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

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Comparison of $X_{\text{max}}$ distributions measured by Auger and TA

Data (8 years in both experiments):
Auger: PRD 90 (2014) 122005, 122006

Energy range: $\lg(E/\text{eV}) = 18.2 - 19.0$

Interaction model: QGSJet-II.04

Mass compositions: proton, AugerMix (composition describing Auger data)

“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”
Changes in the current analysis

Data:
Auger: PRD 90 (2014) 122005, 122006;
J. Bellido, PoS (ICRC2017) 506, 11 years of data

Telescope Array: ApJ 858 (2018) 76, 8.5 years of data

Energy range: $\lg(E/eV) = 18.2 - 19.0$

Interaction model: EPOS-LHC

Mass composition: AugerMix
Data

common energy range: $\lg(E/\text{eV}) > 18.2$

### Pierre Auger

4 FD sites

11 years of data (12/2004 – 12/2015)

[J. Bellido, ICRC (2017), PoS 506]

10558 events

### Telescope Array

FD sites: Black Rock Mesa and Long Ridge

8.5 years of data (05/2008 – 11/2016)


3330 events
Detector acceptance bias

(A) and (B): nearly vertical showers close to FD site, events with deep and shallow $X_{\text{max}}$ are outside the FOV

(A + B + C): all events, tails of $X_{\text{max}}$ distribution are biased by the detector acceptance

(A) : $R = 5.5 \text{ km}$
$\theta = 22^\circ$
$\phi = -180^\circ$

(B) : $R = 9 \text{ km}$
$\theta = 7^\circ$
$\phi = -180^\circ$

(C) : $R = 11.5 \text{ km}$
$\theta = 36^\circ$
$\phi = 180^\circ$
Detector acceptance bias: different analysis strategies

Auger and TA $X_{\text{max}}$ measurements can not be compared directly

**Auger**

fiducial FOV selection:
flat acceptance for major part of data events

$\langle X_{\text{max}} \rangle$, $\sigma(X_{\text{max}})$
unbiased, compare to ideal MC

**TA**

no fiducial FOV selection:
maximize size of the data set

$\langle X_{\text{max}} \rangle$, $\sigma(X_{\text{max}})$
biased, compare to MC in TA detector

$X_{\text{max}}$ distributions in both Auger and TA:
compare to MC in corresponding detectors
Method to transport Auger data into TA detector

**Step 1:** find MC mix of nuclei reproducing the best Auger $X_{\text{max}}$ distributions (AugerMix in the following)

**Step 2:** pass AugerMix through TA detector simulations, reconstruction, analysis; compare AugerMix in TA detector to TA data

Examples of fits of $X_{\text{max}}$ distributions:

points — Auger data

histograms — (p, He, N, Fe) nuclei in AugerMix

$X_{\text{max}} [\text{g cm}^{-2}]$
Choice of the interaction model

QGSJet-II.04: p-values for AugerMix vs Auger data are \( \approx 0.01 \) for \( \lg(E/eV) = 17.8 - 19.2 \)

width of the \( X_{\text{max}} \) distributions is larger than in data of Auger

AugerMix (QGSJet-II.04) is not equivalent to Auger data, not a best choice for comparison to TA
Choice of the interaction model

EPOS-LHC: good description of $X_{\text{max}}$ distributions measured by Auger

comparison to TA will be done using AugerMix (EPOS-LHC)
AugerMix in TA detector

Step 2: Pass AugerMix through TA detector simulations, reconstruction and analysis

AugerMix $\otimes$ TA: bias on $\langle X_{\text{max}} \rangle$ of $\approx -5$ g cm$^{-2}$

bias on $\sigma(X_{\text{max}})$ of few g cm$^{-2}$

EPOS-LHC simulations are unavailable for TA and are obtained via re-weighting of QGSJet-II.04 simulations [W. Hanlon et al., JPS Conf. Proc. 19, 011013 (2018)]

currently the re-weighting is done up to $\lg(E/\text{eV}) = 19.0$ using AugerMix from [Auger, PRD 90 (2014) 122006]
Auger – TA

\[ \langle X_{\text{TA max}}^{\text{TA}} \rangle < \langle X_{\text{max}}^{\text{Auger}} \rangle \] for almost all energies

agreement within \((\text{stat} + \text{sys})\) errors

\[ \sigma(X_{\text{TA max}}^{\text{TA}}) > \sigma(X_{\text{max}}^{\text{Auger}}) \] for \(\lg(E/\text{eV}) = 18.5 - 19.0\)

A. Yushkov  

Auger – TA working group on mass composition  

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“TA’s ability to resolve individual QGSJet-II.04 elements is degraded owing to the overlap of the confidence intervals. According to these figures, when considering only the joint distributions of $\langle X_{\text{max}} \rangle$ and $\sigma(X_{\text{max}})$, within the data’s systematic uncertainty the data may resemble QGSJet-II.04 proton, helium, or nitrogen.”
$\langle X_{\text{max}} \rangle$: Auger vs different TA measurements

Discrepancy Auger – TA (Black Rock Mesa/Long Ridge) is larger and energy-dependent

TA Middle Drum


TA Black Rock Mesa/Long Ridge


average difference: $\langle \Delta \rangle = (2.9 \pm 2.7 \text{ (stat.)} \pm 18 \text{ (syst.)}) \text{ g/cm}^2$
Summary

\[ \langle X_{\text{TA}}^{\text{max}} \rangle < \langle X_{\text{Auger}}^{\text{max}} \rangle \text{ for almost all energies} \]

agreement within \((\text{stat} + \text{sys})\) errors

\[ \sigma(X_{\text{TA}}^{\text{max}}) > \sigma(X_{\text{Auger}}^{\text{max}}) \text{ for } \lg(E/\text{eV}) = 18.6 - 19.0 \]

Next: comparison to Auger ICRC (2017) data and energies \(\lg(E/\text{eV}) > 19.0\)
Further required steps

Understand differences between Black Rock Mesa/Long Ridge and Middle Drum data

Analyze the differences between TA and Auger in $\sigma(X_{\text{max}})$

Take into account difference in energy scales of Auger and TA

Take into account systematic errors on nuclei fractions in AugerMix

Produce EPOS-LHC simulations for TA
backups
Auger $X_{\text{max}}$ moments from PRD (2014) and ICRC (2017)

![Graph showing $X_{\text{max}}$ moments from PRD (2014) and ICRC (2017)](image)
Auger $X_{\text{max}}$ moments vs MC predictions

[A. Yushkov Auger – TA working group on mass composition]

$\langle X_{\text{max}} \rangle$ [g/cm²] vs $\log(E/eV)$
- proton
- iron

$\sigma$($X_{\text{max}}$) [g/cm²]
- EPOS-LHC
- Sibyll2.3
- QGSJetII-04

Data ± $\sigma_{\text{stat}}$
± syst.

[J. Bellido, PoS (ICRC2017) 506]
Auger: mass composition from fits of $X_{\text{max}}$ distributions

J. Bellido, PoS (ICRC2017) 506
TA Black Rock Mesa/Long Ridge $\langle X_{\text{max}} \rangle$

$$\langle X_{\text{max}} \rangle$$


The systematic uncertainties of $\langle X_{\text{max}} \rangle$ from the sources discussed above are also evaluated and given in Table 2. Adding in quadrature, we obtain 21.1 g cm$^{-2}$ as a conservative estimate. Other sources are added in quadrature, and we find the total systematic uncertainty in $\langle X_{\text{max}} \rangle$ to be 17.4 g cm$^{-2}$. The results are summarized in Table 2.

As seen in Figure 14, within systematic uncertainties, $\langle X_{\text{max}} \rangle$ of the data is in agreement with QGSJet II-04 protons and helium for nearly all energy bins. There is clear separation between the region of systematic uncertainty and heavier elements such as nitrogen and iron. In the last two energy bins there is some overlap between the systematic uncertainty region of the data and the nitrogen, but statistics in the data there are very poor. Care must be taken in interpreting Figure 14, since $\langle X_{\text{max}} \rangle$ by itself is not a robust enough measure to fully draw conclusions about UHECR composition.

When comparing $\langle X_{\text{max}} \rangle$ of data to Monte Carlo, in addition to detector resolution and systematic uncertainties in the data that may hinder resolving the different elements with relatively similar masses, the issue of systematic uncertainties in the hadronic model used to generate the Monte Carlo must also be recognized. This will be discussed in Section 5. Referring back to Figures 12 and 13, we can see that although the $\langle X_{\text{max}} \rangle$ of the data in Figure 14 lies close to QGSJet II-04 helium, the $\langle X_{\text{max}} \rangle$ of the data is larger than the helium model allows for energy bins with good data statistics. For this reason, we will test the agreement of data and Monte Carlo not just by comparing $\langle X_{\text{max}} \rangle$ and $\langle X_{\text{max}} \rangle$, but by using the entire distributions.

The elongation rate of the data in Figure 14 found by performing a t test to the data is found to be $56.8 \pm 5.3$ g cm decade$^{-2}$. The dof of this t is $10.67 \pm 9$. Table 2 summarizes the observed first and second moments of TA’s observed $\langle X_{\text{max}} \rangle$ for all energy bins.
Auger $X_{\text{max}}$ resolution and systematic uncertainties

Auger, PRD 90 (2014) 122005

The diagram shows the resolution and systematic uncertainties of $X_{\text{max}}$ as a function of energy ($E$) for different components: total, detector, aerosols, and molecular. The uncertainties are represented by shaded bands, with calibration, reconstruction, and quadratic sum contributions separately depicted.
TA data – proton (QGSJet-II.04)

TA \langle X_{\text{max}} \rangle is shifted within systematic errors: +17.4 g cm^{-2} for all energies

\langle X_{\text{max}} \rangle and \sigma(X_{\text{max}})

good agreement to TA for \text{lg}(E/eV) < 19.0