Measurement of the UHECR Energy Spectrum using the surface detector of the Pierre Auger Observatory

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for the Pierre Auger Collaboration
Flux of Cosmic Rays

Fluxes of Cosmic Rays

(1 particle per m²-second)

Knee
(1 particle per m²-year)

Ankle
(1 particle per km²-year)
Flux of Cosmic Rays

(Particle flux: 1 particle per m²-second)

Knee
(1 particle per m²-year)

Ankle
(1 particle per km²-year)

Pierre Auger Observatory Energy > 10^{18} eV
Pierre Auger Observatory
research goals

Energy Spectrum of UHECR (E > $10^{18}$ eV)
→ Shape of the spectrum in the region of the GZK feature

Arrival Direction Distribution
→ Search for departure from isotropy - point sources

Mass Composition
→ Nuclei, photons, neutrinos, etc.
Pierre Auger Observatory
research goals

Energy Spectrum of UHECR (E > 10^{18} eV)
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Mass Composition
→ Nuclei, photons, neutrinos, etc.
Pierre Auger as a Hybrid detector
The Surface Detector Station

- Communications antenna
- GPS antenna
- Electronics enclosure
- Solar panels
- Battery box
- 3 – nine inch photomultiplier tubes
- Plastic tank with 12 tons of water
Inside Telescope Station

- 3.4 meter diameter segmented mirror
- 440 pixel camera
- Aperture stop and Optical filter
Surface Array (27 April 2009)

Surface Array
1600 detector stations
1.5 km spacing
3000 km²

Fluorescence Detectors
4 Telescope enclosures
6 Telescopes per enclosure
24 Telescopes total
Event reconstruction: $S(1000\text{m})$

Reconstruction procedure:

- $\chi^2$-method to fit angles ($\theta, \phi$)
- Likelihood method to fit a NKG-type function

$$S(r) = S(1000\text{m}) \left( \frac{r}{1000\text{m}} \right)^\beta \left( \frac{r + r_s}{1000\text{m} + r_s} \right)^\beta$$

Fitting parameters
- core
- $S(1000\text{m})$
- Slope $\beta$ fixed

$S(1000\text{m})$, signal at 1000m, is our Energy estimator
Fluorescence Reconstruction

- Fluorescence energy almost MC independent.

\[ E_{FD} = f_{inv} \times E_{em} \]
Event selection and acceptance

- Physics trigger T4: 3ToT
- Quality trigger T5: Tank with maximum signal surrounded by 6 active stations
- Full efficiency: \( E \sim 3 \times 10^{18} \text{ eV} \)
- Zenith angle range: \([0, 60^\circ]\)
- Data period: Jan 1st, 2004 to Feb 28th, 2007
- Exposure: \(5100 \text{ km}^2 \text{ sr yr}\) uncertainty 3%
Energy Calibration
S(1000m) attenuation

- For the same energy S(1000m) decrease with the zenith angle.

- We extract the shape of the attenuation curve from data.

- We convert S(1000m) to S_{38}, which would be the signal if the shower arrive at 38°

\[ x = \cos^2(\theta) - \cos^2(38°) \]
\[ a = 0.94 \pm 0.06 \]
\[ b = -1.21 \pm 0.27 \]
\[ S_{38} = \frac{S(1000m)}{1 + ax + bx^2} \]
\[ S_{38^\circ} \] and \( E_{FD} \) uncertainties

- **Uncertainties on \( E_{FD} \):**

\[
\sigma^2_{E_{FD}} = \sigma^2_{GH - Fit} + \sigma^2_{Geom.} + \sigma^2_{Inv. Energy} + \sigma^2_{VAOD}
\]

- **Uncertainties on \( S_{38^\circ} \):**

\[
\sigma^2_{S_{38^\circ}} = \sigma^2_{(CIC)} + \sigma^2_{(\cos \theta)} + \sigma^2_{(S(1000m))}
\]

\[
\sigma^2_{(S(1000m))} = \sigma^2_{Shower - Fluctuation} + \sigma^2_{(LDF - Fit)} + \sigma^2_{\beta_{sys}}
\]
Energy calibration fit

$E_{FD} = aS^b_{38^0}$

$a = 1.49 \pm 0.06\text{(stat)} \pm 0.12\text{(syst)} \times 10^{17} \text{ eV}$

$b = 1.08 \pm 0.01\text{(stat)} \pm 0.04\text{(syst)}$

$\chi^2/\text{n.d.f.} = 1.1$
Energy resolution

Mean 0.02 ± 0.01

RMS 0.19 ± 0.01

\[
\frac{\sigma}{E} = \frac{\sigma_{ESD}(\sigma S_{38^\circ})}{E_{SD}} \otimes \frac{\sigma_{EFD}}{E_{FD}} = 19\%
\]

Consistency between estimated SD and FD energy uncertainties and measurements.
Orthogonal pull distribution

\[
x = \log_{10} S_{38°} \\
y = \log_{10} E_{FD} \\
pull = \frac{y - (A + Bx)}{\sqrt{\sigma_y^2 + B^2 \sigma_x^2}}
\]

Mean 0.02 ± 0.01
RMS 1.01 ± 0.01
Systematic uncertainties in the FD energy measurement

<table>
<thead>
<tr>
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**TOTAL SYST.** 24%
Systematic uncertainties in the FD energy measurement

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**TOTAL SYST.** 24%
Energy Spectrum
Relative Flux

$\gamma = 2.69$
Combined Energy Spectrum: SD + Hybrid

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

\[ J(E; E < E_{\text{ankle}}) \propto E^{-\gamma_2} \frac{1}{1 + \exp\left( \frac{\log_{10} E - \log_{10} E_c}{W_c} \right)} \]

\[ \gamma_1 = 3.30 \pm 0.06 \]

\[ \gamma_2 = 2.56 \pm 0.06 \]

\[ \log_{10} E_{\text{ankle}} = 18.65 \pm 0.04 \]

\[ \log_{10} E_c = 19.74 \pm 0.06 \]

\[ W_c = 0.16 \pm 0.04 \]
Summary and conclusions

- Energy calibration using high quality hybrid events.
- Exposure by a factor 2.5 larger than forerunner experiments.
- Systematics and uncertainties are under control. Will be reduced in future.
- Power law fit: \( J \propto E^{-\gamma} \):
  - For \( E \) [4x10^{18}, 4x10^{19}] \text{ eV} \), \( \gamma = 2.69 \pm 0.02 \text{(stat)} \pm 0.06 \text{(syst)} \)
  - For \( E \) above 4x10^{19} \text{ eV}, \( \gamma = 4.2 \pm 0.4 \text{(stat)} \pm 0.06 \text{(syst)}. \)
  - For \( E \) below 4x10^{18} \text{ eV}, spectral index change will be study with hybrid.
- We reject the hypothesis that the cosmic ray spectrum continues with a constant slope above 4x10^{19} \text{ eV}, with a significance of 6 standard deviations.