Measuring the depth of shower maximum at the Pierre Auger Observatory

Implications on composition above $10^{17.2}$ eV

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2 - Full author list at http://www.auger.org/archive/authors_2018_07.html
SD infill array and the **High Elevation Auger Telescopes** allow composition measurements down to $10^{17.2}$ eV.
Reconstruction – Shower Profile

- Pixel Trace
- Shower Plane
- Hybrid Geometry
- Light at Shower
- Profile and $X_{\text{max}}$ Dist
- Aperture Photons + Atmosphere
- Pixel/SD Timing
- Gaisser-Hillas Fit

**Graph**:
- $dE/dx$ vs slant depth [g/cm$^2$]
- $X_{\text{max}}$ region
- $18.4 \leq \log(E/\text{eV}) < 18.5$
- $N=1600$

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Untangling the True $X_{\text{max}}$ Distribution

Quality Selection Criteria:

- Full instrumentation functionality, no clouds and clear atmosphere
- Long tracks in detector ($20^\circ$) with $X_{\text{max}}$ in FoV with a low fit $\chi^2$

Fiducial Selection Criteria:

- Surface Detector proton trigger probability $> 0.9$
- Surface Detector proton - iron trigger efficiency difference $< 0.05$
- FD Fiducial FoV cuts to flatten $X_{\text{max}}$ acceptance

Post-cut $X_{\text{max}}$ distribution still differs from true $X_{\text{max}}$ distribution due to resolution, and detector acceptance.

$$f_{\text{obs}}(X_{\text{max}}^{\text{rec}}) = \int_0^{\infty} f_{\text{true}}(X_{\text{max}}) \varepsilon(X_{\text{max}}) R(X_{\text{max}}^{\text{rec}} - X_{\text{max}}) dX_{\text{max}}$$
Field of View and $X_{\text{max}}$ Acceptance

$X_{\text{max}}$ must be in FoV to pass quality cuts.

Geometry determines which $X_{\text{max}}$ values will be measured.
Distributions biased when $X_{\text{fid low}} < X_{\text{low}}$ or FoV top $X_{\text{fid up}} > X_{\text{up}}$

Fiducial cut flattens $X_{\text{max}}$ acceptance for the majority of selected events. Events with non-flat acceptance up-weighted via acceptance parameterization.
**$X_{\text{max}}$ Resolution and Systematic Uncertainties**

Systematic uncertainties from the atmosphere, FD calibration reconstruction and detector are summed for systematic error of the moments.

$X_{\text{max}}$ Resolution

Effects from the atmosphere and the detector are combined into the $X_{\text{max}}$ resolution to correct the $X_{\text{max}}$ distributions.
$X_{\text{max}}$ Distributions 17.8 – 19.6 ICRC17

Preliminary

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Interesting elongation rate break at 18.27 $\log_{10}(E/eV)$

$79 \pm 1 \text{ g/cm}^2/\text{decade} \rightarrow 26 \pm 2 \text{ g/cm}^2/\text{decade}$
\[ \langle \ln A \rangle = \frac{\langle X_{\text{max}} \rangle - \langle X_{\text{max}} \rangle_p}{f_E} \]

\[ \sigma_{\ln A}^2 = \frac{\sigma^2(X_{\text{max}}) - \sigma_{\text{sh}}^2(\langle \ln A \rangle)}{b \sigma_p^2 + f_E^2} \]

See PRD 90, 122006 (2014) ArxiV:1409.5083 for details
Fitting Mass Ratios

(a) EPOS

(b) QGSJETII-04

(c) Sibyll

Data

Sum

Iron

Nitrogen

Helium

Proton

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Mass Fractions

Model Dependent Results

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**Method – Extending to Higher Energies**

Uses $t_{1/2}$, the time from 10% to 50% of the integrated SD signal per WCD.

\[
\Delta_i = \frac{\delta_i}{\sigma_i}
\]

\[
\delta_i = t_{1/2} - t_{1/2}^{bench}
\]

\[
\Delta_s = \frac{1}{N} \sum_{\text{stations}} \Delta_i
\]

$\Delta_s$, the average of the $\Delta_i$ for all WCD in an event, scales linearly with $\ln A$.

- The $\Delta_s/X_{\text{max}}$ correlation is obtained using HEAT and Full FD Hybrid events to calibrate $\Delta_s$ for conversion to $X_{\text{max}}$ and $\ln A$.
Very close agreement between calibrated Δ Method and FD / HEAT $X_{\text{max}}$ measurements.

Δ-method ln A and $X_{\text{max}}$ measurements may suggest a stalling of the rigidity dependent trend toward higher masses around $10^{19.6}$ eV.
**Summary**

**X\text{max} Moments:**

- Detector effect free, stable $X_{\text{max}}$ moments between $10^{17.2} - 10^{19.8}$ eV
- Very good agreement between FD, HEAT and SD Δ-methods
- Significant change in elongation rate at $10^{18.27}$ eV

**Mass ratios and interpretation**

- No model or energy is consistent with two component (p/Fe) composition.
- All energies best described by mix of p, He, N and Fe
- Minor Fe contributions except at very low and perhaps high energies

**ln A and model validity:**

- All models reinforce heavy $\rightarrow$ light $\rightarrow$ heavy composition trend.
- Rigidity dependent mass increase suggests maximum power of sources.
- Highest energy bins may show an end to rigidity dependent mass increase.
- Unphysical $\sigma^2(\ln A)$ values show tension with QGSJETII-04 models.
Questions?

Depth of Maximum of Air-Shower Profiles at the Pierre Auger Observatory I
Measurements at Energies above 10^{17.8} eV
PHYSICAL REVIEW D 90, 122005 (2014) arXiv:1409.4809

Depth of Maximum of Air-Shower Profiles at the Pierre Auger Observatory II
Composition Implications
PHYSICAL REVIEW D 90, 122006 (2014) arXiv:1409.5083

Contributions to the 35th International Cosmic Ray Conference (ICRC 2017)
Speakers Jose Bellido and Patricia Sanchez-Lucas arXiv:1708.06592

Inferences on mass composition and tests of hadronic interactions from 0.3 to 100 EeV using the water-Cherenkov detectors of the Pierre Auger Observatory
TABLE IV. Coefficients obtained from the calibration of $\Delta_s$ and $X_{\text{max}}$.

<table>
<thead>
<tr>
<th>Calibration parameters</th>
<th>Value (g cm$^{-2}$) 750 m array</th>
<th>Value (g cm$^{-2}$) 1500 m array</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$636 \pm 20$</td>
<td>$699 \pm 12$</td>
</tr>
<tr>
<td>$b$</td>
<td>$96 \pm 10$</td>
<td>$56 \pm 3$</td>
</tr>
<tr>
<td>$c$</td>
<td>$2.9 \pm 1.2$</td>
<td>$3.6 \pm 0.7$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic uncertainty (g cm$^{-2}$) 750 m array</th>
<th>Source</th>
<th>Systematic uncertainty (g cm$^{-2}$) 1500 m array</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty on calibration</td>
<td>10.0</td>
<td>Uncertainty on calibration</td>
<td>5.0</td>
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<tr>
<td>Seasonal effect</td>
<td>2.0</td>
<td>Seasonal effect</td>
<td>2.0</td>
</tr>
<tr>
<td>Diurnal dependence</td>
<td>1.0</td>
<td>Diurnal dependence</td>
<td>1.0</td>
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<tr>
<td>Aging</td>
<td>3.0</td>
<td>Aging</td>
<td>3.0</td>
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<tr>
<td>HEAT systematic uncertainty</td>
<td>8.5</td>
<td>HEAT systematic uncertainty</td>
<td>8.5</td>
</tr>
<tr>
<td>Angular dependence</td>
<td>$&lt;1.0$</td>
<td>Angular dependence</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>14.0</strong></td>
<td><strong>Total</strong></td>
<td><strong>11.0</strong></td>
</tr>
</tbody>
</table>
fit to 17.7-17.8 $\Delta_s$ values
between 1 and 1.05 sec $\theta$
used as 750m array benchmark

fit to 19.1-19.2 $\Delta_s$ values
between 1 and 1.05 sec $\theta$
used as 1500m array benchmark

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### SD/FD Δ Calibration

#### 750 m array

<table>
<thead>
<tr>
<th>Quality cuts</th>
<th>Events</th>
<th>$e$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEAT data</td>
<td>12,003</td>
<td>100.0</td>
</tr>
<tr>
<td>FD &amp; SD reconstruction</td>
<td>2461</td>
<td>20.5</td>
</tr>
<tr>
<td>sec $\theta &lt; 1.30$</td>
<td>2007</td>
<td>16.7</td>
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<tr>
<td>6T5 trigger</td>
<td>714</td>
<td>5.9</td>
</tr>
<tr>
<td>$\geq 3$ selected stations</td>
<td>660</td>
<td>5.5</td>
</tr>
<tr>
<td>$\log(E/eV) \geq 17.5$</td>
<td>252</td>
<td>2.1</td>
</tr>
</tbody>
</table>

#### 1500 m array

<table>
<thead>
<tr>
<th>Quality cuts</th>
<th>Events</th>
<th>$e$ (%)</th>
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</thead>
<tbody>
<tr>
<td>FD data</td>
<td>19,759</td>
<td>100.0</td>
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<tr>
<td>FD &amp; SD reconstruction</td>
<td>12,825</td>
<td>65.0</td>
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<tr>
<td>sec $\theta &lt; 1.45$</td>
<td>9625</td>
<td>49.0</td>
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<tr>
<td>6T5 trigger</td>
<td>7361</td>
<td>37.0</td>
</tr>
<tr>
<td>$\geq 3$ selected stations</td>
<td>4025</td>
<td>20.0</td>
</tr>
<tr>
<td>$\log(E/eV) \geq 18.5$</td>
<td>885</td>
<td>4.5</td>
</tr>
</tbody>
</table>

![Graph 1](image1.png)

**Correlation = 0.39**

![Graph 2](image2.png)

**Correlation = 0.46**

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Comparison of TA MD telescope result with Auger composition folded with TA detector response
Shows good agreement between results

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Kolmogorow-Smirnow and Anderson-Darling homogeneity tests show low differentiability between TA proton result and an end to end TA simulation of the Pierre Auger mixed composition.
Mass Fractions – Why Full Distribution

Equally likely $X_{\text{max}}$ distributions with can be built with strongly differing compositions if only Moments are considered.

$X_{\text{max}}$ Moments are not enough to distinguish between mass ratios.

Need full distribution
Single Mass Template distributions with detector effects built via MC

\[ X_{s,j}^m = \frac{1}{N_{MC}} \sum_n a(X_{s,n}^t) p_j(X_{s,n}^m) / N_{MC} \]

Test mass fractions, \( f_s \), are used to form MC predictions

\[ C_j = \frac{N_{data}}{N} \sum_s f_s X_{s,j}^m, \]

where \( N = \sum_s f_s \sum_j X_{s,j}^m \)

and \( \sum f_s = 1 \)

Best fit MC predictions found via bin maximum likelihood

where

\[ L = \prod_j \left[ e^{-C_j} C_j^{n_j} / n_j! \right] / \left[ e^{-n_j} n_j^{n_j} / n_j! \right] \]

is indicative of the goodness of fit and is minimized against \( C_j \) to find the best fit mix

Fit quality is presented as the probability of finding a larger \( L \) value with the data assuming the mix found in the fit is correct

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Mass Fractions – FD Distributions – EPOS LHC

17.8 ≤ lg(E/eV) < 17.9
N = 4567

17.9 ≤ lg(E/eV) < 18.0
N = 4009

18.0 ≤ lg(E/eV) < 18.1
N = 3330

18.1 ≤ lg(E/eV) < 18.2
N = 3408

18.2 ≤ lg(E/eV) < 18.3
N = 2711

18.3 ≤ lg(E/eV) < 18.4
N = 2082

18.4 ≤ lg(E/eV) < 18.5
N = 1600

18.5 ≤ lg(E/eV) < 18.6
N = 1098

18.6 ≤ lg(E/eV) < 18.7
N = 834

18.7 ≤ lg(E/eV) < 18.8
N = 578

18.8 ≤ lg(E/eV) < 18.9
N = 469

18.9 ≤ lg(E/eV) < 19.0
N = 356

19.0 ≤ lg(E/eV) < 19.1
N = 281

19.1 ≤ lg(E/eV) < 19.2
N = 191

19.2 ≤ lg(E/eV) < 19.3
N = 131

19.3 ≤ lg(E/eV) < 19.4
N = 111

X_{max} [g/cm^2]

Preliminary

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Mass Fractions – FD Distributions – QGSJETII-04

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Preliminary
Mass Fractions – FD Distributions – Sibyll2.3

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Mass Fractions – HEAT Distributions

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**Preliminary**
FD $X_{\text{max}}$ – Quality Cuts

<table>
<thead>
<tr>
<th>cut</th>
<th>E &gt; $10^{18}$ eV</th>
<th>events</th>
<th>$\varepsilon$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>pre-selection:</strong></td>
<td></td>
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<tr>
<td>air-shower candidates</td>
<td>2573713</td>
<td></td>
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<tr>
<td>hardware status</td>
<td>1920584</td>
<td>74.6</td>
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<tr>
<td>aerosols</td>
<td>1569645</td>
<td>81.7</td>
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<tr>
<td>hybrid geometry</td>
<td>564324</td>
<td>35.9</td>
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<tr>
<td>profile reconstruction</td>
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<tr>
<td>clouds</td>
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<td></td>
</tr>
<tr>
<td><strong>$E &gt; 10^{17.8}$ eV</strong></td>
<td></td>
<td>111194</td>
<td>25.7</td>
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<tr>
<td><strong>quality and fiducial selection:</strong></td>
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<tr>
<td>$P(\text{hybrid})$</td>
<td>105749</td>
<td>95.1</td>
<td></td>
</tr>
<tr>
<td>$X_{\text{max}}$ observed</td>
<td>73361</td>
<td>69.4</td>
<td></td>
</tr>
<tr>
<td>quality cuts</td>
<td>58305</td>
<td>79.5</td>
<td></td>
</tr>
<tr>
<td>fiducial field of view</td>
<td>21125</td>
<td>36.2</td>
<td></td>
</tr>
<tr>
<td>profile cuts</td>
<td>19947</td>
<td>94.4</td>
<td></td>
</tr>
</tbody>
</table>

Quality Cut data from 2014 PRD

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Atmospherics

Hourly Aerosol Profiles measured with 2 Atmospheric Laser Facilities with automatic end to end calibration

Mie Corrections from GDAS and Balloon Radiosonde

Cloud monitoring from GOES Lidar and IR cloud cameras at FDs

Pressure, temperature and humidity from GDAS and many on-site weather stations

See NIM Sec A (798), 2015 for details

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