Measurement of the energy spectrum of cosmic rays with the Pierre Auger Observatory

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Existing CR detectors at highest energies

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km²
36 fluorescence telescopes

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km²
27 fluorescence telescopes

As any angular distribution on the unit sphere, the flux in each direction of the sky. In principle, the combined directional exposure of cosmic rays turn out to be not larger than few thousandths, yielding to non-uniformities in the observed directional exposure. However, for an unbiased estimator of the flux on an angular scale, the relationship between the sampling process when the function average is the flux of cosmic rays can be decomposed in terms of a multipolar expansion onto the spherical harmonics. With full-sky but non-uniform coverage, the customary parameter, in addition to the ones caused by the Poisson nature of the considered process whose average is the flux of cosmic rays, is given by

$$N_i \sim \left( \frac{2}{4\pi} \right) \cdot \left( \frac{1}{m} \right) \cdot \sum_{n=0}^{m} \frac{d}{n} \cdot \left( \frac{a}{b} \cdot \cos(n \cdot \ell) \right) \cdot \left( \frac{1}{m} \right)$$

where $$\langle r \rangle$$ is the relative directional exposure which is known from a single experiment, the averaged angular distribution by the inverse of the dead times of detectors modulate the directional exposure of each experiment in sidereal time and therefore in right ascension. However, once averaged over several years it will be described below. The resulting uncertainties propagate better than 1%.
The Pierre Auger Observatory

Fluorescence detector (FD)
- 4 sites
  - 0-30°
  - \(E > 10^{18}\) eV
- HEAT
  - 30°-60°
  - \(E > 10^{17}\) eV

Surface detector array (SD)
- Grid of 1500 m
  - 3000 km²
  - 1660 stations
  - \(E > 10^{18.5}\) eV
- Grid of 750 m
  - 24 km²
  - 61 stations
  - \(E > 10^{17.5}\) eV
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Hybrid detection

FD:
- calorimetric measurement of energy
- ca. 13% duty cycle

SD:
- data driven shape of LDF
- optimal distance at 1000 m
- ca. 100% duty cycle

$L S_{1000} \propto E$

Longitudinal profile

$L \propto \int \frac{dE}{dX} \, dX$
Zenith angle range of SD derived spectra

750m: \(0^\circ < \theta < 55^\circ\)
1500m: \(0^\circ < \theta < 60^\circ\)
1500m: \(60^\circ < \theta < 80^\circ\)

- \(E > 3 \times 10^{17}\) eV ‘vertical’
- \(E > 3 \times 10^{18}\) eV ‘vertical’
- \(E > 4 \times 10^{18}\) eV ‘inclined’

Depth of Malargüe site (870 g/cm\(^2\))
Footprint on ground depends on geometry and energy

- 1500 m
- \( \theta < 60^\circ \)
- 100% eff. @ 3 EeV \( E = A S_{38}^B \)

- 1500 m
- \( 60^\circ < \theta < 80^\circ \)
- 100% eff. @ 4 EeV \( E = A N_{19}^B \)
- \( N_{19} \) by definition independent of \( \theta \)

- 750 m
- \( \theta < 60^\circ \)
- 100% eff. @ 0.3 EeV \( E = A S_{35}^B \)

- FD + 1 SD station
- \( \theta < 60^\circ \)
- 100% eff. @ 1 EeV \( E = E_{FD} \)
SD energy estimator for $\theta<60^\circ$

$$S(r) = S(r_{\text{opt}}) f(r)$$

1500 m array: $S(r_{\text{opt}}) = S_{1000}$
750 m array: $S(r_{\text{opt}}) = S_{450}$

$\theta$-dependence (attenuation in atmosphere) corrected for using CIC
SD energy estimator for $\theta<60^\circ$

\[ S(r) = S(r_{opt}) f(r) \]

1500 m array: $S(r_{opt}) = S1000$
750 m array: $S(r_{opt}) = S450$

$\theta$-dependence (attenuation in atmosphere) corrected for using CIC
**SD energy estimator for θ>60°**

- Muonic component dominates
- \(( \approx 20\% \text{ residual e.m. component} )\)
- Energy estimator \(N_{19}\):
  \[
  N_{19} = \frac{\rho_{\mu}}{\rho_{\mu,19}(x,y,\theta,\phi)}
  \]
- Zenith angle independent
SD data: energy calibration

\[ E_{FD} = A S^B \]

Energy resolution
- 750m \( \theta < 55^\circ \): 13 \( \pm \) 1\% @ 0.3 EeV
- 1500m \( \theta < 60^\circ \): 15.3 \( \pm \) 0.4\% @ 3 EeV
- 1500m 60°\( \theta < 80^\circ \): 19 \( \pm \) 1\% @ 4 EeV

Data driven calibration
Air shower simulations are avoided
## FD CORRELATED UNCERTAINTIES

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute fluorescence yield</td>
<td>3.4%</td>
</tr>
<tr>
<td>Fluores. spectrum and quenching param.</td>
<td>1.1%</td>
</tr>
<tr>
<td><strong>Sub total (Fluorescence Yield)</strong></td>
<td><strong>3.6%</strong></td>
</tr>
<tr>
<td>Aerosol optical depth</td>
<td>3% — 6%</td>
</tr>
<tr>
<td>Aerosol phase function</td>
<td>1%</td>
</tr>
<tr>
<td>Wavelength dependence of aerosol scattering</td>
<td>0.5%</td>
</tr>
<tr>
<td>Atmospheric density profile</td>
<td>1%</td>
</tr>
<tr>
<td><strong>Sub total (Atmosphere)</strong></td>
<td><strong>3.4% — 6.2%</strong></td>
</tr>
<tr>
<td>Absolute FD calibration</td>
<td>9%</td>
</tr>
<tr>
<td>Nightly relative calibration</td>
<td>2%</td>
</tr>
<tr>
<td>Optical efficiency</td>
<td>3.5%</td>
</tr>
<tr>
<td><strong>Sub total (FD calibration)</strong></td>
<td><strong>9.9%</strong></td>
</tr>
<tr>
<td>Folding with point spread function</td>
<td>5%</td>
</tr>
<tr>
<td>Multiple scattering model</td>
<td>1%</td>
</tr>
<tr>
<td>Simulation bias</td>
<td>2%</td>
</tr>
<tr>
<td>Constraints in the Gaisser-Hillas fit</td>
<td>1% — 3.5%</td>
</tr>
<tr>
<td><strong>Sub total (FD profile rec.)</strong></td>
<td><strong>5.6% — 6.5%</strong></td>
</tr>
<tr>
<td>Invisible energy</td>
<td>1.5% — 3%</td>
</tr>
<tr>
<td>Statistical error of the SD calib. fit</td>
<td>0.7% — 1.8%</td>
</tr>
<tr>
<td>Stability of the energy scale</td>
<td>5%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>14%</strong></td>
</tr>
</tbody>
</table>

- Total uncertainty: 14% ≈ energy independent
- Largest contribution from FD calibration
- 1500 m array $\theta < 60^\circ$
Exposure for flux measurements

- Jan 2004 - Dec 2014: 42500
- Jan 2004 - Dec 2013: 10900
- Nov 2005 - Dec 2013: 1500 @ 10 EeV
- Aug 2008 - Dec 2014: 150

Exposure in $[\text{km}^2 \text{ sr yr}]$

SD: based on geometrical calculation
Hybrid: based on time-dependent MC simulations
Four measurements of the cosmic-ray flux

Systematic uncertainty on the flux
1500 m $\theta<$60°: 5.8%
1500 m $\theta>$60°: 5%
750 m: 14% (<7%) @ 0.3 (3) EeV
Hybrid: 10% (6%) @ 1 (10) EeV

Deconvolution of SD spectra done to account for finite energy resolution (<15% SD, <3% Hybrid)
Fractional differences

Reference flux:

\[ J(E) \propto E^{-3.26} \]

Positions of ankle and suppression consistent

Differences well within statistical and systematical uncertainties

⇒ Combined spectrum
Combined spectrum

Flux normalizations:
1500 m vertical: 5.7%
1500 m inclined: -0.1%
750 m: 1.8%
Hybrid: -5.8%
**Spectral features**

Flux model:

\[
E < E_{\text{ankle}}:\quad J(E) \propto E^{-\gamma_1}
\]

\[E > E_{\text{ankle}}:\quad J(E) \propto E^{-\gamma_2} \left[ 1 + \left( \frac{E}{E_s} \right)^{\Delta \gamma} \right]^{-1}
\]

\[E_{\text{ankle}} = 4.8 \pm 0.1 \pm 0.8 \text{ EeV}
\]

\[E_s = 42.1 \pm 1.7 \pm 7.6 \text{ EeV}
\]

\[E_{1/2} = 24.7 \pm 0.1^{+8.2}_{-3.4} \text{ EeV}
\]

\[I(E_{1/2}) = \frac{1}{2} \cdot I_0 \cdot \left( \frac{E_{1/2}}{E_s} \right)^{-\gamma_2 + 1}
\]
Discrepancy between TA/Auger due to declination dependent flux?

\[ \theta < 60^\circ \quad \Rightarrow \quad \text{Declination range: } -90^\circ \text{ to } +25^\circ \]
Discrepancy between TA/Auger due to declination dependent flux?

\[ \theta < 60^\circ \]
\[ \Rightarrow \text{Declination range: } -90^\circ \text{ to } +25^\circ \]

No indication of a declination-dependent flux
(differences between sub-spectra and all-sky flux < 5% below \( E_s \) and <13% above)

Auger-TA difference not explained
(still room, if TA flux is significantly larger above +25° than below)
Hint of a dipole anisotropy above 8 EeV

<table>
<thead>
<tr>
<th>E [EeV]</th>
<th>d</th>
<th>d_d</th>
<th>a_d</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-8</td>
<td>(2.7±1.2)%</td>
<td>-81°±17°</td>
<td>15°±115°</td>
</tr>
<tr>
<td>&gt;8</td>
<td>(7.3±1.5)%</td>
<td>-39°±13°</td>
<td>95°±13°</td>
</tr>
</tbody>
</table>

Amplitude in right ascension suggests a large-scale anisotropy with significance > 4σ
**Declination dependence of the flux**

Comparison with expectation from dipolar modulation measured obtained using data with $\theta < 80^\circ$ (gray band)

Observed sky divided into 2 declination bands to compute:

$$\frac{N_{\text{South}}}{N_{\text{North}}} = \frac{N(\delta < -29.47^\circ)}{N(\delta > -29.47^\circ)}$$

Observation compatible with dipole expectation within uncertainties.
Summary

• Four independent measurements using either SD and FD

• Using same energy scale derived from FD: Syst. uncertainty of 14%

• Combined spectrum above $3 \times 10^{17}$ eV up to beyond $10^{20}$ eV using data collected over more than 10 years

• declination dependence of measured flux:
  • TA/Auger discrepancy: No significant indication of variation in 4 declination bands
  • Ratio $N_{\text{South}}/N_{\text{North}}$ compatible with dipole anisotropy