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Towards uncovering the origin of ultra-high energy cosmic rays at the Pierre Auger Observatory

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Introduction. Since the discovery of cosmic rays with energies in excess of 10^{19} eV nearly 60 years ago, the question of their origin remains unanswered. The investigation and understanding of such particles has been demanding for more and more precise data, both from the statistical and from the systematical point of view. The Pierre Auger Observatory in Argentina, conceived in the 1990s to study cosmic rays via extensive air showers in the 10^{18} eV energy range, has fulfilled this demand yielding a harvest of data and results that mostly challenge long-held wisdom of cosmic rays and provide an unprecedented framework for probing their origin and transport. The French scientists have played a key role in this endeavor, from the conception of the different instruments up to the production of the physics results. The Observatory, fully operating since 2008, is a multi-component instrument, including an array of water-Cherenkov detectors, fluorescence telescopes and an array of radio receivers. The world's largest cosmic ray detector, it will remain the leading experiment for studying ultra-high energy cosmic rays (UHECRs) in the next decade.

The numerous results obtained in recent years at the Observatory have provided us with important constraints on the acceleration mechanisms operating in the astrophysical sites producing UHECRs and on the environments of these sites. But to validate unambiguously the insights obtained until now and, ultimately, to identify the sources of UHECRs, there are still important questions to be clarified, such as the composition at the highest energies. The Auger collaboration has set up a program of upgrade of the Observatory, whose exploitation is planned beyond 2025. This upgrade aims to improve the characterization of the air showers for a better identification of the nature of the primary cosmic rays.

Understanding the steepening at the highest energies with the upgrade of the Observatory. The first challenge is to understand how the steepening of the intensity observed above $\approx 5 \times 10^{19}$ eV is produced. The founding works of Greisen, Zatsepin and Kuz'min (GZK) in the 1960s had already predicted such a steepening due to the interaction of extragalactic protons propagating in the cosmic microwave background radiation. Further work followed, showing that a stronger steepening (or similar in the case of iron nuclei) was also expected for heavier nuclei. Such an interpretation implies that UHECRs are accelerated well beyond 10^{20} eV in astrophysical sites uniformly distributed across the Universe. However, composition-sensitive measurements show a gradual increase of the average mass with energy, with a little presence of protons, if any, above $\approx 10^{19}$ eV. Models fitting simultaneously the spectrum and composition-sensitive data then favor a scenario in which extragalactic UHECRs are accelerated in proportion to their electric charge or escape from the accelerators in proportion to their mass. Yet this interpretation relies on an extrapolation of the composition-related results beyond $\approx 4 \times 10^{19}$ eV. This is because these results rely on the measurement of the longitudinal profile of the showers directly observed by fluorescence telescopes. These detectors operate during dark nights only, and thus fall short in statistics at the highest energies. Determining the mass in this energy range is therefore the main motivation for the upgrade of the Observatory. If it turns out that the gradual increase of the average mass observed between $\approx 10^{18}$ eV and $\approx 4 \times 10^{19}$ eV is confirmed at higher energy, the composition of UHECRs with energy beyond $\approx 7 \times 10^{19}$ eV would be dominated by iron nuclei. From the point of view of the mechanisms of acceleration, the consequences would be important. On the one hand, this would mean that the sources exhaust their ability to accelerate particles above $\approx 10^{20}$ eV. On the other hand, the hard value of the spectral index at the sources needed to reproduce the data would also imply that the escape of the particles from the sources plays an important role to shape the ejected spectra of the individual nuclear components. Together with the inferred element abundances at the sources, this will allow us to constrain the source environments and thus to identify source candidates.

The Auger collaboration therefore defined a program for extending the potentialities of the surface detector to allow a measurement on an event-by-event basis of mass-sensitive parameters of the showers. The improved surface detector, complementing the water-Cherenkov detectors with scintillators and MHz antennas, will provide different measurements of the muonic and electromagnetic components of the showers, in order to characterize each of them separately. Up to now, the measurement of the shower characteristics with the surface detector array is based on empirical principles: a model of the lateral profile of the showers is used to extract an estimator of the size of the showers, estimator then calibrated with the energy measured by the fluorescence detector on the subset of events triggering simultaneously both detection techniques. This approach does not allow for relating measurements one to another. By contrast, the upgraded surface detector will allow a coherent description of these characteristics. This description is based on the principle of universality of atmospheric showers.

This principle is well known for describing an electromagnetic cascade. After the succession of the first interactions, any cascade can be described by reproducible macroscopic states because of the million of interactions that occur. In the same way as the characteristics of emission or absorption of a black body as a function of the frequency of the radiation can be described by a universal function from the knowledge of the temperature, the longitudinal development of the cascades as a function of the atmospheric depth can be universally described from a few macroscopic parameters. Thus, whether an electromagnetic cascade is initiated by a proton or an iron nuclei, the profile of this cascade can be fully described using only a few parameters, including, in addition to the arrival directions, the energy, E, and the depth of maximum development, X_{max}. The muonic cascade, whose contribution to the water-Cherenkov detectors signal is important, is a priori less universal because muons that survive to decay propagate without catastrophically interacting from their points of production to the ground. However, Monte-Carlo studies have shown that a universal description of the profiles of these muonic cascades remains possible beyond an energy around $\approx 10^{17}$ eV. Thus, it is the complete profile of the showers that can be described using E, X_{max} and an indicator of the number of muons, N_μ. Following this principle, the shape of large signals (that is, signals containing enough particles to be smooth, so signals close enough to the shower cores) detected at ground level can be predicted parametrically, introducing in particular E, X_{max} and N_μ for parameters. With independent measurements of the different components of the showers such as provided by the upgraded detector, simulations show that it then becomes possible to infer these parameters with a good precision.

The interpretation of X_{max} and N_μ quantities relies on the comparison of their measured values with those predicted by shower simulations, which are resorting to hadronic interaction properties at very high energies and in phase-space regions not well covered by accelerator experiments. Currently, the systematic uncertainties in X_{max} and in muon number-related quantities predicted by these simulations are dominated by the differences between hadronic interaction models, even after recent updates based on LHC data on parameters governing the interactions. The muon content of showers stems from a multi-step cascade process, mostly driven by interactions of secondary pions and kaons with air. N_μ-related quantities thus depend on properties of pion-air collisions over a wide range of energies, for which a detailed knowledge is lacking. By contrast, X_{max} depends more strongly on the properties of the primary particle interaction with air nuclei. Here, the inelastic cross section and the forward spectra of the secondary hadrons play a key role. In this regard, models maximally benefit from the studies of proton-proton and proton-nucleus collisions at the LHC. An internally consistent hadronic interaction model should reproduce simultaneously the different facets of the showers captured in every constraining observable sensitive to the primary mass. The future insight in the composition-sensitive parameters as a function of the energy will provide new light on the hadronic processes at energies above those which are achievable with current particle accelerators.

Our contribution to the analysis of the upgraded Observatory will thus help in probing better the internal relationships between the shower characteristics, and therefore in constraining the modeling of the showers. This will enable us, ultimately, to uncover the cosmic-ray composition at the highest energies.

Implications of the anisotropies. The search for anisotropies in the distributions of arrival directions is in principle the most direct way to identify/map the sources of UHECRs. Only recently has the long-held belief that such particles are of extragalactic origin been demonstrated experimentally with the discovery of an anisotropy in their arrival directions above 8×10^{18} eV, significant with more than 5 σ confidence, well described by a dipole pattern the amplitude of which increases from $\simeq 6\%$ to $\simeq 10\%$ as the energy rises up to $\simeq 4 \times 10^{19}$ eV. At higher energies, particles are expected to have sufficient magnetic rigidity to approximately maintain their initial arrival directions provided that the electric charge is not too large. Moreover, the horizon of the highest energy particles is limited as compared to that of particles of lower energies, because of the GZK effect. In this way, only the foreground sources are expected to populate the observed sky maps at these energies.

The erasure of the contribution of remote sources provides a natural mechanism to decrease the unresolved isotropic "background", as UHECRs should originate from the nearby Universe. Searches for excesses of events in the directions of those of nearby starburst galaxies have recently revealed a correlation with 4.5 σ confidence. The signal fraction, of the order of 10%, is relatively small. This result is surprising if the particular environment of starburst galaxies is responsible for the acceleration, so that it may trace another phenomenon. Interestingly, for redshifts $z < 2$, starburst galaxies are responsible for $\approx 15\%$ of the total star formation rate. Proportionality between UHECR production rate and star formation rate may thus constitute an interesting framework. If the rate of star formation is a good tracer of the number of short-lived massive stars giving rise to cataclysmic events releasing considerable energy, then starburst galaxies are a good tracer of events such as Gamma-Ray Bursts, hypernova or other powerful explosions. In this scenario, any galaxy could host such highly transient events in proportion to the rate of star formation, and starburst galaxies would naturally be hosting a considerably larger number of such events. The low level of anisotropies would be caused by the time delays caused by the magnetic deflections in space, larger for more distant sources. This would induce a stationary image of distant sources, whereas the UHECRs locally produced in the past would have escaped since a long time. After having led the effort to uncover the anisotropy indication, we started to explore this scenario, and further investigations are necessary in the future.

The method used to reveal the correlation is based on a likelihood test with two free parameters which characterize the signal fraction on the one hand and the angular correlation scale on the other hand. The predicted fluxes in each direction are constructed from the positions of starburst galaxies smoothed at the correlation angle and weighted by a tracer of the non-thermal flux of the objects (radio flux here). This approach has the advantage of introducing only one free parameter to take into account in an effective manner the magnetic deflections; but the captured scale, namely 13°, does not make it possible to tackle the common issue in astronomy that is source confusion. Because of the magnetic deflections, the unresolved isotropic background should be largely reduced by selecting events with low electric charges. Yet, this is hardly achievable in practice due to the large overlap of the mass-sensitive observables. Another approach that we started to design consists then in relying on the possibility to separate the *average* mass in sky maps filtered at some angular scale. By combining directional-intensity data with directional-composition data, a cross-correlation coefficient can then capture whether the non-uniformities in the directional intensity are preferentially shaped by lighter elements or not. First studies show that for modest 2 σ modulation of the average mass over right ascension, the cross-correlation coefficient can detect the underlying physics with more than 99.99% confidence in more than 99% of the cases. In the future, we will take advantage of this powerful tool to test the consistency of the different scenarios of source candidates and to constrain quantitatively the impact of the intervening magnetic fields upon the propagation of UHECRs.

The role of the energy range below 10^{18} eV. The gradual fall-off of the cosmic-ray intensity in the second knee- (or Iron knee-) to-ankle region ($\approx 10^{17}$ eV to $\approx 10^{18.7}$ eV) has long been puzzling. A widespread view is that the intensity of each individual nuclear component of the bulk of Galactic CRs falls off steeply at a magnetic rigidity near 3×10^{15} V, as a consequence of the difficulty for diffusive shock acceleration in supernova remnants to produce particles beyond this limit. The observed intensity beyond 10^{17} eV does not, however, turn down so sharply, suggesting that one or several other components take over to make up the total cosmic-ray energy spectrum from the second knee to the ankle, where the rate of fall becomes less steep. One possibility, originally referred to as the "B component" by Hillas, is an additional Galactic component originating from a different population of sources than the ones producing the bulk of Galactic CRs of lower energies. Auger data provide some support to this hypothesis, through the presence of a significant fraction of intermediate nuclei combined with the absence of iron nuclei around 10^{18} eV and above. Another possibility, not necessarily excluding the first one, is that the extragalactic component smoothly takes over the Galactic one(s), so that all components add up to the observed intensity.

There exists a viable mechanism to support that some fraction of cosmic rays below the ankle energy are the low-energy counterpart of UHECRs. The luminosity of the source candidates is governed, among other things, by the level of the radiation density. While getting accelerated in a magnetic environment confining them, UHECRs can interact with the radiation. The ejection spectra of the particles and the amount of the different ejected nuclei can thus differ from the spectrum resulting from the acceleration process for the injected nuclei. In particular, the nuclei-gamma interactions in the bath of photons permeating the source environments can create a copious flux of neutrons below 10^{18} eV. Neutrons escaping from the sources will decay into protons on their way to Earth, so that the ejection spectrum of the neutrons can be absorbed into that of protons. Although the precise ejection spectra depend on the considered source environments through the optical thickness and on the amount of the different injected nuclei, some generic expectations are as follows. For primary injection spectra scaling with E^{-2}, the nuclei-photon interactions are expected to shape the ejection spectra of the charged UHECRs in a much harder way due to the behavior of the nuclei-photon cross section at high energies. The ejection spectrum of the produced neutrons through these interactions, in contrast, is expected to be much softer because neutrons are not magnetically confined in the bath of photons and basically escape freely from the source environments. In this scenario, protons are expected to escape the sources following a special spectral index parameter, differently from that of the other nuclei.

The role of the energy range below 10^{18} eV is thus extremely important to constrain further the UHECR source environments. We have recently extended the measurement of the energy spectrum down to $10^{16.5}$ eV by making use of the various low-energy enhancements of the Observatory. This allowed us to report on the second knee with unprecedented precision. We will continue to improve to even lower energies anisotropy, mass composition and energy spectrum measurements. Extending the interpretation tools to this energy range could ultimately enable us to pinpoint the UHECR source candidates, if the spectral index required for the protons turns out to be steeper than that of nuclei of higher energies.

Entering into the multi-messenger era at the highest energies? Besides the different wavelengths of traditional astronomy, neutrinos, cosmic rays, very high-energy gamma rays and gravitational waves provide complementary information to study the most energetic objects of the Universe. The final boost to the multi-messenger astronomy took place quite recently with the emergence of both neutrino and gravitational-wave astronomy. The discovery of gravitational waves from the merging of a neutron star binary system by LIGO and Virgo triggered a spectacular series of observations in the full electromagnetic spectrum from radio to the very high-energy gamma rays and searches for neutrino fluxes with ANTARES, IceCube, and the Pierre Auger Observatory. The combined effort marks an unprecedented leap forward in astrophysics, revealing many aspects of the Gamma-Ray Burst induced by the merger and its subsequent kilonova. It is now quite clear that there is much potential in the combined analysis of data from different experiments and multi-messenger astronomy has excellent prospects of making many more significant contributions in the near future, see also the contribution *Multi-messenger astroparticle physics* by N. Leroy *et al.* for these IN2P3 prospectives.

Multi-messenger observations at the Pierre Auger Observatory were foreseen from the beginning, in terms of unprecedented sensitivities to ultra-high energy photons, neutrinos, and neutrons. Observations of photons or neutrinos in the so far dark Universe beyond 10^{17} eV would be a major breakthrough by itself. Yet, the non-observation of point sources and diffuse fluxes of photons and neutrinos allowed the derivation of upper bounds that constrain models very effectively. The bounds to diffuse photon and neutrino fluxes have ruled out the top-down models of UHECR origin motivated by particle physics and also started to constrain the GZK-effect as a dominant process for explaining the observed flux suppression of the most energetic UHECRs. Many TeV gamma-ray sources are observed at energy fluxes of the order of 1 eV cm^{-2} s^{-1}. Such sources would be visible to the Auger Observatory as strong photon and Galactic neutron sources if their energy spectrum would continue with a Fermi-like energy distribution up to about 10^{17} eV. Their absence suggests that their maximum source energy does not reach out to the threshold energy of the Observatory and/or that their spectrum is significantly softer than E^{-2}.

Point source searches now routinely include also mergers of compact binaries alerted by gravitational wave interferometers. The most spectacular event so far was the neutron star merger GW170817 at a distance of about 40 Mpc. Within the predefined ± 500 s search window, the Auger Observatory reached a neutrino flux sensitivity above 10^{17} eV that was over an order of magnitude better than of any other neutrino observatory presently operated. The absence of neutrinos at Auger, IceCube and ANTARES allowed constraining the jet properties of the neutron star merger. Many more events are being expected in the near future. To accommodate for this, mechanisms are set up to automatically react to gravitational wave or other astrophysical alerts and search for neutrinos and photons.

Photons also provide the possibility to constrain models of super-heavy dark matter. This is because copious fluxes are expected from the decay of super-heavy dark matter particles. In these models, dark matter is made of supermassive particles gravitationally produced at the end of inflation, when a fraction of fluctuations are not stretched beyond the horizon but remain as particles because the inflation slows down. To have an abundance cosmogically relevant today, these particles must be supermassive. From the (non-)detection of photons, constraints upon the mass and the lifetime of the particles can be obtained. Furthermore, these hypothetical particles can also be tested with CMB precision measurements. This is because the production of such particles during inflation gives rise to isocurvature perturbations that become sources of gravitational potential energy, implying primordial tensor-to-scalar r ratio in the CMB power spectrum. The combination of the constraints in the mass/lifetime/r space can yield interesting constraints on the Hubble rate at the end of inflation. We are currently initiating these inter-disciplinary studies in the collaboration and will develop them in the future.

The contributions of the French scientists to the capabilities of the Observatory to search for photons and neutrinos have been important. The various capabilities of the upgraded Observatory will open up many new possibilities for improved searches. This suit of enhancements will further strengthen the prominent role of the Observatory as a multi-messenger one for the next decade. We will take an active part in this program.

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Outlook. Together with increased exposures, the resolutions on the arrival directions, energies and mass-composition observables provided by ground-based observatories relying on multiple detection techniques are necessary to improve the understanding of UHECRs. The Pierre Auger Observatory will remain, together with the enlarged Telescope Array in the northern hemisphere, the leading experiment dedicated to the study of UHECRs in the next decade.

If future data confirm that iron nuclei dominate the highest energies, then any increase in exposure by a factor of a few will not be the key to resolve the foreground sources better than presently around 4×10^{19} eV. The key is the precision of the measurements. The upgraded version of the Observatory will provide data enabling us to measure with unprecedented accuracy the characteristics of the showers, accuracy not foreseen elsewhere. This will help in constraining the hadronic interaction models and in allowing a better control of the inferred mass composition. We will contribute to this scientific endeavor along the lines described in this document.