Air shower physics with CORSIKA 8

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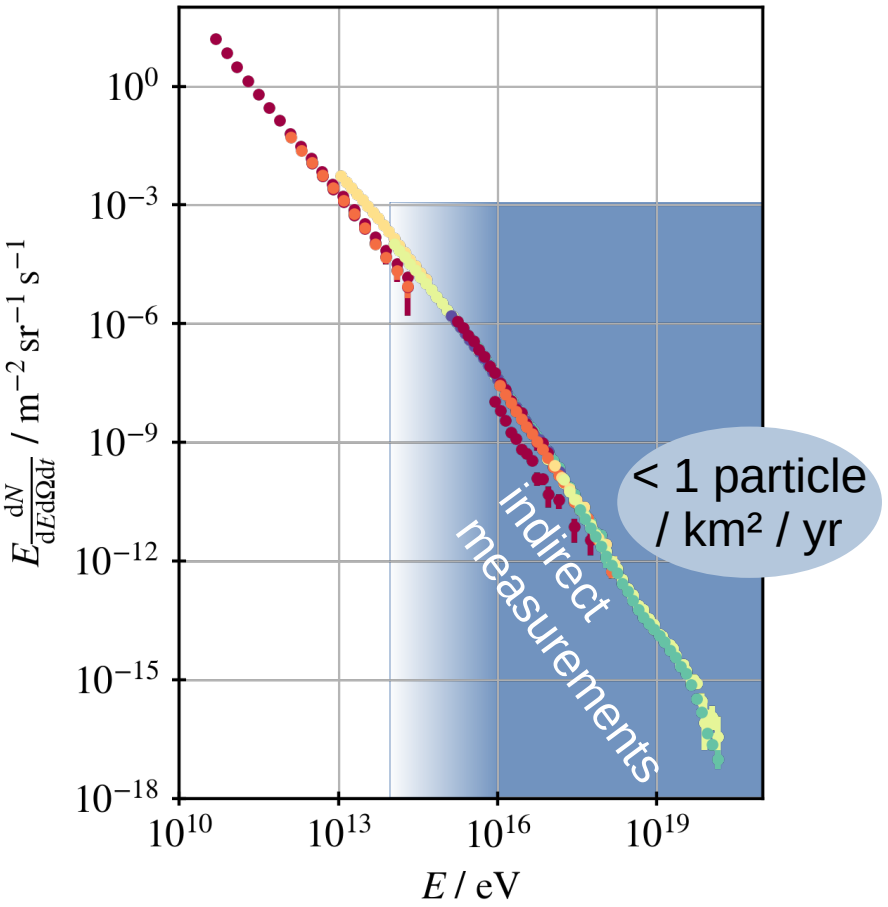
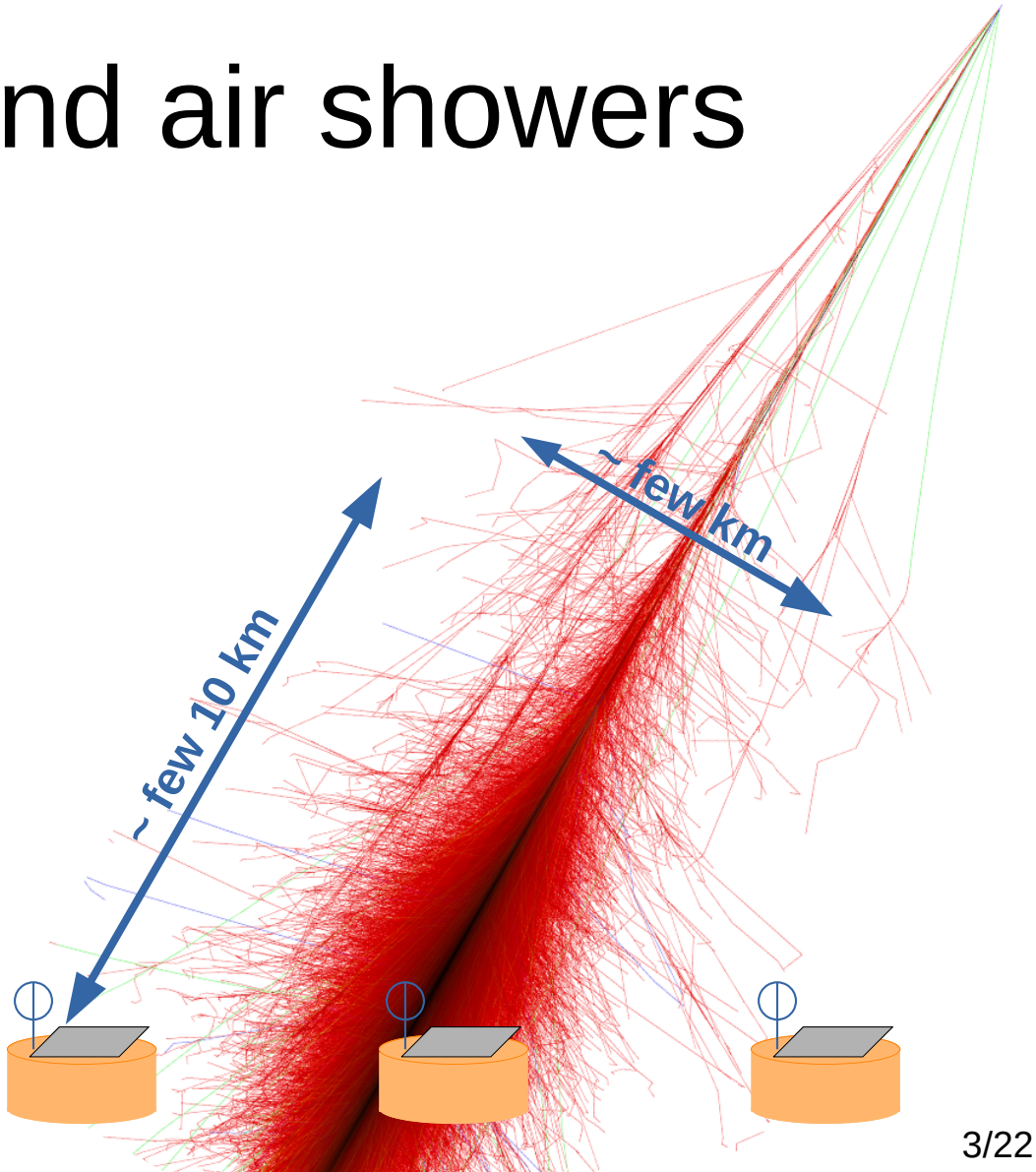
Outline

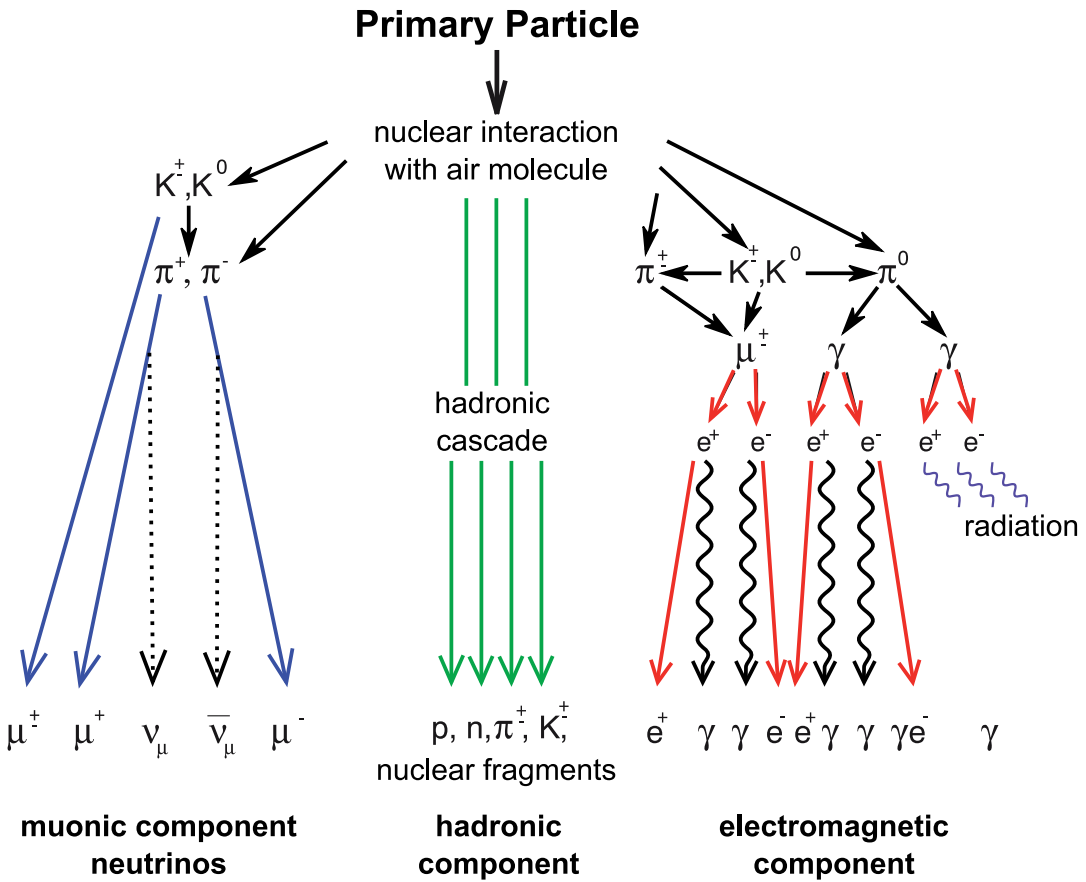
- Introduction
- Comparisons C8 with others
- Studies on muon production
- Modified physics scenarios
- Conclusions

Cosmic rays and air showers





Air shower physics

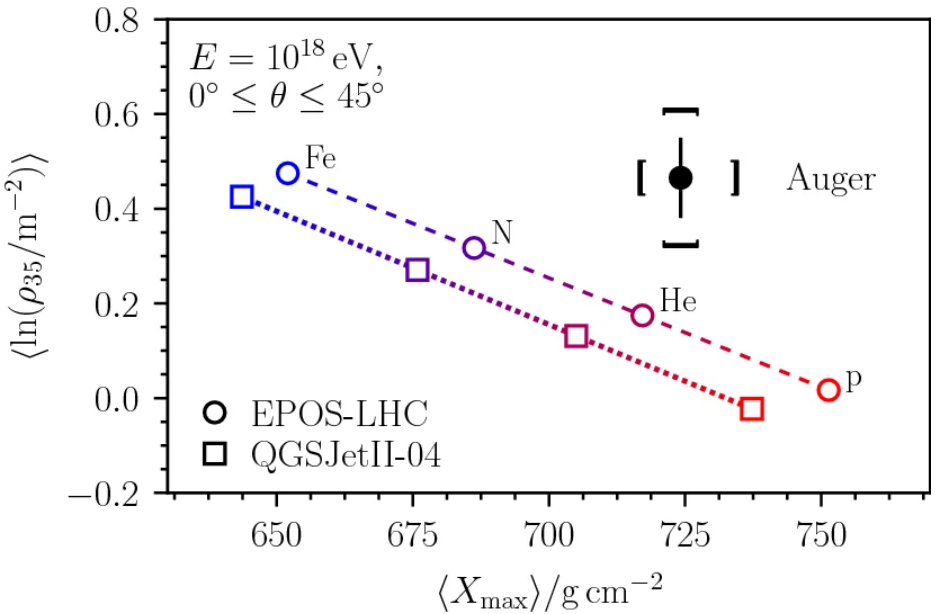


- > 30 particle species involved
- interactions up to ZeV (10^{21} eV) energies

- accurate simulations and physics models crucial
- reliable tools are a must-have
- **performance of astroparticle physics experiments limited by simulations**

Haungs, Rebel, Roth, Rept. Prog. Phys. 66 (2003) 1145

The muon puzzle



> 40% too few muons in simulations

- exotic/new physics above LHC energies?
- effects at lower energies insufficiently constrained by collider/fixed-target experiments?

X_{max}: depth of shower maximum
ϱ_{35}: muon density at ground (normalized)

more flexible, modular simulations needed to investigate muon puzzle

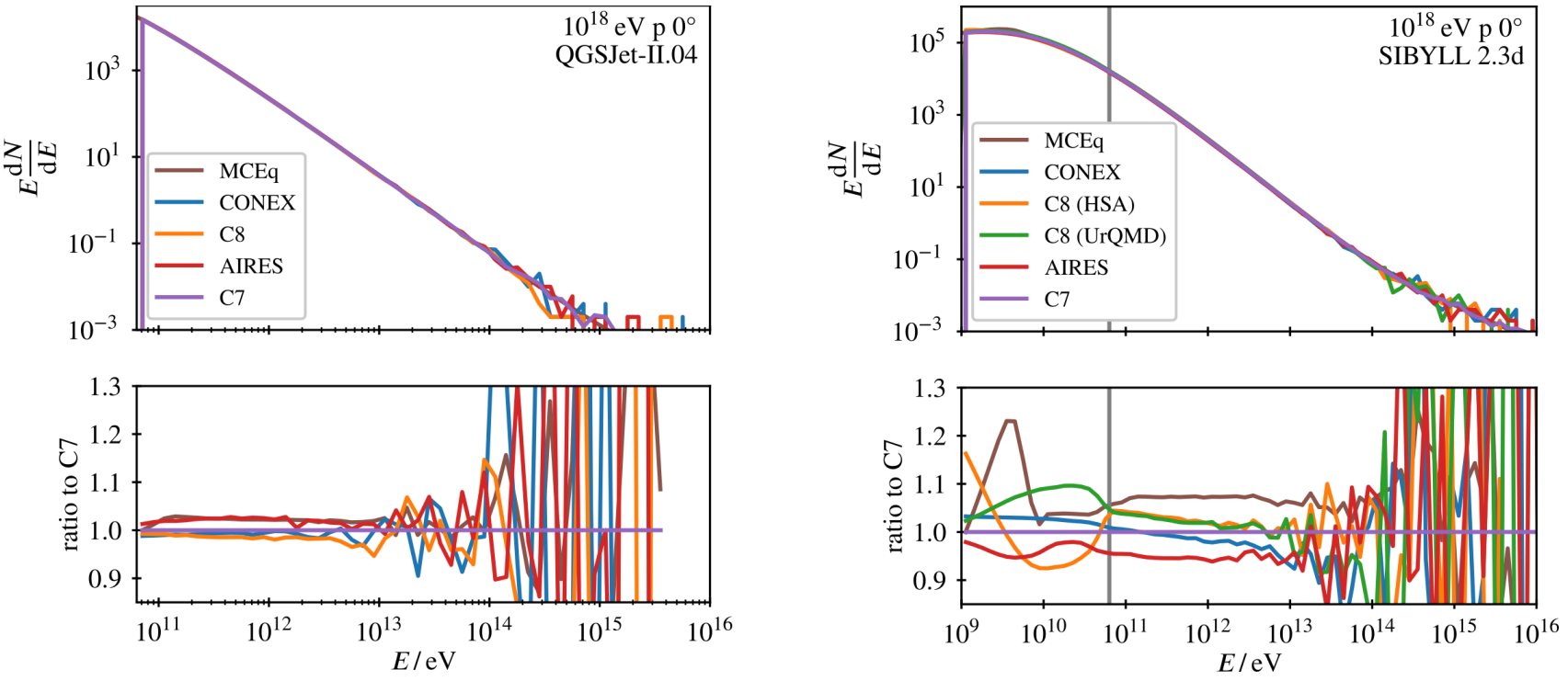
CORSIKA 8

Pierre Auger Collaboration, EPJ C 80, 751 (2020)

Air showers with CORSIKA 8

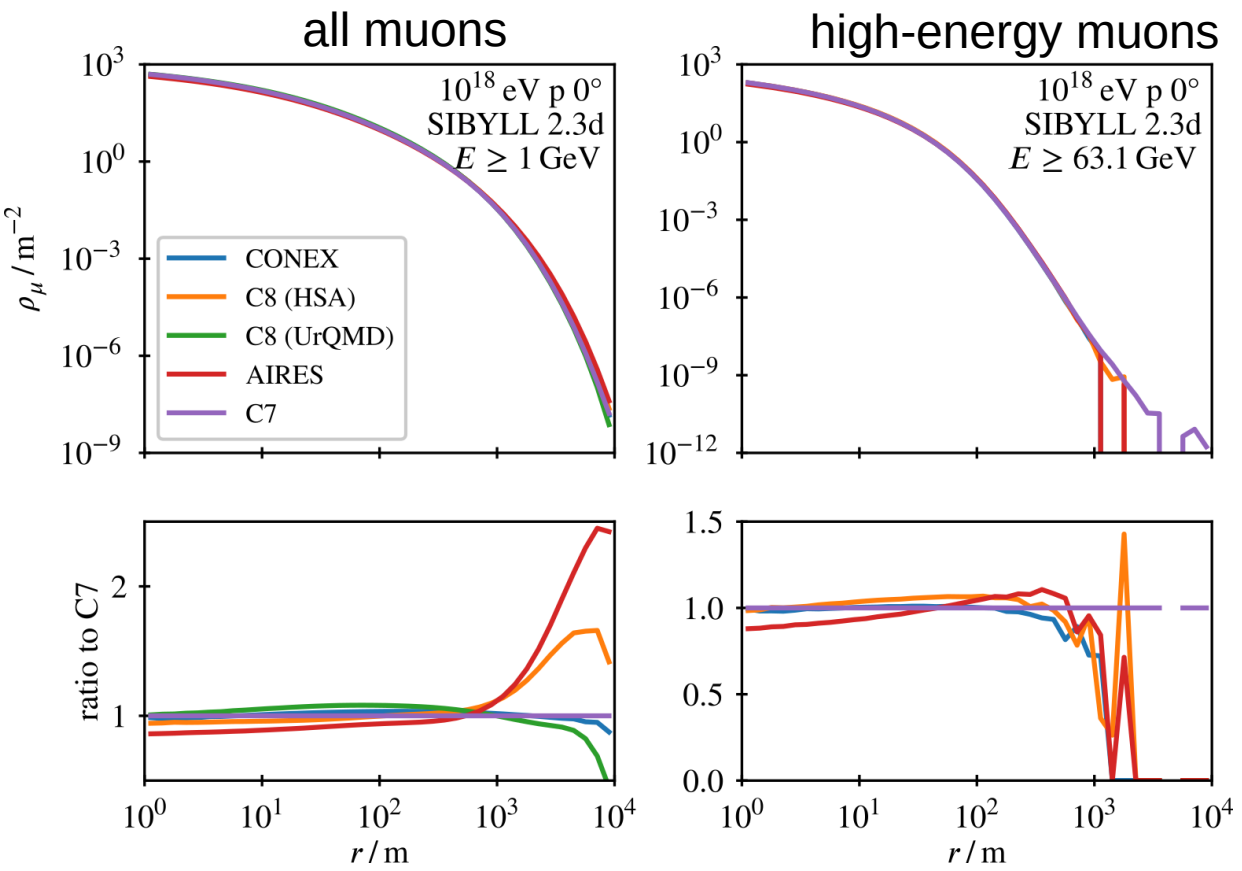
- comparisons of C8 with other codes
- phase space of muon production with particle lineage
- modified physics scenarios

Comparison study: Muon spectra



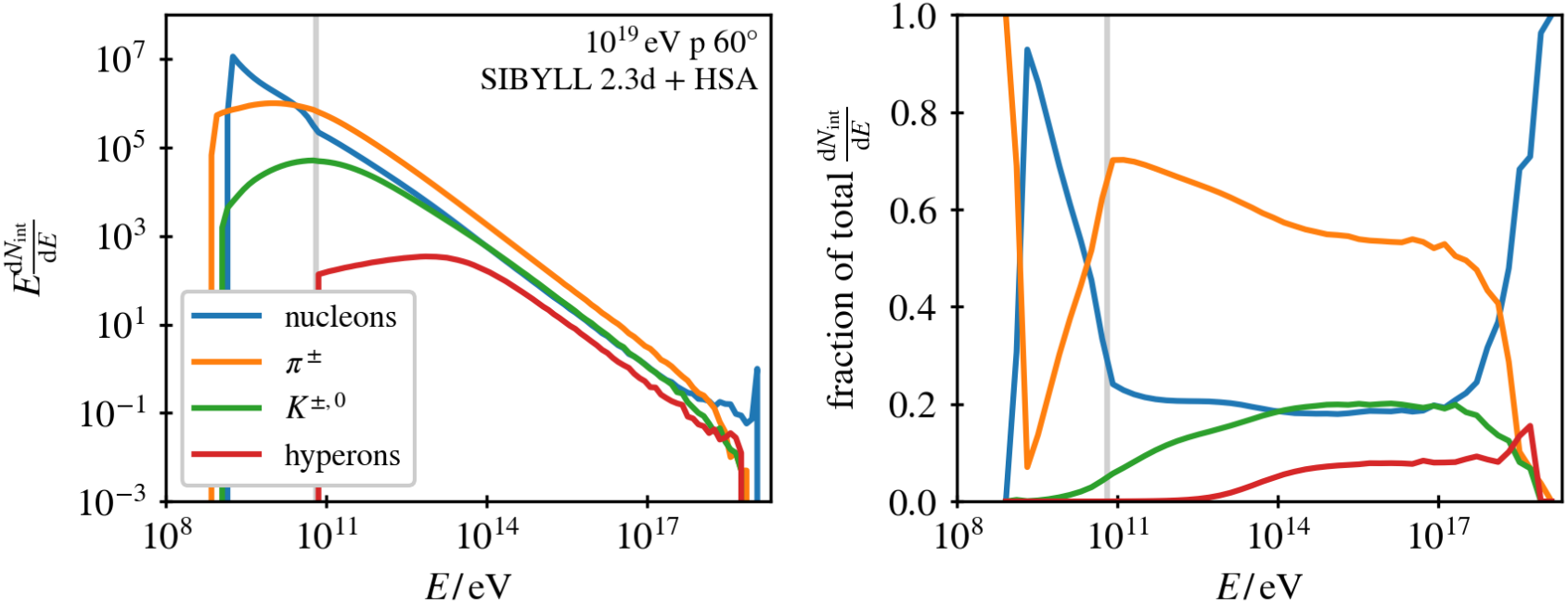
- mostly excellent agreement on few % level
- notable remaining cases with ~10 % differences between programs
- runtime still an issue!

Comparison study: lateral distribution



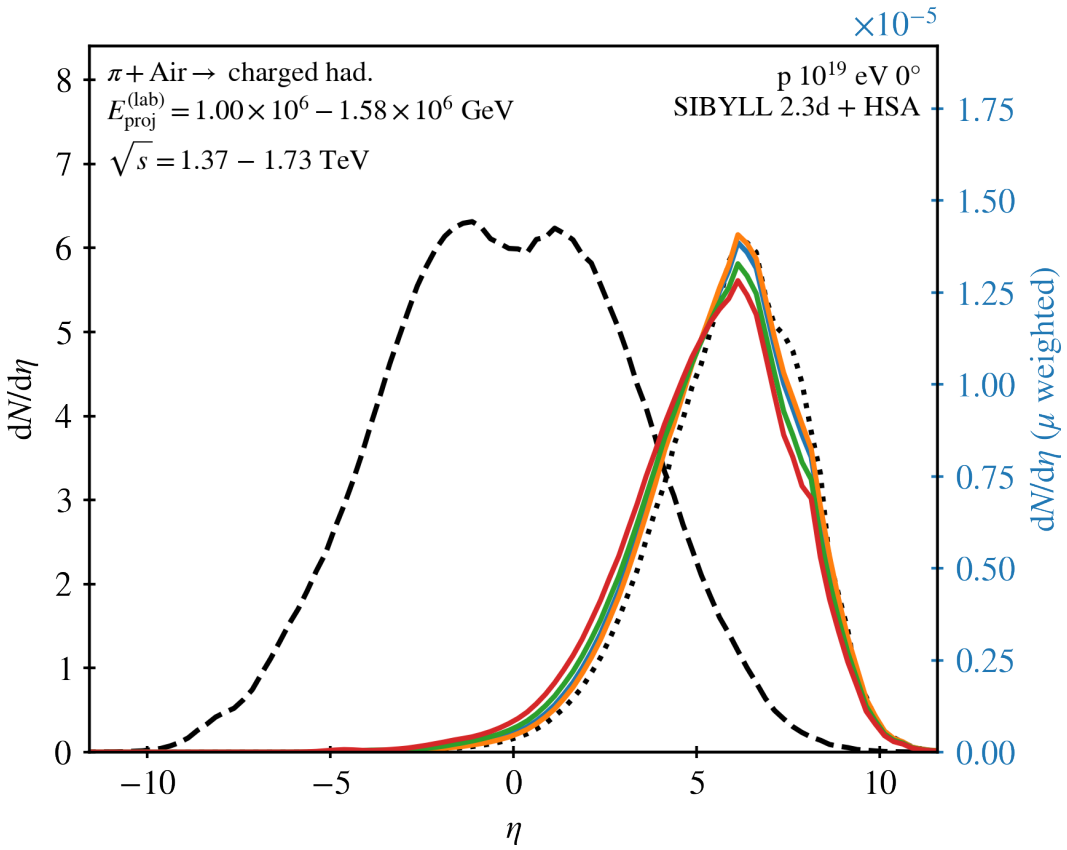
- low-energy interactions important at large distances
- potential new analysis uncertainties
- **CORSIKA 8 ideal place to address remaining general modelling uncertainties**

Hadronic interactions in EAS



$\pi^{\pm}$-Air interactions
most important

Pseudorapidity



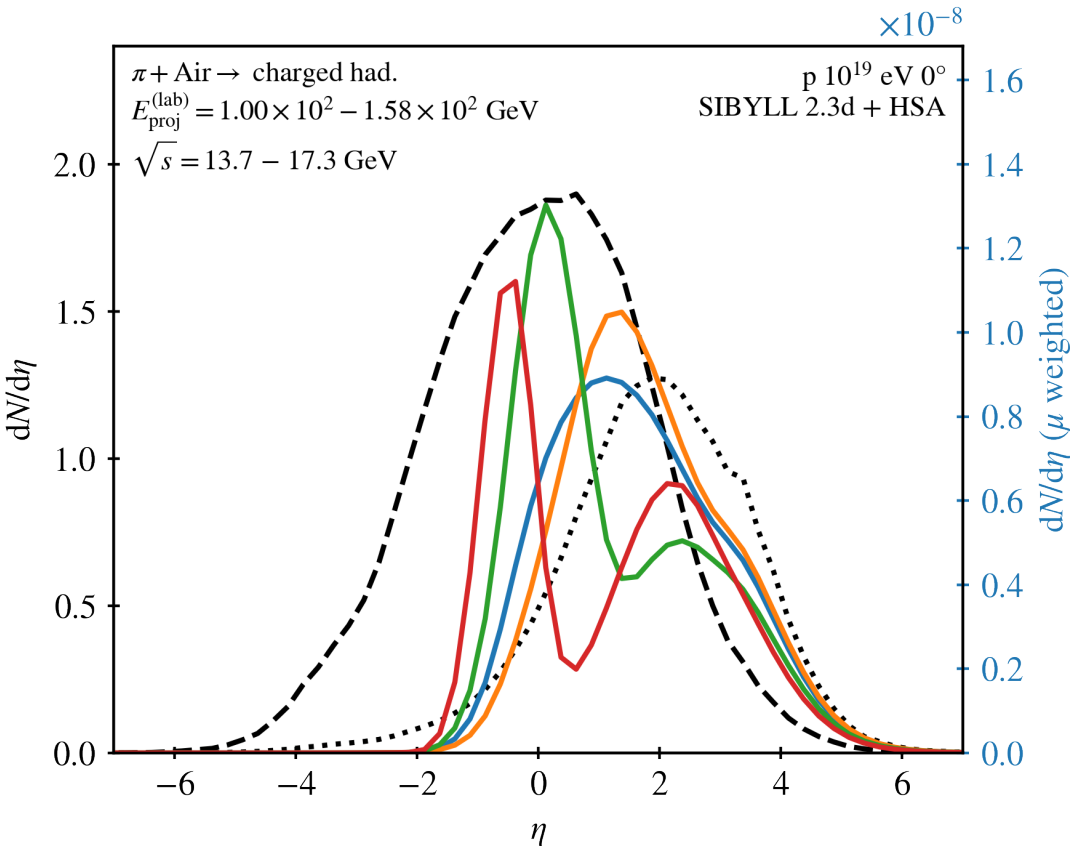
$$\eta \equiv -\ln \tan \frac{\theta}{2}$$

E_{lab} ~ 1 PeV

- excellent agreement with $E^{0.93}$ scaling
- importance of forward phase-space quantified

MR, Ulrich, Pierog, PoS ICRC2021 463

Pseudorapidity



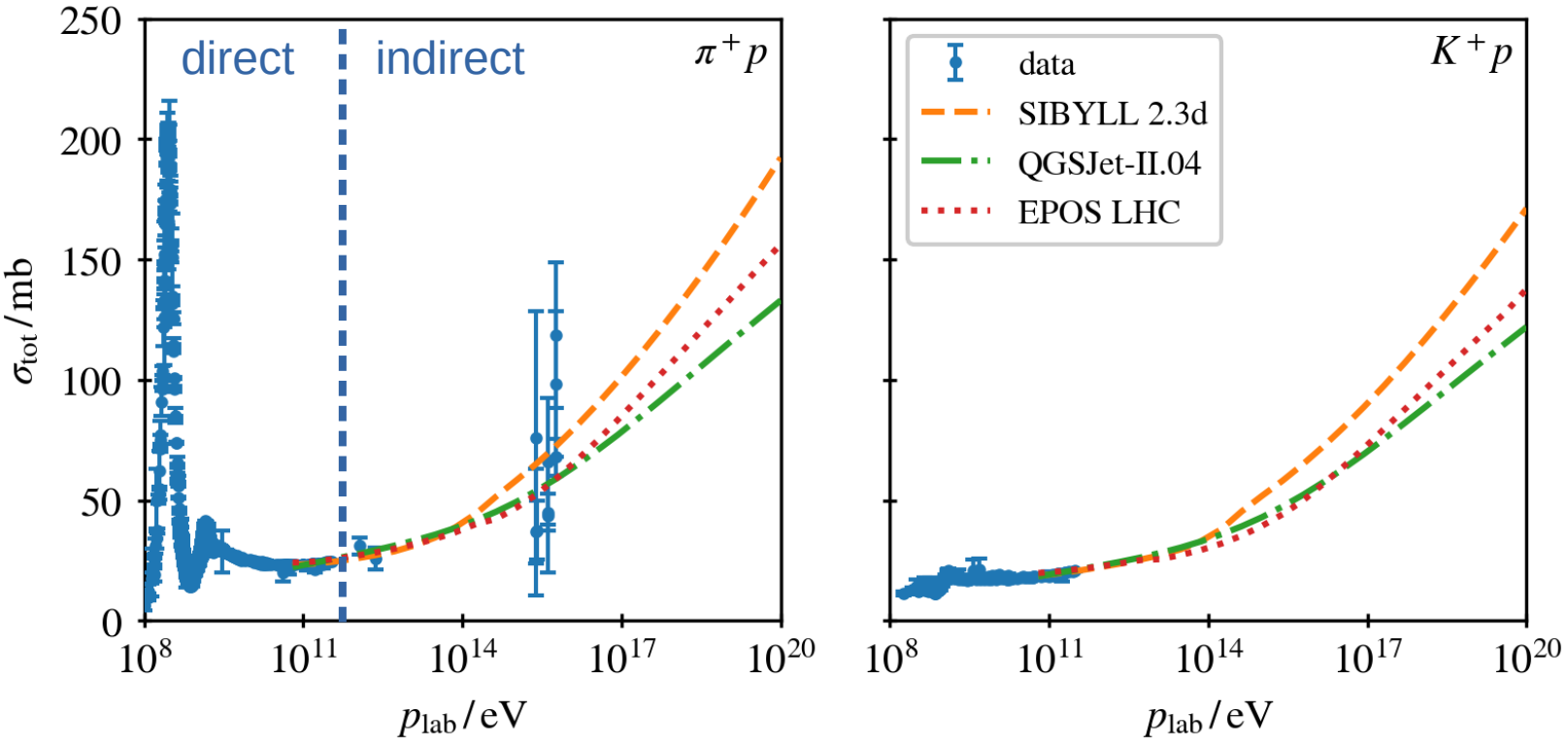
$$\eta \equiv -\ln \tan \frac{\theta}{2}$$

E_{lab} ~ 100 GeV

- Heitler-Matthews model breaks down
- central particle production becomes important

MR, Ulrich, Pierog, PoS ICRC2021 463

Meson-proton cross-sections



Meson-air cross-sections

- precise measurements only up to ~500 GeV
- extrapolation uncertainty
- impact on air shower simulations?

"f_{19} approach" *Ulrich et al. [1010.4310]*

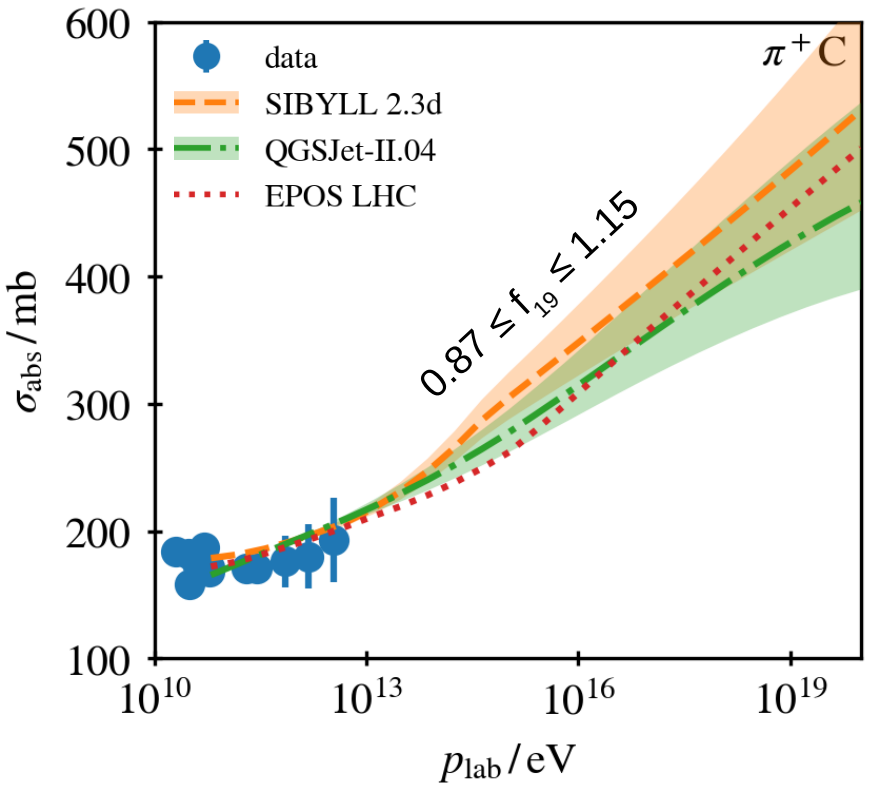
$$\sigma_{\mathrm{inel}}(E) = \hat{\sigma}_{\mathrm{inel}}(E) \times \left(1 + \frac{f_{19} - 1}{\log \frac{E_{\mathrm{th}}}{10^{19}\,\mathrm{eV}}} \max\left(0, \log \frac{E}{E_{\mathrm{th}}}\right)\right)$$

ad hoc modification factor

This work:

- independent f_{19} for π, K, N
- E_{th} = 1 TeV

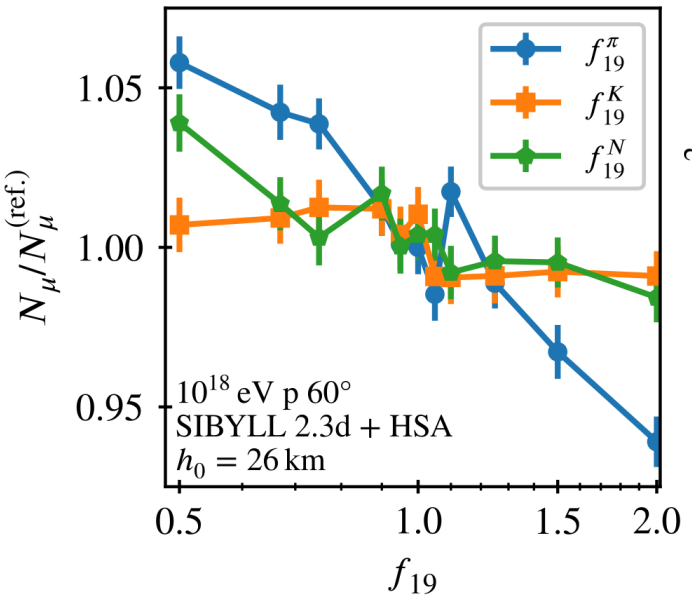
$^{12}C \approx {}^{14}N, {}^{16}O$



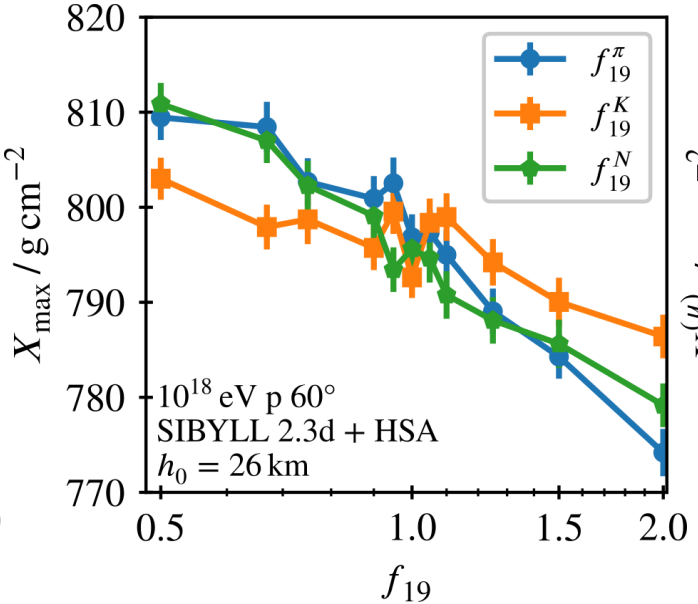
Impact on observables

composition dependent

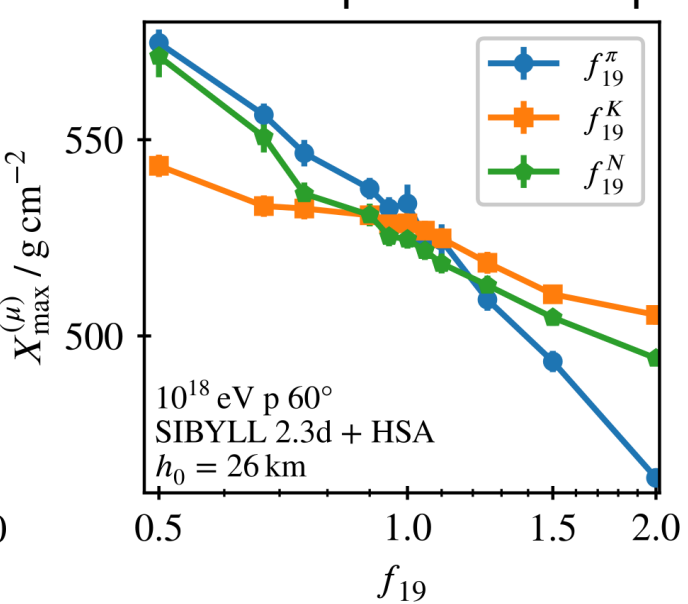
number of muons



shower maximum



max. muon production depth

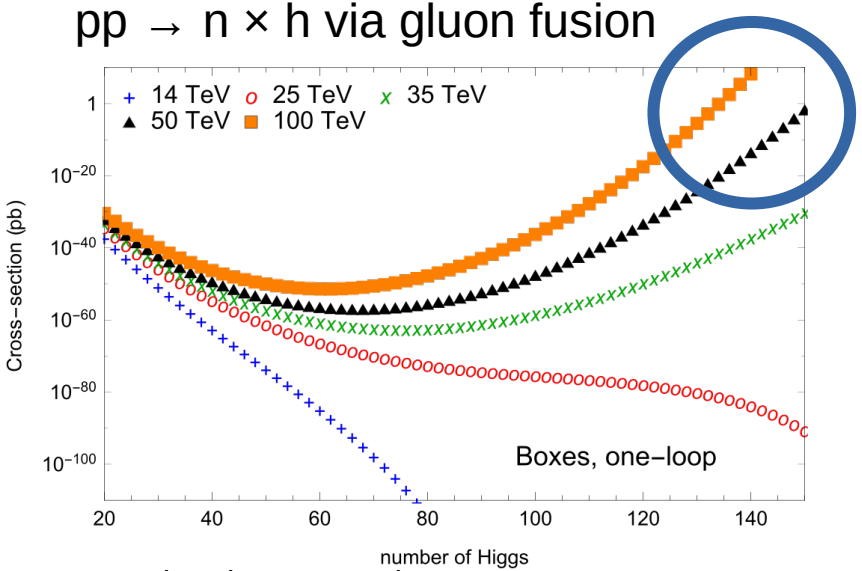


- **modification affects mainly (hadronic) longitudinal development**
- **pions have greatest impact, kaons smallest**

“Higgsplosion” in EAS

$h^*(p^2 \gg m_{\mathrm{h}}^2) \to n \times h$ transition rate growing with ***n!***

pp → n × h via gluon fusion



Degrande, Khoze, Mattelaer
PRD 94, 085031 (2016)

energy fraction converted to Higgs:

$$\frac{n \times m_{\mathrm{h}}}{\sqrt{s}} \gtrsim 0.20$$

- ≳ 100 mb cross-sections reachable?!
- observable impact on EAS?

n.b.: theoretical foundations of the mechanism still under discussion:
Monin, 1808.05810
Khoze, Spannowsky, 1809.11141
Dine, Patel, Ulbricht, 2002.12449

Implementation in CORSIKA 8

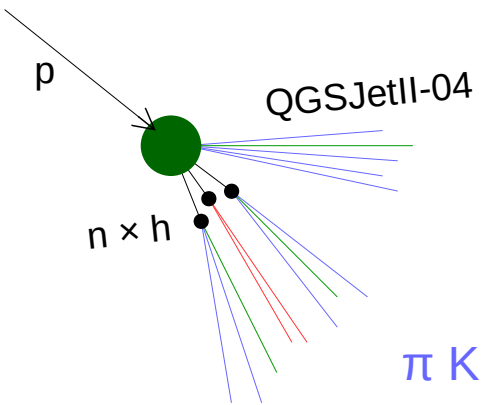
$$\sqrt{\hat{s}} = f\sqrt{s_{NN}} = f\sqrt{\frac{s}{14.5}}$$

energy fraction
for Higgs production

$$n_{\mathrm{h}} = \frac{\sqrt{\hat{s}}}{m_{\mathrm{h}}(1+\varepsilon)}$$

fractional kinetic energy, ≲ ~ few

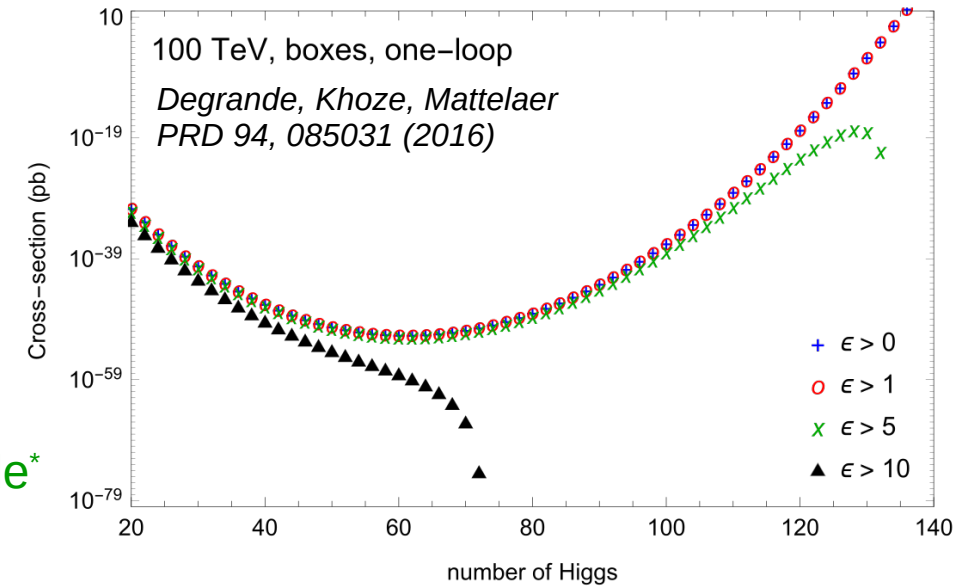
$(1-f)\sqrt{s}$ remaining energy for underlying event



↦ e.m. cascade*

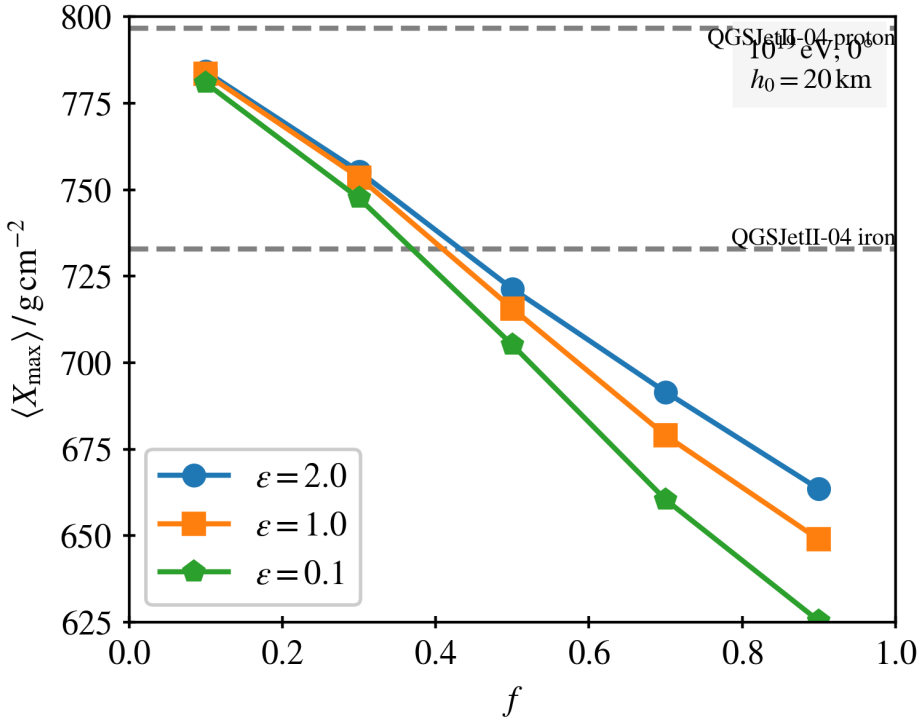
π K τ μ (+ν) e γ

↳ had. cascade



* simulated with CONEX

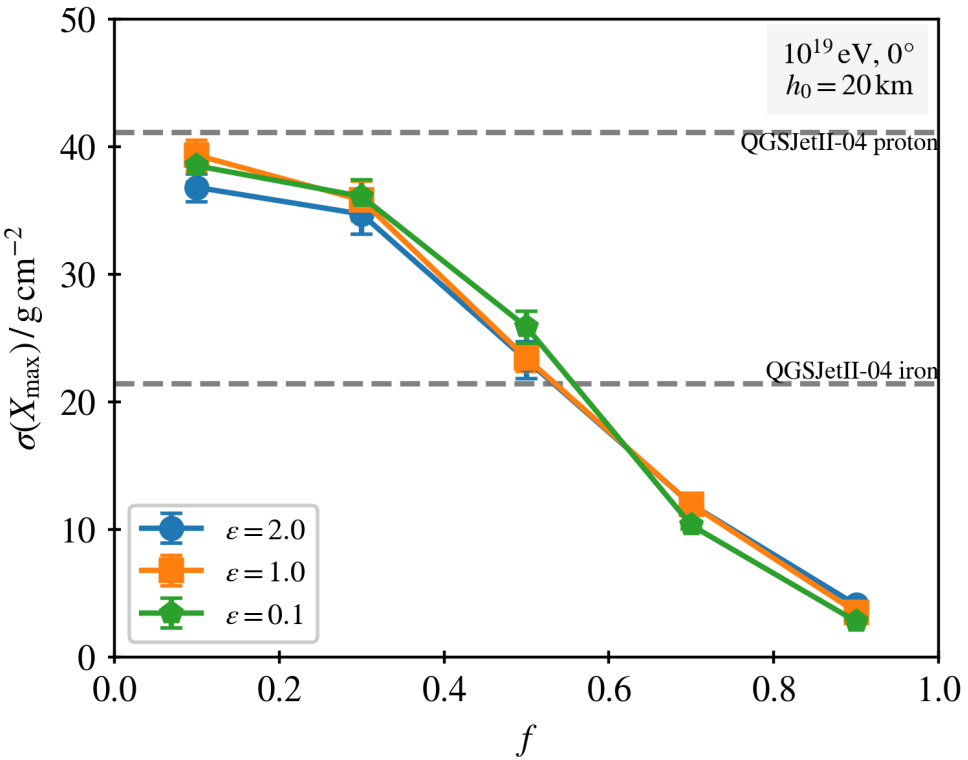
Shower maximum: X_{max}



- cross-section not known
- study shower development with **fixed point of first interaction**

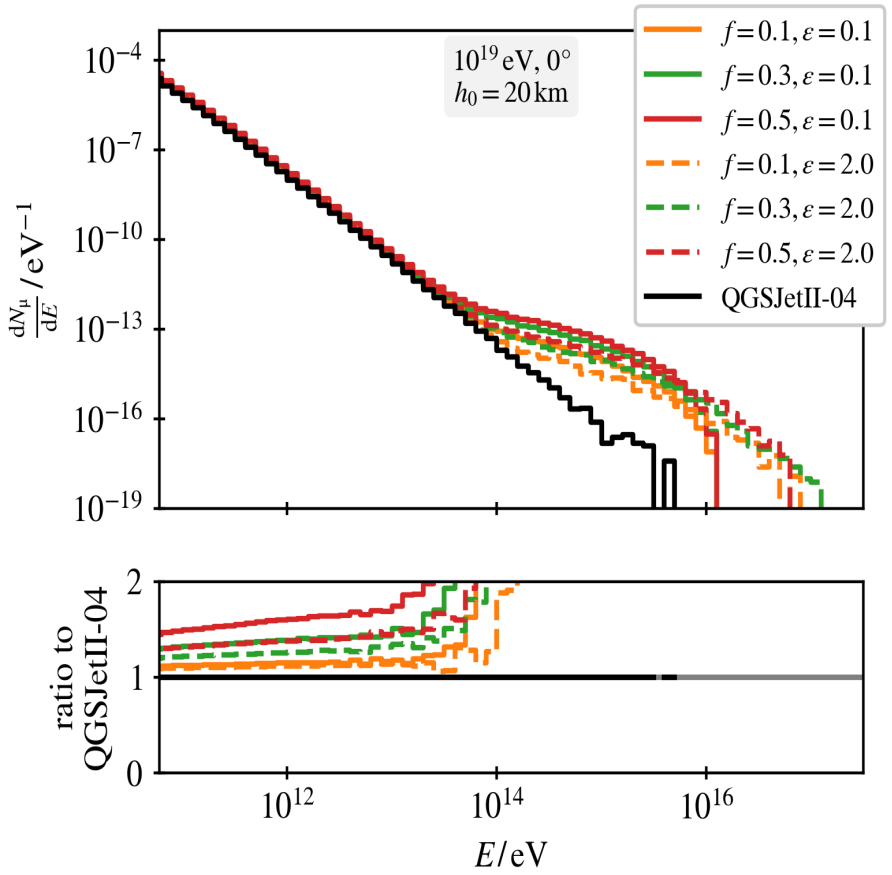
- strong dependence on f
- weak dependence on ε

X_{max} fluctuations



- fluctuations caused mainly by standard hadronic interactions
- possibly artifact of oversimplified model implementation
- N = 50 events probably insufficient statistics

Muon energy spectrum



- bump of ~PeV prompt muons from Higgs decay
- overall increase of muon number
- muon production increasing with f
- decreasing with ε

f	ratio N_μ	
	ε = 0.1	ε = 1.0
0.1	1.11	1.08
0.3	1.31	1.21
0.5	1.49	1.38
0.9	1.82	1.82

$$\frac{N_\mu^{(\mathrm{Fe})}}{N_\mu^{(\mathrm{p})}} = A^{0.1} = 1.50$$

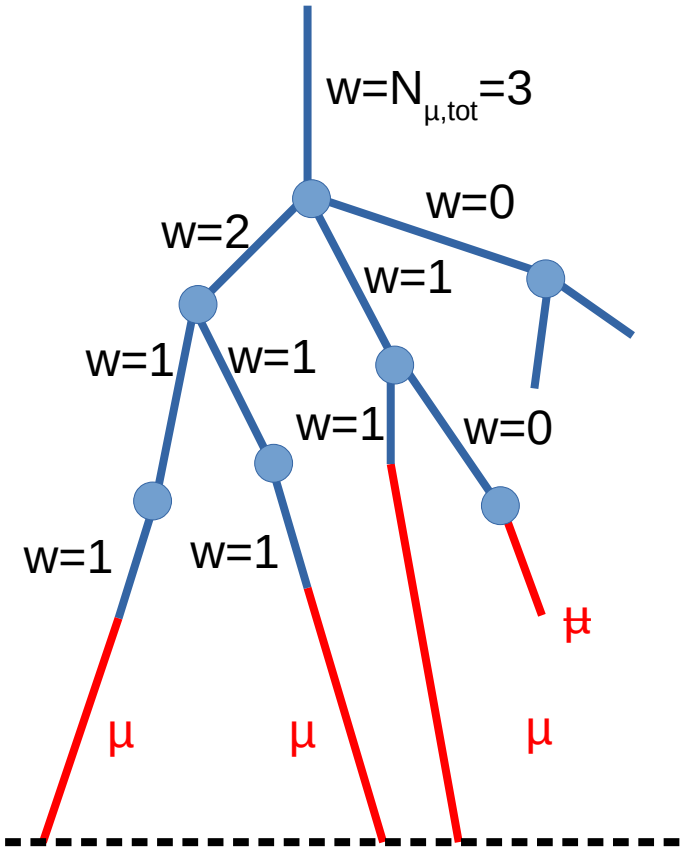
Conclusions

- **CORSIKA 8**
  - next-generation framework
  - modularity & flexibility
  - ready to tackle problems previously impossible to address
- **muon production**
  - relevance of phase-space regions in hadronic interactions quantified
  - several altered/exotic physics scenarios in EAS w.r.t. muons investigated
  - relevant directions to better understand muon production pointed out

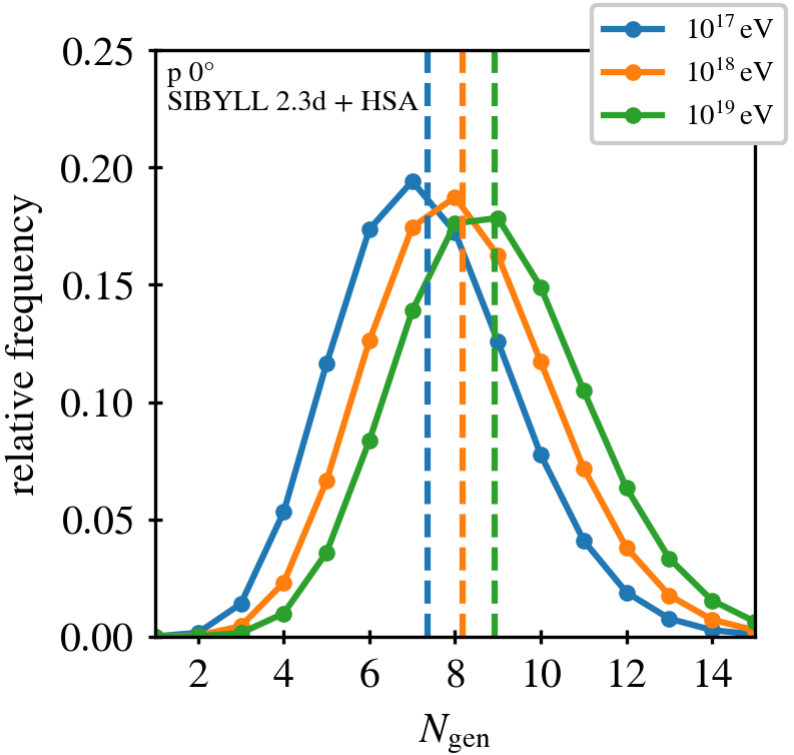
"muon weighted" phase space

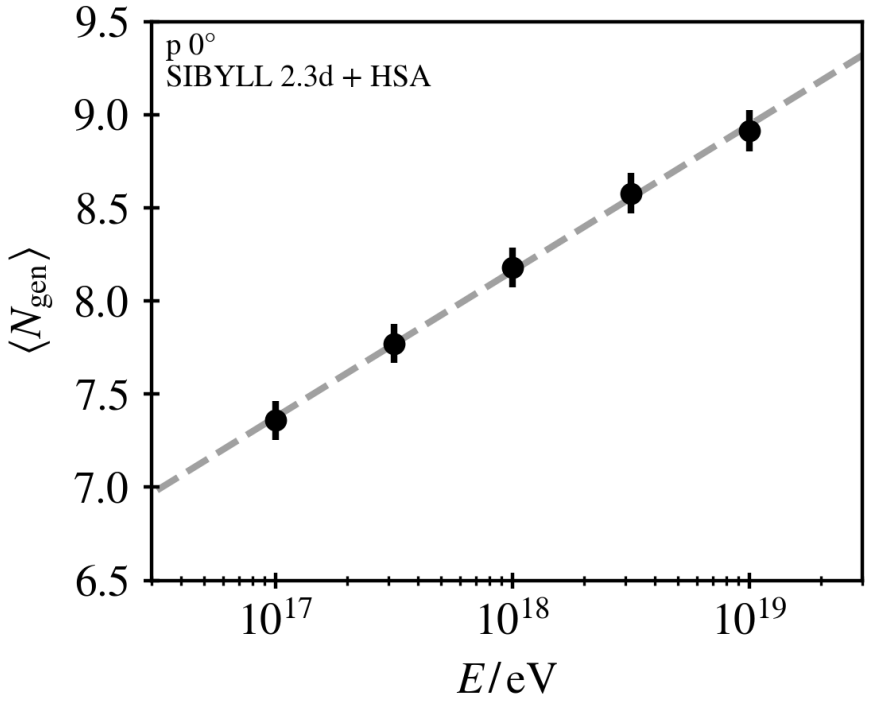
How to quantify relevance / importance of individual particles for muon production?

→ assign weight given by number of (observed) muon descendants



Number of generations





confirms expectations from Heitler-Matthews toy model