PROCEEDINGS OF SCIENCE

Testing the agreement between the $X_{\max}$ distributions measured by the Pierre Auger and Telescope Array Observatories

Vitor de Souza[*a] **for the Pierre Auger Collaboration**[b] **and the Telescope Array Collaboration**[c]

[a] *Instituto de Física de São Carlos, Universidade de São Paulo, São Paulo, Brazil*
[b] *Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina*
E-mail: auger_spokespersons@fnal.gov
Full author list: http://www.auger.org/archive/authors_icrc_2017.html
[c] *Telescope Array Project, 201 James Fletcher Bldg, 115 S. 1400 East, Salt Lake City, UT 84112-0830, USA*
E-mail: ta-icrc@cosmic.utah.edu
Full author list: http://www.telescopearray.org/research/colaborators

The Auger-TA composition working group reports on a comparison of $X_{\max}$ distributions measured by the Pierre Auger and Telescope Array Observatories. The shapes of the $X_{\max}$ distributions measured by the Auger and TA Observatories are evaluated and a quantitative compatibility test is presented. A direct comparison of the measured $X_{\max}$ distributions is not correct due to different detector acceptances and resolutions as well as different analysis techniques. In this contribution, a method developed to allow a correct comparison of the $X_{\max}$ distributions is explained and used. A set of showers compatible to the composition measured by the Auger detectors was simulated and reconstructed using the official TA software chain. This procedure simulates an energy-dependent composition mixture, which represents a good fit to Auger $X_{\max}$ distributions, exposed through the detector acceptance, resolution and analysis procedure of the TA experiment. Two compatibility tests are applied to the $X_{\max}$ distributions: Kolmogorov-Smirnov and Anderson-Darling. Both tests shows that TA data is within the systematic uncertainties compatible to a mixed composition such as the one measured by the Auger detectors.

35th International Cosmic Ray Conference — ICRC2017
10–20 July, 2017
Bexco, Busan, Korea

*Speaker.

PoS(ICRC2017)522

1. Introduction

The mass composition is a crucial ingredient in our understanding of Ultra-High Energy Cosmic-Rays (UHECR) origin and production mechanism.The complete UHECR puzzle can only be solved on the basis of a reliable composition measurement. The depth at which air-showers reach their maximum energy deposit (X_{max}) correlates with the primary particle mass [1]. The fluorescence measurement technique was developed to measure X_{max} with good resolution [2] and extract the mass composition from a sample of showers. The construction of the next generation of fluorescence telescopes [3, 4] and new analysis procedures brought the technique to a high standard level. Today X_{max} can be measured with a resolution better than 25 g/cm^2 by Auger and TA Observatories.

The work presented here is a comparison of the X_{max} distributions measured by the Auger and TA Observatories in the energy range from $10^{18.2}$ to 10^{19} eV. The energy range of this study is limited to $E < 10^{19}$ eV due to the lack of events in TA's data above this energy. The TA collaboration wishes to understand better what is the potential effect of under-sampling bias in energy bins with small statistics.

A direct comparison of the X_{max} distributions and its moments as published by both collaborations is wrong because of the different detector resolutions, acceptance and analysis procedures. The acceptance and biases of fluorescence telescopes depend on X_{max} and therefore the raw distribution of measured shower maxima is always biased by detector effects. Each collaboration (Auger and TA) chose a different analysis procedure to deal with the particularities of the fluorescence technique. Therefore no conclusion about possible discrepancies between Auger and TA composition measurements is possible when a comparison is based directly on the published results of both collaborations.

In the next sections, a procedure to pass the composition which best fits the Auger X_{max} measurements[1] through the official TA simulation, reconstruction and analysis chain is described. This method imposes the TA resolution, acceptance and biases onto the AUGERMIX. This is the only way to compared the X_{max} results of both collaborations and therefore to make conclusions about possible discrepancies. This method was already applied to the the first moment of the distribution ($\langle X_{max} \rangle$) and presented at the ICRC2015 [7] and UHECR2016 [8] conferences. The comparison showed that the mean of the distributions measured by the Auger and TA collaborations are in agreement within the systematic uncertainties. No discrepancy is seen in the mean of the X_{max} distributions when the proper comparison is done.

In this contribution, the same method is applied to the entire X_{max} distribution. The argument and the conclusion of previous studies based on the moments of distribution is valid for a detailed analysis of the full distribution. A quantitative comparison of the X_{max} distributions is done after the simulation of the AUGERMIX composition thought the TA detectors and analysis chain. No discrepancy is found between the TA data and AUGERMIX composition. In other words, within the systematic uncertainties, the TA data is compatible to the composition measured by the Auger detectors. The details of the analysis are shown in the next sections.

[1] The composition which best fits the Auger X_{max} distributions is named AUGERMIX from now on.

2. Main differences of the analysis procedures used by the Pierre Auger and TA Collaborations

The analysis strategies used by the collaborations are different from the start. The Pierre Auger Collaboration elaborated an analysis procedure aimed on minimizing detection and reconstruction bias such as to publish the moments of the X_{max} distributions as close as possible to the true values [5]. The TA collaboration elaborated an analysis procedure using minimal cuts. This maximizes available statistics, and the published data has detection and reconstruction biases. These are dealt with by carefully simulating the detector in MC and comparing the biased data to similarly biased MC simulations [6].

Figure 1 illustrates the effect of the differences in analysis and detectors in the X_{max} distribution measured by the two experiments. The black line in the figure represents a fit of a X_{max} distribution for proton shower simulated with Conex [9] and QGSJetII-04 [10] hadronic interaction model. This sample of simulated showers was passed through the Auger and TA detector simulation and analysis chains. The green distribution represent the X_{max} distribution that would be published by the TA collaboration if this pure proton composition impinged the detector. The orange distribution represents the X_{max} distribution that would be published by the Auger collaboration if this pure proton composition impinged the detector. These two distributions are clearly different due to differences in the analysis strategies. This example illustrates why a direct comparison of the published X_{max} distributions and their moments is not possible. The number of events in the orange (green) distribution is 814 (311) according to the number of events published by each collaboration in this energy range. The first and second moments of the Simulation, Auger and TA distributions are 766.6, 764.6, 760.9 and 63.3, 60.9, 58.4 g/cm^2, respectively.

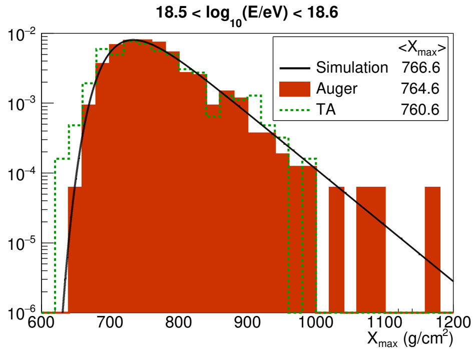

Figure 1: Illustration of Auger and TA analysis strategies. Black line corresponds to proton simulation (Conex [9] and QGSJetII-04 [10]). Green distribution represents these simulated showers as reconstructed by the TA. The orange distribution represents this simulated showers as reconstructed by he Auger.

The Auger Collaboration publishes X_{max} values (X_{max}^{Auger}) different from values published by the TA Collaboration X_{max}^{TA} due to particular treatment of biases and detector efficiency. A proper comparison of the published data is only possible if detector simulation is used to convert X_{max}^{Auger} to X_{max}^{TA}. In the next section, a method to convert X_{max}^{Auger} as measured by Auger to ${}_{Auger}X_{max}^{TA}$ as measured by TA is explained[2]. Only after a proper conversion of the quantities, is it possible to draw conclusions about the compatibility of the two data sets.

3. Method to compare X_{max} measurements done by the Pierre Auger and TA Observatories

Ultimately it would be desirable to have the Auger and TA detectors running side-by-side for a certain period of time measuring the same air showers. This would lead to the best cross-

[2] ${}_{Auger}X_{max}^{TA}$: AUGERMIX simulated through TA telescopes and analysis chain.

calibration of the detectors and an event-by-event comparison of the reconstructed values. Since this is not possible, simulations were done to mimic TA detection of events with an Auger-like mass composition.

The procedure starts by using the model developed to describe the $X_{\max}^{\text{Auger}}$ data as published in reference [11]. In this study, the $X_{\max}^{\text{Auger}}$ distributions were fit using simulated air showers from different primary nuclei. The study varied the flux of four primary particles and calculated the mix of elements which best describes the $X_{\max}^{\text{Auger}}$ distributions. Figure 2 shows the fraction of each primary that best describes Auger data when the QGSJETII-04 hadronic interaction model is used. The composition which best describes Auger data in the energy range from $10^{18.2}$ to $10^{19.0}$ eV is a mix of Proton, Helium and Nitrogen nuclei which is named as AUGERMIX. In this paper, the fit of the Auger data done with QGSJetII-04 is used for illustration. The same calculations were repeated with the EPOS-LHC [12] hadronic interaction model and the same conclusion on the compatibility of the TA and Auger $X_{\max}$ distributions was reached.

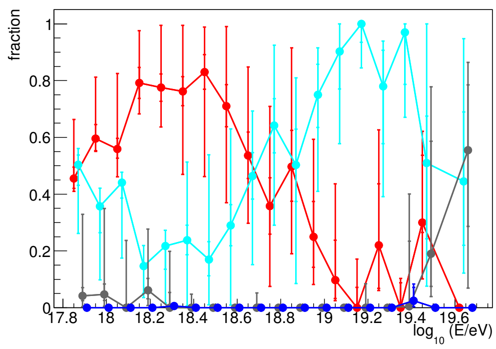

Figure 2: Fraction of primary nuclei which best describes $X_{\max}$ distributions measured by Auger when fitted with QGSJetII-04. Red, cyan, gray and blue corresponds to Pr, He, N and Fe nuclei, respectively. Statistical (smaller) and systematic (larger) uncertainties are shown. Points were shifted in x-axis for clarity. Only $18.2 < \log_{10}(E/\text{eV}) < 19.0$ is used in this paper.

The AUGERMIX is simulated thought the TA detectors using the official simulation package of the TA Collaboration. The simulated events are analyzed using the same procedure applied for the data measured by the TA telescopes. The result of this exercise is the transformation of the AUGERMIX into ${}_{\text{Auger}}X_{\max}^{\text{TA}}$. Figure 3 shows the distributions of ${}_{\text{TA}}X_{\max}^{\text{TA}}$ ($X_{\max}$ distributions as published by TA including detector resolution and acceptance) and ${}_{\text{Auger}}X_{\max}^{\text{TA}}$ ($X_{\max}$ distributions that would be published by TA if a mix composition of showers equivalent to the one measured by the Auger detectors (AUGERMIX) impinged the TA detectors).

4. Comparison of $X_{\max}$ distributions

The distributions in figure 3 can now be compared directly because they both include the biases and efficiency of the TA detectors. Two tests of compatibility of distributions were used: Kolmogorov-Smirnov and Anderson-Darling (see e.g. [13]). The Kolmogorov-Smirnov (KS) test is one of the most used compatibility procedures used in the literature with a response enhanced near the peak of the distribution. The Anderson-Darling (AD) test is optimized to probe differences in the tails of the distributions. Both tests calculate the probability (P1) that two distributions were generated by the same parent distribution. The probability calculated that ${}_{\text{TA}}X_{\max}^{\text{TA}}$ and ${}_{\text{Auger}}X_{\max}^{\text{TA}}$ are generated from the same parent distribution is named P1^{data}.

In order to normalize these probabilities and extract a measure of compatibility, a distribution of compatible P1 was generated by the following procedure. The ${}_{\text{Auger}}X_{\max}^{\text{TA}}$ distributions were fitted by a Gaussian convoluted with a exponential function [14]. One hundred thousand distributions

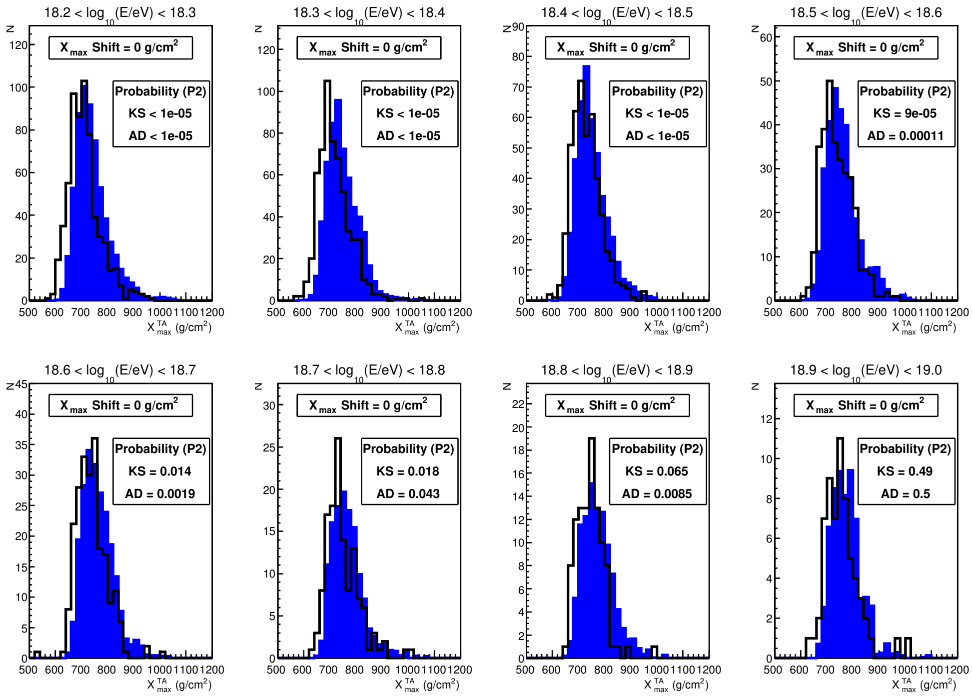

Figure 3: $X_{\max}$ ^{TA} distributions. Black is TA data and blue hatched is AUGERMIX simulated thought the TA detector and reconstruction chain (${}_{\rm Auger}X_{\rm max}^{\rm TA}$). For each energy bin the value of P1 and P2 are shown as defined in section 4.

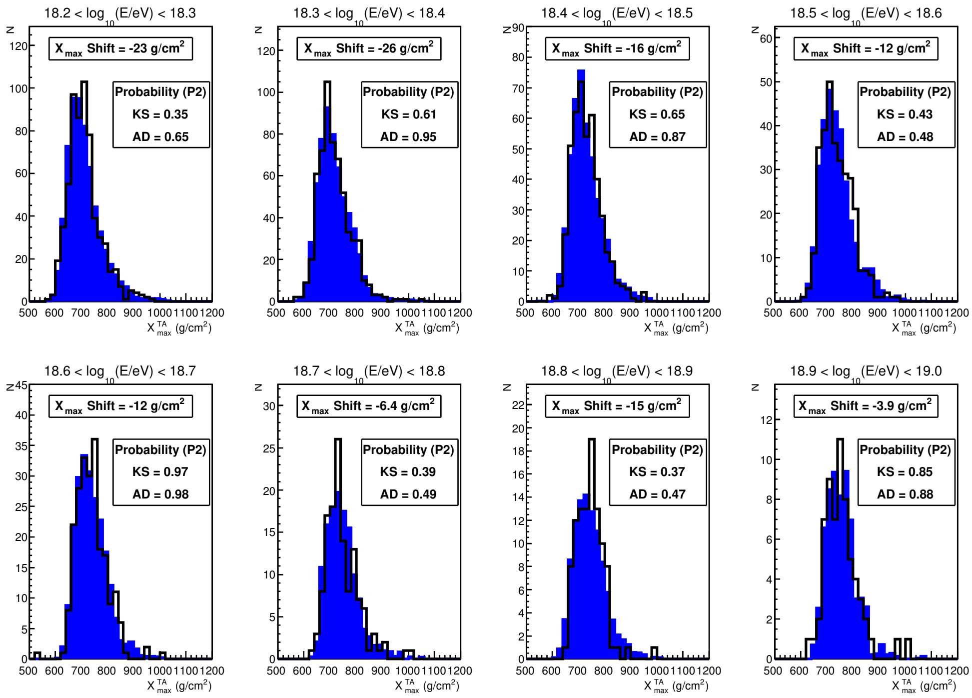

Figure 4: $X_{\max}$ ^{TA} distributions. Black is TA data and blue hatched is AUGERMIX simulated thought the TA detector and reconstruction chain (${}_{\rm Auger}X_{\rm max}^{\rm TA}$). For each energy bin the value of P1 and P2 are shown as defined in section 4. The shift in $X_{\max}$ ($\langle {}_{\rm TA}X_{\rm max}^{\rm TA}\rangle - \langle {}_{\rm Auger}X_{\rm max}^{\rm TA}\rangle$) done to match the distributions mean is also shown.

of ${}_{\rm Auger}X_{\max}^{\rm TA}$ were randomly generated from the fitted function using standard Monte Carlo (MC) techniques. Each MC ${}_{\rm Auger}X_{\max}^{\rm TA}$ distribution had the same number of events as ${}_{\rm TA}X_{\max}^{\rm TA}$ distributions, i.e. the number of events measured by TA detectors. The P1 probability that the original ${}_{\rm Auger}X_{\max}^{\rm TA}$ distribution and each MC ${}_{\rm Auger}X_{\max}^{\rm TA}$ distribution was calculated ($\mathrm{P1}^{MC}$). Figure 5 shows an example of the $\mathrm{P1}^{MC}$ distribution. Given that MC ${}_{\rm Auger}X_{\max}^{\rm TA}$ distributions were generated from the original ${}_{\rm Auger}X_{\max}^{\rm TA}$ distribution, figure 5 shows the distribution of P1 for compatible distributions.

Finally, the compatibility probability (P2) between ${}_{\rm TA}X_{\max}^{\rm TA}$ and ${}_{\rm Auger}X_{\max}^{\rm TA}$ is given by the probability to find $\mathrm{P1}^{MC}$ larger than $\mathrm{P1}^{data}$. In other words, P2 measures the probability to find in a random set of distributions generated from ${}_{\rm Auger}X_{\max}^{\rm TA}$, a distribution as compatible as ${}_{\rm TA}X_{\max}^{\rm TA}$ and ${}_{\rm Auger}X_{\max}^{\rm TA}$. Typically values of P2 larger than 0.01 express large probability of compatibility between the distributions. Table 1 (column "No $X_{\max}$ shift") shows the P2 values as a function of energies corresponding to the distributions in figure 3. The values of P2 in the studied energy shows a general incompatibility of the distributions for energies below $10^{18.6}$ eV, a marginal compatibility for $18.6 < \log_{10}(\mathrm{E/eV}) \leq 18.9$ and a good agreement in the last energy bin $18.9 < \log_{10}(\mathrm{E/eV}) \leq 19.0$ eV ($P2_{KS} = 0.49$ and $P2_{AD} = 0.5$).

If the distributions are allowed to be shifted by the systematic uncertainties quoted by the Auger and TA collaborations the agreement gets evidently better. Figure 4 show the distributions shifted to have the same mean. Table 1 (column "$X_{\max}$ shift") shows the results of the compatibility analysis. ${}_{\rm Auger}X_{\max}^{\rm TA}$ distributions were shifted by the values shown in the figure to match the mean of ${}_{\rm TA}X_{\max}^{\rm TA}$ distributions. Figure 6 shows the comparison of the values by which ${}_{\rm Auger}X_{\max}^{\rm TA}$ distributions were shifted with the sum of the systematic uncertainties of both experiments. The Auger Collaboration quotes systematic uncertainties as a function energy [5] of about $\pm$ 8 g/cm^2 and the TA Collaboration quotes systematic uncertainties of $\pm$ 20.3 g/cm^2 [8].

Figure 7 shows the P2 values between ${}_{\rm TA}X_{\max}^{\rm TA}$ and ${}_{\rm Auger}X_{\max}^{\rm TA}$ distributions after the shift (TA <-> AUGERMIX). The values of P2 show a very good agreement between ${}_{\rm TA}X_{\max}^{\rm TA}$ and ${}_{\rm Auger}X_{\max}^{\rm TA}$ distributions. As a reference, the same comparison was data using instead of the AUGERMIX a pure proton composition (TA <-> Proton). The same level of agreement between the TA data and proton is seen between TA data and the AUGERMIX composition.

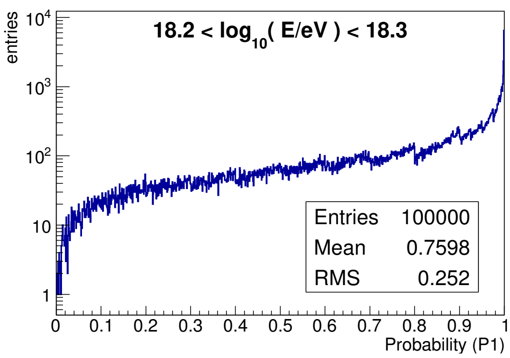

Figure 5: Example of a distribution of $\mathrm{P1}^{MC}$ for the Anderson-Darling test.

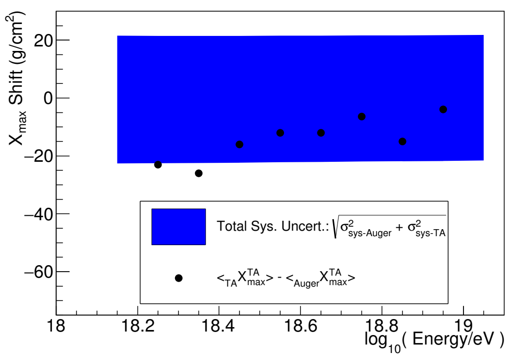

Figure 6: Comparison of the shift in $X_{\max}$ with the systematic uncertainty in $X_{\max}$.

Energy bin $\log_{10}$(E/eV)	Compatibility Probability (P2)							
	No $X_{\rm max}$ shift		$X_{\rm max}$ shift $\langle {}_{\rm TA}X^{\rm TA}_{\rm max}\rangle - \langle {}_{\rm Auger}X^{\rm TA}_{\rm max}\rangle$					
	KS	AD	TA $\leftrightarrow$ AUGERMIX			TA $\leftrightarrow$ Pr		
			Shift (g/cm^2)	KS	AD	Shift (g/cm^2)	KS	AD
18.2 - 18.3	$< 10^{-5}$	$< 10^{-5}$	-23	0.35	0.65	-31	0.14	0.21
18.3 - 18.4	$< 10^{-5}$	$< 10^{-5}$	-26	0.61	0.95	-33	0.99	0.99
18.4 - 18.5	$< 10^{-5}$	$< 10^{-5}$	-16	0.65	0.87	-22	0.57	0.62
18.5 - 18.6	9×10^{-5}	1.1×10^{-4}	-12	0.43	0.48	-21	0.41	0.53
18.6 - 18.7	0.014	0.0019	-12	0.97	0.98	-24	0.92	0.95
18.7 - 18.8	0.018	0.043	-6.4	0.39	0.49	-20	0.67	0.88
18.8 - 18.9	0.065	0.0085	-15	0.37	0.47	-31	0.55	0.26
18.9 - 19.0	0.49	0.5	-3.9	0.85	0.88	-20	0.98	0.98

Table 1: Compatibility probability between the ${}_{\rm TA}X^{\rm TA}_{\rm max}$ and ${}_{\rm Auger}X^{\rm TA}_{\rm max}$ and between ${}_{\rm TA}X^{\rm TA}_{\rm max}$ and pure proton distributions as defined by two methods: Kolmogorov-Smirnov (KS) and Anderson-Darling (AD). See section 4 for details about P2.

5. Conclusion

In this paper, a) Monte Carlo simulation of air-showers, b) simulation of the TA detectors and c) the TA reconstruction and analysis chain were used to produce the $X_{\rm max}$ distributions that would be published by the TA collaboration in case a mixed composition that describes the $X_{\rm max}$ distributions measured by the Auger detectors impinged the TA detectors. This method converts the $X_{\rm max}$ measurement done by Auger in the $X_{\rm max}$ measurements done by TA.

Throughout this paper, ${}_{\rm Auger}X^{\rm TA}_{\rm max}$ refers to $X_{\rm max}$ distributions which best describes the Auger data simulated and analyzed thought the TA detectors. ${}_{\rm TA}X^{\rm TA}_{\rm max}$ refers to the $X_{\rm max}$ distributions published by TA which includes the detector and analysis effects. The plots presented were done using the best description of the Auger data when analyzed with the QGSJetII-04 hadronic interaction. The complete study was repeated using the best description of the Auger data when analyzed with the EPOS-LHC hadronic interaction model. The conclusions presented below do not depend on the hadronic interaction model used to describe the Auger data.

A direct comparison of ${}_{\rm Auger}X^{\rm TA}_{\rm max}$ and ${}_{\rm TA}X^{\rm TA}_{\rm max}$ is the only way to quantify possible discrepancies between the two data sets measured the Auger and TA. Direct comparison of the results published by each collaboration independently is not possible. Interpretations of UHECR composition involving Auger and TA results should refer to the results presented here and in previous conferences [7, 8] as agreed by both collaborations.

Two quantitative compatibility tests were applied to ${}_{\rm Auger}X^{\rm TA}_{\rm max}$ and ${}_{\rm TA}X^{\rm TA}_{\rm max}$ distributions: Kolmogorov-Smirnov and Anderson-Darling. The methods are complementary because these focus on the peak (KS) or tails (AD) of the distributions respectively. The compatibility tests show very good agreement between ${}_{\rm Auger}X^{\rm TA}_{\rm max}$ and ${}_{\rm TA}X^{\rm TA}_{\rm max}$ distributions within the systematic uncertainties.

The conclusion of the study presented here is that the $X_{\rm max}$ data measured by TA is compatible to a mixed composition which best describes the Auger $X_{\rm max}$ data. No significant departure from

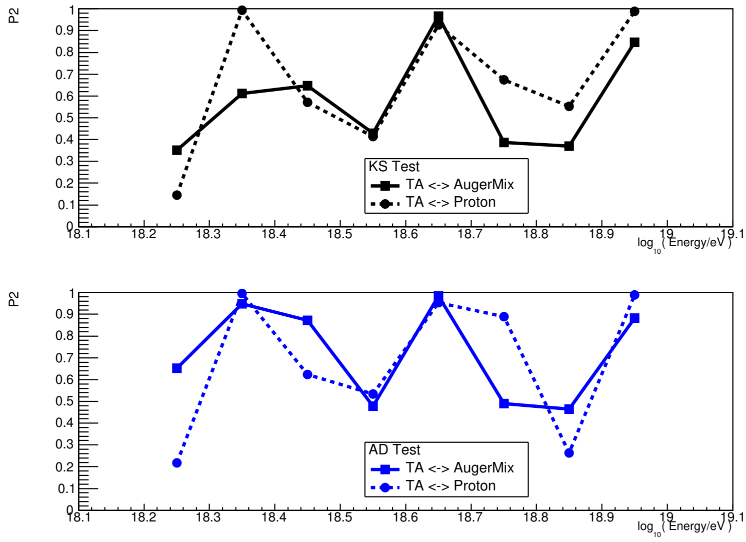

Figure 7: Compatibility probability between the ${}_{\rm TA}X_{\rm max}^{\rm TA}$ and ${}_{\rm Auger}X_{\rm max}^{\rm TA}$ distributions as defined by two methods: Kolmogorov-Smirnov (KS) and Anderson-Darling (AD). See section 4 for details about P2.

the hypothesis that both distributions were generated from the same parent distribution was found. At the current level of statistics and understanding of systematics, the TA data is consistent with the proton models used in this paper for energies less than 10^{19} eV and it is also consistent with the AUGERMIX composition as described above. More TA data is needed to confirm the trend to a heavier composition seen in Auger data above $\sim 10^{19}$ eV.

References

[1] J. Matthews, Astroparticle Physics, 22 (2005) 387.

[2] The High Resolution Fly's Eye Collaboration, The Astrophysical Journal, 622 (2005) 910.

[3] The Pierre Auger Collaboration, NIM A 620 (2010) 227-251.

[4] The Telescope Array Collaboration, NIM A, 676 (2012) 54.

[5] The Pierre Auger Collaboration, Physical Review D 90, 122005 (2014).

[6] The Telescope Array Collaboration, Astroparticle Physics 64 (2015) 49.

[7] M. Unger for the Pierre Auger and TA Collaborations, ICRC 2015, page 10, arXiv 1511.02103.

[8] W. Hanlon for the Pierre Auger and TA Collaborations, UHECR Conference 2016.

[9] T. Bergmann et al., Astroparticle Physics, 26 (2007) 420.

[10] S. Ostapchenko, Physical Review D, 83 (2011) 014018.

[11] The Pierre Auger Collaboration, Physical Review D 90, 122006 (2014).

[12] T. Pierog et al., Physical Review C, 92 2015, 034906.

[13] Frank Porter, arXiv 0804.0380.

[14] C.J.T. Peixoto et al., Astroparticle Physics 47 (2013) 18.