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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Abstract

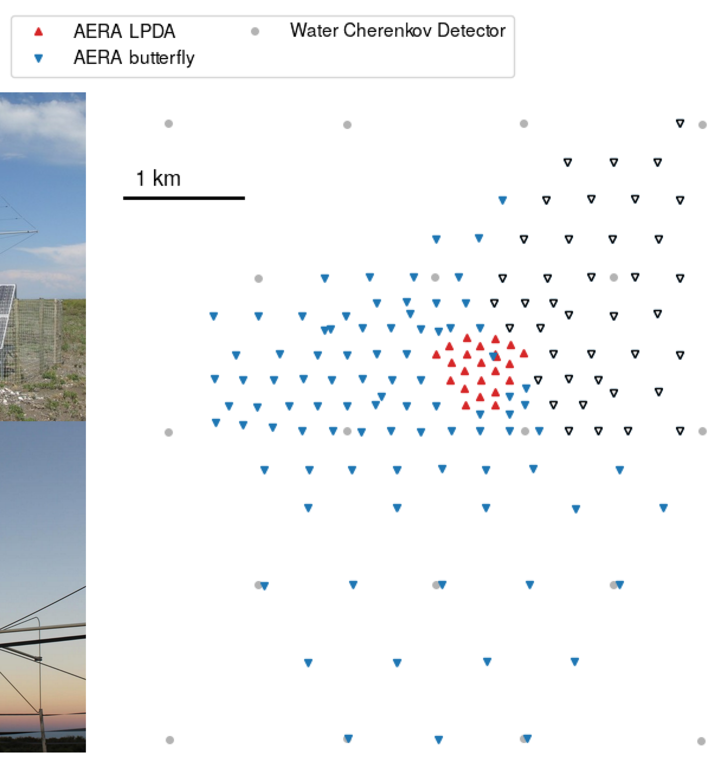
In this proceeding, we present a proof of principle study for estimating the number of muons of inclined air showers proportional to their energy using hybrid radio and particle detection. We use the radiation energy of an air shower to estimate its electromagnetic energy and measure the muon number independently with the water-Cherenkov detector array (WCD) of the Pierre Auger Observatory. We select 32 high-quality events in almost six years of data with electromagnetic energies above 4 EeV to ensure full efficiency for the WCD reconstruction. The muon content in data is found to be compatible with the one for an iron primary as predicted by current-generation hadronic interaction models. This can be interpreted as a deficit of muons in simulations as a lighter mass composition is expected from Xmax measurements. Such a muon deficit was already observed in previous analyses of the Auger collaboration and is now confirmed for the first time with radio data. Currently, this analysis is limited by low statistics due to the small area of AERA of 17 km² and the high energy threshold. We will outline the advantages of using radio detection instead of the Auger Fluorescence Detector in future analyses allowing for high-statistic measurements of the muon content as a function of energy.

Pierre Auger Observatory & analysis outline

- Hybrid Detection of radio emission, particles and fluorescence light
- 1600 water Cherenkov detector (WCD) on a hexagonal grid with 1.5 km spacing. Total area of 3000 km²
- Auger Engineering Radio Array (AERA) consist of 153 antennas distributed on an area of 17 km²
- Challenge: High energy threshold from WCD and small area of AERA
- Proof of concept for measuring the muon content proportional to energy with hybrid events reconstructed with the WCD for the number of muons and AERA for the energy estimator
- Advantage of radio wrt FD: uptime of almost 100% and increased geometrical phase space for high-quality event reconstruction

Energy estimation with AERA

- Different antenna types and station electronic. Each station has 2 channels aligned NS – EW, 30 – 80 MHz
- 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 used as estimator of the electromagnetic energy E_{EM}. Solid energy scale will be established in a future analysis

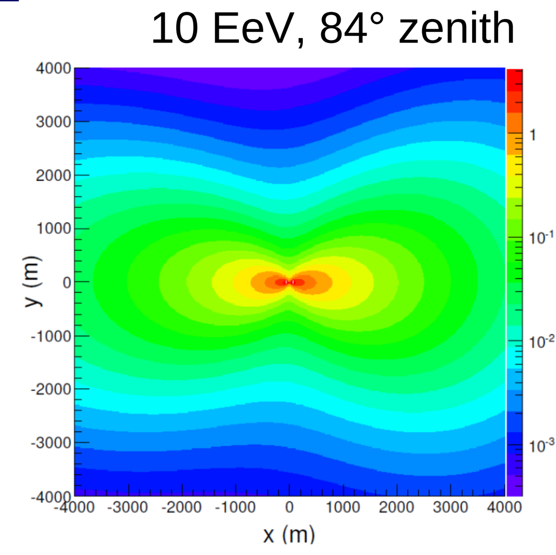


37 signal stations
θ = (70.1 ± 0.1)°
φ = (10.36 ± 0.03)° west of south

Muon number measured with the WCD

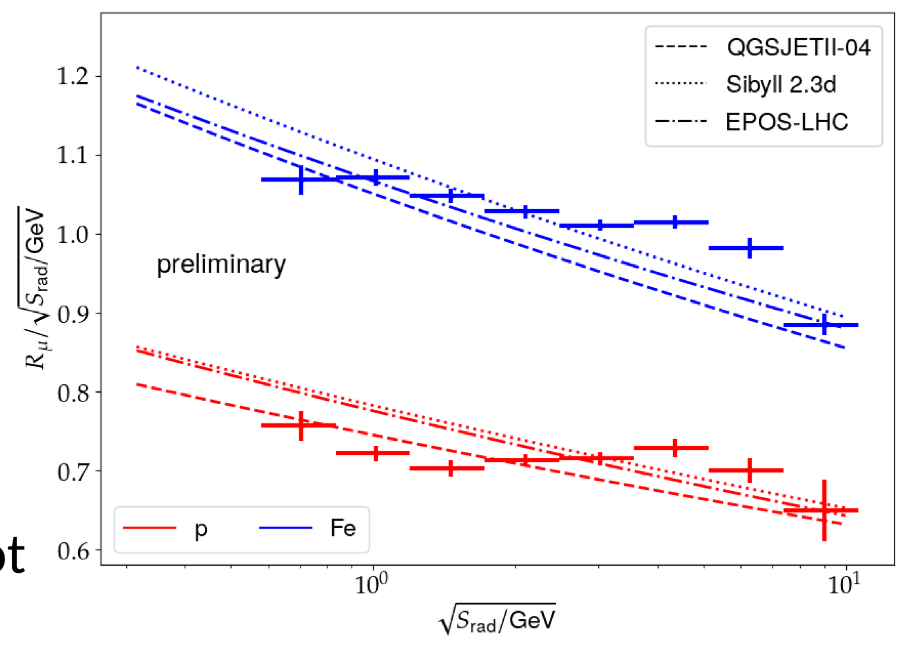
- For inclined showers WCD performs pure measurement of muons
- Fit data to scaled reference muon distrubtions on ground
- Rescaling factor can be interpreted as relative muon number wrt a 10^{19} proton shower

Muon density map
10 EeV, 84° zenith



Validation of reconstruction with CoREAS simulations

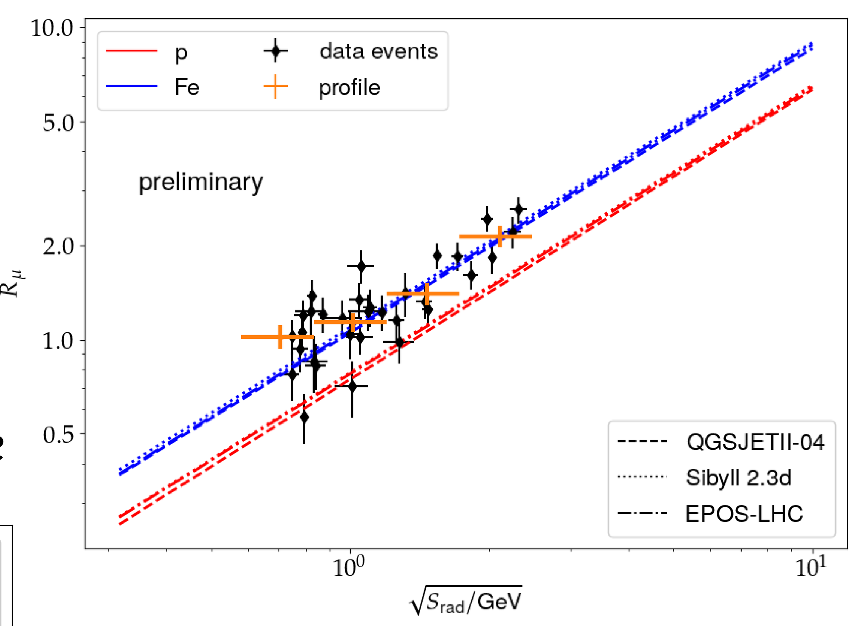
- Realistic reconstruction of more than 1000 CoREAS simulations with AERA stations using p and Fe as primary and addition of measured noise
- Sufficient agreement of model prediction and reconstruction
- Difference due to bias in S_{rad} reconstruction as LDF model not yet optimized for AERA

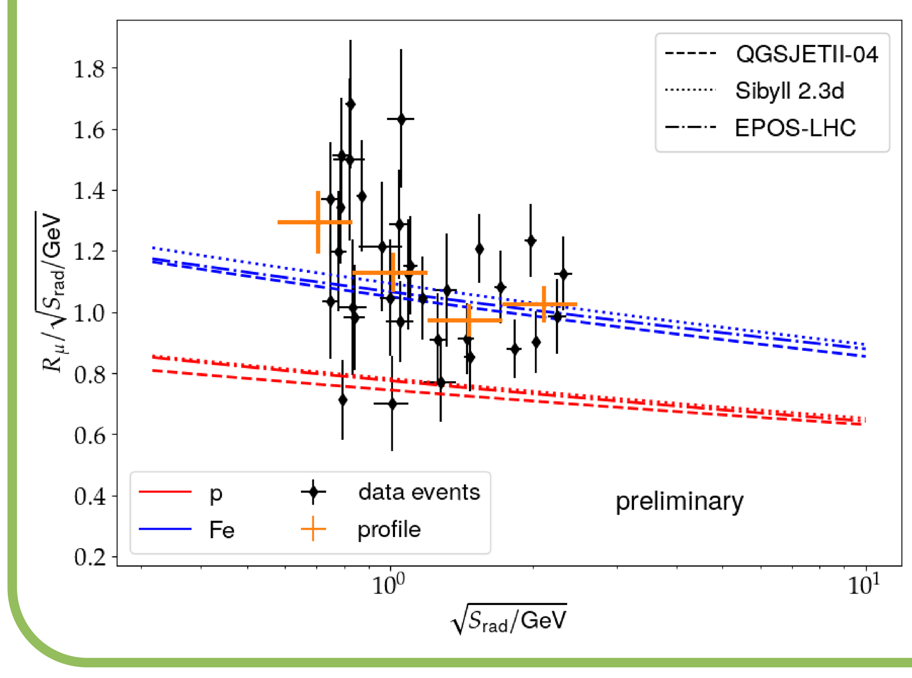


Measured muon content

- Data period: 26.06.2013 - 01.05.2019
- 32 high-quality events after cuts
- Strongest cut: E_{EM} > 4 EeV (full efficiency of the WCD for inclined showers)
- Muon number increasing with increasing energy estimator
- Muon content in data consistent with model prediction for iron primaries but ligher composition expected from X_{max} → *muon puzzle*

cut	number of events after cut
$60° \leq \theta_{SD} \leq 80°$	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





- Also observed with other Auger analyses in different energy ranges
- Confirmed by Working Group for Hadronic Interactions and Shower Physics (WHISP)

Summary and outlook

- Proof of concept that muon content as a function of energy can be measured with hybrid radio and WCD events
- Confirmation of the known muon deficit in simulations with hybrid radio events for the first time
- Future hybrid measurements with the AugerPrime radio detector and the 1500m WCD array at the highest energy with great statistics
- Hybrid events with AERA and the 750m WCD at EeV energies with great statistics