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Mass composition of cosmic rays with energies above $10^{17.2}$ eV from the hybrid data of the Pierre Auger Observatory

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We present updates on the measurements of the depth of the shower maximum X_{max} and the correlation between X_{max} and the signal in the water-Cherenkov stations of events registered simultaneously by the fluorescence and the surface detectors of the Pierre Auger Observatory. The measurements of X_{max} are performed for $E > 10^{17.2}$ eV using observations of the longitudinal development of air showers by the fluorescence telescopes. The evolution of the mean and the fluctuations of X_{max} with energy, as extracted from the data taken during 2004 – 2017, is interpreted in terms of the evolution of the mean logarithmic mass and the spread of the masses in the primary beam using post-LHC hadronic interaction models.

The measurements of the correlation between X_{max} and the signal in the surface stations allow one to obtain constraints on the spread of the masses in the primary beam. These constraints are weakly sensitive to the experimental systematic errors and to the uncertainties in the modelling of air showers. Previously, using data taken during 2004 – 2012, we excluded with a significance of 5σ pure compositions and compositions consisting of only protons and helium for energies $10^{18.5} - 10^{19.0}$ eV. In the update of the analysis presented here using the data from years 2004 – 2017 and nearly doubled statistics, these conclusions are confirmed with a significance $> 6.4\sigma$ in the energy range $10^{18.5} - 10^{18.7}$ eV alone, while for higher energies, the correlation in data becomes consistent with less mixed compositions.

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1. Introduction

During the last decade, significant progress was achieved in the studies of the mass composition of the ultra-high energy cosmic rays (UHECR). While at energies near and above the flux suppression $E \gtrsim 10^{19.5}$ eV the inferences on the composition still suffer from statistical limitations and uncertainties in the extrapolations of the properties of hadronic interactions, in the region of the possible transition from galactic to extragalactic origins and near the ankle in the UHECR spectrum several results, important for the development and validation of astrophysical models, were obtained.

Measurements of the depth of shower maximum, $X_{\max}$, published by the Pierre Auger Observatory (Auger) in 2010 [1] were a significant step towards a better understanding of the evolution of the mass composition for $E > 10^{18}$ eV. For the first time, it was shown and later confirmed with higher significance [2, 3, 4] that the mean mass of the UHECRs is decreasing up to $\sim 10^{18.3}$ eV and starts increasing afterwards. This qualitative statement can be derived from the energy dependence of the mean and standard deviation of $X_{\max}$ alone without resorting to hadronic interaction models. The observations, being interpreted in terms of $\ln A$ moments and fractions of individual species, indicate that for energies below the ankle the spread of the masses in the primary beam is larger than for higher energies.

These findings were corroborated by the analysis of the correlation between $X_{\max}$ and the signal in water-Cherenkov detectors (WCD) reported by Auger in 2016 [5]. The observed correlation for energies $10^{18.5} - 10^{19.0}$ eV was found to be negative and compatible with a spread of the masses in the primary beam of $\sigma(\ln A) = 1.35 \pm 0.35$. Since in simulations for all proton-helium mixes the correlation is non-negative, this result is robust evidence that nuclei with $A > 4$ can be accelerated to ultra-high energies and escape the source environment.

In these proceedings, the update of the $X_{\max}$ measurements [4] is presented with data from the years 2016 and 2017 using the latest improvements in the fluorescent technique implemented in Auger [6].

The correlation analysis is updated with five more years of data ($2013 - 2017$) and contains nearly two times larger event statistics with respect to the published results [5].

2. Data selection

At the Pierre Auger Observatory, the longitudinal development of air showers is measured with the fluorescence detector (FD) consisting of 24 fluorescence telescopes each covering 30° in azimuth and $1.5^\circ - 30^\circ$ in elevation. The telescopes are grouped in units of six at four sites around the surface detector (SD) array of 3000 km^2 in area. Three additional high-elevation ($30^\circ - 58^\circ$) Auger telescopes (HEAT) for the detection of air showers with energies below 10^{18} eV have been operating since 2009 at the Coihueco FD site.

Monitoring of atmospheric conditions, mandatory for the accurate reconstruction of $X_{\max}$ and energy of air showers, is regularly performed at the Observatory (see [7] for more details). Pressure, humidity, temperature profiles, vertical aerosol optical depth (VAOD), the presence of clouds in the field of view of the FD telescopes are monitored in intervals from 15 minutes to 3 hours (depending on the type of monitoring) using a variety of instruments.

Both analyses presented in these proceedings are performed using hybrid events, i.e. events registered by the FD and having at least one triggered SD station. The data selection follows the procedure described in detail in [2]. Good atmospheric conditions are required, meaning that the value of the integral of the VAOD up to 3 km above ground should be lower than 0.1 and that the observations of the longitudinal profile should not be affected by the presence of clouds. The depth of the shower maximum should be in the observed part of the profile and have the expected reconstruction uncertainty $< 40\ \mathrm{g\,cm^{-2}}$. To avoid a mass composition bias, the difference between SD trigger probabilities for proton and iron should be smaller than 5%. Finally, a fiducial field-of-view selection is applied to guarantee an unbiased FD acceptance of the showers almost independently of their X_{max} and geometries.

Measurements of X_{max} and the analysis of the correlation between SD and FD data from the standard FD sites are performed for the period $12/2004-12/2017$. For HEAT/Coihueco (HeCo), the X_{max} measurements from the ICRC 2017 [4] are presented using the period $06/2010-12/2015$. All events with energies below $10^{18.1}$ eV detected by HeCo are excluded from the data set of the standard FD. Thus these two data sets are completely independent.

In the analysis of the correlation, for an accurate estimation of the signal at 1000 meters from the core, only events for which at least five stations are active in the hexagon around the WCD with the highest signal are accepted. Events containing saturated stations are excluded, and the analysis is performed up to a zenith angle of 65° where SD reconstruction biases are small. The SD selection applied here is the same as in [5].

3. Measurements of the depth of shower maximum

Measurements of X_{max} with the standard FD are performed at energies above $10^{17.8}$ eV. Showers of lower energies reach their maximum higher in the atmosphere and because of their fainter profiles are observed only at distances closer to the telescopes. These showers can be reconstructed using information from the combined HeCo telescopes. The extension of X_{max} measurements with the help of HeCo down to $10^{17.2}$ eV was previously presented in [3, 4].

Energies and X_{max} of the selected events are corrected for small reconstruction biases determined using Monte-Carlo (MC) simulations generated with CONEX [8] and detector simulations and reconstruction using the $\overline{\text{Off}}\underline{\text{line}}$ Auger software [9] that reproduces the real-time state of the FD and SD. Mean $\langle X_{\mathrm{max}}\rangle$ and $\sigma(X_{\mathrm{max}})$ are calculated using a correction for the residual acceptance biases, and the detector resolution is subtracted from the width of the observed X_{max} distributions. This way, the X_{max} moments measured at Auger are free from detector effects and can be directly compared to predictions from MC simulations. The resolution for the standard FD is $\sim 25\ \mathrm{g\,cm^{-2}}$ at $10^{17.8}$ eV and improves to $\sim 15\ \mathrm{g\,cm^{-2}}$ at the highest energies. The resolution of HeCo at $\sim 10^{18.0}$ eV is slightly worse than that of the standard FD because of the time-dependent corrections required to level the relative calibrations of the HEAT and Coihueco. Systematic uncertainties are below $10\ \mathrm{g\,cm^{-2}}$ for most of the energy range (more details can be found in [2]).

The results of the measurements of $\langle X_{\mathrm{max}}\rangle$ and $\sigma(X_{\mathrm{max}})$ as a function of energy, presented in Fig. 1, agree well with our previous publications [1, 2, 4]. The observed rate of change of $\langle X_{\mathrm{max}}\rangle$ with energy is 77 ± 2 (stat) $\mathrm{g\,cm^{-2}}$/decade below $E_0 = 10^{18.32\pm0.03}$ eV and is 26 ± 2 (stat) $\mathrm{g\,cm^{-2}}$/decade at the higher energies. In simulations, the elongation rates for the constant primary compo-

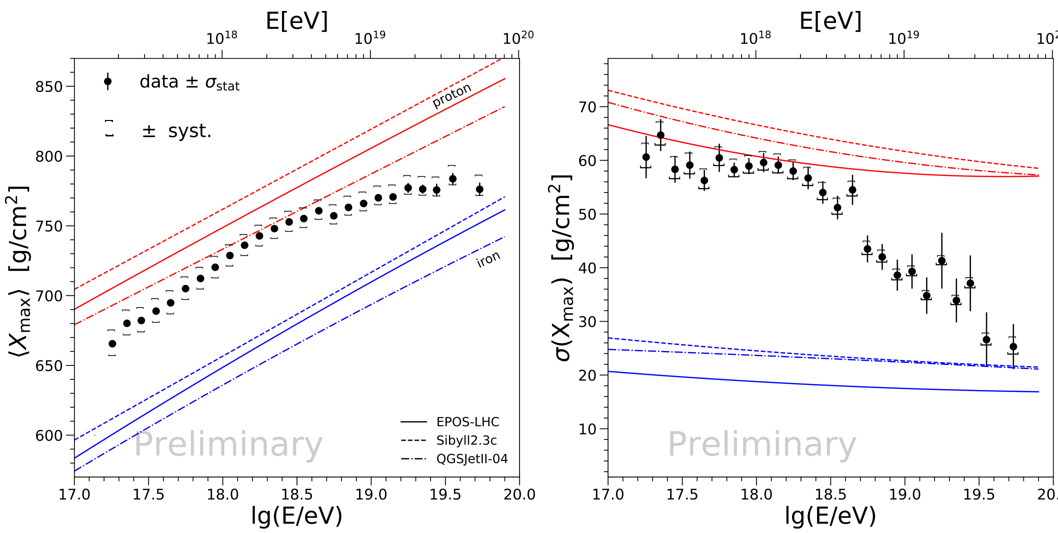

Figure 1: Measurements of $\langle X_{\rm max}\rangle$ (left) and $\sigma(X_{\rm max})$ (right) at the Pierre Auger Observatory compared to the predictions for proton and iron nuclei of the hadronic models EPOS-LHC, Sibyll 2.3c and QGSJetII-04.

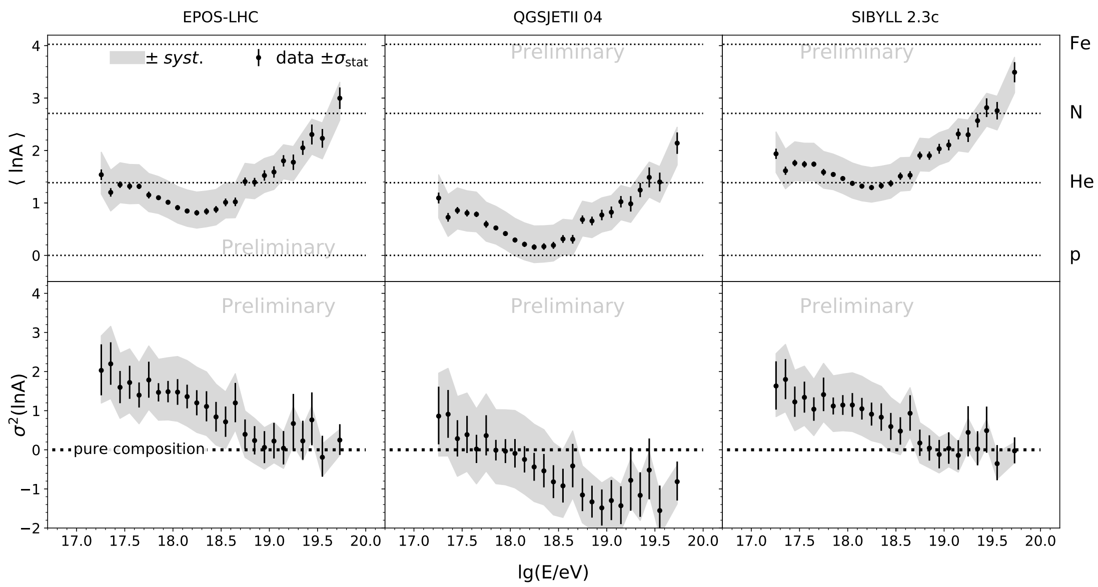

Figure 2: Moments of $\ln A$ distributions from the conversion of the moments of $X_{\rm max}$ distributions with EPOS-LHC, QGSJetII-04, Sibyll 2.3c.

sitions are close to ~ 60 g cm^{-2}/decade independently of the interaction model used. Thus the mean mass of the UHECRs as a function of energy decreases until E_0 and increases afterwards. The narrowing of the $X_{\rm max}$ distributions for energies above E_0 (right panel in Fig. 1) is as well in agreement with the MC predictions for $\sigma(X_{\rm max})$ of heavier nuclei.

Using the method described in [10] the moments of the $X_{\rm max}$ distributions can be converted to the moments of $\ln A$ distributions. From Fig. 2 one can see that $\langle \ln A\rangle$ reaches the minimum around E_0. Depending on the interaction model, the values at the minimum vary from ~ 0 for QGSJetII-

04 to 1.4 for Sibyll 2.3c. The spread of the masses is decreasing up to the energies around the ankle ($\sim 10^{18.7}$ eV) and becomes more constant afterwards. In case of QGSJetII-04, the variance of the masses takes non-physical negative values, indicating that using this model the compositions that are preferred are too light and, due to their larger shower-to-shower fluctuations, they do not describe the data well.

4. Correlation between depth of shower maximum and signal in WCDs

The spread of the masses in the primary beam can be estimated from the correlation between $X_{\rm max}$ and the signal in WCDs at 1000 meters from the core, $S(1000)$ [5, 11]. In this analysis, a general aspect of the development of air showers [12] is used: a smaller $X_{\rm max}$ ($\Delta X_{\rm max} \sim -\Delta \ln A$) and larger muon content[1] ($N_\mu \sim A^{1-\beta}$, $\beta \simeq 0.9$ [13]) are expected in showers initiated by heavier primary nuclei. While for pure compositions non-negative correlations are found in simulations using CORSIKA [14] and post-LHC hadronic models, in mixed samples smaller values of $X_{\rm max}$ will be more often found for showers initiated by heavier nuclei with larger N_μ. In this way, an anticorrelation between $X_{\rm max}$ and N_μ is expected for mixed compositions. The larger the spread of the masses in the primary beam, the more negative is the correlation. Due to the use of general principles of the development of air showers, the correlation analysis is rather insensitive to the particular details in the modeling of hadronic interactions.

To avoid a decorrelation due to the spreads of energies and zenith angles, we use $X_{\rm max}$ and $S(1000)$ scaled to a reference energy of 10 EeV. $S(1000)$ is additionally scaled to a zenith angle of 38°. The scaled variables are denoted further as $X^*_{\rm max}$ and S^*_{38} and thus they are the values of $X_{\rm max}$ and $S(1000)$ one would have observed, had the shower arrived at 38° and 10 EeV. The correlation between $X^*_{\rm max}$ and S^*_{38} is evaluated using a ranking correlation coefficient $r_{\rm G}$ proposed in [15]. The conclusions do not change when other correlation coefficients are used. In Fig. 3 examples of distributions of $X^*_{\rm max}$ and S^*_{38} are shown for proton and iron showers generated with EPOS-LHC.

The statistical uncertainty can be approximated [5] by $\Delta r_{\rm G} \simeq 0.9/\sqrt{n}$, where $n = 2652$ is the number of events in the data set and thus $\Delta r_{\rm G}(\text{data}) = 0.017$. The systematic uncertainty is $\Delta r_{\rm G}(\text{sys.}) = ^{+0.01}_{-0.02}$, the negative error is larger due to a small decorrelation (we do not apply any corrections for this effect) in the data sample introduced by long term performances of Auger FD and SD.

As shown in Fig. 3, the correlation found in data is $r_{\rm G} = -0.069 \pm 0.017$, while in [5] the value of $r_{\rm G} = -0.125 \pm 0.024$ was reported. We could not individuate any detector effects that could lead to such a change and thus we conclude that it is a result of changes in reconstruction and a statistical fluctuation as will also be discussed below. The main conclusions of [5] remain unchanged: the negative correlation found in data cannot be reproduced using any pure composition. Since the correlation is found to be non-negative for all proton-helium mixes, the data can be explained only by mixed compositions containing primary nuclei heavier than helium $A > 4$. Both these conclusions substantiate our findings from the analysis of $X_{\rm max}$.

The spread of the primary masses $\sigma(\ln A)$ can be estimated from Fig. 4 where the correlation found in data is compared to the values in simulated mixtures with all possible combinations of

[1] The muon contribution to $S(1000)$ is 40% to 90% depending on zenith angle.

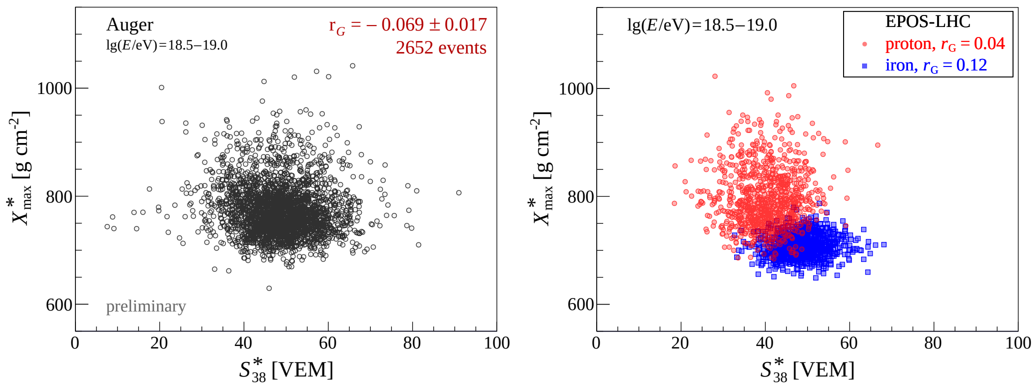

Figure 3: Distribution of $X^*_{\rm max}$ and S^*_{38} for $\lg(E/{\rm eV}) = 18.5 - 19.0$ in data (left) and for 1000 proton and 1000 iron showers simulated with EPOS-LHC (right).

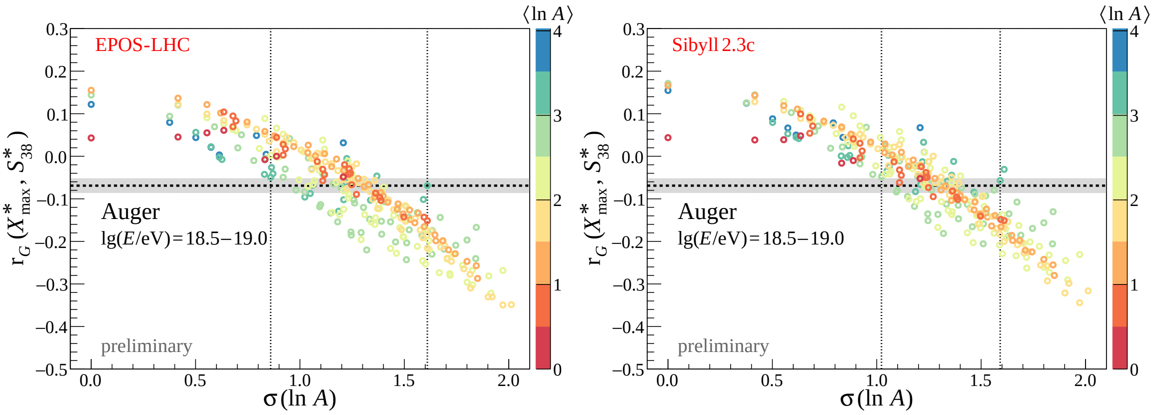

Figure 4: Dependence of the correlation coefficients $r_{\rm G}$ on $\sigma(\ln A)$ for EPOS-LHC (left) and Sibyll 2.3c (right). Each simulated point corresponds to a mixture with different fractions of (p, He, O, Fe) nuclei, the relative fractions change in 0.1 steps (four points for pure compositions are grouped at $\sigma(\ln A) = 0$). Colors of the points indicate $\langle \ln A \rangle$ of the corresponding simulated mixture. The shaded area shows the observed value for the data. Vertical dotted lines indicate the range of $\sigma(\ln A)$ in simulations compatible with the observed correlation in the data.

relative fractions of (p, He, O, Fe) nuclei changing with a step of 0.1. The correlation $r_{\rm G}(X^*_{\rm max}, S^*_{38})$ gets more negative for the larger spreads of the masses in the mixes. For all models (for QGSJetII-04, not shown in the figure, the results are similar to Sibyll 2.3c) the spread of masses corresponding to the correlation found in data lies in the range compatible to [5]: $0.85 \lesssim \sigma(\ln A) \lesssim 1.6$.

The comparison of the energy dependence of $r_{\rm G}$ in data to the predictions for proton, iron and extreme mix $\text{p/Fe} = 1/1$ for EPOS-LHC and Sibyll 2.3c interaction models (for QGSJetII-04, not shown here, $r_{\rm G}$ (proton) is > 0.1 for all energies) is shown in Fig. 5. Compared to [5] an additional energy bin $\lg(E/{\rm eV}) = 19.0 - 19.5$ has been added.

Combining data in the range $\lg(E/{\rm eV}) = 18.5 - 18.7$ the observed correlation is $r_{\rm G} = -0.141 \pm 0.022$, which significantly ($6.4\sigma$) differs from zero. For higher energies, the correlation in data becomes consistent with the compositions with smaller mixings. Comparing new data in Fig. 5 to the results of [5] one can see that the change of the correlation in the whole energy range $\lg(E/{\rm eV}) =$

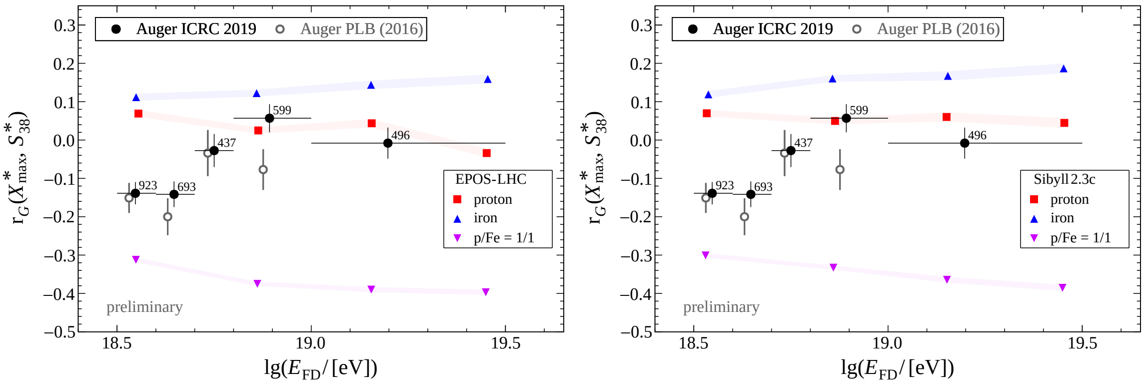

Figure 5: The correlation coefficients r_G for data (full circles) in the energy bins $\lg(E/\mathrm{eV}) = 18.5 - 18.6$; $18.6 - 18.7$; $18.7 - 18.8$; $18.8 - 19.0$; $19.0 - 19.5$. Numbers of events in each bin are given next to the data points. For comparison, results from our previous publication [5] are shown with open circles (points are slightly shifted along x-axis to improve visibility). The data sets are statistically compatible with $\chi^2/\mathrm{ndf} = 5.4/4$ (p-value $= 0.25$). Predictions for proton, iron and extreme mix p/Fe $= 1/1$ are given for EPOS-LHC (left) and Sibyll 2.3c (right), the widths of the colored bands for the MC results correspond to statistical errors.

$18.5 - 19.0$ from -0.125 to -0.069 is mostly caused by the change of r_G for $\lg(E/\mathrm{eV}) = 18.8 - 19.0$ to more positive values. The more negative r_G in [5] for 287 events available then, could result from a statistical fluctuation. With more statistics in the current data set, the results are compatible to a decrease of $\sigma(\ln A)$ above the ankle, as also suggested by the decrease of $\sigma(\ln A)$ in the X_{max} analysis.

5. Summary

In this proceedings, earlier findings of Auger about the evolution of the UHECR composition for $E > 10^{17.2}$ eV have been confirmed with higher significance. The conclusions listed below hold true for all pre- and post-LHC hadronic interaction models, and in the case of the analysis of the correlation between X^*_{max} and S^*_{38} the results, in addition, are robust to modifications of various parameters of nuclear interactions [5].

From the analysis of X_{max}, it follows that the mean mass of the UHECR is getting lighter up to $10^{18.3}$ eV and is becoming heavier afterwards. The spread of the masses $\sigma(\ln A)$ is becoming smaller up to the ankle ($E \sim 10^{18.7}$ eV) and more constant at higher energies. The spread of the masses near the ankle, determined from the analysis of the (X^*_{max}, S^*_{38}) correlation, is compatible with $0.85 \lesssim \sigma(\ln A) \lesssim 1.6$. For energies below the ankle ($10^{18.5} - 10^{18.7}$ eV) a significantly negative correlation $r_G = -0.141 \pm 0.022$ is observed in the data, that allows us to exclude pure compositions and proton-helium mixes all of which have non-negative correlations.

The conclusions on the increase of the primary mass for $E > 10^{18.3}$ eV, obtained here using hybrid events, are supported by the analysis of the Auger SD data [16]. In the extension of the SD analysis presented at this conference, due to the higher duty cycle of the SD the evolution of the UHECR mass is probed for the energies well beyond 10^{19} eV [17].

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