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Observation of the Moon shadow using a new reconstruction technique in the CLUE experiment(*)

B. Bartoli(3), D. Bastieri(4), C. Bigongiari(4), R. Biral(5)
M. A. Ciocci(6)(**), M. Cresti(4), V. Dokoutchaeva(1), D. Kartashov(1)
F. Liello(8), N. Malakhov(1), M. Mariotti(4), G. Marsella(2), A. Menzione(1)
R. Paoletti(6), L. Peruzzo(4), A. Piccioli(6), R. Pegna(5), F. Rosso(5)
A. Saggion(4), G. Sartori(4), C. Sbarra(4), A. Scribano(6), E. Smogailov(1)
A. Stamerra(7) and N. Turini(6)

(1) *INFN - Sezione di Pisa, Italy*
(2) *Dipartimento di Fisica, Università di Lecce and INFN - Sezione di Lecce, Italy*
(3) *Dipartimento di Fisica, Università di Napoli and INFN - Sezione di Napoli, Italy*
(4) *Dipartimento di Fisica, Università di Padova and INFN - Sezione di Padova, Italy*
(5) *Dipartimento di Fisica, Università di Pisa and INFN - Sezione di Pisa, Italy*
(6) *Dipartimento di Fisica, Università di Siena and INFN - Sezione di Pisa, Italy*
(7) *Dipartimento di Fisica, Università di Torino and INFN - Sezione di Torino, Italy*
(8) *Dipartimento di Fisica, Università di Trieste and INFN - Sezione di Trieste, Italy*

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Summary. — The CLUE experiment, located in La Palma island at 2200 m a.s.l., is an array of 3×3 telescope, detecting the UV (190–230 nm) Čerenkov light produced by atmospheric showers. Due to the higher atmospheric absorption in the UV range than in the visible one, CLUE cannot apply existing algorithms normally used in IACT experiments to determine primary cosmic ray direction. In this paper we present a new method developed by CLUE. The algorithm performances were evaluated using simulated showers. CLUE experiment collected data in the last two years pointing to AGN sources and to Moon. The preliminary results obtained using the new technique on *Crab Nebula* and on *Markarian 421* were presented in a previous paper. Here, we present the preliminary observation of *Moon Shadow* employing the new method. As described in the paper, we expect in a near future improvements on AGN sources and on *Moon Shadow* measurement.

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(**) E-mail: ciocci@pi.infn.it

1. – Introduction

In the past, CLUE [1, 2] used a maximum likelihood method approach [3] to determine primary cosmic ray direction comparing observed distributions of Čerenkov photons detected with simulated ones. The best angular resolution ($\Delta\alpha$ or $\Delta\beta$, see sect. **2** for α- and β-angles definition) on shower y direction was 0.8° for energy $E > 2$ TeV and the reconstructed angle was affected by a large systematic error for off-axis showers (1° systematic error for showers with 2° off-axis angle). Recently CLUE developed a new reconstruction algorithm, called Thrust, adapting a method [4] widely used in accelerator physics experiments to determine particle jet direction and collimation.

2. – Thrust method

The Thrust method relies on shower symmetry properties, assuming that the momentum of Čerenkov photons is distributed with axial symmetry around the primary direction. This method determines the shower direction estimating the versor which maximizes the overall longitudinal momentum of photons. Experimentally, an UV photon direction is associated, through a proper backtracking onto the parabolic mirror, to each charge cluster found in the CLUE chambers. We introduce a versor $\hat{n}_{\mathrm{T}}$, called *Thrust axis*, and a scalar T, called *Thrust*, defined by

$$T = \frac{\sum_{k=1}^{N_{\mathrm{c}}} Q_k \mid \hat{r}_k \cdot \hat{n}_{\mathrm{T}} \mid}{\sum_{k=1}^{N_{\mathrm{c}}} Q_k}\,, \tag{1}$$

where N_{c} is the number of charge clusters, $\hat{r}_k$ is the direction versor associated to the k-th cluster and Q_k its charge. The direction versor components of each UV photon are given by

$$\begin{cases} r_k^x = \alpha_k = \dfrac{X_k}{F}\,, \\ r_k^y = \beta_k = \dfrac{Y_k}{F}\,, \\ r_k^z = \gamma_k = \sqrt{1 - {\alpha_k}^2 - {\beta_k}^2}\,, \end{cases}$$

where X_k and Y_k are the k-th cluster centroid coordinates and F is the mirror focal length. The $\hat{n}_{\mathrm{T}}$ which maximizes T is the Thrust estimate of the shower axis (primary cosmic ray direction).

The *Thrust axis* could be expressed as a function of zenith (θ) and azimuth (ϕ) angles:

$$\hat{n}_{\mathrm{T}} = (\alpha, \beta, \gamma) = (\sin(\theta)\cos(\phi), \sin(\theta)\sin(\phi), \cos(\theta))\,. \tag{2}$$

Since our detector acceptance in α (or β) is ± 4°, $\theta \simeq \sqrt{\alpha^2 + \beta^2}$.

3. – Test and performances

The method has been applied and tested on simulated showers samples after the full detector simulation.

The MC showers were generated everywhere with an energy between 1 and 10 TeV, sampled according to primary cosmic ray spectrum (spectral index −2.7).

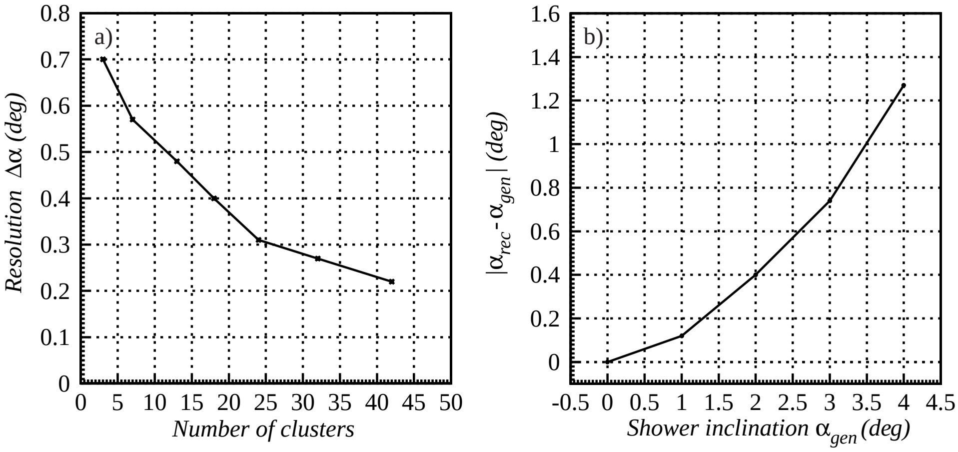

Fig. 1. – a) Vertical showers with impact point in the CLUE array center simulation: angular resolution on the reconstructed α-angle *vs.* the number of clusters in the event. b) Showers with fixed impact point simulation: systematic on the reconstructed α-angle ($\alpha_{\rm gen} - \alpha_{\rm rec}$) *vs.* α-angle ($\alpha_{\rm gen}$).

3·1. *Fixed shower impact point.* – Firstly we evaluated the performances of this new method with respect to the old one, using proton and γ shower samples (11000 showers) where both samples were generated using CORSIKA [5] with a zenith angle between 0° and 4° (mirror axes are assumed vertical) and the shower impact point was fixed in the CLUE array center. The α and β angular resolution for vertical showers is 0.7° with the minimum requirement of three clusters (trigger request) and it improves increasing the number of clusters, as expected (see fig. 1a as an example). The previous method

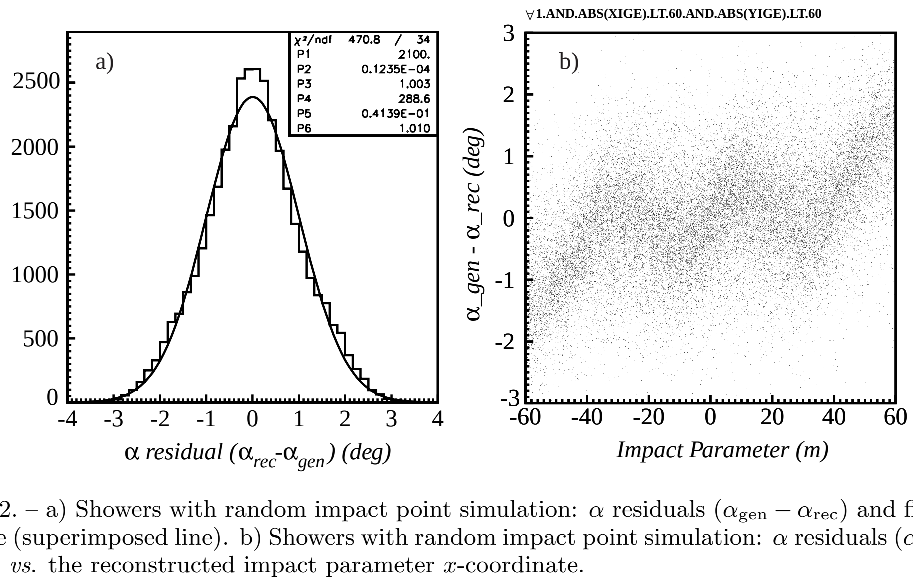

Fig. 2. – a) Showers with random impact point simulation: α residuals ($\alpha_{\rm gen} - \alpha_{\rm rec}$) and fitting curve (superimposed line). b) Showers with random impact point simulation: α residuals ($\alpha_{\rm gen} - \alpha_{\rm rec}$) *vs.* the reconstructed impact parameter x-coordinate.

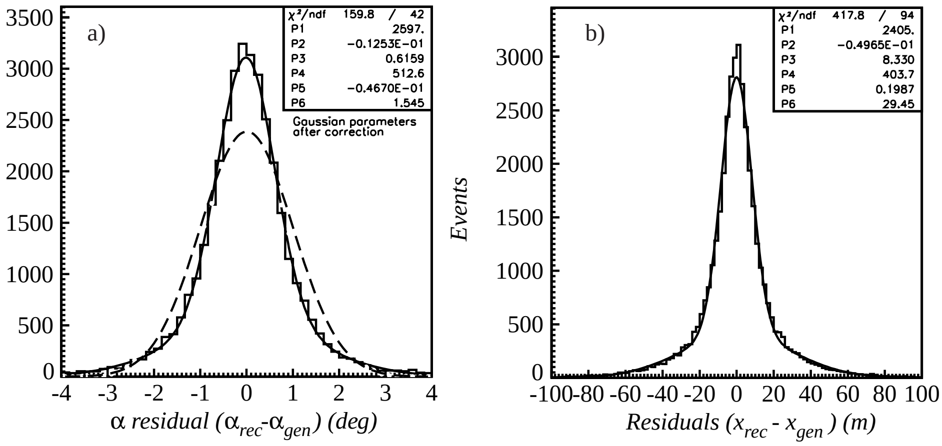

Fig. 3. – a) Showers with random impact point simulation: α-angle residuals after corrections and corresponding fitting curve after (continuous line) and before corrections (dashed line). b) Showers with random impact point simulation: impact parameter x-coordinate resolution.

gave a resolution of 0.8° with nine clusters to be compared with the actual one of 0.5°. Furthermore, the Thrust angle α([1]) is affected by a systematic error for off-axis showers with a much weaker dependence on off-axis angle (see fig. 1b) than the old likelihood method: only 0.4° for showers with 2° off-axis angle. Those improved results were found for showers originated both by protons and gammas.

3˙2. *Random shower impact point.* – To evaluate effects due to the impact parameter, we generated vertical showers with impact point randomized on a 300 m $\times$ 300 m square centered on the array center (250000 samples) using HDS [6]. From simulation, the trigger request selects only events impinging on a square of 120 m $\times$ 120 m.

In that case, the resolution on α (β) is worse (fig. 2a) than the previous one (fig. 1a). But we have found a clear correlation between α (β) residuals and the $x(y)$ coordinate of the reconstructed impact point (fig. 2b). Using the correlation, we can apply a correction on the measured Thrust angles (α and β): a big improvement on the Thrust angular resolution on the non-zero impact parameter showers is obtained (fig. 3a). The impact point coordinates of a shower were measured using a standard technique employed in high energy physics to measure particle lifetime. In fig. 3b are shown, as an example, the residuals for the reconstructed impact parameter x-coordinate([2]).

4. – The Moon shadow

The data collection periods and their details are resumed in table I. Before employing the reconstruction strategy outlined in sect. **2**, on the data was applied the standard clean-up [3] to remove odd behaviours caused by electronic noise and faults during data collection. The offline analysis is applied to all events that triggered with at least three clusters. We obtained for the Moon data a list of primary directions properly rotated

([1]) A very similar result is obtained for the β-angle.
([2]) We obtain the same result for the y-coordinate.

TABLE I. – *Data acquisition information about used data.*

	DAQ period	Entries	Time
Moon	May 98–May 2000	141500	157 h

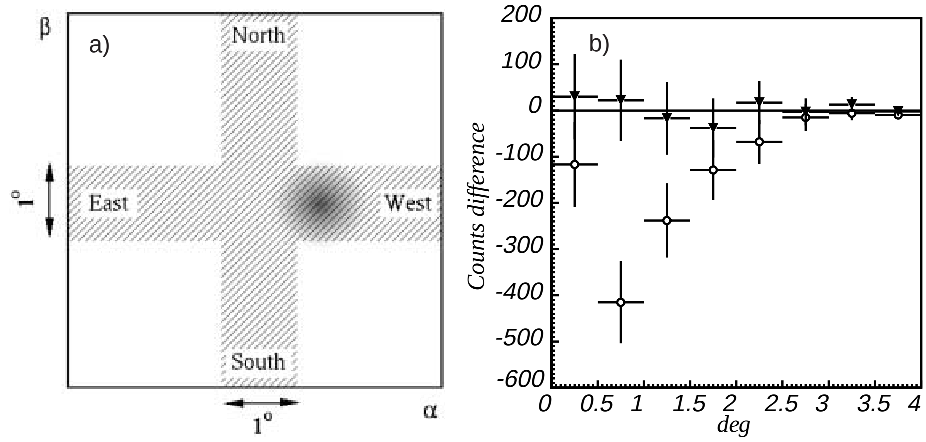

Fig. 4. – *Moon shadow*: a) Picture of the expected *Moon dip*. b) Counts difference between *West* and *East* (empty circles) where signal is expected and *North-South* (black triangles) where no signal is expected.

in a such a way to have the proton shadow fixed along the α-axis in the negative side. Given the asymmetry due to the presence of the Moon dip, we then procedeed taking two slices of the histogram of β *vs.* α (see fig. 4a) 1° wide around the direction axis α and β, respectively. The Moon dip lies along the α-axis in the positive side (the *West* of the sky) so it must be evidenced in the difference between the corresponding *Western* and *Eastern* bin contents of the slice [8]. The experimental result for that difference is shown in fig. 4b (empty circles). In the same figure is reported also the corresponding bin contents difference between the positive and negative side along the β-axis (black triangles) where we expect no signal. The error bars reported are the statistical ones. The *Moon shadow* effect is clearly visible (fig. 4b), even if no correction for non-zero shower impact parameter was applied. If the observed asymmetry is entirely due to the *Moon shadow*, then the energy threshold of the CLUE detector should be around one TeV.

5. – Conclusion

The Thrust method was applied succesfully on a sample of the data collected tracking the Moon. A clear signal of the *Moon shadow* has been observed 1° displaced in the *West* side with respect to the *Moon position* and in a near future, we will apply also the correction for non-zero shower impact parameter on the data collected. About the latter, we hope that improving our detector angular resolution we should be able to set an upper limit on the relative abundance in cosmic rays of antiprotons in the TeV range.

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