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Simulation study of the correlation (X^{μ}_{max}, N^{μ}) in view of obtaining information on primary mass of the UHECRs

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ABSTRACT

In this paper we study, using Monte Carlo simulations, the possibility to discriminate the mass of the Ultra High Energy Cosmic Rays (UHECRs) by combining information obtained from the maximum X^{μ}_{max} of the muon production rate longitudinal profile of Extensive Air Showers (EAS) and the number of muons, N^{μ}, which hit an array of detectors located in the horizontal plane. We investigate the sensitivity of the 2D distribution X^{μ}_{max} versus N^{μ} to the mass of the primary particle generating the air shower. To this purpose we analyze a set of CORSIKA showers induced by protons and iron nuclei at energies of 10^{19} eV and 10^{20} eV, at five angles of incidence, 0°, 37°, 48°, 55° and 60°. Using the simulations we obtain the 2D Probability Functions $Prob(X^{\mu}_{max}, N^{\mu} \mid p)$ and $Prob(X^{\mu}_{max}, N^{\mu} \mid Fe)$ which give the probability that a shower induced by a proton or iron nucleus contributes to a specific point on the plane (X^{μ}_{max}, N^{μ}). Then we construct the probability functions $Prob(p \mid X^{\mu}_{max}, N^{\mu})$ and $Prob(Fe \mid X^{\mu}_{max}, N^{\mu})$ which give the probability that a certain point on the plane (X^{μ}_{max}, N^{μ}) corresponds to a shower initiated by a proton or an iron nucleus, respectively. Finally, a test of this procedure using a Bayesian approach, confirms an improved accuracy of the primary mass estimation in comparison with the results obtained using only the X^{μ}_{max} distributions.

1. Introduction

The mass composition of the primary UHECRs together with their energy spectrum and arrival directions are the fundamental data when searching for the sources and the acceleration mechanisms of the cosmic rays. Various detection techniques, such as surface detectors (scintillation modules [1] or water Cherenkov tanks [2]), fluorescence detectors [3,4], radio antennas [5], microwave detection [6], have been proposed to study these observables. Despite concerted efforts in many experiments, such as Pierre Auger Observatory [7], Telescope Array [8], HiRES [9], AGASA [10] to answer these fundamental questions, a clear answer is not yet given.

In the present work we focus on the problem of the properties of the primary particle which initiates the EAS using the informations from the ground particle detectors.

One observable which is sensitive to the mass of the primary particle is the atmospheric depth where the density of the secondary charged particles reaches its maximum. This observable decreases roughly proportionally with the logarithm of the mass A of the primary particle. Its sensitivity to A is illustrated by the difference in the values for p and Fe induced showers of about 100 g cm^{-2} [11] at the same energy. It can be obtained experimentally by measuring the shower UV light with fluorescence detectors (FD) [3,7,8,9]. Indeed, the intensity of UV light emitted from an elementary volume consequent to the excitation of the nitrogen molecules in the atmosphere by the secondary charged particles in EAS, is proportional with the charge density. Thus, with the FDs the dependence of the charged particle density on atmospheric depth can be obtained. The drawback of this technique is the low duty cycle of FD measurements (up to ~15% [7]), due to the fact that the UV light from an EAS can be measured only during moonless nights and only in good atmospheric conditions. This fact, combined with the low statistics of the UHECRs at $E > 10^{19}$ eV, has a significant contribution to the uncertainty of mass reconstruction by FDs measurements.

To increase the observational duty cycle, the reconstruction of the primary mass on the basis of the signal of the surface

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detectors (duty cycle ∼100%) would be advantageous. This can be done using the reconstructed profile of the muon production depth (MPD) from EAS on the basis of the signal of the surface detectors, as proposed by Cazon et al. [12,13] in the case of the Pierre Auger Observatory. The individual muon production depth (the muon production point expressed in units of atmospheric depth) can be calculated using the muon arrival time in the detectors and the arrival time of the shower core. Then, the longitudinal profile of the muon production rate can be obtained as the depth dependence of the number of muons produced per unit of atmospheric depth. The maximum X^{μ}_{max} of this profile was proposed as an observable sensitive to the primary mass.

The number of muons in the shower is also sensitive to the primary mass. However, it has a stronger dependence on the energy of the primary particle than on the primary mass, and due to this fact the uncertainty of energy determination has a high impact on mass discrimination using this observable.

In a preliminary study [14,15] we have shown that by using the information included in the correlation X^{μ}_{max} versus N^{μ}, the accuracy of the primary mass reconstruction can be improved in comparison with the method which uses only the X^{μ}_{max} distribution. This correlation could also be used to test the high energy interaction models. Our preliminary study was based on simulations done with the CORSIKA code [16,17] using the thinning option, without applying a resampling scheme. In the present work the study is extended by applying the resampling scheme proposed by Billoir [18]. Also, the parameterization of the 2D distribution X^{μ}_{max} versus N^{μ} is improved. The study is done both in the case when N^{μ} corresponds to all the muons from a given radial range where the muon production depth is reconstructed from the arrival times of all these muons and in the realistic case when N^{μ} and the production depth correspond to the muons which hit the detectors from an array like AMIGA surface detector array [19–21] of the Pierre Auger Observatory. In order to test the principle of the method, in this exploratory work the experimental uncertainties are not included and the detector simulation is not done. However, some results of the effects of uncertainties in the arrival time and in the reconstruction of the shower parameters are presented.

In Section 2 the observables X^{μ}_{max} and N^{μ} are introduced. In Section 3 the simulations used are presented and the data analysis for obtaining the muon production depth and the muon number is discussed; the resampling scheme applied is briefly described. In Section 4 the 2D distribution X^{μ}_{max} versus N^{μ} is presented and parameterized. In Section 5 a Bayesian approach is applied in order to test the mass discrimination performance on the basis of this 2D distribution. Section 6 concludes the paper.

2. The X^{μ}_{max} and N^{μ} observables

During the development of an EAS, various types of secondary particles are produced, which further interact in the atmosphere or decay. Thus, the number of secondary particles increases after the first interaction, reaching a maximum at a certain atmospheric depth, where the value depends on the mass and energy of the primary particle. The dependence of the number of charged particles on the atmospheric depth represents the longitudinal shower profile. The number of muons in the shower reaches a maximum on its development much deeper than the electromagnetic component, due to the increased production of muons when the energy of the parent pions decreases and to the larger mean free path of the muons in the atmosphere. Both the maximum of the charged particles longitudinal profile and the maximum of the longitudinal profile of the muon production rate are sensitive to the mass of the primary particle and can also provide additional information useful to constrain the high-energy interaction models [22,23].

X^{μ}_{max} can be evaluated after the reconstruction of the MPD. Experimentally the MPD can be reconstructed more accurately from the signal of the detectors from a specific radial range. This is due to the fact that the electromagnetic component of the shower can contribute to some extent to the signal of the muon detectors. Therefore, the detectors located close to the shower core, where the electromagnetic component has a much higher contribution, would introduce an uncertainty in the muon reconstruction. On the other hand, far from the shower core the number of muons decreases dramatically and also the uncertainty of the reconstruction of the MPD increases. Therefore, even if we do not simulate the detectors in our analysis we reconstruct the MPD using the muon arrival time in the observational plane (the ground plane where the detectors are located) in several radial ranges, from 1000, 1400 or 1800 m to 4000 m.

It is intuitive that for the same geometry of the shower axis, the mean number of muons on the ground will be higher for an iron induced shower compared to a proton shower of the same energy, due to the higher multiplicity at the first interactions. In fact a gross estimation of the dependence of the number of muons on primary mass and energy can be obtained using the Matthews–Heitler model [24]

$$N^{\mu}_{t} = A\left(\frac{E/A}{\xi_c}\right)^{\beta}, \tag{1}$$

where below the critical energy ξ_c all the charged pions are assumed to decay yielding muons, and the parameter $\beta \simeq 0.9$. As can be seen from this equation, N^{μ}_{t} has a strong, almost linear, dependence on energy whereas the dependence on mass is much weaker. Therefore, the direct use of N^{μ}_{t} for mass discrimination requires a very accurate determination of energy; also, the evaluation of N^{μ}_{t} from the signal of the detectors requires a good description of the muon lateral distribution function, i.e. a good reproduction of the experimental dependence by the theoretical functions.

In our study the muon number is obtained from simulations and N^{μ} represents the number of muons which hit the detectors from a specific array with an energy threshold of 300 MeV. In addition, for the purpose of comparison with an ideal situation, we consider also the case when N^{μ} represents the total number of muons which reach the ground in a given radial range.

3. Simulation data and evaluation of X^{μ}_{max} and N^{μ}

3.1. Simulations

The statistics of this analysis is based on 120 CORSIKA simulations for each primary particle type (*proton* and *iron*), energy (10^{19} eV and 10^{20} eV) and incidence angle (0°, 37°, 48°, 55° and 60°). Thus in total 2400 simulated showers were analyzed. In the simulations the EPOS hadronic interaction model for high energies [25] and FLUKA for low energies [26] were used. The thinning level (see Section 3.3) was set to 10^{-6} and the maximum weight to 1000. For concreteness, the simulations were done with the Earth's magnetic field corresponding to the location of the Pierre Auger Observatory and the data analysis was based on a detector array with detector separation of 750 m, similar with the AMIGA array [19].

3.2. Muon arrival times from EAS

The idea of using the information of the muon arrival times in order to estimate the nature of the primary UHECR was previously studied in [27–29] in the context of the KASCADE experiment [30] and later in [12,13,31,32]. The principle of the method is to reconstruct the longitudinal distribution of the MPD in EAS