Measurement of the angular resolution of the ARGO-YBJ detector

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Abstract: The ARGO-YBJ experiment is a full coverage EAS-array installed at the YangBaJing Cosmic Ray Laboratory (4300 m a.s.l., Tibet, P.R. China). We present the results on the angular resolution measured with different methods with the full central carpet. The comparison of experimental results with MC simulations is discussed.

Introduction

The ARGO-YBJ detector is constituted by a single layer of Resistive Plate Chambers (RPCs). This carpet has a modular structure, the basic unit is a cluster, composed by 12 RPCs (2.8×1.25 m^2 each). Each chamber is read by 80 strips, logically organized in 10 independent pads[1]. The central carpet, constituted by 10×13 clusters with $\sim 93\%$ of active area, is enclosed by a guard-ring partially instrumented ($\sim 40\%$) in order to improve rejection capability for external events. A lead converter 0.5 cm thick will uniformly cover the apparatus in order to improve the angular resolution. Since December 2004 the pointing accuracy of the detector has been studied, during the detector setting-up, with 3 different carpet areas: 42 clusters (ARGO-42, ~ 1900 m^2), 104 clusters (ARGO-104, ~ 4600 m^2) and the full central carpet, 130 clusters (ARGO-130, ~ 5800 m^2), yet without any converter sheet. The data have been collected with a so-called *"Low Multiplicity Trigger"*, requiring at least 20 fired pads on the whole detector.

Estimation of the angular resolution

Searching for cosmic γ-ray point sources with ground-based arrays the main problem is the rejection of the background of charged cosmic rays, therefore a good angular accuracy in estimating the arrival direction is necessary. The angular resolution has in general two components: a statistical one, due to fluctuations of the shower development and the detector noise, and a systematic error (i.e., the pointing error) arising from a possible misalignment of the detector, an asymmetry of the array geometry and some systematic bias induced in the shower reconstruction process (systematic error on core position determination, the change of EAS front conical slope with size, etc.). The standard method to estimate the statistical angular resolution of an EAS array is the so-called "Chessboard Method". The pointing error, instead, can be studied by observing the shadowing effect of cosmic rays from the Moon direction. Other systematic errors can be investigated by means of MC simulations comparing the true and reconstructed primary directions. In this paper we have studied the angular resolution of the increasing ARGO-YBJ detector with the following techniques: (1) chessboard method, which splits the detector into two parts and compares the two measured arrival directions; (2) MC simulation; (3) a preliminary study of the Moon shadow.

Event reconstruction

To find the optimal selection method we have to rely on MC calculations, thus we have simulated, via the Corsika/QGSJet code [2], proton-induced showers with particle spectrum $\propto E^{-2.78}$ ranging from 300 GeV to 1 PeV and a Crab-like spectrum $\propto E^{-2.49}$ for photons ranging from 300 GeV to 100 TeV. The detector response has been simulated
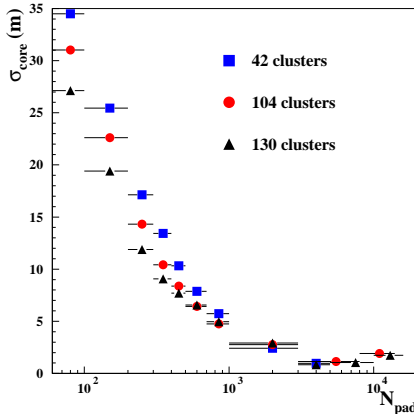
Figure 1: Shower core position resolution of internal selected protons as a function the pad multiplicity for different detector dimensions.

via a GEANT3-based code. The core positions have been randomly sampled in an energy-dependent area large up to $1000 \times 1000 \ m^2$, centred on the detector. For ARGO-130, showers are considered internal if they satisfy the following condition: the particle density in the inner 8×11 clusters is higher than that of the outer ring constituted by 42 clusters. The shower core positions of the selected events are hence reconstructed by means of the Maximum Likelihood Method: any core lying outside the detector edge is further rejected. In Fig.1 the shower core position resolution of internal selected protons is shown for ARGO-42, ARGO-104 and ARGO-130 detectors. The resolution worsens due to the detector saturation at very large shower sizes (the total pad number goes from 5040 for ARGO-42 to 15600 for ARGO-130). For details about the analysys with smaller carpets see [3]. From the figure it results that the core position is reconstructed with a resolution better than $2 \ m$ for $N_{pad} \geq 1000$ (median energy $E_p \sim 10 \ TeV$). The majority of the incorrectly accepted and rejected events are located near the carpets boundary, making the contamination less a concern, as the core of these events can still be located with small errors.

Analysis with the Chessboard Method
In this analysis the shower primary direction is

reconstructed by means of an iterative procedure, with a conical correction to the shower front fixed to the value $\alpha = 0.03$ ns/m, applied to events reconstructed inside the carpet area. The relative time offset (due to differences in cable length, etc.) among different pads has been estimated with the so called "Characteristic Plane Method"[4, 5]. The analysis presented in this paper refers to showers with a zenith angle $\theta < 15°$. About $\sim 10^7$ events have been selected and analyzed with the procedure described in the previous section. We require that the difference in the number of fired pads in both sub-arrays must be less than 10%. This guarantees that both reconstructions have a similar systematical and statistical error. In order to estimate the pointing accuracy of the detector we used the ψ_{72} parameter, a measure of the angular resolution defined as the value in the angular distribution which contains $\sim$72% of the events. This is a useful definition because, assuming that the Point Spread Function (PSF) for the entire detector is a Gaussian, it describes a solid angle which maximizes the signal/background ratio from a point source on an uniform background [6]. The rms projected angular resolution of the detector is given by the relation $\sigma_\theta \approx \psi_{72}/1.58$. In Fig.2 the opening angle ψ_{72} for ARGO-130 calculated via the chessboard method with data is compared, as a function of pad multiplicity N_{pad} (i.e., the sum of even and odd pads), to the MC simulation. As it can be seen from the plot, there is a satisfactory agreement of the simulated result with the experimental one. The ψ_{72} parameter improves roughly proportionally to $N_{pad}^{-0.7}$ for ARGO-42, ARGO-104 [3] and ARGO-130. In a shower flat temporal profile approximation, neglecting any dependence on the core position, one would expect, on a simple statistical basis, that ψ_{72} decreases as $N_{pad}^{-0.5}$. However, as the increased number of fired pads also means an increased shower size, and therefore an increased number of particles detected on the single pad, the intrinsic error in timing (due to the disc thickness and curvature) decreases, leading to a steeper than $N_{pad}^{-0.5}$ behaviour in the overall angle estimate.

Analysis with the MC simulation
The true shower direction of the MC events is known, therefore the angular resolution can be
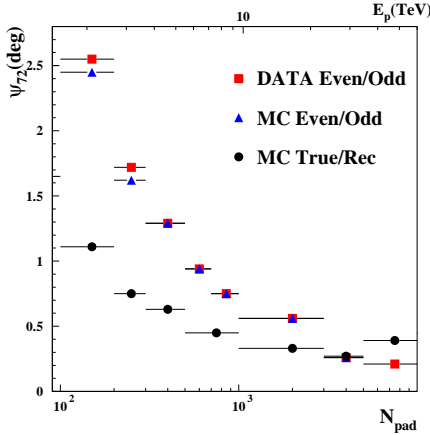
Figure 2: The opening angle ψ_{72} as a function of pad multiplicity measured with ARGO-130 compared with MC simulations. The upper scale shows the estimated median energy for proton-induced showers. The error bars refer to the width of the pad multiplicity bins.

computed directly from the differences $\Delta\theta_{true/rec}$ between true and reconstructed shower directions. In Fig.2 the filled circles refer to the parameter ψ_{72} calculated via MC simulations. The opening angle worsens due to the detector overflows at very large shower sizes (a behaviour similar to that of the shower core position resolution in Fig. 1). Unlike the chessboard method, the calculation of the angular resolution in this case is sensitive to the shower core position resolution and to the accuracy of the temporal profile description. As a consequence, these systematic errors can be limiting factors for $\Delta\theta_{true/rec}$. If the two sub-arrays are totally independent, the even-odd angular difference is expected to be approximately twice the angular resolution of the entire detector: $[\sigma_{true/rec}]/[\sigma_{eo}] \sim 0.5$ [8]. As it can be seen from Fig.2, this hypothesis is not correct: a dependence of the ratio $[(\psi_{72})_{true/rec}]/[(\psi_{72})_{eo}]$ on the total pad multiplicity is evident. This ratio varies from ~0.5 for very small showers to ~1 for large showers ($N_{pad} \sim$ few thousands). This is due to the effect of systematical errors which add quadratically to the statistical ones estimated by the chessboard method. At very low multiplicity the effect of the statistical errors is dominant

and $[(\psi_{72})_{true/rec}]/[(\psi_{72})_{eo}] \sim 0.5$. When this factor is about 0.7 the systematical and statistical errors are equivalent. As a consequence, we have calculated with a simulation the factor by which the measured angle $(\psi_{72})_{eo}$ must be multiplied to obtain the angular resolution. As an example, the *average statistical angular resolution* for the ARGO-130 detector measured with the chessboard method, up to $\approx$4000 fired pads ($E_p \sim 30\ TeV$), can be described by the following equation:

$$\sigma_{eo}(deg) = \frac{(\psi_{72})_{eo}}{1.58} \cdot [0.42 + 1.4 \cdot 10^{-4}\ N_{pad}].$$

Obviously, this measured angular resolution refers to proton-induced air showers. The angular resolution for photon-induced showers is slightly lower due to their better defined temporal profile at low multiplicities. The opening angle ψ_{72} as a function of pad multiplicity for protons and photons is compared in Fig. 3.

Another probable source of systematical error may be an inaccurate shower profile description. Indeed, as it is well known, the conical slope of the shower front lowers with increasing shower size. These systematical errors affect both directions reconstructed by the sub-arrays in the same way, tilting the result in the same direction. In view of making conservative estimates of the angular resolution for $N_{pad} \geq 4000$ we use the worse resolution, i.e. that determined via MC simulations: $\sigma \approx 0.2°$. The addition of a 0.5 cm lead sheet on top of the RPCs will lead to an improvement of the angular resolution by a factor of at least 30% for low pad multiplicity (below some hundreds fired pads)[7].

Analysis with the shadow of the Moon

The analysis of the deficit of cosmic rays from the direction of the Moon is a well known method to determine the angular resolution and the systematical pointing error of an EAS array based on the deficit profile and the peak shift from the Moon position. From July 2006 to February 2007 ARGO-130 observed the Moon for $\sim$558 h. A very preliminary analysis of the shadow of the Moon has been performed filling a 2-dimensional sky map around the Moon position [9]. The statistical significance of the deficit of cosmic ray events is $\approx$ 11σ for $N_{pad} >120$ ($E_p \approx 3$ TeV). We note that
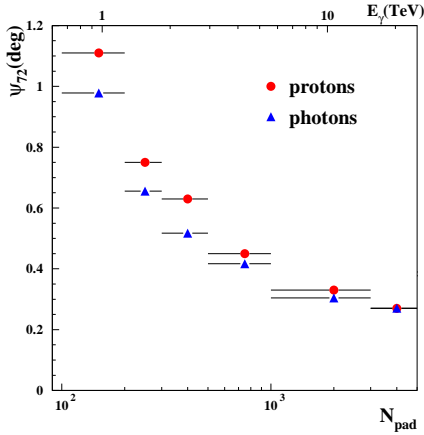
Figure 3: The opening angle ψ_{72} as a function of pad multiplicity for protons and photons. The error bars refer to the width of the pad multiplicity bins. The upper scale shows the estimated median energy for photon-induced events.
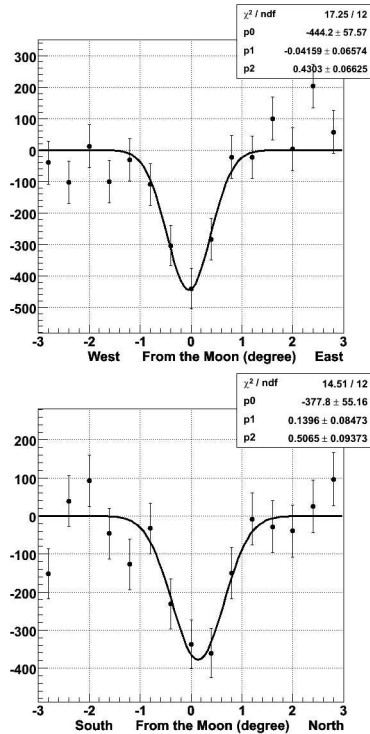

Figure 4: The distribution of observed deficit event number projected to the W-E and N-S axes.

the low energy threshold and the pointing accuracy of the detector lead to a Moon shadow detection in a very short observation time. As an example, in Fig. 4 the distribution of observed deficit event number projected to the W-E and N-S axes are shown. The events are selected with a pad multiplicity > 500 ($E_p \approx 5$ TeV) and with the core reconstructed inside the ARGO-130 boundaries. The projections are fitted with a Gaussian function with $\sigma_{W-E} = 0.43°$, $\sigma_{N-S} = 0.51°$, consistent with MC calculations. A residual systematic pointing error of about $0.14°$ is visible in N-S direction.

Conclusions

Since December 2004 increasing fractions of ARGO-YBJ detector have been put in data taking even with a reduced duty-cycle due to installation and debugging operations. In this paper we presented a measurement of the pointing accuracy of the ARGO-130 detector. The capability of reconstructing the primary shower direction has been investigated with the chessboard method and with a preliminary Moon shadow analysis. Studies are in progress in order to determine the final angular resolution.

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