Air shower genealogy for muon production

with CORSIKA 8

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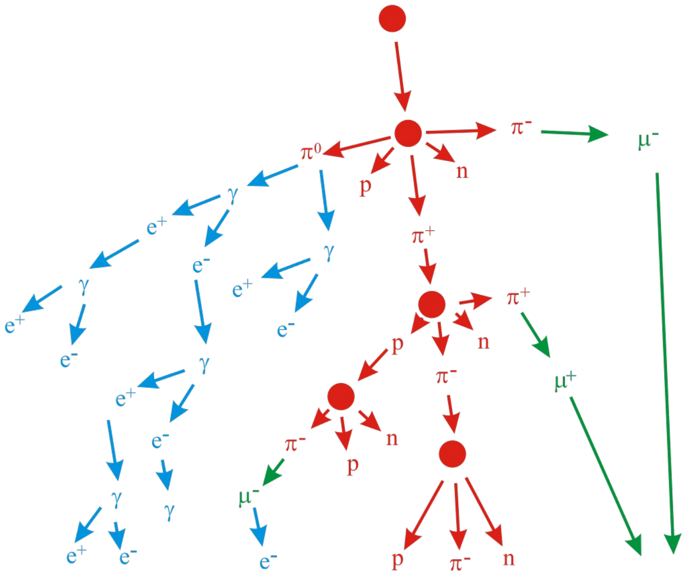
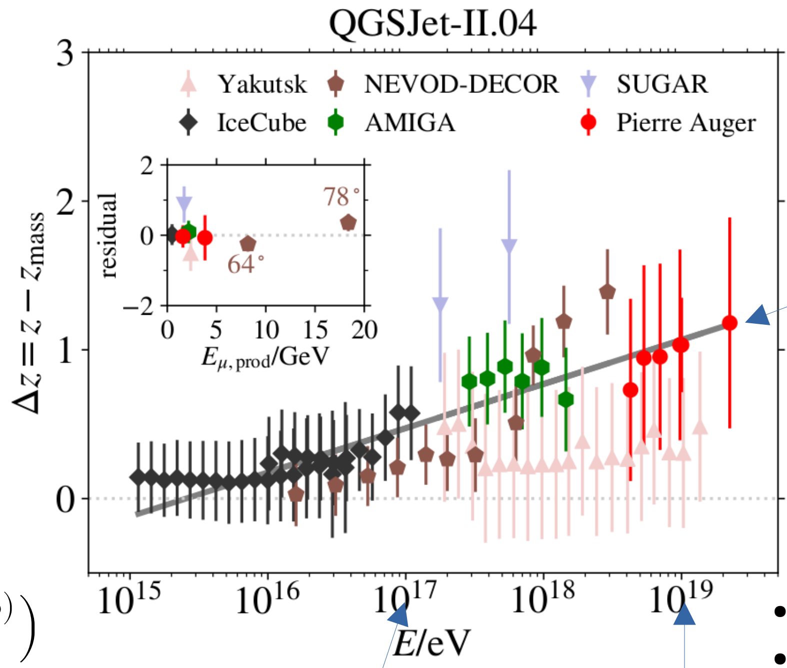
ITeDA
bw|HPC

"muon puzzle"





slope non-zero with 8 σ significance

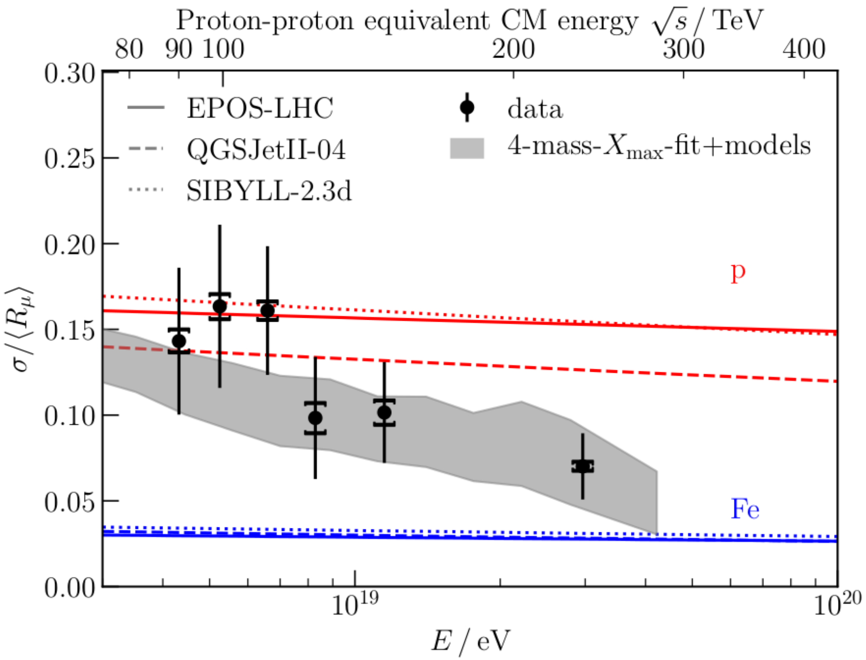
$$z = \frac{\ln\left(N_\mu^{(\mathrm{meas.})}/N_\mu^{(\mathrm{p})}\right)}{\ln\left(N_\mu^{(\mathrm{Fe})}/N_\mu^{(\mathrm{p})}\right)}$$

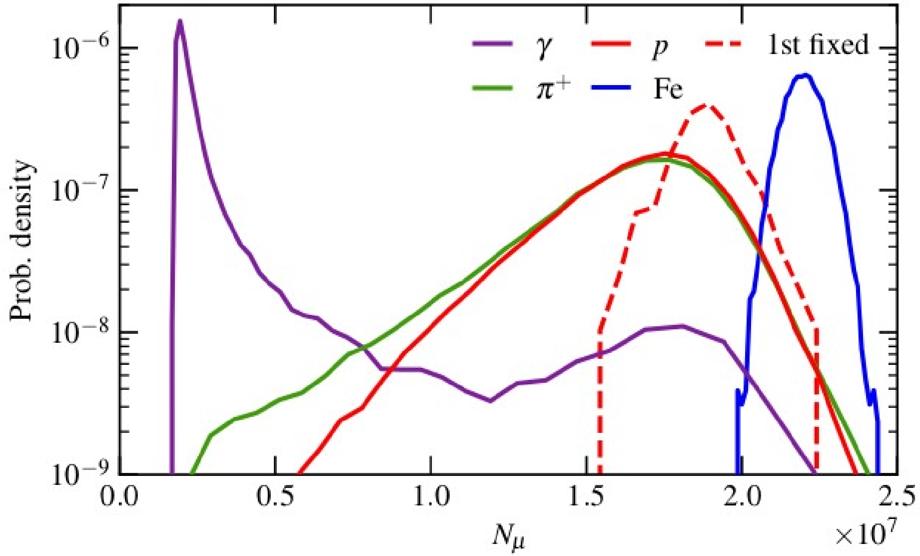
$\sqrt{s} = 14\,\mathrm{TeV}$ $\quad$ $140\,\mathrm{TeV}$

- new physics?
- bad extrapolations to highest energies?

WHISP report, 2001.07508; muon puzzle review 2105.06148

N_μ fluctuations





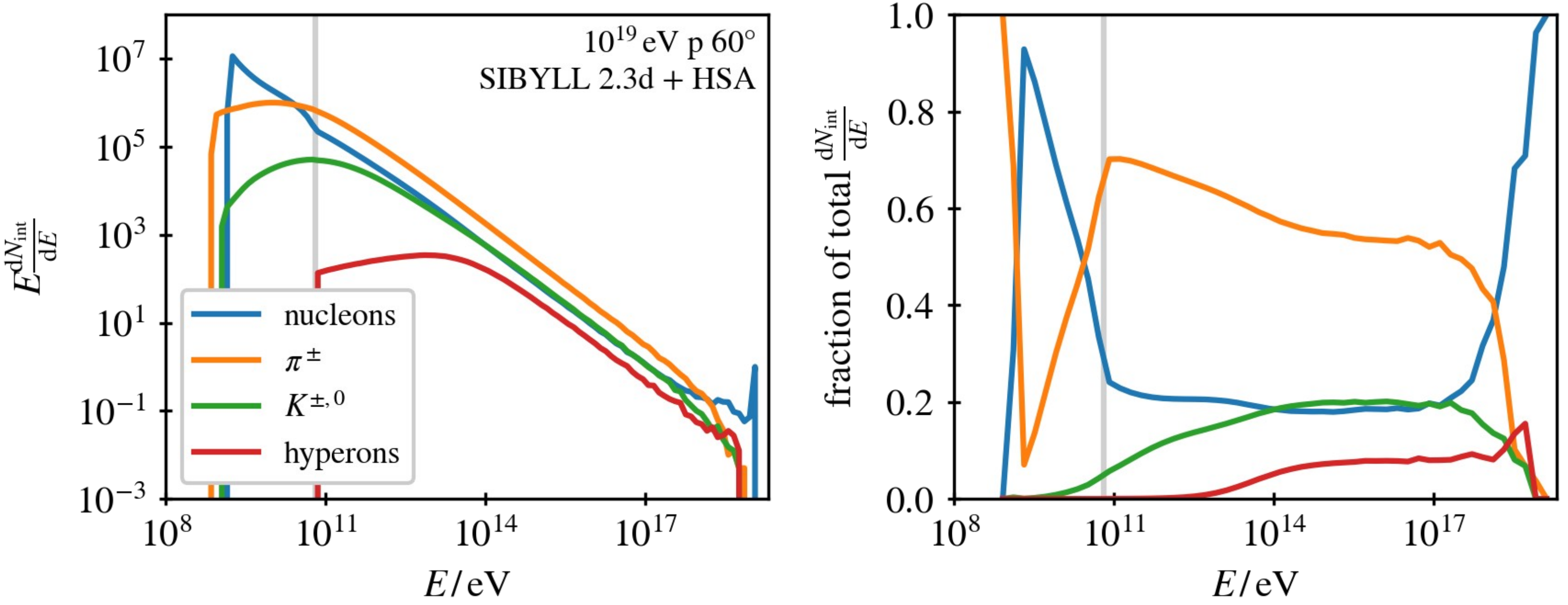
→ fluctuations dominated by first interaction

→ suggests cause of muon deficit cumulative effect of whole cascade

Pierre Auger Collaboration, PRL 126, 152002 (2021)

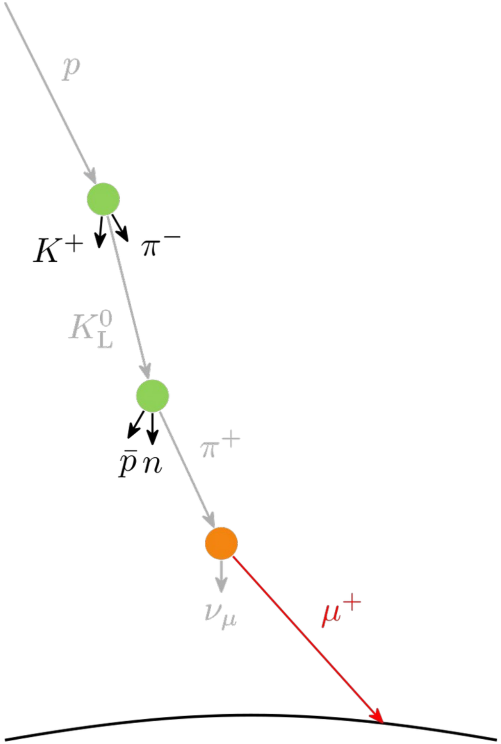
Cazon et al., PLB 784, 68 (2018)

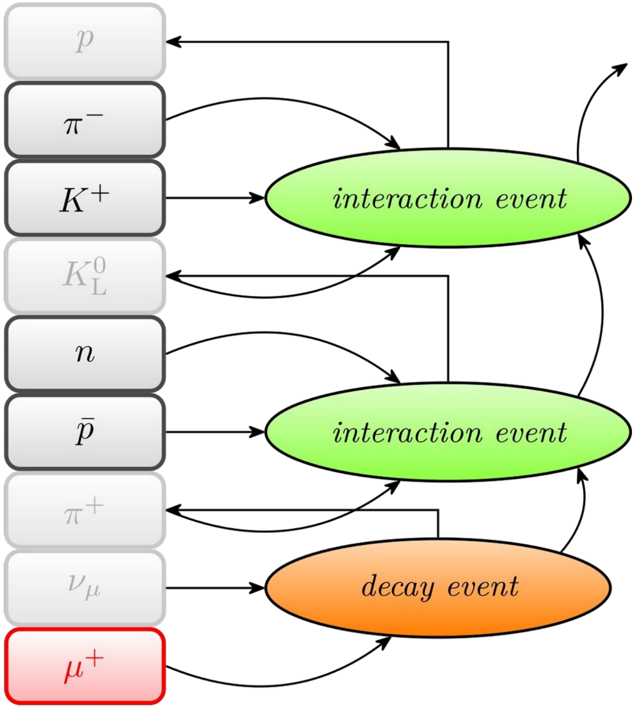
Hadronic interactions in EAS



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

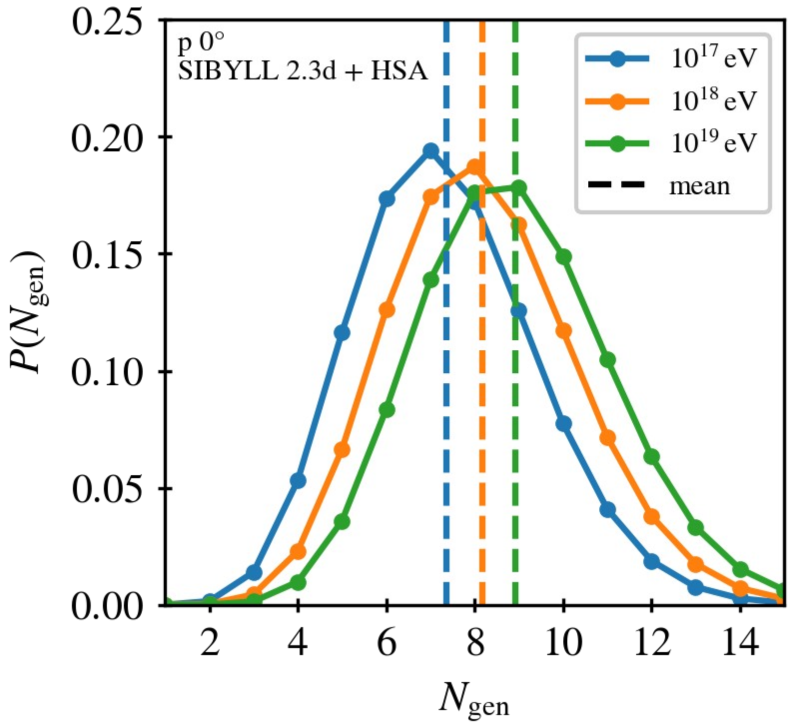
Particle lineage in CORSIKA 8

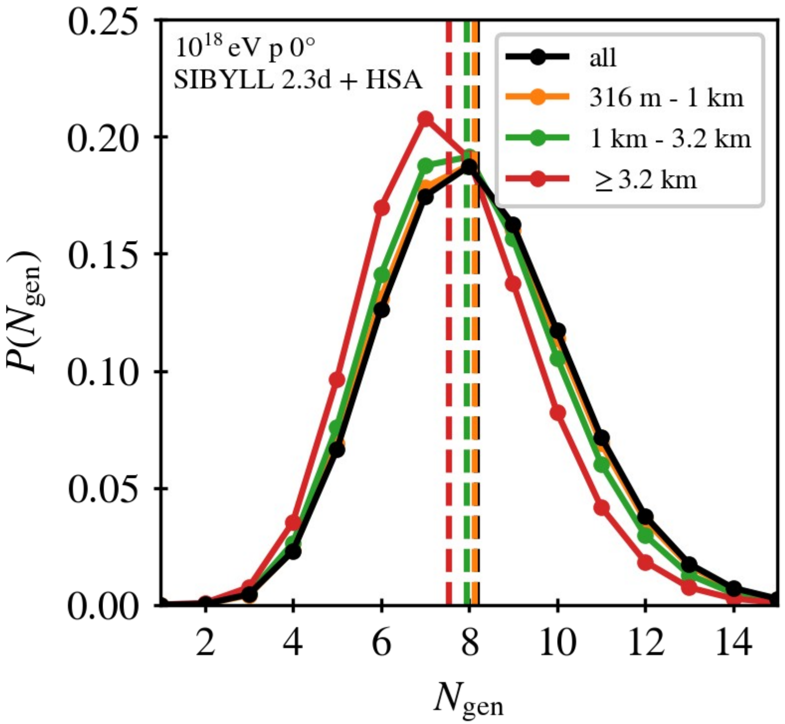




technical details: Alves et al., Proc. of 25th CHEP conf., to appear

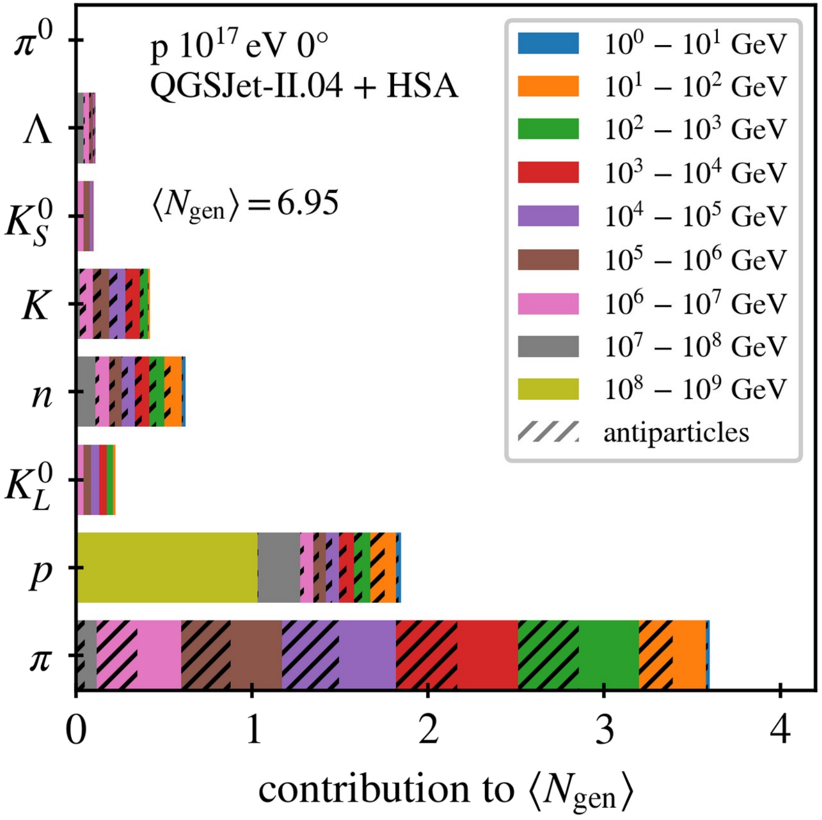
Number of generations



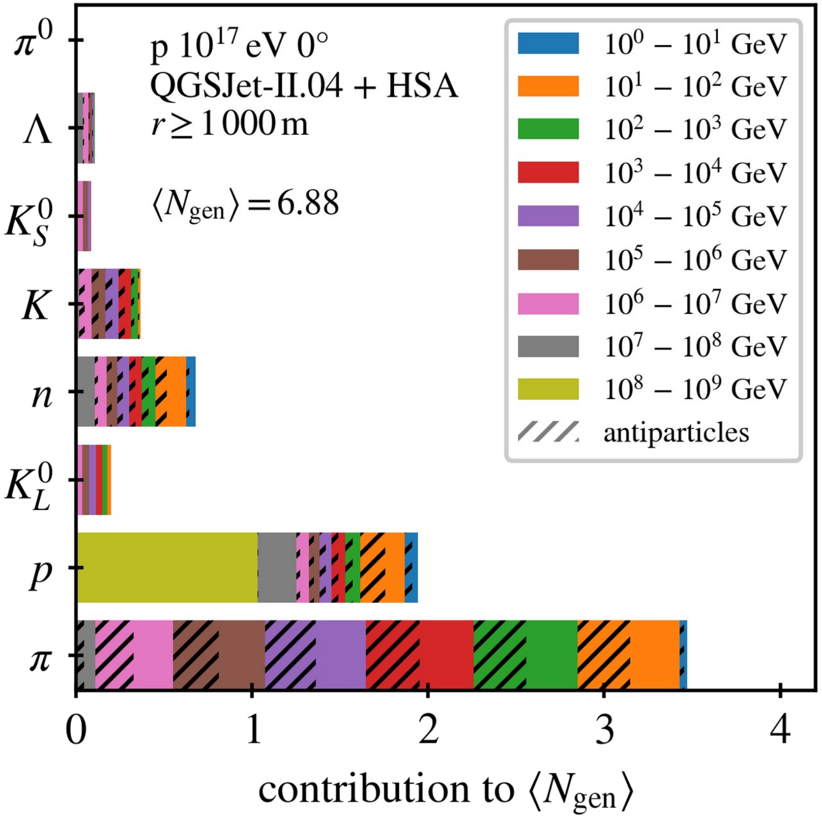


- 0.785(17) generations / decade
- Heitler-Matthews model multiplicity 18.8(1.2)

all muons



muons with r > 1 km



low-energy (<100 GeV) interactions more emphasized

A.M. Hillas / Nuclear Physics B (Proc. Suppl.) 52B (1997) 29–42

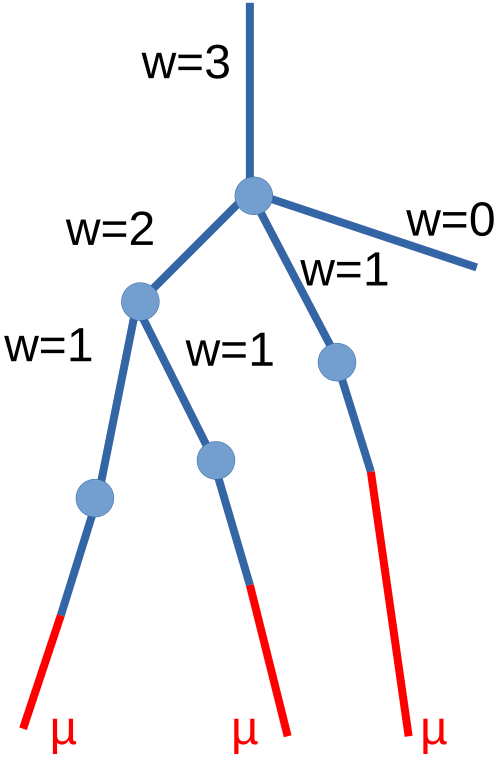
ıe, the accuracy of $\langle N_e \rangle$
at 10^{15} eV without thin-
given here is the r.m.s.
.gst n simulated showers,
tion for longer cpu times
ıre correctly estimates the
ates of $\langle N_e \rangle$ or $\langle \rho_e(r) \rangle$ ob-
ımple of n showers. Thus
verage, when many show-
vary inversely with the
computing time.
ırticle density at a p
f course greater tha
number of particles

3. WHAT DETAILS OF HADRONIC INTERACTIONS ARE "IMPORTANT"?

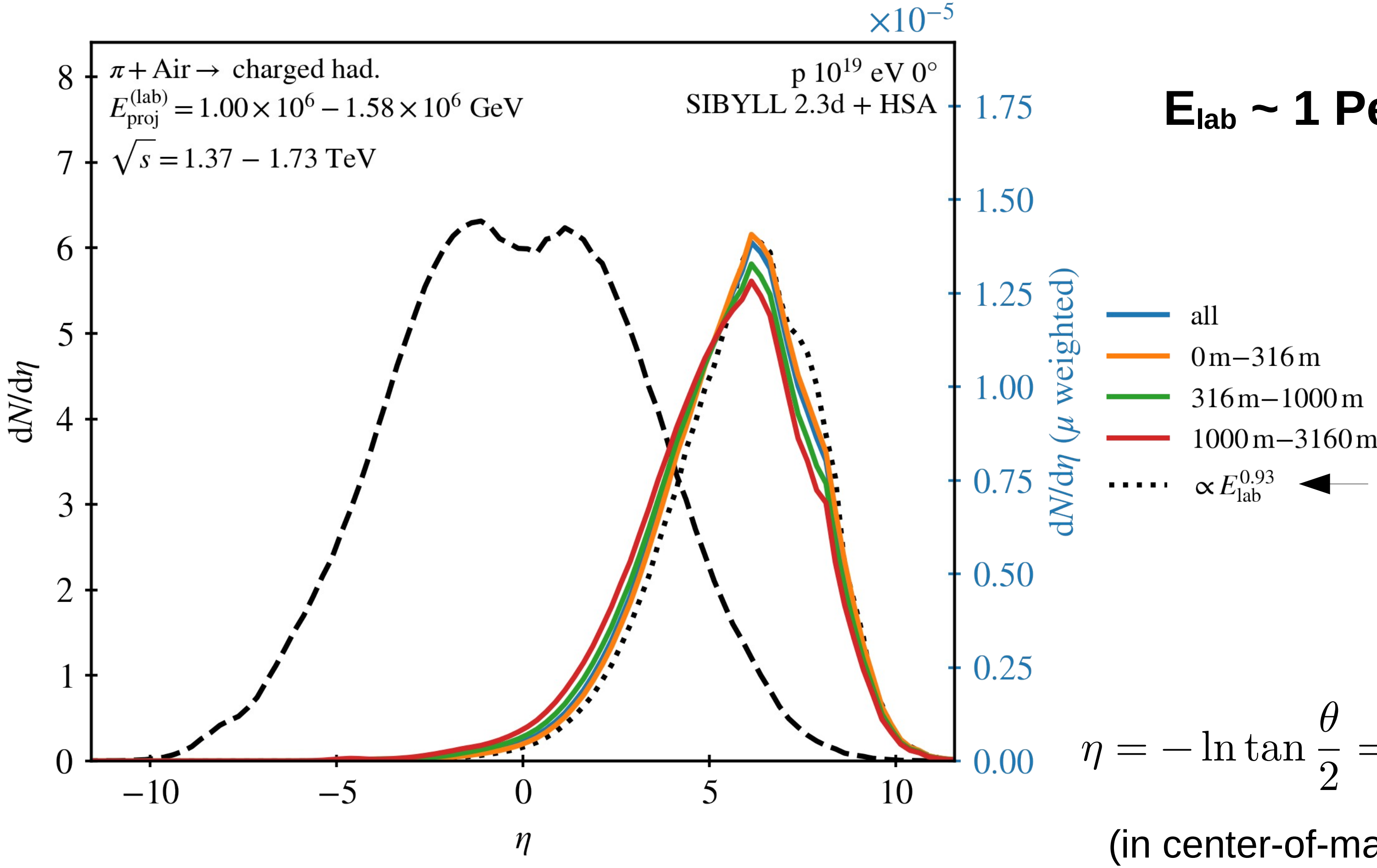
For reasons explained in the next section, the current versions of MOCCA (e.g. MOCCA92) used an algorithmic hadron interaction simulator which was greatly simplified (ignoring production and decay of very short-lived intermediate particles, for example, and avoiding most Lorentz transformations), and hence this model attracted criticism especially from people developing very

These qualitative considerations may be tested directly as follows.

When running a Monte-Carlo shower simulation, one can look back at a stored history of any particle reaching the ground, and thus find out what events in the development of the shower lead to most of the particles observed at the ground.



Pseudorapidity



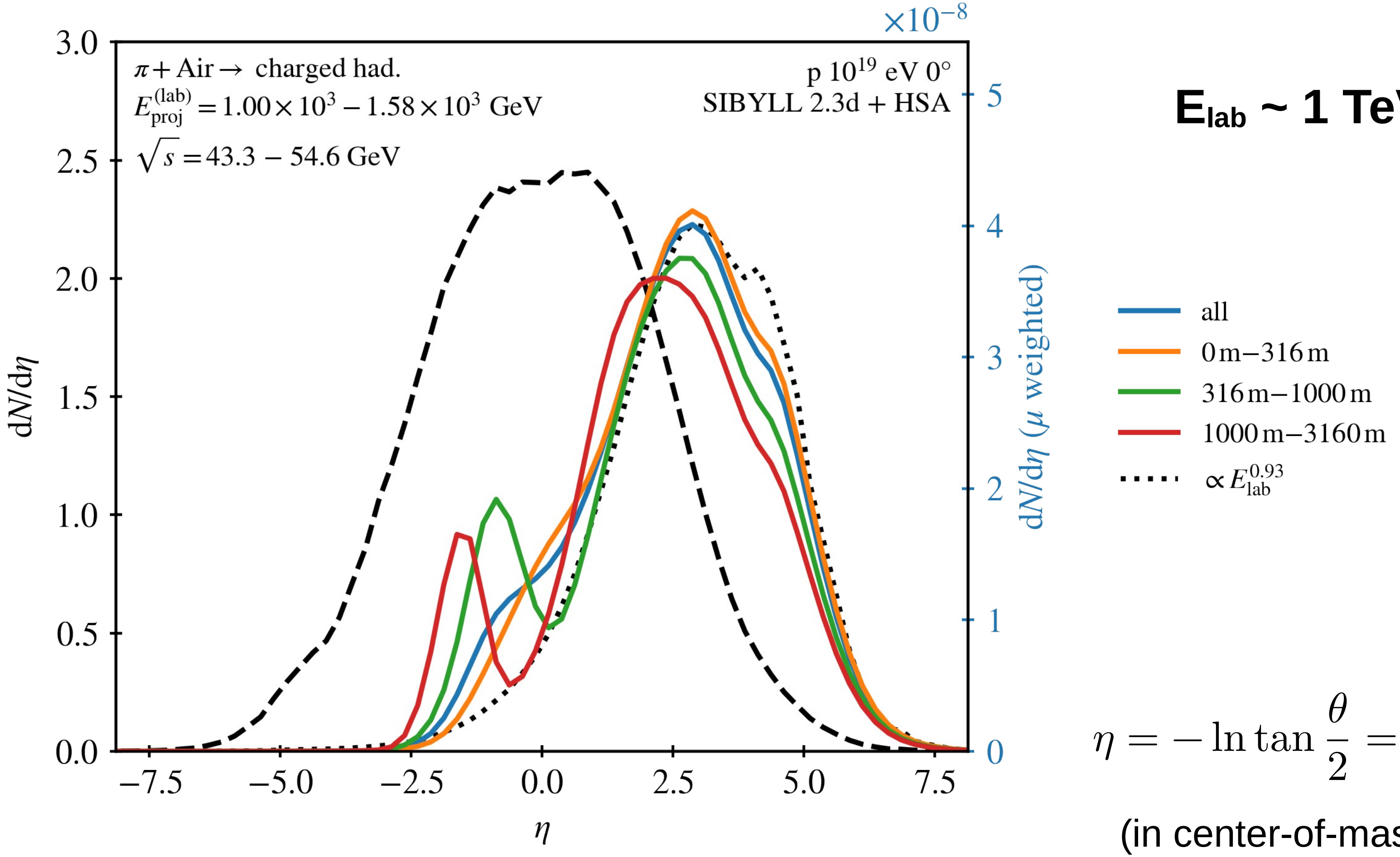
E_{lab} ~ 1 PeV

from Heitler-Matthews

$$\eta = -\ln \tan \frac{\theta}{2} = \frac{1}{2} \ln \frac{p + p_{\parallel}}{p - p_{\parallel}}$$

(in center-of-mass system)

Pseudorapidity

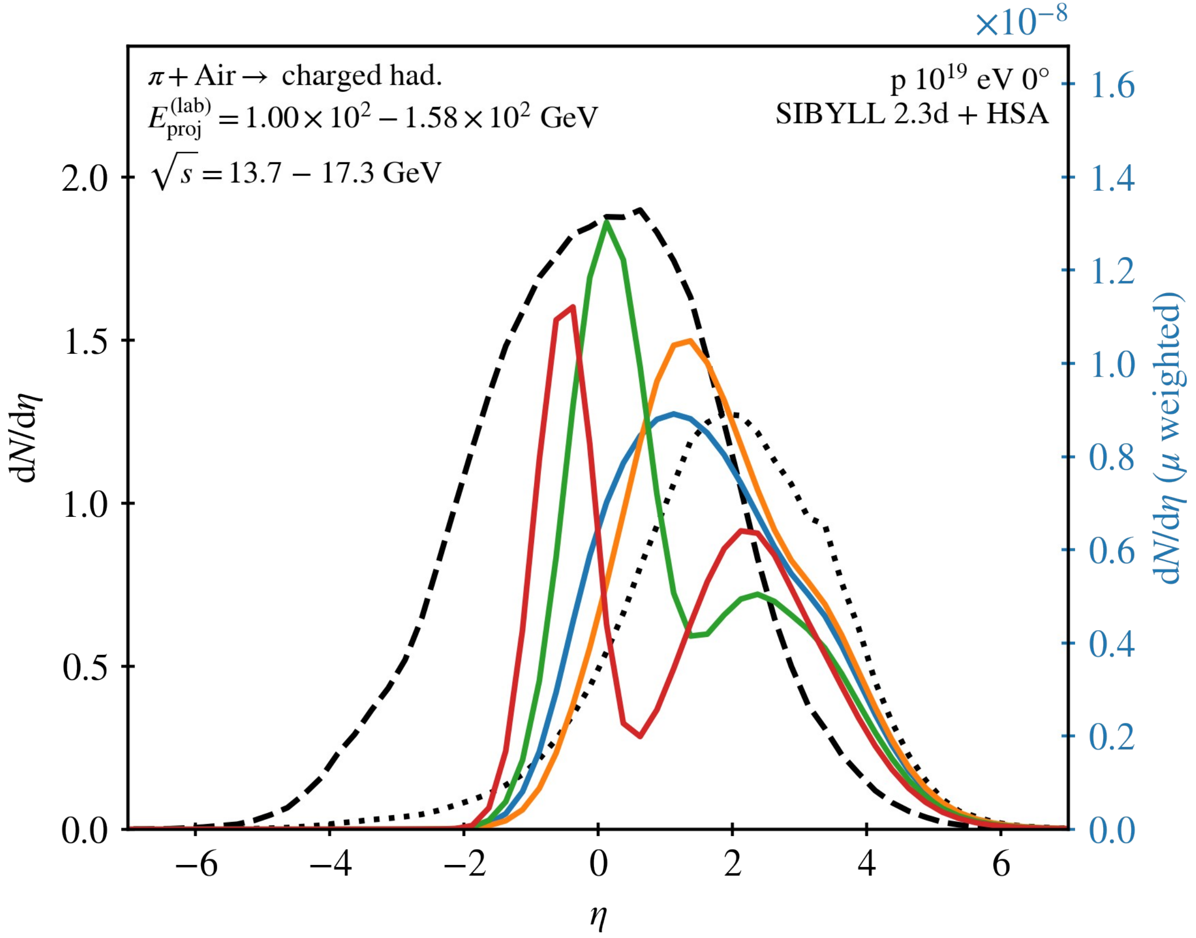


E_{lab} ~ 1 TeV

$$\eta = -\ln\tan\frac{\theta}{2} = \frac{1}{2}\ln\frac{p+p_\parallel}{p-p_\parallel}$$

(in center-of-mass system)

Pseudorapidity



E_{lab} ~ 100 GeV

$$\eta = -\ln \tan \frac{\theta}{2} = \frac{1}{2} \ln \frac{p + p_{\parallel}}{p - p_{\parallel}}$$

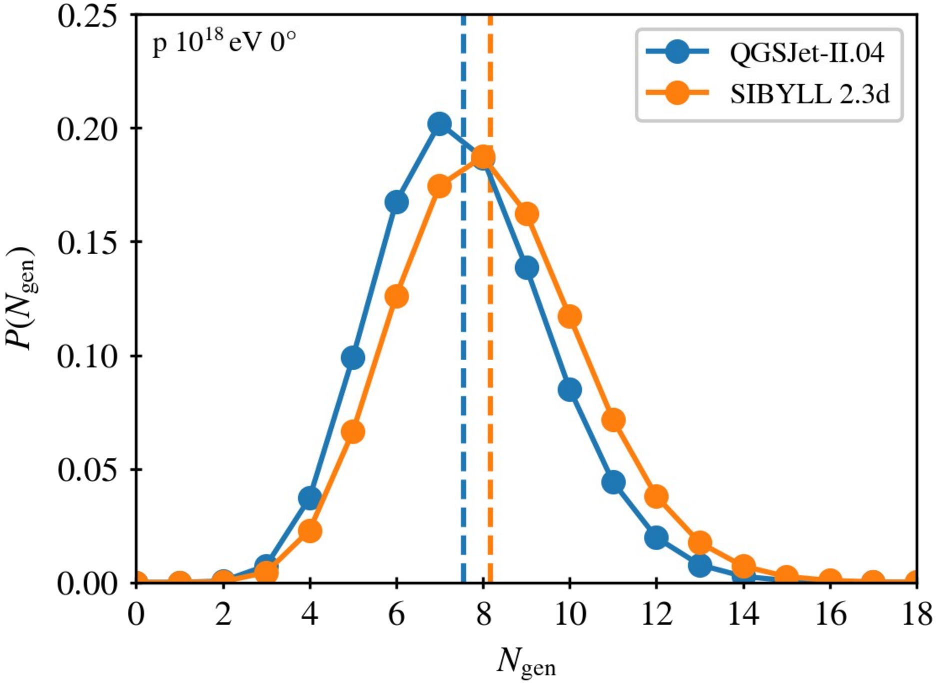
(in center-of-mass system)

Summary

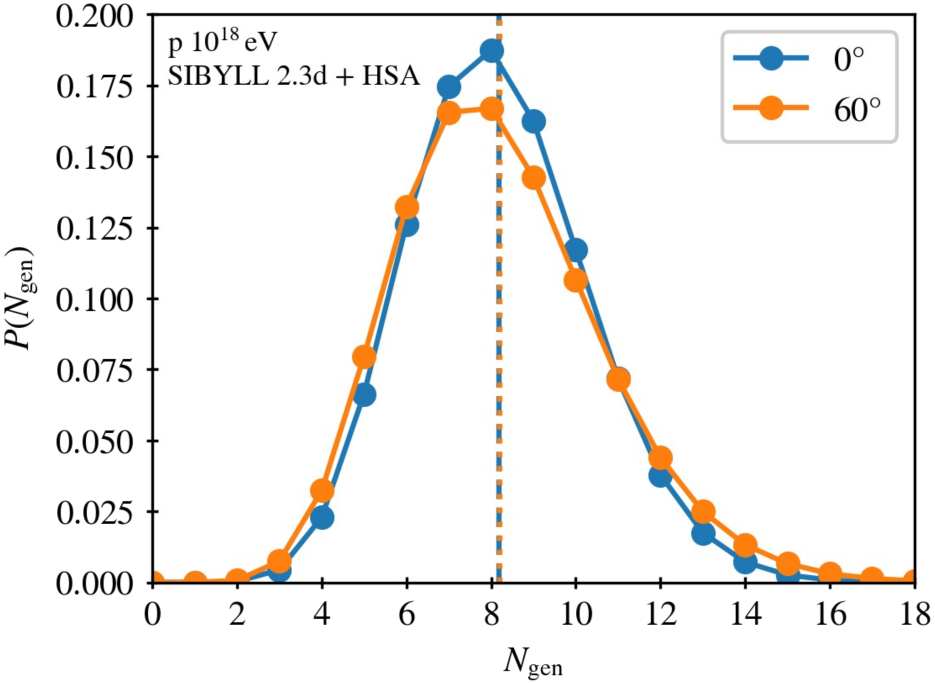
- CORSIKA 8 allows to inspect complete cascade history
- we study number of generations w.r.t. muon lateral distance
- we apply *muon weighting* to η distributions to quantify importance

Supplementary material

dependency on interaction model



dependency on zenith angle



fit log(E) vs N_{gen}