Results from ARGO-YBJ

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Abstract. The ARGO-YBJ experiment has been put in stable data taking at the YangBaJing Cosmic Ray Laboratory (Tibet, P.R. China, 4300 m a.s.l.). In this paper we report a few selected results in Gamma-Ray Astronomy (Crab Nebula and Mrk421 observations, search for high energy tails of Gamma Ray Bursts) and Cosmic Ray Physics (Moon and Sun shadow observations, proton-air cross section measurement, preliminary measurement of the antiproton/proton ratio at TeV energies).

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THE DETECTOR

The ARGO-YBJ experiment, located at the YangBaJing Cosmic Ray Laboratory (Tibet, P.R. China, 4300 m a.s.l.), is an air shower array exploiting the full coverage approach at very high altitude, with the aim of studying the cosmic radiation with a low energy threshold (a few hundreds of GeV).

The detector is constituted by a central carpet $\sim$74$\times$ 78 m^2, made of a single layer of Resistive Plate Chambers (RPCs) with $\sim$92% of active area, enclosed by a guard ring partially instrumented ($\sim$20%) up to $\sim$99$\times$111 m^2. The apparatus has a modular structure, the basic data acquisition element being a cluster (5.7$\times$7.6 m^2), divided into 12 RPCs (2.8$\times$1.25 m^2 each). Each chamber is read by 80 strips of 6.75$\times$61.8 cm^2 (the spatial pixels), logically organized in 10 independent pads of 55.6$\times$61.8 cm^2 which are individually acquired and represent the time pixels of the detector (see Fig. 1). In order to extend the dynamic range up to PeV energies, a charge readout has been implemented by instrumenting every RPC also with two large pads of dimension 140$\times$125 cm^2 each. The full detector is composed of 154 clusters for a total active surface of $\sim$6700 m^2 [1].

ARGO-YBJ is operated in two independent acquisition modes: the *shower mode* and the *scaler mode*. In shower mode, all the events giving a number of fired pads $N_{pad} \geq N_{trig}$ in the central carpet in a time window of 420 ns are recorded. The spatial coordinates and the time of each fired pad are then used to reconstruct the position of the shower core and the arrival direction of the primary particle[2]. To perform the time calibration of the 18480 pads, a software method has been developed [3].

In scaler mode the total counts of the signals coming from the 120 pads of each cluster are added up and put in coincidence in a narrow time window of 150 ns, thus giving the coincidence rates of $\geq$1, $\geq$2, $\geq$3, $\geq$4 pads with a 2 Hz frequency. The corresponding measured rates are respectively $\sim$40kHz, $\sim$2kHz, $\sim$300Hz, $\sim$120Hz for each cluster [4]. Since November 2007 the detector has been in stable data taking with a trigger multiplicity threshold N_{pad}=20 and a duty cycle $\geq$85% with a trigger rate of $\sim$4 kHz.

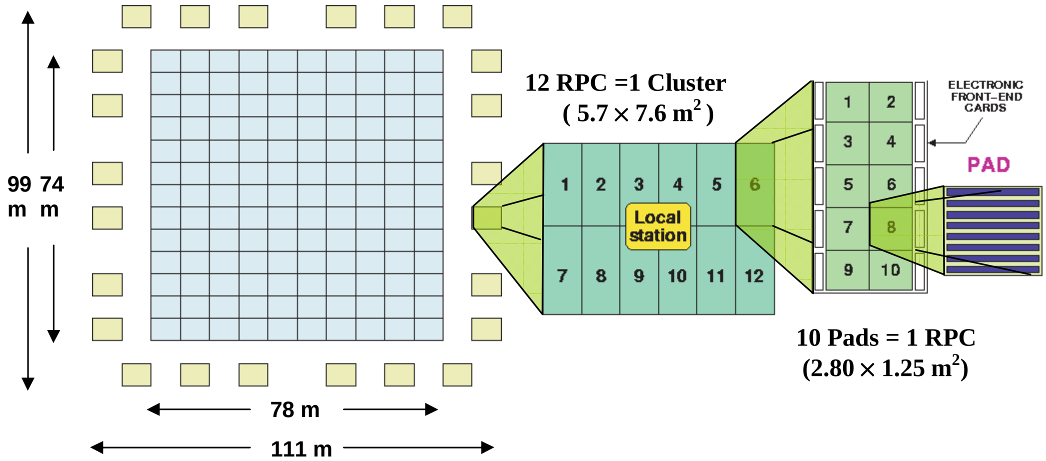

FIGURE 1. Layout of the ARGO-YBJ experiment.

THE MOON AND SUN SHADOWS

Since the Moon and the Sun have an angular radius of about 0.26°, they must cast a shadow in the cosmic ray flux. As first suggested by Clark in 1957 [5], the shadowing of cosmic rays from the direction of the Moon or Sun is useful in measuring the angular resolution of an air shower array directly, without the need of Monte Carlo (MC) simulations. In fact the shape of the shadow provides a measurement of the detector point spread function, and its position allows to find out possible pointing biases.

In addition, due to the geomagnetic field, positively charged particles are deflected towards East by an angle of about 1.6°/E(TeV), where E is the particle energy. This effect produces a displacement of the shadow towards West with respect to the Moon position and smears the shape in the East-West direction, especially at low energies. The observation of the displacement of the Moon provides a check of the relation between the shower size and the primary energy, that means an absolute energy calibration.

ARGO-YBJ is observing the Moon shadow with a sensitivity of about 10 standard deviations per month for events with a multiplicity $N_{pad} \geq 40$ and zenith angle $\theta < 50°$, corresponding to a proton median energy of about 1.8 TeV.

Fig. 2 shows the Moon shadow obtained in 802 hours of measurements, from December 2007 to August 2008, for events with $N_{pad} \geq 40$. A deficit of about 26 standard deviations is visible, slightly shifted towards West by the geomagnetic field.

The upper left panel of Fig. 3 shows the shift of the shadow in the East-West direction obtained with data taken in different time periods, as a function of the minimum pad multiplicity on the central carpet, compared with the shift expected by a MC simulation that propagates protons in the Earth-Moon system. The agreement is quite good, even in 2006 and 2007 data, when the detector was still in the installation and debugging phase.

The lower left panel of the same figure shows the shadow shift in North-South direction. According to simulations, given the ARGO-YBJ geographic location, this shift should be equal to zero. The observed shift of about 0.2° towards North is due

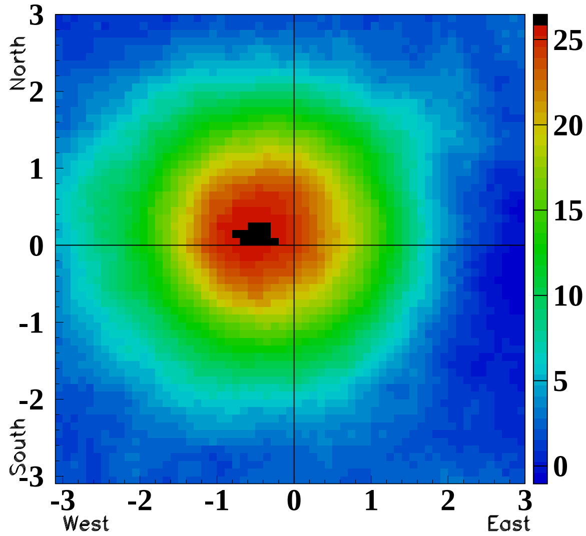

FIGURE 2. Significance map of the Moon region obtained in 802 hours of observation, for events with $N_{pad} \geq 40$. The color scale shows the significance of the deficit in standard deviations. The axes report the distance in degrees from the Moon position. The shift towards West is due do the deflection of cosmic rays by the geomagnetic field.

to a systematic pointing error that we are currently investigating.

Finally, the right plot of Fig. 3 shows the angular resolution of the detector, measured observing the Moon shadow along the North-South direction in 2007 and 2008, as a function of the minimum pad multiplicity. The data are compared with expectations from MC simulation of proton-induced showers. The upper axis reports the median energy of protons corresponding to the given pad multiplicity. As can be seen, the values are in fair agreement: the angular resolution of the ARGO-YBJ experiment is less than 0.6° for $N_{pad} \geq 200$ ($E_{50} \approx 6$ TeV).

This measured angular resolution refers to cosmic ray-induced air showers. The angular resolution for γ-induced events has been evaluated by MC simulations: it results about 20% better due to a more defined temporal profile.

The Sun too casts a shadow on the cosmic rays background, but it appears more smeared because of the additional particle deflection due to the interplanetary magnetic field, whose intensity is related to the solar activity. The Sun shadow is more visible during periods of low solar activity, like in years 2006 - 2008. The left plot of Fig. 4 shows the Sun shadow obtained in 954 hours of measurements, from December 2007 to August 2008, for events with $N_{pad} \geq 40$. A deficit of 24 standard deviations is visible.

THE CRAB NEBULA

The Crab Nebula is the most luminous TeV γ-ray source in the Northern hemisphere and is used as a standard candle for VHE gamma-ray astronomy in order to check the detector sensitivity and the analysis procedure. At the Yangbajing latitude the Crab

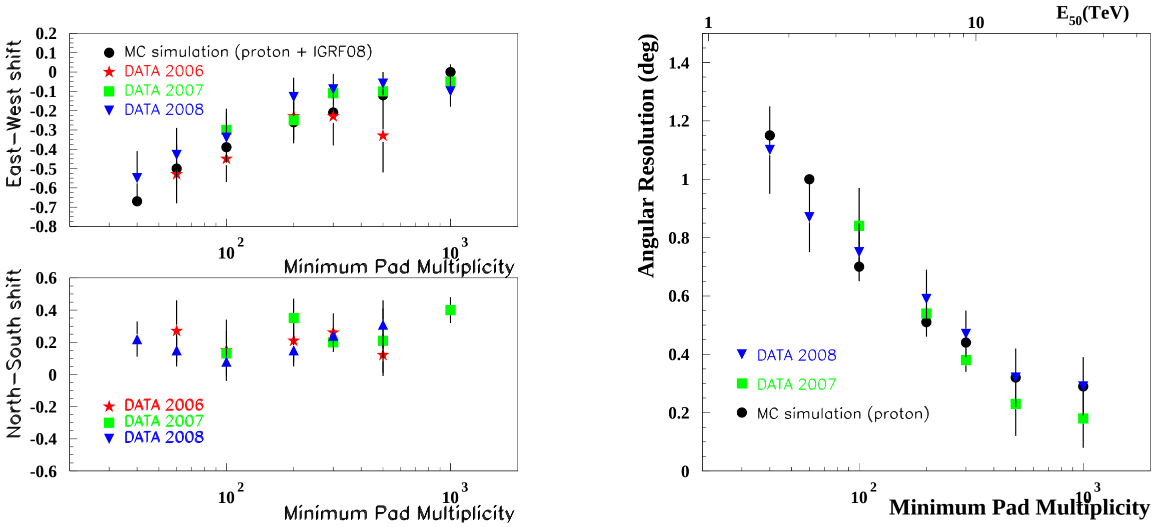

FIGURE 3. Left plot: Shift of the Moon shadow (in degrees) with respect to the Moon position, as a function of the minimum pad multiplicity, in the East-West (upper panel) and North-South direction (lower panel). Right plot: Angular resolution of the detector measured with the Moon shadow technique compared with MC simulations as a function of the minimum pad multiplicity. The upper axis refers to the median energy of protons corresponding to the given pad multiplicity.

culminates at zenith angle $\theta_{culm} = 8.1^\circ$ and it is observable every day for 5.8 hours with a zenith angle $\theta < 40^\circ$.

The Crab Nebula has been observed from 2007 December 13 to 2008 August 17, for a total of 1133 hours on-source, equivalent to about 194 transits of the source. The right plot of Fig. 4 shows the significance map of the Crab Nebula region obtained by ARGO-YBJ, using the events with $N_{pad} \geq 40$ and zenith angle $\theta < 40^\circ$.

The Crab is visible with a statistical significance of about 6 standard deviations. The map has been obtained by *smoothing* with a window of radius $r = 1.2^\circ$ the original event map with bins of size $0.1^\circ \times 0.1^\circ$. The chosen value of r corresponds to the radius of the circular window that maximizes the signal to noise ratio, according to simulations. The median primary energy of photons with $N_{pad} \geq 40$ from a source with the Crab spectrum slope and following the Crab path in the sky is about 1.1 TeV. We note that this is the first time that an air shower experiment detects photons from a point source at this low energy. The number of gamma rays detected per day is 165 ± 35 for $N_{pad} \geq 40$, and 19 ± 7 for $N_{pad} \geq 200$, in fair agreement with simulations of the Crab Nebula spectrum as measured by Cherenkov telescopes.

No event selection and no γ/hadron discrimination has been used in this analysis. An increase of the sensitivity by a factor of about 1.5 is expected by using *topology-based* selection criteria to reject a fraction of background protons, currently under study [6].

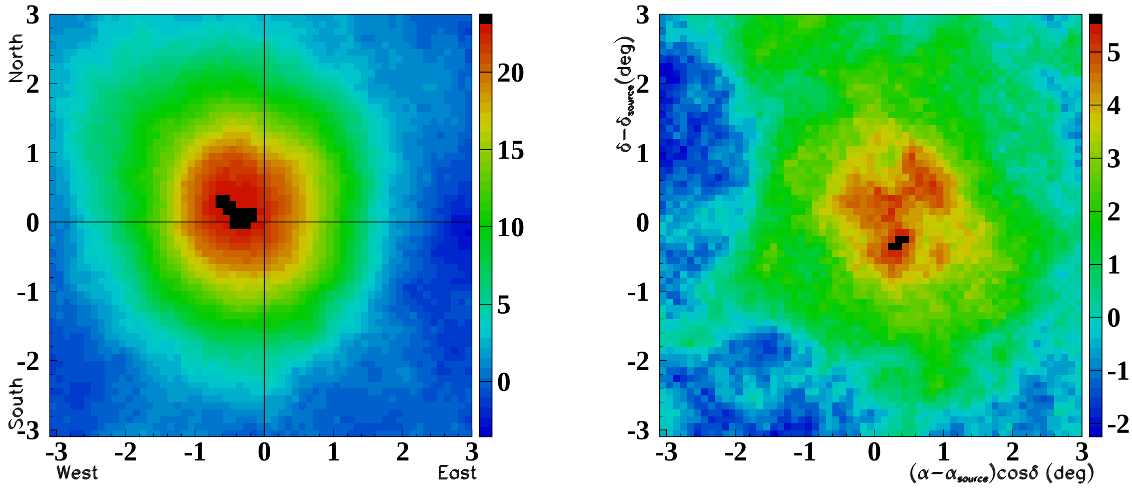

FIGURE 4. Left plot: Significance map of the Sun region obtained in 954 hours of observation, for events with $N_{pad} \geq 40$. The axes report the distance in degrees from the Sun position. Right plot: Significance map of the Crab Nebula region in 194 days of measurements, obtained with showers with $N_{pad} \geq 40$ and zenith angle $\theta < 40°$. The color scale shows the significance of the signal in standard deviations.

MARKARIAN 421

Markarian 421 is the blazar closest to our Galaxy and the first extragalactic source observed in the TeV energy range. It is extremely variable at any wavelength. The X-ray and TeV fluxes are often correlated, and in many occasions the latter becomes several times larger than the Crab Nebula one.

As the Crab Nebula, Mrk421 culminates at the ARGO-YBJ location with a zenith angle of 8.1°, but it is observable every day for 6.3 hours with a zenith angle $\theta < 40°$.

In 2008, Mrk421 entered a very active phase and was one of the brightest sources in the TeV sky, showing strong and frequent flaring. With the ARGO-YBJ experiment we performed a continuous TeV monitoring over the whole year.

The left plot of Fig. 5 shows the significance map of the Mrk421 region, obtained sampling showers with $N_{pad} \geq 40$ and zenith angle $\theta < 40°$ from 2007 December 13 to 2008 August 17, for a total of 1217 on-source hours.

The significance of the signal is more than 6 standard deviations. The observed average flux is comparable with the Crab one, but the signal intensity varies with time, reaching a value of 3-4 Crab units during 10 days, in February and June. The flux shows a strong correlation with the X-ray flux measured by the All Sky Monitor detector aboard the RXTE satellite, in the 1.5-12 keV energy range.

The right plot of Fig. 5 shows the number of events per hour with $N_{pad} \geq 40$ and ≥ 100 (averaged over 10 days) observed by ARGO-YBJ in a circular window of radius 0.9° around the source, as a function of time, compared to the daily averaged counting rate of the All Sky Monitor detector [7]. The median energy of events with $N_{pad} \geq 40$ (100) is 1.1 (2.4) TeV.

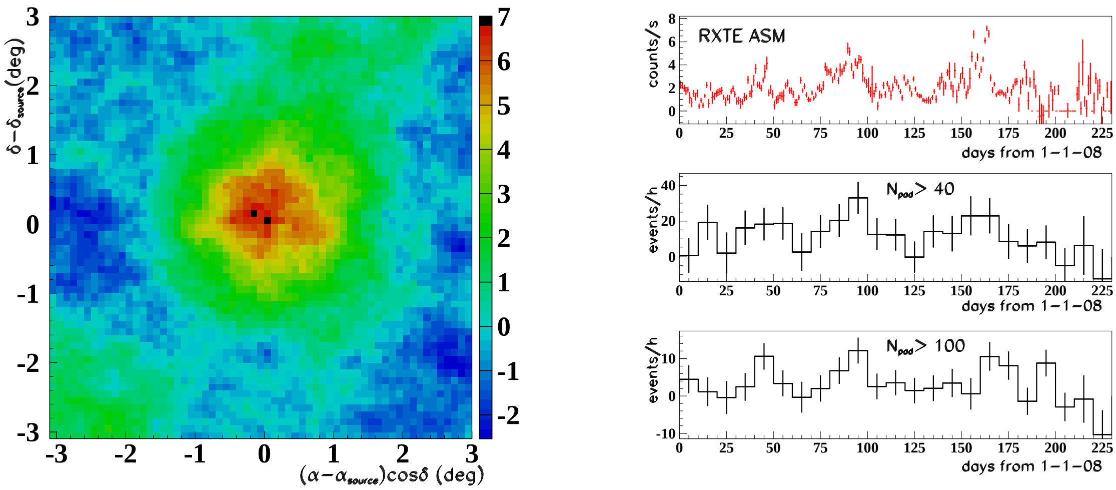

FIGURE 5. Left plot: Signifi cance map of the Mrk421 region observed from December 2007 to August 2008 for events with $N_{pad} \geq 40$ and zenith angle $\theta < 40°$. Right Plot: Correlation between daily averaged X-ray data and TeV photons for two multiplicity values during 230 days of 2008.

GAMMA RAY BURSTS

The scaler mode technique allows ground based experiments to study GRBs in the GeV energy range, where gamma rays are less affected by the absorption due to pair production in the extragalactic space [8].

The search for high energy tails of GRBs has been done in coincidence with 39 GRBs detected by satellites (mainly Swift), from November 2004 to June 2008, in the ARGO-YBJ field of view ($\theta < 45°$). During this period the detector surface increased from $\sim$693 to $\sim$6628 m^2. Among these events, 35 belong to the so called *long* GRB class, (i.e. the duration is T>2 s), and 4 are *short* (T≤2 s).

For each GRB, the search has been done by looking for an excess of the single particle counting rate during the T90 time, i.e. during the time when the satellite instruments detected 90% of the emission. No excess has been found in coincidence with any satellite observation.

Fig. 6 shows the fluence upper limits (99% confidence level) in the energy range 1-100 GeV obtained for the 39 GRBs, as a function of the zenith angle [9]. The upper limits have been calculated assuming a GRB power law spectrum with a differential index α= -2.5, corrected by an exponential factor to account for the extragalactic absorption. The absorption factor has been evaluated according to [10], using the measured redshift when available (in 8 cases), otherwise setting the redshift z=1.

In order to extract the maximum information from the data, other two GRB searches have been implemented: (1) stacked search for a signal of fixed duration; (2) phase pile-up of all GRBs.

The resulting significances for the 9 time bins Δt=0.5, 1, 2, 5, 10, 20, 50, 100, 200 s show that there is no evidence for emission at a certain Δt. The resulting overall significance of the GRBs stacked in time with respect to random fluctuations is 0.27

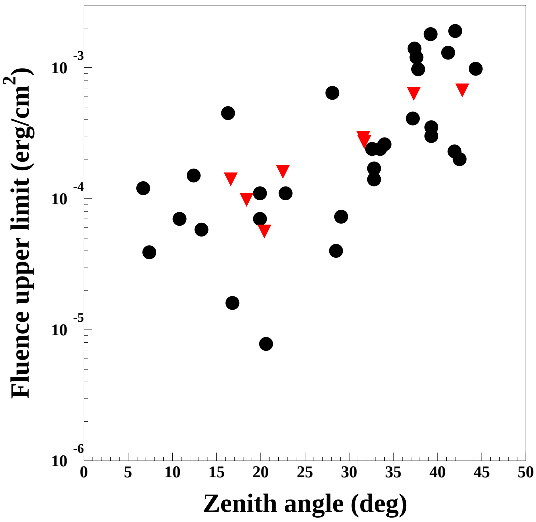

FIGURE 6. Fluence upper limits for 39 GRBs in the energy range 1-100 GeV, as a function of the zenith angle. The absorption of gamma rays in the intergalactic space has been taken into account using the measured GRB redshift when available (red triangles) or assuming z=1 when the distance is unknown (black circles).

σ. In the other analysis the resulting significances for 10 phase bins show no evidence for emission at a certain phase and the overall significance of the GRBs stacked in phase with respect to background fluctuations is 0.36 σ.

MEASUREMENT OF THE PROTON-AIR CROSS SECTION

A measurement of the proton-air cross section has been performed by exploiting the attenuation of the cosmic ray flux with the increasing of zenith angles θ (i.e., atmospheric depth), namely $I(\theta) \simeq I(0)exp(-x_0(sec\theta - 1)/\Lambda_{obs})$, where x_0 is the vertical atmospheric depth at the detector location and Λ_{obs} is the observed attenuation length of air showers related to the mean free path λ_{int} of the primary particle through the parameter $K = \Lambda_{obs}/\lambda_{int}$. This parameter, which takes into account the fluctuations both in the shower development and in the shower sampling, is calculated via MC simulation. In order to cover a wide energy range the strip multiplicity has been used to estimate the energy; accordingly 6 multiplicity bins have been defined corresponding to median energies going from 300 GeV up to $\sim$ 80 TeV. The measured p-air cross section values are reported in the left plot of Fig.7; the estimated p$-$p cross section values are shown in the right plot [11].

The analog readout of RPCs will allow the extension of the investigated energy range up to the PeV region.

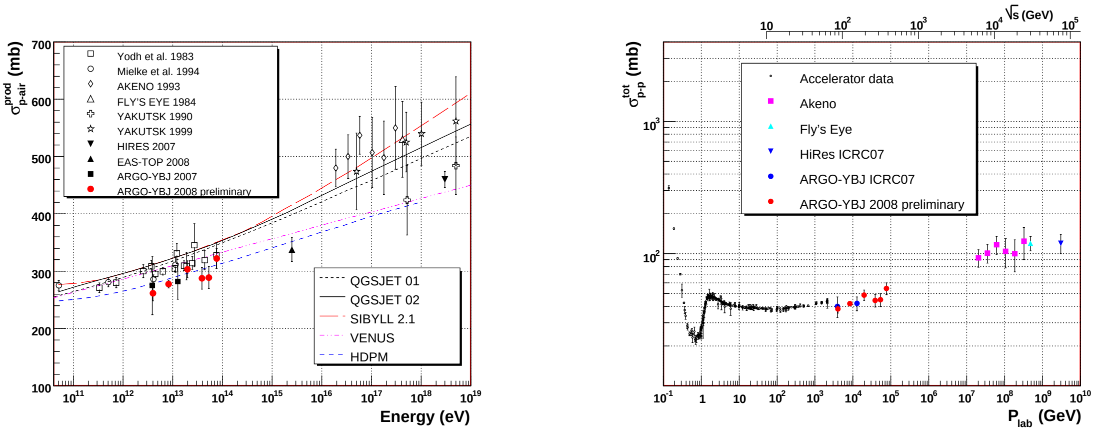

FIGURE 7. Left plot: Current data of proton-air cross section measurements; the predictions of some hadronic interaction models are also shown. Right Plot: Current data of proton-proton cross section measurements.

MEASUREMENT OF THE ANTIPROTON/PROTON RATIO

In order to measure the $\overline{p}/p$ ratio at TeV energies we exploit the Earth-Moon system as an ion spectrometer: if protons are deflected towards East, antiprotons are deflected towards West. If the energy is low enough and the angular resolution small we can distinguish, in principle, between two shadows, one shifted towards West due to the protons and the other shifted towards East due to the antiprotons. If no event deficit is observed on the antimatter side an upper limit on the antiproton content can be calculated. A preliminary measurement has been performed with the ARGO-YBJ experiment for $N_{pad} \geq 40$ in the period December 2007 - August 2008 (802 hours on-source). For this multiplicity the Moon shadow shifts westward by about 0.45°, at a median energy $\approx$2 TeV (mode energy $\approx$0.5 TeV). The data are in fair agreement with MC simulation. The deficit events around the Moon shadow (in the range $\pm 4°$ for the East-West direction and $\pm 2°$ for the North-South direction) are fitted with a Gaussian formula: protons are estimated to be $\sim$70% of cosmic rays. A preliminary upper limit on the antiproton/proton ratio with 90% confidence level is calculated to be about 10% and reported in Fig. 8, which also shows the status of the antiproton/proton measurements. We note that in the multi-TeV range this result is among the lowest available.

CONCLUSIONS

The ARGO-YBJ experiment has been completely installed and since November 2007 is taking data with a duty cycle $\geq$85%.

The detection of the Moon and Sun shadows, and the observation of gamma rays from the Crab Nebula and Mrk421 show that the detector is properly working, with good angular resolution and sensitivity.

The Crab Nebula has been observed with a statistical significance of about 6 standard deviations in 194 days, at a median gamma ray energy of about 1.1 TeV.

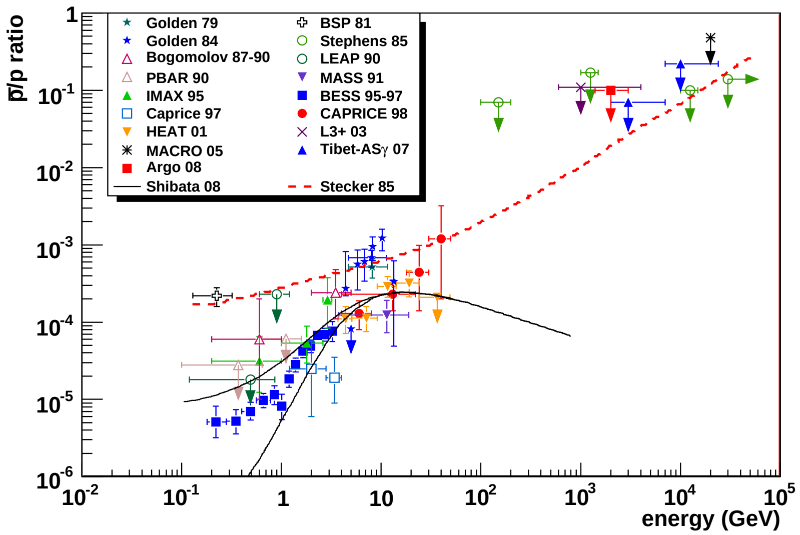

FIGURE 8. Status of the measurements of the $\overline{p}/p$ ratio.

Mrk421 has been detected with a statistical significance of more than 6 standard deviations in the first 8 months of 2008. In particular the data show a strong variability, and a correlation with the X-ray emission has been observed during the whole period.

Working in *scaler mode* ARGO-YBJ has performed a search for emission from GRBs in coincidence with 39 events observed by satellites, setting upper limits on the fluence between 8×10^{-6} and 2×10^{-3} erg cm^{-2} in the 1-100 GeV energy range.

The p-air cross section has been measured in the range 1 - 100 TeV and the corresponding p-p cross section inferred. A preliminary measurement of the $\overline{p}/p$ ratio at TeV energies has been performed. Un upper limit of about 10% (90% c.l.) has been put with only 8 months of data.

In the next future improvements of the detector capability are expected from the application of γ/hadron separation algorithms to data and from the analog readout operation.

REFERENCES

1. G. Aielli at al., *NIM* **A562**, 92 (2006).
2. G. Di Sciascio et al., in Proc. *30th ICRC*, Merida (2007) in press.
3. G. Aielli et al., *Astrop. Phys.* **30**, 287 (2009).
4. G. Aielli et al., *Astrop. Phys.* **30**, 85 (2008).
5. G.W. Clark, *Phys. Rev.* **108**, 450 (1957).
6. M. Dattoli et al., in Proc. *30th ICRC*, Merida (2007) in press.
7. http://xte.mit.edu/.
8. S. Vernetto, *Astrop. Phys.* **13**, 75 (2000).
9. T. Di Girolamo et al., in Proc. *21st* ECRS, Kosice (2008) in press.
10. T.M. Kneiske et al., *A&A* **413**, 807 (2004).
11. I. De Mitri et al., in Proc. *ISVHECRI '08*, Paris (2008) in press.