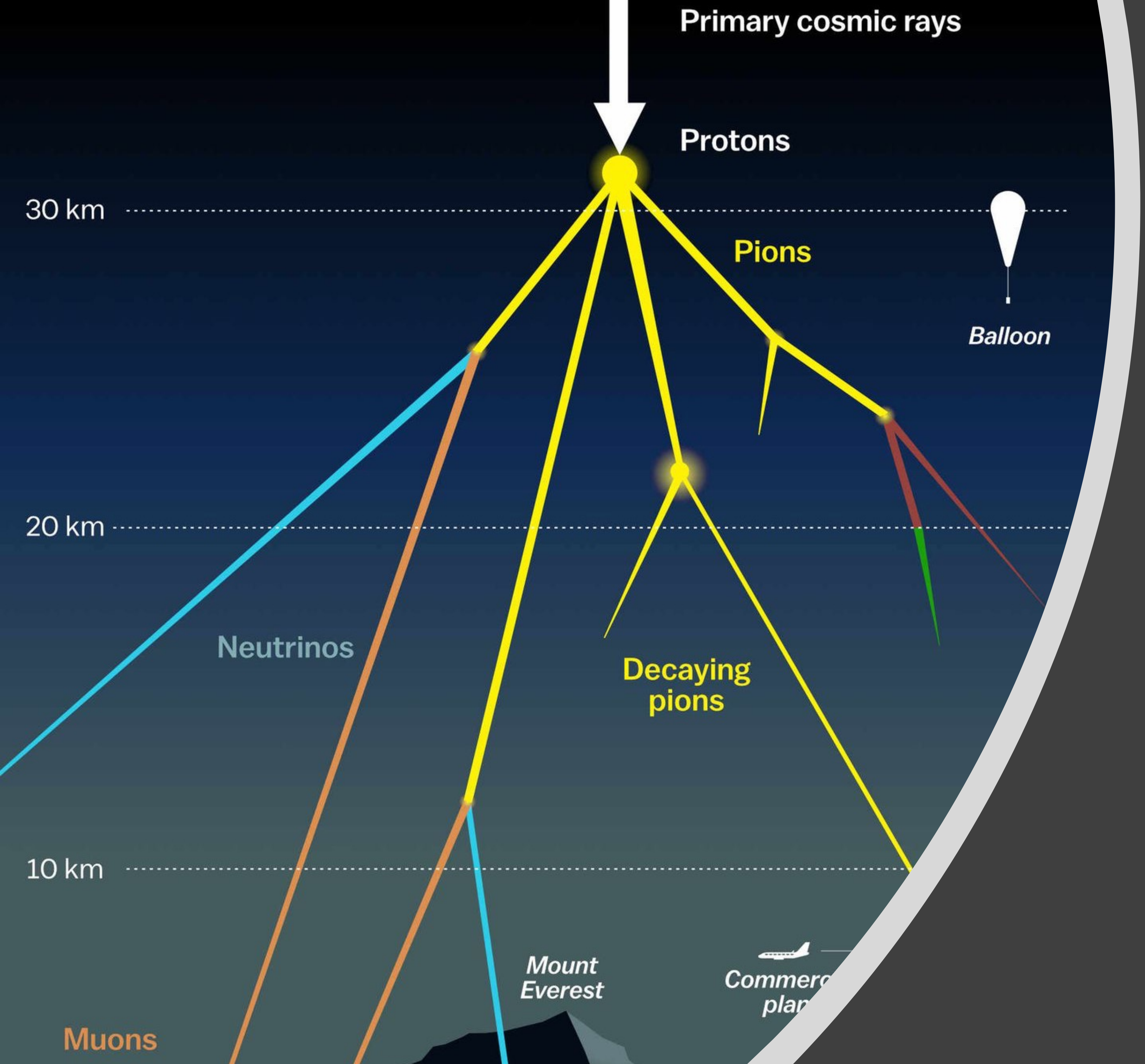


https://www.vox.com/the-highlight/2019/7/16/17690740/cosmic-rays-universe-theory-science

Measuring the prompt component of the atmospheric muon flux

Ludwig Neste and Pascal Gutjahr

F3/F4 Meeting

Dortmund 2023

Definition of the muon flux

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

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

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

Xi(c)~0
Lambda(c)~-
D(s)-
D~0
D-
rho(770)0
eta
omega(782)
eta'(958)
phi(1020)
D+
D0
D(s)+
J/psi(1S)
Lambda(c)+
Xi(c)0

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:

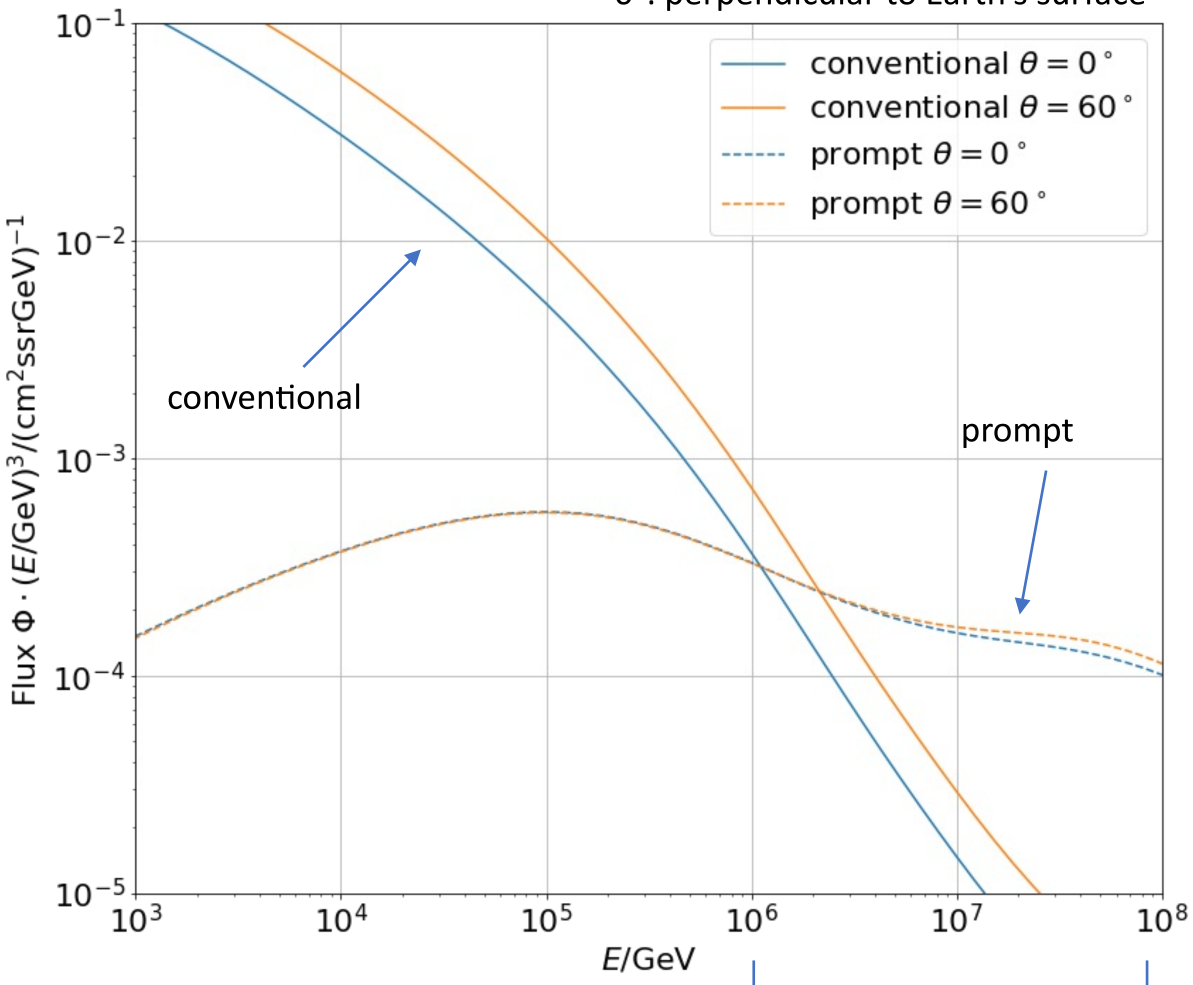
$$\underset{\propto E^{-2.7}}{p} \rightarrow \overbrace{D^+}^{\tau = 1.04\cdot 10^{-12}\,\mathrm{s}} \rightarrow \bar{K}^0 + \underset{\propto E^{-2.7}}{\mu^+} + \nu_\mu$$

Muon flux

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

- 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

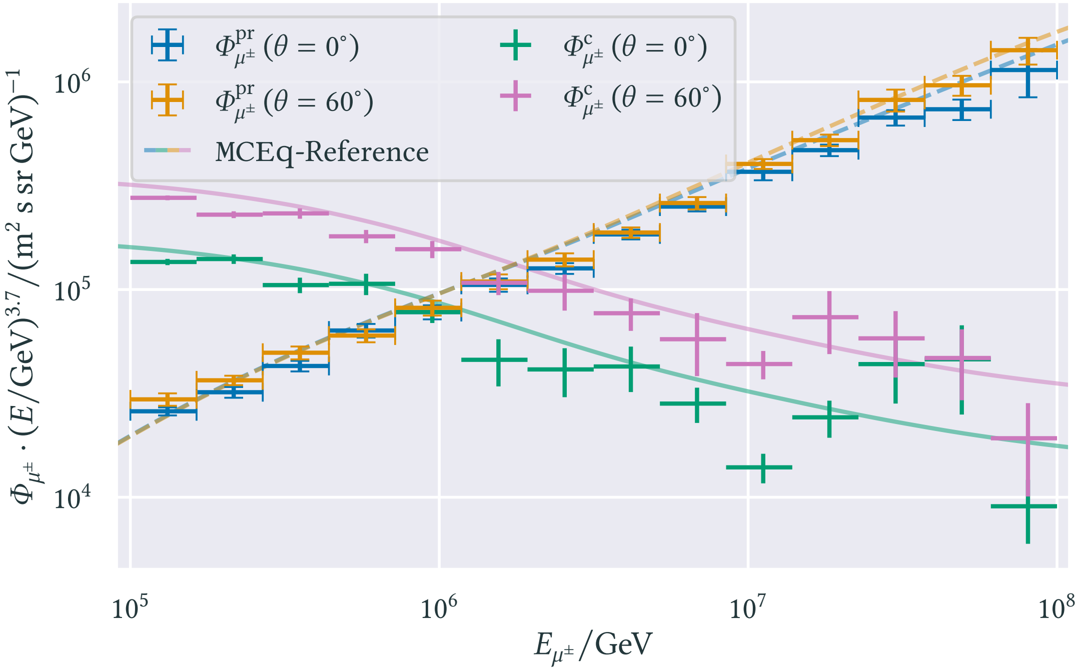
Ideas to measure the prompt component

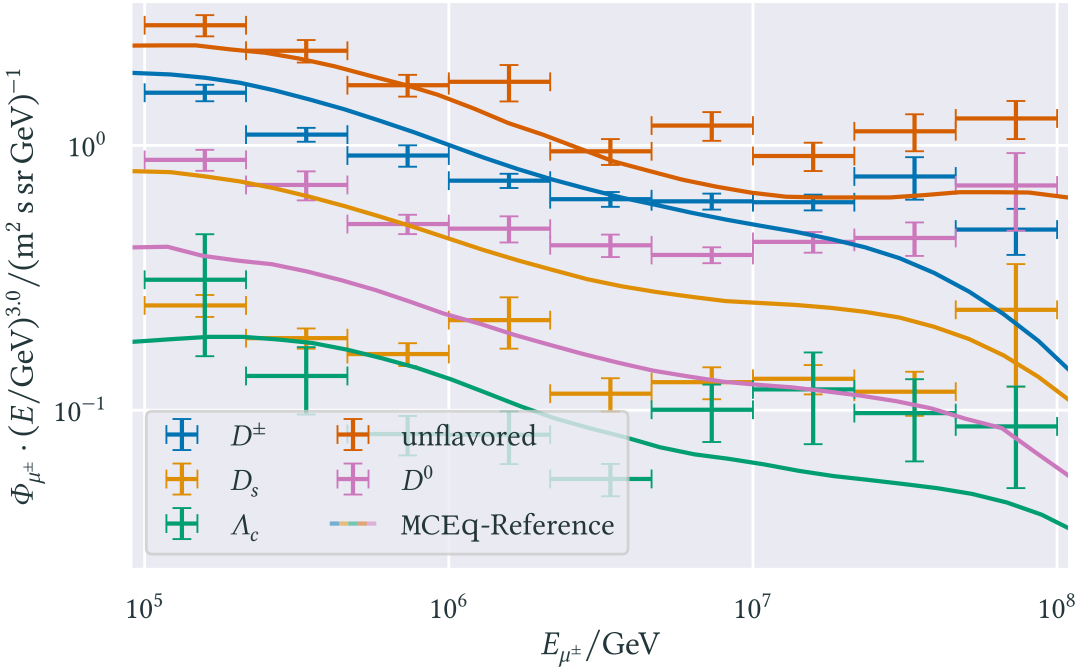
- CORSIKA 7
- SIBYLL 2.3d → charm included
- Use extended history option in CORSIKA → parent information
  - Tag muon parent particles in MC (prompt/conv)
- Scale amount of prompt particles to create several datasets
  - Fit of prompt flux normalization
  - Get handle on hadronic interaction models
  - 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
```

✓ First simulations produced

Identify prompt particles in air shower





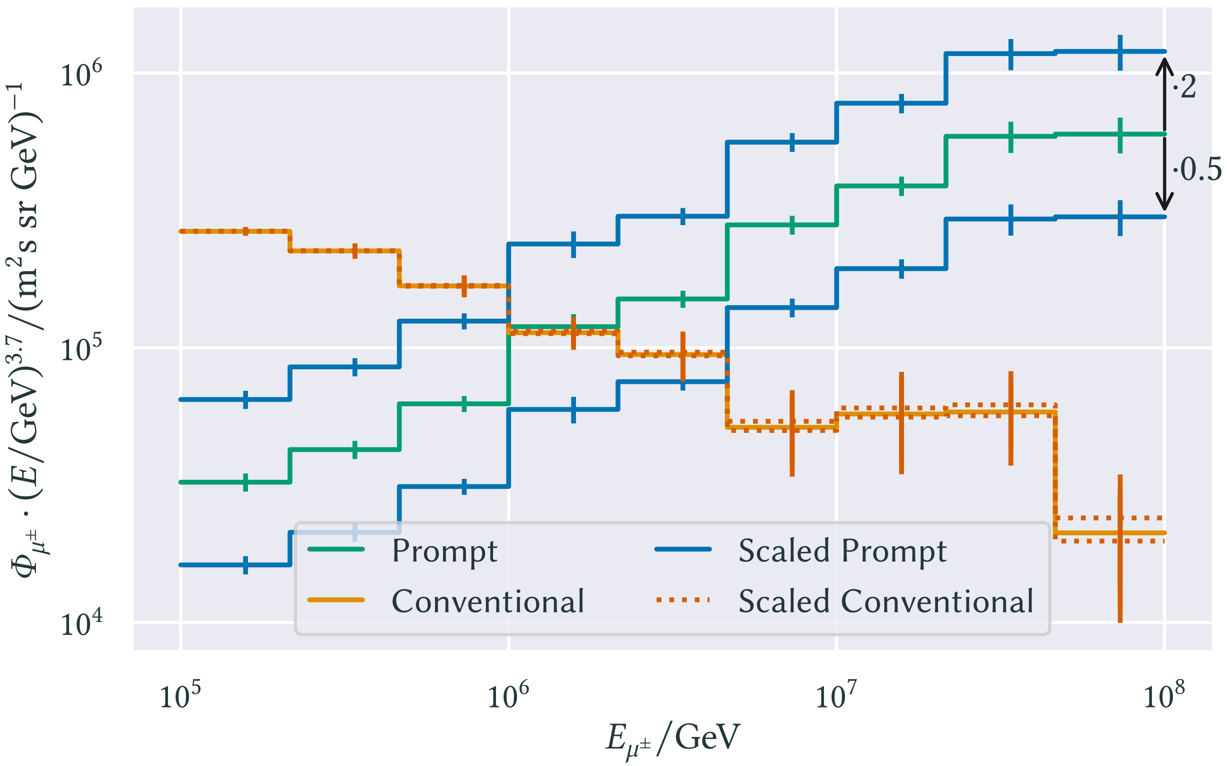
- Good agreement between CORSIKA and MCEq in total
- Mismatches between the production of D_s and D_0

MCEq: tool to numerically solve the cascade equations that describe the evolution of particle densities as they propagate through gaseous a dense medium
https://github.com/mceq-project/MCEq

Scaling of the prompt component (sketch)

- Amount of prompt particles is re-weighted with 0.5 and 2
- 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

➢Used for likelihood fit



Summary

- CORSIKA 7 with SIBYLL 2.3d
- Tag muon parents
- Good agreement with MCEq in total, but mismatch in D_s and D_0

We will provide:

- Normalization of the prompt muon flux in dependence of muon energy and zenith angle
- Unfolding at Earth's surface

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

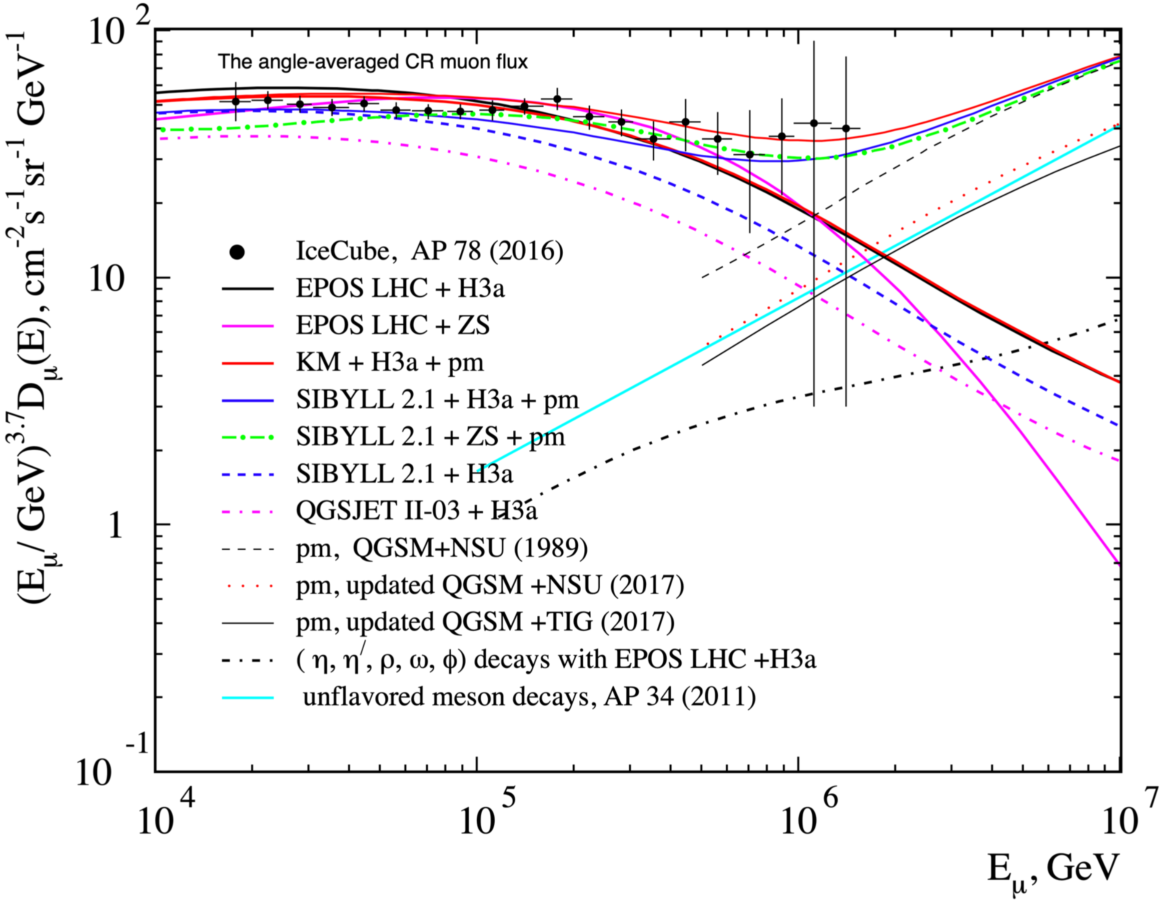
Thank you for your attention ☺️ pascal.gutjahr@tu-dortmund.de

Backup

Observations

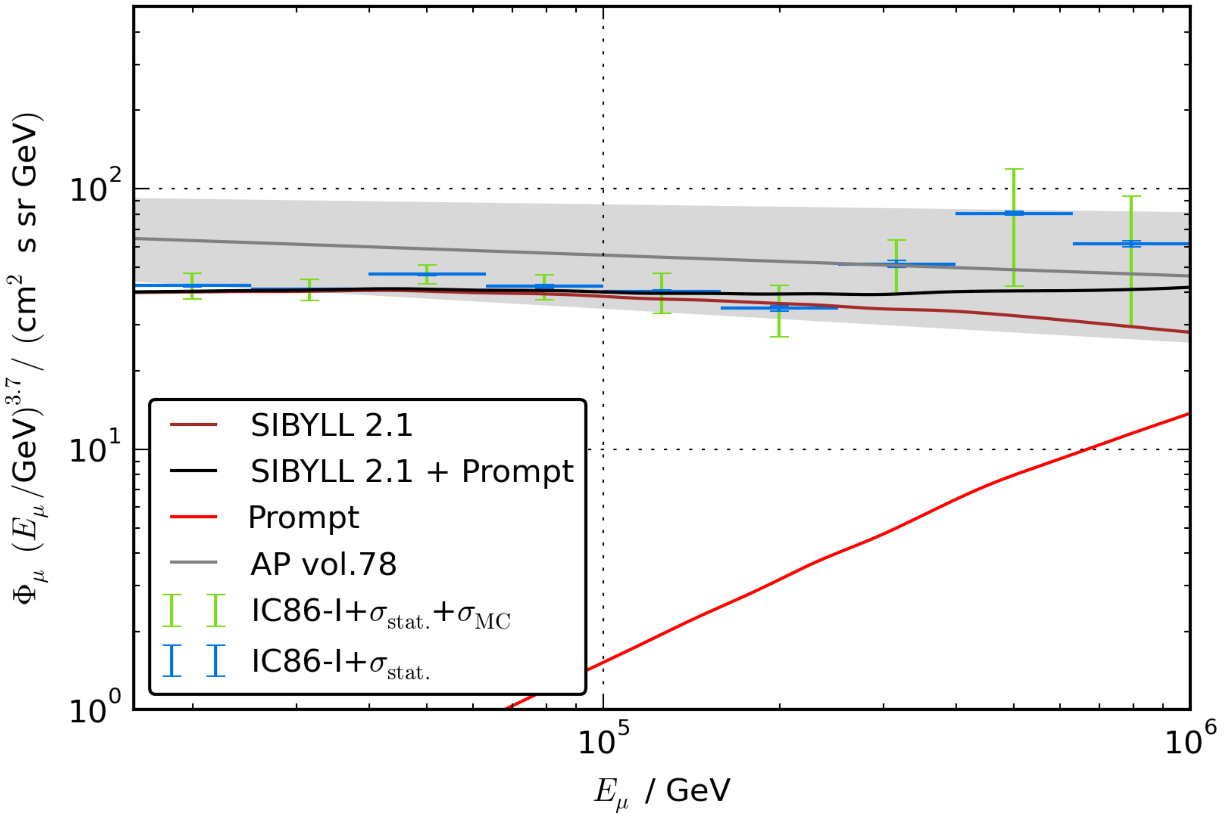
- Mismatch between data and hadronic interaction models
- No charm included in the past
- Prompt was neglected
- Fits better by adding prompt model

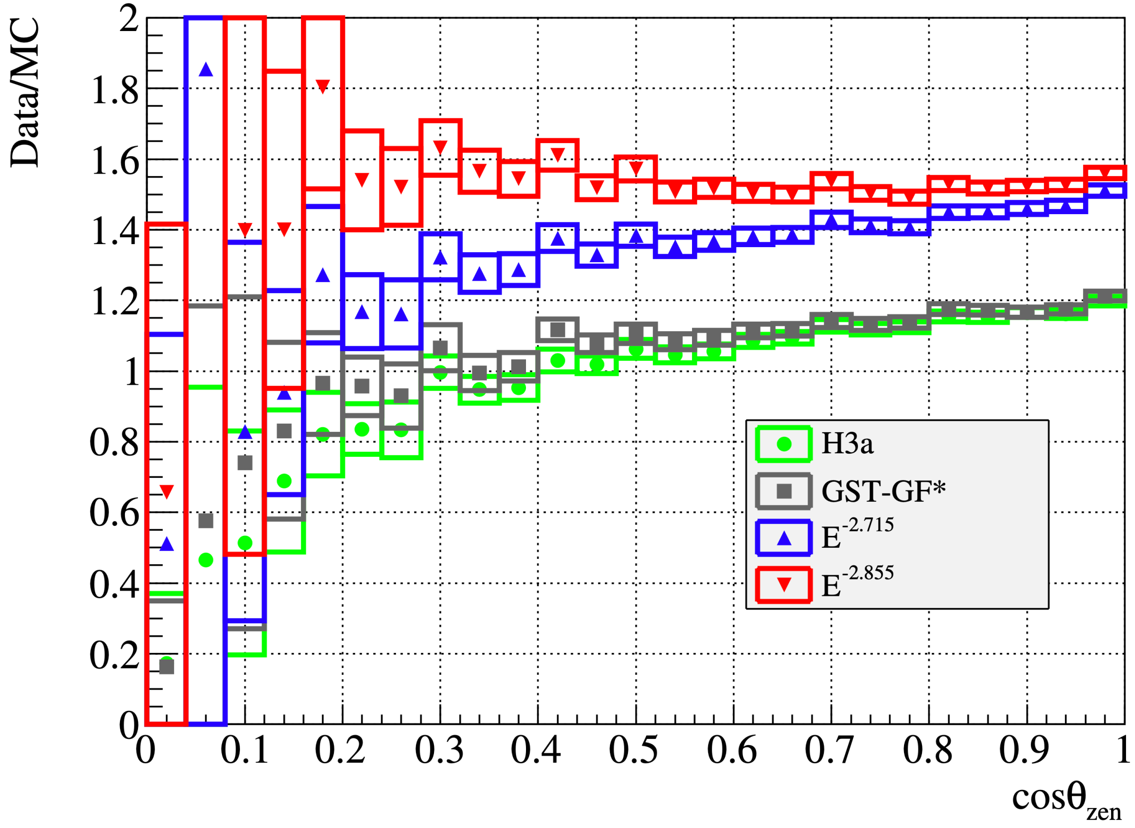
➢ New simulations including charm



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

Previous analyses



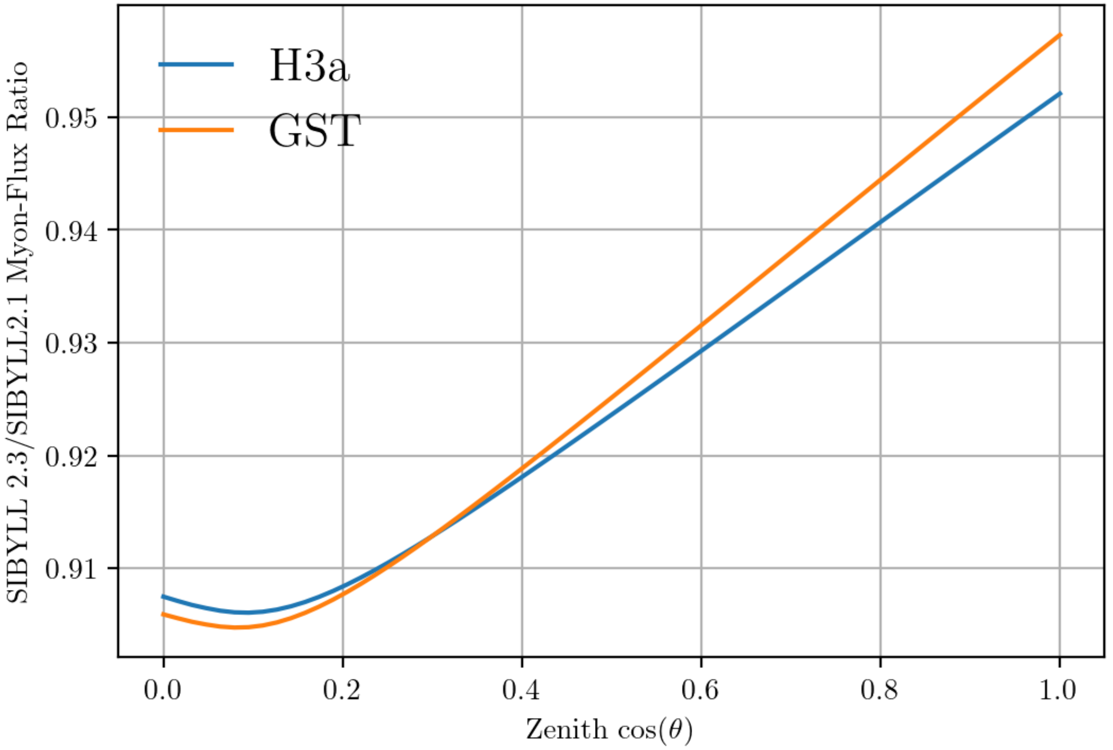


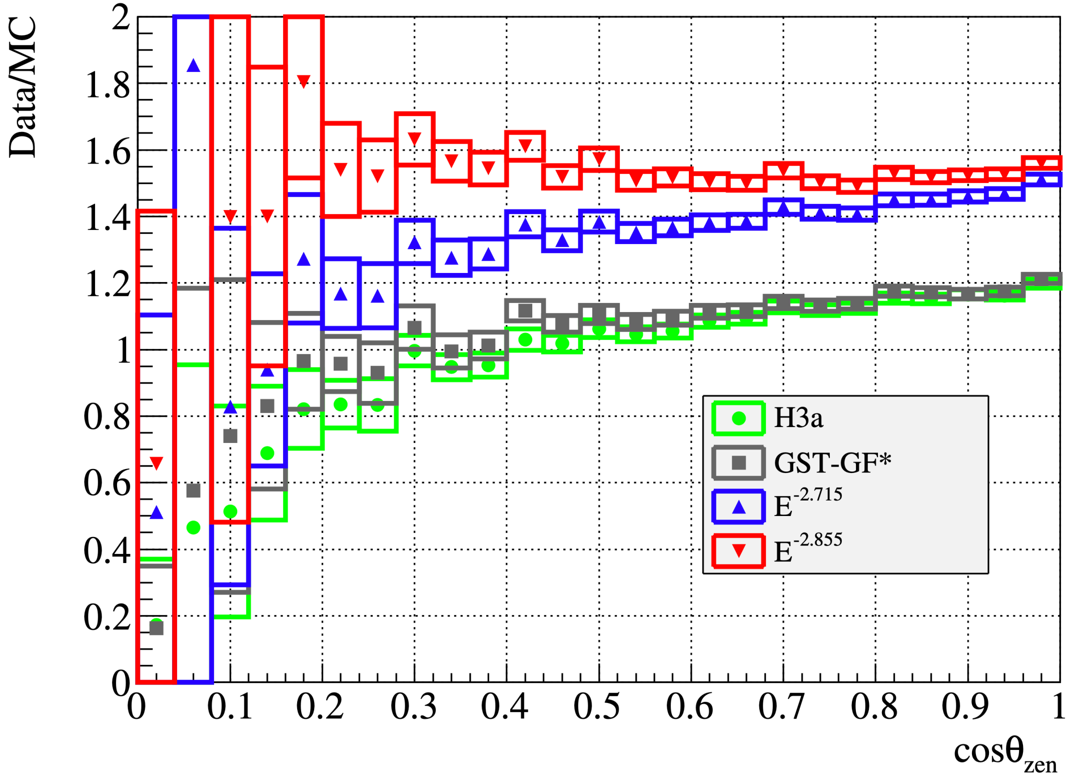
- Fit compatible with zero
- MC uncertainties too large

- Results promising, but zenith problem

[T. Fuchs, PhD Thesis, 10.17877/DE290R-17241]
[IceCube Collaboration, Astroparticle Physics, 10.1016/j.astropartphys.2016.01.006]

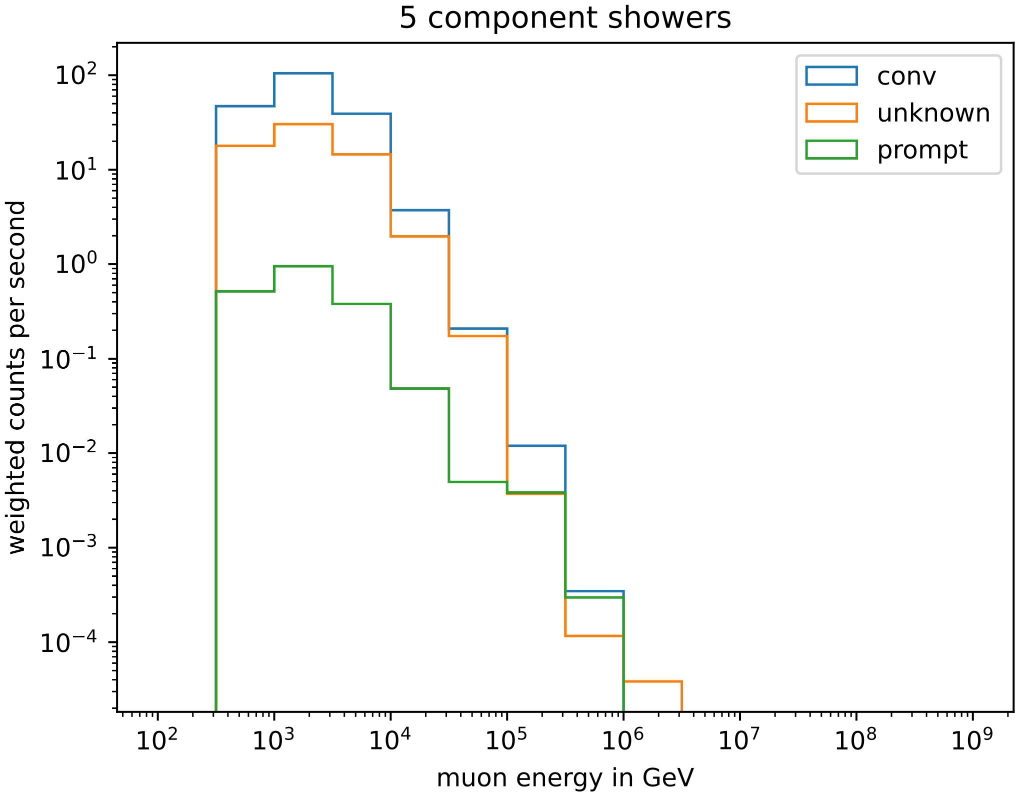
Solution to zenith problem?

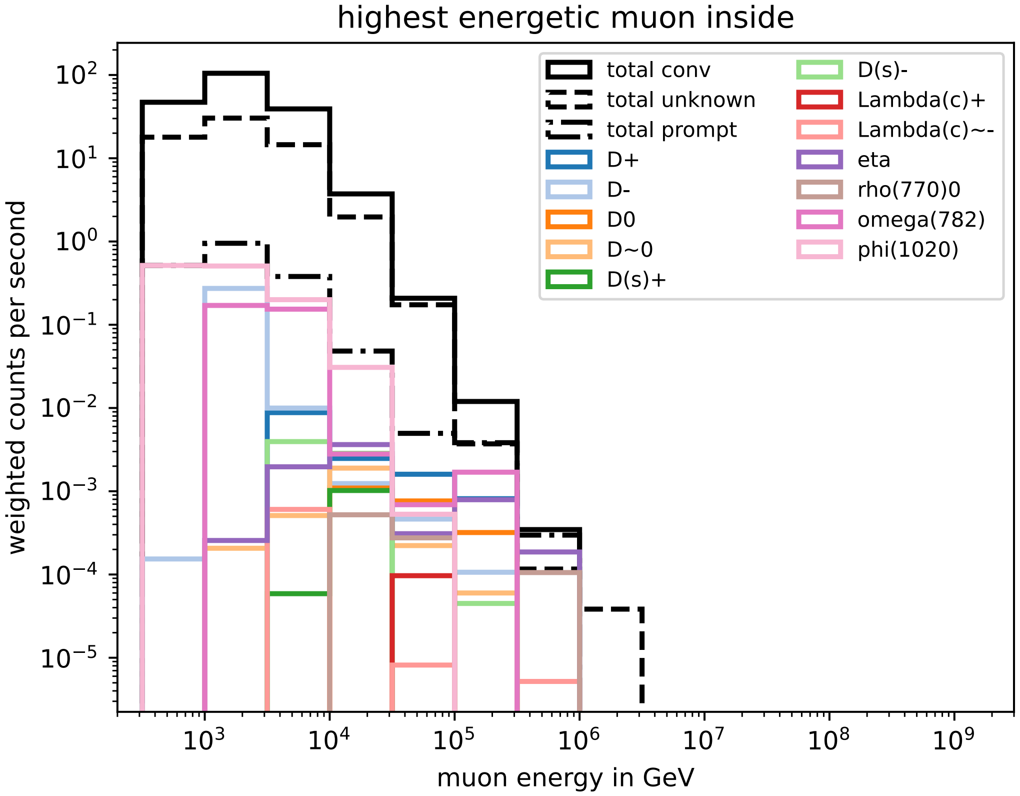




➢ No complete solution, but a step in the right direction

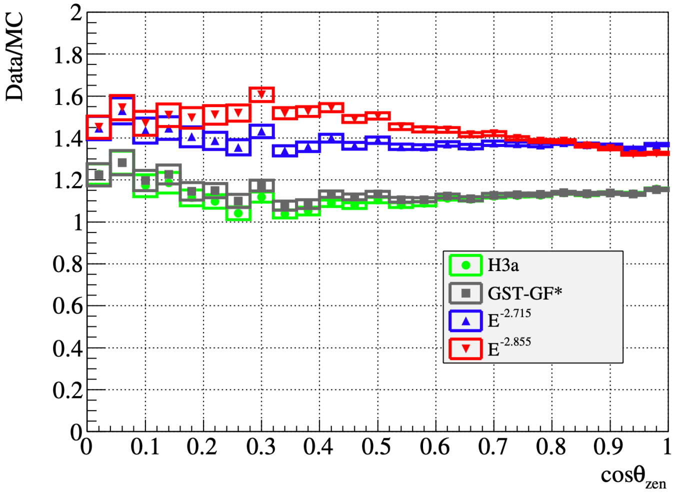
Muon energy distributions



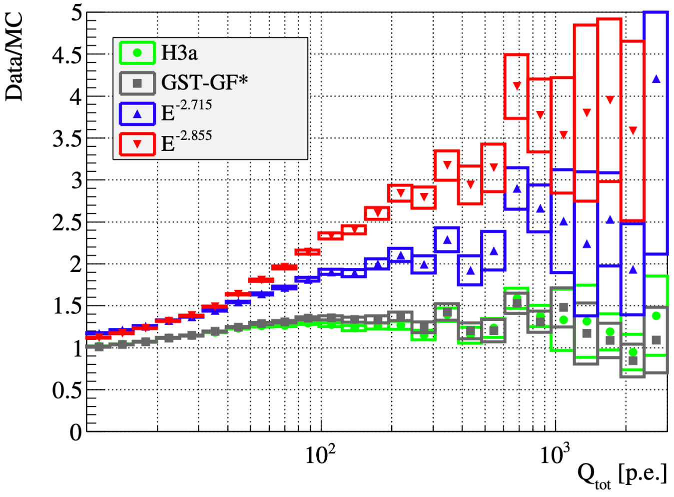


- Highest energetic muon per shower/tree inside detector is shown
- Too less statistics at high energies
- Unknown: parent particle is not known → generation counter indicates, that there are particles between mother and muon → conventional

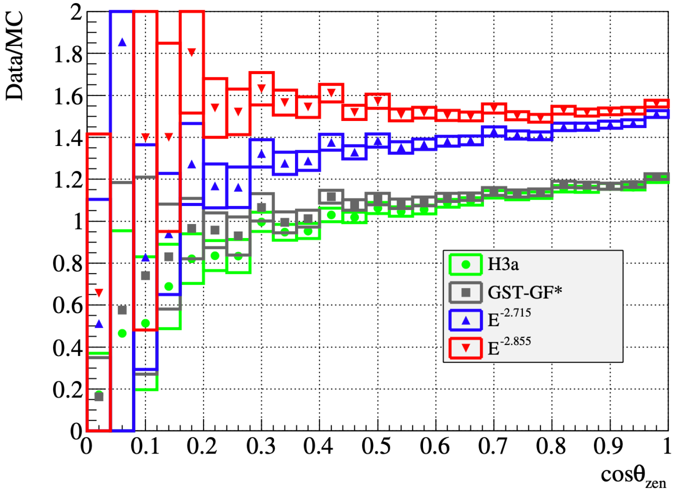
Backup: Zenith problem



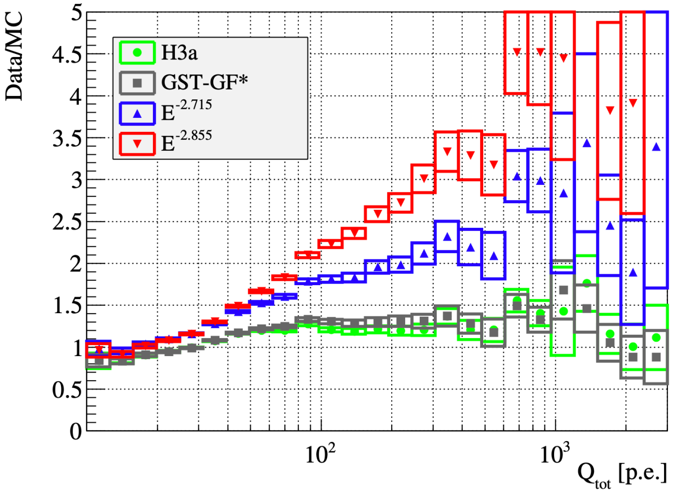
(a) cos θ_{zen}, Trigger Level



(b) Q_{tot}, Trigger Level



(c) cos θ_{zen}, High-Quality Tracks

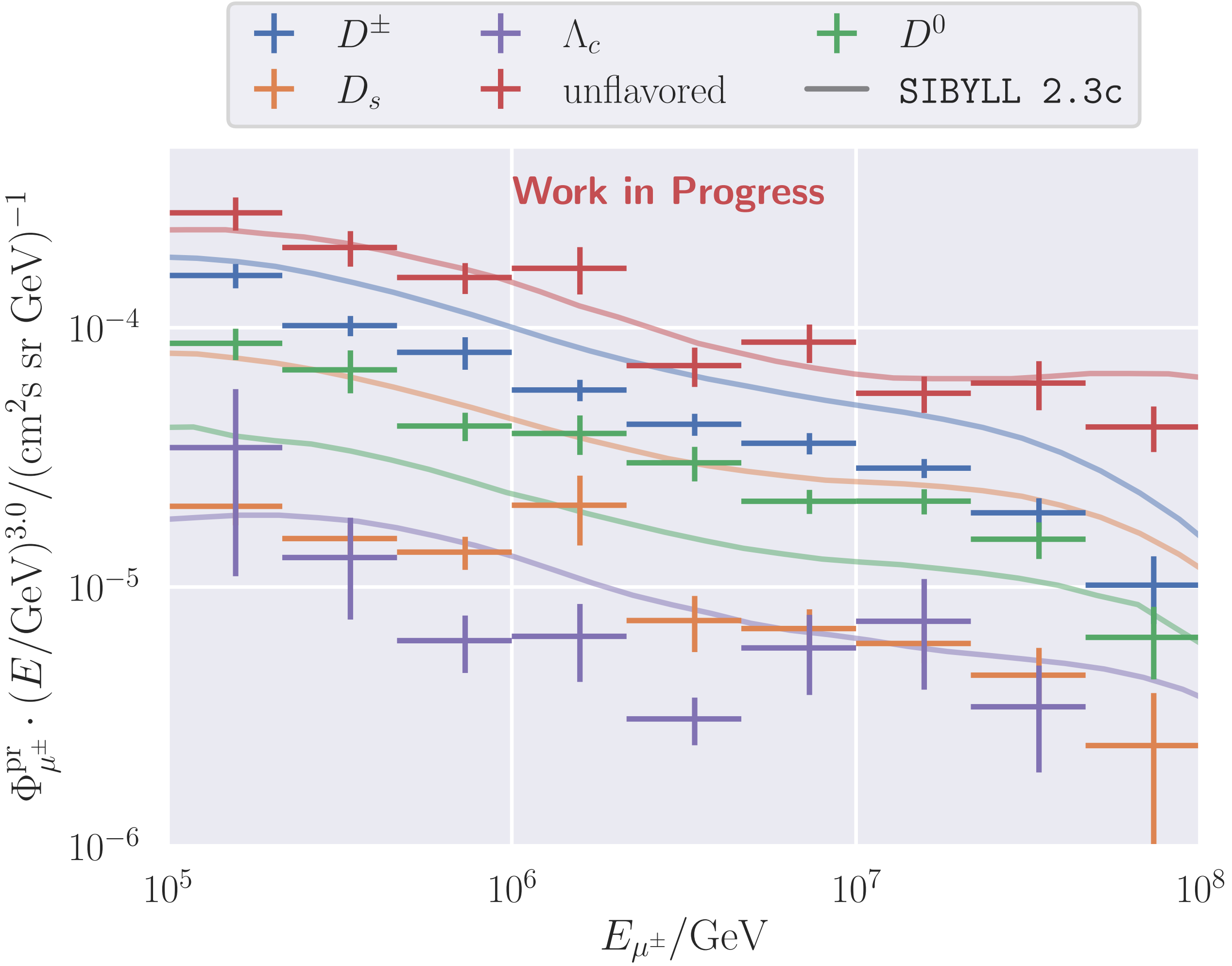


(d) Q_{tot}, High-Quality Tracks

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.

Specific parent particle identification

- CORSIKA 7 using SIBYLL 2.3d vs. SIBYLL 2.3c[1]
- 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

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 → K^+ (>50%) removing prompt parents removes conv. muons as well

Scaling via Modification of CORSIKA7