An alternative method for determining the energy of hybrid events at the Pierre Auger Observatory

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***Abstract*. An important feature of the Pierre Auger Observatory is the detection of hybrid events; i.e., extensive air showers simultaneously detected with at least one water-Cherenkov detector (surface detector) and one fluorescence telescope. Here we describe an alternative method of estimating the energy of these events. The shower axis is determined using data from both detector systems. The shower energy is determined from the integrated surface detector signals and the distance of each detector from the shower axis. The energy estimate is facilitated by the characterisation of an average lateral distribution function as a function of the shower energy and zenith angle. The method requires only the signal from one surface detector. Thus, it is useful for estimating the energy of hybrid events for which the geometry cannot be estimated with the surface detectors alone and the longitudinal profile measured by the fluorescence telescopes is not well determined. In the energy range $0.4 < E < 1$ EeV, the method doubles the number of hybrid events that can be given an energy estimate. The statistical uncertainty of this energy estimate is dependent on the shower energy and geometry. For events with energy greater than 0.4 EeV, the median statistical uncertainty is 26% and the 90% quantile is 44%.**

***Keywords*: Extensive air shower reconstruction**

I. Introduction

The Pierre Auger Observatory detects the highest energy cosmic rays with over 1600 water-Cherenkov detectors arranged as an array on a triangular grid with 1500 m spacing. The 3000 km^2 array is collectively called the surface detector array (SD). The SD is overlooked by the fluorescence detector (FD), which consists of 24 fluorescence telescopes grouped in units of 6 at four locations on the periphery of the SD. The Auger Observatory was designed so that events recorded by the FD are generally recorded also by the SD. Cosmic ray showers detected with both detectors are referred to as hybrid events.

There are two standard methods for reconstructing the geometry (shower axis) and energy of hybrid events. The first method, SD reconstruction, uses only data from SD stations. The shower geometry and station signal at 1000 m from the shower axis $S(1000)$ are estimated. The shower energy is derived from S(1000) and zenith angle through a set of calibration equations (e.g., [1]). The requirements for SD reconstruction are that the intersection of the shower axis with the ground (core position) be contained within an equilateral triangle of operating stations and that at least three stations record shower particles [2].

The second method, hybrid reconstruction, is best described as a two-step sequence. First, data from the FD telescopes and one SD station are used to estimate the shower geometry [3]. This estimate is referred to as the hybrid geometry. Second, the hybrid geometry and the signal levels recorded by the FD telescopes are used to determine the shower longitudinal profile and the shower energy [4]. This energy estimate is referred to as the FD energy. The requirements for the hybrid geometry estimate are that at least one telescope and one SD station record shower particles. The requirements for the FD energy estimate are much more restrictive. One of the most critical requirements is that the FD records a significant fraction of the longitudinal profile.

Many hybrid events do not meet the requirements for SD reconstruction or the FD energy estimate. Events in this category are mostly low energy events where the three SD stations closest to the axis did not all record shower particles and the FD recorded only a small fraction of the longitudinal profile. For events in this category, it is still possible to obtain an energy estimate with an alternative method.

This alternative method proceeds in three steps. First, the shower geometry is estimated with the hybrid geometry method. Second, $S(1000)$ is estimated based on the hybrid geometry and the integrated signals from the SD station(s). Third, the shower energy is derived from $S(1000)$ and zenith angle following the same procedure used in standard SD reconstruction. The requirements for this alternative method are the same as for the hybrid geometry method. We call this energy estimate the alternative-SD (alt-SD) energy estimate. In this paper, we describe the details of the alt-SD energy estimate and motivate its utility.

II. The Lateral Distribution Function

The $S(1000)$ parameter has been shown to be correlated with shower energy [5]. To estimate $S(1000)$ from the signal levels in one or more SD stations, we must know the average shape of the lateral distribution function (LDF), i.e., the station signals as a function of distance from the shower axis. We have previously shown [6] that the LDF for Auger events is well described by the modified Nishimura Kamata Greisen (NKG) function

$$S = S(1000)(r/1000)^{\beta}(r + 700/1700)^{\beta},$$

where S is the SD station signal calibrated in vertical equivalent muons (VEM), r is the distance the station is from the shower axis, and β is the slope parameter. The slope parameter β describes the LDF shape, i.e., the rate at which station signals decrease with distance. The slope parameter is a function of $S(1000)$ (or shower energy) and shower zenith angle θ. We have parameterised $\beta = \beta(S(1000), \theta)$ for $S(1000) > 3$ VEM and $\theta < 60°$ using SD data. For a 0.4 EeV shower with $\theta = 38°$, $S(1000) \approx 3$ VEM.

For an unbiased parameterisation, it is important that the SD have 100% trigger efficiency for the showers used in the parameterisation. The main SD array has a detector spacing of 1500 m and has near 100% trigger efficiency above 3 EeV [7]. However, a small area of the SD array, part of the AMIGA enhancement, has a detector spacing of 750 m and has near 100% trigger efficiency above 0.4 EeV [8]. The 750 m array was used to obtain an unbiased sampling of β for showers with $0.4 < E < 3$ EeV.

III. Details of the Alt-SD Method

Given $\beta(S(1000), \theta)$ and the hybrid geometry, it is possible to estimate $S(1000)$ with a minimum of one SD station. We calculate the total integrated signal S of each station, and estimate the statistical uncertainty on S as $\Delta S = 1.06\sqrt{S}$ [9]. Using the hybrid geometry, we calculate the distance r each station is from the shower axis. The station radius uncertainty Δr is obtained from the axis uncertainty (i.e., the uncertainty on core position and arrival direction) via a bootstrap method [10].

To obtain an estimate of $S(1000)$, we minimize the following function

$$\chi^2 = \sum_{i=1}^{N} \frac{\left(S_i - S(1000)\left(\frac{r_i}{1000}\right)^{\beta}\left(\frac{r_i+700}{1700}\right)^{\beta}\right)^2}{(\Delta S_i)^2 + (\Delta r_i dS/dr)^2}.$$

where N is the number of stations. The statistical uncertainty on $S(1000)$, i.e., $\Delta S(1000)$, is obtained by varying $S(1000)$ until χ^2 increases by 1.

Since the number of stations and average signal per station increases with energy, $\Delta S(1000)/S(1000)$ tends to decrease as shower energy increases. However, $\Delta S(1000)/S(1000)$ also depends on the shower geometry. For example, the value(s) of r is important. There are actually two opposing trends. First, S increases as r decreases, which tends to decrease $\Delta S(1000)/S(1000)$. Second, $|dS/dr|$ increases as r decreases, which tends to increase $\Delta S(1000)/S(1000)$. This implies that for a given shower energy and Δr, there is an optimum value for r. This value increases with shower energy. In the energy range $0.4 < E < 3$ EeV, the optimum range of r is approximately 500 m to 1000 m.

The process of obtaining an energy estimate from $S(1000)$ proceeds exactly as in the standard SD reconstruction algorithm. First, the dependence of $S(1000)$ on zenith angle is removed by calculating S_{38} for each event, i.e., the value of $S(1000)$ if the zenith angle of the event was 38°. The attenuation function used to calculate S_{38} is derived directly from the data using the constant intensity cut (CIC) technique.

Second, S_{38} is converted to energy through a calibration equation. This calibration equation is derived from the subset of events with an estimate of FD energy and an alt-SD estimate of S_{38}. In this way, the FD energy estimate sets the energy scale for the alt-SD method. For the details of the CIC and energy calibration procedure, see [11].

IV. Energy Resolution

In Fig. 1, we show the results of the energy calibration step. We applied the alt-SD method to Auger hybrid events recorded from 2004 through 2008 using the following SD station selection criteria: signal not saturated, $S > 10$ VEM, and $r > 200$ m. We selected events with an S_{38} uncertainty $< 20\%$ and which met the strict FD energy criteria reported in [1]. Then, we fit the S_{38} and FD energy data with a broken power-law function:

$$E = \begin{cases} b(S_{38})^a & : S_{38} \leq S_B \\ b(S_B)^{a-c}(S_{38})^c & : S_{38} > S_B \end{cases},$$

where $a = 1.245 \pm 0.005$, $b = 0.100 \pm 0.001$, and $c = 1.030 \pm 0.007$. The break point was fixed at $S_B = 20$ VEM. This function is shown in Fig. 1. The reduced χ^2 of the fit was 1.49. During the fitting process, we rejected events below an anti-bias cut line shown as a dotted line in Fig. 1. The line intersects the fitted function at log(3 VEM).

A broken power law describes the data better than a single power law. This shows that the calibration equation flattens slightly (i.e., the S_{38} exponent becomes larger) as shower energy decreases. We are currently investigating this phenomenon.

Fig. 2 shows the fractional difference between the alt-SD energy and the FD energy estimates for events that passed the above selection criteria and with $E > 3$ EeV. The RMS is 21%. This is similar to the difference between the FD and standard SD energy estimates in the same energy range. The main contributions to the width of the distribution are the statistical uncertainty on the FD and alt-SD energy estimates and inherent shower-to-shower fluctuations (including the lack of knowledge of the true LDF shape). At lower energy, the width of this distribution increases slightly. For example, in the energy range $0.4 < E < 3$ EeV the RMS is 26%.

For the energy calibration procedure, it was necessary to use events which passed a set of strict selection rules. We have also examined the energy uncertainty of events that passed a set of less restrictive selection rules. To do this, we selected events with the following criteria: FD track length $> 15°$, at least one station within 850m of

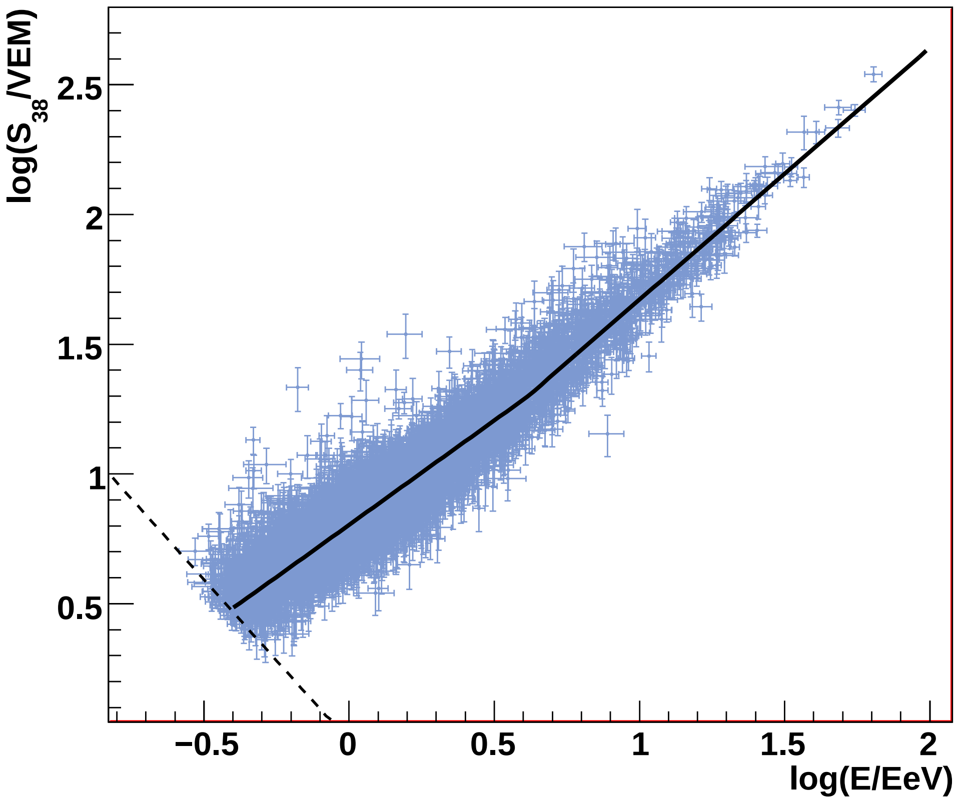

Fig. 1: S_{38} (from the alt-SD method) vs. FD energy for high quality events. The solid line is the energy calibration equation

the shower axis, at least one unsaturated station with $r >$ 200 m and $S > 10$ VEM, $\theta < 60°$, and $E > 0.4$ EeV. We derived the uncertainty on the energy estimate from the uncertainty on $S(1000)$. The median uncertainty is 26%, and the 90% quantile is 44%.

V. Discussion and Conclusions

The alt-SD energy method expands the number of hybrid events with an energy estimate. The method is most useful for showers with energy below the 100% trigger efficiency of the SD. In the energy range $0.4 < E < 1$ EeV, the number of hybrid events that can be given an alt-SD energy estimate is approximately twice the number that can be given either a standard SD energy estimate or an FD energy estimate. This ratio increases as shower energy decreases.

Expanding the number of hybrid events with an energy estimate is particularly useful for point source studies. Generally, the hybrid geometry method returns a more accurate estimate of the shower axis direction compared to SD reconstruction. This is especially noticeable for low energy events. For example, for events where only 3 SD stations trigger, the angular resolution of SD reconstruction is approximately $1.75°$ [12]. However, for events in the same energy range, the angular resolution of the hybrid geometry is approximately $0.6°$ [13]. Expanding the number of hybrid events with an energy estimate allows for point source searches in narrow energy bands.

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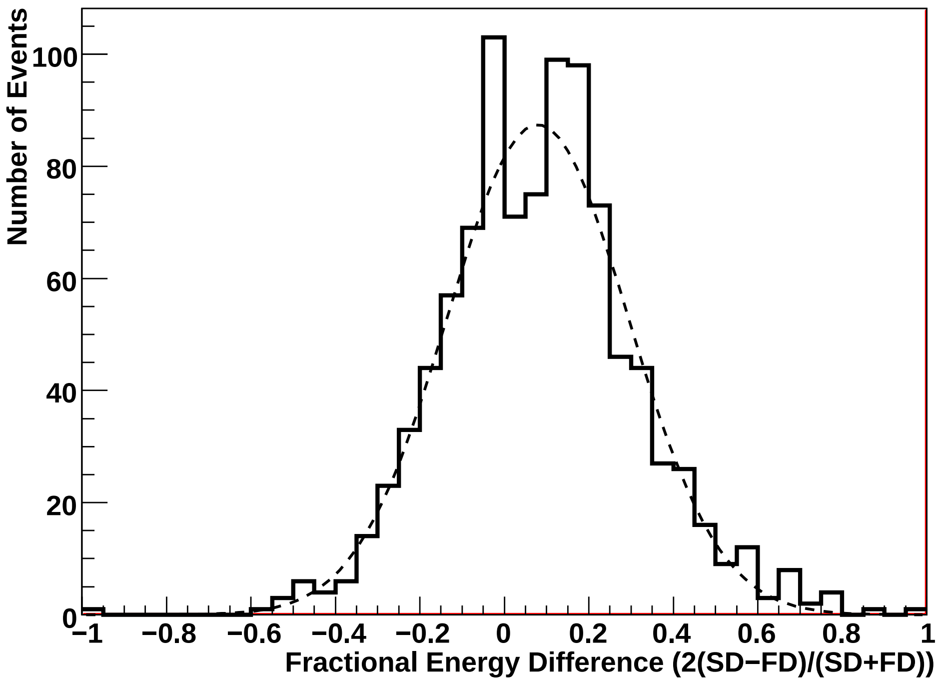

Fig. 2: Fractional difference between the FD and alt-SD energy for hybrid events above 3 EeV. The dotted line is a Gaussian with a standard deviation of 21%