Energy determination of air shower array based on the "full" Monte Carlo simulation for the Telescope Array

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***Abstract*. We developed a new air shower simulation system for the precision measurement of ultrahigh energy cosmic rays by the Telescope Array (TA).**

***Keywords*: Extensive Air Showers, Ultra High Energy Cosmic Ray, Monte Carlo Simulation**

I. Introduction

The surface particle detector (SD) of TA is composed of two layers of plastic scintillators each with 3 m^2 area and overlaid on top of each other. A total of 507 SDs are deployed in a grid of 1.2 km spacing on the ground and forms an air shower array. The primary energy of the cosmic ray is reconstructed from the pattern and the amount of energy depositions recorded in the array of SDs.

The energy deposition in the SD is caused not only by the charged particles but also by the neutral components such as much abundant soft gamma rays and delayed neutrons produced in the air shower. In order for the air shower Monte Carlo (MC) to reproduce the SD energy depositions properly, effects of all the particles will have to be taken into account. A thin sampling method creates air shower events in a short time but it reproduces the SD energy deposition only in a statistical manner when many events are accumulated. A full simulation reproduces the proper energy deposition event by event, but the calculation time is prohibitive for sufficient numbers of events to be simulated. Here we developed a hybrid method to create a full spectrum of particles incident on the SD in a limited time based on the scaling features of air shower with the shower age and the Moliere unit (mu). It is based on a fast generation of thinned event and "wearing" it with a particle spectrum obtained from a pre-generated fully simulated event.

II. Basic Concept

We produced more than 100 fully simulated events using parallel computing COSMOS using a PC cluster. Up to 10^{19} eV, they are produced by the full simulation and a quasi full method with an approximation is used above 10^{19} eV [1]. The samples are made at the primary energies of 10^{17}, 10^{18}, 10^{19} and 10^{20} eV, and the zenith angle θ of $0.5 < \cos\theta < 1.0$ at the interval of 0.025. A large part of the samples are for the proton and Iron primaries, and some are for He, Nitrogen and gamma ray primaries. Hadronic interaction models of DPMjet3 and QGSjet2 are used. A large amount of information (particle types, momentum vectors, timing etc.) are stored as the FDD (Four dimensional Development Data) data base at each stage of the shower development.

In the thin sampling method, integral quantities such as the total number of particles, lateral and arrival time distributions at a given depth are well reproduced if the appropriate thinning parameters are used. We produced 100 to 1000 shower events with thinning for a fixed set of parameters: the energy, the zenith angle, the primary particle species and the hadronization model. The results are stored as the LDD (Longitudinal and Lateral Development Data) database. The major components of LDD are the total number of particles, lateral and arrival time distribution for each particle species.

In our method, a "full" simulation results are obtained in a short time by combining the LDD and FDD databases. It is predicted that shower parameters scale with the shower age in the longitudinal development and with the Moliere unit in the lateral development. It has been shown that in case of photons and electrons, good scaling parameters are the shower age and the Moliere length, and in case of muons and hadrons, the parameter cog (averaged depth of electrons) and the Moliere length are good parameters [2]. By taking the advantage of scaling, we can associate each part of the LDD event with the corresponding part of the FDD event with the same shower age/cog and the core distance measured in the unit of Moliere length. In this way, a single FDD event can be recursively used by many LDD events. The distribution also scales with the primary energy, and the LDD can be associated with the FDD at the different primary energy if properly scaled. In the next section, we demonstrate good examples of the scaling.

III. Scaling of shower parameters

A. Energy spectrum and direction vector

We show one example of the scaling; the energy distributions of photons in the shower of different primary energies, 10^{18} and 10^{19} eV, are compared in Fig. 1. Both showers are generated for a proton using full simulation (FDD) and the DPMjet3 was used as the hadronic interaction model. The distributions at the same shower age of 1.20 are taken and the total number of photons are normalized.

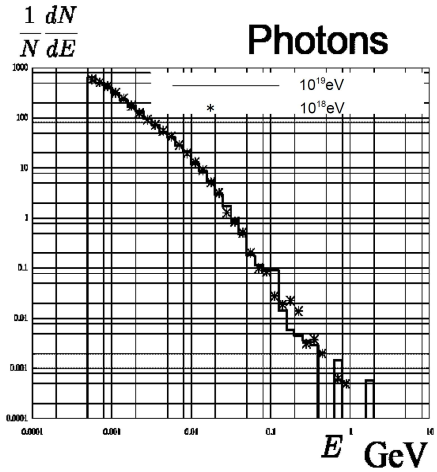

Fig. 1. Photon energy spectrum comparison between different showers.Solid line:primary particle is 10^{19}eV(s = 1.208) proton Dots:primary particle is 10^{18}eV(s = 1.207) proton , cosine(zenith angle of the primary particle) is 0.900, DPMjet3 model

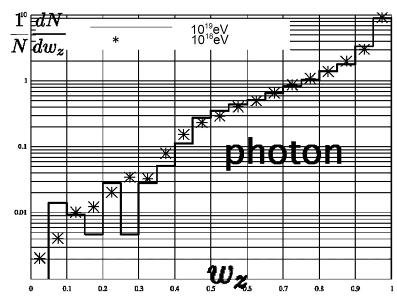

Fig. 2. Photon direction vector distribution comparison between different showers. Solid line:primary proton 10^{19}eV (s = 1.208) Dots:primary proton 10^{18}eV (s = 1.207), cosine(zenith angle of the primary particle) is 0.900, DPMjet3 model

Another example of the scaling for the distribution of the direction vector of photons are shown in Fig. 2. The showers are the same ones used for Fig. 1.
It should be noted that the three dimensional cascade theory also support an approximate primary energy independence in the meaning of average feature of the shower particles.[3]

B. Arrival time distribution

Arrival time distribution does not have the same scaling feature as the energy spectrum and the direction vector distributions have.

Here, we test scaling features of two temporal parameters; T10 timing and the signal duration. We define T10 as the timing that 10% of all number of particles are given to the SD. The $t = 0$ timing of the shower is defined as the time when the shower core hits the ground.

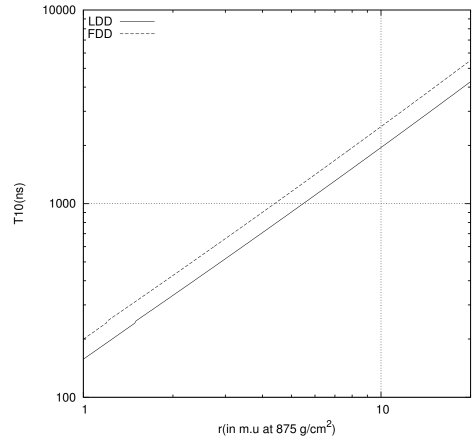

Fig. 3. Photon T10 core distance dependence comparison between 10^{20}eV primary proton cosine(zenith angle)=0.850 inclined LDD and FDD shower . Right line:first interaction point depth is deep(239.3 g/cm^2)and age s = 0.988, moliere unit = 86.0m, depth = 875 g/cm^2 LDD shower example, Left line:typical FDD shower T10 core distance dependence(age s = 0.988, moliere unit = 107.3m, depth = 680 g/cm^2)at the same age as this LDD.

Distributions of the T10 for photons at different showers are plotted in Fig. 3 for some of the FDD events. We use the reduced time (t + $r(\cos\psi{+}1)\sin\theta/c$) to compare timings of inclined showers avoiding the negative timing. Here, r is the distance from the shower core, ψ is the azimuth angle from the shower axis. θ is the incident angle of the shower as shown in the schematic drawing of Fig. 10.

In Fig. 3, two showers in largely different longitudinal development are compared. The left line shows the T10 timing distribution of a shower with a typical longitudinal development and the right line is that of a shower with exceptionally deep penetration. The parallelism of two lines is impressive.
The distributions of T10, T50 and T90 timings are shown in Fig. 4). Here the parallelism of the lines means that the duration of the shower signal scales with the timing itself. We then are able to apply the FDD timing information to the LDD particles if once T10 timing is adjusted between the FDD and LDD.

IV. Generation of events

A. Extraction of FDD information for LDD

By using the three scaling features shown in the previous section, we can extract FDD particle information for any part of each LDD shower. Firstly, we decide the location of the observation (=the position of the SD) and decide the core distance. Secondary, we extract particle density, T10 timing, shower age and cog, and Moliere distance from the LDD at the corresponding core distance. Thirdly, we use extracted particle vectors from the FDD of nearest primary energy as the LDD. We then correct the timing information by using LDD T10 data.

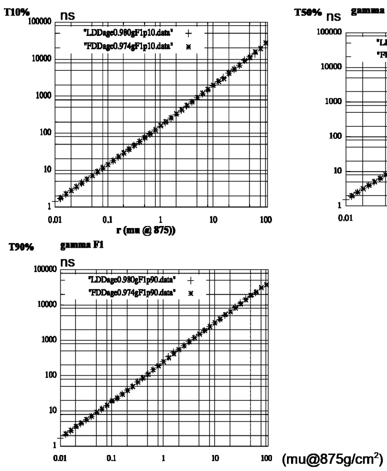

Fig. 4. Photon T10 , T50 and T90 timing distribution comparison between 10^{20}eV primary proton cosine(zenith angle)=0.850 inclined LDD shower and scaled FDD shower.T10 and T50 and T90 FDD timings are scaled just by using T10 timing scaling factor(FDD/LDD).In this case, LDD example:age s = 0.98, moliere unit = 86m, FDD example:age s = 0.974, moliere unit = 110.4m.

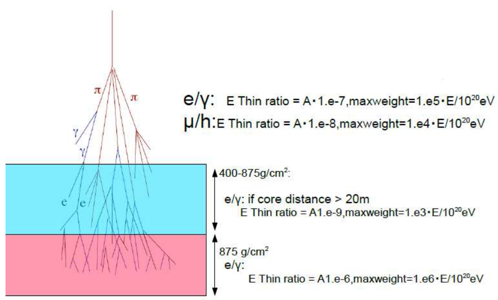

Fig. 5. Thinning condition for TA.

B. generation of thin sampled LDD

We searched an appropriate set of thinning parameters in order to obtain sufficient statistics for the lateral distribution and the timing distribution, down to the SD far away from the shower core. Such parameters we obtained are shown in Fig. 5.

C. Detector simulation

The detector response is evaluated using GEANT4. Two layers of scintillators of 3 m^2 area and 1.2 cm thickness are installed in the box made of 1.2mm and 1.5mm thick stainless steel. The box is placed under the roof made of 1.2mm thick steel. A layer of 1.0mm thick stainless steel is placed in between the top and bottom scintillators.

Here we take the average of the energy deposition in two layers of scintillators as the signal.

V. Results

We define $S_\theta(r)$ as the total energy deposited in the SD which locates at the distance of r [m] from the shower core. The incident zenith angle of the primary particle is defined as θ. The parameter $S_\theta(r)$ is approximately proportional to the primary energy and has been used as an useful energy estimator of ultra-high energy cosmic rays. It is also known that the fluctuation of $S_\theta(r)$ is small at certain distances from the shower core [4] [5]. Fig.6 shows the primary energy dependence of $S_0(800)$ obtained using a QGSjet2 hadron interaction model[6]. Fig.7 shows a distribution of $S_0(800)$ obtained for 10^{20}eV proton using a QGSjet2 hadron interaction model.

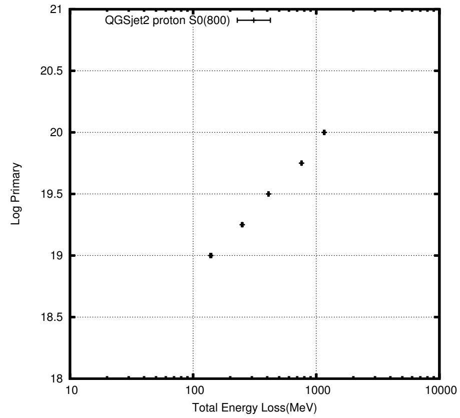

Fig. 6. Primary energy dependence of the total energy deposition S0(800), primary proton, QGSjet2 interaction model

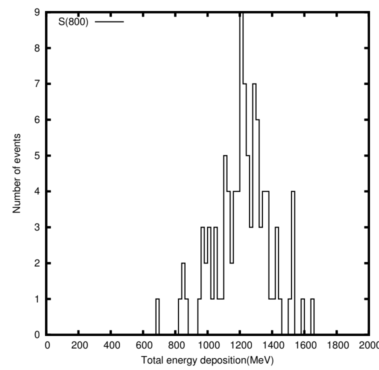

Fig. 7. Energy deposition S0(800) for TA. Primary proton 10^{20}eV, QGSjet2 interaction model

The fluctuation of $S_0(800)$ is about 10-15% and it determines the limiting accuracy of the primary energy determination by this parameter. It can be shown that the resolution is improved if the first interaction point of the air shower can be better determined.

In Fig. 8, zenith angle dependence of $S_\theta(800)$ is shown. The feature of this dependence reflects the longitudinal development of the shower, the average behavior of which is plotted in Fig. 9. The observation site of TA is close to the shower maximum for the proton primary particles simulated with QGSjet2. It is reflected as a flat distribution around the vertical axis (θ=0).

In the case of inclined shower, $S_\theta(r)$ varies on the rotation angle around the shower axis even if the distance

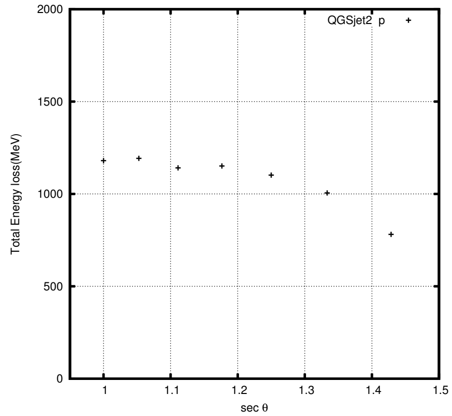

Fig. 8. Zenith angle dependence of the energy deposition S(800) in case of primary proton 10^{20}eV, QGSjet2 interaction model.We averaged the azimuth angle dependence of S(800) from the shower core.

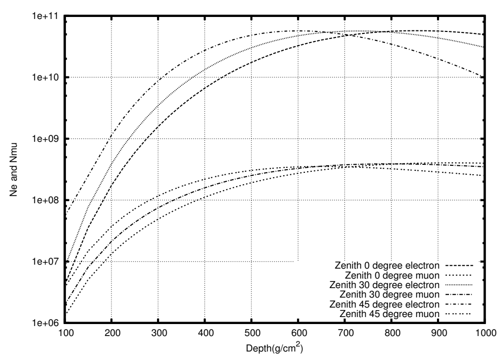

Fig. 9. Electrons and muons longitudinal development of primary proton 10^{20}eV, QGSjet2 interaction model showers(100 events average).Our observation level is around 875 g/cm^2

from the shower axis is the same. An example of the rotation angle dependence is shown in Fig.11 This is because the stage of shower development differs at different rotation angle. We need to pay attention on this feature when we plan to measure the shower energy using this parameter.

VI. Summary and Discussion

We developed a new air shower simulator for TA and studied the energy deposition in SD as an energy estimator of the primary particles. We showed the correlation between the longitudinal development of each shower and the zenith and azimuthal angle dependence of the energy deposition.

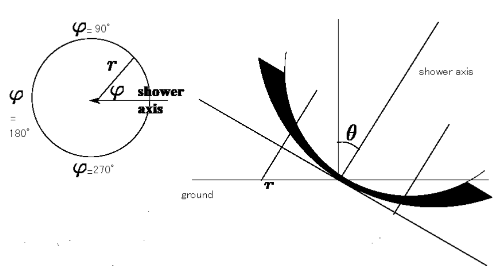

Fig. 10. Schematic view of shower front geometry.Incident angle of the air shower is defined as θ, and the azimuth angle from the shower axis is defined as ψ.

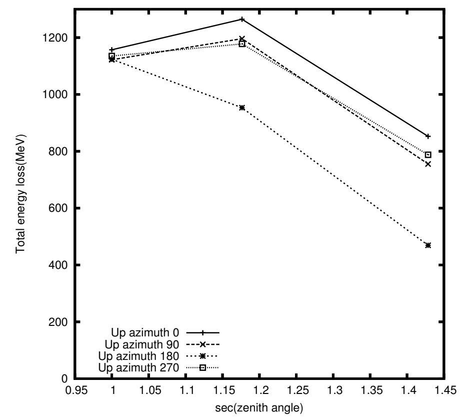

Fig. 11. Azimuth angle dependence of energy deposition S(600) in case of primary proton $10^{19.5}$eV, QGSjet2 interaction model. S(600) is the average result of 100 showers. Here, the azimuth angle is the same definition as in Fig. 10

We will study how to include the azimuthal dependence in our event reconstruction and also about other chemical composition of the primary particles. An extension of the MC system to analyze the fluorescence detector (FD) data and the SD/FD coincidence events are also under way. For the verification of the energies measured by the SD and the FD, the use of unified air shower Monte Carlo is important and this remains as the next step of the development of our simulator.

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