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THE PIERRE AUGER OBSERVATORY: STUDYING THE HIGHEST ENERGY FRONTIER

We highlight the main results obtained by the Pierre Auger Collaboration in its quest to unveil the mysteries associated with the nature and origin of the ultra-high energy cosmic rays, the highest-energy particles in the Universe. The observatory has steadily produced high-quality data for more than 15 years, which have already led to a number of major breakthroughs in the field contributing to the advance of our understanding of these extremely energetic particles. The interpretation of our measurements so far opens new questions which will be addressed by the on-going upgrade of the Pierre Auger Observatory.

Keywords: astroparticle physics, high-energy cosmic rays, multi-messenger astrophysics, hadronic interactions.

1. Introduction

Over a century after the discovery of cosmic rays, there are still a number of open, fundamental questions about their nature, especially about those with energies above 10^{17} eV, referred to as ultra-high energy cosmic rays (UHECRs). The Pierre Auger Observatory [1], the largest ultra-high energy cosmic-ray detector built so far in the world, was conceived to unveil the most important questions, namely the origin, propagation, and properties of UHECRs, and to study the interactions of these, the most energetic particles observed in Nature. To achieve the scientific goals, the Observatory was designed as an instrument for the detection of air showers initiated by the cosmic rays in Earth's atmosphere. Measured properties of the extensive air showers (EAS) allow determining the energy and arrival direction of each cosmic ray and provide a statistical determination of the distribution of primary masses.

Apart from measuring UHECRs, the Pierre Auger Observatory is a multi-purpose observatory for the extreme energy Universe with multi-messenger observations. In fact, it has shown an excellent sensitivity to EeV neutrino and photon fluxes due to its vast collecting area and its ability to efficiently discriminate between those neutral particles and hadronic cosmic rays. The Auger Observatory also offers a unique window to study particle physics at the high-energy frontier, held by UHECRs, easily reaching centre-of-mass energies ten times larger than the Large Hadron Collider (LHC) at CERN. Observables from the EAS allow improving our understanding of hadronic interactions at the higher energies.

2. The Pierre Auger Observatory

The Auger Observatory is located in a vast, high area near the small town of Malargüe in western Argentina at the latitude of about 35.2° S and the altitude of 1400 m above the sea level. Completed in 2008, it is a hybrid detector that combines an array of particle detectors, the Surface Detector array (SD), to observe the secondary shower particles that reach the ground, and Fluorescence Detector (FD) telescopes to collect the ultraviolet-light emitted by nitrogen air molecules during the shower development in the atmosphere. The SD comprises 1660 water-Cherenkov detectors (WCDs) laid out on a triangular grid with 1500 m spacing, covering an area of about 3000 km^2. Nested within this array is a low-energy extension to the SD which is comprised of 61 identical detectors with half the grid-spacing, 750 m, covering an area of 23.5 km^2. The FD comprises 24 telescopes at four perimeter buildings viewing the atmosphere over the array. A single telescope has a field of view of $30° \times 30°$ with a minimum elevation of $1.5°$ above the horizon. Three additional telescopes, the High Elevation Auger Telescopes (HEAT), cover an elevation up to $60°$ to detect the low-energy showers in coincidence with the 750 m array. The hybrid technique developed in the Auger Observatory exploits the large aperture of the SD, operating continuously, as well as the nearly calorimetric measurement of the shower energy deposited in the atmosphere obtained with the FD which, by contrast, has its on-time limited to clear moonless nights ($\sim$13%). Thanks to the combination of the FD and SD measurements, the energy scale of the Observatory is set with the FD measurement with a good control over the associated systematic uncertainties. Given the fact that the atmosphere acts as a calorimeter for the FD, a comprehensive monitoring of the atmosphere, particularly of the aerosol content and the cloud cover, is undertaken accurately with a set of high-quality monitoring devices, as described in [1].

The Observatory setup is complemented by two more detector types. The Auger Muons and Infill for the Ground Array (AMIGA) enhancement consists of coupling WCD and buried scintillation detectors deployed in two superimposed hexagon grids: the 750 m array and an even denser array with a 433 m spacing covering an area of 1.9 km^2. AMIGA provides direct measurements of the muon content in air showers. The Auger Engineering Radio Array (AERA) complements the Auger Observatory with a 17 km^2 array of more than 150 radio-antenna stations, colocated with the 750 m array, that measures EAS with energies between 10^{17} eV and several 10^{18} eV via their radio emission in the 30–80 MHz frequency band. The Auger Observatory layout is shown in Fig. 1.

3. Latest Results

Collecting scientific data since 2004, the results of the Pierre Auger Observatory have dramatically advanced our understanding of UHECRs during the last decade. In this section, a brief review of the recent highlights is given.

3.1. Energy spectrum

The measurement of the cosmic-ray energy spectrum is one of the cornerstones of astroparticle physics, since it encodes the very important information about the mechanisms of CR generation and propagation. The distribution of their sources, propagation effects, transitions over the types of particles, and classes of sources shape the spectrum.

The cosmic-ray energy spectrum above $10^{16.5}$ eV up to its very end above 10^{20} eV has been measured at the Auger Observatory with unprecedented statistics [2]. Five independent and complementary data sets collected between 1 January 2004 and 31 August 2018 have been used, with a total exposure of approximately 80000 km^2 sr yr. The method to derive the spectra is unique in this energy region, because it is entirely data-driven and nearly free of model-dependent assumptions about hadronic interactions in air showers. Two of these data sets have allowed the recent extension of the flux measurement to lower energies. An extension down to $E > 10^{17}$ eV was made possible using the 750 m array, thanks to the implementation of a new algorithm at the

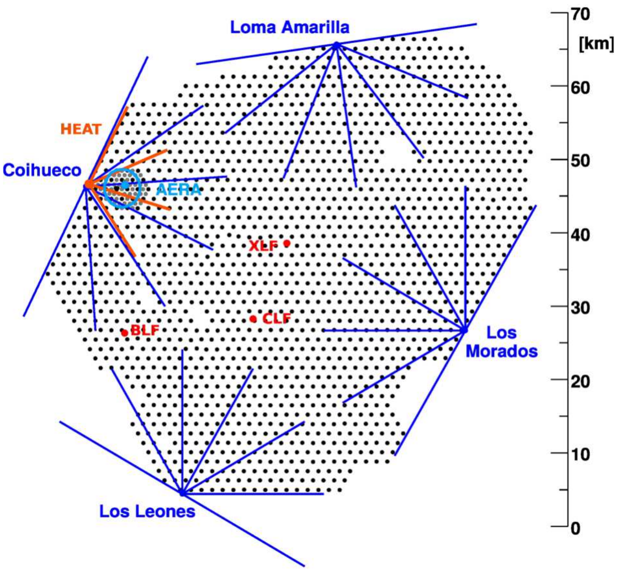

Fig. 1. Layout of the Pierre Auger Observatory. Black dots represent the WCD positions, blue and orange lines show the azimuthal field of views of the fluorescence telescopes. The location of the two laser facilities (CLF and XLF) for the monitoring of the atmospheric conditions are shown with red dots, and the area equipped with radio antennas (AERA) is marked with a light-blue circle

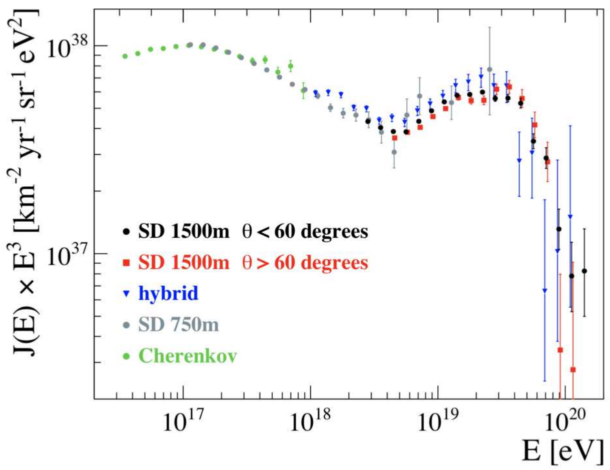

Fig. 2. Energy spectrum of cosmic rays measured using the Pierre Auger Observatory

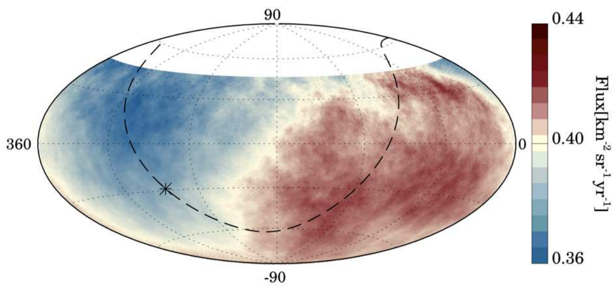

Fig. 3. Map of the CR flux above 8 EeV in equatorial coordinates, averaged on top-hat windows of 45° radius. The location of the Galactic plane is shown with a dashed line, and the Galactic centre is indicated with a star

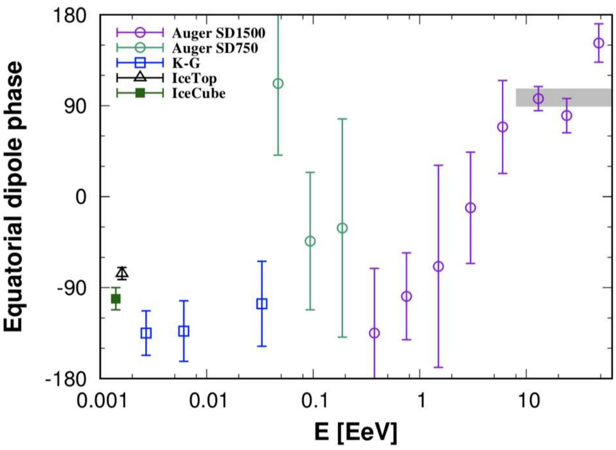

Fig. 4. Phase of the equatorial dipole amplitude determined with Auger Observatory data in different energy bins. Results from other experiments are also shown. Figure taken from [7]

WCD level [3]. This is the highest precision measurement near the region of the so-called *second-knee* or *iron-knee*, where previous experiments have shown a change in the spectral index. In addition, using for the first time events detected by HEAT in which the detected light is dominated by Cherenkov radiation, an extension of the spectrum down to $E > 10^{16.5}$ eV has been achieved [4]. Both new measurements allow studying the spectral features precisely around the *second-knee*. In total, the Auger spectrum spans over three decades in energy as shown in Fig. 2, where three relevant spectral features are observed: the softening in the spectrum at about 10^{17} eV (the *second-knee* region), the hardening at about $5{\times}10^{18}$ eV (the *ankle*), and a strong suppression of the flux at about 50×10^{18} eV.

3.2. Anisotropies

To understand the origin of UHECRs, the study of the distribution of their arrival directions has always been of capital importance, despite the difficulties that arise from the deflection they suffer due to the Galactic and extragalactic magnetic fields. Moreover, given the suggested trend towards a heavier composition with increasing energy that is inferred to happen above few EeV, only at the highest observed energies, the average deflections of CRs from an extragalactic source are expected to be smaller than a few tens of degrees, smearing point sources into *warm/hot* spots in the sky.

The Pierre Auger Collaboration has performed several anisotropy searches by using different techniques at different angular scales and by covering 85% of the celestial sphere. Among the various results, the observation of a large-scale anisotropy in the directions of CRs with energies larger than 8 EeV stands out (post-trial significance of 5.4σ) [5]. As shown in Fig. 3, the direction of the discovered dipole strongly favoured an extragalactic origin for the UHECR sources beyond the *ankle*. A new analysis was performed in [6] by splitting the events with $E > 4$ EeV into four energy bins, finding an indication at the 3.7σ level of growth of the dipolar amplitude with energy, expected from models, and consistent with the extragalactic origin in all bins. An update of this work by extending the study down to energies $\sim$0.03 EeV is presented in [7]. As shown in Fig. 4, the results suggest that the transition from the predominantly Galactic origin to the extragalactic one for the dipolar anisotropy is taking place somewhere between 1 and few EeV.

At higher energies, with more than 15 years of data and with an exposure exceeding 100000 km^2 sr yr, searches for an intrinsic anisotropy at small angular scales at energies exceeding 38 EeV have revealed an interesting possible correlation with nearby starburst galaxies, with a post-trial significance reaching 4.5σ in the most recent update [8]. A slightly weaker association (3.1σ) with active galactic nuclei emitting γ-rays is also found in events above 39 EeV. The region with the most significant flux excess is densely populated with different types of nearby extragalactic objects, with its centre at 2° away from the direction of Cen A, the nearest radio-loud active galaxy, at a distance of less than 4 Mpc.

3.3. Multi-messenger observations

The Pierre Auger Observatory has demonstrated capability to significantly contribute to Multi-messenger Astrophysics (MM) by searching for ultra-high energy (UHE) particles, particularly neutrinos and photons which, being electrically neutral, point back to their origin (see [9] for a recent review).

Given the non-observation of neutrino or photon candidates in data collected up to 31 August 2018, upper bounds on their diffuse fluxes were obtained [10, 11], allowing one to constrain the parameter space of cosmogenic neutrinos and photons. Scenarios assuming sources that accelerate only protons with a strong evolution with redshift are strongly constrained by the Auger Observatory results at more than 90% C.L.

In the MM context, the Auger Observatory can also search for neutrinos with energies above 100 PeV from point-like sources, monitoring a large fraction of the sky (from $\sim -80°$ to $\sim +60°$) in the equatorial declination with peak sensitivities at declinations around $-53°$ and $+55°$, unmatched for arrival directions in the northern hemisphere. An excellent sensitivity can also be obtained in the case of transient sources of order an hour or less, if they occur, when the source is in the field of view of the detection channels. The Auger Collaboration has performed several searches for UHE neutrinos following the detections of various types of transient astrophysical sources [12]. These include binary black hole (BBH) mergers, detected via gravitational waves (GWs) by the LIGO Scientific Collaboration and the Virgo Collaboration (LVC) instruments. Follow-up searches for the 21 events reported by LVC as BBH merger candidates till 2 June 2019 have been made, resulting in no candidates found in coincidence with any of them. As a consequence, the upper limit on a universal isotropic UHE neutrino luminosity as a function of the time after the merger was obtained, as shown in Fig. 5. Another source of interest is TXS $0506+056$, a powerful blazar that was found to emit an energetic neutrino candidate event correlated to a gamma-ray flare, along with a burst of events earlier in the same direction [13]. This blazar is thus the first identified source of neutrinos in the hundreds of TeV range. The Auger Collaboration performed follow-up searches for UHE neutrinos from the direction of TXS $0506 + 056$ during the periods of increased emission of high-energy photons and neutrinos, resulting in the non-observation of neutrino candidates. Regarding UHE photons, the search for point-like sources yielded no significant deviations from background expectations for Galactic sources and nearby extragalactic sources, the only targets accessible with photons in the EeV range.

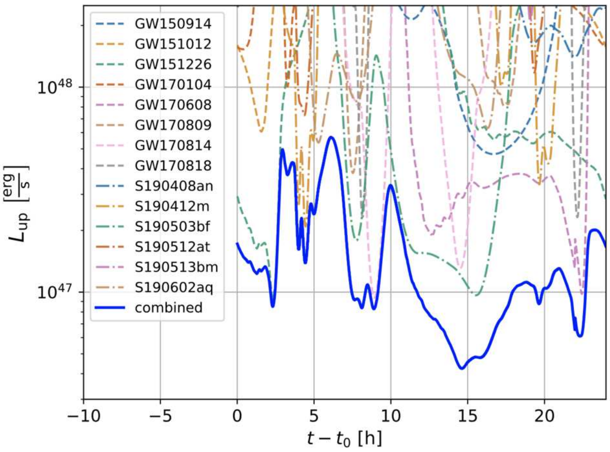

Fig. 5. A 90% C.L upper limit on the time-dependent universal isotropic luminosity (solid line), together with the contributions from the single sources (dashed lines). Sources not indicated here are above the $L_{\rm up}$-range drawn

The prominent role of the Pierre Auger Observatory as a multi-messenger observatory at the EeV range made it both a triggering and a follow-up partner in the Astrophysical Multi-messenger Observatory Network (AMON) [14], which establishes and distributes alerts for cimmediate follow-up by subscribed observatories.

3.4. Particle Physics at UHE: measurement of the muon content in cosmic-ray showers

In the quest of understanding how particles interact with another ones at energies much higher than those attainable at human-made particle accelerators, the UHECRs entering Earth's atmosphere play a key role in providing such high-energy collisions. The showers analyzed by the Auger Collaboration come from atmospheric cosmic-ray collisions with centre-of-mass energies ten times higher than the collisions produced at the LHC. Using these showers, the Auger Collaboration found, for the first time, an excess in the number of muons that arrive at the ground from cosmic-ray showers in comparison with expectations from models using LHC data as input [15–17]. One of the most direct measurements demonstrating this excess at 10^{19} eV is shown in the top panel of Fig. 6. The level of discrepancy depends on the hadronic model, and only SYBILL 2.3 c predictions are barely compatible with data within systematic uncertainties. The results of the Auger Collaboration are included in a recent meta-analysis of muon measurements in air showers with energies from PeV up to tens of EeV performed by eight air-shower leading experiments [18]. They found the muon measurements seem to be consistent with simulations based on the latest generation of hadronic interaction models up to about 10^{16} eV. Above this energy, most experimental data show a muon excess with respect to model predictions that gradually increases with energy. This result may, therefore, suggest that our understanding of hadronic interactions at the higher energies is incomplete.

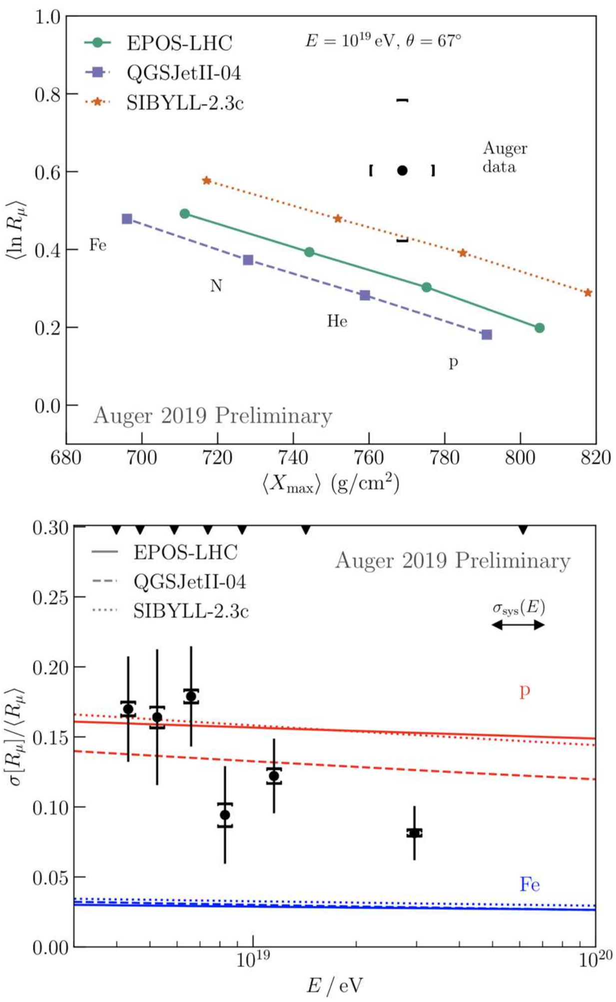

Fig. 6. Top: Average number of muons as a function of the depth of the shower maximum development. Bottom: Shower-to-shower fluctuations in the number of muons as a function of the primary cosmic-ray energy [17]

The measurement of shower-to-shower fluctuations in the number of muons in air showers allows one to constrain the available phase space for exotic explanations of the muon excess. In [17], the Pierre Auger Collaboration presents the first measurement of the fluctuations in the number of muons in inclined air showers with energies above 4×10^{18} eV. As shown in the bottom panel of Fig. 6, the observed fluctuations fall in the range of the predictions from air shower simulations with current models and, in fact, are compatible with the expectation from composition data [19]. As discussed in [17], this result suggests that the first high interaction in the shower is reasonably well described by models in this energy range. The likely explanation for the disagreement in the average value is that a small discrepancy in the particle production exists at all energies, which then is accumulated as the showers develop to create the deficit in the number of muons finally observed at the ground in simulations.

4. AugerPrime, the Observatory Upgrade

Despite a large number of valuable results as those described above, the many unknowns about UHECRs and hadronic interactions prevent the emergence of a uniquely consistent picture that would help us to understand the very complex astrophysical scenario

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Fig. 7. Photograph of an upgraded station of the SD, featuring the SSD on top of the WCD

resulting from the Pierre Auger Observatory measurements. The understanding of the nature and the origin of the highest-energy cosmic rays remains an open science case that calls for an upgrade of the Observatory, called AugerPrime [20]. AugerPrime aims for the collection of a new information about the primary mass of the cosmic rays on a shower-by-shower basis from a high statistics sample of UHE events, by discriminating the electromagnetic and muonic components in air showers with SD-based observables.

The main element of the upgrade consists of 3.8 m^2 plastic scintillator detectors (SSD) on the top of each of the 1660 WCDs as illustrated in Fig. 7. The different sensitivity of the two detectors to the electromagnetic and muonic shower components is used to disentangle them. Other key elements of AugerPrime are an additional small photomultiplier (PMT) installed in the WCD for the extension of the dynamic range, and new SD electronics to process signals with higher sampling frequency and enhanced amplitude resolution. The upgrade will also be complemented by extending the FD measurements into the periods of a higher night-sky background, to increase the on-time of the FD about 50%. Finally, based on the AERA results, a new project for adding a radio antenna on the top of each WCD is now on-going [21]. The new detectors will operate together with the WCD+SSD, forming a unique setup to measure the properties of showers above $10^{17.5}$ eV.

The Engineering Array of 12 upgraded stations has been taking data in the field since late 2016. As of July 2019, over 300 SSDs have been deployed, of which 77 are operational, and the production of all the SSDs is nearing its end. The deployment of the AugerPrime should be completed in 2020. Operations and full data-taking are planned at least until 2025.

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ОБСЕРВАТОРІЯ ПЬЄРА ОЖЕ
ВИВЧАЄ ГРАНИЦІ НАЙВИЩИХ ЕНЕРГІЙ

Р е з ю м е

Ми представляємо основні результати, отримані Колаборацією Pierre Auger, метою яких є пошук загадкових джерел космічних променів надвисоких енергій – частинок з найвищою енергією у Всесвіті. Обсерваторія постійно, вже впродовж 15 років, продукує якісні дані, які привели до низки відкриттів в області фізики частинок надвисоких енергій. Інтерпретація отриманих результатів породжує також нові питання, відповідь на котрі дасть нинішня модернізація (upgrade) Обсерваторії Pierre Auger.