

## Simulation of Arrival Time Distribution of Shower Particles At Large Distances From Core

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### Abstract

By a Monte Carlo simulation, we have simulated the arrival time ( delay time ) distribution of shower particles at large distance (  $>100$  m ) from the air shower core. The distribution is found depending strongly on the distance from the core, but almost independent of the age, zenith angle, primary energy, primary compositions. An apparent difference is seen in some cases in the distribution from event to event when the number of particles is small. This is only due to statistical fluctuation.

### I. Introduction

The details of interaction models used for the present simulation (program provided by Kasahara) are described in Ref. [1]. Among the Interaction models Involved In the simulation program, we use 'QCD' model which is considered as the best at present.

In such an arrival time distribution simulation, the treatment of the cascade process is the key point. We only state three points here.

(1) Multiple scattering is treated with Fermi's Gaussian approximation which includes an angular and lateral correlation. No discernible difference is seen in the use of Mollere's scattering theory.

(2) The scattering formula which takes into account the energy loss and the change of air density has been developed. Its approximation does not seem appropriate for our purpose, so the maximum path through which an electron or charged particle can run is limited. As a result, the energy loss of the particle and the change of air density might be neglected, and the zigzagging path might be replaced by a line approximation.

(3) The path length from the simulation is about 10% shorter than in the real case due to the above approximation, so the distribution width is also shrunk by about 10%.

### II. Results of the Simulation

Our simulation was performed at 100 TeV and at an observation level  $600 \text{ g/cm}^2$  ( near the maximum development depth of  $500 \text{ g/cm}^2$  ) so as to get enough number of particles.

The simulation results from a proton primary,  $\sec \theta = 1.0$  are shown in Fig. 1. Fig. 1(a) shows the scattering plot of arrival time distribution of shower particles in linear scale. while Fig. 1(b) shows the scattering plot in logarithmic scale. The crosses and lines in Figs. 1(a), (b) indicate the average arrival time in each distance bin. From Fig. 1(a) we can see that the dispersion of arrival time is rather small near the core, but it increases with distance rapidly. Fig. 1(c) shows a few examples of the differential arrival time distribution at various bins and Fig. 1(d) shows the integral arrival time distribution for these bins. From Fig. 1(c) we found that until a distance of about 1500 m from the core, the arrival time distribution is concentrated on the front part with a long tail. At the largest distance, due to the small number of particles, this character becomes ambiguous.

To check the zenith angle dependence of the arrival time distribution, we have simulated events with different zenith angles ( $\sec \theta = 1.0, 1.1, 1.2, 1.3, 1.4, 1.5$ ). Fig.2 shows the variation of the parameter  $\sigma$  with distances at different zenith angles.  $\sigma$  defined as

$$\sigma^2 = \sum_{i=1}^n (\bar{t} - t_i)^2 / (n-1) ,$$

where  $t_i$  is the arrival time of the  $i$ -th particle,  $\bar{t}$  is the average arrival time. From Fig.2 we found that there is no definite zenith angle dependence for the zenith angles  $0^\circ$ -  $50^\circ$ . This means that the arrival time distribution is nearly independent of the height of the first interaction.

The fluctuation at large distance is very large, the number of particles in this distance is about 10 to 20. This means these parameters will undergo a severe fluctuation if the number of particles is not sufficiently large. This limits the application of the Linsley effect [2,3].

To check the fluctuation from event to event, we have simulated five events with energy 50 TeV,  $\sec \theta = 1.0$  (proton). The results are plotted in Fig.3. It is found that the fluctuation from event to event is not so large except for the largest distance, where the number of particles is limited. Comparing Fig.3 with Fig.2, we found no obvious energy dependence of the parameter.

Fig.4 shows the result about an iron primary. Comparison of Fig.4 with Fig.2 shows no distinct difference. So we conclude that the arrival time distribution is also independent of the primary composition. As we shall show below, at large distances, the front is populated by muons which are deficient in the  $\tilde{a}$  primary case. Therefore it will have some difference in the arrival time distribution for  $\tilde{a}$  and hadronic primary cases. However, we do not mean that the difference can be used to distinguish  $\tilde{a}$  from hadron primary.

There are very few hadrons scattered to distance greater than 100 m. Almost all of the particles are electrons ( $\sim 90\%$ ) and muons ( $\sim 10\%$ ). In a shower disc, the fastest part contains energetic muons which come from high interaction points directly. The electrons will undergo the cascade process and the arrival time (in logarithmic scale) appear approximately a Gaussian distribution (the deviation from the Gaussian distribution increases with distance). The particle type distribution and energy distribution are shown in Figs.5 and 6.

From the simulation, we found that  $\langle \log t \rangle$  increases with  $\log r$  almost linearly as shown in Fig.7. If we fit the arrival time distribution (in logarithmic scale) approximately by a Gaussian distribution function, it is found that the logarithmic dispersion  $s$  decreases with distance (see Fig.8). By simple fitting, we get the arrival time distribution

$$\begin{aligned} \langle \log t \rangle &= -(2.45 \pm 0.05) + (1.85 \pm 0.02) (\log r) \\ &\quad - (0.033 \pm 0.004) (\log r)^2 \\ \ddot{a} &= (0.015 \pm 0.018) + (0.424 \pm 0.007) (\log r) \\ &\quad - (0.107 \pm 0.001) (\log r)^2 \end{aligned}$$

These two formulae can be used to construct the arrival time distribution in a certain approximation up to a distance of 3000 m.

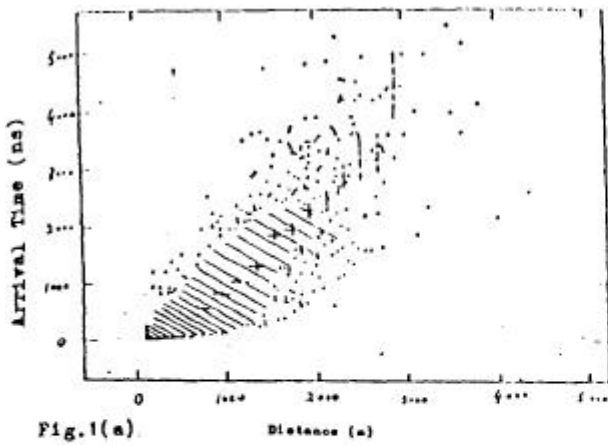


Fig.1(a)

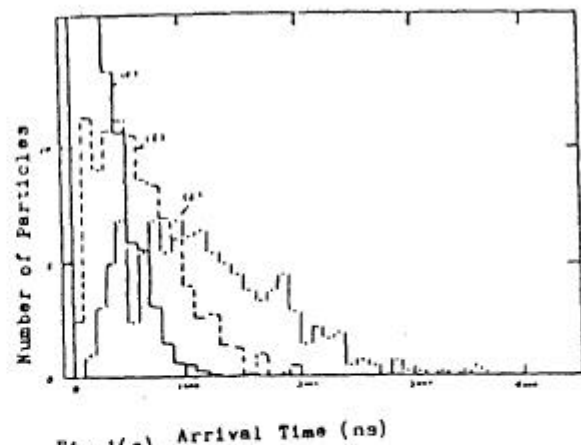


Fig.1(o) Arrival Time (ns)

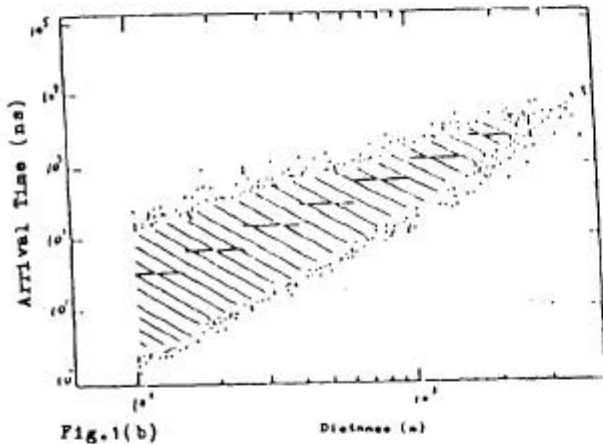


Fig.1(b)

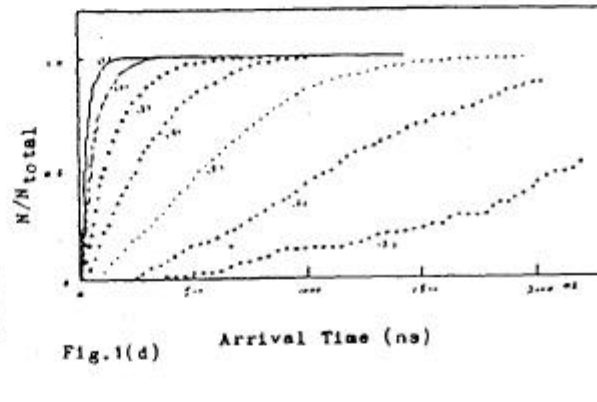


Fig.1(d) Arrival Time (ns)

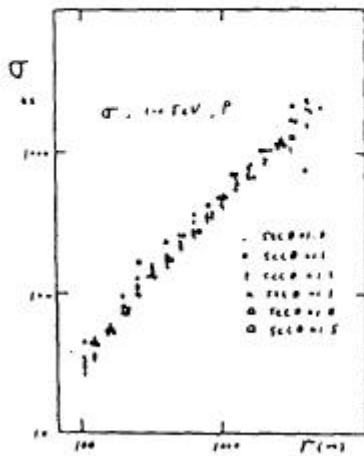


Fig.2

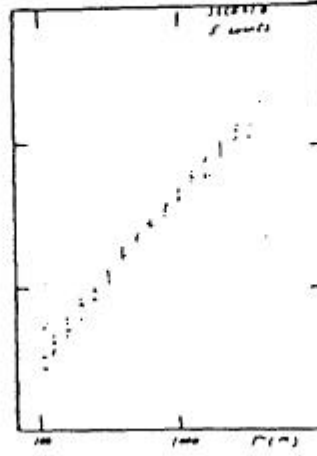


Fig.3

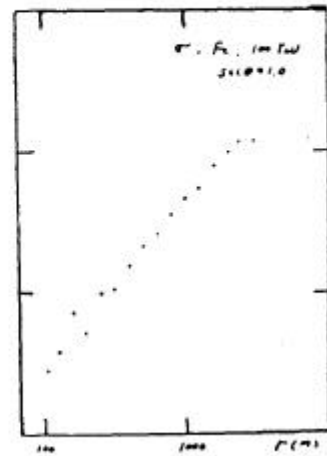


Fig.4

Fig. 1 (a) Scattering plot of arrival time distribution of shower particles (time in linear scale)  
 (b) Scattering plot of arrival time distribution of shower particles (time in logarithmic scale)  
 (c) Differential arrival time distribution in different distance bins.  
 (1) 100 m < r < 150 m, (2) 150 m < r < 251 m  
 (3) 251 m < r < 390 m, (4) 390 m < r < 631 m  
 (5) 631 m < r < 1000 m, (6) 1000 m < r < 1500 m  
 (7) 1500 m < r < 2000 m  
 (d) integral arrival time distributions for different distance bins (bin definition is same as (c))

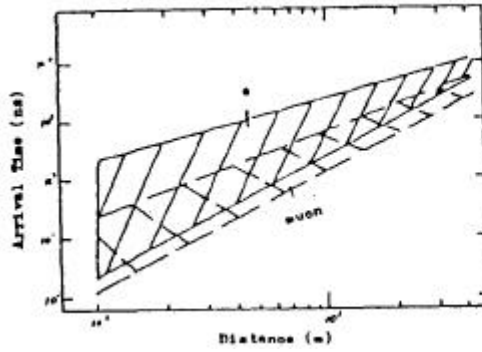


Fig. 5

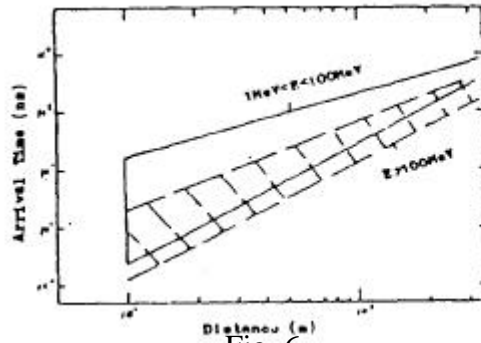


Fig. 6

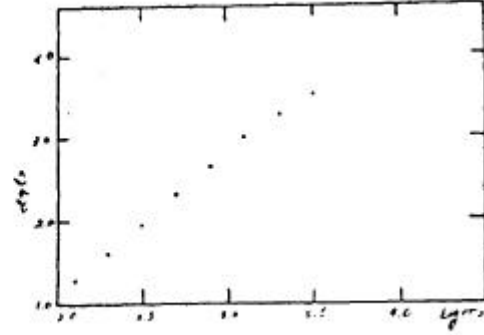


Fig. 7

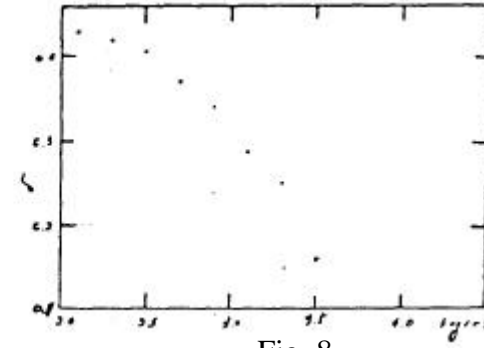


Fig. 8

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

The zenith angle dependence of p- (proton primary, 100 TeV)

 $\sigma$  distribution for 5 independent events (Proton, 50 TeV). $\sigma$  for iron primary, 100 TeV.  $\text{Sec}\theta = 1.0$ 

Particle (electrons and muons) distribution area in a shower disc.

Energy distribution in shower disc.

The average arrival time distribution (In logarithmic scale) varies with distance.  $t$ : arrival time;  $r$ : core distance.

The standard deviation of arrival time distribution (In logarithmic scale, fitted by Gaussian distribution) Varies with distance.

### Conclusion

From our simulation, we draw the following conclusions

- (1) The arrival time distribution is nearly independent of energy and zenith angle and of the primary composition either.
- (2) The fluctuation of arrival time from event to event is small. The apparent fluctuation is due to the limited number of particles.
- (3) Electrons and muons construct the shower disc at large distance, its fastest part containing energetic muons.

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### Reference

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