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# Measurements of the muon content of air showers at the Pierre Auger Observatory

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**Abstract.** The Pierre Auger Observatory offers a unique window to study cosmic rays and particle physics at energies above 3EeV (corresponding to a centre-of-mass energy of 75 TeV in proton-proton collisions) inaccessible to accelerator experiments. We discuss the different methods of estimating the number of muons in showers recorded at the Pierre Auger Observatory, which is an observable sensitive to primary mass composition and to properties of the hadronic interactions in the shower. The muon content, derived from data with these methods, is presented and compared to predictions from the post-LHC hadronic interaction models for different primary composition. We find that models do not reproduce well the Auger observations, displaying a deficit of muons at the ground. In the light of these results, a better understanding of ultra-high energy extensive air showers and hadronic interactions is crucial to determine the composition of ultra-high energy cosmic rays. We report on the upgrade plans of the Pierre Auger Observatory to achieve this science goal.

## 1. Introduction

Understanding the mass composition of ultra-high energy cosmic rays (UHECR) is fundamental to unveiling their production and propagation mechanisms. The interpretations of observed anisotropies [1, 2] and of features of the flux, such as the ankle at an energy of about  $5 \times 10^{18}$  eV and the strong suppression above  $4 \times 10^{19}$  eV [3], rely on the assumed mass composition at Earth.

Ultra-high energy cosmic rays can only be observed indirectly through air showers initiated in the Earth's atmosphere. The mass composition can be inferred from certain shower observables, which are also dependent on the properties of the hadronic interactions in the shower. Inferring the mass composition from these measurements is subject to some level of uncertainty because it relies on the use of simulated showers generated by assuming a hadronic interaction model [4]. Such models are based on extrapolation from accelerator data over more than two orders of magnitude in energy in the centre-of-mass frame and in different phase space regions of interest. Disentangling the composition from models is of utmost importance and is one of the most compelling challenges in UHECR physics.

The number of muons in an air shower at ground-level is a powerful tracer of the cosmic-ray mass. It has been shown that the number of muons produced scales nearly linearly with the cosmic-ray energy,  $E$ , and increases with a small power of the cosmic-ray mass,  $A$ , as [5]:

$$N_{\mu} = A^{1-\beta} \left( \frac{E}{\xi\pi} \right)^{\beta}, \quad (1)$$



where  $\xi_c^\pi$  is the critical energy at which particle production by charged pions ceases and  $\beta$  is predicted by simulations to be  $\approx 0.9$ . Simulations also show further dependences on several properties of hadronic interactions, including the multiplicity, the charge ratio and the baryon antibaryon pair production [6, 7].

The Pierre Auger Observatory [8], conceived to characterise the properties of the UHECRs with energies above  $10^{18}$  eV, is a hybrid instrument of air-shower detection. It combines an array of particle detectors, the Surface Detector array (SD) [9], to sample the air-shower front as it reaches the ground, and Fluorescence Detector (FD) telescopes to collect the ultraviolet light emitted by nitrogen as showers develop in the atmosphere [10]. The FD is used to monitor the atmosphere, on dark clear nights, above the  $3\,000\text{ km}^2$  area over which the SD 1660 water-Cherenkov stations (separated by 1.5 km) are laid out. The site is located near the town of Malargüe, Argentina, at an altitude of about 1425 m above sea-level and at an average altitude of  $35.2^\circ$  S.

In this paper, we present the average muon content in showers measured with the Pierre Auger Observatory using different analysis techniques. We also compare these measurements to predictions of the post-LHC hadronic interaction models QGSJETII-04 [11] and EPOS LHC [12] for different primary masses. Finally, we discuss the potential upgrades of the Pierre Auger Observatory to enhance the capabilities of the SD array in order to achieve a clean measurement of the muon number. This is the key to estimating the primary composition on an event-by-event basis, and to study fundamental interactions at energies inaccessible to accelerator experiments.

## 2. Measurement with highly inclined showers

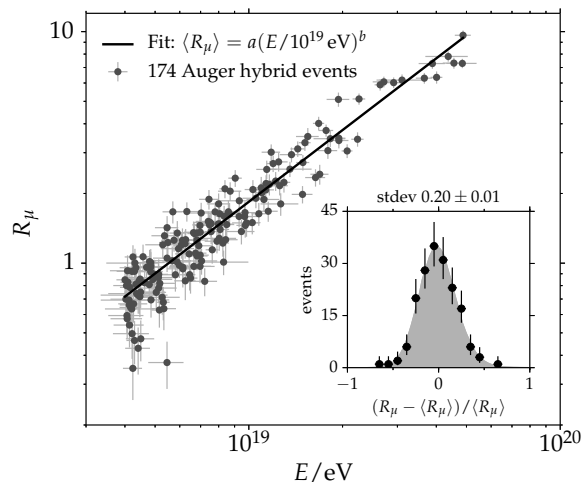
Highly inclined showers, those arriving at ground with zenith angle  $\theta > 60^\circ$ , are characterised by the dominance of secondary energetic muons at the ground, since the electromagnetic (EM) component has been largely absorbed in the greatly enhanced atmospheric depth crossed by the shower before reaching ground. Such inclined showers provide an almost direct measurement of the muon number at ground-level [13, 14].

The approach to measuring the number of shower muons follows from developments that have been introduced to reconstruct inclined showers [15]. It is based on the observation that the shape of the muon distribution is universal for a given shower direction and that only the overall normalisation of the muon distribution depends on the shower energy and primary mass. It has also been shown that the lateral shape of the muon density is consistently reproduced by different hadronic interaction models and software packages used for air-shower simulations. These universal characteristics allow one to model the muon density  $\rho_\mu(\vec{r})$  as:

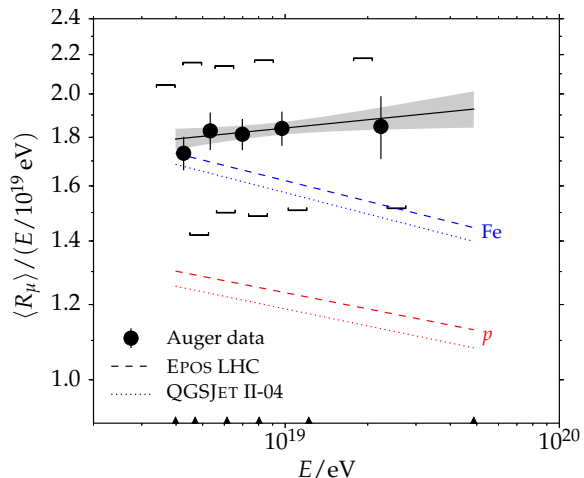
$$\rho_\mu(\vec{r}) = N_{19} \rho_{\mu,19}(\vec{r}; \theta, \phi), \quad (2)$$

where  $N_{19}$  is defined as the scale factor of a particular event with respect to a reference muon distribution  $\rho_{\mu,19}$ , conventionally chosen to be the average muon density for primary protons of  $10^{19}$  eV simulated with the hadronic interaction model QGSJETII-03 [16].  $N_{19}$  at a given zenith angle is a relative measure of the number of muons produced  $N_\mu$  (addressed in Eq. 1), and is inferred from fitting the measured signals at the SD stations to the expected muon patterns for a given reconstructed arrival direction.

Simulations show that  $N_{19}$  deviates, on average, around 5% from the true relative content of muons in a shower,  $R_\mu^{\text{MC}}$  [13, 14, 15]. This ratio is computed for each event by counting the total number of muons  $N_\mu$  at the ground in the simulation and dividing by the total number of muons  $N_{\mu,19}$  in the reference muon distribution:  $R_\mu^{\text{MC}} = N_\mu/N_{\mu,19}$ . Hence to get an unbiased estimator, the measured value  $N_{19}$  is corrected for this average bias, and renamed  $R_\mu$ . By combining the uncertainty attributed to the hadronic interaction model assumption with that of the simulated muon response of the SD detectors at  $\theta > 60^\circ$  [17], the systematic uncertainty of  $R_\mu$  is estimated to be 11%.



**Figure 1.** Fit of the calibration  $\langle R_\mu \rangle = a(E/10^{19} \text{ eV})^b$  to the selected hybrid events. Only statistical uncertainties are shown.



**Figure 2.** Average muon content  $\langle R_\mu \rangle$  per shower energy  $E/10^{19} \text{ eV}$  as a function of the shower energy  $E$ . The brackets indicate the systematic uncertainties and systematic shifts due to 14% of the energy scale uncertainty [18]. Theoretical curves for proton and iron showers are shown for comparison.

The muon content  $R_\mu$  of showers with zenith angles  $62^\circ < \theta < 80^\circ$  is studied as a function of the calorimetric measurement of the cosmic-ray energy  $E$  from high-quality events measured simultaneously with the SD and the FD. Only events well-contained in the SD array with energies above  $4 \times 10^{18} \text{ eV}$  (corresponding to 100% SD trigger probability) are accepted for the analysis. More quality selection criteria and fiducial cuts used in this analysis are explained in detail in [14]. For the period from 1 January 2004 to 31 December 2012, a total of 174 events were accepted.

The correlation between  $R_\mu$  and  $E$  can be described by fitting the parametrisation

$$R_\mu = a (E/10^{19} \text{ eV})^b, \quad (3)$$

to the selected data. The  $a$  parameter represents the average muon content at  $10^{19} \text{ eV}$ , and the  $b$  parameter the logarithmic gain  $d\langle \ln R_\mu \rangle / d \ln E \simeq d \ln N_\mu / d \ln E$  of muons with increasing energy. The data and results of the fit are shown in figure 1. The average muon content at  $10^{19} \text{ eV}$  obtained is  $(1.841 \pm 0.029 \pm 0.324 \text{ (sys.)})$ , which corresponds to  $(2.68 \pm 0.04 \pm 0.48 \text{ (sys.)}) \times 10^7$  muons with energies larger than  $0.3 \text{ GeV}$  that reach  $1425 \text{ m}$  altitude in an average  $10^{19} \text{ eV}$  shower with a zenith angle of  $67^\circ$ .

A simple comparison between data and predictions for proton and iron-induced showers simulated at the mean zenith angle of  $67^\circ$  with the hadronic interaction models QGSJETII-04 and EPOS LHC is shown in figure 2. The absolute values of  $\langle \ln R_\mu \rangle$  in data correspond to masses close to or even heavier than iron. This interpretation is in contradiction with recent studies based on the depth of shower maximum,  $X_{\text{max}}$ , that show an average logarithmic mass  $\langle \ln A \rangle$  between proton and iron in this energy range [19]. To reach consistency between data and predictions based on  $\langle \ln A \rangle$  data, the mean muon number around  $10^{19} \text{ eV}$  in simulations would have to be increased by 30% to 80%, depending on the model.

The logarithmic gain  $d\langle \ln R_\mu \rangle / d \ln E$  is also large compared to predictions for constant pure composition. The hypothesis of a constant proton (iron) composition is disfavoured at the level

of  $2.2\sigma$  ( $2.6\sigma$ ). Our measurement favours a transition from lighter to heavier elements in the considered energy range. If all statistical and systematic uncertainties are added in quadrature, the deviation between the measured logarithmic gain  $d\langle \ln R_\mu \rangle / d \ln E$  and predictions based on the energy evolution of  $\langle \ln A \rangle$  estimated from the  $X_{\max}$  measurements [19] is 1.3 to 1.4  $\sigma$ .

### 3. Measurement from temporal structure of signals in surface detectors

The number of muons in less inclined air showers has also been explored, but the measurement in this case is complicated by the need to separate the electromagnetic and the muonic signals recorded in the SD stations.

Sophisticated methods have been developed to extract the muon information by analysing the time structure of the signal generated by shower particles in the detector [20, 21, 22]. These methods are based on two features of the signals which depend on the type of shower component: the amplitude distribution of the particle responses and the arrival time distributions. On one hand, the mean amplitude of a single EM particle is much smaller, and the number of EM particles are, on average, an order of magnitude larger than the number of muons. On the other hand, muons typically arrive earlier than EM particles. These two features make the muon signal short and spiky, and the EM signal long and smooth.

The two methods presented below [22], measure the mean fraction of the SD signal due to muons of air showers with energy  $E = 10^{19}$  eV at a reference distance of  $r = 1000$  m from the shower axis. Due to the similar energy scaling of the total and muon signals in the detectors at about 1000 m, the muon fraction is mostly insensitive to the systematic uncertainty of the reconstructed energy, which is 14 % [18]. The main source of uncertainty is due to high-energy photons ( $\gtrsim 300$  MeV) that can produce a signal similar to that of a muon. Their contribution is estimated to be less than 10 % to 15 % for proton and iron primaries, respectively, in the considered energy and angular range.

Note that the muon signal,  $S_\mu$ , is the pure muonic signal, so the electromagnetic halo produced by muon interactions and muon decays in the atmosphere [23] is not included in  $S_\mu$  and is treated as an EM component. Therefore, the smooth part of the signal is assumed to be the sum of the primary EM component and the EM muon halo. For vertical showers, the contribution of the EM muon halo ranges from  $\sim 8\%$  at  $\theta < 40^\circ$  up to  $\sim 12\%$  at  $60^\circ$ .

#### 3.1. Multivariate method

The basic idea of this method is to combine a large number of muon-content-sensitive observables of the FADC signal<sup>1</sup> to estimate the muon fraction,  $f_\mu$ , using a multivariate regressor. The optimal estimator found is:

$$\hat{f} = a + b\hat{\theta} + c g_{0.5}^2 + d\hat{\theta} P_0 + e\hat{r} \quad (4)$$

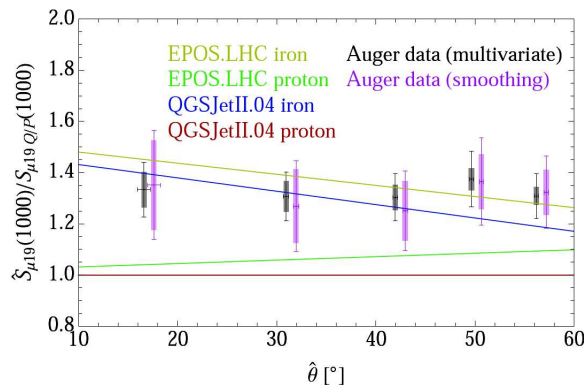
where  $\hat{\theta}$  is the reconstructed zenith angle of the shower and  $\hat{r}$  is the distance of the detector from the reconstructed shower axis. The observable  $g_{0.5}^2$  is the portion of the signal in FADC bins greater than 0.5 VEM.  $P_0$  is the normalised zero-frequency component of the power spectrum. Both  $g_{0.5}^2$  and  $P_0$  are sensitive to large relative fluctuations in temporal structure of individual traces and short signal peaks, which are signatures of high muon content.

The fit parameters ( $a, b, c, d, e$ ) are estimated using simulations as described in [22]. Simulations for different models and primary particles show that  $\hat{f}$  deviates, on average, about 2 % from the true muon fraction, and that the average resolution is about 8 %.

<sup>1</sup> The Cherenkov photons produced by the shower particles in the detectors are sampled by three photomultipliers. The analogue signal is digitised with FADCs in 25 ns bins within a 10 bit dynamic range. The raw signal is calibrated such that the integrated signal of a typical vertical atmospheric muon traversing the detector through its centre is 1. The signal in each time bin is thus measured in units of “vertical equivalent muon” of VEM [24].

### 3.2. Smoothing method

The basic idea of this method is to apply a low-pass filter a few times on the signal to gradually separate the low-frequency smooth EM component from the high-frequency component which is attributed to muons. In each step, the muon estimate is subtracted from the output of the previous iteration and the signal is re-smoothed. The final muonic signal is the sum of the non-smooth positive differences between the original trace and the smoothed one at each step (more details can be found in [20, 22]). The muon fraction,  $\hat{f}$ , is then estimated by dividing the muonic signal by the total signal. Simulations show that  $\hat{f}$  deviates, on average, about 5% from the true muon fraction, and that the average resolution is about 8%.



**Figure 3.** The measured muon signal rescaled to  $E = 10^{19}$  eV and at 1000 m from the shower axis as a function of the shower zenith angle, with respect to the reference based on QGSJETII-04 proton simulations. The boxes indicate the systematic uncertainties and the error bars represent the total uncertainty, also including the statistical uncertainties.

### 3.3. Muon signal rescaling

Both methods are used to estimate the muon fraction  $\hat{f}$  for every detector in the distance range  $\hat{r} \in [950, 1050]$  m of SD events with zenith angle below  $60^\circ$  and reconstructed energy  $\log_{10}(\hat{E}/\text{eV}) \in [18.98, 19.02]$ . For the period from 1 January 2004 to 31 December 2012, a total of 521 SD signals were analysed.

The muon signal for every detector can be retrieved by multiplying the muon fraction by the total signal at 1000 m from the shower axis. The results with respect to the chosen reference based on proton showers simulated with QGSJETII-04 are shown in figure 3, with an average value of  $(1.33 \pm 0.02 \pm 0.05(\text{sys.}))$  (multivariate) and  $(1.31 \pm 0.02 \pm 0.09(\text{sys.}))$  (smoothing). The two analysis methods show a good agreement. The measurement is bracketed by model predictions for proton and iron primaries with QGSJETII-04 and EPOS LHC within the systematic uncertainties.

A simple comparison of these results with the measurement from highly inclined showers can be performed by accounting the scale factor of the muon number densities derived for QGSJETII-04 proton showers relative to those for QGSJETII-03, which is  $\sim 1.2$  [15]. We found that vertical and inclined measurements are compatible within uncertainties.

## 4. Measurement with hybrid vertical events

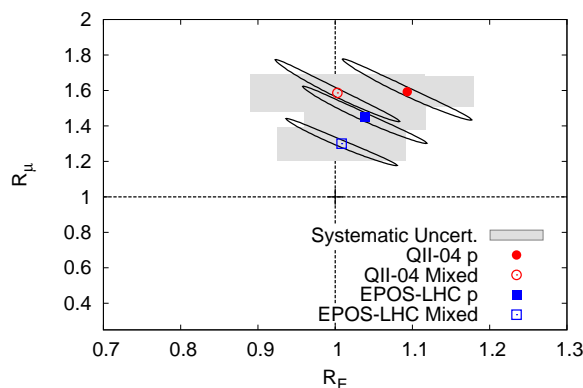
The interplay between SD and FD data can be further explored using showers that have been well recorded by both detectors. For each observed event, showers are picked from a simulated library of pure proton or mixed composition so their FD longitudinal profiles show the best match

with the observed one. Then the ground signal of the selected simulated events is compared to the observed one in data [21, 25].

Since the Monte Carlo predictions in general do not match the observed signals, regardless of the hadronic model being used, two independent rescaling factors are introduced in order to achieve an agreement. These factors are  $R_E$  which acts as a rescaling of the primary energy (it rescales the total signal of the event uniformly), and  $R_\mu$  which acts as a rescaling of the muon size<sup>2</sup> (it rescales only the contribution to the ground signal of inherently hadronic origin).

The data used for this study were narrowed down to the energy bin  $10^{18.8} < E < 10^{19.2}$  eV, sufficient to have adequate statistics while being small enough that the primary cosmic-ray mass composition does not evolve significantly. For the period from 1 January 2004 to 31 December 2012, a total of 411 hybrid events were accepted after applying quality selection cuts [18, 26].

Each event of the dataset was compared with the results obtained from simulations using the hadronic interaction models QGSJETII-04 and EPOS LHC, both for a set of proton showers and for a set of mixed composition based on the  $\langle \ln A \rangle$  estimated from the  $X_{\max}$  measurements for this energy bin [19]. The values of the scaling parameters that best reproduce the data are shown in figure 4. The results suggest that while the predicted energy is compatible with the observed one ( $R_E$  is compatible with 1 within the systematics on the absolute energy scale), the muon rescaling parameter demands an increase of a factor 1.3 to 1.6 of the muon size in simulations, depending on the model.



**Figure 4.** Value of the energy rescaling parameter  $R_E$  and of the hadronic rescaling parameter  $R_\mu$  that best represent the hybrid data at  $10^{19}$  eV.

## 5. Conclusions

The Pierre Auger Observatory has unique capabilities to measure several observables sensitive to both the mass composition of cosmic rays and hadronic interaction properties. Despite not being originally designed for such a purpose, the Pierre Auger Observatory is able to measure the muon content in showers at the ground under various conditions. These measurements provide relevant information to constraint the models that attempt to describe the hadronic interactions at extremely high energies inaccessible to accelerator experiments. The observed muon content in  $10^{19}$  eV air showers ( $E_{\text{CM}} = 135$  TeV) suggests a muon deficit in simulations using the latest hadronic interaction models tuned to LHC and lower energy accelerator data, even for the best

<sup>2</sup> Note that the factor  $R_\mu$  is not directly comparable to direct muon number determinations obtained from inclined showers [13, 14] or from the FADC traces of vertical showers [22], which have been reported in the previous sections.

case of EPOS LHC with mixed composition. In addition, the result from the analysis of hybrid vertical showers proves that none of the tested models calls for an overall rescaling of the energy.

Further progress is expected with more data, particularly thanks to the currently planned upgrade aimed at a more precise muon measurement by improving the discrimination between the electromagnetic and muonic components of the showers at the highest energies. A precise measurement of the number of muons is the key to estimating the primary mass on an event-by-event basis, to improve our sensitivity to photon/neutrino searches and to study fundamental interactions at centre-of-mass energies an order of magnitude above those presently attainable at the LHC. After testing in the field several prototypes based on different ideas to measure muons with the required precision, the solution agreed by the collaboration is to deploy scintillators on top of all the water-Cherenkov detectors to measure charged particles. The combination of two independent measurements will allow us to obtain an estimation of the two shower components. The upgrade is expected to be completed by 2018 with Observatory operation through 2023.

### Acknowledgments

The successful installation, commissioning, and operation of the Pierre Auger Observatory would not have been possible without the strong commitment and effort from the technical and administrative staff in Malargüe. We are very grateful to all the national agencies and organisations for financial support. The author thanks the organisers for the nice scientific atmosphere and hospitality.

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