ARGO-YBJ Detector Simulation Using GEANT4

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on behalf of the ARGO-YBJ Collaboration

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***Abstract*. 'G4argo', a GEANT4-based simulation package for ARGO-YBJ detector, is described in this paper. G4argo incorporates in the simulation the true RPC time resolution and another 0.5 ns time uncertainty which is introduced from the offline calibration of TDC. In addition, the correct RPC geometry and the true materials for the ARGO-YBJ experimental hall are implemented. As a result, G4argo simulation shows a very good agreement with real data.**

***Keywords*: ARGO-YBJ detector, GEANT4, Cosmic rays, Extensive air showers**

I. Introduction

ARGO-YBJ is a "full-coverage" air shower detector, consisting of a single layer of Resistive Plate Chambers (RPCs), presently in data taking at Yangbajing Cosmic Ray Obervatory (Tibet, China) at 4300 m a.s.l. (lat=30.11^{0}N, long=90.53^{0}E).

The RPCs, operated in streamer mode, are grouped into 153 units called clusters (130 central clusters and 23 guard ring clusters) [1]. Each cluster ($5.7 \times 7.6\ m^2$) is made by 12 RPCs and each RPC is divided into 10 pads, which are read out by 8 strips each one [2] as shown in Fig. 1. Pads and strips represent respectively the time and space pixels of the detector. Apart such space and time digital information, the readout of streamer charge induced on big pads (two for each RPC) has been also implemented (Fig. 1), by using a system of ADCs ('Analog Setup'). Thanks to the high altitude, good time resolution and considerable detector granularity, ARGO-YBJ can image with high efficiency and sensitivity the extensive air showers initiated by primaries of energy in the range from few hundreds of GeV up to about 100 TeV (1 PeV) with digital (analog) read-out. The experiment is devoted to the investigation of many fundamental issues in astroparticle physics. In several cases, a very reliable simulation of the geometry and materials of the detector as well as of its response to air showers is crucial for the data analysis. Until now, the ARGO-YBJ Monte Carlo program (named 'ARGO-G') was based on the GEANT3 (v3.21) package. Now a more powerful detector simulation program has been developed, based on the Object Oriented GEANT4 [3] software package, 'G4argo'. As far as the same materials and geometry implemented in ARGO-G are used, the results of the two programs are similar. Anyway, the new Monte Carlo includes the definition of all the materials of the whole experimental hall and a more realistic simulation of the detector performance, thus giving a better agreement between MC and experimental data concerning several observable quantities. Moreover, the big pad readout setup is fully simulated.

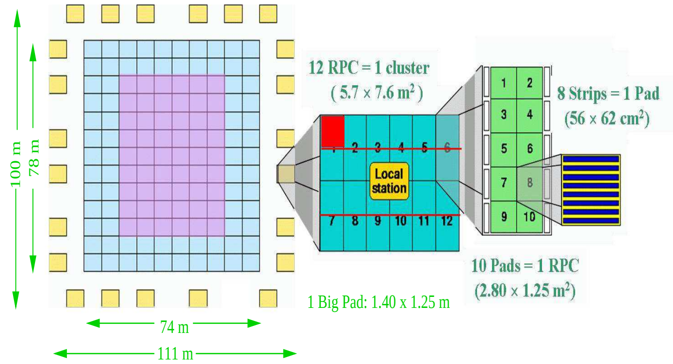

Fig. 1. ARGO-YBJ detector layout: 130 central clusters and 23 ring clusters, each make up of 12 RPCs. Each RPC is divided to 10 Pads, that are read out by 8 strips.

II. Parameters Updated from ARGO-G to G4argo

Following the track of ARGO-G, the full simulation program G4argo includes event generator, detector geometry, particle interaction with materials, signal digitization, noise consideration, trigger simulation and output interface. The main parameters implemented in G4argo (in particular the improvements with respect to the previous MC program), in order to fully simulate ARGO-YBJ detector and its response, are discussed in this section.

A. Detector configuration

As in the real detector geometry, also in the G4argo MC program the basic setup unit is the cluster. At each cluster location, there is one indicator number, by which the user can control the detector setup according to the parameter cards. Like every RPC unit for pad and strip signals, the big pad detector is set as a sensitive volume (named 'BPAD'). For every charged particle passing through this sensitive volume, a hit is generated

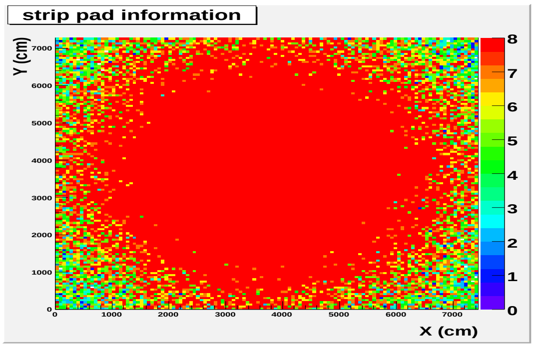

Fig. 2. A Monte Carlo event induced by a vertical 1 PeV proton hitting the center of array as imaged through the signals given by strip-pads.

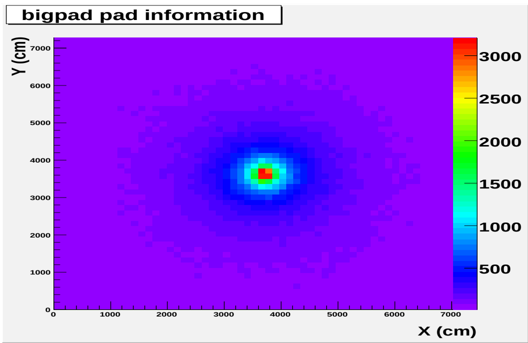

Fig. 3. A Monte Carlo event induced by a vertical 1 PeV proton hitting the center of array as imaged through the big pad signals.

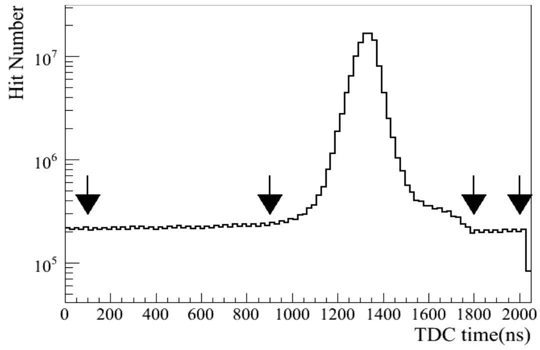

Fig. 4. TDC time distribution: the entries at the side bands, from 100ns to 900ns and from 1800ns to 2000ns, are marked as noise hits.

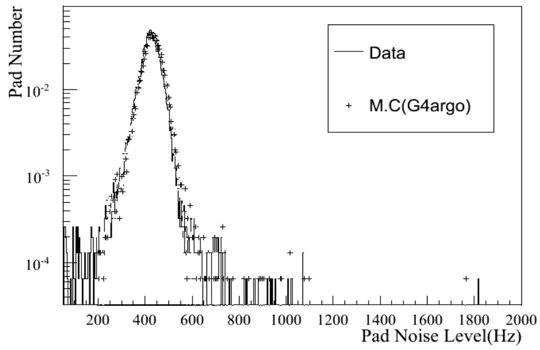

Fig. 5. Distribution of single pad noise rate: solid line is for real data, dots and error bars for MC.

containing: identifying number, position and multiplicity of the fired big pad. A simulated event with both informations, strip-pad and big-pad signal, is shown in Fig. 2 and Fig. 3.

B. Noise Simulation

The dominant noise comes from accidental single hits in coincidence with cosmic ray events. The time window of ARGO-YBJ trigger system is 420 ns, while the registered event extends over 2048 ns. When one shower satisfies the trigger condition, some more uncorrelated hits (from radioactivity, secondary shower particles, etc.) can also occur on the detector during the event time window and give some contributions. Another important source of spurious hits is due to the electronics noise. Compared with the true (i.e. main shower) signal, the arrival times of noise signals should be randomly and uniformly distributed. Based on this property, the noise can be estimated from the real data. As shown in Fig. 4, the entries at the side bands from 100 ns to 900 ns and from 1800 ns to 2000 ns in the event time window, are marked as noise hits. Such a distribution can be extracted pad by pad, so that the noise rate for every pad can be obtained. Fig. 5 shows the calculated noise rate distribution resulting from the individual pads. It can be observed that the average noise rate is about 400 Hz, with a certain spread. Therefore, by implementing the noise rate simulation pad by pad, rather than using an average rate of 400 Hz for each one, a more realistic comparison between real data and MC sample can be performed, with a very good agreement (Fig. 5).

C. Digitization

The actual time resolution of RPCs, which is measured using a 5-folds RPC telescope [4], is considered in the simulation. In order to compensate for additional, not simulated effects, like the TDC time offsets from cable lengths and other hardware factors, a 0.5 ns TDC time calibration error is used [5]. So the final TDC time is smeared using two independent Gaussian distributions.

D. ARGO-YBJ Hall Simulation

The real materials of ARGO-YBJ hall, including the matter of columns, beams and roof material are all taken into account properly.

III. Comparison with Experiment

Here we compare the simulation sample with real data for the following parameters: trigger rate, hit multiplicities, shower direction reconstruction, shower core position reconstruction and angular resolution.

A. The trigger rate

The trigger rate depends on composition, power law spectral indexes, interaction model and threshold energy of the primary cosmic rays. Just to make the comparison with real data, we use as trial model the ”poly-gonato model” described in [6] concerning the composition. The corresponding fluxes and power law spectral indexes

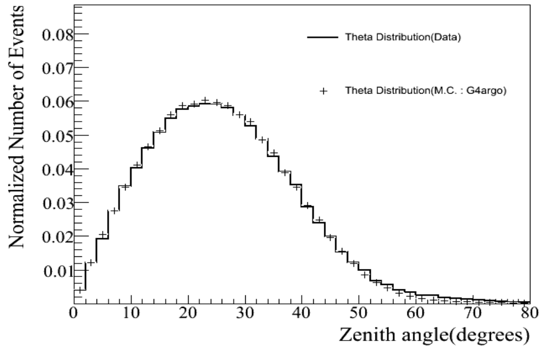

Fig. 6. Comparison of the zenith angle distributions for simulated and real data.

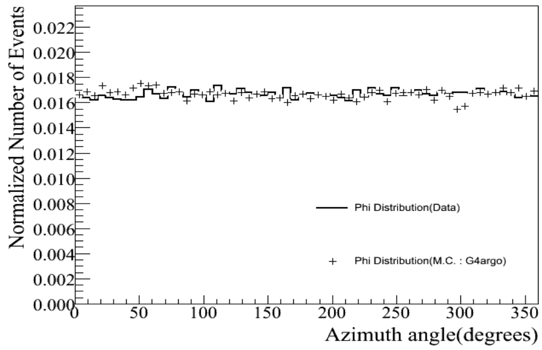

Fig. 7. Comparison of the azimuth angle distributions for simulated and real data.

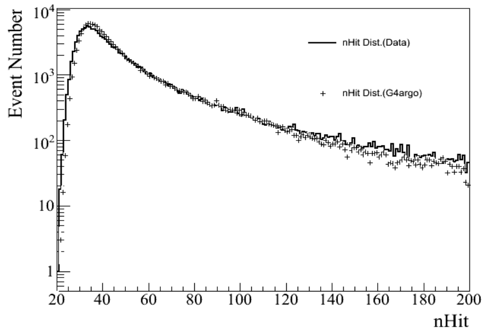

Fig. 8. The distribution of hit multiplicities.

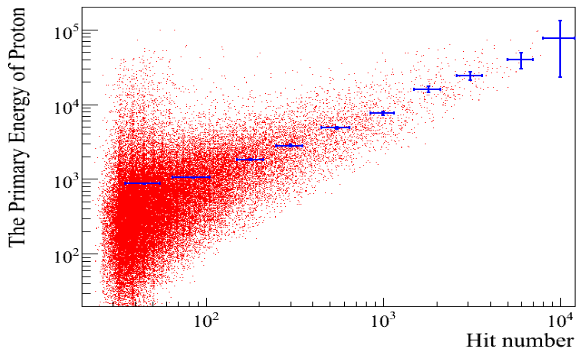

Fig. 9. The primary energy of proton vs the multiplicity of pads.

for the different primary cosmic ray nuclei are reported in Table 1. In the simulation, the well-used CORSIKA ('COsmic Ray Simulation for Kascade') program [7] is used to simulate evolution and properties of extensive air showers in the atmosphere. The energy range for Proton and Helium is from 20 GeV to 100 TeV, while for heavier elements it is from 200 GeV to 100 TeV. The sampling area is 2000×2000 m^2 in G4argo. Before comparing the trigger rate, the differences concerning incident zenith and azimuth angle as well as pad multiplicity between real data and MC samples have been checked. Fig. 6 shows the distribution of incident zenith angle and Fig. 7 the distribution of incident azimuth angle as obtained from real data and MC samples. It is easy to see that the distribution of MC sample for azimuth and zenith is quite consistent with real data. Another parameter, which is directly correlated with the energy of primaries, is the pad multiplicity. Also in this case, we have found a good consistency between MC and real data, as shown in Fig. 8. Fig. 9 gives the primary energy of proton vs pad multiplicity. It is clearly shown that the threshold energy of ARGO detector is several hundreds GeV.

Concerning the trigger rate from real data, we assumed the average rate value on one year basis, that is 3.6 kHz, with a variation of about 5% mainly due to the environmental condition changes (atmospheric pressure, temperature, and so on).

The simulated trigger rates from different elements are shown in Table 1. Taking into account the 4% reduction due to the dead time the corrected MC total trigger rate is ~3.7 kHz. So the MC trigger rate is consistent with real data at 3% level, which is well inside the real variation in time due to the environmental condition changes.

B. The Shower Core

The air shower core position has been reconstructed using an algorithm based on the likelihood method applied to the detected lateral density profile of the shower. The correct reconstruction of the core position is crucial also for the direction reconstruction because we adopt a conical fit (i.e. the sampled shower front is fitted to a cone with the vertex in the core position). Fig. 10 shows the distribution of the reconstructed shower core relative to the center of the detector. From the figure it is clear that G4argo's result is quite consistent with the

TABLE I
THE TRIGGER RATE COMPARISON

Primary	Flux $(m^{-2}sr^{-1}s^{-1}TeV^{-1})$	$Rate^{MC}$ (Hz)	σ_{stat}
Proton	$8.73 \times 10^{-2}E^{-2.71}$	2773.5	15.3
He	$5.71 \times 10^{-2}E^{-2.64}$	773.7	8.1
Li	$2.08 \times 10^{-3}E^{-2.54}$	22.8	1.4
C	$1.06 \times 10^{-2}E^{-2.66}$	72.2	2.5
O	$1.57 \times 10^{-2}E^{-2.68}$	84.4	2.7
Ne	$4.60 \times 10^{-3}E^{-2.64}$	21.6	1.4
Mg	$8.01 \times 10^{-3}E^{-2.64}$	32.5	1.7
Si	$7.96 \times 10^{-3}E^{-2.75}$	23.8	1.4
Fe	$2.04 \times 10^{-2}E^{-2.59}$	57.8	2.2
Total	MC	3860	18
	MC (4% dead time corr)	3700	17
	Data (year average)	$\sim$ 3600	

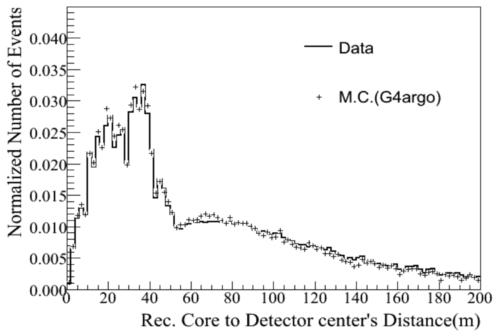

Fig. 10. Distribution of the distances between detector center and position of the reconstructed shower core.

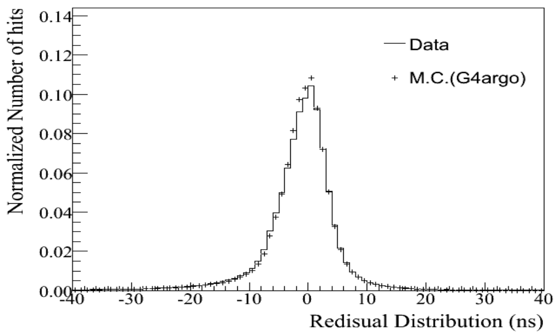

Fig. 11. The distribution of the time residual during direction reconstruction.

data.

C. The angular resolution

For a simpler comparison between MC and data, the sample of shower events having the core reconstructed inside the ARGO-YBJ central carpet has been selected. Before comparing the angular resolution, some basic parameters such as residuals and χ^2 of the conical fit have been checked firstly. Fig. 11 shows the residual distribution of data and MC: the comparison demonstrates a very good consistency. As a consequence, we expect a good consistency also in the comparison of χ^2, as shown in Fig. 12. The direction of the primary cosmic ray has been estimated using the Conical Fit with IRLS method [8]. A chessboard (or even and odd pad) method has been used to estimate the angular resolution both for data and MC: the result is given in Fig. 13, where the average value of Ψ_{50}, the median of the distribution of the angle between true and reconstructed shower direction, is reported as a function of the pad multiplicity. Also for this quantity a good agreement between G4argo and real data is clearly evident.

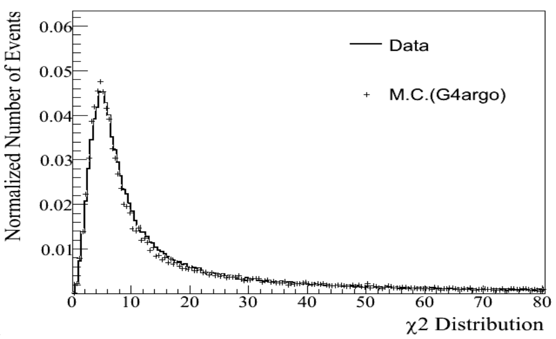

Fig. 12. The distribution of the χ^2 during direction reconstruction.

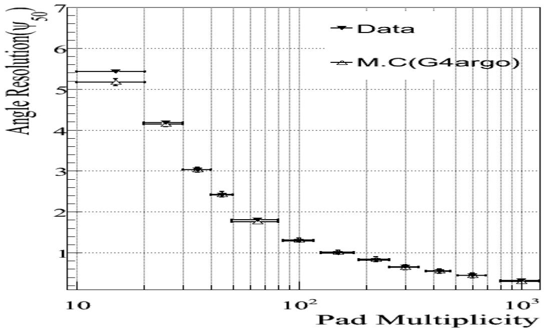

Fig. 13. The angular resolution vs the multiplicity of pads used in the direction reconstruction

IV. Summary

A GEANT4-based simulation code has been developed. In this new simulation, the geometry of ARGO-YBJ experimental hall including pillars, steel and roof has been implemented. Moreover the detector time resolution and the TDC offline calibration resolution have been simulated according to the real performance. As a result, the Monte Carlo sample shows good consistency compared with real data for what concerns the reconstructed shower direction, the shower core position and the angular resolution.

References

[1] The ARGO-YBJ Collaboration, Nuclear Instruments and Methods A 562 (2006) 92
[2] B. Wang et al., ICRC2007, Mexico
[3] Geant4 Collaboration, CERN/LHCC 98-44; web site: http://geant4.web.cern.ch/geant4/ and references therein
[4] Chaoyong Wu et al. (ARGO-YBJ Collaboration), this Conference
[5] The ARGO-YBJ Collaboration, Astroparticle Physics 30 (2009) 287
[6] Jorg R. Horandel, Astroparticle Physics 19 (2003) 193
[7] D. Heck et al., Report FZKA 6019(1998)
[8] B. Wang et al., this Conference