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$\langle X_{\max} \rangle$ measurements and tests of hadronic models using the surface detector of the Pierre Auger Observatory

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The time structure of the signals from air showers, recorded with the water-Cherenkov detectors of the Pierre Auger Observatory, contains information that can be related to the mass composition of primary cosmic rays and to hadronic multi-particle production. We can study both because the recorded signals contain a mix of the muonic and electromagnetic components. Using information from the time structure, we define observables that enable a comparison of observations with predictions from hadronic models. We have found that the interpretation obtained from a comparison of our data to these predictions is inconsistent with the interpretation obtained by comparing fluorescence measurements and model predictions, over a greater energy range, and with higher precision, than in previous studies. Information about mass composition is obtained by calibrating the observables based on time structure with fluorescence measurements. Following this approach, we infer the depth of shower maximum, $X_{\max}$, from 0.3 EeV to over 100 EeV. In particular, above 30 EeV, our sample is nearly fourteen times larger than currently available from fluorescence measurements. With this novel approach we find good agreement with previous studies and, with our larger sample, we have extended the measurement of $\langle X_{\max} \rangle$ to greater energies than hitherto.

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1. Introduction

The measurement of the mass composition is one of the most important questions related to uncovering the origin of ultra-high-energy cosmic rays (UHECRs) but the study of the mass spectrum is especially difficult for two reasons. On the one hand, to interpret the data one must use assumptions about the hadronic models at centre-of-mass energy around $\sqrt{s} \sim 300\,\text{TeV}$, well beyond what is accessible in particle accelerators. On the other hand, the observable X_{max} is based on fluorescence measurements, restricted to clear moonless nights, with the consequent reduction of statistics.

To overcome the limitations imposed by the small number of events accumulated with the fluorescence technique, use can be made of data recorded with the 1660 water-Cherenkov detectors of the Pierre Auger Observatory [1] which are operational nearly 100% of the time. Nevertheless, most of the observables obtained from these detectors cannot be used to make inferences about the mass composition because they are related to the hadronic component of the extensive air showers (EASs) and thus the comparison with models results in unreliable predictions. In this paper, we describe a new method for extracting information about the development of air showers from the time profiles of the signals in the water-Cherenkov detectors which compose the surface detector (SD).

2. The Risetime and the Delta method

For the study described below, we characterise the signal at each detector by the risetime, $t_{1/2}$, defined as the time taken by the total signal to increase from 10% to 50% of its final level. It is a function of distance, zenith angle and energy. $t_{1/2}$ is sensitive to the state of the development of the shower and so directly related to the mass of the primary particle. In inclined showers, $t_{1/2}$ shows an asymmetry around the azimuthal angle in the shower plane, ζ, which strongly depends on the zenith angle [2]. For the present study, this asymmetry is corrected for, by referencing each risetime to $\zeta = 90^\circ$.

The uncertainty in a measurement of $t_{1/2}$ is found empirically from the data using pairs of detectors that are 11 m apart and also detectors that are at similar distances from the shower core. The uncertainty in a risetime measurement, $\sigma_{1/2}$, is given by

$$\sigma_{1/2} = \frac{\sqrt{\pi}}{2} \langle |t^1_{1/2} - t^2_{1/2}| \rangle, \tag{2.1}$$

where the superscripts define each detector. $\sigma_{1/2}$ is parameterized as a function of total signal, distance and zenith angle. Full details of the methods used and of the results are given in [3].

When a large number of risetimes is recorded in an event it is desirable to characterise the whole event with a single parameter. To do this, we have determined, for the two arrays of the Observatory, independent relationships that describe the risetimes as a function of distance and zenith angle in a narrow energy range. We call these functions *benchmarks*. Risetimes at particular stations are compared with the relevant times from the benchmark, $t^{\text{bench}}_{1/2}$, in units of the accuracy with which they are determined, leading to a new parameter called Δ_i. This approach, *the Delta method*, is illustrated in Fig. 1. Each shower is then characterised by the average value of the Δ_is, Δ_s, for the selected stations, N.

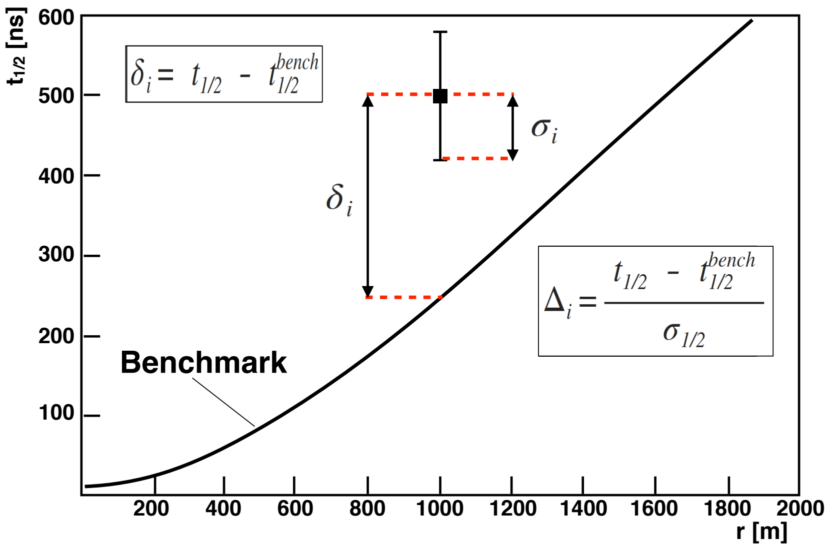

Figure 1: Schematic concept of the Delta method.

3. Data Selection

We have used data collected with the two arrays of the Pierre Auger Observatory. For the 1500 m array (750 m array) data from January 2004 (January 2008) to December 2014 with energies above 3 EeV (0.3 EeV) are selected. A cut in zenith angle, $\sec\theta < 1.45$ ($\sec\theta < 1.30$) is imposed to avoid short risetimes close to the electronics resolution. The events are required to satisfy the standard trigger levels and at least three selected detectors are required for an event to be included in the data sample. For these detectors, the low-gain trace must not be saturated. The recorded signal must be larger than 5 VEM (3 VEM)[1] and the stations must lie between 300 m and 1400 m (800 m). For the highest energies this upper limit on distances has been extended to 2000 m. After application of these cuts a total of 27553 events for the 750 m array and 54022 for the 1500 m array remain. Further details of the selection are described in [3].

4. Benchmark Determination

The determination of the benchmarks is fundamental to the success of the technique. Essentially the same procedure has been adopted for both arrays. For each station two time traces are recorded on high-gain and low-gain channels. $t_{1/2}$ is always calculated from the trace of the high-gain channel unless there is saturation in this channel, in which case we are forced to recover the trace from the low-gain channel. If there is saturation in the low-gain channel $t_{1/2}$ cannot be measured.

Benchmarks are obtained for the high-gain and low-gain traces independently. The energy bins chosen for the benchmarks of the 750 and 1500 m arrays are $17.7 < \lg(E/\text{eV}) < 17.8$ and

[1] 1 VEM is the signal produced by a vertical and central through-going muon.

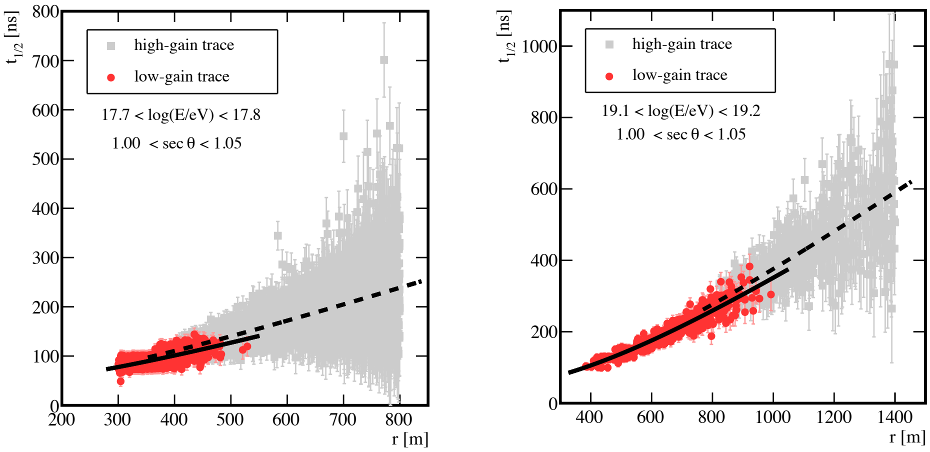

Figure 2: Example of benchmark fits for the 750 m array (left panel) and the 1500 m array (right panel). The solid (dashed) line corresponds to the fit done to the risetimes from the low-gain (high-gain) traces.

$19.1 < \lg(E/\mathrm{eV}) < 19.2$ respectively. A fit is first made to the data from the low-gain channels using the relation

$$t_{1/2}^{\text{low-gain}} = C + \sqrt{A(\theta)^2 + B(\theta)r^2} - A(\theta), \tag{4.1}$$

where A and B are free parameters and $C = 40\,\mathrm{ns}$. Having used low-gain traces to evaluate A and B, the risetimes from the high-gain traces are now fitted with the function

$$t_{1/2}^{\text{high-gain}} = C + N(\theta)\left(\sqrt{A(\theta)^2 + B(\theta)r^2} - A(\theta)\right), \tag{4.2}$$

in which there is only one free parameter, $N(\theta)$, describing the shift between the measurements in the two channels. Examples of these fits in a particular $\sec\theta$ bin are shown in Fig. 2 for both arrays.

Fits were made for A, B and N in six and nine intervals of $\sec\theta$ of width 0.5 for the 750 m and 1500 m array in their respective $\sec\,\theta$ ranges. Fuller details can be found in [3].

5. Δ_{s} as a function of energy and comparison with model predictions

Once the benchmarks have been determined we can describe the observed variation of $\langle\Delta_{\mathrm{s}}\rangle$, the mean of Δ_{s} for a set of events, as a function of energy. The variation of $\langle\Delta_{\mathrm{s}}\rangle$ with energy for the two arrays is shown in Fig. 3. Note that at the benchmark energies, $\langle\Delta_{\mathrm{s}}\rangle = 0$, as expected by definition. The overall systematic uncertainties in $\langle\Delta_{\mathrm{s}}\rangle$ are 0.07 and 0.11 for the 750 m and 1500 m array, respectively [3].

We can use $\langle\Delta_{\mathrm{s}}\rangle$ to test the validity of hadronic models. In previous works [2][4][5][6] strong evidence has been found showing that the models do not adequately describe the data and that the problem is related to the description of the muonic component in the showers. As muons dominate the early part of the shower front, $t_{1/2}$ is particularly useful for studying this effect further. For the comparison with the models, simulations with QGSJetII-04 [7] and EPOS-LHC [8] for proton and

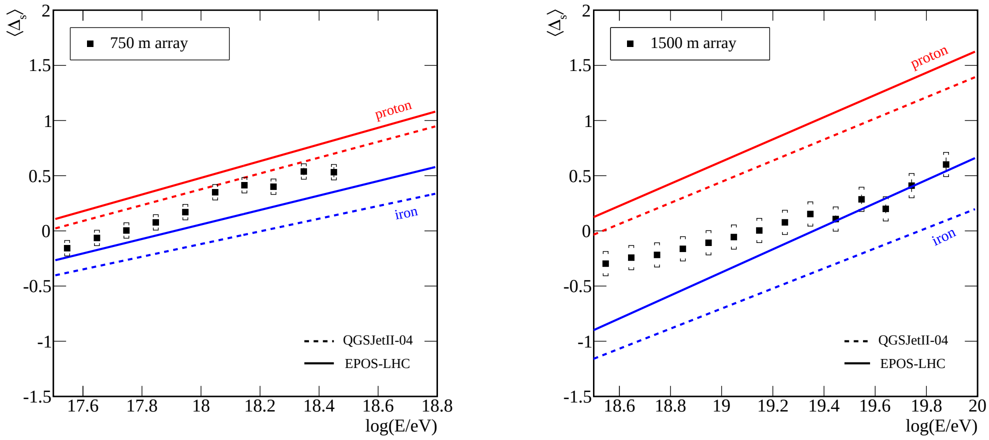

Figure 3: $\langle\Delta_s\rangle$ as a function of energy for the two surface arrays. Brackets correspond to the systematic uncertainties. Data are compared to the predictions obtained from simulations.

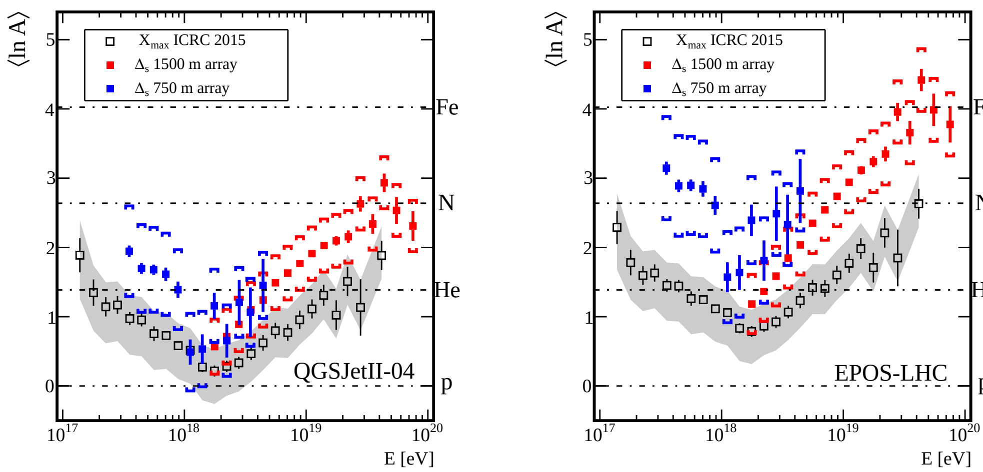

Figure 4: $\langle \ln A\rangle$ as a function of energy for the Delta Method and for X_{max} measurements done with the FD. QGSJetII-04 and EPOS-LHC have been used as the reference hadronic models.

iron primaries with zenith angles $\theta < 45°$ and $17.5 < \lg(E/\text{eV}) < 20.0$ have been produced. For consistency, in making the comparisons, only the benchmarks determined from the data are used. The values of $\langle\Delta_s\rangle$ obtained for the different primaries and models are also shown in Fig. 3. These can be transformed to a prediction of the composition of the UHECRs in terms of $\langle \ln A\rangle$ (Fig. 4) where the results are compared with the Auger measurements of X_{max} made with the fluorescence detector (FD) [9]. While the absolute values of $\langle \ln A\rangle$ for the Delta method and the FD X_{max} differ from each other, the trend with the energy is very similar. The difference probably arises because the electromagnetic cascade dominates the FD measurements whereas Δ_s is a parameter describing a mixture of the muonic and the electromagnetic components. The inconsistency between data and models is observed over a greater energy range than hitherto.

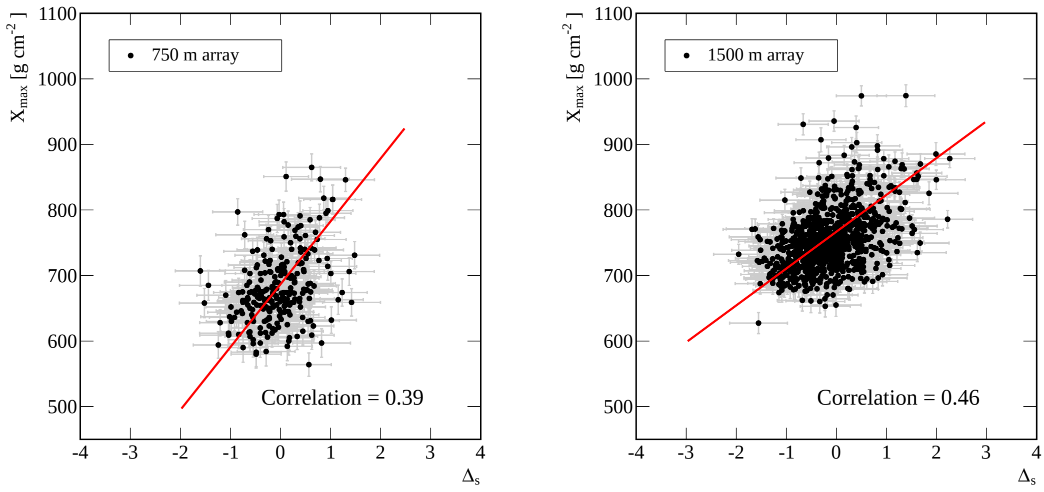

Figure 5: (Left) Correlation of $X_{\max}$ and Δ_s for the 252 events from the 750 m array. (Right) Correlation of $X_{\max}$ and Δ_s for the 885 events of the 1500 m array.

6. Correlation of Δ_s with $X_{\max}$

We now address the correlation of Δ_s with $X_{\max}$ for hybrid events. We would not expect a 1:1 correlation between these parameters because $X_{\max}$ is dominated by the electromagnetic component whereas Δ_s is dependent on a muon/electromagnetic mix. The $X_{\max}$ and Δ_s for the events selected for the calibration are shown in Fig. 5. These events have been taken from the FD data set discussed in [9]. There are 252 and 885 events for the 750 m and 1500 m arrays respectively available for calibration. The selected samples of events are unbiased.

For the calibration of the two data sets we fit functions of the form

$$X_{\max} = a + b\Delta_s + c\,\mathrm{lg}(E/\mathrm{eV}). \tag{6.1}$$

The maximum likelihood method was used to make the fits which give the following values for the parameters a, b and c for the 1500 m (750 m) array: $a = 699 \pm 12(636 \pm 20)\,\mathrm{g/cm^2}$, $b = 56 \pm 3(96 \pm 10)\,\mathrm{g/cm^2}$ and $c = 3.6 \pm 0.7(2.9 \pm 1.2)\,\mathrm{g/cm^2}$.

The values of $\langle X_{\max}\rangle$ found from this analysis are shown as a function of energy in Fig. 6. The overall systematic uncertainties in $\langle X_{\max}\rangle$ are 14 and 11 $\mathrm{g/cm^2}$ for the 750 m and 1500 m array, respectively [3]. From Fig. 7 one can see that they agree well with the measurements made with the fluorescence detectors [9]. The comparison with hadronic models allows the average depth of shower maxima to be expressed in terms of $\langle \ln A\rangle$. The evolution of $\langle \ln A\rangle$ as a function of energy is shown in Fig. 8. In the energy range where the FD and the SD measurements overlap, the agreement is good and the SD measurements confirm the trend towards a heavier mass composition with increasing energy. Above 40 EeV the last two energy bins might suggest that the increase of the primary mass is stopping for the highest energies. However we still need to further reduce statistical and systematic uncertainties to be able to draw strong conclusions.

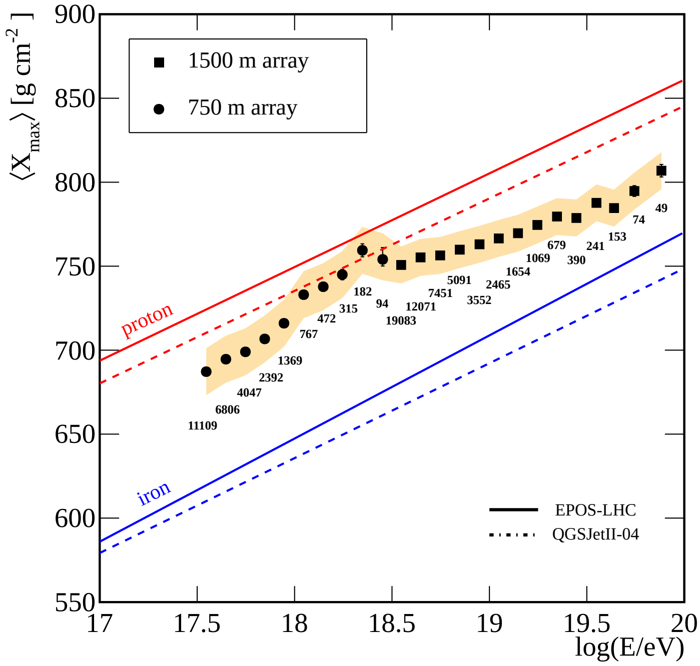

Figure 6: $\langle X_{max} \rangle$ obtained independently with the data from the 750 and 1500 m arrays as a function of energy. The shaded area indicates the systematic uncertainty. Data are compared to the predictions of $\langle X_{max} \rangle$ in showers initiated by protons and iron nuclei assuming two different models.

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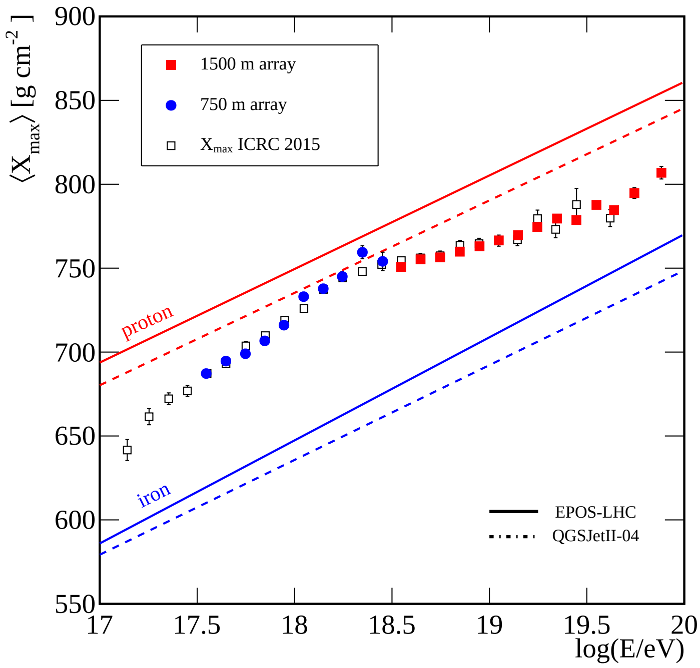

Figure 7: Comparison of $\langle X_{max} \rangle$ measured using the fluorescence and surface detectors. The systematic uncertainties have been removed for a clearer view.

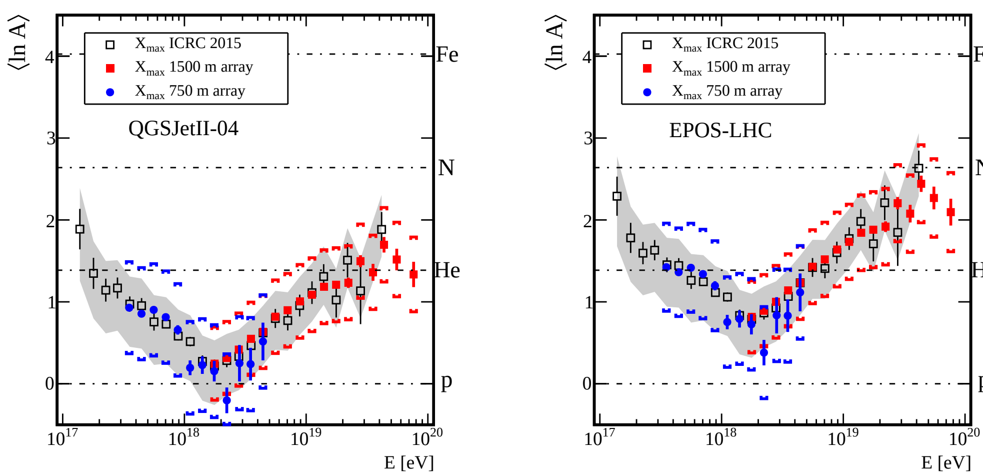

Figure 8: $\langle \ln A \rangle$ as a function of energy. QGSJetII-04 and EPOS-LHC have been used as the reference hadronic models. The results of the Delta method are compared with those based on X_{max} measurements done with the FD [9]. Brackets correspond to the systematic uncertainties.