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The Pierre Auger Observatory: Latest Results and Prospects for the Future

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The Pierre Auger Observatory is the world's largest cosmic ray detector. It employs a hybrid technique combining a 3000 km^2 surface detector (SD) array comprising 1660 water Cherenkov stations with 27 fluorescence telescopes, arranged in 4 sites, that overlook the atmosphere above the SD array. In stable operation since 2004, we have published numerous breakthrough results regarding the properties of the highest energetic particles in the Universe with unprecedented statistics. Envisaging a deeper understanding of the highest energy cosmic rays, AugerPrime, the upgrade of the Pierre Auger Observatory, will mark the transition from Phase I to Phase II allowing us to improve inferences on the mass composition and acceleration mechanisms, probe hadronic interactions at the $\sqrt{s} \sim 100$ TeV scale and increase search sensitivity for the sources of ultra-high-energy cosmic rays (UHECR). We summarize our most significant results with the Phase I data (2004 – 2021) and outline prospects for the next decade of AugerPrime operations.

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1. The Pierre Auger Observatory

The Pierre Auger Observatory is the largest operating UHECR detector in the world [1]. Located near Malargüe, Argentina, in the province of Mendoza, it has collected data since 2004, reaching a total exposure of more than 135 000 km^2 sr y, thus providing an unprecedented record of high-quality UHECR events. The Surface Detector (SD) of the Pierre Auger Observatory consists of 1660 water Cherenkov detectors (WCD) covering a 3000 km^2 area with a spacing of 1500 m. In two areas of 23.5 km^2 and 1.9 km^2, a denser WCD spacing of 750 m and 433 m correspondingly is used. For the nearly completed AugerPrime upgrade [2], Surface Scintillator Detectors (SSDs) and Radio Detector (RD) antennas are being installed at each WCD, along with new electronics and small PMTs. The SD is overlooked by 27 fluorescence telescopes (the Fluorescence Detector, FD) distributed at four locations on its periphery, which includes 24 telescopes for the range $0° - 30°$ of elevation and 3 for the range $30° - 60°$ of elevation, the latter named High Elevation Auger Telescopes (HEAT). The hybrid nature of the observatory allows us to exploit the respective advantages of each detector, ensuring the large duty cycle to accumulate statistics, with near-direct measurements of energy, and access to a range of mass-sensitive observables. The SD energy scale is established by calibrating the shower size measured by the SD to the nearly calorimetric energy measurements obtained from the FD.

The results reached over the years on the UHECR field are numerous, but yet new questions have been opened which still remain to be answered. The measured energy spectrum presents new features [3, 4], while the nuclear mass composition is mixed and becomes heavier with increasing energy [5]. In recent years, the extragalactic origin of UHECR above 8 EeV has been claimed due to the discovery of a large-scale dipole anisotropy above that energy [6, 7]. In this proceeding, the latest results on energy spectrum, mass composition, anisotropy studies and hadronic interations will be presented.

2. Energy Spectrum

The measurement of the energy spectrum of UHECRs is fundamental in clarifying their origin, acceleration mechanisms, and propagation processes. The energy spectrum is measured using different detectors and techniques in different energy ranges [3, 4, 8, 9]. The HEAT telescopes are used to measure the spectrum at energies below 10^{17} eV. Between 10^{17} eV and $10^{18.4}$ eV, the SD with 750 m spacing provides the most precise measurement, while above these energies, the FD telescopes and the SD with 1500 m spacing are used. All measurements combined together are presented in Fig. 1 [9]. The spectrum of cosmic rays above 10^{18} eV is well described by a series of power laws, $J \propto E^{-\gamma}$, with a spectral index $\gamma \sim 3.2 - 3.3$ below the "ankle" feature around 5×10^{18} eV, hardening to $\gamma \sim 2.6$ beyond the ankle, and steepening to $\gamma \sim 5.3$ beyond $\approx 5 \times 10^{19}$ eV. An additional spectral feature, the "instep", has been revealed which corresponds to a spectral index change around 10^{19} eV from $\gamma \sim 2.6$ to $\gamma \sim 3.0$. Combining spectrum and composition data, which as mentioned indicates heavier composition at the highest energies, one can conclude that the steepening is caused by a combination of nuclei photodisintegration and maximum acceleration energy at the sources close to 10^{20} eV.

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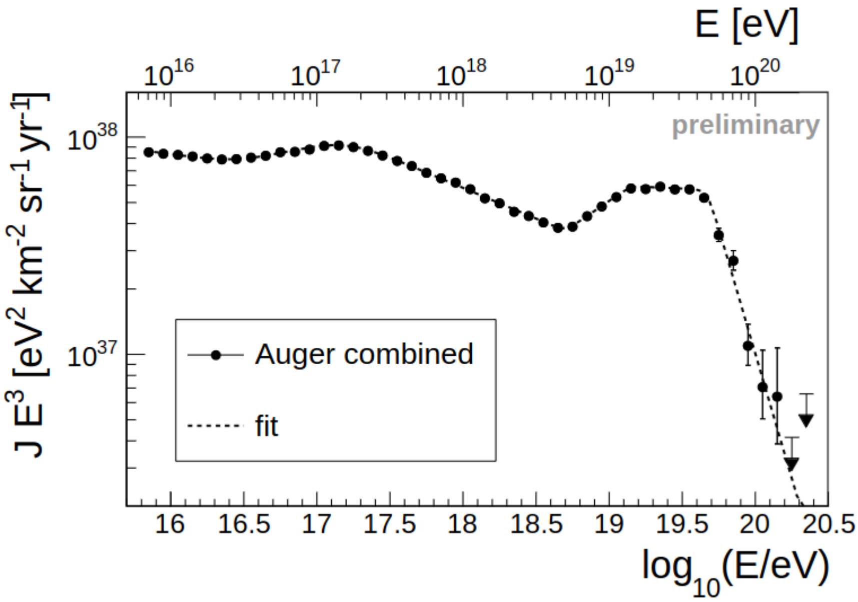

Figure 1: The combined energy spectrum, multiplied by E^3 to better reveal the features [9].

3. Mass Composition and Hadronic Interactions

The most detailed inferences on the UHECR mass composition are currently made from the FD measurements of the depth of the maximum of air-shower profiles, $X_{\max}$. Around a decade ago, from the observed energy evolution of the first central moments of $X_{\max}$ distribution, $\langle X_{\max}\rangle$ and $\sigma(X_{\max})$, it was established with a high significance [5] that above $10^{18.3}$ eV the UHECR mass composition becomes heavier with a decreasing spread of masses in the primary beam. The most recent results for the Phase I data set of $\sim$ 75000 events (3.8 times increase with respect to [5]), including improvements in the treatment of the atmospheric aerosols and shower profile reconstruction, further reinforce previous findings [10]. Most crucially, the established mass composition evolution is invariant to uncertainties associated with air-shower simulations. From fits of the measured $X_{\max}$ distributions with templates consisting of (p, He, N, Fe) mixes simulated with EPOS-LHC and Sibyll 2.3d hadronic models, it follows that the observed trends can be explained by the consecutive extinction of the proton and helium nuclei components so that at the highest available FD energies the primary beam is dominated by CNO nuclei.

Recently, for the first time in the UHECR field, an event-by-event $X_{\max}$ estimation was performed using the SD data and custom-designed deep neural networks (DNN) [12, 13]. Due to the nearly 100% SD duty cycle and less strict event selection in comparison to the FD analysis, the $\langle X_{\max}\rangle$ and $\sigma(X_{\max})$ measurements were extended up to 10^{20} eV with around a 10-fold increase of statistics at $E > 10^{18.5}$ eV with respect to the FD data. The DNN results are in good agreement with the FD measurements (Fig. 2). Due to much larger statistics, the reliable observation of small $X_{\max}$ fluctuations at $E > 10^{19.5}$ eV excludes the presence of a significant fraction of light nuclei in the primary beam at the highest energies. In the $\langle X_{\max}\rangle$ elongation rate, indications for new features at $E > 10^{18.5}$ eV were found. Specifically, the constant elongation rate is excluded at 4.4σ, taking into account systematic uncertainties, and the best broken-line fit is achieved with three breaks in

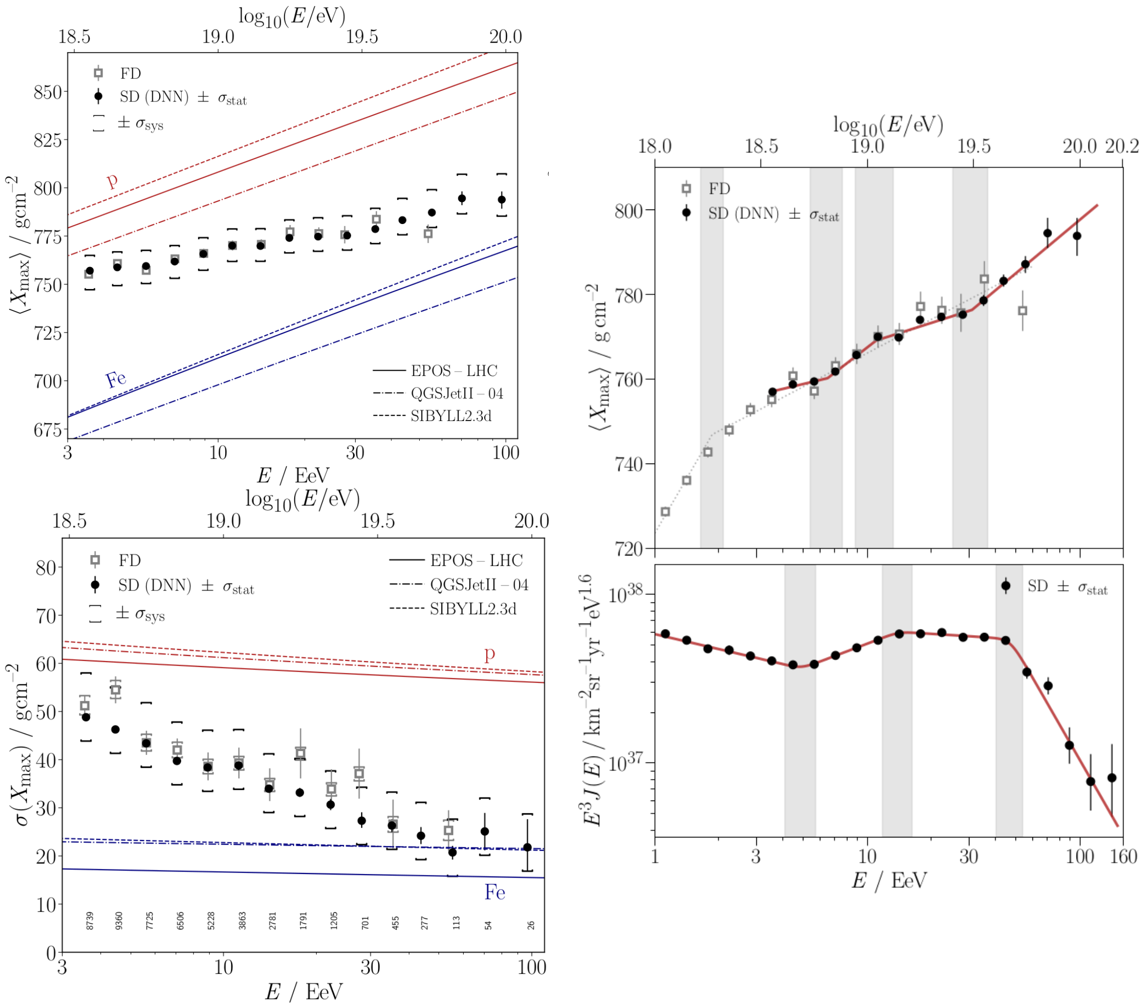

Figure 2: Left: energy evolution of $\langle X_{max}\rangle$ and $\sigma(X_{max})$ inferred from the SD data with DNNs [12, 13] in comparison to the FD data [11]. Right: broken-line fit of DNN $\langle X_{max}\rangle$ and the energy spectrum features. $\langle X_{max}\rangle$ breaks and spectral features are indicated with shaded areas.

the vicinity of the features of the UHECR energy spectrum (Fig. 2). These new findings provide further constraints for astrophysical models developed in Auger where indications on such breaks already exist [14].

While the general trends in the mass composition discussed above are nearly invariant with the uncertainties in the hadronic interaction models, their influence on inferences of $\langle \ln A\rangle$ remain large. To test the predictions on the X_{max} and muon number scales, a data-driven method was recently applied where measured two-dimensional X_{max} and SD signal distributions ($E = 10^{18.5} - 10^{19.0}$ eV) were fitted with simulated templates using nuclear fractions, X_{max} and SD-signal scales as free fit parameters [15]. It was shown that for all three interaction models used in the test, the best data fit is achieved when their X_{max} prediction are shifted by 20 – 50 g cm^{-2} deeper in the atmosphere and hadronic signals increased by 15% – 25% (Fig. 3). After these modifications, the inferences on the mass composition become more consistent between all three models with a heavier $\langle \ln A\rangle$ than for non-modified models, and significant contribution of CNO and iron nuclei near the 'ankle'. In the

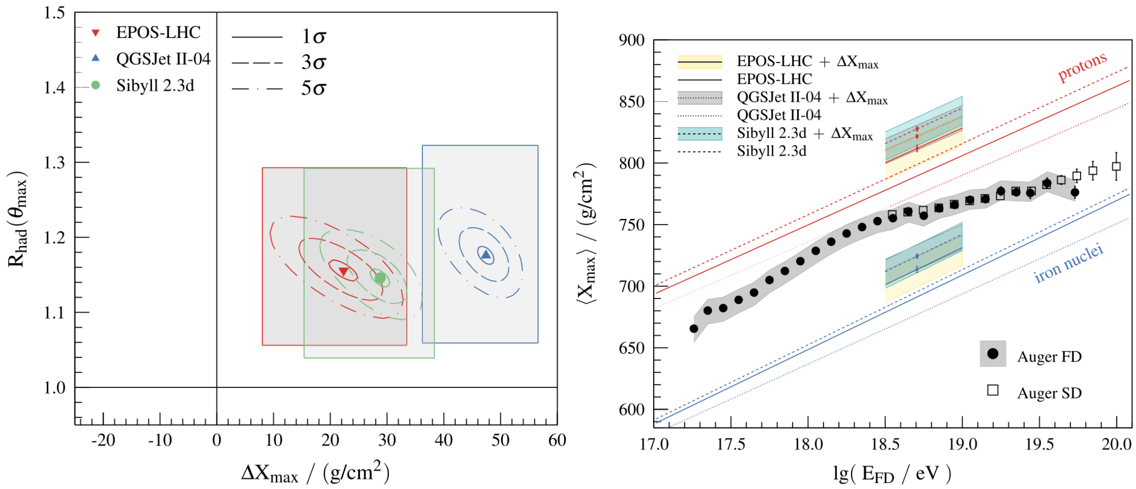

Figure 3: Left: modifications of $X_{\max}$ and hadronic-signal scales in hadronic models required to fit observed distributions of $X_{\max}$ and SD signal. Right: FD $\langle X_{\max} \rangle$ compared to the model predictions with and without modifications of their $X_{\max}$ scales.

future, with updates of the method together with the use of AugerPrime data, the uncertainties on the UHECR mass composition and hadronic interactions will be reduced further.

4. Anisotropy Studies

The search for anisotropies in the arrival directions of UHECRs plays a key role in the efforts to understand their origin, aiming at backtracking the sources through the consideration that magnetic deflections are proportional to the rigidity of cosmic rays E/Z and the horizon available to them decreases with increasing energy. Among the major discoveries in recent years in the long lasting searches for the origin of UHECRs, a dipolar modulation in right ascension (R.A.) at cumulative energies above 8 EeV has been discovered with a significance above 6.9σ, with a direction of $\sim 115^\circ$ away from the Galactic Center (Fig. 4), suggesting an extragalactic origin of cosmic rays above this energy threshold [6, 7, 16]. For the energies between 8 EeV and 16 EeV, the significance of the observed modulation is 5.7σ. The search for correlations with catalogs of potential sources gives indications of mild UHECR overdensities in directions of the Centaurus region (Cen A, NGC4945, M83) and in a region close to the Galactic South Pole (NGC253) [16]. Results on intermediate and small scale anisotropy can be summarized with the presence of an overdensity at the Centaurus region, having a post-trial p-value of 3.0×10^{-5} corresponding to 4σ and a likelihood test for correlation with a starburst galaxies catalog exhibiting a post-trial p-value of 6.6×10^{-5} (3.8σ) [16]. The inclusion of mass-composition estimators on an event-by-event basis with AugerPrime by means of the SSD and the improved mass estimators with Phase I data, as using DNN methods, will allow more insight into the arrival direction results in the near future.

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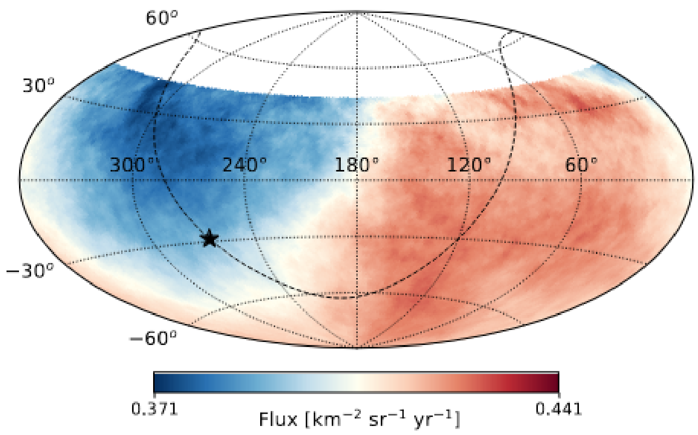

Figure 4: Flux above 8 EeV in equatorial coordinates. The star marks the position of the Galactic Center, the dashed line indicates the Galactic Plane [16].

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