The Pierre Auger Observatory – why and how

A.A. Watson
School of Physics and Astronomy, University of Leeds, UK

1 Some historical background

Cosmic rays were discovered by an intrepid Austrian balloonist, Victor Hess, in 1912. In a remarkable series of balloon flights, one of which took him above 5000 m, he showed that the rate of formation of ions in a closed chamber increased with altitude. He concluded that the Earth was being bombarded by radiation from outer space which was given the name 'cosmic radiation (or cosmic rays)' by R.A. Millikan in 1926. He thought that γ rays, then the most penetrating radiation known, caused the enhanced ion production observed by Hess.

We now know that only about 10^{-4} of the incoming radiation is in the form of γ rays. Most of the radiations are atomic nuclei with about 1% primary electrons. The energy range extends from about 1 GeV (where the solar magnetic field can deflect the particles) to at least 10^{20} eV. Because the particles are charged, and interstellar and intergalactic space are threaded with magnetic fields, it has not been possible to trace the particles back to their point of production. Above about 10^{14} eV the flux of cosmic rays is so low that it is barely practical to detect them directly using instruments carried on balloons or spacecraft and instead one must rely on the extensive air showers (EAS) that the particles create when they hit the Earth's atmosphere. Above 10^{14} eV, where the maximum number of $\sim 10^5$ particles is reached at $\sim$ 6 km above sea-level, some particles survive so that remnants of the primary are detectable. Because of scattering, electrons and photons can be found at large distances from the axis of such showers although about 50% lie within the Molière radius which is about 70 m at sea-level. The discovery of extensive air showers is usually credited to Pierre Auger [1] who, in 1938, observed an unexpectedly high rate of coincidences between counters separated by a few metres. Further investigations by his team showed that even when the counters were as far as 300 m apart, the rate of coincidence was significantly in excess of the chance expectation. Speculating that the primaries were photons, and using the newly developed ideas of quantum electrodynamics, Auger demonstrated that the incoming entities had energies as high as 10^{15} eV. Earlier Rossi [2] had reported experimental evidence for extensive groups of particles ("sciami molto estesi di corpscoli") which produced coincidences between counters rather distant from each other. Kolhörster and colleagues [3] made very similar observations to those of Auger and his group with counter separations out to 75 m. It was Auger, however, who was in a position to follow up the discovery of this new phenomenon and through his inferences about the primaries extend the range of energies then known by nearly 6 orders of magnitude. Cosmic rays remain the most extreme example of the departure of matter from thermal equilibrium.

One of the early motivations for studying cosmic rays using extensive air showers was the expectation that anisotropies would be discovered as the technique allowed the exploration of an energy regime where deflections by a galactic magnetic field might be small enough to permit the observation of point sources. This led to the construction of larger and larger shower arrays where 'large' eventually meant an area of a few square kilometres. Such detectors were developed at Volcano Ranch, USA (8 km^2, with scintillators), Haverah Park, UK (12 km^2, with water-Cherenkov detectors), SUGAR, Australia ($\sim$ 100 km^2, with buried scintillators) and Yakutsk, Siberia (25 km^2, with scintillators, muon detectors, and air-Cherenkov detectors). In 1963 Linsley reported the detection of an event of 10^{20} eV (or 100 EeV) with the Volcano Ranch array [4]. The significance of this energy was not immediately appreciated but soon after the discovery of the 2.7 K cosmic microwave radiation in 1966, Greisen and Zatsepin and Kuz'min [5] pointed out that if the highest energy particles were protons and if their sources were uniformly distributed throughout the Universe, then there would be interactions between the cosmic rays and the microwave background that would modulate the spectrum of the highest energy particles.

A particularly important reaction is the following:

$$\mathrm{p} + \gamma_{2.7\mathrm{K}} \rightarrow \Delta^+(1232) \rightarrow \mathrm{p} + \pi^0 \quad \text{or} \quad \mathrm{n} + \pi^+ \ . \tag{1}$$

In the rest frame of the proton (the cosmic ray), the microwave background photon will look like a very-high-energy γ ray. When the Lorentz factor Γ of the proton is $\sim 10^{11}$, the Δ^+ resonance will be excited. In each reaction (1) the proton loses about 15% of its energy. Over cosmological distances, sufficient reactions take place for the observed spectrum to become significantly depleted of ultra-high-energy cosmic rays (UHECRs) compared with what might have been present at the time of acceleration. It follows that if protons of $\sim 10^{20}$ eV are observed, they must have originated from nearby. For example, a cosmic ray of 50 EeV has a 50% chance of having come from beyond 100 Mpc. This opens the prospect of seeing point sources of cosmic rays at the very highest energies as the intergalactic magnetic fields are not expected to bend the trajectories of the particles by too large an amount.

If high-energy particles can escape from the acceleration region as nuclei, then the CMB radiation, supplemented by the diffuse infrared radiation field, are important factors. The key resonance is now the giant dipole resonance (typical energy $\sim$ 10 MeV), and the mixture of species that arrives at the Earth can be very complex depending upon the paths travelled through the radiation fields. Both protons and nuclei also lose energy by pair production, the threshold here corresponding to $\Gamma \sim 10^9$. The energy losses are small but nearly continuous and may be important if protons of energies 1–10 EeV are of extragalactic origin. The reactions of Eq. (1) are also important in the context of γ and ν astronomy while the neutrons from photodisintegration are also a source of neutrinos.

2 Detectors and measurements from the pre-Auger era

In Fig. 1 a representation of the cosmic-ray energy spectrum due to Gaisser [6] is displayed. Nearly all of the data shown above 10^{14} eV are from air-shower measurements. It is relevant in the context of the CERN–CLAF School to point out the position of the Tevatron and the LHC on the energy axis. The arrows indicate the energies that a cosmic ray hitting a stationary nucleon must have for the centre-of-mass energy to be the same as achieved in a Tevatron or LHC collision.

Thus it is evident that knowledge of the particle physics interactions, even from the LHC, will not cover the energy range of relevance to cosmic rays of the highest energy. Furthermore, the region of rapidity space that will be observed at the LHC (Fig. 2) excludes the diffractive region that is of great importance in the development of an air shower. In a shower, the energy carried by the leading particle from each collision, which may be $\sim$ 0.5 of the incoming energy, is crucial for the development of the shower, just as the multiplicity of the charged meson component radiating from the collision is crucial to the development of the muon signal. Neutral pions play a key role in the development of the electromagnetic cascade.

It follows that significant extrapolation is required to infer what has initiated an air shower from what is observed at ground-level. Ideally, knowledge of the mass and of the hadronic physics is required at the energies of interest, where the hadronic physics must cover details of pion–nucleus collisions and nucleus–nucleus collisions at extreme energies.

In the 1970s an alternative technique to that of deploying particle detectors over greater and greater areas emerged. This relies on the excitation of atmospheric nitrogen by the electrons of the shower as it traverses the atmosphere. The nitrogen emits fluorescence radiation isotropically, predominantly in the 300–400 nm band, and this can be observed at distances of $\sim$ 20 km with arrays of photomultipliers on dark, clear nights. The technique was pioneered by a group from the University of Utah. With their original Fly's Eye detector they recorded an event of 300 EeV, still the highest cosmic-ray energy ever claimed. This event is shown in Fig. 3(a) together with a schematic of a photomultiplier array [Fig. 3(b)] in which each tube is orientated in a different direction. The magnitudes of the signals in the tubes are used to estimate the number of particles along the track of the shower while the positions of the tubes

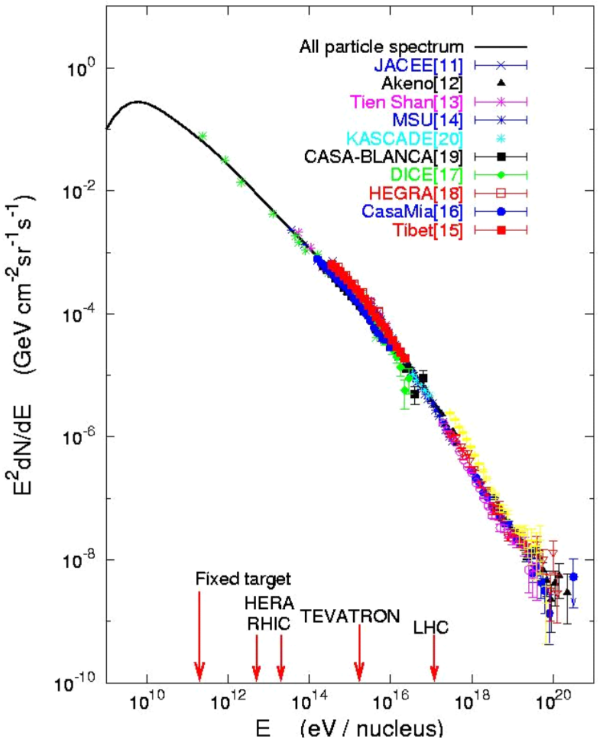


Fig. 1: Data summary made by Gaisser [6]. Below about 10^{14}eV it is possible to make observations directly in spacecraft or, after correcting for the atmospheric overburden, from balloons. Above this energy the data are deduced almost exclusively from studies of extensive air showers. The spectrum is rather featureless: the marked bend at around 1 GeV is caused by the solar magnetic field; there is a small steepening in the spectrum at about 3×10^{15} eV (known as the knee) and around 3×10^{18} eV the spectrum flattens again at the 'ankle'. What the details are above 10^{19} eV (or 10 EeV) remains to be resolved.

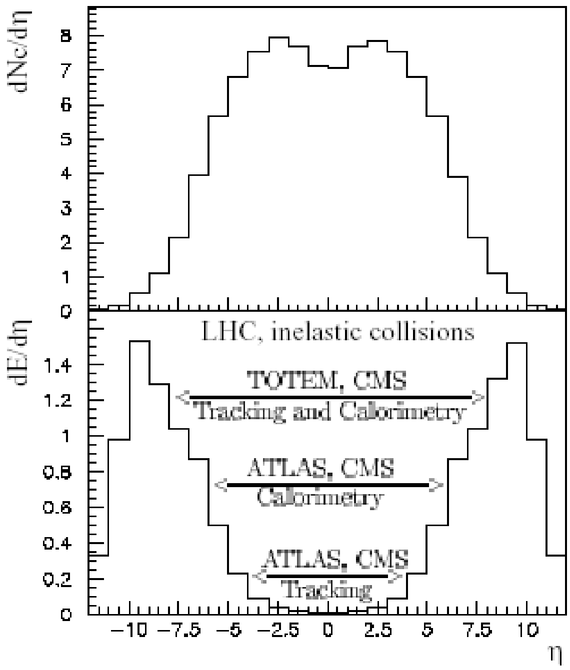
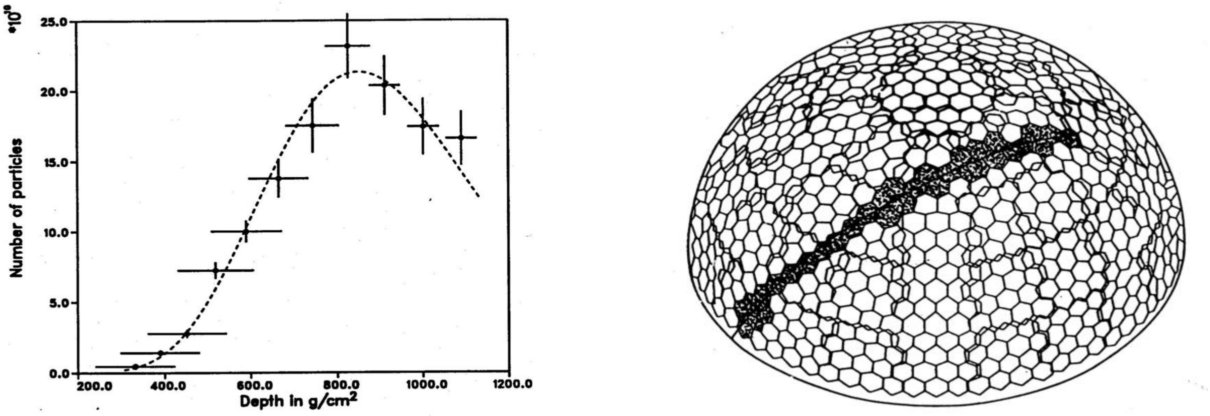


Fig. 2: The pseudo-rapidity (η) distribution of charged particles (upper panel) and of the energy flow (lower panel) predicted for pp collisions at the LHC [7]

define a plane in which the axis of the shower lies (the shower detector plane). The primary energy is then derived by integrating under the longitudinal development curve (the track length integral) and multiplying the result by the appropriate (-dE/dx). This gives a calorimetric estimate of the total energy deposited in the atmosphere.



(a) (b)

Fig. 3: (a) The longitudinal development of a shower created by a primary cosmic ray of 300 EeV as recorded by the Fly's Eye detector [8]; (b) A schematic diagram illustrating a shower crossing the array of photomultiplier tubes in the Fly's Eye detector.

To find the energy of the primary particle, this estimate of the ionization energy loss must be augmented by about 7–10% to allow for energy carried by high-energy muons and neutrinos into the ground. This correction is slightly dependent on the mass and hadronic interaction model assumed but has a much smaller systematic uncertainty than has the conversion to primary energy from observations with a surface detector alone.

Neither the early large surface detector arrays at Volcano Ranch, Haverah Park, SUGAR or Yakutsk, nor the Fly's Eye detector proved big enough to establish the shape of the cosmic-ray spectrum above 10 EeV. Accordingly, second-generation detectors were constructed by the Fly's Eye group (the HiRes instrument) and by a Japanese team who built a detector of 100 km^2. This array, known as AGASA, comprised 111 scintillation detectors each of 2.2 m^2 spaced on a grid of about 1 km spacing. The scintillators were 5 cm thick and so respond mainly to electrons and muons. The detectors were connected and controlled through a sophisticated optical fibre network. The largest events detected have energies of 2 and 3 $\times 10^{20}$ eV and one of these is shown in Fig. 4 [9]. The AGASA array was closed down in January 2004.

Since mid-1998 the HiRes [10] instrument has been taking data at a site in the Dugway desert, near Salt Lake City. This instrument is a stereo system which is used to measure the depth of shower maximum to within 30 g cm^{-2} on an event-by-event basis. This precision was designed to be usefully smaller than the expected difference in the mean depth of maxima for proton or Fe initiated showers. The two locations for the detectors are separated by 12.5 km. The increase in aperture and in $X_{\rm max}$ resolution over Fly's Eye comes from the reduction in the aperture of each photomultiplier from 5 $\times$ 5 to 1 $\times$ 1 and the increase in the diameter of the mirrors from 1.5 to 2 m. Each mirror is viewed by 256 close-packed photomultipliers: there are 42 mirrors at one site and 22 at the other. The HiRes instrument will cease operation in March 2006.

The energy spectra reported by AGASA [11] (essentially the final version) and by the HiRes group [12] are compared in Fig. 5. It is clear that while the general shape is the same between about 3 and 70 EeV, there are significant differences in intensity at the lower and upper ends of the energy range. In particular, the difference in the number of events claimed above 100 EeV is marked with 11 reported

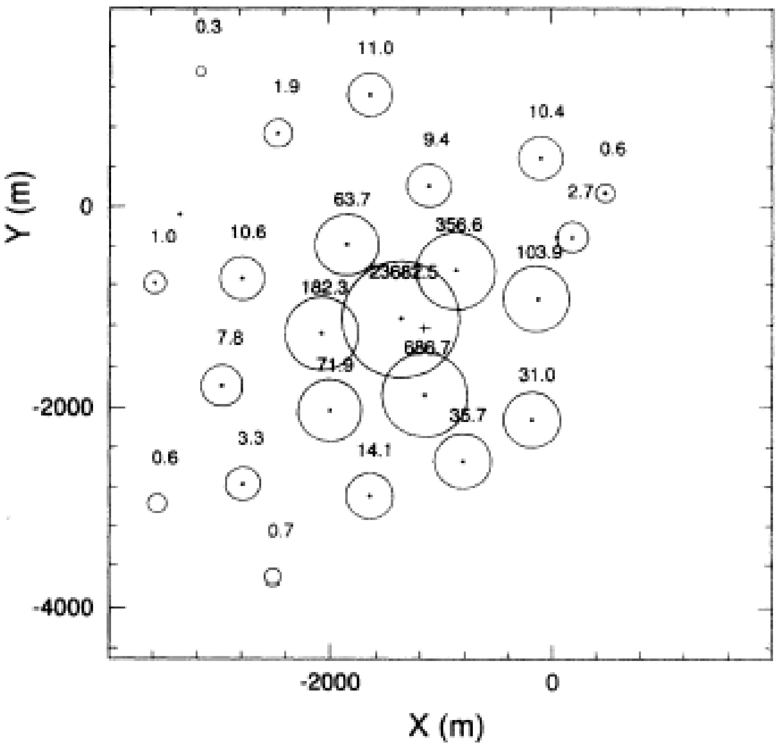


Fig. 4: Map of the detectors struck by the largest event recorded at AGASA. The radius of each circle represent the logarithm of the density recorded at that location. The cross shows the estimated position of the shower core.

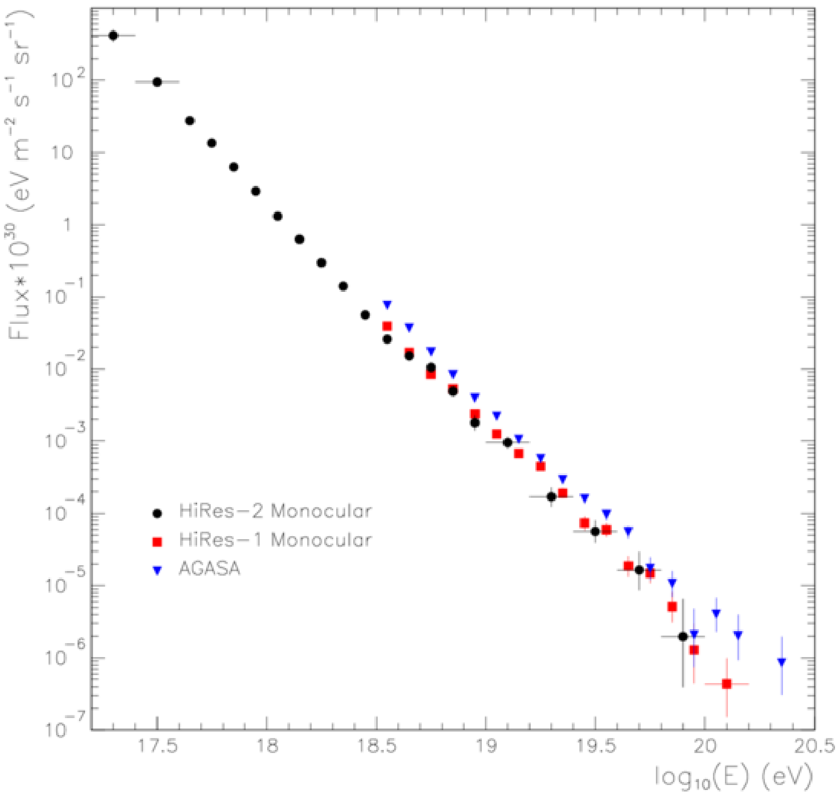


Fig. 5: A comparison of the energy spectra reported by the AGASA and HiRes groups

by AGASA compared with only 2 by HiRes in an exposure that is about three times as great. The reason for these differences is not understood but it is clear that the statistical sample is simply too small.

This problem of low statistics was recognized in the 1980s, even before the AGASA and HiRes detectors had completed construction, and led to the idea that 1000 km^2 of instrumented area was needed if progress was to be made [13]. Jim Cronin argued that 1000 km^2 was insufficiently ambitious and in the summer of 1991 he and Alan Watson decided to try to form a collaboration to build a detector of 5000 km^2, initially without any fluorescence devices. An international workshop [14], organized in Paris by Murat Boratav in 1992, led to a number of focused studies that culminated in a 6-month Design Study during 1995 hosted at the Fermi National Accelerator Laboratory by the then Director, John Peoples.

3 The design of the Auger detector and formation of the collaboration

The philosophy that guided the early phases of the Auger Design Study was to 'let a thousand flowers bloom'. While there was little choice in the form of fluorescence detector that could be used, the possibility of resistive plate counters, scintillators, radio detectors and water-Cherenkov detectors as the devices for the surface array were all discussed and evaluated intensively during the first three months of the workshop. Eventually the choice of water-Cherenkov detectors was made with the intention of having the surface detector (SD) array overlooked by a set of fluorescence detectors (Fig. 6). The water tanks have a significant advantage over scintillators in that their depth (1.2 m of water in the Auger and Haverah Park designs) means that the SD responds to showers coming from a very wide range of zenith angles with relatively high efficiency. Not only does this increase the aperture in a very useful way, but it also opens the possibility of the detection of very high energy neutrinos.

The beauty and power of the Auger Observatory lies in its hybrid nature. The potential of the combination of a SD array and a set of fluorescence detectors (FDs) is still being discovered as it clearly extends the ideas of 1995, but the initial concept of being able to calibrate the 'shower size' recorded with the SD using the 10% or so of events that fall during clear moonless nights has already proved its worth. In addition, the improved geometrical reconstruction available if there is a signal in even one of the 10 m^2 water tanks is very powerful and extends the energy reach of the array to well below 1 EeV. During the Design Study, many aspects of the design and of the projected physics output were explored using an extensive set of Monte Carlo calculations. Detailed simulations of the performance of the ground array for energy and direction measurement were made. At 40 EeV the energy resolution, with the ground array of particle detectors alone, was predicted to be $\sim$10% and the angular resolution $\sim$1.5: on average about 11 detectors were predicted to be struck. The energy resolution and angular accuracy improve as the energy increases. All of these numbers have now been confirmed with real data.

At the design stage the area to be covered at a single site was reduced to 3000 km^2 while it was recognized that with the water-Cherenkov detectors it was possible to envisage all-sky coverage with only two such detectors.

It is one thing to make a design and quite another to find places that might host such large devices. Site surveys were carried out contemporaneously with the Design Study, by Ken Gibbs and Antoine Letessier-Selvon who visited many countries around the world, in both hemispheres. Their brief was to locate places between 1000 and 200 m above sea-level, at a latitude between 30° and 45° north and south of the equator, of 3500 km^2 area and relatively flat with low cloud cover, good visibility, and few local light sources. In addition, access to radio licences, and suitable infrastructure support from national scientists were deemed essential. Argentina was able to offer several potential sites and in November 1995 the decision was made to go there rather than to possible sites in South Africa and Australia. About a year later Millard County in Utah, USA was chosen for the northern site, though the northern location was changed to South Eastern Colorado in 2005.

From the earliest days, a major problem with developing the project was lack of money. Here the influence of Jim Cronin was of immense importance as he was able to get access to people (and

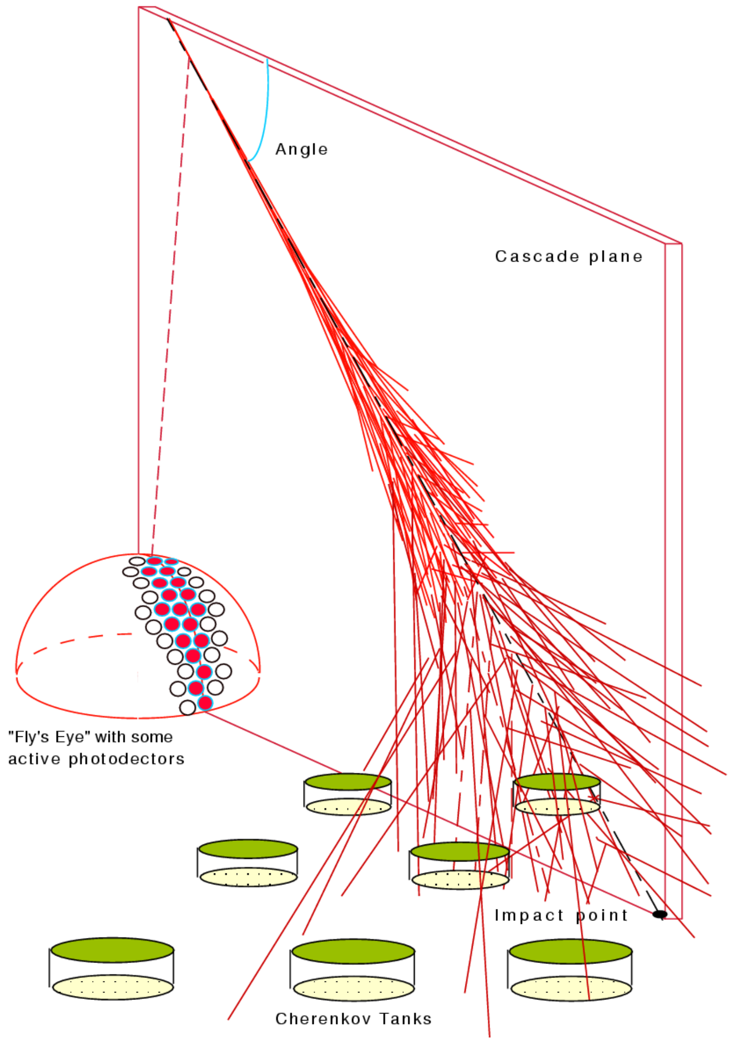


Fig. 6: The conceptual design of the Pierre Auger Observatory. A fluorescence detector overlooks an array of water-Cherenkov detectors. This instructive diagram is due to Enrique Zas (Santiago de Compostela).

extract money from them) when for most of us it would have been difficult to knock on the right door! In particular, money was obtained from the Director-General of UNESCO (although the USA was not a member) and from private individuals whom Jim Cronin knew. The UNESCO money allowed scientists from countries such as Russia, China, and Vietnam to be involved in the design phase. Money for research and development was found from local sources within the laboratories that showed an early interest in the project. For example, at the University of Leeds, lead that had been used for muon shielding and the aluminium lids of the Haverah Park water tanks were sold to help the development of the GPS method that is used to make the relative timing measurements at the detectors [15].

A further problem was the need to fight to have the project recognized as one worthy of attention. Now astroparticle physics is almost an established discipline but this was not so a decade ago and many talks had to be given to raise the awareness of top-class scientists who might be persuaded to join the project and others who might be part of the financial decision-making process. The capital cost was estimated as \$100 M for the twosites and forming from scratch the critical mass of competent people that could command this sort of support for a cosmic-ray project was not easy. A particular vulnerability, as with high-energy neutrino astronomy and, to a lesser extent, ground-based gamma-ray astronomy, is that there are no hard theoretical numbers demanding the construction of an instrument of a certain size. This is quite different from the situation with the search for the W and Z, or for the Higgs particle.

Additionally there was the issue of how the project was to be assessed. In particle physics or astrophysics one has become accustomed to umbrella organizations such as CERN, FNAL, ESO and ESA that have developed well-trusted mechanisms over the years for evaluating proposals—no matter how crazy they may seem. We had no such umbrella, so Jim Cronin had the idea of forming our own evaluation panel of scientists of the highest reputation. It was chaired by Professor Ian Axford (a well-known cosmic-ray physicist and then the Director of the Max Planck Institute at Lindau) and included J. Steinberger and M. Koshiba in the committee of six. An extremely favourable report was delivered that was useful in dealing with some agencies, although one agency remarked "of course it was favourable: you chose the panel"!

A major hurdle to overcome was funding from the US. Although no country supplies a majority of the funding, several agencies saw the outcome of debates within the SAGENAP Committee of NSF and DoE as being important input to their own decision making. In the end, in the spring of 1998, the SAGENAP Committee awarded the US groups funding but for only one site and stated that construction should be carried out first in Argentina. By mid-March 1999, a sufficiently strong collaboration from 12 countries (Argentina, Australia, Brazil, Czech Republic, France, Germany, Italy, Mexico, Poland, Slovenia, United Kingdom and the United States) and with sufficient funding to take the first steps had been created: a ground-breaking ceremony took place. Spain joined the Collaboration in 2001 and the Netherlands in 2005. From the beginning, Bolivia and Vietnam were associate members that contribute no funds but students from these countries have the opportunity of training within member countries, thus continuing the spirit behind the early UNESCO support.

The Argentinian site chosen is close to the town of Malargüe (Fig. 7), about five hours by road, south of the city of Mendoza, capital of Mendoza province in western Argentina. The town is well-equipped with hotels and restaurants and a campus site on the edge of the town was made available. It houses an assembly building and office block, designed and built for the project.

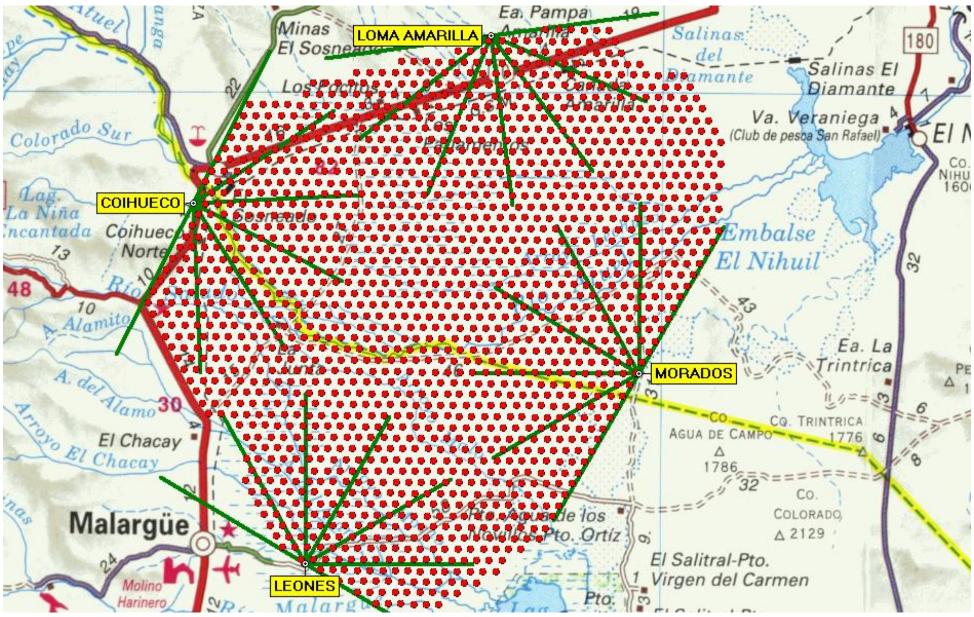


Fig. 7: The planned layout of the Pierre Auger Observatory with 1600 water tanks overlooked by four fluorescence detectors. The water-tank spacing is 1.5 km. As of 31 December 2005 over 1000 surface detectors were taking data, with three of the four fluorescence detectors fully operational. A laser facility, near the centre of the array, is discussed in the text.

4 Early phases of construction and preliminary results

4.1 Characteristics of the detector

The project has associated with it a Finance Board, set up by, and with membership from, the various funding agencies. The Board required that the Collaboration should first construct an engineering array of 40 water tanks and a section of a fluorescence detector. This work was completed in September 2001 and favourably reviewed by an international panel. All of the sub-systems of the Observatory were demonstrated to have achieved or exceeded their specifications. The first ‘hybrid’ events were recorded in December 2001 when construction of the full instrument commenced.

Fluorescence detectors and water-Cherenkov detectors had been operated before, though not at quite such difficult locations. A new challenge, however, was how to monitor and trigger with 1600 water tanks, distributed over 3000 km^2 (Fig. 7) and each filled with 12 tonnes of water and viewed by three 9" photomultiplier tubes. It is impractical, for reasons of cost and logistics, to connect such an array by cables or optical fibres. Instead each detector was conceived as an autonomous device, as had been done at the SUGAR array [16], but taking advantage of more than 30 years of technological development. The time of each local tank trigger is determined using the GPS technique [15], power is acquired with solar panels and cellular phone technology is used to bring the autonomous signals to the office building where a computer is used to search for trigger signals that are spatially and temporally clustered. When this happens at the level of three stations (currently about 1000 times per day) all of the data associated with the trigger cluster is acquired. The fluorescence detectors use a conventional source of power and their signals are sent to the centre over commercial microwave links. Details of the Engineering Array have been described [17]: the performance of the production instruments does not differ in significant detail.

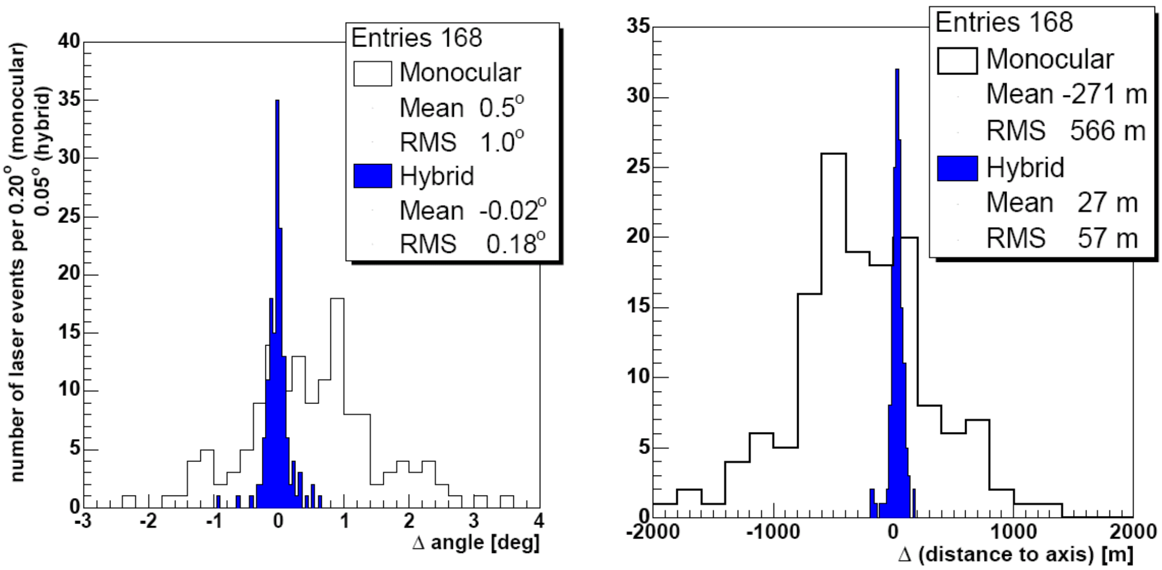
The high level of understanding that is derived from being able to make simultaneous observations of the fluorescence signals and the tank signals is well-illustrated by results from the detection of the scattered light from the Central Laser Facility [18]. This facility, located close to the centre of the array, hosts a 355 nm frequency-tripled YAG laser that generates pulses of up to $\sim$7 mJ. Like the fluorescence detectors, this device is operated remotely from the office building in Malargüe. The scattered light seen at a fluorescence detector from such a pulse is comparable to what is expected from a shower initiated by a primary of 100 EeV. The laser can be pointed in any direction. Some of the light from it is fed into an adjacent tank via an optical fibre so that correlated timing signals can be registered. In this way it has been established that the angular resolution of the surface detectors is $\sim 1.7^\circ$ for $3 < E < 10$ EeV and $\sim 0.6^\circ$ for hybrid events. It has been shown [19] that the accuracy of reconstruction of the position of the laser, using the hybrid technique, is < 60 m. The corresponding figure for the root-mean-square spread, if a monocular reconstruction, is made is ~ 570 m. As there is always at least one tank response in coincidence with each detection at a fluorescence station, these data give a preliminary indication of the geometrical power of the technique. Some results are shown in Fig. 8.

Some idea of the timing accuracy achievable at an individual detector is acquired experimentally from two tanks placed 11 m apart. The data for the twin pair (Carmen and Miranda) of the Engineering Array is shown in Fig. 9. The r.m.s. spread of 23 ns includes the measurement at each detector and the spread in the angles of incidence. After deconvolution, the accuracy is estimated as ~ 12 ns.

The Carmen–Miranda pair is shown in Fig. 10 and in the distant background a fluorescence detector site, Los Leones, is just visible.

In Fig. 11 the 3.5 m $\times$ 3.5 m spherical mirror, filter window, and the camera in one of the bays at Los Leones can be seen. Each fluorescence site has six bays. The camera accommodates the 30° azimuth $\times$ 28.6° elevation field of view. Each pixel has a field of view of 1.5°.

The data from the surface detectors are displayed on a computer screen at the central office building very shortly after they occur. In Fig. 12 the display for one event is shown. The left-hand part of the top left-hand panel shows the sequence of event triggers with the time and the number of stations triggered



(a) (b)

Fig. 8: (a) Comparison of the angular accuracy achieved by fluorescence detector with and without the benefit of a signal in one water tank; (b) As for Fig. 8(a) but for the distance from the central laser facility.

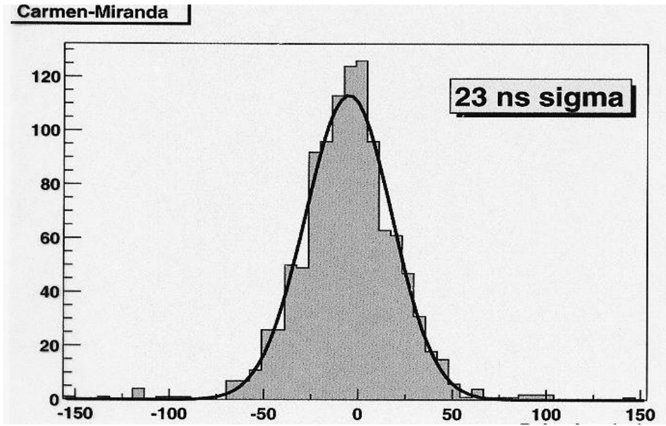


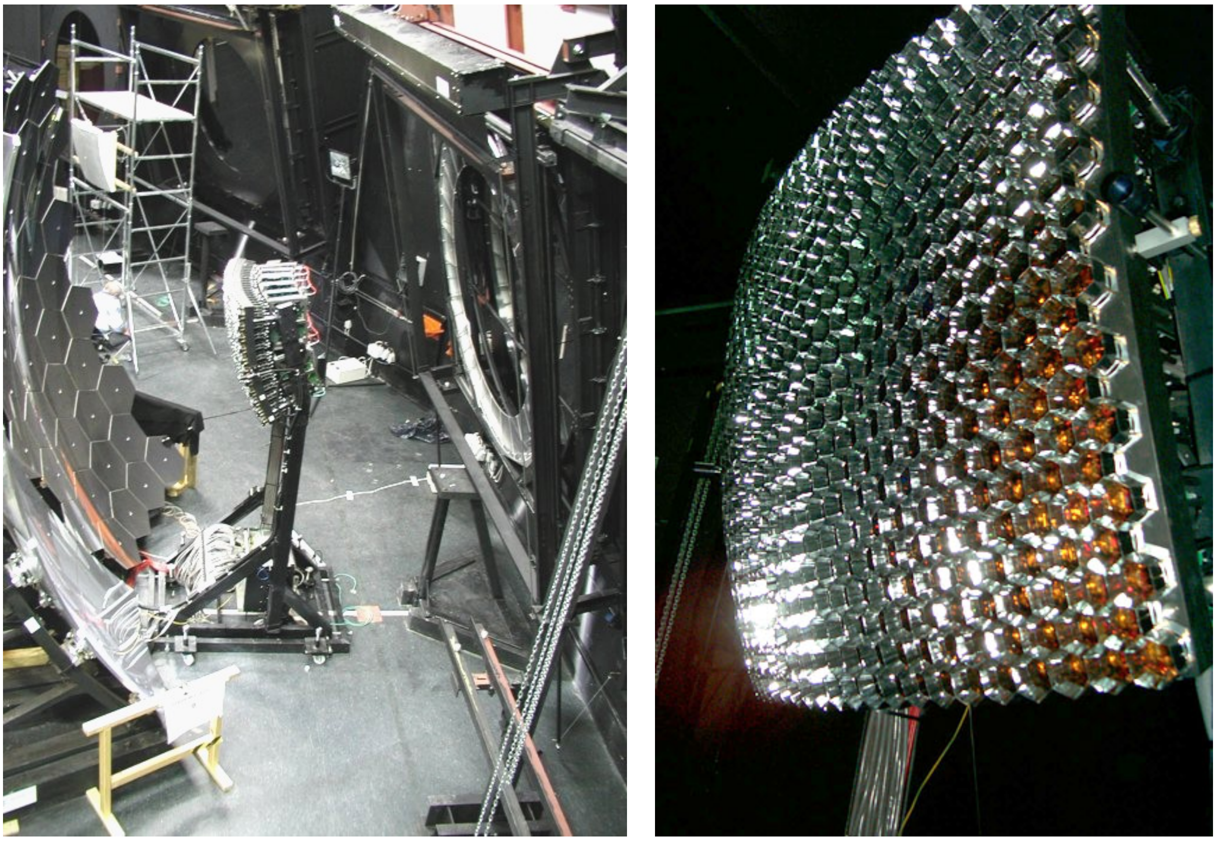
Fig. 9: The timing resolution as deduced from a pair of detectors 11 m apart. The r.m.s. spread of 23 ns includes the measurement at each detector and the spread in the angles of incidence. After deconvolution, the accuracy is estimated as $\sim$ 12 ns.

indicated. Details of the highlighted event are shown in the other panels, including the trigger time and signals at each of the stations (e.g., station 203 had a signal of 625 VEM 3916 ns after the trigger of tank 205). The signal size is measured in units of the signal produced by a 'vertical muon' (VEM). In the event shown fourteen stations have the temporal and spatial characteristics expected and these are displayed in the lower left-hand panel. In the upper-right-hand panel, the fall-off of the signals with distance can be seen. The results of a preliminary analysis are in the lower-right-hand panel.

4.2 Some typical events

In Fig. 13 the signal pattern of a very inclined event (zenith angle = 72°) is shown. The struck detectors are spread out in the azimuthal direction of arrival of the event. The event is about 15 km long and about 5 km wide. Estimating the primary energy of the particles that initiated events such as this is not

Fig. 10: The detector pair of the Engineering Array, Carmen and Miranda, used for estimating the timing accuracy with which signals are recorded at the detectors. Signal size accuracy is also determined from such pairs, of which there are two on the production array. The Los Leones fluorescence site is visible in the distance between the detectors.



(a) **(b)**

Fig. 11: (a) A view of the 3.5 m $\times$ 3.5 m spherical mirror (left) and the aperture/filter through which light is received; (b) One of the 24 cameras used to photograph the fluorescence light. The camera mount can be seen in Fig. 11(a). There are 440 photomultipliers in each camera.

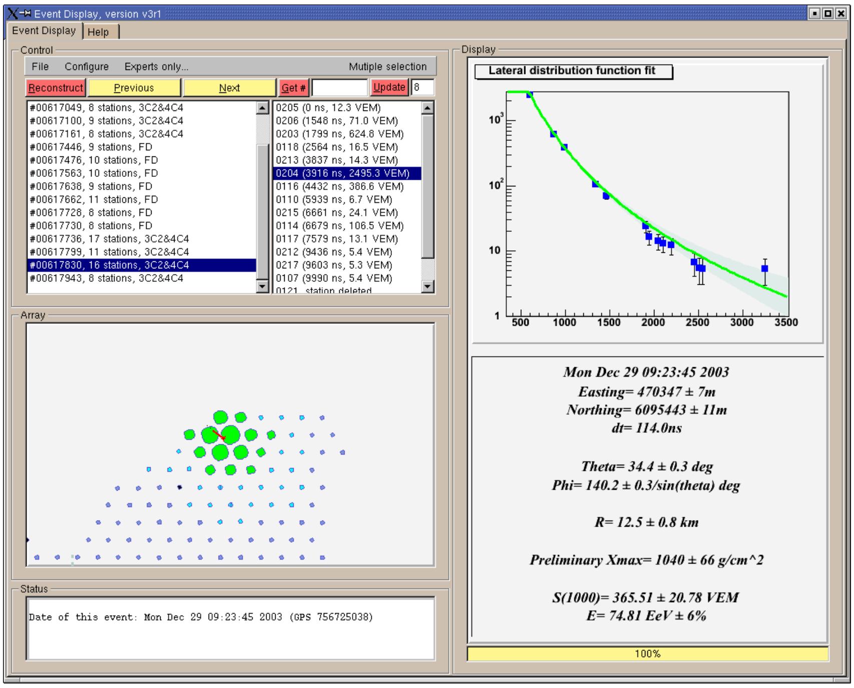


Fig. 12: An example of an event with energy above 10 EeV at 34° from the zenith. Fourteen stations have been struck (see bottom left) and the fall-off of the signal size with distance (the lateral distribution function) shown in the upper-right-hand corner is consistent with expectation. The shower data in the bottom-right-hand panel are taken from the real-time analysis facility and are very preliminary.

straightforward as the shower loses the near-circular symmetry of smaller angles because of bending of the muons (the dominant surviving particles) by the geomagnetic field.

There is great interest in studying inclined events as they may offer a route to the detection of very high energy neutrinos. This idea, first proposed by Berezinsky and Smirnov [20], was re-examined in the context of the Auger Observatory by Capelle *et al.* [21]. The trick is to study the properties of showers that arise at very large angles (>70°) from the vertical (see Fig. 14). A neutrino can interact anywhere in the atmosphere with equal probability. However, if one restricts a search to large zenith angles then it should be possible to identify occasions when the neutrino has interacted deep in the atmosphere. The mode of identification depends on the detection technique. A neutrino-induced shower arriving at a large zenith angle has distinctive characteristics that make it possible to envisage detecting it with a conventional, ground-based, air shower array. Most showers detected at large zenith angles will have been produced by nucleonic primaries. The vast majority of the particles detected in such events will be high-energy muons as at >70° the large atmospheric thickness of more than ~ 2500 g cm^{-2} (at the depth of the Auger Observatory) filters out the electromagnetic radiation that arises from neutral pion decay. The muons are accompanied by a small fraction of electromagnetic component (around 20%) that is in time and spatial equilibrium with the muons. This electromagnetic component has its origin in muon bremsstrahlung, pair production, knock-on electrons, and muon decay. These showers have large radii of curvature as the source of the muons is far from the shower detector. The particles in the shower disc arrive tightly bunched in time and the distribution of the signal size is rather flat across the array. By contrast, a shower produced by a neutrino, if it interacts in the volume of air over the detector, will have a curved shower front, a steep fall-off of particle signal with distance from the shower core and a distinctively broad time spread of the particles at the detectors.

The only instrument which is currently large enough to have any prospect of detecting neutrinos, and with the ability to exploit these characteristics, is the Pierre Auger Observatory.

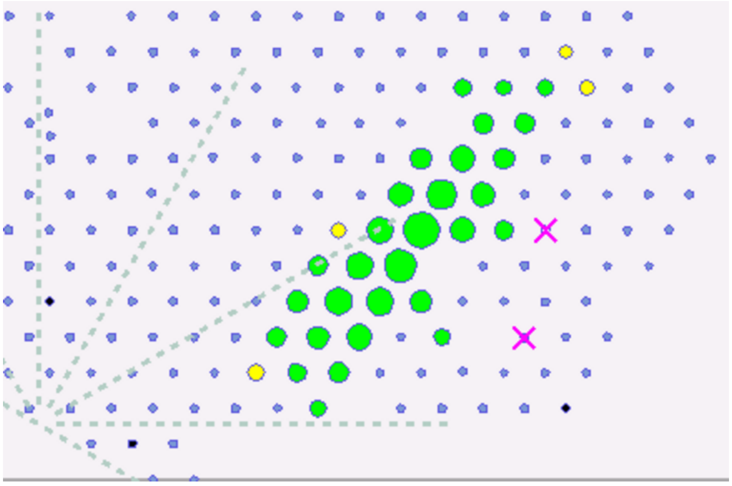
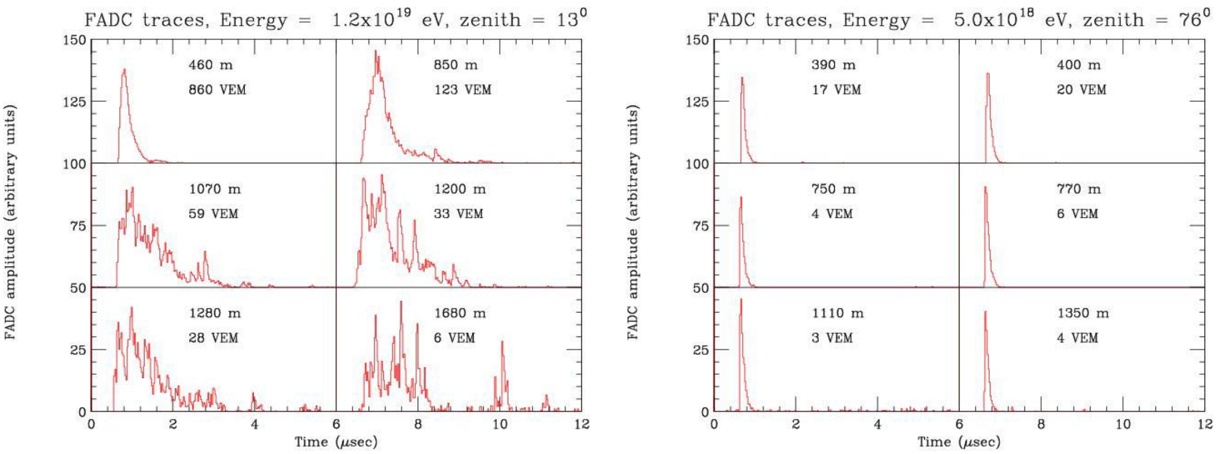


Fig. 13: The density pattern in an inclined event at 72° from the vertical. Thirty-three detectors have been triggered. Those marked with a cross are chance coincidences within the trigger window and are not part of the event. Estimates of the energy of events such as this is made complicated because of the deflections of the constituent muons in the geomagnetic field.



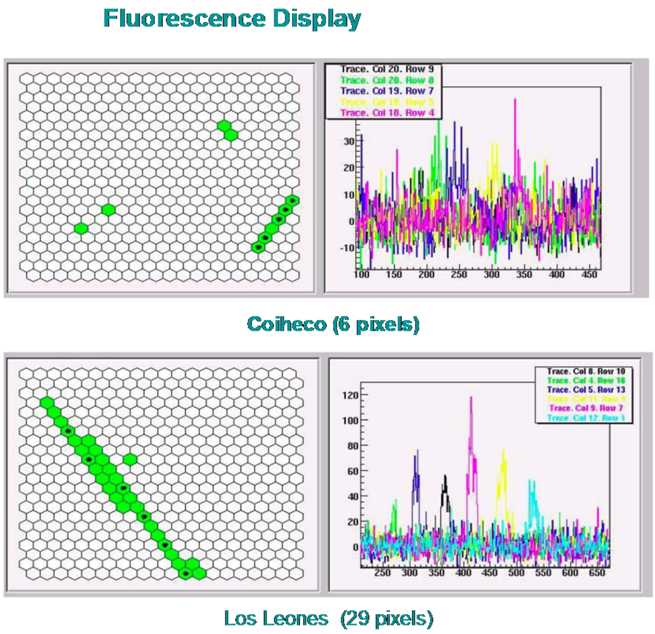
(a) **(b)**

Fig. 14: (a) The FADC signals from a nearly vertical air-shower. It is evident that the signals become broader as the distance from the shower axis (shown in each panel) increases. The gradient in signal size is also evident (compare the detail in the top right-hand panel in Fig. 12). (b) The FADC signals in an inclined shower. By contrast with Fig. 14(a), the time spread is very small and nearly independent of axial distance. A shower with the characteristics of Fig. 14(a) but at a zenith angle above 70° might well be produced by a neutrino.

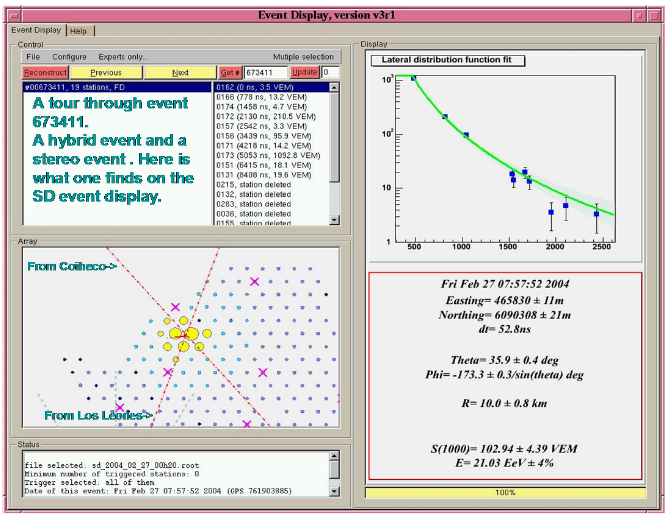
An example of a hybrid event is shown in Fig. 15. Figure 15(a) serves also as an example of the type of data that comes from a fluorescence detector. The signals are clearly visible above the night sky background.

Figure 15(b) shows the event display for the surface detectors (compare Fig. 12).

The improvement in the geometrical reconstruction in a hybrid event is shown in Fig. 15(c) (compare Fig. 8 where data from the central laser facility were used).



(a) The fluorescence signals recorded by the FD cameras at Coihueco and Los Leones. The signals from the highlighted pixels are shown in the right-hand panels standing above the signal from the night sky background



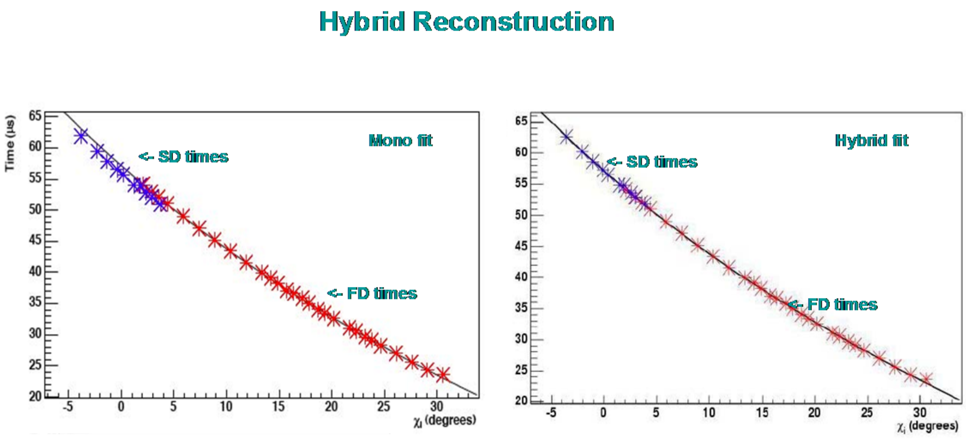
(b) The event display for the SD signals in event 673411 for which the FD signals are shown in Fig. 15(a). The dotted lines in the lower left-hand panel indicate the shower planes derived from the FD signals.

Fig. 15: The hybrid event 673411

4.3 The primary energy spectrum

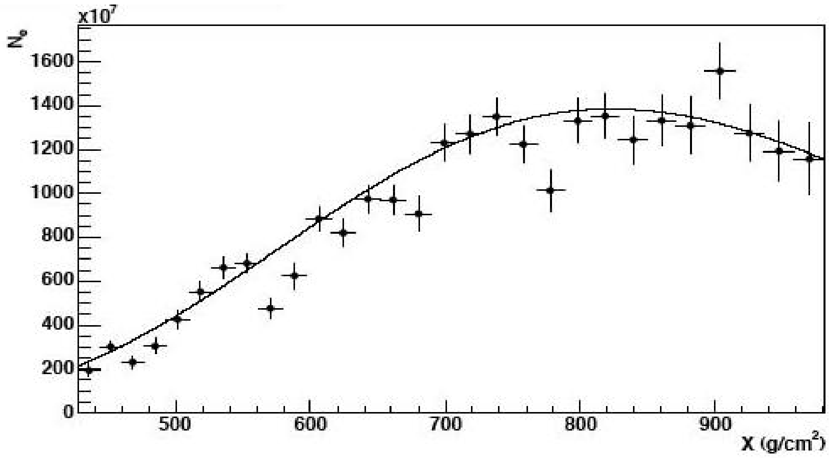
The Auger Collaboration has reported [22] the first precision measurement of the high-energy cosmic ray spectrum made from the Southern Hemisphere.

For this analysis attention was restricted to events with zenith angle $\theta < 60^{\circ}$. The strategy was to reconstruct the arrival direction for each event recorded by the SD and to estimate the magnitude of the signal at 1 km from the shower axis, S(1000), as a measure of the size of the shower in units defined by the signal from a muon that traverses the tank vertically. The shower axis S(1000) is chosen as the ground-parameter as it can be measured to better than 10%. In addition, as shown in the pioneering studies of Hillas [23], the size of this ground-parameter is ~ 3 times less susceptible to stochastic fluctuations and variations in primary mass than are measurements made close to the shower axis.



	Hybrid (Los Leones)	Surface	Difference
Easting	465960 ± 80	465830	130 m
Northing	6090234 ± 20	6090308	-74 m
Theta	36.7 deg	35.9 deg	0.8 deg
Phi	185.8 deg	186.7 deg	-0.9 deg

(c) This diagram illustrates the power of using the times at which the shower particles trigger the surface detectors. The left-hand plot shows the poor agreement between the FD times and the SD times from a monocular reconstruction. The combination is shown in the right-hand panel. The difference in distance and angular reconstruction is shown in the table below the panels.



(d) The longitudinal development curve deduced from the fluorescence data. Estimates of the primary energy can be obtained from the number of particles at shower maximum and by integrating under the curve.

Fig. 15: The hybrid event 673411 (*cont.*)

Two cosmic rays of the same energy, but incident at different zenith angles, will yield different values of S(1000). Thus a necessary step is to find the relation between the ground-parameter measured at one zenith angle and that measured at another. The approach adopted here is to use the well-established technique of the constant intensity cut (CIC) method which has been recently reappraised [24]. The principle of this method is that the high level of isotropy of cosmic rays leads to the proposition that showers created by primaries of the same mass and energy will be detected at the observation level at the same rate. Here the rate of events above different S(1000) is found for different zenith angles and all azimuth angles so that events come from a broad band of sky. This method is used to establish the relationship between $S(1000)_{38^\circ}$ and $S(1000)_\theta$, where the subscripts refer to a reference angle, chosen as 38°, and θ is the angle of incidence. The average thickness of the atmosphere above the Auger Observatory is 875.5 g cm^{-2}.

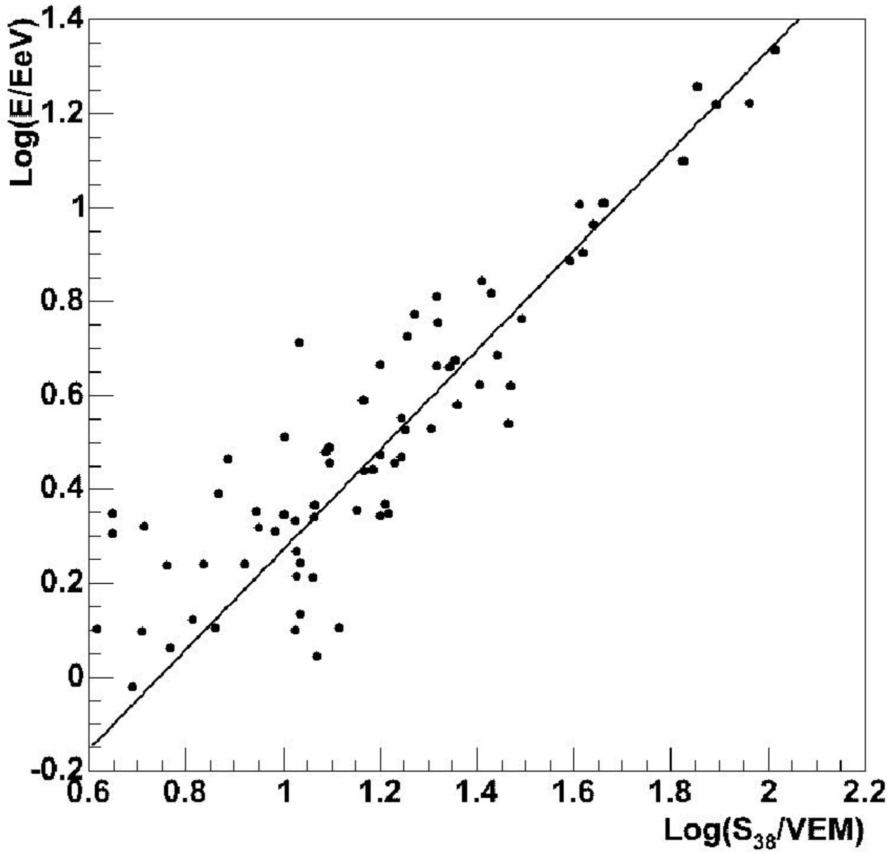
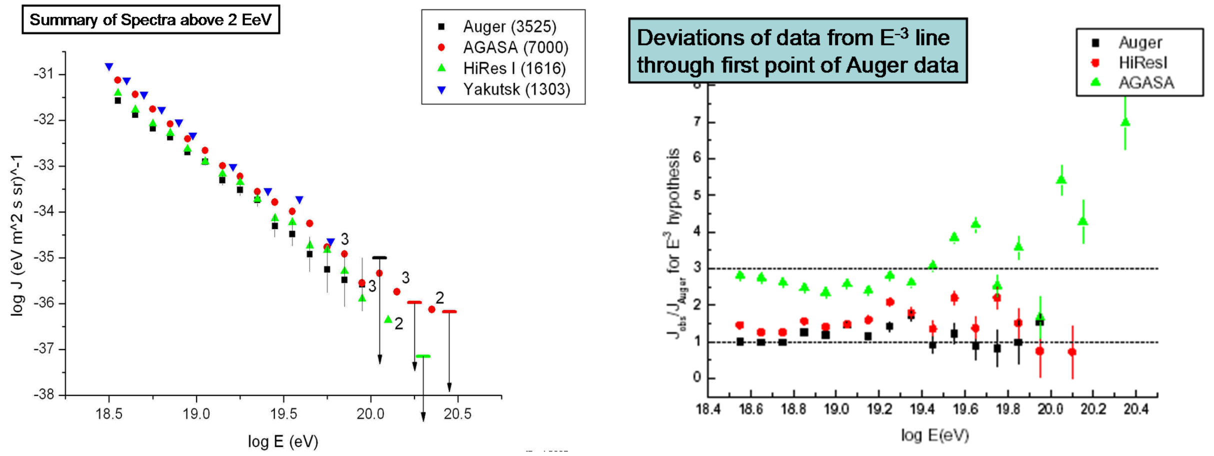


Fig. 16: A comparison of the energy estimated from the fluorescence detectors with the signal size (normalized to 38°) observed at 1000 m from the axis of the shower. The FD energy has been corrected by ∼10% for the missing energy carried into the ground by high-energy muons and neutrinos.

The link between $S(1000)_{38^\circ}$ and the primary energy is established using data from the fluorescence detectors rather than through model calculations. On clear, moonless nights, it is possible to observe fluorescence signals simultaneously with the SD events: this 'hybrid' approach, a key characteristic of the Auger Observatory, offers several advantages. For every FD event for which the shower core falls within the instrumented SD area, at least one tank is struck so that the time at which the tank was triggered can be used to enhance the reconstruction of the FD geometry. Further, as the FD instruments are used primarily as calibration devices in this application, the selection of events can be made in a highly selective manner. This was done in Ref. [22], where the FD tracks had to be longer than 350 $\mathrm{g\,cm^{-2}}$, the contribution of the Cherenkov light to the signals collected less than 10%, and there were contemporaneous measurements of the aerosol content of the atmosphere, as was possible in the latter part of the data run. There are significant systematic uncertainties currently present in the Auger spectrum arising largely from the lack of knowledge of the fluorescence yield of atmospheric nitrogen and from the low statistics available for the $S(1000)_{38^\circ}$ energy calibration. At 3 EeV the systematic uncertainty is about 30% growing to 50% at 100 EeV.

When estimating the energy of an event from the fluorescence yield (Fig. 16), a correction must be made for 'missing energy' carried by high-energy muons and neutrinos. A study of this conversion factor has recently been made for nucleonic primaries with a variety of hadronic interaction models. At 10 EeV the correction for missing energy is ∼10% with a systematic uncertainty, due to our lack of knowledge of the nuclear mass and the hadronic interactions, estimated as ∼7% [25]. The corrections and the associated systematic uncertainties may have to be revised when LHC data are available.



(a) The differential spectra from Auger, AGASA, HiResI and Yakutsk are compared on a plot of log J vs. log E. The numbers shown in the legend correspond to the events reported above 3 EeV. The numbers (3, 2) by some points refer to the last bin of each data set in which > 0 events were recorded.

(b) The ratio of the values of each point with respect to a fit of E^{-3} to the first point of the Auger spectrum at 3.55 EeV which contains 1216 events. The purpose of the plot is to illustrate the differences between the different measurements in a straightforward manner. Yakutsk data are not included in this plot as they are so discordant.

Fig. 17: Experimental spectra obtained by different groups

A comparison of the spectra reported by the different groups is made in Fig. 17. The agreement is poor, even at 10 EeV where there may still be differences of ~ 2 between the fluxes from the different instruments.

There is clearly scope for much further work on analysis and on understanding hadronic interactions and perhaps some of this will appeal to students of the School.

Acknowledgements

I would like to thank the organizers of the CERN–CLAF School of 2005 for the invitation to give a talk about the Pierre Auger Observatory. It was a pleasure to spend time with such bright and interesting students. The Auger Observatory would not have reached its present stage without the efforts of many people but I would particularly like to mention the efforts of Murat Boratav, Jim Cronin and Paul Mantsch. I am most grateful to Joerg Hoerandel for making me aware of Köhlhorster's work cited in Ref. [3]. Research on ultra-high-energy cosmic rays at the University of Leeds is supported by the Particle Physics and Astronomy Research Council, UK.

References

[1] P. Auger *et al., Comptes Rendus* **206** (1938) 721; P. Auger *et al., Rev. Mod. Phys.* **11** (1939) 288.

[2] B. Rossi, *Supplemento a La Ricerca Scientifica* **1** (1934) 579.

[3] W. Kolhörster *et al., Naturwissenschaften* **26** (1938) 576.

[4] J. Linsley, *Phys. Rev. Lett.* **10** (1963) 146.

[5] K. Greisen, *Phys. Rev. Lett.* **16** (1966) 748; G.T. Zatsepin and V.A. Kuz'min, *Zh Eksp. Teor. Fiz. Pis'ma Red* **4** (1966) 144.

[6] T.K. Gaisser, from talk at Leeds Symposium, July 2004.

[7] K. Eggert, *Nucl. Phys. B (Proc. Suppl.)* **122** (2003) 447.

[8] D. Bird *et al., Astrophys. J.* **441** (1995) 144.

[9] M. Hayashida *et al., Phys. Rev. Lett.* **73** (1994) 3491.

[10] P. Sokolsky, *AIP Conference Proceedings,* **433** (1998), p. 65.

[11] M. Takeda *et al., Astropart. Phys.* **18** (2003) 135.

[12] R.U. Abbassi, *Phys. Lett.* **B619** (2005) 271.

[13] A.A. Watson, *Nucl. Phys. B (Proc. Suppl.)* **22B** (1991) 116.

[14] Proceedings of the International Workshop on Techniques to Study Cosmic Rays with Energies $> 10^{19}$ eV, *Nucl. Phys. B (Proc. Suppl.)* **28B** (1992), Eds. M. Boratav, J.W. Cronin and A.A. Watson; J.W. Cronin, *Nucl. Phys. B (Proc. Suppl.)* **28B** (1992) 213.

[15] C.L. Pryke and J. Lloyd-Evans, *Nucl. Instrum. Methods* **A354** (1995) 560.

[16] M.M. Winn *et al., J. Phys. G* **12** (1986) 675.

[17] J. Abraham *et al.* [Auger Collaboration], *Nucl. Instrum. Methods* **A523** (2004) 50.

[18] F Arqueros *et al.* (Pierre Auger Collaboration), *Proc. 29th ICRC*, Pune, India, 2005 (Tata Institute of Fundamental Research, Mumbai, India, 2005), vol. 8, pp. 335–338. `http://icrc2005.tifr.res.in/htm/Vol-Web/Vol-18/18335-usa-malek-M-abs1-he15-poster.pdf`

[19] M.A. Mostafá (Pierre Auger Collaboration), *Proc. 29th ICRC 2005*, Pune, India, 2005 (Tata Institute of Fundamental Research, Mumbai, India, 2005), vol. 7, pp. 369–372. `http://icrc2005.tifr.res.in/htm/Vol-Web/Vol-17/17369-usa-mostafa-M-abs1-he14-oral.pdf`

[20] V.S. Berezinsky and A.Yu. Smirnov, *Astrophys. Space Sci.* **32** (1975) 461.

[21] K.S. Capelle *et al., Astropart. Phys.* **8** (1998) 321.

[22] P. Sommers (Pierre Auger Collaboration), *Proc. 29th ICRC*, Pune, India, 2005 (Tata Institute of Fundamental Research, Mumbai, India, 2005), vol. 7, pp. 387–390 [astro-ph/0507150]. `http://icrc2005.tifr.res.in/htm/Vol-Web/Vol-17/17387-usa-sommers-P-abs1-he14-oral.pdf`

[23] A.M. Hillas, *Acta Phys. Acad. Sci. Hung.* **29** *Suppl. 3* (1969) 355; A.M. Hillas *et al., Proc. 12th ICRC*, Hobart, Australia, **3** (1971) 1001.

[24] J. Alvarez-Muñiz *et al., Phys. Rev.* **D66** (2002) 123004 [astro-ph/0209117].

[25] T. Pierog *et al.*, (Pierre Auger Collaboration), *Proc. 29th ICRC*, Pune, India, 2005 (Tata Institute of Fundamental Research, Mumbai, India, 2005), vol. 7, pp. 103–106. `http://icrc2005.tifr.res.in/htm/Vol-Web/Vol-17/17103-ger-engel-R-abs2-he14-oral.pdf`