Measuring the muon content of inclined air showers using AERA and the water-Cherenkov detector array of the Pierre Auger Observatory

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Take-home messages

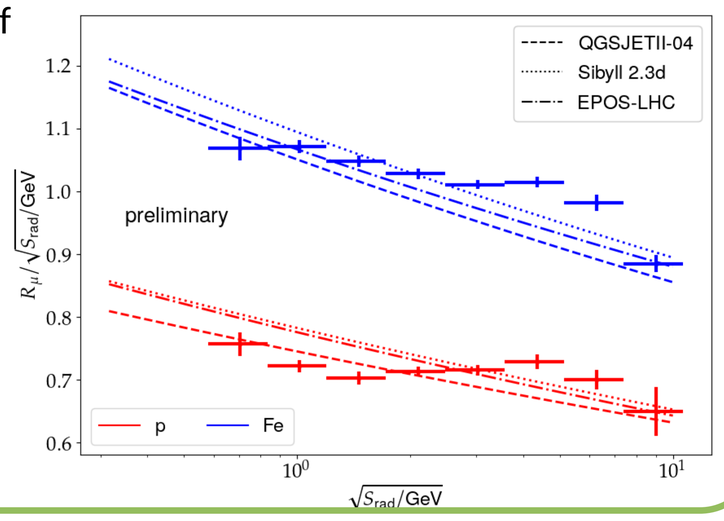
- Measurement of muon number and energy estimator independently with hybrid radio and particle detection at the Pierre Auger Observatory
- 32 high-quality events in almost six years of data with electromagnetic energies above 4 EeV
- Muon content in data compatible with the one predicted for iron primaries by hadronic interaction models
- Can be interpreted as a deficit of muons in simulations as a lighter mass composition is expected from X_{max} measurements. Known muon deficit confirmed for the first time with radio data
- Proof of principle study as analysis is limited by low statistics.
- Advantages of using radio detection will allow for advanced analyses with high-statistics in the future

Pierre Auger Observatory & analysis outline

- Hybrid detection of radio emission, particles and fluorescence light
- 1600 water Cherenkov detectors (WCD) on a hexagonal grid with 1.5 km spacing. Total area of 3000 km² → **muon number R_μ**
- Auger Engineering Radio Array (AERA) consists of 153 antennas distributed on an area of 17 km² → **energy estimator S_{rad}**
- Challenge: Low statistics due to high energy threshold from WCD and small area of AERA → **proof of principle study**
- Advantages of a radio detector compared to a fluorescence detector:
  1. uptime of almost 100%
  2. increased geometrical phase space for high-quality event reconstruction

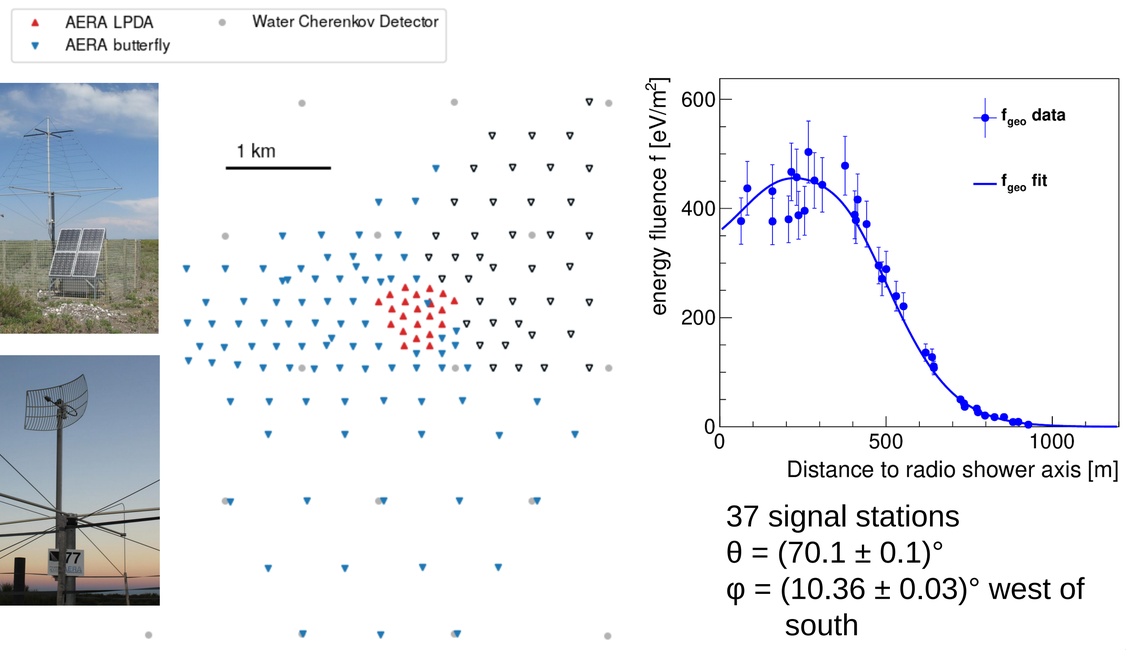
Validation of reconstruction with CoREAS simulations

- Realistic reconstruction of more than 1000 CoREAS simulations
- Sufficient agreement of model prediction and event reconstruction
- Difference due to bias in S_{rad} reconstruction as LDF not yet optimized for AERA



Energy estimation with AERA

- Radiation energy S_{rad} estimated by integrating the lateral signal distribution on ground. Model developed for inclined showers detected by the AugerPrime radio detector.
- S_{rad} can be related to the electromagnetic energy E_{EM}. Solid energy scale will be established in a future analysis

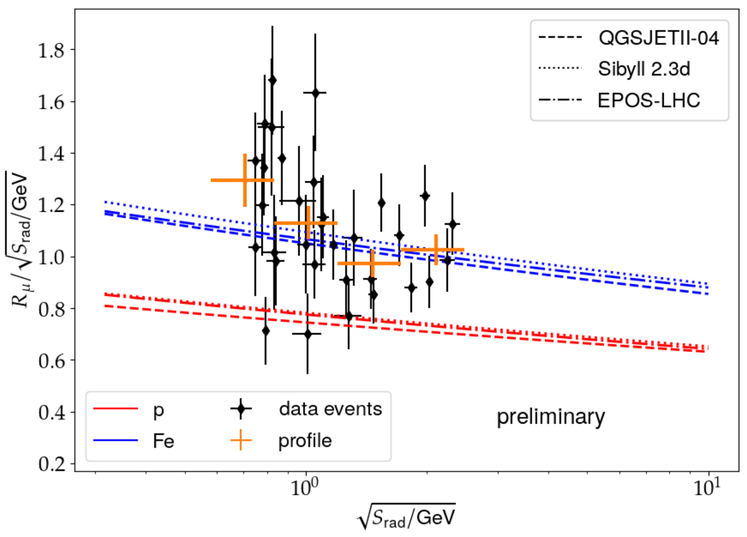


37 signal stations
θ = (70.1 ± 0.1)°
φ = (10.36 ± 0.03)° west of south

Measurement of the muon content

- Data period: 26.06.2013 - 01.05.2019
- 32 high-quality events
- Strongest cut: E_{EM} > 4 EeV (enforces full efficiency of the WCD for inclined air showers)

cut	number of events after cut
$60° \le \theta_{SD} \le 80°$	2002
number of candidate stations ≥ 5	1108
Full hexagon of stations	953
no thunderstorm conditions	849
SD-RD opening angle < 2.08°	788
has LDF fit with a station inside Cherenkov radius	532
E_{EM} > 4 EeV	50
number of stations > 5	40
reduced χ^2 of LDF fit < 5	37
relative E_{EM} uncertainty < 0.2	32

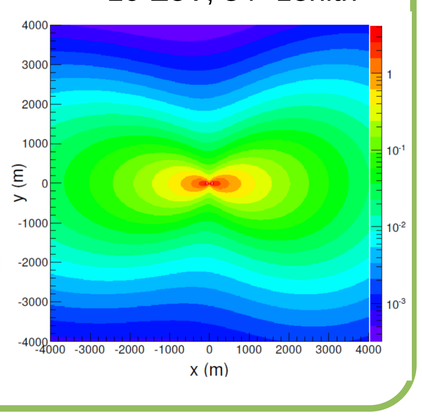


- Muon content in data consistent with model prediction for iron primaries
- Lighter composition expected from X_{max} → *muon puzzle*
- Muon deficit also observed with independent Auger analyses in different energy ranges

Muon number measured with the WCD

- For inclined air showers WCD performs pure measurement of muons
- Fit station signal to scaled reference muon distributions on ground
- Rescaling factor can be interpreted as relative muon number wrt a 10 EeV proton shower

Muon density map
10 EeV, 84° zenith



Future high-statistics measurements

- Hybrid events with the AugerPrime radio detector and the 1500m WCD array at the highest energies
- Hybrid events with AERA and the 750m WCD at EeV energies between 10^{17} eV and 10^{19} eV
- High-statistics measurements allowing for more advances analysis beyond simple average muon number