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Longitudinal Development Studies of Air Showers with the Pierre Auger Observatory

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The Pierre Auger Observatory is a hybrid instrument which provides a powerful environment for the measurement of different independent experimental observables that carry information on the characteristics of the longitudinal development of ultra-high energy air showers. In this contribution we present a comparison of the results obtained with the fluorescence detector on the depth of shower maximum with complementary information derived from asymmetry properties of the particle signal in the surface detector stations and the depth profile of muon production points, also derived from surface detector data. The dependence of the measurements with energy by comparison to predictions for proton- and iron-induced showers is finally discussed.

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1. Introduction

The properties of ultra-high energy cosmic rays (UHECR) can only be studied through the extensive air showers (EAS) they produce in the atmosphere. The Pierre Auger Observatory [1] can infer information on the longitudinal profile, and hence on mass composition using both the Surface Detector (SD) and the Fluorescence Detector (FD). The measurement of the shower profile, in particular the depth of shower maximum ($X_{\rm max}$) and its fluctuations, provide very valuable information about the primary mass. The size of both the electromagnetic and the muonic component of an EAS at ground strongly depends, for a given energy, on the distance to the shower maximum and therefore it depends also on the primary mass. Different particles in the shower disc do not arrive to the detector simultaneously. The water Cherenkov detectors cannot explicitly discriminate between the signals produced by the electromagnetic and muonic components of the shower. However, it is possible to study properties of the signal allowing to infer the arrival time distributions of different particles in the shower.

2. Analysis and Results

In this section three different techniques used in the Pierre Auger Observatory to measure mass sensitive observables are presented. The measurement of the longitudinal profile of the energy deposit in the atmosphere is described in detail in [2]. In this analysis, hybrid events, consisting in the simultaneous detection of showers by the FD and at least by one SD detector, have been used. The longitudinal profile of the energy deposit is reconstructed from the light recorded by the FD using the fluorescence and Cherenkov yields. The light collected by the telescopes is corrected for the attenuation between the shower and the detector using data from atmospheric monitoring devices. The longitudinal shower profile is reconstructed as a function of the atmospheric depth and $X_{\rm max}$ is obtained by fitting the profile with a Gaisser-Hillas function. A typical longitudinal profile of the energy deposit is shown in Fig. 1 left panel. The average values of the shower maximum, $\langle X_{\rm max}\rangle$, as a function of energy are displayed in Fig. 2 third panel, alongside predictions from several models for proton and iron showers. Uncertainties of the atmospheric conditions, calibration, event selection and reconstruction give rise to a systematic uncertainty of $\leq$13 g/cm^2 [2] which corresponds to $\lesssim$ 13% of the proton-iron separation predicted by the models. Since the $X_{\rm max}$ resolution of the FD is at the level of 20 g/cm^2 above a few EeV, the intrinsic shower-to-shower fluctuations, RMS($X_{\rm max}$), can be measured as well, see lower panel of Fig. 2.

For the detectors in each SD event, the first portion of the signal is dominated by the muon component which arrives earlier and over a period of time shorter than the electromagnetic (EM) particles, since muons travel in almost straight lines whereas the electromagnetic particles suffer multiple scattering. Due to the absorption, the amount of EM particles at ground depends, for a given energy, on the distance to the shower maximum and therefore on the primary mass. As a consequence, the time profile of particles reaching ground is sensitive to cascade development as the higher is the production height the narrower is the time pulse. The time distribution of the signal is characterised by the risetime, (the time to go from 10% to 50% of the total integrated signal), $t_{1/2}$, which depends also on the zenith angle θ and the distance to the core. In previous studies [3] the risetime was related with the shower maximum using a subset of hybrid events. For inclined

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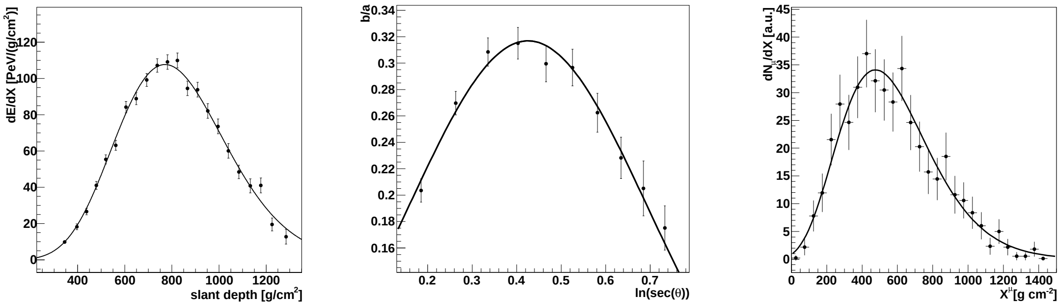

Figure 1: Typical longitudinal development of the energy deposit (left panel), of the asymmetry in the risetime (center panel) and the muon production depth (right panel).

showers the path traversed for the particles is different for stations at ground at different azimuth angles. This fact produces an asymmetry in the signal and in the time distribution in the "early" and "late" stations that are determined by the angle ζ, the azimuth angle in the shower plane (the plane perpendicular to the shower axis). The $t_{1/2}$ asymmetry is obtained by grouping events in bins of energy and $\sec\theta$. For each bin a fit of $\langle t_{1/2}/r \rangle = a + b\cos\zeta$ provides the asymmetry factor b/a which changes with the zenith angle, i.e. distance to the shower maximum. Therefore the evolution of b/a with zenith angle, is reminiscent of the longitudinal development of the shower and has a maximum which is different for different primaries [3]. For each energy bin, the asymmetry longitudinal development is fitted using a Gaussian function, which plays a similar role as the Gaisser-Hillas function in the longitudinal shower development, allowing the determination of the position of the maximum, Θ_{max}, defined as the value of $\sec\theta$ for which the asymmetry factor maximises. In Fig.1 center panel, an example of the asymmetry longitudinal development and the corresponding fit is shown. The measured values of Θ_{max} obtained for energies above detector full efficiency are shown in Fig. 2 second panel. The systematic uncertainty in the measured values of Θ_{max} has been evaluated taking into account the reconstruction of the core of the shower, event selection and risetime vs. core distance parameterisation and amounts to $\lesssim 10\%$ of the proton-iron separation predicted by the models. We note that muon numbers predicted by EAS simulations differ from those observed in data [4]. A preliminary study, using a normalization of 1.6 [4], indicates a change of about $\leq 5\%$ of the proton-iron difference.

Using the time information of the signals recorded by the SD it is also possible to obtain information about the longitudinal development of the hadronic component of extensive air showers in an indirect way. In [5] it is shown that it is possible to reconstruct the Muon Production Depth (MPD), i.e. the distance to the production of the muon measured parallel to the shower axis, using the traces of detectors far from the core. From the MPDs a new observable can be defined as the depth along the shower axis where the number of produced muons reaches a maximum (X^{μ}_{max}). The MPD technique allows to convert the time distribution of the signal recorded by the water Cherenkov into muon production distances using an approximate relation between production distance, transverse distance and time delay. The method is restricted to inclined showers where muons dominate the signal at ground level.

Once the MPD is obtained for each event, the value of $X^{\mu}_{\rm max}$ is obtained fitting to a Gaisser-Hillas function. An example of the MPD profile and the result of the Gaisser-Hillas fit of a particular event with is shown in Fig. 1 right panel. The measured values of $\langle X^{\mu}_{\rm max}\rangle$ are presented in the upper panel of Fig. 2. The systematic uncertainty due to reconstruction bias, core position, rejection of the EM component and quality cuts amounts to 11 $\mathrm{g/cm^2}$, corresponding to about 14% of the proton-iron separation predicted by the models [5]. The predictions of $X^{\mu}_{\rm max}$ from different hadronic models (such as those shown in Fig. 2) would not be affected if a discrepancy between a model and data [4] is limited to the total number of muons. However, differences in the muon energy and spatial distribution would modify the predictions. The evolution of the parameters with energy is similar, despite the fact that the three analyses come from completely independent techniques, that have different sources of systematic uncertainties. In particular, at the highest energies all three analyses show consistently that data resemble more the simulations of heavier primaries than pure protons. A definitive statement about the nature of UHECR awaits a better understanding of hadronic interaction models.

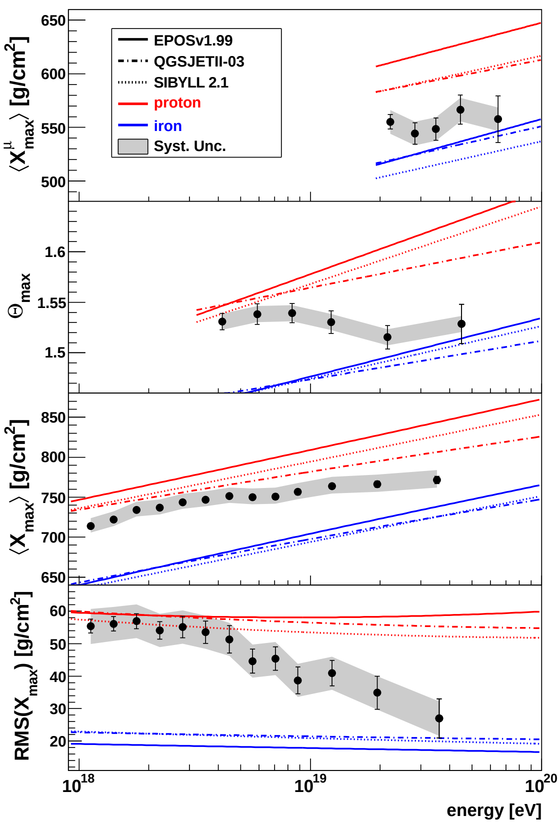

Figure 2: Results on shower evolution sensitive observables compared with model prediction for proton (upper lines) and iron (lower lines). The error bars correspond to the statistical uncertainty. The systematic uncertainty is represented by the shaded bands.

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