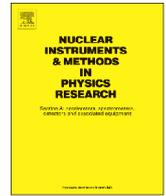




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Calibration of the RPC charge readout in the ARGO-YBJ experiment with the iso-gradient method



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ABSTRACT

The ARGO-YBJ experiment is a full coverage array of Resistive Plate Chambers (RPCs) with an active area of 5800 m². In order to eliminate the response difference of the charge readout from the RPCs, a calibration procedure is carried out with the iso-gradient method. This method also allows the extension of the absolute calibration with the muon telescope including scintillation detectors to all the RPCs in the array. The overall systematic uncertainty in measurements of the number of particles by the RPCs is

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10.7%. In general, the method gives results consistent with those from a totally different approach also used in the experiment.

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1. Introduction

Detector arrays were widely used in cosmic ray air shower experiments, e.g., KASCADE [1], Tibet AS γ [2] and Pierre Auger Observatory [3], and will be built up in the near future, e.g., the LHAASO project [4]. The evaluation of the response differences among the detectors in an array is an important issue, because the response differences among the detectors introduce a systematical uncertainty into shower samples and consequently affect the accuracy of measurements of shower parameters. Thus, a calibration, i.e., a response alignment of all the detectors, is a mandatory job in order to remove systematical differences among detectors and obtains the full response consistency in the whole array. Using a well calibrated probe and moving it over all the detectors is a traditional way to carry out the calibration. This probe method is strongly limited in large dynamic range measurements, because of small size and low flux of air showers, and it could be practically difficult if the number of the detectors is large enough, such as in the ARGO-YBJ experiment [5–7] described below. In order to carry out the complete alignment of the analog charge readout of the Resistive Plate Chambers (RPCs) in the ARGO-YBJ experiment, a calibration method based on a statistical average response of the detectors to the recorded cosmic ray air showers has been developed. For the consistency in the response of the different detectors, the calibration method relies on the assumption of a symmetry of the secondary particle distribution with respect to the axis along the direction of the shower. Density of particles on the detector shows a maximum around the core (the intersection point of the shower axis with the detector), while it decreases with the distance from the core. In this paper, the distance from the core and the density of particles are measured on the projected plane orthogonal to the shower direction. Therefore, the method can be named as “iso-gradient calibration”. This paper is devoted to the description of this method developed using the ARGO-YBJ experimental data and suitable to calibrate the RPC charge readout in the array. Exploiting an existing absolute calibration for number of particles crossing a RPC and scintillator telescope [8], the calibration is extended to all the RPCs in the array.

2. Experimental set-up

The ARGO-YBJ experiment at the YangBajing Laboratory, Tibet, PR China (4300 m a.s.l.) has been run for several years, until the end of data taking. ARGO-YBJ is the only air shower array exploiting the full coverage approach at very high altitude, aiming at the study of cosmic radiation with an energy threshold of a few hundreds of GeV. It is made by a single layer of RPCs housed in a large building ($111 \times 100 \text{ m}^2$). The detector has a modular structure (Fig. 1), the basic module being a cluster ($7.6 \times 5.7 \text{ m}^2$) made of 12 RPCs ($1.25 \times 2.80 \text{ m}^2$ each). A full coverage carpet of 5800 m^2 with active area $\sim 93\%$ is formed with 130 clusters, and this carpet is surrounded by 23 additional clusters with a coverage of $\sim 40\%$ (guard ring) to improve the core location reconstruction. The detector installation was completed in 2007 and data was collected smoothly until February 2013.

Each RPC is read via 80 strips ($61.8 \times 6.75 \text{ cm}^2$), which represent the space pixels, thus ensuring a high detector granularity. The 80 strips are logically organized in 10 pads of $61.8 \times 55.6 \text{ cm}^2$ which are individually recorded and provide the temporal information with Time to Digital Converter (TDC) counting. In addition, the signal of each RPC is read out by two large size pads ($1.23 \times 1.39 \text{ m}^2$ each), named BigPads, in analog mode with a 12 bits Analog to Digital Converter (ADC) saturated at 4095 counts. The full ARGO-YBJ carpet is composed of 3120 BigPads. The Local Station (LS) is the DAQ unit providing local trigger and readout. A dynamic gain set provides 8 input values for full scale (f.s.) setting, however in practice four f.s. were used: 0.29 V, 2.13 V, 16.2 V and 32.4 V. This extends the range of measured particle densities up to 10^4 particles/ m^2 and the primary cosmic ray energy from some tens of TeV up to several PeV. Therefore, the measurement of showers by means of the BigPads offers a great benefit to research on hadronic interactions and the cosmic ray spectrum around the so-called “knee” in the PeV primary energy region.

Besides, a muon telescope [8] with RPCs and scintillators was set up for detector monitoring and calibration purposes, and it has been used to calibrate the RPC charge readout of the particles hitting the detector, as described in this paper. Secondary particles in cosmic

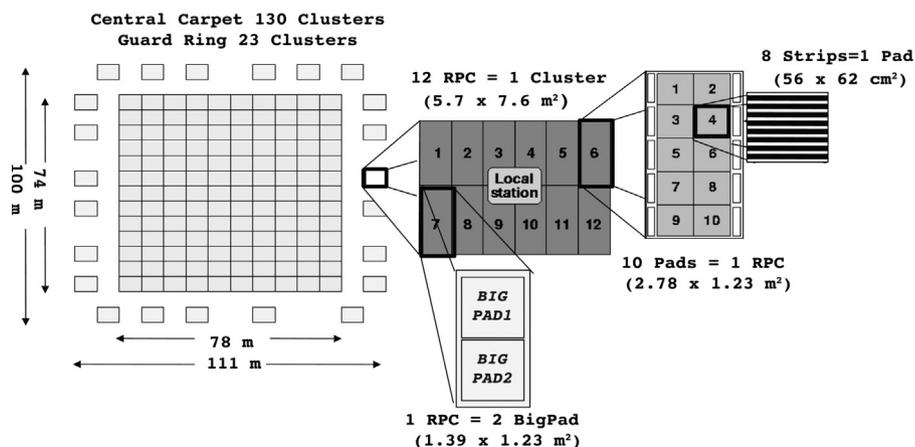


Fig. 1. The ARGO-YBJ detector setup.

ray air showers are taken as the calibration beam. The telescope is composed of two scintillation detectors, to measure impinging charged particles, and five RPCs stacked together with the scintillators. One of the five RPCs between the two scintillators is that to be calibrated, other two RPCs provide pad and strip information and can also be used to check the calibration, and the remaining two RPCs help us to pick up coincident events from the ARGO-YBJ data.

3. The iso-gradient method

The idea of the calibration method introduced in this paper is a kind of self-calibration of the detector data. In a cosmic ray air shower, which is approximately symmetric with respect to the shower axis, the number of particles at the same distance from the shower core is almost constant. In practice, some response differences in the BigPads are observed so that the pulse heights (H) of the signals are not the same. Therefore, since the responses of the BigPads are expected to be the same if these are at the same distance from the shower core, the average value of H over the BigPads at the same distance, denoted as $\langle H \rangle$, after electronics calibration (see Section 4), should be a rather good measurement of the number of particles, at the leading order of approximation. Consequently, for a BigPad, the deviation R is defined as

$$R = \frac{H - \langle H \rangle}{\langle H \rangle} \quad (1)$$

is a measurement of the response difference of the BigPad including shower fluctuations. This variation can be further reduced by using the average value of R over a large number of showers, denoted as \bar{R} . Therefore, \bar{R} can be used to compensate the response difference of each BigPad through the correction term

$$H_1 = \frac{H}{1 + \bar{R}} \quad (2)$$

and this procedure can be applied repeatedly. After n iterations

$$H_n = \frac{H_{n-1}}{1 + \bar{R}_n} = C \times H \quad (3)$$

where

$$C = \frac{1}{\prod_{k=0}^n (1 + \bar{R}_k)} \quad (4)$$

is the final coefficient of the response difference correction for the considered BigPad.

This procedure, named the iso-gradient method, has been tested with events simulated by CORSIKA [9] using QGSJETII and GHEISHA as the hadronic interaction models. Primary energies of the air showers were generated from 10 TeV to 10 PeV, zenith angles from 0° to 45° , and azimuthal angles from 0° to 360° . The observation level is that of YangBajing, that is, 4300 m a.s.l. The primary composition consists of light (H and He), moderate (C, N, O, Mg, Al and Si) and heavy nuclei (Fe). The primary energy

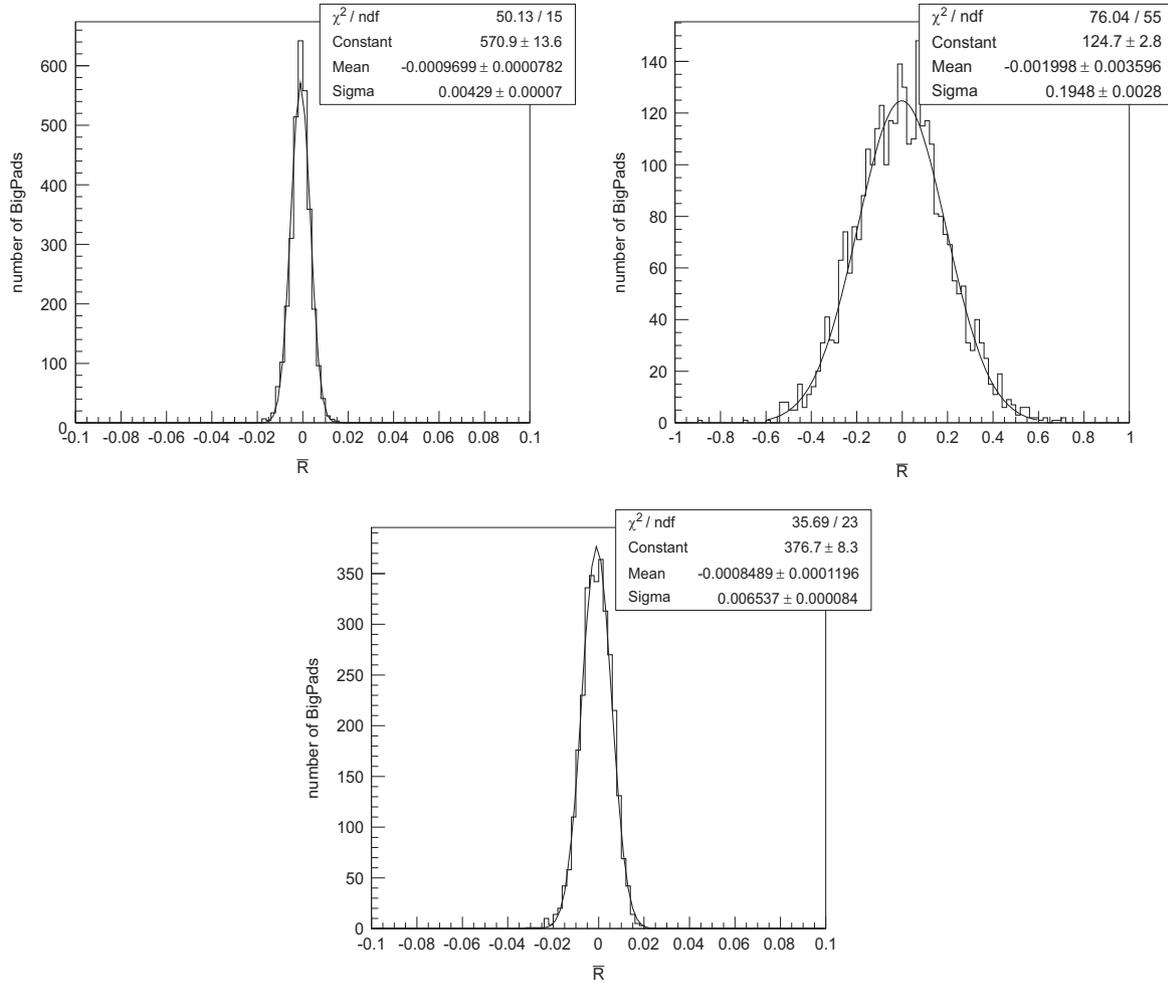


Fig. 2. The distribution of \bar{R} for all the BigPads from Monte Carlo simulation. Upper left panel: without response difference; upper right panel: after insertion of a response difference; lower panel: after correction of the response difference.

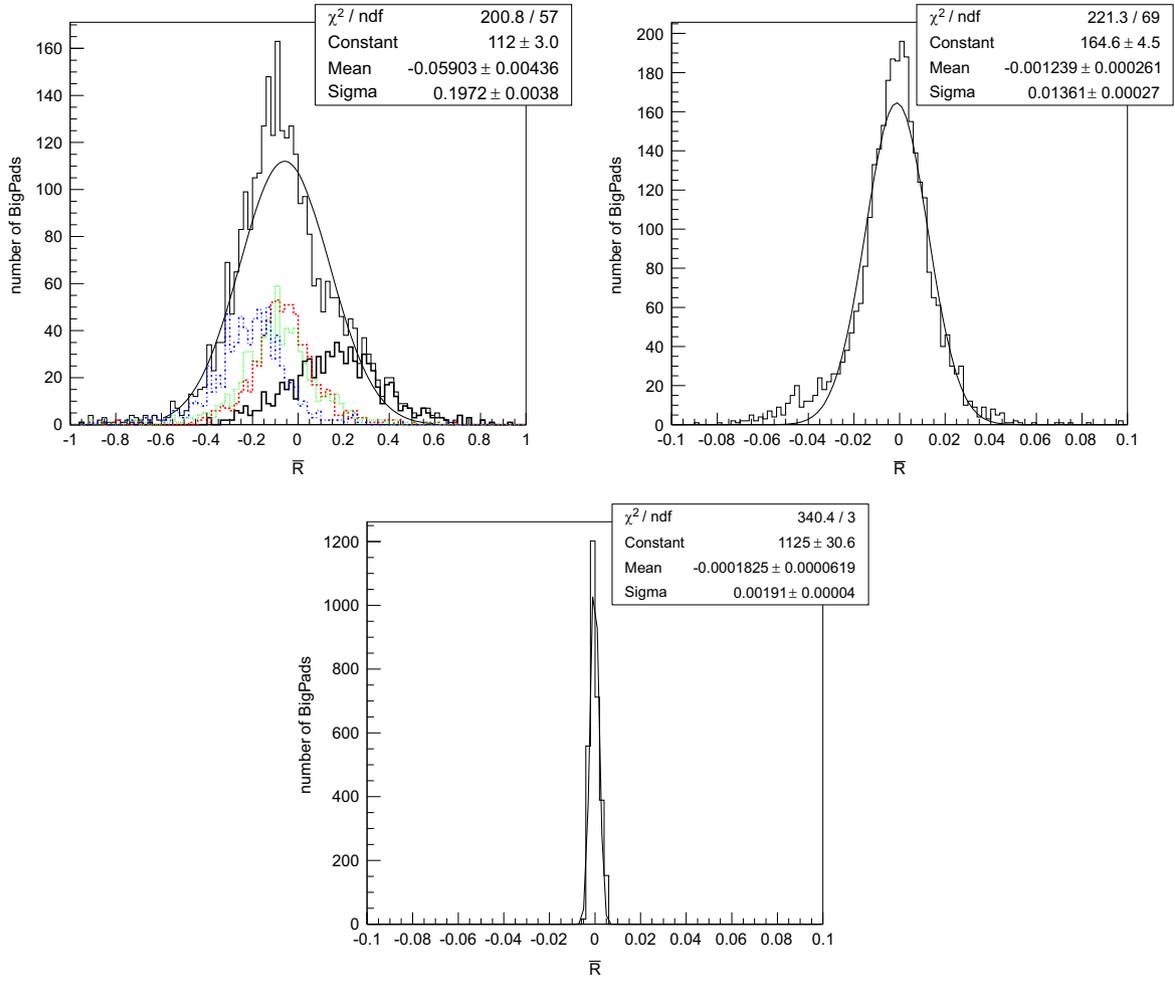


Fig. 3. Distribution of \bar{R} for all BigPads from real data taken in one month. Upper left panel: after the electronics calibration; black thick line: total; black solid line: BP0; red dashed line: BP1; green dotted line: BP2; blue dot-dashed line: BP3. Upper right panel: after two iterations of correction of the response difference. Lower plot: after 9 iterations of correction of the response difference. (For interpretation of the references to color in this figure, the reader is referred to the web version of this paper.)

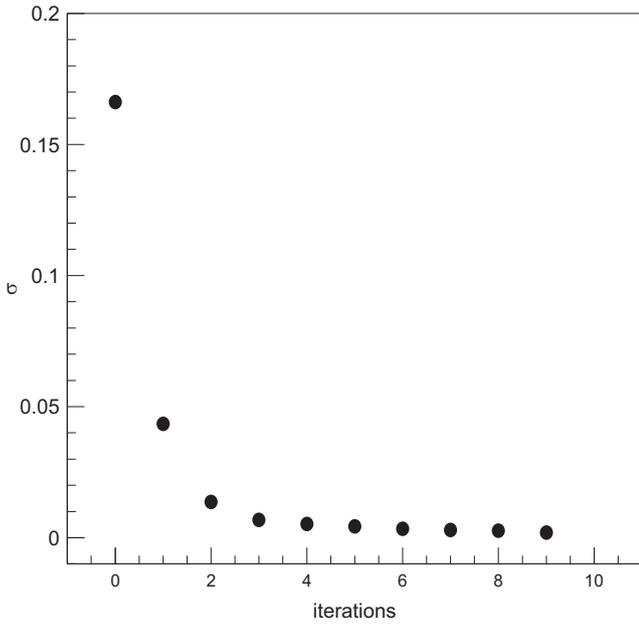


Fig. 4. The sigma of the distribution of \bar{R} as a function of the number of iterations. Error bars are not appreciable.

Table 1
Dependence of the response difference correction on the range of pulse height.

Pulse height range (V)	Sigma (%)
0–1	3.1
1–3	4.9
3–16.2	10

spectrum of each component is set as in [10]. In total, 1.6×10^5 events are generated corresponding to the amount of data taken by ARGO-YBJ during 3 days. Firstly, all the BigPads in the simulation are assumed completely aligned with each other, the distribution of \bar{R} has a width (sigma of the Gaussian fit) of 0.43% and is shown in Fig. 2 (the upper left panel), indicating that the effect of the shower fluctuations is very small. After inserting an artificial response difference of 20% randomly sampled among all the BigPads, the distribution of \bar{R} has a width of 20%, as expected, and is shown in Fig. 2 (the upper right panel). After correcting the response difference, the distribution of \bar{R} is restored to the width of 0.65% (the lower panel in Fig. 2), close to what expected in the pure simulated samples. In the correction procedure, the location of the “hottest” BigPad which has the largest number of particles in the shower is treated as the shower core. According to our

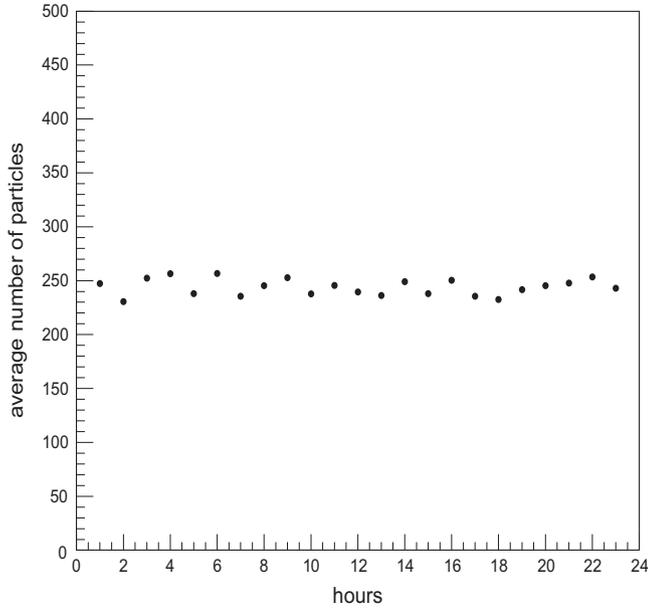


Fig. 5. Daily variation of a BigPad response. The x-axis gives the hours of a day and the y-axis the average number of particles in one hour with value larger than 100.

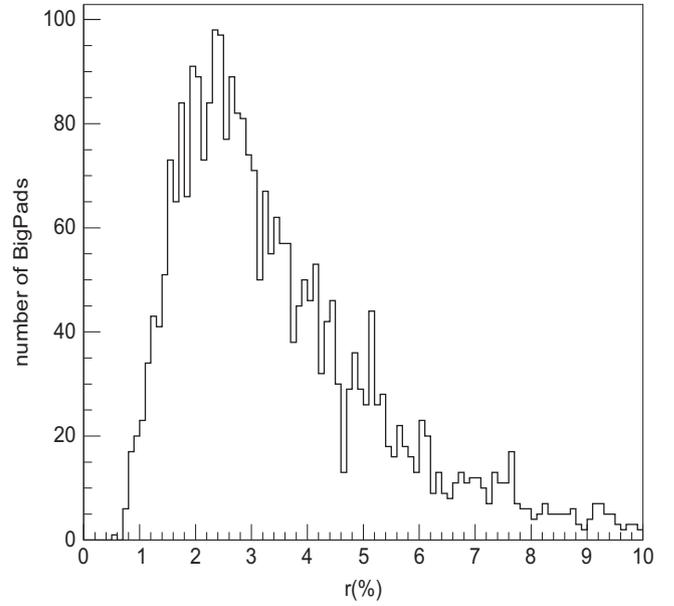


Fig. 6. The variation of the response difference correction from each BigPad in one year of data taking.

simulation, the shower core position resolution is 0.7 m, and it causes an uncertainty of 0.85%. Besides, the shower angular resolution is 0.4° , and the uncertainty caused by it is 0.2%.

4. Calibration of the number of particles

4.1. Correction of the response difference

Before applying the iso-gradient method to real data, electronics calibration for raw data is needed [7]. For each BigPad readout channel, this calibration is made with an input pulse generated with a Digital to Analog Converter (DAC), and the subsequent ADC readout from the same BigPad channel. These calibrated data are then used to translate ADC counts into pulse height H , which is a measurement of number of particles in the BigPad.

After the electronics calibration, the correction of the response difference with the iso-gradient method described in Section 3 is performed for real data with the full scale setting of 16.2 V. The core of a shower is defined by the position of the BigPad with the maximum ADC count. Fig. 3 refers to data collected in a month. Several selections are applied: ADC counts larger than 20 are accepted, only BigPads at a distance less than 12 m from the shower core are considered in each event, and the maximum ADC count in the event must be larger than 500 in order to use only “big” events to calibrate BigPads. As shown in the figure, after electronics calibration, the Gaussian fit to the distribution of \bar{R} has a sigma of 19.7% (upper left plot). Moreover, the mean value is -0.059 and the distribution is not symmetric. In fact, gas detectors are delicate and their responses strongly depend on the environmental parameters. The single gas channel is a couple of RPCs in series (bicamera) which has as input a capillary tube (made of glass, 32 mm long and with diameter of 0.6 mm) with an impedance so high that the gas flux in the bicamera does not depend on the length of the distribution pipes. Since the bicamera consists of two adjacent RPCs, i.e., four BigPads, the entire carpet from the gas point of view can be considered essentially as a set of four different kinds of BigPads (BP0, BP1, BP2 and BP3) [7]. As a

consequence, the four different BigPad types have different distributions of \bar{R} , shown in Fig. 3 (the upper left panel).

After two iterations of correction of the detector response difference, the pulse heights H' are obtained, and the distribution of \bar{R} has a sigma of 1.36% (the upper right panel in Fig. 3). The iteration ends when the difference between two steps is small enough. In general, 9 iterations are carried out, and the sigma decreases to 0.2% (the lower panel in Fig. 3). It has been observed that the sigma of the distribution of \bar{R} decreases as the number of iterations increases and becomes flat after the 7th iteration (Fig. 4). It is worth mentioning that detector response differences due to the gas flow are also corrected with the iso-gradient method.

4.2. Absolute calibration for particle measurement by BigPads

The telescope [8] permits a measurement of number of particles in a dynamic range from 5 particles/m² up to 200 particles/m², with a deviation from linearity of less than 6%. By means of the iso-gradient method, the calibration for the number of particles measured by the scintillator in the telescope can be propagated to all the BigPads. In total, 1.6×10^4 events triggering both the telescope and the RPC carpet have been considered. As mentioned above (Section 4.1), after the electronics calibration and the correction for the response difference, the corrected pulse heights H' of all the BigPads are obtained. Now the H' value of each BigPad is divided by an arbitrary conversion factor α , thus extracting the BigPad response in term of number of particles, N' . In a shower $\langle N' \rangle$, the average value of N' on the BigPads located at the same distance of the scintillator from the shower core is obtained, and the relative deviation from the number of particles N_s measured by the scintillator is

$$R_s = \frac{\langle N' \rangle - N_s}{N_s} \quad (5)$$

The average value for all the matching events is \bar{R}_s . The conversion factor α is tuned until the absolute value of \bar{R}_s is less than 0.01. Finally, $\alpha = 1.52$ mV/particle, and the absolute numbers of particles for all the BigPads are obtained.

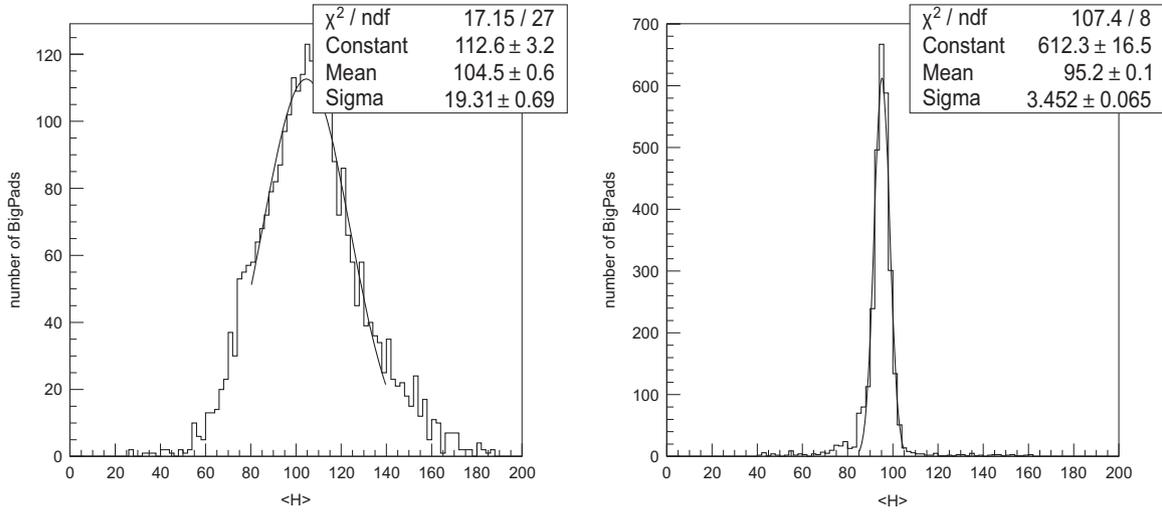


Fig. 7. Distribution of the average pulse height on BigPads for a month of events. Left: after electronic calibration; right: after correcting for response difference.

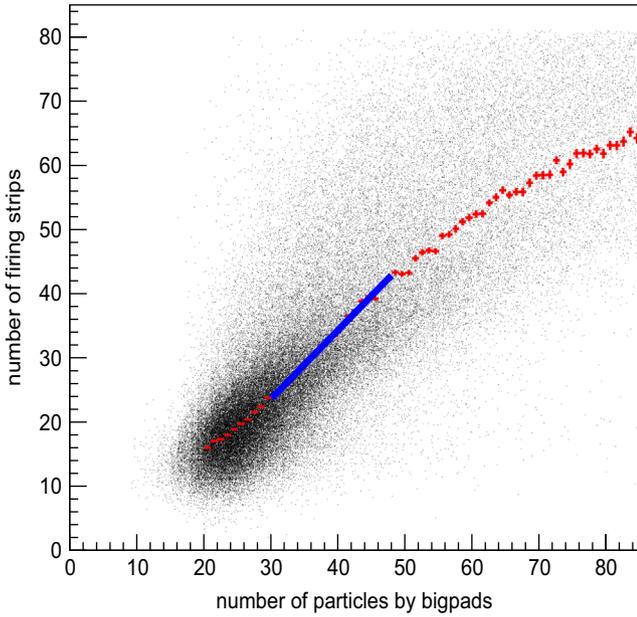


Fig. 8. Scatter plot of number of strips vs. number of particles obtained with BigPads. The profile (red crosses) is fitted with a linear function (blue line). (For interpretation of the references to color in this figure, the reader is referred to the web version of this paper.)

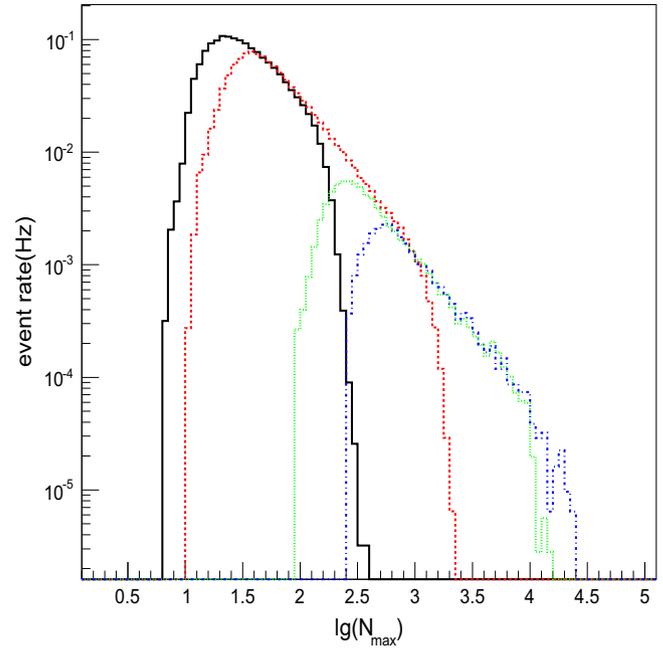


Fig. 9. N_{max} distributions for all f.s.: Black solid line: 0.29 V; Red dashed line: 2.13 V; Green dotted line: 16.2 V; Blue dot-dashed line: 32.4 V. (For interpretation of the references to color in this figure, the reader is referred to the web version of this paper.)

5. Results

The possible dependence of the response difference correction on the range of pulse height is studied (Table 1). For different intervals of pulse height, the calibration procedure is taken to obtain the correction value C . The range of 0–16.2 V is taken as “standard”. The sigma in Table 1 is the standard deviation of the distribution of the differences between the correction C in each range and the standard one. The dependence of the response difference correction on the range of pulse height produces a systematic uncertainty of 10% in the particle measurement.

Besides, the correlation between correction values and environment (temperature and pressure) is also studied. As an example, Fig. 5 shows that the daily variation of a BigPad is almost flat. One

month of data are folded for this study. All the BigPads are individually checked and results are the same. As a consequence, no daily modulation larger than 5% due to environment is found.

Furthermore, the variation of the correction for response difference in one year of data taking is also studied. For each BigPad the parameter r , defined as the RMS divided by the mean value of the distribution of C values in one year, is obtained. Fig. 6 shows the r distribution for all the BigPads, which indicates that the variation of the response difference correction in one year has a mean value of 3.5%.

The improvement of data after the calibration can be revealed by the following comparison. Fig. 7 is the distributions of the average pulse height $\langle H \rangle$ for a month of analog data before and

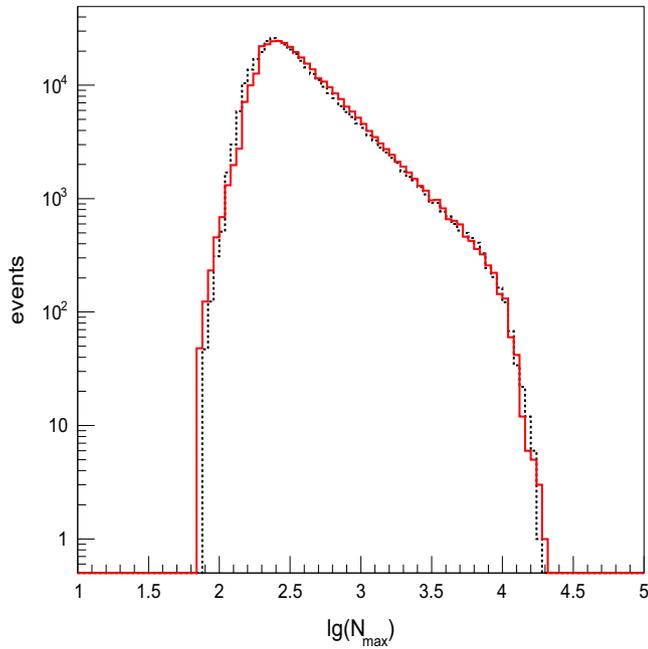


Fig. 10. N_{max} distributions (f.s. 16.2 V) for the same events with the two different calibration methods. Black dashed line: with the iso-gradient method; Red solid line: with the method of [7]. (For interpretation of the references to color in this figure, the reader is referred to the web version of this paper.)

after the calibration. After the calibration, the ratio of the sigma to the mean value of the distribution decreases from 18.5% to 3.63%.

The effects of the calibration performed through the iso-gradient method are checked using real data as described in the following. Firstly, a check is carried out using strip multiplicity. Data from the lowest f.s. 0.29 V are taken. In Fig. 8, the profile of scatter plot of the number of strips vs. the number of particles is fitted with a linear function in a range avoiding nonlinearity of BigPads at low number of particles and saturation of strips at high number of particles. The slope of the fitting linear function is 1.07 ± 0.01 strips/particle, which is consistent with the result (1.10 ± 0.02 strips/particle) of a totally different approach also used in the experiment [7], which exploits strips to calibrate particle measurement by BigPads.

Secondly, cosmic ray primary energy spectrum obeys a power law function below “the knee region”, and it could be reflected by distribution of N_{max} which is the maximum number of particles in one shower, positively correlated to cosmic ray primary energy. The calibration method is applied to all the f.s. data. The distributions of N_{max} at all f.s., normalized to event rates, are consistent (Fig. 9), although the one corresponding to the 2.13 V scale has a 4.6% deviation from the others. The showers with ADC counts larger than 20 and less than 4095 (no saturation) and zenith angle less than 15° are selected. It is worth mentioning that the N_{max} distributions from the two different calibration methods are consistent (Fig. 10): except for the low efficiency region, the difference between the two calibration is 3.7% on average.

Finally, as an example, Figs. 11 and 12 show the effect of the calibration on an individual shower. They indicate that the calibration removes some false shower sub-cores and recovers a clean lateral structure of the shower.

6. Conclusions

The iso-gradient method results in a generally useful procedure to study the response difference of detectors in an air shower array. It is developed and applied to correct the response of the

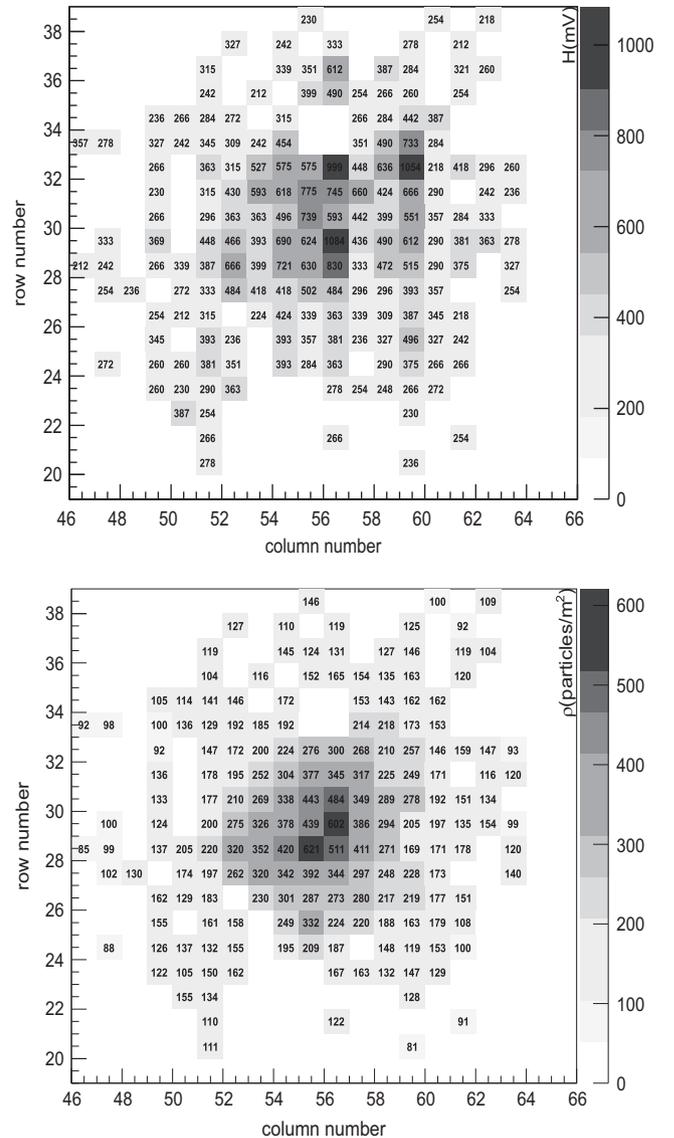


Fig. 11. Display of an experiment event. The BigPads with ADC count larger than 20 are selected. The x- and y-axes give column and row numbers of the BigPads, respectively. Upper: pulse heights (gray scale and values) after electronic calibration; Lower: density of particles (gray scale and values) after correcting for response difference.

RPCs in the ARGO-YBJ experiment. After the calibration, the response difference of the RPCs is 0.2%. The uncertainty due to the determination of the core position by the maximum number of particles is 0.85%. The dependence of the response difference correction on the range of pulse height is 10%. The variation of the response difference correction in 1 year has a mean value of 3.5%. After adding up these different contributions, the overall systematic uncertainty in the particle measurement by the RPCs is 10.7%. This method gives results consistent with those of a totally different approach also used in the experiment. The iso-gradient method can be also applied to other large surface array detectors for cosmic ray detection.

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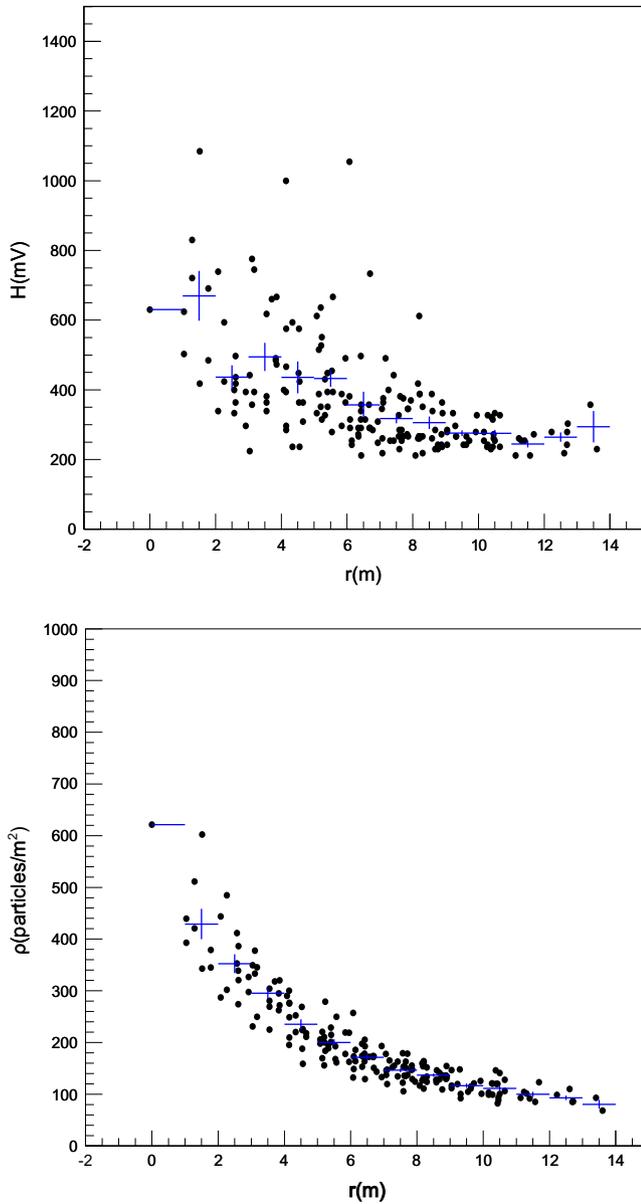


Fig. 12. Lateral distribution of the same event given in Fig. 11. The x-axis gives the distance from the shower core, the y-axis the pulse height after electronic calibration (upper) and the density of particles (lower) after correcting for response difference. The points correspond to values in the BigPads while the crosses to profiles.

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