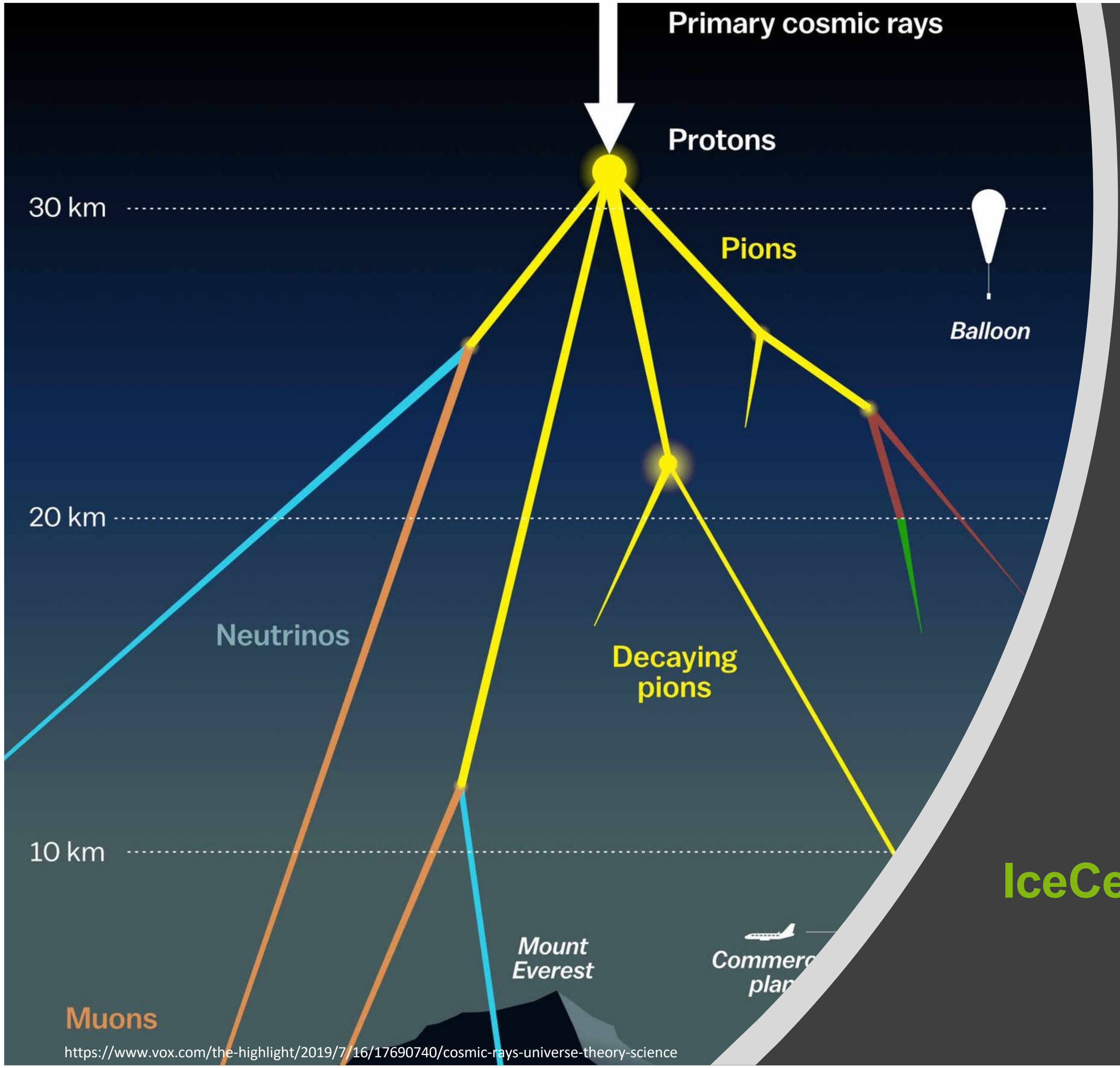


Ideas to measure the prompt component of the atmospheric muon flux

Ludwig Neste and Pascal Gutjahr

IceCeub Spring Collaboration Meeting

Aachen 2023

technische universität dortmund

IceCube Neutrino Observatory   SFB1491

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:

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

prompt component:

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

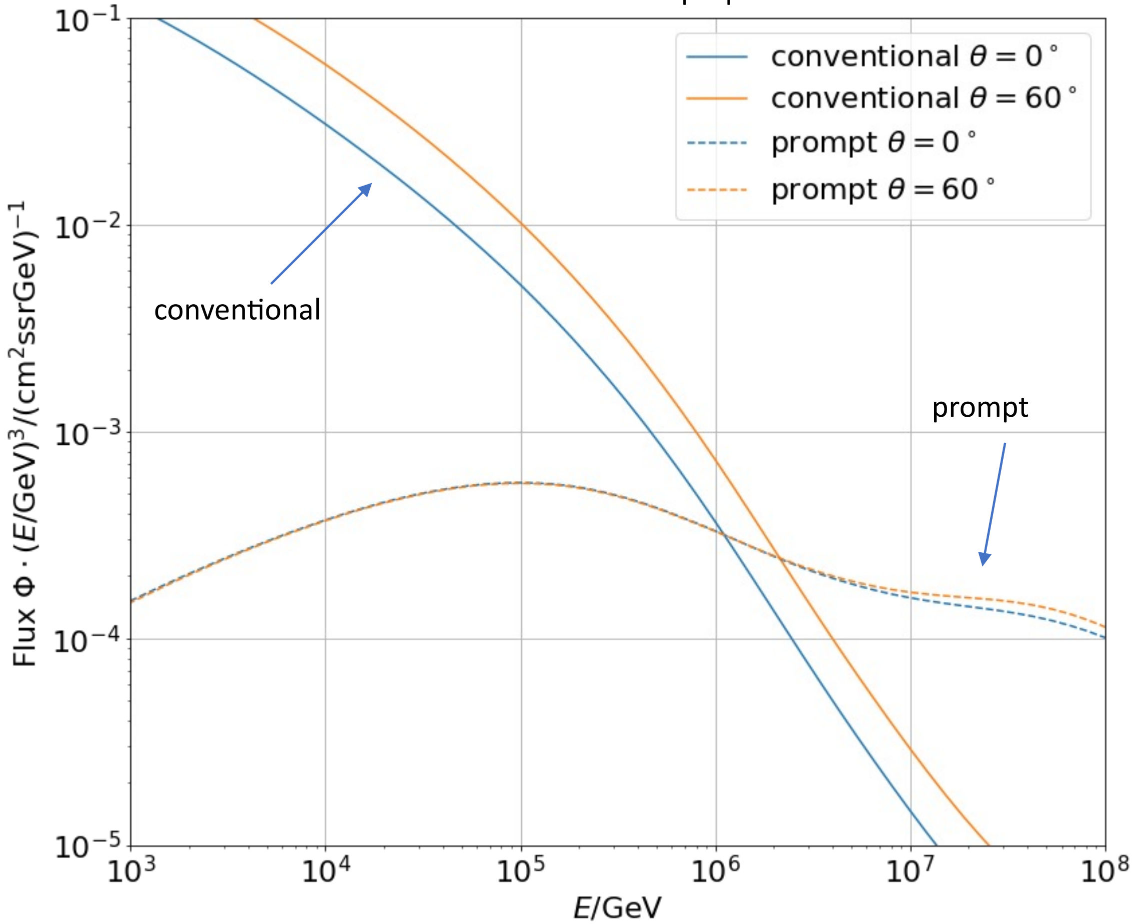
$\Phi_{tot} = \Phi_{conv} + \Phi_{prompt}$
- Prompt dominates at energies larger than PeV
- Conventional particle flux depends on zenith angle

Muon flux

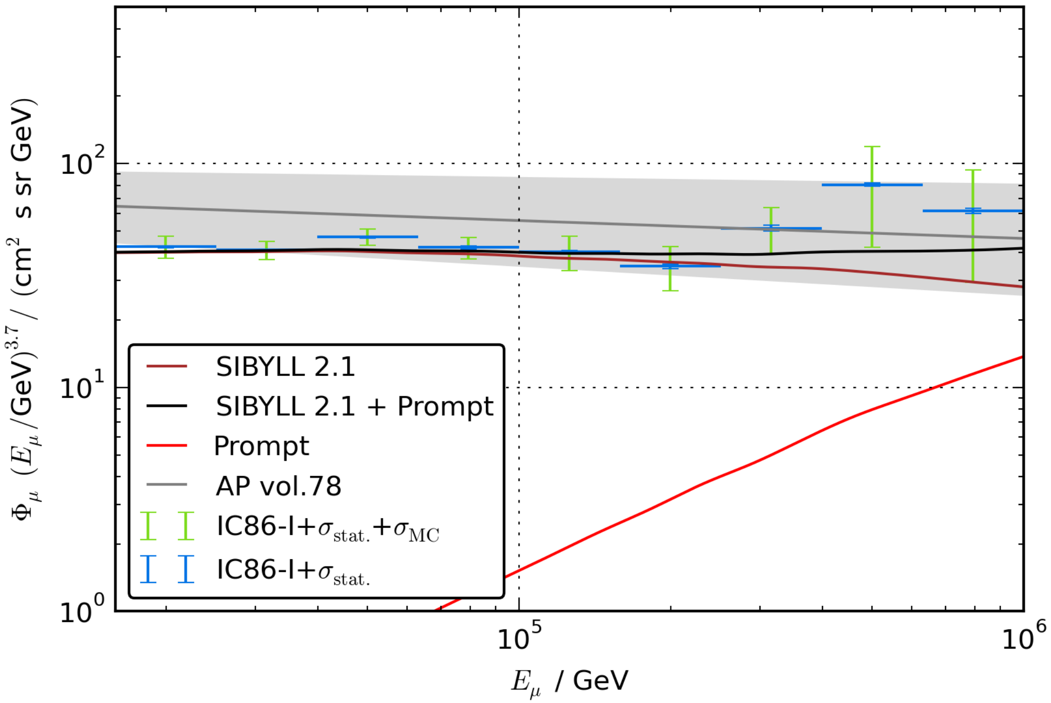
$$\Phi_{\text{tot}} = \Phi_{\text{conv}} + \Phi_{\text{prompt}}$$

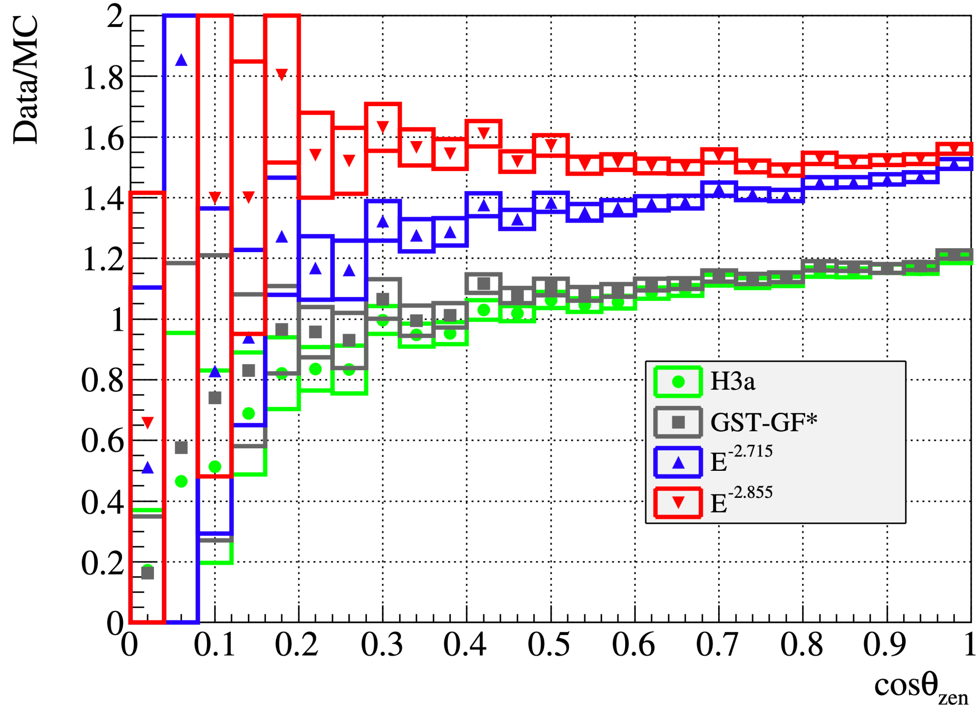
- Prompt dominates at energies larger than PeV
- Conventional particle flux depends on zenith angle

0°: perpendicular to Earth's surface



Previous analyses



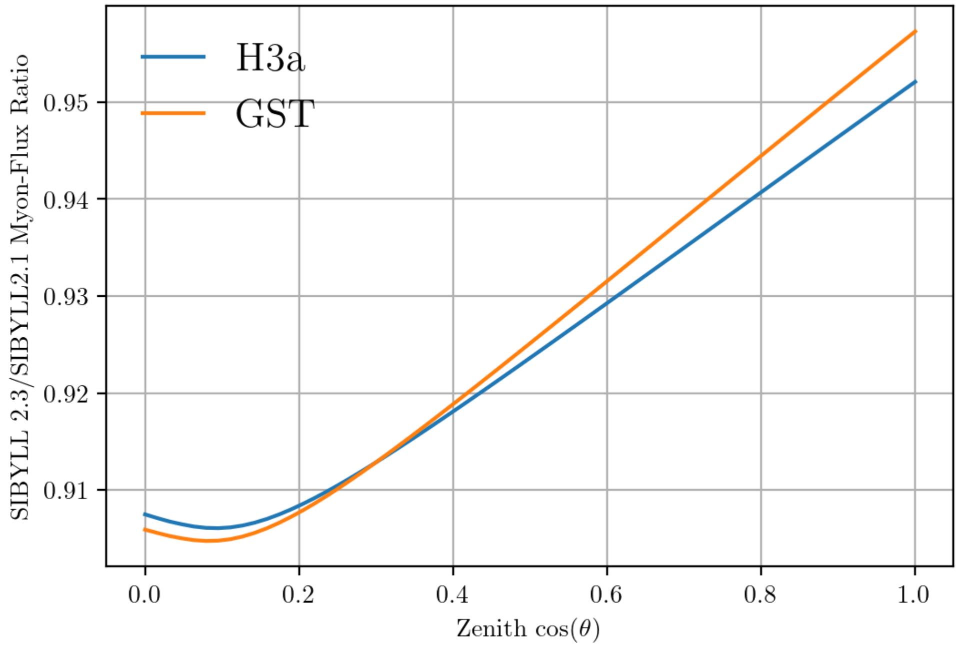


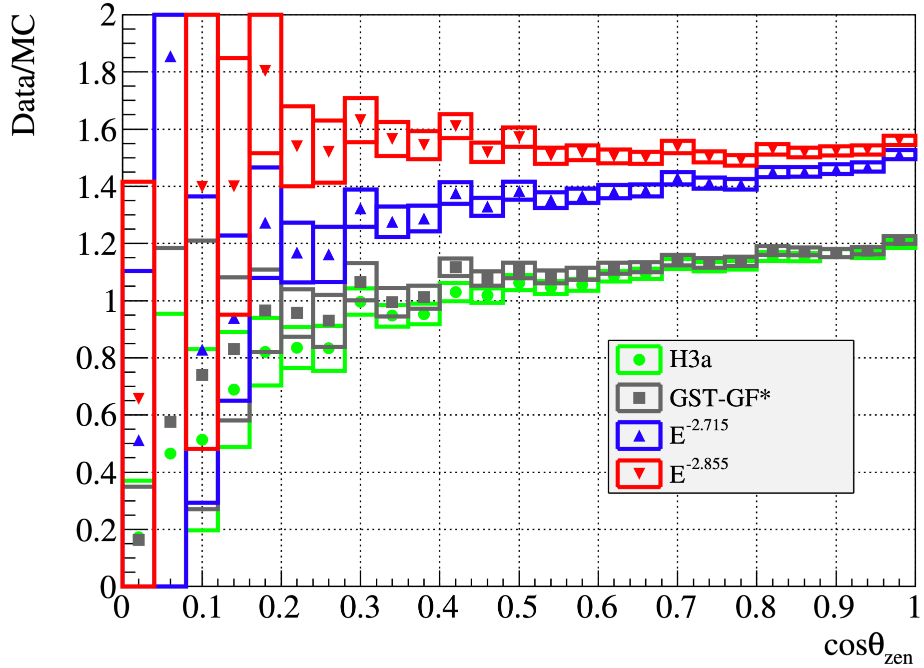
- Fit compatible with zero
- MC uncertainties too large

- 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?



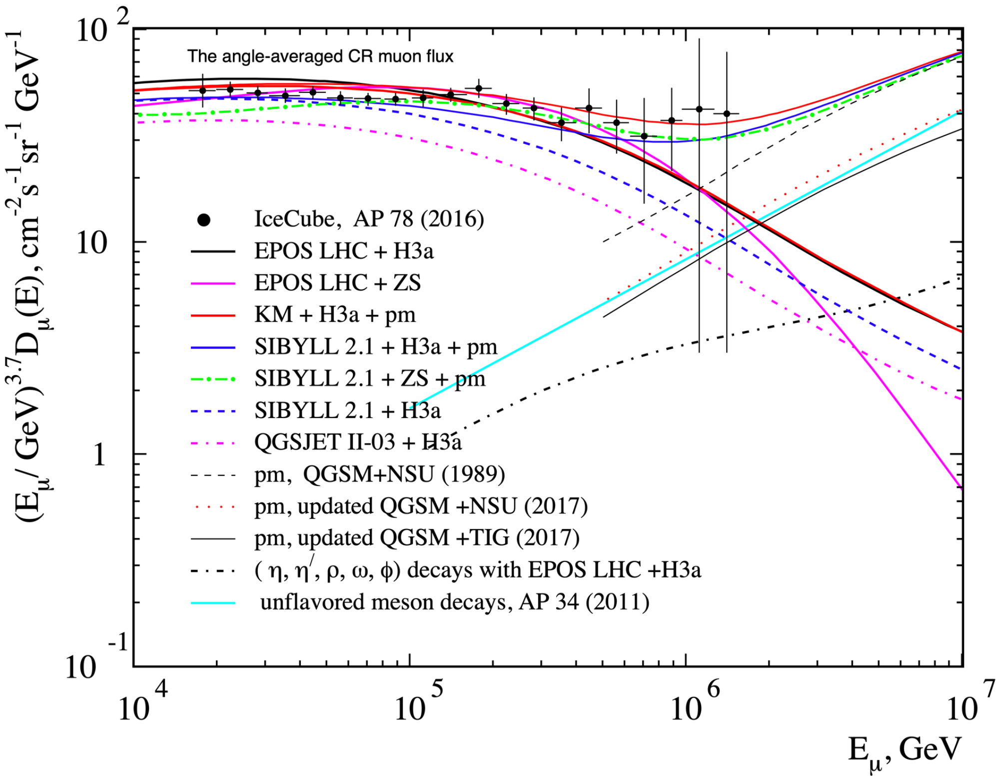


- ➢ No complete solution, but a step in the right direction

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
```

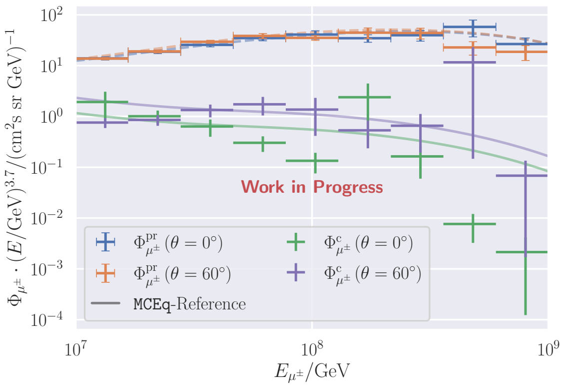
- ✓ CORSIKA reader adopted
- ✓ First simulations running
- ✓ `/data/sim/IceCube/2023/generated/CORSIKA_EHISTORY/`

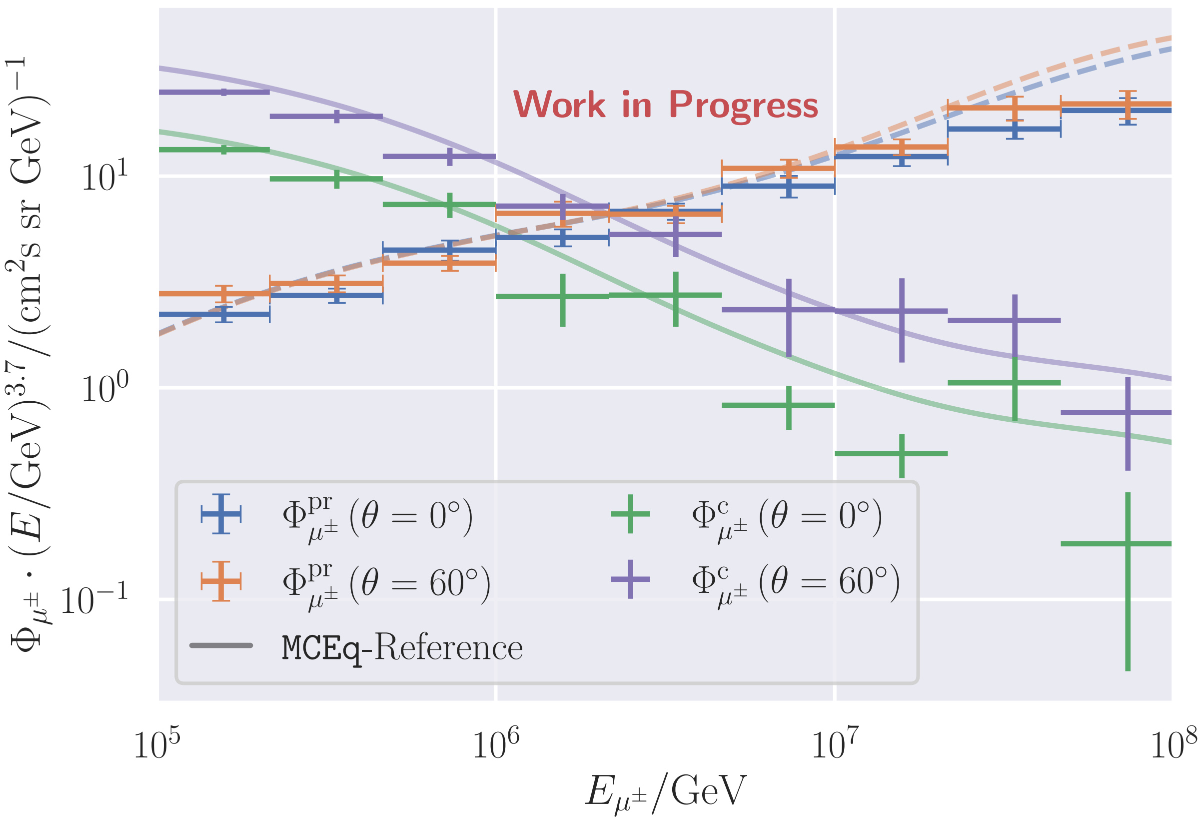
Identify prompt particles in air shower

- 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 ~5 * 10^{10} GeV)
- MCEq: SIBYLL 2.3c

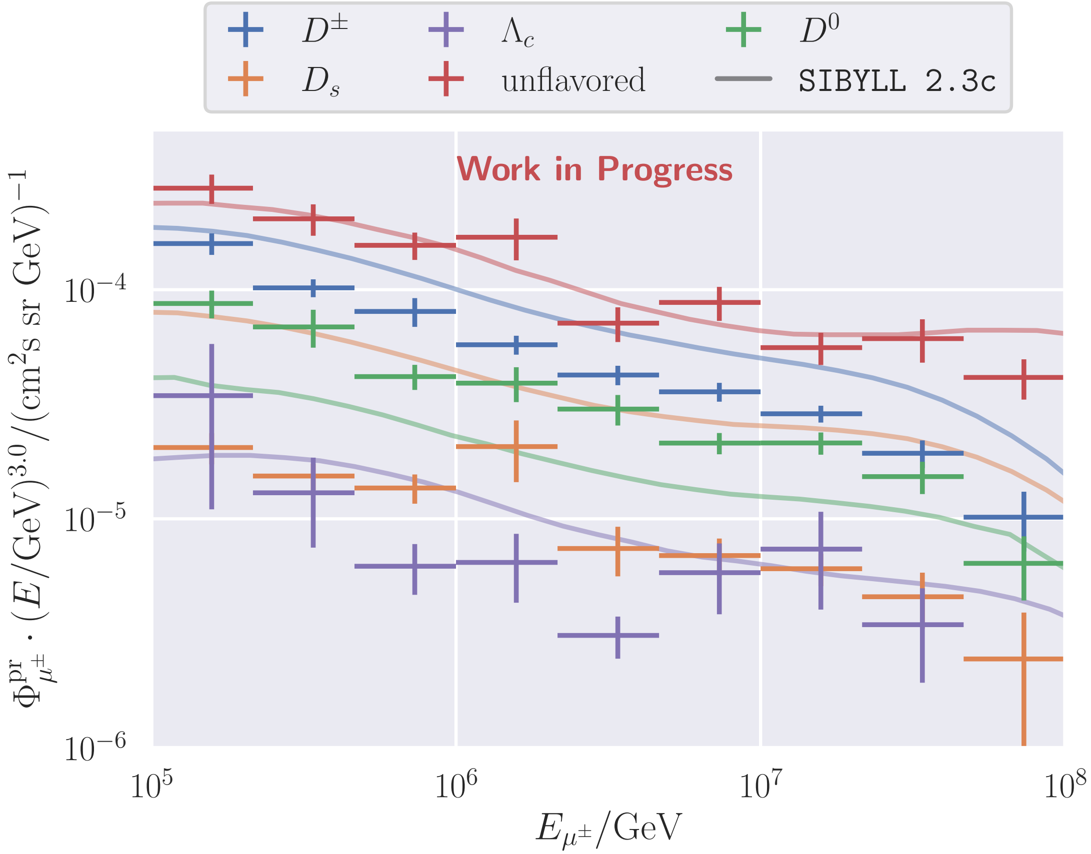




✓ Good agreement between CORSIKA and MCEq

Specific parent particle identification

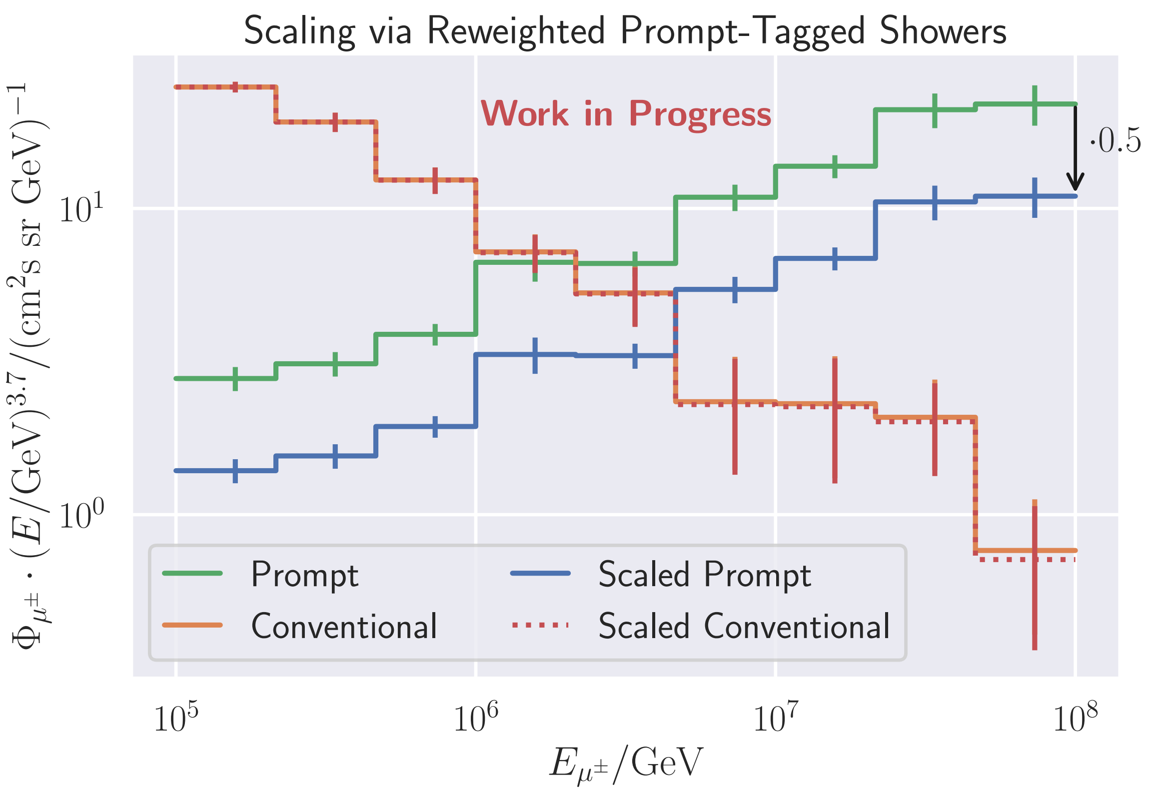
- CORSIKA 7 using SIBYLL 2.3d vs. SIBYLL 2.3c[1]
- Good agreement with unflavored particles
- Mismatches occur for all the D-mesons
  - Issue not yet solved
  - Only protons simulated with CORSIKA



[1] Phys. Rev. D 100 (2019) 103018

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



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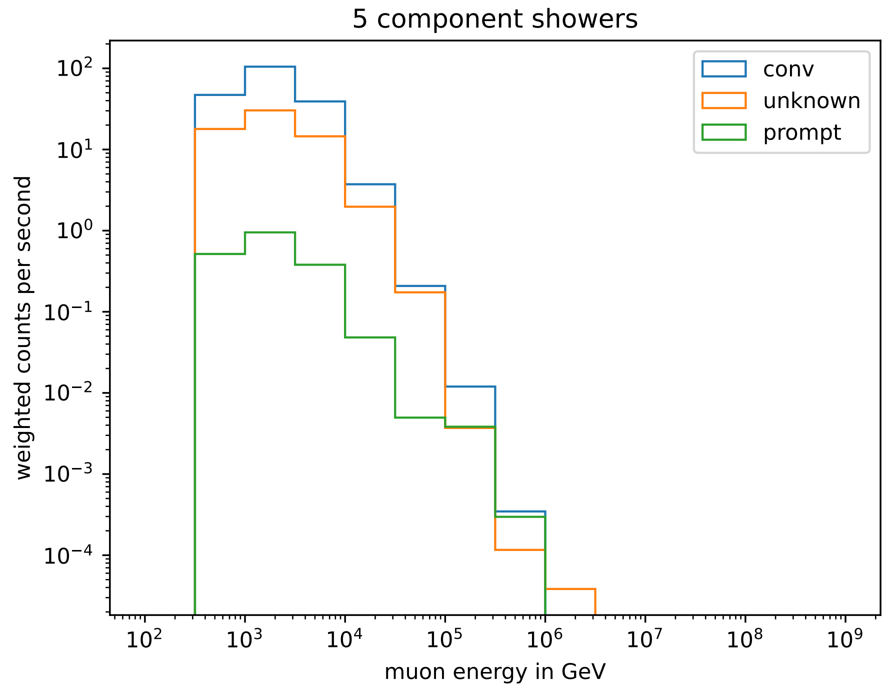
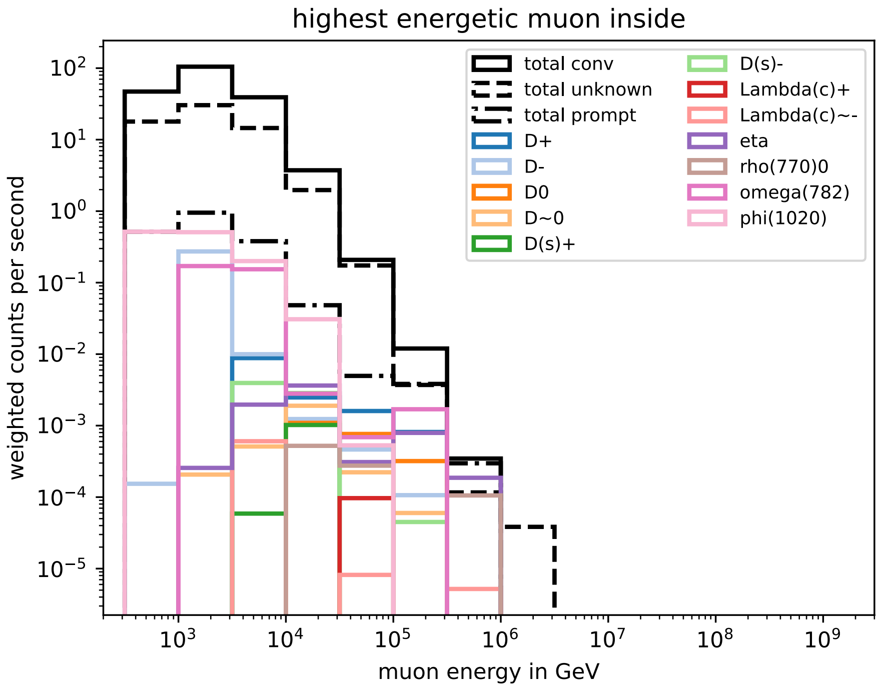
Muon energy distributions





- 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

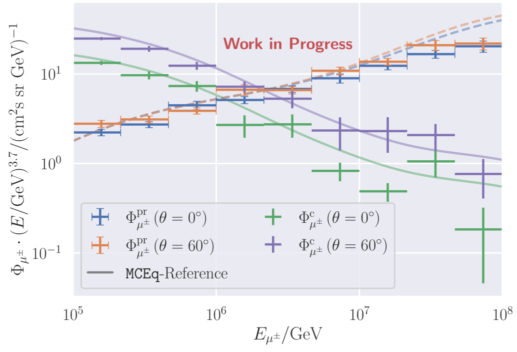
- CORSIKA_EHIST works
- Parent particles can be tagged
- Good agreement with MCEq
- Ready for the simulation/analysis

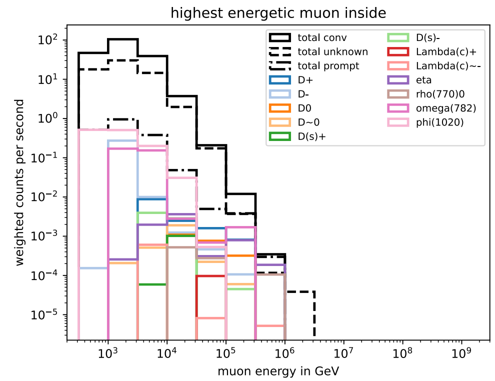
Next steps:

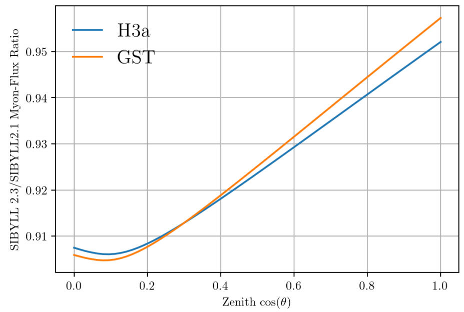
- Simulate test data set
- New event selection using DNN
- Start analysis chain
- Analyze *zenith problem* with new simulations

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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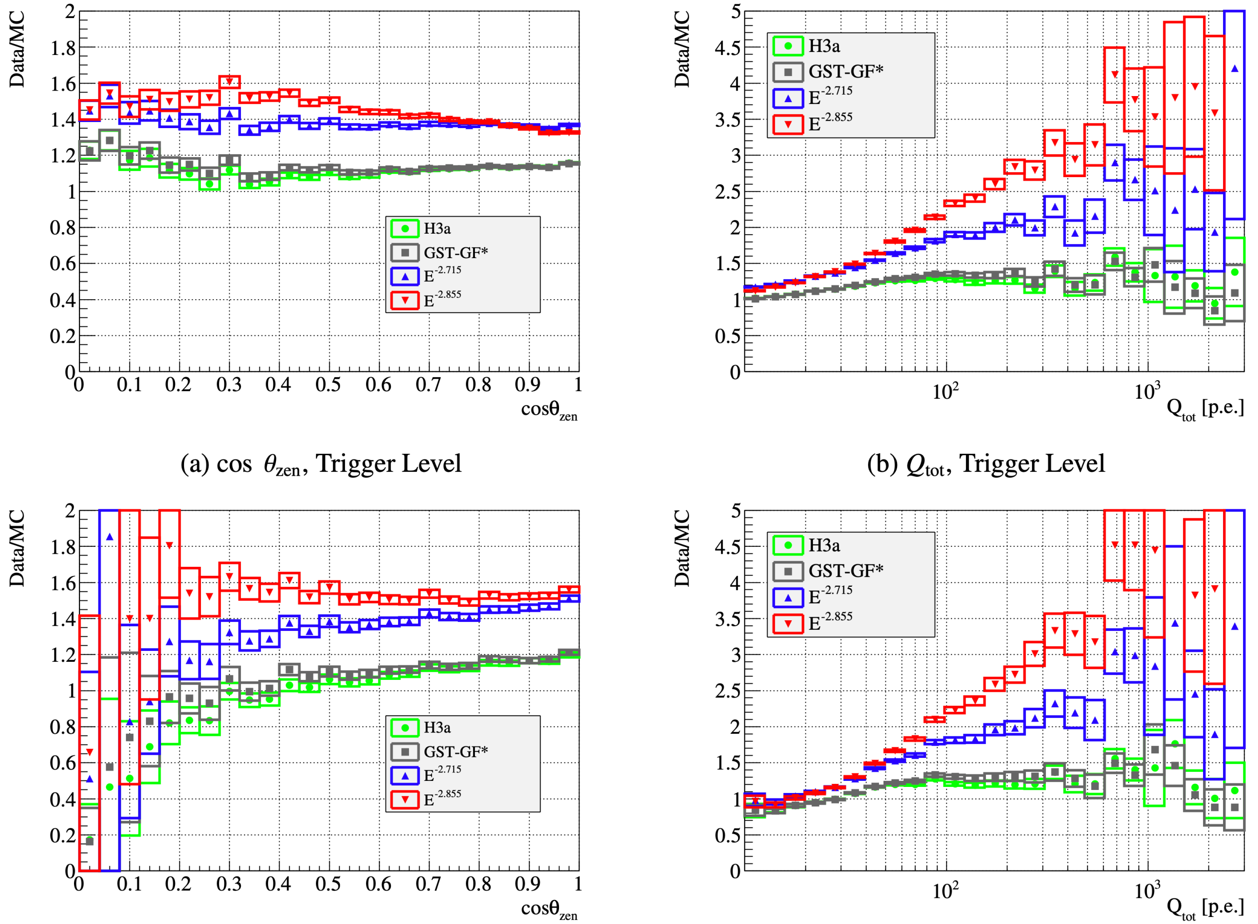
```

Thank you for your attention ☺️ @pgutjahr@icecube.wisc.edu

Backup

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.

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