Detection of EASs at high altitude with ARGO-YBJ

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Abstract. The ARGO-YBJ experiment has been in stable data taking for about 5 years at the YangBaJing Cosmic Ray Observatory (Tibet, P.R. China, 4300 m a.s.l., 606 g/cm$^2$). With a duty-cycle greater than 86% the detector collected about $5 \times 10^{11}$ events in a wide energy range, from few hundreds GeV up to about 10 PeV. Exploiting the full coverage approach with a high segmentation of the readout at high altitude, ARGO-YBJ imaged the front of Extensive Air Showers (EAS) with unprecedented resolution and detail. A number of important problems in galactic cosmic ray physics has been faced through different analyses. In this contribution we summarize the latest results in gamma-ray astronomy and in cosmic ray physics.

1. The ARGO-YBJ experiment

ARGO-YBJ is a multipurpose experiment consisting in a dense sampling air shower array with 93% sensitive area located at very high altitude and devoted to the integrated study of gamma rays and cosmic rays with an energy threshold of a few hundreds GeV (for a summary of the ARGO-YBJ results see [1]).

The detector, located at the Yangbajing Cosmic Ray Observatory (Tibet, PR China, 4300 m a.s.l., 606 g/cm$^2$), is constituted by a central carpet $\sim 74 \times 78$ m$^2$, made of a single layer of resistive plate chambers (RPCs) with $\sim 93\%$ of active area, enclosed by a guard ring partially instrumented ($\sim 20\%$) up to $\sim 100 \times 110$ m$^2$. The apparatus has a modular structure, the basic data acquisition element being a cluster ($5.7 \times 7.6$ m$^2$), made of 12 RPCs ($2.85 \times 1.23$ m$^2$ each). Each chamber is read by 80 external strips of $6.75 \times 61.80$ cm$^2$ (the spatial pixels), logically organized in 10 independent pads of $55.6 \times 61.8$ cm$^2$ which represent the time pixels of the detector [2]. The readout of 18,360 pads and 146,880 strips is the experimental output of the detector. The relation between strip and pad multiplicity has been measured and found in fine agreement with the Monte Carlo prediction [2]. In addition, in order to extend the dynamical range up to PeV energies, each chamber is equipped with two large size pads ($139 \times 123$ cm$^2$) to collect the total charge developed by the particles hitting the detector [3]. The RPCs are operated in streamer mode by using a gas mixture (Ar 15%, Isobutane 10%, TetrafluoroEthane 75%) for high altitude operation [4]. The high voltage settled at 7.2 kV ensures an overall efficiency of about 96% [5]. The central carpet contains 130 clusters (hereafter ARGO-130) and the full detector is composed of 153 clusters for a total active surface of $\sim 6700$ m$^2$ (Fig. 1). The total instrumented area is $\sim 11,000$ m$^2$. The information on strip multiplicity and the arrival times recorded by each pad are received by a local station devoted to manage the data of each cluster. A central station collects the information of all the local stations. The time of each fired pad in a window of 2 µs around the trigger time and its location are used to reconstruct the position of the shower core and the arrival direction of the primary particle. In order to perform
the time calibration of the 18,360 pads, a software method has been developed [6]. To check the stability of the apparatus a control system monitors continuously the current of each RPC, the gas mixture composition, the high voltage distribution as well as the environment conditions (temperature, atmospheric pressure, humidity).

The detector is connected to two different data acquisition systems, working independently, and corresponding to the two operation modes, shower and scaler. In shower mode, for each event the location and timing of every detected particle is recorded, allowing the reconstruction of the lateral distribution and the arrival direction [7, 8]. In scaler mode the total counts on each cluster are measured every 0.5 s, with limited information on both the space distribution and arrival direction of the detected particles, in order to lower the energy threshold down to ∼1 GeV [9].

In shower mode, a simple, yet powerful, electronic logic has been implemented to build an inclusive trigger. This logic is based on a time correlation between the pad signals depending on their relative distance. In this way, all the shower events giving a number of fired pads $N_{pad} \geq N_{trig}$ in the central carpet in a time window of 420 ns generate the trigger. This trigger can work with high efficiency down to $N_{trig} = 20$, keeping negligible the rate of random coincidences.

Because of the small pixel size, the detector is able to record events with a particle density exceeding 0.003 particles $m^{-2}$, keeping good linearity up to a core density of about 15 particles $m^{-2}$. This high granularity allows a complete and detailed three-dimensional reconstruction of the front of air showers at an energy threshold of a few hundred GeV, as can be appreciated in Fig. 2 (left plot) where a typical shower detected by ARGO-YBJ is shown. Showers induced by high energy primaries (>100 TeV) are also imaged by the charge readout of the large size pads (see Fig. 2, right plot), which allow the study of shower core region with unprecedented resolution [3].

The whole system, in smooth data taking since July 2006 with ARGO-130, has been in stable data taking with the full apparatus of 153 clusters from November 2007 to January 2013, with the trigger condition $N_{trig} = 20$ and a duty cycle $\geq 86\%$. The trigger rate is $\sim 3.5$ kHz with a
dead time of 4%.

1.1. Event reconstruction and data selection in shower mode

The reconstruction of the shower parameters is carried out through the following steps.

At first, a plane surface is analytically fitted (with weights equal to 1) to the shower front. This procedure is repeated up to 5 times, each iteration rejecting hits whose arrival time is farther than 2 standard deviations from the mean of the distribution of the time residuals from the fitted plane surface. This iterative procedure is able to reject definitively from the reconstruction the time values belonging to the non-Gaussian tails of the arrival time distribution [10]. After this first step the problem is reduced to the nearly-vertical case by means of a projection which makes the fit plane overlapping the detector plane. Thereafter, the core position, i.e. the point where the shower axis intersects the detection plane, is obtained fitting the lateral density distribution of the secondary particles to a modified Nishimura-Kamata-Greisen (NKG) function. The fit procedure is carried out via the maximum likelihood method [7]. Finally, the core position is assumed to be the apex of a conical surface to be fitted to the shower front. The slope of such a conical correction is fixed to $\alpha = 0.03 \text{ ns/m}$ [10].

The capability of reconstructing the primary arrival direction can be further enhanced by applying robust statistical methods in the analysis of the shower front, conveniently weighting the contribution of the most delayed particles. In detail, we first fit a conical surface to the shower image, by minimizing the sum of the squares of the time residuals. At this stage, all the particles hitting the detector have the same weight $w_i=1$. After computing the RMS of the time residual distribution with respect to such a conical surface, we set $K = 2.5 \cdot \text{RMS}$ as a ‘scale parameter’ and perform the minimization of the square of the time residuals weighted sum, where $w_i=1$ if the particle is onward the shower front, $w_i=f((t_{\text{exp}}^i - t_{\text{fit}}^i)/K)$ otherwise. The function $f(x)$ is a common Tukey biweight function [11]. The fit procedure is iterated, every time refreshing the scale parameter, until the last reconstructed direction differs from the previous one for less than 0.1°.

1.2. Scaler Mode Technique

The study of transient phenomena (such as GRBs, solar flares) can be successfully performed by ground-based experiments such as EAS detectors down to about 1 GeV working in “single
particle mode”, i.e. counting all the particles hitting the individual detectors, independently of whether they belong to a large shower or they are the lone survivors of small showers [12]. Because of the cosmic ray spectrum steepness, most of the events detected with this technique are in fact due to solitary particles from small showers generated by 1–100 GeV cosmic rays.

The power of this technique is in its extreme simplicity: it is sufficient to count all the particles hitting the detectors during fixed time intervals (i.e. every second or more frequently, depending on the desired time resolution) and to study the counting rate behaviour versus time, searching for significant increases. The observation of an excess in coincidence with a transient phenomenon detected by a satellite would be an unambiguous signature of the nature of the signal. The single particle technique does not allow one to measure energy and direction of the primary particle, because the number of detected particles (often only one per shower) is too small to reconstruct the shower parameters. For this technique, an accurate knowledge of the detector and its sensitivity to both environmental and instrumental parameters is of crucial importance in order to correctly evaluate the statistical significance of the detected signals.

In ARGO-YBJ, the counting rate of each cluster is measured every 0.5 s, with no measurement of the lateral distribution and arrival direction of the detected particles. For each cluster the signal coming from the 120 pads is added up and put in coincidence in a narrow time window (150 ns), giving the rate of counts $\geq 1$, $\geq 2$, $\geq 3$, $\geq 4$, read by four independent scaler channels. The corresponding measured rates are, respectively, $\sim 40$ kHz, $\sim 2$ kHz, $\sim 300$ Hz and $\sim 120$ Hz for each cluster. The counting rates for a given multiplicity are then obtained with the relation $n_i = n_{\geq i} - n_{\geq i+1}$ for $i = 1, 2, 3$.

The study of the counting distribution for each cluster is important in order to monitor the stability of the detector and its statistical (Poissonian) behaviour. Fig. 3 shows the experimental distributions of the counting rates and their Gaussian fits for a typical cluster: (a) $C_{\geq 1}$, (b) $C_{\geq 2}$, (c) $C_{\geq 3}$ and (d) $C_{\geq 4}$ for 30 minutes data accumulation. The standard deviation of the Gaussian fit ($\sigma_{\text{exp}}$) is compared with the square root of the mean of the experimental distribution ($\sigma_{\text{th}}$) to check the compatibility with the Poisson distribution.

![Figure 3](image-url)
counting rates for multiplicities $\geq 1$, $\geq 2$, $\geq 3$, $\geq 4$ for a typical cluster during 30 minutes of data acquisition. The distributions for all $C_{\geq i}$ are Poissonian, meaning that the environmental parameter variations have negligible effects over such a time scale. Detailed discussions can be found in [9].

1.3. Angular resolution and energy scale calibration

The performance of the detector and the operation stability are continuously monitored by observing the Moon shadow, i.e., the deficit of cosmic rays detected in its direction. Indeed, the size of the deficit allows the measurement of the angular resolution and its position allows the evaluation of the absolute pointing accuracy of the detector. In addition, since charged particles are deflected by the geomagnetic field (GMF), the observation of the displacement of the shadow of the Moon provides a direct calibration of the relation between shower size (the recorded pad/strip multiplicity) and primary energy. The calibration of the absolute energy scale of ground-based detectors is one of the main problems affecting indirect measurements of cosmic rays.

ARGO-YBJ observes the Moon shadow with a sensitivity of about 9 standard deviations (s.d.) per month for events with a multiplicity $N_{\text{strip}} \geq 40$ and zenith angle $\theta < 50^\circ$, corresponding to a proton median energy $E_p \sim 1.8$ TeV. The significance map of the Moon region obtained with all data from July 2006 to November 2010 is shown in Fig. 4. The CR Moon shadowing effect is observed with a significance of about 70 s.d. The data analysis and a full account of the results are described in [14]. The measured angular resolution is better than 0.5° for CR-induced showers with energies $E > 5$ TeV (Fig. 5), in excellent agreement with the MC evaluation. With the same simulation codes we find that the angular resolution for $\gamma$-rays is smaller by about 30–40%, depending on the multiplicity, due to the better defined time profile of the showers.

In Fig. 6 the displacement of the Moon shadow in the East-West direction as a function of
the particle multiplicity, i.e. the number of fired strips $N_{\text{strip}}$ on ARGO-YBJ central carpet, is shown. The observed westward shift is compared to the MC simulation of the cosmic ray primary propagation in Earth-Moon system [15]. The rigidity scale refers to the rigidity (TeV/Z) associated to the median energy in each multiplicity bin. The good agreement between data and simulation allows the attribution of this displacement to the combined effect of the detector point spread function (PSF) and the GMF, making us confident in the energy calibration of the detector. Therefore, the rigidity scale can be fixed in the multiplicity range 20-2000 particles, where the Moon shadow is moving under the bending effect of the GMF. The absolute rigidity scale uncertainty in the ARGO-YBJ experiment is estimated to be smaller than 13% in the energy range from 1 to 30 (TeV/Z) [14].

The displacement of the center of the Moon shadow in the North-South direction enables us to estimate the systematic error in pointing accuracy and its long-term stability aside from Monte Carlo simulations, since the East-West component of the GMF is almost zero at YangBaJing. The amount of CR deficit due to the Moon provides a good estimation of the size of the shadow, therefore of the angular resolution. The position of the Moon shadow measured with the ARGO-YBJ experiment turned out to be stable at level of 0.1° and the angular resolution is stable at level of 10%, on a monthly basis [14].

2. ARGO-YBJ recent highlights in Gamma-Ray Astronomy

2.1. The Fermi Cocoon in the Cygnus region

The Cygnus region is the brightest portion of the gamma ray northern sky, where several complex structures have been observed at different wavelengths. This region is rich in potential cosmic ray acceleration sites, including Wolf-Rayet stars, OB associations, supernova remnants, pulsars, microquasars and superbubbles. Various Very High Energy (VHE) gamma ray sources have been detected within the Cygnus region, the brightest ones being the extended MGRO J2031+41/TeV J2032+4130 and MGRO J2019+37 [16], whose locations are consistent with two Fermi pulsars [17].

![Figure 6](image-url)

**Figure 6.** Measured westward displacement of the Moon shadow as a function of multiplicity (black squares). The data are compared to MC simulation (red circles). The upper scale refers to the median energy of rigidity (TeV/Z) in each multiplicity bin.
The significance map of the Cygnus region as observed by ARGO-YBJ using events with $N_{\text{pad}} > 20$ is shown in Figure 7 [18]. The four known TeV sources and the 24 GeV sources in the second Fermi/LAT catalogue are also marked in the figure. An excess is observed over a large part of the region, indicating a possible diffuse gamma ray emission (see next section).

A signal with a significance larger than 6 s.d. is detected at the position of MGRO J2031+41. The source extension is determined to be $\sigma_{\text{ext}} = (0.2^{+0.4}_{-0.2})^\circ$, consistent with the previous estimations by HEGRA [19] and MAGIC [20] experiments. Assuming an intrinsic extension $\sigma_{\text{ext}} = 0.1^\circ$, the energy spectrum measured in the range 0.6-7 TeV is $dN/dE = (1.40 \pm 0.34) \times 10^{-11} (E/1 \text{ TeV})^{-2.83^{+0.37}_{-0.34}} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ and is reported in Figure 8. The integral flux above 1 TeV is $\sim 0.3$ Crab unit, in agreement with Milagro results [21, 22] but about a factor 10 higher than the fluxes determined by HEGRA and MAGIC.

In a location consistent with MGRO J2031+41, Fermi/LAT detected a complex extended source, attributed to the emission by a “cocoon” of freshly accelerated cosmic rays which fill the cavities carved by stellar winds and ionization fronts from young stellar clusters [23]. After reanalysing the complete ARGO-YBJ data set, subtracting the contribution of the overlapping TeV sources and using a larger region to evaluate the excess map (since Fermi/LAT observations revealed a large extended source), ARGO J2031+4157 resulted with an extension $\sigma_{\text{ext}} = 1.8^\circ \pm 0.5^\circ$, consistent with that of the Cygnus Cocoon as measured by Fermi/LAT, i.e., $\sigma_{\text{ext}} = 2.0^\circ \pm 0.2^\circ$ [24]. The ARGO-YBJ view of the Cygnus Cocoon region (for $N_{\text{pad}} \geq 20$) is given in Figure 9, where the largest statistical significance is 6.1 s.d., at the position of ARG J2031+4157.

The spectrum also shows a good connection with that determined by Fermi/LAT in the 1-100 GeV energy range, as shown in Figure 10. Therefore, ARG J2031+4157 is identified as the counterpart of the Cygnus Cocoon at TeV energies. The combined differential spectrum of Fermi/LAT and ARGO-YBJ data is fitted with the power law function $dN/dE = (3.5 \pm 0.3) \times 10^{-9} (E/0.1 \text{ TeV})^{-2.16^{+0.04}_{-0.04}} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ (dot-dashed line in Figure 10).

In order to reproduce the gamma ray emission from the Cygnus Cocoon, a purely hadronic
model [26] can be adopted, in which the observed gamma rays are due to the decay of \( \pi^0 \) mesons resulting from inelastic collisions between accelerated protons and target gas. Assuming that the primary proton spectrum follows a power law with exponential cutoff, the maximum cutoff energy allowed by the ARGO-YBJ highest energy upper limit is \( E_c = 150 \) TeV (solid line in Figure 10). Taking into account also the Milagro data, \( E_c \) would be around 40 TeV (dotted line).

Concerning MGRO J2019+37, which is the second brightest source after the Crab Nebula with Milagro data at \( \sim 12 \) TeV, having an extension \( \sigma_{\text{ext}} = 0.32^\circ \pm 0.12^\circ \) [27], the ARGO-YBJ map does not show any excess above 3 s.d., and flux upper limits were set at 90% confidence level (c.l.) [18]. The VERITAS observatory imaged MGRO J2019+37, resolving it into two different sources: the faint point-like VER J2016+371 and the bright extended (\( \sim 1^\circ \)) VER J2019+368, which likely contributes to the bulk of the emission observed by Milagro and is spatially coincident with the pulsar PSR J2021+3651 and the star formation HII region Sh 2-104 [28]. The flux of VER J2019+368 is in agreement with the ARGO-YBJ upper limit. All these results are reported in Figure 11.

Considering also the ARGO-YBJ results for MGRO J1908+06 [29] and HESS J1841-055 [30], as for the Milagro air shower detector, the fluxes measured in extended sources are systematically larger than those measured with Cherenkov telescopes. The origin of this discrepancy, which is not present for point-like sources, is not clear. For ARGO-YBJ, the overall systematic error on the flux measurements has been estimated to be \( < 30\% \) [31]. There could be some systematic effect related to the methods for background evaluation of the different experimental techniques [30].

**Figure 9.** Significance map around ARGO J2031+4157 as observed by ARGO-YBJ. The large circles indicate the positions and 68% contours of ARGO J2031+4157, MGRO J2031+41 and the Cygnus Cocoon. The positions and extensions of TeV J2032+4130 [19] and VER J2019+407 [25] are marked with crosses.

**Figure 10.** Spectrum of the Cygnus Cocoon as measured by different detectors. The arrows below 1 GeV indicate the upper limits set by Fermi/LAT, the Milagro data refer to MGRO J2031+41, at 12 TeV corrected for the extrapolation of TeV J2032+4130 [23]. The dot-dashed line shows the power law best fit to the combined Fermi/LAT and ARGO-YBJ data. The solid and dotted curves are predicted by a purely hadronic model with proton cutoff energy at 150 TeV and 40 TeV, respectively.
Figure 11. Observational results for MGRO J2019+37 from different experiments (figure taken from [28]). The Milagro power law with cutoff best fit, with its 1σ error band (shadowed area), is taken from [22].

A contribution from the diffuse gamma ray emission, according to ARGO-YBJ measurements, it is different for each extended source but always less than 15% of the detected flux [32].

2.2. Diffuse Gamma-Ray emission from the Galactic Plane

Diffuse gamma rays are produced by relativistic electrons by bremsstrahlung or inverse Compton scattering on background radiation fields, or by protons and nuclei via the decay of π⁰ produced in hadronic interactions with interstellar gas. Thus, the space distribution of this emission can trace the location of the cosmic ray sources and the distribution of interstellar gas. On the other hand, the diffuse emission provides a background in the search for point sources.

In the GeV energy range, the EGRET data showed a significant excess compared to expectations (the ‘EGRET GeV excess’) [33] likely due to instrumental effects [34] because not confirmed by the more recent and accurate Fermi-LAT data [35, 36]. A diffuse gamma ray flux at TeV energies from the 30° < l < 110° longitude range of the Galactic plane has been reported by Milagro [37, 38, 39].

The measured flux, once connected to the EGRET data by a power law with differential spectral index of −2.61, reveals a “TeV excess” in the diffuse gamma ray spectrum, being this flux 5–10 times higher than expectations [40]. However, as will be discussed in the following, the Milagro result does not take into account the contributions from the Cygnus cocoon and from the overlapping point or extended sources TeV J2032+4130, VER J2019+407 and VER J2016+372.

The events collected by ARGO-YBJ have been analysed to determine the diffuse gamma ray emission in the Galactic plane at Galactic longitudes 25° < l < 100° and Galactic latitudes |b| < 5° [32]. This analysis was carried out in the energy range from ∼350 GeV to ∼2 TeV, connecting the region explored by Fermi-LAT with that investigated by Milagro. In particular, the analysis was focused on two selected regions of the Galactic plane, i.e., 40° < l < 100° and 65° < l < 85° (the Cygnus region), where Milagro observed an excess with respect to what predicted by current models.

In the Galaxy region 40° < l < 100°, |b| < 5°, after masking the discrete sources and subtracting the residual contribution, an excess with a statistical significance of 6.1 s.d. above the background is found. The spectral analysis provides the three fluxes shown in Figure 12, at median energies 350 GeV, 680 GeV and 1.47 TeV (with uncertainties of about 30%). The fit to the ARGO-YBJ data with a power law gives a spectral index −2.90±0.31, and the corresponding
Figure 12. Energy spectrum of the diffuse gamma ray emission measured in the Galactic region $40^\circ < l < 100^\circ$, $|b| < 5^\circ$ [32]. The line indicates the energy spectrum expected from the Fermi/LAT template (with spectral index -2.6, which also rules its short-dashed extension) [43].

Figure 13. Energy spectrum of the diffuse gamma ray emission measured by ARGO-YBJ and EGRET in the Galactic region $65^\circ < l < 85^\circ$, $|b| < 5^\circ$, by Milagro in the region $65^\circ < l < 85^\circ$, $|b| < 2^\circ$ and by Fermi/LAT in $72^\circ < l < 88^\circ$, $|b| < 15^\circ$ [32]. The different lines indicate the energy spectra expected from the Fermi/LAT template (with spectral index -2.6, which also rules their short-dashed extensions) in the different sky regions investigated by the detectors [43].

On the other hand, as mentioned, the first measurement of the diffuse TeV (integral) flux from the Galactic plane made by Milagro [41] revealed a “TeV excess” in the diffuse gamma ray spectrum with respect to expectations [42]. This Milagro measurement, converted into differential flux, is only 34% greater than the value expected from the extrapolation of the Fermi/LAT template, and within the experimental uncertainties (see triangle with error bars in Figure 12). Moreover, considering that the Milagro result does not take into account the contributions from the Cygnus Cocoon (not yet discovered at the time of the measurement) and from overlapping point and extended sources, the discrepancy with the Fermi/LAT predictions is almost cancelled out. Therefore, the full set of measurements with ground-based detectors is in agreement with direct observations by Fermi/LAT, and the evidence of any “TeV excess”, requiring additional sources or particle production processes other than those producing Galactic cosmic rays, is ruled out.

Table 1. Diffuse gamma-ray emission from the Galactic plane for $|b| < 5^\circ$.

| Locations          | Statistical Significance | Spectral Index |
|--------------------|-------------------------|----------------|
| $25^\circ < l < 100^\circ$ | 6.9 s.d.                | $-2.80 \pm 0.26$ |
| $40^\circ < l < 100^\circ$ | 6.1 s.d.                | $-2.90 \pm 0.31$ |
| $65^\circ < l < 85^\circ$  | 4.1 s.d.                | $-2.65 \pm 0.44$ |
| $25^\circ < l < 65^\circ$ & $85^\circ < l < 100^\circ$ | 5.6 s.d.            | $-2.89 \pm 0.33$ |
In the Galactic region $65^\circ < l < 85^\circ$, $|b| < 5^\circ$, after masking the discrete sources and the Cygnus Cocoon and subtracting the residual contribution, an excess of 4.1 s.d. is left. This direction points into our spiral arm at the remarkable Cygnus star-forming region, located at a distance of about 1.4 kpc. The spectral energy distribution of gamma ray emission is shown in Figure 13 (filled stars) [32] together with the spectrum expected from the Fermi/LAT template (dot-dashed line) [43]. Milagro measured the diffuse gamma ray emission from the region $65^\circ < l < 85^\circ$, $|b| < 2^\circ$ at a median energy of 15 TeV [39], obtaining the flux reported as a filled triangle in Figure 13. For comparison, the long-dashed line shows the expected energy spectrum for this region according to the Fermi/LAT template. The Milagro flux results about 75% higher than the Fermi template, suggesting the presence of an excess. The spectral analysis of ARGO-YBJ data provides the three fluxes shown in Figure 13 at median energies 440 GeV, 780 GeV and 1.73 TeV (with uncertainties of about 40%). The fit to ARGO-YBJ data with a power law gives a spectral index $-2.65 \pm 0.44$, and the corresponding flux at 1 TeV is about 10% lower than the extrapolation of the Fermi/LAT template. These data do not show any excess at energies around 1 TeV which corresponds to the excess found by Milagro at a median energy of 15 TeV. Again, this discrepancy can be explained taking into account that the contribution of all the discrete gamma ray sources was not completely removed from the Milagro data. According to the ARGO-YBJ data, the 1 TeV flux associated to the Cygnus Cocoon is of the same order of the diffuse flux.

The spectral indexes measured by ARGO-YBJ in different regions of the Galactic plane are reported in Table 1 [32]. The statistical significance of the observations in standard deviations (s.d.) is shown in the second column. The TeV flux averaged over the Cygnus region $65^\circ < l < 85^\circ$ covers the energy range 400 GeV – 2 TeV and follow a power law with spectral index $-2.65 \pm 0.44$, a value very close to that found for TeV emission from the Cygnus Cocoon, indicating the presence of young cosmic rays accelerated by a nearby source.

2.3. 4.5 years observations of the blazar Mrk 421
Active Galactic Nuclei (AGNs), one of the most luminous sources of electromagnetic radiation in the universe, are galaxies with a strong and variable non-thermal emission, believed to be the result of accretion of mass onto a supermassive black hole (with a mass ranging from $\sim 10^6$ to $\sim 10^{10} \, M_\odot$) lying at the center of the galaxy.

To understand the emission variability and the underlying acceleration and radiation mechanisms in jets, continuous multi-wavelength observations, particularly in X-rays and VHE $\gamma$-rays, are crucial. A simultaneous Spectral Energy Distribution (SED) could provide a snapshot of the emitting population of particles and also constrain the model parameters at a given time [44, 45]. The shape of particle energy distribution could bring information on the underlying acceleration processes (e.g.[46, 47, 48, 49]). In the VHE band, Cherenkov telescopes cannot regularly monitor AGNs, because of their limited duty cycle and narrow field of view. Wide-FOV EAS arrays, with high duty cycles, are more suitable for this purpose.

During 5 years ARGO-YBJ continuously monitored the blazar Mrk 421, extending at higher energies the multi-wavelength survey carried out by the Owens Valley Radio Observatory (OVRO), the satellite-borne X-ray detectors Swift, the Rossi X-ray Timing Explorer (RXTE), the Monitor of All-sky X-ray Image (MAXI) and the GeV $\gamma$-ray detector Fermi-LAT. In particular, thanks to the ARGO-YBJ and Fermi-LAT data, the high energy component of Mrk 421 SED has been completely covered without any gap from 100 MeV to 10 TeV from August 2008 to February 2013, a period that includes several large flares of Mrk 421. Such a long-term multi-wavelength observation is rare and provides a unique opportunity to investigate the emission variability of Mrk 421 from radio frequencies to TeV $\gamma$-rays ([50] and references therein).

Fig. 14 shows the light curves of Mrk 421, as obtained by the data of different experiments,
Figure 14. Mrk 421 light curves in different energy bands, from 2008 August 5 to 2013 February 7 [50]. Each bin of the ARGO-YBJ data contains the event rate averaged over 30 days.
covering the energy range from radio to the TeV band [50]. The time integration is chosen taking into account the sensitivity of the instruments. For ARGO-YBJ each point corresponds to one month (30 days) of data, while for Fermi-LAT, Swift-BAT, RXTE-ASM and MAXI-GSC the data are averaged over one week (see [50] and references therein). Thanks to the ARGO-YBJ and Fermi data, the whole energy range from 100 MeV to 10 TeV is covered without any gap. The main results of the multiwavelength analysis can be summarized as follows [50]:

- Mrk 421 showed both low and high activity phases at all wavebands during the 4.5 year period analyzed. The variability increases with energy for both the SED components. Concerning the synchrotron component, the variability amplitude increases from 21% in radio and 33% in UV to 71%-73% in soft X-rays and 103%-137% in hard X-rays. For the Inverse Compton component, the amplitude is 39% at GeV energies and increases to 84% at TeV energies.
- The variation of the X-ray flux is clearly correlated with the TeV γ-ray flux. This result is consistent with many previous observations, supporting the idea that the X-ray and VHE γ-ray emissions originate from the same zone. For the first time we observed a moderate correlation between GeV and TeV γ-ray fluxes. On the contrary, X-ray and γ-ray fluxes are weakly or not correlated with radio and UV fluxes.
- Seven large flares, including five X-ray flares and two GeV γ-ray flares with variable durations (3–58 days), and one X-ray outburst phase were identified and used to investigate the variation of the spectral energy distribution with respect to a relative quiescent phase.
- During the outburst phase and the seven flaring episodes, the peak energy in X-rays is observed to increase from sub-keV to few keV. The TeV γ-ray flux increases up to 0.9–7.2 times the flux of the Crab Nebula. The behavior of GeV γ-rays is found to vary depending on the flare, a feature that leads us to classify flares into three groups according to the GeV flux variation.
- The one-zone synchrotron self-Compton (SSC) model was adopted to describe the emission spectra. Two out of three groups can be satisfactorily described using injected electrons with a power-law spectral index around 2.2, as expected from relativistic diffuse shock acceleration, whereas the remaining group requires a harder injected spectrum. The underlying physical mechanisms responsible for different groups may be related to the acceleration process or to the environment properties.

2.4. Search for Gamma Ray Bursts in scaler mode

In scaler mode, the energy threshold for photons is about 1 GeV, lower than the highest energies detected by satellite experiments. Moreover, the modular structure of the ARGO-YBJ detector allowed the collection of data during the different mounting phases. Therefore a search for emission from Gamma Ray Bursts (GRBs) in coincidence with satellite detections started in November 2004, when the Swift satellite was launched [51]. Until February 2013 a sample of 206 GRBs was analysed, 24 of them with known redshift $z$. This is the largest sample of GRBs investigated with a ground-based detector at high energies. Figure 15 shows the distribution of the resulting significances for all the 206 GRBs (black solid line). No significant excess is found, the largest being 3.52σ for GRB 080727C, with a post-trial chance probability of $4.5 \times 10^{-2}$. Since long GRBs (duration $T_{90} > 2$ s) typically show a softer spectrum, the same distribution is shown in Figure 15 only for the 27 short GRBs ($T_{90} \leq 2$ s, red dashed area). Also in this case, no significant excess is found, the most significant event being GRB 051114 with 3.37σ and a post-trial chance probability of $1.0 \times 10^{-2}$.

Besides the coincidence analysis for each GRB, a stacked analysis was carried out in order to search for common features of all GRBs in time or in phase. In the time analysis the counting rates for all the GRBs were added up in nine windows ($\Delta t = 0.5, 1, 2, 5, 10, 20, 50, 100$ and
200 s), starting at the trigger time, in order to investigate a possible common duration of the high energy emission. In the phase analysis only the 165 GRBs with duration T90 ≥ 5 s were added up, dividing their time length into ten bins each sampling 10% of T90 and scaling their duration to a common phase plot (in this case the lower limit on the GRB duration is due to the minimum interval, 0.5 s, for the scaler mode data acquisition and the number of bins considered). However, there is no evidence of any integral effect in both these analyses.

Since no significant signal was found in the data, for each GRB fluence upper limits in the 1-100 GeV energy range were determined at 99% c.l. assuming two different power law spectra: a) the index measured by satellite detectors in the keV-MeV energy range; b) the conservative differential index -2.5. For case a), when double power law spectral features have been identified, the higher spectral index (i.e., that above the peak in the keV-MeV region of the $E^2 \cdot dN/dE$ spectrum) has been used. For the set of 24 GRBs with known redshift the ranges of upper limits between the values corresponding to the two spectral assumptions are represented by rectangles in Figure 16, while a simple arrow is shown if the low energy spectrum is a cutoff power law, and thus only case b) is considered. These are the only upper limits set at GeV energies for these GRBs. For GRB090902B (which was the GRB in the ARGO-YBJ field of view with the highest photon energy detected) the fluence extrapolated from Fermi/LAT observations in the same energy range is also shown [52]. Only for this GRB the GeV spectral index measured by Fermi/LAT was used and the dashed area in Figure 16 was obtained with a maximum energy of the GRB spectrum ranging from 30 GeV (about the maximum energy measured by Fermi/LAT) to 100 GeV. More results and details about this search can be found in [53].
3. ARGO-YBJ recent highlights in Cosmic Ray Physics

3.1. Measurement of the Cosmic Ray Energy Spectrum

A measurement of the CR primary energy spectrum (all-particle and light nuclei component) is under way with ARGO-YBJ in the wide energy range from few TeV up to about 10 PeV exploiting different approaches:

- **'Digital-Bayes' analysis**, based on the strip multiplicity, i.e. the picture of the EAS provided by the strip/pad system, in the few TeV – 300 TeV energy range. The selection of light elements (i.e. p+He) is based on the particle lateral distribution. The energy is reconstructed, on a statistical basis, by using a bayesian approach [54, 55].

- **'Analog-Bayes' analysis**, based on the RPC charge readout [3], covers the 30 TeV – 10 PeV energy range. The energy is reconstructed (as in the previous analysis), on a statistical basis, by using a bayesian approach [56].

- **'Hybrid measurement'**, carried out by ARGO-YBJ and a wide field of view Cherenkov telescope, in the 100 TeV - 3 PeV region. The selection of (p+He)-originated showers is based on the shape of the Cherenkov image and on the particle density in the core region measured by the ARGO-YBJ central carpet [57, 58].

In the ARGO-YBJ experiment the selection of (p+He)-originated showers is performed not by means of an unfolding procedure after the measurement of electronic and muonic sizes, but on an event-by-event basis exploiting showers topology, i.e. the lateral distribution of charged secondary particles. This approach is made possible by the full coverage of the central carpet, the high segmentation of the read-out and the high altitude location of the experiment that retains the characteristics of showers lateral distribution in the core region.

The all-particle energy spectra measured by ARGO-YBJ by reconstructing showers with three different approaches [56, 59, 60] are shown in the Fig. 17. The statistical uncertainty is shown by the error bars. A systematic uncertainty, due to hadronic interaction models, selection criteria, unfolding algorithms, aperture calculation and energy scale, of ±15% is estimated. The ARGO-YBJ all-particle spectrum clearly shows a knee-like structure at few PeVs in fair agreement with the results obtained by Tibet ASγ [68], IceTop-73 [69], KASCADE [70] and KASCADE-Grande [71] experiments.

3.2. Light component (p+He) energy spectrum of Cosmic Rays

As described in [54, 55], by using the read-out provided by the strip/pad system and applying a selection criterion based on the particle density to quasi-vertical showers (θ < 35°), a sample of events induced by p and He nuclei, with the shower core well inside the ARGO-YBJ central carpet, has been selected. The contamination by heavier nuclei is found negligible. An unfolding technique based on the bayesian approach has been applied to the strip multiplicity distribution in order to obtain the differential energy spectrum of the light component.

The light component (p+He) energy spectrum measured by ARGO-YBJ in the few TeV – 300 TeV energy range is shown in Fig. 18 [54, 55]. Data agree remarkably well with the values obtained by adding up the p and He fluxes measured by CREAM both concerning the total intensities and the spectral index [64]. The value of the spectral index of the power-law fit to the ARGO-YBJ data is -2.64±0.01 [55]. ARGO-YBJ is the only ground-based experiment that overlaps with the direct measurements for more than two energy decades.

This measurement has been extended to higher energies exploiting an "hybrid measurement" with a prototype of the future Wide Field of view Cherenkov Telescope Array (WFCTA) of the LHAASO project [61]. The telescope, located at the south-east corner of the ARGO-YBJ detector, about 78.9 m away from the center of the RPC array, is equipped with 16×16 photomultipliers (PMTs), has a FOV of 14°×16° with a pixel size of approximately 1° [62].
Figure 17. All-particle energy spectrum of primary CRs measured by ARGO-YBJ. Data analyzed with different techniques are compared. The statistical uncertainty is shown by the error bars. For comparison all-particle spectra measured by other experiments (Tibet ASγ [68], IceTop 73 [69], KASCADE [70], KASCADE-Grande [71]) are shown.

Figure 18. Light (p+He) energy spectrum of primary CRs measured by ARGO-YBJ with the digital readout (strip/pad system) using the full 2008–2012 data sample [55]. The error bars represent the total uncertainty. Previous measurement performed by ARGO–YBJ in a narrower energy range by analyzing a smaller data sample is also reported (blue squares) [54]. The green inverted triangles represent the sum of the proton and helium spectra measured by the CREAM experiment [64]. The proton (stars) and helium (empty stars) spectra measured by the PAMELA experiment [65] are also shown. The light component spectra according to the Gaisser-Stanev-Tilav (dashed–dotted line) [66] and Hörandel (dashed line) [67] models are also shown.
The idea is to combine in a multiparametric analysis two mass-sensitive parameters: the particle density in the shower core measured by the analog readout of ARGO-YBJ and the shape of the Cherenkov footprint measured by WFCTA [57].

From December 2010 to February 2012, in a total exposure time of 728,000 seconds, the ARGO-YBJ/WFCTA system collected and reconstructed 8218 events above 100 TeV according to the following selection criteria: (1) reconstructed shower core position located well inside ARGO-130, excluding an outer region 2 m large; (2) more than 1000 fired pads on ARGO-130; (3) more than 6 fired pixels in the PMT matrix; (4) a space angle between the incident direction of the shower and the telescope main axis less than 6°. This selection guarantees that the Cherenkov images are fully contained in the FOV, an angular resolution better than 0.3° and a shower core position resolution less than 2 m.

According to the MC simulations, the largest number of particles $N_{\text{max}}$ recorded by a RPC in a given shower is a useful parameter to measure the particle density in the shower core region, i.e. within 3 m from the core position. For a given energy, in showers induced by heavy nuclei $N_{\text{max}}$ is smaller than in showers induced by light particles. Therefore, $N_{\text{max}}$ is a parameter useful to select different primary masses. In addition, $N_{\text{max}}$ is proportional to $E_{\text{rec}}^{1.44}$, where $E_{\text{rec}}$ is the shower primary energy reconstructed using the Cherenkov telescope. We can define a new parameter $p_L = \log_{10}(N_{\text{max}}) - 1.44 \cdot \log_{10}(E_{\text{rec}}/\text{TeV})$ by removing the energy dependence [57].

The Cherenkov footprint of a shower can be described by the well-known Hillas parameters [63], i.e. by the width and the length of the image. Older showers which develop higher in the atmosphere, such as iron-induced events, have Cherenkov images more stretched, i.e. narrower and longer, with respect to younger events due to light particles which develop deeper. Therefore, the ratio between the length and the width (L/W) of the Cherenkov image is expected to be another good estimator of the primary elemental composition.

Elongated images can be produced, not only by different nuclei, but also by showers with the core position far away from the telescope, or by energetic showers, due to the elongation of the cascade processes in the atmosphere. Simulations show that the ratio of L/W is nearly proportional to the shower impact parameters $R_p$, the distance between the telescope and the core position, which must be accurately measured. An accurate determination of the shower...
Figure 21. Light component (p+He) energy spectrum of primary CRs measured by ARGO-YBJ/WFCTA hybrid experiment (filled red squares) in the energy range 100 – 700 TeV, compared with other experimental results. The ARGO-YBJ data at lower energies are published in [54].

Figure 22. Composition-sensitive parameters $p_L$ and $p_C$ for (p+He) (solid contours) and heavier masses (dashed contours) including 1:1:1 mixing of CNO, MgAlSi, and Iron. The primary energy of the plotted events is in the range 100 TeV – 10 PeV. Numbers on the contours indicate the percentage of contained events.

geometry is crucial for the energy measurement. In fact, the number of photoelectrons collected in the image recorded by the Cherenkov telescope $N_{pe}$ varies dramatically with the impact parameter $R_p$, because of the rapid falling off of the lateral distribution of the Cherenkov light. Only an accurate measurement of the shower impact parameters $R_p$, and a good reconstruction of the primary energy allow to disentangle different effects. A shower core position resolution better than 2 m and an angular resolution better than 0.3°, due to the high-granularity of the ARGO-YBJ full coverage carpet, allow to reconstruct the shower primary energy with a resolution of 25%, by using the total number of photoelectrons $N_{pe}$. The uncertainty in absolute energy scale is estimated about 10%.

Therefore, in order to select the different masses we can define another new parameter $p_C = L/W - 0.0091 \cdot (R_p/1 m) - 0.14 \cdot \log_{10}(E_{rec}/TeV)$ by removing both the effects due to the shower distance and to the energy [57].

The values of these parameters for showers induced by different nuclei are shown in the Fig. 19. The events have been generated assuming a -2.7 spectral index in the energy range 10 TeV – 10 PeV for all the five mass groups (p, He, CNO, MgSi, Fe) investigated. The primary masses have been simulated in the same relative percentage. As can be seen from the figure, a suitable selection in the $p_L - p_C$ space allows to pick out a light composition sample with high purity. In fact, by cutting off the concentrated heavy cluster in the lower-left region in the scatter plot, i.e. $p_L \leq -0.91$ and $p_C \leq 1.3$, the contamination of nuclei heavier than He is less than 5%. About 30% of H and He survives the selection criteria [57].

The aperture of the ARGO-YBJ/WFCTA system has been estimated using the Horandel model for the primary spectrum [67]. Its value, $\sim 170$ m$^2$sr above 100 TeV, shrinks to $\sim 50$ m$^2$sr after the selection of the (p+He) component (see Fig. 20). In the sample of 8218 events recorded...
above 100 TeV by the hybrid system, 1392 showers are selected in the (p+He) sub-sample.

The light component energy spectrum measured by the ARGO-YBJ/WFCTA hybrid system is shown in the Fig. 21 by the filled red squares. A systematic uncertainty in the absolute flux of 15% is shown by the shaded area. The error bars show the statistical errors only. The spectrum can be described by a single power-law with a spectral index of $-2.63 \pm 0.06$ up to about 600 TeV. The absolute flux at 400 TeV is $(1.79 \pm 0.16) \times 10^{-11}$ GeV$^{-1}$ m$^{-2}$ sr$^{-1}$ s$^{-1}$. This result is consistent for what concern spectral index and absolute flux with the measurements carried out by ARGO-YBJ below 200 TeV and by CREAM. The flux difference is about 10% and can be explained with a difference in the experiments energy scale of $\pm 3.5\%$ [57].

This result is very important to fix the energy scale of the experiment. Below 10 TeV the absolute energy scale of ARGO-YBJ is calibrated at 10% level exploiting the westward displacement of the Moon shadow under the effect of the GMF. Above this energy the overposition with CREAM allows to fix the energy scale at few percent level.

### 3.3. Observation of the knee in the (p+He) energy spectrum

The measurement of the light component energy spectrum has been extended above PeVs exploiting two different approaches.

1. The ARGO-YBJ/WFCTA hybrid experiment with different selection cuts in the $p_L-p_C$ space [58].

2. A Bayesian unfolding technique applied to data recorded with the RPC charge readout [56].

**1. ARGO-YBJ/WFCTA hybrid experiment.**

In order to extend the measurement of the ARGO-YBJ/WFCTA hybrid experiment to the PeVs, we modified the selection cuts in the $p_L-p_C$ space: events for which $p_L \geq -4.53$ and $p_C \geq 0.78$ are rejected (see Fig. 22) [58]. The aperture is a factor 2.4 larger (see Fig. 20). The contamination increase and the purity of the p+He sample below 700 TeV reduces to 93% with respect to 98% estimated with the original cuts. At 1 PeV the contamination is less than 13% increasing to 44% around 6 PeV. About 72% of p+He events survive the selection criteria.

The resulting energy spectrum is shown in Fig. 23 and can be fitted with a broken power-law function

$$ J(E) = \begin{cases} J(E_k) \cdot \frac{(E/E_k)^{\beta_1}}{} & (E < E_k) \\ J(E_k) \cdot \frac{(E/E_k)^{\beta_2}}{} & (E > E_k) \end{cases} $$  \hspace{1cm} (1)$$

with $E_k=700 \pm 230$ TeV, $J(E_k)=(4.65 \pm 0.27) \times 10^{-12}$ GeV$^{-1}$ m$^{-2}$ sr$^{-1}$ s$^{-1}$, $\beta_1=-2.56 \pm 0.05$ and $\beta_2=-3.24 \pm 0.36$. The relatively large error on the breaking energy $E_k$ is due to the limited statistics. Considering a systematic uncertainty in the absolute energy scale of about 10% (see [58] for a detailed discussion), the systematic uncertainty in $E_k$ is estimated to be $\sim 70$ TeV.

The number of expected events in the three energy bins above the knee are 82, 39 and 20, respectively. The difference between the observed number of events and the expectation from a single power law spectrum corresponds to a deficit with a statistical significance of 4.2 standard deviations.

**2. Bayesian unfolding technique.** The shower structure in the core region has been deeply investigated thanks to the peculiar characteristics of the ARGO-YBJ detector. According to MC simulations, the truncated shower size ($N_h$), defined as the number of particles within a radius of 8 m from the shower core, is a good estimator of the primary energy for a given mass and is not affected by bias effects due to the finite detector size [72].

In a shower produced by heavy nuclei a substantial amount of secondary particles is spread further away from the core region. On the contrary, in a shower produced by light elements, the largest amount of particles is concentrated in a small region around the shower core. The ratio between the particle density measured at several distances from the core and the one
Figure 23. Light (p+He) component energy spectrum measured by the hybrid experiment ARGO-YBJ/WFCTA [58]. The error bar is the statistical error, and the shaded area represents the systematic uncertainty. The (p+He) spectra measured by CREAM [64], ARGO-YBJ [55], Tibet ASγ [68], KASCADE [70] and the hybrid experiment [57] below the knee are shown for comparison.

measured very close to the core can be exploited in order to identify showers produced by light elements. According to Monte Carlo simulations, the parameters $\beta_5 = \rho_5/\rho_0$, where $\rho_0$ and $\rho_5$ are respectively the particle density measured in the core region and at 5 m from the core and $\beta_{10} = \rho_{10}/\rho_0$, where $\rho_{10}$ is the particle density measured at 10 m from the core, are sensitive to primary mass. The resolution of the core position reconstruction in ARGO-YBJ determines an uncertainty of about 5% on the measurement of the parameters $\beta_5$, $\beta_{10}$. As an example in Fig. 24 the distributions of $\beta_5$ and $\beta_{10}$ are reported for data and Monte Carlo events weighted according to the composition model given in [67]. Primaries have been grouped into two mass groups: light (H, He) and heavy (CNO, NeMgSi, Fe). The distributions show a different behaviour depending on the primary mass. The parameters $\beta_5$ and $\beta_{10}$ have been combined in order to estimate the probability that showers have been produced by primaries of different mass.

The determination of the primary energy from the measured quantities is a classical unfolding problem that can be dealt by using an iterative procedure based on the Bayes’ theorem [56]. In a probabilistic approach the probability $P(N_8, \beta_5, \beta_{10}|E, A)$ of measuring a shower size $N_8$ and a certain value of $\beta_5$ and $\beta_{10}$ given a primary energy $E$ and mass $A$, relates the characteristics of the primary particle to the experimental observables. In a discrete formulation $P(N_8, \beta_5, \beta_{10}|E, A)$ represents the response matrix defined by the following integrals:

$$P(N_8, \beta_5, \beta_{10}|E, A) = \sum_A \int_{E_0} \int_{\Delta E_0} dE \int d\Omega \int dS \Phi_M(E_0) \cdot P(N_8, \beta_5, \beta_{10}|E, A)$$

where the flux model and the conditional probability are integrated over the primary energy bin $E_i$, the solid angle $\Omega$ and the area $S$ projected on a plane perpendicular to the shower direction. The response matrix is normalised to the flux integrated over each bin. The flux model affects
weighting events in each bin, but since the energy bins result independent, the flux normalisation

can cancel out in the response matrix. The quantity \( P(N_8, \beta_5, \beta_{10}|E, A) \) can be evaluated by means

of a full Monte Carlo simulation of the shower development in the atmosphere and of the detector

response giving the primary energy and mass. The number of showers \( N(N_8, \beta_5, \beta_{10}) \) in the

bin \((i, j, k)\) of the measured quantities \((N_8, \beta_5, \beta_{10})\) is therefore related to the number of primaries

\( N(E_l, A_m) \) by the equation

\[
N(E_l, A_m) = \sum_{i,j,k} P(E_l, A_m|N_{8,i}, \beta_{5,j}, \beta_{10,k}) \cdot N(N_{8,i}, \beta_{5,j}, \beta_{10,k}),
\]

where \( P(E_l, A_m|N_{8,i}, \beta_{5,j}, \beta_{10,k}) \) is the probability that a shower of size \( N_{8,i} \) and \( \beta_{5,j}, \beta_{10,k} \) values

has been generated by a nucleus \( A_m \) with energy \( E_l \). The probability \( P(N_{8}, \beta_5, \beta_{10}|E, A) \) has to be

inverted to obtain the primary energy spectrum.

An iterative procedure based on the Bayes’ theorem allows to solve the equation (3) taking

into account the bin–to–bin migration due to the fluctuations. Starting from a prior distribution

\( P_0^{(n)}(E_l, A_m) \) in the \( n \)th iteration:

\[
P^{(n)}(E_l, A_m|N_{8,i}, \beta_{5,j}, \beta_{10,k}) = \frac{P^{(n)}(N_{8,i}, \beta_{5,j}, \beta_{10,k}|E_l, A_m)P_0^{(n)}(E_l, A_m)}{\sum_{p,q} P^{(n)}(N_{8,i}, \beta_{5,j}, \beta_{10,k}|E_p, A_q)P_0^{(n)}(E_p, A_q)}.
\]

An estimate of the energy spectrum for a given mass \( A_m \) is therefore obtained from the distribution

of the experimental observables

\[
N^{(n)}(E_l, A_m) = \sum_{i,j,k} P^{(n)}(E_l, A_m|N_{8,i}, \beta_{5,j}, \beta_{10,k}) \cdot N(N_{8,i}, \beta_{5,j}, \beta_{10,k}),
\]

and is used to obtain an updated value of the prior \( P_0^{(n)}(E_l, A_m) \). The iterative procedure ends

when a variation of the measured flux in two consecutive steps is less than 1%.

Figure 24. Distribution of \( \beta_5 \) and \( \beta_{10} \) in size bins \( 4.5 \leq \log(N_8) \leq 5.0 \) and \( 5.0 \leq \log(N_8) \leq 5.5 \)

[56].

\[
\text{Figure 24. Distribution of } \beta_5 \text{ and } \beta_{10} \text{ in size bins } 4.5 \leq \log(N_8) \leq 5.0 \text{ and } 5.0 \leq \log(N_8) \leq 5.5
\]

[56].

\[
\text{Figure 24. Distribution of } \beta_5 \text{ and } \beta_{10} \text{ in size bins } 4.5 \leq \log(N_8) \leq 5.0 \text{ and } 5.0 \leq \log(N_8) \leq 5.5
\]

[56].

\[
\text{Figure 24. Distribution of } \beta_5 \text{ and } \beta_{10} \text{ in size bins } 4.5 \leq \log(N_8) \leq 5.0 \text{ and } 5.0 \leq \log(N_8) \leq 5.5
\]

[56].

\[
\text{Figure 24. Distribution of } \beta_5 \text{ and } \beta_{10} \text{ in size bins } 4.5 \leq \log(N_8) \leq 5.0 \text{ and } 5.0 \leq \log(N_8) \leq 5.5
\]

[56].

\[
\text{Figure 24. Distribution of } \beta_5 \text{ and } \beta_{10} \text{ in size bins } 4.5 \leq \log(N_8) \leq 5.0 \text{ and } 5.0 \leq \log(N_8) \leq 5.5
\]

[56].
In a discrete formulation of the Bayesian unfolding approach, the width of the bins has been chosen in order to better evaluate the conditional probabilities namely minimizing the statistical error, reducing bin-to-bin migration effects and stabilizing the iterative procedure. Data and Monte Carlo events have been sorted in 20 \( N_8 \) logarithmic bins in the range \((3 \div 6)\) and 3 \( \beta_5 \) bins \((0 \div 0.5)\) and 3 \( \beta_{10} \) bins \((0 \div 0.25)\). Monte Carlo events have been sorted in 25 logarithmic energy bins taking into account the energy resolution and 2 mass bins. The fraction of selected light elements increases with energy and is about 60% above 50 TeV, while contamination is well below 10% over the whole energy range [56].

The energy spectrum of the p+He component measured by the ARGO-YBJ charge read-out is shown in the Fig. 25 where is compared to all measurements carried out by ARGO-YBJ in the energy range TeV - PeV. The p+He measured by CREAM [64] is also shown for comparison. As can be seen, the different analyses show clear evidence of a knee-like structure starting from about 500 TeV. The energy spectrum measured by the analog read-out can be described by the broken power-law formula (1) with these parameters [73]: \( E_k = 805 \pm 27 \) TeV, \( J(E_k) = (2.74 \pm 0.25) \times 10^{-12} \text{ GeV}^{-1} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \), \( \beta_1 = -2.63 \pm 0.004 \) and \( \beta_2 = -3.76 \pm 0.05 \), in good agreement with the results obtained by the ARGO-YBJ/WFCTA measurement.

An overall picture of the energy range TeV - 100 PeV is shown in the Fig. 26 where p+He component and all-particle energy spectra measured by ARGO-YBJ are summarized. Results obtained by other experiments are also reported. For comparison, the parametrization of the light component provided by Horandel [67] is shown by the dashed line.

As can be seen, ARGO-YBJ confirms the observation of the knee in the all-particle energy spectrum at few PeV, but the clear observation of a knee in the p+He energy spectrum below the PeV suggests that the elemental composition in the few PeV range is heavier than Helium, differently from what suggested by the Horandel parametrization [67].

These results demonstrate the possibility of exploring the cosmic ray properties in a wide energy range with a single ground-based detector without exploiting the measurement of the muon size, thus reducing the uncertainties due to hadronic interaction models.

4. Conclusions
The ARGO-YBJ detector exploiting the full coverage approach and the high segmentation of the readout imaged the front of atmospheric showers with unprecedented resolution and detail in the wide TeV - PeV energy range.

The physics of Galactic and extragalactic CRs has been studied with a combined measurement of photon- and charged particle-induced showers and a number of important issues in Astroparticle Physics has been investigated (for a summary of the ARGO-YBJ results see [1])

- cosmic ray physics (energy spectrum, elemental composition, anisotropy, p-air and pp cross section measurement) starting from TeVs
- gamma-ray astronomy (galactic and extragalactic) starting from few hundreds GeV
- search from GRBs in the full GeV–TeV energy range
- search for antiproton in the cosmic ray primary flux at TeV energies
- study of the solar and heliosphere physics above GeV.

These achievements represent the accomplishment of the aims which motivated the proposal and the design of the experiment. Final analysis with the full statistics of the analog data will give new inputs to the hadronic interaction models currently used to describe particle physics and CRs up to the highest energies.

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Figure 25. Light (p+He) component energy spectrum of primary CRs measured by ARGO-YBJ. The (p+He) energy spectrum measured by CREAM [64] is shown for comparison. The statistical uncertainty is shown by the error bars.

Figure 26. Cosmic ray all–particle and (p+He) energy spectra as measured by ARGO–YBJ compared with other experimental results [64, 68, 69, 70, 71] and with the parametrizations given in [67].
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