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ARGO-YBJ: Status and First Results

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Very high energy gamma ray astronomy is one of the scientific goals of the ARGO-YBJ experiment. The detector, which is located in Tibet (China) at 4300 m a.s.l., is a full coverage Extensive Air Shower array consisting of a carpet of Resistive Plate Chambers (RPCs) of about $7000\,\mathrm{m}^2$. The high altitude and the full coverage ensure a very low energy threshold (few hundreds of GeV for primary photons), while the detector time resolution ($\sigma_t \simeq 1\,\mathrm{ns}$) gives a good pointing accuracy, thus allowing a high sensitivity to γ-ray sources, with a field of view of more than 2 sr and a duty cycle close to 100%.

The detector layout, performance and location, offer a unique possibility to make also a deep study of several characteristics of the hadronic component of the cosmic ray flux up to energies of several hundreds of TeV. In particular, the topological structure of the shower, the lateral distribution, the energy spectrum and the space and time flux modulations can be measured with high sensitivity. Moreover, the use of a full coverage detector with a high space granularity gives detailed images of the shower front, that can be used to test different hypotheses on the cosmic ray interaction model, the shower development in the atmosphere and particle physics at very high energies.

In this work the general layout of the detector and its performance will be described, together with the first results coming from the analysis of a data sample collected with a relevant fraction of the apparatus that is already in continuous data taking.

1. The ARGO-YBJ experiment: detector layout and operation

The ARGO-YBJ experiment is the result of a collaboration between Italian and Chinese institutions, aiming at the study of several characheristics of the high energy cosmic radiation with a full coverage extensive air shower array [1]. The laboratory is located near Lhasa in the Tibet region (People's Republic of China) at an altitude of 4300 m above sea level, corresponding to an atmospheric depth of about $600\,\mathrm{g/cm}^2$. The detector, extensively described in [1], is logically divided into 154 units called *clusters* ($7.64 \times 5.72\,\mathrm{m}^2$) each made by 12 Resistive Plate Chambers (RPCs) operated in streamer mode with a mixture of argon (15%), isobutane (10%) and tetrafluoroethane (75%), and read out by a single Local Station. As shown in Fig.1, each RPC ($1.26 \times 2.85\,\mathrm{m}^2$) is read out by using 10 pads ($62 \times 56\,\mathrm{cm}^2$), which are further divided into 8 different strips ($62 \times 7\,\mathrm{cm}^2$) providing a larger particle counting dynamic range [2]. The FAST-OR of the signals coming from all the strips of a given pad are sent to the same channel of a multihit TDC. The whole system is designed in order to provide a single hit (pad) time resolution at the level of 1 ns, which allows a complete and detailed three-dimensional reconstruction of the shower front, determining also the incoming direction of the primary particle. Finally a 0.5 cm thick lead converter will uniformly cover the detector in order to reduce the time fluctuactions of the detected shower particles and then to further improve the angular resolution [1].

Data gathered with ARGO-YBJ will allow to face with a wide range of fundamental issues. These include:

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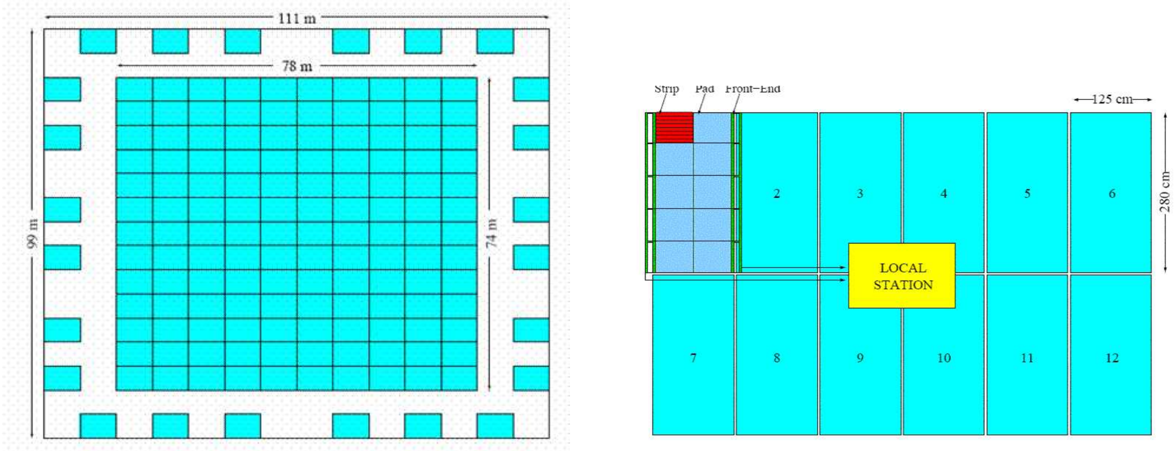

Figure 1. *Left side (a): Layout of the 154 RPC clusters for the full ARGO-YBJ configuration. Right side (b): The structure of a single RPC cluster. Also shown is the layout of pads and strips in a given RPC (see text).*

- Hadronic Cosmic Ray (hereafter CR) physics between about 1 TeV and 1000 TeV: measurement of the primary energy spectrum, mass composition, antiproton/proton ratio, hadron-air cross section , etc.;

- γ-ray astronomy between few hundreds of GeV and few tens of TeV:
search for point or diffuse (galactic and extra-galactic) sources, with a field of view of more than 2 sr and a duty cycle close to 100%;

- Gamma Ray Burst (GRB) physics:
extending the satellite measurements over the GeV-TeV energy range;

- Sun and Heliosphere physics ($E > 10$ GeV): looking for CR modulations, Forbush decreases, monitoring the interplanetary magnetic field and observing flares of high energy photons and neutrons from the Sun.

Two different operation modes have been designed for the data acquisition: the *shower mode* and the *scaler mode*. In the first one, the trigger requires a minimum pad multiplicity on the central carpet, with a space/time pattern consistent with the one expected from a shower front [3]. In the *scaler mode* the pad rate is measured from each cluster, with an integration time of 0.5 s (see Sec.2.3 for further details). This last DAQ mode is devoted to the apparatus monitoring and the detection of unexpected variations in CR flux, as an effect of GRBs, or solar activity [4]. The RPC operation is also successfully monitored by a Detector Control System (DCS), able to record HV, currents, temperature, humidity, pressure and gas flow [5].

From November 2003 to December 2004, 16 clusters have been operated for a complete and successful data taking test. Afterward, from December 2004 to July 2005, 42 clusters have been in data taking for more than 2140 hours. In this period about $2 \cdot 10^9$ cosmic ray events have been recorded, corresponding to about 7 TB of data on tapes. Nowadays 130 clusters of RPCs are in continuous data taking, covering a surface of about 6000 m^2, corresponding to the whole central detector carpet (see Fig.1(a)). The last 24 RPC clusters, corresponding to the external guard ring,

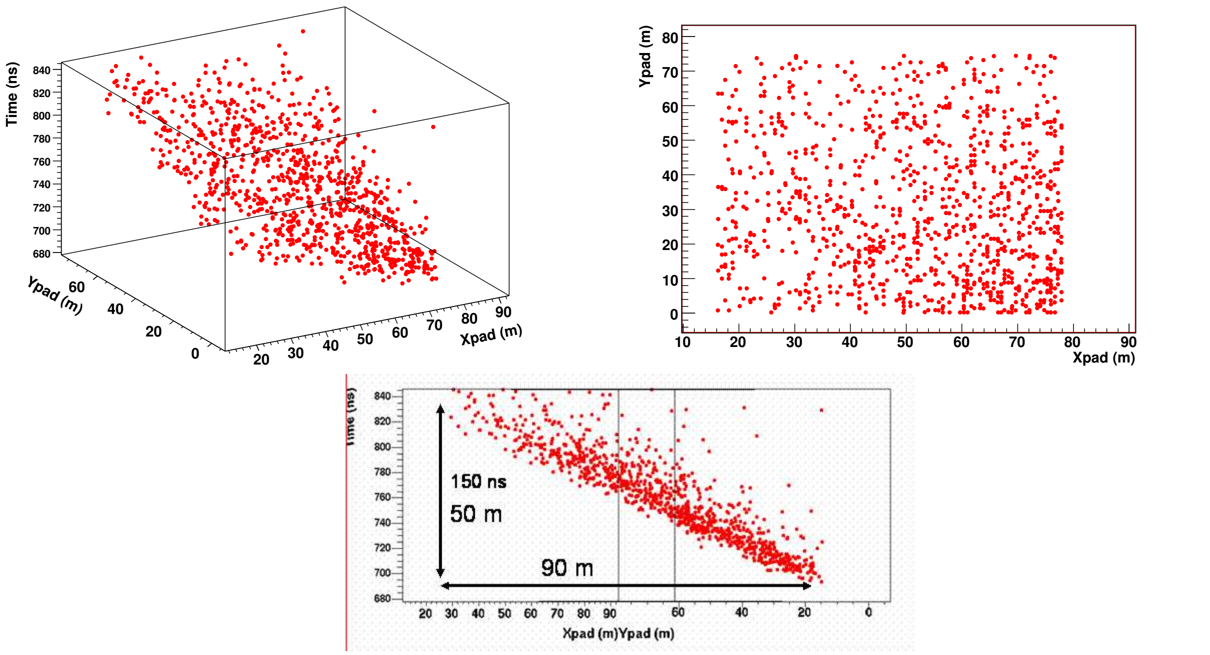

Figure 2. *Three different views of the same event recorded by ARGO-YBJ in an intermediate configuration (104 RPC clusters in acquisition).*

are now being installed to complete the full detector design by the end of 2006.

In this paper some of the results concerning the analysis of data collected with 42 clusters will be presented. These are in full agreement with those coming from data collected with 16 clusters and with what is expected from CR and EAS properties.

2. Detector Performance and First Physics Results

As mentioned above, the use of a full coverage detector with a high space-time resolution gives detailed images of the shower front. An example is reported in Fig.2 where three different views of the same event are shown. The detector capabilities are clearly evident.

As a first step towards event analysis, an offline time calibration procedure has been set in order to remove systematic time offsets among the pads, due to different cable lengths or any other electronic effect [6]. Corrections in the range ± 4 ns have been introduced by using the so-called Characteristic Plane Method [7]. As an effect of this procedure, the residuals with respect to the fit of the shower front are minimized and the event azimuth distribution becomes uniform [8]. Once the time calibration has been performed, the angular resolution of the 42 clusters carpet has been estimated by dividing the detector into two independent sub-arrays (made by "odd" and "even" pads respectively) and studying the angular difference $\Delta\psi$ between the reconstructed shower directions. In Fig. 3(a), the value of ψ_{70}, defined as the width of the $\Delta\psi$ distribution which contains 70% of the events, is reported as a function of the hit multiplicity for the 42 clusters configuration. As can be seen there is a complete agreement between data and simulations. The value of ψ_{70}

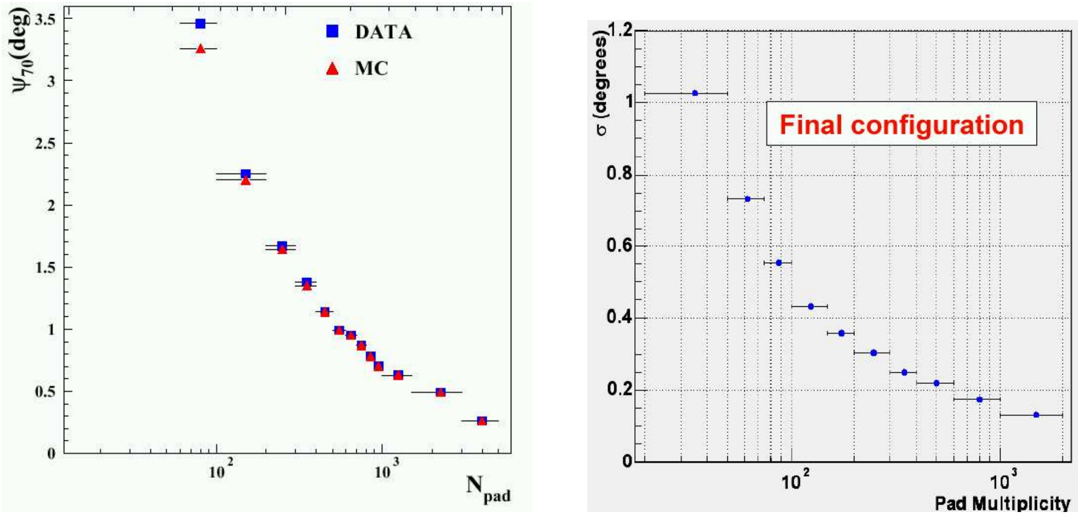

Figure 3. *Left side (a): Simulated and measured values of ψ_{70}, as estimated with the "even-odd pads" method for the 42 clusters configuration (see text). Right side (b): Angular resolution referring to the full detector configuration (simulated only).*

is directly related to the angular resolution [9]. In Fig. 3(b) the expected angular resolution, as given by the simulations, is reported for the full detector configuration.

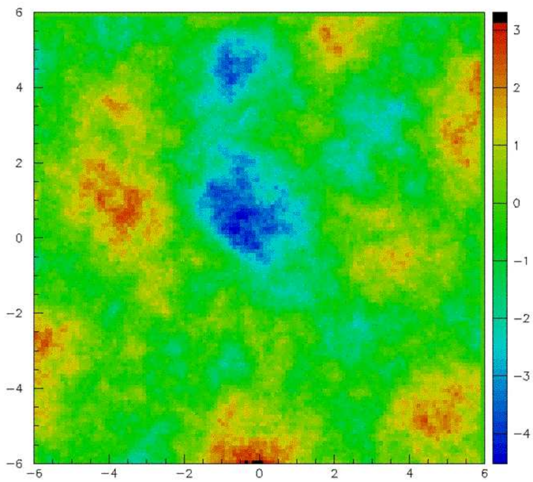

Figure 4. *Moon shadow detected in cosmic ray flux (see text).*

A check of both the detector estimated angular resolution and absolute pointing can be made by looking at the Moon shadow in the cosmic ray flux [10,11]. The shadow shape and dimensions give an independent measurement of the angular resolution, while its position in the sky must be consistent with the expected shift, with respect to the Moon real position, due to the effect of magnetic fields on CR particles trajectories. Two independent analyses were perfomed on the 42 clusters data in order to detect this effect. They are in good agreement with each other and are consistent with the estimated detector figures (angular resolution, etc.). Moreover the statistical significance of the detected deficit (about 4σ) and, principally, its increasing rate with exposure, exactly follow the expectations. The resulting map is reported in Fig.4, where the axes indicate the angular deviation (in degrees) from the Moon real position, while the color code gives the differences from the average flux in units of standard deviations. The shown map refers to events with at least 60 detected hits, which correspond to a data sample with an average energy of about 4 TeV. The same analysis has also been repeated with a larger hit multiplicity (i.e. pri-

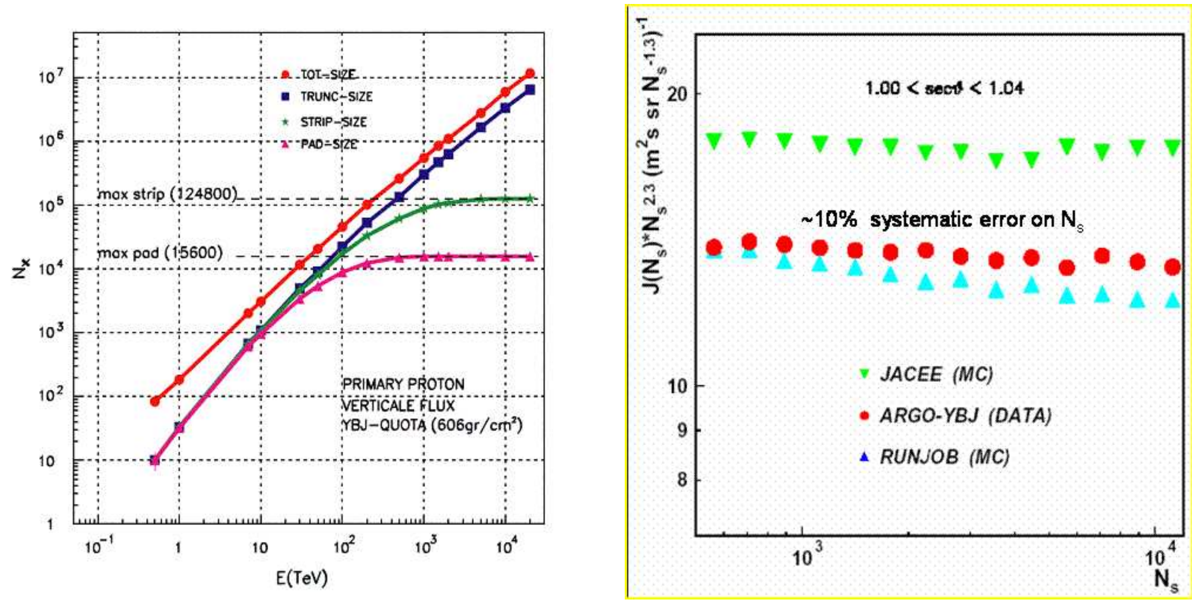

Figure 5. *Left side (a): average pad and strip multiplicity as a function of primary hadron energy. Also reported are the total shower size and the truncated one (due to the finite detector surface). Right side (b): Strip spectrum as measured by ARGO-YBJ (in the 42 clusters configuration) compared with those resulting from the use of RUNJOB and JACEE data [13].*

mary energy) threshold. As expected, in the high energy sample ($N_{hits} > 200$, correponding to an average energy $E \sim 20$ TeV), the shadow is not shifted with respect to the Moon real position.

As a further check of the detector operation, the distribution of the reconstructed shower axis zenith angle θ has been studied and compared with what is expected from the CR flux and the atmosphere properties. The results are in excellent agreement with previous measurements [1].

In the following some of the physics results obtained will be briefly mentioned and discussed. More details can be found in [12].

2.1. Cosmic Ray Spectrum below 100 TeV

As outlined above, the detector layout, performance and location, offer a unique possibility to make a deep study of several characteristics of the hadronic component of the cosmic ray flux in the $\sim 1 \div 1000$ TeV energy range, thus providing an excellent "bridge" in the transition region from direct to indirect measurements.

Interesting results on the primary energy spectrum, mass composition, antiproton/proton ratio, hadron-air cross section , can be obtained from ARGO-YBJ data. Moreover, the use of a full coverage detector with a high space granularity (see Fig.2) allows a deep study of the *"shower phenomenology"* including figures like the time structure of the front (both shape and width), the lateral distribution, etc.

In order to have an energy estimator the number of particles in the shower has to be determined. This is done by just counting the number of fired pads in a given event. Obviously this assumption is valid untill saturation is reached, then the strip multiplicity can be used to extend the energy region (see Fig.5(a)). As a further extension, the analog output of each RPC is readout, thus allowing a detector response which is linear up to energies of the order of about 1000 TeV. Here we will report the first results concerning the energy spectrum, as obtained with data from the detector in the 42 clusters config-

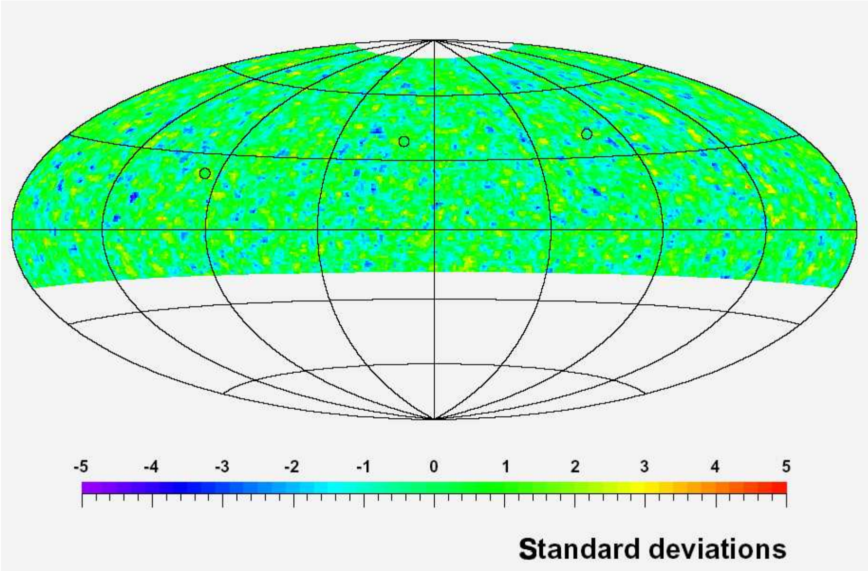

Figure 6. *Sky map resulting from the search for point γ-ray sources performed with the 42 clusters configuration (see text).*

uration. A preliminary study of the strip size (N_s) spectrum has been performed. Values up to $N_s = 10^4$ have been considered in the analysis, corresponding to primary hadrons with energies up to about 100 TeV. As reported in Fig.5(b), the result shows a fair agreement of the data with the RUNJOB model, in particular at energies smaller than 50 TeV [13]. The errors are still large (at the level of 10%), but this preliminary result can be considered as a good test of the analysis, which is going to be applied to the data with the full detector configuration.

2.2. All Sky Survey for Point γ-ray Sources and GRBs

Based on the angular resolution found above, a full simulation has been performed in order to evaluate the ARGO-YBJ sensitivity to point gamma ray sources. The detector has been found to be able to detect TeV gamma ray emission from a standard source like the Crab at a significance level of 18 σ per year. The ARGO-YBJ experiment, in one year of observation, will be then able to detect any point source above the horizon with a flux of 0.3 Crab units at a 5σ level [12]. A proper γ/hadron discrimination method would significantly increase the detector sensitivity. Relative studies are under way and are showing promising results [14].

Here we report the results of a first analysis performed with the 42 clusters data recorded from December 24, 2004 to March 23, 2005, for a total running time of 1007 hours. The average event rate is about 160 Hz. The events with zenith angle $\theta \leq 50°$ have been considered. The declination band $-20° < \delta < 80°$, corresponding to 8.3 sr (66% of the celestial sphere) is monitored. No gamma-hadron discrimination is applied in this preliminary analysis. In the 1007 hours of measurement no gamma ray source with an average flux larger than 5 Crab units has been observed. The resulting sky map, giving no statistically significant excess, is reported in Fig. 6 using celestial equatorial coordinates. A data analysis looking for GRBs has also been performed: it gives no evidence for a significant transient of duration between 10 s and 300 s. More details on γ-ray sky survey and GRB searches (with the detector operated in the *shower mode*) are given in [15].

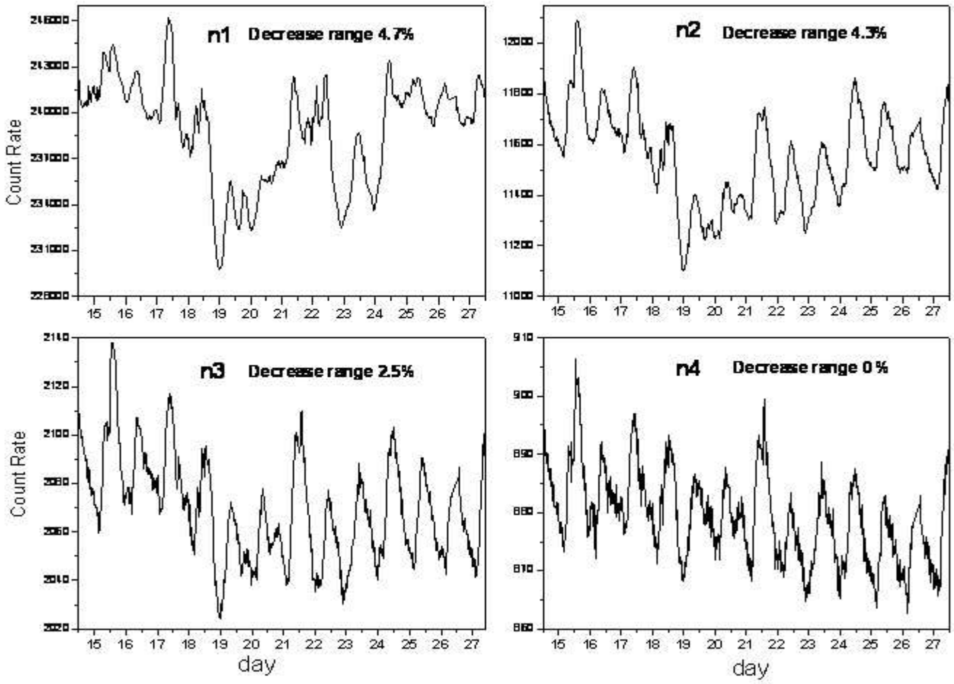

Figure 7. *Scaler mode count rates, before weather effect corrections, from January 15 to 27, 2005, showing the detection of a Forbush decrease by ARGO-YBJ. The n1,..,n4 labels refer to the counting rates with at least 1,2,3 or 4 hits respectively (see text).*

2.3. Gamma Ray Burst Search using the Scaler Mode

The detector shower energy threshold can be lowered to about 1 GeV by operating it in the *scaler mode*, i.e. recording the counting rate at fixed time intervals (see Sec.1). At these energies local (e.g. solar Ground Level Enhancements, GLEs) and cosmological (e.g. GRBs) effects are expected as a significant enhancement of the counting rate over the background. As stated in Sec.1, the counting rate of each RPC cluster is measured every 0.5 s, without any information on the primary particle arrival direction and on the hits space distribution. For each cluster four different scalers are used in order to record the event rates with at least 1, 2, 3, or 4 hits, in a 150 ns wide coincidence window, the average detected rates amounting to about 40 kHz, 2 kHz, 300 Hz and 120 Hz respectively. The counting rate for a given multiplicity (up to three) can then be obtained from the relation: $R_i = R_{\geq i} - R_{\geq i+1}$ for $i = 1, 2, 3$. The corresponding primary particle energies increase with the multiplicity, depending on the assumed flux spectral index (see [16] for further details).

The GRB search is done in coincidence with Swift [1] and the other detectors hosted on satellites. Here the results referring to a fraction of the detector are reported, a more complete discussion is done in [16]. The search for GRBs with zenith angle $\theta < 40°$ in the ARGO-YBJ field of view has given no positive result. Nevertheless the adopted technique has already shown a good sensitivity with typical fluence upper limits of $10^{-3} \div 10^{-5}$ erg/cm^2 in the $1 \div 100$ GeV energy range, while more than a factor two improvement

[1] As a member of the Swift Follow-Up project, ARGO-YBJ can carry out a complete GRB analysis in real time.

is expected with the detector completion.

2.4. The Forbush Decrease in January 2005 and the Solar Activities Analysis Using the Scaler Mode

After correction for air pressure, the data taken in *scaler mode* from January 15 to 27, 2005 have been used to search for the Forbush Decrease (FD) that has been well measured at lower energies by devices such as neutron monitors [12]. The FD around noon on January 17, 2005 has been observed by our detector. The counting rates with multiplicity greater than 1 and 2 clearly decrease correspondingly (see Fig.7). Moreover all the detailed structures of the light curves are similar to the results from neutron monitors. The maximum amplitudes of the FD are about -5% and -4%, respectively. The SPT rates with multiplicities greater than 3 and 4 show no statistically significant signs of decrease. Furthermore the solar flare (Class X7) of Jan 20, 2005, connected to a GLE and detected by the Milagro scaler system [12], has been studied. There is no evidence for it in the ARGO-YBJ data, the reason for this being due to the large difference in the longitudes of the two experimental sites.

3. Conclusions

The first results coming from the analysis of a data sample collected with a relevant fraction of the ARGO-YBJ apparatus have been described, showing the experiment capabilities in facing a wide range of cosmic ray physics issues. In particular, the results of the first data analyses on hadronic cosmic ray physics, γ-ray astronomy, GRB search, and solar physics have been given. The detector capability in providing an unprecedented information on the shower front space-time pattern, which gives new insights into shower development processes and surface arrays observables, has also been reported.

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