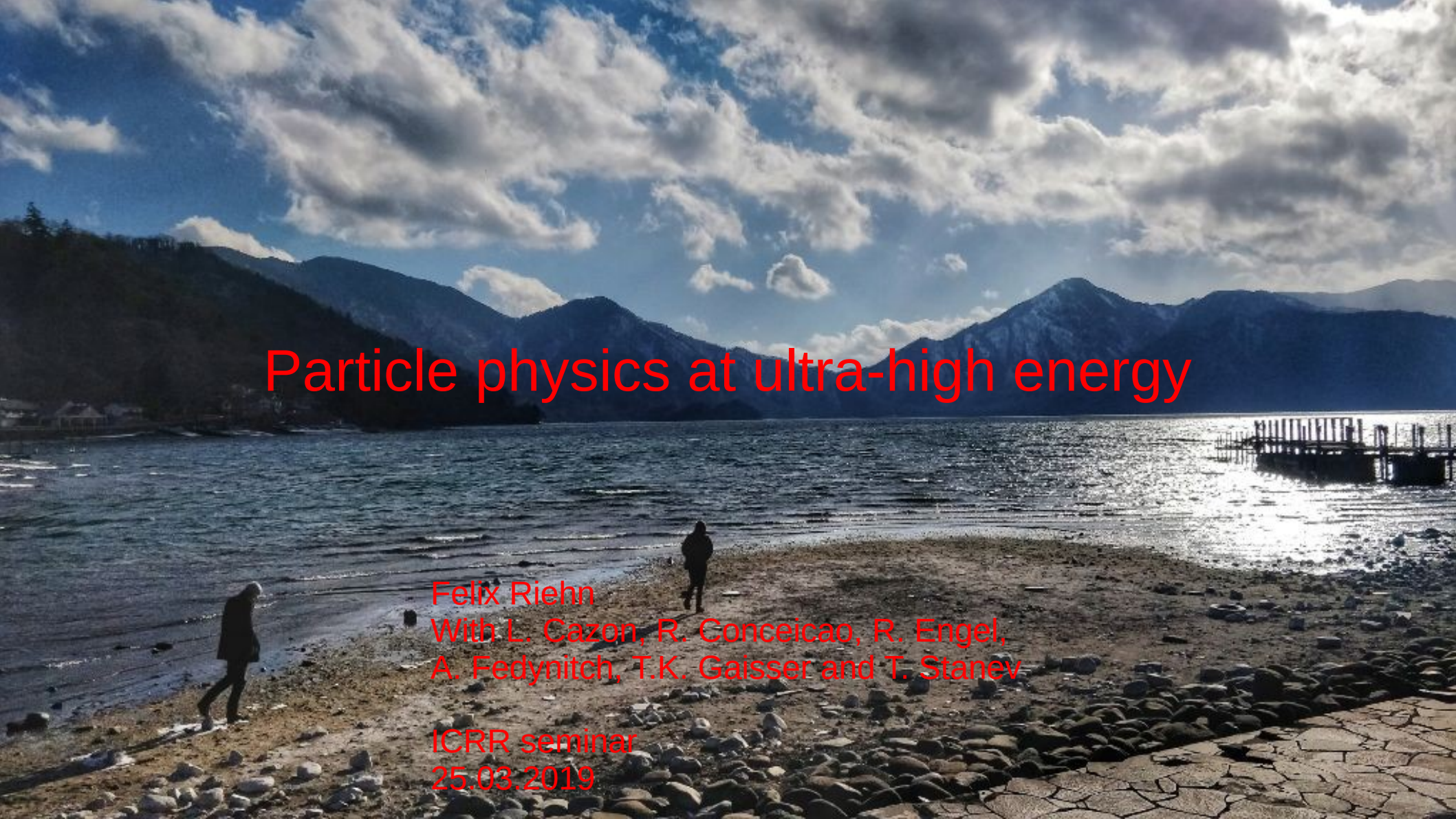
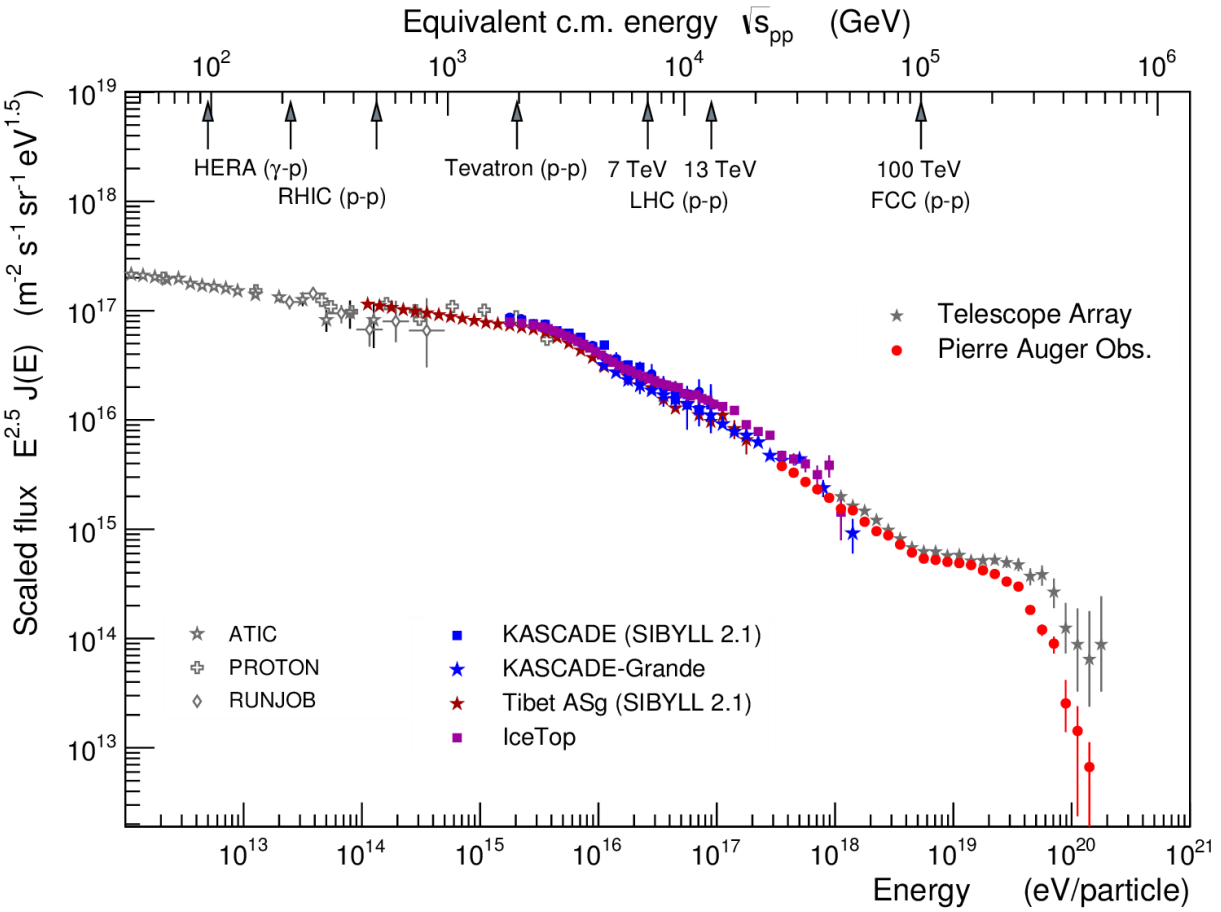


Particle physics at ultra-high energy

Felix Riehn
With L. Cazon, R. Conceicao, R. Engel,
A. Fedynitch, T.K. Gaisser and T. Stanev

ICRR seminar
25.03.2019

Spectrum of CR



Natural UHE beam

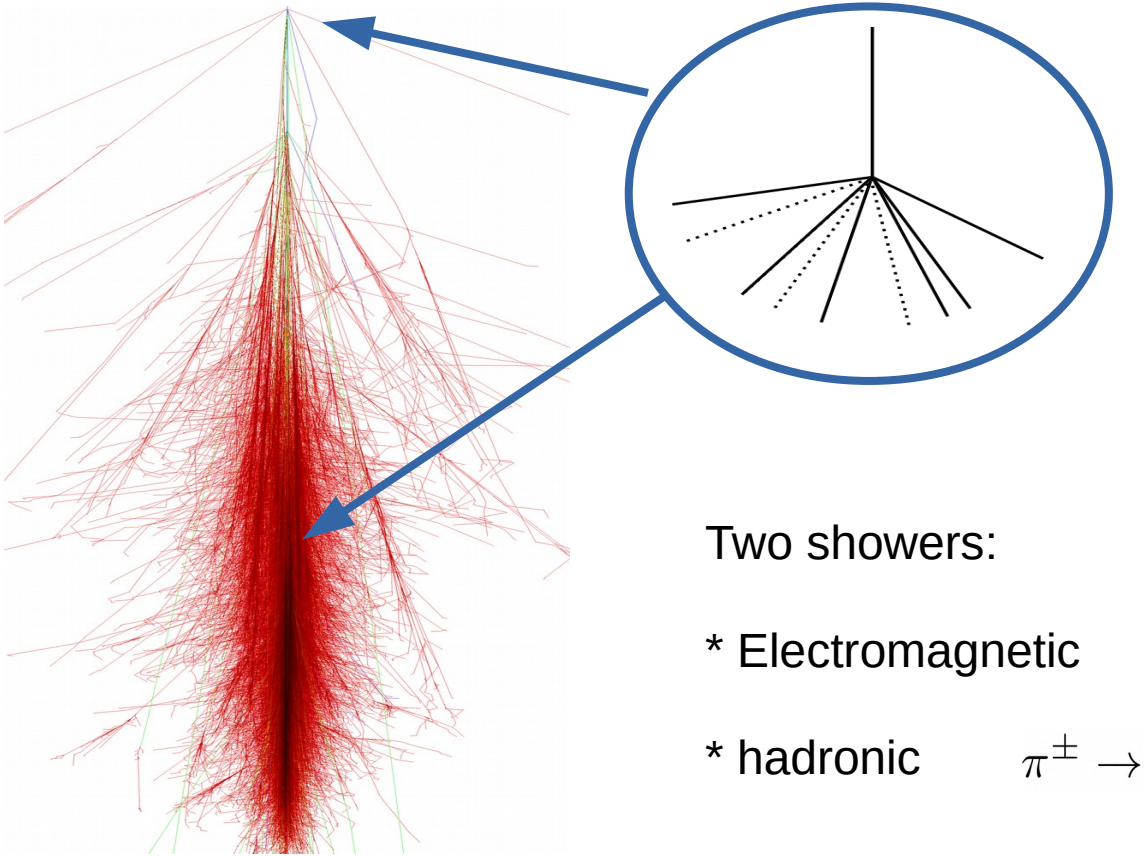
Three problems:

I. indirect measurement

II. unknown composition

III. muon mystery

Problem I: extensive air showers



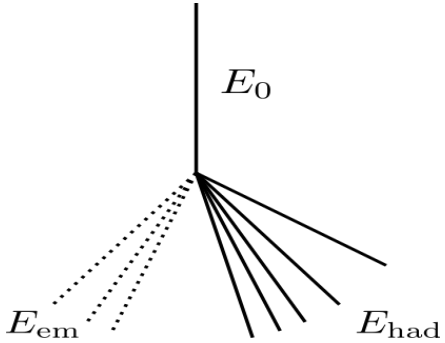
Many particles
many interactions !

can’t see first
interaction

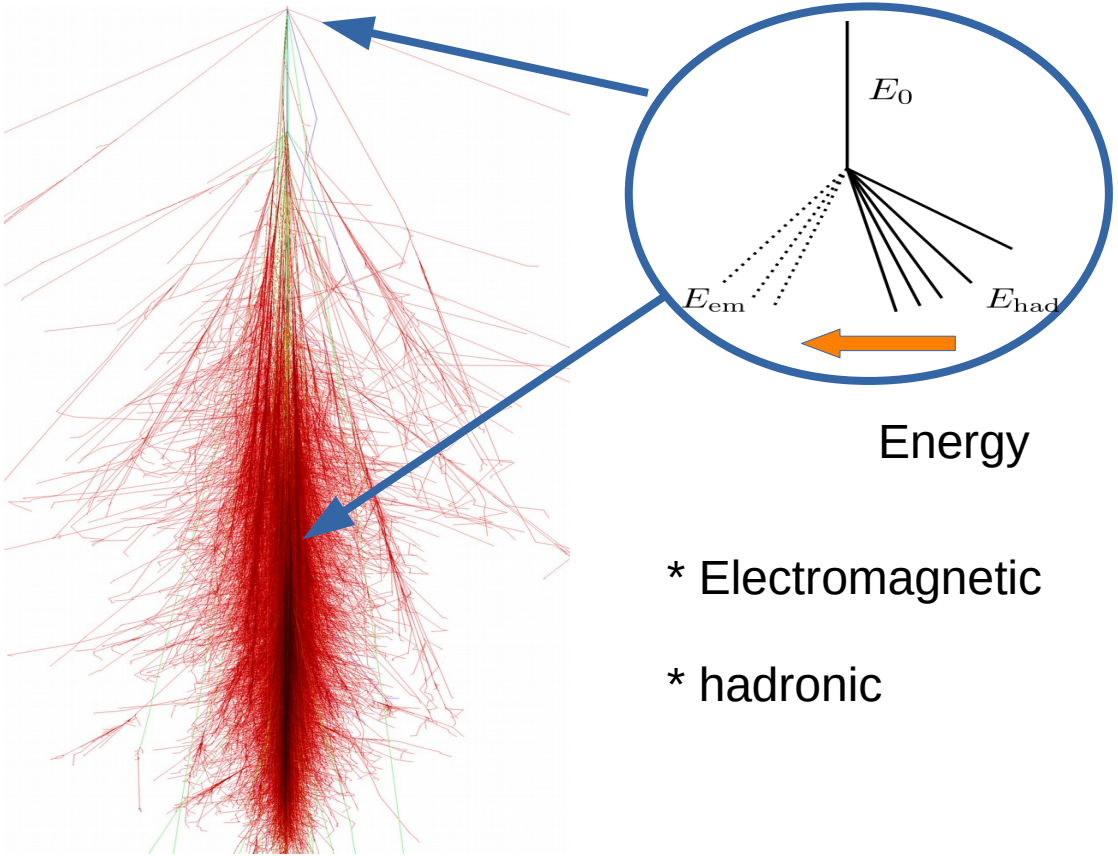
Two showers:

* Electromagnetic $\pi^0 \rightarrow \gamma\gamma$

* hadronic $\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$



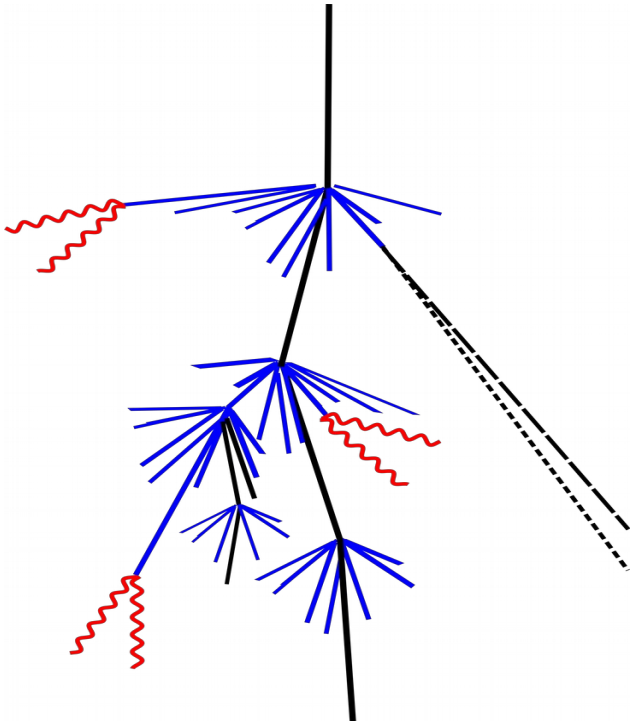
EAS development



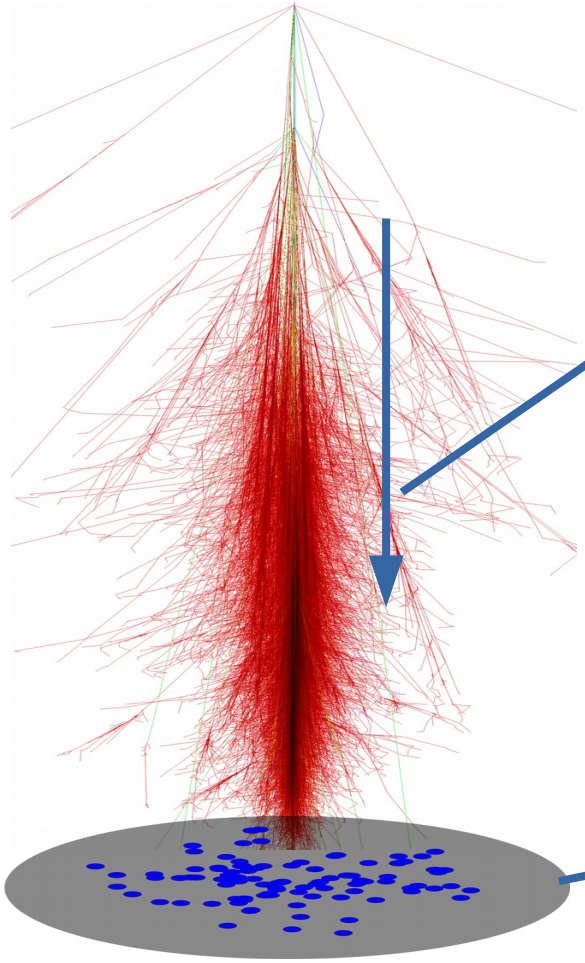
Energy

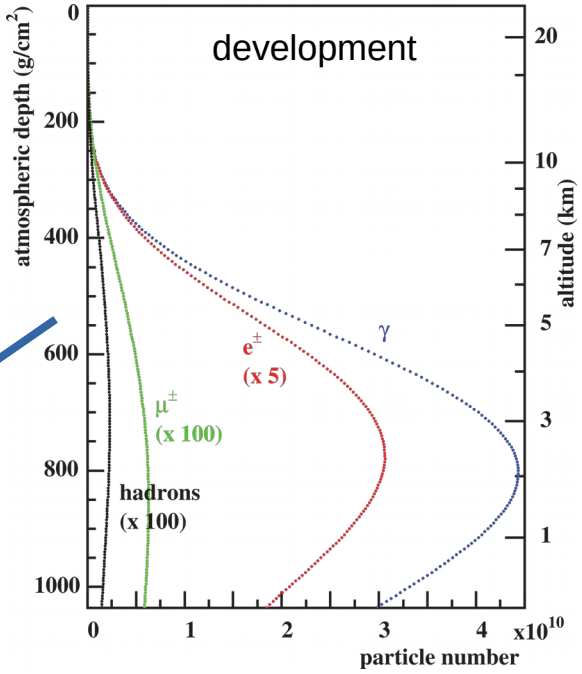
* Electromagnetic

* hadronic



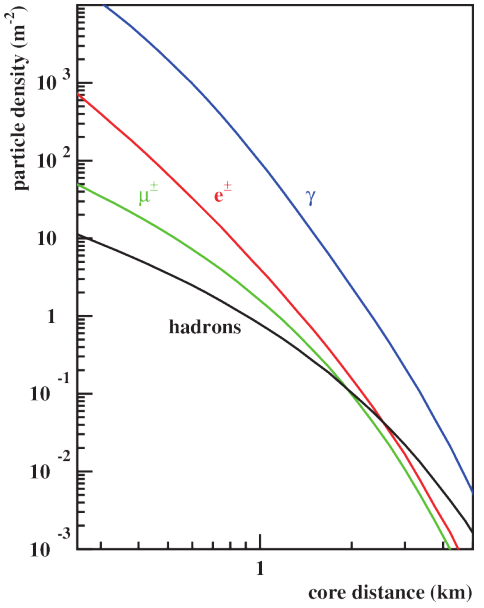
EAS observables





EM dominated

foot-print

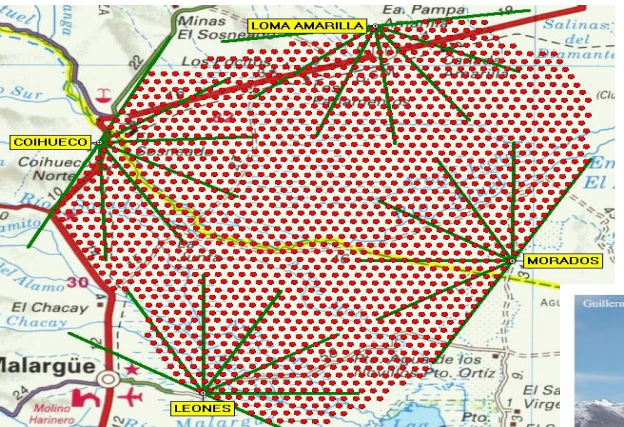


EM & had.

How do we measure EAS?

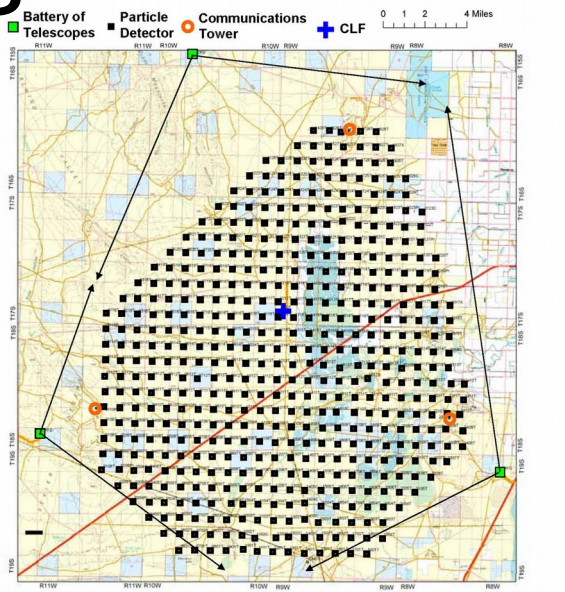
EAS experiments

Low flux → giant detector arrays

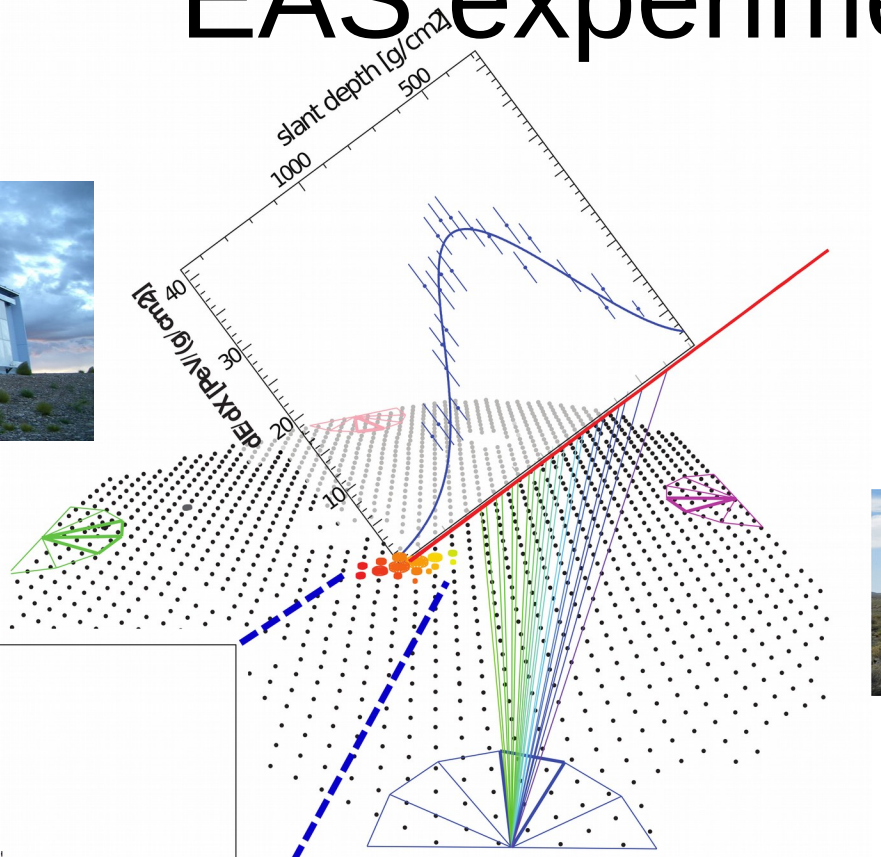


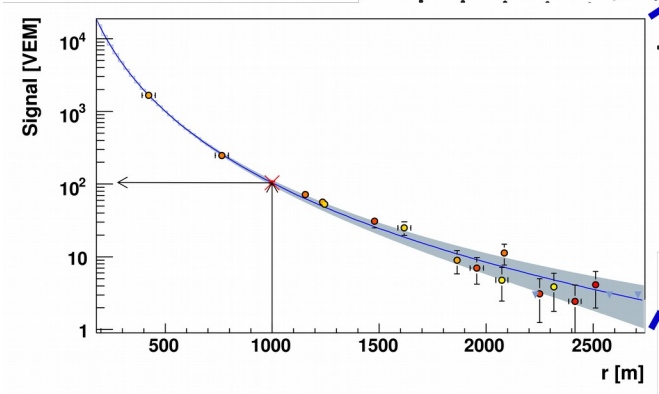
Pierre Auger Observatory

Telescope Array Project (TA)



EAS experiments





Pierre Auger Observatory

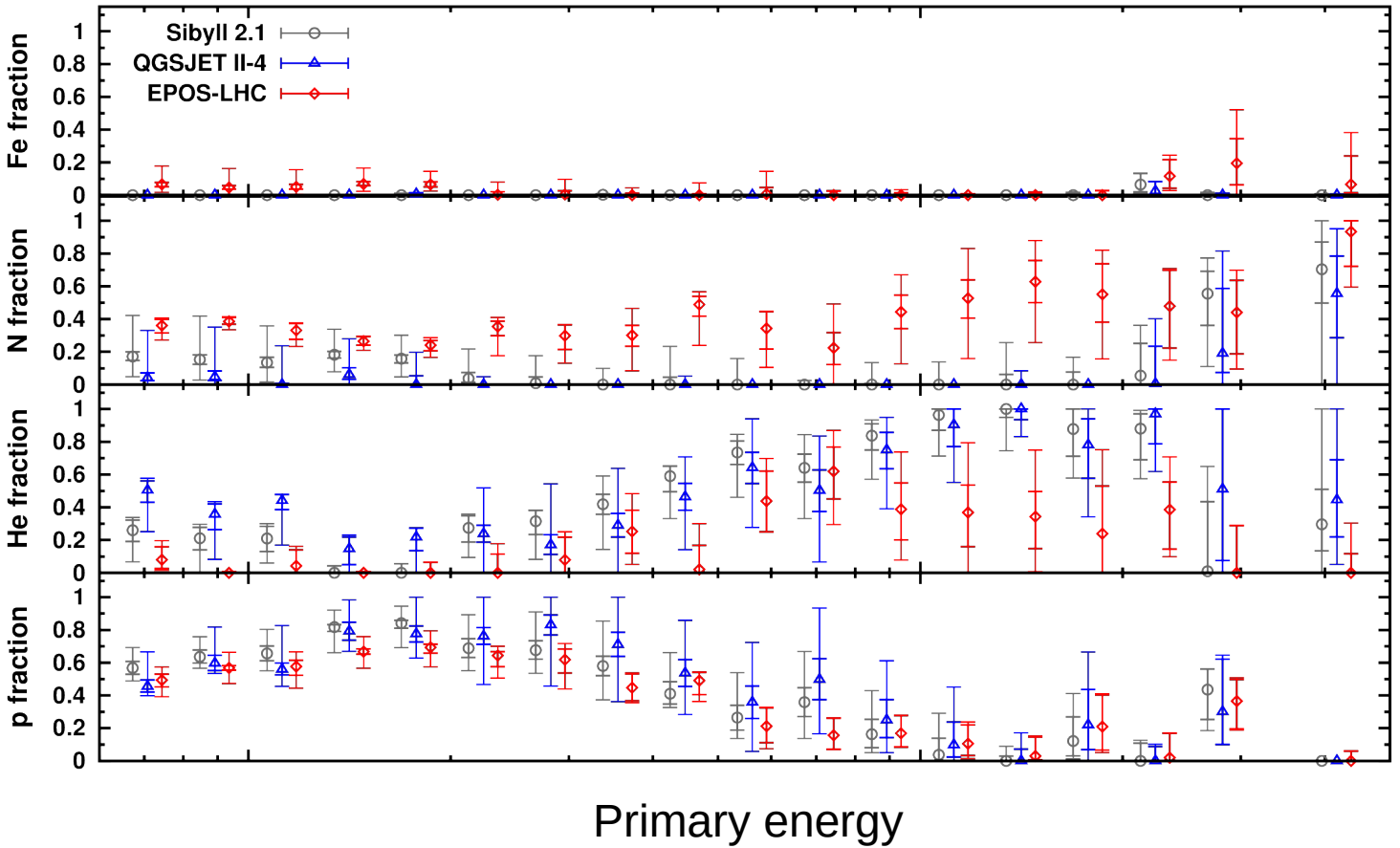
Telescope Array Project

Hybrid:
Telescopes + particle detectors
Development + foot-print

Scintillator vs. water

→ infer primary properties from thin sample of EAS particles

Problem II: primary composition



Inferred from Long. Development

→ EM shower

Shower-to-shower beam unknown

Problem III: muon mystery

Physics

VIEWPOINT

Cosmic-Ray Showers Reveal Muon Mystery

The Pierre Auger Observatory has detected more muons from cosmic-ray showers than predicted by the most up-to-date particle-physics models.

by Thomas Gaisser*

The Large Hadron Collider at CERN produces proton collisions with center-of-mass energies that are 13 thousand times greater than the proton's rest mass. At such extreme energies these collisions create many secondary particles, whose distribution in momentum and energy reveals how the particles interact with one another. A key question is whether the interactions determined at the LHC are the same at higher energies. Luckily, nature already provides such high-energy collisions—albeit at a much lower rate—in the form of cosmic rays entering our atmosphere. Using its giant array of particle detectors, the Pierre Auger Observatory in Argentina has found that more muons arrive on the ground from cosmic-ray showers than expected from models using LHC data as input [1]. The showers that the Auger collaboration analyzed come from atmospheric cosmic-ray collisions that are 10 times higher in energy than the collisions produced at the LHC. This result

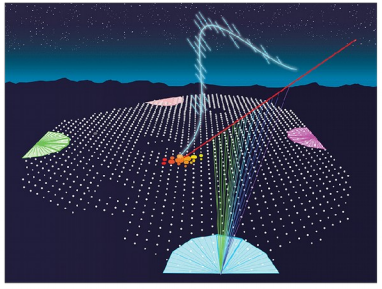
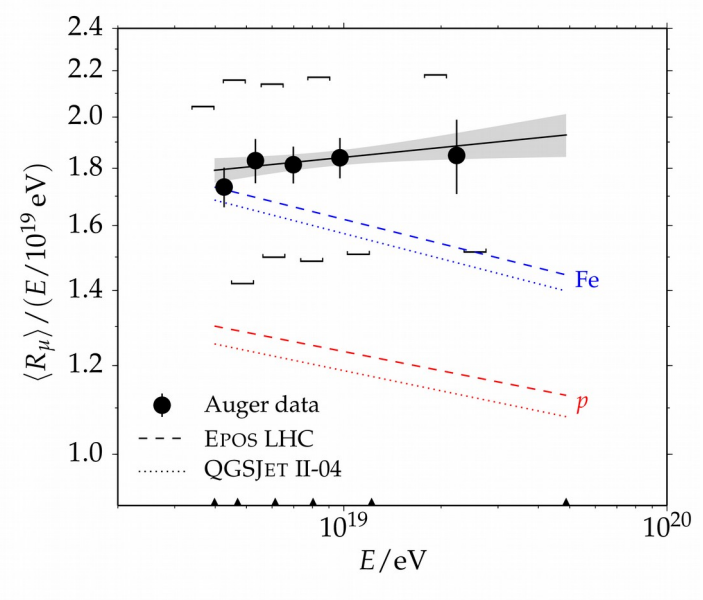
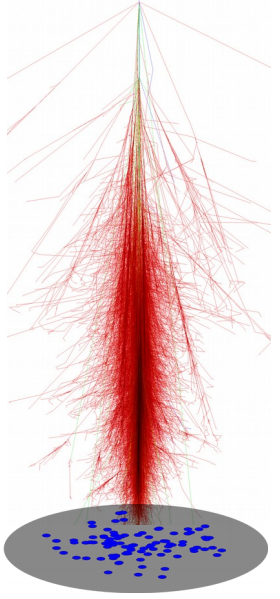


Figure 1: This illustration shows the detection of a hybrid event





More muons in measured in shower foot-print than in simulations

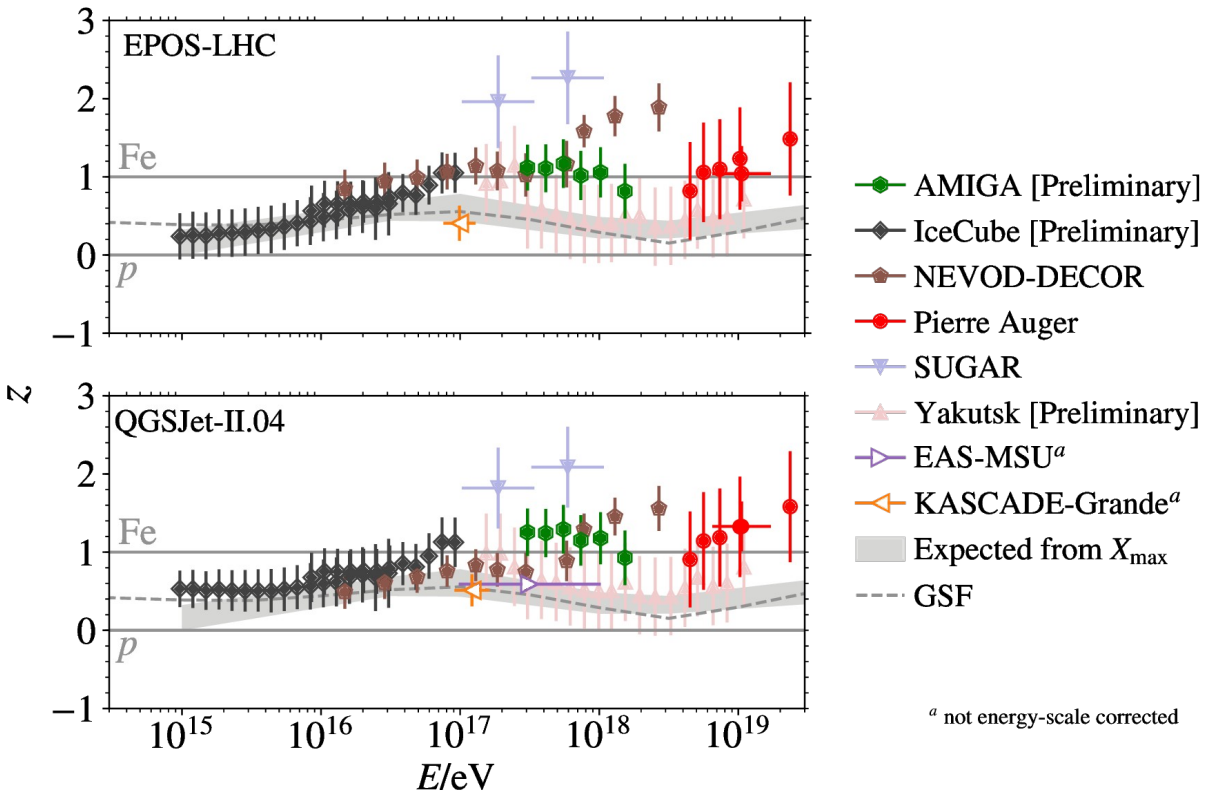
Problem III: muon mystery

Many experiments

Experimental conditions very different

Unified muon scale

$$z = \frac{\ln N_\mu - \ln N_\mu^{\mathrm{ref}\,p}}{\ln N_\mu^{Fe} - \ln N_\mu^{p}}$$

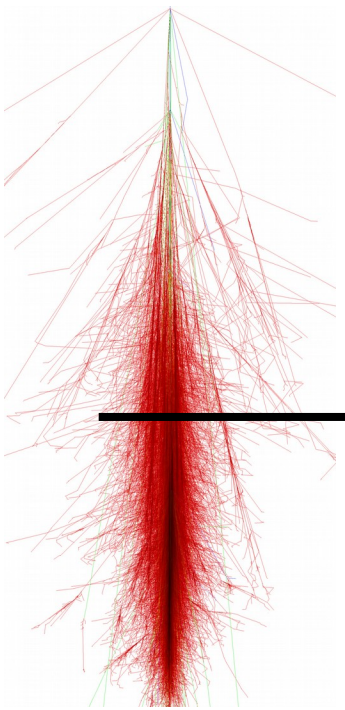


(Working group: had. Int. and shower physics, UHECR 2018)

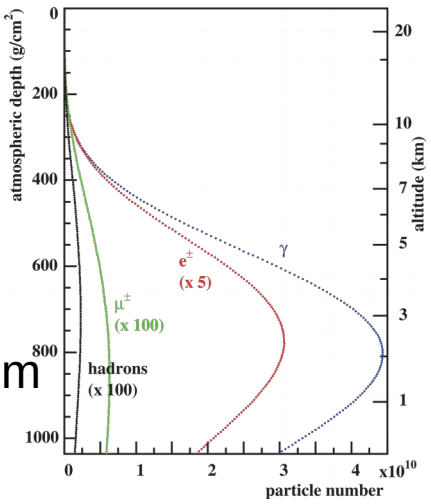
Interlude: the cross section measurement

Cross section measurement

1st interaction

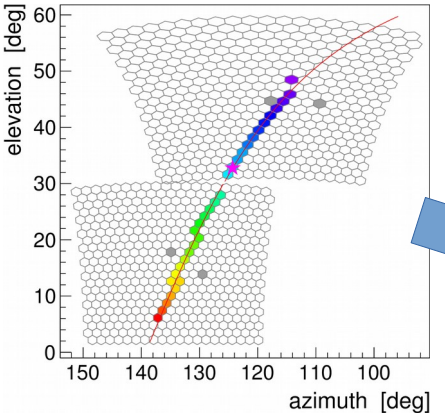


maximum

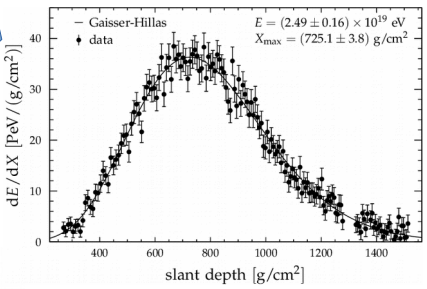


Fluctuations !!

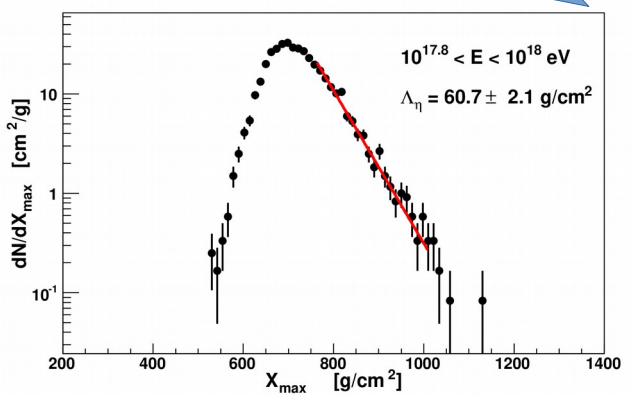
Light emission



Energy deposit

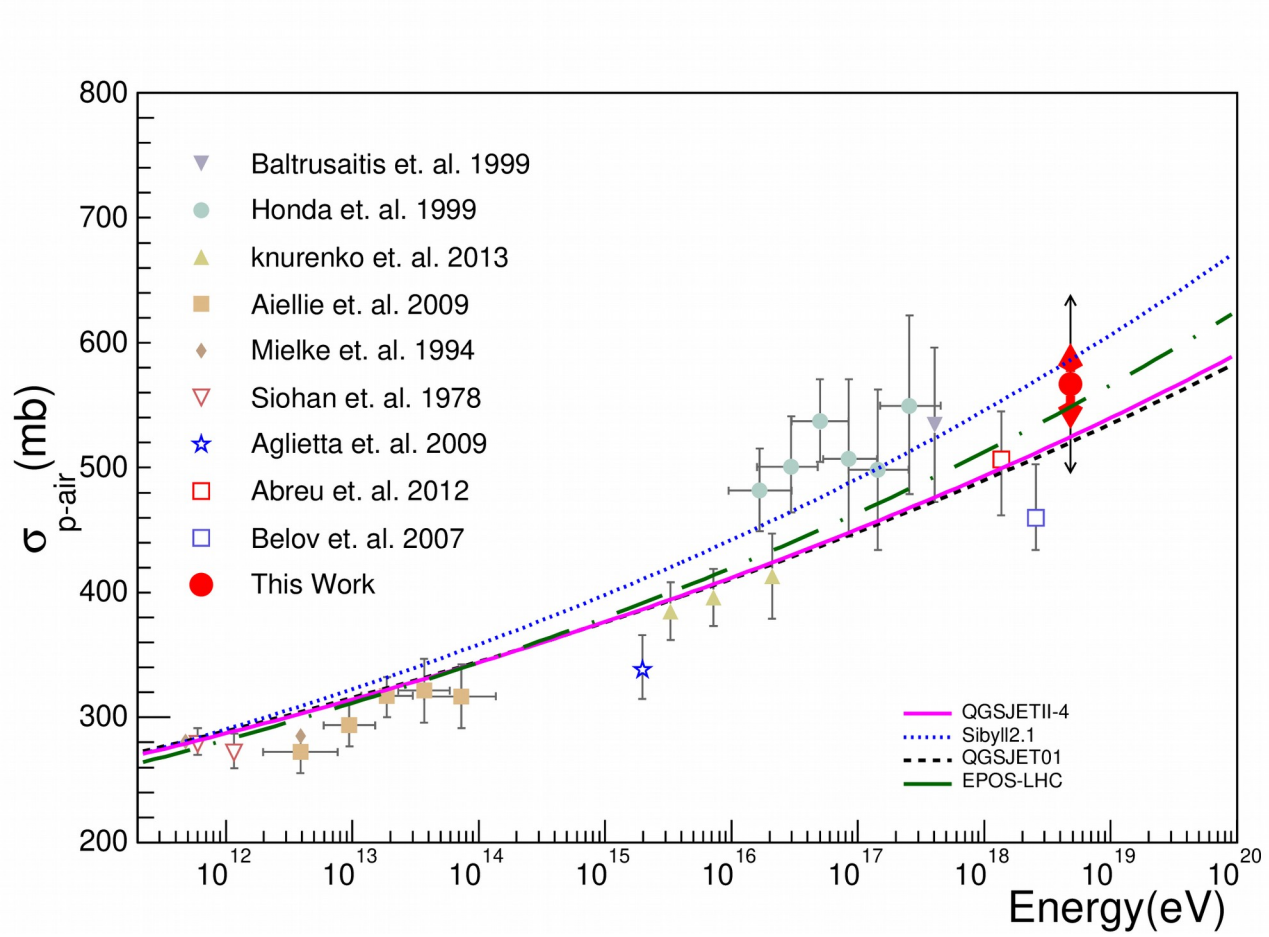


Distribution of Xmax



Cross section

Proton-air cross section



UHECR

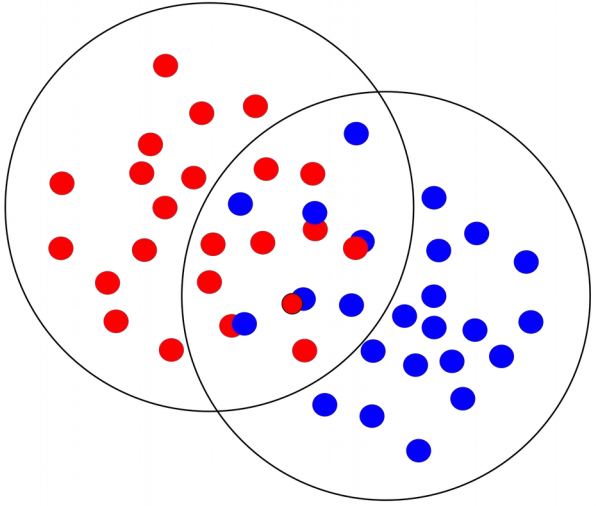
particle physics

Attacking Problems I,II,III ...

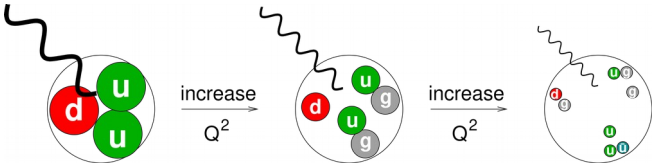
Problem III: the missing muons

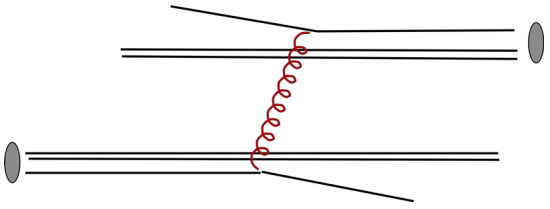
How can we miss that many muons?

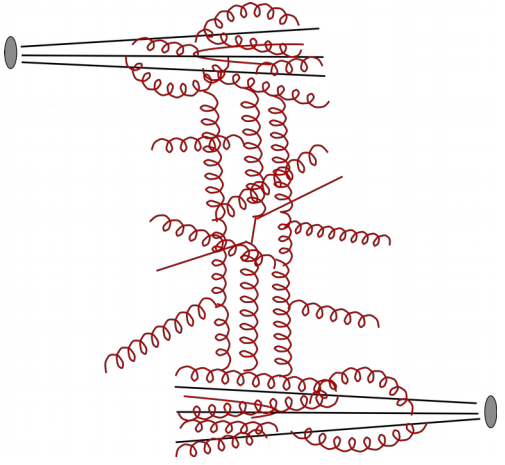
→ hadrons are composite particles difficult to describe



High energy
→ resolve structure of hadrons





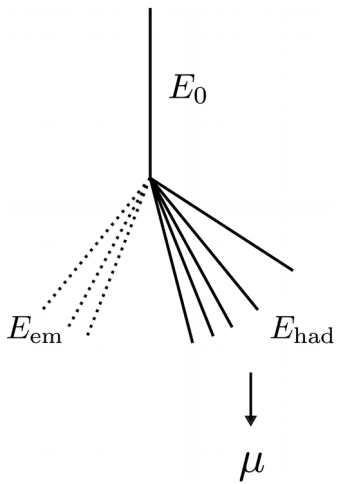


analytic

Sizeable uncertainty

Problem III: the missing muons

How to increase
muon production in EAS?



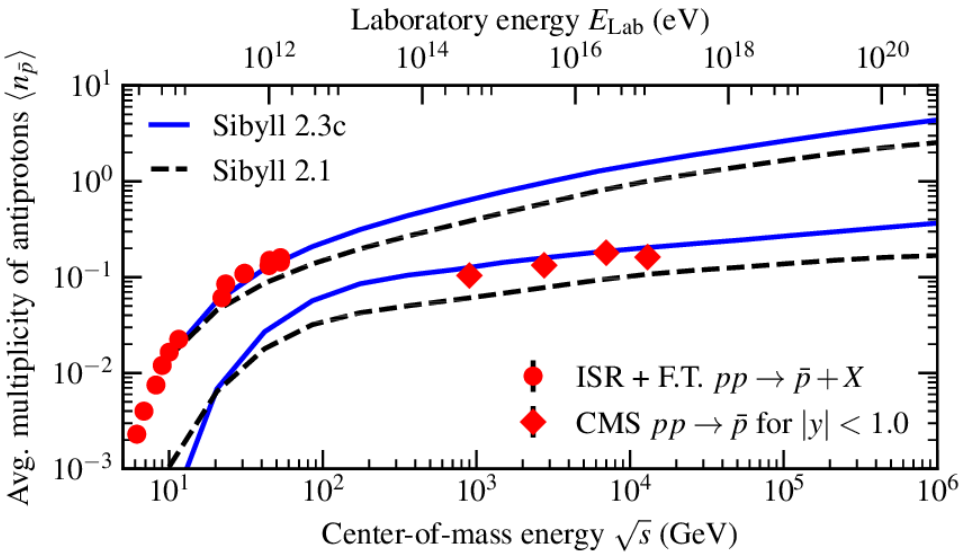
How?

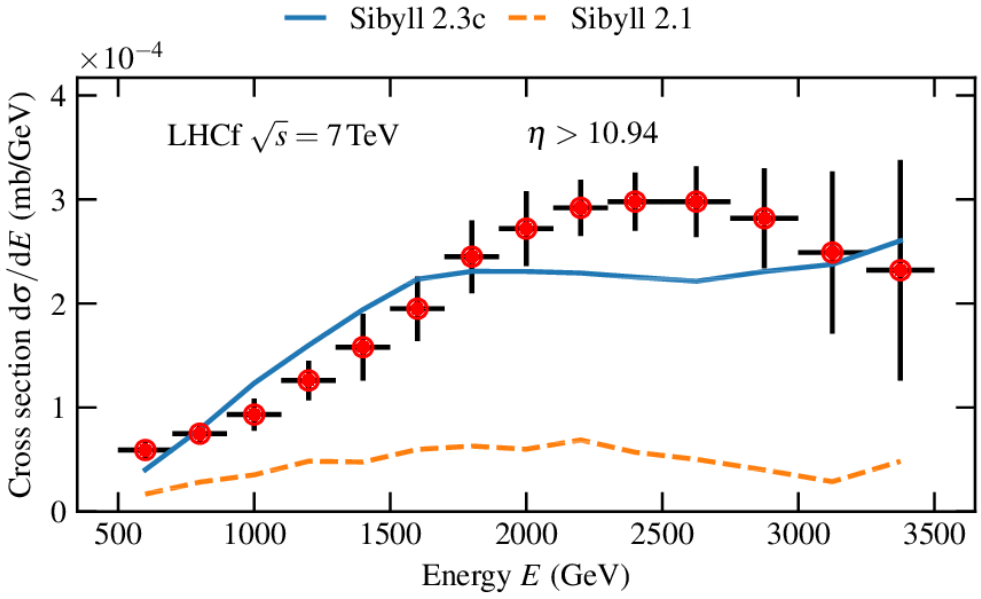
* decrease neutral pion production
* increase baryon production
* ...

Modify interactions based on
LHC & fixed target experiments

Increase energy in hadronic component

Baryon production

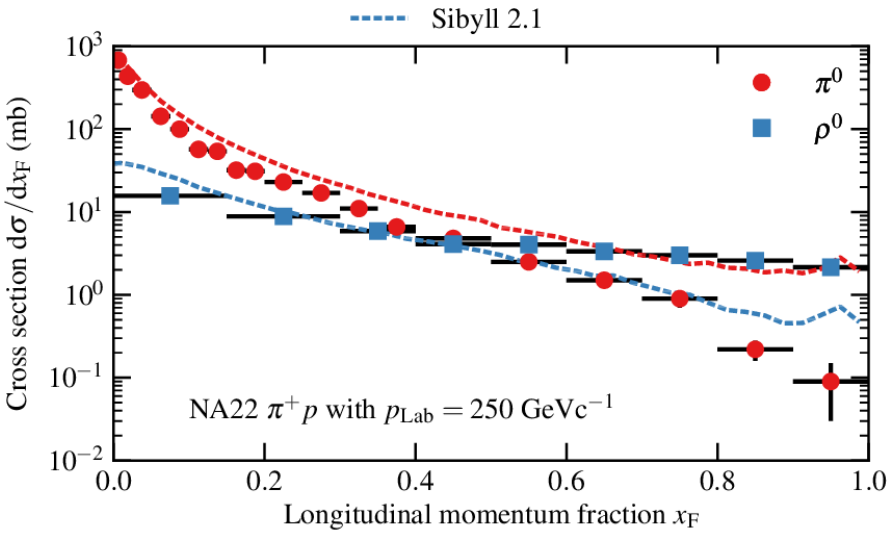


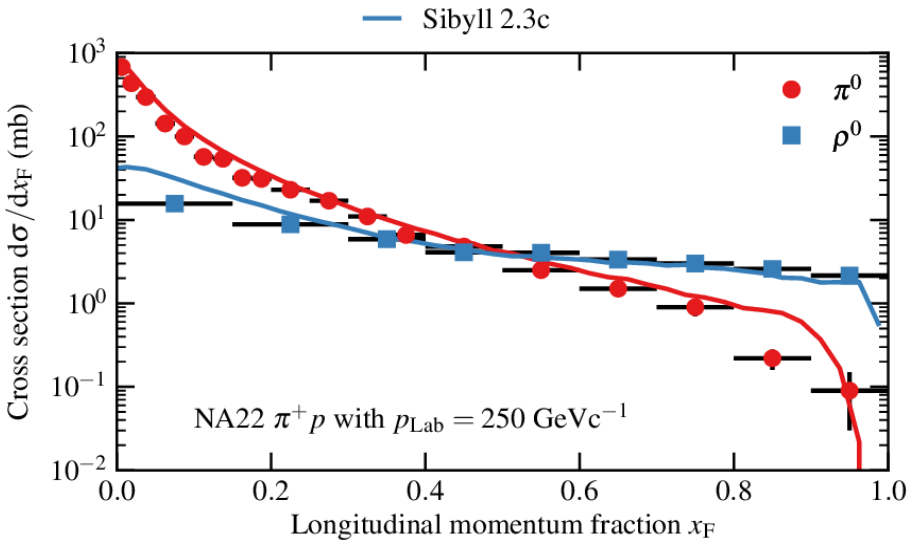


More subshowers,
smaller inelasticity

Neutral pions

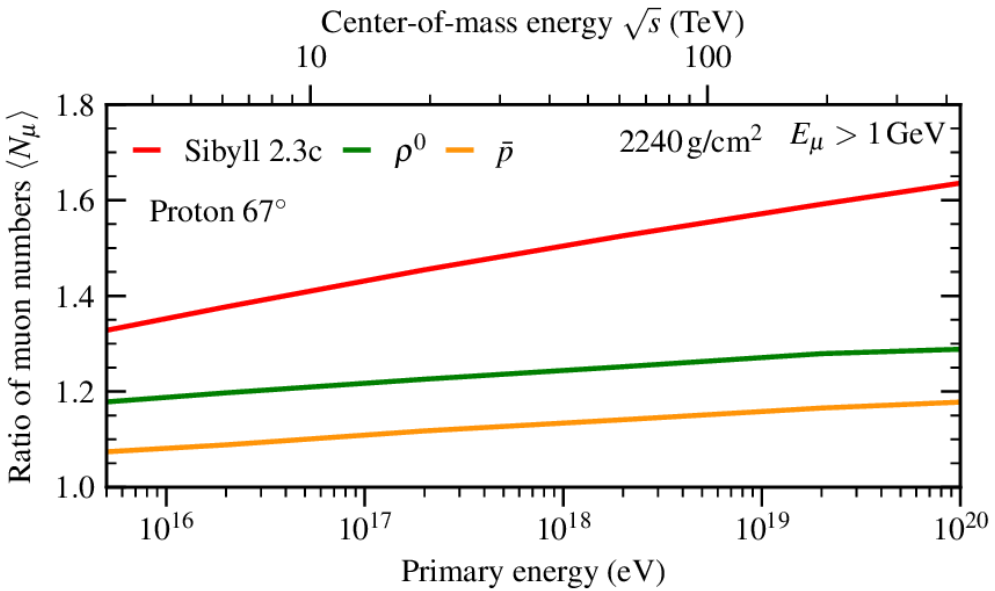
$\pi^+ + p \rightarrow \text{leading} + X$ $\qquad$ $\text{leading} : \pi,\ \rho$

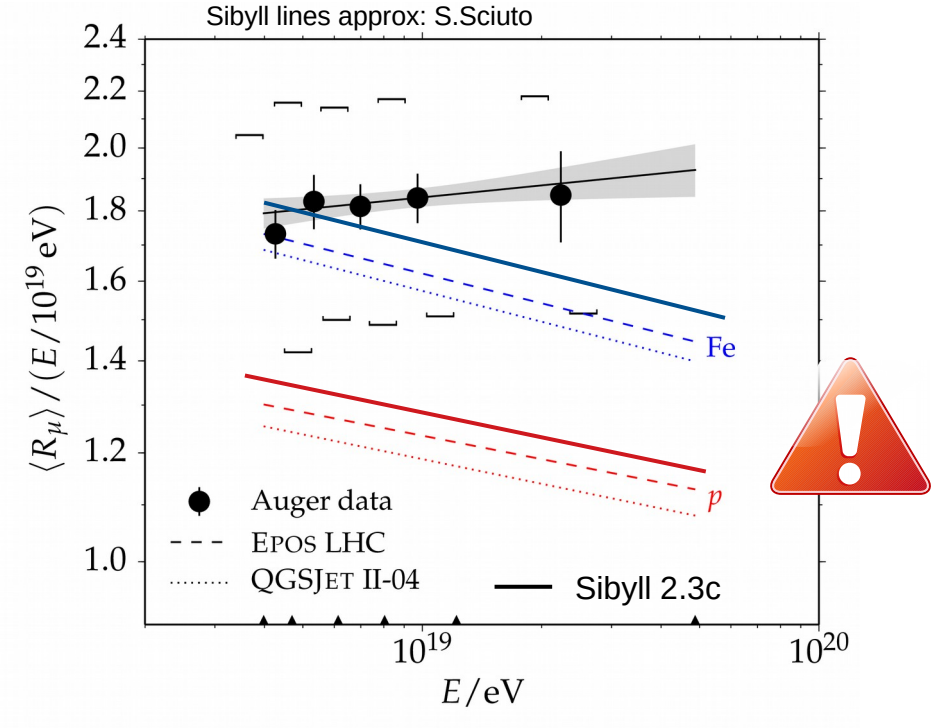




Increased muon production

Baryon prod. & pi0 decreas
→ 40-60% more muons





(Auger, Phys. Rev. D, 91, 032003 (2015))

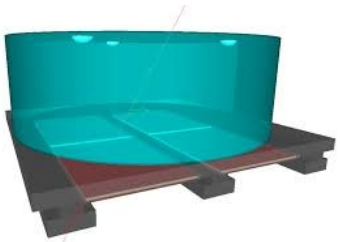
But not final word.
LHC RunII measurements (LHCf+Atlas,Castor) tuning

Problem II: overcoming composition

More simultaneous measurements

AugerPrime:

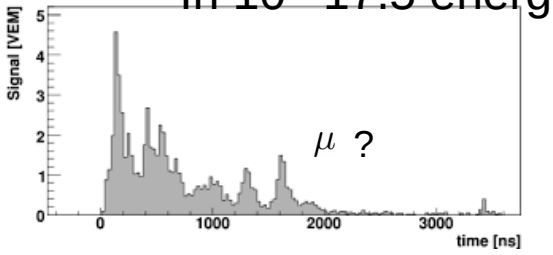
* scintillators (foot-print)
* radio measurement (development)



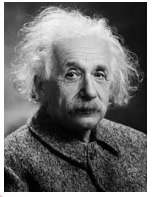
Additional:

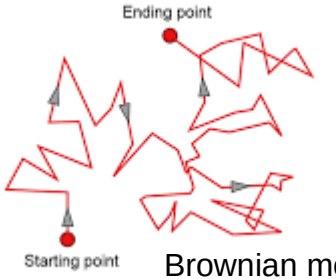
* buried muon detectors (AMIGA)
* track counters (RPCs, MARTA)

Specify SSD+water tank
In 10**17.5 energy range



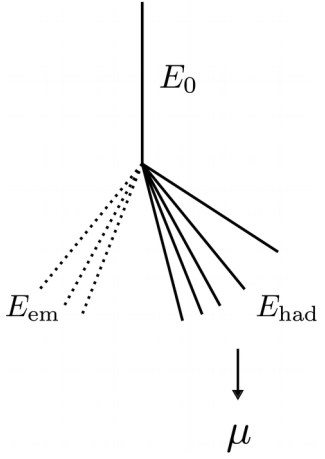
Problem I: accessing first interaction



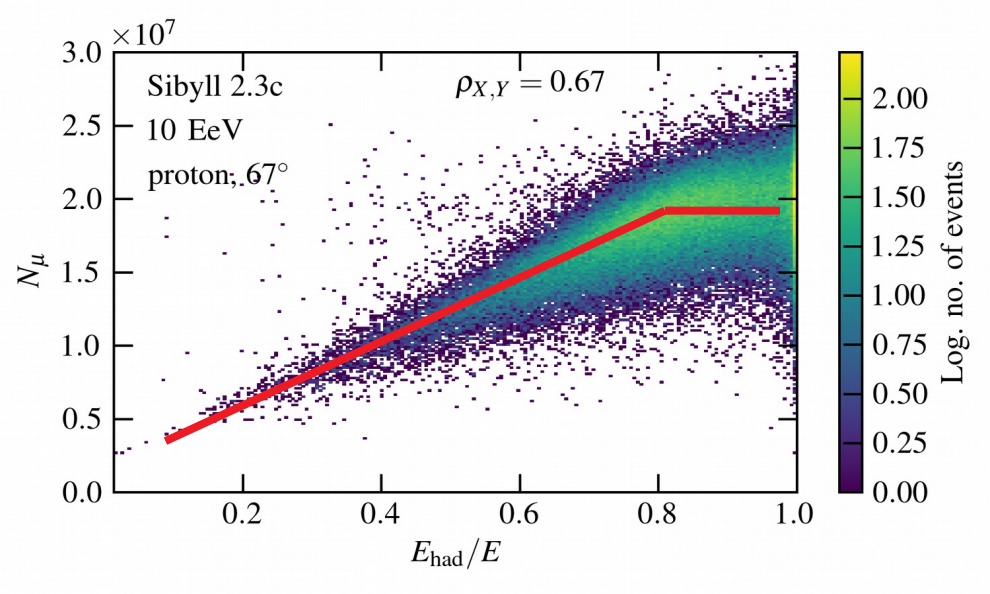


Fluctuations reveal existence of atoms!

Brownian motion



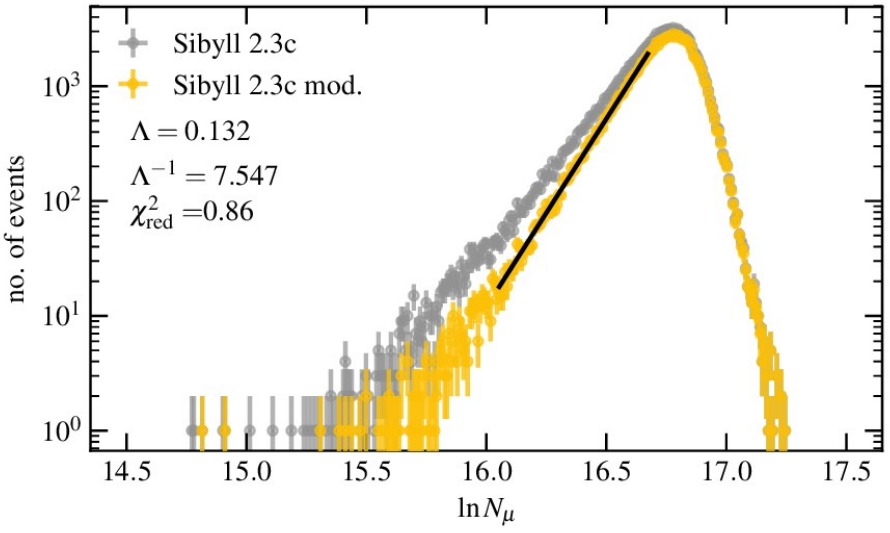
$$N_\mu \sim E_{\rm had}$$



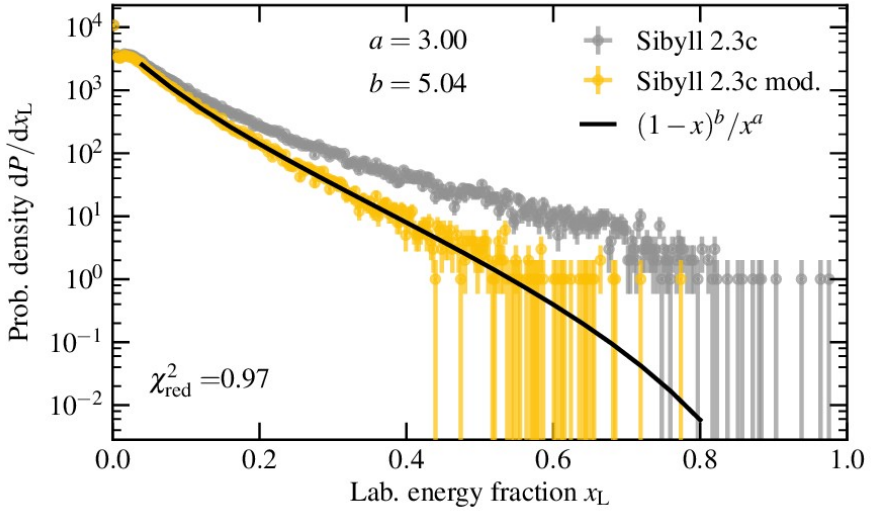
(L. Cazon, R. Conceição, FR: PLB 784 (2018) 68-76)

2nd HEP measurement with EAS

Distribution of number of muons



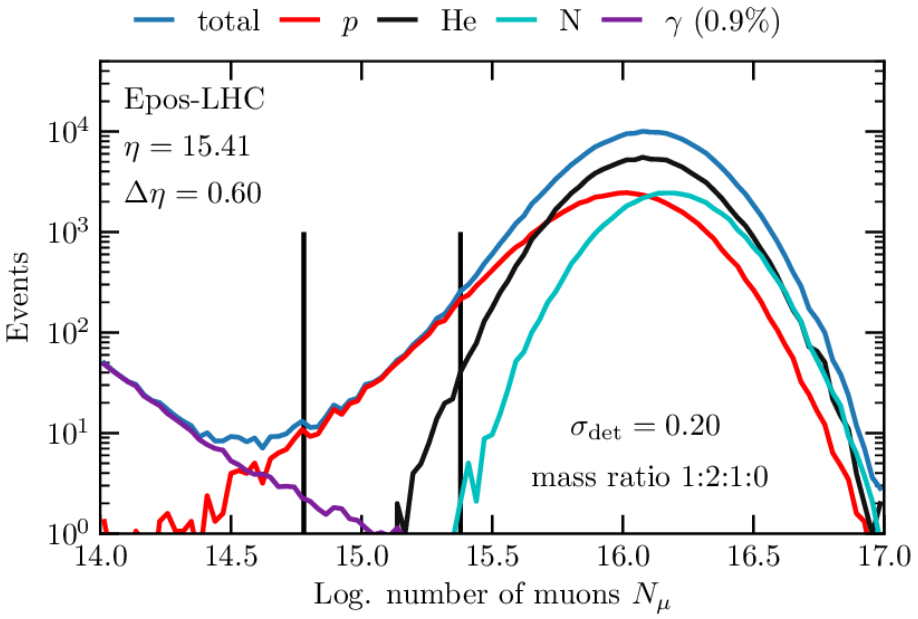
Inclusive pion prod. spectrum

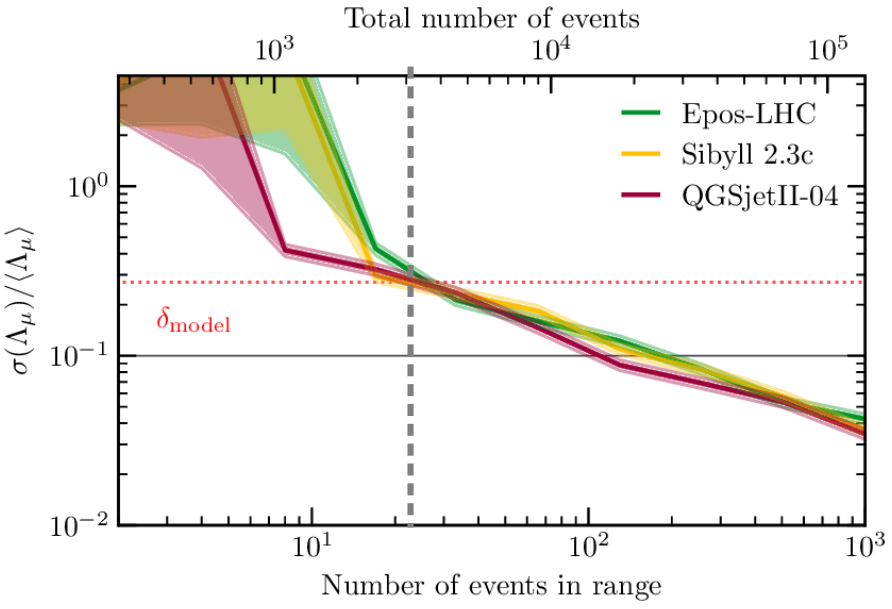


Remember cross section !

A scenario

$\approx 10^{18.7}\,\mathrm{eV}$





Summary

* UHECR probe particle interactions

  but particle physics entangled with astrophysics

* Disentangle by:

  - additional measurements,

    shower-to-shower composition

  - LHC experiments

  - focus on fluctuations

* muon fluctuations could allow

  measurement of pion production spectra