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Composition at the “ankle” measured by the Pierre Auger Observatory: pure or mixed?

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We report for the first time on the measurement of the correlation between the depth of shower maximum and the signal in water-Cherenkov stations for events reconstructed by both the fluorescence and the surface detectors of the Pierre Auger Observatory. Such a correlated measurement is a unique feature of a hybrid air-shower observatory and allows us to determine the purity of the cosmic-ray composition. The observed correlation in the energy range around the “ankle” $\lg(E/\mathrm{eV}) = 18.5 - 19.0$ differs significantly from the expectations for pure beams, indicating that the primary composition in this range is mixed, unless the hadronic interactions at these energies behave very differently than in conventional, LHC-tuned event generators.

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1. Introduction

The determination of the mass composition of ultra-high-energy cosmic rays (UHECRs) is one of the most challenging problems for extensive air-shower (EAS) experiments; for a recent review, see [1]. Parameters of hadronic interactions at these energies are only loosely constrained by accelerator data and thus the evolution of the behavior of EAS properties with energy can in general be interpreted in terms of both changes of the primary mass and/or of the characteristics of the particle interactions. One way to try to resolve this ambiguity is to find shower parameters or their combinations that rely on more general aspects of EAS physics and are thus relatively insensitive to the uncertainties in the properties of the hadronic interactions.

In particular, in [2] it was proposed to use the correlation between the depth of the shower maximum $X_{\rm max}$ and the number of muons N_μ of the EAS for the determination of the degree of purity of the beam, i.e., whether it is composed of several or just one nuclear species. In the present work we adapt this idea to the conditions of the Pierre Auger Observatory [3]. In place of N_μ we use the total signal in water-Cherenkov detectors at 1000 meters from the core, $S(1000)$, a substantial fraction of which is due to muons: from 40% to 90% for zenith angles from 20° to 60° [4]. We show that the correlation $(X_{\rm max}, S(1000))$ for pure primary beams for all current interaction models turns out to be close to zero or positive, while for well-mixed compositions with a large spread of masses it becomes negative (see [2]). Thus the correlation coefficient can be used to determine the dispersion, $\sigma(\ln A)$, of primary masses, given by $\sigma(\ln A) = \sqrt{\langle \ln^2 A\rangle - \langle \ln A\rangle^2}$ where $\langle \ln A\rangle = \sum_i f_i \ln A_i$ and $\langle \ln^2 A\rangle = \sum_i f_i \ln^2 A_i$ with f_i being the relative fraction of mass A_i.

An estimation of the degree of purity of the primary beam in the energy range $\lg(E/{\rm eV}) = 18.5 - 19.0$ is of particular interest as a test of the 'dip' scenario [5]. In this scenario the break in the energy spectrum at around $\lg(E/{\rm eV}) = 18.7$ results from electron-positron pair-production by extragalactic protons interacting with the cosmic microwave background. The 'dip' is well pronounced only if the fraction of heavier nuclei at the acceleration site is $\lesssim 15\%$ (see [6] and references therein).

2. Data and simulations

The analysis is based on the same hybrid events as used in [7] recorded by both fluorescence (FD) and surface detectors (SD) of the Pierre Auger Observatory during the period from 01.01.2004 to 31.12.2012. The procedure of data selection, described in [7], guarantees that only high quality events are included in the analysis and that the mass composition of the selected sample is unbiased. The use of the signal in ground stations requires an additional application of the fiducial trigger cut [8] (the station with the highest signal should have at least 5 working neighbour stations), and exclusion of events with stations having saturated signal traces. The final data set for energies $\lg(E/{\rm eV}) = 18.5 - 19.0$ and zenith angles $\theta = 0° - 65°$ contains 1376 events.

Monte-Carlo (MC) simulations are performed with CORSIKA [9] for high-energy interaction models QGSJetII-04 [10], Epos-LHC[11] and Sibyll 2.1 [12]. FLUKA [13] is used to treat low energy interactions. For CORSIKA events, full detector simulation and reconstruction procedures with the Auger $\overline{\rm Off}\underline{\rm line}$ software [14] are performed, and the event selection follows that applied to

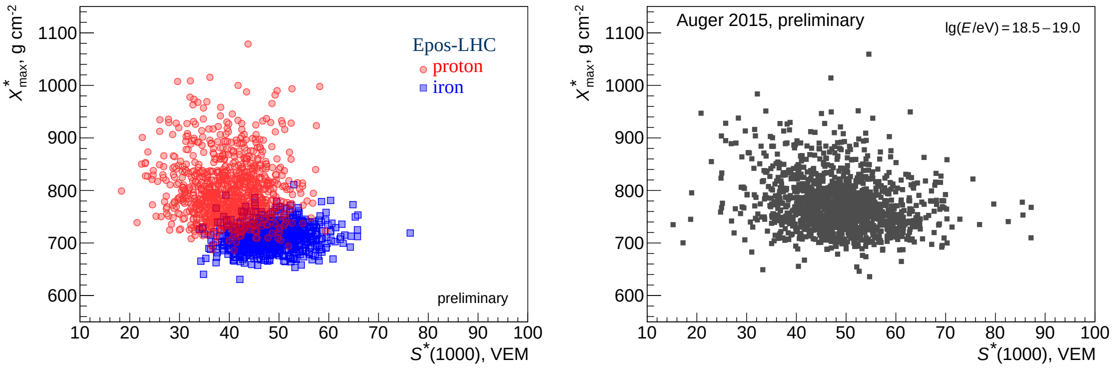

Figure 1: Scatter plot of X^*_{max} vs $S^*(1000)$ for protons and iron of Epos-LHC from full detector simulations (left) and for data (right) for $\lg(E/\mathrm{eV}) = 18.5 - 19.0$.

data. After selection, the proton samples for all models contain $\simeq 10^4$ showers; for heavier nuclei the samples vary from $5 \cdot 10^3$ to 10^4 showers.

Since $S(1000)$ and X_{max} of an air shower depend on the energy and, in the case of $S(1000)$, also on the zenith angle, we scale $S(1000)$ and X_{max} to a reference energy and zenith angle. In this way, a decorrelation between the observables from combining different energies and zenith angles in the data set is avoided. We scale $S(1000)$ to 38° and 10 EeV using the calibration curves from [15] and X_{max} to 10 EeV using an elongation rate of 58 $\mathrm{g\,cm^{-2}}$/decade. These scaled quantities will be marked with an asterisk: X^*_{max}, $S^*(1000)$. Fig. 1 (right panel) shows the correlation between X^*_{max} and $S^*(1000)$ observed in data. Also shown, for illustration purposes, are the simulations for proton and iron primaries with Epos-LHC.

3. Method and results

As a measure of the correlation between X^*_{max} and $S^*(1000)$ we take the ranking coefficient r_{G} introduced by Gideon and Hollister in [16]. All events are ranked in both X^*_{max} and $S^*(1000)$, and the measured values of these observables are replaced by ranks for calculating the correlation. Further, the values of ranks are not used directly to calculate r_{G}, but rather the general statistical dependence between X^*_{max} and $S^*(1000)$ is estimated counting numbers of events with ranks deviating from the expectations for perfect correlation and anti-correlation. With respect to the classical Pearson and Spearman coefficients, r_{G} provides a more robust estimate of the correlation [16, 17]. In particular, r_{G} is less sensitive to the removal of the most influential events or to outliers. We also note that the difference between correlation coefficients found in data and MC simulations for pure beams gets larger using Pearson and Spearman coefficients (or a number of other correlation coefficients considered in [17]) compared to using r_{G} so that the choice of r_{G} can be also viewed as conservative. The statistical uncertainty of r_{G} is determined using dedicated simulations and for the sample of size N it is $\sigma_{\mathrm{stat}}(r_{\mathrm{G}}) \approx 0.9/\sqrt{N}$.

In Table 1 we present the r_{G} values for data and for the simulations for pure beams. Compared to data, where the correlation is significantly negative $r_{\mathrm{G}}(X^*_{\mathrm{max}}, S^*(1000)) = -0.125 \pm 0.024\,(\mathrm{stat})$, the smallest difference is found for Epos-LHC protons and it is around $5\sigma_{\mathrm{stat}}$. Pre-LHC versions

Table 1: $r_G(X^*_{\max}, S^*(1000))$ for data and for MC simulations of pure beams (preliminary). Statistical uncertainties on the MC values are $\sigma_{\text{stat}} \approx 0.01$.

data	$-0.125 \pm 0.024\,(\text{stat})$

	Epos-LHC	QGSJetII-04	Sibyll 2.1
p	0.00	0.08	0.07
He	0.08	0.15	0.15
O	0.09	0.15	0.14
Fe	0.08	0.12	0.12

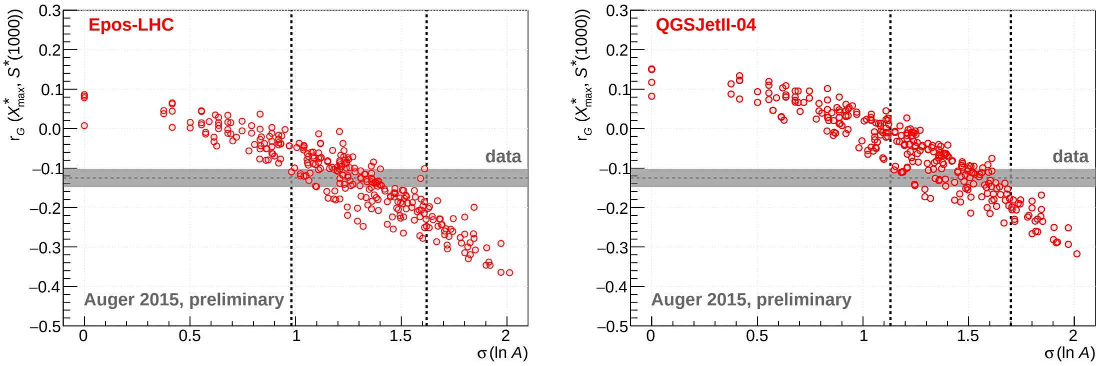

Figure 2: Dependence of the correlation coefficients r_G on $\sigma(\ln A)$ for Epos-LHC (left), QGSJetII-04 (right). Each MC point corresponds to a mixture with different fractions of protons, helium, oxygen and iron, the relative fractions change with 0.1 steps (4 points for pure beams are grouped at $\sigma(\ln A) = 0$). The shaded band shows the $1\sigma_{\text{stat}}$ interval for data. Vertical dotted lines indicate the range of $\sigma(\ln A)$ in simulations compatible with the observed correlation in data.

of Epos and QGSJetII produce values of correlations similar to Epos-LHC and QGSJetII-04. The differences between data and simulations are larger for pure beams other than protons. Using Pearson and Spearman coefficients one gets the same or slightly more positive values for pure beams as with r_G, and more negative correlation for data: $r(\text{Pearson}) = -0.210 \pm 0.038\,(\text{stat})$; $r(\text{Spearman}) = -0.199 \pm 0.027\,(\text{stat})$. This result shows that the composition in the considered energy range is not pure but mixed.

Fig. 2 presents the dependence of the correlation $r_G(X^*_{\max}, S^*(1000))$ on the dispersion of primary masses $\sigma(\ln A)$. Each MC point in this plot represents a mixture containing different fractions of protons, helium, oxygen and iron. The relative fractions f_i of each species change with 0.1 steps between different mixtures. There are four points corresponding to beams of pure p, He, O, and Fe, grouped on the left side at $\sigma(\ln A) = 0$; of these, the proton beam has the smallest r_G (cf. Table 1). The maximum possible value of $\sigma(\ln A) \simeq 2.01$ corresponds to the $0.5\,p - 0.5\,\text{Fe}$ mix.

The value of the correlation in data, indicated with the shaded band, is compatible with the MC samples with dispersions of primary masses $\sigma(\ln A) \gtrsim 1$. The conclusions on $\sigma(\ln A)$ are similar for all models considered (for Sibyll 2.1 one gets almost identical results to QGSJetII-04, cf. Table 1) and thus is weakly sensitive to the uncertainties in the description of the high-energy hadronic interactions.

The robustness of the presented approach makes it suitable for testing the self-consistency of the hadronic interaction models. For example, using the fractions of primary nuclei obtained from the fits of Auger X_{max} distributions [18] for QGSJetII-04 and Sibyll 2.1, which in the $\lg(E/\text{eV}) = 18.5-19.0$ energy range are close to $0.5\,p-0.5\,\text{He}$ ($\sigma(\ln A) \approx 0.7$), one gets $r_{\text{G}} \approx 0.07-0.09$. The incompatibility of this value with the results of the present correlation analysis may be an indication of deficiencies in these two interaction models. The composition found in [18] from X_{max} fits with Epos-LHC is close to $\approx 0.35\,p-0.30\,\text{He}-0.35\,\text{O}$ mix ($\sigma(\ln A) \approx 1.17$), and the corresponding correlation $r_{\text{G}} = -0.084$ is within 2σ from the r_{G} value in data.

4. Uncertainties

A number of standard tests were performed for estimation of the robustness of the obtained results. These checks include analysis of data recorded in various time periods and by different FD telescopes, separation of data in several angular ranges, and study of r_{G} in smaller energy bins. Results were consistent in all cases.

The ranking correlation coefficients are invariant with respect to any transformations not affecting ranks of the events. Thus r_{G} is insensitive to the systematic effects on X^*_{max} or $S^*(1000)$ that might lead to shift or multiplication of these observables by a constant value. In particular we have checked that the recent changes in Auger energy and X_{max} scales [19, 7] do not change the observed correlation. The same insensitivity of r_{G} was observed with respect to the application of various FD selection cuts which have been used in our publications from 2010 [20] until 2014 [7]. Finally, we introduced arbitrary energy and zenith angle dependent biases in X^*_{max} (up to 10 $\text{g}\,\text{cm}^{-2}$) and $S^*(1000)$ (up to 10%) and this changed r_{G} by $\simeq 0.01$. We take that value as a conservative estimate of the systematic error on r_{G}.

We checked whether moderate changes of hadronic interaction parameters could make the value of r_{G} predicted for a pure proton composition consistent with observations. Using the approach described in [21] we performed simulations with Epos-LHC modifying the cross-section, multiplicity, elasticity and pion charge ratio in proton–air interactions by a factor $f_{19} = 1.5$, i.e. increasing them by a factor linearly growing with $\lg E$ from 1.0 at 10^{15} eV to 1.5 at 10^{19} eV with respect to the nominal values [21]. CONEX [22] with 3D option was used for approximate estimation of the signal in Auger stations at 1000 meters from the core. It turned out that r_{G} is practically insensitive to the modifications of these interaction parameters decreasing only by $\Delta r_{\text{G}} \lesssim 0.03$. The change in r_{G} due the increase of cross-section, still being small compared to the difference between data and pure proton expectations, is found to be zenith angle dependent and it would also lead to zenith angle dependent (and thus contradictory) conclusions on $\sigma(\ln A)$. Such a scenario is constrained additionally by other Auger findings (e.g. regarding the proton-air cross section derived for $\lg(E/\text{eV}) = 17.8-18.5$ [23, 24]), making it implausible as an explanation of our observations.

A possible under-production of muons by the current interaction models [25, 26, 27] could lead to changes in the ordering of events in the (X^*_{max}, $S^*(1000)$) plane due to the presence of events with largely varying muon fractions of $S^*(1000)$. We performed a number of studies using CORSIKA showers and showers fully reconstructed with $\overline{\text{Off}}\underline{\text{line}}$ with the numbers of muons increased by the factors ranging from 1.1 to 1.9 and we have found that for the muon scaling by a factor ≈ 1.3, as suggested by data for Epos-LHC [25, 26], the $r_{\rm G}$ value decreseas by $\lesssim 0.03$.

5. Summary

The observed correlation $r_{\rm G}(X^*_{\rm max}, S^*(1000))$ between depth of shower maximum and total signal at 1000 meters from the core differs significantly from the correlations for any pure beam for simulations with Epos-LHC, QGSJetII-04 and Sibyll 2.1. The result is invariant with respect to additive and multiplicative scale transformations of the two variables and to any other transformations of $X_{\rm max}$ and $S(1000)$ which leave ranks of events unchanged, and hence is robust against many possible experimental systematic uncertainties. Several modifications of hadronic interactions were studied. The conclusions remain robust also with regard to hadronic uncertainties, unless hadronic interactions at these energies behave very differently than in conventional, LHC-tuned event generators. The results are compatible with a mixed primary composition around the 'ankle' with the dispersion of masses $1.0 \lesssim \sigma(\ln A) \lesssim 1.7$ and question the 'dip' scenario.

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