An update on the measurements of the depth of shower maximum made at the Pierre Auger Observatory

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Abstract: Data continue to be collected at The Pierre Auger Observatory. The Fluorescence telescopes of the Pierre Auger Observatory can be used to measure the depth of shower maximum ($X_{\rm max}$) with high precision (20 g/cm^2 on average). Thus the measurement of the $X_{\rm max}$ distribution is the best way to infer properties of the primary cosmic ray, such as its composition, and even the interaction cross-section for the proton component. During the Conference we will present our latest measurements of average $X_{\rm max}$ and fluctuations of $X_{\rm max}$ as a function of energy. In this paper we give a general outline of the $X_{\rm max}$ analysis and the improvements made with respect to previously published results.

Keywords: Pierre Auger Observatory, ultra-high energy cosmic rays, depth of shower maximum, mass composition

1 Introduction

Data have been collected continuously at the Pierre Auger Observatory since 1 January 2004. In the poster to be displayed at this Conference we will show the results of measurements of the depth of shower maximum from events recorded up to 31 December 2012. The data are described in terms of the first and second moments of the distributions as a function of energy as is common practice in this work. A major aim is to obtain information on the mass composition as a function of energy but interpretation is strongly limited by the uncertainties that remain over features of the hadronic interactions at centre-of-mass energies well-beyond what can be reached at any man-made accelerators. Important parameters are the cross-section for hadronic interactions and the multiplicity and the inelasticity associated with them.

The Pierre Auger Collaboration has faced the composition challenge in several ways: a) $X_{\rm max}$ measurement [1], b) muon production depth [2] and c) rise-time asymmetry measurements [3]. Despite recent advances in composition estimates at ultra-high energies with surface detectors, the traditional $X_{\rm max}$ measurement using fluorescence telescopes remains the one with smallest systematic uncertainties [4] and therefore has been used as the most reliable source of information in these studies. Besides that, $X_{\rm max}$ is directly related to the properties of the interaction of the primary particle with air. This feature increases the value of the $X_{\rm max}$ measurement as it is possible to estimate the proton-air cross-section by studying the tail of the $X_{\rm max}$ distribution.

In this paper we discuss the recent improvements in the event reconstruction and in the procedure followed for creating an unbiased sample of $X_{\rm max}$ distributions. The updated results will be presented at the conference.

2 Data analysis

All of the events used for this analysis were obtained from the hybrid mode: that is, events measured by the fluorescence and by surface detectors. The fundamental steps in the analysis procedure are unchanged from those used for our previous publications [1, 5] with information from the surface detector array and the fluorescence detector being used to reconstruct the shower geometry and the longitudinal development [6]. From the latter we obtain both the energy of the shower and the depth of maximum of the shower [7, 8].

We have paid particular attention to: i) choosing selection cuts which guarantee small reconstruction uncertainties, ii) obtaining a data set free from selection biases and iii) making realistic estimates of the uncertainties. The first and second steps are accommodated through selection cuts which reduce the number of events available for the $X_{\rm max}$ analyses while we resort to Monte Carlo calculations to deal with the third point.

The quality cuts have been determined using Monte Carlo simulations of the showers and of the telescopes with the goal of selecting events in which the uncertainty in the measurement of $X_{\rm max}$ is < 40 g/cm^2. The first quality cut relates to the requirement of having clear nights in which an accurate measurement of the aerosol profile was possible. Dusty periods with the Vertical Atmosphere Optical Atmospheric Depth (VAOD) at 3 km above ground less that 0.1 were excluded. Measurements of the cloud cover and of the aerosol content are made routinely [9, 10].

The second set of quality cuts relates to the reconstruction of the longitudinal profile of the shower. Events which have their axis within a cone of 20° around the direction of orientation of the telescope are rejected as these showers cross the camera at high angular-speed making the systematic offset in time between the fluorescence detector and the relevant water-Cherenkov detector an important source of uncertainty in the reconstruction procedures.

The depth of shower maximum is a key parameter derived from the reconstruction. $X_{\rm max}$ is required to lie within the field of view of the telescope as an extrapolation beyond the measured data would degrade the accuracy of measurement. The quality of the fit to the data is assured by rejecting events with χ^2/NDOF > 2.5. The statistical precision of the measurement is derived from the fitting procedure: if the uncertainty in X_{max}, after taking into account both geometrical reconstruction and atmospheric conditions, is > 40 g/cm^2 then the event is rejected.

The detection efficiency of a fluorescence telescope depends upon the geometry of the shower with respect to it and on the nature of the primary particle that initiated the event. To make an unbiased estimate of primary composition one must be certain that the detector has an acceptance that is independent of the mass of the incoming particle. This is achieved by selecting only those events that have, for the given shower geometry and energy, a large enough acceptance range to bracket the X_{max} distribution. Full details are given in [13, 14].

2.1 Improvements in the data analysis

This paper is an update of earlier publications [1, 5]: previous interpretations remain valid [15]. The improvements that will be presented at the Conference are three-fold: i) the increased number of events from 27 additional months of data-taking leads to a reduction in the statistical uncertainties; ii) an improved understanding of our detector which has led to a reduction in the systematic uncertainties in X_{max} and iii) the development of more detailed methods of analysis with the aim of correcting the acceptance of the detector. The update given at the Conference will use the post-LHC interaction models, QGSJETII-04 and EPOS-LHC, as guidelines for interpretation. The inclusion of the LHC data in the models has had the effect of reducing the differences between them [16] and of predicting a large value of X_{max} than given previously for a primary of a particular type and energy.

An important result to be presented by the Auger Collaboration at this Conference relates to the energy of the measured events. A better understanding of our detectors has led to change of about 15% at 10^{18} eV to the energy scale and this will be included in the update of the X_{max} results. Details of the new energy scale are given in [17].

Knowledge of the atmospheric conditions at the Observatory has also improved with a model based on GDAS [18] now being used. The new model allows an event-by-event description of the atmosphere. This replaces the monthly average profiles used in the earlier analyses [19]. The GDAS model has been validated using local balloon launches and has therefore been chosen as the standard description of the atmosphere at the site. The use of GDAS has led to a fall in the systematic uncertainties in $\langle X_{max} \rangle$ of ~ 0.5 g/cm^2 and in RMS(X_{max}) of ~ 2 g/cm^2 at 10^{18} eV and ~ 3.5 g/cm^2 at higher energies. Recent measurements of the aerosol attenuation have been upgraded and two analyses techniques have been implemented to give a better determination of the uncertainties [10, 11, 12].

Further we now have a better understanding of the lateral spread of the light signal across the photomultipliers in the cameras [20, 17] which leads to changes of the reconstructed X_{max}. In the new analysis procedure, the lateral spread of the light from the shower is convolved with the size of the optical spot of the telescope. The combination of these factors results in light being spread over a large area away from the shower axis. This light loss has been parametrized as a function of shower distance and shower age. The correction will be introduced for the data that will be reported.

Quality and fiducial cuts have been tailored to provide an unbiased measurement of the X_{max} distribution. Therefore the data set available after the selection cuts should have constant acceptance for most of the X_{max} values. However, events with very deep X_{max} values may have a smaller acceptance. To study the effect of the smaller acceptance in the tails of the X_{max} distribution we have used Monte Carlo events. The effect of the smaller acceptance in the tails of the X_{max} distribution is less than 5 g/cm^2 in the estimated $\langle X_{max} \rangle$ and in the estimated RMS(X_{max}). Despite the effect of this correction being smaller than 5 g/cm^2 for both $\langle X_{max} \rangle$ and RMS(X_{max}), we are estimating the appropriate acceptance correction for each energy bin: the results will be shown at the Conference.

3 Conclusion

We have presented in this report a short review of the data analysis developed by the Pierre Auger Collaboration. The final analysis will be presented at the Conference and will include:

- new energy scale;
- detailed corrections due to the lateral width of the shower image;
- new aerosol data analysis;
- GDAS atmospheric models;
- acceptance correction.

Besides the improvements in the data analysis briefly described above, the increase in the number of events (27 more months of data) and the new energy scale allow us to introduce additional bins below 10^{18} eV and above 10^{19} eV.

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