Latest results from the Pierre Auger Observatory

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Abstract. The Pierre Auger Observatory, located in the Province of Mendoza, Argentina, is the World’s largest detector for cosmic rays at ultra-high energies. In its seven years of operation it has collected an exposure of more than 20000 km² sr yr, larger than all previous experiments combined. Its original design, optimized for the energy range $10^{18}$ eV to $10^{20}$ eV, is currently enhanced to cover energies down to almost $10^{17}$ eV. We give an overview of the latest results with a focus on the prospect to study nuclear interactions with cosmic rays and conclude with a brief outlook on developments and extensions of the observatory.

1. Introduction

Cosmic rays are light to heavy nuclei (up to iron). The Pierre Auger Observatory uses two techniques to study them, exploiting the induced extensive air showers in Earth’s atmosphere. Charged particles and photons of the shower which arrive at ground are measured with more than 1600 water-Cherenkov detectors, distributed on a 1.5 km triangular-grid over 3000 km² (Surface Detector Array, SD [1]). In addition, charged particles in the air generate ultra-violet light by excitation/de-excitation of nitrogen, which is observed by 27 fluorescence telescopes (Fluorescence Detector, FD [2]) under suitable atmospheric conditions.

The FD follows the longitudinal development of the shower in the air. It allows one to reconstruct the shower energy in an almost model-independent way and the slant depth $X_{\text{max}}$ of the shower maximum [3]. The latter is sensitive to the mass of the cosmic ray and the properties of its hadronic interactions in the atmosphere. The FD can only operate in dark, moonless nights with a field of view free of clouds, which limits its duty cycle to about 1/10 of the total time. The SD has a duty cycle of almost 100 % and collects the main bulk of events. Its observes the lateral profile of particle density around the shower axis at ground level. Its energy scale is derived from coincident measurements with the FD [4].

2. Cosmic ray flux and sources

Two of the main objectives of the observatory are to measure the cosmic ray flux between $10^{18}$ eV and $10^{20}$ eV and to discover its extra-galactic sources. In conventional scenarios, cosmic rays well above $10^{18}$ eV are accelerated in distant extragalactic objects and travel through the intergalactic medium until they eventually reach Earth. The rather fundamental prediction of the Greisen-Zatsepin-Kuz’mín (GZK) cut-off [5] limits the maximum distance which cosmic rays of $6 \times 10^{19}$ eV and higher can travel to about 50-100 Mpc. Interactions with the cosmic microwave background become frequent above this energy that strip energy from the cosmic ray.
Empirically, the cosmic ray flux is well described by a broken power law model with a break at $4 \times 10^{18}$ eV and a smooth Fermi-type suppression at higher energies. The HiRes result [6] is compared. Both results are compatible if shifted within the systematic uncertainties of their respective energy scales (22 % for Auger [7]).

The GZK effect severely reduces the horizon for sources that could reach Earth at the highest energies and therefore it should lead to a flux suppression.

The cosmic ray flux measured by the Pierre Auger Observatory is shown in figure 1. It depicts a break around $4 \times 10^{18}$ eV and a suppression at the highest energies compatible with the GZK effect. The features are compatible with earlier results from the HiRes experiment [6].

An anisotropy was found in the arrival directions of cosmic rays with the highest energies [8, 9]. Flux suppression and anisotropy make conventional acceleration likely, but some tension remains as the anisotropy signal has not become stronger since its original publication [10].

3. Mass composition and hadronic interactions

The slant depth $X_{\text{max}}$ of the shower maximum is measured by the FD. It depends on the mass of the cosmic ray and scales with the logarithm of the energy $E$ as more energetic showers penetrate deeper into the atmosphere. The $X_{\text{max}}$ of a particular shower is the sum of the depth $\lambda$ of its first interaction (anti-proportional to the cross-section) and the slant depth $\Delta X$ that the shower needs to develop to the maximum.

The mean value $\langle X_{\text{max}} \rangle$ and the spread RMS($X_{\text{max}}$) of $X_{\text{max}}$ are depicted in figure 2. Cuts on the data set pick events of sufficiently quality without biasing the sample in favor of deeply penetrating (proton-like) or shallow (iron-like) showers [11]. Soft hadronic interactions drive...
the development of the shower which cannot be computed from first principles. Thus, $\lambda$ cannot be extracted directly from $X_{\text{max}}$, because theoretical predictions for $\Delta X$ are rather uncertain. Also uncertain is the functional relation between $\lambda$ and the energy $E$ and mass of the cosmic ray. For these reasons, the $X_{\text{max}}$ predictions from different hadronic interaction models show a considerable spread in figure 2. Nevertheless, we observe a trend compatible with a gradual increase of the average mass of cosmic rays with energy up to $5.9 \times 10^{19}$ eV.

SD observables that depend on the mass composition are also under study [16]. SD observables benefit from the higher duty cycle of the SD which improves the statistics, but typically they are less sensitive to the mass composition.

The most striking difference between observation and predictions is an apparent muon deficit in simulations. The SD does not contain dedicated muon detectors so far, but analyses of the time traces of the signal in individual detectors, the use of shower universality properties and hybrid events (simultaneous observation of the shower in SD and FD) allow one to extract the muon component [17]. The apparent muon deficit is depicted in figure 3 in form of a rescaling factor required to adjust the number of muons in simulations to the data as a function of a shifted FD energy scale. The analyses prefer a FD energy scale increased by about 25 % (still compatible with its systematic uncertainty of 22 % [7]) and about 50 % more muons.

An interesting idea [18] is to study the impact of changes to the hadronic interaction models on shower observables. An example is shown in figure 4. If inverted, such a relation could be used to fit a parameter like multiplicity or cross-section directly to air shower data. This would allow to study these parameters in energy ranges inaccessible to collider experiments. However, if the cosmic rays are a mixture of elements, such an analysis will become rather complex.

4. Limits on photons and neutrino fluxes
The Observatory also is a powerful photon and a competitive neutrino detector in the ultra-high energy range. Photons of high energy induce air showers like normal cosmic rays, but with a much
deeper $X_{\text{max}}$ and few muons since the first interaction is not strong but electromagnetic. Photon-induced showers are easier to predict, since electromagnetic interactions can be calculated from first principles. The main obstacle in photon searches is the large background of normal cosmic rays. The sensitivity mainly depends on the efficiency of the background rejection. So far, no photons have been found and limits are placed on their fractional flux [19].

Neutrinos barely interact with atmospheric nuclei at all. Almost horizontal showers yield the best separation between the rare neutrino events and the background of normal cosmic rays. Even slightly up-going showers are considered, caused by tau-neutrinos that skim Earth’s crust where they are converted into $\tau$’s that leave Earth to decay over the observatory. The sensitivity of the observatory is significantly increased by including this detection channel. No neutrinos have been found and limits are placed on their flux [20, 21].

5. Summary and outlook

The cosmic ray flux and the $X_{\text{max}}$ distribution have been determined with the Pierre Auger Observatory to unprecedented precision. An anisotropy in the arrival directions of the cosmic rays with the highest energies has been observed. Competitive limits have been placed on the fluxes of photons and neutrinos above $10^{18}$ eV. The analyses are continuously refined with the help of the large statistics collected. Systematic uncertainties decrease and new ways of extracting the mass composition and parameters of the hadronic interactions are developed.

The observatory recently has been enhanced to study cosmic rays down to about $10^{17}$ eV. The SD now includes an infill array with a 750 m grid, which will feature dedicated muon detectors [22]. Three High Elevation Auger Telescopes (HEAT) have been added to the FD, which can be tilted to look at higher elevations and observe air showers with shallower $X_{\text{max}}$ [23].

Finally, there is an ongoing effort to study the radio emission of air showers with the goal to use this signal for cosmic ray detection [24].

References

[1] Allekotte I et al. 2008 Nucl. Instr. Meth. A 586 409
[2] Pierre Auger Collaboration 2010 Nucl. Instr. Meth. A 620 227
[3] Unger M et al. 2008 Nucl. Instrum. Meth. A 588 433
[4] Pierre Auger Collaboration 2010 Phys. Lett. B 685 239
[5] Greisen K 1966 Phys. Rev. Lett. 16 748; Zatsepin GT and Kuzmin VA 1966 JETP Lett. 4 78
[6] Hires Collaboration 2009 Astropart. Phys. 32 53
[7] Di Giulio C et al. (Pierre Auger Collaboration) 2009 Proc. 31st ICRC (Lódz, Poland) arXiv:0906.2189
[8] Pierre Auger Collaboration 2007 Science 318 938
[9] Pierre Auger Collaboration 2008 Astropart. Phys. 29 188
[10] Pierre Auger Collaboration 2010 Astropart. Phys. 34 314
[11] Pierre Auger Collaboration 2010 Phys. Rev. Lett. 104 091101
[12] Kalmykov NN and Ostapchenko SS 1993 Phys. At. Nucl. 56 346
[13] Ostapchenko SS 2006 Nucl. Phys. B Proc. Suppl. 151 143
[14] Ahn EJ, Engel R, Gaisser TK, Lipari P and Stanev T 2009 Phys. Rev. D 80 094003 arXiv:0906.4113
[15] Pierog T and Werner K 2008 Phys. Rev. Lett. 101 171101
[16] Wahlberg H et al. (Pierre Auger Collaboration) 2009 Proc. 31st ICRC (Lódz, Poland) arXiv:0906.2319
[17] Castellina A et al. (Pierre Auger Collaboration) 2009 Proc. 31st ICRC (Lódz, Poland) arXiv:0906.2319
[18] Ulrich R, Engel R and Unger M 2011 Phys. Rev. D 83 054026 arXiv:1010.4310
[19] Pierre Auger Collaboration 2009 Astropart. Phys. 31 399
[20] Pierre Auger Collaboration 2008 Phys. Rev. Lett. 100 211101
[21] Pierre Auger Collaboration 2009 Phys. Rev. D 79 102001
[22] Platino M et al. (Pierre Auger Collaboration) 2009 Proc. 31st ICRC (Lódz, Poland) arXiv:0906.2354
[23] Kleifges M et al. (Pierre Auger Collaboration) 2009 Proc. 31st ICRC (Lódz, Poland) arXiv:0906.2354
[24] van den Berg AM et al. (Pierre Auger Collaboration) 2009 Proc. 31st ICRC (Lódz, Poland) arXiv:0906.2354