Measurement of the energy spectrum of ultra-high energy cosmic rays using the Pierre Auger Observatory

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Hybrid Observatory

Surface Detector array (SD)
1661 water-Cherenkov detectors on 1500 m and 750 m triangular grid

(+) duty cycle ~ 100%
(-) shower size at ground $\propto E$ (systematics)

Fluorescence Detector (FD)
27 telescopes in 4 sites

(-) duty cycle ~ 15%
(+) calorimetric measurement of $E$

- energy scale of the Observatory set by the FD with a 14% systematic uncertainty
- precise measurement of the flux up to $10^{20}$ eV
energy spectrum over 4 decades in energy

SD 1500 m
θ < 60°
E > 10^{18.4} eV

discovery
improved analysis

FD + SD stat. hybrid
(15% duty cycle)
E > 10^{18} eV

SD 1500 m
60° < θ < 80°
E > 10^{18.6} eV

signal ~ N\(_μ\)

FD-HEAT Cherenkov

SD 750 m
θ < 40°

A. Coleman #225
E > 10^{17} eV

V. Novotny #374
E > 10^{16.5} eV
energy estimation for 1500 m array $\theta < 60^0$ events

fit the lateral distribution of the signals to get $S(1000)$

D. Mockler #353

use the CIC method to remove the zenith angle dependence of $S(1000)$. CIC at different intensity thresholds

note: correction determined from data (no use of simulations)
energy estimation for 1500 m array
θ < 60° events

high-quality events triggered independently by SD and FD

correlation well described by a power-law relationship

maximum-likelihood fit using a “bootstrap” estimate of the p.d.f. and event-by-event uncertainties
raw energy spectrum using 1500 m array
\( \theta < 60^0 \) events

\[
J = f_{\text{res}} J_{\text{raw}} = f_{\text{res}} \frac{N}{\varepsilon \Delta E}
\]

measurements done with full trigger efficiency

\( \varepsilon = (60400 \pm 1800) \text{ km}^2 \text{sr yr} \)

215030 events
with \( E > 10^{18.4} \text{ eV} \)
ingredients to calculate $f_{\text{res}}$ from hybrid data

$E \approx 1 \text{ EeV}$

$E \approx 10 \text{ EeV}$

$E_{SD}$ resolution knowing the $E_{FD}$ one

also $E_{SD}$ bias and trigger efficiency at lower energies
unfolded spectrum

$f_{\text{res}}$ calculated using a forward-folding technique

- new function: sequence of 4 power-laws with 3 inflection points
- previous function: slow transition between ankle and suppression
- $f_{\text{res}}$ small at all energies

previous function discarded with a significance of 3.2$\sigma$
full trigger efficiency
exposure (30% more)
17447 km² sr yr

above $10^{18.6}$ eV
24209 events

similar data-driven
approach but
completely different
reconstruction
technique

energy resolution
22% - 10%
13655 events above $10^{18}$ eV

full time-dependent simulation of FD events

exposure [km$^2$ sr yr]
1 EeV 265 km$^2$ sr yr
10 EeV 2248 km$^2$ sr yr

energy resolution $\approx 7.4\%$
A. Coleman #225

full trigger efficiency
exposure
105 km² sr yr

569285 events
above $10^{17}$ eV

data-driven
approach similar
to the ones of the
1500m array
69793 events above $10^{16.5}$ eV

Energy deposited from a profile constrained geometry fit and invisible energy correction inferred from muon data

Exposure from full time-dependent simulation of FD events
fluxes in good agreement among them once rescaled by normalization factors that are consistent with the systematic uncertainties
combined spectrum

\[ \log_{10}(E/\text{eV}) \]

\[ J(E) \times E^3 \text{ [km}^{-2} \text{ yr}^{-1} \text{ sr}^{-1} \text{ eV}^2] \]

\[ \gamma_0 = 2.92 \pm 0.05 \]
\[ \gamma_1 = 3.27 \pm 0.05 \]
\[ \gamma_3 = 3.2 \pm 0.1 \]
\[ \gamma_4 = 5.4 \pm 0.6 \]

Auger combined (preliminary)

\[ E_{01} = 0.15 \pm 0.02 \]
\[ E_{12} = 6.2 \pm 0.9 \]
\[ E_{23} = 12 \pm 2 \]
\[ E_{34} = 50 \pm 7 \]

(energies in EeV units)

‘previous’ function discarded at the 4σ level
OUTLOOK

• improved 1500 m array $\theta < 60^0$ spectrum (no use of simulations)
• independent measurements with 1500 m array $\theta > 60^0$ and hybrid events
• lower the threshold down to $10^{16.5}$ eV with the 750 m and Cherenkov events

- combined spectrum with a common energy scale:
  - second knee and ankle
  - an indication of a further inflection point at $E \sim 10$ EeV
  - abrupt suppression at the highest energies
THANKS
1500 m array $\theta < 60^0$ spectrum: ICRC2019 vs ICRC2017
$J \sim E^{-\gamma}$

A. Castellina highlight