ARGO-YBJ Experiment: Cosmic Ray physics results

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0.1. Observation of TeV Cosmic Ray anisotropies

Galactic Cosmic Rays at TeV energies are expected to appear highly isotropic, since during their propagation from the sources to the Earth they undergo complex processes, such as the deflection by the large scale Galactic magnetic field and the interaction with background photons and interstellar medium. Thus the study of the galactic CR anisotropy is a useful tool in probing the magnetic field structure in our interstellar neighbourhood as well as the source distribution.

Several experiments have reported two large-scale anisotropic structures, the so-called *'tail-in'* and *'loss-cone'* regions. With two years of data, ARGO-YBJ [1] carried out a two-dim. (2D) measurement to investigate the detailed structural information of the large scale CR anisotropy beyond the simple Right Ascension (R.A.) profiles. The two anisotropic regions, correlated to an enhancement or deficit of CRs, are clearly visible with a significance of about 20 s.d. (Fig. 1). A new excess component with a ∼0.1% increase of the CR intensity in the Cygnus region is observed with a significance of about 10 s.d.. To quantify the scale of the anisotropy we fitted the 1D R.A. projection of the 2D map with the first two harmonics for three different energies. The preliminary results (E = 0.7 TeV, A_1=(3.6±0.1)·10^{-4}, ϕ_1=63.4°±0.9°; E = 1.5 TeV, A_1=(6.8±0.1)·10^{-4}, ϕ_1=41.0°±0.7°; E = 3.9 TeV, A_1=(9.0±0.1)·10^{-4}, ϕ_1=35.3°±0.6°) are in good agreement with other experiments.

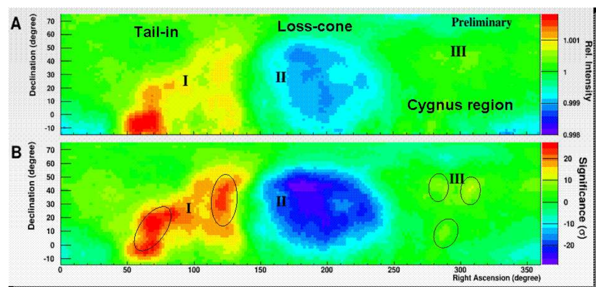

Figure 1. Large scale CR anisotropy observed by ARGO-YBJ at energies ∼ 2 TeV. In the upper plot the colour scale gives the relative CR intensity, in the lower plot the statistical significance in standard deviations.

Using different analysis methods, ARGO-YBJ is able to observe anisotropies in all scale, including the intermediate one. Fig. 2 shows the sky map for events with $N_{pad} \geq 40$ fired pads and zenith angle $\theta < 40°$ (corresponding to a proton median energy ∼ 2 TeV), obtained with a 5° smoothing radius. The analysis has been performed in order to be insensitive to the CR large-scale anisotropy which is roughly one order of magnitude greater. The map clearly shows two large hot spots in the region of the Galactic anti-center. The two excesses (>10 s.d., corresponding to a flux increase of ∼0.1%), observed by ARGO-YBJ around the positions $\alpha \sim 120°$, $\delta \sim 40°$ and $\alpha \sim 60°$, $\delta \sim$ -5°, are the same visible in the already shown tail-in region. They are in agreement with a similar detection of the Milagro experiment [2]. However, the maximum of the second excess is slightly shifted towards lower declinations, probably because ARGO-YBJ can observe

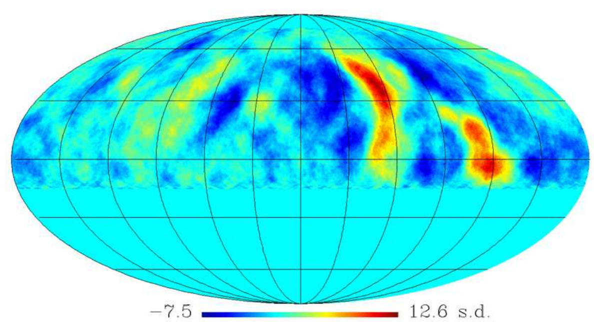

Figure 2. Medium scale anisotropy of CRs at energies ∼ 2 TeV. The colour scale gives the statistical significance in standard deviations.

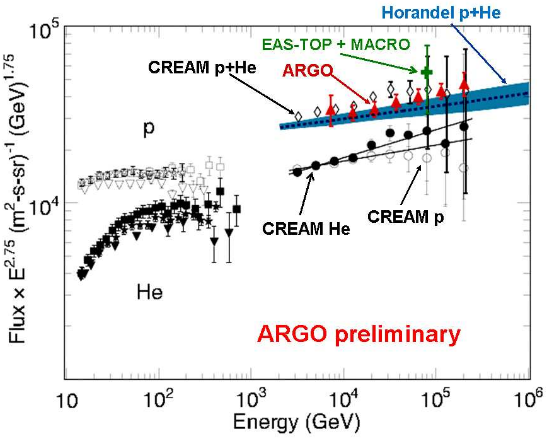

Figure 3. Light-component (p+He) differential spectrum of primary CRs measured by ARGO-YBJ, compared with other experimental results.

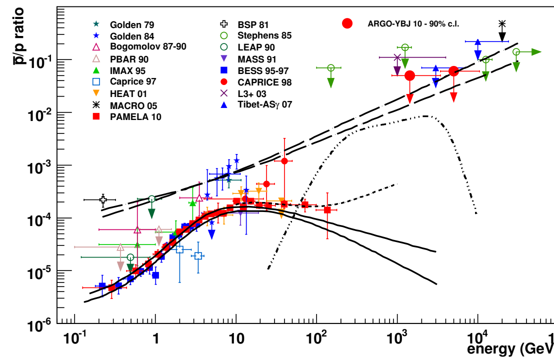

Figure 4. The measure of the $\overline{p}/p$ ratio obtained with the ARGO-YBJ experiment compared with all available measurements. The solid curves refer to a direct production model. The dashed lines refer to a model of primary $\bar{p}$ production by antigalaxies. The rigidity-dependent confinement of cosmic rays in the Galaxy is assumed to be $\propto$ $\mathrm{R}^{-\delta}$, and the two dashed curves correspond to the cases of $\delta = 0.6$, 0.7. The dotted line refers to the contribution from a heavy Dark Matter particle annihilation.

the southern regions of the sky with more efficiency, being located at a lower latitude than Milagro. The deficit regions parallel to the excesses are due to a known effect of the analysis, that uses also the excess events to evaluate the background, artificially increasing the background.

The origin of this anisotropy is puzzling. In fact, these regions have been interpreted as excesses of hadronic CRs, but TeV CRs are expected to be randomized by the magnetic fields. Understanding these anisotropies should be a high priority as they are probably due to a nearby source of CRs, as suggested by some authors [3].

0.2. Light-component Cosmic Ray spectrum

A first measurement of the differential energy spectrum of the primary CR light component (p+He) has been performed by ARGO-YBJ applying a Bayesian unfolding approach to the strip multiplicity spectrum. The results are briefly outlined here, more details can be found in We selected showers with zenith angle $\theta < 30°$ and with reconstructed core position inside a fiducial area 50×50 m^2 large by applying a selection criterion based on the fired strip density. According to Monte Carlo (MC) simulations, in the investigated energy range, the contamination of nuclei heavier than Helium (mainly CNO and Iron) is found to be negligible, not exceeding a few percents (thanks to the event selection cuts). On the other side, the present analysis does not allow the determination of the individual proton and Helium contribution to the measured flux.

In Fig. 3, the result by ARGO-YBJ (filled triangles) in the energy region $(5 - 250)$ TeV is compared with other experiments. We note that the ARGO-YBJ measures agree remarkably well with the values obtained by adding up the proton and helium fluxes measured by the CREAM experiment in the same energy range, concerning both the total intensities and the spectrum (Ahn H.S. et al., 2010). The value of the spectral index of the power-law fit representing the ARGO-YBJ data is -2.61 ± 0.04, which should be compared to $\gamma_p = -2.66 \pm 0.02$ and $\gamma_{He} = -2.58 \pm 0.02$ obtained by the CREAM experiment.

It is worth to stress that for the first time direct and ground-based measurements overlap for a wide energy range thus making possible the cross-calibration of the different experimental techniques.

0.3. Measurement of the $\overline{p}/p$ ratio

The study of the Moon shadow permits to measure the $\overline{p}/p$ ratio in CR flux: 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. In the ARGO-YBJ experiment, the angular resolution is small enough for events with at least ~ 40 fired pads, thus allowing such a measurement at few TeV energy range.

As showed in Section 2, with all data up to December 2009 we detected the Moon shadow on CRs with a significance of about 55 s.d. (3200 hours on-source). We selected 2 multiplicity bins,

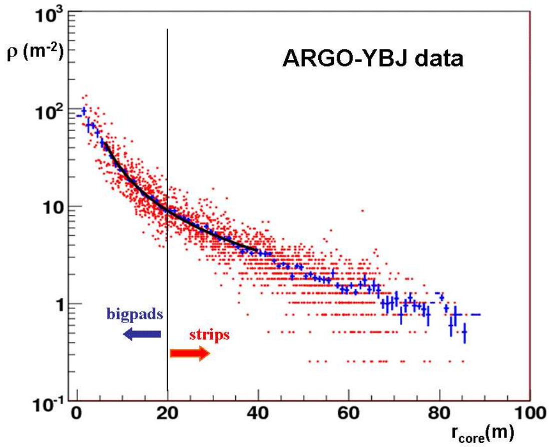

Figure 5. Lateral density function of showers detected by ARGO-YBJ, as reconstructed from RPC charge information up to $\sim$ 20 m from the core, while the strip information are used for larger distances.

40<N<100 and N>100. In the first interval the statistical significance of the Moon shadow is 34 s.d., the measured angular resolution is $\sim$1° and the median energy is 1.4 TeV. For N>100 the significance is 55 s.d., the angular resolution is $\sim$0.6° and the median energy is 5 TeV. With all the data up to December 2009 we set two upper limits to the $\overline{p}/p$ ratio at the 90% confidence level: 5% at 1.4 TeV and 6% at 5 TeV. The upper limits calculated with ARGO-YBJ are compared in Fig. 4 with all the available $\overline{p}/p$ measurements and with some theoretical models for antiproton production.

0.4. Measurement of the total p-p cross section

From the ARGO-YBJ data, the proton-air production cross section has been measured in the p enery range $\sim 10^{12} - 10^{14}$ eV, while a well known theoretical approach has been used to infer the corresponding p-p total cross section in an energy region until now unexplored by accelerator experiments. Such an analysis has been entirely carried out by the Lecce group and has been extensively described in [5]. Analysis details can be found in [6] and [7].

Presently, the possible development of this analysis is under investigation by using the data from the RPC analog charge readout, which allow to extend the study to collisions with center-of-mass energies up to the $\sim$ TeV region. On the other hand, these data will provide a much more accurate shower size and lateral density profile determination, thus giving a more reliable reconstruction of physical quantities (Fig. 5). Moreover, further improvements are expected from the use of several detailed information on the shower front (curvature, rise time, time width, etc.), that ARGO-YBJ is able to record with very high precision (see Section 9.1 above). This could give a better constraint on the longitudinal shower profile and X_{max} depth, which, as already stated, is a crucial point for minimizing shower development fluctuations (thus reducing the sistematic uncertainty).

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