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Test of hadronic interaction models with data from the Pierre Auger Observatory

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Abstract: The Pierre Auger Observatory allows the measurement of both longitudinal profiles and lateral particle distributions of high-energy showers. The former trace the overall shower development, mainly of the electromagnetic component close to the core where the latter reflect the particle densities in the tail of the shower far away from the core and are sensitive to both the muonic and electromagnetic components. Combining the two complementary measurements, predictions of air shower simulations are tested. In particular the muon component of the tank signals, which is sensitive to hadronic interactions at high energy, is studied with several independent methods. Implications for the simulation of hadronic interactions at ultra-high energy are discussed.

Introduction

During the last decade, air shower simulation codes have reached such a high quality that there is good overall agreement between the predicted and experimentally observed shower characteristics. The largest remaining source of uncertainty of shower predictions stems from our limited knowledge of hadronic interactions at high energy. Hadronic multiparticle production has to be simulated at energies exceeding by far those accessible at man-made accelerators and in phase space regions not covered in collider experiments. Therefore it is not surprising that predictions for the number of muons or other observables, which are directly related to hadron production in showers, depend strongly on the adopted hadronic interaction models [1].

In this work we will employ universality features of the longitudinal profile of the electromagnetic shower component to combine fluorescence detector and surface array measurements of the Pierre Auger Observatory. Using the measured shower depth of maximum, $X_{\rm max}$, the muon density at ground is inferred without assumptions on the primary cosmic ray composition. This allows a direct test of the predictions of hadronic interaction models.

Parameterisation of surface detector signal using universality

Universality features of the longitudinal profile of showers have been studied by several authors [2]. Here we exploit shower universality features to predict the surface detector signal expected for Auger Cherenkov tanks due to the electromagnetic and muonic shower components at 1000 m from the shower core. In the following only a brief introduction to the method of parameterising the muonic and electromagnetic tank signals is given. A detailed description is given in [3].

A library of proton and iron showers covering the energy range from 10^{17} to 10^{20} eV and zenith angles between 0° and 70° was generated with CORSIKA 6.5 [4] and the hadronic interaction models QGSJET II.03 [5] and FLUKA [6]. For comparison, a smaller set of showers was simulated with the combinations QGSJET II.03/GHEISHA [7] and SIBYLL 2.1/FLUKA [8, 9]. Seasonal models of the Malargue molecular atmosphere were used [10]. The detector response is calculated using look-up tables derived from a detailed GEANT4 simulation [11].

Within the library of showers, the predicted surface detector signal for the electromagnetic component of a shower at the lateral distance of 1000 m is found to depend mainly on the energy and the distance between the shower maximum and the ground (distance to ground, $DG = X_{\rm ground} - X_{\rm max}$). Here the signal of electromagnetic shower component is defined as that of all shower particles except muons and decay products of muons. The signal at 1000 m depends only slightly on the mass of the primary particle (13% difference between proton and iron primaries) and the applied interaction model ($\sim$ 5%). The functional form, however, is universal. The situation is similar for the expected tank signal due to muons and their decay products. In this case the shower-to-shower fluctuations are larger and the difference between proton and iron showers amounts to 40%.

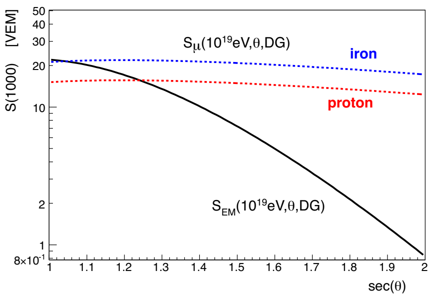

Figure 1: Electromagnetic and muon contributions to the detector signal as a function of zenith angle. Results of QGSJET II/FLUKA simulations are shown for 10^{19} eV showers.

After accounting for geometrical effects such as the projected tank surface area, the proton-iron averaged electromagnetic shower signal is parameterised in dependence on the energy E, distance to shower maximum DG, and zenith angle θ. The difference between proton and iron shower profiles is included in the calculation of the systematic uncertainties later. Similarly the universal shape of muon signal profile is parameterized simultaneously for all model primaries, taking the overall normalisation from proton showers simulated with QGSJET II/FLUKA. The expected detector signal at 1000 m can then be written as

$$S_{\rm MC}(E,\theta,X_{\rm max}) = S_{\rm em}(E,\theta,DG) + N_\mu^{\rm rel} S_\mu^{\rm QGSII,p}(10^{19}\,{\rm eV},\theta,DG), \quad (1)$$

where $N_\mu^{\rm rel}$ is the number of muons relative to that of QGSJET proton showers at 10^{19} eV and $S_\mu^{\rm QGSII,p}$ is the muon signal predicted by QGSJET II for proton primaries. The relative importance of the electromagnetic and muonic detector signal contributions at different angles is shown in Fig. 1.

Constant-intensity-cut method

Within the current statistics, the arrival direction distribution of high-energy cosmic rays is found to be isotropic, allowing us to apply the constant intensity cut method to determine the muon signal contribution. Dividing the surface detector data into equal exposure bins, the number of showers with $S(1000)$ greater than than a given threshold should be the same for each bin

$$\left.\frac{dN_{\rm ev}}{d\sin^2\theta}\right|_{S(1000)>S_{\rm MC}(E,\theta,\langle X_{\rm max}\rangle,N_\mu^{\rm rel})} = {\rm const.} \quad (2)$$

Using the independently measured mean depth of shower maximum $\langle X_{\rm max}\rangle$ [12] the only remaining free parameter in Eq. (2) is the relative number of muons $N_\mu^{\rm rel}$. For a given energy E, $N_\mu^{\rm rel}$ is adjusted to obtain a flat distribution of events in $\sin^2\theta$.

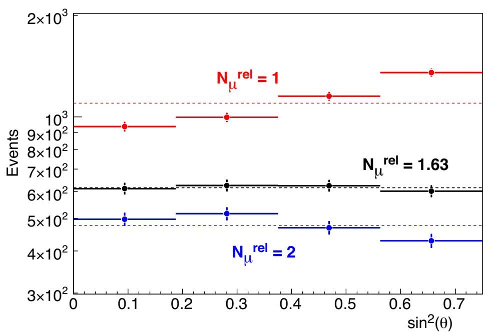

Figure 2: Sensitivity of the constant-intensity-cut method to the muon number for $E = 10^{19}$ eV.

The sensitivity of this method to the muon number parameter in Eq. (1) is illustrated in Fig. 2. The best description of the data above 10^{19} eV requires $N_\mu^{\rm rel} = 1.63$. However, this result was obtained by using the measured mean depth of shower maximum [12] in Eq. (1). Shower-to-shower fluctuations in $X_{\rm max}$ and the reconstruction resolution cannot be neglected and have been estimated with a Monte Carlo simulation. Accounting for

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fluctuations and reconstruction effects, the relative number of muons at 10^{19} eV is found to be $1.45 \pm 0.11(\mathrm{stat})^{+0.11}_{-0.09}(\mathrm{sys})$.

Knowing the muon number and the measured mean depth of shower maximum, the signal size at $\theta = 38^\circ$ can be calculated

$$S_{38}(10^{19}\mathrm{eV}) = 37.5 \pm 1.7(\mathrm{stat})^{+2.1}_{-2.3}(\mathrm{sys})\ \mathrm{VEM}. \quad (3)$$

This value of S_{38} is a measure of the energy scale of the surface detector which is independent of the fluorescence detector. It is within the systematic uncertainties of the energy determination from fluorescence detector measurements, including the uncertainty of the fluorescence yield [13]. It corresponds to assigning showers a $\sim$ 30% higher energy than done in the fluorescence detector-based Auger shower reconstruction ($E = 1.3E_{\mathrm{FD}}$).

Hybrid event and inclined shower analysis

Hybrid events that trigger the surface detector array and the fluorescence telescopes separately are ideally suited to study the correlation between the depth of shower maximum and the muon density at 1000 m. However, the number of events collected so far is much smaller. For each individual event the reconstructed fluorescence energy and depth of maximum are available and the expected $S(1000)$ due to the electromagnetic component can be calculated directly. The difference in the observed signal is attributed to the muon shower component and compared to the predicted muon signal.

For this study, high-quality hybrid events were selected for which the shower maximum was in the field of view of a telescope, $\theta < 60^\circ$, and the Mie scattering length was measured. Furthermore the distance between the telescope and the shower axis was required to be larger than 10 km and the Cherenkov light fraction was limited to less than 50%. The surface detector event had to satisfy the T5 selection cuts which are also applied in [13].

In Fig. 3, we show the muon signal derived from these hybrid events as function of distance to ground. The relative number of muons at 10^{19} eV is found to be

$$N_\mu^{\mathrm{rel}}\big|_{E=1.3E_{\mathrm{FD}}} = 1.53 \pm 0.05$$

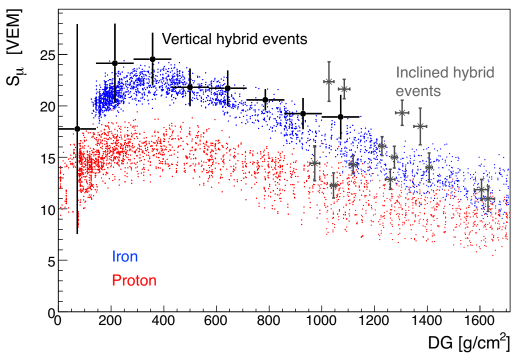

Figure 3: Reconstructed and predicted muon tank signal contribution in dependence on the distance to ground for vertical and inclined hybrid events. The muon profiles expected from QGSJET II simulations are indicated by the red (proton showers) and blue (iron showers) points for the energy scale $E = 1.3E_{\mathrm{FD}}$.

$$N_\mu^{\mathrm{rel}}\big|_{E=E_{\mathrm{FD}}} = 1.97 \pm 0.06, \quad (4)$$

consistent with the analysis above.

A similar study has been performed for inclined hybrid events ($60^\circ < \theta < 70^\circ$). Within the limited statistics, good agreement between muon numbers of the inclined and the vertical data sets is found, see Fig. 3.

In Fig. 4 we compare the results of the different methods applied for inferring the muon density at 1000 m from the shower core. The relative number of muons is shown as function of the adopted energy scale with respect to the Auger fluorescence detector energy reconstruction. Only the constant-intensity-cut method is independent of the energy scale of the fluorescence detector. Very good agreement between the presented methods is found.

Discussion

Assuming universality of the electromagnetic shower component at depths larger than X_{max}, we have determined the muon density and the energy scale with which the data of the Auger Observatory can be described self-consistently. The number of muons measured in data is about 1.5 times bigger

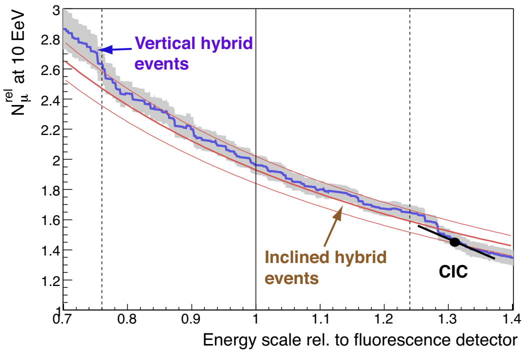

Figure 4: Comparison of the results on the relative muon multiplicity at 10^{19} eV from different methods.

than that predicted by QGSJET II for proton showers. Consistent results were obtained with several analysis methods.

The QGSJET II and SIBYLL 2.1 predictions for iron showers correspond to relative muon numbers of 1.39 and 1.27, respectively. Therefore, interpreted in terms of QGSJET II or SIBYLL 2.1, the derived muon density would correspond to a primary cosmic ray composition heavier than iron, which is clearly at variance with the measured $X_{\max}$ values. The discrepancy between air shower data and simulations reported here is qualitatively similar to the inconsistencies found in composition analyses of previous detectors, see, for example, [14, 15, 16].

Finally it should be mentioned that the results of this study depend not only on the predictions of the hadronic interaction models but also on the reliability of the model used for calculating the electromagnetic interactions (EGS4 in this study [17]).

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