

Observation of Horizontal Air Showers with ARGO-YBJ

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Abstract: The understanding of Cosmic Rays (CRs) origin at any energy is made difficult by the poor knowledge of the elemental composition of the radiation. Inclined showers ($\theta > 60^\circ$) induced by very high-energy CRs are mainly produced by secondary muons, in contrast to the vertical ones dominated by photons and electrons stemming from π^0 decays. Measurements of the CRs rate at different zenith angles give information on the relative number of muons in a shower, which is dependent on the CR elemental composition, thus providing an important tool to probe the CR mass distribution but also the hadronic interaction models. In this paper a study of the non-attenuated shower component at a zenith angle $\theta > 60^\circ$, through the observation of the so-called horizontal air showers by the ARGO-YBJ experiment, is presented. More than 10^7 well-contained horizontal events have been analyzed to study the production and interaction of high energy CR muons and neutrinos.

Keywords: ARGO-YBJ, Horizontal Air Showers, Cosmic Rays, Muons.

1 Introduction

The CR flux is a steeply falling function of zenith angle because the depth of atmosphere traversed by a shower reaching the sea level rises rapidly from 1030 to about 36000 g/cm^{-2} as the zenith angle varies from zero to 90° . Thus near the horizon the interaction point is separated by about 1000 radiation lengths of matter from the detector. Most secondaries such as electrons, pions and kaons are absorbed in the dump and only penetrating particles, such as muons and neutrinos produced in the initial interaction, are able to reach the detector. Therefore, to CRs incident near the horizon the Earth's atmosphere represents a beam dump.

The observation of extensive air showers in nearly horizontal directions provides a "well shielded laboratory" for the detection of penetrating particles: high energy muons, cosmic neutrinos, possible weakly interacting particles produced in the decays of cosmological superheavy particles, will leave a clear signature in this dump.

Measurements of the CRs rate at different zenith angles give information on the relative number of muons in a shower, which is dependent on the CR elemental composition, thus providing an important tool to probe the CR mass distribution [1]. Hadronic interaction models do not reproduce correctly the number of muons in EAS therefore, the study of HAS is useful to investigate the characteristics of muons production and interaction. In addition, for very high energy interactions the decay of charm particles is the dominant source of high energy secondary muons. So counting high energy muons at large zenith angles determines the charm cross section [2, 3, 4]. There is no background from the semi-leptonic decay of pions and kaons which, as a result of time dilation, interact and lose energy rather than decay into high energy muons.

The detection of extensive air showers at large atmospheric zenith angles (Horizontal Air Showers, HAS) has been firstly reported in 1965 at an energy above 10^{14} eV [5]. In the seventies their origin has been studied by Bohm and Nagano [6], but their interpretation was not straightforward, due to the contradiction between the expected and detected muon contents [7]. The EAS-TOP experiment s-

tudied in detail the phenomenology of HAS, finding that they are mainly due to muon-dominated showers produced by UHE cosmic rays interacting at very large distance in the atmosphere [8]. In the last years a big effort has been made to study in detail the phenomenology of these events with accurate MC simulations (see, e.g., [9, 10, 11, 12]).

HAS are believed to be mainly due to the atmospheric muons and their interactions, as an example:

- (a) high energy single muons can interact through bremsstrahlung, pair production or deep inelastic scattering and initiate showers at the depth appropriate for detection. Such showers are essentially electromagnetic, since the remnant muons from the initial shower are dispersed over a very large area.
- (b) Ultra high energy CRs interacting at the top of the atmosphere, at very large zenith angles, produce a "large" amount of muons through the pion decays (favoured, at large angles, with respect to pion interactions due to the low atmospheric density at the interaction altitude). Such showers are therefore composed essentially of muons since the electromagnetic component is completely absorbed.

Neutrino induced showers have some intermediate typology, being more similar to conventional CR air showers or to events (a), when a large amount of their energy is transferred to the electromagnetic cascade. EAS arrays must have the capability of discriminating between the different typologies of events through μ/e identification. Therefore, the study of HAS is a possible tool for UHE cosmic neutrinos measurement [13].

The main experimental requirement for such studies is a good angular resolution in order to reject the background provided by mis-reconstructed conventional CR showers at smaller zenith angles. The ARGO-YBJ experiment is well suited for this analysis due to its good angular resolution and high segmentation of the read-out.

In this paper a study of EAS reconstructed by ARGO-YBJ with zenith angle greater than 60° is reported.

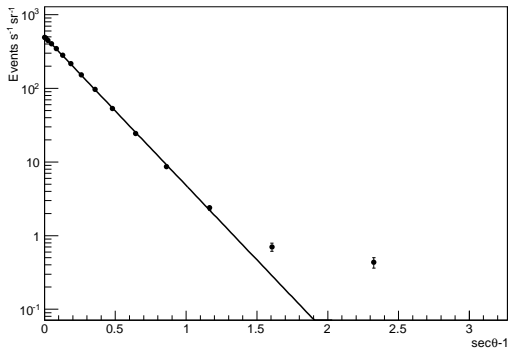


Fig. 1: The zenith angle distribution of EAS measured with ARGO-YBJ. The best fit out to $\sim 60^\circ$ is also shown.

2 The ARGO-YBJ experiment

The ARGO-YBJ experiment, located at the YangBaJing Cosmic Ray Laboratory (Tibet, P.R. China, 4300 m a.s.l., 606 g/cm²), is an air shower array able to detect the cosmic radiation with an energy threshold of a few hundred GeV.

The detector is made of a central carpet $\sim 74 \times 78$ m², made of a single layer of Resistive Plate Chambers (RPCs) with $\sim 93\%$ of active area, enclosed by a partially instrumented guard ring ($\sim 20\%$) up to $\sim 100 \times 110$ m². The apparatus has a modular structure, the basic data-acquisition sector being a cluster (5.7×7.6 m²), made of 12 RPCs (2.85×1.23 m² each). Each chamber is read by 80 external strips of 6.75×61.8 cm² (the spatial pixel), logically organized in 10 independent pads of 55.6×61.8 cm² which represent the time pixel of the detector. The read-out of 18360 pads and 146880 strips are the experimental output of the detector.

The detector, in smooth data taking since July 2006 with the central carpet, was stably taking data with the full apparatus of 153 clusters from November 2007 to February 2013, with a duty cycle $\geq 85\%$. The trigger rate is ~ 3.5 kHz with a dead time of 4%. The detector characteristics are described in [14, 15, 16].

Details on the analysis procedure (e.g., reconstruction algorithms, data selection, background evaluation, systematic errors) are discussed in [17, 18]. The performance (angular resolution, pointing accuracy, energy scale calibration) and the operation stability are monitored on a monthly basis by observing the Moon shadow, i.e., the deficit of CR detected in its direction [18]. The last results obtained by ARGO-YBJ are summarized in [19].

In this analysis showers with the reconstructed core inside a fiducial area 40×40 m² centered on the central carpet have been used. The maximum zenith angle of HAS is 85° .

3 Results

At zenith angles $\theta > 60^\circ$ an excess of events is observed above the rate of EAS as expected from the exponential attenuation (with $\Lambda_{EAS} \approx 220$ g/cm²) of the air shower electromagnetic component in the large atmospheric depth (see Fig. 1), which implies a decrease of the EAS counting rate with $\Lambda_c \approx 130$ g/cm².

The physical nature of these showers with an anomalous arrival direction is confirmed by the absence of events from

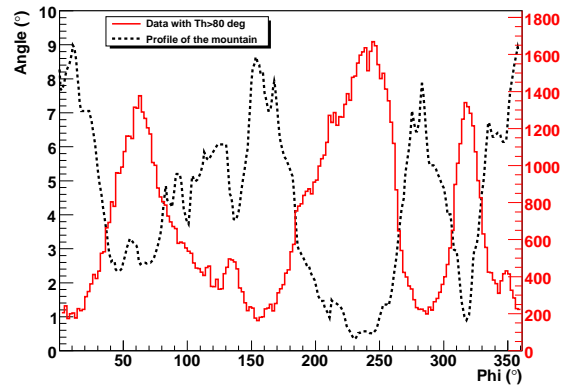


Fig. 2: Azimuthal distribution of showers with a reconstructed zenith angle $> 80^\circ$ (red dashed line) compared to the mountain profile around the ARGO-YBJ detector (black continuous line). The right vertical axis shows the number of events.

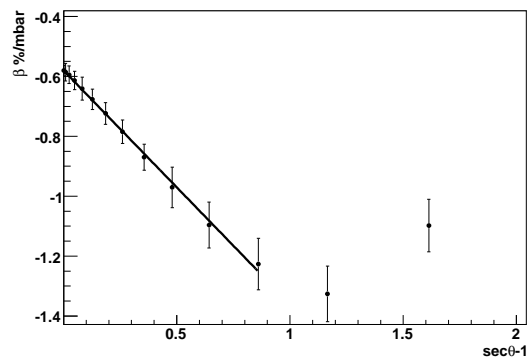


Fig. 3: The barometric coefficient for different zenith angles as measured by ARGO-YBJ.

the direction of the sky shaded by the mountains around the ARGO-YBJ detector, as can be seen in the Fig. 2 where the shower rate as a function of the reconstructed azimuthal angle is compared to the shadow angle due to the surrounding mountains. The expected anti-correlation is clearly visible and the mountain profile is reproduced quite well.

Moreover, the dependence of the barometric effect on the zenith angle, shown in Fig. 3, clearly shows a deviation from the $\sec\theta$ behaviour for $\sec\theta > 2$. In fact, the barometric coefficient $\beta = \frac{1}{n} \frac{dn}{dx}$ ($n =$ counting rate, $x =$ atmospheric pressure) is related to the zenith angle as: $\beta(\theta) = \beta(0^\circ) \sec\theta$. This can be explained by the presence of a "non-attenuated" EAS component that dominates for angles larger than 70° .

Finally, the physical nature of the HAS observed by ARGO-YBJ is demonstrated by the observation of the Moon shadow. In Fig. 4 the significance map of the Moon region observed at a zenith angle $\theta > 60^\circ$ is shown. It contains all the events collected by ARGO-YBJ in 5-years data taking with bin $N > 60$ fired strips on the central carpet. The significance of the maximum deficit is about 5 s.d.. We stress that this is the first time that an air shower array is able to detect the Moon shadow mainly due to muon-

Moon: 2007 - 2011, theta 60 DEG, CUT = 0, N_{STRNF} > 60

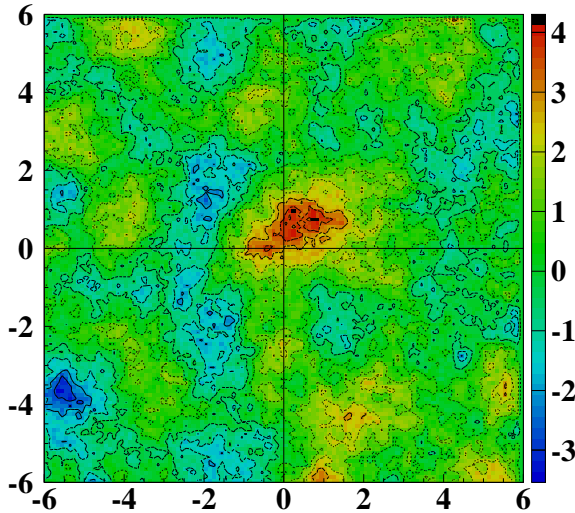


Fig. 4: Moon shadow significance map. The event multiplicity is $N > 60$ and the zenith angle is $\theta > 60^\circ$. The color scale gives the statistical significance in standard deviations.

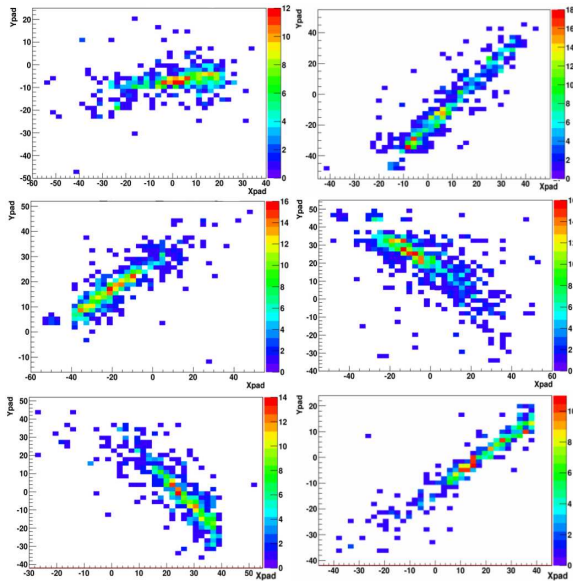


Fig. 5: Events observed by ARGO-YBJ with a reconstructed zenith angle $\theta > 70^\circ$. Only showers with more than 500 fired strips on the central carpet are shown. The pixels represent 4×4 pads (about $2 \times 2 \text{ m}^2$). The color scale refers to the number of particles per pixel.

induced showers in horizontal events. This result makes us confident about the angular resolution and the selection procedure of inclined showers.

Due to the small ARGO-YBJ effective area at large zenith angles, we expect that the observed HAS are due to high energy single muons which interact through bremsstrahlung (which dominate 10:1) or deep inelastic scattering and initiate showers at the appropriate depth (few hundreds g/cm^2 above the detector) for detection, as shown in Fig. 5 where some typical events observed by ARGO-YBJ are displayed. The characteristic elliptical shape of the

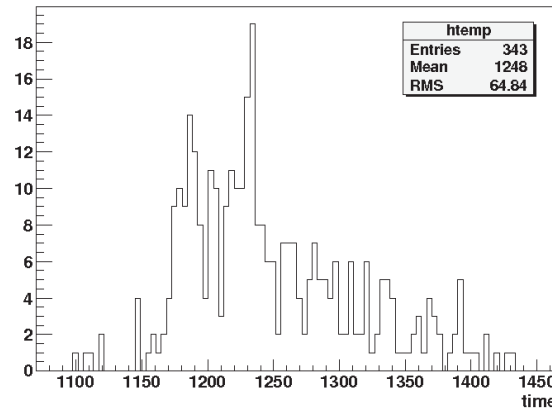


Fig. 6: Time distribution in ns of a HAS shower detected by ARGO-YBJ at a zenith angle of about 82° .

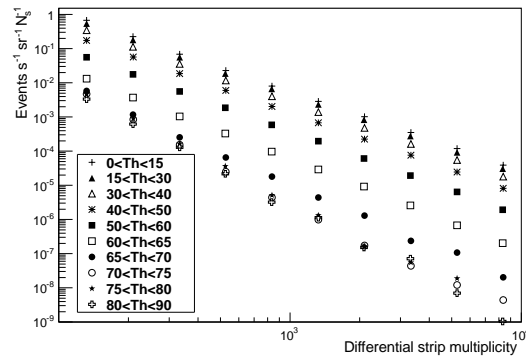


Fig. 7: Differential strip spectra measured by ARGO-YBJ for different zenith angles.

showers, well contained in the central carpet, is clearly visible. Such showers are essentially electromagnetic, since the remnant muons from the initial showers are dispersed over a very large area.

A typical HAS time distribution is shown in Fig. 6. The shower has been detected by ARGO-YBJ at an angle of about 82° . A particle (muon or neutrino) with $\theta > 70^\circ$ interacting deep will present a young shower front. At the ground level, young showers induce signals spread in time over hundreds of nanoseconds in the pads fired by the shower particles, while old showers induce narrow signals spreading over typically tens of nanoseconds,

In Fig. 7 the shower rate measured by ARGO-YBJ is shown, as a function of the fired strips number, for different primary zenith angles. The spectra soften with increasing angle up to about 70° , as can be appreciated in Fig. 8 where the best-fit spectral indices are plotted. In the zenith angle region $50^\circ - 70^\circ$ a quick transition to a value of about -3.6, characteristic of the EAS muon component, is observed.

The rate of HAS measured by ARGO-YBJ in the zenith angle interval $[70^\circ - 75^\circ]$, in which there are no shadow effects due to the surroundings mountains, is compared to expectations in Fig. 9. In this preliminary calculation we have simulated showers induced by muons with the energy spectrum measured by Allkofer and collaborators in 1979 at 75° [20]. The standard errors associated to the counting rates at different muon energies is few percent. In

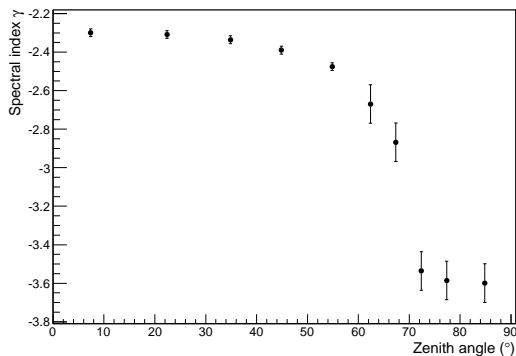


Fig. 8: Best-fit spectral indices calculated for the spectra of Fig. 7.

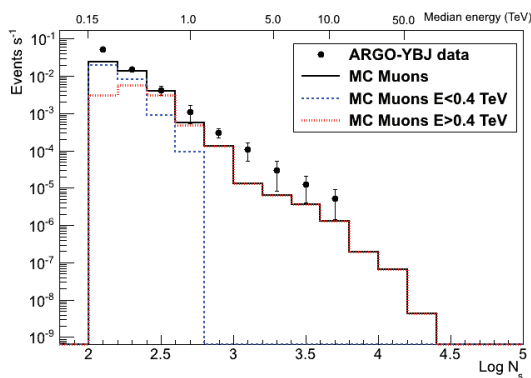


Fig. 9: Comparison between HAS rate measured by ARGO-YBJ and MC expectations for $70^\circ < \theta < 75^\circ$. The upper scale shows the corresponding muon median energy.

the figure the contribution due to muons with energy below and above 400 GeV is separately shown. The spectra have been normalized to study the slope.

Detailed simulations to reproduce the absolute flux are under way, nevertheless, the fair agreement with the expected spectral index makes us confident that the bulk of HAS observed by ARGO-YBJ are due to muon-induced showers.

4 Conclusions

The study of HAS has been long recognized as a useful tool to investigate the interactions of high energy muons and to detect ultra high energy neutrinos.

In this paper the largest sample of HAS never recorded by an EAS array has been analyzed to demonstrate the physical origin of showers with an anomalous arrival direction distribution above 60° . The high segmentation of the ARGO-YBJ readout allows to study with unprecedented detail the space-time characteristics of HAS. For the first time the shower beam dump in the Earth's atmosphere is clearly observed studying the size spectrum as a function of the zenith angle.

The Moon shadow is observed for the first time with showers above 60° demonstrating the capability of the ARGO-YBJ detector in reconstructing HAS.

Further studies are under way to discriminate and select

HAS induced by neutrinos. A preliminary analysis of a possible emission of neutrinos from GRB with ARGO-YBJ is described in [13].

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