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Report of the Working Group on the Mass Composition of Ultrahigh Energy Cosmic Rays

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We report on the progress in understanding the mass composition of cosmic rays at ultrahigh energies. Composition-related results on the shower maximum, $X_{\max}$, from the Pierre Auger Observatory (Auger) and the Telescope Array (TA) are compared. The different approaches to measure $X_{\max}$ by each experiment are explained, and a method to facilitate comparison of $X_{\max}$ measurements is presented. Auger has recently published fits of the mass composition to the $X_{\max}$ distributions using air shower simulations with different hadronic interaction models. In this work, we generate air showers according to these composition fits and pass them through the TA detector simulation. Then, the simulated events are reconstructed in the same manner as TA data is analyzed. This method provides an indirect way to compare the observed TA $X_{\max}$ distributions, which are biased by the detector acceptance and resolution, with the expected ones given the $X_{\max}$ distribution measured by Auger. The results of these comparisons are presented.

KEYWORDS: Pierre Auger Observatory, Telescope Array, UHECR, mass, composition, Xmax

1. Introduction

The Pierre Auger Observatory [1] and the Telescope Array [2,3] employ a similar experimental design to observe ultrahigh energy cosmic rays (UHECRs), but the two experiments use different approaches to analyze the measured depths of shower maximum ($X_{\max}$). Therefore, a direct comparison of the $X_{\max}$ measurements is not appropriate.

The interpretation of $X_{\max}$ measurements in terms of the cosmic-ray composition is model dependent. Details of hadronic models such as cross sections, multiplicities, inelasticities, etc., built into a particular model affect how simulated UHECR induced air showers are developing in the atmosphere. Observable features, such as $X_{\max}$, the depth of maximum shower size in terms of number of secondary particles produced, and the shower-to-shower fluctuations of these observables, are sensitive to details of hadronic interactions in air showers.

The Mass Composition Working Group of Auger and TA was formed at the UHECR 2012 conference [4] to resolve apparent differences in the observation (and interpretation) of X_{max} measurements in the common energy region observed by Auger in the Southern Hemisphere and the TA in the Northern Hemisphere. As a first result, the energy-evolution of the average shower maximum was compared and found to be compatible within uncertainties [5].

In this paper we present an update of this study and for the first time a comparison of the X_{max} distributions measured by the two experiments.

2. Analysis Methodologies

Both Auger and TA employ a hybrid analysis technique to provide the highest quality reconstruction required for accurate measurement of the X_{max} of air showers. This technique relies on the simultaneous measurement of the time-of-arrival of the shower front on the ground by surface detectors, and the observation of the air shower development in the air by fluorescence telescopes. Hybrid observations provide an excellent resolution in the geometry of air showers observed by a single fluorescence station, since the position provided by the surface detectors acts as a powerful constraint in the reconstruction of the core position. Once the geometry is well known, the location of X_{max} can be inferred accurately from the light profile measured with the fluorescence telescopes.

The Auger composition analysis aims to minimize the total bias in X_{max} (combined reconstruction and acceptance bias), by applying fiducial cuts on the field of view of the fluorescence detectors. For each shower geometry and energy, an effective field of view can be determined within which the probability to accept an event does not depend on X_{max}. Only events are selected, for which this field of view is large enough to allow a uniform sampling of the full X_{max} distribution. Due to this procedure the Auger data can be compared directly to simulated air showers without having to account for distortions caused by acceptance or reconstruction biases [6].

The TA composition analysis is done by producing a detailed simulation of the TA detector, throwing large sets of simulated events (at least ten times data statistics), and applying minimal cuts on geometry and shower profile. The same sets of cuts and same analysis procedures are applied to data as well, and data-Monte Carlo comparisons are performed to ensure the efficacy of the simulation. This approach may produce data at detector level that is biased with respect to the actual distribution, depending on the degree of acceptance variation, but the same amount of bias will also be present in the simulated MC showers.

Because of these different approaches, comparing Auger and TA data directly may be problematic if TA biases are significant.

3. Auger Composition Mixture Comparison

To test whether Auger and TA X_{max} measurements are in agreement, we developed a procedure to take into account the different analysis approaches. For this purpose we need a model of the X_{max} distribution that describes the Auger data, but does not include the detector resolution of the Auger fluorescence telescopes. Such a model could be e.g. a simple parametric fit, but we choose to use an energy-dependent mixture of four primary cosmic-ray components, (protons, helium, nitrogen and iron) obtained by interpreting the Auger data with three different hadronic models [7]. The corresponding relative composition fractions are shown in Figure 1. Out of the the three hadronic models studied, EPOS-LHC [8] describes the X_{max} distributions of Auger best, whereas the QGSJetII-04 [9] model can not perfectly describe the data with these four components.

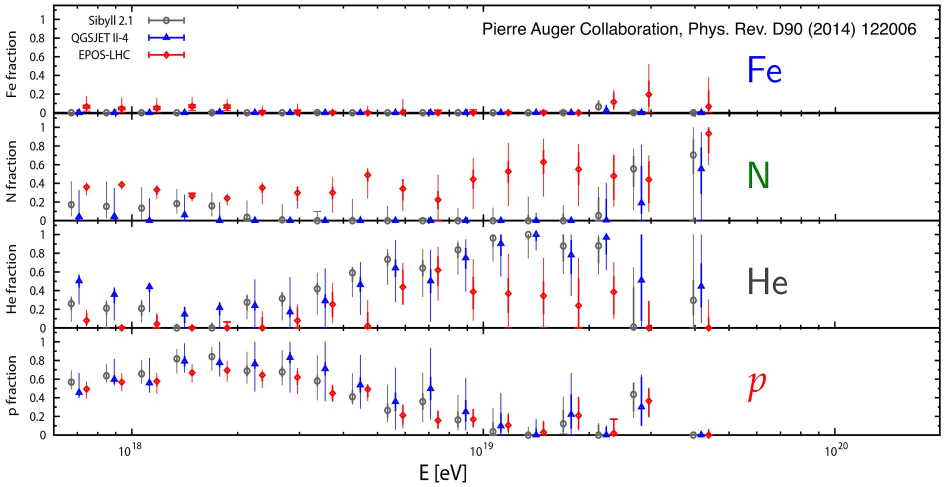

Fig. 1. Relative fractions of a four component composition model fitted to the X_{max} distributions measured by Auger [7]. Three models are shown, but only the fractions obtained with EPOS-LHC and QGSJetII-04 are tested against TA data in this paper.

To compare the agreement between Auger and TA X_{max}, the composition mix model which best fits Auger data is generated by TA using Monte Carlo simulation. Then the normal procedure of reconstructing the simulated events is performed, exposing this composition mixture to the same biases due to detector acceptance and resolution that affects TA data. TA data-Monte Carlo comparisons are examined to measure the level of agreement seen between the theoretical X_{max} distributions that are in known agreement with Auger data but are now biased to reflect TA acceptance, and the TA data which also has the same biases from the true unknown X_{max} distributions. If agreement is observed between TA data and the composition mix Monte Carlo, then there is agreement between the X_{max} distributions observed by Auger and TA up to systematic errors, regardless of the different approaches to measure these distributions.

For this work, the composition mixes obtained with EPOS-LHC and QGSJetII-04 were compared to TA data. EPOS-LHC was chosen because it provides the best agreement with Auger data. TA does not have a library of simulated showers generated with EPOS-LHC and the four primary species required for the mixture. Therefore a weighting procedure was applied to the library of simulated QGSJetII-04 showers to emulate the X_{max} distributions from EPOS-LHC.

Concerning the technical implementation of the re-weighting, we tested two variants of parametrized fits [10, 11] of the true X_{max} distributions of the four input species of the mix and validated them by comparing the resulting X_{max} distributions to the one from the TA shower library. An example is shown in Figure 2 and as can be seen, there is a good agreement between the parametrized and fully simulated distributions. Similar agreement was found for all energies relevant for this work.

Using the composition mix fractions for QGSJetII-04 shown in Figure 1, the TA shower library was then mixed by selecting corresponding fractions of pure proton, helium, nitrogen, and iron induced air showers. A second Monte Carlo set is also produced by weighting the QGSJetII-04 mixture to reproduce EPOS-LHC X_{max} distributions using the aforementioned characterizations. The mean and standard deviation of the X_{max} distributions of these

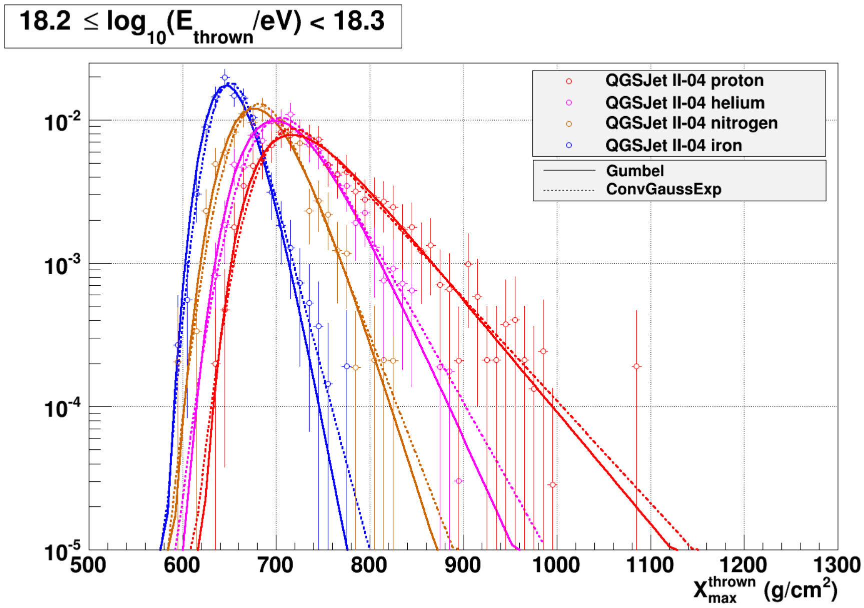

Fig. 2. Comparison of the $X_{\max}$ distribution of CORSIKA-generated showers (QGSJetII-04, $10^{18.2}$ eV $< E <$ $10^{18.3}$ eV) and parametrizations with a Gumbel function [11] and a Gaussian convoluted with an exponential function [10]

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Monte Carlo mixtures at generator level are shown in Figure 3, along with the $X_{\max}$-moments measured by Auger using the same data from which the composition mixtures were determined. Since the Auger data is subject to cuts that minimize bias, we compare these thrown distributions before they are distorted by acceptance and reconstruction biases of the TA reconstruction software. Good agreement is found between unbiased simulated mixes and Auger data. A chi-squared test of the difference in the $\langle X_{\max}\rangle$ results gives 4.8/7 d.o.f. (p-value $= 0.68$) for QGSJetII-04 and 2.5/7 d.o.f. (p-value $= 0.93$) for EPOS-LHC. The same test performed on the standard deviation of unbiased mix and Auger data results in χ^2/dof of 49.5/7 (p-value $= 2 \times 10^{-8}$) for QGSJetII-04 and 10.9/7 (p-value $= 0.14$) for EPOS-LHC. This is in agreement with the conclusions of Ref. [7] in which it was found that the measured Auger distributions cannot be not described well with the QGSJetII-04 model.

The comparison of the QGSJetII-04 mixture after being processed through TA detector simulation and reconstruction software is shown in Figure 4. This procedure introduces biases into the $X_{\max}$ distributions due to detector acceptance, reconstruction, and resolution. Pure QGSJetII-04 protons and iron distributions are also shown. The blue band around the mix shows the expected statistical uncertainties on such a distribution given seven years of TA hybrid exposure.

If we wish to compare the Auger $X_{\max}$ distribution against the TA data, we must use the biased mix, that is, the mix after it has been reconstructed by TA analysis software. Figure 5 shows this comparison of $\langle X_{\max}\rangle$ for the QGSJetII-04-based mixture. The TA systematic uncertainty of 20.3 g/cm^2 is indicated by the red band. Within these systematic uncertainties the TA seven-year hybrid data is consistent with the Auger composition mix after being exposed to TA acceptance and reconstruction. Figure 6 shows the $X_{\max}$ distributions for the TA hybrid data, and for the Auger composition mix generated by the QGSJetII-04 and EPOS-LHC hadronic models. Apart from an offset in the mean value (consistent with the TA systematics) the distributions are in very good agreement. As a reminder, the data shown in

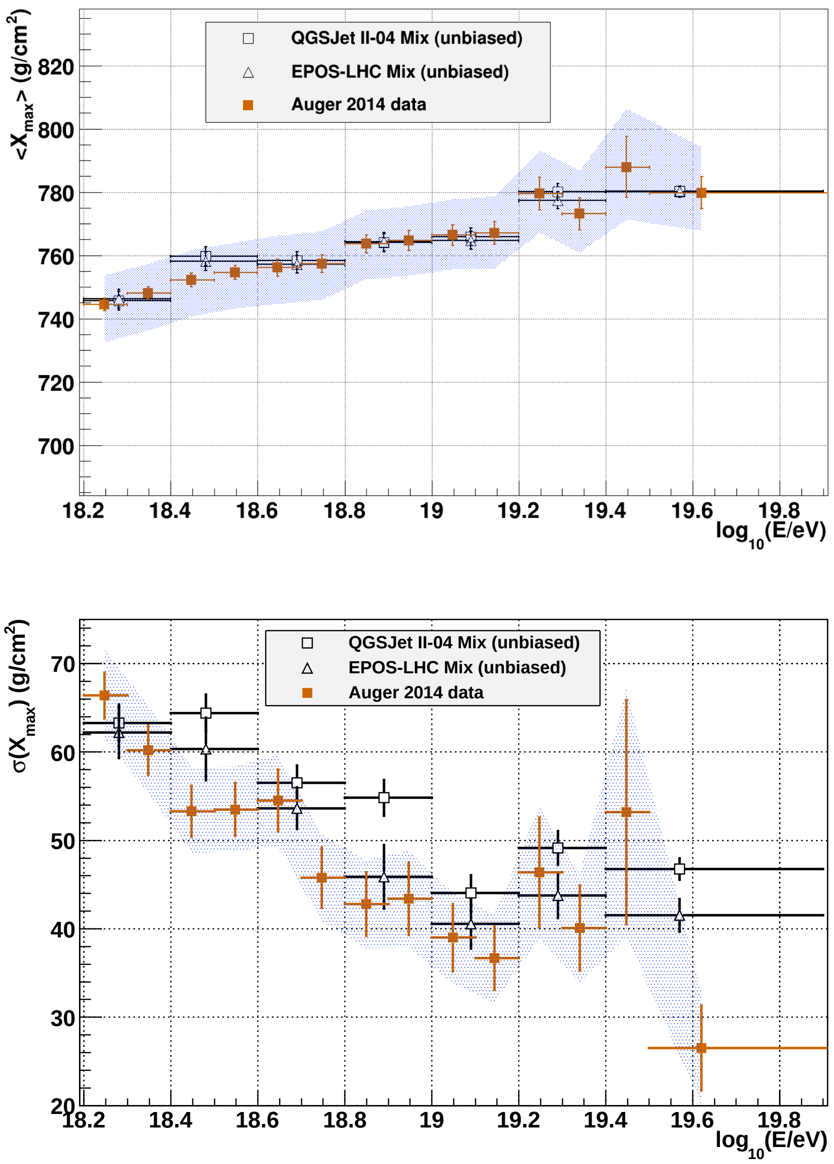

Fig. 3. Generated mean X_{max} (top) and standard deviation (bottom) of the Auger mix based on QGSJetII-04 and EPOS-LHC hadronic models. The Auger data on which the composition mix is based on is also shown, along with its systematic uncertainties.

Figure 3 is unbiased by any detector effects, while the data shown in Figure 4 is fully exposed to TA bias and resolution.

4. Summary

In this work we presented an analysis technique to compare the X_{max} distributions measured by Auger and TA. A large amount of CORSIKA air showers were generated (for proton, helium, nitrogen, and iron primaries), which served as input for the TA detector simulation, event reconstruction, and X_{max} analysis. The relative amounts of proton, helium, nitrogen,

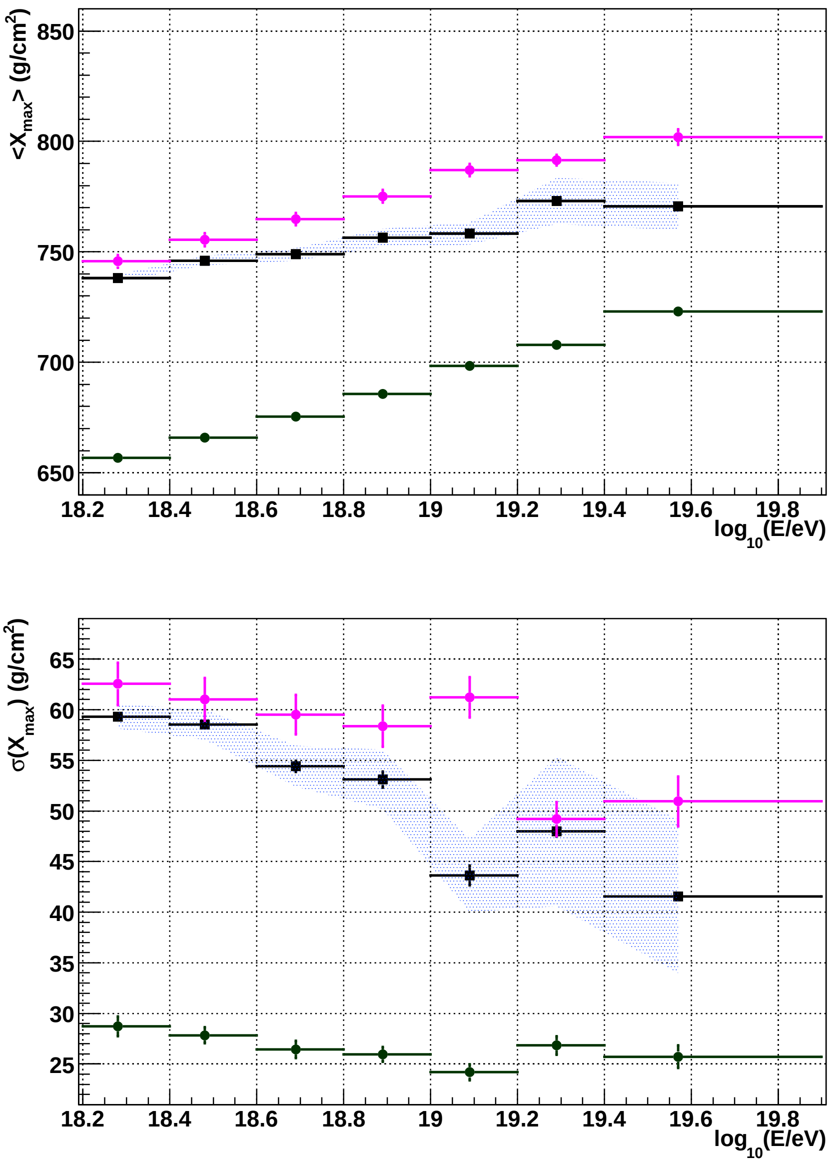

Fig. 4. Mean (top) and standard deviation (bottom) of $X_{\rm max}$ for a composition of 100% proton (magenta points), 100% iron (dark green points) and the Auger mix (black squares), after TA acceptance and reconstruction using QGSJetII-04. Errors expected for seven years of TA hybrid exposure are indicated by the blue band.

and iron as a function of energy were set to the fractions given by a composition model that describes the $X_{\rm max}$ distribution measured by Auger using EPOS-LHC and QGSJetII-04 as hadronic interaction models.

We have first verified that the moments from the $X_{\rm max}$ distributions obtained from CORSIKA simulations produced with amounts of proton, helium, nitrogen, and iron according to the Auger composition models agree with the published Auger $X_{\rm max}$ moments. Since Auger has estimated 'unbiased' $X_{\rm max}$ moments, this means that the effects from the detector acceptance and resolution have been removed and they can be directly compared to the

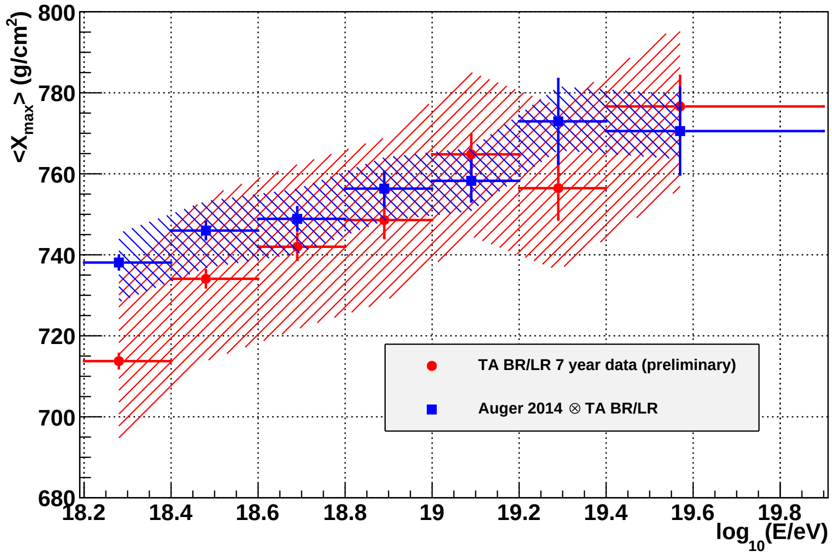

Fig. 5. Preliminary $\langle X_{\max} \rangle$ derived from TA seven-year BR/LR hybrid data compared to the $\langle X_{\max} \rangle$ of the reconstructed Auger composition mix using QGSJetII-04. Systematic uncertainties on the data and mix are also shown. Within systematic uncertainties the TA data agrees with the mix, which is derived from a fit to Auger data.

expectations from air shower simulations. The standard deviation of $X_{\max}$ was found to be not well described by the composition mix based on QGSJetII-04, in accordance with the findings from Ref. [7]. However, given the TA detector resolution and statistics, this difference becomes negligible when comparing the TA reconstructed mean $X_{\max}$ and the full $X_{\max}$ distributions with the corresponding expectations for the Auger composition models.

Using this technique to "carry" the Auger $X_{\max}$ distributions to TA including specifics of the TA acceptance, reconstruction bias and resolution, we performed for the first time a comparison of the Auger and TA $X_{\max}$ distributions. They agree within the systematic uncertainties quoted by the two experiments.

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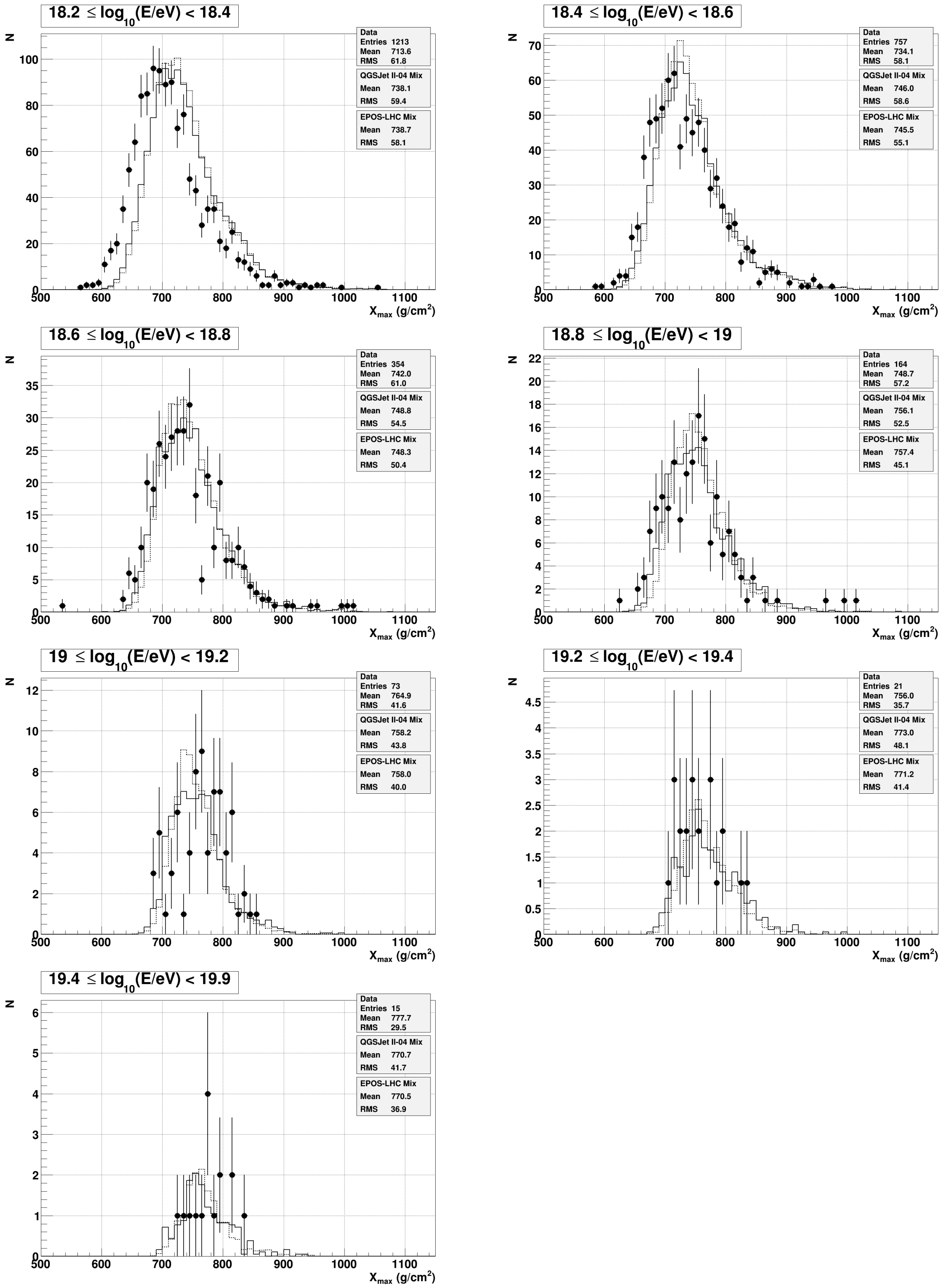

Fig. 6. $X_{\max}$ distributions of preliminary TA seven year BR/LR hybrid data compared to the reconstructed Auger mix in energy bins $18.2 \leq \log_{10}(\mathrm{E/eV}) < 19.9$ for QGSJetII-04 (solid lines) and EPOS-LHC (dashed lines).