Size spectrum and Lateral Distribution of air showers measuread by ARGO-YBJ at high energies (> 100TeV).

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Abstract: ARGO-YBJ is able to measure, with its analog readout, just around the core region of the shower, in a density range which goes from hundreds to many thousands of particles per m^2. We remark that no experiment has ever measured very close to the shower core with an equivalent detail. We will present our first results on size spectrum and lateral distribution in this particle density range.

Keywords: Size Spectrum, Lateral Distribution, Hadronic Interactions

1 Introduction

The ARGO detector [1] is constituted by a central carpet ~78×74 m^2, made of a single layer of Resistive Plate Chambers (RPCs) with ~93% of active area, enclosed by a guard ring partially (~20%) instrumented up to ~110×100 m^2. The apparatus has a modular structure, the basic data acquisition unit being a cluster (7.6× 5.7 m^2), made by 12 RPCs (1.25 ×2.80 m^2 each). The full detector has 153 clusters (130 in the central carpet, 23 in the guard ring) with a total active surface of about 6700 m^2. Each RPC is read out by means of 80 pick-up strips (61.8×6.75 cm^2, the spatial pixels) facing the upper side of the gas volume. The fast-OR signal of 8 contiguous strips defines the logical pad (61.8 × 55.6 cm^2, the time pixel) which is used for timing and triggering purposes. A manifold coincidence ($\geq N_{trig}$) of fired pads of the central carpet (N_{pad}), in a time window of 420 ns, implements the inclusive trigger that starts the event data acquisition. The apparatus, in its full configuration of 153 clusters, is in smooth and stable data taking since November 2007 with the trigger $N_{pad} \geq N_{trig}$ = 20; the trigger rate is $\sim$ 3.5 kHz with a duty cycle $\geq 86\%$. The high granularity of the detector and its time resolution provide a detailed three-dimensional reconstruction of the shower front. The digital pick-up of the RPC, which has a density of 23 strips/m^2, can be used to study the primary spectrum up to energies of a few hundred TeV; above these energies its response saturates as shown in [2]. In order to extend the measurable energy range and fully investigate PeV energies, where particle densities are larger than 10^3/m^2, each RPC has been equipped also with two large size electrodes of dimension 1.23 × 1.39 m^2. These pick-up electrodes, called Big Pads (BP), face the lower side of the RPC gas volume and provide a signal whose amplitude is expected to be proportional to the number of charged particles impinging on the detector.

In this work, we report on preliminary results obtained by using just the information of the core region, both size spectrum and lateral distribution, along with some MC predictions.

2 Approaching higher energies with the analog readout

At present, the analog system has been completely assembled at YBJ in its final form on the 130 central clusters and it has been taking data since December 2009. The RPCs are operated in streamer mode, with a gas mixture of Argon (15%), Isobutane (10%) and R134a (75%). The operating voltage is 7.2 kV. This setting provides a typical efficiency $> 95\%$ with a time resolution of about 1.8 ns . The amplitude of the BP signal ranges from mV to tens of V.

In each cluster a custom crate[4] containing three Analog to Digital Converter (ADC) boards and one control module manages the analog data. The system allows the operation with full scale (f.s) set by a 3-bit programmable register, namely 0.33, 0.66, 1.3, 2.5, 5, 10, 20 and 40 V. The ADC digitization and data collection [3, 4] in each cluster starts when the local multiplicity of hits (trigger) gets higher than a programmable threshold, namely $\geq 16, \geq 32, \geq 64$ and ≥ 73 hits. The data transfer to the central data acquisition system occurs when the local trigger is confirmed by the experiment trigger.

Starting from December 2009, with a local multiplicity threshold of 73, the analog readout system has been operated with different f.s., namely from December 2009 till end of June 210 it was operated at 330 mV f.s., the most sensitive one, whose particle density range overlaps with the particle density measurable by the digital readout system; these data have been used both to study the detector behavior and to calibration purposes. From July to middle August 2010, the system was operated at the intermediate f.s., which corresponds to about 2.5 V; since middle August 2010 the f.s. has been set to 20 V, not the highest one which instead is 40 V. The number of BP in the central carpet is 3120, apart from dead channels or channels with some problems which are in the order of 3%. Typical internal events are reported in Fig.1; it is quite impressive the regularity of the density profile. We stress that no experiment has ever measured very close to the shower core with such a detail.

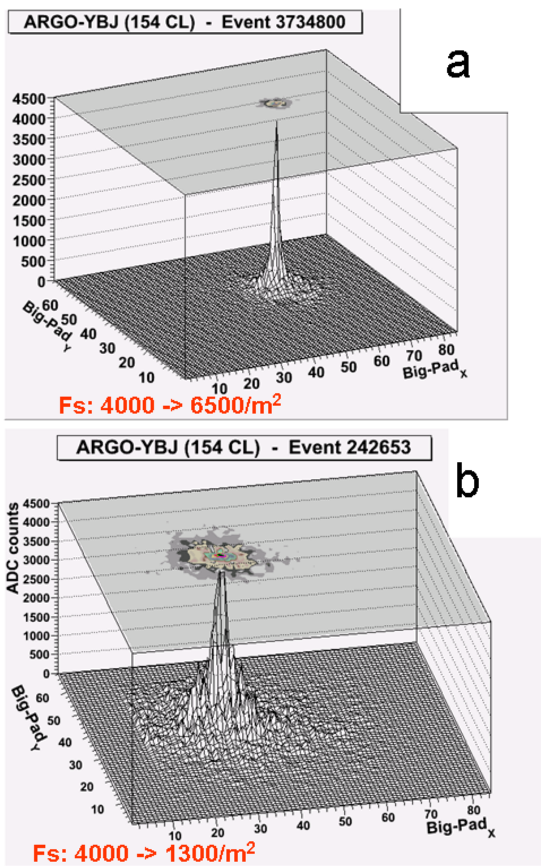

Figure 1: Showers as recorded by ARGO-YBJ through the analog readout system, respectively at 20 V f.s. (a) and 2.5 V (b).

3 First results

The performance of the analog readout system, along with the calibration procedure and detector stability, have been discussed in [7, 8]; all results reported here refer to the calibration procedure shown in [7].

	2,5 V	20 V
event num.	14560383	10863213
core, θ, ADC>10	4%	0.6%
core, θ, ADC>50	2%	0.18%
core, θ, ADC>500	0.3%	0.03%
core, θ, ADC>3000	0.04%	0.002%

Table 1: Sequence of applied cuts and corresponding statistics at different f.s. (percentage refer to starting sample, or event num.)

A simulation has been carried out by means of the CORSIKA/QGSjet code [6] in order to study quasi-vertical showers zenith angle ($< 15\%$) with core in a fiducial area of about 260 m^2 at the center of the carpet (2×3 clusters). An average efficiency of 95% both for detector and trigger has been assumed; the carpet geometry has been taken into account. Primary particles with different masses, from protons to irons, have been considered at fixed energies. Data at different full scales as in [7] have been analyzed,with specific selection of internal events, namely requiring:

1. at least one BP with ADC count > 50;
2. cluster with maximum ADC count inside the internal 54 (6×9) central clusters;
3. zenith angle $\theta \leq 15°$.

The sequence of applied conditions and the selected event statistics are summarized in Tab.1. The distribution of the maximum particle density (ρ_{max}), or particle number on the BP with highest signal (BPmax), is shown in Fig.2 for the two highest scales; the normalization has been done by requiring equal number of events at $\rho_{max} = 300\text{m}^{-2}$. The slopes of the distributions are quite consistent and come out to be 2.23±0.01 (2.5 V) and 2.23±0.02 (20V). In Fig.3 the

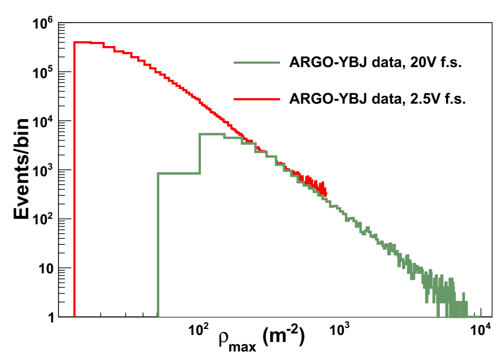

Figure 2: Histogram of the maximum particle density (ρ_{max}) as measured by ARGO-YBJ at two f.s. (2,5 V (red) and 20 V (green)) of the analog readout.

maximum density is reported for p and Fe as for the energy according to MC simulation; it is interesting to see that in both cases the relation between maximum density and energy can be well fitted by a power law, at least up to a few PeV. In Fig.4 are reported the lateral distributions for data

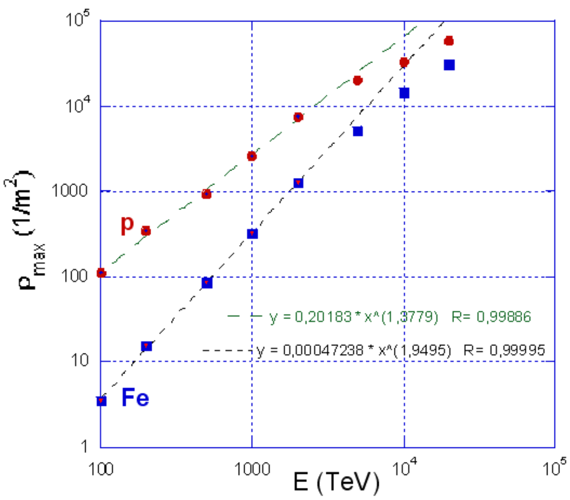

Figure 3: Maximum particle density (ρ_{max}) vs primary energy, both for proton and iron induced showers (see text); the power law that fits the relation up to 2 PeV is also shown.

(red) compared to the expectations coming from MC, both for proton (black) and iron (blue) induced showers; the distributions refer to the BPmax position. Given the sensitivity to the distance, special care has been taken in order to be sure about the localization of the BPmax position. Moreover it has been investigated the lateral distribution dependence on the center (0,0) position: the position of BPmax has been compared to the gravity center of the BP signals calculated in a square of 3×3 BP around BPmax. We concluded that the BPmax position tipically differs (rms of the difference) by tens of cm from the gravity center position; moreover the differences of the density around the core are in the order of 3%, being lower up to ten meters if the gravity center position is taken as reference position. The four distributions for data (red lines) correspond , from top to bottom, to:

a) 20 V f.s. and ADC count of BPmax in 3000-4000 (the highest);

b) 20 V f.s. and ADC count of BPmax in 500-3000 (the second);

c) 2,5 V f.s. and ADC count of BPmax in 3000-4000 (the third);

d) 2,5 V f.s. and ADC count of BPmax in 500-3000 (the lowest).

Both distributions referring to ADC count of BPmax in 500-3000 (**b)**,**d)**) show some flattening above 8 meters: this is related both to the minimum measurable density and, secondly, also to the electronic non-linearity, which could require some additional correction at very low ADC count. The black lines for protons refer to primary energies of 100 TeV (the lowest), 200 TeV, 500 TeV, 1 PeV, and 2 PeV (the highest); the blue lines for irons refer instead to primary energies of 500 TeV (the lowest), 1 PeV, 2 PeV and 5 PeV (the highest). There is a quite good agreement with MC expectation for protons, while data distributions are inconsistent with expectations for irons. An important con-

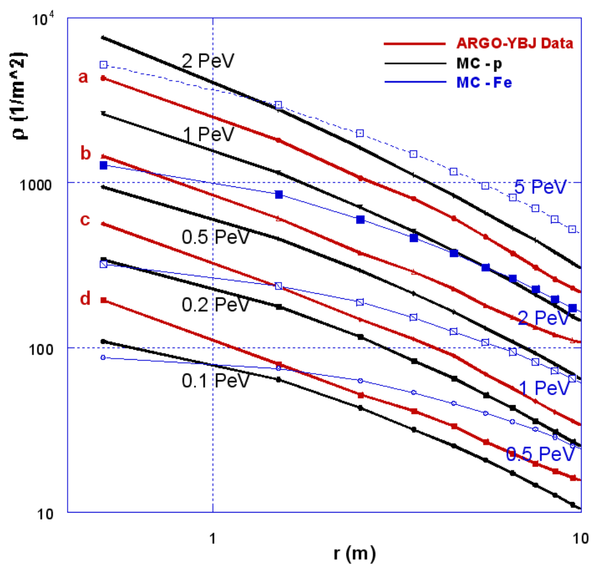

Figure 4: Lateral distribution for data (red lines) for 20 V and 2.5 V f.s. data (see text); the black lines are MC predictions for protons at 100 TeV (the lowest), 200 TeV, 500 TeV, 1 PeV, and 2 PeV (the highest); the blue lines are MC predictions for irons at 500 TeV (the lowest), 1 PeV, 2 PeV and 5 PeV (the highest).

siderations can be done according to MC simulations: the maximum gradient is just near the maximum density and this applies both to protons and irons, moreover it increases with energy. Therefore the product of the maximum density (ρ_{max}) times the radial density gradient at one meter, $(\partial\rho/\partial \mathrm{r})_1$, could increase the difference between the two primary species. In Fig.5 $\rho_0 \times (\partial\rho/\partial \mathrm{r})_1$ is reported vs the number of particles contained in 10 meters ($\mathrm{N}^{10}_{\mathrm{part}}$) around the BPmax position, which is taken as an estimator of the primary energy. It can be seen that, at a given $\mathrm{N}^{10}_{\mathrm{part}}$, there is at least a factor 10 between the values of $\rho_{max} \times (\partial\rho/\partial \mathrm{r})_1$ as calculated for protons and irons. Plotting the same quantity for all data events with $\rho_{max} \geq 130\mathrm{m}^{-2}$ and particle number > 1000 in the 8 BP nearest to BPmax, then reporting the two behaviors for protons (red) and irons (blu) on the same plot, we get the result as shown in Fig.6.

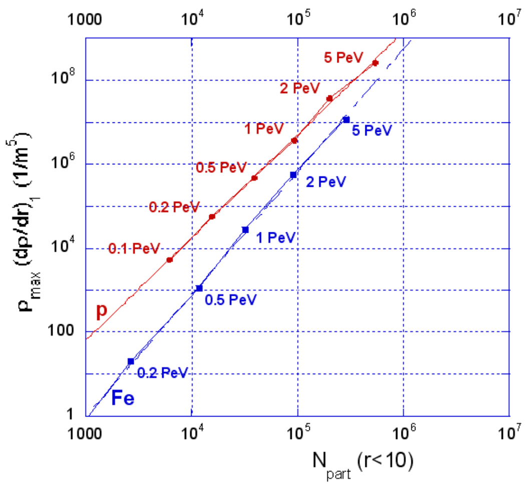

Figure 5: $\rho_{max} \times (\partial\rho/\partial \mathrm{r})_1$ vs $\mathrm{N}^{10}_{\mathrm{part}}$ (see text), both for proton and iron induced showers.

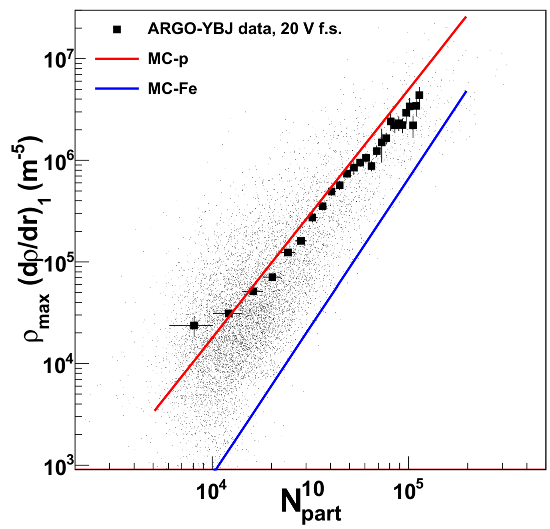

Figure 6: $\rho_{max} \times (\partial\rho/\partial \mathrm{r})_1$ vs $\mathrm{N}^{10}_{\mathrm{part}}$ for data (see text for details) along with expectations both for proton (red line) and iron (blue line) induced showers. The black dots are from profile in $8 \cdot 10^3 \leq \mathrm{N}^{10}_{\mathrm{part}} \leq 1.1 \cdot 10^5$

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4 Conclusions

Since December 2009 the analog readout of the ARGO-YBJ detector is in operation on the central carpet (5800 m^2), so extending the energy range of the detector at high energies (> 100TeV). The core region is measured with unprecedented detail. Preliminary lateral distributions and maximum density distribution have been shown and compared with MC expectations. By using specific combination of shower quantities, just belonging to the core region, it has been shown how promisingly we can approach the problem of the primary particle identification.

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