Selected results from the Pierre Auger Observatory

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Abstract. The Southern Pierre Auger Observatory is complete. Data have been taken since January 2004 while the array was being constructed, what amounts to more than 1 year of exposure with the full array. Results on the energy spectrum of UHECRs above \(10^{18}\) eV measured with vertical and inclined showers are presented. Inclined showers are also used to search for ultra-high energy neutrinos, and a competitive limit on their diffuse flux for energies above \(\sim 10^{17}\) eV has also been placed.

1. Introduction

Ultra High Energy Cosmic Rays (UHECRs) with EeV and higher energies\(^1\) constitute one of the topics that has led to more experimental and theoretical activities in the field of Astroparticle Physics. Many questions related to the origin, nature, acceleration and propagation of the Ultra High Energy Cosmic Rays at these energies are still unsolved [1]. Until very recently the experimental situation was very unclear, mainly because at these extreme energies the flux of cosmic rays is very low: less than 1 particle per km\(^2\) per century for cosmic rays above \(10^{20}\) eV. Due to this, UHECRs can only be observed indirectly through the extensive air showers (EAS) they induce when colliding with a nucleus in the atmosphere, with the added difficulty that the interpretation of the observed EAS relies on models of hadronic interaction at energies that have not been still reached in man-made experiments.

The recently finished Pierre Auger Observatory is the largest experiment ever built for the observation of the UHECRs. The hybrid character of observatory, combining data collected by a surface detector (SD) and by several fluorescence detectors (FD), allows many EAS observables to be measured with redundancy and with greater accuracy than any of the two techniques alone. Moreover, the surface detector array of the Pierre Auger Observatory with its \(\sim 3000\) km\(^2\) of area accumulates UHECR events at an unprecedented rate.

Observations performed with the Pierre Auger Observatory are already shedding light into many of the questions still unsolved. At the highest energies —above \(\sim 5 \times 10^{19}\) eV— the Auger Collaboration has established that the sky is not isotropic and that there is a clear indication for the extragalactic origin of the UHECRs [4, 5]. Despite this important discovery, their actual sources remain to be pinpointed. The mechanisms by which Nature accelerates particles to these high energies are also still a mystery. The measurement of the composition of the UHECR primaries is one of the keys to understanding their origin. Although stringent limits have been put by the Auger Collaboration on the fraction of photons [7] and neutrinos [36] in the UHECR

\(^1\) 1 EeV = \(10^{18}\) eV
flux, it remains to be determined whether they are protons or heavier nuclei or a mixture of both [6].

From a theoretical point of view, if the UHECRs are protons then a suppression of their flux above $\sim 4 \times 10^{19}$ eV is expected because of energy losses in interactions with the Cosmic Microwave Background (CMB) radiation, when they propagate from their extragalactic sources to the Earth. This is the Greisen-Zatsepin-Kuzmin (GZK) effect proposed in the 1960’s [2]. Similarly if the sources accelerate heavy nuclei, these can photo-disintegrate into lighter ones as they interact with the CMB and infrared photons on their journey to us and a suppression of their flux is also expected [3]. A suppression compatible with the GZK cut-off has been already observed in the UHECR flux detected at the Pierre Auger Observatory [14]. This observation provides important hints to the UHECR origin since in any of these two scenarios, the sources of the most extremely energetic cosmic rays at $10^{20}$ eV have to be less than a few tens of Mpc, and only a few nearby sites are large enough and have sufficiently strong magnetic fields to be able to accelerate them.

In this contribution after briefly describing the Pierre Auger Observatory, we concentrate on some selected recent results mainly related to the energy spectrum above EeV energies. The energy distribution of the UHECRs has been measured with the SD and the FD detectors. In the case of the SD, the UHECR spectrum has been determined experimentally with air showers of zenith angles with respect to the vertical smaller than $\theta = 60^\circ$ —the so-called “vertical” showers— and also with those with $\theta > 60^\circ$ —the so-called “inclined” showers. As will be shown below the observation of inclined showers enhances the sensitivity to Ultra High Energy Neutrinos (UHE$\nu$s) in the data, which are expected to be produced in interactions of the UHECRs with matter and radiation in their sources and during their propagation to Earth. In this contribution special attention is paid to the capabilities of the SD of the Pierre Auger Observatory for the observation of UHE$\nu$s.

2. The Southern Site of the Pierre Auger Observatory

The Pierre Auger Observatory is a sophisticated hybrid instrument built by a multi-national collaboration near the town of Malargüe, Mendoza Province, Argentina (35.5°S, 69.3°W), at an altitude of 1400 m above sea level, $\sim 880$ g cm$^{-2}$ of atmospheric depth in the vertical direction. The observatory was recently completed and it comprises more than 1600 water Cherenkov tanks and 24 fluorescence telescopes located in 4 buildings on top of hills in the perimeter of the array, see figure 1.

The SD array of water Cherenkov tanks spreads over an area of 3000 km$^2$ in a hexagonal grid with the tanks located at a distance of 1.5 km from its 6 nearest neighbors. A water Cherenkov station consists of a cylindrical tank of 1.2 m average height and 10 m$^2$ area, containing 12 tonnes of purified water. Each station is an independent unit with low-power electronics, and a GPS and radio communication systems, all powered by a solar panel and two batteries. The Cherenkov light emitted by the particles entering a tank is reflected and diffused in its inner walls and collected by three 9-inch hemispherical photomultipliers. The corresponding signals are digitised by Flash Analog-Digital Converters (FADC) in time slots of 25 ns. The result is a FADC trace, an example of which is shown in figure 4. The signal collected in a tank is calculated integrating in time the FADC trace, and is calibrated in units of Vertical Equivalent Muons (VEM) corresponding to the signal produced by vertical muons crossing the tank through its center. Surface detector stations are calibrated online every few minutes using atmospheric muons. The SD is overlooked by 4 FD sites that hold 6 fluorescence telescopes each which measure the ultraviolet light produced when charged particles in the air shower excite nitrogen molecules in the atmosphere. Each telescope uses Schmidt optics to image a portion of the sky of $\sim 30^\circ \times 30^\circ$. The UV light is focused by spherical mirrors of 3 m$^2$ of area onto a camera of 440 hexagonal photomultipliers each with a field of view of 1.5° diameter.
The Pierre Auger Observatory is the first large aperture instrument to routinely employ the so-called hybrid technique. About 13% of the operating time, the fluorescence light emitted by a shower and the timing and signal information from at least one surface detector is simultaneously recorded. This unique hybrid combination has enormous advantages which stem from the fact that one can simultaneously measure several shower observables with two different techniques. The advantages inherent to the SD are a large collecting area, 24 hour operation and an easily calculable aperture.

The Pierre Auger Collaboration is extending the observatory to the northern hemisphere with plans to construct an even bigger detector near the town of Lamar in the state of Colorado in the US [8].

3. The energy spectrum of UHECRs

The hybrid nature of the Pierre Auger Observatory and the huge collecting area of the SD, allows the energy spectrum of UHECRs to be measured with unprecedented accuracy and statistics. Good quality hybrid events are used to calibrate the SD energy estimator. A direct measurement of the fluorescence light gives the energy deposited in the atmosphere, mainly by the electromagnetic component of the shower, in a near-calorimetric way largely independent on hadronic models and assumptions about primary composition. This must be corrected by the energy carried away by high-energy muons and neutrinos—the so-called “invisible” energy. Due to the different physical characteristics on the ground of “vertical” $\theta < 60^\circ$ and inclined $\theta > 60^\circ$ events, different ground parameters are used to estimate the primary CR energy and hence the primary CR spectrum.

3.1. Measurement of the UHECR energy spectrum with vertical showers

For vertical events the parameter chosen as energy estimator is called $S(1000)$ the signal at a distance of 1000 m from the core. The distribution of particles in the shower at the ground level is sampled at different distances from the core, and a fit to a Lateral Distribution Function (LDF) allows to determine $S(1000)$ [9]. $S(1000)$ has been shown to be rather insensitive to shower-to-shower fluctuations, nor does it require accurate knowledge of the shape of the LDF [10].
For a fixed CR energy, $S(1000)$ depends on the zenith angle of the event due to the attenuation of the shower particles in the atmosphere and other geometrical effects. Under the assumption of an isotropic flux of primary CRs, showers generated by primary particles of the same energy will arrive at the detector with the same frequency regardless of the zenith angle (assuming 100% efficiency). Hence, selecting showers arriving with a fixed intensity (energy) as a function of $S(1000)$, under different zenith angles, allows the measurement of the attenuation of $S(1000)$ with $\theta$ (the CIC curve). This is the classical “constant integral intensity cut” method [11]. This serves to convert $S(1000)$ at any given $\theta$ to $S(1000)$ at $\theta = 38^\circ$ ($S_{38}$) which is used as energy estimator. The calibration curve relating $S_{38}$ and shower energy as obtained with FD data ($E_{FD}$) in hybrid events is shown in figure 2, and it is used to find the energies of the bulk of the events in which there are only SD measurements.

The uncertainties in the parameter $S_{38}$ include those from $S(1000)$ reconstruction ($\sim 10\%$), from the measurement of the CIC curve, and from the accuracy in the angular reconstruction ($< 1.5^\circ$ when > 3 stations are triggered) [12]. Uncertainties in $E_{FD}$ amount to 22% dominated by the fluorescence yield (14%) with an absolute value from [13], the absolute calibration of the FD (10%), and the reconstruction method (10%). Less important sources of uncertainty from atmospheric aerosols and the dependence of the yield on temperature and humidity are at the 5% level each. The uncertainty on $E_{FD}$ due to the model and primary mass dependences of the “invisible” energy is $\sim 4\%$.

Only events passing a chain of 5 trigger levels are given full consideration for the energy spectrum. The chain essentially guarantees that an event is an actual shower whose core is “well contained” inside the array so that the LDF is well sampled and a robust determination of $S(1000)$ can be performed. With these selection criteria, the array becomes 100% efficient to vertical showers at an energy of $3 \times 10^{18}$ eV. Up to 31 Aug. 2007 the exposure amounts to $\sim 7000$ km$^2$ sr yr, which is $\sim 4$ times that of AGASA and $\sim$ twice that of HiRes. The energy spectrum is shown in figure 2. The spectral index of the particle flux $J \propto E^{-\gamma}$.
between $4 \times 10^{18}$ eV and $4 \times 10^{19}$ eV is $\gamma \simeq -2.69 \pm 0.02$ (stat) $\pm 0.06$ (syst), and it increases to $\gamma \simeq -4.2 \pm 0.4$ (stat) $\pm 0.06$ (syst) at higher energies. The number of events expected above $10^{19.6}$ eV and $10^{20}$ eV if a single power law $\gamma = 2.69$ were to hold in all the energy range would be $167 \pm 3$ and $35 \pm 1$ respectively, while the observed numbers are 69 and 1 respectively. The hypothesis of a single power law is then rejected with a significance of $\sim 6\sigma$ [14]. As can be seen in figure 2, the position of the suppression in the spectrum agrees with that measured in the HiRes experiment [16], but the HiRes spectrum is softer.

3.2. Measurement of the UHECR energy spectrum with inclined showers

Inclined showers with zenith angles $60^\circ < \theta < 80^\circ$ are also detected with the Pierre Auger Observatory which enhances the exposure of the SD by $\sim 30\%$. Inclined showers are different from vertical showers and require a separate treatment. They consist mainly of muons at the ground level, since beyond $60^\circ$ the atmospheric slant depth is large enough so that most of the electromagnetic component is significantly attenuated [17]. In inclined events there is a large asymmetry on the distribution of the signal around the shower core that makes the use of the LDF and of the $S(1000)$ parameter unsuitable for the analysis of inclined showers [20]. Instead “muon maps” [18]—2-dimensional distributions of muon densities obtained by Monte Carlo simulations—are fitted to the observed signals in the ground. The shape of the maps is largely independent of energy and composition, and depends on zenith and azimuth angles only [20]. As a consequence, the only parameter to be determined is the map normalization ($N_{19}$) which is used as an energy estimator. The reconstructed $N_{19}$ values are energy-calibrated using the FD energies in the same manner as for vertical events. For this analysis events from 1 Jan. 2004 up to 28 Feb. 2007 were used. There are only 38 hybrid events in this data set that can be used for calibration. Statistical and systematic uncertainties are assigned to both $N_{19}$ and $E_{FD}$, the latter are the same as in the vertical case. The uncertainty in $N_{19}$ associated to the angular reconstruction uncertainty $\sim 1^\circ$ which affects the choice of the muon map is a maximum of 12%. A correction ($\sim 15\%$) due to the presence of electromagnetic signal in the shower—mainly due to muon decay close to the ground—is applied to the conversion of the observed signals into number of muons [17]. Below $65^\circ$ the uncertainty on this correction is tentatively assigned as $7\%$ [21].

At energies where the trigger is fully efficient (above about $6 \times 10^{18}$ eV) the exposure amounts to $1510 \text{ km}^2 \text{ sr yr}$. The first CR energy spectrum ever measured in the angular range between $60^\circ$ and $80^\circ$ is shown in figure 3. The spectrum contains 734 events [21]. The spectral slope above this energy is $\gamma = -2.7 \pm 0.1$, compatible with that inferred from the vertical spectrum. The smaller statistics of the inclined data set prevents extracting conclusions on the steepening of the spectrum at the highest energies.

3.3. Measurement of the UHECR energy spectrum with hybrid events

Exploiting the power of the hybrid technique, hybrid data in which at least one tank is triggered has been used to extend the measurement of the spectrum down to lower energies, near $10^{18}$ eV [22]. The two main sources of systematic uncertainty are associated with the determination of $E_{FD}$ ($\sim 22\%$) and to the calculation of the exposure ($\sim 16\%$). The hybrid spectrum obtained with data taken from 1 Jan. 2004 up to 28 Feb. 2007 is shown in figure 3. It is based on 1092 hybrid events with energies above $10^{18}$ eV. An ankle is seen in the hybrid spectrum at $\sim 10^{18.6}$ eV with the spectral slope decreasing from $\gamma = 3.30 \pm 0.06$ to $\gamma = 2.62 \pm 0.03$. 
**Figure 3.** Energy spectra of cosmic rays obtained with vertical SD, inclined SD, and hybrid events from 1 Jan. 2004 up to 28 Feb. 2007 as presented in [15]. The three spectra have been multiplied by $E^3$ to enhance their features.

**Figure 4.** (a) Typical FADC trace expected in a water Cherenkov tank in a shower having a significant EM component at the ground such as those initiated close to the ground. (b) Typical FADC trace expected when a muonic front generated in a shower initiated high in the atmosphere triggers a water Cherenkov tank at the ground.

4. **Ultra-high energy neutrinos**

Inclined showers are the key to detect UHE neutrinos. This can be done with the SD of the Pierre Auger Observatory in the EeV range and above [33, 34]. Essentially all models of UHECR production predict neutrinos as the result of the decay of charged pions, produced in interactions of the CRs within the sources themselves or in their propagation through background radiation fields [23, 24, 25]. In top-down models of UHECR production neutrinos are copiously produced [26].

The main challenge is to identify $\nu$-induced showers in a large background of cosmic ray-induced showers. The concept for identification is simple: while hadrons and photons interact soon after entering the atmosphere, neutrinos can penetrate large amounts of matter and generate a “young” shower close to the SD. Examining inclined showers enhances the differences between young showers and those produced early in the atmosphere. Young showers are expected to have a significant electromagnetic component at the ground, while the EM component of inclined showers is largely suppressed due to attenuation in the atmosphere. With the SD of $N_{19}$ corresponds to the total number of muons in the event relative to a shower initiated by a proton with $E = 10^{19}$ eV.
4.1. “Earth-skimming” tau neutrinos

The SD of the Pierre Auger Observatory is sensitive to Earth-skimming tau neutrinos [27, 28, 29, 30]. These are expected to be observed through the detection of showers induced by the decay products of an emerging $\tau$ lepton, after the propagation and interaction of a flux of $\nu_\tau$ inside the Earth, see figure 5. $\nu_\tau$s are expected to be heavily suppressed at production, however $\nu$ oscillations over cosmological distances [35], balances the ratio of the three $\nu$ flavours when they reach the Earth. The criteria to identify $\nu_\tau$-induced showers consist on first selecting showers that have most of the signal in tanks with signals sufficiently spread in time. Then the footprint of the shower and the speed of propagation of the signal from tank to tank, are required to be compatible with those expected in an almost horizontal shower [36]. No $\nu$ candidates were found in data collected between 1 Jan. 2004 and 31 Aug. 2007, and an upper limit on the diffuse flux of UHE $\nu_\tau$ was set. For that purpose the acceptance of the SD to UHE Earth-skimming $\nu_\tau$ was computed through an end-to-end simulation involving the calculation of the flux of $\tau$s emerging from the Earth after the passage of a $\nu_\tau$ flux, the decay of the $\tau$ and the development of the shower in the atmosphere, and the simulation of the response of the detector to it [36]. The neutrino limit assuming a differential input $\nu_\tau$ flux $f(E_\nu) \propto E_\nu^{-2}$ is shown in the right panel of figure 5, and corresponds to the most pessimistic value in $E_\nu^2 f(E_\nu) = 1.0^{+0.3}_{-0.5}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. Most of the sensitivity of the SD of the Pierre Auger Observatory is at energies between $10^{17}$ eV and $5 \times 10^{19}$ eV, where a significant fraction of the flux of cosmogenic neutrinos is expected [24, 25].

Systematic uncertainties include those associated to the $\nu$-nucleon cross section (14%), the polarization of the $\tau$ determining the fraction of energy transferred to the shower (30%), and the $\tau$ energy loss (40%). Other uncertainties come from neglecting the topography around the site (18%), and from simulation (25%) [36].
Figure 6. Left panel: Sketch of a down-going shower initiated in the interaction of a $\nu$ in the atmosphere close to the ground. In the “early” (“late”) region of the shower before (after) the shower axis hits the ground we expect broad (narrow) signals in time due to the EM (muonic) component of the shower. Right panel: Width in time of the FADC traces in each of the stations triggered by a simulated neutrino-induced shower with $E_\nu = 3 \times 10^{18}$ eV and $\theta = 80^\circ$ interacting close to ground (bold circles), and in a real inclined event induced by a hadron. The width of the FADC traces is plotted as a function of the time at which the station is hit by the shower. The time assigned to the first triggered station is arbitrarily set to zero.

4.2. “Down-going” neutrinos

The SD is also sensitive to neutrinos interacting in the atmosphere and inducing a shower close to the ground [31, 32, 33, 34], figure 5. This mechanism is sensitive to all $\nu$ flavours, and to both charged and neutral-current weak interactions. Due to the diluted target (atmosphere), the conversion efficiency is lower than in the Earth. The criterium to identify young, inclined, down-going showers consists of looking for broad FADC traces in time as in the case of up-going neutrinos, but only in the early region, i.e. in those tanks triggered before the shower core hits the ground. The physical basis for this criterium is the large asymmetry in the time spread of the signals that one expects for very inclined young showers, in which the late front of the shower typically has to cross a much larger grammage of atmosphere than the early front (depending on the zenith angle), and in consequence suffers more attenuation as illustrated in figure 6. For example, the particles in a $\theta = 80^\circ$ shower, initiated at $X_{\text{inj}} = 800$ g cm$^{-2}$ (as measured in slant from ground) have to cross of the order of 700 g cm$^{-2}$ additional atmosphere to hit a tank at a distance of 3 km from the core of the shower when the tank is located downstream from the first tank struck. One expects to have a thin front of shower muons in the late part of the shower and a thick front of EM particles only in the early region of the shower. This has been confirmed by simulations of UHE neutrinos which suggest that a good identification criterium is to require that there are broad signals in the first few triggered tanks of the event. This is shown in the right panel of figure 6 in which we plot the width in time of the FADC traces in each of the stations triggered by a simulated neutrino-induced shower with $E = 10^{18}$ eV and $\theta = 80^\circ$ initiated close to the ground. The width in time is shown as a function of the time at which the station is hit by the shower. The same quantity is plotted for a real event induced by a hadron high in the atmosphere. One can clearly see broad signals in time in the earliest stations in the shower and narrow ones in the later ones in the case of the neutrino-induced shower.
5. Conclusions
The Pierre Auger Observatory is the first large scale UHECR detector to exploit the power of the hybrid technique, opening up a new era in experimental UHECR physics. The energy spectrum of UHECRs above EeV energies was measured with vertical, inclined and hybrid events. Shower energies are determined in a way that minimizes the dependence on models of hadronic interaction and composition. An ankle in the spectrum at $\sim 4 \times 10^{18}$ eV and a steeping above $\sim 4 \times 10^{19}$ eV consistent with the GZK effect are apparent. Data from the SD have been used to put stringent limits on the photon fraction in the UHECR flux, as well as on the diffuse flux of UHE $\nu_\tau$. The composition of the UHECRs at the highest energies remains to be determined. Preliminary studies suggest that it is not dominated by protons. The sky has been shown to be anisotropic in UHECRs and their sources extragalactic. The exact sources of UHECRs and the mechanisms by which they are accelerated to the highest energies ever observed in an elementary particle remain unknown.

Acknowledgments
We thank Ministerio de Ciencia e Innovación (FPA 2007-65114 and Consolider CPAN); Xunta de Galicia (PGIDIT 06 PXIB 206184 PR) and Consellería de Educación (Grupos de Referencia Competitivos – Consolider Xunta de Galicia 2006/51); and Feder Funds, Spain. We also thank CESGA (Centro de Supercomputación de Galicia) for computing resources.

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