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EAS lateral distribution measured by analog readout and digital readout of ARGO-YBJ experiment

Jing Zhao
Institute of High Energy Physics, Chinese Academy of Sciences Beijing China
E-mail: jzhao@ihep.ac.cn

Xinhua Ma
Institute of High Energy Physics, Chinese Academy of Sciences Beijing China
E-mail: maxh@ihep.ac.cn

Lingling Ma*
Institute of High Energy Physics, Chinese Academy of Sciences Beijing China
E-mail: llma@ihep.ac.cn

on behalf of ARGO-YBJ Collaboration

One of the approaches to the measurement of lateral distribution (LDF) of extensive air showers by the ARGO-YBJ experiment is presented. The ARGO-YBJ experiment has two kinds of readout: a digital readout for small particle densities (<23 strips/m^2) and an analog readout for large particle densities (up to $10^4/m^2$). For lateral distribution studies, the inner core regions can be measured by the analog readout, while farther regions are measured by the digital readout. This allows the study of lateral distributionin a wide interval of distances from the shower core. Up to now, this work is just using the simulated data.

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*Speaker

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1. Introduction

Lateral distribution of extensive air shower (EAS) is of great importance for EAS study. One of the important reasons is the energy and mass of the primary particle can be deduced from lateral distribution of second particles. The shapes of lateral distribution depend on the primary mass. The heavier primaries get, the flatter lateral distributions go. Total number of second particles is used to be one measurement of the primary energy. But in measurements the shower particles are sampled over a limit range of core distance and less than few percents area coverage. So more reliable analysis are needed to get the primary energy and mass from lateral distribution.

One of the well-known functions to describe lateral distribution of electromagnetic shower is Nishimura-Kamata-Greisen (NKG) function[1][2]:

$$\rho_e(r,s,N_e) = \frac{N_e}{R_m^2}\frac{\Gamma(4.5-s)}{2\pi\Gamma(s)\Gamma(4.5-2s)}(\frac{r}{R_m})^{s-2}(1+\frac{r}{R_m})^{s-4.5} \tag{1.1}$$

where N_e is the total number of electrons in the shower, s is the age of the shower and R_m is the Molière radius. Traditionally, NKG function is used with a fixed R_m and variable s and N_e. This function can be used to describe the electromagnetic component of hadronic showers. NKG function is formulated for all particles in purely electromagnetic showers and different experiments have different detectors that their discrimination of particle types and energy thresholds are totally different. Many experiments reported deviations of LDF from the NKG function, so they modified NKG function to fit hadronic showers of different experiments. Like Eq. 1.2 is used for large distance ($r \geq 1km$) by AGASA and Yakutsk[3].

$$\rho_e(r) = \frac{C_e N_e}{R_{m.s.r.}^2}(\frac{r}{R_{m.s.r.}})^{-\alpha}(1+\frac{r}{R_{m.s.r.}})^{\alpha-\beta} \times (1+\frac{r}{10R_{m.s.r.}})^{-\delta} \tag{1.2}$$

where $C_e = 0.28$ is a normalization factor, N_e is the total number of electrons at the observation depth t_{obs}, $\alpha = 1.2$, $\beta = 4.53$, $\delta = 0.6$. The $R_{m.s.r.}$ describes lateral distribution shape dependent on energy, observation depth and primary particle. Many other NKG modification functions are proposed to describe LDF for their experiments[4].

In this paper, we will present one NKG function with modified R_m for ARGO-YBJ experiment by using simulation samples and carry out detailed comparisons of modified NKG function with lateral distribution. Other studies on the near core LDF with the ARGO-YBJ data are currently being performed[5][6].

2. ARGO-YBJ experiment

The ARGO-YBJ experiment stably operated from November 2007 till February 2013 at Yangbajing (4300 m a.s.l.). It is a full coverage carpet ($\sim 78 \times 74$ m^2) of Resistive Plate Chambers (RPC). The carpet has 153 cluster (130 in central carpet and 23 in the guard ring) (Shown in Fig. 1). One cluster is made of 12 RPCs (each 1.25×2.80 m^2). This large full coverage and high altitude allowed the study of cosmic rays at an energy threshold of a few hundred GeV. Each RPC organized in 10 pads (61.8×55.6 cm^2), each pad signal realized by 8 strips (each 61.8×6.75 cm^2) is sent to a time to digital converter. The whole system allows a detailed reconstruction of shower

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front. Those strips with digital readout have a density of $< 23\ strips/m^2$ and can be used to study the primary spectrum up to a few hundred TeV[7][8]. Using the strip multiplicity, the light component spectrum of the primary CR in the energy region 5-200 TeV has been evaluated by a Bayesian approach[9]. To extend spectrum measurement to PeV region, each RPC has two analog charge readout pads (called bigpads, $1.23 \times 1.39\ m^2$) at the opposite side of the gas volume. The analog readout system can be operated at eight different gain scales (G0, G1,...,G7). The highest gain scale G7 allows measurement of few particles $/m^2$ which is overlapping with digital mode. The lowest gain scale is G0 which allows $\sim 10^4/m^2$ measured. Those different gain scales can extended the energy measurement from 100 TeV to few PeV[10][11].

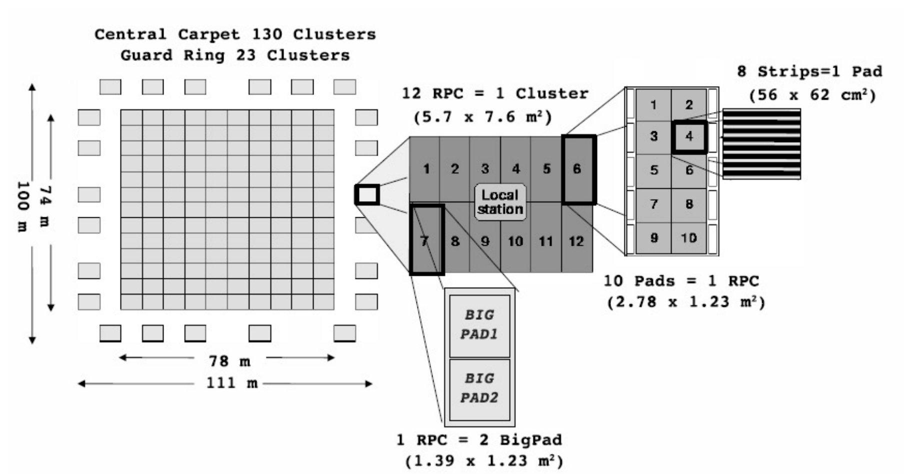

Figure 1: The ARGO-YBJ detector setup.

3. Monte Carlo Simulation

The air shower events have been generated by using CORSIKA code[12] (ver. 6.6161). The electromagnetic part of shower simulation is implemented by means of the EGS4 code. The high energy hadronic interaction is using the QGSJET- II and low energy is using GHEISHA model[13][14]. Several millions air shower events of proton, helium, CNO, MgAlSi, iron in the 100 TeV-10 PeV energy region with zenith angle $\theta < 15^\circ$ have been generated. The energy spectrum slopes' indexes are using H*ö*randel model[15]. Those simulated air showers projected in the center of the ARGO-YBJ carpet have been detector simulated by a full detector simulation based on GEANT4[16][17]. For shower reconstruction, the shower directions are using the original ones and the core position are obtained by the center of gravity. Then the particle density distributions on the shower front plane are been studied.

3.1 R_m Determination

As mentioned in Section 1, the deviation of the hadronic showers' LDF from NKG function are reported by many experiments. NKG function fits the data quite well for ARGO-YBJ experiment but the Molière radius needs to be modified. The conventional assumption of Molière radius is $R_m = 133$ m at 4300 m a.s.l.. Many experiment shows that the best value of R_m is much smaller than the actual one[5][18]. So the first study is to get the best R_m for ARGO-YBJ experiment.

For searching the best R_m, the particle numbers that bigpads recorded are used, not considering electronic scales simulation. The average particle distribution by 1 m/bin has been studied event by event. The fit region is 2 m to r_3 (the radius where the average particle density is $3/m^2$). One LDF is shown in Fig. 2, the NKG function with $R_m = 80$ m fits the LDF very well. Considered of the best R_m is smaller than actual one, so $R_m = 30$ m, 50 m, 80 m, 133 m are used to fit the data separately. The reduced χ^2 distribution (shown in Fig. 3) shows $R_m = 80$ m has the smallest χ^2 and closes to one. To get more detail information of the NKG fit, the deviation of the average particle density and the NKG value is shown in Fig. 4, it seems the the NKG function with $R_m = 80$ m has smallest deviation from lateral distribution. Both the reduced χ^2 and fractional deviation shows that the NKG function with $R_m = 80$ m gives the best fit. /usepackagesubfigure

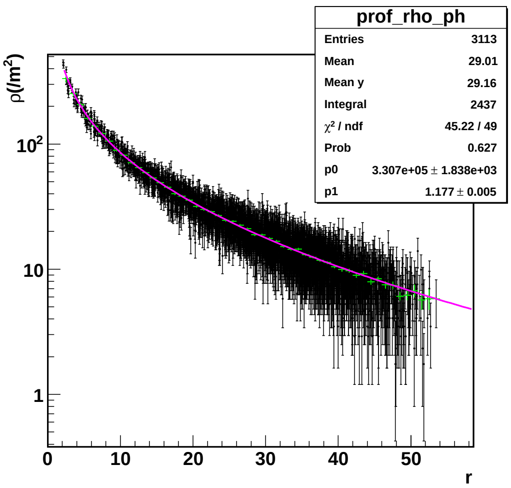

Figure 2: Lateral distribution of charged particles for one event. The green cross dot is the average LDF distribution. The primary particle is proton with E_0=716.4 TeV and $\theta = 11.7°$. The line is NKG function with $R_m = 80$ m.

3.2 The combined LDF study: strips plus bigpads

In reality, bigpads' signals are just recorded in one readout scale, the particle measurement region is limited. Considering the G1 scale running time is the longest one, so in the following paper we present the simulation data of G1 gain scale. The energy region of G1 scale is $\sim 200TeV$ to several PeV for protons. The G1 scale data can be used for particle measurement not far from the shower core ($\sim$ 10 m)[5]. Fortunately, the strip can be used to measure the tail of LDF ($>$ 30 m) with very low densities ($\sim 23/m^2$ with no saturation). So the combined analysis of analog and digital readout are used to get the LDF for every event.

First step is the selections of bigpads and strips signals:

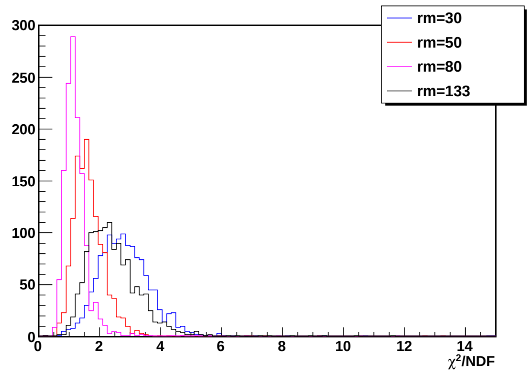

Figure 3: Reduced χ^2 of NKG function of different R_m. The primary particle is proton with 100 TeV$< E <$1 PeV and $\theta < 15°$.

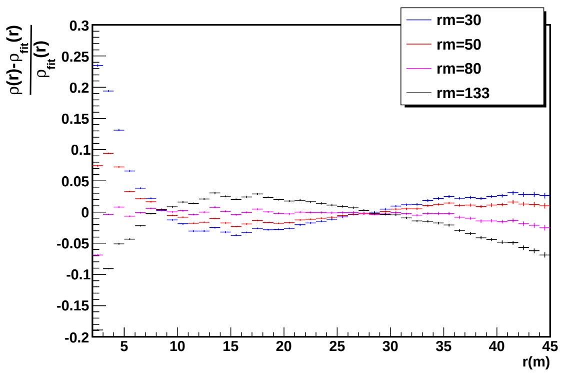

Figure 4: The deviation of average particle density from the NKG function. The primary particle is proton with 100 TeV$< E <$1 PeV and $\theta < 15°$.

- The numbers of particle recorded by bigpad is $N_{bp} > 70$ ($N_{bp} < 70$ corresponds to ADC count <10).
- The numbers of particle recorded by strips on one RPC is $2 < N_{strip} < 50$ to remove saturation range of the strips.

  Then the selections for the LDF study region to improve the quality of NKG fit:
- Considering the strip number much larger than bigpad and the LDF determined by the core center particle distribution, the strip part of LDF is using the average particle distribution of 1 m/bin.
- Considering the truncated particle distribution may cause NKG fit deviates from the LDF, the fit region for bigpad part is 2 m to r_{100} (the radius where the particle density is $100/m^2$) and the fit region for strip part is r_9 (the radius where the particle density is $9/m^2$) to r_3 (as mentioned before).

After these selections, the combined data gives a good measurement of LDF up to 50 m (depends on EAS zenith angle and core position). Lateral distribution of simulation and experiment data are shown in Fig. 5. It shows that NKG function with $R_m = 80$ m can also fit the combined simulation and experiment data very well. Figure 6 and 7 shows the NKG fit parameters size (N_e) and age (s) as a function of the original energy. The age decreases when primary energy increases, this is due to the observation of younger showers at larger energies. In the same energy bin, heavier primary gets a larger age as a result of larger interaction cross section. The size parameter N_e has a good linearity with E_0 for different primary component. So N_e is a good measurement for experiment to analysis the original energy. But it is mass dependent, the detail about how to use the parameter N_e to calibrate primary energy using the size parameter is beyond the scope of this paper.

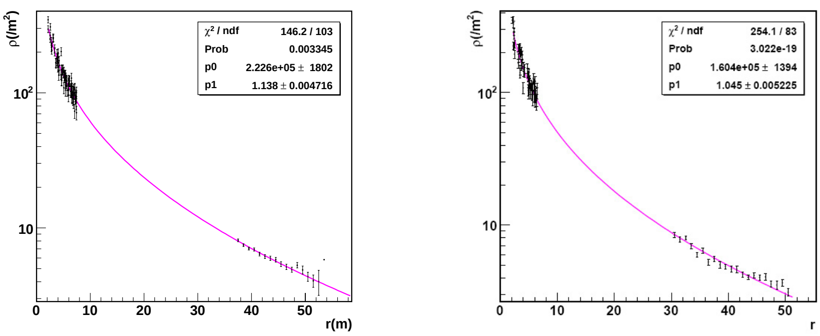

Figure 5: (a) Lateral distribution of one combined simulation event. Near core parts are the bigpad signals and far end parts are the average strip signals. The primary is Proton with E=388.9 TeV and $\theta = 8.2°$. (b)Lateral distribution of one combined experiment event. Reconstructed $\theta = 28.78°$.

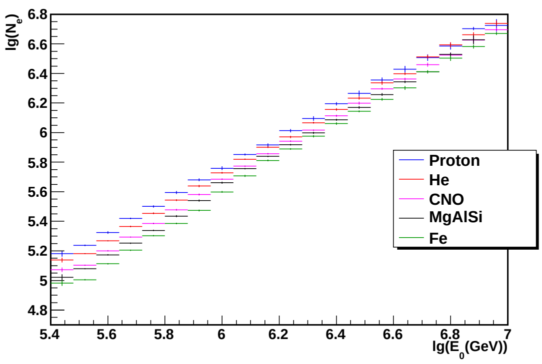

Figure 6: Size N_e as a function of the primary energy. The zenith angle $\theta < 15°$.

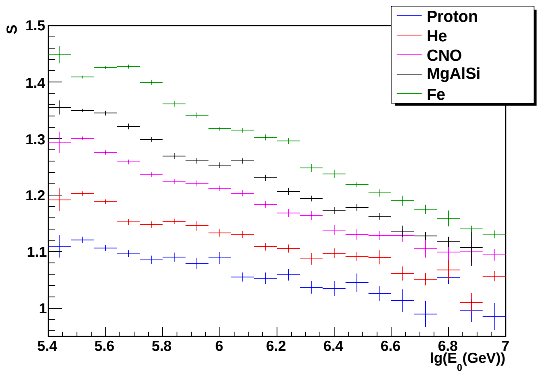

Figure 7: The age s as a function of the primary energy. The zenith angle $\theta < 15°$.

4. Summary and Outlook

ARGO-YBJ experiment (full coverage and wide dynamic range) makes a good measurement of LDF near shower core region. In this paper, we propose one NKG function with $R_m = 80$ m for ARGO-YBJ analog and digital combined LDF measurement. The fit parameter N_e has a good linearity with primary energy which promises for primary energy study. More detailed comparisons of different component and the experimental data and further physical topics such as cosmic ray spectrum are under study.

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