Prompt and Conventional High-Energy Muon Spectra from a full Monte Carlo Simulation via CORSIKA7

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https://arxiv.org/pdf/2502.10951

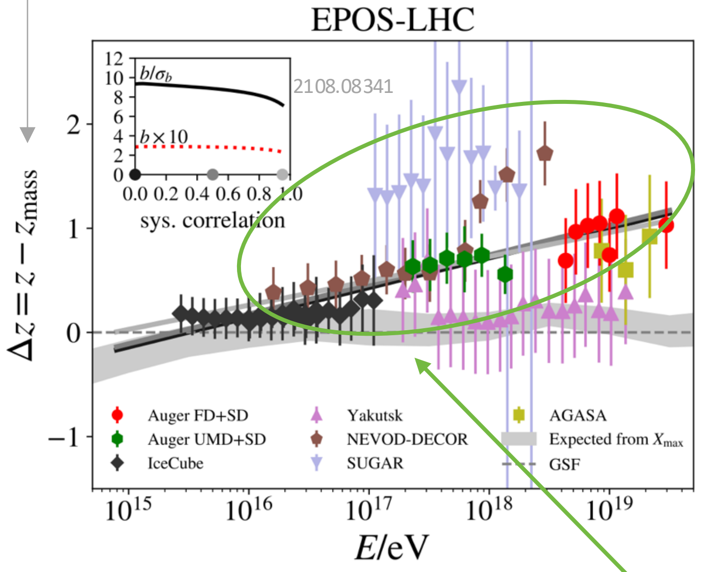
submitted to EPJC on February 18

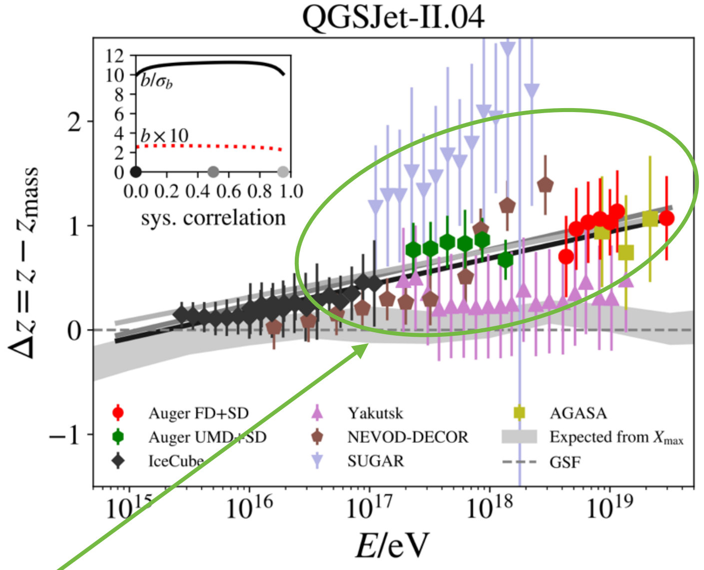
Muon puzzle and hadronic uncertainties

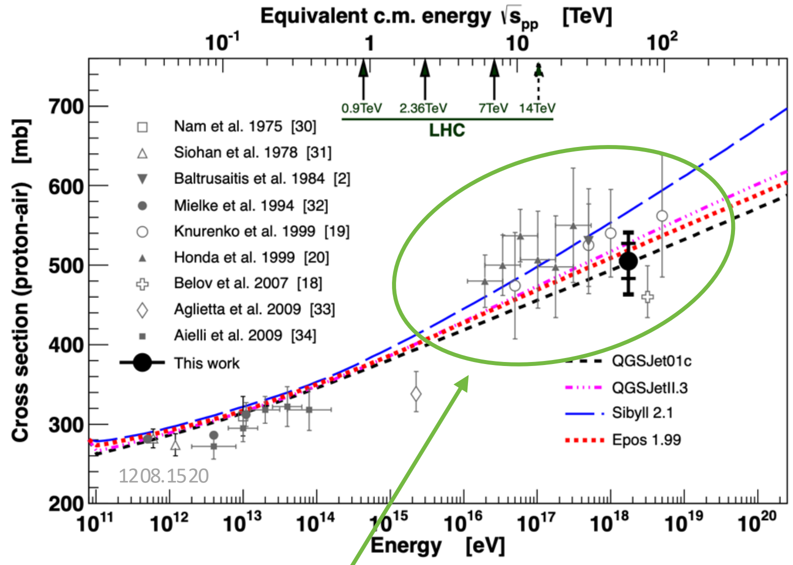
"muon number"

Expected z ("muon number")

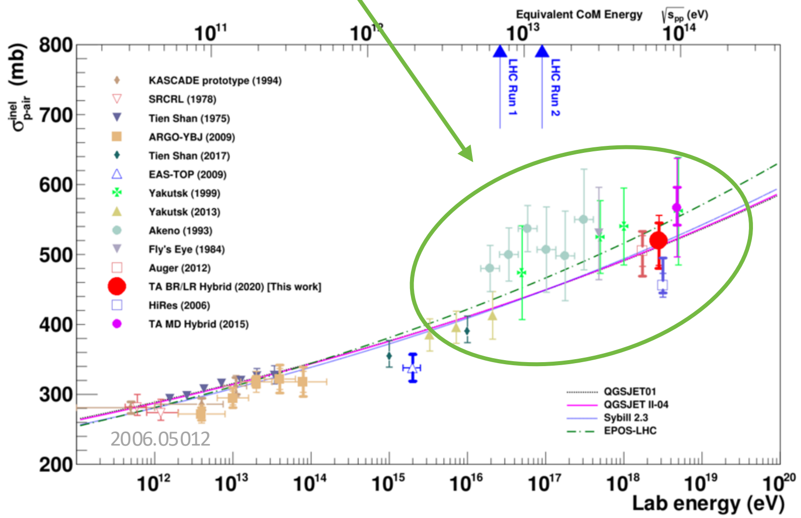
$$z = \frac{\ln\langle N_\mu\rangle - \ln\langle N_\mu\rangle_p}{\ln\langle N_\mu\rangle_{\mathrm{Fe}} - \ln\langle N_\mu\rangle_p}$$







2012



2020

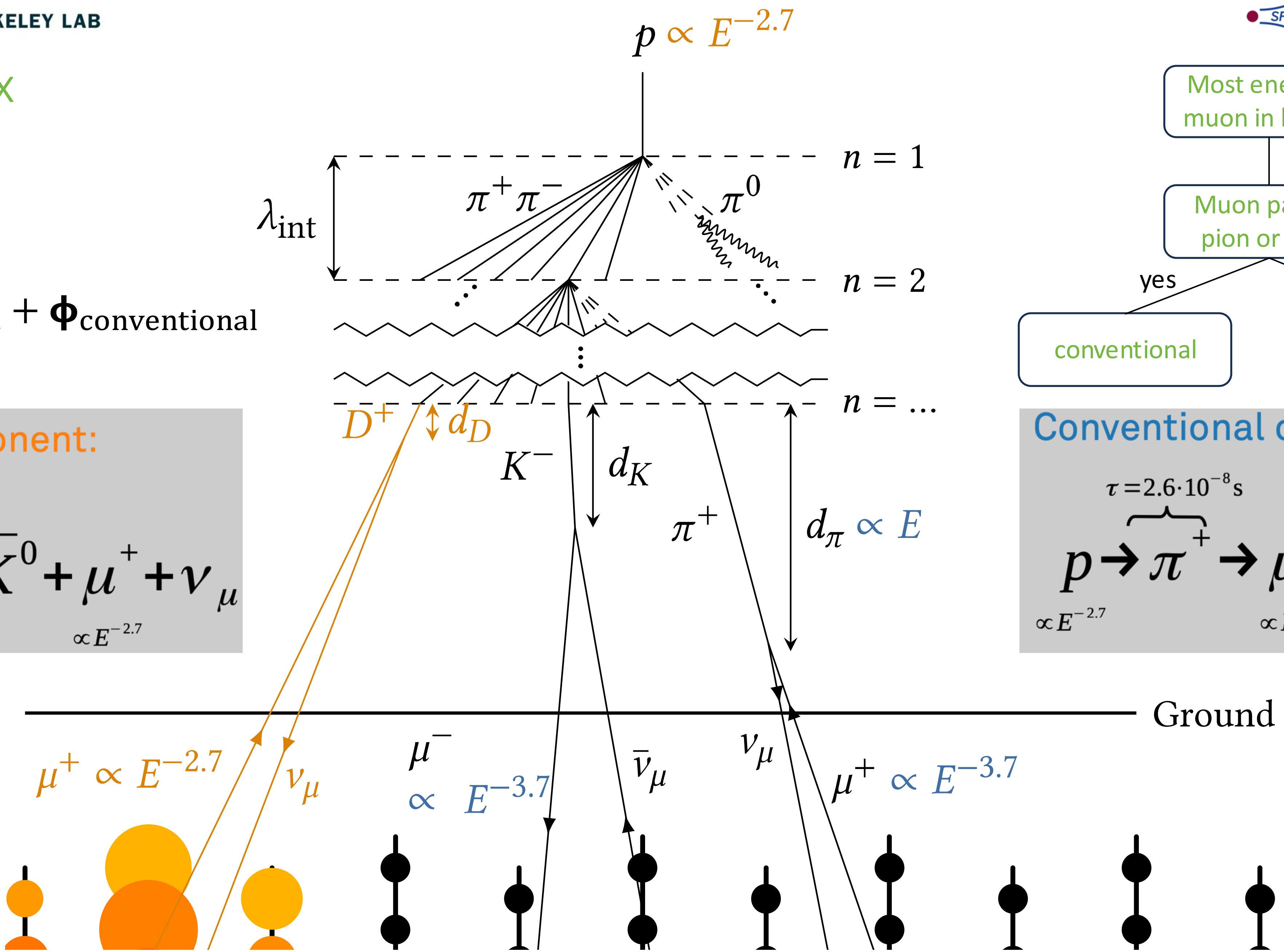
- Uncertainties at E > 10 PeV
- More muons measured than simulated for E > 40 PeV ~ cms 8 TeV

Muon flux

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

prompt component:

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



Most energetic muon in bundle

Muon parent: pion or kaon

yes → conventional

no → prompt

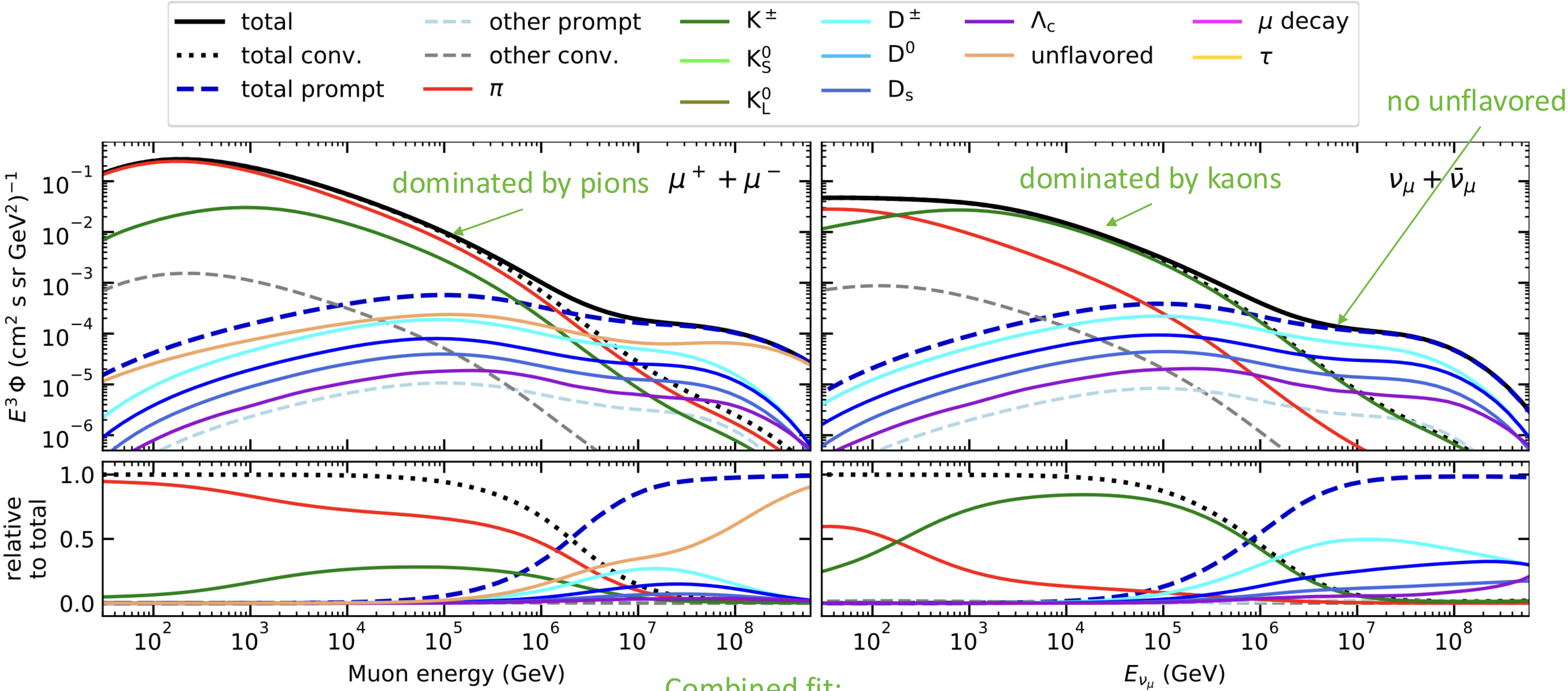
Conventional component:

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

Credit: Ludwig Neste

Prompt atmospheric muons and neutrinos

10.1103/PhysRevD.100.103018



Combined fit:

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

Analysis goals

1) Measure prompt component of the atmospheric muon flux
2) Unfold a muon energy spectrum

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

Future:

- Measure prompt neutrinos
- Combined muon and neutrino fit → pion/kaon ratio

➢ currently worked on by Roman

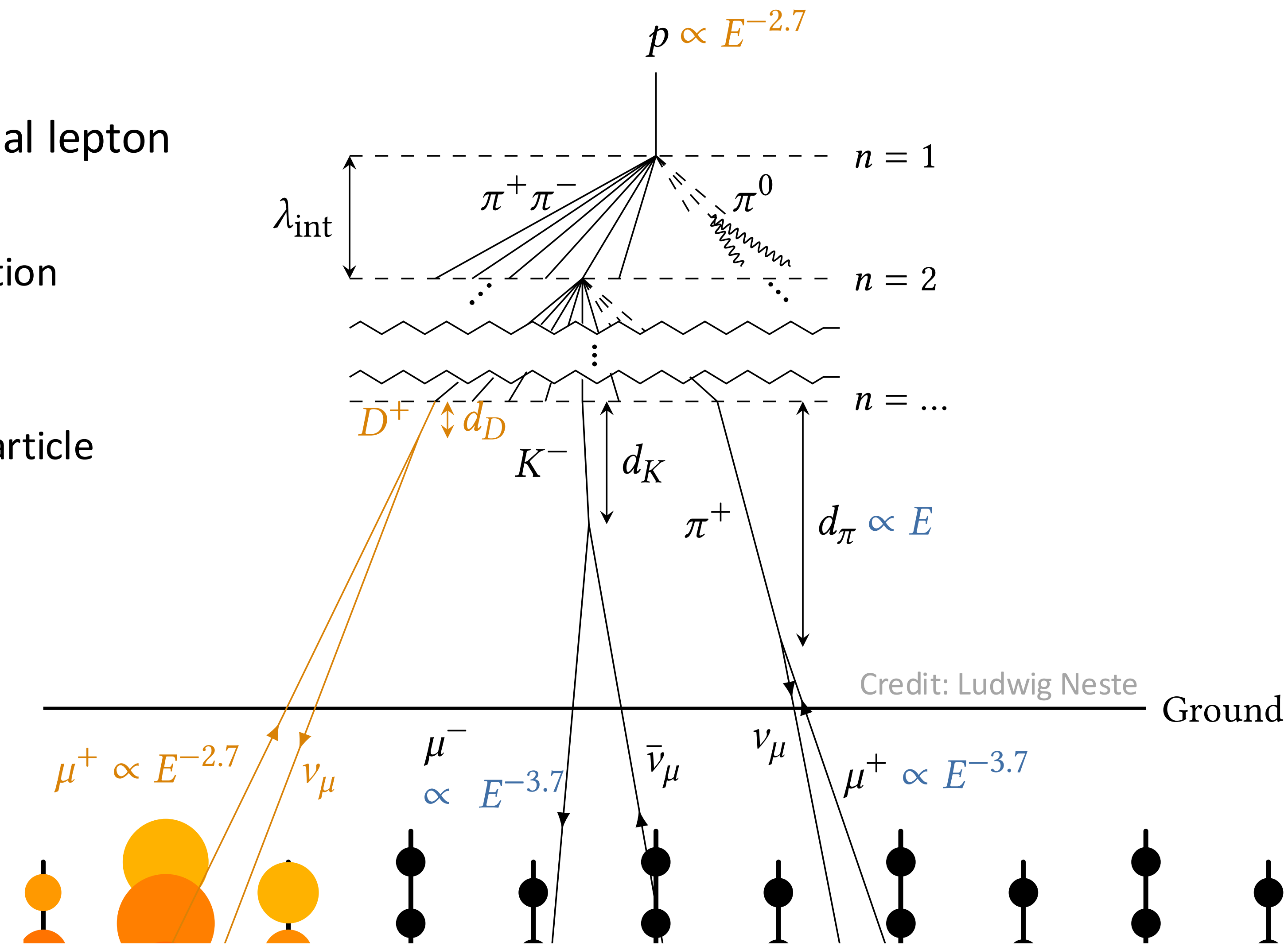
The paper includes…

What is prompt?

The *conventional* part of the lepton flux consists of leptons originating from $\pi^{\pm}$, $K^{\pm}$, K^0_{L}, and K^0_{S} decays. All other leptons are considered part of the *prompt* flux.

Tagging prompt in air shower simulation

- …is not so easy…because: CORSIKA 7
- extended history: add two ancestors of final lepton
- Hadron Generation Counter (HGC)
  - increases by 1 with each hadronic interaction
  - exceptions like +30 for charm decay
  - HGC can be negative
  - parent particle is not always the parent particle
  - …
- Parent particles can be unknown
  - not distinguished between pion and kaon



Credit: Ludwig Neste

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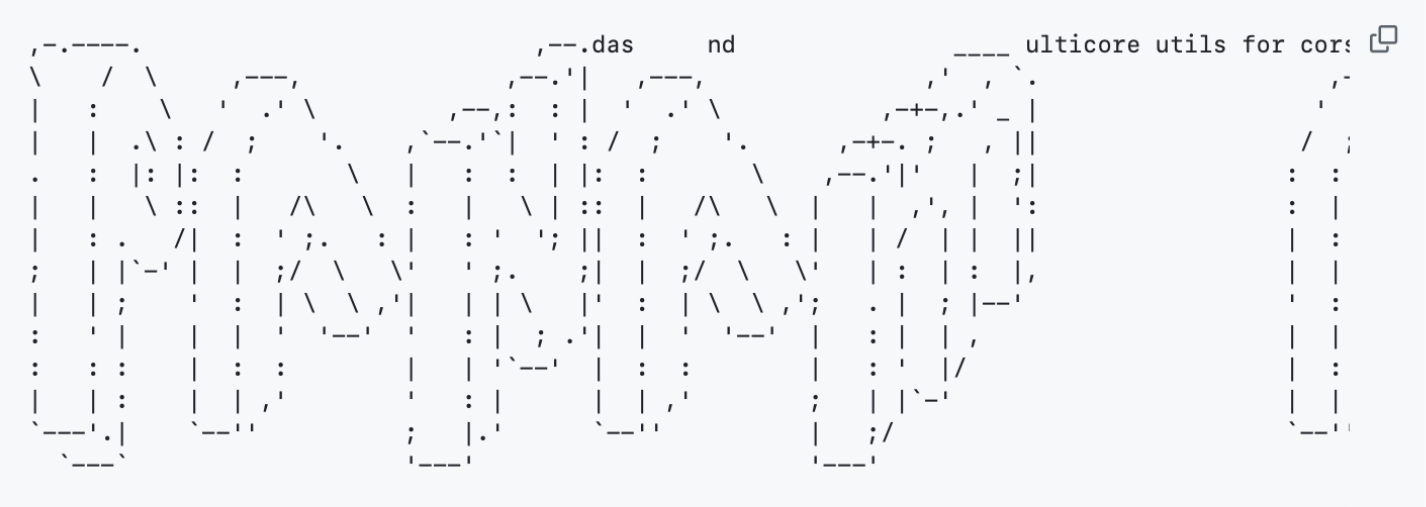
technical details can be found in Ludwig's Master thesis in the nextcloud dortmund university BERKELEY LAB SFB1491 ICECUBE NEUTRINO OBSERVATORY

- new python wrapper for CORSIKA 7
- includes all tagging for prompt and conv
- handles all “issues” with HGC
- easy pip install
- runs on multiple cores
- converts DAT files to hdf5 files



PANAMA - A python toolkit for CORSIKA7.

https://github.com/The-Ludwig/PANAMA

DOCS PASSING

BUILD PASSING | OPEN ISSUES 1 | TEST COVERAGE 100%

PYPI V1.0.4 | DOI 10.5281 / ZENODO.10210623 | LICENSE MIT | CODESYLE BLACK

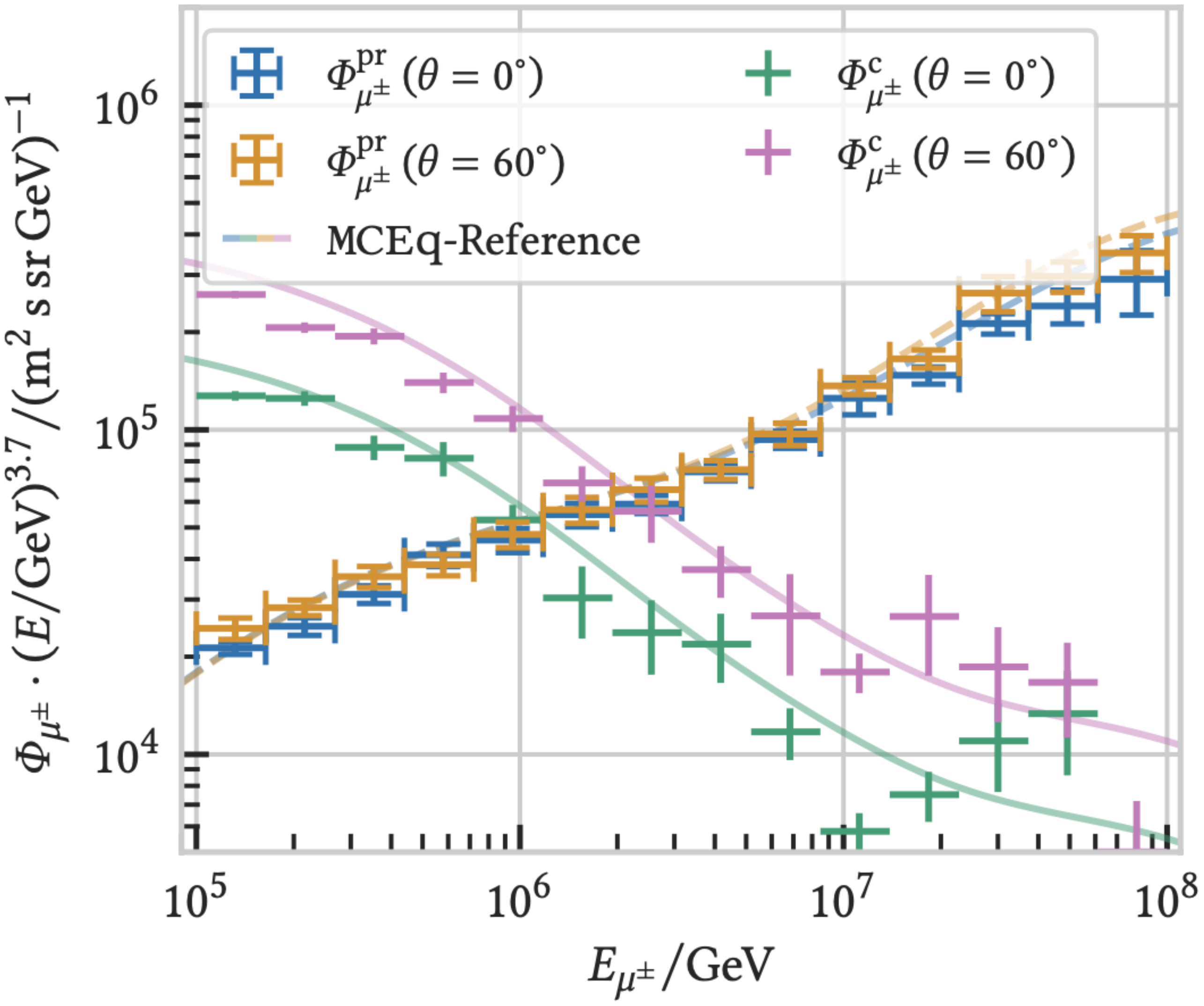
Features

This python package provides multiple features -- each feature can be used independently, but they also work great together.

- Execute CORSIKA7 on multiple cores
- Read CORSIKA7 DAT files ("particle files") to pandas DataFrames
  - Correctly parse output from the `EHIST` option
- Calculate weights for a multiple primary spectra

To see some examples on how to use panama, see the introduction in the documentation. To get an overview of how the features play together, have a look at the example notebook in the documentation. In-depth explanation is provided in the API documentation.

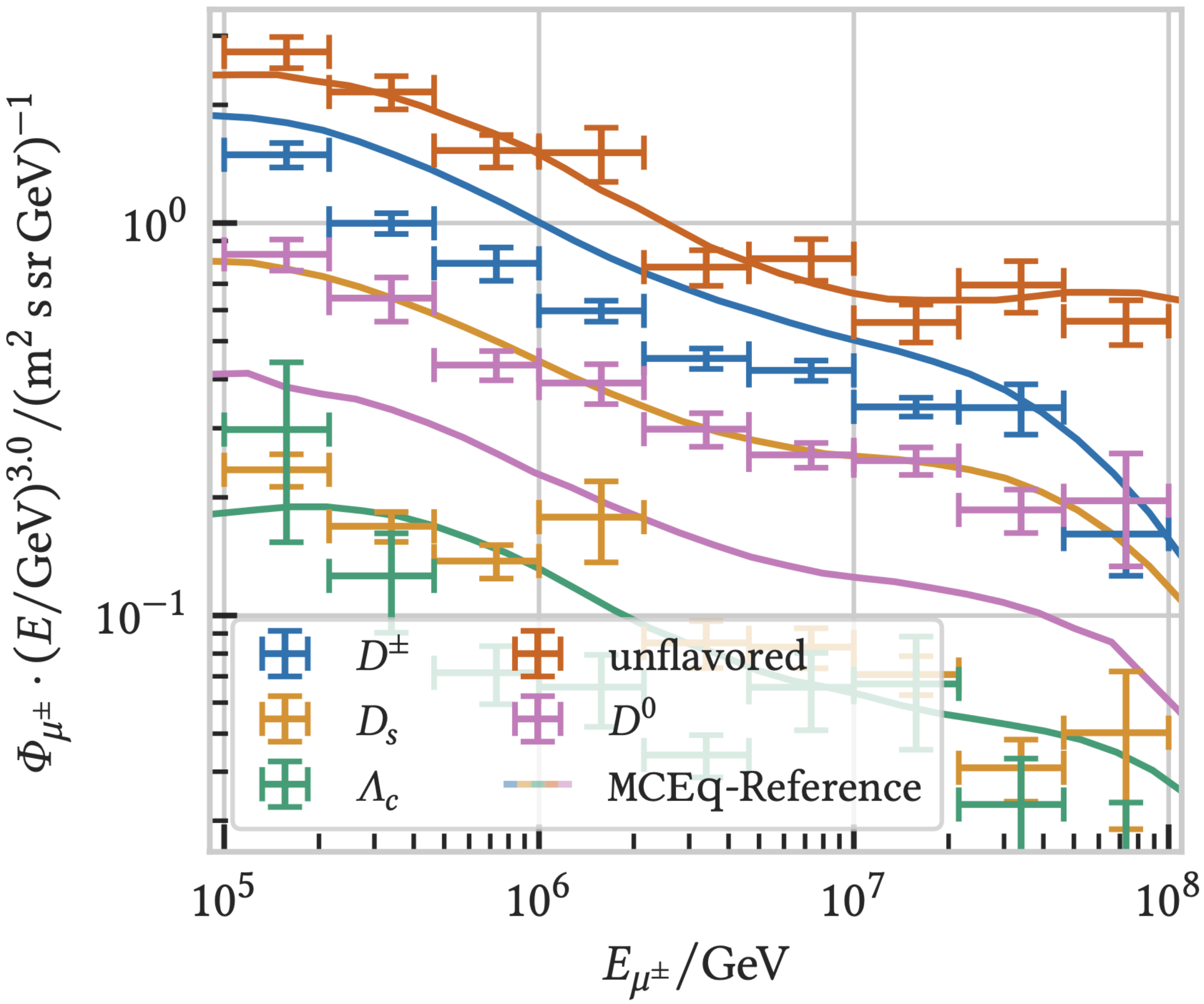
Compare results to MCEq



E_{p}/ GeV	Primary	$n_{\mathrm{P}} \cdot n_\theta \cdot n_{\mathrm{sim}} = n$
$10^5 – 1 \cdot 10^9$	^{1}H, ^{4}He, ^{12}C	$3 \cdot 2 \cdot 10^7 = 6 \cdot 10^7$
	^{28}Si, ^{54}Fe	$2 \cdot 2 \cdot 10^6 = 4 \cdot 10^6$
$10^9 – 5 \cdot 10^{10}$	^{1}H, ^{4}He, ^{12}C	$3 \cdot 2 \cdot 10^5 = 6 \cdot 10^5$
	^{28}Si, ^{54}Fe	$2 \cdot 2 \cdot 10^4 = 4 \cdot 10^4$

- good agreement for inclusive flux
- SIBYLL 2.3c vs. 2.3d

Compare to specific parent particles

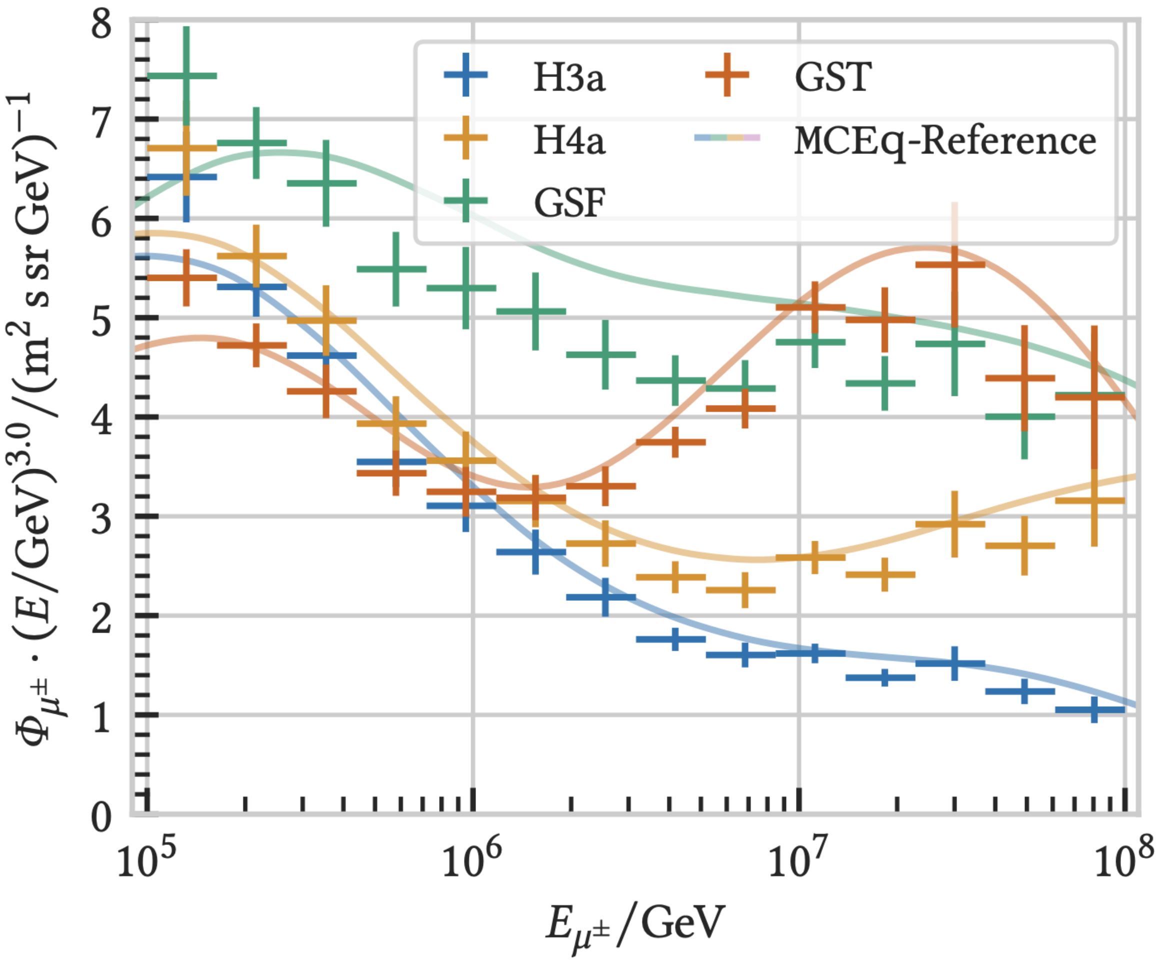


- D0 and DS are swapped in the official MCEq paper
- Deviations for D± and DS

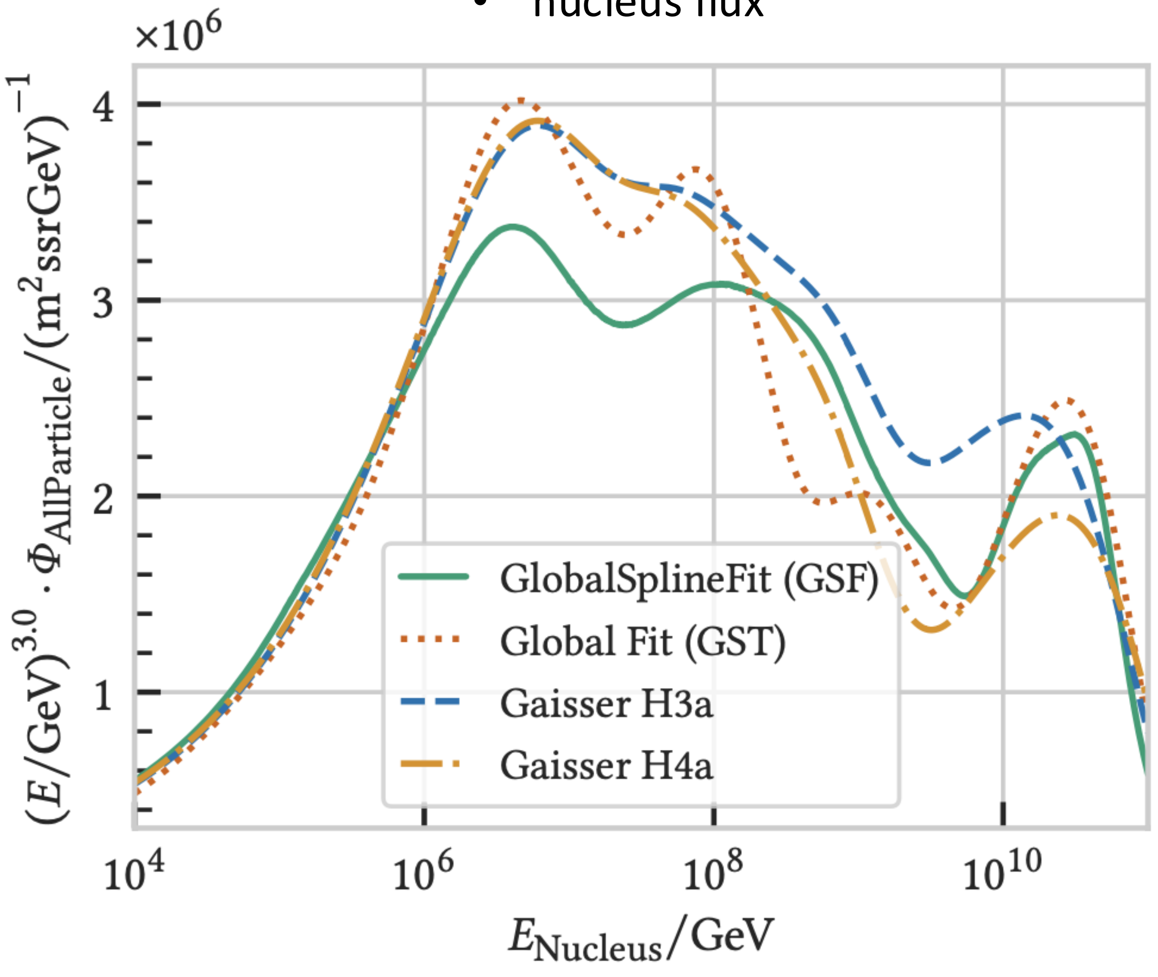
- ➢ Good to have two independent methods
- ➢ Inclusive flux agrees → that's what we can measure

Influence of the primary flux model

- shapes agree



- nucleus flux



How to measure the prompt component?

$$\lambda_m(\eta, \xi) = \lambda_m^{\mathrm{conv}}(\eta_{\mathrm{conv}}, \xi) + \lambda_m^{\mathrm{pr}}(\eta_{\mathrm{pr}}, \xi), \qquad (3)$$

$$\lambda_m^{\mathrm{pr}}(n_{\mathrm{pr}}) = n_{\mathrm{pr}} \cdot \lambda_m^{\mathrm{pr}}, \quad n_{\mathrm{pr}} \geq 0 \qquad (4)$$

Assuming Poisson statistics in each of the M observable bins, the likelihood of observing the data k_m is then given by

$$\mathcal{L}\left(n_{\mathrm{pr}}, n_{\mathrm{conv}}\right) = \prod_{m=1}^{M} p_{\lambda=\lambda_m}\left(k = k_m\right), \qquad (5)$$

with the Poisson distribution $p_\lambda(k)$.

$$\Lambda = -2 \ln \frac{\mathcal{L}\left(n_{\mathrm{pr}} = \hat{n}_{\mathrm{pr}}, n_{\mathrm{conv}} = \hat{n}_{\mathrm{conv}}\right)}{\mathcal{L}\left(n_{\mathrm{pr}} = 0, n_{\mathrm{conv}} = \hat{n}_{\mathrm{conv}}\right)}. \qquad (6)$$

- currently worked on by Leander

Leading muon definition

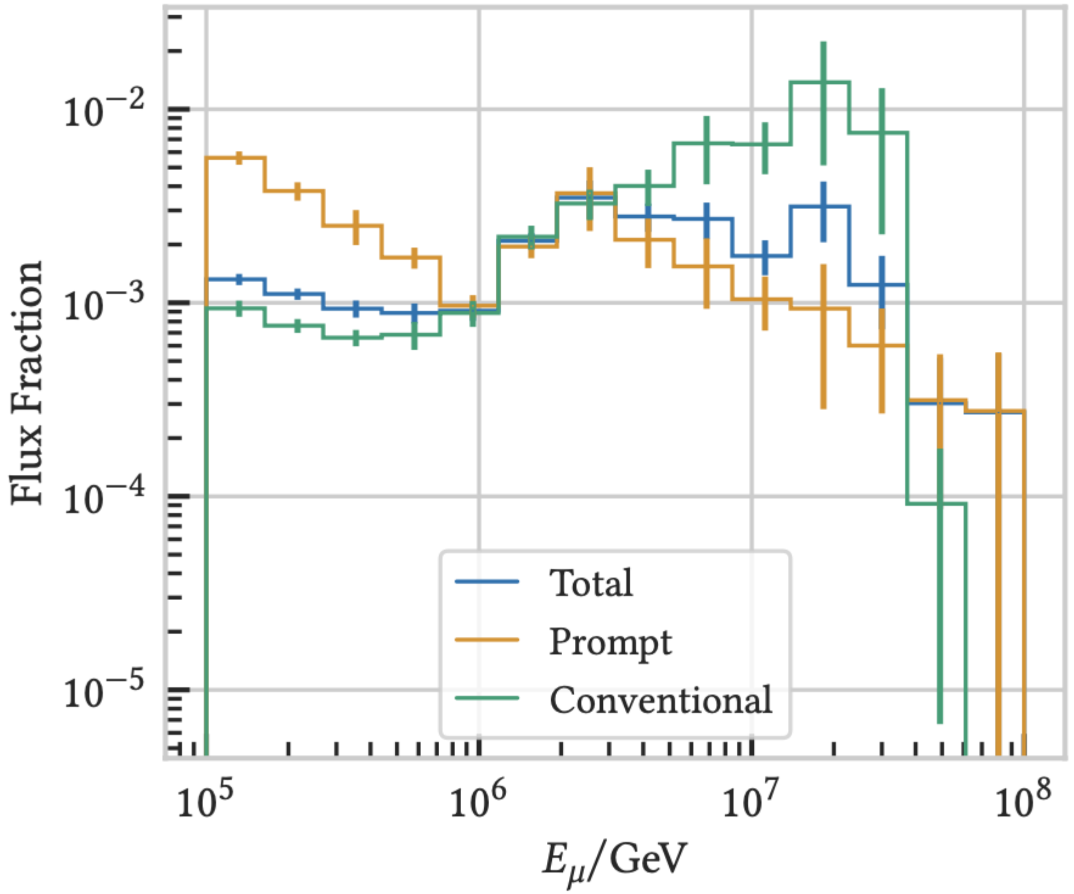


Fig. 6: The fraction of the muon flux which is misattributed if the prompt/conventional tag for every muon in the shower is based on the most energetic (leading) muon. The 60° dataset is weighted with the Gaisser H3a model. For example, the orange line shows the fraction of the prompt flux contained in showers where the leading muon is a conventional particle.

Relation to primary energy

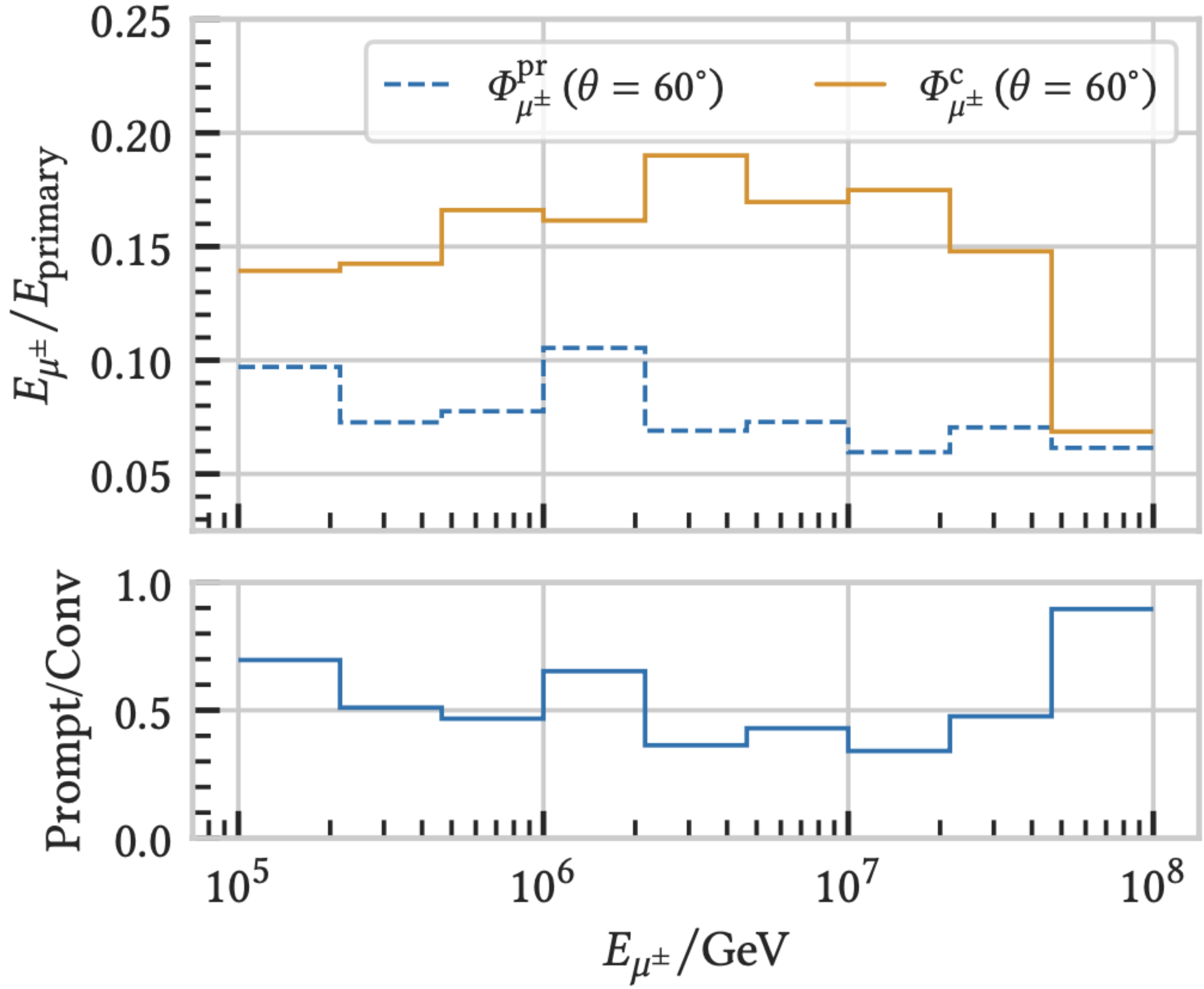


Fig. 8: The energy bin-wise average of the ratio of the muon energy to the primary energy. The events are weighted according to the H3a primary model. The lower panel shows the ratio of the prompt average to the conventional mean value.

Leadingness

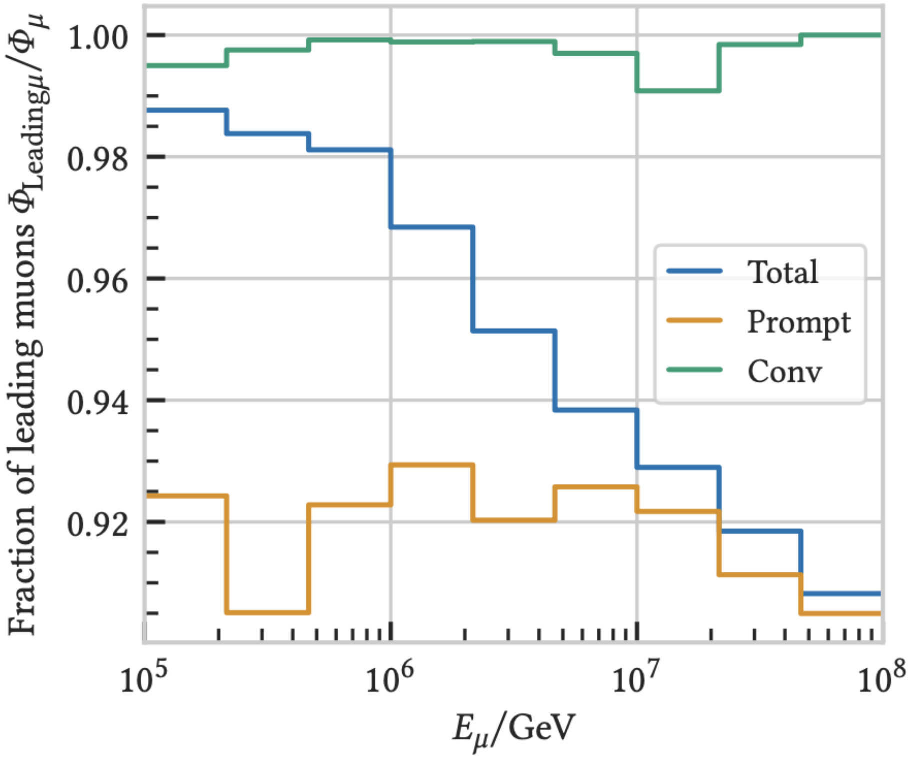


Fig. 10: The leading muon flux divided by the total muon flux per energy bin is shown by the blue line. Also the fraction of leading muons per energy bin, separated into prompt and conventional components, is shown. For example, a value of 0.9 in a given bin indicates that 90 % of the total muon flux in this energy bin originates from leading muons. If the leading muon is conventional for the shown energy range, the entire flux is dominated by more than 99 %. A leading muon is defined as the most energetic muon within a shower. H3a-weighting is used.

Lateral distribution

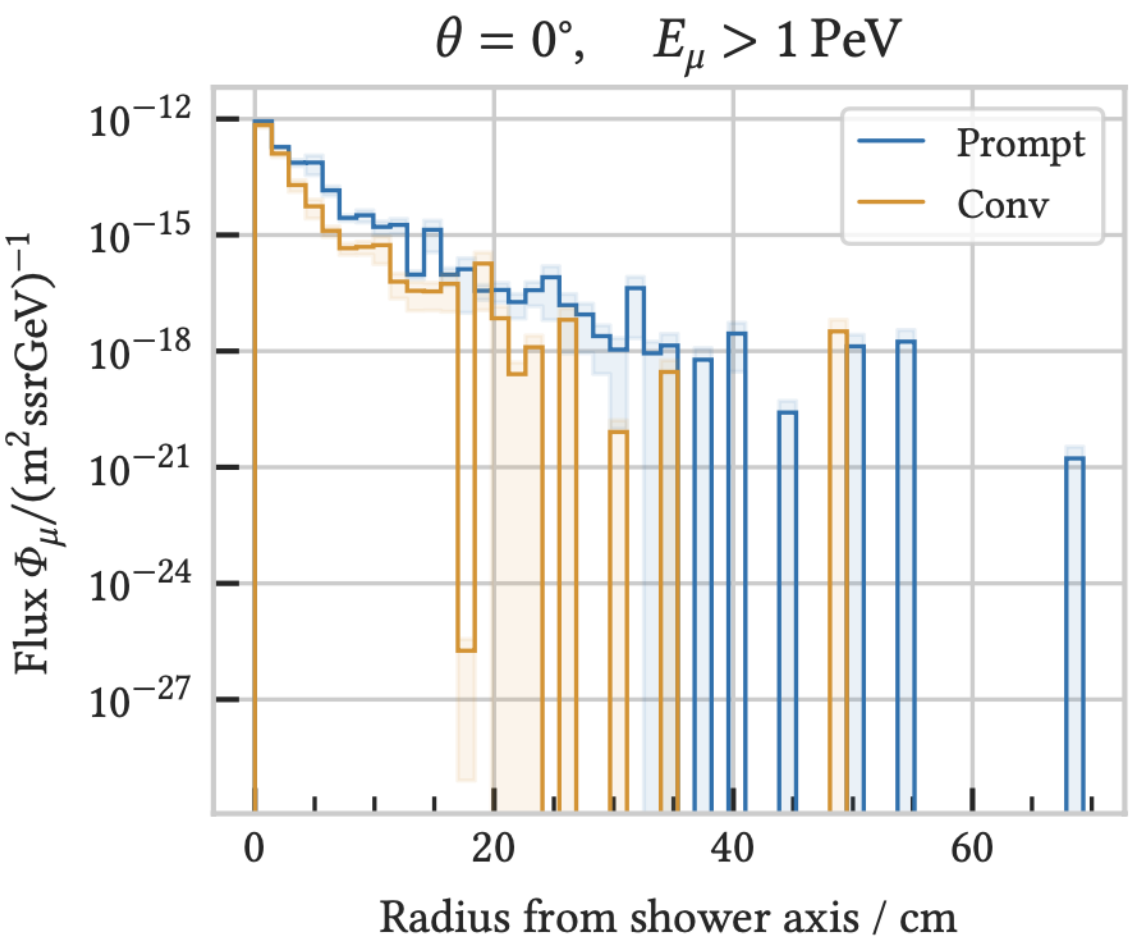


Fig. 11: The lateral flux-distribution of conventional and prompt muons above 1 PeV for down going showers. The H3a CR flux model is used. Prompt muons are expected to have wider distribution since their parents are less forward boosted compared to their conventional counterparts.

Flux parametrization

$$P(\log E) = a\log^3 E + b\log^2 E + c\log E + A$$

	Conventional	Charm	Unflavored	Other Prompt
		H3a		
A	$9.91 \cdot 10^{1}$	$1.59 \cdot 10^{-4}$	$1.18 \cdot 10^{-4}$	$1.71 \cdot 10^{-5}$
B	-	$1.05 \cdot 10^{-6}$	-	-
a	$2.79 \cdot 10^{-6}$	$-3.60 \cdot 10^{-8}$	$-2.46 \cdot 10^{-8}$	$-4.02 \cdot 10^{-9}$
b	$4.23 \cdot 10^{-1}$	$1.77 \cdot 10^{-6}$	$1.26 \cdot 10^{-6}$	$1.98 \cdot 10^{-7}$
c	$-1.28 \cdot 10^{1}$	$-2.90 \cdot 10^{-5}$	$-2.12 \cdot 10^{-5}$	$-3.19 \cdot 10^{-6}$
χ^2/n_{DOF}	5.96	7.22	1.73	3.95

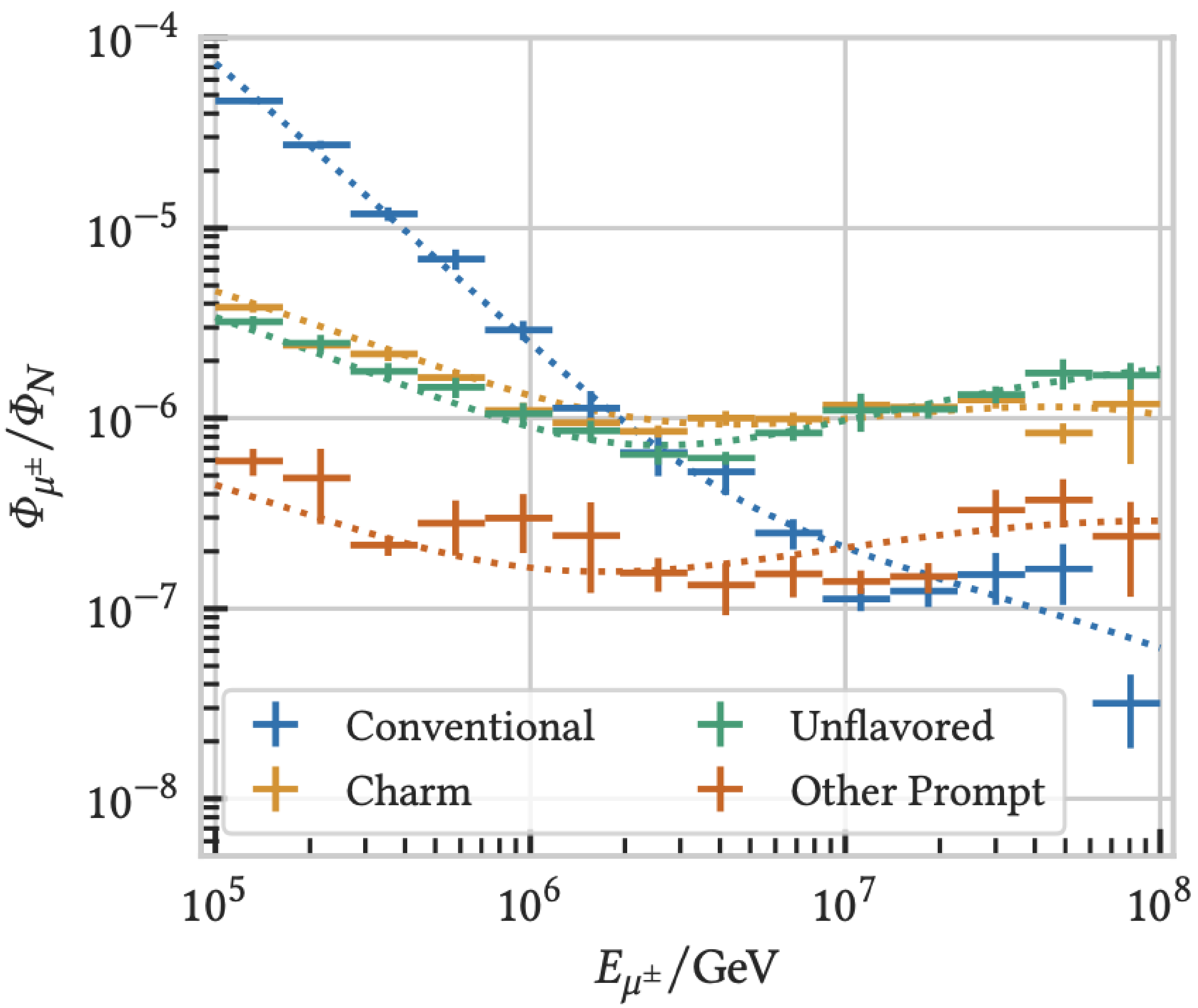


Fig. B2: Weighted, binned, extended likelihood fit assuming an energy dependency in the form of a third order polynomial. The CR flux model is H3a.

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Conclusion

- Prompt and conv definition
- Tag prompt and conv in CORSIKA 7 simulations
    - provide open-source PANAMA tool (already used by Celina)
- Validate results with MCEq comparisons
- Present approach for prompt normalization measurement
- Study prompt properties
    - prompt definition by leading muon
    - leadingness
    - energy relation to primary
    - lateral distribution
- Parametrization for lepton fluxes from different origins for all 4 primary flux models