Composition studies with multi parametric analysis

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***Abstract*. In this contribution we investigate new parameters to infer the mass composition of high energy cosmic rays above 10^{17} eV. Composition studies at these energies are usually limited by large shower fluctuations, reduced number of events and few experimental observables. Trying to overcome these difficulties we studied multi parametric statistical methods based on several measurable features of the longitudinal development of the air shower. Principal component analysis are used to combine three relevant parameters (X_{max}, N_{max} and Asymmetry) in order to maximize the discrimination power or the selection procedure in case of primary photons. The new proposed methods are compared to the traditional ones used in cosmic ray studies. The work is based on Monte Carlo simulations and the capability of the methods are studied as a function of energy.**

***Keywords*: Composition, Gamma Identification and Multiparametric Studies.**

I. Introduction

The recent discoveries of Pierre Auger Observatory such as the confirmation of GZK suppression [1] and the correlation of AGN with the arrival directions of high energy cosmic rays [4] gives valuable information about the astrophysical mechanism accelerating particles up to the highest energies. However, the knowledge of ultra high energy cosmic rays (UHECR) mass composition (above 10^{16} eV) is not yet satisfactory. This information is essential to confirm open questions about the origin and propagation of these particles.

For example, in a model that considers that the transition occurs at the ankle energies around 10^{18} eV [3], the chemical composition of the spectra will be mostly populated by heavy nuclei such as iron. On the other hand, models that considers a dip scenario the transition occurs around 10^{17} eV and the extragalactic component is composed basically by protons (it admits a small fraction of helium nuclei) [2]. Thus, the determination of the chemical composition of cosmic rays above 10^{17} eV is essential to solve this problem

Non acceleration models, such as Z-Bursts [5], topological defects [6] and others [7], called top-down models,predict large fractions of photons. In this way, the determination of photons abundance is of fundamental importance to confirm or rule out these models. The Pierre Auger Collaboration has also reported limits on the photon flux [7], [8], [9]. These results impose severe constrainings to most of the top-down models as possible source mechanisms of high energy cosmic ray above 10^{19} eV, nevertheless not all of them are discarded.

In this work we explore the possibility to discriminate hadron from gamma initiated shower in the energy range between 10^{17} to 10^{19} eV with multi parametric studies. The results presented here are based on three variables X_{max}, N_{max} and asymmetry of the longitudinal shower development. The Pierre Auger Observatory is constructing an extension of its original proposed fluorescence telescopes called HEAT [10] which is going to be able to measure shower in the energy range between 10^{17} to 10^{19} eV. This is achieved by increasing the field of view of the original telescopes to 60 degrees in zenith angle. By doing so, a larger portion of the longitudinal shower profile is going to be measure which guarantees a good measurement of the asymmetries of the profile. The results presented here matches the classification needs and technical capabilities of this experiment.

II. Simulation

We have simulated air showers using the Monte Carlo program CONEX 2r2.0 [11] with QGSJET II [12] as the hadronic interaction model. Showers were simulated for primary particles photon, proton, helium, carbon, nitrogen, oxigen, silicon and iron and energies ranging from 10^{17} eV to 10^{19} eV at fixed zenital angle 60^o. For each combination of energy and primary particle 400 showers were simulated. Along these paper we call hadron showers a sum of proton, helium, carbon, nitrogen, oxygen, silicon and iron at equal ratio.

Despite the number of simulated shower for each case is not very high we understand it is already enough to keep the fluctuations below a few percents. More showers are under production and new results including more hadronic interaction models are going to be presented soon. The mean statistic parameter used in this analysis is the merit factor (see equation). In reference [15] we have evaluated the dependence of the merit factor as a function of the number of simulated events. For 200 events the maximum error on the merit factor is about 0.1 which gives a safe margin for the results presented here.

Figure 1 shows the simulated evolution of the mean and rms of the X_{max} distribution as a function of energy. This plot was extracted from reference [15].

III. Longitudinal Profile Parameters

Composition studies done by fluorescence telescopes are usually based on X_{max} parameter, the atmospheric depth where the shower has its maximum. Figure 2

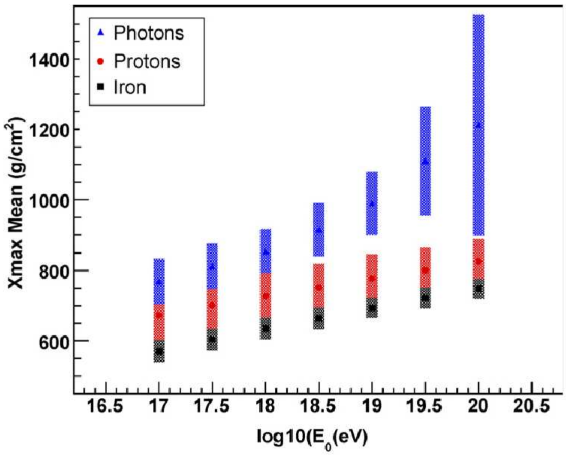

Fig. 1: Simulated elongation rate for gamma, proton and iron primaries.

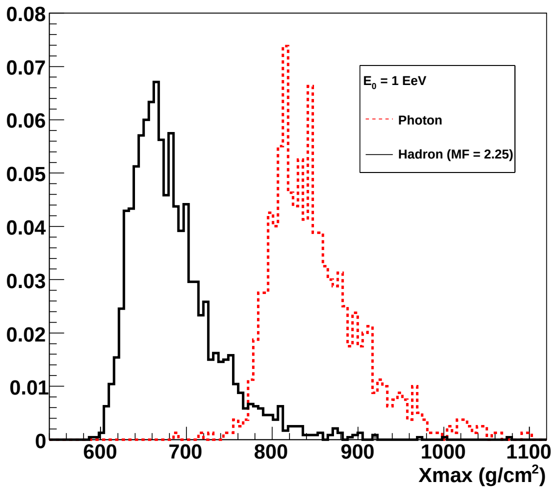

Fig. 2: Distribution of X_{max} for photon and hadron initiated showers.

shows the distribution for photon and hadron primaries simulated with energy of 10^{18} eV. As can be seen, the gamma initiated showers have larger X_{max} than the hadrons.

On a previous work [15] we had studied the relevance of the parameters X_{max}, skewness, kurtosis, asymmetry and N_{max} with Linear Discriminant Analysis (LDA). In this work we have limited our studies to three parameters: X_{max}, N_{max} and asymmetry. The other parameters were left out for simplicity and because their determination is not easy if experimental imprecisions are taken into account.

On the other hand, X_{max} and N_{max} are standard variables reconstruction with resolution around 10% in standard reconstruction procedures. The asymmetry of the longitudinal profile is calculated by fitting an asymmetric gaussian function [15]. Certainly the asymmetry resolution of each telescope influence the results presented here and a carefully study of its dependence is needed. However the larger field of view of HEAT gives us hope that a good accuracy might be achieved.

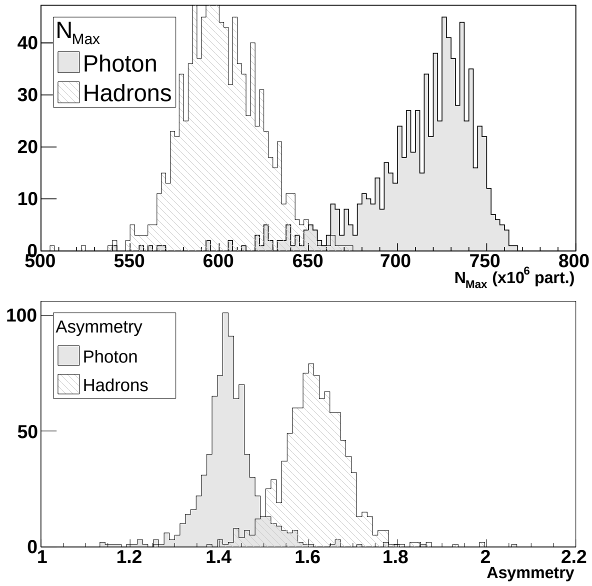

Fig. 3: Distributions of N_{max} and Asymmetry for photon and hadron showers.

IV. Principal Component Analysis

In this work we use multi parametric analysis called principal component analysis (PCA). This is a technique that rewrites a data set into a new set of variables, called principal components, that are the eigenvectors obtained diagonalizing the covariance matrix.

We applied PCA over the parameters X_{max}, N_{max} and asymmetry of the gamma initiated showers (Figure 3) From these variables we extracted their first principal component, related with the first eigenvalue, which carries the largest variance. The others primaries had their parameters projected onto these new base obtained from gamma showers. The principal components were calculated only with photon primaries due to the weak dependence from hadronic interaction models. Figure 4 shows the first component projection for gamma and hadrons with energy 10^{18} eV.

V. Results

To quantify the separation capability hence the discrimination between the different primary particle distributions, we used the merit factor (MF) statistical parameter. The merit factor between two distributions (A and B) is defined as:

$$MF = \frac{\bar{A} - \bar{B}}{\sqrt{\sigma_A^2 + \sigma_B^2}}, \qquad (1)$$

where $\bar{A}$ and $\bar{B}$ are the distributions averages, and σ_A and σ_B the respective standard deviations.

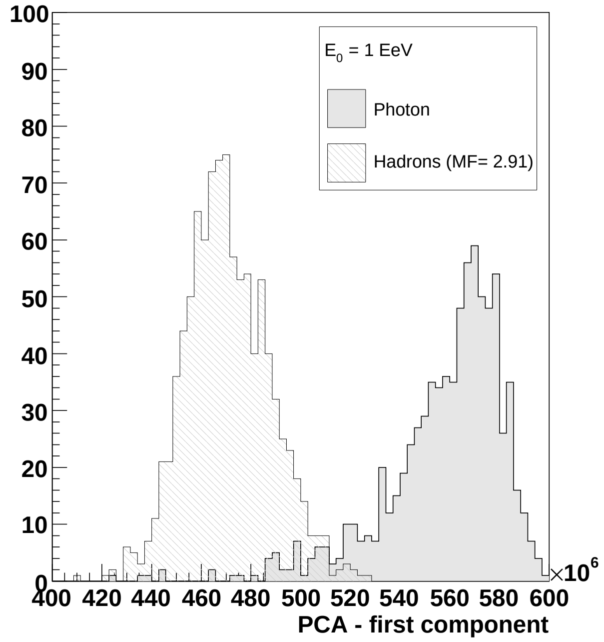

Fig. 4: First Component projection for photon and hadron primaries with energy 10^{18} eV.

TABLE I: Merit factor between hadron and photon primaries.

Energy (eV)	PCA	X_{max}
10^{17}	3.61	1.80
10^{18}	2.91	2.25
10^{19}	1.91	2.65

The merit factor calculated for the separation between photon and hadrons X_{max} distributions is 2.25 at 1EeV. Figure 5 shows the evolution of the merit factor obtained from first principal component for photon and hadrons primaries. Clearly these set of variables has higher discrimination capability at energies lower than 10^{19} eV. The values of the merit factor can be seen in table I.

VI. Conclusion

We applied principal component analysis (PCA) to study the separation capability of longitudinal parameters X_{max}, N_{max} and asymmetry.

These parameters obtained from hadron showers onto the first principal component extracted from the PCA over the gamma showers and calculated a merit factor to quantify the separation between the primaries.

We have shown that use of a more complete set of variables offer an big advantage over an analysis done with one parameter. These parameters can be used to improve the accuracy of composition studies and gamma showers discrimation. Further analysis with more complex and sophisticated statistical separation methods such as hierarchical clustering methods and Linear Discriminant Analysis are presently under study.

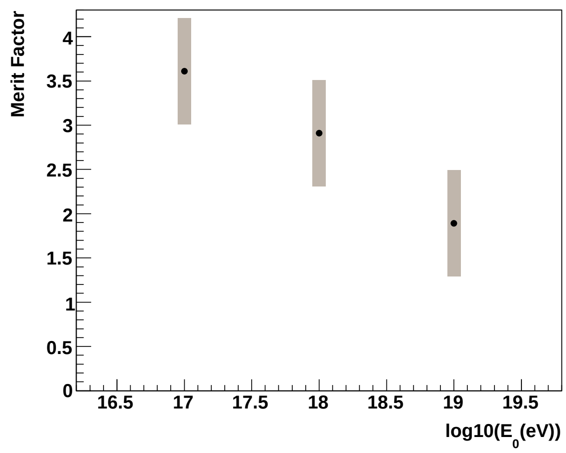

Fig. 5: First principal component Merit Factor as a function of energy

VII. Acknowledgments

Authors acknowledge the Brazilian population for supporting their work. Vitor de Souza thanks FAPESP (Grant: 2008/04259-0).

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