29th International Cosmic Ray Conference Pune (2005) **7**, 369–372

The Hybrid Performance of the Pierre Auger Observatory

M.A. Mostafá for the Pierre Auger Collaboration
Observatorio Pierre Auger, Av. San Martín Norte 304, Malargüe, (5613) Mendoza, Argentina
Presenter: Miguel A. Mostafá (mostafa@phys.unm.edu), usa-mostafa-M-abs1-he14-oral

The Pierre Auger Observatory detects ultra-high energy cosmic rays by implementing two complementary air-shower techniques. The combination of a large ground array and fluorescence detectors, known as the *hybrid* concept, means that a rich variety of measurements can be made on a single shower, providing much improved information over what is possible with either detector alone. In this paper the hybrid reconstruction approach and its performance are described.

1. Introduction

The Pierre Auger Observatory was designed to observe, in coincidence, the shower particles at ground and the associated fluorescence light generated in the atmosphere. This is achieved with a large array of water Cherenkov detectors coupled with air-fluorescence detectors (eyes) that overlook the surface array. It is not simply a dual experiment. Apart from important cross-checks and measurement redundancy, the two techniques see air showers in complementary ways. The ground array measures the lateral structure of the shower at ground level, with some ability to separate the electromagnetic and muon components. On the other hand, the fluorescence detector records the longitudinal profile of the shower during its development through the atmosphere.

A *hybrid* event is an air shower that is simultaneously detected by the fluorescence detector and the ground array. The Observatory was originally designed and is currently being built with a *cross–triggering* capability. Data are recovered from both detectors whenever either system is triggered. If an air shower independently triggers both detectors the event is tagged accordingly. There are cases where the fluorescence detector, having a lower energy threshold, promotes a sub–threshold array trigger. Surface stations are matched by timing and location. This is an important capability because these sub–threshold hybrid events would not have triggered the array otherwise.

The Observatory started operation in *hybrid* production mode in January, 2004. Surface stations have a 100% duty cycle, while fluorescence eyes can only operate on clear moonless nights. Both surface and fluorescence detectors have been running simultaneously 14% of the time. The number of hybrid events represents 10% the statistics of the surface array data.

2. The Hybrid Performance

A hybrid detector has excellent capability for studying the highest energy cosmic ray air showers. Much of its capability stems from the accurate geometrical reconstructions it achieves. Timing information from even one surface station can much improve the geometrical reconstruction of a shower over that achieved using only eye pixel information. The axis of the air shower is determined by minimizing a χ^2 function involving data from all triggered elements in the eye and at ground. The reconstruction accuracy is better than the ground array counters or the single eye could achieve independently [1, 2]. Using the timing information from the eye's pixels together with the surface stations, a core location resolution of 50 m is achieved. The resolution for the arrival direction of cosmic rays is $0.6°$ [2]. These results for the *hybrid* accuracy are in good agreement with estimations using analytic arguments [3], measurements on real data using a bootstrap method [4], and previous simulation studies [5].

The reconstruction uncertainties are evaluated using events with *known* geometries, *i.e.* laser beams. The Central Laser Facility (CLF), described in Ref. [6], is located approximately equidistant from the first three fluorescence sites (see figure 5). Since the location of the CLF and the direction of the laser beam are known to an accuracy better than the expected angular resolution of the fluorescence detector, laser shots from the CLF can be used to measure the accuracy of the geometrical reconstruction. Furthermore, the laser beam is split and part of the laser light is sent through an optical fiber to a nearby ground array station. The resolution of the monocular and hybrid reconstructions are compared in figure 1 for the distance between the eye and the CLF, and in figure 2 for the angle of the axis.

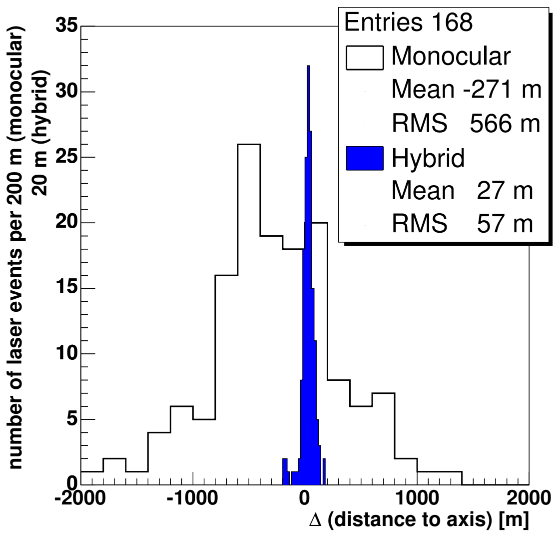

Figure 1. Difference between the reconstructed and true distance from the eye to the vertical laser beam using the monocular and hybrid techniques. The location of the laser is known to 5 m.

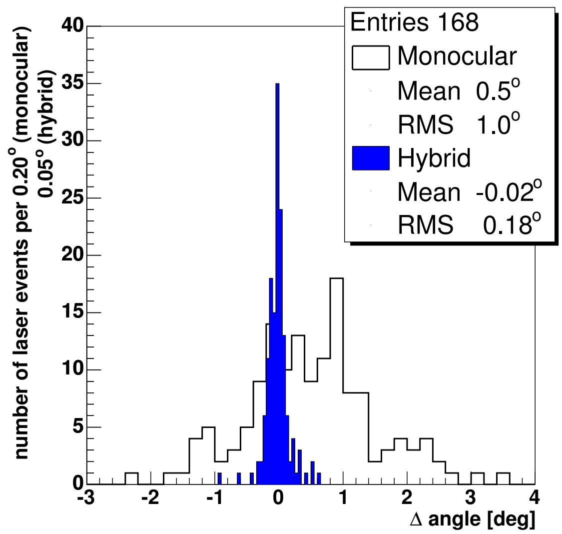

Figure 2. Angular difference between reconstructed and true direction of the laser beam using the monocular and hybrid techniques. The laser beam is vertical within 0.01°.

The laser light from the CLF produces simultaneous triggers in both the surface and (three) fluorescence detectors. The recorded event times can be used to measure and monitor the relative timing between the two detectors. The time offset between the first fluorescence eye and the surface detector is shown in figure 3. This time offset has been measured to better than 50 ns [7]. The contribution to the systematic uncertainty in the core location due to the uncertainty in the time synchronization is 20 m.

Hybrid events can be well reconstructed with as little as one surface station. Thus, the energy threshold of hybrid events is lower than it is for surface array only events, where at least three stations must be triggered. The energy distribution for hybrid events is shown in figure 4. Sub–threshold hybrid events have a lower energy distribution, while the angular resolution is still 0.6°. Another important consequence is the additional number of events. Approximately 60% of the total hybrid events have fewer than three stations, *i.e.* for each event that can independently trigger both the surface array and one fluorescence detector there are two extra low energy events.

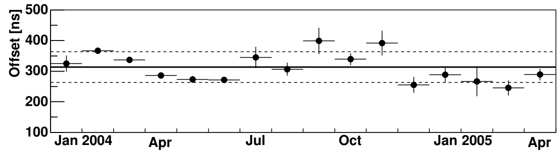

Figure 3. Time offset between the surface detector and Los Leones (eye 1). The variation in time is within the uncertainty of 50 ns.

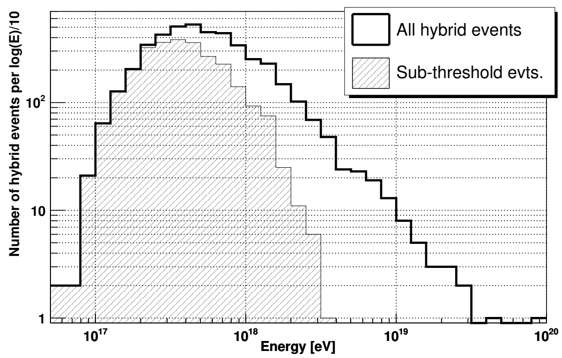

Figure 4. Energy histogram for hybrid events. The shaded histogram represents the energy distribution for the sub–set of hybrid events with fewer than three surface stations. These events are referred to as sub–threshold events.

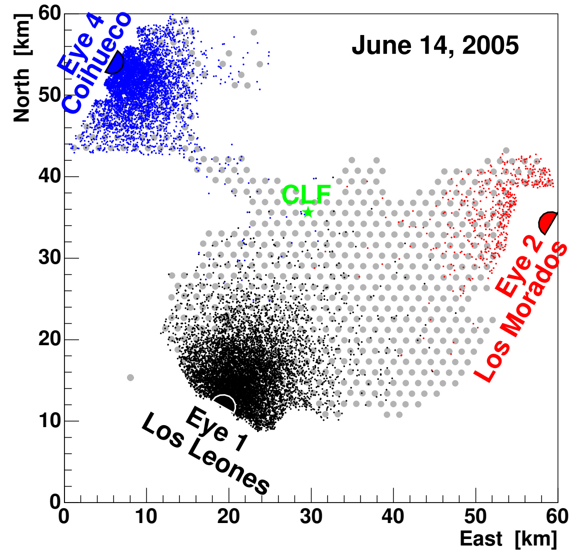

Figure 5. Status of the Pierre Auger Observatory on June 14, 2005. Each gray full circle represents a surface station, each color dot is the core location of a reconstructed air shower (where the color indicates which eye *saw* that event), and each fluorescence site is shown as a colored semi-circle. The Central Laser Facility is shown as a green full star.

The status of the Observatory on June 14, 2005 is summarized in figure 5. There were 740 fully operational tanks at that time. The first two fluorescence sites (eyes 1 and 4 in the figure) were fully operational, *i.e.* running six telescopes each, in June, 2004. The third site (eye 2) started operation on March 18, 2005. The present average rate is 50 hybrid events per night per eye, for a total of 16090 events up to June 14, 2005. At this rate, 4000 hybrid events per month are expected when the Observatory is completed.

3. Hybrid Measurements

Due to the much improved angular accuracy, the *hybrid* data sample is ideal for anisotropy studies and, in particular, for point source searches. Results on a search for a point–like source in the direction of the galactic center using these hybrid events are presented at this conference [8].

Many ground parameters, like the shower front curvature and thickness, have always been difficult to measure experimentally, and were usually determined from Monte Carlo simulations. The hybrid sample provides a unique opportunity in this respect. As mentioned, the geometrical reconstruction can be done using only one ground station, thus all the remaining detectors can be used to measure the shower characteristics.

The combination of the air fluorescence measurements and particle detections on the ground provides an energy measurement almost independent of air shower simulations. The fluorescence measurements determine the longitudinal development of the shower, whose integral is proportional to the total energy of the electromagnetic particle cascade. At the same time, the particle density at any given distance from the core can be evaluated with the ground array. The conversion from particle density to the energy of the shower is where the fluorescence measurements become important. Hybrid events that can be independently reconstructed with both techniques are used to establish an empirical rule for the energy conversion. The procedure to determine the energy of each event is explained in more detail in Ref. [9]. It is important to note that both techniques have different systematics, and results are preliminary at this stage while the Observatory is under construction. The possibility of studying the same set of air showers with two independent methods is valuable in understanding the strengths and limitations of each technique. The *hybrid* analysis benefits from the calorimetry of the fluorescence technique and the uniformity of the surface detector aperture.

4. Conclusions

We have tested the performance of Pierre Auger Observatory in its hybrid configuration. Operation started in January, 2004 and over 16000 hybrid events have been successfully reconstructed up to now. It is important to note that the Observatory is under construction and that results are preliminary. It is already clear that the combination of fluorescence and ground array measurements provides reconstruction of the geometry of the shower with much greater accuracy than is achieved with either detector system on its own. Unprecedented core location and direction precision leads to excellent energy and shower development measurements. Several Auger measurements being presented at this conference profit from the hybrid capability of the Observatory, including the angular resolution [2], energy spectrum [9], and photon limits [10].

References

[1] Pierre Auger Collaboration, “Performance of the Fluorescence Detectors of the Pierre Auger Observatory,” these proceedings, aus-bellido-J-abs1-he14-oral.
[2] Pierre Auger Collaboration, “Angular Resolution of the Pierre Auger Observatory,” these proceedings, bra-bonifazi-C-abs1-he14-oral.
[3] P. Sommers, “Capabilities of a giant hybrid air shower detector,” Astroparticle Physics **3** (1995) 349.
[4] B. Fick for the Pierre Auger Collaboration, “Hybrid Performance of the Pierre Auger Observatory and Reconstruction of Hybrid Events,” astro-ph/0308512, Proceedings of the 28th International Cosmic Ray Conferences, Tsukuba, Japan, (2003) 449.
[5] B.R. Dawson *et al.*, “Simulations of a Giant Hybrid Air Shower Detector,” Astroparticle Physics **5** (1996) 239.
[6] F. Arqueros *et al.* for the Pierre Auger Collaboration, “The Central Laser Facility at the Pierre Auger Observatory,” these proceedings, usa-malek-M-abs1-he15-poster.
[7] P. Allison *et al.* for the Pierre Auger Collaboration, “Time Calibration and Synchronization of Surface and Fluorescence Detectors of the Pierre Auger Observatory,” these proceedings, usa-covault-C-abs2-he15-poster.
[8] Pierre Auger Collaboration, “Anisotropy Studies Around the Galactic Center at EeV Energies with Auger data,” these proceedings, fra-letessier-selvon-A-abs1-he14-oral.
[9] Pierre Auger Collaboration, “First Estimate of the Primary Cosmic Ray Energy Spectrum above 3 EeV from the Pierre Auger Observatory,” these proceedings, usa-sommers-P-he14-oral.
[10] Pierre Auger Collaboration, “Upper limit on the primary photon fraction from the Pierre Auger Observatory,” these proceedings, ger-risse-M-abs2-he14-oral.