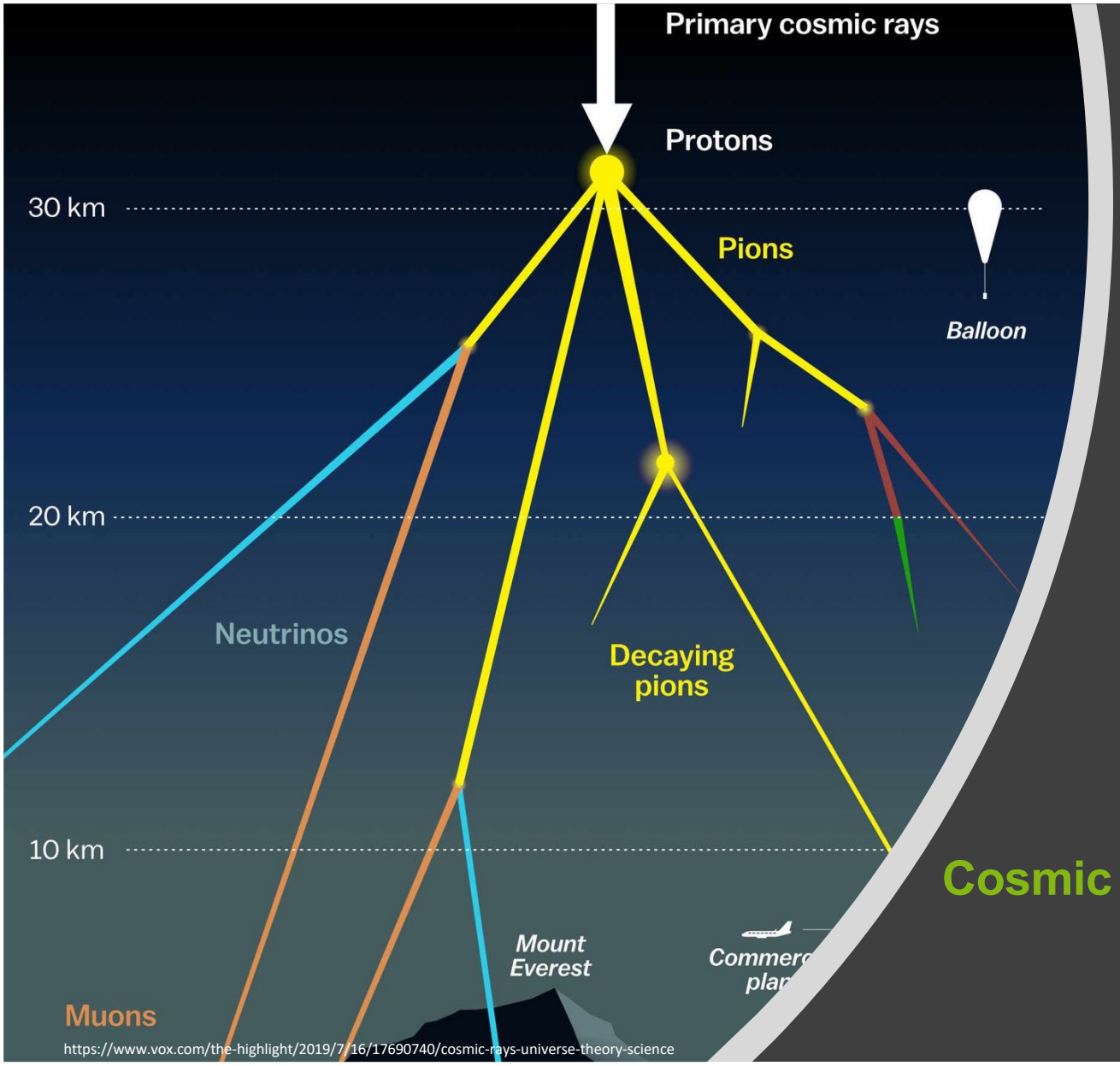


Ideas to measure the prompt component of the atmospheric muon flux

Jean-Marco Alameddine, Ludwig Neste and Pascal Gutjahr

Cosmic Rays in the Multi-Messenger Era

Paris 2022

Definition of the muon flux

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

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

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

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

Conventional component:

$$p \rightarrow \overbrace{\pi^{+}}^{\tau = 2.6 \cdot 10^{-8}\,s} \rightarrow \mu^{+} + \nu_{\mu}$$

$\propto E^{-2.7}$ $\propto E^{-3.7}$

prompt component:

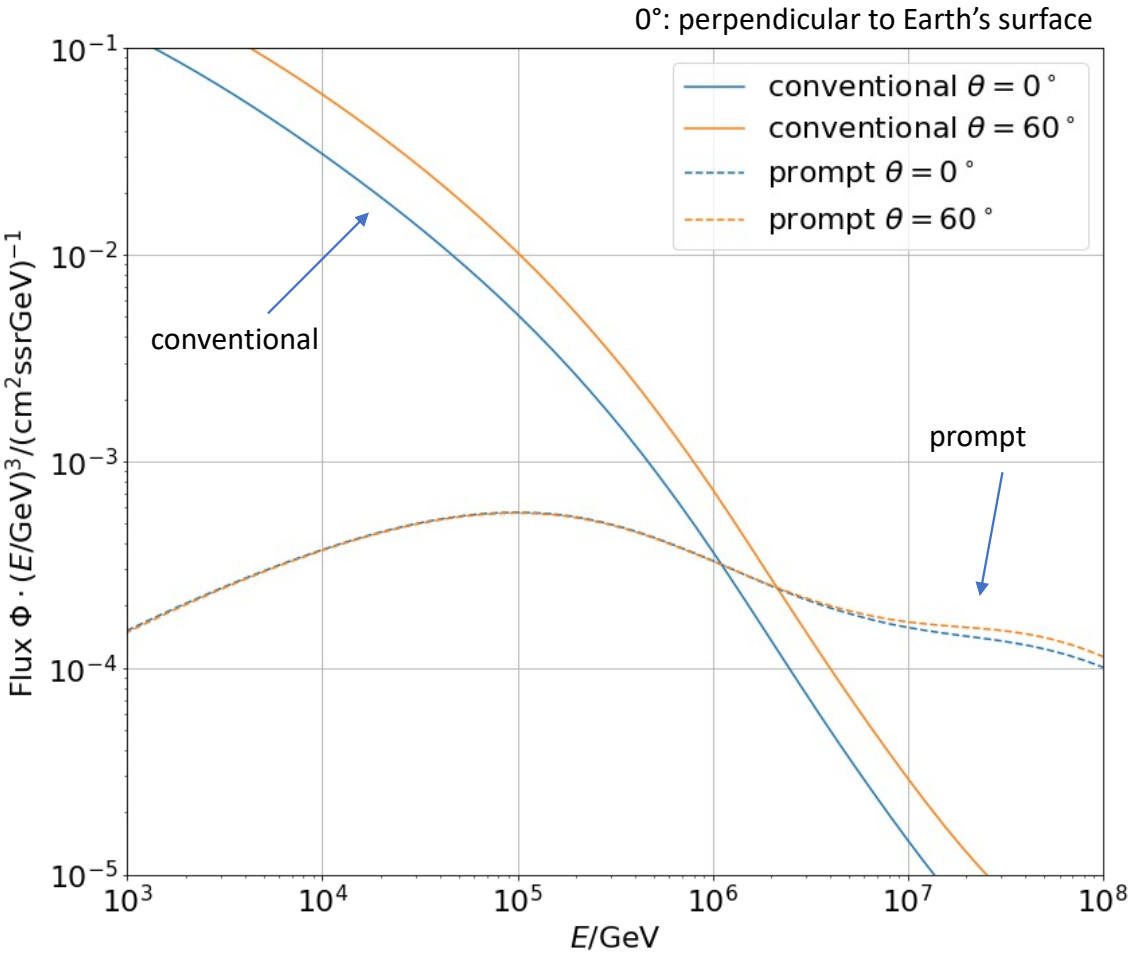
$$p \rightarrow \overbrace{D^{+}}^{\tau = 1.04 \cdot 10^{-12}\,s} \rightarrow \bar{K}^{0} + \mu^{+} + \nu_{\mu}$$

$\propto E^{-2.7}$ $\propto E^{-2.7}$

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

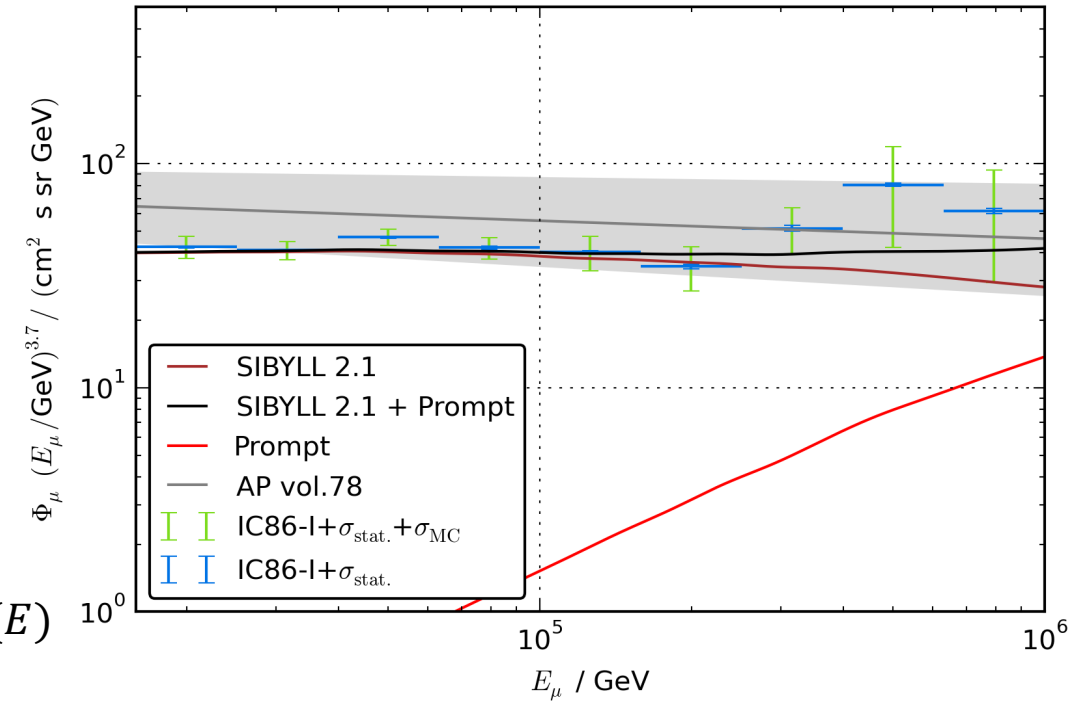


Previous analysis

- Leading muon sample → $\frac{E_{\mathrm{max}}}{E_{\mathrm{tot}}} > 0.5$
- Unfolding of muon energy
- Fit of normalization of prompt
- 1 year of IceCube data used
- Component compatible with zero

$$\boldsymbol{\phi}\,(E) = N_{\mathrm{conv}} * \boldsymbol{\phi}_{\mathrm{conv}}(E) + N_{\mathrm{prompt}} * \boldsymbol{\phi}_{\mathrm{prompt}}(E)$$

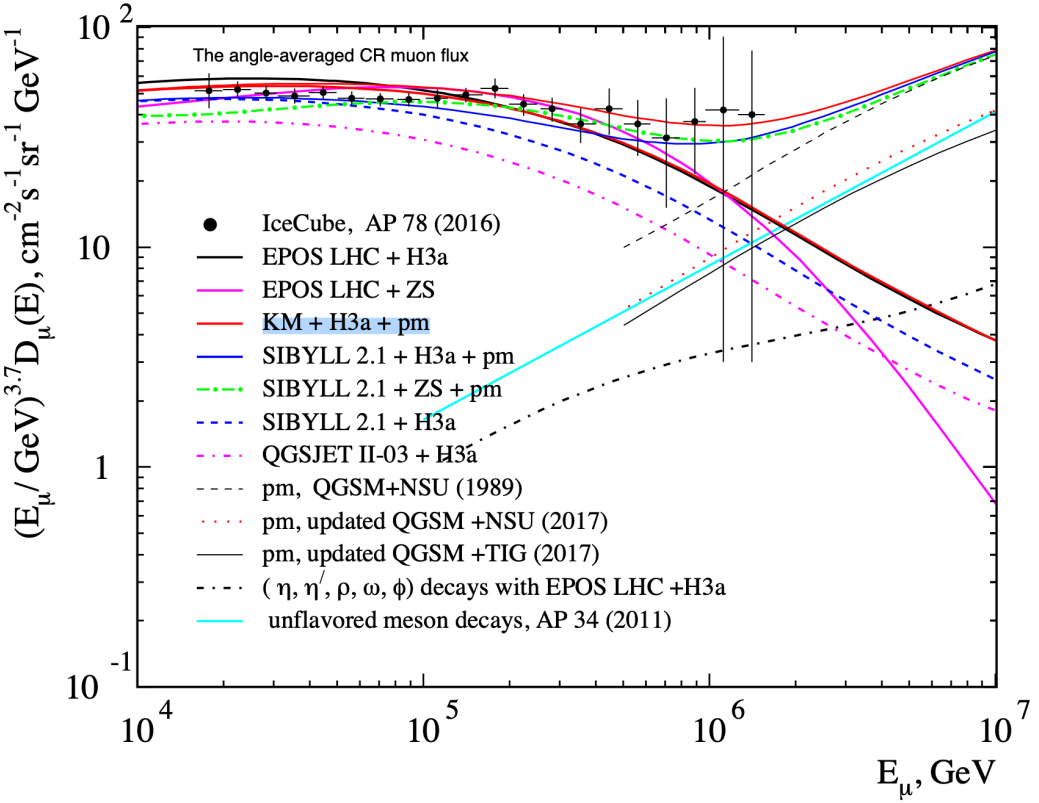
→ Uncertainties dominated by limited MC



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

New ideas to measure the prompt component

- Latest software CORSIKA, PROPOSAL
- SIBYLL 2.3d → charm included
- Scale amount of prompt particles to create several datasets
  - Tag muon parent particles in MC (prompt/conv)
  - If shower contains a prompt particle it is defined as prompt
  - Create splines/estimator of particles per bin in dependency of the scaling factor
  - Fit effective scaling – forward fit
- Analyze:
  - Muon energy
  - Zenith angle
  - Time (seasonal variations)
    - Conventional flux depends on the season



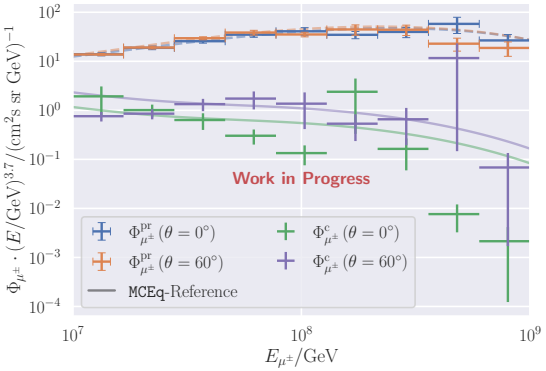
[Journal of Physics: Conf. Series. 2019. V. 1181, 012054]

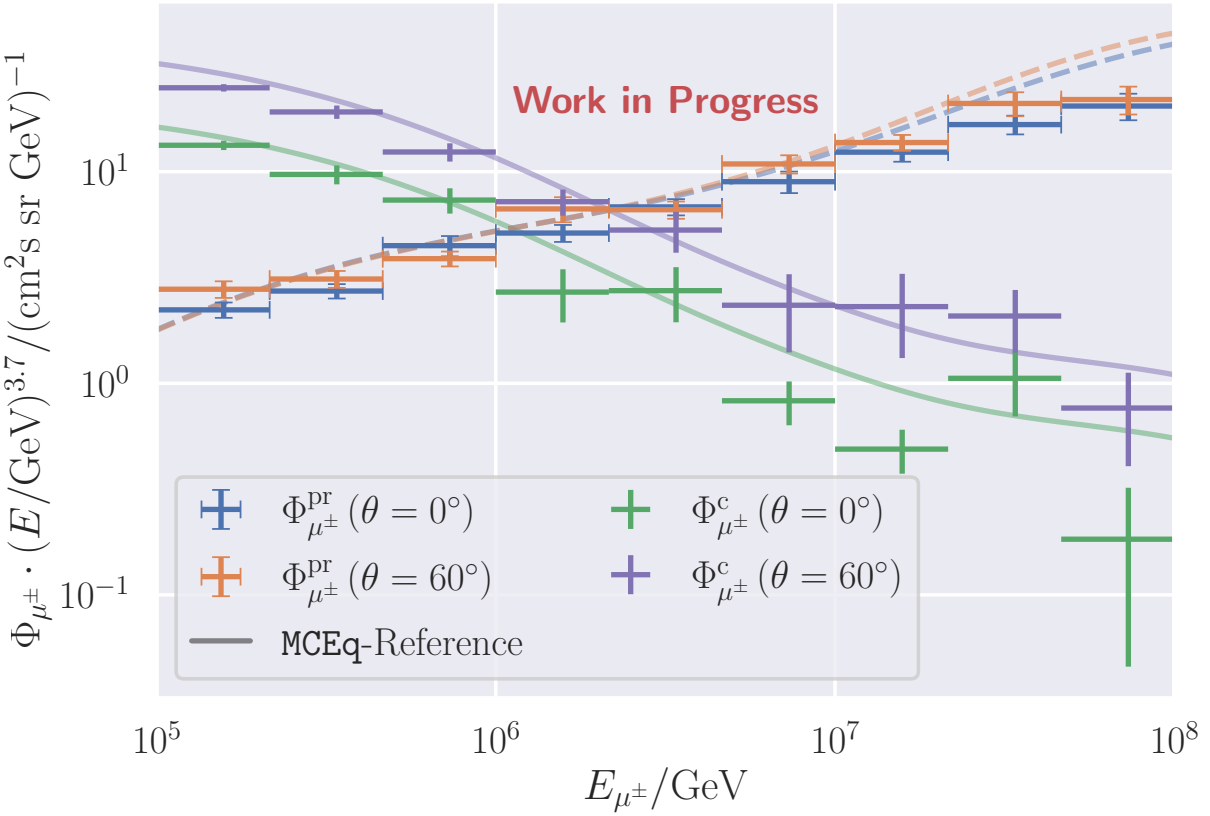
Identify prompt particles in air shower

- 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

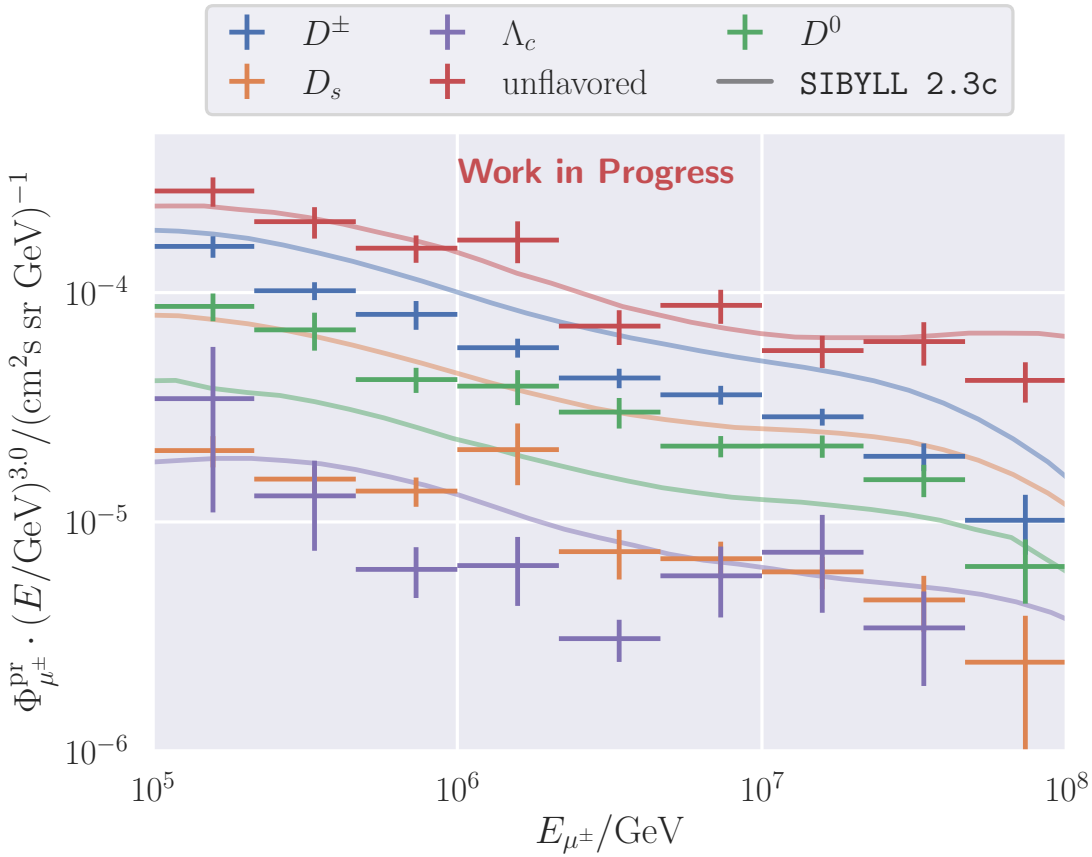
- Maximum injected energy lower than the maximum possible energy (GZK cutoff at ~5 * 10^{10} GeV)
- MCEq: SIBYLL 2.3c





Specific parent particle identification

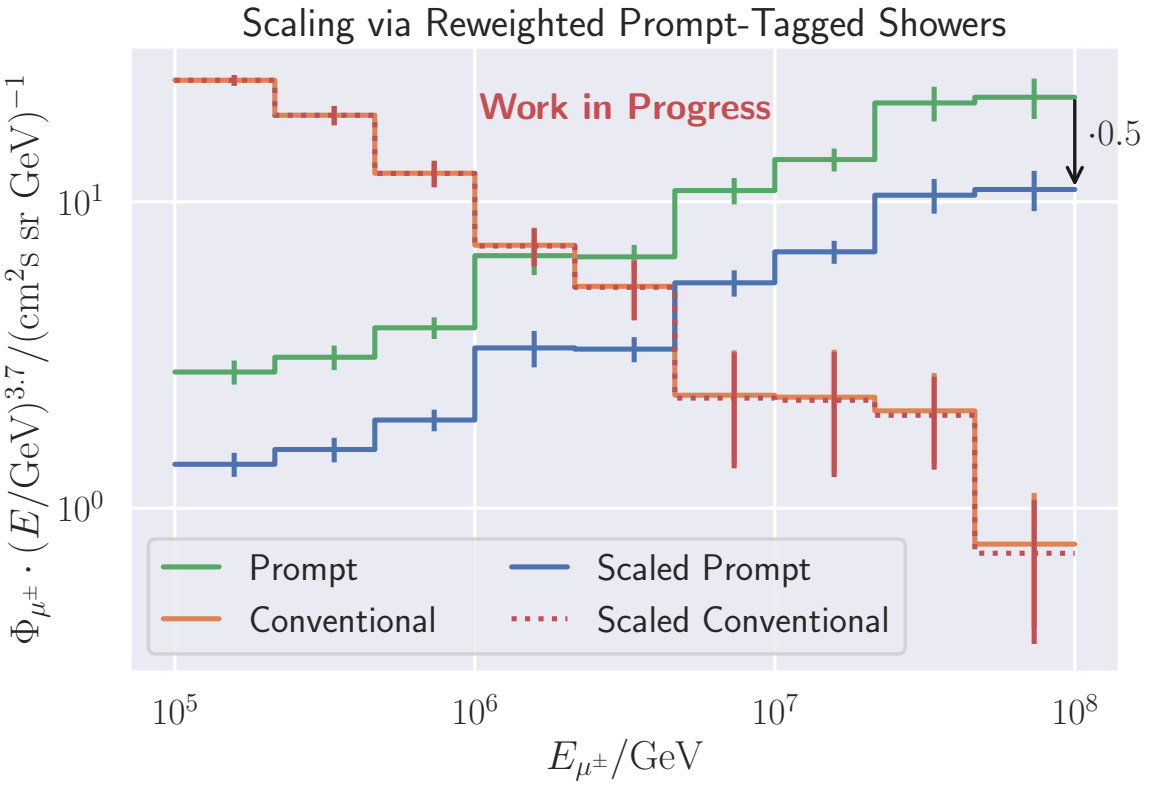
- CORSIKA 7 using SIBYLL 2.3d vs. SIBYLL 2.3c[1]
- Good agreement with unflavored particles
- Mismatches occur for all the D-mesons
  - Issue not yet solved
  - Only protons simulated with CORSIKA



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

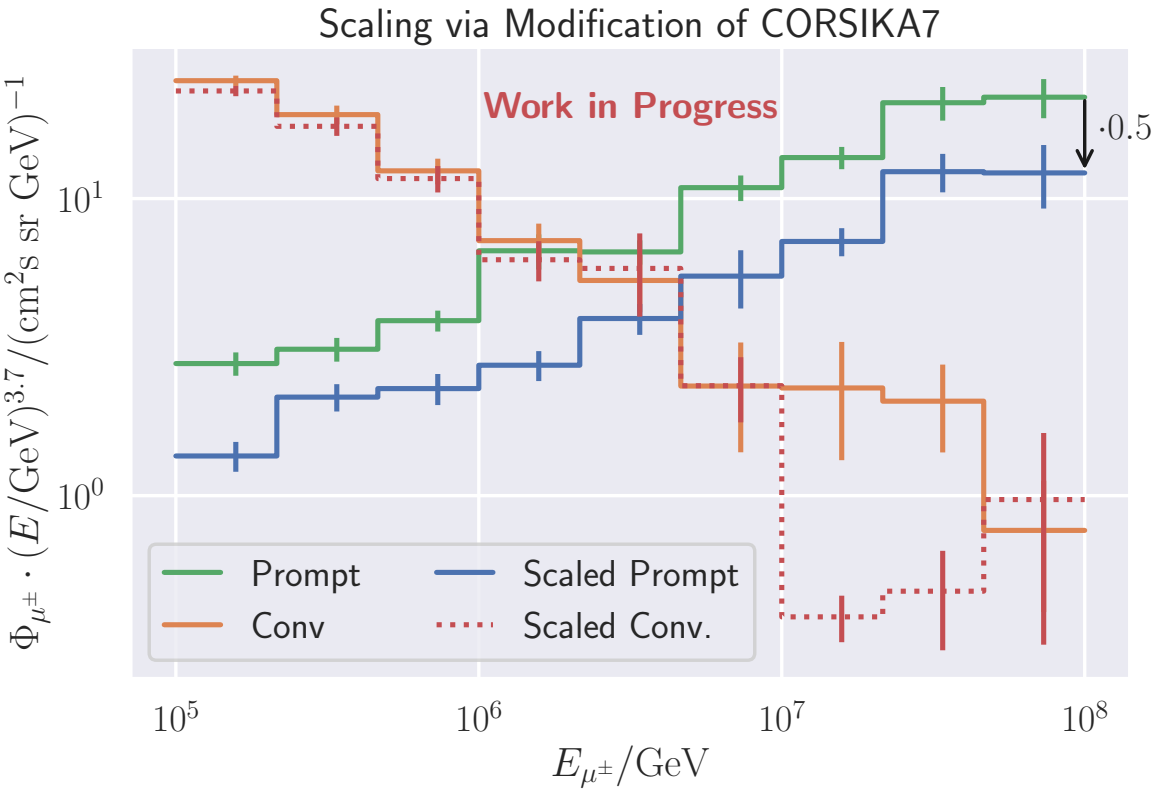
Scaling of the prompt component - tagging

- 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



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



Summary

- Previous analysis compatible with zero prompt
  - No charm particles were simulated

Discussion:

- How to scale prompt > 1?
- How to extract physical parameters?
  - CRC1491 → branching ratios (BR), cross-sections, particle physics
- Scale BR and hadronic models compatible with LHC results

Next steps

- Further cross-checks of prompt tagging (D-Mesons?)
- Comparisons between DYNSTACK and CORSIKA scaling
- Simulate new CORSIKA datasets with SIBYLL 2.3d
  - Charm included
  - Tagging of prompt particles
  - Scale prompt
- Unfolding of the muon flux in energy and zenith bins (+seasonal variations)
- Fit of the normalization/ *effective scaling factor* of prompt – forward fit
- Analysis could be done with a neutrino telescopes such as the IceCube Neutrino Observatory

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Thank you for your attention!

We are happy about further inspiration ☺️

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