PROCEEDINGS OF SCIENCE

The Underground Muon Detector of AugerPrime

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The Underground Muon Detector (UMD) of the Pierre Auger Observatory is designed to conduct a precise assessment of the muon component within air showers from cosmic rays with energies surpassing $10^{16.6}$ eV. The muon content serves as a valuable indicator of the mass composition of primary particles. It consists of segmented modules of plastic scintillation bars buried at a depth of 2.3 m to shield them from the electromagnetic component of the showers. This work is an overview of the characteristics of the detector regarding its mechanics and electronics, the main results obtained during its prototype phase, as well as an update regarding the current status of the detector's deployment and long-term performance monitoring.

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1. Introduction

The Pierre Auger Observatory is aimed at unraveling the open questions surrounding ultra-high energy cosmic rays. It consists of a triangular grid of Water-Cherenkov Detectors (WCDs) with an area of 3000 km^2 where each WCD is separated from each other by a distance of 1500 m. Also, to extend the detection of the observatory to lower energies, there are two nested denser arrays with a separation between detectors of 750 m and 433 m. These three arrays form the Surface Detector (SD). Additionally, 27 Fluorescence Detectors (FD) located at four sites surrounding the SD overlook the atmosphere to measure the longitudinal development of the air-showers developed by the primary cosmic rays.

In order to further improve the sensitivity of the SD to the different components of the shower, the AugerPrime upgrade was designed. One of its instrumental components, the Underground Muon Detector (UMD), plays an important role in achieving this goal. The UMD is designed to directly measure the muon content within the air-showers generated by cosmic rays. This is an observable directly related to the primary particle mass since it scales with energy E and mass number A as $N_\mu \propto AE^\beta/(A\xi_c)^\beta$, where ξ_c is the critical energy below which charged pions are likely to decay into muons ($\xi_c \sim 20$–$30\,\mathrm{GeV}$, $\beta \sim 0.9$) [1, 2].

2. Mechanics and Deployment

Each UMD station comprises three 10 m^2 modules, each segmented into 64 plastic scintillator strips, as shown in Figure 1 (left). These strips are equipped with wavelength-shifter optical fibers, which serve as light conductors. When a particle impinges on and excites a scintillator strip, fluorescence photons are emitted. These photons are channeled by the optical fibers towards a 64 Silicon Photo Multipliers (SiPMs) array nestled at the center of each module [3].

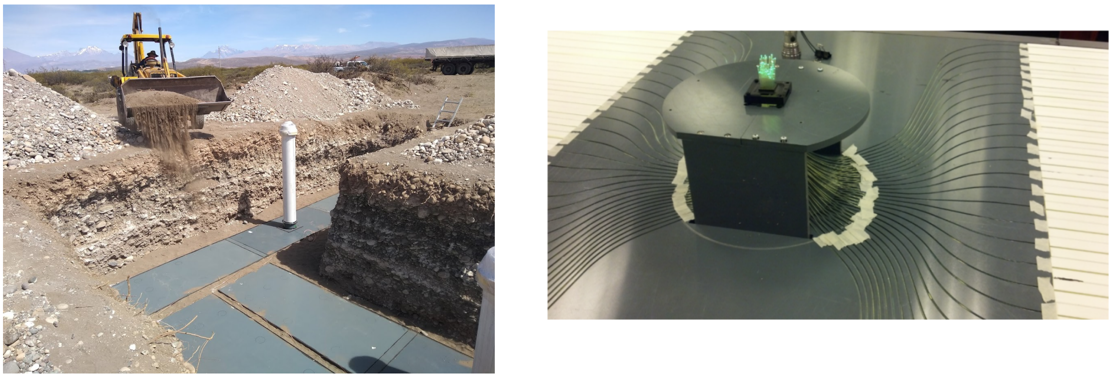

Figure 1: Left: Modules are buried, the tubes give access to the electronics dome from the surface for maintenance and repair. Right: Electronics dome of a UMD module before is closed, it can be observed how the optical fibers carry the light to the cookie where the SiPM array is afterward placed.

The electronics dome is shown in Figure 1 (right). Characteristics of the acquisition modes and the UMD electronics will be discussed in Section 3.

Each UMD detector is buried 2.3 m deep. The depth, which is approximately equivalent to 540 $\mathrm{g\,cm^{-2}}$ overburden, as determined by the local soil density, is such that the electromagnetic part of extensive air-showers is predominantly attenuated. However, muons possessing energy greater than roughly 1 GeV can still penetrate the UMD. Each detector is positioned at a minimum distance of 7 meters from the center of a partner surface detector, ensuring that particles from air-showers with zenith angles up to 45° can reach the scintillators without needing to traverse the surface detector. The set up can be seen in Figure 2. The current plan is to install a UMD paired with all the WCDs of the 750 m or the 433 m arrays respectively.

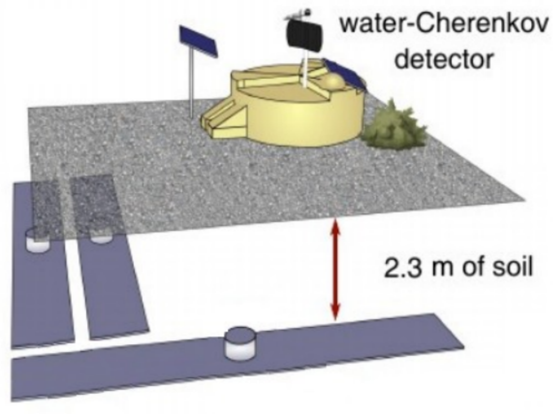

Figure 2: Final design and set-up of the UMD: Three 10 m^2 modules buried at a depth of 2.3 m and paired to a WCD station located either in the 750 m or the 433 m array.

3. The UMD acquisition modes

To achieve an extensive dynamic range, the readout electronics within the UMD modules incorporate both **binary** and **integrator** modes [4–6].

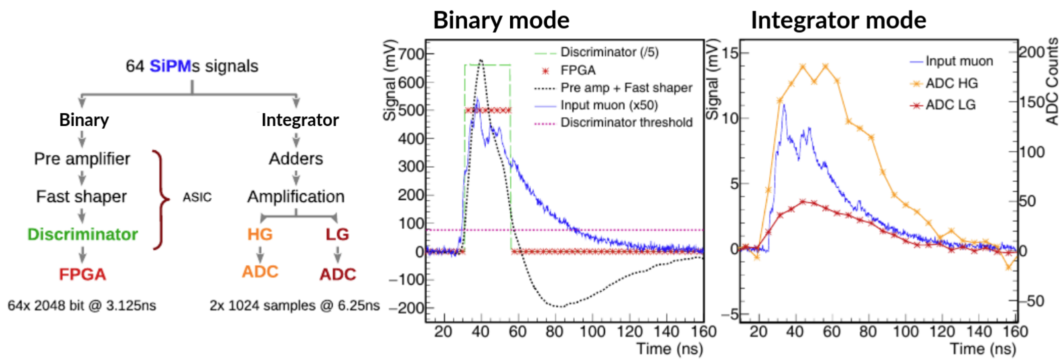

Figure 3: Acquisition modes of the UMD. In the binary mode, the signal from each SiPM is treated independently and outputs 64 traces of 2048 samples. The square signal of the discriminator (dashed green line) is sampled every 3.125 ns. A “1” is produced every time this signal is above threshold, otherwise a “0” is stored. In the integrator mode, two waveforms corresponding to the high and low-gain amplification are obtained.

In the binary mode, the output of each SiPM is read separately. Each signal goes through a pre-amplifier, a fast-shaper, and a discriminator. The discriminator threshold is set at 2.5 photon equivalents (PE) to avoid dark-rate and cross-talk noise. Then, if the signal is above this threshold, it is stored as a “1” in a 2048-bit trace with a Field-Programmable Gate Array (FPGA) at 320 MHz.

If the signal is below the threshold, a "0" is stored, obtaining 64 binary traces as output. To ascertain the quantity of particles arriving at the UMD using the binary mode, it is essential to establish a counting approach. Therefore, a counting strategy based on the time span of the muon signal and noise, as well as an inhibition window, was studied and tested in the laboratory. From these studies, it was obtained that an inhibition window of 37.5 ns and a minimum width of 12.5 ns maximize the signal-to-noise-ratio.

On the other hand, the integrator mode adds up analogically the signals of the 64 SiPMs and the output is then low and a high-gain amplified. Then, the signals are sampled with analog-to-digital converters (ADCs) into two waveforms of 1024 samples. To obtain the number of muons, the integrated waveforms are divided by the mean muon charge, which is obtained via the calibration of the total charge in the ADC, with the number of muons estimated with the binary acquisition mode.

4. Current status and long term performance

As of now, approximately 52% of the UMD positions have been deployed, as can be seen in Figure 4. Based on the current rate, it is anticipated that the entire UMD array will be fully operational by the end of 2024. The functionality of the UMD system is linked to the external triggers originating from the SD stations and organized in a hierarchical structure. Whenever a local trigger is generated within an SD station, a signal is sent to the electronics of its corresponding UMD modules, prompting them to archive their data in their internal memory [7].

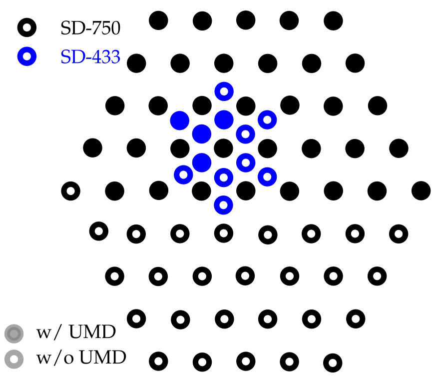

Figure 4: Current deployment status of the UMD modules. The filled circles represent positions in the 750 m (black) and 433 m (blue) arrays where the UMD have already been deployed.

To assure the good performance of the detector, several studies are taking place. For example, fiber attenuation plays a major role in signal fluctuations. When a muon strikes the nearest position to the SiPMs, it generates nearly twice as many photon-equivalents as when it strikes the position farthest away. In the left panel of Figure 5 this phenomenon becomes evident in the binary mode, where there is a discernible anti-correlation between the length of the optical fiber manifold and the average number of "1s" in the signal. This translates into a notable divergence of approximately 5% in the count of ones between the shortest and longest fiber configurations. Furthermore, the impact of fiber attenuation is equally pronounced in the ADC, as strips with longer fibers exhibit diminished single-muon charge values. This discrepancy results in an appreciable discrepancy of around 15% in charge values between the shortest and longest fiber setups, underscoring the crucial role that fiber attenuation plays in signal processing and data analysis.

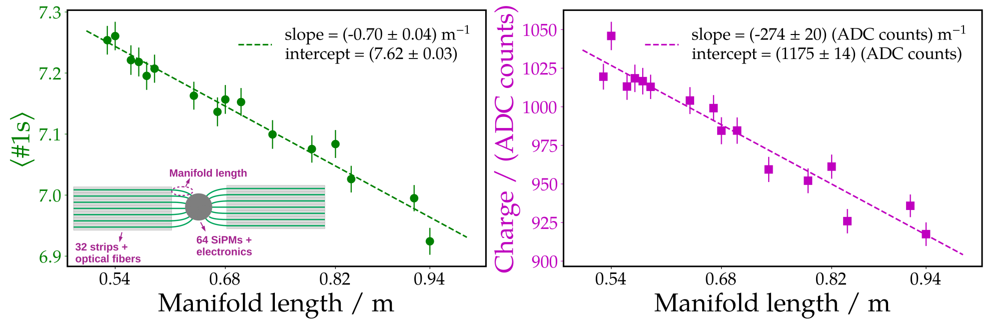

Figure 5: Mean number of "1s" (left) and mean single-muon charge (right) as a function of the manifold length of the optical fibers (shown in inset).

Furthermore, an evaluation of the evolution of the SiPMs gain was conducted. It is known that a SiPM gain decreases with temperature, therefore, a compensation mechanism is employed in each module to correct the gain for seasonal fluctuations. In any case, a long-term analysis of this effect was performed to check for possible residual fluctuations. As can be seen in Figure 6, these fluctuations result in a $\sim \pm 1\%$ of the gain and, correspondingly, of the mean number of 1s and the single-muon charge. This level of fluctuation is negligible and has no impact on the detector measurements.

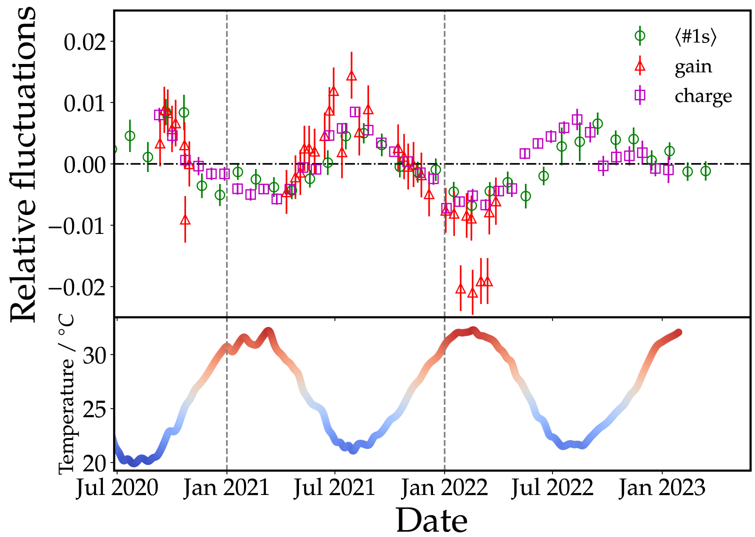

Figure 6: Seasonal fluctuations of the SiPMs gain. An anti-correlation with the measured temperature is observed. The fluctuations are of $\sim \pm 1\%$ having no impact on the detector's performance. A period of one year is enclosed between the gray dotted lines.

5. Results obtained with the Engineering Array

During its prototype phase, seven UMD stations were deployed for testing and proof of concept. This phase was known as the Engineering Array (EA), and important results regarding the air-shower muon content and discrepancies between measurements and simulations were obtained. As one of these results, an estimation of the muon content in air-showers and a comparison with the expected values from simulations with the quantity ρ_{35} as shown in Figure 7. More results that show discrepancies between measurements and simulations can be found in [8].

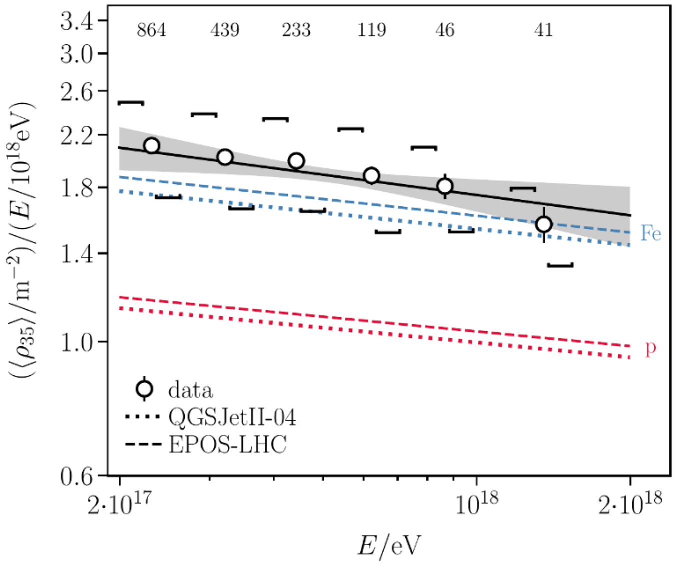

Figure 7: Comparison of the muon content obtained with measurements with the one expected from simulations.

6. Summary

In this work, the Underground Muon Detector of the Pierre Auger Observatory was presented. Its mechanics and deployment operations were described, as well as its two complementary acquisition modes. An update of its current deployment status was reported, followed by a description of some of the analyses that take place to assure a good detector's performance. Finally, the first muon content measurements obtained in the prototype phase of the UMD were presented.

References

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