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Measurements of the Mass Composition of UHECRs with the Pierre Auger Observatory

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As a hybrid cosmic ray detector, the Pierre Auger Observatory can measure the longitudinal air shower development with the fluorescence detector, and the lateral distribution of particles reaching the ground with the surface detector. We report on the measurements of the first two moments of the $X_{\max}$ distribution measured as a function of energy with the fluorescence detector and convert them to $\langle \ln A \rangle$ and $\sigma(\ln A)$. This conversion depends on the adopted hadronic interaction model. To obtain an almost model-independent estimation of dispersion of primary masses $\sigma(\ln A)$ near the 'ankle' we use the correlation between $X_{\max}$ and the signal in the water-Cherenkov stations at 1000 m from the shower core $S(1000)$. The correlation analysis is robust with respect to uncertainties in hadronic models and to experimental systematic uncertainties. The observed correlation between $X_{\max}$ and $S(1000)$ differs significantly from expectations for pure primary compositions and is well described by a mixed composition with $\sigma(\ln A) > 1.0$.

KEYWORDS: cosmic rays, mass composition, extensive air shower

1. Introduction

The mass composition of ultra high energy cosmic rays (UHECRs) ($E > 10^{17}$ eV) is still unknown and a key to understand the origin of the 'ankle' and 'cut-off' features of the measured energy spectrum. Theoretical models predict different scenarios to describe these by either a pure proton composition or by mixed composition scenarios. The Pierre Auger Observatory [1] is a hybrid cosmic-ray observatory located in Mendoza province, Argentina which measures extensive air showers using 5 fluorescence detectors (FD) comprised of 27 telescopes and a surface-detector (SD) comprised of 1660 water-Cherenkov stations. FD measurements provide high-quality data of the shower energy as well as the atmospheric depth of the maximum shower development ($X_{\max}$) for UHECRs above 10^{17} eV by measuring the longitudinal shower profile. SD stations measure the lateral distribution of an air shower on the ground. SD can measure the primary energy and electromagnetic/muonic component of the air showers above $10^{17.5}$ eV. The combination of both detectors allows a detailed measurement of the same shower with two different techniques. The distribution of $X_{\max}$ as a function of energy is very sensitive to the primary mass composition of UHECRs. Additionally, the correlation of the SD signal at 1000 m from the shower core $S(1000)$ and FD's $X_{\max}$ is used to study the mass composition around the 'ankle' at $\log(E/\text{eV}) = 18.5$-19.0.

2. Average atmospheric depth of maximum shower development

The interpretation of the primary mass composition of cosmic rays is derived from the distribution of the measured $X_{\max}$ value for a given energy bin. The first two moments of the $X_{\max}$ distribution [2] ($\langle X_{\max}\rangle$ and $\sigma(X_{\max})$) are connected to the first two moments of the distribution of the logarithm of masses of primary particles ($\langle \ln A\rangle$ and $\sigma(\ln A)$) by

$$\langle X_{\max}\rangle = \langle X_{\max}\rangle_p + f_E\,\langle \ln A\rangle, \tag{1}$$

$$\sigma^2(X_{\max}) = \langle \sigma^2_{\rm sh}\rangle + f_E^2\,\sigma^2(\ln A), \tag{2}$$

where $\langle X_{\max}\rangle_p$ is the average $X_{\max}$ for protons and $\langle \sigma^2_{\rm sh}\rangle$ is the composition-averaged intrinsic shower-to-shower fluctuation. f_E depends on a parametrization given by the interaction models. The data set used consists of the high quality hybrid air showers including the events taken by the low energy enhancement 'High Elevation Auger Telescopes' (HEAT). The systematic uncertainties include the uncertainties of the detector system, the atmospheric conditions, the reconstruction and the analysis. More details on these can be found in [3, 4]. In

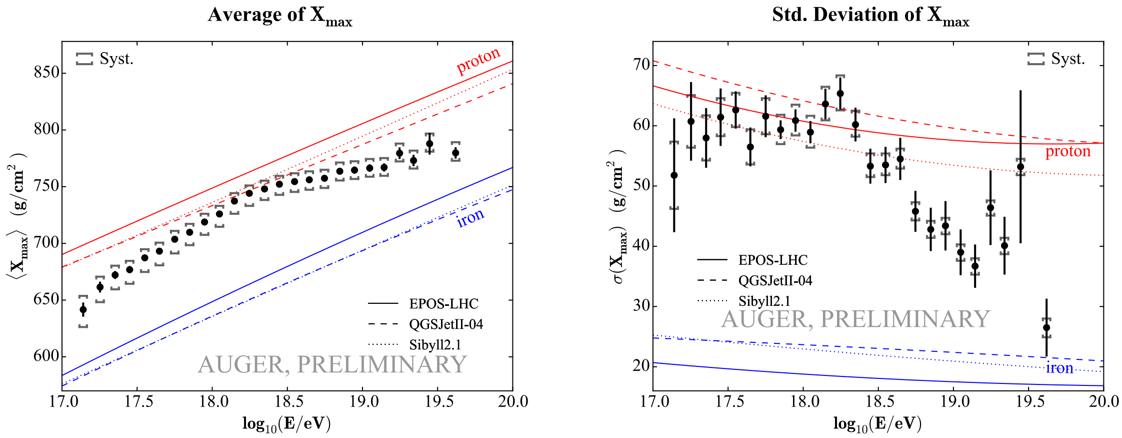

Fig. 1. The mean (left) and the standard deviation (right) of the measured $X_{\max}$ distributions as a function of energy compared to air-shower simulations for proton and iron primaries of different interaction models.

figure 1 (left) is shown that the $\langle X_{\max}\rangle$ value per decade of energy increases by around 85 g cm^{-2} between $10^{17.0}$ eV and $10^{18.3}$ eV. For a constant mass composition of UHECRs, this value should be around 60 g cm^{-2} per decade, which indicates the transition to a lighter mean primary mass. Around an energy of $10^{18.3}$ eV the observed changing rate of $\langle X_{\max}\rangle$ becomes significantly smaller (26 g cm^{-2}/decade), which indicates that the composition is becoming heavier. In figure 1 (right) is shown that the measured fluctuations of $X_{\max}$ start to decrease at around the same energy $10^{18.3}$ eV, also indicating a change in the mass composition. Derived from equations 1 and 2, the mean logarithmic mass is shown in figure 2 and the variance of logarithmic mass is shown in figure 3. Both interaction models show a similar development with energy for $\langle \ln A\rangle$ and $\sigma^2(\ln A)$. The primary mass of UHECRs decreases, reaching the minimum value at around $10^{18.3}$ eV and starts to increase again with higher energies. The variance of the logarithmic masses is almost constant until $10^{18.3}$ eV and then starts to decrease. $\langle \ln A\rangle$ shows reasonable results for both interaction models over the whole energy range, but the $\sigma^2(\ln A)$ values derived from QGSJetII-04 [5] for energies $> 10^{18.4}$ eV

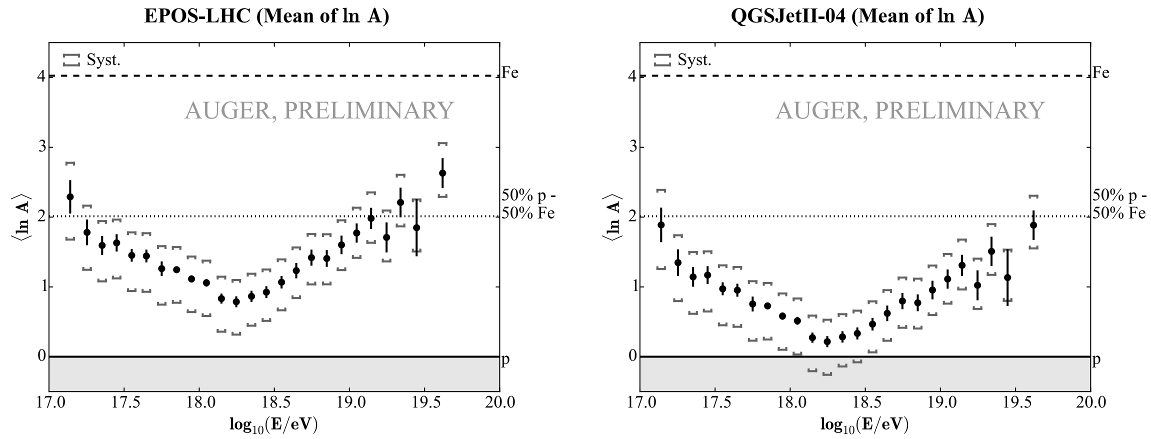

Fig. 2. The mean of $\ln A$ estimated from data with EPOS-LHC [6] (left) and QGSJetII-04 [5] (right).

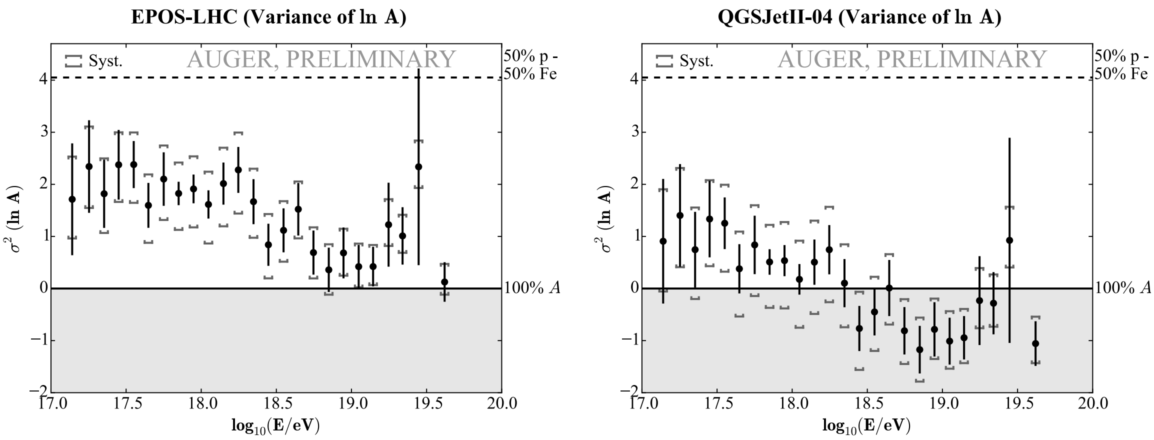

Fig. 3. The variance of $\ln A$ estimated from data with EPOS-LHC [6] (left) and QGSJetII-04 [5] (right).

become negative, which is unphysical and could indicate some tension between the measured data and the theoretical interaction model. However, the current systematic uncertainties do not allow any strong claims concerning the interaction model predictions. Combined with the behavior of $\langle \ln A \rangle$ this might indicate that the fraction of protonlike UHECRs becomes smaller for the energies above $10^{18.3}$ eV.

3. Correlation of SD and FD data

To take advantage of the hybrid detector design, a signal correlation analysis of FD and SD data is performed in the energy range of $10^{18.5} - 10^{19.0}$ eV around the ‘ankle’, where as an example the ‘dip’ model [7, 8] predicts an almost pure cosmic-ray composition with small spread in primary masses. In the ‘dip’ model, the two observed features of the energy spectrum could be understood as a signature of proton interactions during propagation through the intergalactic space, where the ankle at $\log(E/\mathrm{eV})$=18.7 is caused by pair-production and the flux suppression at $\log(E/\mathrm{eV}) = 19.6$ is caused by photopion production. With the correlation analysis method an almost interaction model independent study of the mass composition purity is performed by using only air shower observables proportional to the general shower characteristics, namely FD's $X_{\max}$ and SD's $S(1000)$. Since $X_{\max}$ and $S(1000)$ of an air shower depend on the energy and $S(1000)$ also on the zenith angle, the measured values of $S(1000)$ and $X_{\max}$ are scaled 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. The $S(1000)$ values are corrected for their zenith angle dependency from the air shower attenuation in the atmosphere with a Constant Intensity Cut (CIC) method [10] and are scaled to the median zenith angle of 38° and a reference energy of 10 EeV. $X_{\max}$ is scaled to a reference shower energy of 10 EeV using an elongation rate of 58 g cm^{-2}/decade, which is the average elongation rate derived from simulation values for a fixed mixed composition from different interaction models. The scaled values of $X_{\max}$ and $S(1000)$ will be marked with an asterisk as X^*_{max} and S^*_{38}. The ranking coefficient r_G introduced by Gideon and Hollister [11] is used to measure the correlation between the scaled values X^*_{max} and S^*_{38}, in which $r_G = \pm 1.0$ would represent a perfect correlation/anticorrelation. The correlation

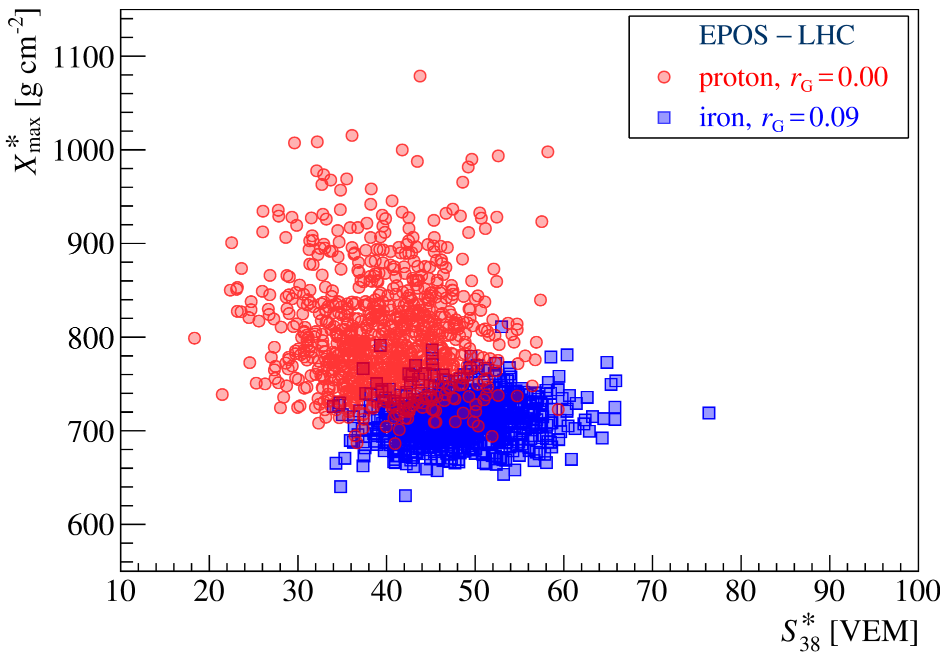

Fig. 4. Measured X^*_{max} vs. S^*_{38} from simulation of UHECRs with energies log(E/eV)=$10^{18.5}$ – $10^{19.0}$ eV. The simulation data consist of each 1000 proton and iron air shower simulated with EPOS-LHC [6].

between X^*_{max} and S^*_{38} observed in simulation for pure primary composition of proton and iron showers is shown in figure 4. In figure 5 the reconstructed X^*_{max} and S^*_{38} for data is shown together with the calculated correlation coefficient r_G. Table I gives the value for the observed $r_G(X^*_{max}, S^*_{38})$ along with simulated r_G values for pure compositions (σ(ln $A = 0$) and for the maximum spread of masses 0.5 p - 0.5 Fe (σ(ln A) = 2) for different interaction models. A negative correlation of $r_G(X^*_{max}, S^*_{38}) = -0.125 \pm 0.024$ (stat) is found for the chosen data set. The correlation factors for pure proton simulations are close to zero or positive in all used interaction models. A pure composition of heavier primaries shows an even more positive correlation ($r_G = 0.09$) than for protons. On that account, the observations in this energy range cannot be reproduced by any pure composition, irrespective of the chosen interaction model. A negative correlation coefficient is explainable by a mixture of light and heavy

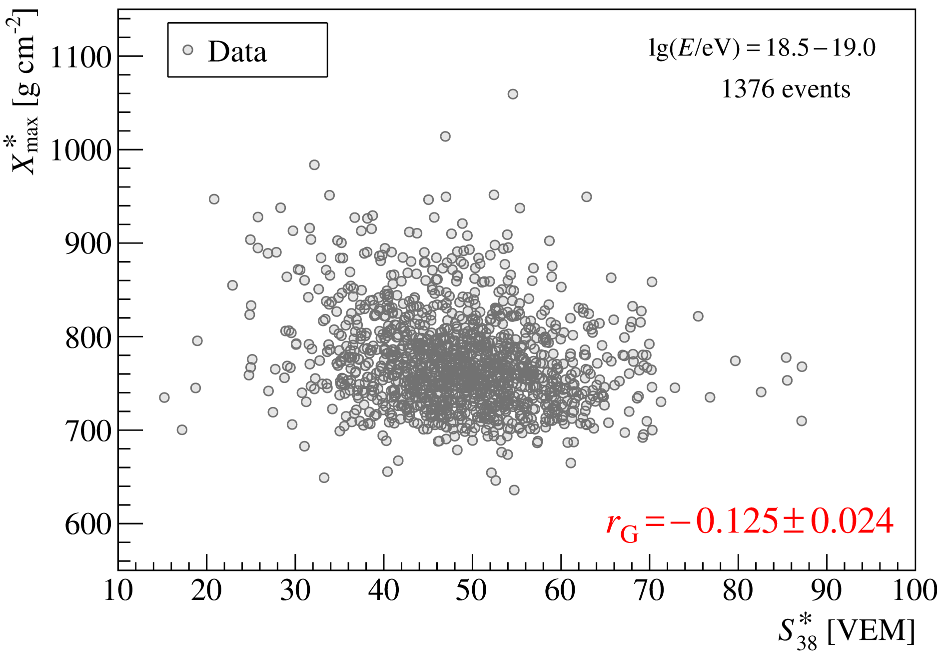

Fig. 5. Measured X^*_{max} vs. S^*_{38} from reconstructed air shower data with energies $\log(E/\text{eV})=10^{18.5} - 10^{19.0}$ eV. Correlation coefficient is $r_G = -0.125 \pm 0.024$.

Table I. Observed $r_G(X^*_{max}, S^*_{38})$ with statistical uncertainty and $r_G(X^*_{max}, S^*_{38})$ in simulations with different interaction models for different composition scenarios.

Data	-0.125 ± 0.024(stat)	
Simulation	EPOS-LHC	QGSJetII-04
p	0.00	0.08
He	0.10	0.16
O	0.09	0.16
Fe	0.09	0.13
0.5 p + 0.5 Fe	-0.37	-0.32
0.8 p + 0.2 He	0.00	0.07

primary cosmic rays, as even a mixture of protons with helium leads to an $r_G \geq 0$. More details on this analysis method, the data selection, the uncertainties and the systematics are given in [12].

4. Conclusion

The development of the X_{max} moments as a function of energy compared to recent interaction models shows a changing primary composition from rather heavy to light to intermediate masses in the studied energy range from $10^{17.0} - 10^{19.6}$ eV. The studied correlation between the results from FD and SD shows that around the 'ankle' the measured data are incompatible with a pure composition or a mix of only light (proton-Helium) elements. Therefore theoretical model predictions, like the 'dip' scenario, are disfavored as the sole explanation of ultrahigh-energy cosmic rays. The analyses presented using the experimentally measured data from the Pierre Auger Observatory give a strong indication that the mass composition of UHECRs does not consists of a pure element composition, but a rather mixture including heavy nuclei with $A > 4$ at the highest energies.

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