

First results on the angular resolution of the ARGO-YBJ detector

G. Di Sciascio^a, D. Campana^a, N. Cheng^b, T. Di Girolamo^a, E. Rossi^a and X.D. Sheng^b
for the ARGO-YBJ Collaboration

(a) *INFN, sez. di Napoli and Dipartimento di Scienze Fisiche dell'Università, Napoli, Italy*

(b) *Cosmic Rays and High Energy Astrophysics Laboratory, IHEP, 100039 Beijing, China*

Presenter: G. Di Sciascio (giuseppe.disciascio@na.infn.it), ita-disciascio-G-abs1-he11-poster

A carpet of about 1900 m² of Resistive Plate Chambers (about 1/3 of the whole ARGO-YBJ detector) has been put in data taking at the Yangbajing High Altitude Cosmic Ray Laboratory (Tibet, P.R. China, 4300 m a.s.l.). We present the first results on the angular resolution. The comparison of experimental results with MC simulations is discussed.

1. Introduction

The ARGO-YBJ experiment at the YangBaJing Cosmic Ray Laboratory (Tibet, P.R. China, 4300 m a.s.l.), will be operating over the next years with the aim of studying cosmic rays, mainly cosmic γ -radiation, with an energy threshold of a few hundreds of GeV, by detecting small size air showers. The ARGO-YBJ apparatus will consist of a full coverage array of dimension $\sim 74 \times 78$ m² realized with a single layer of Resistive Plate Counters (RPCs), 280×125 cm² each. The area surrounding this central carpet, up to $\sim 110 \times 100$ m², will be partially ($\sim 50\%$) instrumented with RPCs. The basic detection unit is the Cluster, a set of 12 contiguous RPCs. A lead converter 0.5 cm thick will uniformly cover the detector. For a more detailed description of the experiment see [1].

The main features of the ARGO-YBJ experiment are: (1) time resolution ~ 1 ns; (2) space information from strips 6.7×62 cm² large; (3) time information from pads 56×62 cm² large. Due to the small size pixels the detector is able to image the shower profile with an unprecedented granularity.

Since December 2004 a carpet of about 1900 m² of RPCs (42 Clusters, $\sim 47 \times 41$ m², corresponding to about 1/3 of the whole central detector) has been put in stable data taking, yet without any converter sheet. In this paper we present the first results concerning the reconstruction of the shower direction. Moreover, criteria are investigated to identify showers with core outside the detector.

2. Estimation of the angular resolution

In a search for cosmic point γ -ray sources with ground-based arrays the main problem is the rejection of the background due to charged cosmic rays, therefore a good angular resolution (i.e., the accuracy in estimating the arrival direction) is necessary and the identification of a firm way to calibrate it is fundamental. The shadowing effect of cosmic rays from the direction of the Moon can be exploited to measure the angular resolution and obtain a straightforward calibration of the absolute energy scale of an array, without any Monte Carlo simulation, using the Earth's magnetic field as a magnetic spectrometer. However, a large sample of events is necessary to obtain a statistically significant result, since the dip in intensity is small.

At present we have to rely on some consistency arguments and MC calculations: (1) the even-odd method, which splits the detector into two parts and compares the two measured arrival directions; (2) the examination of the distribution of the arrival directions, which should be peaked at the zenith.

2.1 Reconstruction procedure of the shower direction

The usual method for the reconstruction of the shower direction is a χ^2 fit to the recorded arrival times t_i by minimization of $\chi^2 = \sum_i w(f - t_i)^2$, where the sum is over the fired pads. Usually the function f describes a plane, a cone with a fixed slope, or a plane with curvature corrections depending on the distance from the shower core and on the number of charged particles N_{ch} registered in the detector. The weights w are generally chosen to be an empirical function of N_{ch} . An improvement to this scheme can be achieved by excluding from the analysis the time values belonging to the non-gaussian tails of the arrival time distributions with successive χ^2 minimizations for each shower [2]. In this work we reconstructed the primary direction of the showers sampled by the present ARGO-YBJ carpet by means of the following iterative procedure:

a) Planar fit

In the first step we recover the shower direction cosines $\{l_p, m_p\}$ by means of a planar fit performed minimizing the function $\chi^2(ns^2) = \frac{1}{c^2} \sum_i w\{lx_i + my_i + nz_i + c(t_0 - t_i)\}^2$. The sum includes all pads with a time signal t_i , c is the velocity of light, $(x_i, y_i, z_i \equiv 0)$ are the coordinates of the centre of the i -th pad and the weights are the number of fired strips inside the i -th pad. The parameters of the fit are the time offset t_0 and the direction cosines l, m . After each minimization the time signals which deviate more than $K \cdot \sigma$ from the fitting function are excluded from further analysis and the fit is iterated until all times do not verify this condition or the reconstructed angle difference between consecutive fits is less than 0.1° . If the remaining hits number is ≤ 5 the event is discarded. Here σ is the standard deviation of the time distribution around the fitted plane (i.e., $\sigma = \sqrt{\frac{\chi^2}{N-3}}$).

b) Conical correction

With this first determination of the arrival direction $\{l_p, m_p\}$ we calculate the conical correction $\delta t_i = \frac{\alpha}{c} \cdot R_i$, where $R_i = \sqrt{(\Delta x_i^2 + \Delta y_i^2) - (\Delta x_i l_p + \Delta y_i m_p)^2}$ and $\Delta x_i = x_i - x_c$, $\Delta y_i = y_i - y_c$ are the pad distances from the shower core position $\{x_c, y_c\}$. Then we correct the experimental time values $t_i \rightarrow t'_i = t_i - \delta t_i(l_p, m_p)$. In this approach the slope parameter α is not a fit parameter but is fixed to a value that maximizes the angular resolution.

c) New planar fit

With the time values t'_i we reconstruct a new shower direction by means of a further planar fit.

A systematic study via MC simulations led us to the following best tuning of the reconstruction procedure for proton induced showers: $K = 1.5 - 2$ with the maximum number of iterations in the range 8 - 12. A further improvement of the angular resolution is obtained by fixing the slope of the successive conical correction to the value $\alpha = 0.03 \text{ ns/m}$.

2.2 Identification of showers with core outside the array

In order to obtain a good angular resolution it is crucial to select internal showers (i.e., events with core inside the detector) since the direction of the showers with core outside the detector in general is badly reconstructed due to the conical shape of the shower front and to the unknown core position. To find the optimal selection method we have to rely on MC calculations, thus we have simulated, via the Corsika/QGSJet code [3], proton induced showers with energy spectrum $\sim E^{-2.75}$ ranging from 400 GeV to 1 PeV. The detector response has been simulated via a GEANT3-based code. The core positions have been randomly sampled in an energy-dependent area large up to $800 \times 800 \text{ m}^2$, centred on the detector. For a detector as small as the present carpet a large fraction of the triggering showers have their core outside its boundaries. In order to select a sample of events with a small contamination from external EAS we consider showers as internal if they satisfy the following conditions: (1) the particle density of the inner 20 Clusters is higher than that of the outer ring; (2) the most fired Cluster is one of the 6 central Clusters; (3) at least one of the 6 central Clusters has a multiplicity

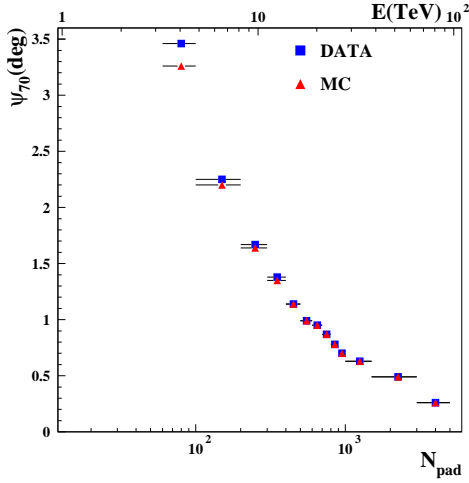


Figure 1. The opening angle ψ_{70} measured via the even-odd method on 42 Clusters as a function of pad multiplicity (squares) compared to the MC simulation (triangles).

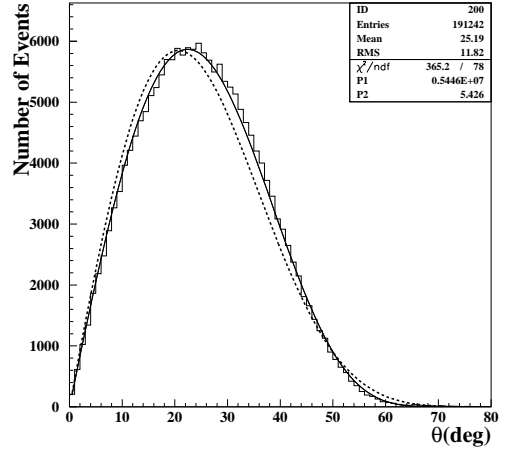


Figure 2. Measured zenith angle distribution for internal events. The "exponential" (solid line) and " $\cos^n \theta$ " (dashed line) best fits are also shown.

> 16 . We find that for a multiplicity threshold of 60 the resulting contamination by external events is $\sim 7\%$. The median energy of such internal events is ≈ 4 TeV. The shower core positions $\{x_c, y_c\}$ of the selected events are hence reconstructed by means of the Maximum Likelihood Method [4]. The analysis which follows refers to showers selected as internal with the above procedure and with a zenith angle $\theta < 40^\circ$.

2.3 Analysis with the even-odd method

In order to estimate the performance of the algorithms we used the ψ_{70} parameter, defined as the value in the angular distribution which contains 71.5 % of the events. In Fig.1 the opening angle ψ_{70} calculated via the even-odd method with data from 42 Clusters (squares) is compared, as a function of pad multiplicity N_{pad} (i.e., the sum of even and odd pads), to the MC simulation (triangles). The upper scale shows the estimated median energy of triggered events for the different multiplicity bins. The data have been collected with a so-called "Low Multiplicity Trigger", requiring at least 60 fired pads on the whole detector [1]. The relative time offset (due to differences in cable length etc.) among different pads has been estimated with the method described in [5]. In this analysis we used the core parameters deduced from information from the the full detector instead of using two separately fitted cores, one for each sub-array. As a consequence, the assumption of two independent measurements is not completely correct. As can be seen, there is a fine agreement of the simulated result with the experimental one. Fig.1 also shows that the angular resolution improves roughly proportionally to $1/\sqrt{N_{pad}}$.

However, a small angle between even and odd directions does not necessarily guarantee a good angular resolution. In fact, angular resolution studies with subarrays only give information on statistical errors and the resulting angle difference may be not related to the true angular resolution. Studies are in progress to investigate the systematic pointing error and to determine the angular resolution by observing a depletion of cosmic ray events due to the shadowing by the moon and the sun.

2.4 Analysis with the zenith angle distribution

In general, most of the showers should come from the zenith and this fact can be used to check if the estimated arrival direction has any systematic error, although we cannot state anything about the magnitude of the angular resolution. In Fig.2 the measured zenith angle distribution of internal events is shown. The best fit is provided by an $\exp(-n/\cos\theta)$ law, with $n = \gamma x_0/\lambda = 5.426 \pm 0.008$, where γ is the index of the primary energy spectrum and x_0 the observation depth. The resulting absorption mean free path of showers is $\lambda \approx 195 \text{ g/cm}^2$, consistent with the EAS measurements [6], and the barometric effect $\beta = \gamma/\lambda = -(\Delta n/\Delta x)/n \approx 0.9\% \text{ mbar}^{-1}$. The difference in fitting the angular distribution with an exponential (solid line of Fig.2) or with a $\cos^n\theta$, $n = 7.05 \pm 0.02$ (dashed line) function shows that the shape is dominated by the physical effect of atmospheric absorption. Distributions dominated by instrumental effects are better fitted with $\cos^n\theta$ behaviors [7]. The fitted curve reaches the maximum at zenith angle $\theta \approx 22^\circ$, while the average value is $\langle \theta \rangle = 25.19^\circ$. Only about 5 % of the showers have zenith angles larger than 45° . The direction distribution of recorded showers is centred around the zenith, and does not display features indicative of inaccurate timing.

The distributions of the direction cosines l and m both exhibit a Gaussian shape around the zenith suggesting that residual systematic timing shifts are negligible. Their peak positions, obtained by fitting a Gaussian curve around the zenith, are -0.002 ± 0.003 and 0.005 ± 0.003 , respectively.

In addition, assuming that the distribution of the shower axis projected zenith angles follows a $\cos^n\theta$ function, it is possible to calculate the value of n which would give the observed dispersion of the projected zenith angle. It can be shown that $D(\sin\theta_\perp) = 1/(n+2)$, where $D(\sin\theta_\perp)$ is the dispersion of the sine of the projected zenith angles [8]. From the measured dispersion ($D(\sin\theta_\perp) = 0.10$) we obtain $n \sim 7.8$, in good agreement with the results of the fitting of the differential zenith angle distribution.

3. Conclusions

Since December 2004 a carpet of about 1900 m^2 of RPCs (42 Clusters, corresponding to about 1/3 of the whole central detector) has been put in stable data taking. In this paper we presented first results on the capability of reconstructing the primary shower direction. We found a fine agreement between data and MC calculations, as well as a good consistency of all the investigated parameters with results of other EAS experiments. Because of this consistency, we are confident about our reconstruction algorithms. Studies are in progress to investigate the systematic pointing error and to determine the angular resolution.

References

- [1] Zhen Cao et al., "Status of the ARGO-YBJ experiment", these proceedings.
- [2] D. Campana, B. D'Ettorre Piazzoli and G. Di Sciascio, Nucl. Instr. and Meth. **A344** (1994) 250.
C. Bacci et al., Astrop. Phys. 17 (2002) 151.
- [3] D. Heck et al., Report **FZKA 6019** Forschungszentrum Karlsruhe (1998).
- [4] G. Di Sciascio et al., Proc. 28th ICRC, Tsukuba (2003) p. 3015.
- [5] P. Bernardini et al., "Time calibration of the ARGO-YBJ experiment", these proceedings.
- [6] M. Aglietta et al., Astrop. Phys. 10 (1999) 1.
- [7] G. Cocconi, Handbuch der Physik, Vol. XLVI/1 (1961) 215.
- [8] P. Bassi, G. Clark and B. Rossi, Phys. Rev. 92 (1953) 441.