Air shower genealogy

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bw HPC

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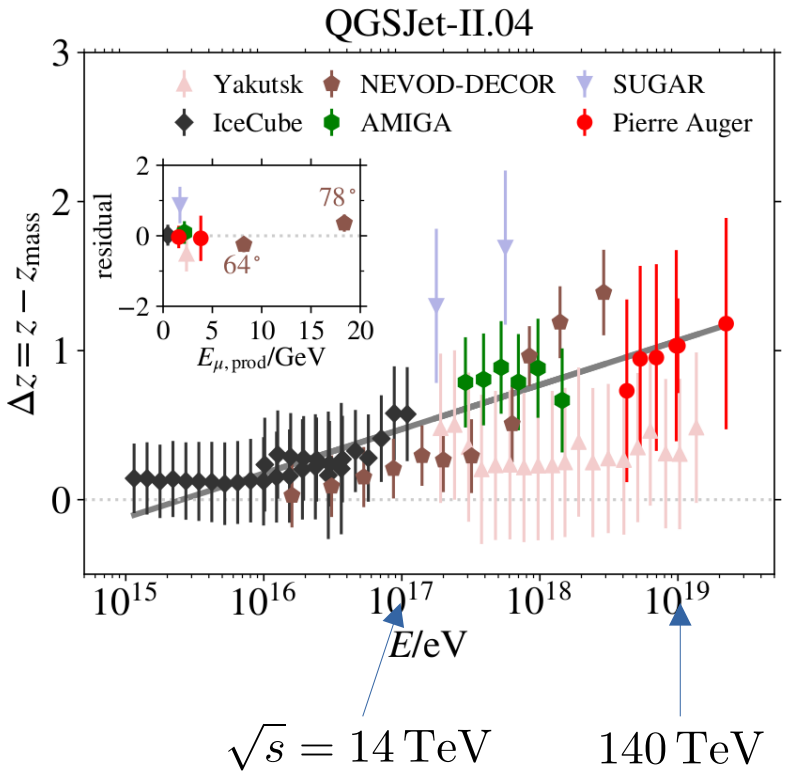
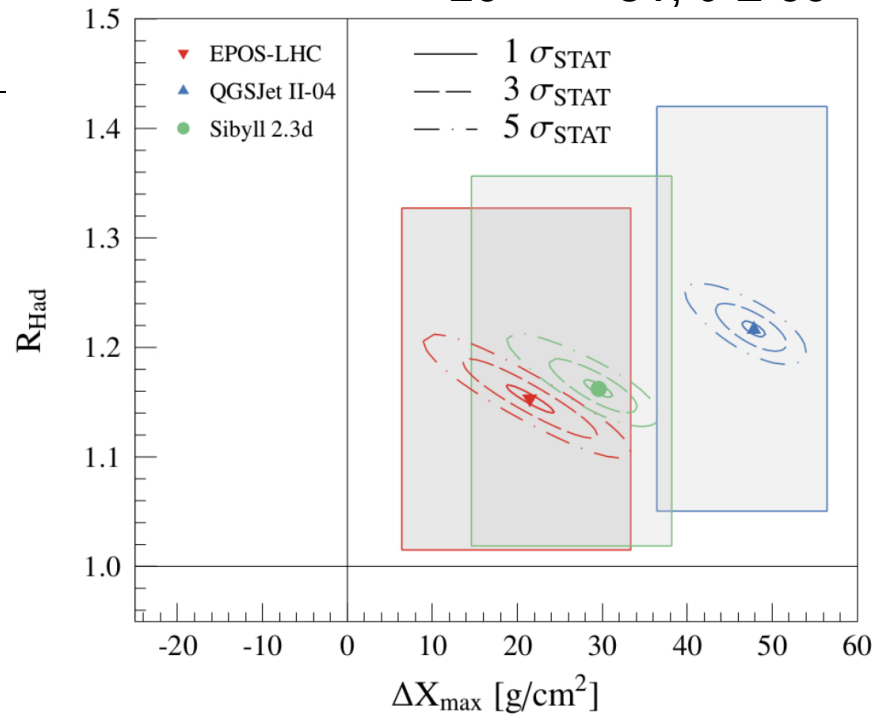
Motivation



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

$10^{18.5...19}$ eV, $\vartheta \leq 60°$

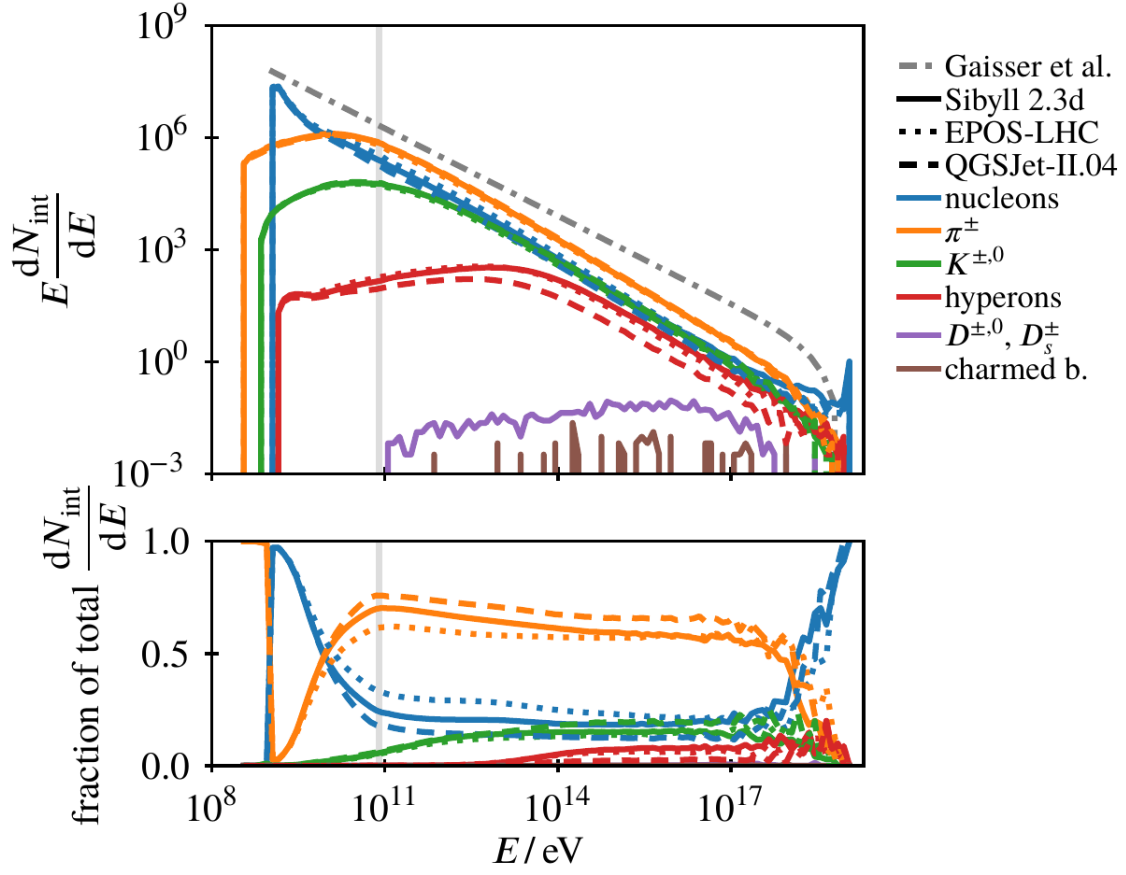


- new physics?
- bad extrapolations to highest energies?

WHISP report, 2001.07508

J. Vícha, 2303.14788

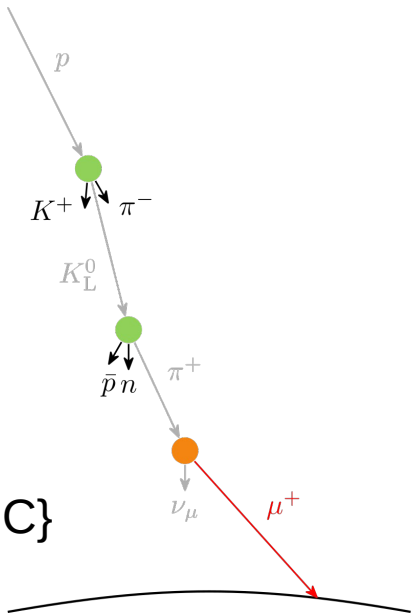
Interaction spectrum

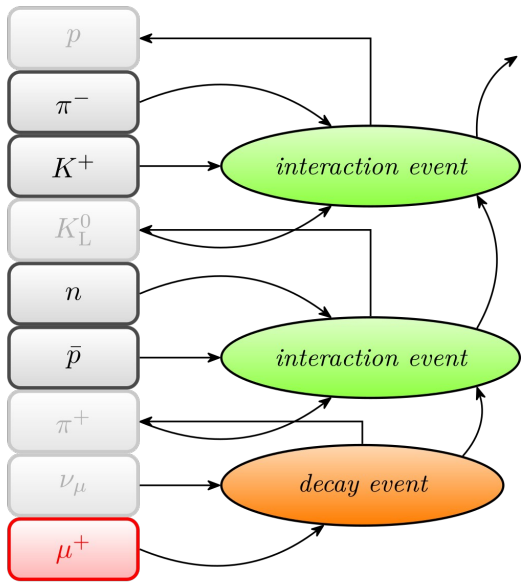


$$\frac{\mathrm{d}N_{\mathrm{int}}}{\mathrm{d}z} \sim \delta(1-z) + \frac{1}{z} + 0.77\frac{(1-z)^3}{z^{1.78}}$$

Shower genealogy

Look into the lineage of particles to gain insights!



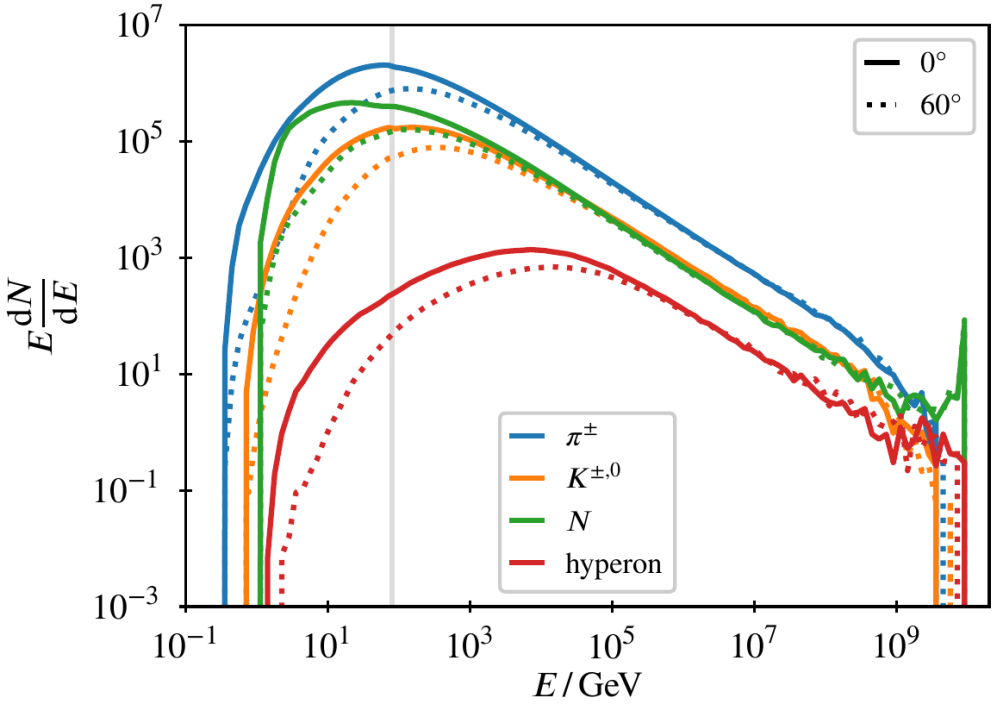


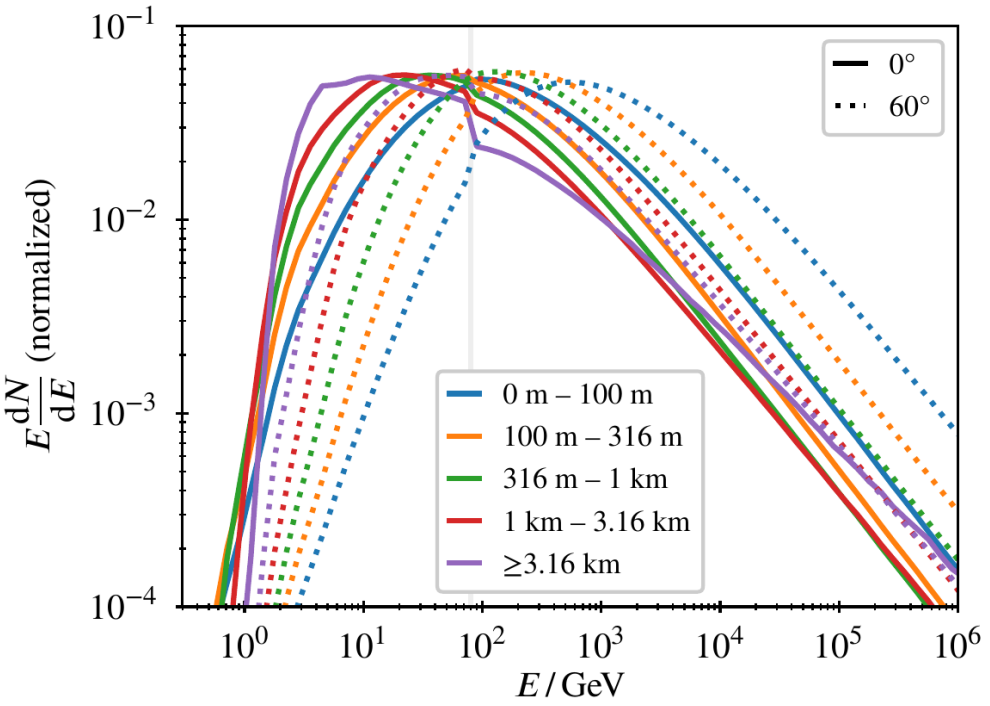
hybrid simulation study with CORSIKA 8 + CONEX:

- full Monte Carlo treatment of hadrons & muons
- EM profiles via cascade equations
- 300 proton showers @ {10^{17} eV ... 10^{19} eV} × {0°, 60°} × {Sibyll 2.3d, QGSJet-II.04, EPOS-LHC}

Alves Jr., MR, et al. (2021)

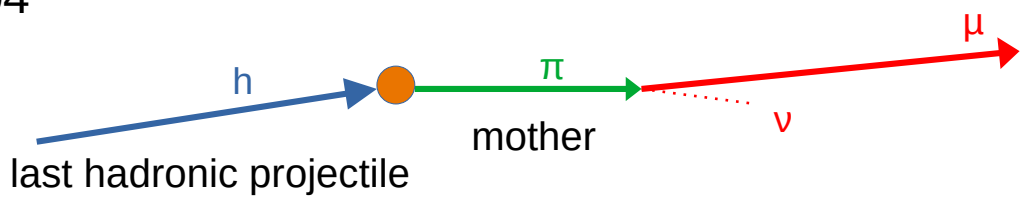
Last hadronic projectile





10^{19} eV, QGSJet-II.04

normalized by N_μ in ring



Heitler-Matthews model

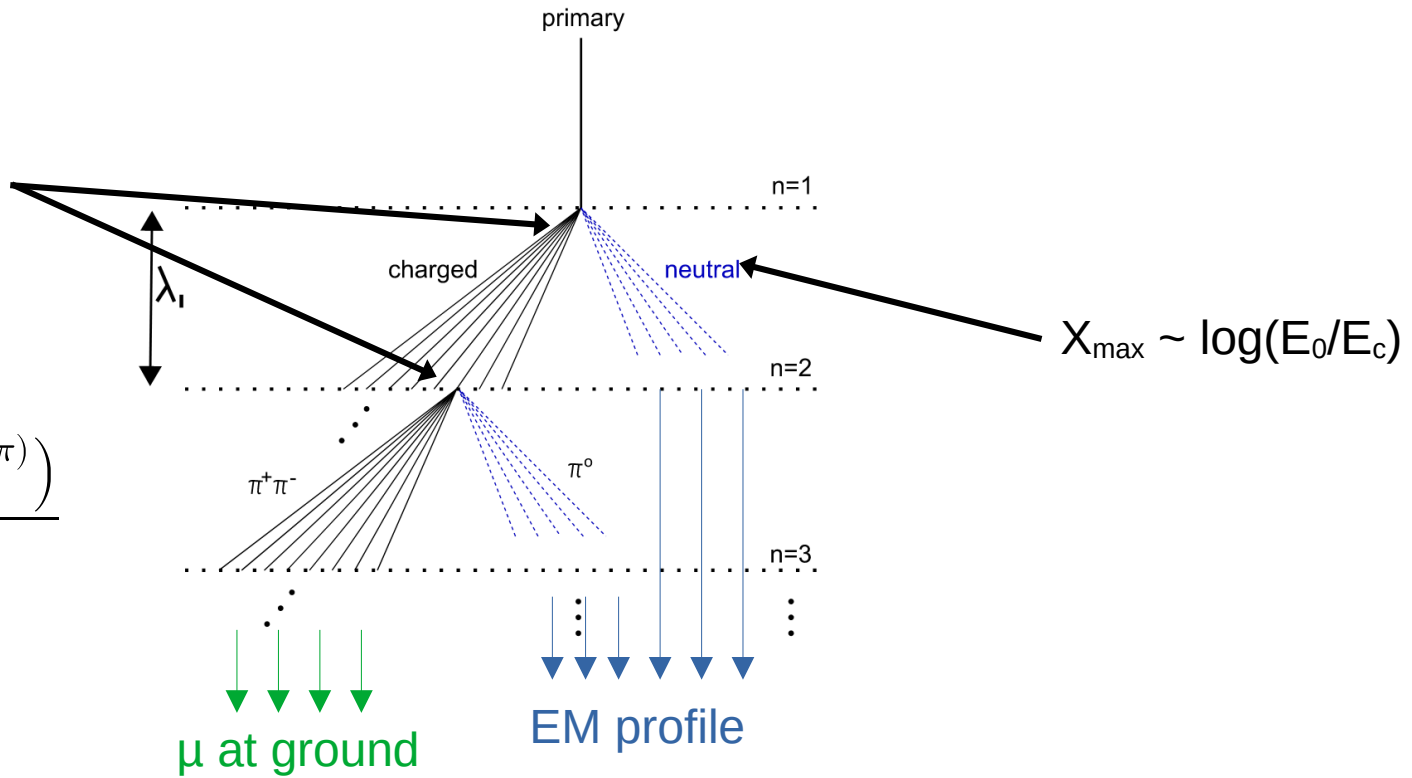
multiplicity *m*,
fraction *R* long-lived

$$E_{n+1} = E_n / m$$

cascade stops at

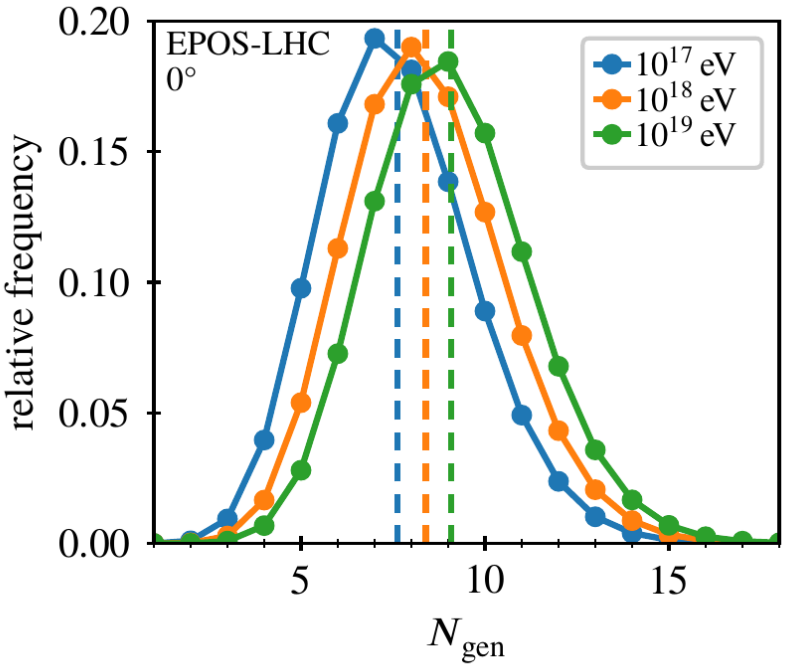
$$N_{\mathrm{gen}} = \frac{\log\left(E_0 / E_{\mathrm{c}}^{(\pi)}\right)}{\log m}$$

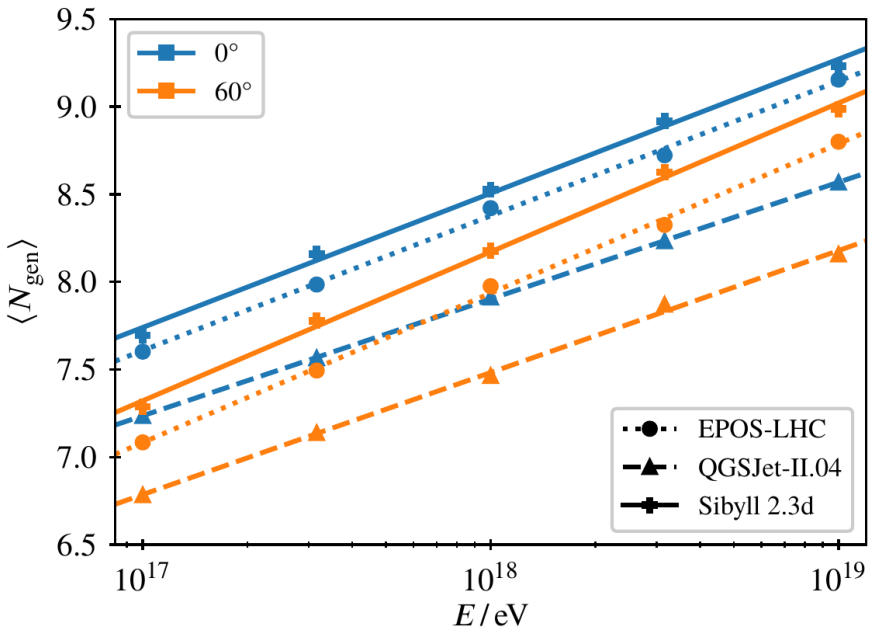
$$E_{\mathrm{c}}^{(\pi)} \simeq 50\,\mathrm{GeV}$$



J. Matthews, Astropart.Phys. 22 (2005) 387

Number of generations





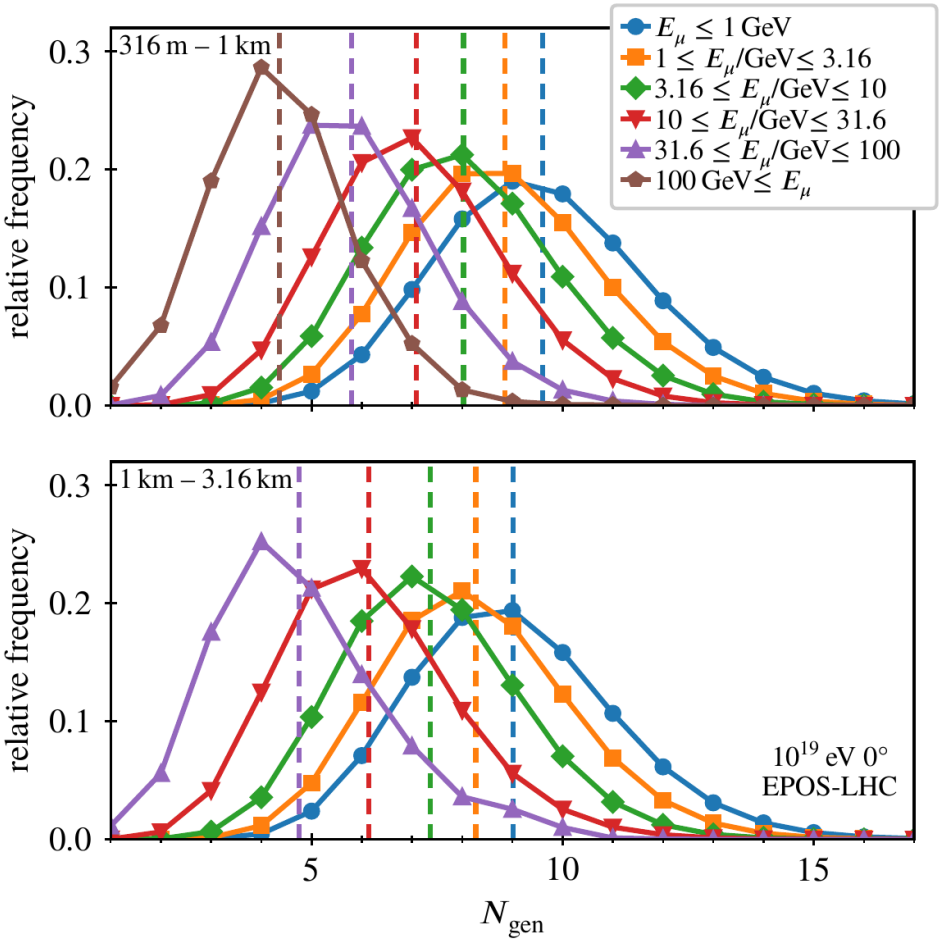
multiplicity

	0°	60°
QGSJet-II.04	34 ± 4	29 ± 1
EPOS-LHC	24 ± 2	16 ± 1
Sibyll 2.3d	18 ± 1	13 ± 1

Heitler-Matthwes multiplicity
$m = 10^{1/slope}$

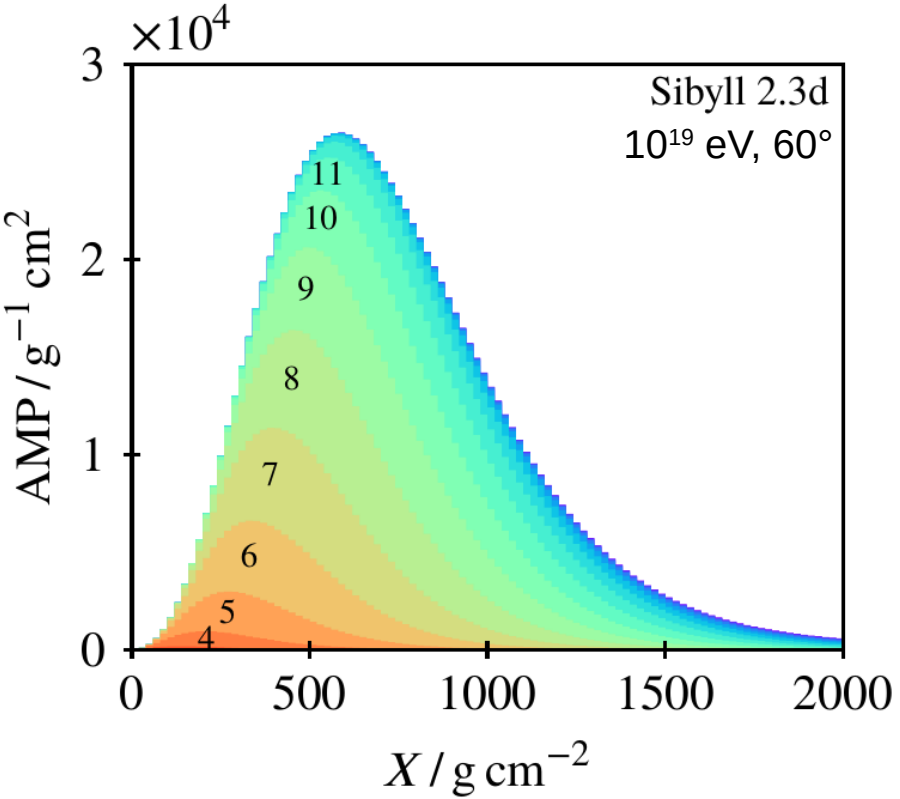
← from cutting off shower at ground

Number of generations



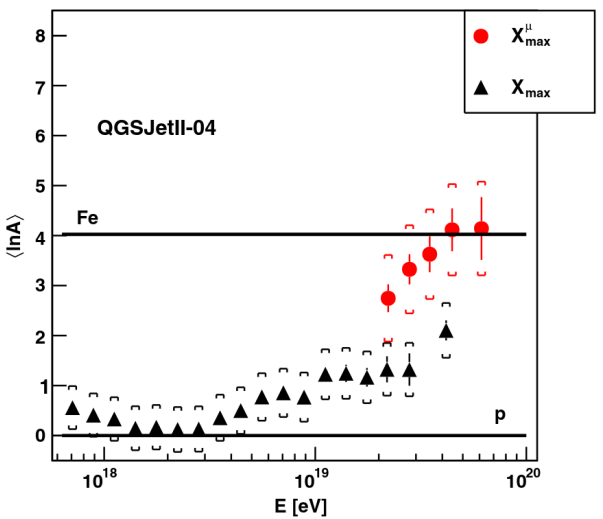
- higher energies → fewer generations
- larger distances → fewer generations

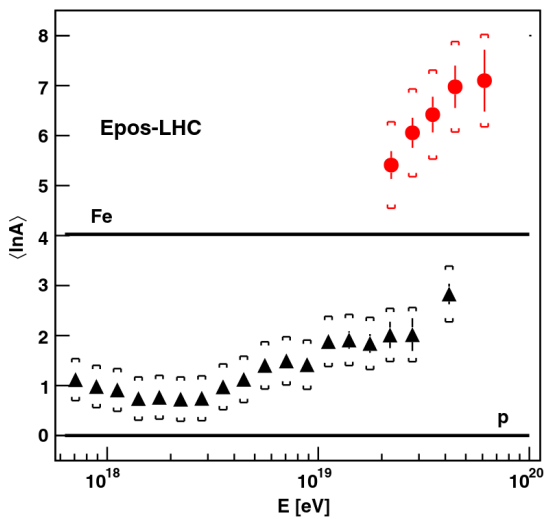
Muon production depth



***apparent* MPD** = production depth of muons reaching ground

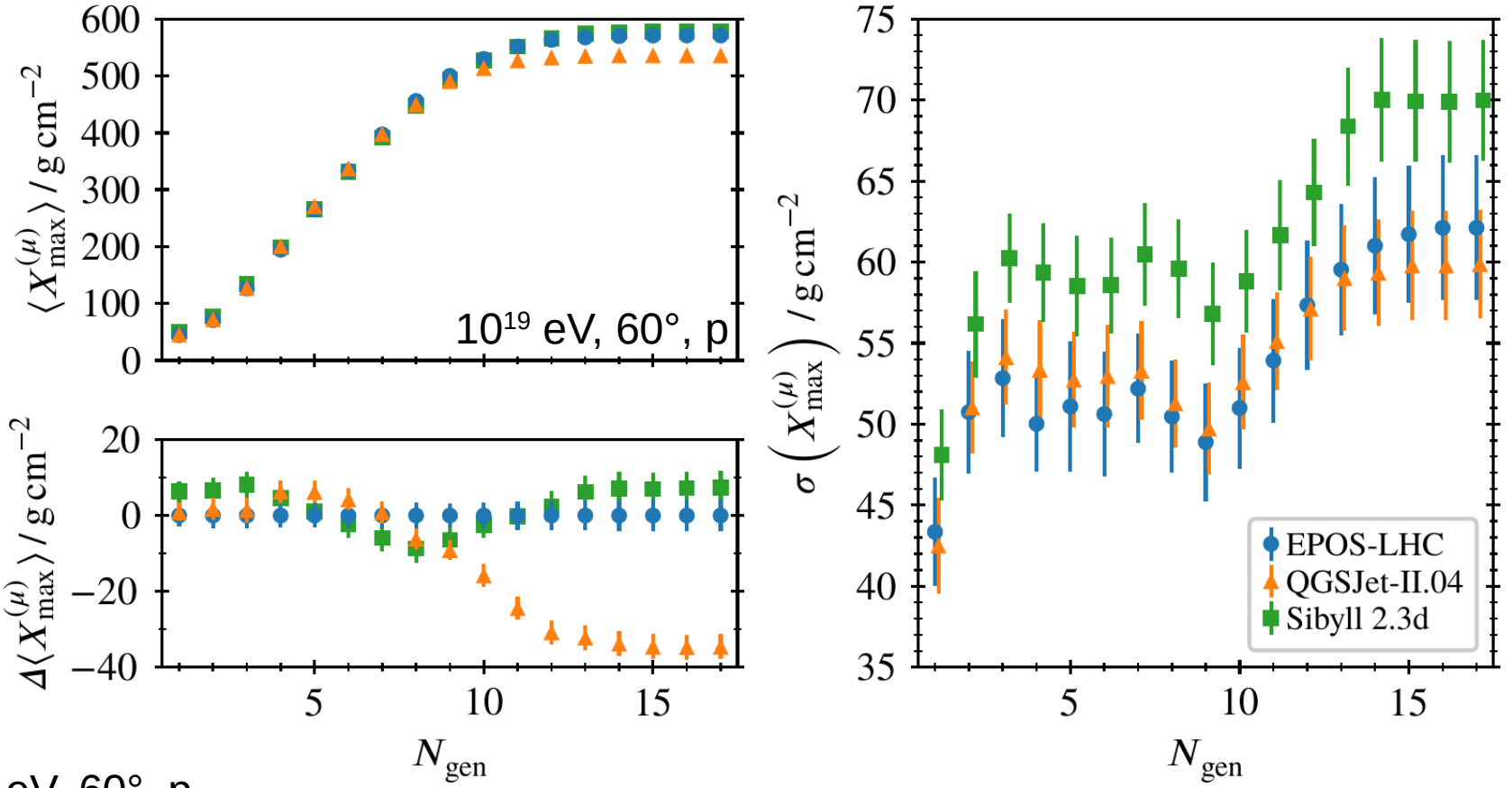
maximum $X_{\max}^{(\mu)}$ is composition-sensitive





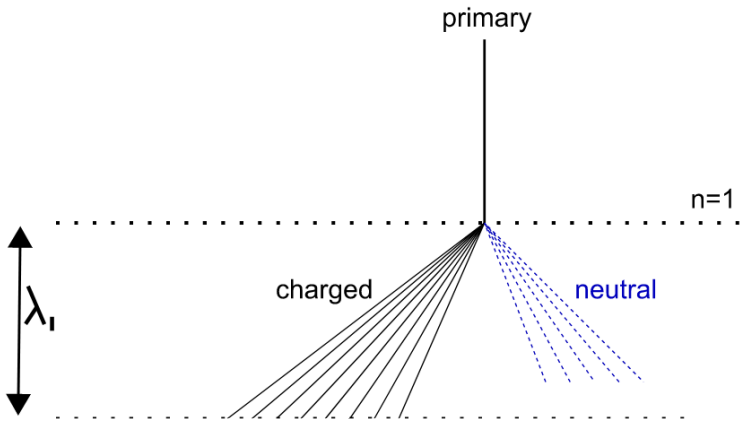
Pierre Auger Collaboration, 1407.5919

X^{μ}_{max}

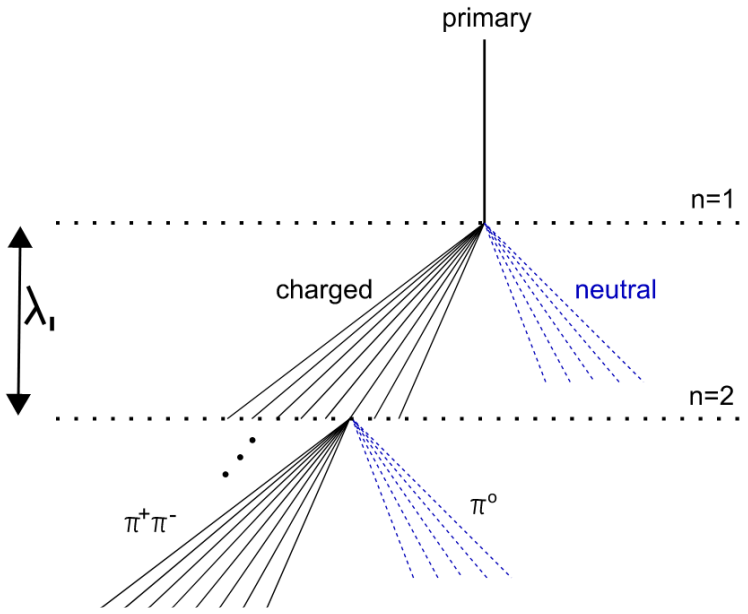


10^{19} eV, 60°, p

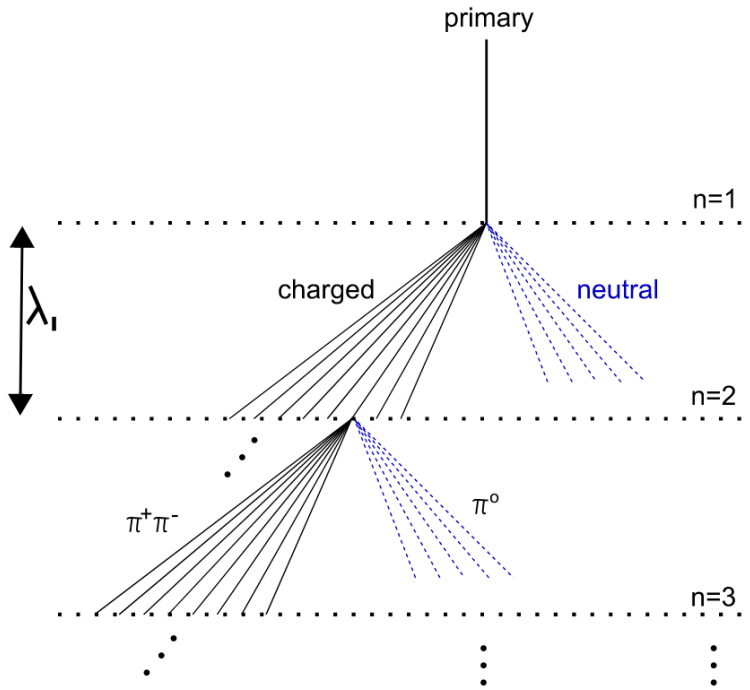
EM profiles by hadron generation

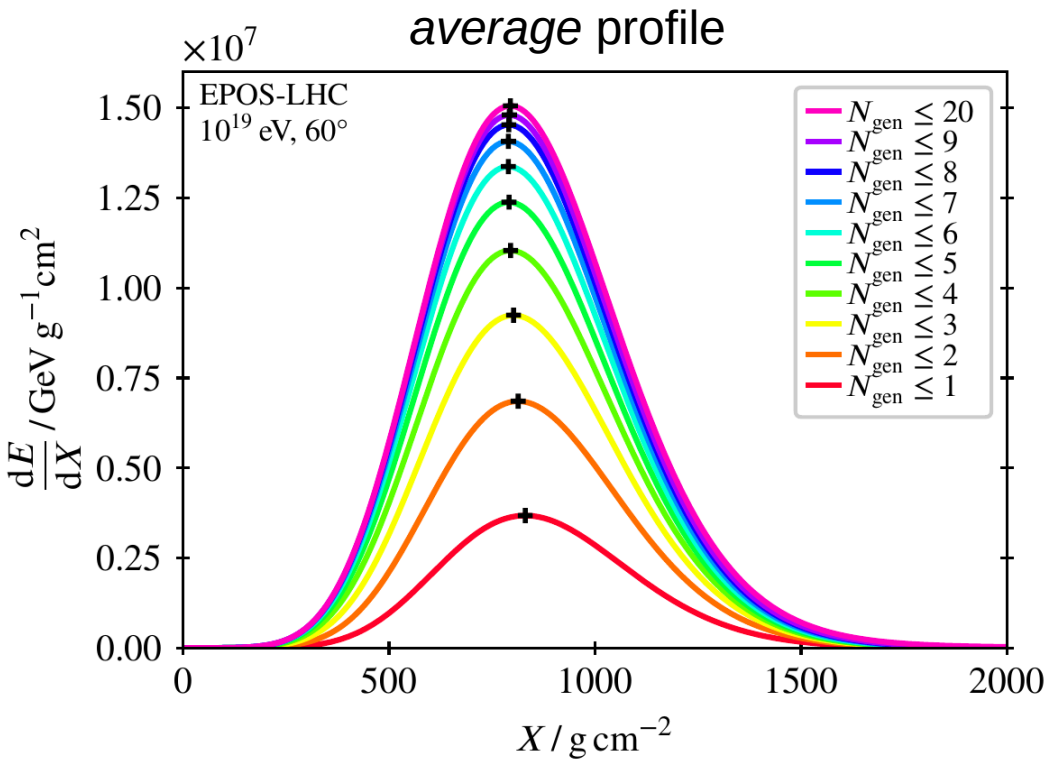


EM profiles by hadron generation



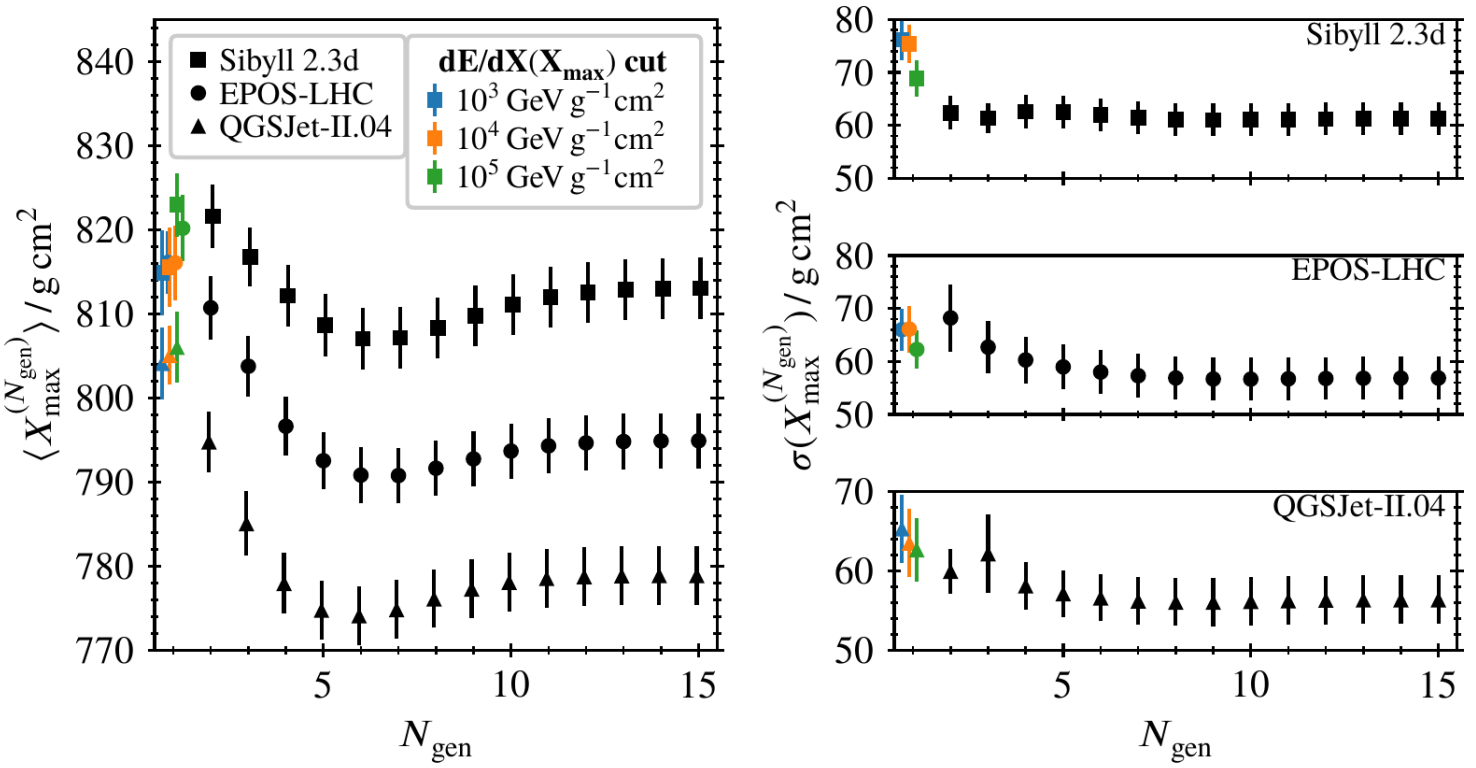
EM profiles by hadron generation





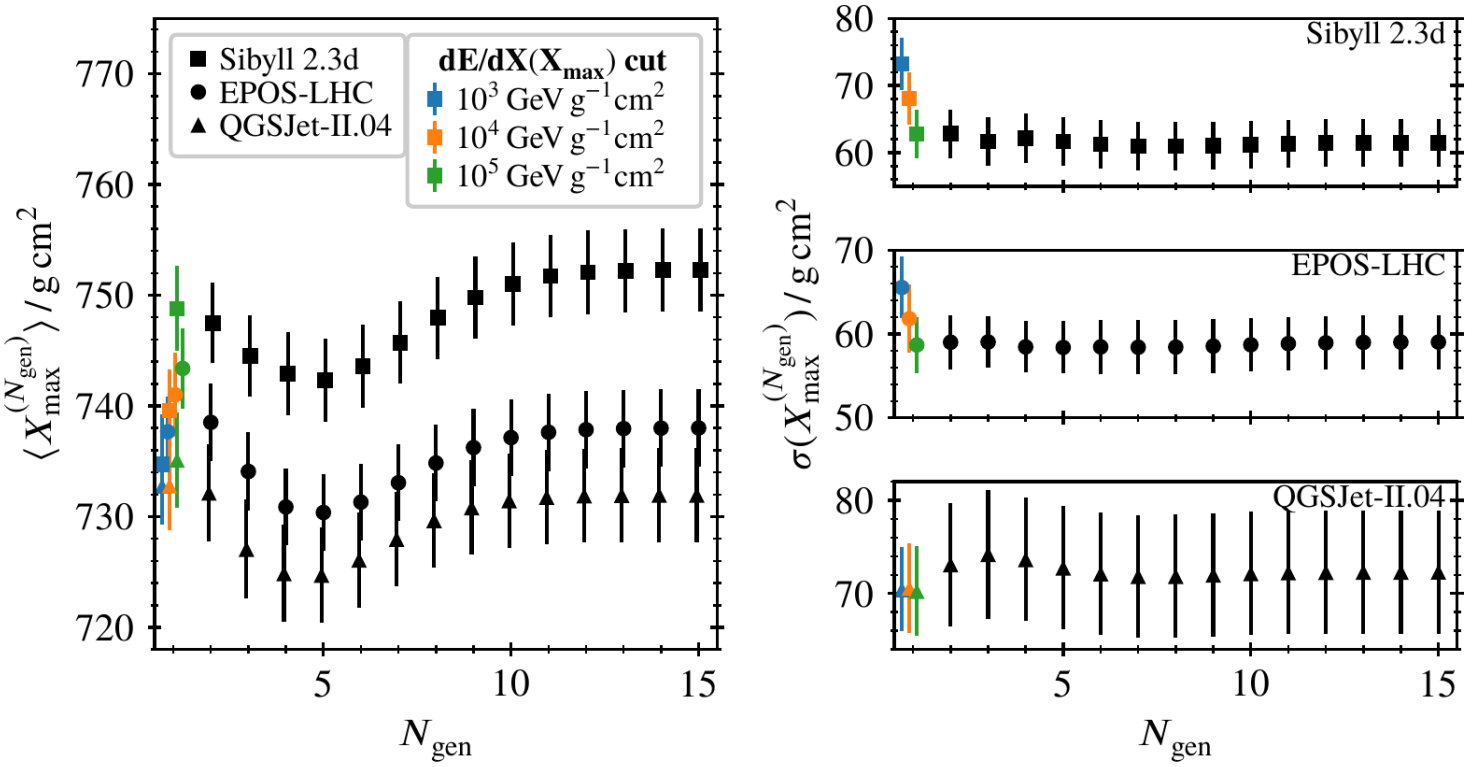
later generations start deeper, but develop shallower (on average!)

X_{max} by generation



10^{19} eV, 60°, p

X_{max} by generation



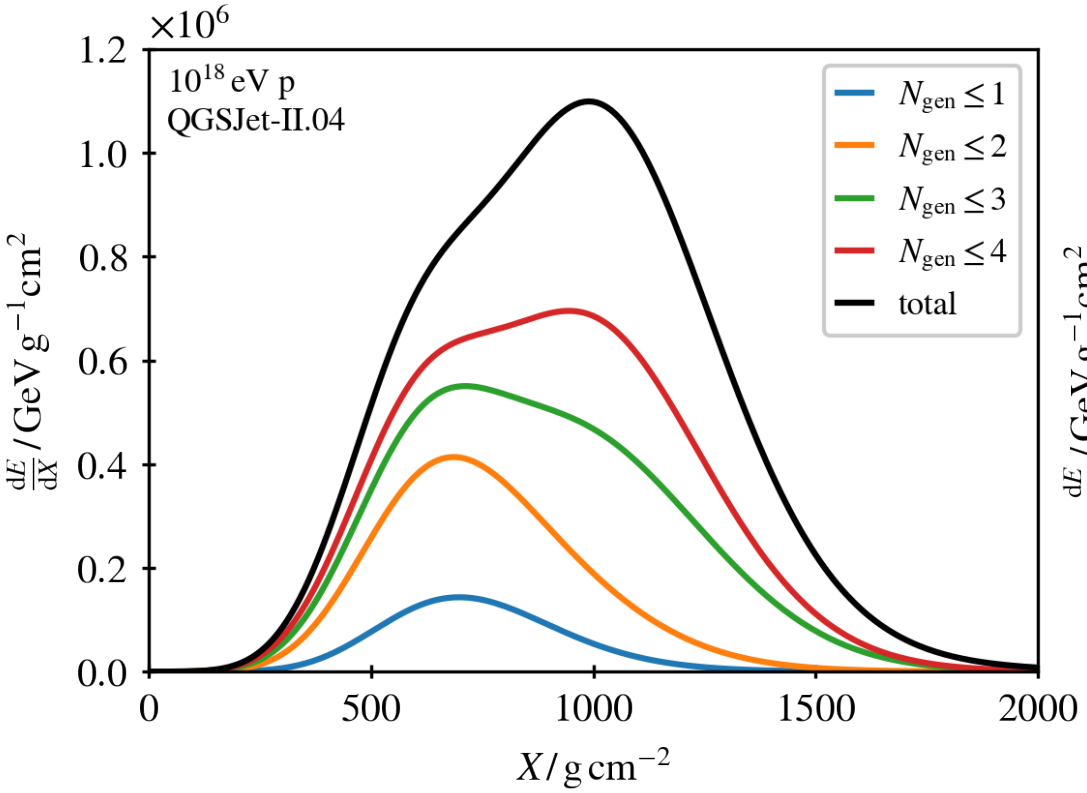
10^{18} eV, 60°, p

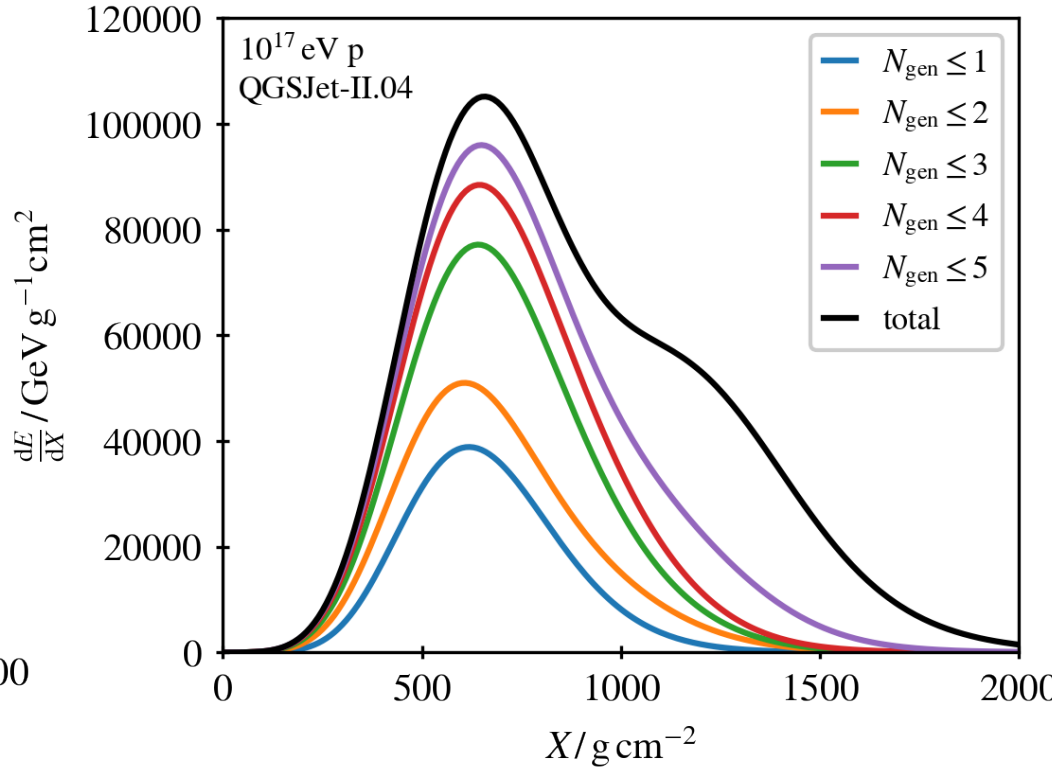
Energy transfer had. → EM cascade

		last hadronic projectile				
		π	K	N	other	sum
decaying particle	π^0	0.37	0.088	0.35	0.039	0.84
	η	0.058	0.013	0.046	4.7×10^{-3}	0.12
	$\mu^{\pm}$	3.1×10^{-3}	3.1×10^{-4}	1.2×10^{-3}	6.8×10^{-6}	5×10^{-3}
	other	0.015	3.1×10^{-3}	0.010	1.8×10^{-3}	0.03
	sum	0.45	0.10	0.40	0.046	1 (= total E_{cal})

10^{19} eV, 60° p, Sibyll 2.3d

Outlook: anomalous showers



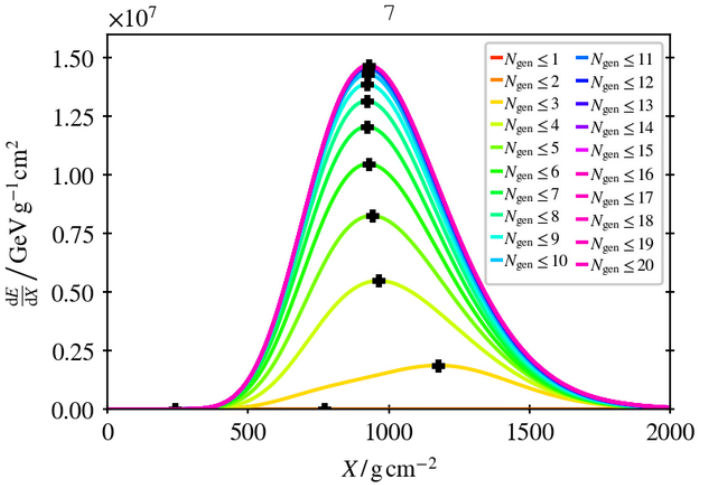


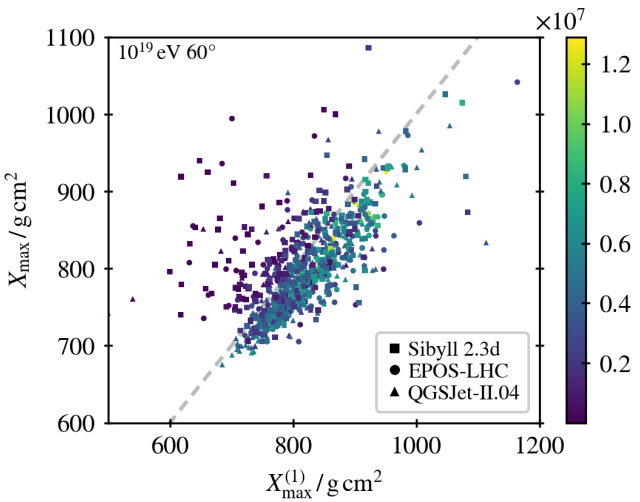
see also Baus et al. (2011), Blazek (2017), Novotny et al. (2019)

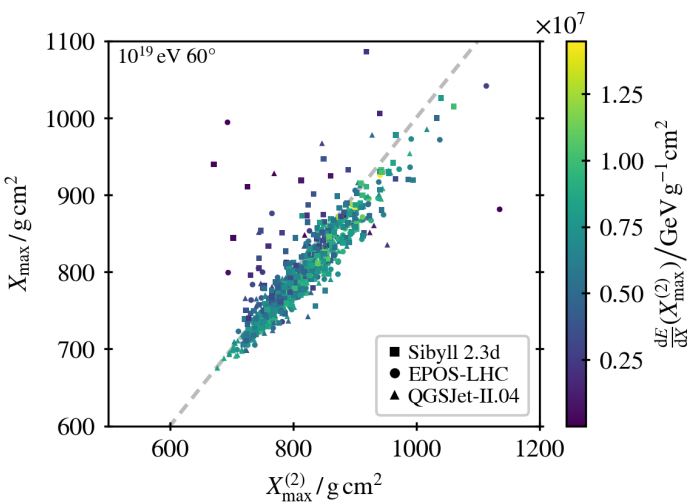
Summary

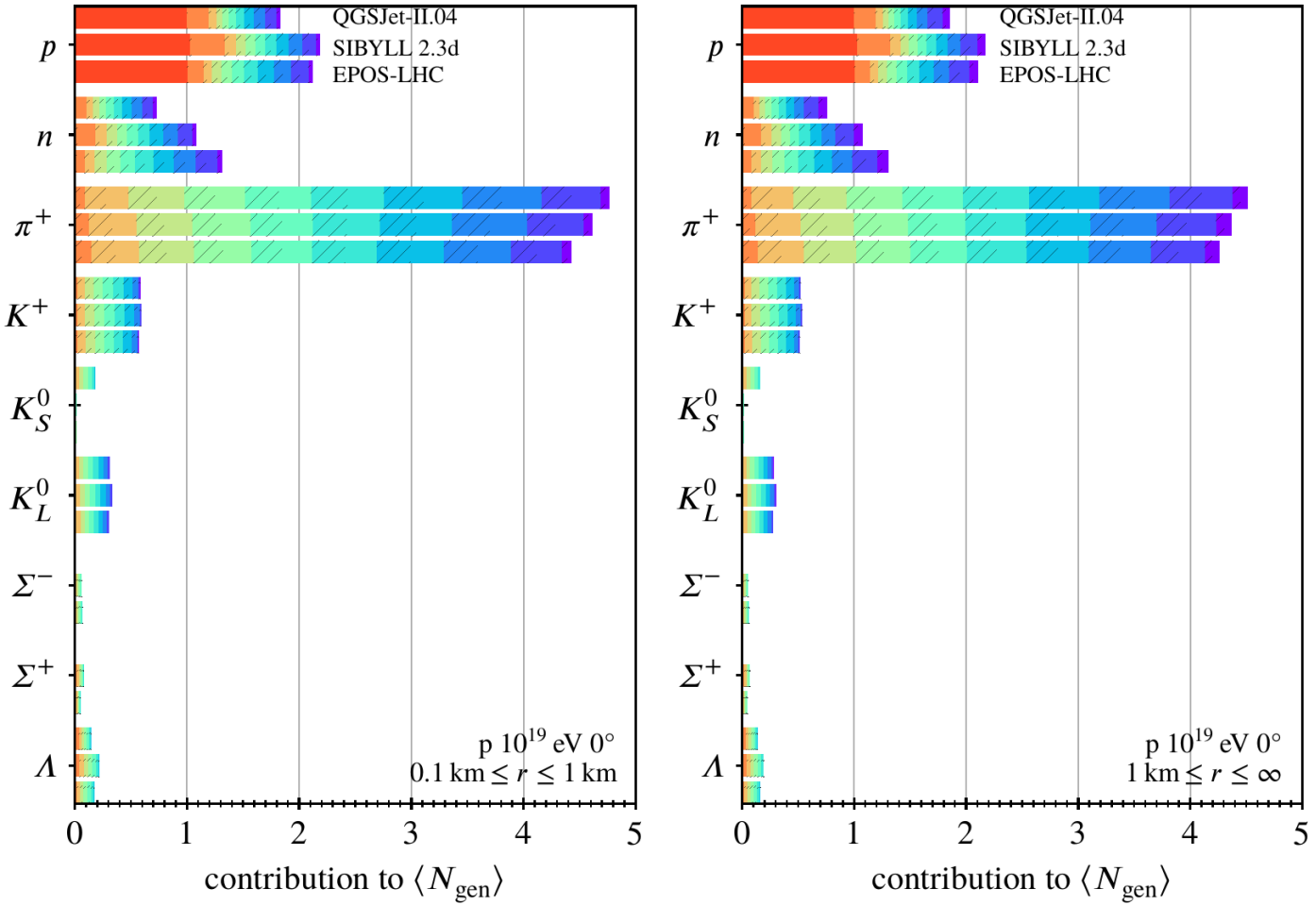
- genalogical information available in CORSIKA 8
- useful tool to
  - test validity of toy models
  - quantify relevant phase-space in air showers
  - enable exotic studies (double bump)

Backup

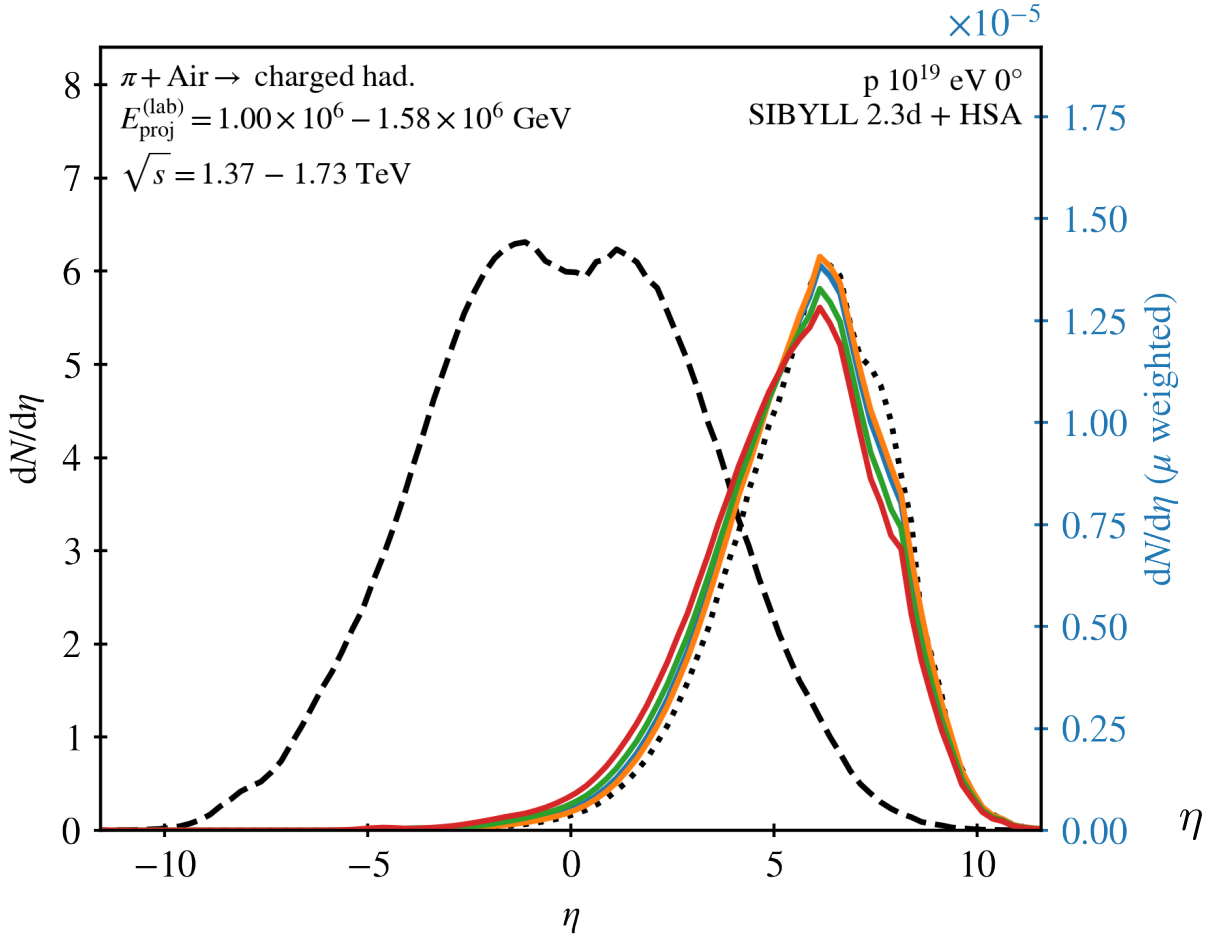

×10^7
7
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0
500
1000
1500
2000
X / g cm^−2
dE/dX / GeV g^−1 cm^2
N_gen ≤ 1
N_gen ≤ 2
N_gen ≤ 3
N_gen ≤ 4
N_gen ≤ 5
N_gen ≤ 6
N_gen ≤ 7
N_gen ≤ 8
N_gen ≤ 9
N_gen ≤ 10
N_gen ≤ 11
N_gen ≤ 12
N_gen ≤ 13
N_gen ≤ 14
N_gen ≤ 15
N_gen ≤ 16
N_gen ≤ 17
N_gen ≤ 18
N_gen ≤ 19
N_gen ≤ 20


×10^7
10^19 eV 60°
1100
1000
900
800
700
600
600
800
1000
1200
X_max / g cm^2
X_max^(1) / g cm^2
1.2
1.0
0.8
0.6
0.4
0.2
Sibyll 2.3d
EPOS-LHC
QGSJet-II.04


×10^7
10^19 eV 60°
1100
1000
900
800
700
600
600
800
1000
1200
X_max / g cm^2
X_max^(2) / g cm^2
1.25
1.00
0.75
0.50
0.25
dE/dX(X_max^(2)) / GeV g^−1 cm^2
Sibyll 2.3d
EPOS-LHC
QGSJet-II.04


QGSJet-II.04
SIBYLL 2.3d
EPOS-LHC
p
n
π^+
K^+
K^0_S
K^0_L
Σ^-
Σ^+
Λ
p 10^{19} eV 0°
0.1 km ≤ r ≤ 1 km
1 km ≤ r ≤ ∞
0
1
2
3
4
5
contribution to $\langle N_{\rm gen} \rangle$

Pseudorapidity

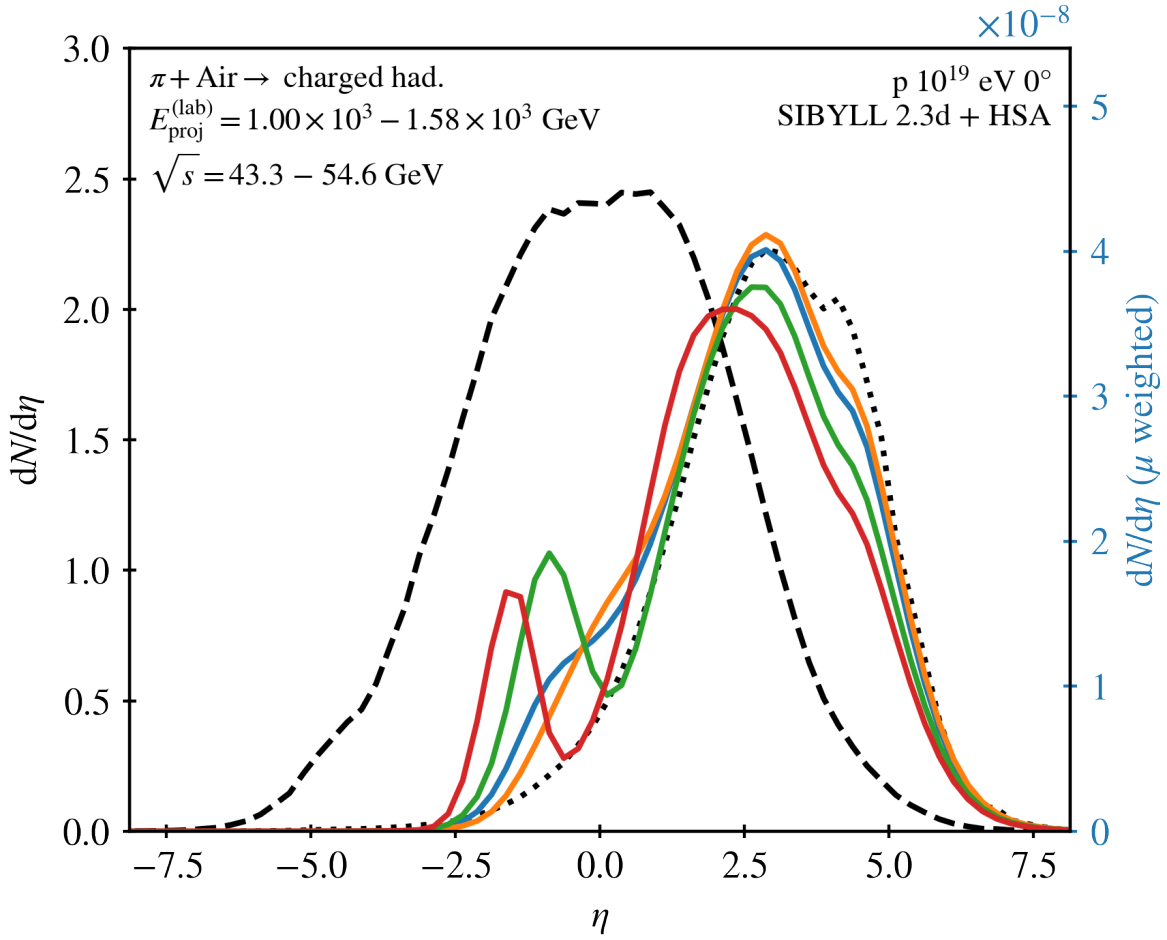


E_{lab} ~ 1 PeV

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

(in center-of-mass system)

Pseudorapidity

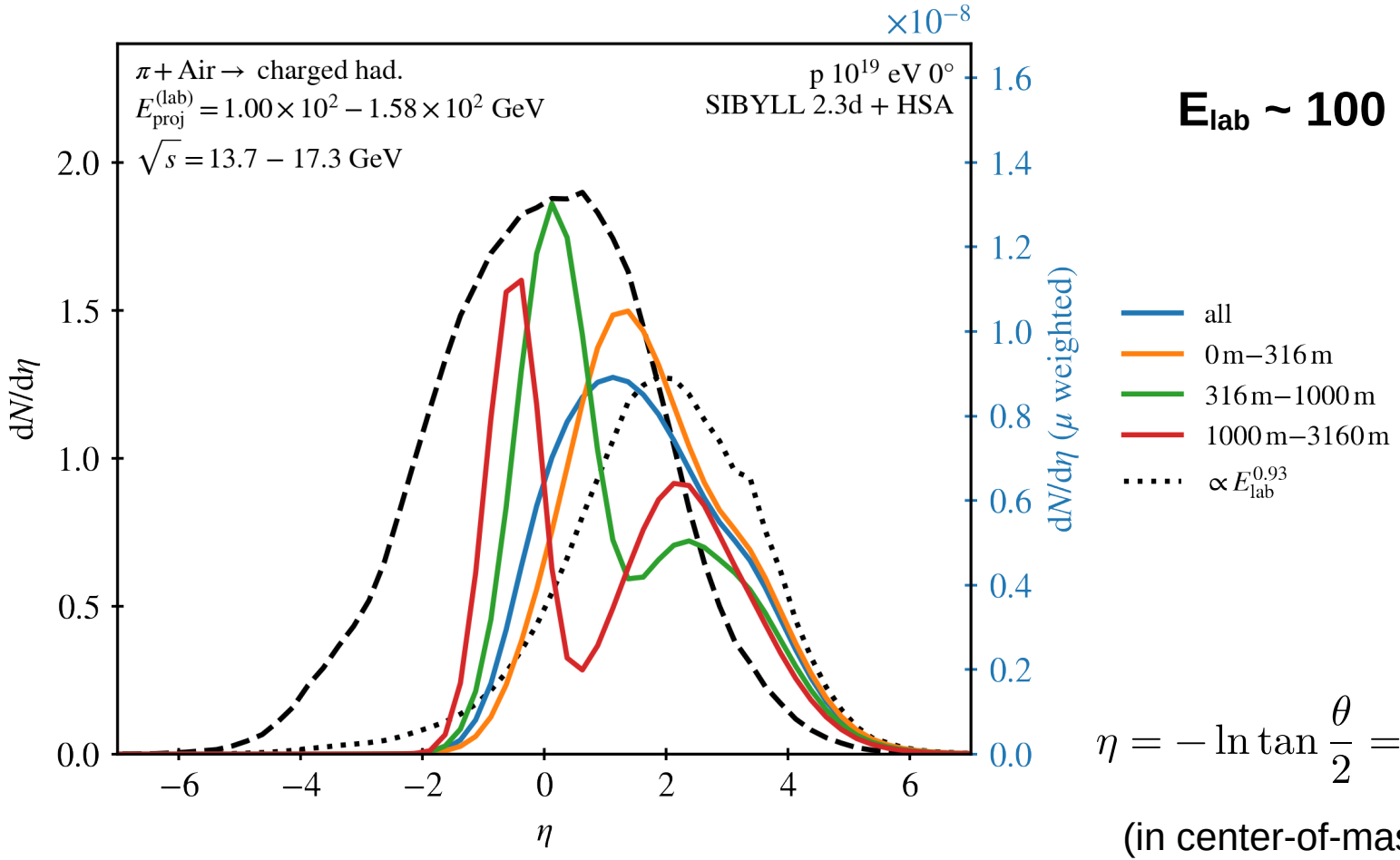


E_{lab} ~ 1 TeV

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

(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)