The distribution of shower maxima of UHECR air showers

PEDRO FACAL SAN LUIS1 FOR THE PIERRE AUGER COLLABORATION2
1Enrico Fermi Institute & Kavli Institute for Cosmological Physics, University of Chicago, Chicago IL 60637, USA
2Observatorio Pierre Auger, Av. San Martin Norte 304, 5613 Malargüe, Argentina
(Full author list: http://www.auger.org/archive/authors_2011_05.html)
auger_spokespersons@fnal.gov

D01: 10.7529/ICRC2011/V02/0725

Abstract: We present the measurement of \( X_{\text{max}} \), the depth of the maximum of the longitudinal development of ultra high energy air showers, with the fluorescence detector of the Pierre Auger Observatory. After giving an update on the average and fluctuations of \( X_{\text{max}} \) with 80% more data than previously published, we discuss the distributions of \( X_{\text{max}} \) for different energies and compare it to the predictions of air shower simulations for different primary particles.

Keywords: UHECR, The Pierre Auger Observatory, mass composition, shower maxima.

1 Introduction

Measuring the cosmic ray composition at the highest energies, along with other measurements such as the flux and the arrival direction distribution, is a key to separate the different scenarios of origin and propagation of cosmic rays. The composition cannot be determined from direct measurements but must be inferred from measurements of the shower that the cosmic ray primary produces in the atmosphere. The atmospheric depth at which this shower attains its maximum size, \( X_{\text{max}} \), carries information about the mass of the primary particle and the characteristics of hadronic interactions at very high energy. For a given shower, \( X_{\text{max}} \) will be determined by the depth of the first interaction of the primary in the atmosphere, plus the depth that it takes the cascade to develop. The depth of the first interaction is expected to be a decreasing function of the logarithm of the primary energy, while the depth of the shower development rises as \( \ln(E) \) [1]. The measured distribution of \( X_{\text{max}} \) results from the folding of the distribution of the depth of the first interaction, the shower to shower development fluctuations, and the detector resolution.

The superposition model allows a qualitative treatment of different nuclear primaries of mass \( A \): at a given energy \( E \), it describes the shower as a superposition of \( A \) showers of energy \( E/A \). Under this assumption the depth of the maximum of the cascade will be linear with \( (\ln(E) - \ln(A)) \). Showers of heavier nuclear primaries will develop faster that lighter ones. At the same time the fluctuations of the first interaction will be reduced (by less than \( 1/\sqrt{A} \) due to correlations between the interactions of the different nucleons). Thus not only the mean value of \( X_{\text{max}} \) carries information about the mass of the primary cosmic ray, but the whole distribution is sensitive to the mass composition. We expect the maximum of the shower to behave as

\[
\alpha(\ln E - \ln A) + \beta
\]

as function of the energy \( E \) and the mass \( A \) of the primary. The *elongation rate* is defined as the change of \( \langle X_{\text{max}} \rangle \) with energy \( D_{10} = d\langle X_{\text{max}} \rangle /d\log E \). The parameters \( \alpha \) and \( \beta \) encode the dependency of \( X_{\text{max}} \) on the properties of the hadronic interactions. There are different theoretical calculations extrapolating the available data to the energies of the interaction between the primary and the atmospheric nucleon [2]. In fact \( X_{\text{max}} \) can be used to study the properties of the hadronic interactions at the highest energies [3, 4]. The different hadronic models predict different values for \( X_{\text{max}} \), but its dependence on the mass of the primary is qualitatively compatible with the model described here: at a given energy, we expect that for lighter primaries the distribution of \( X_{\text{max}} \) will be deeper and broader than the one for heavier primaries.

We use data from the Fluorescence Detector (FD) of the Pierre Auger Observatory [5] to measure the distribution of \( X_{\text{max}} \) for ultra high energy cosmic ray showers. First we present an update of the measurements of \( \langle X_{\text{max}} \rangle \) and RMS (\( X_{\text{max}} \)) as a function of energy with 80% more statistics than previously reported [6]. In addition, we present, for the first time, the measured \( X_{\text{max}} \) distributions.

2 Data Analysis

Data taken by the Pierre Auger Observatory between December 2004 and September 2010 are used here. The Sur-
face Detector (SD) has 1660 water detector stations arranged in a 1.5 km triangular grid and sensitive to the shower particles at the ground. The FD has 27 telescopes overlooking the SD, housed in 5 different stations, recording UV light emitted in the de-excitation of nitrogen molecules in the atmosphere after the passage of the charged particles of a shower. The shower geometry is reconstructed from the arrival times of the data. The number of fluorescence photons emitted is proportional to the energy deposited in the atmosphere by the shower. Using the shower geometry and correcting for the attenuation of the light between the shower and the detector, the longitudinal profile of the shower can be reconstructed. This profile is fitted to a Gaisser-Hillas function [7] to determine $X_{\text{max}}$ and the energy of the shower [8].

We follow the analysis already reported in [6]. We consider only showers reconstructed using FD data and that have at least a signal in one of the SD stations measured in coincidence. The geometry for these events is determined with an angular uncertainty of 0.6° [9]. The aerosol content in the atmosphere is monitored constantly during data taking [10] and only events for which a reliable measurement of the aerosol optical depth exists are considered. Also the cloud content is monitored nightly across the array and periods with excessive cloud coverage are rejected. Furthermore, we reject events with a $\chi^2$/Ndf greater than 2.5 when the profile is fitted to a Gaisser-Hillas, as this could indicate the presence of residual clouds. The total statistical uncertainty in the reconstruction of $X_{\text{max}}$ is calculated including the uncertainties due to the geometry reconstruction and to the atmospheric conditions. Events with uncertainties above 40 g/cm$^2$ are rejected. We also reject events that have an angle between the shower and the telescope smaller than 20° to account for the difficulties of reconstructing their geometry and for their high fraction of Cherenkov light. Finally, in order to reliably determine $X_{\text{max}}$ we require that the maximum has been actually observed within the field of view of the FD. 15979 events pass this quality selection. Another set of cuts is used to ensure that the data sample is unbiased with respect to the cosmic ray composition. Since we require data from at least one SD station, we place an energy dependent cut on both the shower zenith angle and the distance of the SD station to the reconstructed core so the trigger probability of a single station at these energies is saturated for both proton and iron primaries.

Finally, requiring that the shower maximum is observed means that, for some shower geometries, we could introduce a composition dependent bias in our data. This is avoided using only geometries for which we are able to observe the full range of the $X_{\text{max}}$ distribution. At the end 6744 events (42% of those that pass the quality cuts) remain above $10^{18}$ eV. The systematic uncertainty in the energy reconstruction of the FD events is 22% The resolution in $X_{\text{max}}$ is at the level of 20 g/cm$^2$ over the energy range considered. This resolution is estimated with a detailed simulation of the detector and cross-checked using the difference in the reconstructed $X_{\text{max}}$ when one event is observed by two or more FD stations (Fig. 1).

### 3 Results and discussion

In Fig. 2 we present the updated results for $\langle X_{\text{max}} \rangle$ and RMS$(X_{\text{max}})$ using 13 bins of $\Delta \log E = 0.1$ below $10^{19}$ eV and $\Delta \log E = 0.2$ above. An energy dependent correction ranging from 3.5 g/cm$^2$ (at $10^{18}$ eV) to $-0.3$ g/cm$^2$ (at 7.3 $\times$ $10^{19}$ eV, the highest energy event) has been applied to the data to correct for a small bias observed.
Figure 3: Distribution of $X_{\text{max}}$. The values of the energy limits and the number of events selected are indicated for each panel.
distribution as the energy increases can be clearly observed from the figures. This reduction is even more striking for the tail of the distribution towards deep $X_{\text{max}}$; the proton-like tail at low energy gives gradually way to much more symmetric distributions with smaller tails.

For most of the models, the data would have to be adjusted within their systematic uncertainties to simultaneously match both $\langle X_{\text{max}} \rangle$ and RMS $(X_{\text{max}})$ to a given composition mixture $(X_{\text{max}})$ downward and RMS $(X_{\text{max}})$ upward and/or the energy scale upward. As can be seen in Fig. 2, the MC predictions are more uncertain for the $\langle X_{\text{max}} \rangle$ than for the fluctuations. This is mainly due to the additional dependence of $(X_{\text{max}})$ on the multiplicity in hadronic interactions [3]. In Fig. 4 we therefore compare the shape of the distributions, $X_{\text{max}} - \langle X_{\text{max}} \rangle$ to MC predictions for different compositions and hadronic interaction models. As can be seen, in this representation the various models predict a nearly universal shape. At low energy, the shape of the data is compatible with a very light or mixed composition, whereas at high energies, the narrow shape would favour a significant fraction of nuclei (CNO or heavier). It is, however, worthwhile noting, that both the mixed composition and the pure iron predictions are at odds with the measured $\langle X_{\text{max}} \rangle$. Also, a significant departure from the predictions of the available hadronic models would modify this interpretation (see [4] for an estimate of the properties of hadronic interactions up to $10^{18.5}$ eV using these data and [12] for a comparison between our data and some of the model predictions).

**References**