Agreement between the Xmax distributions measured by the Pierre Auger and Telescope Array Observatories


Presenter: Vitor de Souza
University of São Paulo
Take away message

TA and Auger composition measurements (Xmax) agree within the systematics

$$18.2 < \log_{10}(E/eV) < 19.0$$
Don’t jump into conclusions

Different detectors and analysis.
Auger bias ≠ TA bias

Auger
- Xmax at the atmosphere
- Approx. unbiased

TA
- Xmax in the detector
- Enhance statistics

Xmax ATM ≠ Xmax DET
Auger bias $\neq$ TA bias

$18.5 < \log_{10}(E/eV) < 18.6$

$\langle X_{\text{max}} \rangle$
- Simulation: 766.6
- Auger: 764.6
- TA: 760.6
How to compare $X_{\text{max}}$ from Auger and TA?

$X_{\text{max}}^{\text{Auger}}$ and $X_{\text{max}}^{\text{TA}}$ always in g/cm$^2$

18.2 < $\log(E/\text{eV})$ < 18.3

$N = 1953$ for $X_{\text{max}}^{\text{Auger}}$

$N = 625$ for $X_{\text{max}}^{\text{TA}}$
Auger Data

Mean = 744
RMS = 66

Xmax\textsuperscript{Auger}

Mean = 738
RMS = 60

Xmax\textsuperscript{TA (Auger)}

TA Detector Simulation

TA Analysis
AugerMix

$\log(E/eV) = 17.8-17.9$

Fe  N  He  P  Auger

$X_{\text{max}}^{\text{Auger}}$

SAME RESULTS WITH EPOS-LHC

TA Detector Simulation

Mean = 738  RMS = 60

$X_{\text{max}}^{\text{TA}(\text{AugerMix})}$

TA Analysis
Are these distributions compatible?
Get $P_1^{\text{data}}$

$P_1 = 5.34 \times 10^{-21}$

- **TAD**: Data
- **AugerMix**

$P_2 < 10^{-5}$

Compatibility tests:
- Anderson-Darling and
- Kolmogorov-Smirnov

Normalize $P_1$ probabilities

Get $10^5 P_1^{\text{MC}}$ probabilities

Count ($N$) how many times $P_1^{\text{MC}} < P_1^{\text{data}}$

Compatibility Probability

$P_2 = N/10^5$
Systematic Uncertainties

Xmax Systematic Uncertainty

TA = 20.3 g/cm$^2$

Auger ~ -10 and +8 g/cm$^2$

Shift Xmax to match the mean of the distributions.

Recalculate the compatibility tests.
Xmax Shift versus Systematic Uncertainties

\[
X_{\text{max}} \text{ Shift (g/cm}^2\text{)}
\]

Total Sys. Uncert.: \(\sqrt{\sigma^2_{\text{sys-Auger}} + \sigma^2_{\text{sys-TA}}}\)

\(<_{\text{TA}} X^{\text{TA}}_{\text{max}} > - <_{\text{Auger}} X^{\text{TA}}_{\text{max}} >\)
Compatibility between TA data and AugerMix
Repeat the same analysis but now calculates the compatibility probability $P_2$ between TA data and pure proton Xmax distributions.
Comparison of TA data with AugerMix and Protons
Conclusion

\[ 18.2 < \log_{10}(E/eV) < 19.0 \]

TA Xmax distributions are compatible to AugerMix Xmax distributions within the systematic uncertainties.
Conclusion

$18.2 < \log_{10}(E/eV) < 19.0$

TA $X_{\text{max}}$ distributions are as compatible to pure proton composition as they are to AugerMix.
# Xmax Compatibility Table

$18.2 < \log_{10}(E/eV) < 19.0$

<table>
<thead>
<tr>
<th>Auger</th>
<th>Mixed</th>
<th>Iron</th>
<th>Auger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auger</td>
<td>Compatible</td>
<td>Incompatible</td>
<td>Compatible</td>
</tr>
<tr>
<td>TA</td>
<td>Compatible</td>
<td>Incompatible</td>
<td>!!!</td>
</tr>
</tbody>
</table>

### Proton only
- Compatible

### Mixed
- Incompatible

### Iron only
- Compatible

### Auger
- Compatible
Request to the UHECR community

Proper comparison demands use of detector simulation and analysis chain of both experiments.

Please refer to this common (Auger/TA) analysis in your studies.

Do not propagate an unsustainable controversy.
Extras
Compatibility tests

- Kolmogorov-Smirnov and Anderson-Darling

- Calculate the probability \( (P1_{\text{data}}) \) that the two distributions were generated from the same parent distribution

\[
\text{DET}_{\text{Xmax}}^{\text{TA}} \text{ (AugerMix)} \text{ versus } \text{DET}_{\text{Xmax}}^{\text{TA}} (\text{TAData})
\]

- Draw \( 10^5 \) MC distributions of \( \text{DET}_{\text{Xmax}}^{\text{TA}} \) (AugerMix)
  - Use fit \( \text{Gauss} \otimes \text{Exponential} \)
  - Calculate \( 10^5 \) \( P1_{\text{MC}} \)
  - Get \( P1_{\text{MC}} \) distribution \( \rightarrow \) Compatibility distribution

- Using the distribution \( P1_{\text{MC}} \) calculate the probability \( P2 \) of finding a \( P1 \) worse than \( P1_{\text{data}} \)

\[
P2 = \text{Compatibility Probability}
\]
## Comparison of TA data with AugerMix and Protons

<table>
<thead>
<tr>
<th>Energy bin log$_{10}$(E/eV)</th>
<th>Compatibility Probability (P2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No $X_{\text{max}}$ shift</td>
</tr>
<tr>
<td></td>
<td>KS</td>
</tr>
<tr>
<td></td>
<td>Shift (g/cm$^2$)</td>
</tr>
<tr>
<td>18.2 - 18.3</td>
<td>$&lt; 10^{-5}$</td>
</tr>
<tr>
<td>18.3 - 18.4</td>
<td>$&lt; 10^{-5}$</td>
</tr>
<tr>
<td>18.4 - 18.5</td>
<td>$&lt; 10^{-5}$</td>
</tr>
<tr>
<td>18.5 - 18.6</td>
<td>$9 \times 10^{-5}$</td>
</tr>
<tr>
<td>18.6 - 18.7</td>
<td>0.014</td>
</tr>
<tr>
<td>18.7 - 18.8</td>
<td>0.018</td>
</tr>
<tr>
<td>18.8 - 18.9</td>
<td>0.065</td>
</tr>
<tr>
<td>18.9 - 19.0</td>
<td>0.49</td>
</tr>
</tbody>
</table>

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

Fig. 5. Preliminary $\langle X_{\text{max}} \rangle$ derived from TA seven-year BR/LR hybrid data compared to the $\langle X_{\text{max}} \rangle$ 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.
Mean Xmax Comparison

\[ \langle X_{\text{max}} \rangle \ [\text{g/cm}^2] \]

- TA MD 2014
- Auger 2014 \( \otimes \) TA MD

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