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The ARGO-YBJ experiment in Tibet

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Abstract

The setting up of the ARGO detector at the YangBaJing Cosmic Ray Laboratory (4300 m a.s.l., Tibet, P.R. China) has been completed during the last spring (2007). It consists of a central carpet made of 130 identical sub-units of 12 RPCs each (a "cluster"), covering a surface of about 5800 m^2 with 93% active area, and a guard ring of 24 further clusters of the same type surrounding the central carpet with a lower sampling density. Signals are picked up by external electrodes of small size, thus allowing the sampling of EAS with high space-time granularity. Shower events are detected at a trigger rate of about 4 kHz. Events with a few particles detected by a single cluster are counted in scaler mode on a time base of 500 ms. The intrinsic modularity of the ARGO detector allowed us to collect data even during the setting-up period, using only the central carpet (or even part of it). Some preliminary results from the analysis of events collected in a few months of data taking are presented.

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Keywords: Extended air showers; Cosmic rays; Gamma ray sources; Gamma ray bursts

1. Introduction

ARGO-YBJ is an Extended Air Shower Detector optimized to work in the TeV range, with a threshold of few hundreds of GeV and a dynamical range extending to the PeV. Its experimental approach is of measuring both charged and gamma ray induced showers on a compact detector covering an equipped area of the order of 10,000 m^2, located at very high altitude (4300 m a.s.l) in Tibet. The instrumental requirements of ARGO-YBJ include a good angular resolution, at the level of a fraction of a degree, a field of view of 2 sr, allowing to survey almost completely the northern hemisphere, with a declination range spanning from 70°N to 10°S, a continuous monitoring with a duty cycle only limited by the maintenance and experimental shutdown needs. This paper reports on the preliminary analysis of some of the main physics items addressed by ARGO-YBJ:

- *Gamma ray source detection*: The wide angular range and the high duty cycle enable ARGO to detect both already identified sources as well as still undisclosed emitting sources with a sensitivity of a fraction of the CRAB intensity in the TeV energy range.
- *Cosmic Ray study*: The ARGO energy range overlaps both with the higher end of the direct measurements of satellite experiments and the lower end of sampling ground EAS experiments, ending up in the knee region. Its detection approach enables a detailed study of the shower front structure and therefore a large piece of information is expected as far as the proton–Air cross-section is concerned, as well as the extension of the composition studies above the satellite energy range.
- *Gamma Ray Burst study*: The detection of a sudden increase in the expected background, mainly in connection with GRB detection by satellite experiments within the ARGO field of view can be interpreted and analyzed

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as GRB high energy counterparts with an energy threshold of few GeV.

The preliminary analysis of the data collected during the ARGO-YBJ detector setting-up period will be outlined, as well as the description of the main detector features.

2. The ARGO-YBJ experiment

ARGO-YBJ is located 30°06′38″N, 90°31′50″E, at the Yang Ba Jing Cosmic Ray Laboratory (Tibet, China), at an altitude of 4300 m a.s.l.

2.1. The detector

It consists of a $74 \times 78\,\mathrm{m}^2$ continuous carpet of Resistive Plate Counters (RPCs), with 93% coverage of the equipped area, surrounded by a guard ring with coarse coverage, extending the equipped area to a total surface of $111 \times 99\,\mathrm{m}^2$, with $6700\,\mathrm{m}^2$ of sensitive area, as outlined in Fig. 1.

The RPCs ($2.8 \times 1.25\,\mathrm{m}^2$ each) are operated in streamer mode, and their performance is described in detail in Ref. [1]. The RPCs are logically grouped in "clusters" of 12. The cluster is the fundamental detector module, both for triggering and DAQ purpose. The full ARGO Detector consists, of 154 clusters. The central carpet is made by 130 clusters, the guard ring by 24 clusters more. The RPC signal is picked up by means of induction strips, covering the RPC surface. Each strip is $7 \times 56\,\mathrm{cm}^2$ large. This dimension represents the ARGO space granularity, i.e. the pixel size on which particle hit are digitized and hence counted. The signals of 8 adjacent strips are ORed into an almost squared PAD ($62 \times 56\,\mathrm{cm}^2$ wide) as far as the hit arrival time is concerned. The PAD signal is in fact sent to a TDC converter and represents the time pixel, allowing a resolution of the order of 1 ns in determining the hit arrival time. In order to extend the detector dynamical range beyond the limit imposed by the digitized strips, the charge collected on the chambers is also measured. Each RPC of the central carpet is, therefore, equipped with two BIG PADs ($140 \times 125\,\mathrm{cm}^2$ wide), from which the analog signal proportional to the number of particles is picked up. The resulting signal shows a linearity up to $>10^4$ particles/m^2, corresponding to an energy of ~10 PeV. This feature, which is till date implemented only in 54 clusters, will be extended to the full central carpet by the first half of 2008.

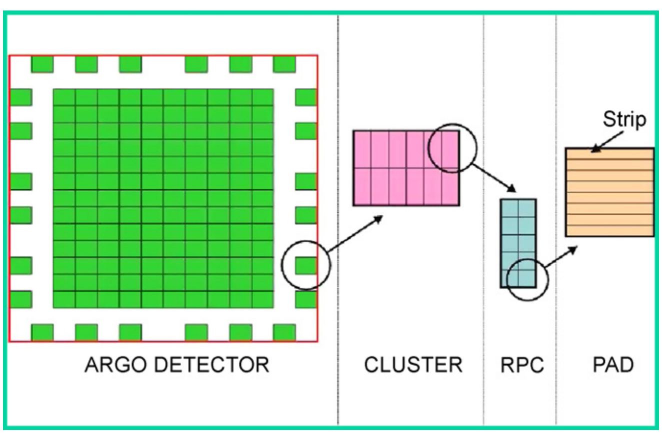

Fig. 1. The ARGO-YBJ detector.

2.2. Data taking

As far as data taking is concerned, ARGO-YBJ operates in two modes, the "shower mode" and the "scaler mode". The shower mode consists essentially of a majority trigger logic: a number of fired pads $N_{\mathrm{pad}} \geqslant N_{\mathrm{trig}}$ in the central carpet, within a time coincidence window of 420 ns triggers the "shower" data taking. The current threshold is set to $N_{\mathrm{trig}} = 20$, which corresponds to a gamma energy threshold of a few hundreds of GeV. The trigger rate is of ~4 kHz in this configuration.

To reconstruct the shower direction and the core position from the collected data the calibration of the

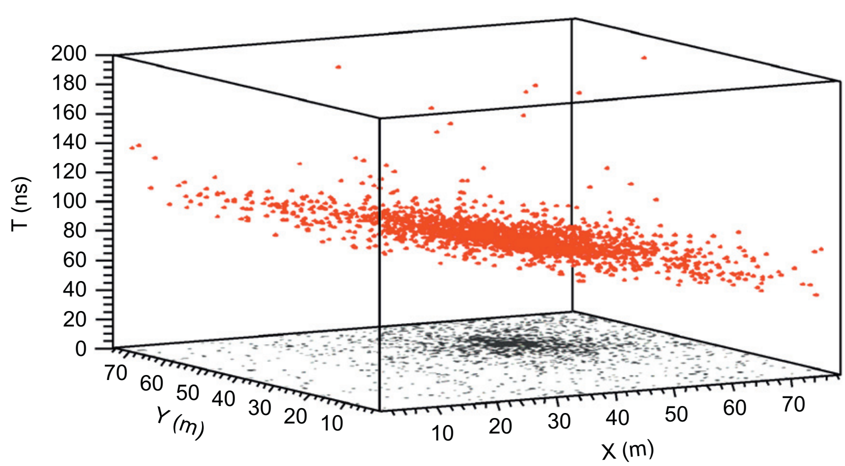

Fig. 2. A typical hit pattern of an event triggered in shower mode. The space hit density can be derived from the pattern in x–y projection, whereas the arrival direction is reconstructed from the time distribution, shown on the vertical coordinate.

18480 PADs has to be kept under careful control [2] and has to be periodically repeated to prevent any time dependence introducing dangerous systematics in the reconstructed data. In Fig. 2 an example of the hit space and time pattern of a triggered event is shown, after taking into account the calibration correction.

In the "scaler mode" the counting rate of each cluster is continuously recorded every 0.5 s, for four different level of hit majority in a single cluster: $n \geqslant 1$, $\geqslant 2$, $\geqslant 3$, $\geqslant 4$ in a coincidence window of 150 ns. The recorded counting rates, for the different levels of coincidence, are respectively, 40, 2 kHz, 300 kHz and 120 Hz per cluster. Showers initiated by primaries with an energy threshold of the order of 1 GeV, unable to trigger the detector in shower mode, can produce such a faint signal. These events are analyzed for a sudden increase in their rate, to provide an evidence for >1 GeV counterparts in time coincidence with GRBs detected by satellites at the time of the event detection. Also Solar Ground Level Enhancements and cosmic ray modulation due to the solar activity can be monitored in this mode. No direction measurement is obviously possible for such events. The detector is taking data with the full central carpet since July 2006. The guard ring, whose setting up has been completed during the spring 2007, is actually being tested for its addition to data taking at the end of this year. The results presented in this paper, therefore, refer to a preliminary data taking performed in the period July 2006–March 2007 in shower mode (130 active clusters) and December 2004–April 2007 (with an increasing detector active surface from $\sim 700\,\mathrm{m}^2$ to $5500\,\mathrm{m}^2$) as far as the scaler mode is concerned.

2.3. The detector performance

2.3.1. The angular resolution

ARGO angular resolution has been estimated using three independent ways and, cross-checking the results, we found a rather good agreement.

The first method was a pure Monte Carlo one, obtained estimating the angular distance between injected events and reconstructed direction.

The second one is based on the data, using the so-called chessboard method. The direction of a single triggered shower is derived by using alternatively the data from the even-numbered PADs and those from the odd-numbered PADs. The consistency of the two measurements gives an estimate of the angular resolution.

Figs. 3 and 4 show the result as a function of the number of fired PADs in the event. The angular resolution estimator is ψ_{72}, defined as the angular spread, which contains the 71.5% of the events. For a Gaussian behavior of the point spread function, ψ_{72} is the radius of the observation window which maximizes the signal-to-noise ratio for the signal centered on a point-like source. The angular resolution is correlated to the ψ_{72} parameter by a factor $\sigma = \psi_{72}/1.58$.

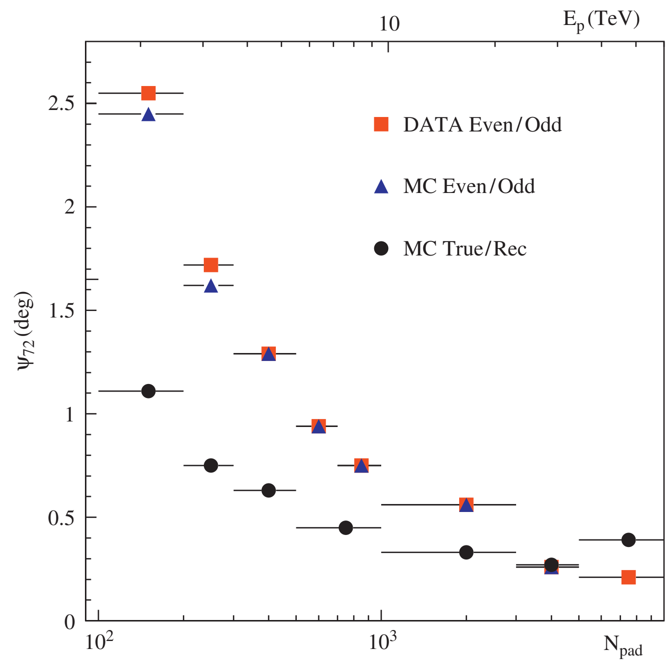

Fig. 3. The angular resolution estimator Ψ_{72} as a function of the number of PAD hitted in the event.

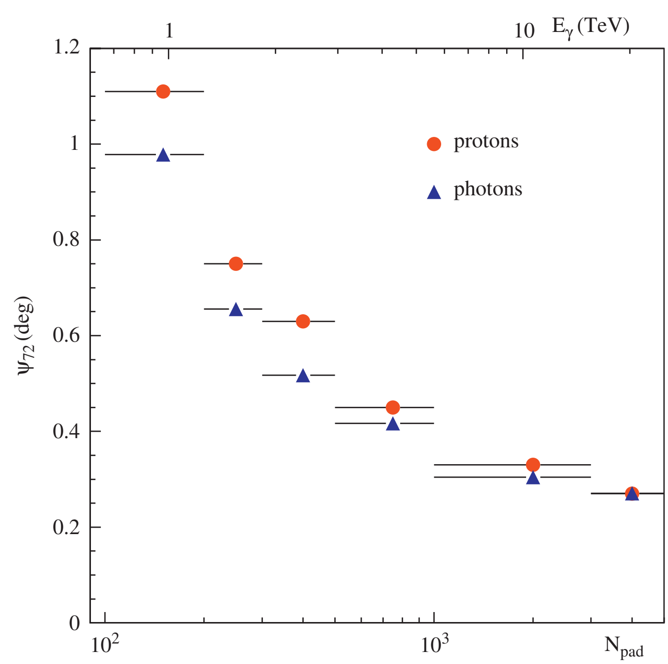

Fig. 4. ψ_{72} as a function of the number of hitted PADs for proton and photon induced showers.

Fig. 3 shows ψ_{72} as a function of the number of fired PADs. The expected angular distance between generated and reconstructed Monte Carlo events, as well as the results obtained with the chessboard method, both for Monte Carlo and real events are shown. The chessboard method is expected to give [3] an estimate twice larger than the full detector one, on a purely statistical basis.

The presence of any systematics causes a deviation from this factor 2.

A detailed discussion of the ARGO angular resolution can be found in Ref. [4].

Fig. 4 shows the expected behavior of the angular resolution as a function of the number of hitted PADs both for proton and photon induced showers.

Finally, the third method relies on the accuracy of the reconstruction of the Moon position, as derived from its shadowing effect on the incoming cosmic ray flux. Fig. 5 shows the width of the Moon shadow as preliminarily observed from the analysis of ARGO real data. The consistency of the observed width and of its position is an important cross-check of the calibration and reliability of the first collected data.

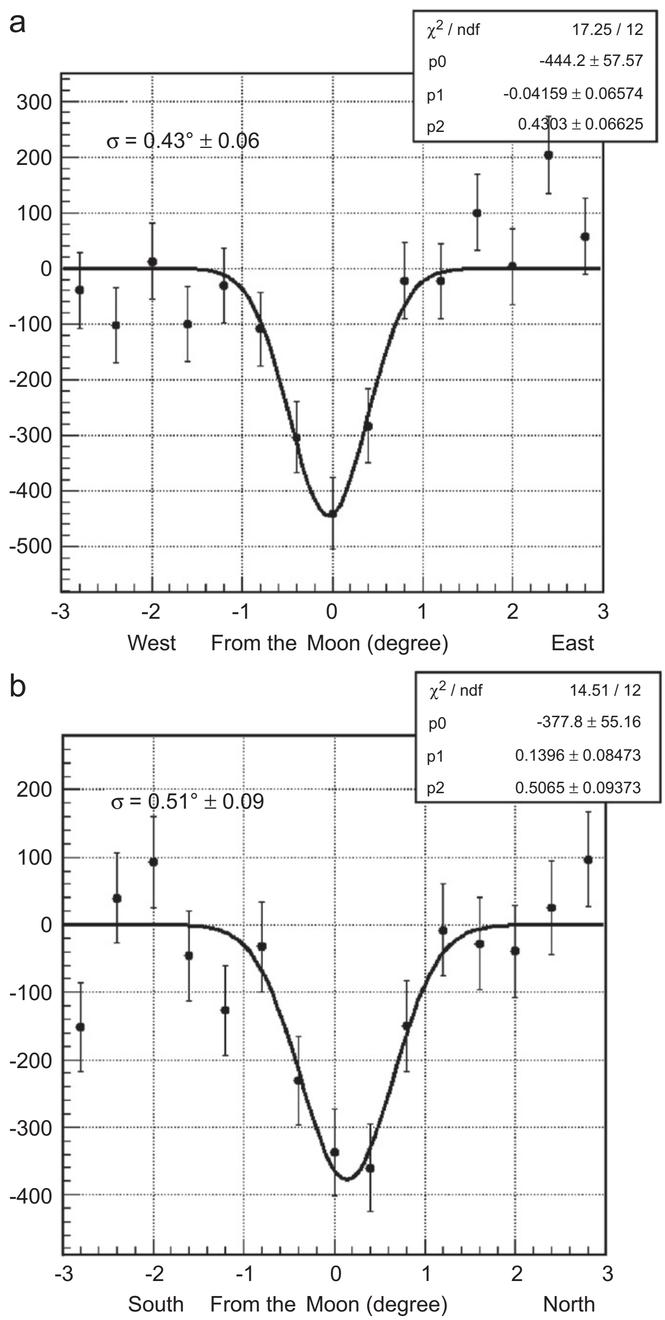

Fig. 5. The profile of the shadow of the Moon in the cosmic ray flux: (a) in the East–West direction and (b) in the North–South direction.

The observed deviation from the nominal Moon position is 0.14° in the North–South direction, where there is no magnetic deflection and the expected position coincides, therefore, with the nominal one, and 0.04° Westward, to be compared with an expected shift of ~0.3° Westward, due to the magnetic deflection on the charged component. The study of the systematics and the careful analysis of the residual deviation from the expected nominal position are in progress [5]. A further improvement of the angular resolution is expected adding a 0.5 cm thick lead pre-converter on top of the RPC layer. This upgrade is scheduled during 2008.

2.3.2. *Duty cycle*

After the setting-up period, an encouraging result of 86% for the ARGO duty cycle has been obtained during the month of May 2007, confirming thus the expected performance.

3. Experimental results

We report in this section the preliminary results obtained analyzing the ARGO data taken in the setting-up period.

3.1. *Moon and Sun shadows*

The Moon shadowing effect, mainly used for calibration purposes and angular resolution cross-check, has been clearly observed during the period July 2006–March 2007.

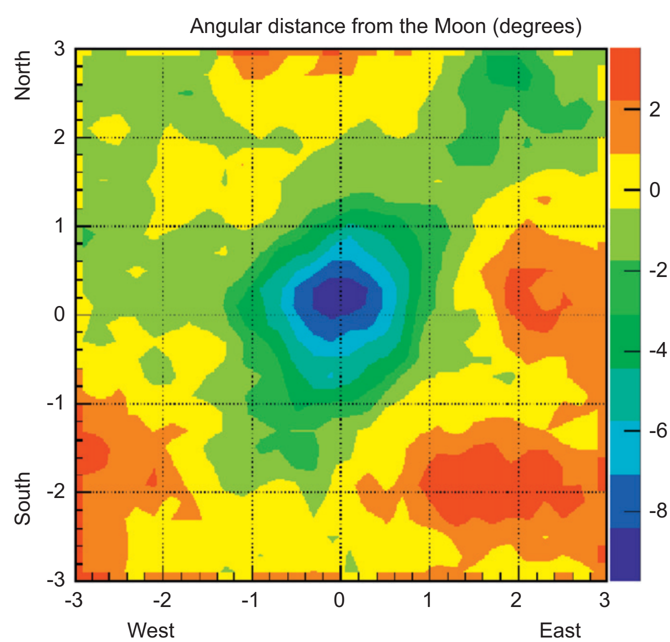

Fig. 6. Map of the Moon region. The color scale indicates the significance of the deficit/excess with respect to the mean flux. The axes show the distance in degrees with respect to the nominal position.

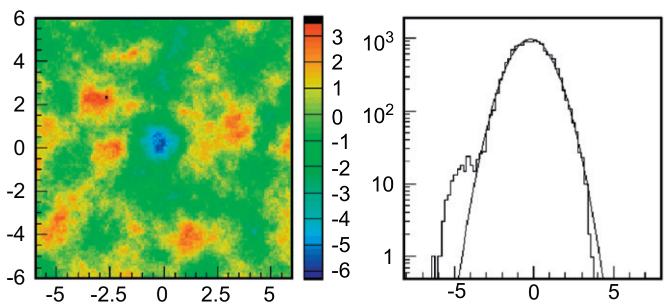

Fig. 7. The Sun shadow showing up in the ARGO data as a 6σ cosmic ray deficit from the Sun direction. The data refer to 208 h in the second half of 2006, a period of low solar activity.

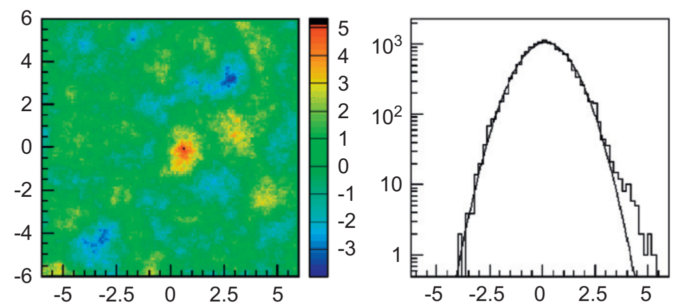

Fig. 8. Map of the Crab region. The plot on the left shows the excess distribution in the area selected, with respect to a Gaussian distribution, where each counts refers to a 0.6° wide pixel.

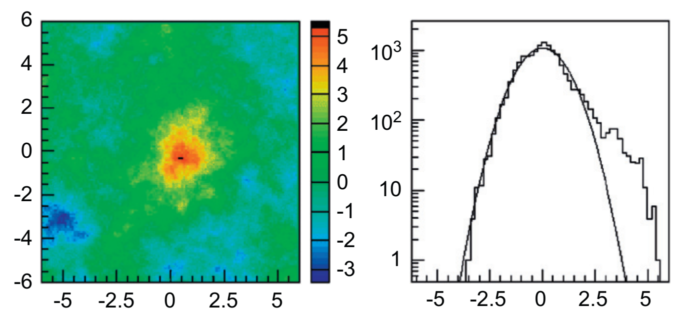

Fig. 9. Map of the Mkn 421 region, worked out for 80 h of observation time in the July–August 2006 period. The plot on the left shows the excess distribution in the area selected, with respect to a Gaussian distribution, where each bin refers to a 0.6° wide pixel.

Fig. 6 shows the Moon image, observed as a deficit with a statistical significance of $\sim 10\sigma$ of the cosmic ray flux, integrating 558 h of observation. To reduce the effect of magnetic deflection the events have been selected to be of relatively high energy, requiring a minimum number of PADs to be hit, $N_{\mathrm{pad}} \geqslant 500$, corresponding to a median energy $E \cong 5$ TeV.

Fig. 7 shows the Sun shadow, obtained with the same technique. A shorter observation time has been selected in this case, selecting only 208 h in the 2006 period corresponding to a minimum in the solar activity, in order to minimize the effect due to the high variability of the solar magnetic field. A signal with 6σ statistical significance shows up in this case.

3.2. Gamma ray sources

VHE gamma ray astronomy is one the main scientific topics addressed by ARGO-YBJ. Amongst the known sources the Crab Nebula has a well-studied spectrum and is often used as a standard candle to calibrate the experimental sensitivity. Fig. 8 shows the result obtained selecting the direction of the Crab out of the ARGO data, integrating ~ 290 h of observation time in the period July 2006–March 2007, corresponding to 50 transits (~ 5.8 h/transit). The events with $N_{\mathrm{pad}} \geqslant 200$ and a direction $\theta \leqslant 40°$ from the zenith have been selected. A 5σ excess is clearly visible in the data. A careful estimate of the experimental sensitivity is being derived, taking into account and correcting for all the experimental condition of data taking.

During the period July–August 2006 the AGN Markarian 421 underwent a period of intense activity, registered as a strong X-ray flux by the All Sky Monitor of the Rossi X-ray Time Explorer (ASM/RXTE, [6]). X-ray outbursts are generally accompanied by an increase also in the emission in the TeV range. In July–August 2006 Mkn 421 was visible during the daytime, and this excludes Cherenkov detector from detecting the high energy component of the flare. Argo setting up was just completed at that time and the detector was taking data with the full central carpet. The preliminary result obtained by selecting the region around the Mkn 421 position is shown in Fig. 9. The plot corresponds to an 80 h-long observation, selecting the triggering showers with $N_{\mathrm{pad}} \geqslant 60$ (i.e. an estimated median energy of ~ 600 GeV) and a zenith angle $\theta < 40°$. The convincing excess with $> 5.9\sigma$ of statistical significance disappears when analyzing the data collected out from the RXTE detected flare period. The analysis is still in progress to fix all the systematics and to derive the corresponding flux in the energy region of the detected excess.

3.3. Cosmic ray analysis

Another of the main topics addressed by ARGO is the detailed analysis of the cosmic ray flux, in the energy region overlapping the highest range of satellite measurement and the typical range of ground based Extended Air Showers experiments, up to the knee region. A totally preliminary result has been obtained analyzing the collected data to work out the estimate on inelastic p–Air cross-section.

The method is based on the assumption of a behavior of the shower intensity as a function of the zenith angle:

$$I(\theta) = I(0)\mathrm{e}^{-(ho/\Lambda)(\sec\,(q)-1)}; \quad \Lambda = k\lambda_{\mathrm{int}}$$

where the intensity $I(\theta)$ is derived from the data and the parameter k is deduced from Monte Carlo simulation, as it

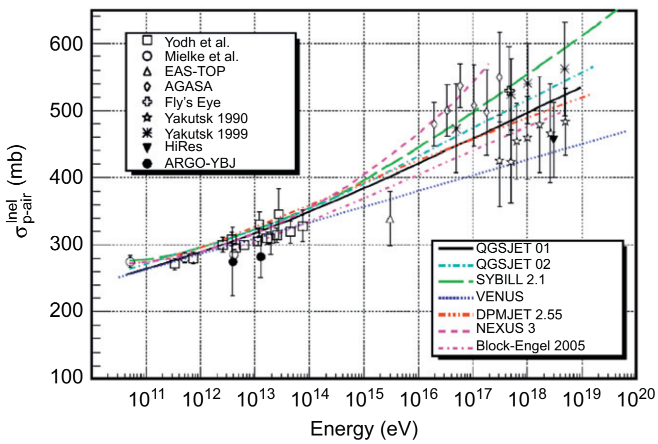

Fig. 10. The p–Air inelastic cross-section preliminary estimate. ARGO data are shown together with other experimental results, taking into account also the contribution from heavier primaries.

is dependent from the shower development and its fluctuations, folded to the detector response. It is only slightly dependent on the interaction model. λ_{int} , the proton–Air interaction length, is the free parameter determined by the data. The cosmic proton contamination by means of heavier primary has obviously to be taken into account. Finally one can get

$$\sigma_{\mathrm{inel(p-Air)}}(\mathrm{mb}) \cong 2.4 \times 10^4/\lambda_{\mathrm{int}}.$$

A detailed discussion of the analysis can be found in Ref. [7]. Fig. 10 shows the result, obtained in two primary energy bins, defined by selecting the N_{pad} range of the reconstructed showers: $300 < N_{\mathrm{pad}} \leqslant 1000$, with an estimated median energy $E \sim 4$ TeV, and $N_{\mathrm{pad}} > 1000$, corresponding to a median energy $E \sim 13$ TeV of the cosmic primary.

3.4. The Gamma Ray Burst analysis

The scaler mode technique is used to monitor the behavior of the single particle rate in the ARGO detector. Each cluster is continuously monitored and the single particle counting rate is registered every 0.5 s, as well as the n-particle majorities $n \geqslant 2$, $n \geqslant 3$, $n \geqslant 4$, within a time coincidence window of 150 ns. A primary gamma ray of $E > 1$ GeV can produce such a weak signal in the detector and a sudden increase of their rate, in a limited period of time, uniformly in the detector, could be interpreted as a signature for the high energy tail of a Gamma Ray Burst. The arrival direction of the event cannot, however, be reconstructed.

A temporal coincidence with a GRB detection by the existing satellites is, therefore, searched for, as a further signature for interpreting the recorded signal as the evidence for the detection of a GeV counterpart of the Gamma Ray Burst. This analysis is presented in detail also at this conference [8], as well as the statistical significance of the recorded excesses. No evidence is detected analyzing

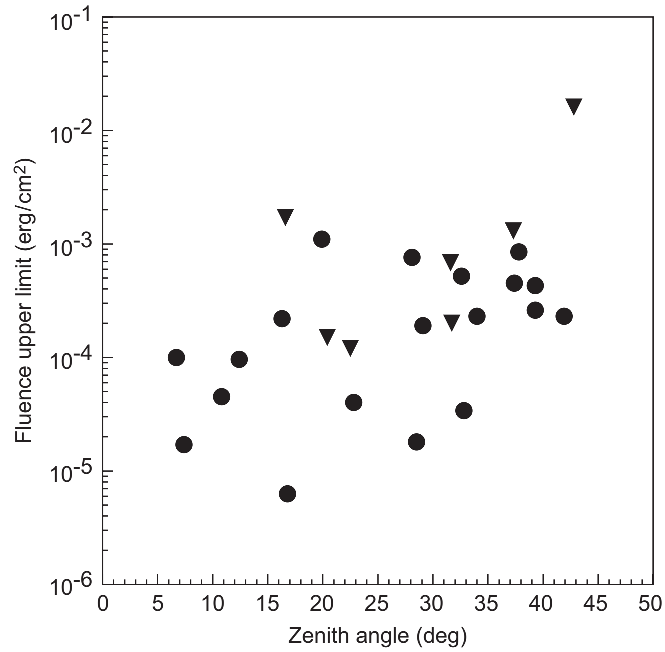

Fig. 11. The GRB fluence limit in the $E > 1$ GeV energy range, with reference to 26 detectable GRBs within the ARGO field of view. The spectral index is assumed extrapolating to the 1–100 GeV range the value measured by satellites in the keV–MeV region. Full dots identify GRBs with unknown redshift. For GRBs whose redshift is given (triangles) the spectrum is corrected for extragalactic absorption.

26 GRB detected by satellites (mainly SWIFT) while orbiting within the ARGO field of view in the period December 2004–April 2007. An existing excess is searched for, both in exact time coincidence and in a time interval preceding or following the satellite detection time, to look for a delayed/anticipated emission of the possible high energy counterpart. Fig. 11 summarizes the fluence limit for $E > 1$ GeV, with reference to these 26 GRB, as a function of the zenith angle, assuming for the emission spectral index in the 1–100 GeV region the value measured by the satellites at lower energy. When the GRB distance is given the corresponding spectrum is corrected for the extragalactic absorption.

4. Conclusion

ARGO-YBJ experiment is taking data since July 2006 with its central carpet (130 clusters covering $\sim$5500 m^2 with 93% active area).

During the first half of year 2007 the installation of an external guard-ring including 24 clusters with coarse active area ($\sim$42%) has been completed. They will be included in data taking by the end of year 2007.

The data collected in the period July 2006–Spring 2007 have been used for a preliminary analysis, with the main goal of checking the experimental performance and calibrate the detector.

The angular resolution, checked with the chessboard method on the experimental data fits the expectations, as well as the accuracy of the Moon deficit reconstructed position and width. A fine analysis of the residuals is still in progress.

The Moon and Sun deficit are observed with, respectively, 10σ and 6σ statistical significance.

As far as the Gamma ray sources is concerned, the Crab Nebula signal has been worked out with 5σ significance, integrating $\sim$290 observation hours. The Markarian 421 flare, observed in ASM/RXTE data, has been confirmed by the preliminary analysis of ARGO data, showing-up an energy threshold well below the TeV.

The study of the charged cosmic rays flux allowed a preliminary estimate of the p–Air cross-section. The collection of more data will allow both to reduce the experimental error and to increase the energy range of the measurements.

As a general remark, the improvement of the analysis procedure is still in progress, mainly to fully exploit the compactness of ARGO and its capability of carefully describing the details of the pattern of the shower front, both in terms of space and time distribution of the incoming secondaries.

The scaler mode finally allowed to work out an upper limit for the GRB fluence (between 6×10^{-6} and $2\times10^{-2}\,\mathrm{erg}\times\mathrm{cm}^{-2}$ as a function of the zenith angle) for $E>1\,\mathrm{GeV}$. The result refers to the analysis of 26 GRB detected in the period December 2004–April 2007 by satellites (mainly SWIFT). The expected improvement of the ARGO Detector has been also outlined, including:

- The extension of the actual detector to $6700\,\mathrm{m}^2$ of active area through the inclusion of the guard ring in the data taking by the end of this year.
- The completion, during the first months of 2008, of the analog read-out system of the whole central carpet, with the aim of extending the dynamic range up to $10^{15}\,\mathrm{eV}$.
- The addition of a layer of lead preconverter (0.5 cm thick) to the central carpet RPCs, with the aim of improving the detector angular resolution mainly for low energy showers, to be completed at the end of 2008.

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