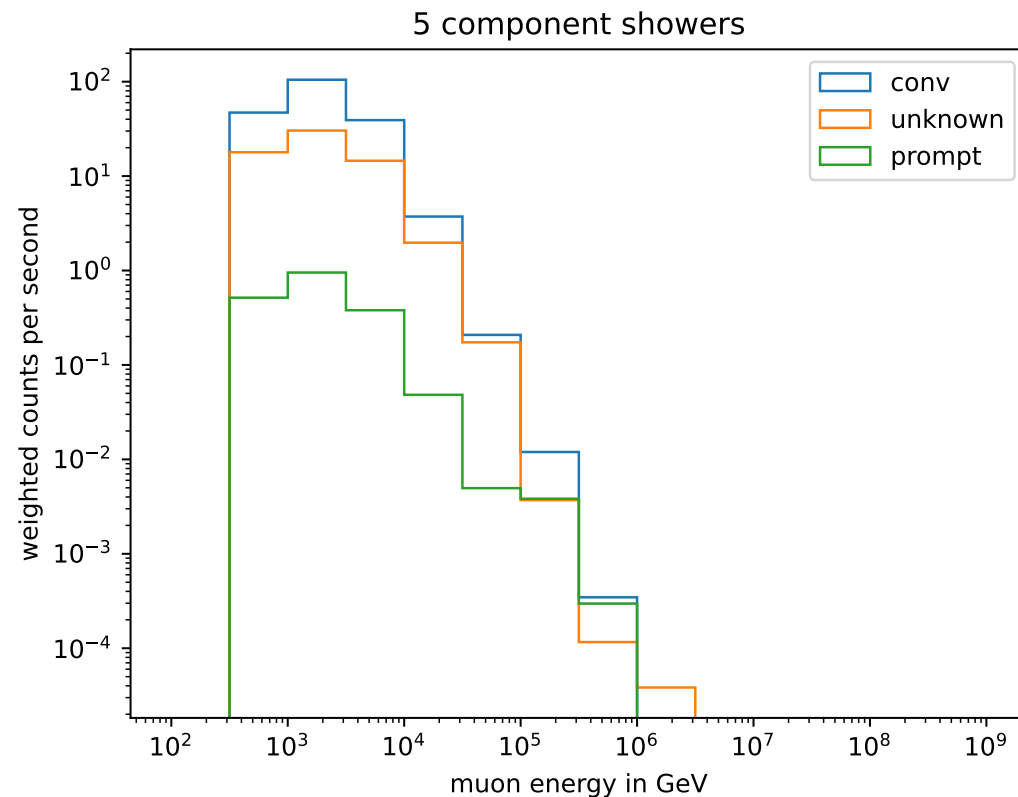
¹ Phys. Rev. D 100 (2019) 103018

Scaling of the prompt component- tagging

- Amount of prompt particles is re-weighted with 0.5
- Use tagging of prompt in CORSIKA MC
- Conventional component is not much affected
 - If a shower contains prompt, almost no conv. particles in the shower arrive at the surface



Muon energy distributions



- Highest energetic muon per shower/tree inside detector is shown
- Too less statistics at high energies
- Unknown: parent particle is not known → generation counter indicates, that there are particles between mother and muon → conventional

Who simulates what?

- Many similar CORSIKA simulations are performed
 - Simulations are done on own branches
-
- We should organize this and combine simulations
 - Saves time, resources and avoids unnecessary work

Summary

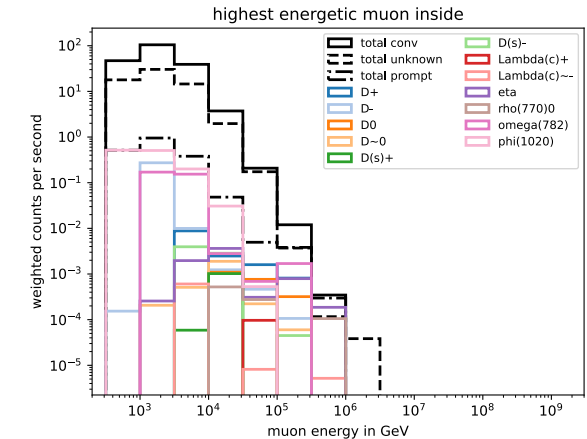
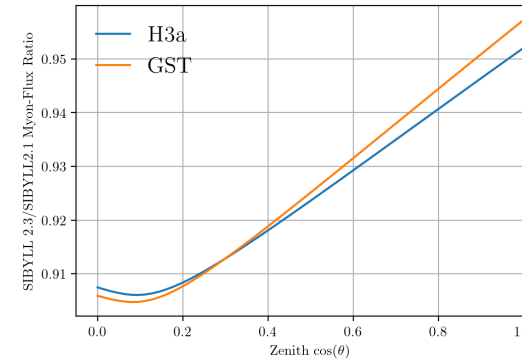
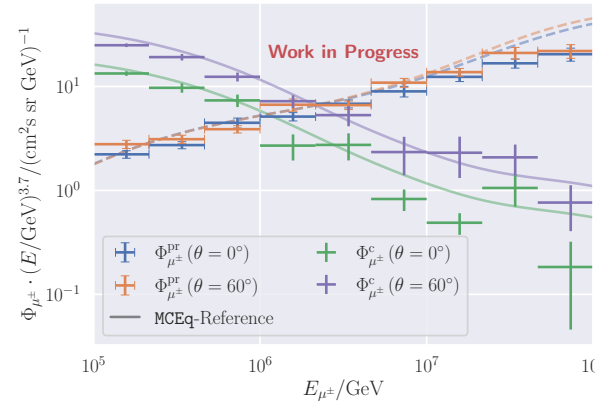
- CORSIKA_EHIST works
- Parent particles can be tagged
- Good agreement with MCEq
- Ready for the simulation/analysis

Next steps:

- Simulate test data set
- New event selection using DNN
- Start analysis chain
- Analyze *zenith problem* with new simulations

Future discussion:

- How to extract physical parameters from *effective scaling*?
 - branching ratios (BR), cross-sections, particle physics
- Scale BR and hadronic models compatible with LHC results

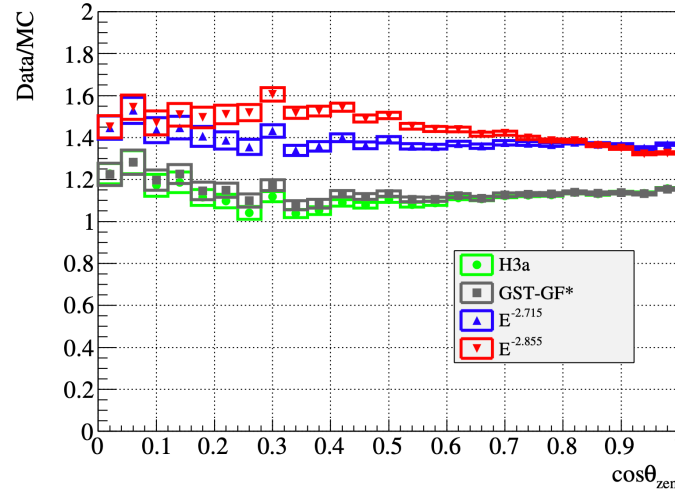


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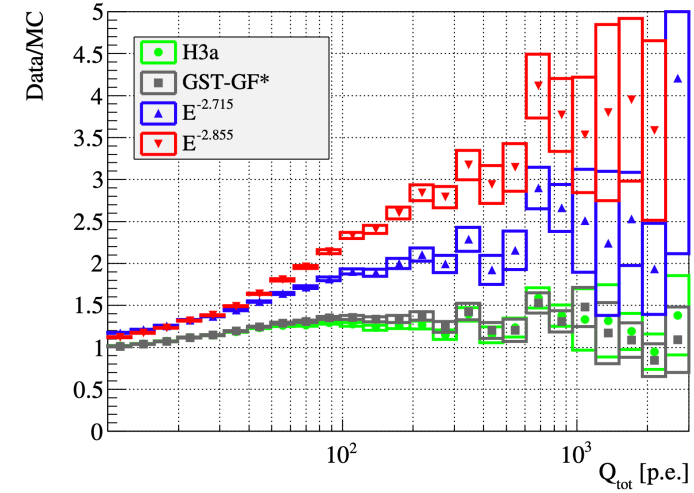
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Backup

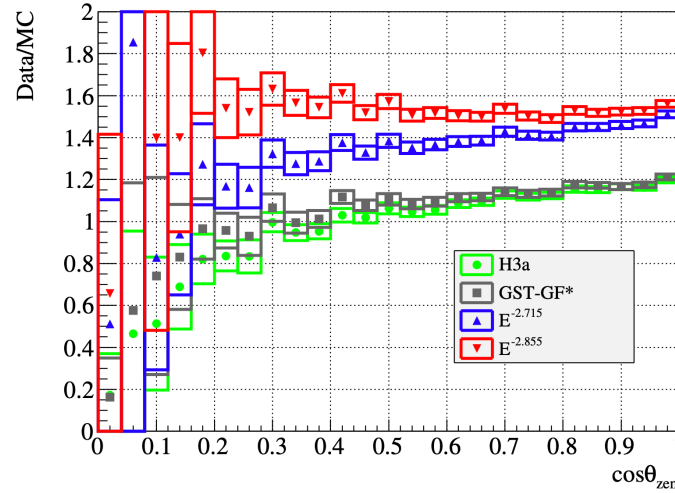
Backup: Zenith problem



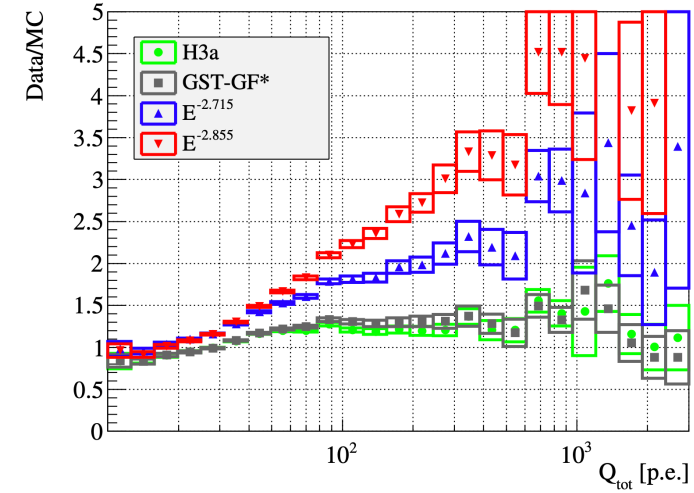
(a) $\cos \theta_{\text{zen}}$, Trigger Level



(b) Q_{tot} , Trigger Level



(c) $\cos \theta_{\text{zen}}$, High-Quality Tracks



(d) Q_{tot} , High-Quality Tracks

Figure 8: Ratio of experimental data to simulation in terms of reconstructed zenith angle θ_{zen} and total amount of registered photo-electrons Q_{tot} . The primary flux models used in this comparison are discussed in Section 4.2.

Backup: Scaling of the prompt component - DYNSTACK

- Use DYNSTACK
 - CORSIKA extension to manipulate stack
- Replace prompt particles with conv. (π , K) while shower simulation
 - adapt kinetic energy
- Issue?
 - More conv. particles in shower, but less in the high energy region
 - $D^0 \rightarrow K^+$ (>50%) removing prompt parents removes conv. muons as well

