Measurement of the cosmic ray energy spectrum above 1 EeV at the Pierre Auger Observatory

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PIERRE AUGER OBSERVATORY

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

Ultra High Energy Cosmic Rays (UHECR)

- most energetic source of elementary particles available to scientists macroscopic energies $E > 1$ EeV (10^{18} eV)
- but very low flux !

$\Rightarrow$ Identifying them and their origin: the aim of UHECR study

Extensive air shower

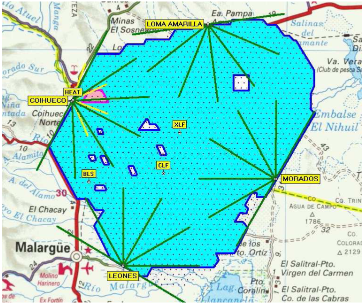
- UHECR produce large shower of particles in Earth's atmosphere (calorimeter)
- cosmic particle characteristics obtained from the measured properties of extensive air showers

Pierre Auger Observatory: to study the cosmic rays above 1 EeV

Hybrid detector → capability to measure:

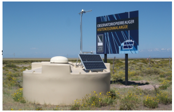
- longitudinal development in atmosphere with fluorescence light telescopes
- lateral spread at ground level with ground based particle detectors

The largest cosmic ray detector in operation

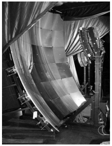


Data taking started in 2004, detector completed in 2008

- 3000 km^2 in pampa Amarilla, Argentina
- surface detector (SD)
  - 1660 water Cherenkov detectors, triangular grid, 1500 m spacing
  - $\sim$ 100% duty cycle



- fluorescence detector (FD)
  - 24 optical detectors in 4 buildings
  - $\sim$ 13% duty cycle

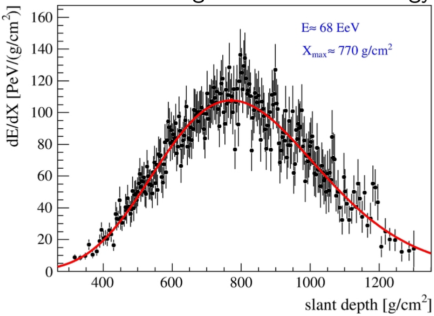


Shower geometry

Timing information from the FD and the SD station with the largest signal
Angular resolution better than 1°

Calorimetric energy measurement

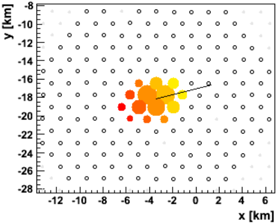
- Collected light converted in energy deposit as a function of traversed matter



- Longitudinal shower profile: Gaisser-Hillas function
- Energy of the cosmic ray
  - integral over the entire longitudinal profile
  - correction for E_{inv} carried away by ν and high energy μ ($\sim$ 9%)
- FD energy resolution: 7.6% (constant with energy)

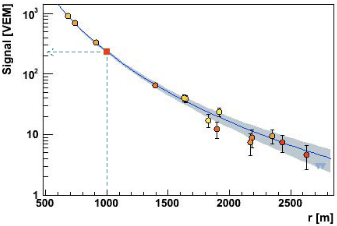
Shower geometry and lateral distribution

- shower axis from particle arrival time
  angular resolution $< 1^{\circ}$ if $N_{\rm st} \geq 6$
- impact point and lateral distribution from a global likelihood



SD Energy estimator

- $S(1000)$: signal at 1000 m (fluctuations of the LDF minimized)
- Constant Intensity Cut (CIC) method to correct for the attenuation
  based on data $\Rightarrow$ no resort to simulation
- $S_{38} = \frac{S(1000)}{CIC(\theta)}$

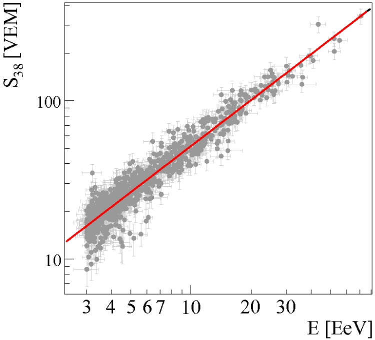


Calibration of the SD energy estimator: with hybrid events

Energy calibration

Aim: relate the SD energy estimator to the FD energy measurement

- subset of high quality hybrid events reconstructed by both SD and FD: 839 selected events with $E_{FD} \geq 3$ EeV
- relation between S_{38} and E_{FD} well described by : $E_{FD} = A\ S_{38}^{B}$
- Systematics uncertainty: 7% at 10 EeV, 15% at 100 EeV



Hybrid concept ⇒ calibration method ∼ independent of MC simulation

SD energy resolution

- inferred from $\frac{E_{SD}}{E_{FD}}$ distribution
- from 16% at threshold to 12% for $E > 10$ EeV

SD spectrum I

Event selection

- zenith angle $< 60^\circ$
- station with greatest signal surrounded by a hexagon of operating stations

$\sim$ 64000 events above 3 EeV, $\sim$ 5000 events above 10 EeV

SD exposure

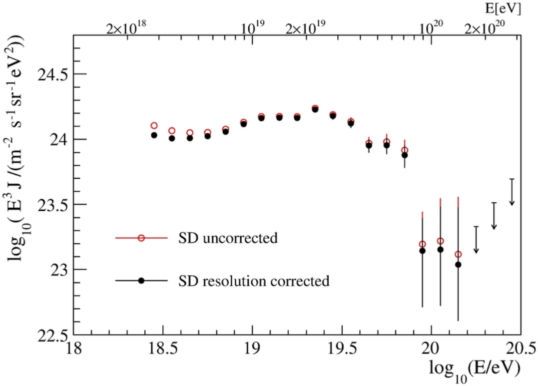
- Integrating the number of active stations over time
  - for $E > 3$ EeV, acceptance saturated
  - acceptance free of MC assumption
  - uncertainty on exposure: 3%
- from Jan 2004 to Dec 2010: 20905 km^2 sr yr

Determination of the flux

- Influence of the bin-to-bin migration due to the energy resolution
- corrected by a foward folding approach
- weakly energy dependant, $< 20\%$ on the energy range

SD spectrum II

- total systematic incertainty on the flux: 6% (exposure + forward folding)



- energy scale affected by a systematic error of 22% due to the uncertainty on the fluorescence energy assignment.

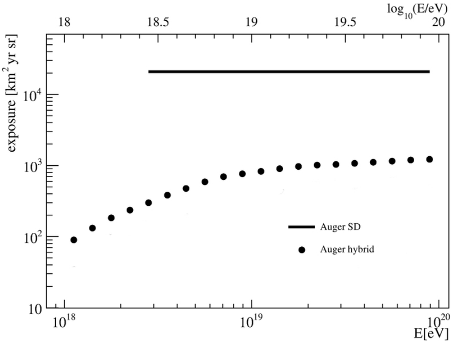
Hybrid spectrum I

Event selection

- zenith angle $< 60^\circ$
- strict quality criteria and anti-bias cuts $\Rightarrow$ to minimize the influence of mass composition on the exposure

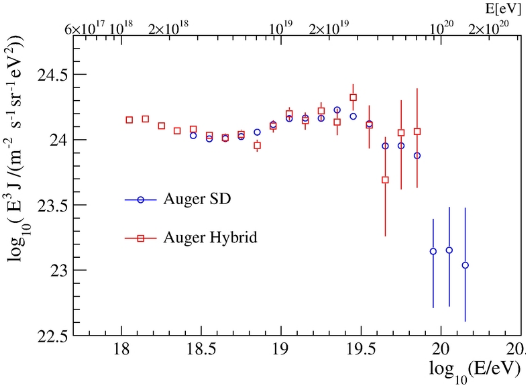
Hybrid exposure

- challenge: energy dependant hybrid exposure calculation
- time dependant MC simulation (every 10 minutes)
  - detector conditions (SD and FD)
  - measured atmospheric conditions
  - monitoring informations
- Nov 2005 - Sep 2010



Hybrid spectrum II

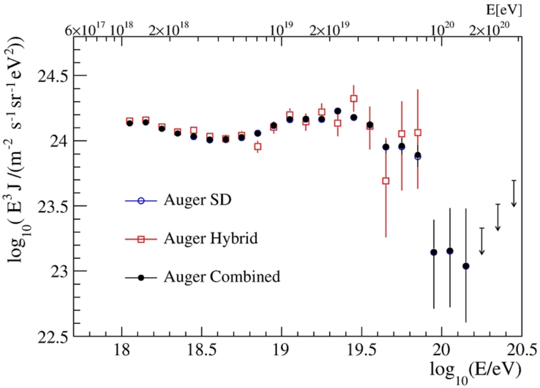
- systematic uncertainty in the hybrid spectrum dominated by exposure calculation: 10% at 1 EeV, 6% for $E > 10$ EeV



- very good agreement between SD and hybrid energy spectra

Combined energy spectrum I

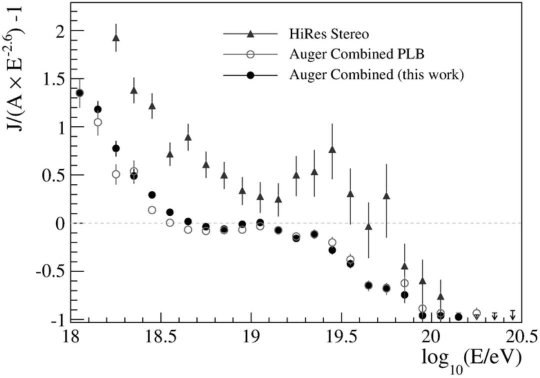
- Using a maximum likelihood method to combine spectra



- common systematic uncertainty on energy scale for both data sets: 22%
- matching scale factors: $k_{SD} = 1.01$, $k_{FD} = 0.99$

Fractional difference

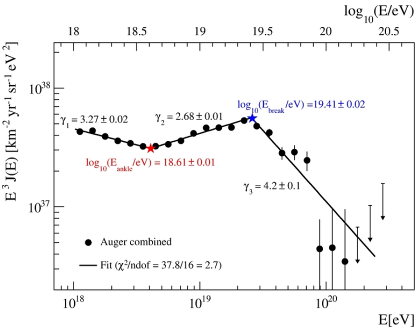
- combined energy spectrum / assumed flux $\propto E^{-2.6}$



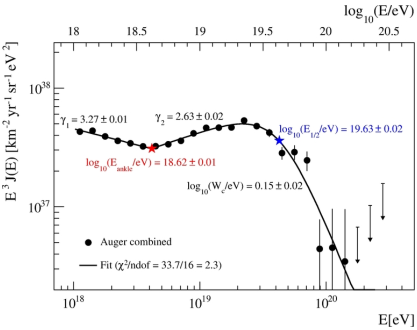
- compatible within the systematic uncertainties with previous publication (*Phys. Lett. B 685 (2010) 239–246*) (changes in calibration)
- measurements (stereo mode) from the HiRes experiment: for comparison

Main features of the measured UHECR spectrum

Three power laws with free breaks



Two power laws + smoothly changing function



- break between the 2 power laws: the *ankle*, observed at $\sim$ 4 EeV
  - traditionally: transition from the galactic component to a flux dominated by extragalactic sources.
- suppression of the flux above 40 EeV
  - compatible with the predicted Greisen-Zatsepin-Kuz'min (GZK) effect (energy loss in interactions with CMB photons)

Pierre Auger Observatory

- largest cosmic ray detector in operation, highest precision ever achieved
- hybrid detection: the SD provides huge aperture easily calculable, the FD nearly calorimetric energy measurement, and calibrates SD energy scale
- minimal use of simulations in the production of key scientific outputs

UHECR spectrum

- Two independent methods (SD and Hybrid)
    - compatible results
    - precise measurement over a wide energy range from 1 EeV to 100 EeV.
- The combined Auger spectrum has been derived: precise measurement of both the ankle and the flux suppression at highest energies.

Furthermore

- The Pierre Auger experiment has produced many other results concerning the UHECR mass composition, the search for anisotropies: next talks !
- Low energy enhancements of the Observatory to investigate the flux spectrum and the composition of cosmic rays with $E > 0.1$ EeV: poster !