Anisotropy and Mass Composition Studies with the Pierre Auger Observatory

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Introduction

Anisotropies studies in the arrival direction of cosmic rays are, together with the spectrum and chemical composition studies, the major goals of any cosmic rays observatories and play an important role in the identification of the sources. The cosmic rays flux is very close to isotropic, so very careful studies are needed to measure the anisotropies.
For cosmic rays particles above several EeV (1 EeV=10^{18} eV) the magnetic deflections are expected to be small, the particles have sufficient magnetic rigidity to maintain their direction to better than a few degrees traveling through the Galaxy. At energy larger than 5×10^{19} eV the GZK cut-off limits the distance from which cosmic rays can arrive, then we might expect to observe only events coming from nearby sources. In 2007 the Auger Collaboration reported on the discovery of anisotropies in the arrival directions of cosmic rays [1] above an energy threshold of 55 EeV. This very important result triggered much interest in the community and was recently updated by the Pierre Auger Collaboration in 2010 [2].
Up to now the search of the cosmic ray sources has been performed without any kind of discrimination upon the mass composition of the primaries particles. In general, the issues of anisotropies are discussed separately from the chemical composition studies. But measurement of the anisotropy in the arrival direction of cosmic rays complemented with the studies of mass composition should provide more information about the nature of their sites of acceleration.
A study of the arrival directions of cosmic rays complemented with studies of mass composition is performed using the data of the Pierre Auger Observatory to discuss the implications of the anisotropy signal.

Data Set
The total number of 83 events with E > 55 eV used in this analysis are divided in two subsamples: correlating and not correlating events. An event with energy above ~ 55 EeV is defined as correlating if its angular distance from the nearest AGN with redshift $z < 0.018$ is less than $3.1°$, all other events above ~ 55 EeV are defined as non-correlating.

Analysis

The Pierre Auger Observatory can measure the chemical composition of the primary particles through several parameters sensitive to the mass composition. Cosmic rays corresponding to a lighter composition could be better tracked to the source with respect to the heavier component. Thus selecting a set of events corresponding to a lighter composition the correlation signal could improve, assuming that at the highest energies there is a mixed cosmic rays composition.
Three observables which have different behavior for nuclear primaries [6] are chosen for this study: S_3 [7], the Radius of Curvature of the shower front [8] and the Δ_{1000} [9].

Properties of the AGN Showers

The main difference found so far between the correlating and not correlating events is that the five highest events do not correlate. To try to answer at this question tree techniques are used to investigate the difference between these two distributions.

Degree of Correlation
The degree of correlation $P_{data} = k/N$ is defined as the number of correlating events (k) di-

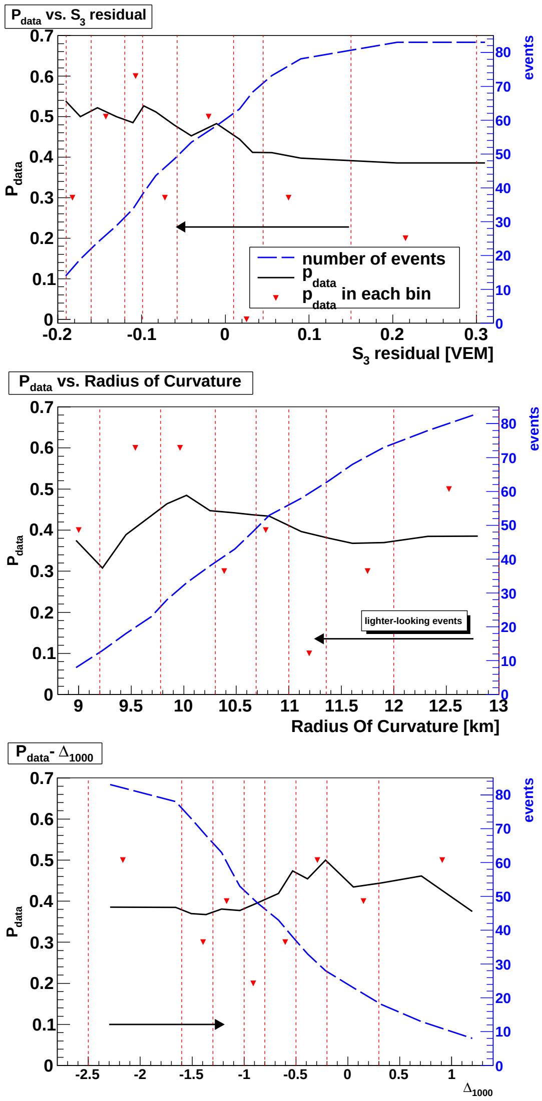

Figure 1. Fraction of correlating events above 55 EeV as a function of the mass parameters. The arrow indicates that we select events with S_3 residual and Radius of Curvature always lower than the corresponding value in the x-axis (lighter-looking events) while the Δ_{1000} always larger. The blue dashed line indicates the number of events that pass the cut (right scale) while the black full line shows the integral evolution of the P_{data} for these parameters. The red triangles are the P_{data} values in each bin delimited by the vertical dotted red lines (differential analysis). The bins are chosen to divide the sample in groups of 10 events each.

vided by the total number of events (N). The degree of correlation $P_{data} = k/N$ indicates the association of the events with energy $E > 55$ EeV with the AGNs of the VCV catalogue having $z < 0.018$.

The degree of correlation is studied selecting events on the based on mass parameters. Only sets of events with mass parameter values corresponding to an increasingly lighter mass composition are selected and for every set the P_{data} value is calculated. For the first two parameters, S_3 and Radius of Curvature, to enrich the amount of lighter primaries, the events are selected with lower values while for the Δ_{1000} events with larger values are selected.
In Figure 1 there is the evolution of the degree of correlation as a function of each mass parameter. The P_{data} values are also studied for groups of ten events (differential analysis). The data set is divided in groups of ten events where each groups corresponding to a lighter-looking set of events. The red triangles show the differential evolution of P_{data} in each bin, delimited by the vertical dotted lines, which identifies a set of ten events. In the Figure 1 only the P_{data} referred to the S_3 residual shows a steady upward while for the other two mass parameters no clear structure emerge. Even from the differential analysis there is no particular increase considering events corresponding to a lighter mass composition.

Correlation Signal

The previous method uses the correlation signal as a function of each mass parameters to study possible differences between the correlating and not correlating events. Following the assumption that light nuclei are expected to be more associated to the sources than heavy nuclei, the correlation can be studied even selecting a set of events corresponding to a lighter composition (regardless if a event is correlating or not). It can be assumed that the data set enriched with lighter nuclei should show a stronger correlation signal than the whole data set. The method proposed by Hillas is used [10] to analyze the correlation signal as a function of each mass parameter. To estimate the level of correlation this method uses the average angular distance $< d >$ between the cosmic rays arrival direction and the position of the nearest AGN. A chance probability is assigned to this value and it is defined as the frequency to obtain a mean angular distance equal or lower than the observed one from a set of 83 isotropically distributed cosmic rays arrival directions (weighted by the detector exposure).
In the Figure 2 there is the probability $P(< d >)$ as a function of each mass parameter. The black full line refers to the evolution of this probability whereas the red dotted line refers to the same probability evolution considering only the events outside the Galactic Plane. From the Figure 2 it can be seen that the probability $P(< d >)$ does not increase significantly as function of the mass parameters used. For each mass parameter there

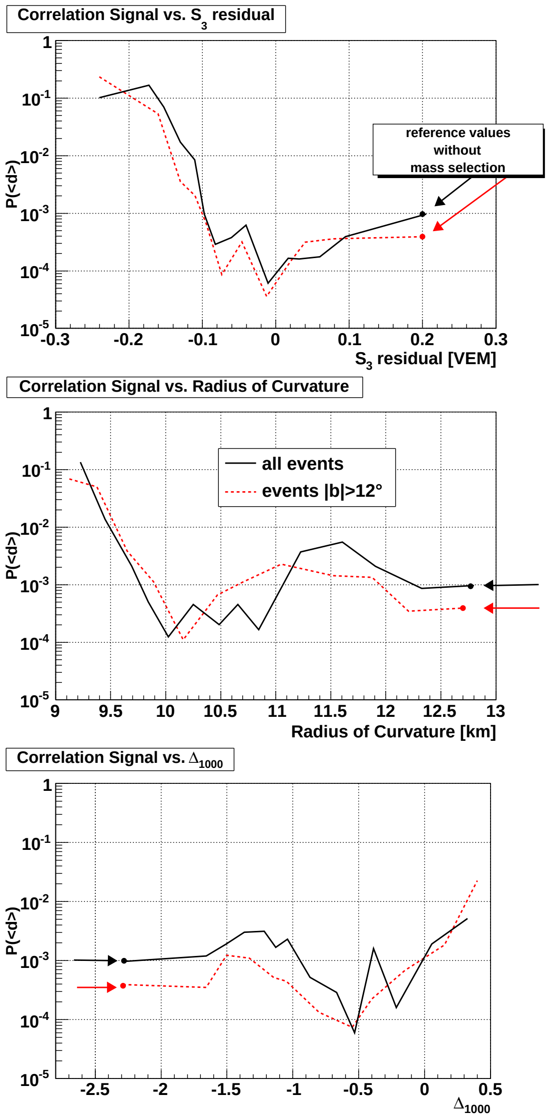

Figure 2. Hillas estimator as a function of the mass parameter. The black full lines refer to the evolution of the probability $P(<d>)$ for different cuts in the mass parameters going towards an increasingly lighter composition. The red dotted lines refer to the same evolution considering only the events outside the Galactic Plane. The dots are the $P(<d>)$ values without mass selection.

is a minimum but is not particularly significant to believe in a real different in composition between the correlating and non correlating events. Even considering the events outside the Galactic Plane the probability $P(<d>)$ does not change significantly. The Hillas estimator selecting events on the base of the mass parameters, see Figure 2 does not increase significantly. Therefore the two samples, correlating and not correlating events, do not show any significant discrepancy on the sensitive mass parameters used in this analysis.

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