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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: 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 starting its full operation at Utah, USA. We use a method of distributed-parallel processing of an event [1] , 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. Mutually correlated various physical quantities in a shower generated by this method are put in a database. A number of fully fluctuating longitudinal development of air showers, which could be model dependent, is 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 can generates AS very quickly while keeping full M.C accuracy.

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 to use thinning algorithm[2] where only some weighted individual particles are followed. This procedure can reduce the amount of data and computation time (both depend on thinning level decided by the user).

Apart from thinning, a number of papers treats about techniques to simulate ultra high energy air showers; parameterization (longitudinal profile, lateral distribution...), or using shower librairies induced by pions at lower energies, or extracting systematics of showers at lower energy and extrapolate it to GZK region; however, it is not so easy to get accurate results and all have some limitations. 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-

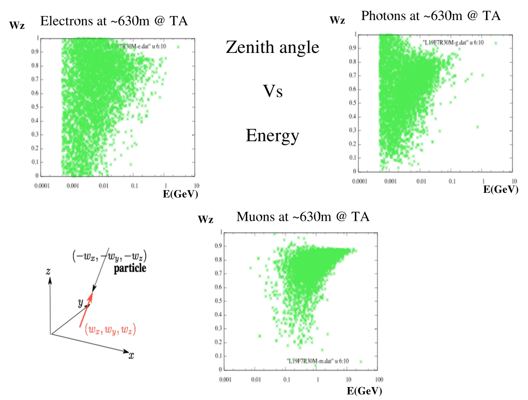

Figure 1: Cosine zenith angle versus Energy (GeV) for a full MC air shower at 10^{18}eV by a proton primary at 630 meters from the core at Telescope Array observation level (880 g.cm^{-2}).

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 showers 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 0.01 to 100 mu). In case of muonic part, age is not a good parameter. 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 follows :

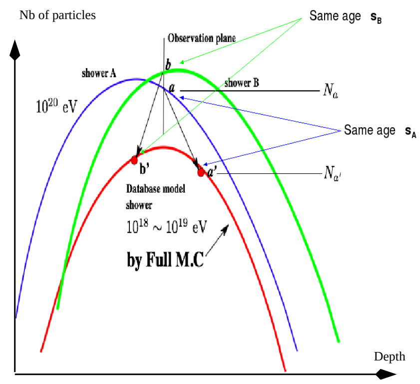

Figure 2: Basic Idea.

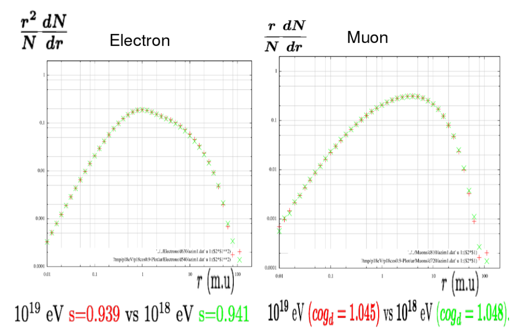

Figure 3: Lateral distribution of shower at 10^{19}eV (red cross) and at 10^{18}eV (green star). Distance from 0.1 to 100 Moliere unit (mu)

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

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: :

- LDD: Longitudinal Development Database.

Many showers (default is 1000) containing depth *vs.* $N_{particles}$.

- FDD: Four-dimensional Development Database.

  One or few showers with detailed particle information.

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 and dE/dx. We simulate from cosine zenith angle equal 1 to 0.5 with step 0.025. The hadronic interaction model is dpmjet3 and qgsjetII at present. We record such profile at every 25 g.cm^{-2} step (horizontal plane). It take ∼10 hours to generate 1 000 events by using 25 CPU's 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 as lateral, arrival time, energy distribution, etc...) will be problematic.

Four Dimensionnal Database (FDD)

The second part of the DB is detailed particle information at each depth. For a set of primary zenith angles which are the same as those in LDD part, we generate 1 (or at most few) full MC shower at 10^{18}eV and 10^{19}eV and quasi-full MC [1] at 10^{20}eV for each zenith angle. During simulation, we record particles at 35 depths (every 25 g·cm^{-2} from 175 g·cm^{-2} to the sea level). At each observation level, we build spider-web like observation areas (cf. Fig.4); we split the lateral distance into 42 bins from 0.01(Moliere unit) with step 0.1 in $\log_{10}$ and azimuthal angle into 12 bins. In each sector, a maximum of 7 500 randomly selected particles are recorded with detailed information (*x*, *y*, *t*, *E*, angles, particle code). The value of 7 500 is enough to reproduce the particles distribution (lateral distribution, energy spectrum...). To record one shower, ∼ 35 GB memory is needed without compression.

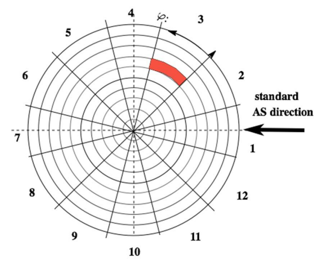

Figure 4: spider-web: Observation area at each depth

Relation between FDD and LDD.

The information for a sector in FDD is :

- The total number of particles falling in the sector N'_{TOT}
- The number of recorded particles (with detailed information) N'_{REC}
- The total number of particles falling in all sectors at each observation level 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 at each observation level, N_{GROUND}. We do not know the particle distribution at the level. But we know that the particle distribution is the same as the one in a shower with the same age. If we call N_{TOT} the total number of particles falling in a given sector (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 sector, we can compute the density :

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

However, to get the particle density at the detector location, we use interpolation using surrounding sectors and the detector location. With such ρ, we can compute the number of particles falling in the detector of area S_d as

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

and we will sample n_D particles. However, we must be careful of the arrival time. So far, we have been using r in Moliere unit. We consult a FDD sector in the same age as LDD shower and in the same Moliere unit as the detector location. This results in an inaccurate distribution of arrival time. In view of the fact that the other physical quantity distribution changes very slowly with the lateral distance, we consult particle distribution in a FDD sector in the same real lateral distance (not in Moliere unit) as the detector location, although we use Moliere unit correspondence for particle numbers. Further, we must make a correction of arrival time of particles in a given sector so that it corresponds to the one at the detector location (correction is needed by the lateral distance, azimuthal angle and detector height).

How to use it ?

First, the user specifies some basic input like primary energy, primary type, zenith angle (cosine), observation level and FDD shower to be consulted. Then, one shower from the LDD database is chosen.

Then, the user may give a detector location to get particle density there. The user may sample a number of particles (photons, electrons..) which are extracted from the FDD database.

One simple example to show the distribution of number of detectors triggered with some threshold is shown in Fig.6 using 1000 10^{20} eV proton showers with various zenith angles. The time needed for this is about 1 min (Detector response simulation is not included).

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.

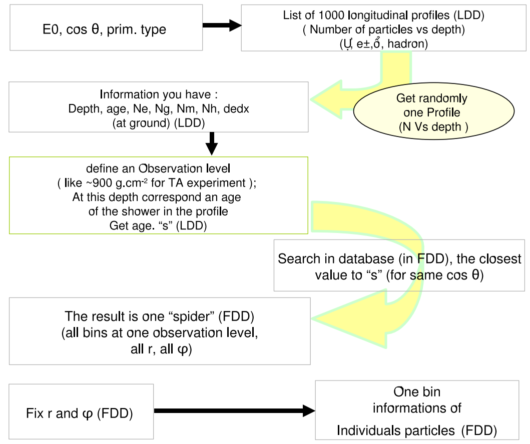

Figure 5: Scheme how to use it

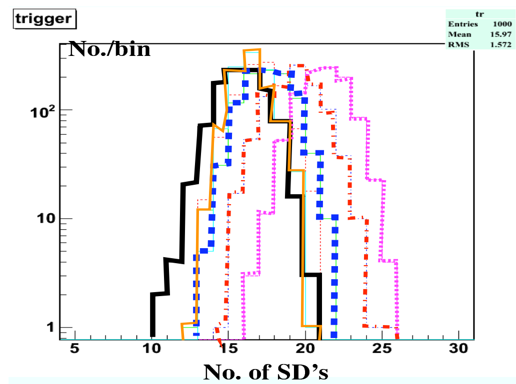

Figure 6: Simple example to show the number of detectors hit by a 10^{20} eV proton shower for various zenith angles ($\cos\theta = 1 \sim 0.6$)

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References

[1] K.Kasahara and F.Cohen, this conference ID199.

[2] A.M,Hillas, Proc. IX-th ISVHECI, Nucl. Phys.B(Proc. Suppl.) 52B(1997)139.