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

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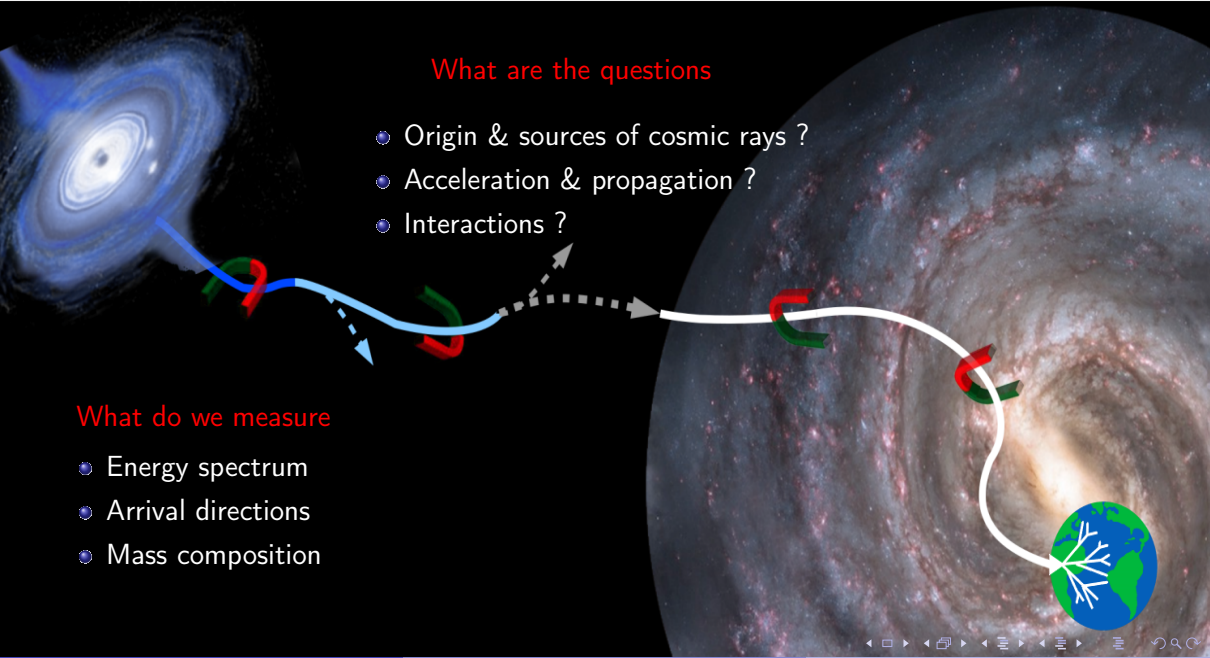
on behalf of the Pierre Auger Collaboration

New Trends in High Energy and Low-x Physics

What are the questions

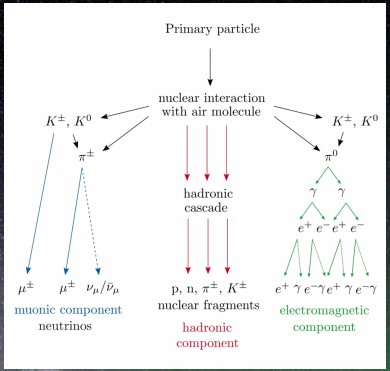
- Origin & sources of cosmic rays ?
- Acceleration & propagation ?
- Interactions ?



What do we measure

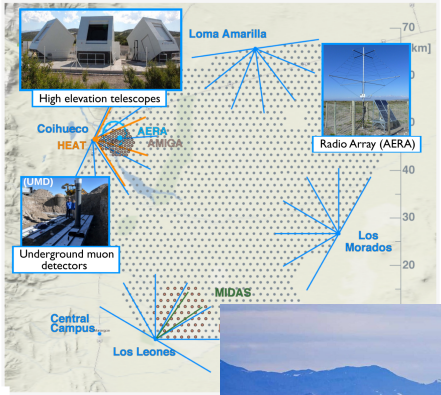
- Energy spectrum
- Arrival directions
- Mass composition

Extensive Air Showers

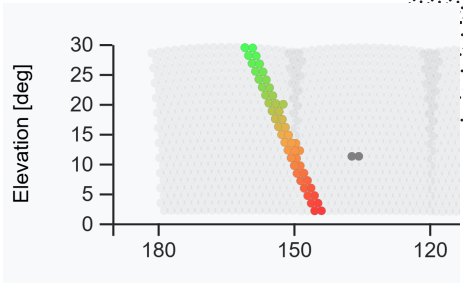


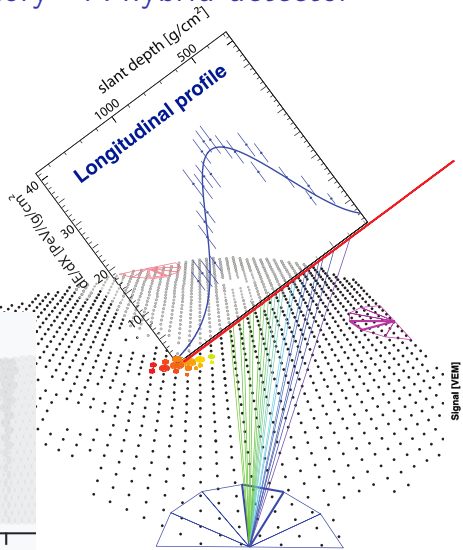
The Pierre Auger Observatory

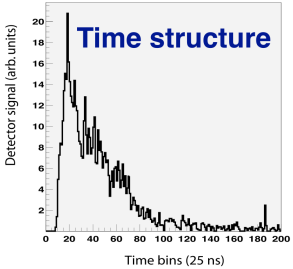
- Located in **Malargue, Argentina**
- Total area of **3000 km^2**
- **Surface Detector** (SD)
  - 1660 stations
  - 100% duty cycle
- **Fluorescence Detector** (FD)
  - 27 telescopes
  - 15% duty cycle
- **Radio and muon detectors**
- **Phase I**: 2004-2022
- **AugerPrime** upgrade: completed in 2023
- **Phase II**: till $>$ 2035

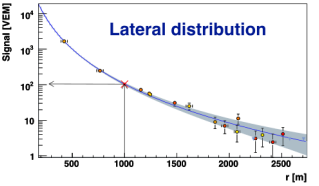


The Pierre Auger Observatory - A hybrid detector





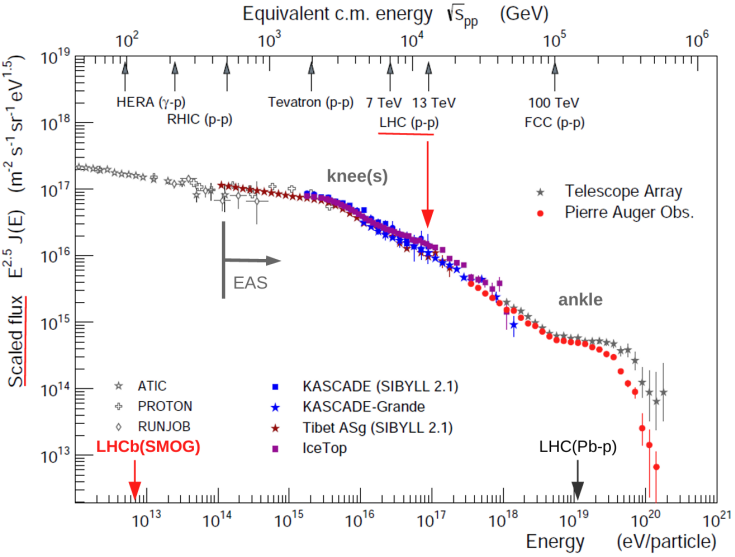




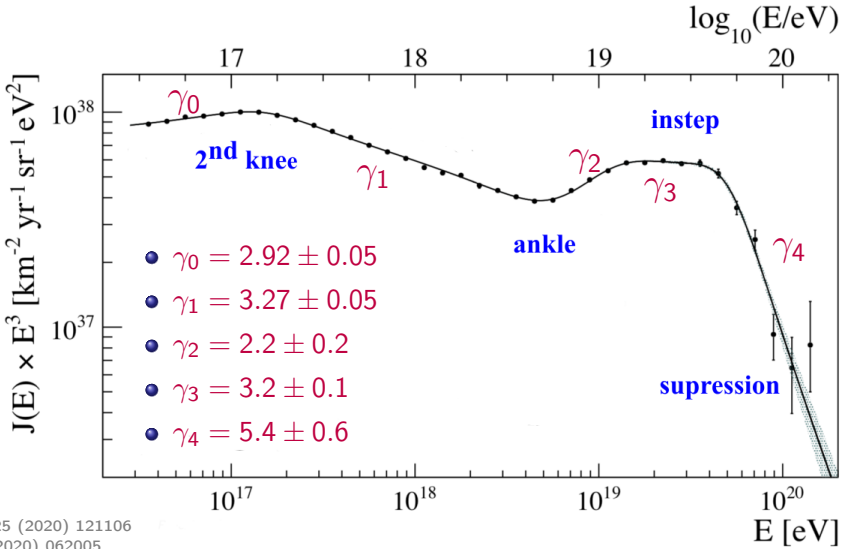
The Pierre Auger Collaboration

Argentina
Australia
Belgium
Brazil
Colombia
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
USA

Energy Spectrum



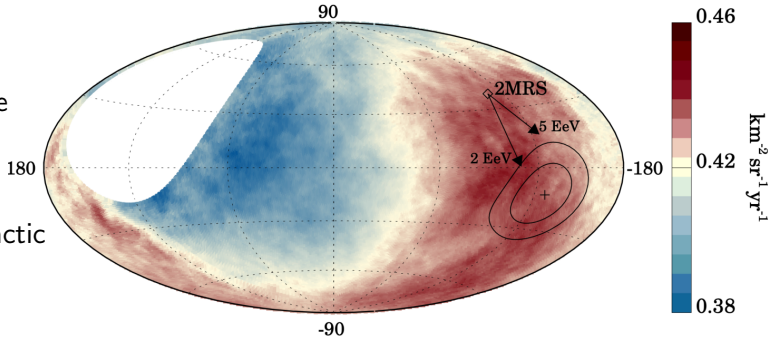
Energy spectrum



Phys. Rev. Lett. 125 (2020) 121106
Phys. Rev. D102 (2020) 062005
Eur. Phys. J. C81 (2021) 966

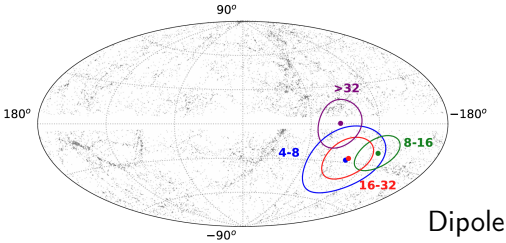
Cosmic Ray Arrival Directions: Large Scale Anisotropy

- 3D dipole above 8 EeV
- $\sim 55^\circ$ away from 2MRS dipole
- 6.6σ significance
- $(l,\, b) = (233^\circ,\, 13^\circ)$
- Strong indication for extragalactic origin of UHECRs at > 8 EeV



Sky map in Galactic coordinates

Science 357 (2017) 1266

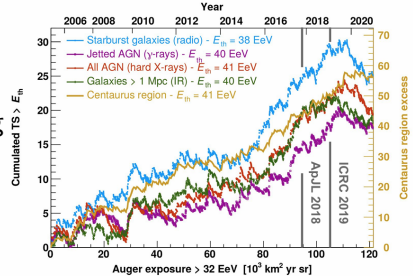


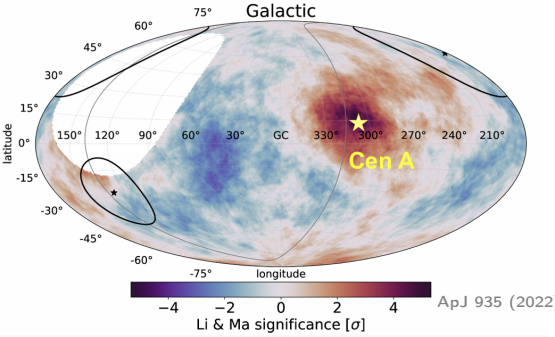
Dipole direction at different E

PoS(ICRC2023)252

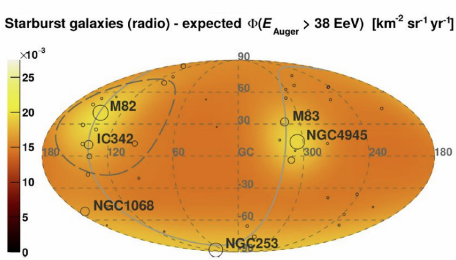
Intermediate-scale anisotropy: search for sources

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

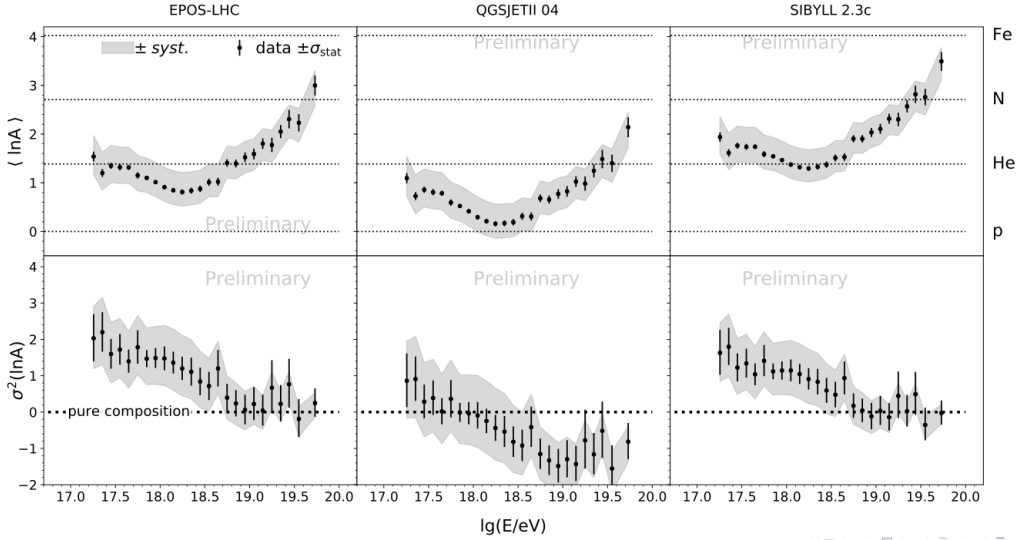




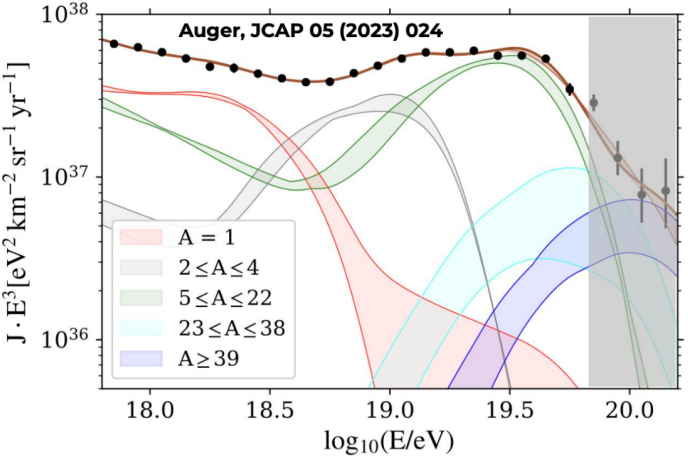
ApJ 935 (2022) 170



Mean logarithmic mass



Combining spectrum and composition measurements

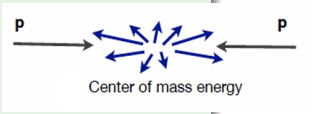


- Acceleration $\sim$ A
- Transition to heavier nuclei
- Hard injection spectrum $\sim E^{1.5...2}$

Particle Physics with UHECR

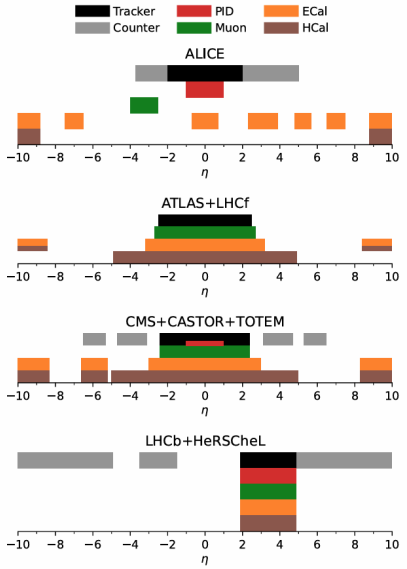
LHC

- $\sqrt{s}$ =14 TeV (p-p) ==> $E_{\rm CR} \sim 10^5$ TeV
- $\eta \leq 5$
- p-p, Pb-Pb, p-Pb, Pb-p



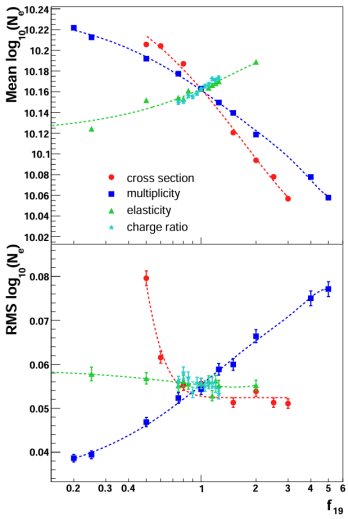
EAS

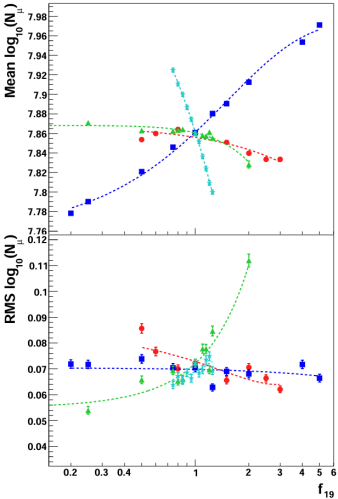
- $E_{\rm CR} \geq 10^6$ TeV
- $\eta \approx$ 7-11
- p-air, He-air...Fe-air, π-air

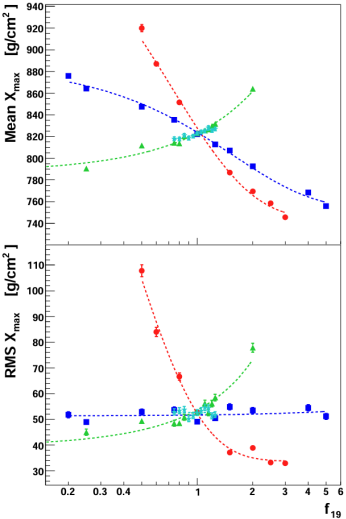


J. Albrecht *et al.* Astrophys. Space Sci. 367, 2022

Hadronic interaction properties





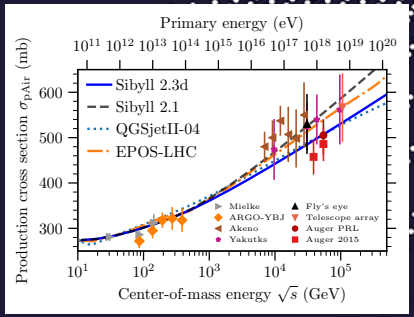


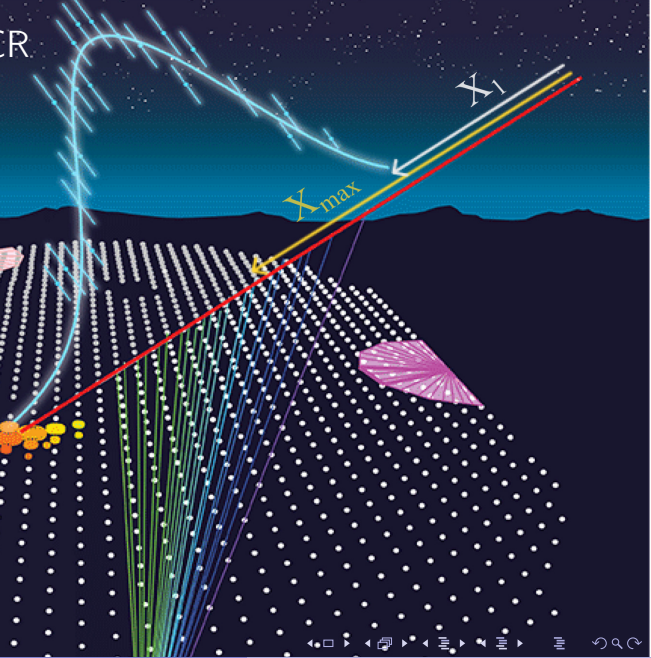
Interaction cross sections for UHECR

(see Kevin Cheminant's presentation)

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

$$\sigma^{\rm int} = \frac{m_{\rm air}}{\lambda^{\rm int}}$$





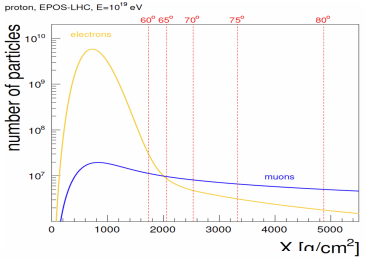
Muon Measurements with Auger

(see Jan Ebr's presentation)

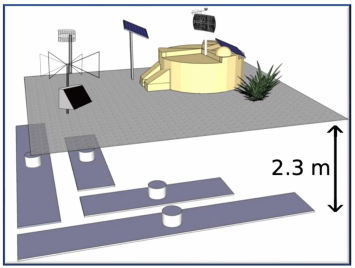
- Muon Production Depth in SD
- Hybrid showers (<60°)
- Inclined hybrid showers (60-80°)
- Direct measurement with undeground detectors
- Neural Network to extract the muon signal from SDs
- Radio detection

Improvements with AugerPrime

- Scintilator plates on top of each SD: better separation between muonic and electromagnetic components
- Extension of the undeground muon detector



Underground Muon Detector (UMD)



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:
  - Obervation of the **large-scale anisotropies** pointing at the **extragalactic origin** of UHECR
  - Correlation of the **intermediate scale** anistropy 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