Measurement of the average depth of shower maximum and its fluctuations with the Pierre Auger Observatory

J. A. Bellido* **for the Pierre Auger Collaboration**†

* *Physics Department, The University of Adelaide, S.A. - 5005, Australia*
† *Observatorio Pierre Auger, Av. San Martin Norte 304, 5613 Malargüe, Argentina*

Abstract. **The atmospheric depth $X_{\max}$ where an air shower reaches its maximum size is measured shower-by-shower with a resolution of 20 g cm^{-2} on average using the air fluorescence telescopes of the Pierre Auger Observatory. The mean value $\langle X_{\max} \rangle$ and the RMS width of the Xmax distribution will be reported for 13 different logarithmic energy intervals above 1 EeV.**

Keywords**: mass composition, elongation rate, fluorescence detector.**

I. INTRODUCTION

The Pierre Auger Observatory has recently taken steps towards unveiling the mysterious origin of the most energetic cosmic rays. In a recent publication we reported the measured energy spectrum [1], which has confirmed, with improved statistics, a suppression in the spectrum beyond about $10^{19.6}$ eV. This is consistent with the predicted GZK pion photoproduction or nuclear photodisintegration [2], but it could also be the result of the intrinsic source spectrum. Another important feature observed in the energy spectrum at energies between 10^{18} and 10^{19} eV is the so-called ankle or dip. It is suggested that a source transition from galactic to extragalactic is the cause of this feature [3], but it has also been suggested that the galactic-extragalactic transition happens at a lower energy and that at around $10^{18.5}$ eV cosmic rays are mainly extragalactic protons that interact with the CMB radiation producing the dip by $e^{\pm}$ pair production [4] (see [5] for a discussion of both models). Another Auger publication has shown evidence for an anisotropy in the arrival directions of the most energetic cosmic rays [6].

A great deal of information on the nature of the cosmic ray sources and the characteristics of the particle propagation is contained in the energy spectrum and in the observed anisotropy. Additional information on the cosmic ray mass composition can help to complete the overall picture.

The fluorescence detector (FD) of the Pierre Auger Observatory can be used to measure with good resolution the shower longitudinal profile and the depth at which the shower reaches its maximum size ($X_{\max}$). At a given energy, the average $X_{\max}$ and the width of the $X_{\max}$ distribution are both correlated with the cosmic ray mass composition [8]. Proton showers penetrate deeper into the atmosphere (larger values of $X_{\max}$) and have wider $X_{\max}$ distributions than heavy nuclei.

The mass composition interpretation of the measured mean and width of the $X_{\max}$ distribution depend on the assumed hadronic model. The problem is that at these high energies, the uncertainties on the predictions from the models are unknown because they are an extrapolation of the physics from lower energies.

II. DATA ANALYSIS

We have used hybrid events to measure the longitudinal profiles of air showers. These are events observed simultaneously by the FD and by at least one surface detector. The information from the surface detector allows us to constrain the geometry of the air shower. This hybrid constraint on the geometry is not efficient when the time duration of the event as seen by the FD is small (less than 0.5 μs), because the time synchronization between the surface detectors and the FD is of the order of 0.1 μs. To exclude such short-duration events we have rejected showers with directions pointing towards the FD by requiring that the minimum viewing angle be greater than 20° (this cut also removes events with a large fraction of direct Cherenkov light). The hybrid reconstruction has an average angular resolution of 0.6° [10]. Good resolution in the reconstructed geometry is the first step towards good resolution in $X_{\max}$ measurements.

Profile quality cuts: Our aim is to measure $X_{\max}$ with an average resolution of 20 g cm^{-2}. To achieve this goal we have used Monte Carlo simulated data to design a set of quality cuts for the observed profiles. The reconstructed [7] $X_{\max}$ should lie within the observed shower profile, the length, in g cm^{-2}, of the observed profile should be at least 320 g cm^{-2}, and the reduced χ^2 of a fit with a Gaisser-Hillas function [11] should not exceed 2.5. Moreover, shower profiles with insignificant curvature around the reconstructed $X_{\max}$ are rejected by requiring that the χ^2 of a linear fit to the longitudinal profile exceeds the Gaisser-Hillas fit χ^2 by at least four. Finally, the estimated uncertainties of the shower maximum and total energy must be smaller than 40 g cm^{-2} and 20%, respectively.

To check the $X_{\max}$ resolution we have used stereo events. Stereo events have an average energy of 10^{19} eV. Figure 1 shows a comparison between the $X_{\max}$ values independently reconstructed with each FD. The factor $1/\sqrt{2}$ (in the x axis) is to take into account that the RMS of the $\Delta X_{\max}$ would correspond to the convolution of the two resolutions,

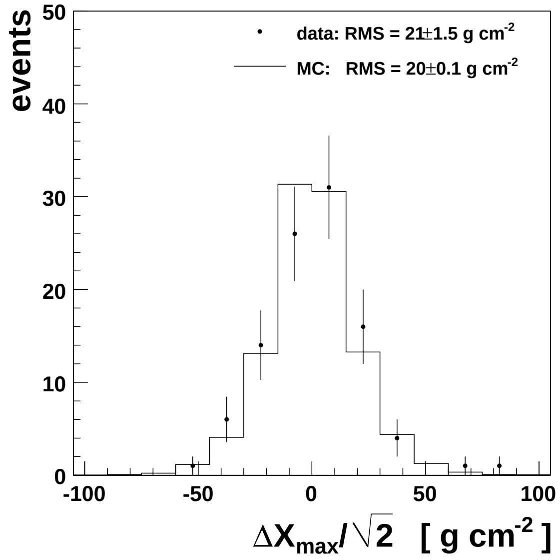

Fig. 1. Difference of $X_{\max}$ reconstructions for showers that have been observed by at least two FD sites (in real data and in MC).

$$\mathrm{RMS}(\Delta X_{\max})^2 = \sigma_1^2 + \sigma_2^2. \tag{1}$$

The two $X_{\max}$ resolutions, σ_1 and σ_2, are not necessarily the same, however we can approximate them to an average $X_{\max}$ resolution ($\sigma_1 \approx \sigma_2 \approx \sigma$) and rewrite equation 1,

$$\sigma = \mathrm{RMS}(\Delta X_{\max}/\sqrt{2}). \tag{2}$$

The average resolution (σ) for the reconstructed $X_{\max}$ in stereo events is $21 \pm 1.5\,\mathrm{g\,cm^{-2}}$ (obtained from figure 1). This resolution is consistent with the resolution obtained with stereo events generated with MC simulations (also shown in figure 1).

Cuts for an unbiased measurement of the $X_{\max}$ distribution: To ensure a trigger probability close to unity for protons and iron at energies above 10^{18} eV, we apply energy-dependent cuts on the zenith angle and the maximum distance from the shower core to the nearest surface detector. The Auger FD has a field of view ranging from 1.5° to 30° in elevation, and care must be taken that this limited field of view does not impose a bias on $X_{\max}$ measurements.

To avoid such a bias, an event is included only if its geometry is such that $X_{\max}$ could be seen and measured at any slant depth between 500 and $1000\,\mathrm{g\,cm^{-2}}$. This is a "conservative" cut removing more events than necessary. The optimum slant depths for this cut are energy dependent and they are selected according to the observed $X_{\max}$ distribution at the corresponding energy . We have experimented with the conservative and the optimum choices and obtained consistent results. To maximize the statistics, we have used the optimum choice for the slant depth limits.

In addition to the cuts described above, we have applied preselection criteria. We excluded data taken during bad calibration periods, or when no information on the atmospheric aerosol content was available, or when the fraction of clouds above the array, as estimated from the LIDARs, was above 25%.

The systematic uncertainty on $\langle X_{\max}\rangle$ becomes larger below 10^{18} eV, so we will only present results for energies above 10^{18} eV. Measurements of $\langle X_{\max}\rangle$ and its fluctuations below 10^{18} eV will soon be obtained using HEAT [12], the new set of fluorescence telescopes installed at the Auger Observatory which view an elevation range from 30° to 60°.

III. RESULTS

The results of this analysis will be reported at the conference. We will present our measurements of the mean and RMS of the $X_{\max}$ distribution as a function of energy with data collected until March 2009.

REFERENCES

[1] J. Abraham *et al.* [Pierre Auger Collaboration], Phys. Rev. Lett., **101**, 061101, (2008).
[2] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966).; G. T. Zatsepin and V. A. Kuzmin, JETP Lett. **4**, 78 (1966).
[3] J. Linsley, Proc. 8th ICRC, **4**, 77 (1963).
[4] V. Berezinsky, *et al.* Phys. Lett. B, **612**, 147 (2005).
[5] D. Allard, *et al.* Astropart. Phys., **27**, 61 (2007).
[6] J. Abraham *et al.* [Pierre Auger Collaboration], Science **318**, 938, (2007).
[7] M. Unger *et al.*, Nucl. Instrum. Meth. **A588**, 433 (2008).
[8] T.K. Gaisser et al., Proc. 16th ICRC **9**, 258 (1979); J. Linsley and A.A. Watson, Phys. Rev. Lett. **46**, 459 (1981); J. Matthews, Astropart. Phys. **22**, 387 (2005); W. Heitler, "The Quantum Theory of Radiation", Oxford University Press, 1954.
[9] M. Unger [Pierre Auger Collaboration], Proc. 30th ICRC, **4**, 373 (2008).
[10] C. Bonifazi [Pierre Auger Collaboration], Proc. 29th ICRC, **7**, 17 (2005).
[11] T.K. Gaisser and A.M. Hillas, Proc. 15th ICRC, **8**, 353 (1977).
[12] H.O. Klages [Pierre Auger Collaboration], Proc. 29th ICRC, **7**, 17 (2005).