The observation of a muon deficit in simulations from data of the Pierre Auger Observatory

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Abstract. We present evidence from the Pierre Auger Observatory that the models currently used in simulation of cosmic ray air showers at the highest energies predict less muons than observed in data in the energy range around \(10^{19}\) eV. We explain the different methods used to estimate the number of muons, apply them to observations, and compare the results to predictions from simulations of air showers. The number of muons in EAS derived from the observations of the Pierre Auger Observatory is a factor of 1.5 to 2.2 higher than that predicted in simulations. The exact discrepancy depends on the zenith angle and, to a lesser extent, on the hadronic interaction model and analysis technique.

1. Introduction
One of the goals of the Pierre Auger Observatory [1, 2] is the determination of the mass composition of the cosmic rays at the highest observed energies, above \(\approx 10^{19}\) eV. This requires the simultaneous measurement of different observables of air showers. The extraction of information on the nature of the primary particle, which initiated the shower, depends on numerical modeling of the development using Monte Carlo methods. The modeling of hadronic interactions is one of the important elements in the simulation [3]. It is therefore important to verify and, if required and possible, to correct predictions of air shower simulations.

The hybrid nature of the Pierre Auger Observatory allows us to measure the longitudinal development as well as lateral and temporal signal distribution on the ground. In the following we will discuss several methods for estimating the number of muons in an observed air shower in a way that avoids or minimizes biases due to the unknown nature of the primary particle.

2. Techniques to determine the muon content
The signal measured by the surface detector of the Pierre Auger Observatory is a composition of a signal generated by the electromagnetic and muonic components of the air shower reaching the ground. Hadrons contribute a minor amount, which will be neglected:

\[ S_{\text{tot}} = S_{\text{EM}} + S_{\mu} + S_{\text{hadrons}} \]

Several methods have been developed to separate these two components and to construct reliable estimators for the number of muons on the ground. See figure 1 for a simulation of a total signal (sum of 3 PMT FADC traces in a detector station) and its decomposition.

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that satisfy the quality cuts used in the FD-SD energy
predicted with GEANT4 and extensively tested [12]. We
based on the simulation of individual high quality hybrid
predictions on an event-by-event basis with a technique
band.

2.1. Smoothing of FADC traces
The signal in the surface detector stations of the Pierre Auger Observatory is recorded by FADCs
as a function of time. The electromagnetic contribution to the signal is generated by a large
number of particles, which leads to a smooth contribution to the signal as a function of time.
Sufficiently far away from the core, muons are more separated and contribute identifiable spikes
to the signal (figure 1). Smoothing the signal by averaging over \( N_{\text{bin}} \) bins provides an estimate
for the electromagnetic contribution \( S_{\text{EM}} \) and the difference is assigned to the muonic component \( S_{\mu} \). This process is repeated a fixed number of iterations \( N_{\text{iter}} \). The values for \( N_{\text{bin}} \) and \( N_{\text{iter}} \)
are optimized using Monte Carlo simulations to minimize the bias in the evaluation of the EM
component for proton and iron primaries over the largest possible angular range. The systematic
uncertainties of this method are below 8% and the resolution is close to 20% [4] (see figure 2).

2.2. Multivariate muon counting
One can also try to estimate the muon contribution by counting the times the trace jumps by
more than 0.1 VEM (VEM is the signal generated by a vertically crossing muon) from one bin
to the next, weighted by the size of the jump:

\[
J = \sum_{i \in \text{bins}} (x_{i+1} - x_i) H(x_{i+1} - x_i - 0.1),
\]

where \( H \) denotes the Heaviside function. This predictor for the number of muons on the ground
can be improved by combining it with 171 additional variables which plausibly correlate with
the number of muons. A principal component analysis reduces them to 19 variables which best
characterize the details of FADC traces. An artificial neural network was trained to predict the
number of muons in a detector station and its uncertainty. Fitting a lateral distribution

\[
N_\mu(r | \nu, \beta, \gamma) = \exp \left( \nu + \beta \log \frac{r}{1000 \text{ m}} + \gamma \log \left( \frac{r}{1000 \text{ m}} \right)^2 \right)
\]

permits to estimate \( N_\mu(1000 \text{ m}) \) as a reference value. The variable \( r \) is the distance from the
shower core, and \( \nu, \beta, \) and \( \gamma \) are parameters of the fit. The systematic uncertainty of this method
is 6% from composition uncertainty and \(+10\% -6\% \) from hadronic models.
2.3. Muon number for inclined air showers
In very inclined air showers, at zenith angles above 60°, only the muonic component reaches the ground. The other components get absorbed higher in the atmosphere. The distribution of the muons on the ground can be fitted by a two-dimensional density

\[ n_\mu = N_{19} \rho_{\mu}^{19} (x - x_c, y - y_c, \theta, \phi) A_\perp(\theta). \]

The reference distribution \( \rho_{\mu}^{19} \) is obtained from simulations and normalized to showers at an energy of \( 10^{19} \text{ eV} \). \( A_\perp \) is the projection of the area on the ground to the shower plane, and \( x_c \) and \( y_c \) are the coordinates of the shower core. The scale factor \( N_{19} \) is correlated to the energy and calibrated as a function of the energy estimated by the fluorescence detector in hybrid events [6] (see figure 3).

2.4. Shower universality
Shower universality [7] provides yet another tool to estimate the muon contents of an air shower, using the observation that the dependence of \( S_\mu/S_{EM} \) on the vertical shower maximum \( X_{max}^v \) is almost independent of primary energy and composition (figure 4.) This leads us to the estimator

\[ S_{fit}^{\mu} = S_{tot}/ \left[ 1 + \cos^\alpha(\theta)/ \left( (X_{max}^v/A)^{1/b} - a \right) \right]. \]

The parameters \( A, a, \) and \( b \) depend on the model for hadronic interactions and \( \alpha = 1.2 \). The resulting estimator has an uncertainty of 15%.

3. Application to data
The number of muons on the ground has been determined for air showers recorded from January 1, 2004 to September 30, 2010. The extracted number of muons, relative to simulations, is summarized in figure 5. The observed number of muons is systematically above that predicted from simulations. The effect of changes in the assumed composition is not sufficient to reconcile simulations and observations.

The discrepancy varies slightly with the zenith angle, but it shows no dependence on the analysis method. The relative difference is \( 1.6 - 1.7 \) for \( \theta \) below \( 45^\circ \) and \( 1.9 - 2.0 \) above \( 55^\circ \). For the largest zenith angles, above \( 65^\circ \), the analysis of inclined showers finds about 2.13 more muons than predicted by simulations.
Using simulations we find that a 50% fraction of helium would reduce the actual value of depth and the total signal. The most direct way to investigate the muon content of cosmic ray time traces to build an estimator correlated with the number of muons. The universality method together with di...

Figure 5. Observed number of muons at 1000 m from the core compared to simulations for protons at 10^{19} eV using QGSJET-II. Also displayed is the prediction for iron primaries.

4. Direct fitting and rescaling
In well-measured hybrid events, one can perform simulations to fit simultaneously longitudinal and lateral distributions of the observed shower [8]. As one can see in figure 6, one achieves a good agreement of simulation and data for the longitudinal profile, but the ground signal predicted is systematically lower than observed. The number of muons in simulations has to be increased by a factor of 2.2 to reach agreement with observation.

5. Conclusions
We presented different analyses of the data of the Pierre Auger Observatory which are sensitive to the number of muons reaching the ground. We notice that air shower simulations predict less muons than needed to explain the observations. We conclude that work is needed on simulations to describe physics at the highest energies before we can extract primary composition reliably.

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