

Overview of the Past, Present, and Future of the Pierre Auger Observatory: Advantages and limitations concerning accelerator data

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on behalf of the Pierre Auger Collaboration

Theory and Experiment in High Energy Physics workshop
Prague, 2024

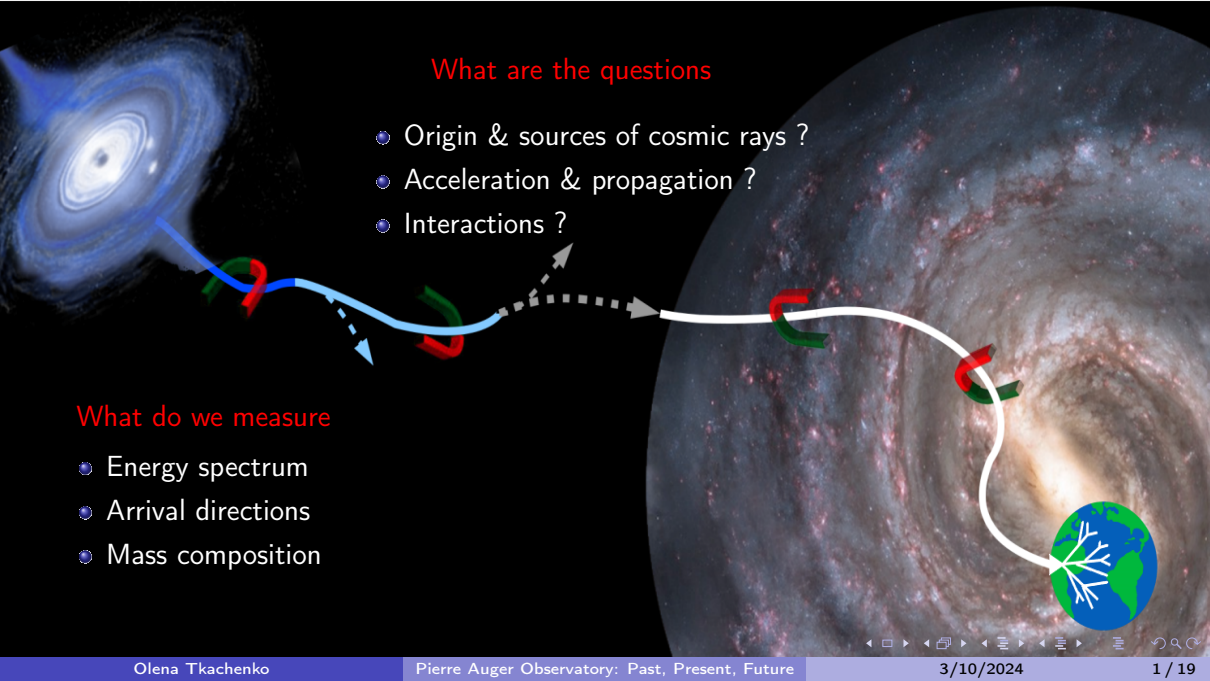


What are the questions

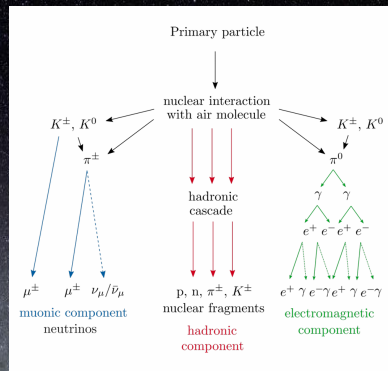
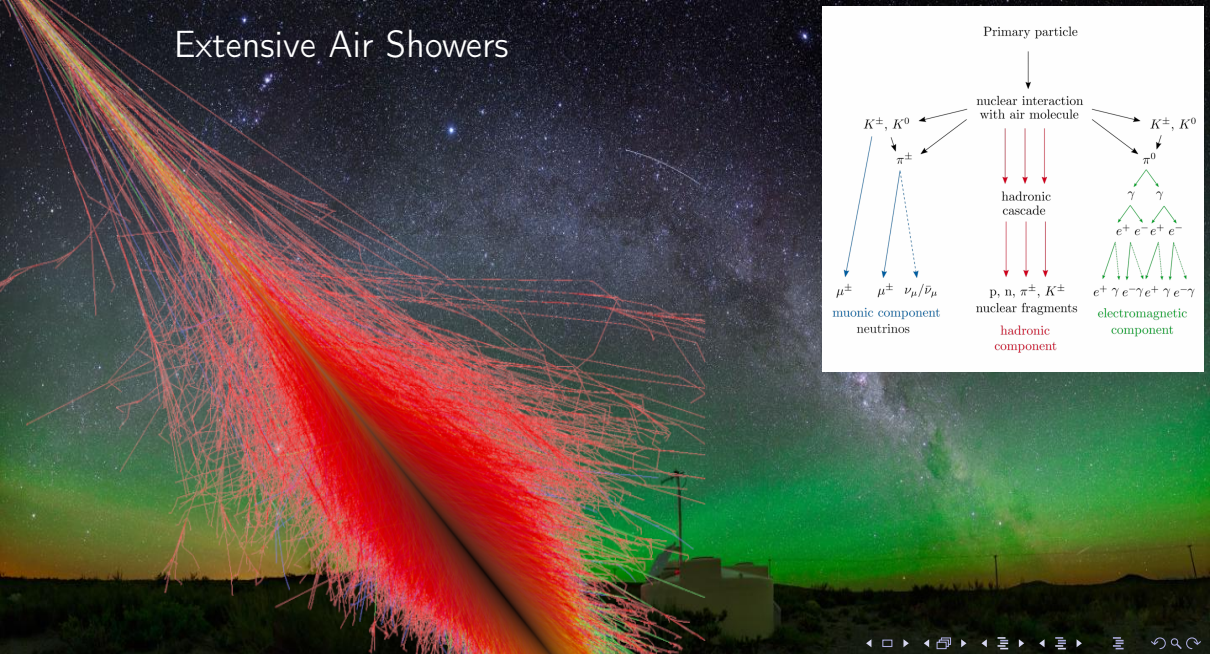
- Origin & sources of cosmic rays ?
- Acceleration & propagation ?
- Interactions ?

What do we measure

- Energy spectrum
- Arrival directions
- Mass composition

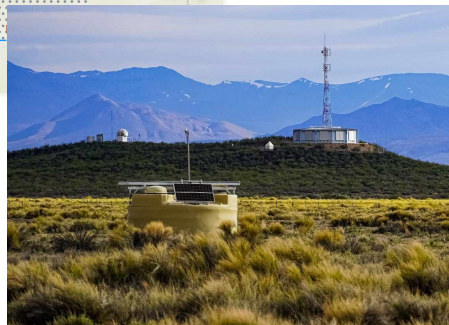


Extensive Air Showers

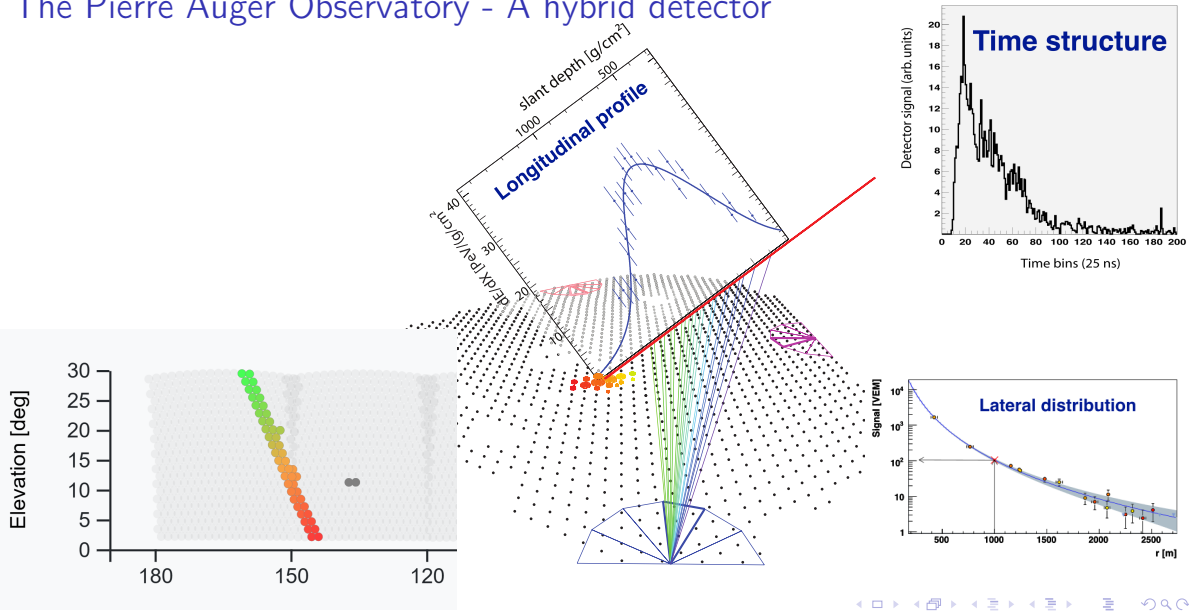


The Pierre Auger Observatory

- Located in **Malargue, Argentina**
- Total area of **3000 km²**
- **Surface Detector (SD)**
 - ▶ 1660 stations
 - ▶ 100% duty cycle
- **Fluorescence Detector (FD)**
 - ▶ 27 telescopes
 - ▶ 15% duty cycle
- **Radio and muon detectors**
- **Phase I:** 2004-2022
- **AugerPrime** upgrade: completed in 2023
- **Phase II:** till > 2035



The Pierre Auger Observatory - A hybrid detector



The Pierre Auger Collaboration

Argentina

Australia

Belgium

Brazil

Colombia

Czech Republic

France

Germany

Italy

Mexico

Netherlands

Poland

Portugal

Romania

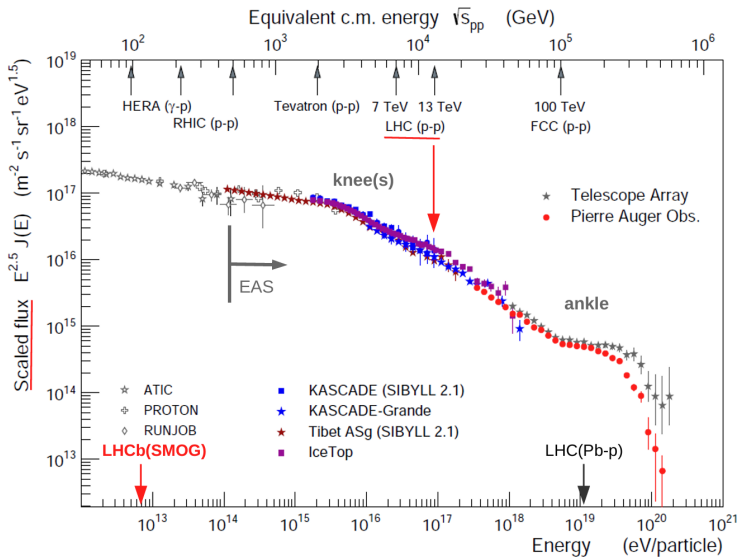
Slovenia

Spain

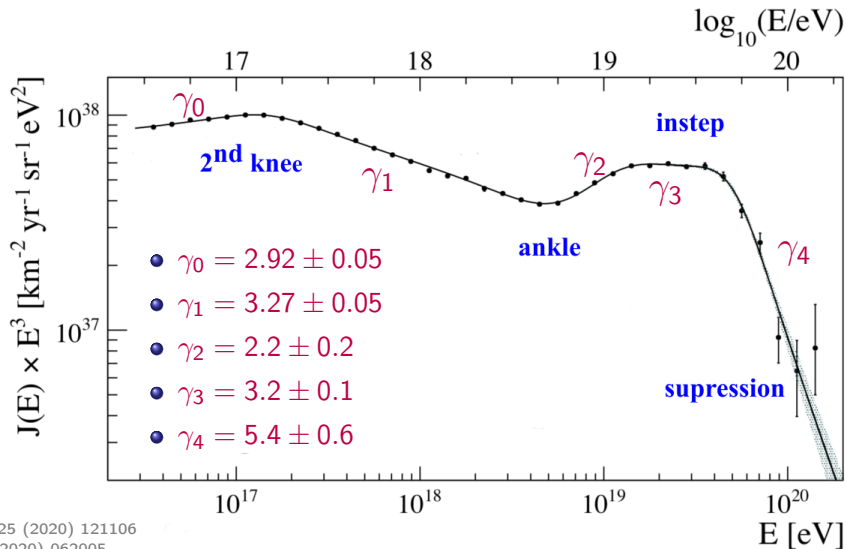
USA



Energy Spectrum



Energy spectrum

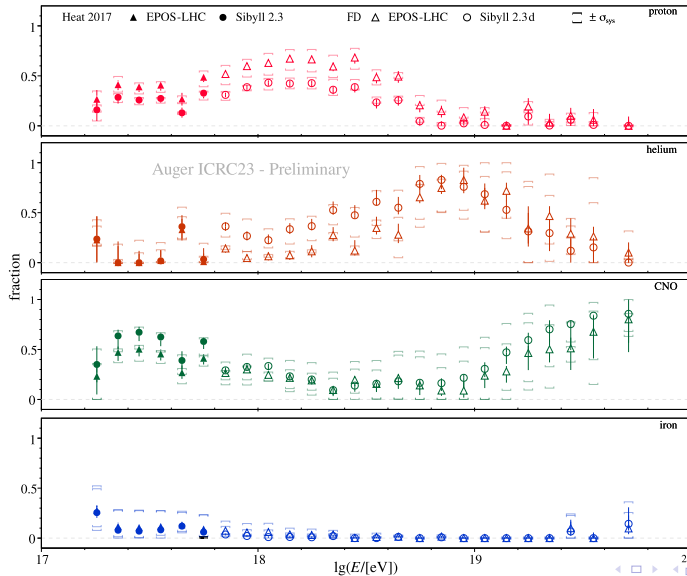


Phys. Rev. Lett. 125 (2020) 121106

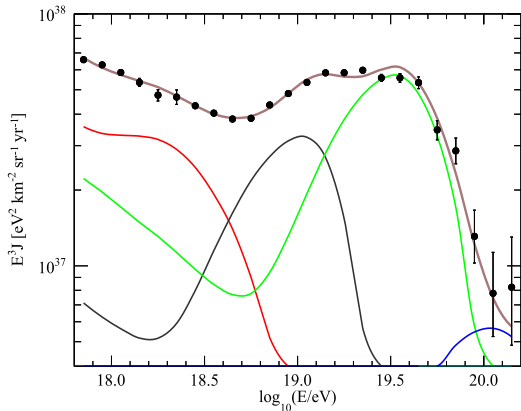
Phys. Rev. D102 (2020) 062005

Eur. Phys. J. C81 (2021) 966

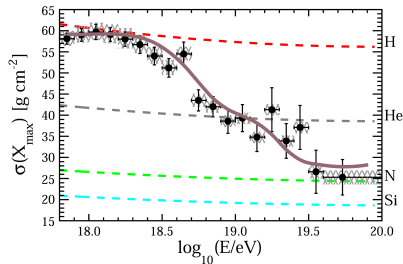
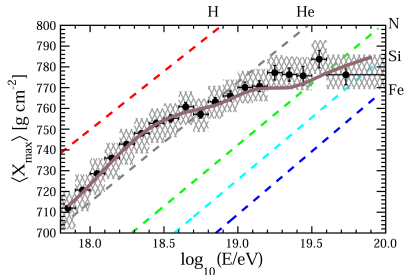
Cosmic-ray mass composition



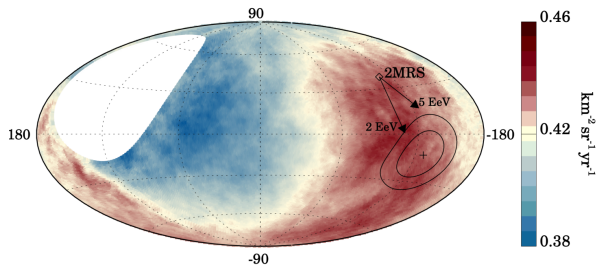
Combining spectrum and composition measurements



- Acceleration $\sim A$
- Transition to heavier nuclei
- Hard injection spectrum



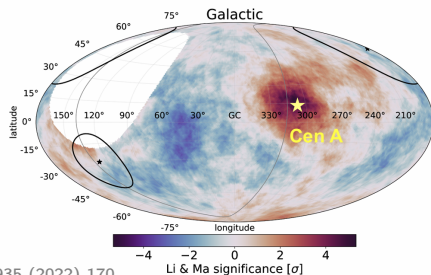
Cosmic Ray Arrival Directions



Science 357 (2017) 1266

- Hotspot of 4σ at Cen A/M83/NGC4945 direction
- Signal at 3.8σ for Starburst Galaxies catalog
- 5σ is expected in the Phase II operation

- 3D dipole above 8 EeV
- $\sim 55^\circ$ away from 2MRS dipole
- 6.6σ significance
- Strong indication for extragalactic origin of UHECRs at > 8 EeV



ApJ 935 (2022) 170

Particle Physics with UHECR

LHC

- $\sqrt{s} = 14 \text{ TeV (p-p)} \implies E_{\text{CR}} \sim 10^5 \text{ TeV}$

- $\eta \leq 5$

- p-p, Pb-Pb, p-Pb, Pb-p

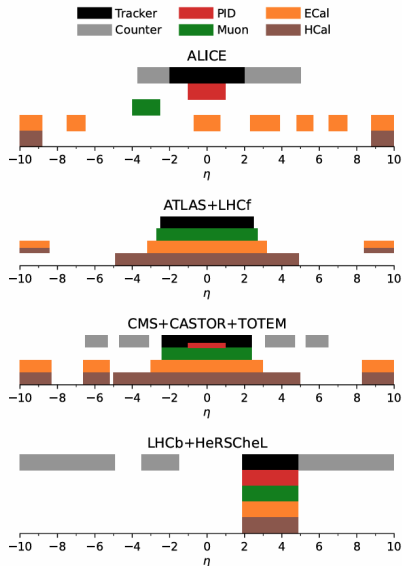


EAS

- $E_{\text{CR}} \geq 10^6 \text{ TeV}$

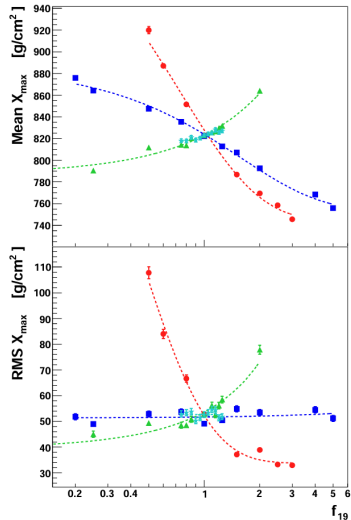
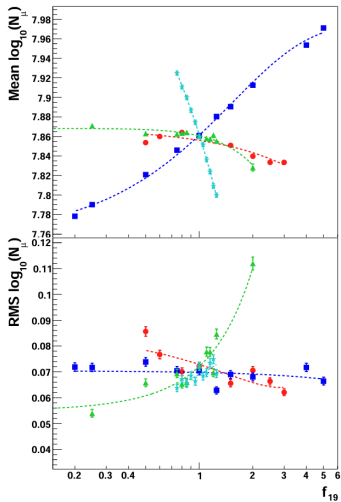
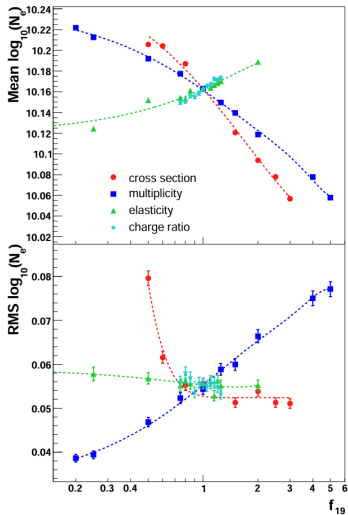
- $\eta \approx 7-11$

- p-air, He-air...Fe-air, π -air



J. Albrecht et al. *Astrophys. Space Sci.* 367, 2022

Hadronic interaction properties

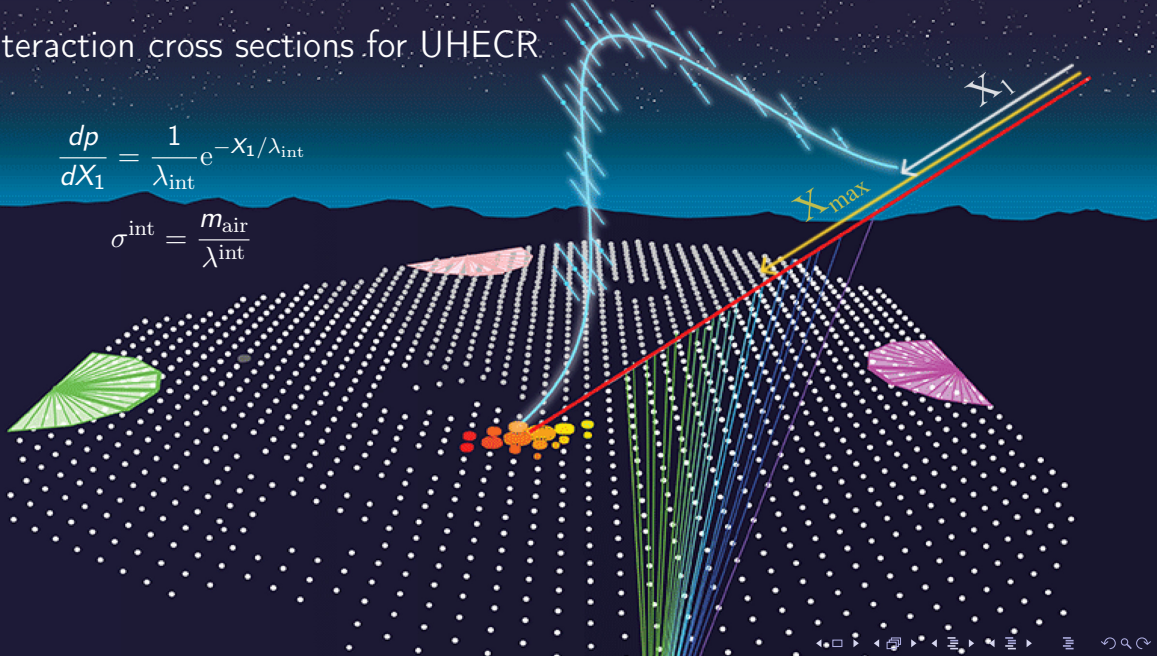


R. Ulrich *et al.* Phys. Rev. D 83, 054026 (2011)

Interaction cross sections for UHECR

$$\frac{dp}{dX_1} = \frac{1}{\lambda_{\text{int}}} e^{-X_1/\lambda_{\text{int}}}$$

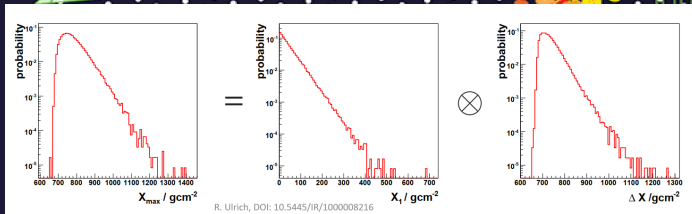
$$\sigma_{\text{int}} = \frac{m_{\text{air}}}{\lambda_{\text{int}}}$$



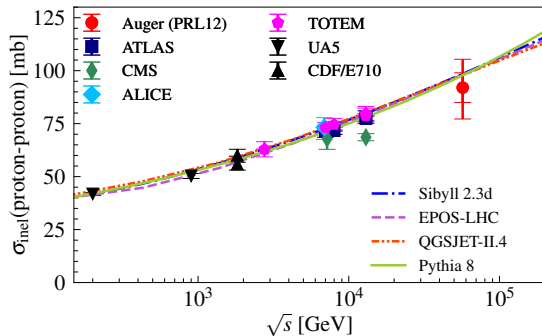
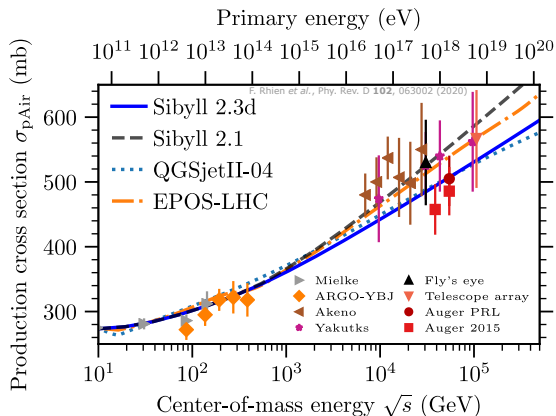
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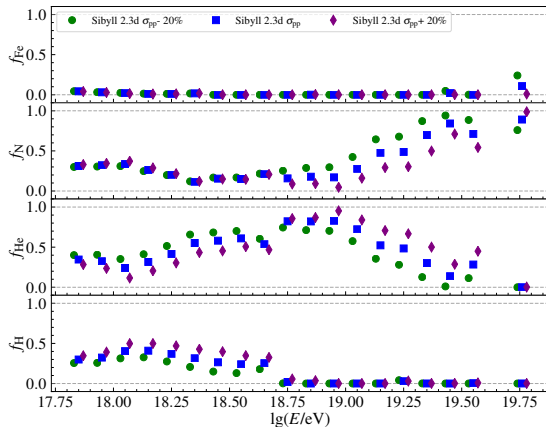
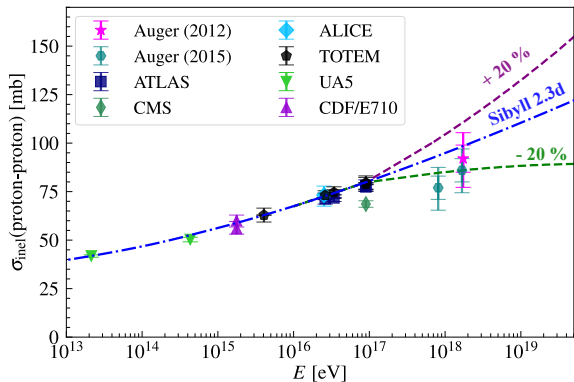
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Interaction cross sections for UHECR



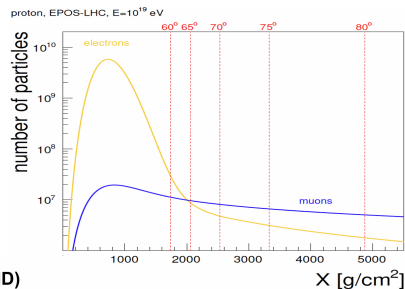
Interplay between mass composition interaction cross section



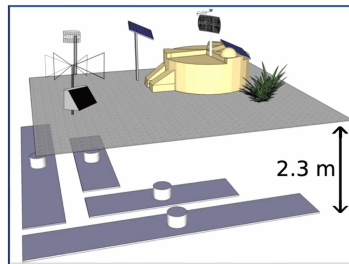
PoS (ICRC2023) 438

Muon Measurements with Auger

- Muon Production Depth in SD
- Hybrid showers ($<60^\circ$)
- Inclined hybrid showers ($60-80^\circ$)
- Direct measurement with underground detectors
- Radio detection

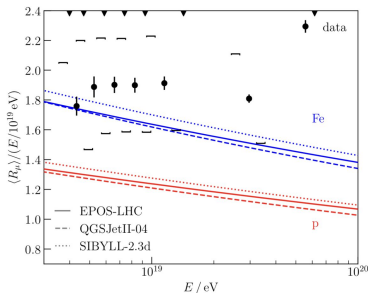
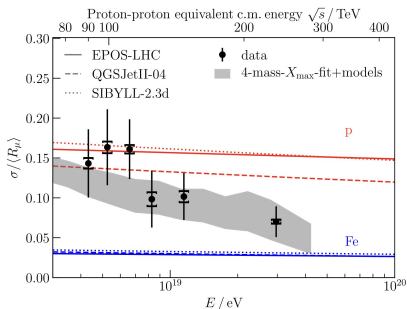
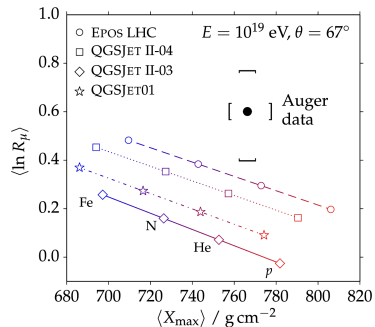


Underground Muon Detector (UMD)



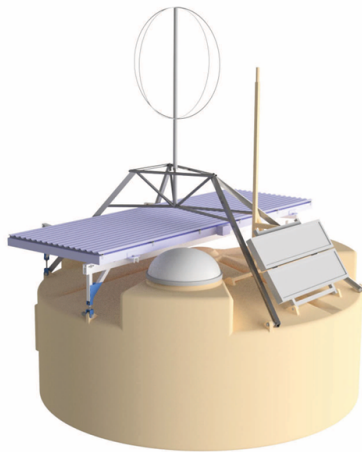
Muon Measurements with Auger: inclined showers

- Average number of muons exceed the model predictions
- Fluctuations are within within the expected range from the models
- In a conflict with X_{\max} measurements



The AugerPrime Upgrade

- Scintillator plates on top of each SD:
 - ▶ better separation between muonic and electromagnetic components
- Upgraded SD electronics:
 - ▶ better time structure of traces, more channels
- Installation of small PMTs:
 - ▶ increased dynamic range
- Extension of the underground muon detector:
 - ▶ direct muon measurements
- Radio antenna on top of each SD



Summary

The Pierre Auger Observatory has been **successfully taking data** since 20 years:

- Precise measurement of the energy spectrum at the highest energies
- Detailed evolution of **mixed** primary mass composition with energy
- Astronomy at the highest energies:
 - ▶ Observation of the **large-scale anisotropies** pointing at the **extragalactic origin** of UHECR
 - ▶ Correlation of the **intermediate scale** anisotropy with **starburst galaxies**
- Particle Physics at the highest energies:
 - ▶ Studies on the particle interactions beyond LHC range
 - ▶ Observed inconsistencies in the hadronic interaction models \Rightarrow muon puzzle

What's next? \Rightarrow Stay tuned!

- Upgrade AugerPrime is finalized
- The Phase II of operation has already started