Air shower physics

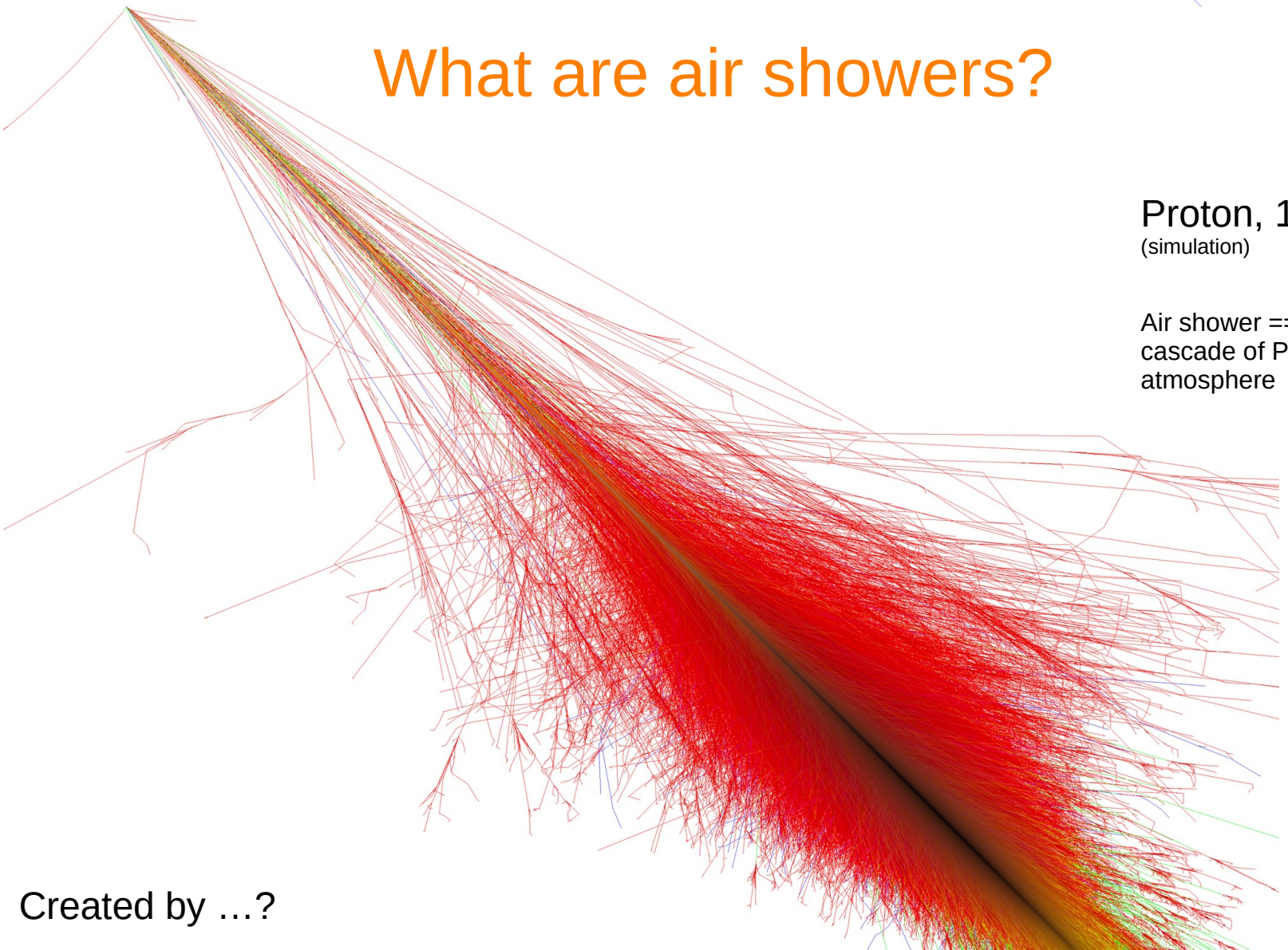
SHINE autumn school

27. 10. 2020

Felix Riehn

Universidad de Santiago de Compostela / LIP

What are air showers?



Proton, 100 TeV
(simulation)

Air shower ==
cascade of Particle interactions in atmosphere

10^7 particles

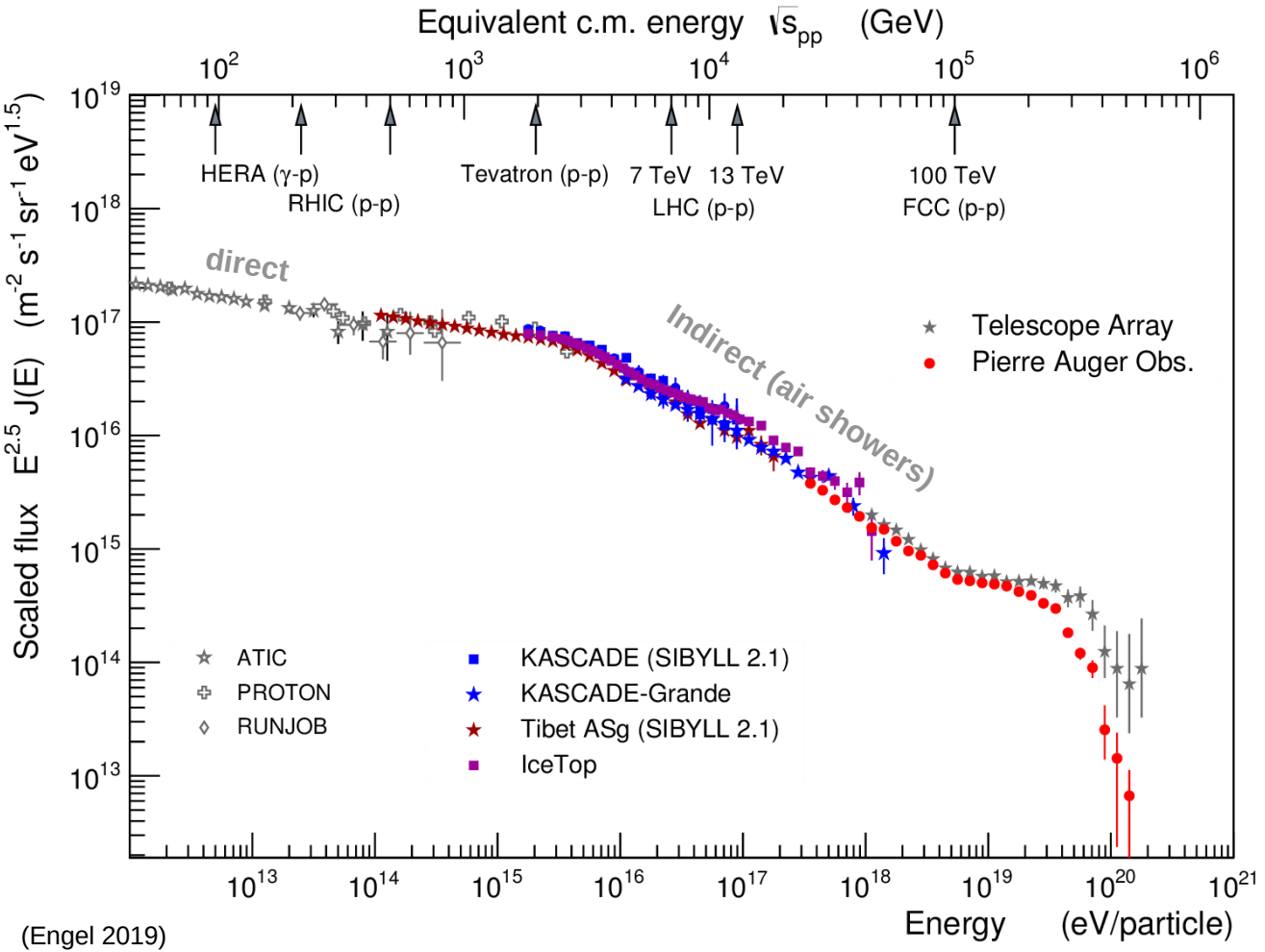
$\gamma, e^{\pm}$

$\mu^{\pm}$

hadrons

Created by …?

Cosmic rays



(Engel 2019)

Astrophysics:

Origin of features ?
Acceleration ?

(Unger 2006)

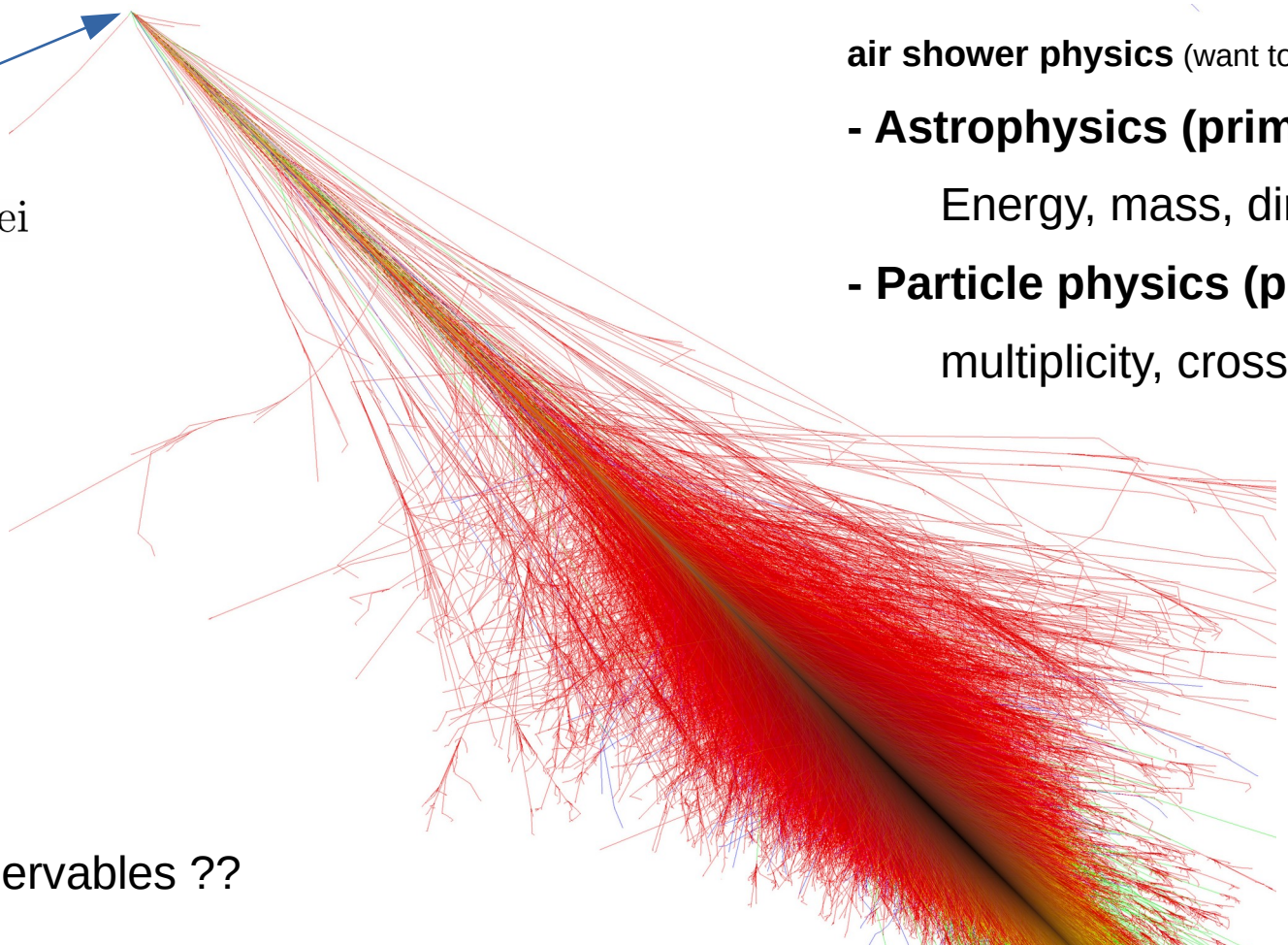
Particle physics:

$$\sqrt{s_{pp}} > 100\,\mathrm{TeV}$$

CRs through extensive air showers

CR interaction

$\gamma, \nu, p, n, \mathrm{Nuclei}$



air shower physics (want to know):

- Astrophysics (primary particle)

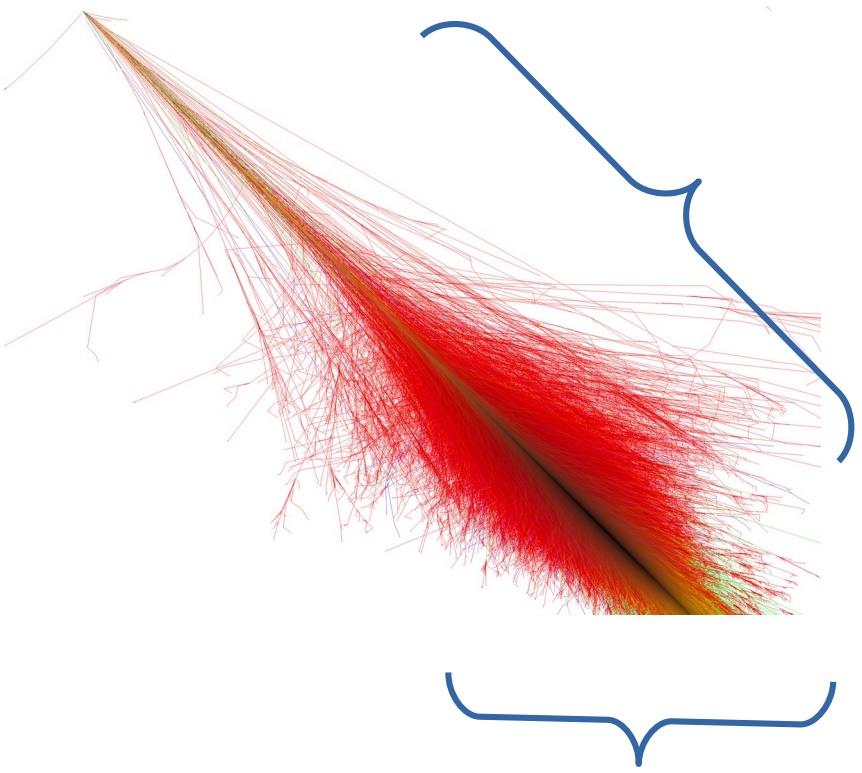
Energy, mass, direction

- Particle physics (primary interaction)

multiplicity, cross section …

Observables ??

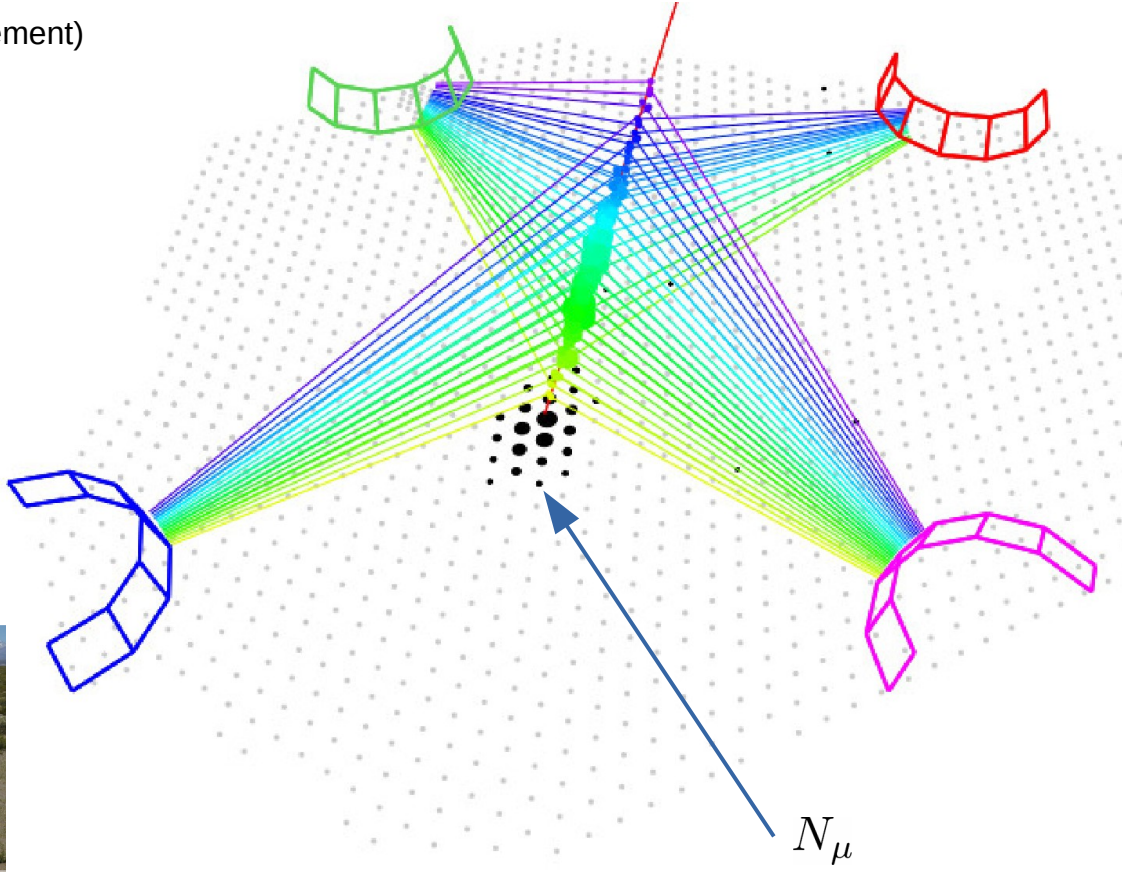
CR air shower observables

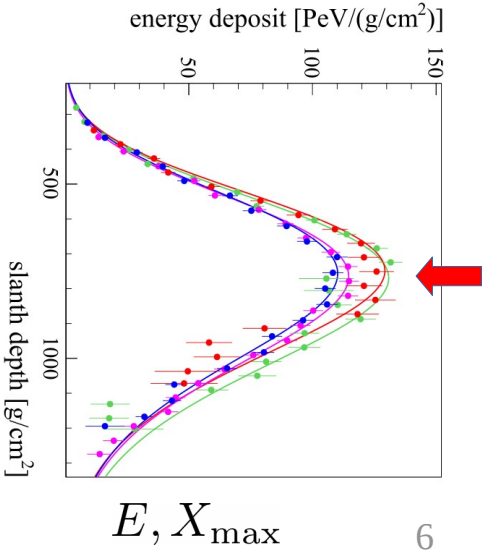


* particles at (under)ground
* energy deposit along path

Example: Pierre Auger Observatory

Both! (Hybrid measurement)

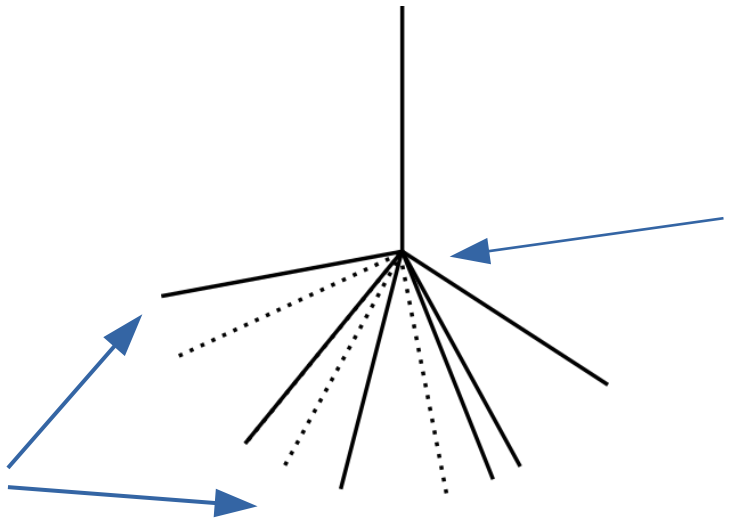




Related to primary?

Air shower development: the start

CR particle $(\gamma, \nu, p, n, \mathrm{Nuclei})$



UHE secondaries (~100 TeV)

- Pions, kaons, charmed ...
- New (exotic) particles?
- Lorentz invariance?

UHE interaction (~100 TeV)

- Hadronic!
- Exotic?
  - Black holes?
  - Fireball?
  - Chiral symmetry?

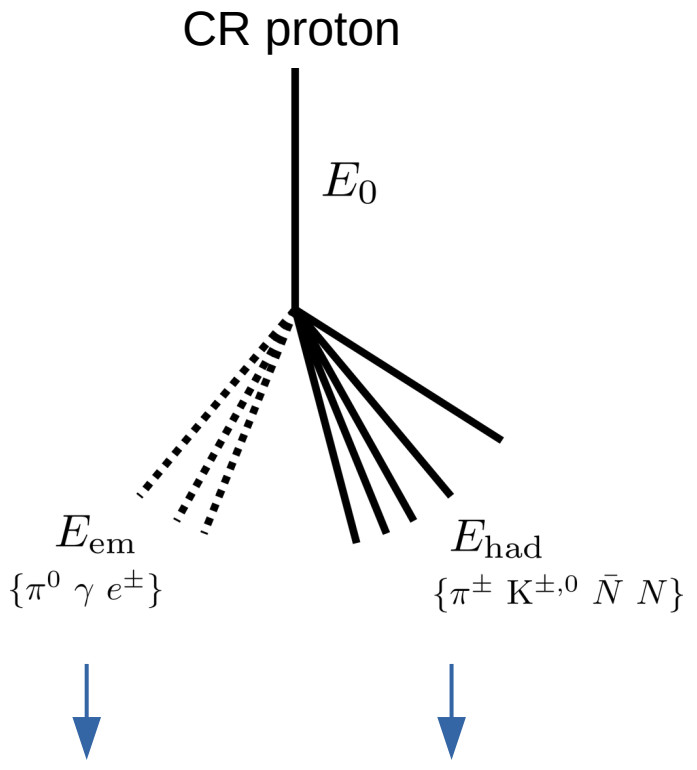
EAS according to SM ??

EAS according to the Standard Model

Hadronic interaction: $\pi^{\pm}, \pi^{0}$

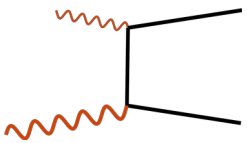
$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu} \qquad c\tau_{\pi^{\pm}} = 7.8\,\mathrm{m}$$

$$\pi^{0} \to \gamma\gamma \qquad c\tau_{\pi^{0}} = 25\,\mathrm{nm}$$

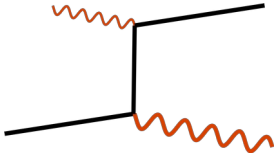


Successive interactions: **EM cascade** **hadronic cascade**

EM cascade



Pair creation



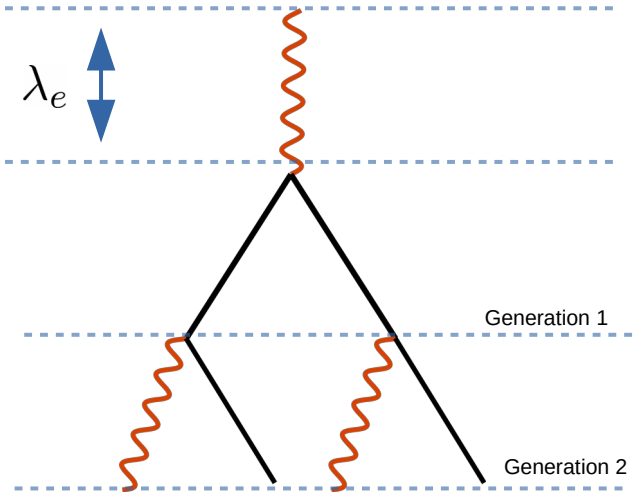
Bremsstrahlung

Ionisation (continuous energy loss)

Equal sharing of energy

All with same interaction length

Multiplicity: 2



Etc.

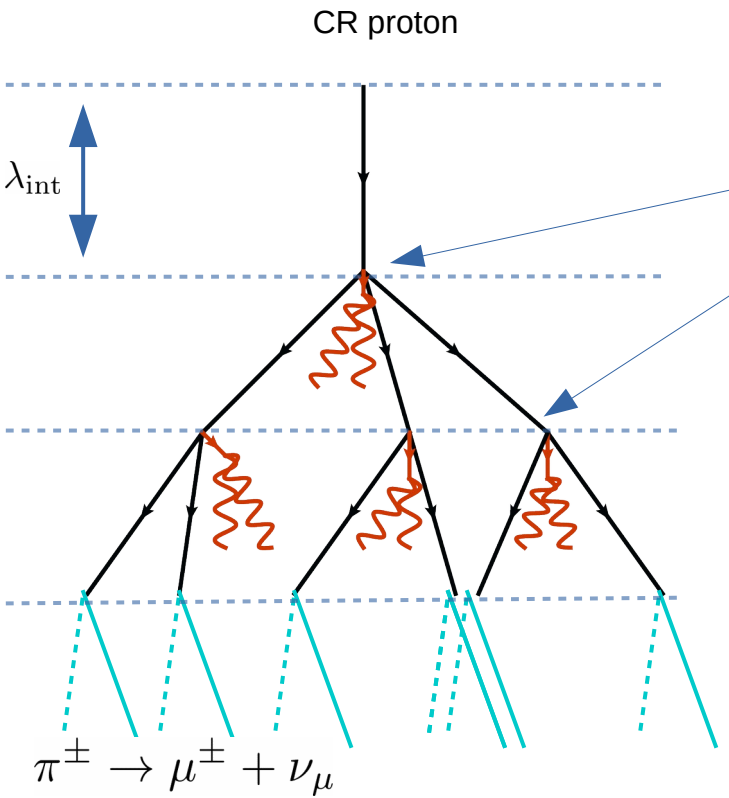
$$N_i = 2^i \qquad E_i = \frac{E_0}{2^i}$$

$$E_i \leq E_{crit}$$ Until continuous energy loss dominant

$$n_{crit} = \ln\left(\frac{E_0}{E_{crit}}\right)$$ ‘generation z’

$$X_{\max}^{(\mathrm{EM})} \sim \lambda_e \ln\left(\frac{E}{E_{crit}}\right)$$

Hadronic cascade



Assume pions only $n_{\rm ch} : n_{\rm tot} = 2:3$

Equal sharing of energy

Multiplicity: fixed $n_{\rm ch} = (2/3)\, n_{\rm tot}$

(Matthews 2005)

$$N_i = n_{\rm ch}^i \qquad E_i = \frac{E_0}{n_{\rm tot}^i}$$

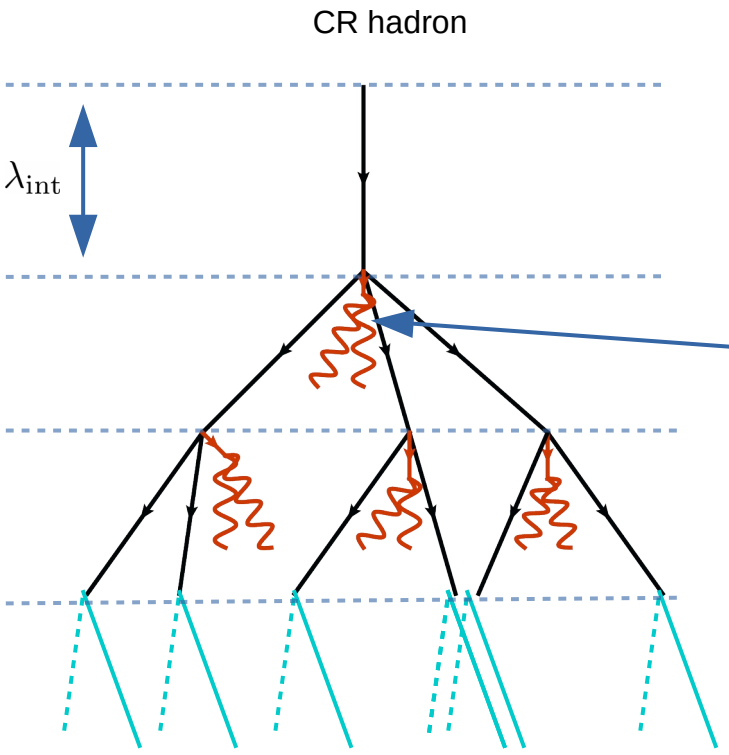
$$E_{{\rm ch},i} = (2/3)^i\, E_0 \qquad E_{{\rm neutral},i} = (1-(2/3)^i)\, E_0$$

Until pions likely decay $E_i = E_{crit,\pi}$

$$\langle N_\mu \rangle = \left(\frac{E_0}{E_{\rm dec}}\right)^{\beta}, \quad \beta = \frac{\ln n_{\rm ch}}{\ln n_{\rm tot}}$$

$\beta \approx 0.82 \ldots 0.94$

Hadronic cascade



Assume pions only $n_{\rm ch} : n_{\rm tot} = 2:3$

All with same energy

Multiplicity: fixed $n_{\rm ch} = (2/3)\, n_{\rm tot}$

(Matthews 2006)

$$X_{\rm max}^{\rm (had)}(E_0) = \lambda_{\rm int} + X_{\rm max}^{\rm (EM)}(E_0/(2n_{\rm tot})$$
$$\sim \lambda_{\rm int} + \ln\left(\frac{E_0}{2n_{\rm tot}E_{crit}}\right)$$

$$X_{\rm max}(E_0) \sim \ln(E_0)$$

Primary mass dependence

$$\langle X_{\rm max}^{\rm (p)}(E_0)\rangle \;=\; \mathcal{D}\,\ln(E_0) \qquad\qquad \langle N_\mu^{\rm (p)}(E_0)\rangle \;=\; \mathcal{C}\,E_0^{\beta}$$

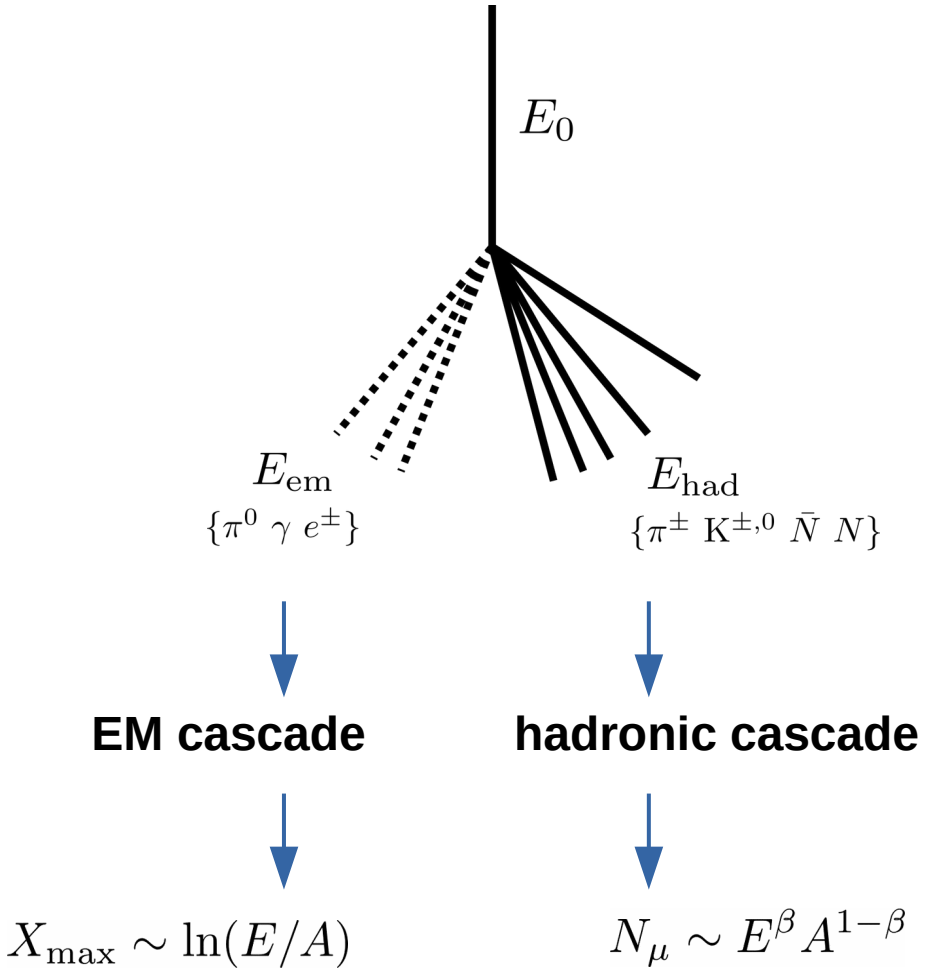
Superposition

$$\text{nucleus } A \text{ with } E_0 \;\rightarrow\; A \;\times\; \text{proton with } \; E_0/A$$

$$\langle X_{\rm max}(E_0,A)\rangle \;=\; \mathcal{D}\,\ln\left(\frac{E_0}{A}\right) \qquad \langle N_\mu(E_0,A)\rangle \;=\; A\times\mathcal{C}\left(\frac{E_0}{A}\right)^{\beta}$$

$$= A^{1-\beta}\langle N_\mu^{(p)}(E_0)\rangle$$

Summary: EAS according to the Standard Model



Data...?

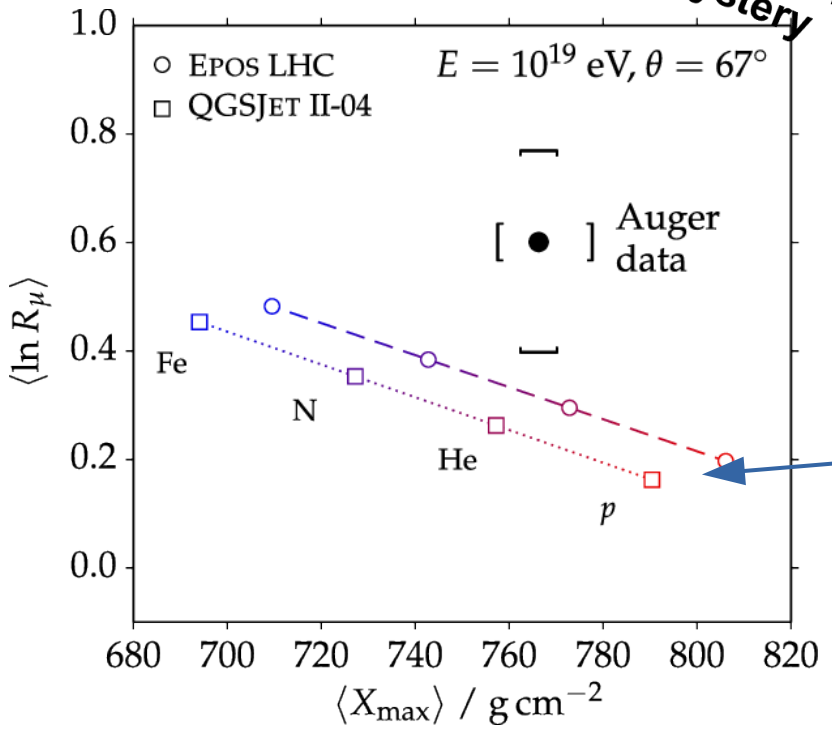
Measurement of Xmax and Nmu

Fix primary energy and compare

$$N_\mu \sim E^\beta A^{1-\beta}$$

$$X_{\max} \sim \ln(E/A)$$

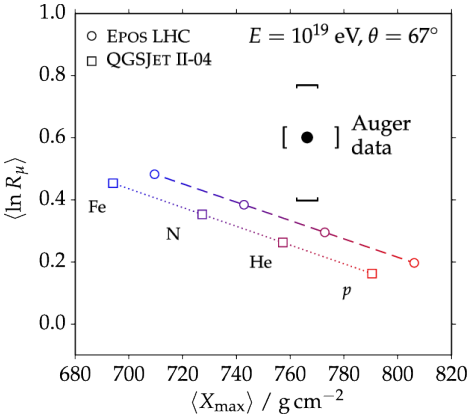
$$\ln N_\mu \sim (1-\beta)\ln A \sim X_{\max}$$

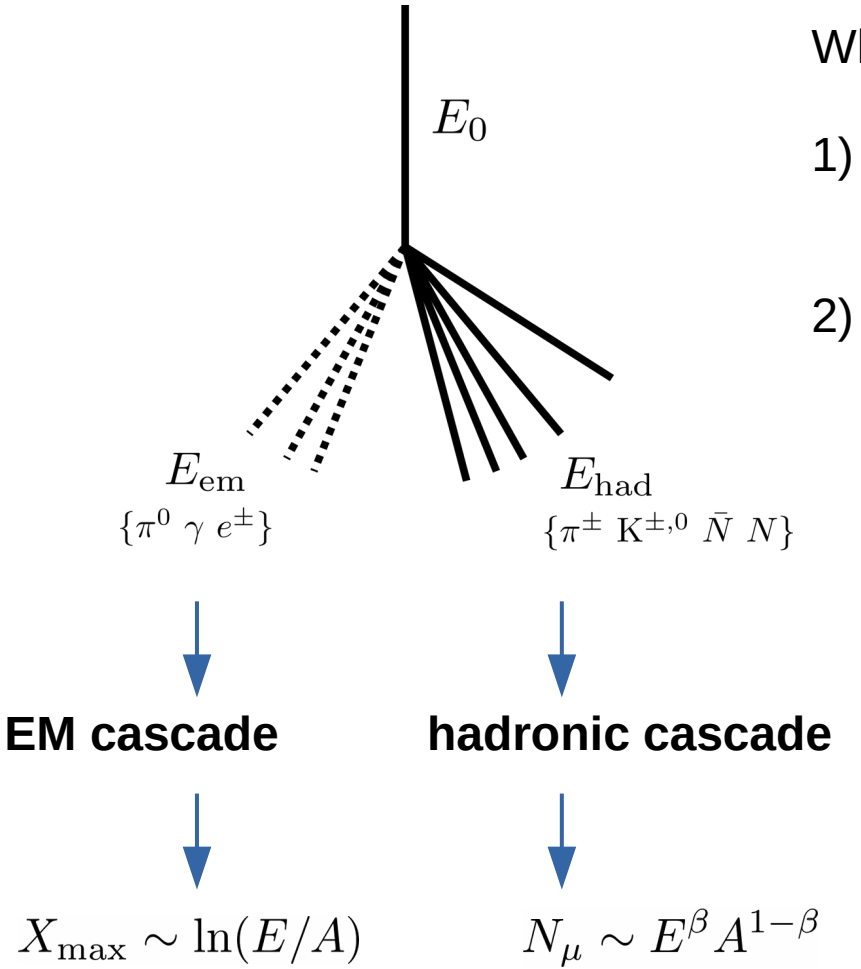


SM prediction

Post-LHC interaction models

EAS according to the Standard Model ?



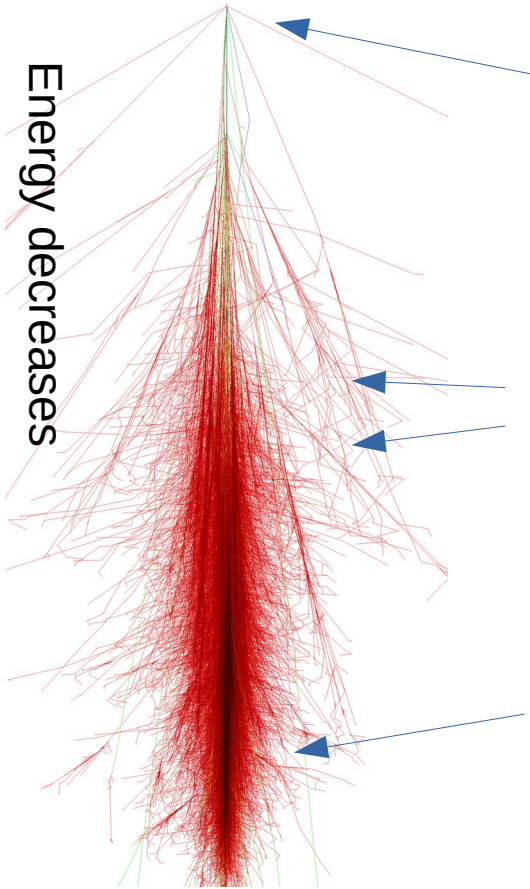


Whats going on?

1) First interaction
   Beyond SM?

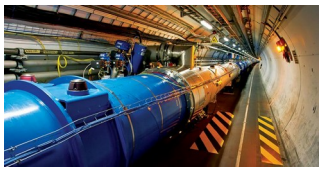
2) SM predictions correct?

Interactions in air showers



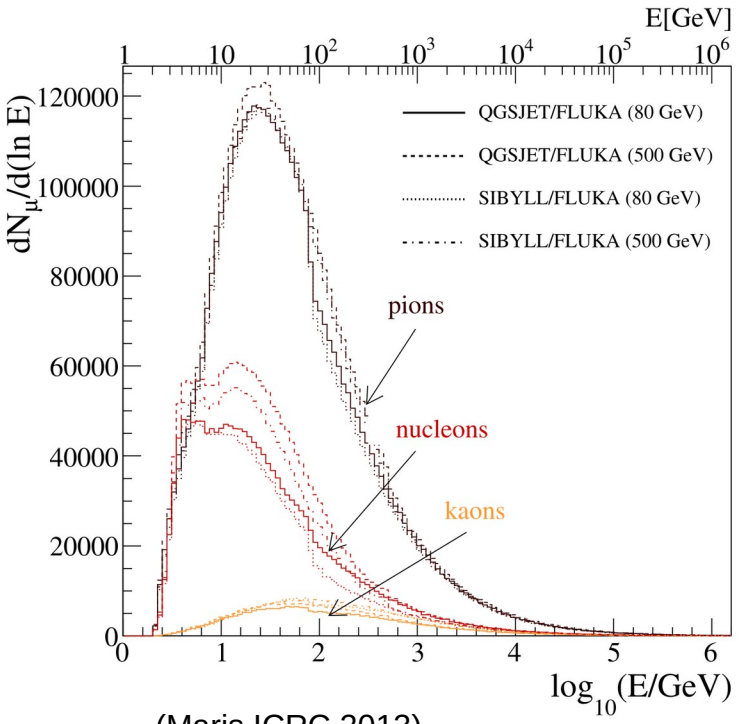
FCC?

p+Air



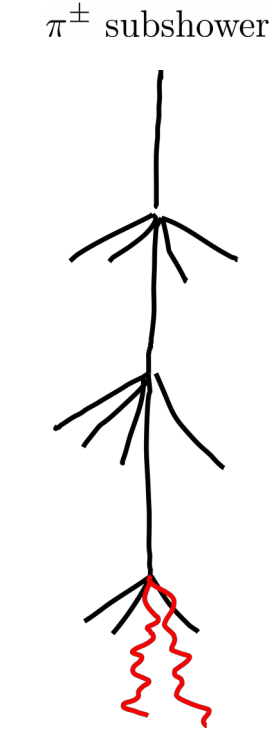
pion+Air
kaon+Air

energy of last hadron interaction



(Maris ICRC 2013)

A way to get more muons



$$N_\mu \sim E^\beta A^{1-\beta}$$

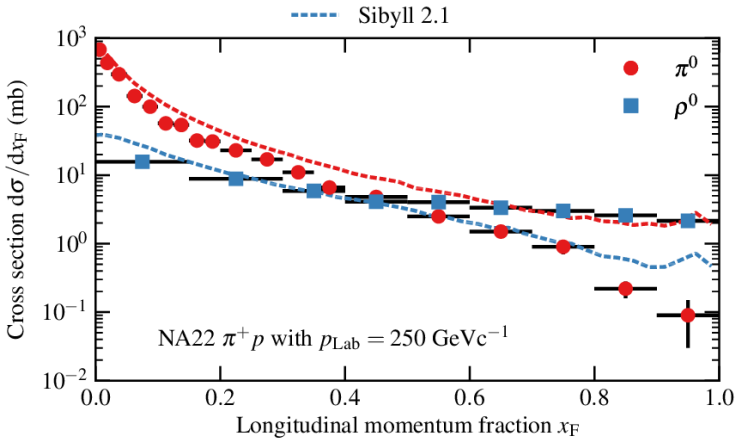
increase $\pi^{\pm} : \pi^0$

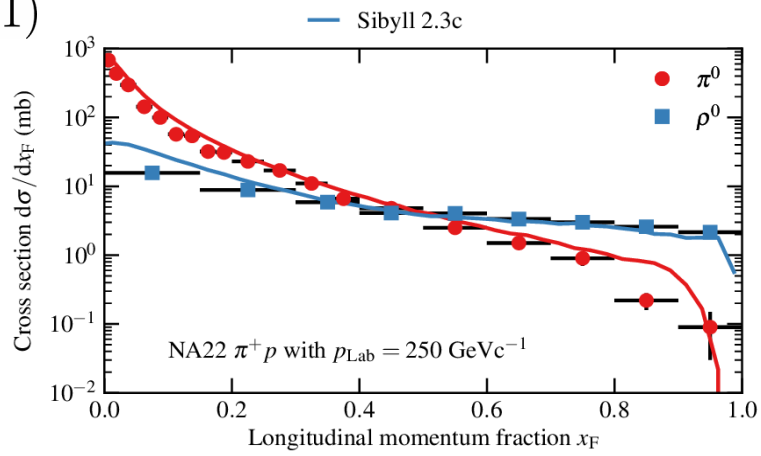
$$\pi^+ + p \rightarrow \text{leading} + X$$

$$\text{leading} : \pi(\text{spin} - 0) \text{ or } \rho(\text{spin} - 1)$$

$$\rho^0 \rightarrow \pi^{\pm}$$

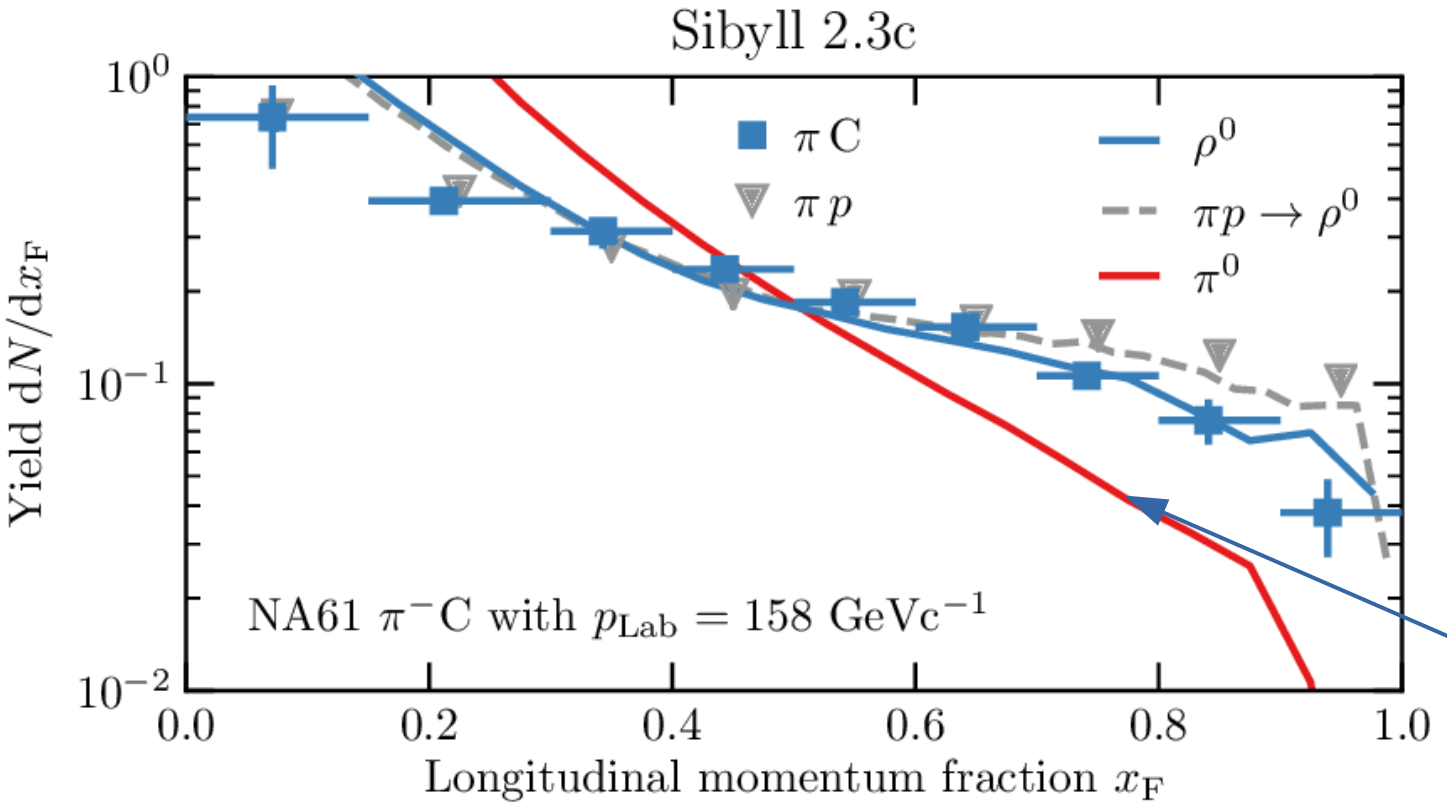
$$\pi^0 \rightarrow 2\gamma$$





Also in pion+Air ?

Rho mesons in NA61

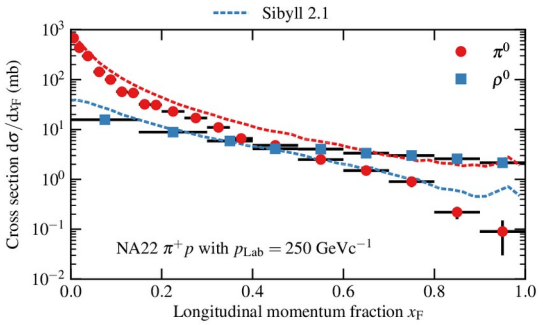


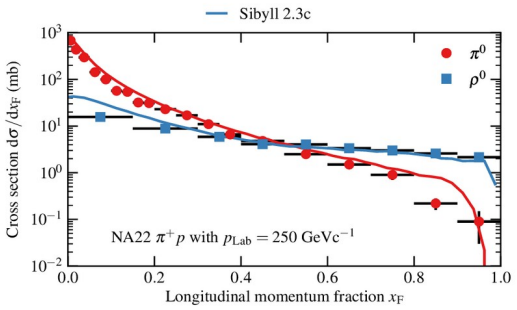
Model was build on NA22 data

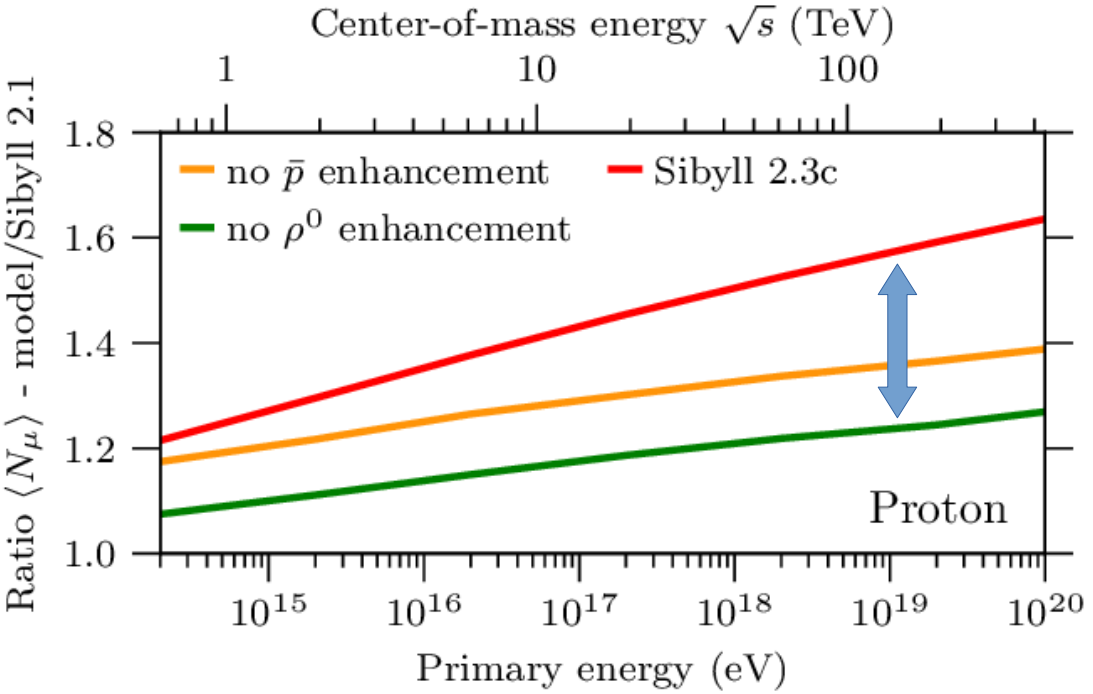
Prediction for NA61!

Ultimate confirmation: Measurement of neutral pions!

Effect on muons in EAS

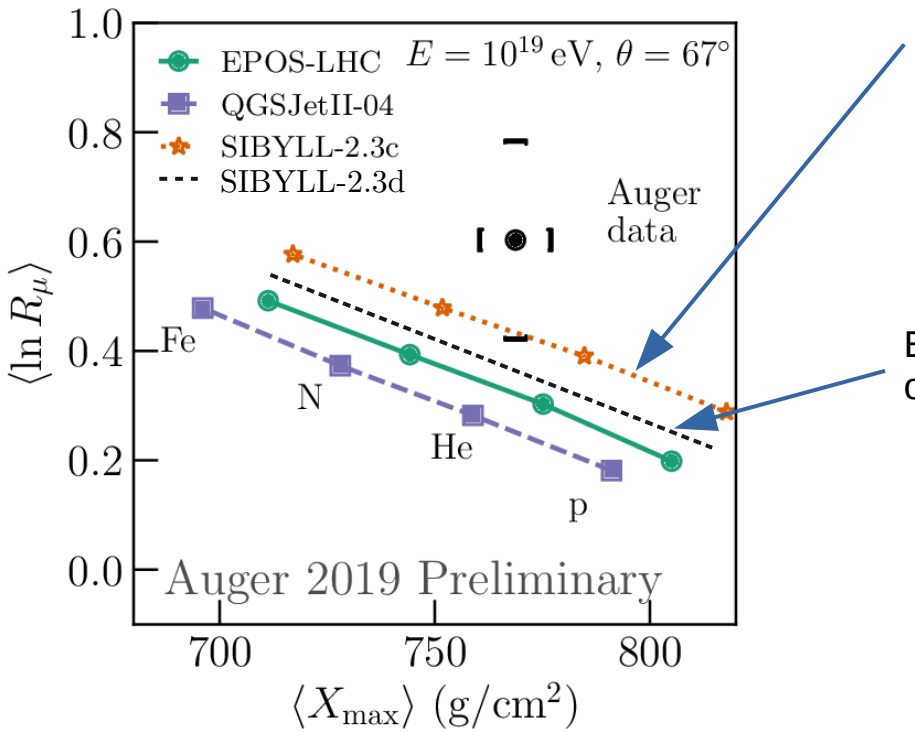






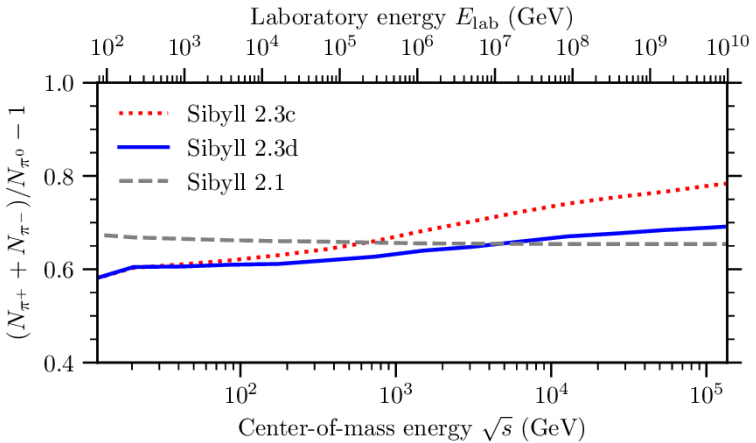
~40% increase

Muon data vs. post-LHC models



Universal rho meson enhancement.
Probably overestimated.

Enhancement only in NA61

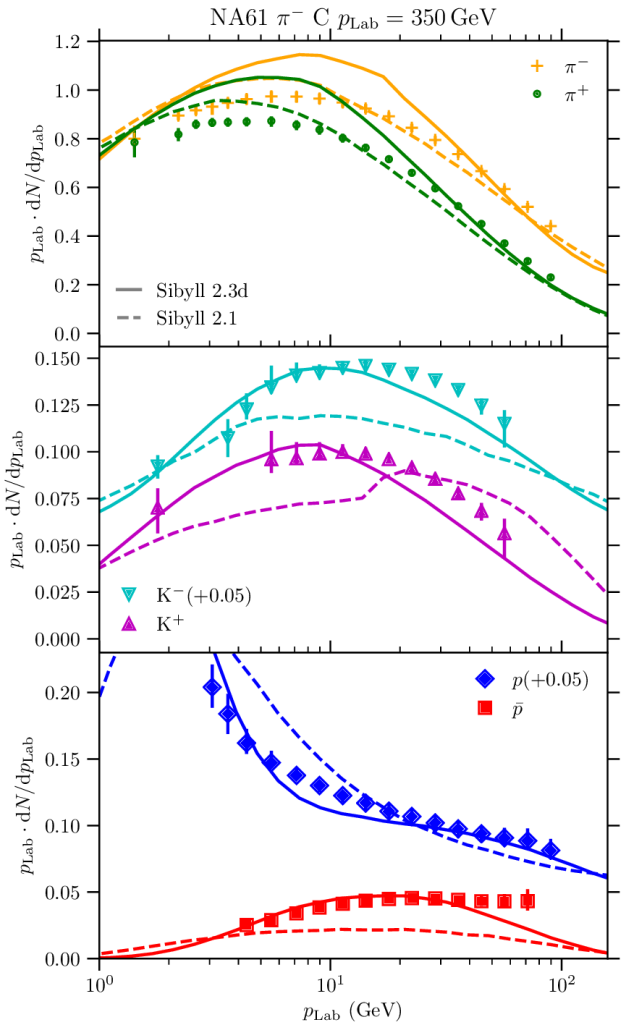


Close remaining gap → motivate larger $\pi^{\pm} : \pi^0$

* QGP effects?

* Kaon interactions?

More from NA61



NA61 & Sibyll:

* forward kaons,

* forward antiprotons underestimated

* central pions overestimated

→ work for post-NA61 Sibyll

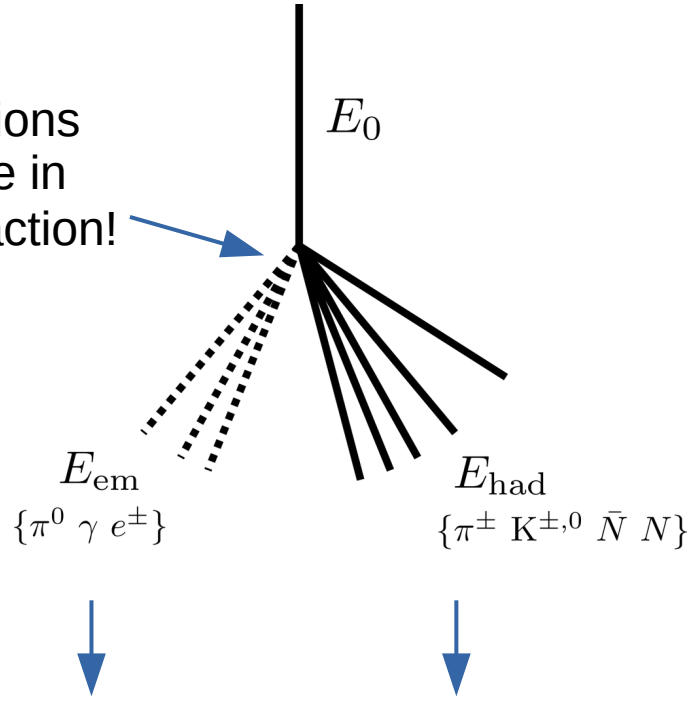
So far: $\pi^- + \mathrm{C}$

Needed / Possible? : $K^{\pm} + \mathrm{C} \to \pi, K, p, \bar{p}$

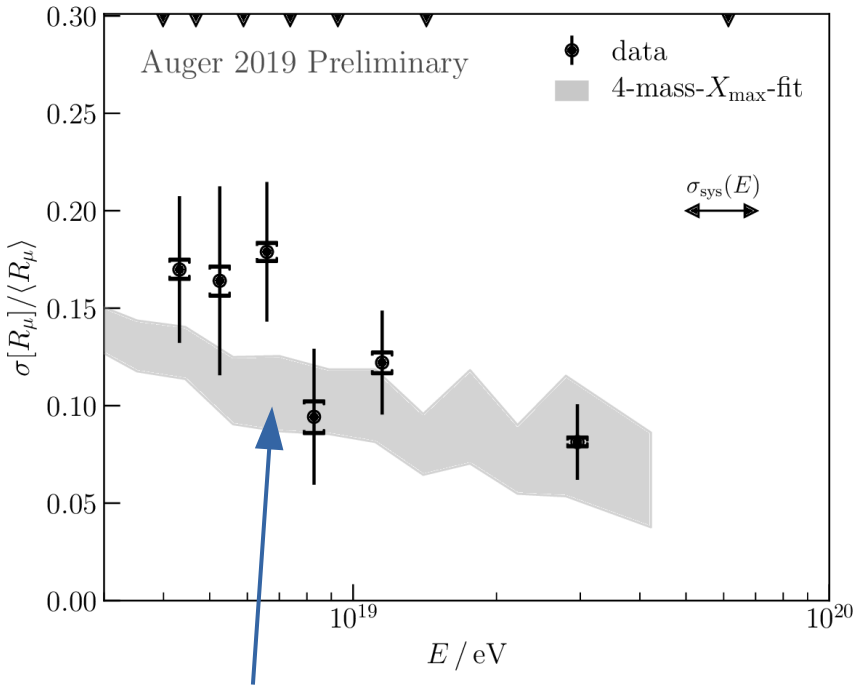
Diffraction in $\pi^- + \mathrm{C}$

BSM physics for the muon puzzle?

Fluctuations
Originate in
1st interaction!



EM cascade **hadronic cascade**



SM predictions

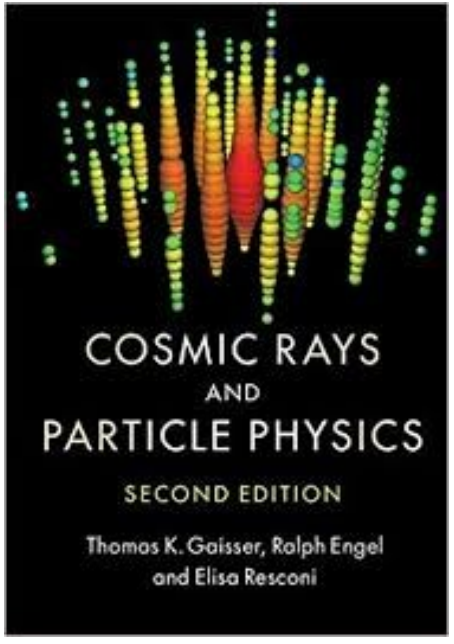
BSM not needed!

Summary

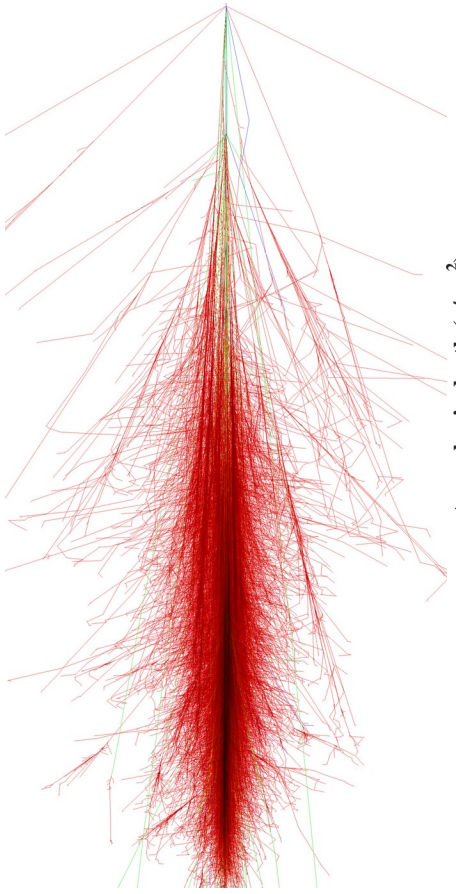
* EAS produce more muons than anticipated by interaction model –> muon puzzle
* Muon production in EAS sensitive to broad spectrum of particle interactions

* Probably no exotic physics needed to explain muon puzzle
    * More accurate implementation of SM physics needed (NA61,LHCf tunes)
    * More accelerator data to validate models needed (NA61: kaon interactions!)

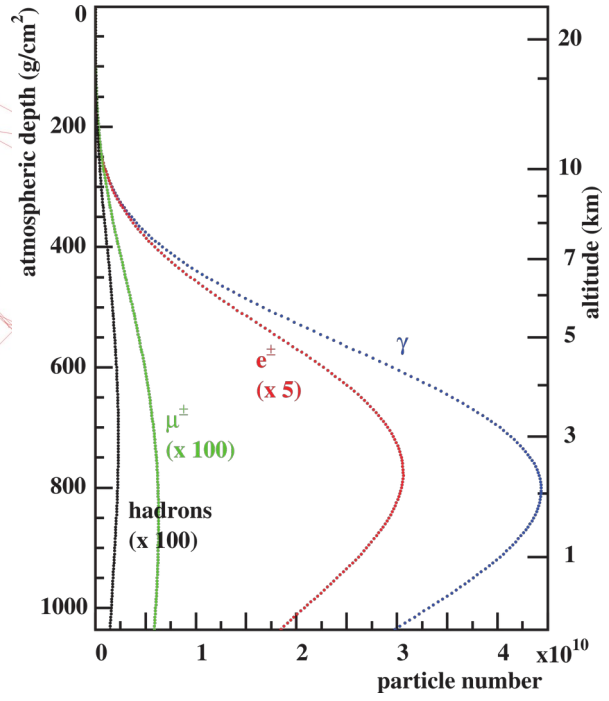
Bibliography



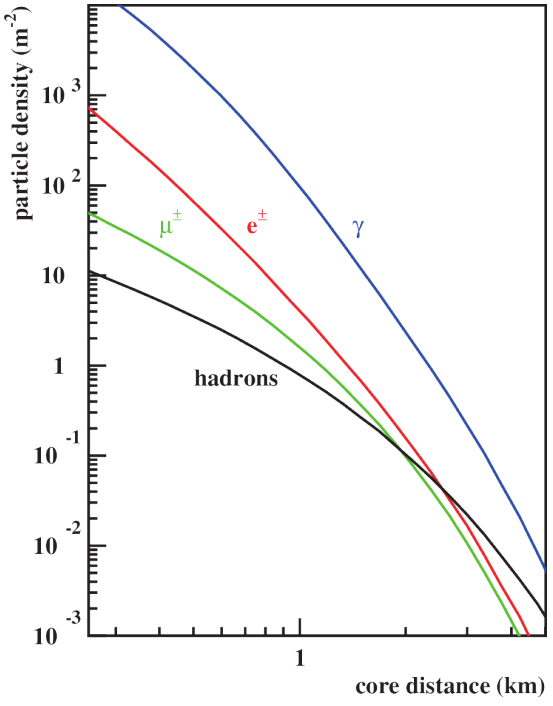
Full shower

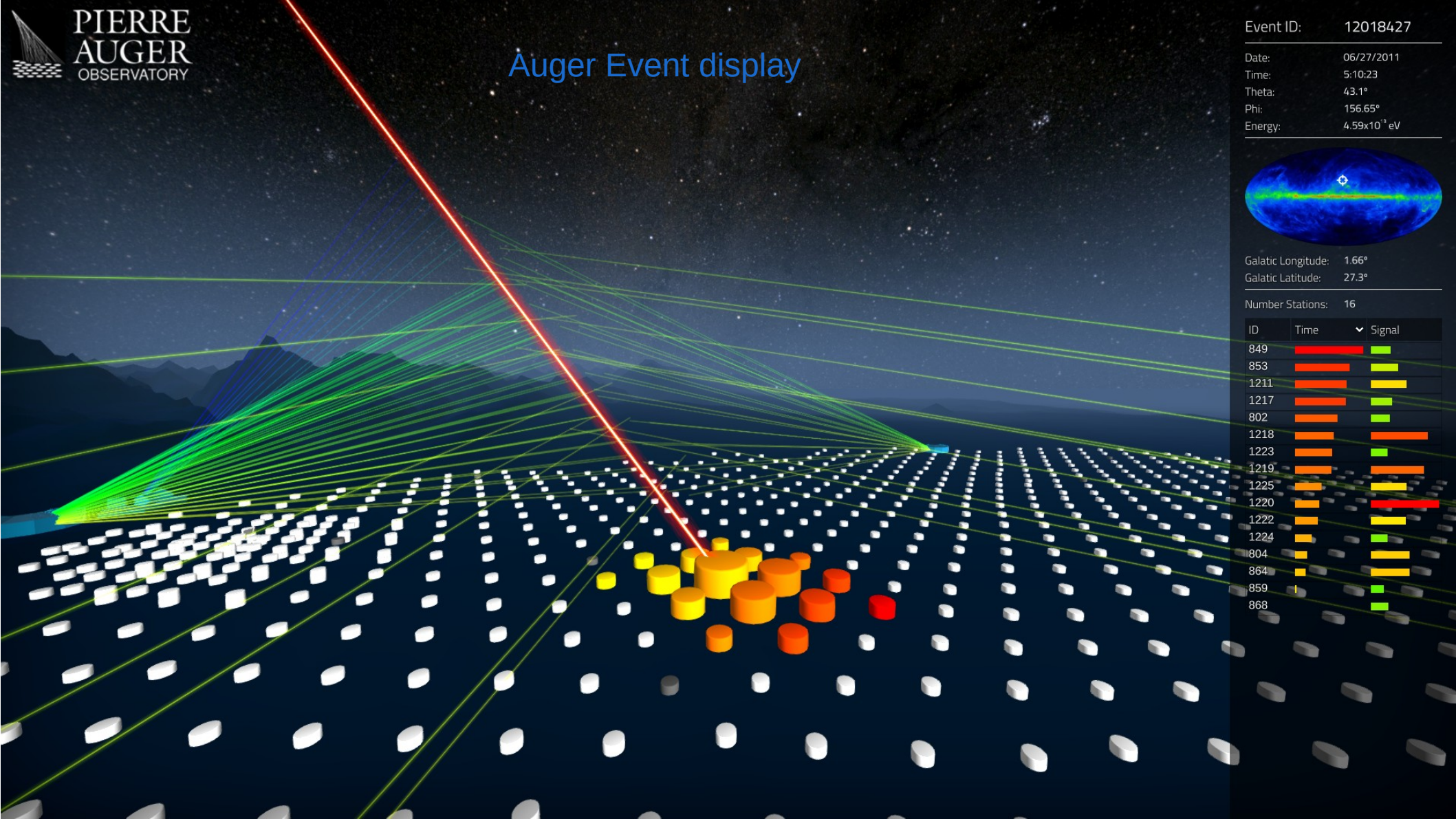


Profile: EM dominates



At the ground: more mixed




PIERRE AUGER OBSERVATORY
Auger Event display
Event ID: 12018427
Date: 06/27/2011
Time: 5:10:23
Theta: 43.1°
Phi: 156.65°
Energy: 4.59x10^19 eV
Galatic Longitude: 1.66°
Galatic Latitude: 27.3°
Number Stations: 16
ID Time Signal
849
853
1211
1217
802
1218
1223
1219
1225
1220
1222
1224
804
864
859
868