Measurement of the Second Knee in the Spectrum of Cosmic Rays with the Surface Detector of the Pierre Auger Observatory

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The SD-433

Densest array of the Auger Surface detector (SD)

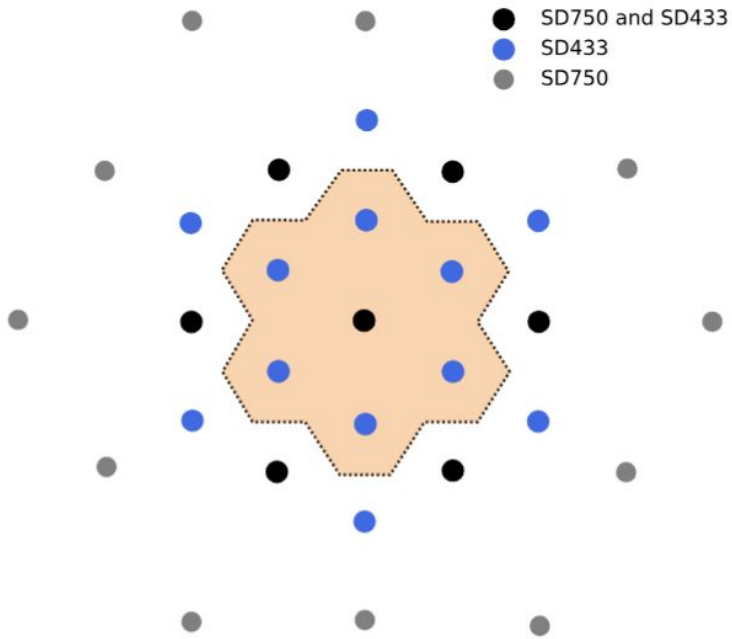
19 WCD

1.9 km^2 area / 1.1 km^2 effective area

ε = (3.87± 0.15) km^2 sr yr

Offline Reconstruction from ICRC 2023

Phase I spectrum from Jan 2018 - Dec 2021



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SD433 Efficiency

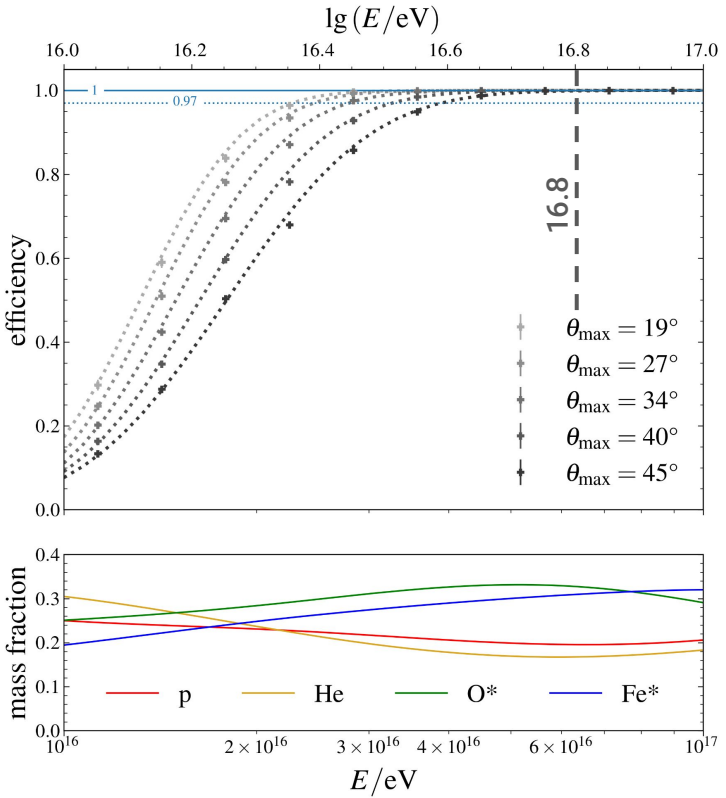
Estimated with CORSIKA simulations

EPOS-LHC and FLUKA

Mass fraction using GSF Mix

Full efficiency at $10^{16.8}$ eV for θ<45°

Test of the core distribution uniformity to verify full efficiency



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Signal correction by zenith angle

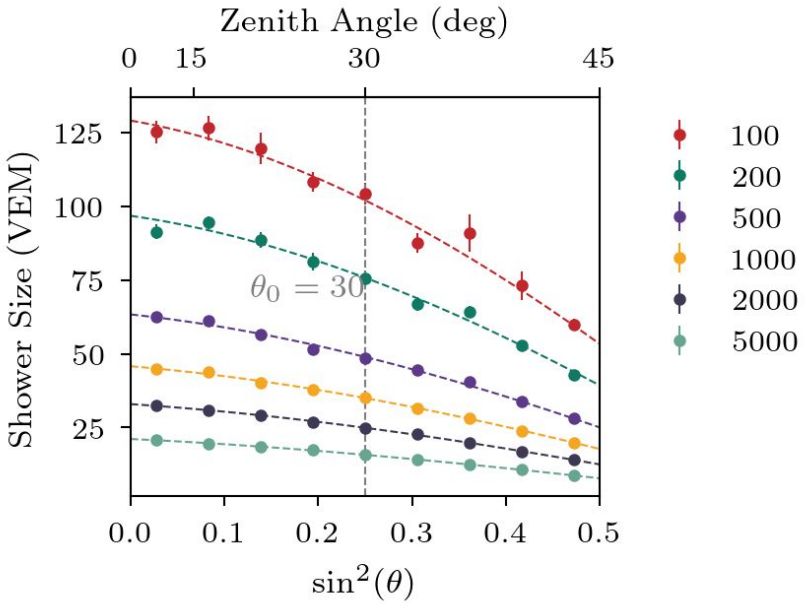
Shower size corrected via Constant Intensity Cut

Countdown method with energy dependence

3rd degree polynomial in x = $\sin^2(\theta) - \sin^2(\theta_0)$

1st degree polynomial in y = $\lg(S_{30} / 40\,\mathrm{VEM})$

$$f_{att}(x, y) = 1 + (\alpha_0 + \alpha_1 y)\, x + (\beta_0 + \beta_1 y) x^2 + \gamma_0 x^3$$



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Energy Calibration

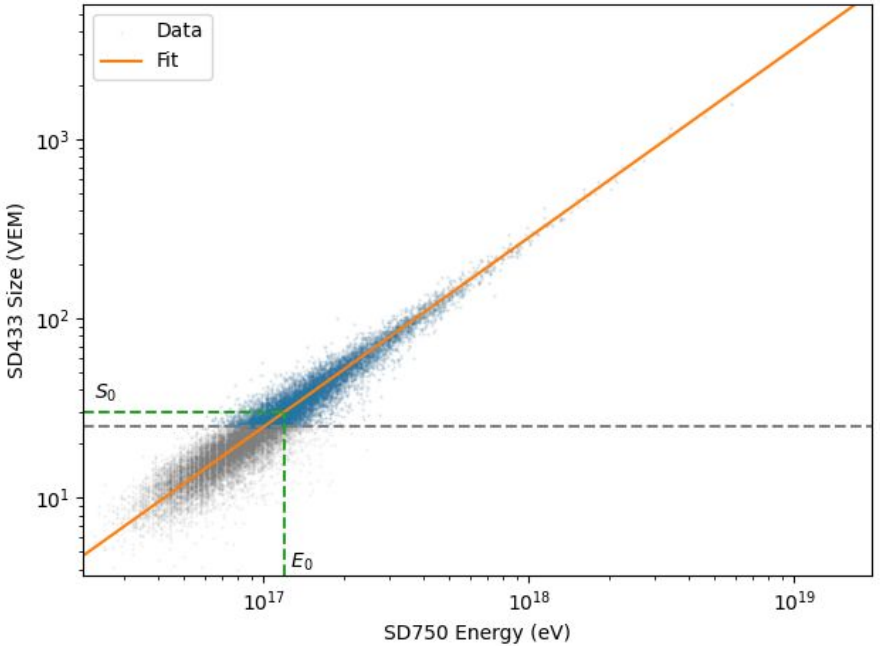
Calibration made with the SD-750 and SD-433 simultaneous events

Events from Herald SD-750 dataset from EPJ 2020 Wiki

Likelihood fit with the correlation between the detectors included

$$E = A\left(\frac{S_{30}}{30\ \mathrm{VEM}}\right)^{B}$$

$A = (117.0 \pm 0.4)\,\mathrm{PeV}$ $B = 0.963 \pm 0.003$



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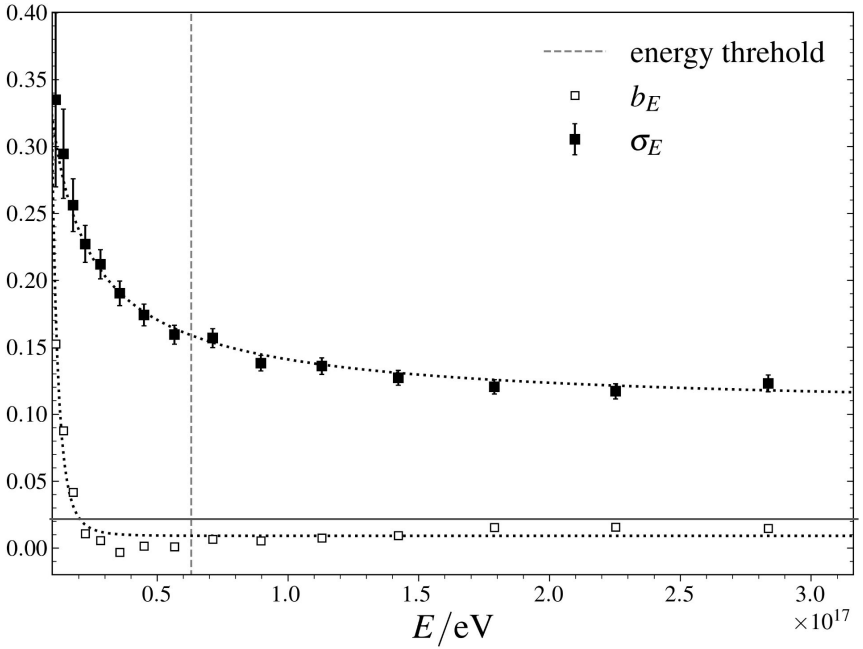
Energy bias and resolution

Bias and resolution measured from Simulations.

Less than 2% from the 16.6 bin

Resolution ~15% at the full efficiency threshold

Elements needed to fit and unfold the spectrum



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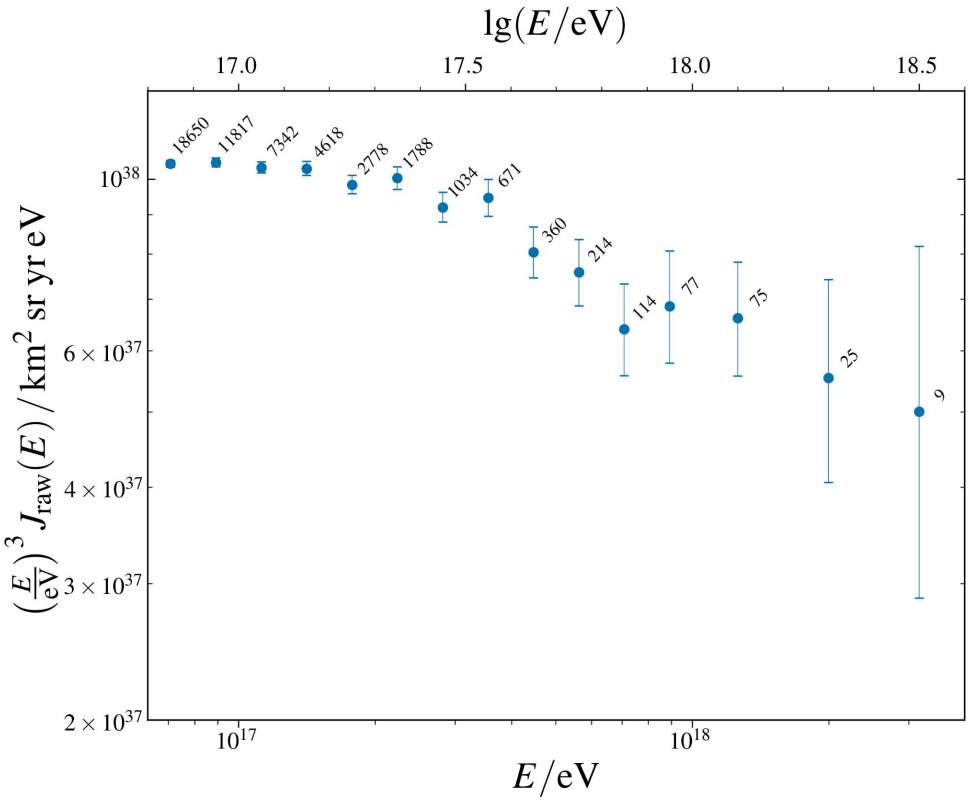
Raw spectrum

6T5 Events

$\theta < 45^{\circ}$

The 2nd knee is hinted even before unfolding



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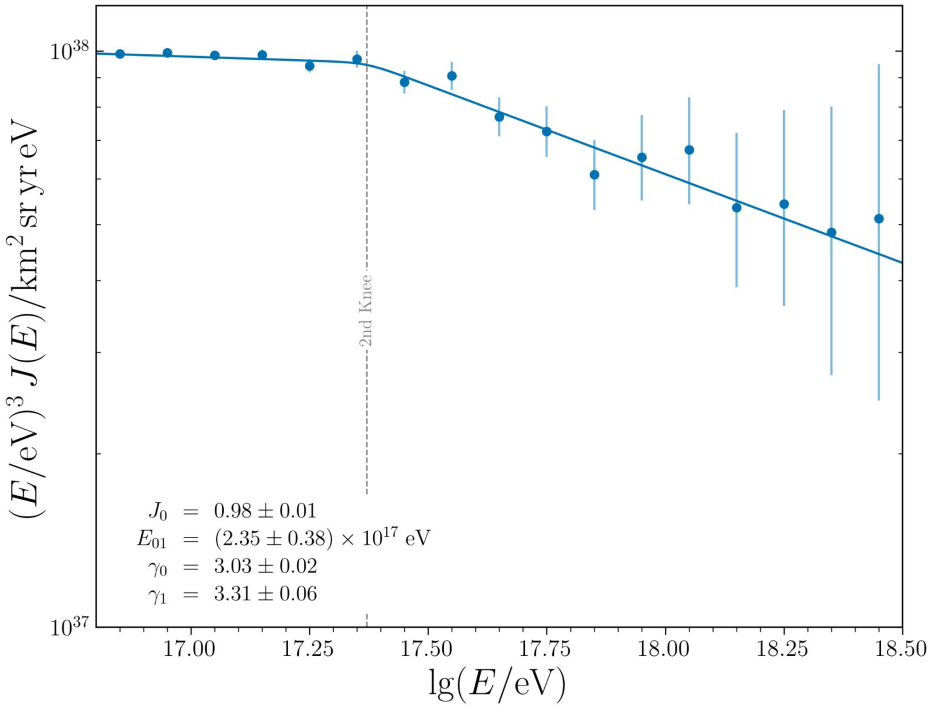
Unfolded spectrum

First measurement of the 2nd knee with Auger SD

Correction factors between 0.9 and 1.0 in all the spectrum energy range.

Proper characterization of spectral indexes before and after the 2nd knee.

p-val = 0.66



Spectrum systematics

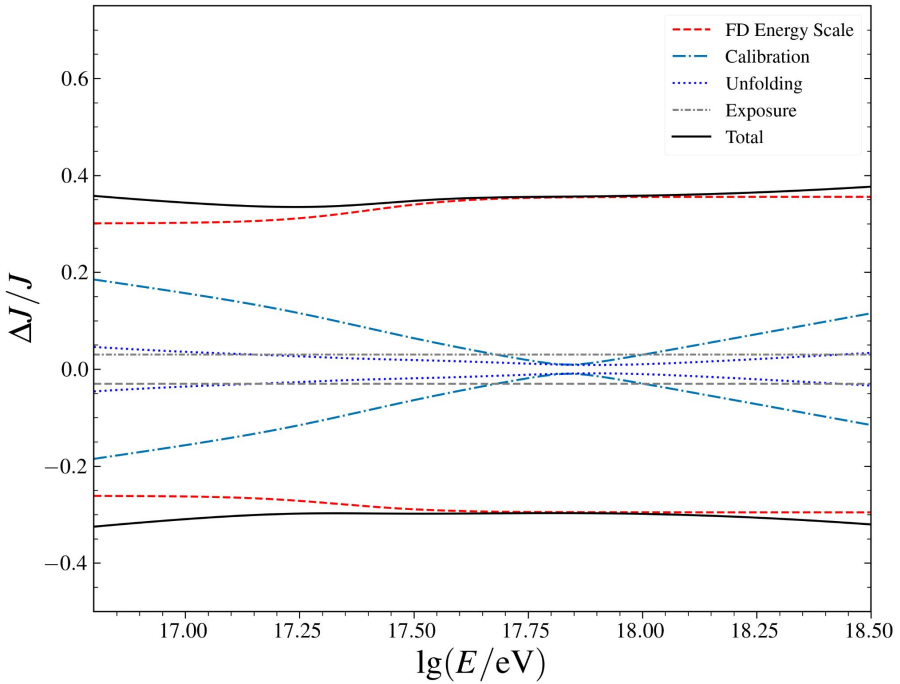
14% uncertainty in the FD energy scale

Calibration systematics

Unfolding assumptions

Exposure uncertainty

~ 37% overall systematic uncertainty in the flux



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Combined SD-433 and SD-750 spectrum

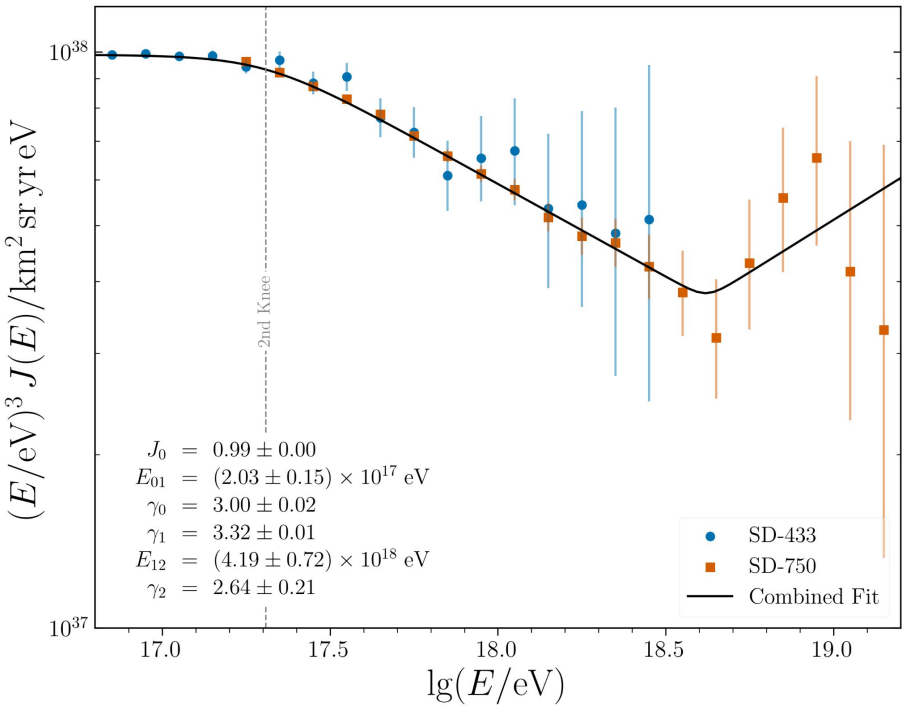
The combination requires no adjustments

The model fits well the observed data

p-val = 0.58

SD-433 dominates at lower energies allowing the measurement of the 2nd Knee

SD-750 provides coverage up to the ankle



The two features are measured simultaneously

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Conclusions

- First measurement of the 2nd Knee with the Auger Surface Detector
- The energy threshold of the SD-433 enables the characterization the 2nd Knee
- Systematic uncertainties under control
- Out of the box combination of SD-433 with the SD-750 spectra
- Simultaneous measurement of the 2nd Knee and the Ankle

Further work:

Update the reconstruction to Offline ICRC 2025

Update the SD-750 calibration

SD-433 Paper

Editorial board conformed:

- Gabriel Brichetto Orquera
- Piera Ghia
- Diego Ravignani
- Markus Roth
- Darko Veberic
- Brian Wundheiler

Weekly meetings

Paper already drafted

More info on the wiki!

Measurement of the Second Knee in the Spectrum of Cosmic Rays with the Surface Detector of the Pierre Auger Observatory

The Pierre Auger Collaboration

Abstract

Determining the energy spectrum features with low systematic uncertainty is crucial for interpreting the nature of cosmic rays. In this study, we measured the energy spectrum at the Pierre Auger Observatory using a surface detector with a calorimetric energy scale indirectly set by a fluorescence detector. The surface detector consists of an array of water-Cherenkov detectors that extends over 3000 km^2 with 1500 m spacing. In addition, two nested arrays of the same kind with 750 m and 433 m spacing were utilized to lower the energy threshold of the measurements. This contribution presents, for the first time, the spectrum measured with the 433 m array, which reduces the energy threshold to 63 PeV, nearly half the energy at which we previously published a steepening using the 750 m array. Our measurements include a characterization of the spectral features of the steepening of the flux around 230 PeV, known as the second knee. The study benefits from a nearly 100% duty cycle and geometrical exposure. Notably, this is the first simultaneous measurement of the second knee energy and spectral indices before and after the break, using a surface detector with an energy scale predominantly independent of air shower simulations and assumptions regarding hadronic interaction models.

1 Introduction

Multiple evidence suggests that the transition from Galactic to extragalactic cosmic rays occurs for their energies between 100 PeV and a few EeV [1]. Thus, different astrophysical phenomena, which overlap and intertwine, are expected to be at play in this energy region. To disentangle possible scenarios, it is crucial to precisely measure the all-particle energy spectrum and the abundance of the different elements as a function of energy. The "Second Knee" is a feature of the cosmic-ray spectrum that is believed to be related to the transition from galactic to extragalactic sources. The KASCADE experiment first discovered this feature [2], which was later confirmed by the TUNKA [?] and TALE [?] experiments. However, given the energy ranges of these experiments, a proper characterization of the feature is yet to be achieved.

To enable high-statistics measurements of the spectrum in this region, the Pierre Auger Collaboration has within the Pierre Auger Observatory built two denser surface arrays spaced at 750 m (SD-750) and 433 m (SD-433), both nested inside the larger main array (SD-1500) spaced at 1500 m. The observatory is currently undergoing an AugerPrime upgrade [?] to enable a multi-hybrid detection that will allow the estimation of the mass composition of primary cosmic rays [3] and search for primary photons [4].

Using data from SD-750, we previously measured the energy spectrum down to 100 PeV [5], where we observed a broad softening of the spectrum. In this work, we report on the measurement of the energy spectrum made with SD-433 that for the first time reaches down to 63 PeV, thus enabling a comprehensive characterization of the "Second Knee".

The SD-433 consists of 19 water-Cherenkov detectors (WCDs), identical to those used in the other two Auger surface arrays [6]. It is nested within SD-750, sharing seven detectors, as shown in Fig. 1. Data collection began in the year 2013 with a single hexagon of WCDs installed surrounding a central detector. The array was progressively expanded and reached its current configuration comprised of seven hexagons in May 2019. The data-taking period concluded in December 2021 with the upgrade of the detector electronics.

In Section 2.2, we describe the SD-433 array and its response obtained from simulations. Section 3 focuses on the event reconstruction performed with SD-433, also describing the energy calibration and the estimation of its resolution and bias. The following is Section 4, where we present the spectrum measurement based on data collected from 01 January 2018 until including 31 December 2021. We also describe the method to unfold the detector effects on the measurement. Finally, in Section 4.2 we combine the SD-433 measurement with the SD-750 results to report a spectrum over a wider energy range.

2 Acquisition of the dataset

2.1 The Pierre Auger Observatory

Located in the Pampa Amarilla, near Malargüe in Mendoza, Argentina, the Pierre Auger Observatory (PAO) has pioneered the hybrid cosmic-ray detection technique. A detailed description of the observatory can be found in Ref. [6]. Since 2021, the observatory has undergone a major upgrade with new detectors to transition towards a multi-hybrid observatory [?]. To measure the spectrum at low energies, we rely on the 100% duty cycle of the Surface Detector (SD). The SD consists of three nested arrays of water-Cherenkov detectors (WCDs) in a triangular grid with 1600 detectors with 1500 m spacing, 71 with 750 m spacing, and 19 separated by 433 m. Each WCD consists of a 3.6 meter-diameter tank filled with ultra-pure water where three photomultipliers detect the Cherenkov radiation emitted by passing charged particles. All data are stored in the central data centre located in Malargüe and are reconstructed with the

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