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

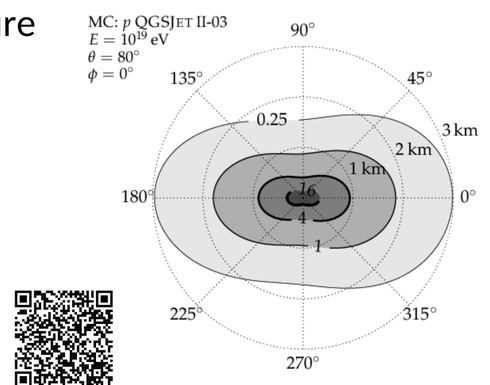
- Independent measurement of muon number and energy estimator with hybrid radio and particle detection at the Pierre Auger Observatory.
- 37 high-quality events in almost eigth years of data with electromagnetic energies above 4 EeV.
- Muon content in data compatible with the one predicted for iron primaries by current-generation 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 triangular grid with 1.5 km spacing. Total area of 3000 km² → **muon estimator N19**
- 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

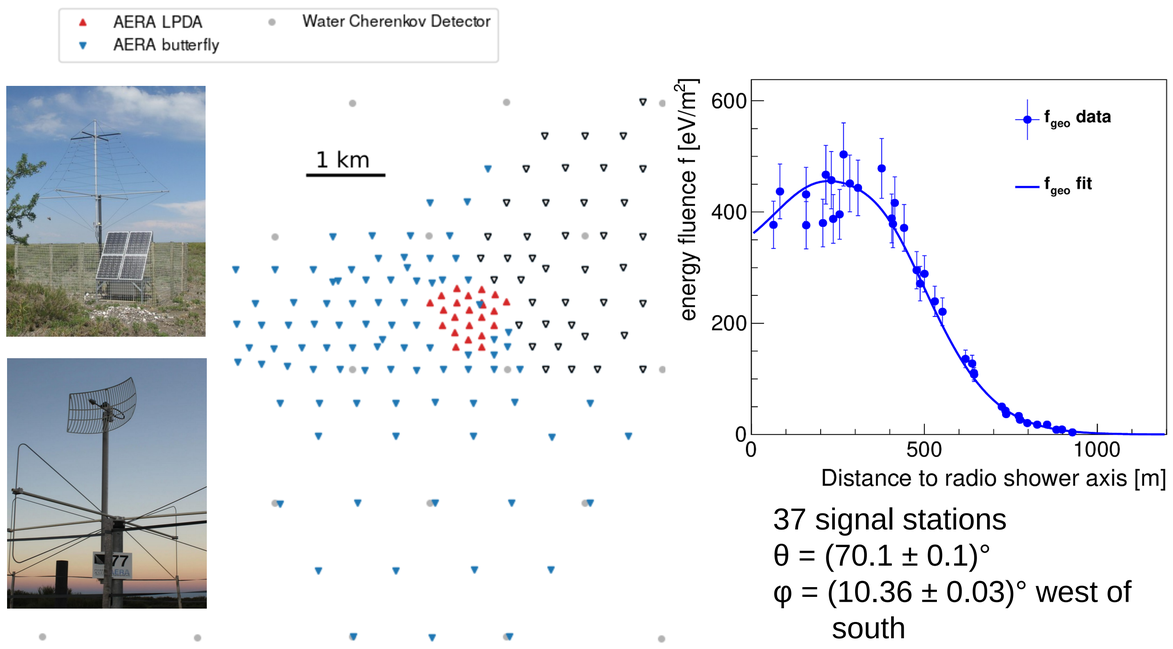
Muon number measured with the WCD

- For inclined air showers WCD performs pure measurement of muons on the ground.
- Fit station signal to scaled reference muon distributions on ground.
- Rescaling factor, N19, can be interpreted as relative muon number wrt a 10 EeV proton primary.



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 (RD).
- S_{rad} can be related to the electromagnetic energy E_{EM}. Solid energy scale will be established in a future analysis.

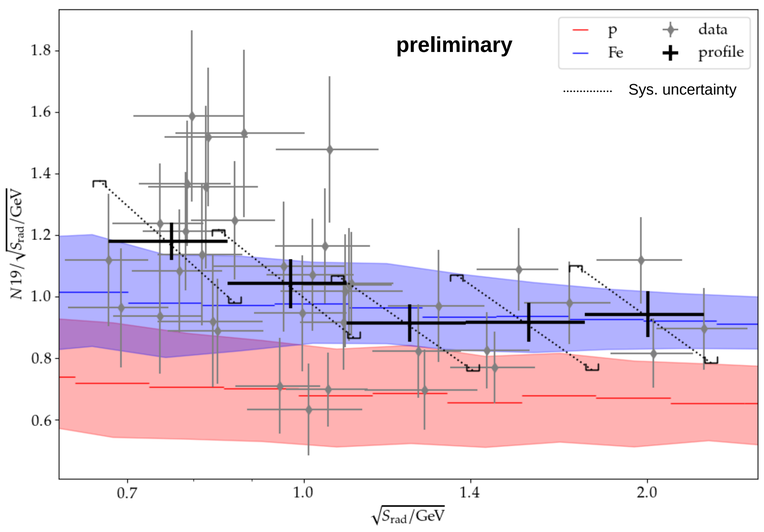


37 signal stations
θ = (70.1 ± 0.1)°
φ = (10.36 ± 0.03)° west of south

Measurement of the muon content

- **Predicted muon content** based on large set of CORSIKA simulations.
- Central 68% of the reconstructed N19 distribution for p and Fe primaries, S_{rad} calculated from E_{EM}.
- EPOS-LHC used here, but very similar band for other models.
- **Data period** (Auger Phase 1): 26.06.2013 - 31.08.2021
- 37 high-quality events with WCD energies between ~4 to 12 EeV.
- Strongest cut: E_{EM} > 4 EeV, enforces full efficiency of the WCD for inclined air showers.
- Systematic uncertainties: 10% on N19, ~28% on S_{rad} (~14% on E_{EM})

cut	number of events after cut
$65° \leq \theta_{SD} \leq 80°$	2360
number of candidate stations ≥ 5	1352
Full hexagon of stations	1087
no thunderstorm conditions	974
SD-RD opening angle $< 2.08°$	907
$E_{EM} > 4$ EeV	109
station inside Cherenkov radius	54
reduced χ^2 of LDF fit < 5	47
number of stations > 5	41
relative E_{EM} uncertainty < 0.2	37



- 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.
- **Future prospects**: high-statistics measurements allowing for more advanced analyses beyond simple average muon number
  - AERA and the 750 m WCD array at lower energies and
  - RD and the 1500 m WCD array at the highest energies.

Validation of the radio LDF model for AERA

- Realistic reconstruction of more than 1000 CoREAS simulations
- LDF model performs well for high-quality events above 65° zenith
- Remaining bias of 2% likely due to signal loss during trace processing
- Accounted for as a systematic uncertainty