PROCEEDINGS OF SCIENCE

Depth of maximum of air-shower profiles: testing the compatibility of the measurements at the Pierre Auger Observatory and the Telescope Array

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The Pierre Auger Observatory (Auger) and the Telescope Array (TA), located, respectively, in the Southern and Northern hemispheres, are the largest ultra-high-energy cosmic ray (UHECR) observatories. The Auger and TA Collaborations have collected unprecedented statistics providing us with a unique opportunity to search for the differences between the UHECR energy spectra and mass compositions in the complementary sky regions. To correctly attribute such differences to the properties of the UHECR sources or propagation, the systematic effects in the measurements of each observatory should be considered properly. In this context, the task of the Auger – TA mass composition working group is to identify possible differences of astrophysical origin in the measurements of the depth of the maximum of air-shower profiles, X_{max}, performed at both observatories using the fluorescence technique. Due to distinct approaches to event selection and analysis at Auger and TA, the working group uses a specially designed method to transfer the Auger X_{max} distributions into the TA detector. To this end, dedicated air-shower and detector simulations for the TA Black Rock Mesa and Long Ridge fluorescence detector stations were performed with the Sibyll 2.3d hadronic interaction model. From the comparison of the first two moments and the shapes of X_{max} distributions for energies above $10^{18.2}$ eV, no significant differences between the Auger and TA measurements were found.

38th International Cosmic Ray Conference (ICRC2023)
26 July – 3 August, 2023
Nagoya, Japan

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1. Introduction

In this report, the mass composition working group presents the results of the comparison of the measurements of the depth of maximum of air-shower profiles, $X_{\max}$, performed at the Pierre Auger Observatory (Auger) [1] and the Telescope Array (TA) [2]. At both observatories, the measurements are performed using fluorescence detectors (FD) however due to different strategies to the event selection and corrections of the detector effect discussed below, the comparison of the $X_{\max}$ data sets is not direct and should be performed taking these differences into consideration.

In previous analyses of the working group, a good agreement between the Auger and TA data was found regarding the energy evolution of the two first central $X_{\max}$ moments and the compatibility of the $X_{\max}$ distributions, see [3, 4] for the most recent results. In this report we present an update of the analysis presented at the UHECR 2022 Symposium [4] with the improved testing of the compatibility of the $X_{\max}$ distributions.

2. Data sets

The Auger data set consists of events detected with the FD and having at least one triggered SD station required for an accurate shower geometry reconstruction. The reconstruction of the longitudinal air-shower profiles is performed using hourly measurements of aerosol optical depth profiles [1] that has a substantial impact on the accuracy of the determination of the FD energy and $X_{\max}$ compared to the usage of a static atmospheric model [5]. The events pass the selection criteria of the Auger $X_{\max}$ analysis [6] including a fiducial field-of-view selection ensuring an unbiased acceptance of the showers almost independently of their $X_{\max}$. The mean $\langle X_{\max}\rangle$ and the standard deviation $\sigma(X_{\max})$ of the measured $X_{\max}$ distributions are corrected for the residual acceptance

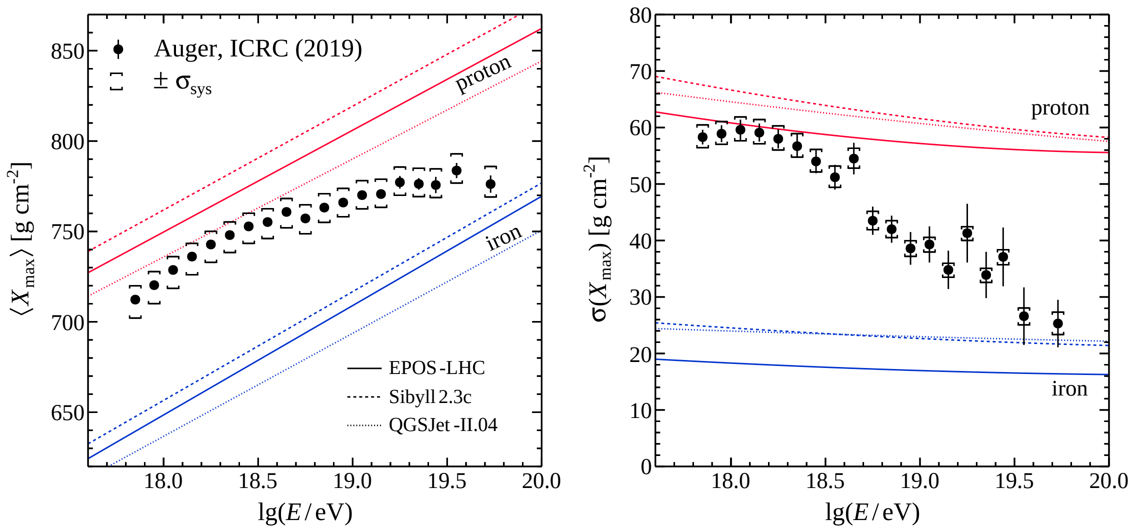

Figure 1: Measurements of $\langle X_{\max}\rangle$ and $\sigma(X_{\max})$ at Auger [7] presented at the ICRC (2019) compared to predictions for proton and iron nuclei of the hadronic interaction models EPOS-LHC, Sibyll 2.3c and QGSJet-II.04. Measured $X_{\max}$ moments are corrected for the experimental biases. The error bars denote the statistical uncertainties, the systematic uncertainties are shown with brackets.

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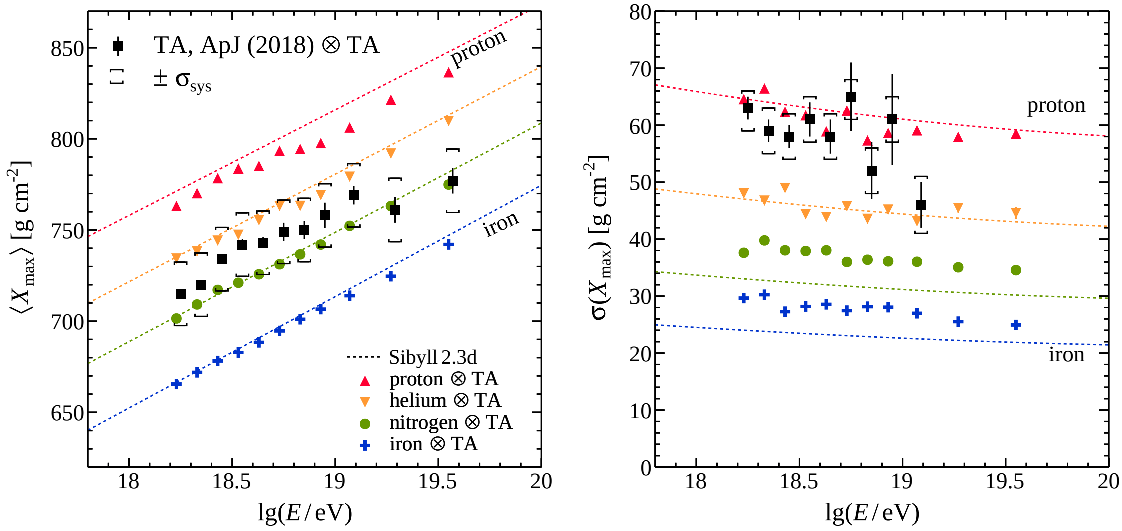

Figure 2: Measurements of $\langle X_{\max} \rangle$ and $\sigma(X_{\max})$ at TA [8] compared to predictions of the hadronic interaction model Sibyll 2.3d. Measured $X_{\max}$ moments and Sibyll 2.3d predictions shown with points contain experimental biases (⊗ TA), while predictions at the MC level are shown with lines.

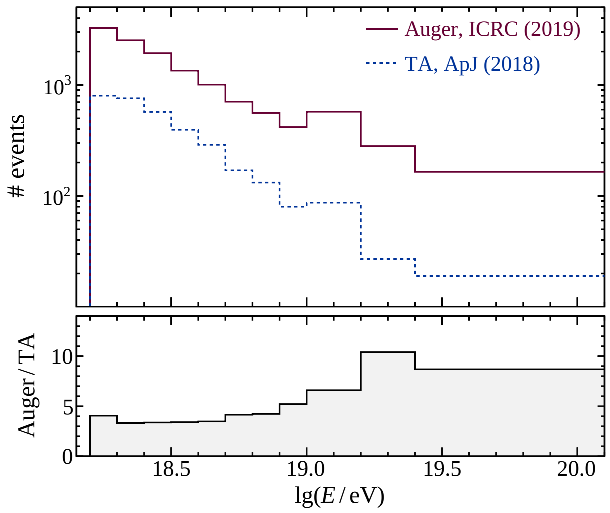

Figure 3: Number of events in Auger [7] and TA [8] data sets (top) and their ratio (bottom) in the common energy range $\lg(E/\text{eV}) > 18.2$. The energy binning is the same as used by TA [8]. Data are binned using the respective energy scales of each observatory.

biases and resolution effects and can be compared directly to the predictions from Monte Carlo air-shower simulation codes not including any detector effects (MC level). The energy evolution of the $X_{\max}$ moments measured at Auger in comparison with the predictions of EPOS-LHC [9], Sibyll 2.3c [10] and QGSJet-II.04 [11] hadronic models for protons and iron nuclei is presented in Fig. 1.

The TA data set contains events recorded with the fluorescence telescopes installed at the Black Rock Mesa and Long Ridge sites [8]. To be accepted, the events used in the $X_{\max}$ analysis

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should trigger the FD and three SD counters adjacent to each other. The complete details on the reconstruction and selection of the events can be found elsewhere [8]. Differently from the Auger analysis, to increase the event statistics, the fiducial field-of-view selection is not applied in the TA analysis, and $X_{\max}$ moments are not corrected for the reconstruction and acceptance biases. As a result, the TA data can be compared only to simulations processed through the TA analysis chain and including the analysis biases and the effects of the TA detector. In Fig. 2, the TA $X_{\max}$ measurements are presented along with predictions of the hadronic interaction model Sibyll 2.3d [12] at the MC level and in simulations including the TA experimental effects (⊗ TA). The experimental biases of a few g cm^{-2} on $\langle X_{\max}\rangle$ of protons and helium nuclei can be explained by a lower acceptance of the TA FD to deeper showers, while the effect of the detector resolution is visible in $\sigma(X_{\max})$ of nitrogen and iron nuclei.

The Auger data set used in this report was recorded during the period 12/2004 – 12/2017 [7] and consists of 12773 events in the energy range $\lg(E/\text{eV}) > 18.2$ common with the TA. The period of the TA data taking is 05/2008 – 11/2016, the data set contains 3330 events. The energy distributions of the events in both data sets together with the energy distribution of their relative sizes are shown in Fig. 3.

3. Comparison of $X_{\max}$ measurements

As explained in the previous section, the TA $X_{\max}$ measurements can be compared only to other measurements or simulations folded with the TA experimental effects. To transfer the Auger data to the TA detector, we use as a proxy simulated $X_{\max}$ distributions for the mass compositions with

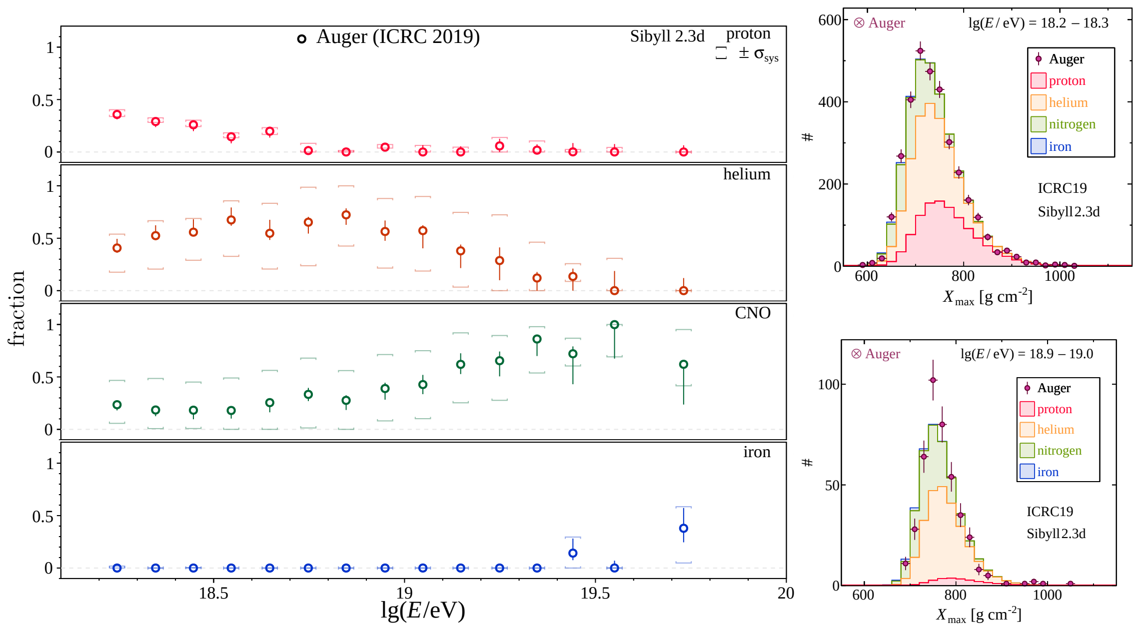

Figure 4: Left: energy evolution of nuclear fractions in AugerMixes obtained with Sibyll 2.3d. Statistical and systematic errors on fractions are shown with error bars and brackets correspondingly. Right: examples of $X_{\max}$ distributions measured at Auger compared to the simulated distributions for AugerMixes modified with the Auger detector acceptance and resolution (⊗ Auger).

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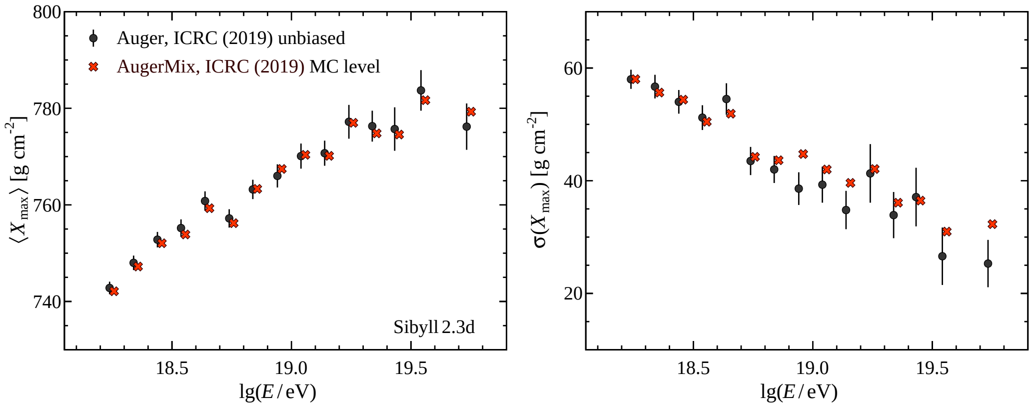

Figure 5: Comparison of $\langle X_{\rm max}\rangle$ and $\sigma(X_{\rm max})$ measured at Auger and for the AugerMix compositions obtained with Sibyll 2.3d.

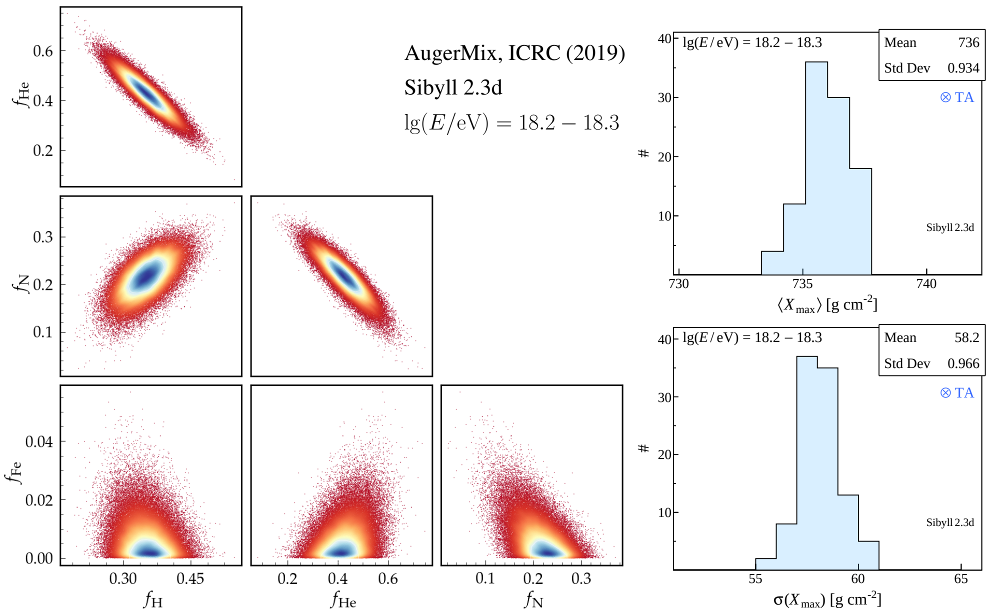

Figure 6: Left: posterior probability density distributions of nuclear fractions from the MCMC fit of the Auger $X_{\rm max}$ distribution in the energy bin $\lg(E/\rm eV) = 18.2 - 18.3$. Right: distributions of $\langle X_{\rm max}\rangle$ and $\sigma(X_{\rm max})$ in the TA detector for 100 AugerMixes with the fractions sampled from the posterior distributions shown in the left panel.

which the best description of the Auger $X_{\rm max}$ distributions in each energy bin is achieved. These mixes, referred to hereafter as AugerMixes, are then processed using the TA detector simulation, event reconstruction and analysis chain as described in [4]. The number of events in AugerMixes in each energy bin is the same as the respective number of events in the Auger data.

In this work, to fit the Auger $X_{\rm max}$ distributions [13], we use simulations with Sibyll 2.3d and the Markov Chain Monte Carlo (MCMC) method [14]. The advantage of the MCMC method is the possibility of sampling posterior probability distributions of the fit parameters (nuclear fractions) preserving this way complete information about their correlation. In Fig. 4 the energy evolution of

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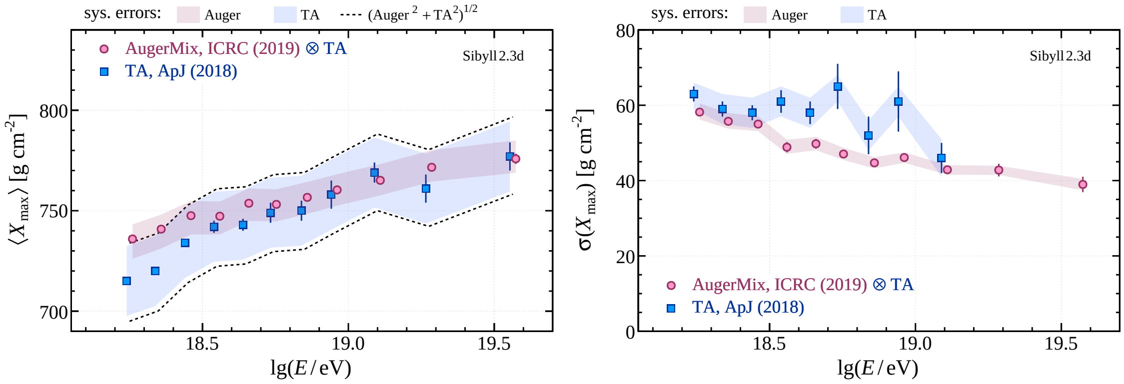

Figure 7: Comparison of $\langle X_{\rm max}\rangle$ and $\sigma(X_{\rm max})$ measured at TA and for the Auger data transferred into the TA detector (AugerMix). Statistical and systematic errors of each observatory are shown with error bars and shaded areas correspondingly. In the $\langle X_{\rm max}\rangle$ plot, Auger and TA systematic uncertainties combined in quadrature are shown with a dashed line.

the mass fractions in AugerMixes is presented along with the examples of the $X_{\rm max}$ distributions measured at Auger and the AugerMixes distributions in two energy bins. The shapes of the Auger and AugerMixes distributions agree well as a comparison of their $\langle X_{\rm max}\rangle$ and $\sigma(X_{\rm max})$ presented in Fig. 5 shows. Results for AugerMixes in Figs. 4, 5 are obtained using maximum a posteriori point estimates of nuclear fractions from the full posterior distributions, one example of which for $\lg(E/{\rm eV}) = 18.2-18.3$ is shown in Fig. 6. To exploit information from posterior distributions, we randomly sample from them 100 AugerMixes in each energy bin and process the mixes through the TA analysis chain obtaining this way 100 AugerMixes ⊗ TA. Standard deviations of $\langle X_{\rm max}\rangle$ and $\sigma(X_{\rm max})$ distributions for 100 mixes (see an example in Fig. 6) are then used as an estimation of statistical errors on $X_{\rm max}$ moments of AugerMixes ⊗ TA.

The comparison of the $X_{\rm max}$ moments for the TA data and AugerMixes is presented in Fig. 7. The TA $X_{\rm max}$ fluctuations are not shown at $\lg(E/{\rm eV}) > 19.2$ since for these energies $\sigma(X_{\rm max})$ can not be reliably estimated due to the relatively low TA event statistics. One can see that $\langle X_{\rm max}\rangle$ measurements of the two observatories agree within the statistical and systematic errors with shallower $\langle X_{\rm max}\rangle$ TA values at the low-energy end $\lg(E/{\rm eV}) < 18.5$. At the moment, we cannot identify the reasons for the observed energy-dependent behaviour of this discrepancy. The $X_{\rm max}$ fluctuations are generally in good agreement except for two energy bins ($\lg(E/{\rm eV}) = 18.7-18.8$, $18.9-19.0$) where TA $\sigma(X_{\rm max})$ have larger values. These larger fluctuations are due to the presence of very deep events in the TA data as can be seen in Fig. 8 where examples of $X_{\rm max}$ distributions for the TA data and AugerMixes are shown. In this figure to compare the shapes of the distribution we remove the mismatch between $\langle X_{\rm max}\rangle$ of the two data sets by shifting the TA distributions by the values indicated in each panel. Visually, the details of the TA and AugerMix distributions look very similar. For a quantitative characterization of their compatibility, we apply the Anderson-Darling (AD) statistical test in which each of 100 AugerMixes ⊗ TA is compared to the TA $X_{\rm max}$ distributions shifted to match $\langle X_{\rm max}\rangle$ of an individual mix. We perform the same tests also for the Auger data and AugerMixes folded with the Auger detector effects. The distributions of p-values for these tests in the energy bin $\lg(E/{\rm eV}) = 18.9-19.0$ are shown in Fig. 9. The

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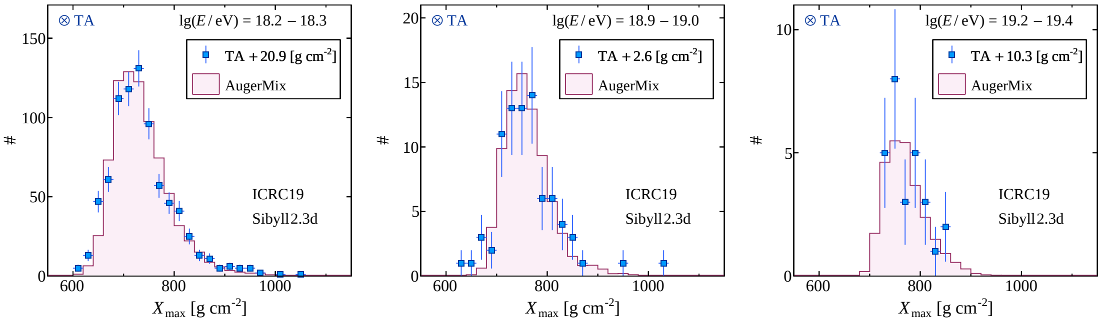

Figure 8: Comparison between X_{max} distributions measured at TA and distributions for AugerMixes (using fractions averaged over 100 samples). To compare shapes, TA distributions are shifted to match $\langle X_{\text{max}} \rangle$ of AugerMixes by the values indicated in legends.

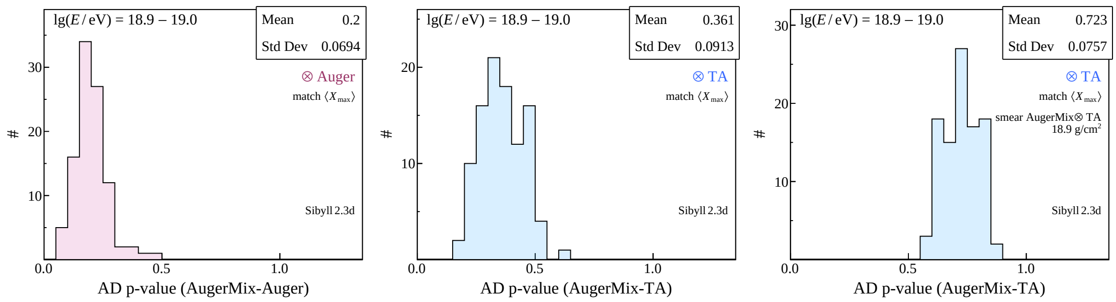

Figure 9: Examples of distributions of AD p-values for compatibility tests of 100 AugerMixes and data distributions. Left: test for the Auger data; center: test for the TA data; right: test for the TA data with AugerMixes smeared by 18.9 g cm^{-2}.

standard deviations of these distributions are used further for the estimation of the statistical errors on p-values. One can see that a good agreement between the TA and AugerMixes distribution shapes is observed in this energy bin despite the relatively large TA $\sigma(X_{\text{max}})$ value discussed above. In the panel on the right in Fig. 9, the distribution of the AD p-values is given for AugerMixes to which additional Gaussian smearing of the X_{max} values by 18.9 g cm^{-2} was applied. This is done to take into account the effect of using an average vertical aerosol optical depth in the TA X_{max} reconstruction. The reconstruction with the aerosols measured at TA with the interval of 30 minutes would result in a decrease of the measured $\sigma(X_{\text{max}})$ by 18.9 g cm^{-2} (in quadrature), this estimation is independent of the primary energy [8]. The same effect can contribute to the consistently larger TA $\sigma(X_{\text{max}})$ compared to AugerMix values shown in Fig. 7.

In Fig. 10 we show the AD p-values for AugerMixes ⊗ TA without and with the correction for the effect of using the average atmospheric aerosol content in the TA X_{max} reconstruction. A good agreement between the X_{max} distributions measured at TA and AugerMixes is observed at all energies. Due to lower statistics in the TA data set, the AD test is less sensitive in the comparison of AugerMixes to the TA data, therefore larger p-values than for the AugerMix-Auger comparison is an expected outcome.

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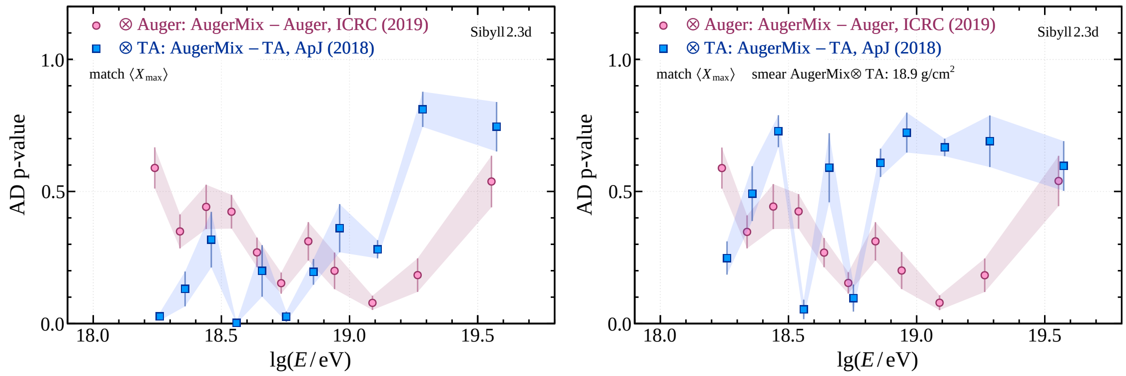

Figure 10: Energy evolution of AD p-values for AugerMix-TA and AugerMix-Auger tests. In the right panel additional Gaussian smearing of 18.9 g cm^{-2} is applied to AugerMixes ⊗ TA.

4. Discussion

In this report, we have presented a comparison of the X_{max} measurements performed at Auger and TA. No discrepancies beyond the statistical and systematic errors in $\langle X_{\mathrm{max}} \rangle$ and $\sigma(X_{\mathrm{max}})$ of the two observatories could be identified. In the comparison of X_{max} distributions performed using the AD test, a good agreement between the TA and Auger data was also found. Therefore, at the current statistics and understanding of the detector effects, the TA and Auger X_{max} measurements are found to be consistent with each other.

To finalize the analysis, we plan to perform the estimation of the systematic errors on the Auger data transferred into the TA detector and to take into consideration the difference between the Auger and TA energy scales [15].

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Acknowledgments

The successful installation, commissioning, and operation of the Pierre Auger Observatory would not have been possible without the strong commitment and effort from the technical and administrative staff in Malargüe. We are very grateful to the following agencies and organizations for financial support:

Argentina – Comisión Nacional de Energía Atómica; Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT); Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET); Gobierno de la Provincia de Mendoza; Municipalidad de Malargüe; NDM Holdings and Valle Las Leñas; in gratitude for their continuing cooperation over land access; Australia – the Australian Research Council; Belgium – Fonds de la Recherche Scientifique (FNRS); Research Foundation Flanders (FWO); Brazil – Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq); Financiadora de Estudos e Projetos (FINEP); Fundação de Amparo à Pesquisa do Estado de Rio de Janeiro (FAPERJ); São Paulo Research Foundation (FAPESP) Grants No. 2019/10151-2, No. 2010/07359-6 and No. 1999/05404-3; Ministério da Ciência, Tecnologia, Inovações e Comunicações (MCTIC); Czech Republic – Grant No. MSMT CR LTT18004, LM2015038, LM2018102, CZ.02.1.01/0.0/0.0/16_013/0001402, CZ.02.1.01/0.0/0.0/18_046/0016010 and CZ.02.1.01/0.0/0.0/17_049/0008422; France – Centre de Calcul IN2P3/CNRS; Centre National de la Recherche Scientifique (CNRS); Conseil Régional Ile-de-France; Département Physique Nucléaire et Corpusculaire (PNC-IN2P3/CNRS); Département Sciences de l'Univers (SDU-INSU/CNRS); Institut Lagrange de Paris (ILP) Grant No. LABEX ANR-10-LABX-63 within the Investissements d'Avenir Programme Grant No. ANR-11-IDEX-0004-02; Germany – Bundesministerium für Bildung und Forschung (BMBF); Deutsche Forschungsgemeinschaft (DFG); Finanzministerium Baden-Württemberg; Helmholtz Alliance for Astroparticle Physics (HAP); Helmholtz-Gemeinschaft Deutscher Forschungszentren (HGF); Ministerium für Kultur und Wissenschaft des Landes Nordrhein-Westfalen; Ministerium für Wissenschaft, Forschung und Kunst des Landes Baden-Württemberg; Italy – Istituto Nazionale di Fisica Nucleare (INFN); Istituto Nazionale di Astrofisica (INAF); Ministero dell'Università e della Ricerca (MUR); CETEMPS Center of Excellence; Ministero degli Affari Esteri (MAE), ICSC Centro Nazionale di Ricerca in High Performance Computing, Big Data

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and Quantum Computing, funded by European Union NextGenerationEU, reference code CN_00000013; México – Consejo Nacional de Ciencia y Tecnología (CONACYT) No. 167733; Universidad Nacional Autónoma de México (UNAM); PAPIIT DGAPA-UNAM; The Netherlands – Ministry of Education, Culture and Science; Netherlands Organisation for Scientific Research (NWO); Dutch national e-infrastructure with the support of SURF Cooperative; Poland – Ministry of Education and Science, grants No. DIR/WK/2018/11 and 2022/WK/12; National Science Centre, grants No. 2016/22/M/ST9/00198, 2016/23/B/ST9/01635, 2020/39/B/ST9/01398, and 2022/45/B/ST9/02163; Portugal – Portuguese national funds and FEDER funds within Programa Operacional Factores de Competitividade through Fundação para a Ciência e a Tecnologia (COMPETE); Romania – Ministry of Research, Innovation and Digitization, CNCS-UEFISCDI, contract no. 30N/2023 under Romanian National Core Program LAPLAS VII, grant no. PN 23 21 01 02 and project number PN-III-P1-1.1-TE-2021-0924/TE57/2022, within PNCDI III; Slovenia – Slovenian Research Agency, grants P1-0031, P1-0385, I0-0033, N1-0111; Spain – Ministerio de Economía, Industria y Competitividad (FPA2017-85114-P and PID2019-104676GB-C32), Xunta de Galicia (ED431C 2017/07), Junta de Andalucía (SOMM17/6104/UGR, P18-FR-4314) Feder Funds, RENATA Red Nacional Temática de Astropartículas (FPA2015-68783-REDT) and María de Maeztu Unit of Excellence (MDM-2016-0692); USA – Department of Energy, Contracts No. DE-AC02-07CH11359, No. DE-FR02-04ER41300, No. DE-FG02-99ER41107 and No. DE-SC0011689; National Science Foundation, Grant No. 0450696; The Grainger Foundation; Marie Curie-IRSES/EPLANET; European Particle Physics Latin American Network; and UNESCO.

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Acknowledgments

The Telescope Array experiment is supported by the Japan Society for the Promotion of Science(JSPS) through Grants-in-Aid for Priority Area 431, for Specially Promoted Research JP21000002, for Scientific Research (S) JP19104006, for Specially Promoted Research JP15H05693, for Scientific Research (S) JP19H05607, for Scientific Research (S) JP15H05741, for Science Research (A) JP18H03705, for Young Scientists (A) JPH26707011, and for Fostering Joint International Research (B) JP19KK0074, by the joint research program of the Institute for Cosmic Ray Research (ICRR), The University of Tokyo; by the Pioneering Program of RIKEN for the Evolution of Matter in the Universe (r-EMU); by the U.S. National Science Foundation awards PHY-1806797, PHY-2012934, PHY-2112904, PHY-2209583, and PHY-2209584 as well as AGS-1613260, AGS-1844306, and AGS-2112709; by the National Research Foundation of Korea (2017K1A4A3015188, 2020R1A2C1008230, & 2020R1A2C2102800); by the Ministry of Science and Higher Education of the Russian Federation under the contract 075-15-2020-778, IISN project No. 4.4501.18, by the Belgian Science Policy under IUAP VII/37 (ULB), by National Science Centre in Poland grant 2020/37/B/ST9/01821. This work was partially supported by the grants ofThe joint research program of the Institute for Space-Earth Environmental Research, Nagoya University and Inter-University Research Program of the Institute for Cosmic Ray Research of University of Tokyo. The foundations of Dr. Ezekiel R. and Edna Wattis Dumke, Willard L. Eccles, and George S. and Dolores Doré Eccles all helped with generous donations. The State of Utah supported the project through its Economic Development Board, and the University of Utah through the Office of the Vice President for Research. The experimental site became available through the cooperation of the Utah School and Institutional Trust Lands Administration (SITLA), U.S. Bureau of Land Management (BLM), and the U.S. Air Force. We appreciate the assistance of the State of Utah and Fillmore offices of the BLM in crafting the Plan of Development for the site. We thank Patrick A. Shea who assisted the collaboration with much valuable advice and provided support for the collaboration's efforts. The people and the officials of Millard County, Utah have been a source of steadfast and warm support for our work which we greatly appreciate. We are indebted to the Millard County Road Department for their efforts to maintain and clear the roads which get us to our sites. We gratefully acknowledge the contribution from the technical staffs of our home institutions. An allocation of computing resources from the Center for High Performance Computing at the University of Utah as well as the Academia Sinica Grid Computing Center (ASGC) is gratefully acknowledged.

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