Astroparticles at the High Energy Frontier: Results from the Pierre Auger Observatory

Gonzalo Parente* for the Pierre Auger Collaboration†‡
Departamento de Física de Partículas &
Instituto Galego de Física de Altas Enerxías (IGFAE)
Universidade de Santiago de Compostela
E-15782 Santiago de Compostela, Galiza, Spain

Abstract

An overview of selected results from the world's largest cosmic ray observatory Pierre Auger is given. The status of the Observatory is presented with a brief description of the detectors and the energy calibration with hybrid events. The search for the nature and origin of ultra-high energy cosmic rays is mainly performed through the study of the energy spectrum, arrival directions and morphology of extensive air showers. The important issue of the search for photons and neutrinos with the observatory detectors is also discussed. In addition, results of interest for particle physics are given. Finally, the future of the Pierre Auger Observatory is addressed.

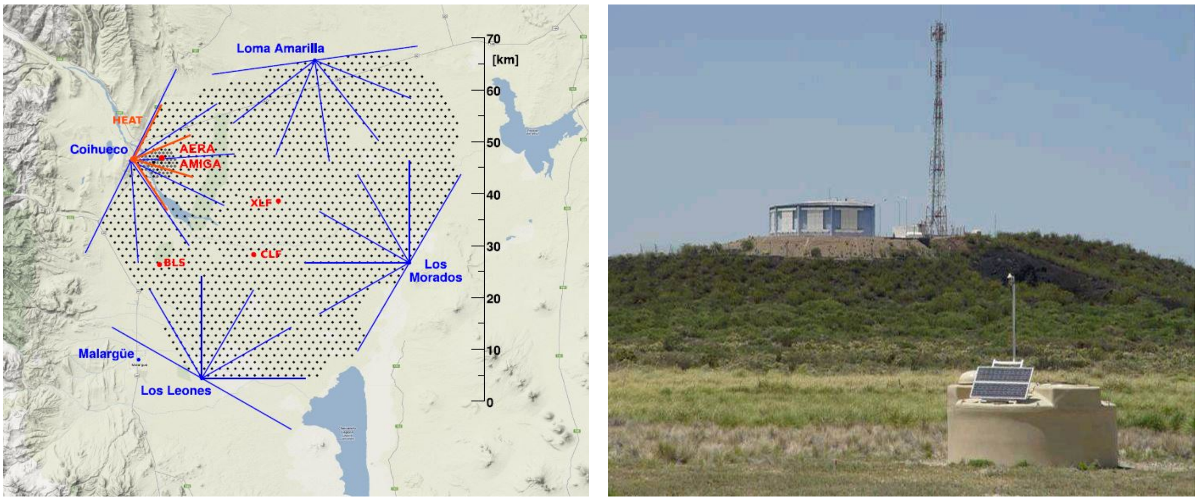
1 Introduction

Cosmic rays are energetic protons and heavy nuclei from outer space with energies up to more than 10^{20} eV, thus reaching three orders of magnitude above accelerator particle (lab) energies. As cosmic rays are the most energetic particles found in nature they can be taken to study the high energy phenomena in our galaxy and in the local universe, as they carry information from production and acceleration sites and from their propagation through the intergalactic media [1]. In addition, the extremely energetic collisions of cosmic rays with atmospheric nuclei provide a unique opportunity to study particle interactions far above the energy reached by current terrestrial accelerators.

Since the pionering work that lead to the discovery of extensive air showers in the 1930s [2], a large effort has been performed to study cosmic rays at the highest energies with a series of important air shower detectors and with them try to answer the fundamental questions on the origin and nature of the ultra-high energy (UHE) cosmic rays [3]. In 2004 the Pierre Auger Observatory in Argentina started registering showers at the highest energies. After the completion of the array in 2008, a huge amount of data is being collected and processed using dedicated tools and novel methods for data analysis and interpretation of the results. From these measurements a more definite picture on the UHE cosmic ray sky is emerging.

The Pierre Auger Observatory [4] is a hybrid system of two detectors, the fluorescence detector (FD) and the surface detector (SD). The SD is a particle detector array consisting of 1600 water Cherenkov stations separated by 1.5 km in a triangle grid over an area of 3000 km^2 (see Fig. 1). To collect lower energy events a denser but smaller array of 61 stations, known as the infill, has been added to the main array in a 750 m grid, covering 23.5 km^2. The

*gonzalo.parente@usc.es
†Av. San Martín Norte 304 (5613) Malargüe, Prov. de Mendoza, Argentina
‡Full author list: http://www.auger.org/archive/authors_2014_12.html



(a) (b)

Figure 1: The Pierre Auger Observatory: (a) Map of the site: the dots represent the SD stations separated by 1.5 km. The blue lines indicate the field of view of the telescopes in the four FD buildings surrounding the array area. (b) A water Cherenkov SD station with one of the FD buildings on the hill.

FD consists of 24 air fluorescence telescopes in four sites overlooking and surrounding the SD array, and three high elevation fluorescence telescopes, HEAT, overlooking the infill array. An additional tool at the Pierre Auger Observatory is an array of 130 antennas being deployed for detecting the radio emission of extensive air showers to provide additional information on the development of the showers.

The hybrid character of the Observatory allows the detection of air showers simultaneously with SD and FD in complementary ways, providing important cross-checks and measurement redundancy. The SD samples the air shower at the ground level through the signal produced by the electromagnetic and muonic components of the shower in the water Cherenkov stations. The FD telescopes record the development of the shower in the atmosphere by detecting the fluorescence light induced by the electromagnetic part of the cascade. The integral of the longitudinal profile is related to the shower energy, and the rate of shower development is sensitive to the mass of the primary particle.

Although only 10% of the total number of events are observed by FD, limited to operate in dark and clear nights, the fluorescence technique plays a fundamental role in the measurement of the energy of the much more numerous SD events as we will see below.

2 Energy

The Pierre Auger Collaboration has released four independent energy spectra from different data sets [5]. Two of them have been measured with the 1.5 km baseline SD array at two zenith angle regions, for which different shower reconstruction procedures are required. For zenith angles exceeding 60° the electromagnetic part of the shower is absorbed in the thicker atmosphere crossed by the shower and thus muons became the dominant component at the ground level. The other two spectra were obtained with the infill array and with the fluorescence detector. With the infill the cosmic ray flux is extended down to energy of $10^{17.5}$ eV.

The reconstruction of the primary energy from the signals left by the shower in the SD is unreliable due to the requirement of extrapolation of hadronic interaction models above current accelerator energies, and the lack of knowledge of the primary particle mass. Instead, the energy of the SD event is obtained by converting the shower size parameter into the energy estimator, corresponding to the energy that would have been measured by the fluorescence detector. This is done through a calibration equation determined with a set of hybrid events, observed simultaneously by both the fluorescence and the surface detectors (see Fig. 2a).

The energy reconstruction for vertical events is based on the estimation of the lateral distribution of secondary particles of an air shower reaching the ground at an optimal distance to the shower core. The shower size estimator is taken as the signal at 1000 m from the shower core [6]. For the infill array the signal is taken at 450 m. The shower size parameter is then corrected for their zenith angle dependence due to air shower attenuation in the atmosphere and converted to the signal it would have if the shower had arrived at 38° (35° in the infill case), assuming a cosmic ray constant intensity for fixed energy.

For inclined events the energy estimator is different [7]. The muon rich showers are characterized by N_{19}, the normalization of the signal with respect to an average muon density in a two-dimensional profile used as a reference (a 10^{19} eV proton shower).

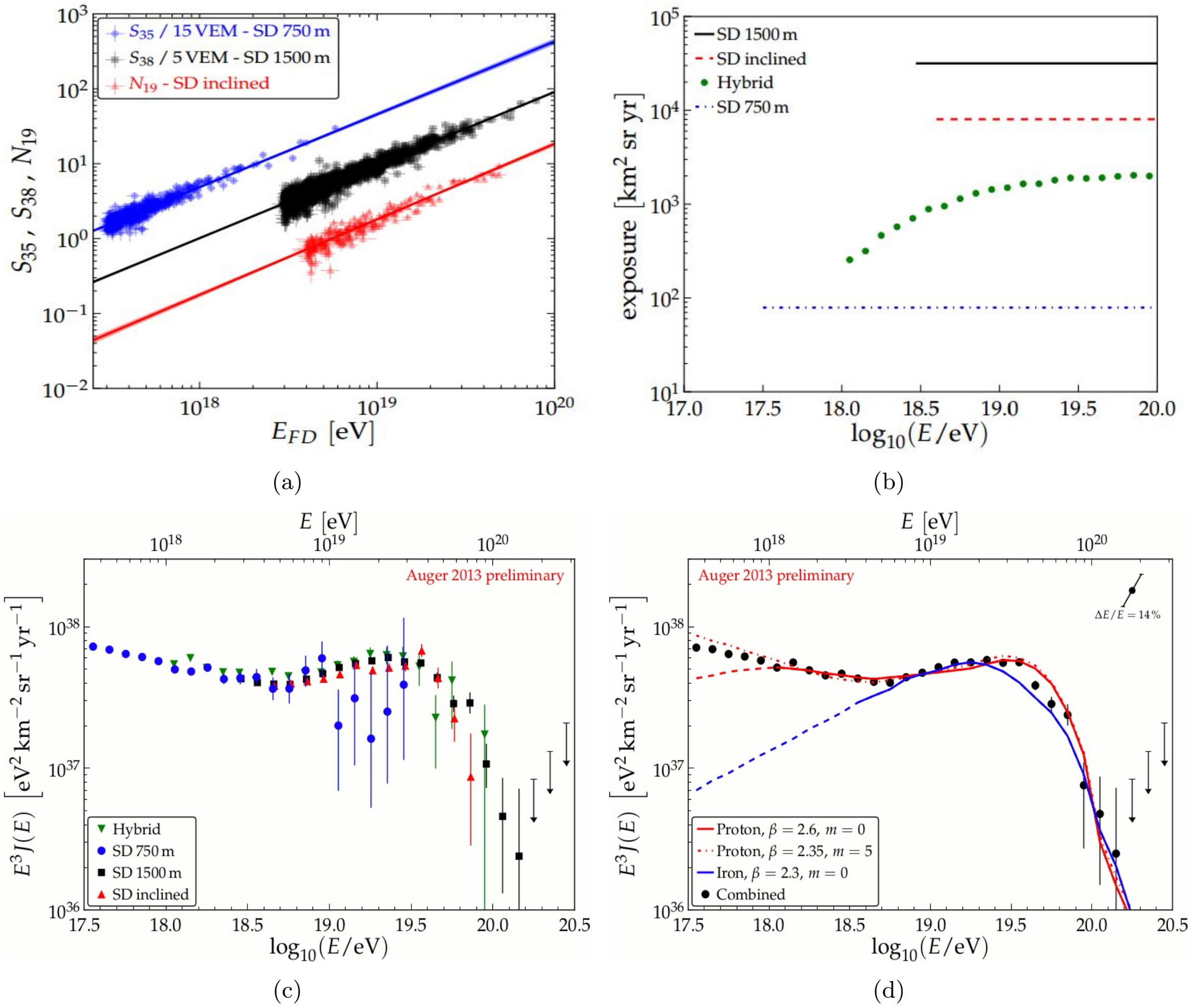


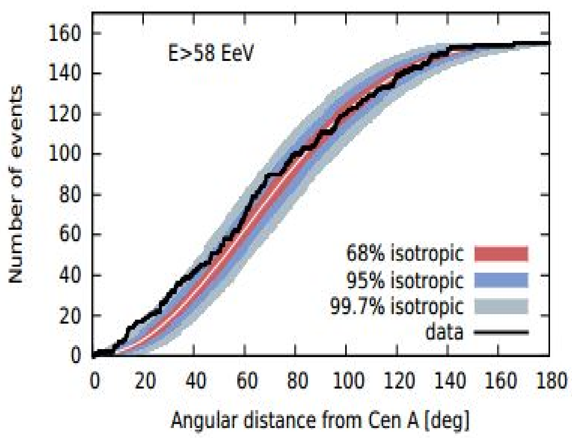
Figure 2: (From Ref. [5]) (a) Energy calibration for vertical, inclined and infill events at the SD. (b) Exposures (ICRC 2013) for the different Auger detectors. (c) Energy spectrum for vertical, inclined, and infill events at the SD, and for simultaneous SD and FD hybrids events. (d) Combined energy spectrum compared with predictions from various astrophysical scenarios.

As can be seen in Fig. 2c the different energy spectra show similar features and have a reasonable agreement within systematics. The four spectra have been combined in a common flux (see

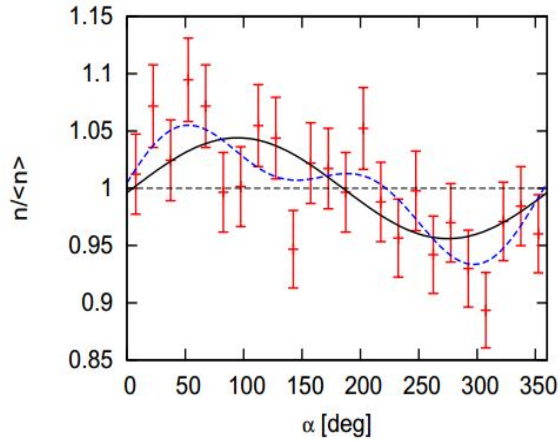
Fig. 2d) that clearly shows the ankle above 5 EeV, and the strong flux suppression, at 20 σ level, above 50 EeV. The latter, although being consistent with the Greisen and Zatsepin-Kuzmin (GZK) effect, can also be explained by nearby sources with limited acceleration power [8].

3 Origin

One of the main goals of the Pierre Auger Observatory is the identification of the sources of UHE cosmic rays. Cosmic rays are not expected to point toward their sources as they are charged particles deflected by interstellar and intergalatic magnetic fields. However, at the highest energies, directionality may not be totally lost. Depending on the energy, the particle type, and the distance to the source, a certain amount of anisotropy can be revealed in data providing evidence of where they are produced or accelerated.



(a)



(b)

Figure 3: (a) Cumulative number of events as a function of the angular distance from the Cen A radio galaxy for the threshold $E_{\text{th}} = 58\,\text{EeV}$ [9]. (b) Observed number of events over the mean as a function of the right ascension with 1 σ error bars for $E > 8\,\text{EeV}$ [11]. The solid line shows the first harmonic modulation while the dashed line shows the combination of the first and second harmonics.

A complete analysis of arrival directions of UHE cosmic rays recorded at the Pierre Auger Observatory in 10 years of operation has been recently performed. From studies of correlations with celestial structures, both in the Galaxy and in the local Universe and with different populations of nearby extragalactic objects, including the VCV AGN catalog, and also from self-clustering of event directions, no statistically significant evidence of anisotropy was found [9]. The strongest departures from isotropy (post-trial probability 1.4%) are obtained for cosmic rays with $E > 58$ EeV in rather large windows around Swift AGNs closer than 130 Mpc and brighter than 10^{44} erg/s (within 18° radius) and around the direction of Centaurus A at 15° radius (see Fig. 3a).

The large scale distribution of arrival directions has also been studied. In a joint study with Telescope Array no clear anisotropy was found and upper bounds to the dipole amplitude were established [10]. More recent studies where more Auger data are analyzed, including large zenith angle events [11], have shown evidence of anisotropy as a dipole component (Fig. 3b). The largest departure from isotropy appears for $E > 8$ EeV, with an amplitude for the first harmonic in right ascension $RA_1 = (4.4{\pm}1.0){\times}10^{-2}$, that has a chance probability $P(\geq RA_1) = 6.4{\times}10^{-5}$. Estimation of the large scale anisotropies can be useful to understand the transition from a Galactic to an extragalactic cosmic ray origin.

4 Nature

The determination of the nature of UHE cosmic rays from observations of extensive air showers is a challenge. For the study of mass composition with FD the observables $X_{\max}$, the atmospheric depth at which the shower reaches the maximum number of particles, and its fluctuation $\sigma(X_{\max})$ are used. Monte Carlo simulation shows that, for a given energy, the lighter the nucleus the larger both, $\langle X_{\max} \rangle$ and the width of the $X_{\max}$ distribution.

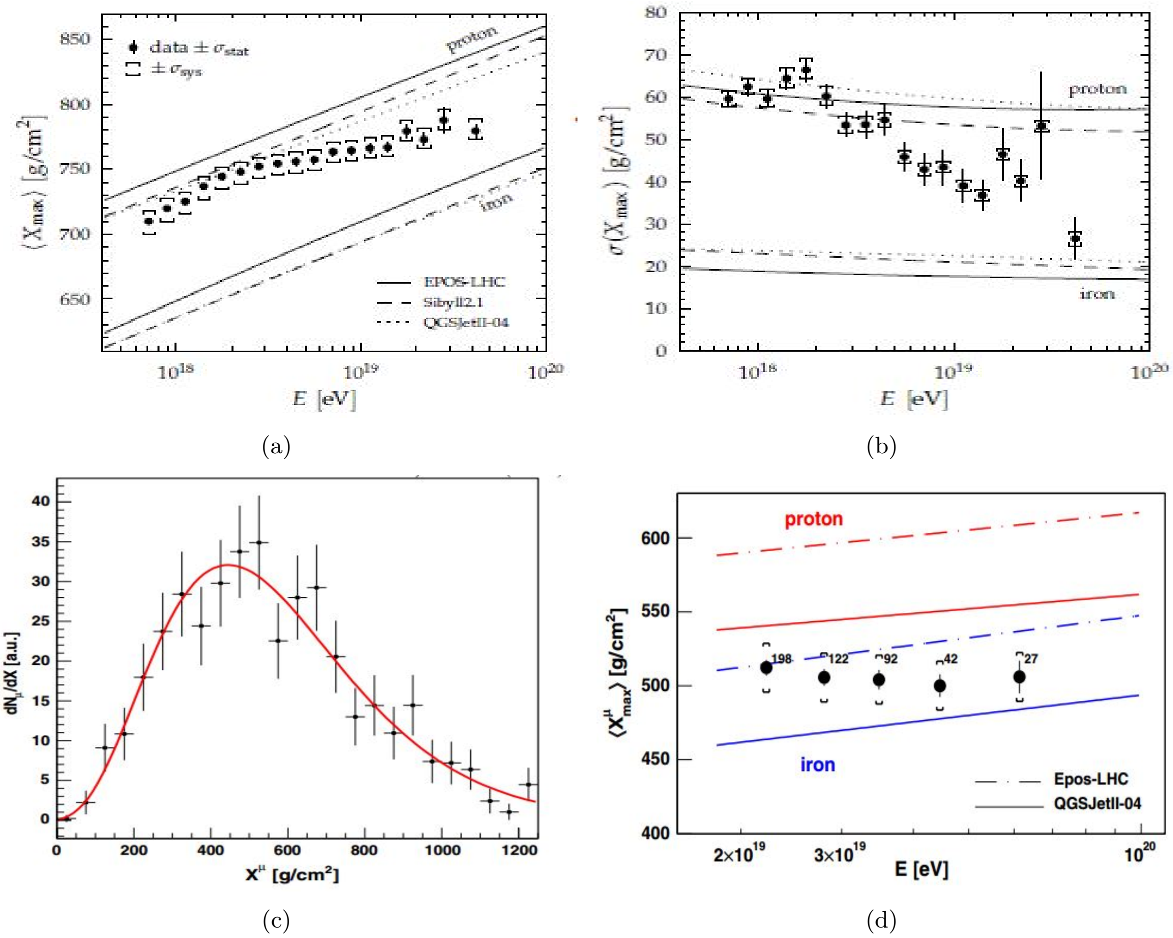


Figure 4: (a) 1st moment (average) and (b) 2nd moment (fluctuation) of $X_{\max}$ distribution as a function of shower energy [12]. (c) The longitudinal profile of muon production depth for a 91 $\pm$ 3 EeV event [14]. The line is the result from a fit to a Gaisser-Hillas function. (d) Average $X^{\mu}_{\max}$ as a function of shower energy [14]. The number of events in each energy bin is indicated and brackets represent the systematic uncertainty. The lines are the result from Monte Carlo simulation.

$X_{\max}$ is extracted from the pattern of fluorescence light registered by the FD optical modules which follows the amount of particles at the different stages of the longitudinal shower development [12]. The results obtained for both average $X_{\max}$ (Fig. 4a) and fluctuation $\sigma(X_{\max})$ (Fig. 4b), when compared to MC simulation, are interpreted as a transition from light to heavier cosmic rays at the highest energies accessible to composition [13]. This is in tension with the explanation of the flux suppression (see previous section) produced by the GZK effect, where lighter nuclei are expected at the highest energies.

An alternative method to study mass composition with SD includes the observable $X^{\mu}_{\max}$, the depth along the shower axis where the production of muons reaches maximum. The reconstruction of the longitudinal profile of the muon production depth for a given shower (Fig. 4c) is performed with the SD array using timing information from the FADC traces at the SD stations far from the shower core [14]. This method has been applied for showers around 60°. The behavior of the measured average $\langle X^{\mu}_{\max} \rangle$ as a function of energy lies between the theoretical predictions for proton and iron (Fig. 4d) similarly to what is obtained for $\langle X_{\max} \rangle$. Likewise, the results can also be used to constrain hadronic interaction models.

5 Particle Interactions

An important contribution of the Pierre Auger Observatory to the study of particle interactions beyond accelerator energies has been the measurement of the cross section for the production of particles in proton-air collisions at the center-of-mass energy per nucleon of 57 TeV [15]. The p-air cross section (see Fig. 5b) is derived from the slope of the $X_{\max}$ distribution tail obtained with FD data (Fig. 5a). Considering events with large $X_{\max}$, which correspond to the most deeply penetrating showers, enhances the contribution of protons in the sample. In addition, the analysis is restricted to shower energies between 10^{18} and $10^{18.5}$ eV (average center-of-mass energy of 57 TeV), where the shape of the $X_{\max}$ distribution is compatible with there being a substantial fraction of protons. To compare with accelerator data, the inelastic and total proton-proton cross sections have been calculated using the Glauber model. The value found is within one sigma of the best extrapolation from the recent LHC data points.

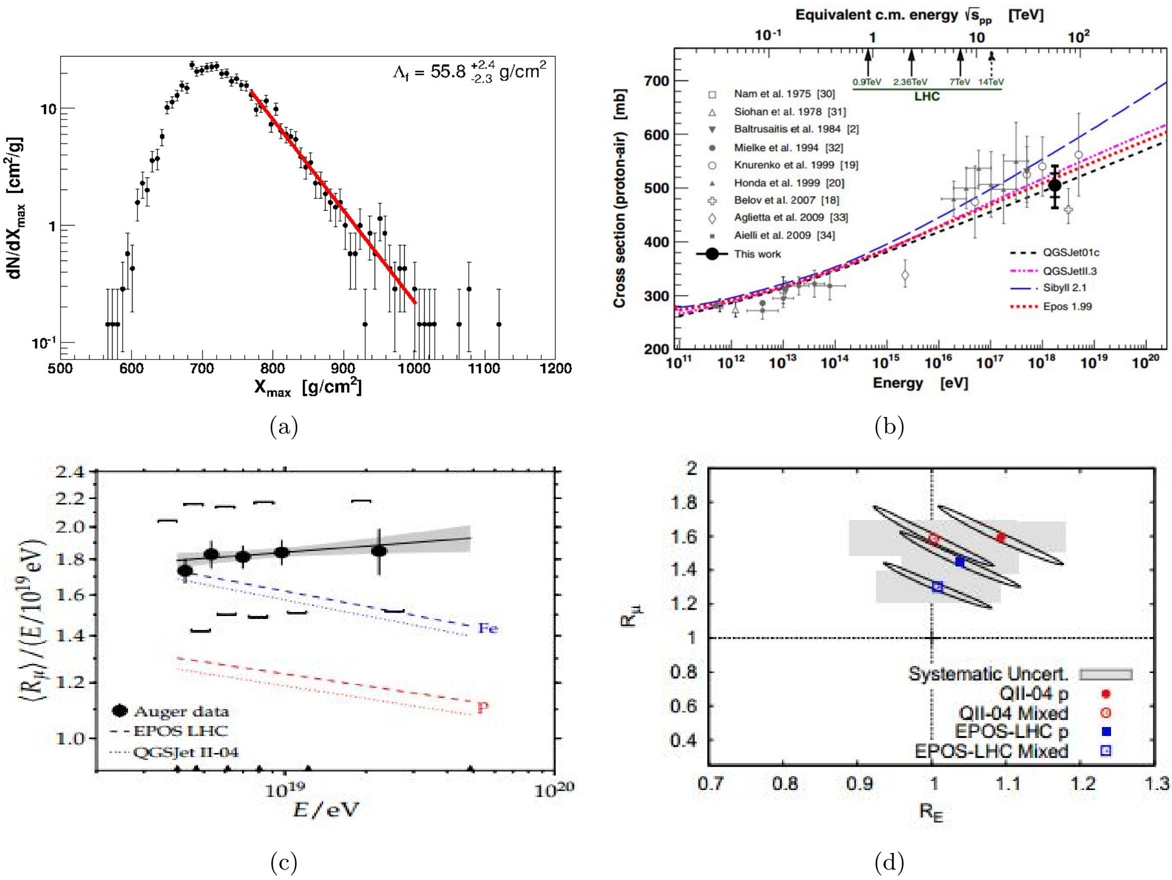


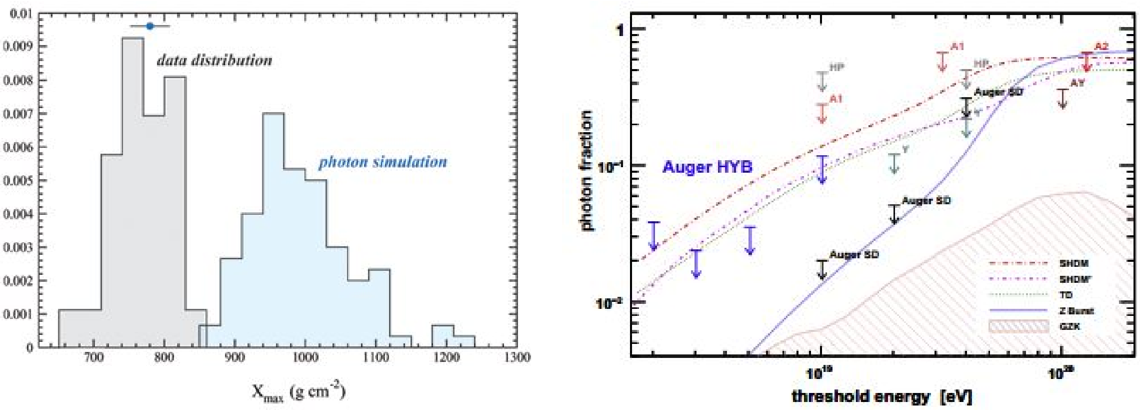
Figure 5: (a) Determination of the pp cross-section: the slope of the $X_{\max}$ distribution tail at large depth is related with the p-air cross-section [15]. (b) The p-air cross-section [15]. (c) Number of muons in inclined showers relative to a 10^{19} eV proton shower used as a reference [16]. (d) Relative muon signal versus electromagnetic signal for vertical 10^{19} eV showers [17].

The Pierre Auger Observatory has also obtained information on the number of muons in air showers using hybrid events at large zenith angles [16]. The number of muons for each shower is derived by scaling a simulated two-dimensional reference profile of the lateral muon density distribution at the ground until it fits the data. The measurements, given in terms of R_μ, the relative number of muons with respect to the reference profile, are shown in Fig. 5c. The results from simulations for proton and iron showers at 67°, the average zenith angle of the measured events, are also shown for comparison. It is interesting to notice that the predictions are well separated, illustrating the sensitivity of R_μ to mass composition, although the large systematic uncertainty, shown in Fig. 5c as squared brackets, limits the power of the method. From Fig. 5c one may conclude that in order to explain the data more muons are required in the calculations. This muon deficit of the models increase with the energy which could be explained assuming a heavier composition, consistent with the results obtained for $X_{\max}$.

There are also indications of a muon number anomaly in the models from less inclined showers [17], but the measurement in this case is complicated by the need to separate the electromagnetic and the muonic signals in the SD stations. The results are shown in Fig. 5d where more muons (R_μ different of 1), and no extra electromagnetic signal (R_E consistent with 1), are required to explain the data. R_μ and R_E are the respective rescaling factors of the muonic and the electromagnetic signal predictions needed to fit the data.

6 More than cosmic rays: neutrinos, photons, ...

The Pierre Auger Observatory can also detect UHE showers induced by photons, neutrons and neutrinos. These neutral particles should point back to their sources and have a common origin related to the production and propagation of UHE cosmic rays [18]. Photons and neutrinos may be produced by pion decay in the interactions of high energy hadrons accelerated by astrophysical shocks at or near the sources. They should also be generated in the collisions of UHE cosmic rays with the cosmic microwave background, which cause the GZK cutoff. There are also predictions of photons and neutrinos given by exotic scenarios of top-down acceleration models, as the decay of topological defects in the early universe or of super-heavy dark matter. Neutrons are expected in pion photo-production and nuclear interactions of protons near the sources. The production of neutrons with the hadronic production of charged pions is necessarily accompanied by photons from decay of similarly produced neutral pions. Thus, the search for photons, neutrons and neutrinos provides important clues on the origin of UHE cosmic rays.



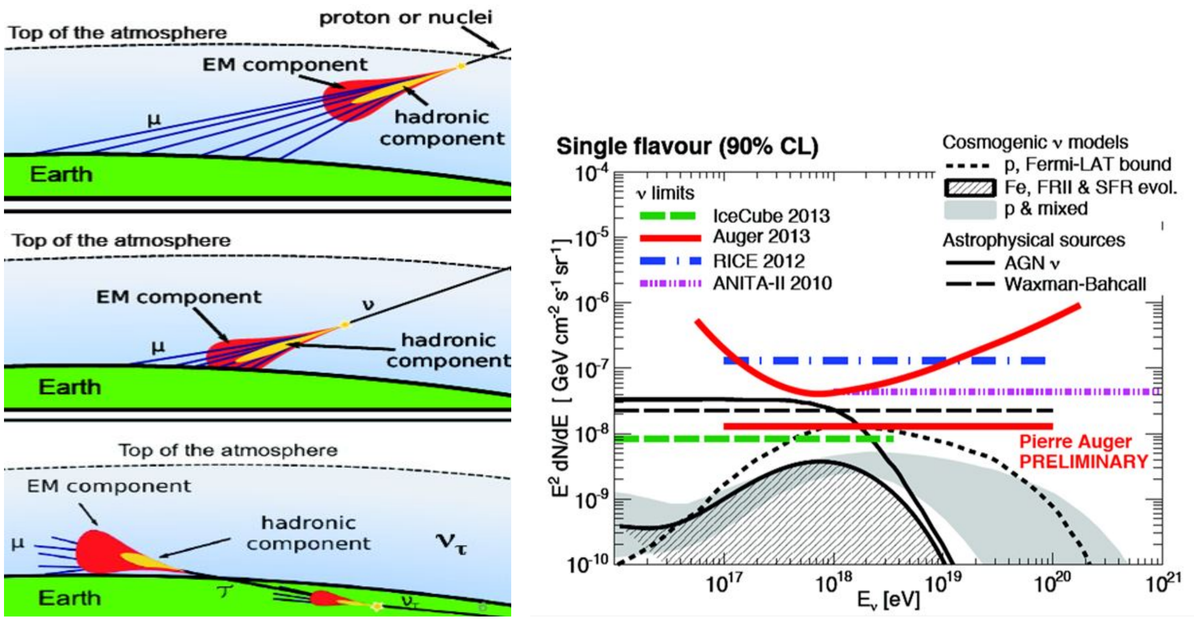
(a) (b)

Figure 6: (a) $X_{\max}$ distribution of data sample (gray) and simulated photon showers (blue) (b) Limits to diffuse photon fluxes [19].

Showers generated by photons can be distinguished from ordinary hadron showers by the different trace they leave in the atmosphere. Photon showers contain in average much less muons than cosmic ray showers and develop more deep in the atmosphere (Fig. 6a). The search for photons in Auger data has yielded no candidates from where upper limits to the photon fraction in cosmic rays at UHE have been established [19] (Fig. 6b). The limit to the photon flux was updated in Ref. [20]. Some of the super-heavy dark matter models can be excluded by the limits.

In addition, a search for point sources of UHE photons has been performed [21]. No photon point source has been detected and an upper limit on the photon flux has been derived for every direction. These upper limits constrain scenarios in which EeV cosmic ray protons are emitted by non-transient sources in the Galaxy.

Air showers produced by neutrons are indistinguishable from proton showers. However, as neutrons are not deflected by magnetic fields and their arrival directions should point back to their sources, they can be searched by identifying an excess of air showers arriving from a single direction. These searches do not find evidence for a neutron flux from any class of candidate sources scrutinized so far [22]. The limits established on fluxes of neutrons significantly constrain models of EeV proton emission from non-transient discrete sources in the Galaxy.



(a) (b)

Figure 7: (a) Neutrino detection channels. (b) Limits to UHE diffuse neutrino fluxes [25].

The surface detector of the Pierre Auger observatory is also sensitive to UHE energy neutrinos [23]. Neutrinos can produce down going showers at large depths in the atmosphere as well as upward-going showers close to the ground in interactions with the Earth crust (Earth skimming) (see Fig. 7a). For cosmic ray showers arriving at large zenith angles, as they were initiated up in the atmosphere, the electromagnetic component is attenuated and the remaining muons reaching the ground leave narrow picks in time in the detector. On the contrary, neutrino induced showers can be generated close to the detector and they still have a large electromagnetic component leaving broad signals in time.

With the surface detector array of the Pierre Auger Observatory the neutrino search is performed [24] separately for the Earth skimming channel and for down going events in two different zenith angle regions. Then, the three searches are combined to give a single limit (Fig. 7b), providing, in the absence of candidates in data from 1 January 2004 until 31 December 2012, a stringent limit to the diffuse flux of ultra-high energy neutrinos [25]. As can be seen in Fig. 7b the current Auger limit is below the Waxman-Bahcall bound on neutrino production in optically thin sources. It is also shown that we are starting to constrain models of cosmogenic fluxes that assume a pure primary proton composition injected at the sources.

7 Conclusions and future

As a summary, after 10 years of operation, the Pierre Auger Observatory has clearly observed the ankle of the cosmic ray spectrum at 5 EeV and a strong flux suppression at 20 sigma level above 50 EeV [5]. The comparison of the shower elongation rate with theoretical results points out to a heavier composition above $10^{18.5}$ eV [12, 13, 14]. The p-air and pp cross-section has been obtained at an average collision energy 57 TeV [15], and a muon deficit in the model predictions of 30 to 60 % is observed in comparison with Auger data [16, 17]. Although cosmic ray sources have not yet been identified, a weak correlation with nearby matter, and a certain excess of events around Centaurus A, has been detected [9]. Importantly, very recently, a dipole anisotropy has been found in Auger data [11].

The Observatory has also searched for photons. Photons are closely associated to cosmic rays and their presence in data could be the proof of the sites where cosmic rays are accelerated. With no candidates found, we have stablished the strongest limits to the photon fraction in the cosmic ray spectrum at UHE, imposing strong constraints on top down models for the origin of UHE cosmic rays [20]. In addition, looking for inclined events the surface detector is also sensitive to neutrinos. Up to date no neutrino events, in the form of elongated and electromagnetic rich showers, have been found in the data, and strong bounds to the diffuse UHE neutrino fluxes have been established [25]. The bounds start to exclude certain scenarios of cosmogenic neutrinos.

Much has been learned from the data, but the fundamental question on the nature and origin of UHE cosmic rays remains unanswered, in part caused by the lack of statistics but also because of the existence of difficulties to separate the effects of mass composition and hadronic interaction models in the observations of extensive air showers. The puzzling results obtained by the Pierre Auger Observatory may indicate that we are close to important discoveries. The detailed study of the cosmic ray mass composition at the energies of the flux suppression will be crucial to disentangle the interpretation of the apparently contradictory results. This will be done with the upgrade of the Surface Detector planned to start in 2015. The separation of the electromagnetic and muon shower components with SD will provide 10 times more statistics for composition studies than the present FD studies. It will also improve our sensitivity to photon and neutrino searches and to study fundamental interactions at center-of-mass energies an order of magnitude above the LHC.

8 Acknowledgements

The speaker wants to thank the organizing committee for the invitation to Quarks 2014 and for the friendly and warm atmosphere created during the meeting in the magnificient town of Suzdal. I also thank Ministerio de Ciencia e Innovación of Spain and Xunta de Galicia for financial support.

The successful results presented in this work would not have been possible without the effort of the entire Pierre Auger Collaboration including the local staff of the Observatory in Malargüe.

References

[1] T. Stanev, High Energy Cosmic Rays, Springer, 2010.

[2] P. Auger et al., Review of Modern Physics 11 (1939) 288-291.

[3] K. H. Kampert and A. A. Watson, EPJ H37 (2012) 359-412 (arXiv:1207.4827).

[4] The Pierre Auger Collaboration, Nuclear Instruments and Methods in Physics Research A 523 (2004) 50-95.

[5] A. Schulz for the Pierre Auger Collaboration, Proc. 33rd ICRC, Rio de Janeiro, Brazil, 2013 (arXiv:1307.5059).

[6] The Pierre Auger Collaboration, Physical Review Letters 101 (2008) 061101.

[7] The Pierre Auger Collaboration, Journal of Cosmology and Astroparticle Physics 08 (2014) 019 (arXiv:1407.3214).

[8] A. A. Watson, Reports on Progress in Physics 77 (2014) 036901 (arXiv:1310.0325).

[9] The Pierre Auger Collaboration, submitted to The Astrophysical Journal (arXiv:1411.6111).

[10] The Pierre Auger Collaboration, The Astrophysical Journal, 794 (2014) 172 (arXiv:1409.3128).

[11] The Pierre Auger Collaboration, submitted to The Astrophysical Journal (arXiv:1411.6953).

[12] The Pierre Auger Collaboration, Physical Review D 90 (2014) 122005 (arXiv:1409.4809).

[13] The Pierre Auger Collaboration, Physical Review D 90 (2014) 122006 (arXiv:1409.5083).

[14] The Pierre Auger Collaboration, Physical Review D 90 (2014) 012012 (arXiv:1407.5919).

[15] The Pierre Auger Collaboration, Physical Review Letters 109 (2012) 062002 (arXiv:1208.1520).

[16] The Pierre Auger Collaboration, accepted for publication in Physical Review D (arXiv:1408.1421).

[17] G. R. Farrar for the Pierre Auger Collaboration, Proc. 33rd ICRC, Rio de Janeiro, Brazil, 2013 (arXiv:1307.5059).

[18] T. K. Gaisser and T. Stanev, Astroparticle Physics 39-40 (2012) 120-128 (arXiv:1202.0310).

[19] The Pierre Auger Collaboration, Astroparticle Physics 31 (2009) 399-406 (arXiv:0903.1127).

[20] M. Settimo for the Pierre Auger Collaboration, Proc. 32nd ICRC, Beijing, China, Vol. 2, p. 55, 2011.

[21] The Pierre Auger Collaboration, The Astrophysical Journal 789 (2014) 160 (arXiv:1406.2912).

[22] The Pierre Auger Collaboration, The Astrophysical Journal, 789 (2014) L34 (arXiv:1406.4038).

[23] K. S. Capelle, J. W. Cronin, G. Parente and E. Zas, Astropart. Phys. 8 (1998) 321 (arXiv:astro-ph/9801313).

[24] The Pierre Auger Collaboration, Advances in High Energy Physics 2013 (2013) 708680 (arXiv:1304.1630).

[25] P. Pieroni for the Pierre Auger Collaboration, Proc. 33rd ICRC, Rio de Janeiro, Brazil, 2013 (arXiv:1307.5059).