A Fast and Accurate Monte Carlo EAS Simulation Scheme in the GZK Energy Region and Some Results for the TA experiment

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Abstract: In this paper, we present a very accurate and fast Monte Carlo (MC) simulation method for air showers in the GZK region. This is developed for the Telescope Array (TA) project now being prepared at Utah, USA. We explored a method of parallel processing of an event, which enables us to make a full and quasi-full MC simulation with energy threshold of particles of 500 keV for primary energy of 10^{19}eV and 10^{20}eV. Various physical quantities, which are mutually correlated, are put in a database by using these detailed MC. A number of fully fluctuating longitudinal development of air showers, which could be model dependent, are generated by other method. For each of these showers, quantities such as energy, arrival time, angular distributions of individual particles are sampled from the database. The method gives AS very quickly while keeping the accuracy as if they were generated by the full MC.

Introduction

In air shower simulation, in general, we should be able to sample the following quantities : number of particles at a given distance from the shower core, type of particles, arrival time, energy and angle falling on detector. Or you would also like to have lateral distribution, energy spectrum, arrival time, angular distribution. Also, we must be able to generate Cerenkov light and air fluorescence.
At 10^{17}eV or more, it is almost or completely impossible to make full MC and generate a number of showers (say, 1 000) both from the point of view of the CPU time and storage size. The most common way to simulate air shower at the GZK region, is using thinning algorithm, as it is used in Corsika or AIRES [**?**, **?**] where all individual particles are not followed but by group of particles; this procedure can reduce the amount of data and computation time (both depend on thinning level decided by the user). In the past, number of papers treat about techniques to simulate faster ultra high energy air showers, like parametrization (longitudinal profile, lateral distribution...), or using shower librairies induced by pions at lower energies, or study the systematics of showers at lower energy and extrapolate it to GZK region; however, it is not so easy and all have some limits. In this paper, we will be presenting quite a different approach as explained next.

Full Monte Carlo Air showers

Correlations in air shower.

Variables, like energy (E), time (T), position $\vec{r}$, angle... in a shower are mutually correlated (see Fig.1). In a fast simulation program, we should be able to reproduce these correlations so that unexpected biases be not included in the final result of MC data analysis. In general, air shower fluctuation is very large; the number of particles at a given depth for fixed primary energy, angle, particle type etc... differs from event to event; in MC, they are also model dependent. However, the shape of particle distribution (such as energy, arrival time, etc... and their correlations) are quite similar if we look into an appropriate place of air shower development. Such a place is normally provided by seeking for the same age and same lateral distance in Moliere unit. Thus the fluctuation and model de-

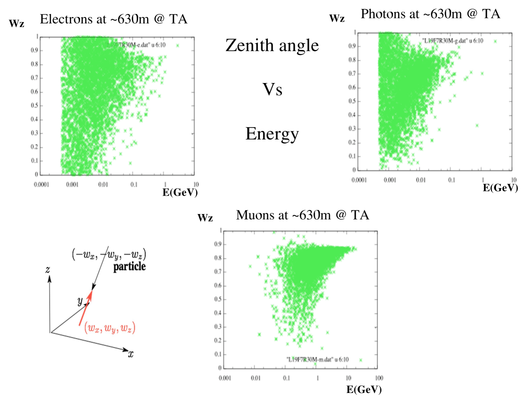

Figure 1: Cosine zenith angle versus Energy (GeV) for a full MC air shower at 10^{18}eV by a proton primary at 630 meters from the core at Telescope Array observation level (880 g.cm^{-2}).

pendence are absorbed in the absolute number of particles.

Figure 2 illustrates these. The red curve shows a longitudinal profile transition of a model shower created by a full (or quasi-full) MC for which we have very detailed information of particles (which will be stored in a database). Its typical energy is 10^{19}eV or 10^{20}eV. Other two are representing showers (typically 10^{20}eV) generated by a quick method and for which we do not have the details of particle distribution. Take a shower *A* for example. We want to know the detailed particle distributions at observation level (point *a*) which is corresponding to shower age S_A. Then we seek for the same age point in the model shower, a' and get the details from the database. If we compare the distribution of particles of two shower (even for shower at different energies) at the same *age* (and normalized to number of particles), they are almost identical. The figure 3 represents the (normalized) lateral distribution for electrons and muon for shower at 10^{18}eV at s=0.941 and 10^{19}eV at s=0.939. The distance is expressed in Moliere Unit (r in mu, from 0.1 to 100 mu). In case of muonic part, age is not well adapted. It would be better to use an other parameter. It is the reason we introduce the *Center Of Graviy* (COG) of the longitudinal profile; COG is calculated as follow :

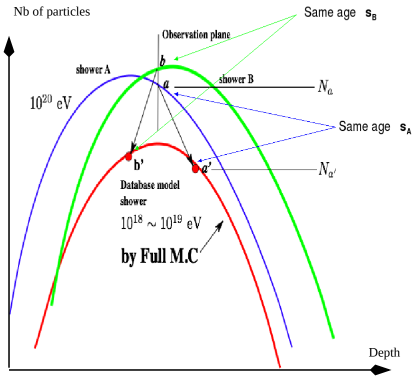

Figure 2: Basic Idea.

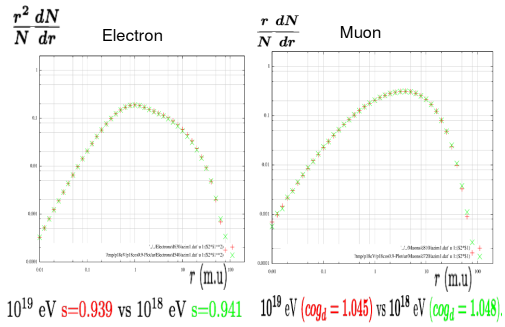

Figure 3: Lateral distribution of shower at 10^{19}eV (red cross) and at 10^{18}eV (green star). Distance from 0.1 to 100 Moliere unit (mu)

$$T_{COG} = \frac{\sum N_e \times t\ (g.cm^{-2})}{\sum N_e} \quad (1)$$

In case of muon, we use cog_d (Fig. 3, right), related to COG by cog_d=1 when the depth is equal to T_{COG}.

We have the same property if we look energy spectrum of particle or angular distribution of particles at observation level.

Database Principle

In this section, we explain the principle of the database (how we build and use it). The database (DB) will be composed by 2 parts: :

- Longitudinal profile : $N_{particles}$ vs depth.

- Particles at each depth : for a given depth, one can obtain information of individual particles.

Longitudinal Development Database (LDD)

First, we will generate longitudinal development database; 1 000 longitudinal profiles for each energy, each zenith angle and each primary particle (we begin by a proton primary). The profile contains list of depth, age, cog$_d$, number of photons, electrons, muons, hadrons. We simulate from cosine zenith angle equal 1 to 0.5 by step 0.025. The hadronic model used for the first try of the database is DPMjet 3 (with QGSJet II will be next step). We record the profile in layers of 25 g.cm^{-2} (horizontal plane). These showers are simulated with Cosmos code (see next section) which allow parallel calculation, and it takes around 10 hours for 1 000 events with 25 CPU with a thinning value of 5×10^{-6}. This thinning value is verified to be quite safe as far as the total number of particles is concerned, although the ingredients (such lateral, arrival time, energy distribution, etc...) will be problematic.

Four Dimensionnal Database (FDD) : particles at ground

The second part of the DB is the particles at each depth. For a set of primary zenith angles which are the same as those in LDD part, we generate 1 full MC shower at 10^{18}eV and 10^{19}eV and quasi-full MC (cf. simulation code section) at 10^{20}eV for each zenith angle. During simulation, we record particles at different depth (33 horizontal plane, every 25 g.cm^{-2} from 400 g.cm^{-2} to the sea level). At each observation level, we build a spider (cf. Fig.4); the spider is divided in bin on distance (42 in moliere unit) and azimuth angles (12 bins of 30 degrees each). For each level, we sample particles falling on each bin. A maximum of 7 500 randomly selected particles are recorded with detailed informations (*x*, *y*, *z*, *t*, *E*, angles) for each type (photon, electron, muon and hadron) falling in a bin. The value of 7 500 is enough to reproduce the particles distribution (lateral distribution, energy spectrum...).

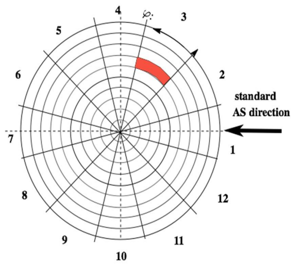

Figure 4: Database part II : Particles recorded for each depth.

Relation between FDD and LDD.

The information containing in a bin in FDD are :

- The total number of particles falling in the bin N'_{TOT}
- The number of recorded particles (with detailed information) N'_{REC}
- The total number of particles falling in all bins at the observation level (where the bin is) N'_{GROUND}

These 3 values are known for each particle type (photon, electron, muon, hadron). In LDD part, we have only the information of the total number of particles for each observation level, N_{GROUND}. We do not know the particle distribution at the level. But we know that the particles distribution will be same than a shower at the same age. If we call N_{TOT} the total number of particles falling in a bin (r,ϕ), we are able to compute this value, using information in FDD, by the formula :

$$N_{TOT} = (\frac{N_{GROUND}}{N'_{GROUND}}) \times N'_{TOT} \qquad (2)$$

Since we know, the number of particles falling in the bin, we can compute the density :

$$\rho = \frac{N_{TOT}}{S_{r\phi}} \qquad S_{r\phi} = bin\ area \qquad (3)$$

We suppose to have a detector at the bin (r,ϕ) of area S_d, we can compute the number of particles falling in the detector, n_D :

$$n_D = \rho \times S_d \ \ (+\,poissonian\ fluct.) \qquad (4)$$

and we will sample n_D particles from N'_{REC} with detailed information to simulate the detector response.

How to use it ?

How to use the entire database ? First, the user will specify some basic input like primary energy, primary type, zenith angle (cosine) and observation level. The first search in the LDD-DB will produce a list of 1 000 profiles (as explained in LDD section). One will be randomly choosen and with the indication of the observation level, the user get the closest value of the specified depth. At this stage, the user has one line of the profile (depth, age_{LDD}, cog_d, number of photon, electron, muon and hadron).

The next step is to search in FDD, the closest value to age$_{LDD}$. The result of the search is a "spider" of FDD (all bins at one observation level, all r, all ϕ). If the user specify one bin by giving information of distance and azimuth, it will be reduced to one bin and we return to the case explained in the previous section.

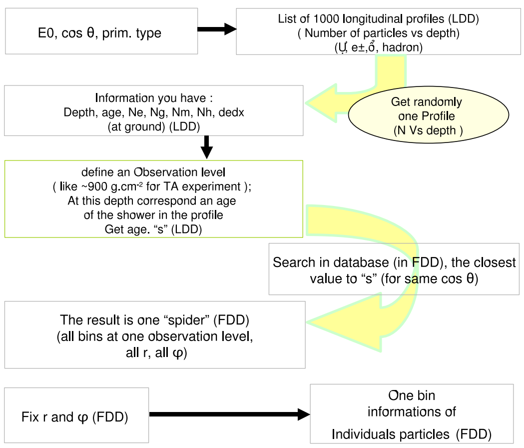

Figure 5: Scheme how to use it

Simulation Code

To perform simulation, we use Cosmos code (http://cosmos.n.kanagawa-u.ac.jp). This code provides a means for full Monte Carlo simulation of air showers but also the thinning method and the hydrid method based on approximmation B on the cascade theory, which allows to simulate very quickly longitudinal profiles. The code also provides the parallel "Skeleton/smash/flesh/assemble" method which allows parallel calculations of a high energy shower. At Skeleton step, you simulate only very high energy particles, and you record all particles information; Once a skeleton is made, it is "smashed" into a number of sub-skeletons which may be sent to different CPU'S and "fleshed". When all sub-showers are simulated, you assemble all parts to make the final shower.

Conclusions

The method proposed will permit to simulate air showers at very high energy and in a very short time very accuratly. It keeps the natural correlations existing between energy, time, position of particles of showers simulated by full Monte Carlo. There is no parametrization and the interaction model dependence can be absorbed in the FDD which can be created in a moderate time.
We will include this air shower generator code to the Telescope Array MC software.

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