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A measurement of the muon number in showers using inclined events recorded at the Pierre Auger Observatory

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Abstract: The average muon content of air showers with zenith angles exceeding 62° is obtained as a function of calorimetric energy from events measured simultaneously with the Surface Detector Array and fluorescence telescopes of the Pierre Auger Observatory using a reconstruction method specifically designed for inclined showers. The results are presented in different energy bins above 4×10^{18} eV and compared to predictions from current hadronic interaction models for different primary particles.

Keywords: Pierre Auger Observatory, ultra-high energy cosmic rays, inclined showers, muons, hadronic interactions

1 Introduction

Understanding the energy dependence of the mass composition of the highest energy cosmic rays is fundamental to unveil their production and propagation mechanisms. Interpretations about observed anisotropies [1, 2] and features in the spectrum such as the break in the power law spectrum around 4×10^{18} eV, the ankle, and the flux suppression above 4×10^{19} eV [3], lead to very different conclusions depending on the assumed mass composition at Earth.

Because of the low flux of cosmic rays at these energies, their composition cannot be measured directly, but has to be inferred from observations of extensive air showers. As a consequence the most sensitive parameters to mass composition are also dependent on the hadronic interaction properties, which are unknown at very high energies and in phase space regions inaccessible to accelerator experiments. In this context, the estimate of the primary mass can only be made using sets of simulated reference showers, which have been generated with hadronic interaction models based on extrapolation from accelerator data over more than two orders of magnitude in energy in the center-of-mass frame. For this reason, it is advisable to study different observables sensitive to both mass composition and hadronic interaction models to minimise the problem (see e.g. [4] for a recent review). One of the most mass-sensitive observables is the number of muons at the ground. An air shower induced by a nucleus with A nucleons contains approximately $A^{1-\alpha}$ ($\alpha \approx 0.9$) more muons than a proton shower of the same energy. In addition, the number of muons in air showers also depends on several properties of hadronic interactions, including the multiplicity, the charge ratio and the baryon anti-baryon pair production [5, 6].

Cosmic rays arriving with zenith angles exceeding 62° induce extensive air showers characterised by the dominance of secondary energetic muons at ground, because the electromagnetic component has been largely absorbed in the enhanced atmospheric depth crossed by the shower before reaching ground. The study of showers with zenith angles $\theta > 62°$, the so-called inclined showers, provides a direct measurement of the muon content at ground level.

In this work we explain how the muon content is measured in inclined showers detected with the Surface Detector (SD) array of the Pierre Auger Observatory [7]. This paper is organised as follows. In Sec. 2, we describe the reconstruction method of the shower size parameter N_{19} and the associated uncertainties. In Sec. 3, we study N_{19} as a function of calorimetric energy in an unbiased sample of high-quality events measured simultaneously with the SD array and the Fluorescence Detector (FD) of the Auger Observatory. Finally, in Sec. 4, we compare the behaviour of the shower size parameter as a function of the energy above 4×10^{18} eV as observed with data to predictions of current hadronic interaction models for different primary masses.

2 Reconstruction of N_{19}

Inclined showers generate asymmetric and elongated signal patterns in the SD array with narrow pulses in time in detectors, typical of a muonic shower front. Events are selected demanding space-time coincidences of the signal patterns of the triggered surface detectors which must be consistent with the arrival of a shower front [8]. After event selection, the arrival direction (θ, ϕ) of the cosmic-ray is determined from the relative arrival times of the shower front at the triggered stations by fitting a model of the shower front. The angular resolution achieved is better than 0.6° for events of interest [9].

Once the shower direction is established, we define the shower size parameter, N_{19}, through the following relation:

$$\rho_\mu = N_{19}\ \rho_{\mu,19}(x, y, \theta, \phi) \qquad (1)$$

where ρ_μ[1] is the model prediction for the muon density at ground used to fit the signals recorded at the detectors. $\rho_{\mu,19}$ is a reference profile corresponding to the inferred arrival direction, obtained as a parameterisation [10] of the muon density at ground of proton showers of 10^{19} eV simulated using CORSIKA [11] with the QGSJetII-03 [12] and FLUKA [13] interaction models. An example of the reference profile $\rho_{\mu,19}$ for $\theta = 80°$ and $\phi = 0°$ is shown in Fig. 1. It has been found [14] that at a given depth the shape

1. It is defined in the plane perpendicular to the shower axis

and attenuation with the zenith angle of the muon density profile are independent of the cosmic-ray energy E and mass A, so the factorisation (1) holds in good approximation.

Introducing N_μ ($N_{\mu,19}$) as the total number of muons reaching ground as predicted by the integral of Eq. 1 (respectively of $\rho_{\mu,19}$), N_{19} is simply the ratio $N_\mu/N_{\mu,19}$. Hence N_{19} carries the dependence on the energy and mass.

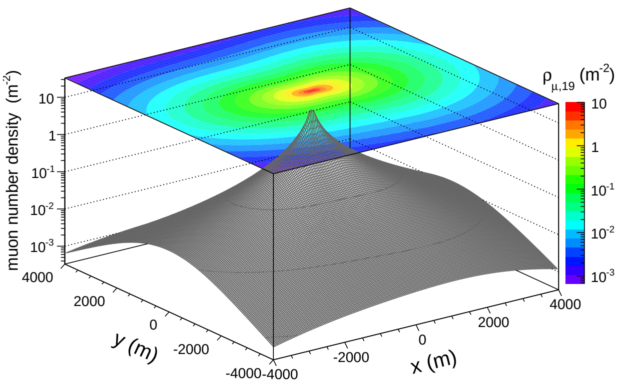

Figure 1: Muon number density in the coordinate plane perpendicular to the shower axis at ground level (transverse plane) for proton-induced showers of 10^{19} eV at $\theta = 80°$ and $\phi = 0°$ (parallel to x-axis) and core at $(x,y) = (0,0)$.

The estimation of N_{19} is done via a maximum-likelihood fit of the predicted ρ_μ to the measured signals and is based on a detailed model of the detector response to the passage of muons, obtained from GEANT4 [15] simulations within the software framework $\overline{\text{Off}}\underline{\text{line}}$ [16] of the Auger Observatory. To perform the fit, the muonic signal is obtained from the measured signal by subtracting the average contribution of a residual electromagnetic component (typically 20% of the muonic signal) parameterised from simulations [17]. The achieved resolution improves from 20% to 8% in the range $\log_{10}(E/\text{eV})$ = [18.6,19.8] and the systematic uncertainty is smaller than 5%. Further details of the reconstruction procedure and validation tests can be found in [9].

2.1 Testing $\mathbf{N_{19}}$ as an estimator of the muon number, $\mathbf{R_\mu}$

In this section we want, using MC simulations, to test the effectiveness of N_{19} as estimator of the total number of muons reaching ground relative to that contained in the reference distribution. We do so by comparing in simulated showers the N_{19} parameter to the true ratio $R_\mu^{MC} = N_\mu^{true}/N_{\mu,19}$, where N_μ^{true} is the true number of muons at ground.

Three different sets of simulated events were used in this study. The first set consists of 100000 proton and 100000 iron showers generated using AIRES [18] with QGSJet01 [19] at a relative thinning of 10^{-6}, following an energy spectrum $E^{-2.6}$ over the energy range $\log_{10}(E/\text{eV})$ = [18.5,20.] and an isotropic angular distribution. The second (third) set consists of 12000 proton and 12000 iron showers generated using CORSIKA with QGSJetII-04 [20] (EPOS LHC [21]) with the same thinning and angular distribution, and an energy spectrum E^{-1} over the energy range $\log_{10}(E/\text{eV})$ = [18.,20.]. Showers subsequently underwent a full simulation of the detector with random core positions on the ground, and were then reconstructed using the procedure adopted for data.

The mean value of the difference between N_{19}^{MC} and R_μ^{MC} is shown in Fig. 2. We note that the bias is less than 5% for showers with $R_\mu^{MC} > 0.6$, value above which the SD array is over 95% efficient. From this result, we can conclude that N_{19} provides a direct measurement of the relative number of muons with respect to the reference distribution with little bias. To parameterise the average bias as shown in Fig. 2, we have chosen the average of the two extreme cases shown, corresponding to iron showers generated with EPOS LHC and QGSJet01. In the following, we will call R_μ the measured N_{19} after correction for this average bias. Its uncertainty is estimated to be 5% from the dispersion of the different hadronic interaction models and compositions explored.

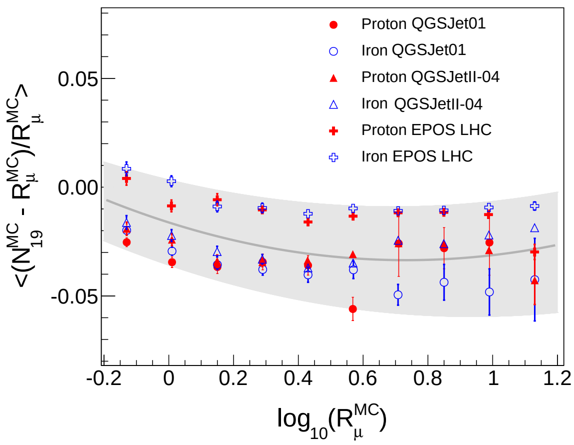

Figure 2: Average of the relative difference between N_{19}^{MC} and R_μ^{MC} for proton and iron showers simulated with QGSJet01, QGSJetII-04 and EPOS LHC. The band indicates the bias region and the solid line indicates the parameterised average bias.

3 Energy dependence of $\mathbf{R_\mu}$

For inclined showers, we use N_{19} for the energy calibration. This is done using the calorimetric energy E_{FD} from high-quality events measured simultaneously with SD and FD (golden hybrid events) [22]. In the same way, here, we obtain the correlation of R_μ with E_{FD} to study the relative muon content of measured showers as a function of the energy. As noted in the introduction, R_μ is sensitive to primary composition and to the properties of the hadronic interactions in the shower.

The data set contains hybrid events with zenith angles $62° < \theta < 80°$ with at least four triggered stations and for which the closest station to the fitted core and its six adjacent stations are all active. In addition, these events have to satisfy a set of quality cuts for the FD specifically designed to ensure an accurate reconstruction of the arrival direction and of the longitudinal profile. The cuts are adapted versions of those used in calibration of events with $\theta < 60°$ [23, 24, 25]. The station closest to the shower core that is used for the geometrical reconstruction must be at a distance below 750 m. For a precise estimation of the E_{FD} we require adequate monitoring of the atmospheric conditions (cloud coverage below 25% in the FD field of view and vertical aerosol optical depth positive and less than 0.1). To obtain accurate values of the shower maximum $X_{\max}$ and of the primary energy we require: a Gaisser-Hillas fit with a χ^2-residual, $(\chi^2 - n_{\mathrm{dof}})/\sqrt{2n_{\mathrm{dof}}}$, less than 3; a maximum "hole" in the longitudinal profile of 20%. In addition to the quality selection criteria, a fiducial cut on the FD field of view (FOV) is performed ensuring this is large enough to observe all plausible values of $X_{\max}$. This "fiducial FOV cut" includes a cut on the maximum uncertainty of $X_{\max}$ accepted (150 g/cm^2) and on the minimum viewing angle of the light in the FD telescope (25°), which avoids cutting on the fraction of Cherenkov light. The uncertainty on E_{FD} is required to be less than 30%. Finally, we only accept FD energies larger than 4×10^{18} eV to assure a trigger probability of 100% for the FD and SD detectors. This selection was applied to inclined events recorded from 1 January 2004 to 31 December 2012; 174 events were kept.

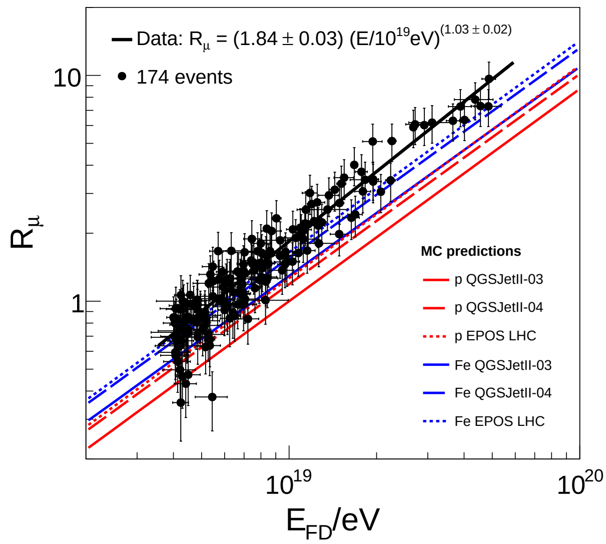

Figure 3: Fit of the correlation of $R_\mu = A\,[E_{\mathrm{FD}}/10^{19}\,\mathrm{eV}]^B$ with E_{FD} in high-quality hybrid data. Theoretical curves for proton (blue lines) and iron (red lines) showers simulated with QGSJetII-03 (solid lines), QGSJetII-04 (dashed lines) and EPOS LHC (dotted lines) are shown for comparison.

A power-law fit of R_μ as a function of the calorimetric energy, E_{FD}, gives the R_μ/E relation as:

$$R_\mu = A\,[E_{\mathrm{FD}}/10^{19}\,\mathrm{eV}]^B \qquad (2)$$

The fit method is based on a maximum-likelihood approach accounting for the estimated uncertainties in the respective R_μ and E_{FD} reconstructions, and fitting the shower-to-shower fluctuations in the total number of muons to a constant value. The corresponding result of the fit is shown in Fig. 3 and the best fit values are $A = 1.84 \pm 0.03 \pm 0.09\,(\mathrm{sys})$ and $B = 1.03 \pm 0.02 \pm 0.05\,(\mathrm{sys})$. The systematic uncertainties are estimated from the dispersion of the different models and compositions explored with simulated events (see Sec. 2) and variations of the quality cuts on the FD and of fitting methods applied.

In this work we provide an update of the method presented previously in [9]. The current measurement of the muon number has changed with respect to that made in the past mainly due to upgrades of the reconstruction algorithms of the shower size parameter N_{19} and of the FD energy scale as presented in this conference [26]. The interpretation of data is also affected by the use of the recent released hadronic interaction models QGSJetII-04 and EPOS LHC as guidelines for the analysis.

4 Results and discussion

Using the formula for the correlation fit (see Eq. 2), it is possible to derive the number of muons in data compared to the predictions for different models and cosmic ray masses. For example, the number of muons at 10^{19} eV deduced from data exceeds that of proton (iron) showers simulated with QGSJetII-03 by a factor 1.8 (1.4). However, the post-LHC versions of the QGSJet and EPOS models, namely QGSJetII-04 and EPOS LHC, predict about 20% more muons than QGSJetII-03 and become more compatible with data.

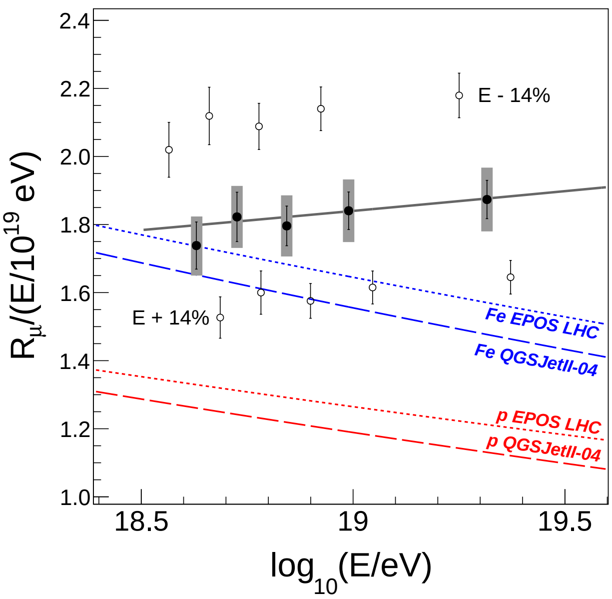

Figure 4: Average value of $R_\mu/(E_{FD}/10^{19}$ eV) as a function of shower energy. Theoretical curves for proton and iron showers simulated with QGSJetTII-04 and EPOS LHC are shown for comparison. Open circles indicate the result if the FD energy scale is varied by its systematic uncertainty. The black line represents the calibration fit from Fig. 3. The gray thick error bars indicate the systematic uncertainty of R_μ.

An alternative and interesting comparison of the measured number of muons with predictions is shown in Fig. 4, where the averaged scaled quantity $R_\mu/(E_{FD}/10^{19}$ eV) is shown in five energy bins containing roughly equal number of events. The measurement of R_μ is rather accurate and can be estimated to have an uncertainty of 5% combining statistical and systematic uncertainties (shown as grey boxes around the points) . The measurement of $R_\mu/(E_{FD}/10^{19}$ eV) is dominated by systematic uncertainties in the energy scale (shown as open circles in the figure). The measured number of muons between 4×10^{18} eV and 2×10^{19} eV is marginally comparable to predictions for iron showers simulated with both QGSJetII-04 and EPOS LHC if we allow the FD energy scale to increase by its systematic uncertainty of about 14% [26].

The slope $\mathrm{d}\ln n_\mu/\mathrm{d}\ln E$ of the muon number, given by the parameter $B = 1.03 \pm 0.02 \pm 0.05\,(\mathrm{sys})$, carries information about possible changes in the average logarithmic mass $\langle \ln A \rangle$. Predictions for proton and iron showers simulated with QGSJetII-04 and EPOS LHC give a slope between 0.93 and 0.94, because the number of muons increases less than linearly with energy if A is constant. In this context, a steeper slope would be indicative of an increase of $\langle \ln A \rangle$ in this energy range. The difference obtained in this work between data and predictions for a constant composition is however not significant (less than 1.7 σ).

Given that the observed distribution of the depth of shower maximum between 4×10^{18} eV and 2×10^{19} eV is not compatible with an iron dominated composition [27, 28] we conclude that the observed number of muons is not well reproduced by the shower simulations. This result is compatible with those of independent studies for showers with $\theta < 60°$ [29][2], in which two different methods have been used to derive the fraction of the signal due to muons at 1000 m from the shower core using the temporal distribution of the signals measured with the SD array.

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2. We note that in [29] the relative number of muons is given with respect to QGSJetII-04 whereas here the result is given with respect to QGSJetII-03. As the relative muon content of showers generated with QGSJetII-04 is about 20% higher than those of QGSJetII-03, this factor should be taken into account for the comparison.