Radboud Universiteit

Nikhef

PIERRE AUGER OBSERVATORY

Muon measurements at the **P**ierre **A**uger **O**bservatory

K. Almeida Cheminant

29th Symposium on Astroparticle Physics in the Netherlands

Soesterberg

Ultra-high energy cosmic rays

★ **Why the knowledge of the mass of UHECR is important?**

- The **rigidity** of UHECR is inversely proportional to their mass → constraints on propagation in magnetic fields and therefore, on candidate sources.
- **Acceleration mechanisms** at the sources can be better understood.
- Study hadronic interactions at the highest energies and search for neutral particles (γ, ν).

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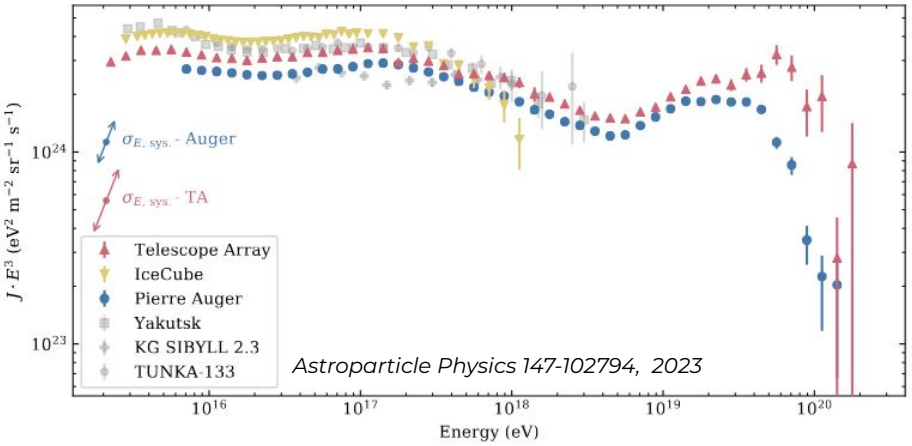


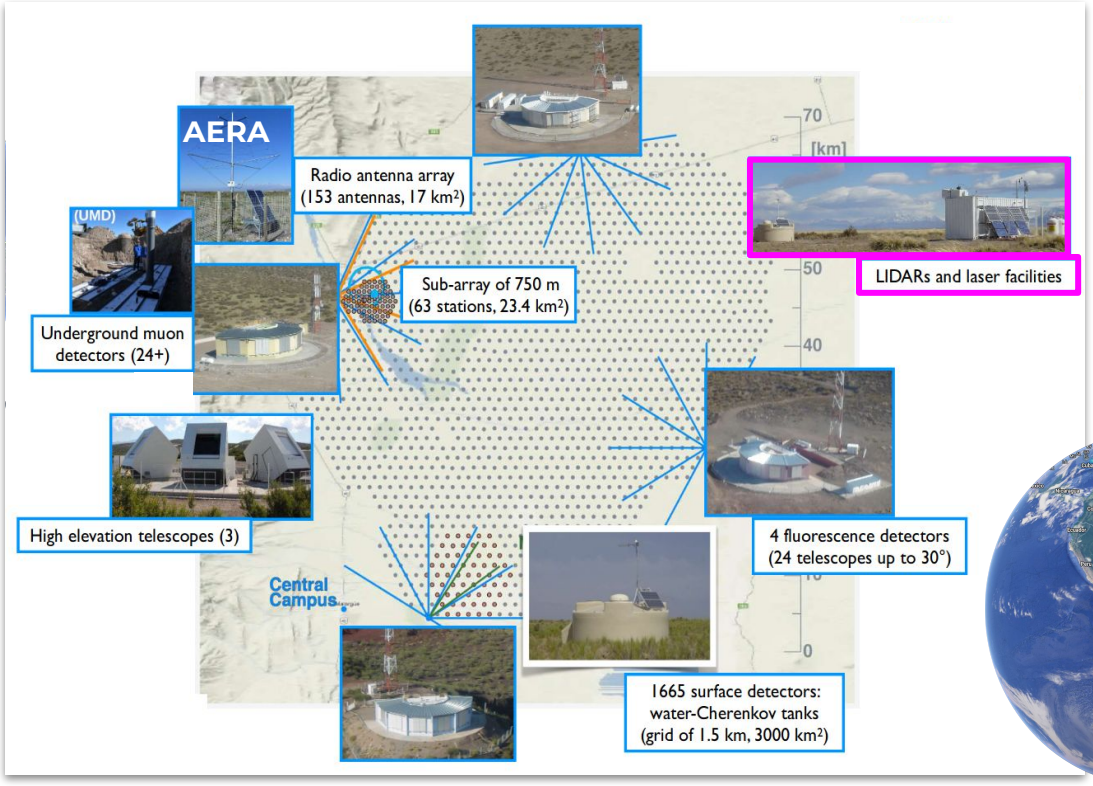
⚠ Major roadblock ⚠

- Extremely low-flux at the highest energies → direct detection unfeasible!
- Indirect inference on the properties of UHECR through their **interaction with the atmosphere**.

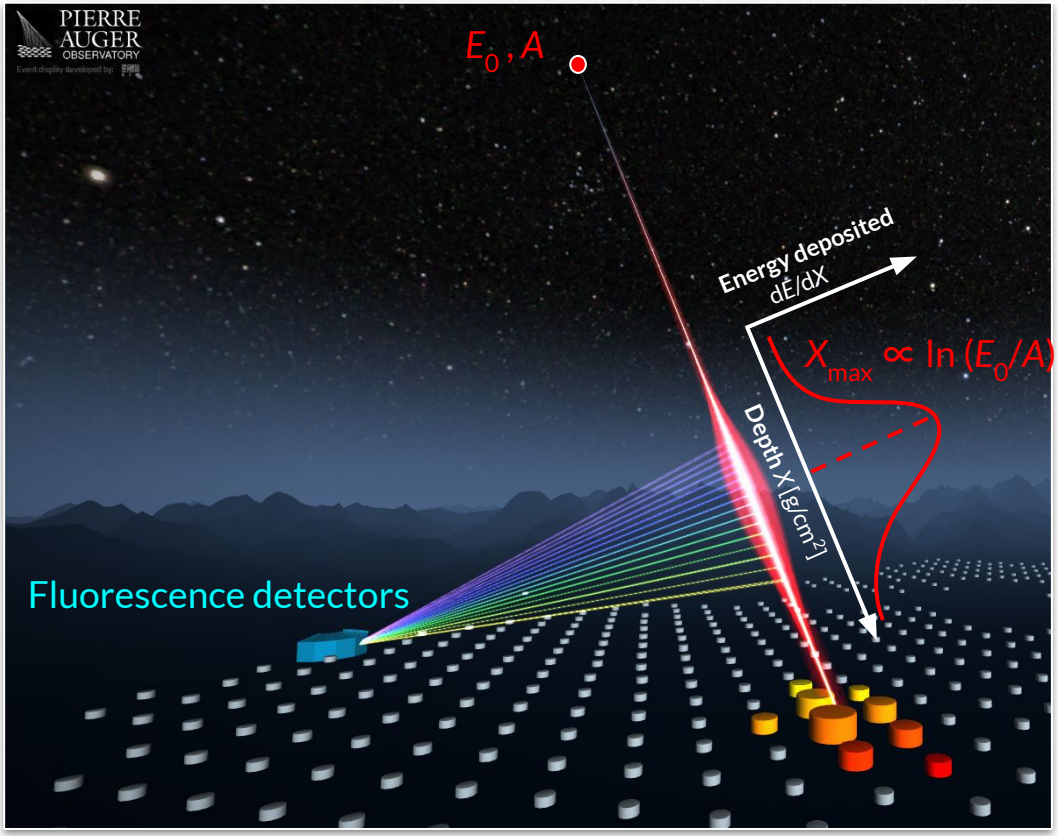
★ Need for **large-scale ground** experiments!

The Pierre Auger Observatory

- ★ **Water-Cherenkov Surface Detectors (SD)**: signal of secondary particles at the ground.
- ★ **Fluorescence Detectors (FD)**: longitudinal development of air showers.
- ★ **Underground Muon Detectors**: muon signal.
- ★ **And many others**: radio antennas, LIDARs, etc...



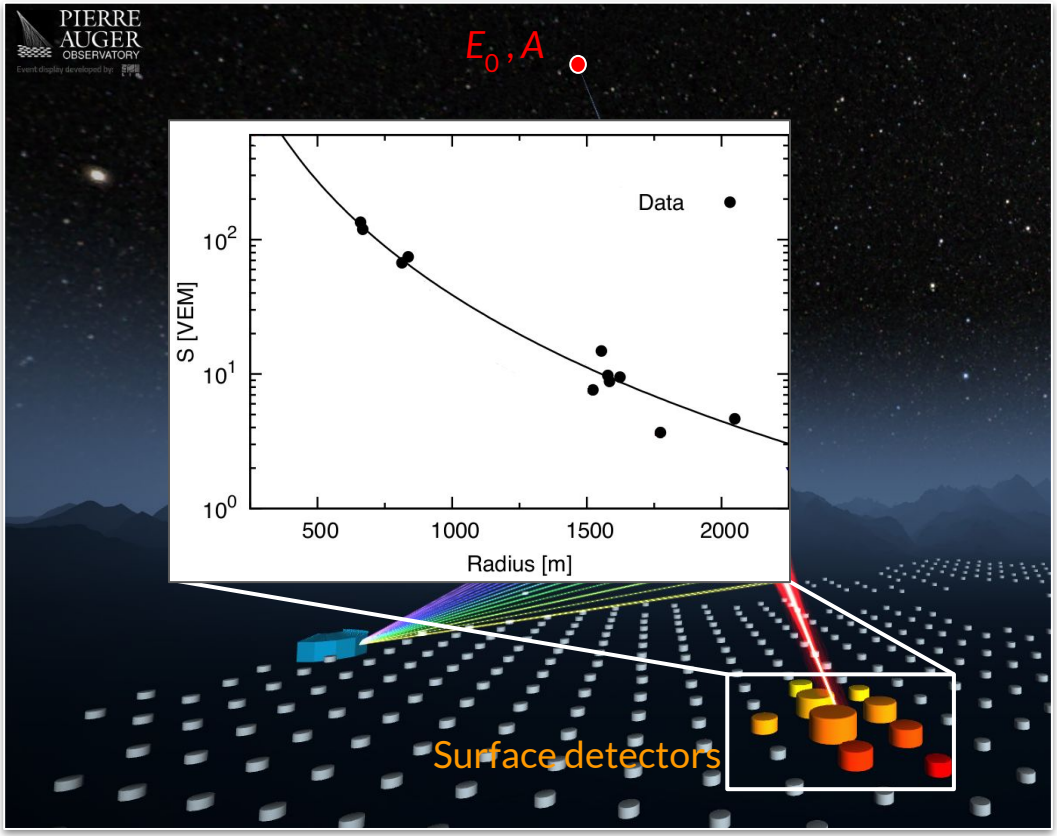
Extensive air showers



Longitudinal profile

- Electromagnetic component formed by the decay of π^0
  - ***depth of maximum development*** X_{max}

Extensive air showers



Longitudinal profile

- Electromagnetic component formed by the decay of π^0
  - *depth of maximum development* X_{max}

Ground distribution

- Electromagnetic and muonic component formed by the decay of $\pi^{+/-}$ and $K^{+/-}$
  - ***number of muons***

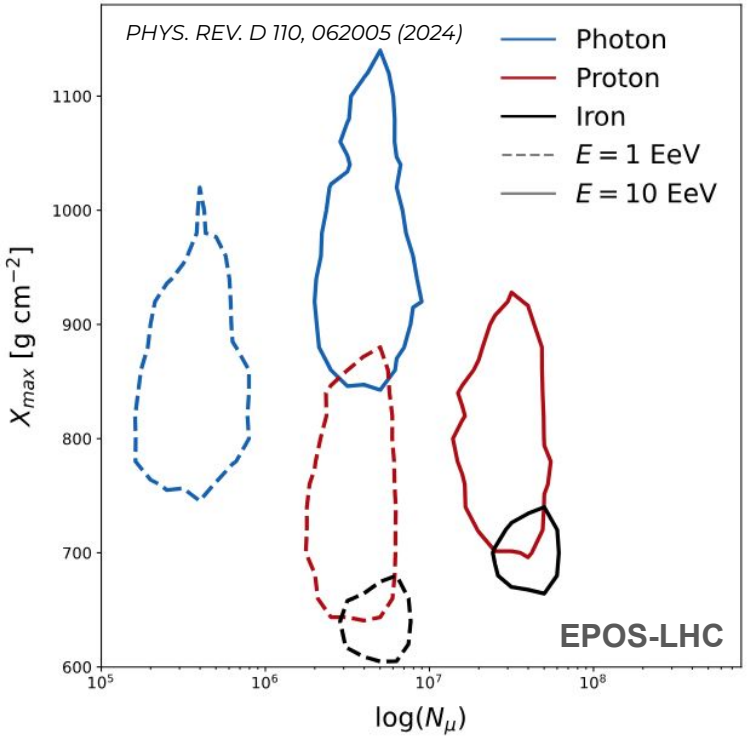
The Pierre Auger Observatory

Fluorescence detectors (FD)

- ★ Sensitive to the electromagnetic component.
- ★ Mass estimation from $\mathbf{X_{max}}$ measurement.
- ★ Low duty cycle: ~15%.

Surface detectors (SD)

- ★ Sensitive to electromagnetic and muonic components.
- ★ Mass estimation from $\mathbf{N_{\mu}}$.
- ★ 100% duty cycle.



Muon measurements at the Pierre Auger Observatory

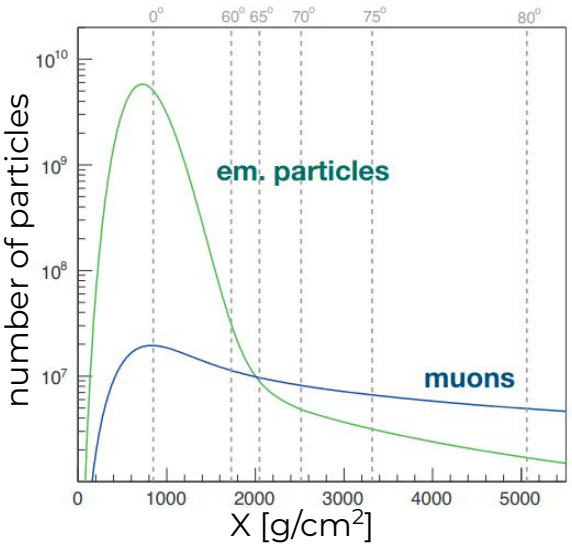
Inclined air showers

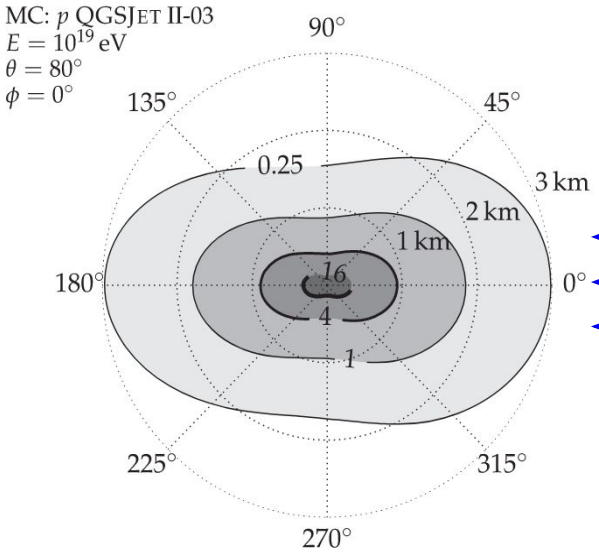
Pierre Auger Collab., PRD 91, 032003 (2015)

- The electromagnetic component is absorbed by the atmosphere.

- SD-1500 array
- $62° < \theta < 80°$
- Above 4×10^{18} eV
- Hybrid events

proton - EPOS-LHC - 10^{19} eV





Arrival direction of muons

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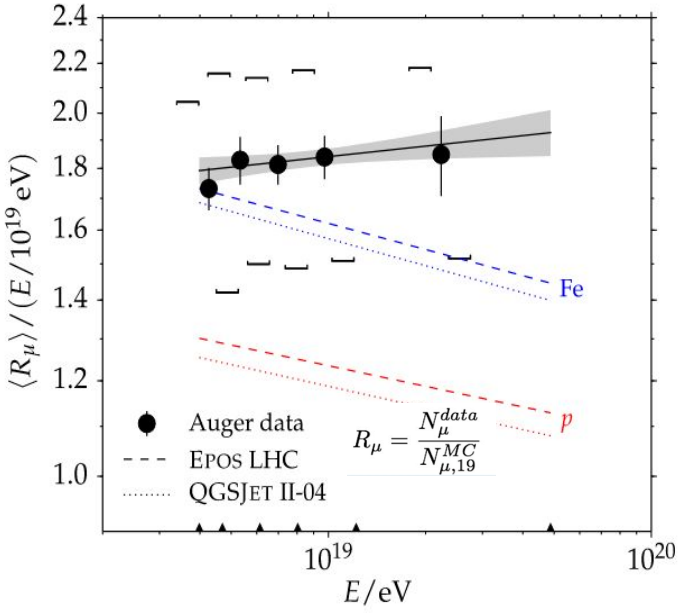
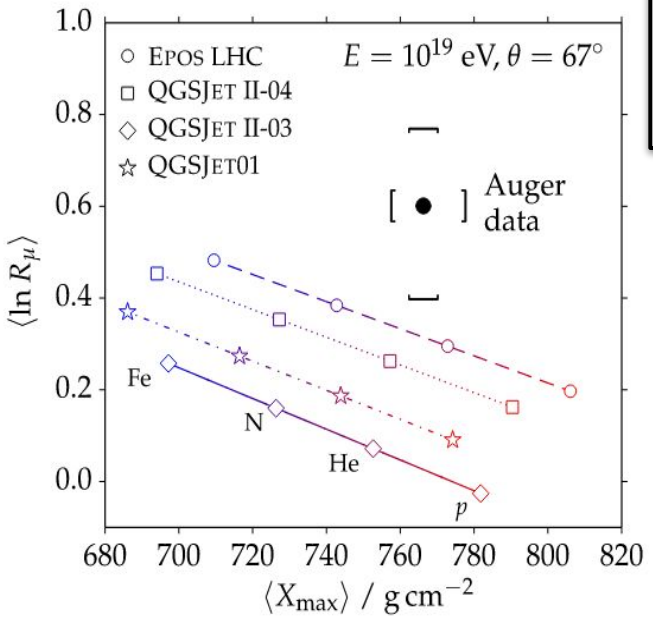




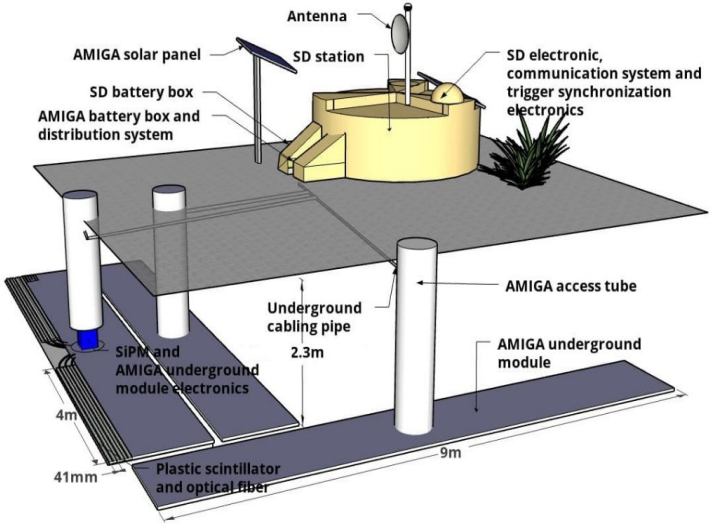
Muon measurements at the Pierre Auger Observatory

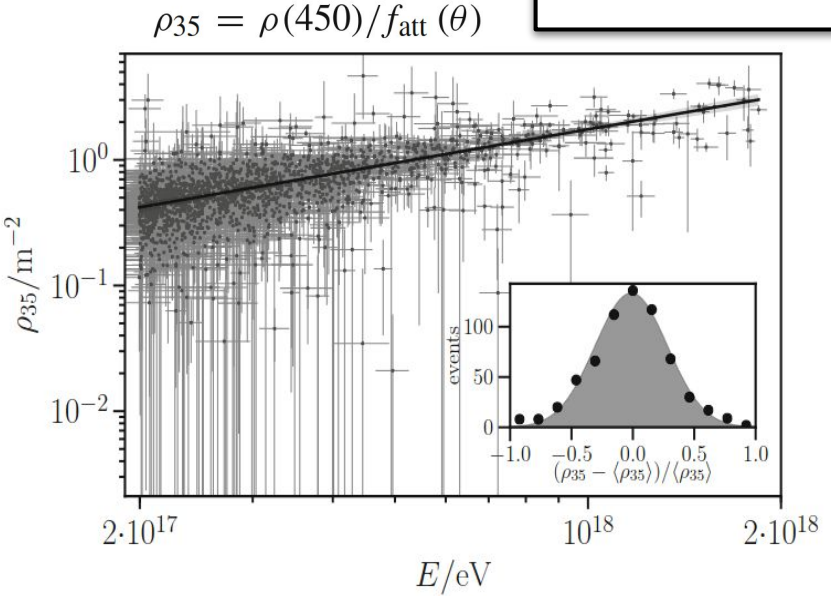
Underground measurements

Pierre Auger Collab., Eur. Phys. J. C (2020) 80:751

- The electromagnetic component is absorbed by the ground.

- ➢ 7 UMD
- ➢ $\theta < 45°$
- ➢ Below 2 x 10^{18} eV





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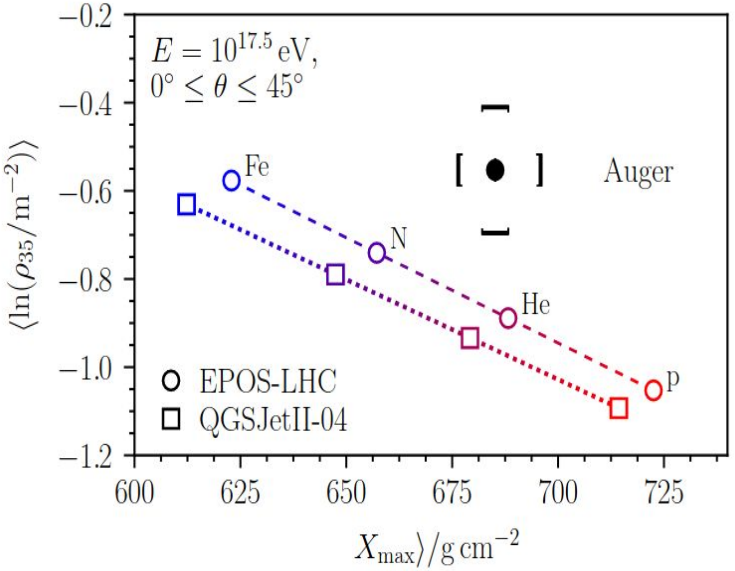
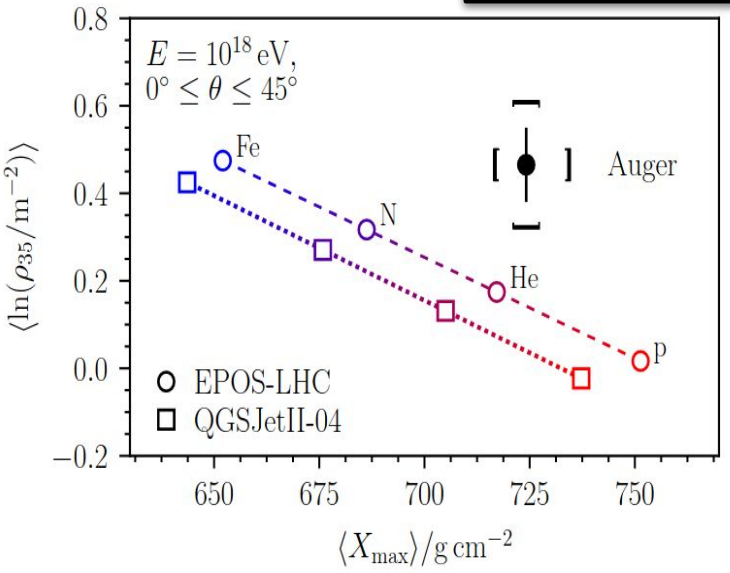




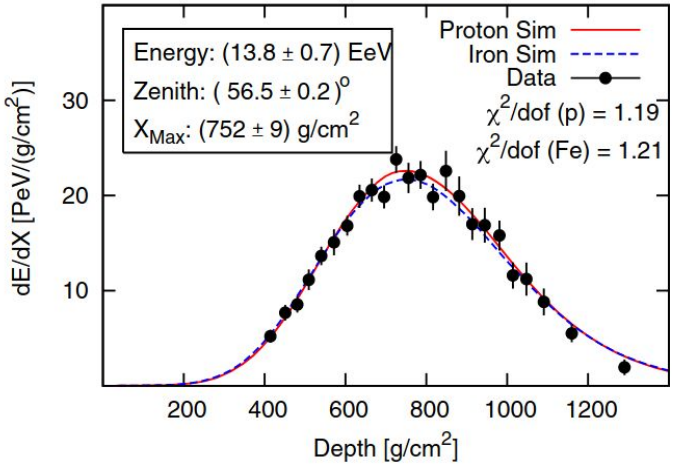
Muon measurements at the Pierre Auger Observatory

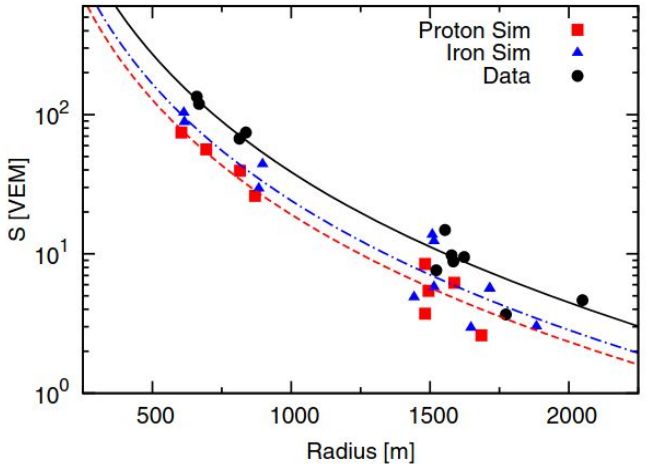
Vertical Hybrid measurements

Pierre Auger Collab., PRL 117, 192001 (2016)

- ➢ SD-1500 array + FD
- ➢ $\theta < 60°$
- ➢ 6×10^{18} eV < E < 16×10^{18} eV

❖ The electromagnetic component is quantified and subtracted.





➢ Top-down simulations : For a given hybrid event (E,θ), find the simulations that fit the longitudinal profile of the event the best.

➢ Lateral profile of ground signal **underestimated** by hadronic models.

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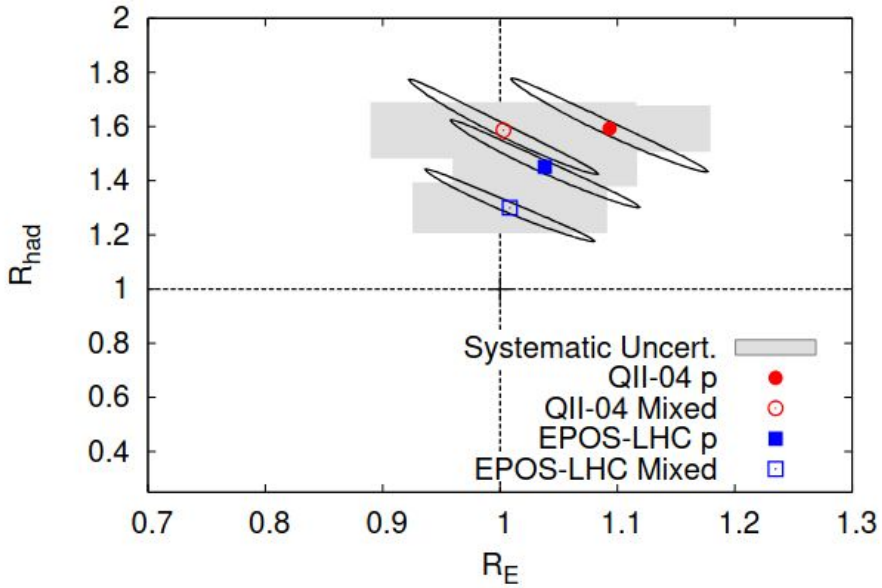

$$S_{\mathrm{resc}}(R_E, R_{\mathrm{had}})_{i,j} \equiv R_E S_{\mathrm{EM},i,j} + R_{\mathrm{had}} R_E^{\alpha} S_{\mathrm{had},i,j}$$

➢ **S_{resc}** - Signal at 1000m once the EM (S_{EM}) and the hadronic (S_{had}) component of simulations for a primary **i** have been rescaled by **R_E** and **R_{had}**, respectively.

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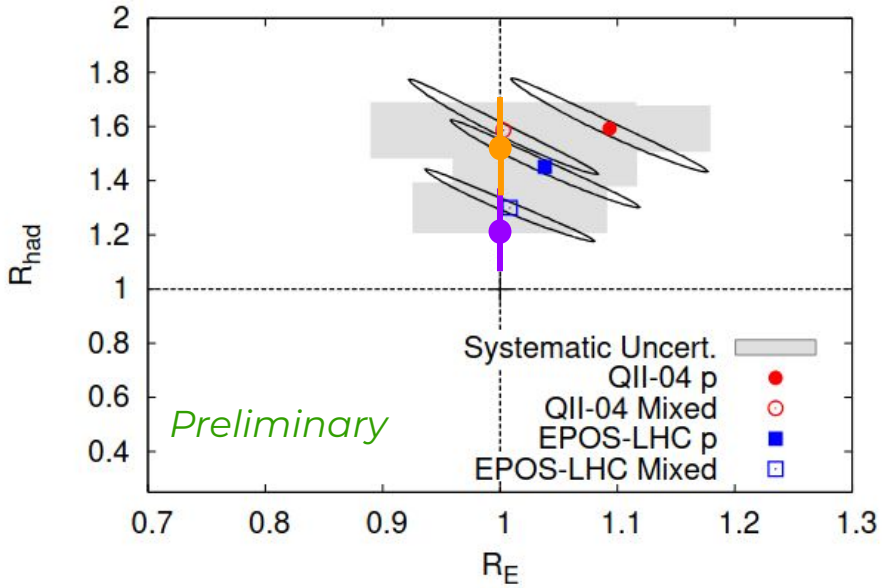

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Results updated with Sibyll 2.3d

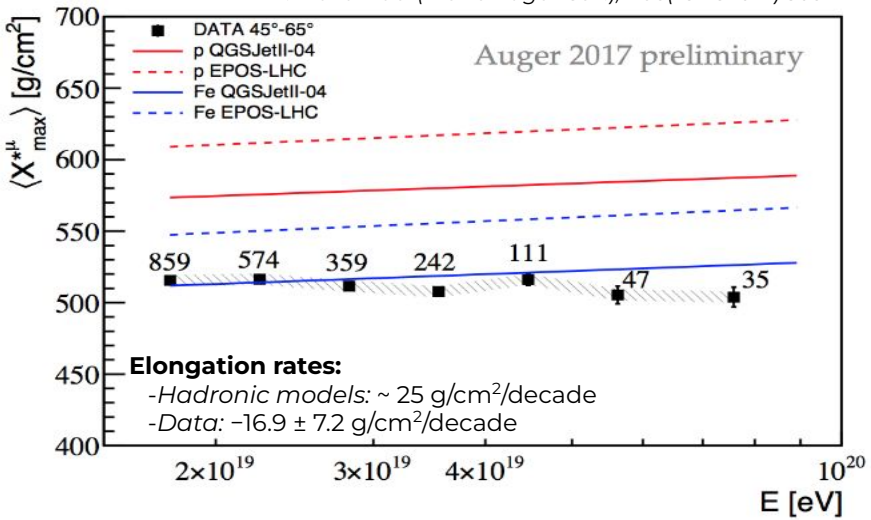
Auger comp.* (based on X_{max})	**1.21 ± 0.17**
Pure proton	**1.53 ± 0.22**

Muon measurements at the Pierre Auger Observatory

This list is not exhaustive…

➢ Muon production depth.

Pierre Auger Collab., PRD 90, 012012 (2014)
M. Mallamaci (Pierre Auger Coll.), PoS(ICRC2017) 509



Muon measurements at the Pierre Auger Observatory

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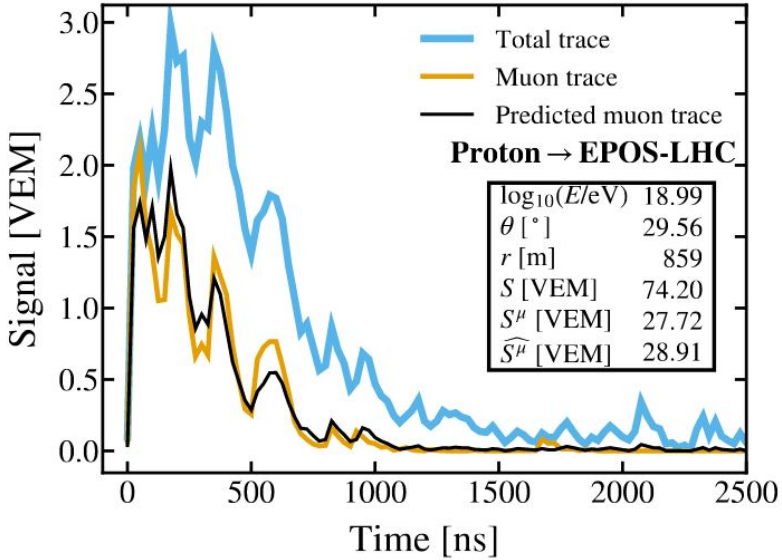
- Neural network for muon traces.

Pierre Auger Collab., JINST (2021) 16 P07016



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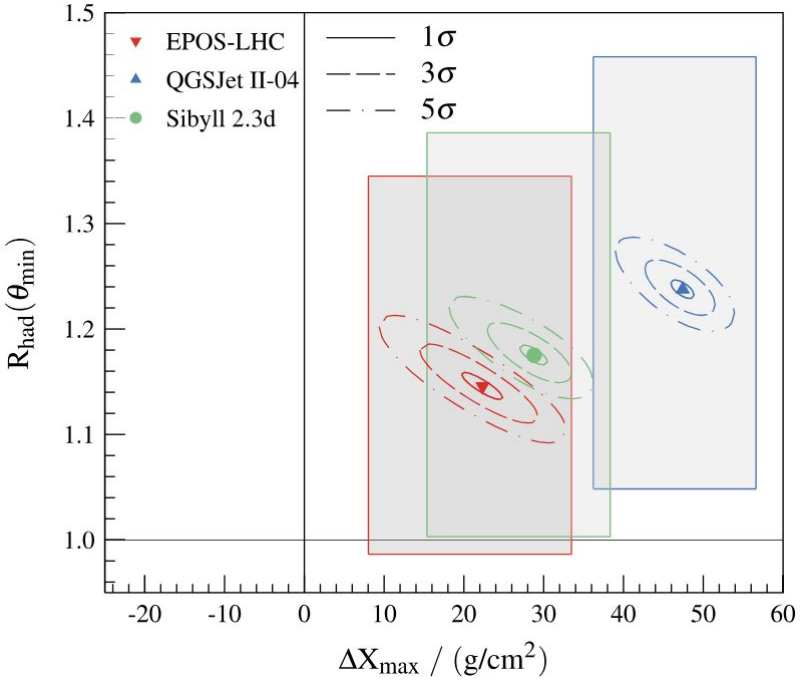
- Combined fit of ground signal and X_{max} .

Pierre Auger Collab., Phys. Rev. D 109, 102001 (2024)



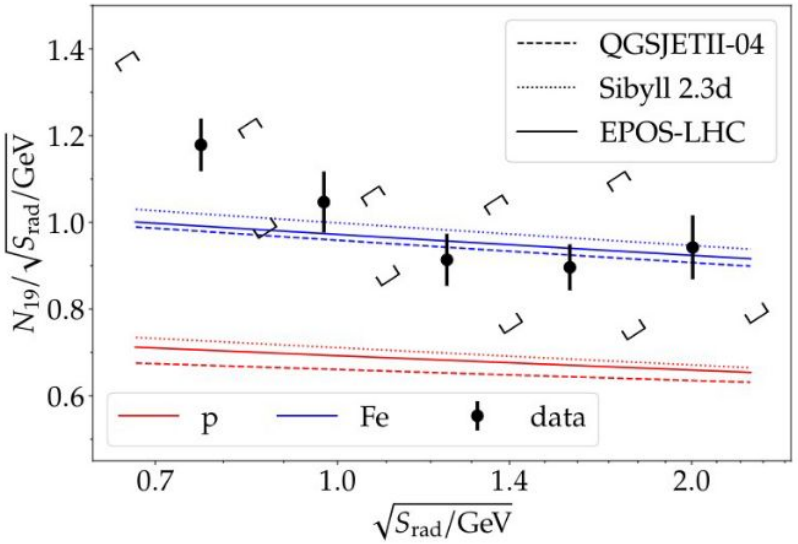
Muon measurements at the Pierre Auger Observatory

This list is not exhaustive…

- Muon production depth.
- Neural network for muon traces.
- Combined fit of ground signal and X_{max} .
- Radio + SD measurements of the muon content.

And many more…

To be submitted…



Summary

★ The Pierre Auger Observatory is an excellent tool to study hadronic interactions and better understand physics at the highest energies.

★ A **muon excess** is observed in the data of the Pierre Auger Observatory:
- for vertical showers.
- for horizontal showers.
- in hybrid observations.

Summary & Outlook

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Exciting times ahead

- **Upgrade** of the Pierre Auger Observatory completed (radio antennas and scintillators).
- **New hadronic interaction models** recently released.
- **p-O run at LHC** planned for this July.