Estimation of Muons on the Surface and Correlation with the Muonic Signal of AugerPrime

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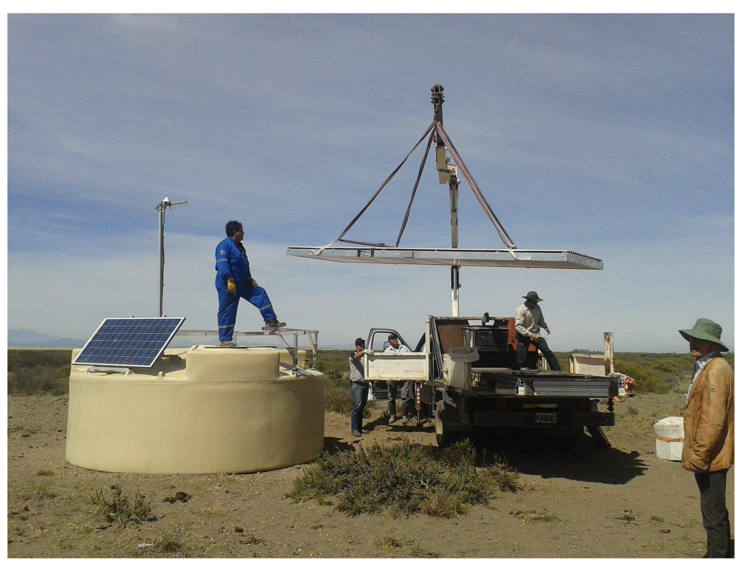
1. Abstract

The AugerPrime project enhances the sensitivity of the Pierre Auger Observatory to cosmic ray composition in the flux suppression region of ultra-high energy cosmic rays (UHECRs) above 10^{19} eV. By improving surface detectors, we distinguish muonic and electromagnetic components of air showers. The Underground Muon Detector (UMD) directly measures the muon component for showers observed by the upgraded surface array, validating extraction methods. Using Extensive Air Shower simulations over the 750 m array, we estimate surface muon density and its correlation with muonic signals from Water-Cherenkov Detectors (WCDs). Our estimations show a bias centered around zero and a resolution of about 25% at $10^{17.8}$ eV, improving at higher energies. Additionally, we find a positive correlation between surface muon density and simulated muonic signals in the WCDs. This study supports improved surface muon density estimations and methods for estimating muonic signals with AugerPrime.

2. Motivation

Absolute estimation of the muon density on the surface with the WCD + SSD at the highest energies validated by the UMD

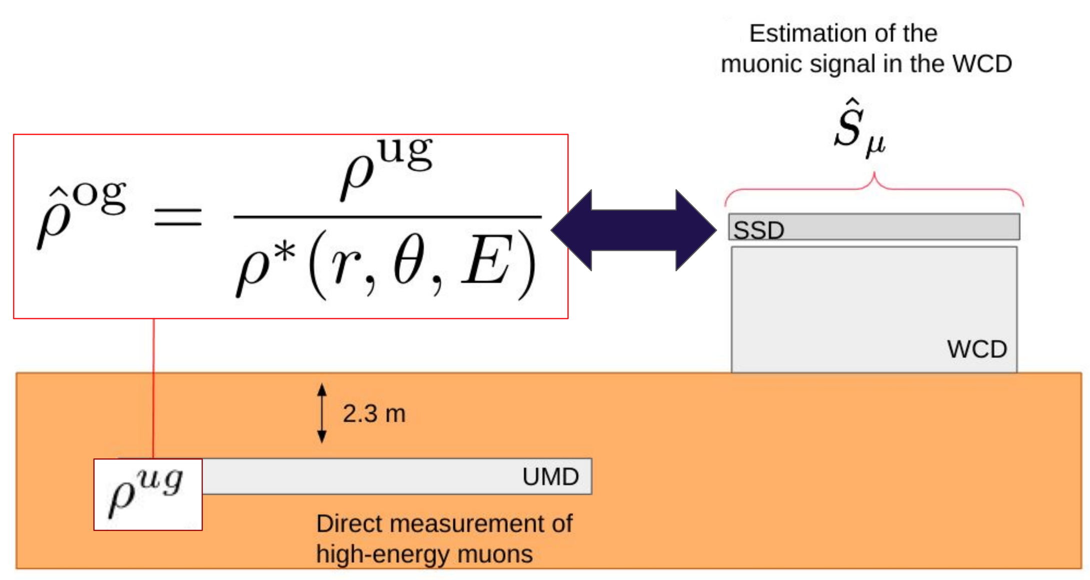


Shower components separation [1]

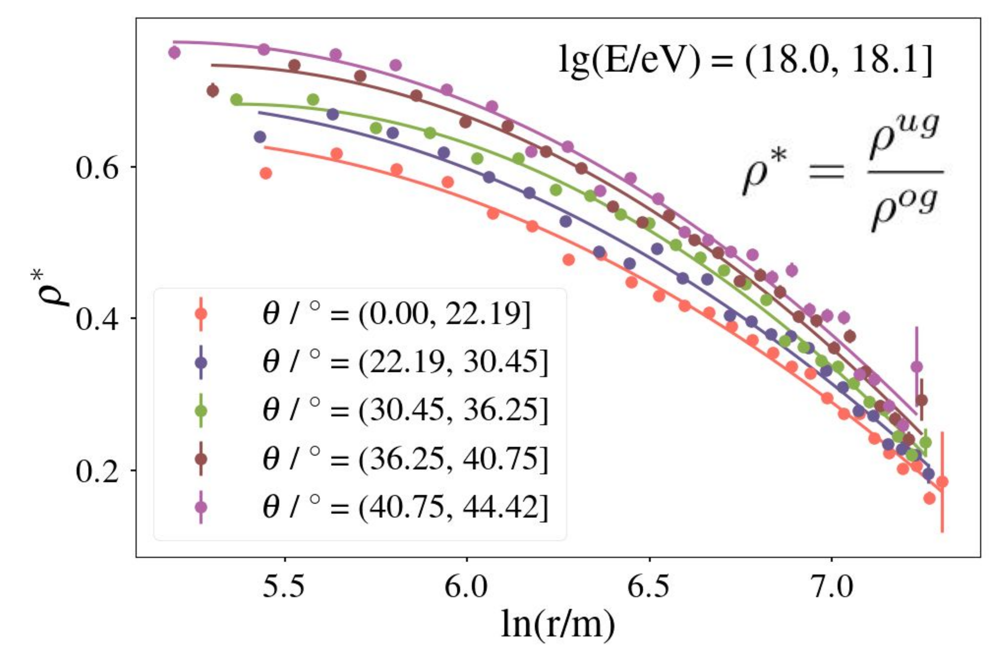
Direct muon measurements [2][3]

3. Methodology

Estimation of muons on-ground, ρ^{og}, from UMD simulations, ρ^{ug}



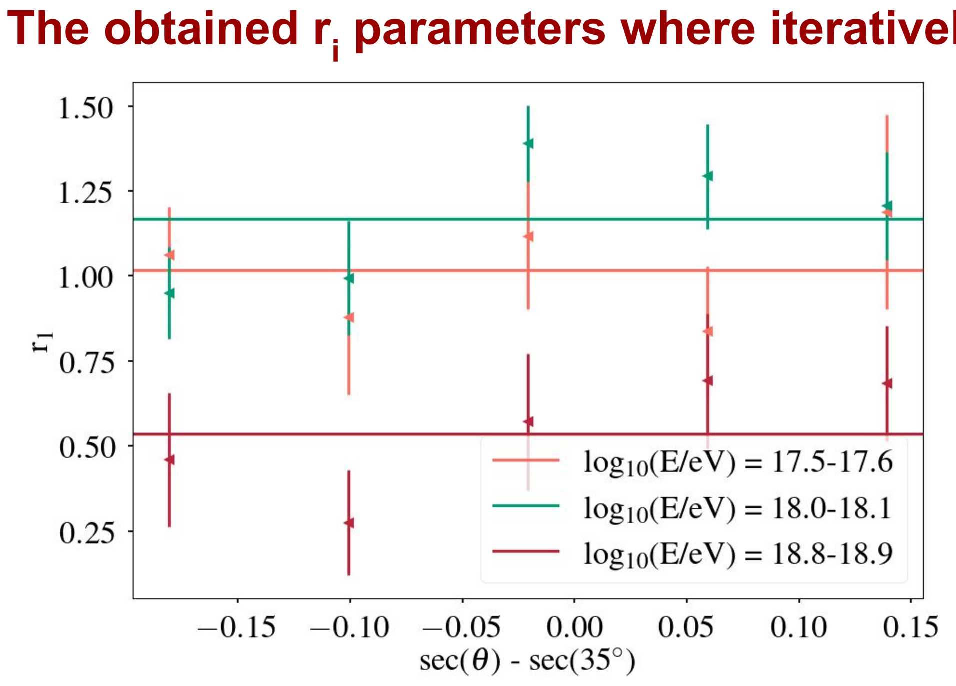
$$\hat{\rho}^{og} = \frac{\rho^{ug}}{\rho^*(r,\theta,E)}$$

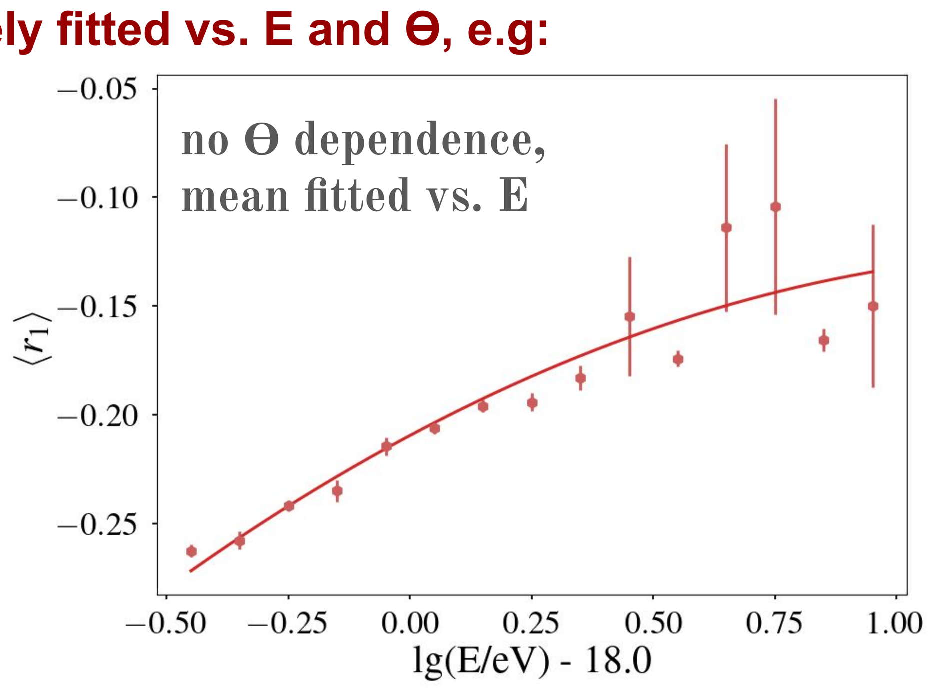


$$\rho^*(r) = \sum_{i=0}^{2} r_i \ln^i(r/\mathrm{m})$$ ➡ **At fix E and Θ bins**

4. Modelling and Optimization

The obtained r_i parameters where iteratively fitted vs. E and Θ, e.g:

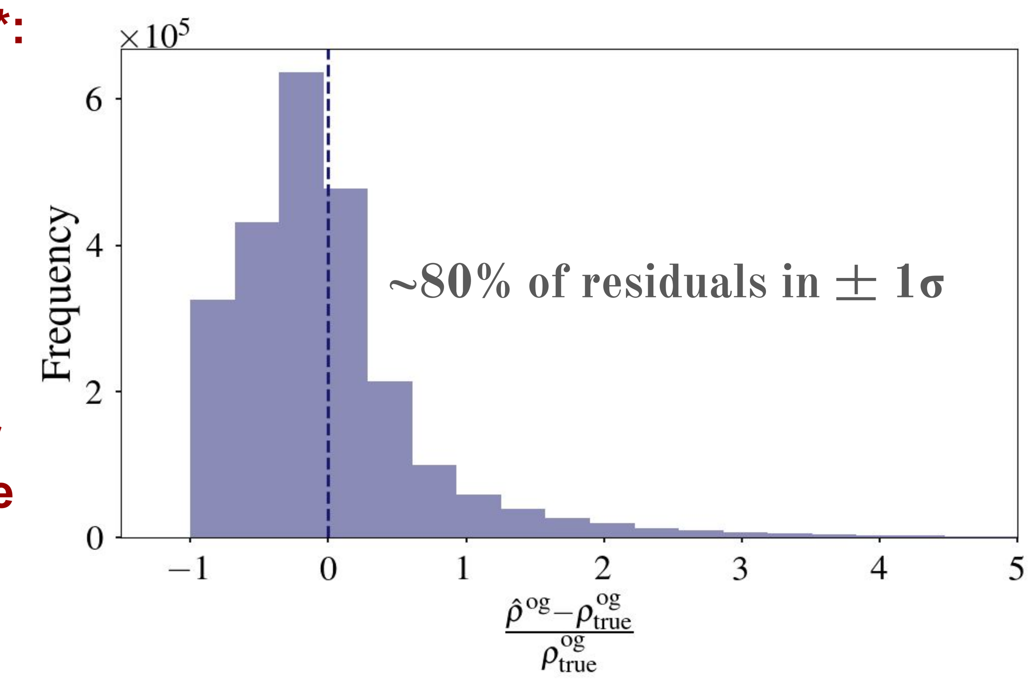




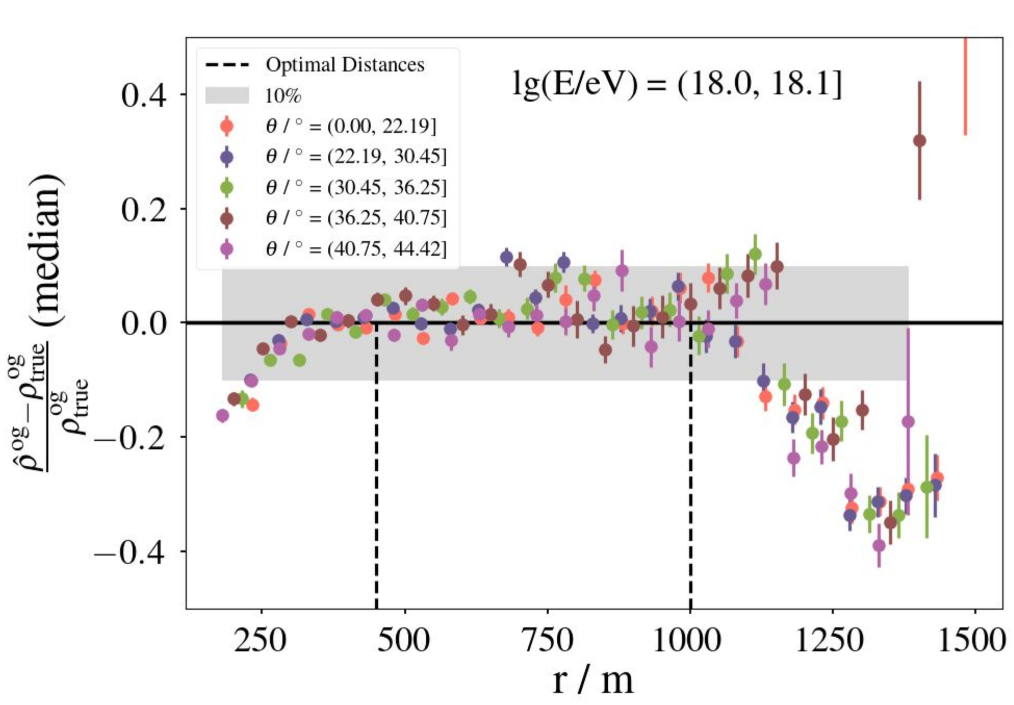
Global parametrization of ρ*:

➡ $$\hat{\rho}^{og} = \frac{\rho^{ug}}{\rho^*(r,\theta,E)}$$

The residuals obtained for the complete dataset have a mean = (-0.001 ± 0.005) with a standard deviation = (0.834 ± 0.004)

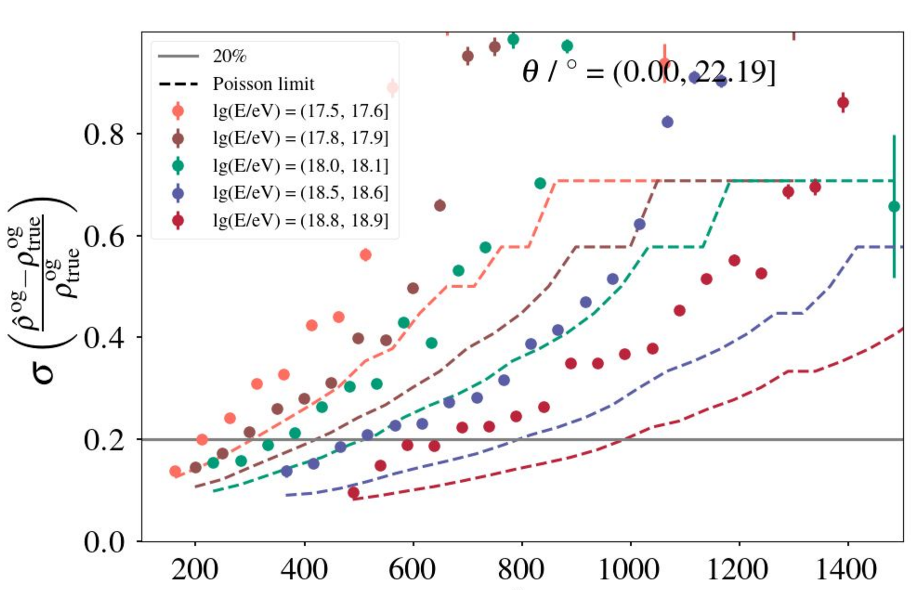


5. Bias and resolution



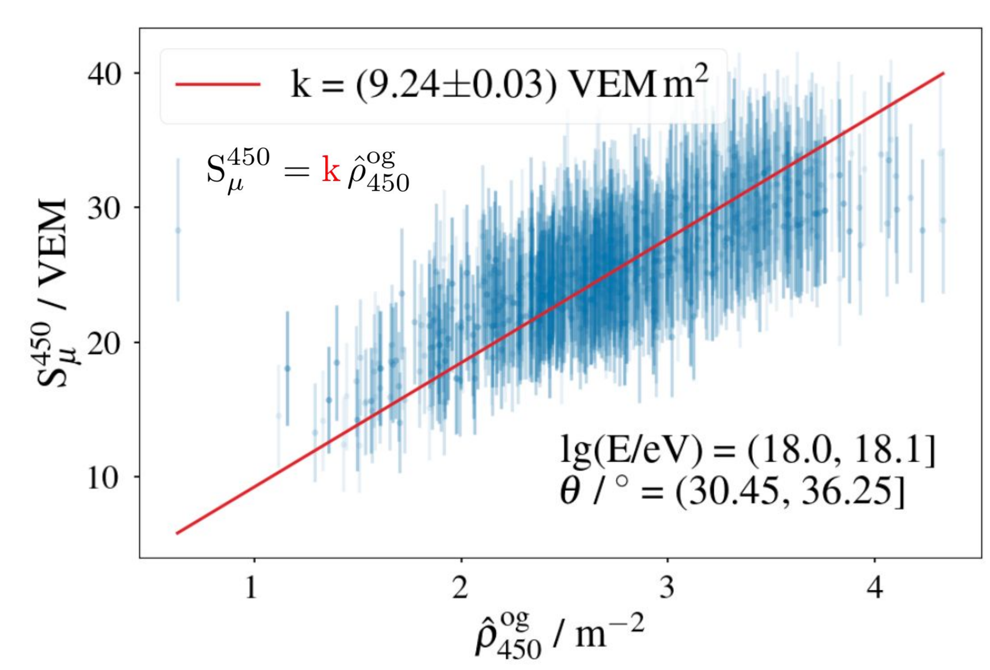
- Zenith independent
- Energy independence also observed
- Zero-centered and less than 10% between ~300 and 1100 m
- ~0 bias at optimal distances

- Better near shower axis and for higher energies
- Minimum given by Poisson fluctuations



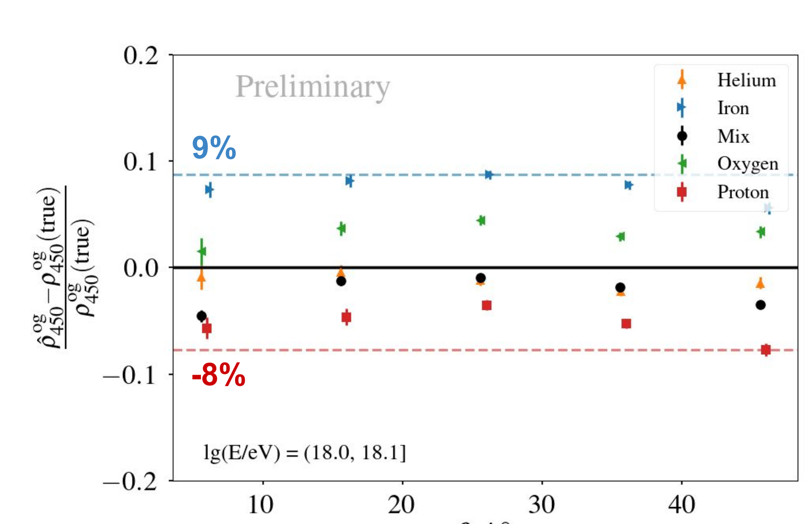
- Bias and resolution evaluated with Auger-Mix composition [4]

6. Correlation with muonic signal



- Simulated muonic signal shows positive correlation with estimated $\hat{\rho}^{og}$ at 450 m (750 m infill optimal distance)
- Validation of muon density estimations with surface detectors

- Mass composition bias within ~ 9%
- Observed for all energies up to lg(E/eV) = 18.4



Summary and next steps

✓ The dependence of the ratio of muon densities underground and on-ground vs. r, Θ, and E were studied and parametrized
✓ Overall bias is centered around 0 and no r, Θ, and E dependencies were observed
✓ Positive correlation with simulated muonic signal in the WCD
➡ Systematics will be identified and quantified
➡ Artificial fluctuations will be introduced in S_μ to estimate limits of the method

References

[1] A. Castellina for the Pierre Auger Collaboration, **UHECR EPJ Volume 210, 06002 (2018)**
[2] M. Scornavacche for the Pierre Auger Collaboration, **UHECR EPJ Volume 283, 06012 (2023)**
[3] J. de Jesús for the Pierre Auger Collaboration, **PoS(ICRC2023)267**
[4] J. Bellido for the Pierre Auger Collaboration, **PoS(ICRC2017)506**

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