Measurements of $X_{\text{max}}$ above $10^{17}$ eV with the fluorescence detector of the Pierre Auger Observatory

CR-EX 1176 – PoS 420

31st July, 2015

Alessio Porcelli$^a$ on behalf of Pierre Auger Collaboration$^b$

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(full author list: http://www.auger.org/archive/authors_2015_06.html)
2 independent datasets:

Standard dataset (18382 events)

- Known by the scientific community (Phys. Rev. D90 12 (2014) 122005 [1409.4809v3])
- Measurement only down to $10^{17.8}$ eV
- 24 fluorescence telescopes with $2^\circ$ to $30^\circ$ FoV in elevation at 4 sites:
  Los Leones (LL), Loma Amarilla (LA), Los Morados (LM), Coihueco (CO)
- All non-HeCo events (see below)

HeCo dataset (5490 events)

- Energy span: $10^{17} \leq E \leq 10^{18.3}$ eV
- Period between 01.06.2010 and 15.08.2012
- 6 standard fluorescence telescopes at CO sites
- 3 High Elevation Auger Telescopes (HEAT)
HEAT (High Elevation Auger Telescopes)

3 fluorescence telescopes with a sampling 2 times faster than standard.
Operation in downward (left) and upward (right) modes:

2° to 30° FoV in elevation

30° to 60° FoV in elevation

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HeCo (HEAT+CO): extended field of view

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HEAT in downward mode

Cross-checks with Coihueco (CO):

**CO-HEAT (downward)**

- **Data**
  - Entries: 464
  - Mean: 2.26 ± 1.77
  - Std. Dev.: 38.05 ± 1.42

- **MC**
  - Entries: 1296
  - Mean: 1.95 ± 1.07
  - Std. Dev.: 38.45 ± 0.88

- **\(X_{\text{max}}\) difference between CO and HEAT compatible with reconstruction systematic uncertainties** (see systematic uncertainties)

- **Data and MC simulation are in agreement: good detector knowledge**

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Same analysis method reported in Phys.Rev. D90 12 (2014) 122005 [1409.4809v3]

Overview of the data selection:

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<tr>
<th>Good data taking condition</th>
<th>good data taking periods and good camera calibration constants require measured aerosol profile reject dust periods (VAOD@3km&lt;0.1) reject events with too much cloud contamination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good (X_{\text{max}}) and Energy measurement</td>
<td>required hybrid geometry reconstruction Minimum track length observed (X_{\text{max}}), with expected resolution &lt;40 g cm(^{-2}) reduced (\chi^2) of profile fit normal distributed</td>
</tr>
<tr>
<td>Field of view analysis</td>
<td>fiducial field of view to unbias the dataset</td>
</tr>
<tr>
<td><strong>HeCo specific</strong></td>
<td>considered higher trigger rate in Surface Detector stations for Fe-like events Surface Detector, HEAT and CO must be able to trigger simultaneously</td>
</tr>
</tbody>
</table>
End-to-End cross-check with MC simulations

**Proton, Iron and 50:50 mixture**, generated (lines) VS reconstructed (markers)

Generated and reconstructed are compatible, with a residual bias in the lowest energy bin: correction using half of the 50:50 mixture (the largest), plus a symmetric systematic uncertainties accounted.

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### Data Set

- **Analysis method**: Systematic Uncertainties

### Results

- **Conclusions**: A. Porcelli for Pierre Auger | $X_{\text{max}}$ above $10^{17}$ eV with the FD of the Pierre Auger Observatory (CR-EX 1176 – PoS 420)

### Backups

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\[ \langle X_{\text{max}} \rangle \text{ systematic uncertainties & resolutions} \]

- reconstruction bias (only left) and detector resolution (right)
- offset in time between SD-FD, calibration and telescopes alignment
- analysis
- atmospheric uncertainty in the geometry reconstruction and fluorescence light yield
2 data set results...

Standard VS HeCo dataset

Average of $X_{\text{max}}$

<table>
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<tr>
<th>Average of $X_{\text{max}}$ (g/cm²)</th>
<th>$\log_{10}(E/eV)$</th>
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<tr>
<td>HeCo dataset</td>
<td>17.0</td>
</tr>
<tr>
<td>Standard dataset</td>
<td>600</td>
</tr>
</tbody>
</table>

Std. deviation of $X_{\text{max}}$

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<th>Std. deviation of $X_{\text{max}}$ (g/cm²)</th>
<th>$\log_{10}(E/eV)$</th>
</tr>
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<tr>
<td>HeCo dataset</td>
<td>20.0</td>
</tr>
<tr>
<td>Standard dataset</td>
<td>60.0</td>
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Compatibility inside the expected uncorrelated systematic uncertainties ($\sim 7$ g cm$^{-2}$)

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Moments from flat acceptance data + exponential tails ($\Lambda$-$\eta$) correction

Average of $X_{\text{max}}$

Std. Deviation of $X_{\text{max}}$

(with Proton and Iron pure composition for EPOS-LHC, Sibyll2.1, QGSJetII-04)

AUGER, PRELIMINARY

A. Porcelli for Pierre Auger | $X_{\text{max}}$ above $10^{17}$ eV with the FD of the Pierre Auger Observatory (CR-EX 1176 – PoS 420)

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Low energy: largest mass dispersion, dominated by intermediate and heavy primaries

High energy: from the lightest at $\sim 10^{18.4}$ eV to heavier with less dispersion of masses.

AUGER, PRELIMINARY

EPOS-LHC (Mean of $\ln A$)

EPOS-LHC (Variance of $\ln A$)
In A moments: QGSJetII-04

**Low energy**: largest mass dispersion, dominated by intermediate and heavy primaries

**High energy**: from the lightest at \( \sim 10^{18.4} \) eV to heavier with less dispersion of masses.
Conclusions

- $X_{\text{max}}$ measured in $\sim 3$ decades of energy (preliminary!):
  extend the lower energy range down to $10^{17}$ eV
- $\langle \ln A \rangle$ as a function of $\log (E/\text{eV})$
  shows a non-constant composition in this energy range:
  the lightest at $\sim 10^{18.4}$ eV,
  heavier at lower and at higher energies

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Backups
Study of the field of view bias

\[ \langle X_{\text{max}} \rangle \text{ vs. } X_{\text{low}} \text{ or } X_{\text{up}} \text{ limit} \]

\[ \log_{10}(E_{\text{cal}}/\text{eV}) \text{ Range: 17.5 ÷ 17.6} \]

No limit of the sample: asymptotic average \( \langle X_{\text{max}}^{\infty} \rangle \)

Data Set

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Study of the field of view bias

$X_{\text{max}}$ distribution

$\log_{10}(E_{\text{cal}}/\text{eV})$ Range: 17.5 ÷ 17.6

$\langle X_{\text{max}} \rangle$ vs. $X_{\text{low}}$ or $X_{\text{up}}$ limit

$\log_{10}(E_{\text{cal}}/\text{eV})$ Range: 17.5 ÷ 17.6

Large $X_{\text{up}}$: $\langle X_{\text{max}} \rangle$ still $\langle X_{\infty} \rangle$

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$\log_{10}(E_{\text{cal}}/\text{eV}) \text{ Range: } 17.5 ÷ 17.6$

Still $\langle X_{\text{max}} \rangle \sim \langle X_{\text{max}}^{\infty} \rangle$: need a study on the distribution tails?

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Too small \( X_{\text{up}} \): \( \langle X_{\text{max}} \rangle < \langle X_{\text{max}}^{\infty} \rangle \) (biased!)

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Small $X_{\text{low}}$: $\langle X_{\text{max}} \rangle$ still $\langle X_{\infty} \rangle$
Study of the field of view bias

\[ \langle X_{\text{max}} \rangle \text{ vs. } X_{\text{low}} \text{ or } X_{\text{up}} \text{ limit} \]

\[ \log_{10}(E_{\text{cal}}/\text{eV}) \text{ Range: } 17.5 \div 17.6 \]

Too large \( X_{\text{low}} \): \( \langle X_{\text{max}} \rangle > \langle X_{\text{max}}^\infty \rangle \) (biased!)
The method uses the data itself optimizing the statistic

$$\log_{10}(E_{\text{cal}}/\text{eV}) \quad \text{Range: } 17.5 \div 17.6$$

$$X_{\text{low}} < X_{\text{fid}}^{\text{low}} \quad \text{and} \quad X_{\text{up}} > X_{\text{fid}}^{\text{up}}: \langle X_{\text{max}} \rangle \simeq \langle X_{\text{max}}^\infty \rangle \quad \text{(unbiased!)}$$

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