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

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This work focuses on estimating the muon density at ground level using simulations and investigating its correlation with the muonic signal recorded by the Water Cherenkov Detectors (WCDs) of the Pierre Auger Observatory. The study is motivated by the need to validate the estimation of the muonic signal in the WCDs. The methodology involves the development of a parameterization for the surface muon density based on simulated muon data from the Underground Muon Detector (UMD) of AugerPrime—an upgrade to the Pierre Auger Observatory. Our results indicate a negligible bias and a resolution better than 40% at energies above $10^{17.5}$ eV. Furthermore, we find a strong positive correlation between the estimated muon density and the simulated muonic signals in the WCDs.

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1. Introduction

The Pierre Auger Observatory [1], with the World's largest exposure to ultra-high energy cosmic rays, has significantly advanced our understanding of their properties. However, key questions remain regarding their sources, primary composition, and the underlying hadronic interactions.

To address these questions, new detection systems have been implemented at the Pierre Auger Observatory, including the Surface Scintillation Detector (SSD) and the Underground Muon Detector (UMD). These systems enhance the observatory's ability to probe the properties of Extensive Air Showers (EAS).

The SSD consists of 4 m^2 plastic scintillator modules mounted on top of each Water Cherenkov Detector (WCD) in the Surface Array. Together, SSD and WCD provide complementary measurements of the electromagnetic and muonic components of EAS, allowing their separation [2].

The UMD, on the other hand, directly measures the muon content of the EAS, a crucial parameter for understanding the primary composition and refining hadronic interaction models. Each UMD station covers 30 m^2 and consists of 64 scintillation bars. These stations are deployed in triangular grids with 750 m and 433 m spacing, covering an area of 23.5 km^2 [3, 4]. The UMD is primarily designed to collect events in the energy range of $10^{17.2}$ eV and does not cover a large enough area to gather statistics for events with energies greater than $10^{18.5}$ eV. Consequently, at the highest energies, the muon content must be estimated indirectly.

The motivation for this work is to provide a method to validate the estimation of the muonic signal in the WCD and to extend this estimation to the 1500 m array of the Pierre Auger Observatory, where the highest-energy events are detected.

The objective of this study is to estimate the density of muons at ground level using simulations and to investigate the correlation between this estimator and the muonic signal in the WCD. Section 2 outlines the methodology, followed by the modelling and optimization of the functional form in Section 3. Section 4 examines the bias and resolution of the model, while Section 5 explores its correlation with the muonic signal in the WCD, denoted as S_μ.

2. Method

The method used to estimate the muon density on-ground and validate the estimations of the muonic signal in the WCD, named S_μ, consisted of the following steps:

First, the following ratio was defined to study its dependencies:

$$\rho^* = \frac{\rho^{\mathrm{ug}}}{\rho^{\mathrm{og}}}, \tag{1}$$

where ρ^{ug} is the simulated muon density underground, reconstructed with the UMD, and ρ^{og} is the muon density on the ground that reaches the WCD, which is the quantity to be predicted. To construct this ratio, simulations were performed using the official software of the Pierre Auger Collaboration, $\overline{\text{Off}}\underline{\text{line}}$ [5, 6]. EAS were simulated with primary energies ranging from $10^{17.5}$ eV to 10^{19} eV and zenith angles up to 45°. The EPOS-LHC hadronic interaction model [7] was used, along with four different primary mass compositions: proton, helium, oxygen, and iron. For each primary mass and energy bin (spanning 0.5 lg(E/eV)), a total of 12500 events were simulated.

Next, for each energy bin, a random sample of events was extracted for each mass composition based on the fractions estimated by the Fluorescence Detector of the Pierre Auger Observatory [8]. Information about the injected muons in both the WCD and UMD was then collected to calculate ρ^* on a per-station basis.

The dependencies of ρ^* on the distance from the shower axis r, the energy of the primary particle E, and the zenith angle θ were studied independently. These dependencies were iteratively fitted to derive a global model for the ratio. The resulting parametrization was optimized using a global χ^2 minimization.

Subsequently, the estimated muon density on-ground, $\hat{\rho}^{\text{og}}$, which depends on the three aforementioned variables, was reconstructed using the direct muon density reconstructed with the UMD. The estimation is given by:

$$\hat{\rho}^{\text{og}} = \frac{\rho^{\text{ug}}}{\rho^*(r, \theta, E)}. \tag{2}$$

Finally, the correlation between the reconstructed muon density and the simulated S_μ was characterized.

3. Modelling and Optimization

To preliminarily explore how ρ^* depends on E, θ, and r, the dependence on r was analysed within fixed energy and zenith bins. An example for a specific energy bin is shown in Figure 1. As can be seen, the dependence of ρ^* on r can be described by a linear function with parameters r_1 (slope) and r_0 (offset):

$$\rho^*(r) = r_1 \left(\frac{r}{450\,\text{m}}\right) + r_0 \tag{3}$$

this fit was performed for each zenith bin, and the resulting parameters were analyzed as functions of θ and E. The dependence of r_1 and r_0 on θ is shown in Figure 2. It can be observed that the parameters also show linear dependencies with θ, therefore, they were modeled as:

$$r_1(\theta) = s_1\ (\sec(\theta) - \sec(35^\circ)) + s_0 \tag{4}$$

$$r_0(\theta) = t_1\ (\sec(\theta) - \sec(35^\circ)) + t_0. \tag{5}$$

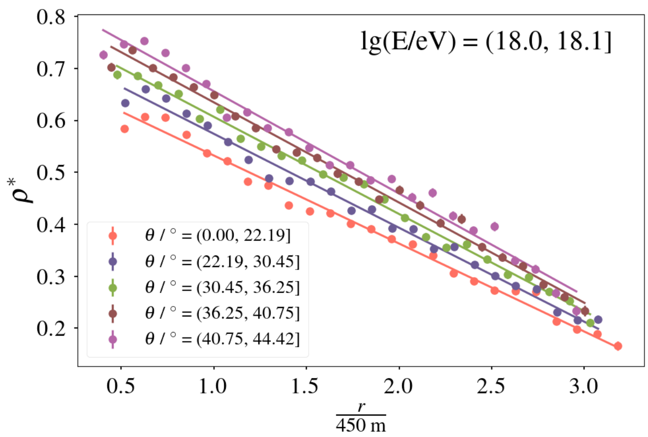

Figure 1: Dependence of ρ^* on r for a fixed energy bin ($18.0 \leq \log_{10}(E/\text{eV}) < 18.1$) and different zenith bins.

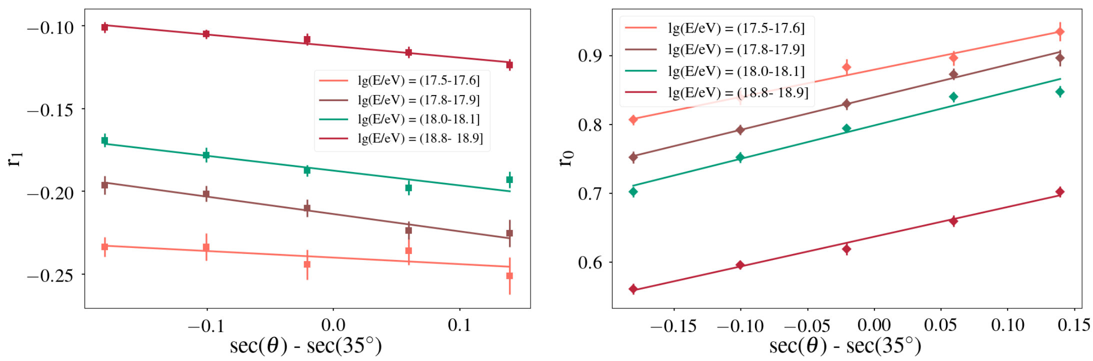

Figure 2: Parameters r_1 (left) and r_0 (right) dependences on θ for different energy bins.

Afterward, to account for E dependencies, the parameters s_1, s_0, t_1, and t_0 were fitted as a function of E, as can be seen in Figure 3.

Studying the aforementioned dependencies and fits provided information on how the global model for ρ^* could be constructed. With these insights, the following parametrization was optimized using a χ^2 minimization method, and the parameters were renamed for simplicity:

$$\begin{aligned}\rho^*(r, \theta, E) = p_0 + p_1 \left(\frac{r}{450\,\text{m}}\right) + p_2(\sec(\theta) - \sec(35^\circ)) \\ + p_3(\lg(E/\text{eV}) - 18.0) + p_4 \left(\frac{r}{450\,\text{m}}\right)(\lg(E/\text{eV}) - 18.0) \\ + p_5 \left(\frac{r}{450\,\text{m}}\right)(\sec(\theta) - \sec(35^\circ)) + p_6 \left(\frac{r}{450\,\text{m}}\right)(\lg(E/\text{eV}) - 18.0)^2. \end{aligned} \quad (6)$$

The optimal parameters obtained are presented in Table 1.

Having obtained the global function and optimal parameters for ρ^*, the muon density on the ground could be estimated using Eq. (2).

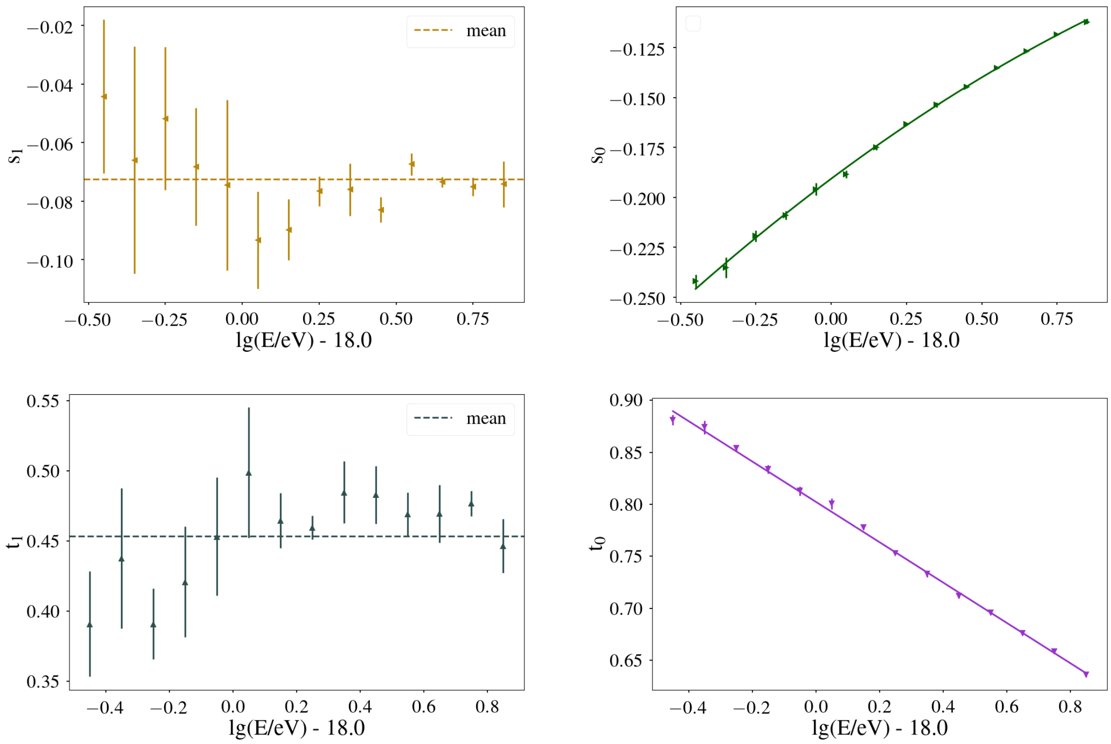

Figure 3: E dependencies of parameters s_1, s_0, t_1, and t_0.

p_0	0.803 ± 0.001
p_1	-0.191 ± 0.001
p_2	0.452 ± 0.009
p_3	-0.193 ± 0.001
p_4	0.111 ± 0.001
p_5	-0.071 ± 0.003
p_6	-0.019 ± 0.003

Table 1: Optimal parameters after minimization.

Subsequently, the relative residuals of $\hat{\rho}^{\mathrm{og}}$ were computed, yielding a distribution with a mean value of 0 and a standard deviation of 0.85. Approximately 85% of the residuals lie within the $\pm 1\sigma$ interval. The residual distribution is shown in Figure 4.

4. Bias and Resolution

To evaluate the dependence of bias and resolution on r, E, and θ, these two metrics were analyzed in separate bins for each of the three variables. Two examples of the results obtained are shown in Figure 5. Although the bias shows a dependence on r, it is observed to be independent across all values of θ and E. Furthermore, the bias remains within 10% for the two distances of interest: 450 m and 1000 m, which correspond to the optimal distances for the 750 m and 1500 m

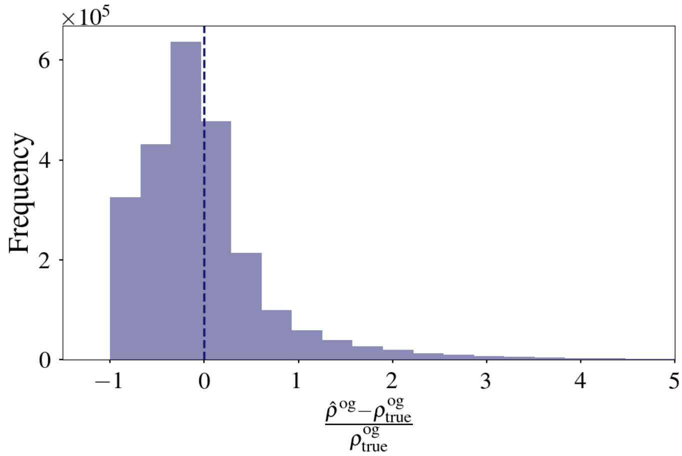

Figure 4: Distribution of residuals for the $\hat{\rho}^{\mathrm{og}}$ parametrization.

arrays, respectively. For this work in particular, only stations at 450 m will be employed. However, it is advantageous to already have a range of distances where the parametrization works, especially at 1000 m for the highest energies, to facilitate future extrapolations of this work to estimations that may be performed for the 1500 m array.

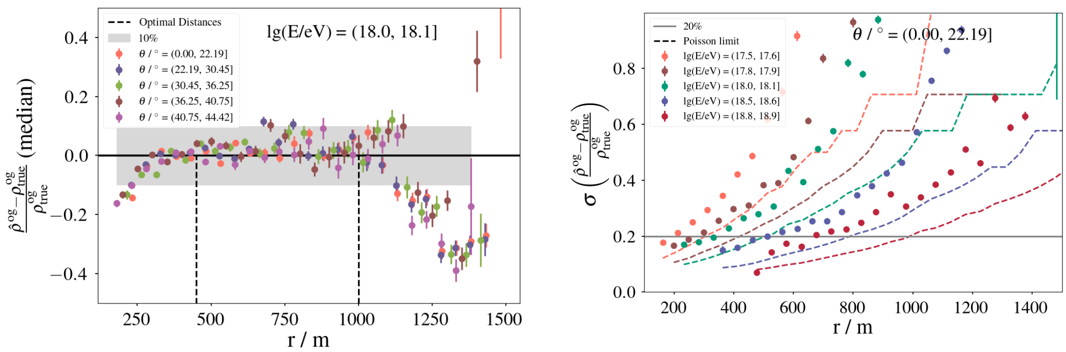

Figure 5: Examples of bias (left) and resolution (right) as functions of the studied variables.

Regarding the resolution, it can be observed that it improves for higher energies and shorter distances to the shower axis. Additionally, the resolution is limited by the Poisson fluctuations of the variable being predicted. The Poisson limits are shown as dashed lines in the same color as the resolution markers in Figure 5 (right).

5. Correlation with Muonic Signal

Finally, as a proof of concept, the correlation with the simulated muonic signal of the Water Cherenkov Detector (WCD) was characterized by a linear dependence with zero offset. This relationship is illustrated in Figure 6. For each energy/zenith bin, the slope parameter shows values of approximately $10\,\mathrm{VEM\,m^2}$. This is an expected value, as it is close to the effective area of the WCD. This implies that for each muon passing through the detector, a signal of approximately 1 VEM is obtained.

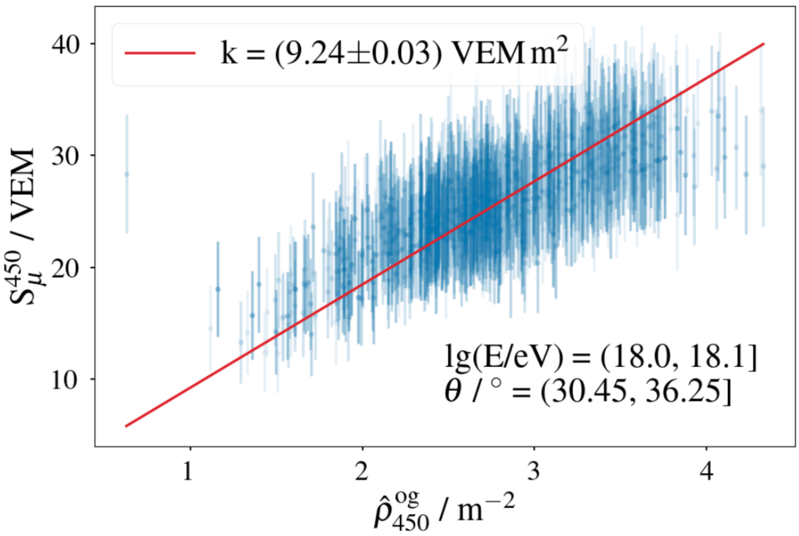

Figure 6: Linear and positive correlation between the simulated S_μ and $\hat{\rho}_\mu^{og}$ at the optimal distance of 450 m.

6. Summary and Conclusions

This work analysed the bias and resolution of a muon density estimator and its correlation with the muonic signal in the Water Cherenkov Detector (WCD).

The bias was found to be independent of the zenith angle and energy. Although a dependence on the distance from the shower axis was observed, it remained within 10% for the two distances of interest. The resolution improves with increasing energy and decreasing distance to the shower axis but is limited by Poissonian fluctuations, as shown in Figure 5 (right). These fluctuations represent the fundamental statistical limit of the predictions.

A linear correlation was observed between the simulated muonic signal (S_μ) and the estimated muon density ($\hat{\rho}_\mu^{og}$). The slope of this correlation, approximately 10 VEM m^2, matches the expected effective area of the WCD. This indicates that each muon passing through the detector generates a signal of about 1 VEM.

These results demonstrate the reliability of the estimator for surface muon densities and its connection to the WCD signal, with potential applications for higher energy ranges in the future.

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