Fermi National Accelerator Laboratory

FERMILAB-FN-612

EM Clusters in Hadron Showers Using the "Hanging File" Data

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November 1993

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

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Introduction

Traditionally, hadronic showers have been presented as "profiles". This average behavior in depth is quite misleading in that it integrates out all the event by event fluctuations in initiation point, in neutral component of the shower development, and in multiplicity of secondaries. The "Hanging File" = HF[1] test apparatus has each active layer read out separately. Therefore, it is a very useful device in looking at longitudinal shower development of distinct individual showers.

The Homogeneous Pb Hadron Data/Model

Data from the HF exist for many different configurations [2]. For the purpose of exploring the fluctuations in the electromagnetic (EM) component of a hadronic shower, the data with 250 GeV pions incident on a homogenous stack of Pb (3/4" plates) interspersed with scintillator (2mm) was used. Since the ratio of radiation length to absorption length in Pb is, $Xo / \lambda o = 18.3$, the EM showers from neutral secondaries largely die out before the charged secondaries interact hadronically. Each 3/4" plates is 3.4 Xo , or 0.186 λo. A typical EM shower is taken to span 7 plates, or 24 Xo (1.3 λo).

The shape of these EM showers ("clusters") is taken to be constant in energy. For the qualitative purposes of this note, the logarithmic energy dependence of the shower shape is ignored [3].

The "profile" of a shower, summed over many showers, is expected to follow the WA1 parametrization [4].

$$\left(\frac{dE}{E}\right)_{\pi} = \left[du\, u^{c} e^{-u} / \Gamma(c+1)\right] Fo + \left[dw\, w^{g} e^{-w} / \Gamma(g+1)\right](1 - Fo) \qquad (1)$$

$$u = dt, t = X / Xo \qquad\qquad w = hv, v = X / \lambda o$$

There are 2 components to the shower, an EM component which develops in depth with a length scale, u, appropriate to EM showers, Xo. The hadronic component, presumably charged pions, propagates with a characteristic distance w whose scale is the nuclear interaction length, λo. The neutral fraction, Fo, is a parameter which, in the WA1 model, increases with incident energy.

One can dig marginally deeper by considering the irreversible nature of the production of neutral pions. If the neutral fraction, fo , is = 1/3 in each interaction, then the fraction Fo is related to fo by the number of generations in the hadronic cascade [5]. Clearly, Fo grows with energy because the number of generations, νmax, grows (slowly) with energy.

$$Fo = fo \sum_{\nu=1}^{\nu max} (1-fo)^{\nu-1},\ fo = 1/3 \qquad dfo \sim fo / \sqrt{<n>_o} \tag{2}$$

The fluctuation in fo is, presumably, due to the fluctuations in the neutral fraction at each generation in the cascade, dfo. Although the mean number of neutral particles, $<n>_o$, depends logarithmically on the incident energy, for the purposes of this note, <n> will be taken to be a constant. Clearly, if the number of generations is 1, then Fo = fo. The other limit with clear physical significance, is that Fo $\rightarrow$ 1, as the number of generations becomes large. This result is due to the irreversible nature of the production of neutrals. Any produced neutral "freezes out" of the hadronic cascade, and ceases to transport energy.

The maximum number of generations may be estimated in a way completely analagous to the depth of shower maximum in an EM shower [5,6].

$$\begin{aligned} Et &= E / [<n>]^{\nu max} \\ Et &\sim 2m_\pi \end{aligned} \tag{3}$$

In Eq. 3, <n> is the mean of the total number of secondaries over which the energy is (evenly) partitioned. The parameter Et is the threshold energy for pion production, Et ~ $2m_\pi$. Thus, Et is analagous to the critical energy in EM showers. For shower particles of energy < Ec (Et) the loss is due to ionization as bremmstrahlung (pion production) is no longer dominant.

This very simplified picture of pion cascades is illustrated in Fig.1. In this figure, <n> = n = 3, with fo = 1/3 (1 π^o per generation). The EM showers (dashed line) die out before the next hadronic interaction. Using Eq. 2 and Eq. 3, one finds that νmax ~ 3 for 250 GeV pions, and <n>=9. The neutral energy (Eo(ν)), energy/particle (e(ν)), and number of cascade particles (n(ν)) is shown in Table 1, for 250 GeV incident pions. In particular, Fo = 0.71 for 3 hadronic generations, in comparison to fo = 1/3.

The Fit Parameters

These simplified assumptions can then be confronted with the data. In comparing the data to the model, a fixed EM shower shape was used, but the energy was varied. The initiation point of a new cluster was searched for as a change in slope of the data. The event was, then, characterized by a number, nclus, of EM clusters of fixed shape, but variable energy e(ν), which begin at plates i(ν) within the HF stack. In fact, then, this variant of the model is more general, since the initiation points are not spaced by the fixed distance of $d\nu = 1$.

Results for typical events are shown in Fig. 2. Clearly, the model tends to die out a bit too soon in the "valleys" but, in general, the quality of the representation of the data is rather good. The existence of localized EM clusters seems to be very evident. In Fig. 2f, in an event with 11 distinct clusters, the EM clustering is obvious. Note that the number of clusters is not the number of generations. In Fig.1, this constraint was assumed for simplicity (it is true on average) although it was dropped in comparing to the data.

One might expect that the number of distinctly observable clusters would be $\geq$ the number of generations, as secondaries from the same generation would hadronically interact a distance 1 interaction length downstream, on average, but with fluctuations which might easily lead to several distinct clusters from a single generation.

In fact, the data fits yield a mean cluster number of <nclus> = 6.7. Looking at Table 1, the expected number of generations is, on average, 3. Note that the minimum number of clusters found was 4, while the maximum was 12. Thus, the fitted results for the nclus parameter seem plausible.

What about the initiation points? The depth location of the first cluster is shown in Fig. 3. The expected exponential depth distribution with scale set by λo is seen. Qualitatively, one expects that subsequent clusters in depth will be characterized by the scale λo also, as indicated schematically in Fig. 1. The distribution of the distances between the first few clusters is shown in Fig. 4. Qualitatively, the length scale appears to be confirmed to be λo for the first 4 interaction points in the cascade.

What about the energies carried in the clusters? The mean and rms fractional energy carried by the clusters as a function of cluster number, ordered in depth, is shown in Fig. 5. The expectation for the mean, as given by Eq. 2, is also shown. Clearly, the simplified model is a reasonable qualitative representation of the data.

One also expects that the spread in EM energy has a large fluctuation, dfo (see Eq. 2). Therefore, one expects a fractional deviation, dfo/fo which is, roughly, independent of depth (generation). The distribution for the fractional cluster energy in the first 4 clusters, ordered in depth, is shown in Fig. 6. Clearly, this naive expectation is also in reasonable agreement with the data.

There are also first order complications which have been ignored so far. Clearly, energy conservation imposes some correlations of a fairly trivial nature. For example, if Eq. 2 is summed to large νmax, Fo $\rightarrow$ 1 means that all energy at very high energies appears as EM showers (ignoring binding energy and invisible energy losses). However, fluctuations in fo in subsequent generations must be correlated, lest energy not be conserved. A first look at this effect is shown in Fig. 7. There is a clear correlation between a fluctuation to large EM energy in the first interaction and a reduced number of clusters. This effect is obviously expected due to energy conservation.

Conclusions

Study of individual pionic cascades yields insights which are obscured by the examination of depth profiles. A simple model for the distribution of distinct EM clusters in number, depth and energy is made. The qualitative agreement of the model to the individual hadronic cascades is quite good. The behavior of the parameters of the model, as abstracted from the events, appears to be in reasonable agreement with the assumptions of a very simplified model where all energy is ascribed to EM clusters.

References

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2. HF paper II - to be submitted to PRL

3. Review of Particle Properties, Phys. Rev. D45 (1992).

4. R.K. Bock, et al., CERN-EP/80-206 (1980).

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6. D.H. Perkins, Introduction to High Energy Physics, Addison-Wesley (1987).

Table 1
250 GeV Incident Pions

Generation ν	$\varepsilon(\nu)$ GeV	$n(\nu)$	$Eo(\nu)$ (GeV)
0	250	1	0
1	28	9	84
2	3.1	54	56
3	0.35	324	38
			178 GeV

fo = 1/3
Fo = 0.71

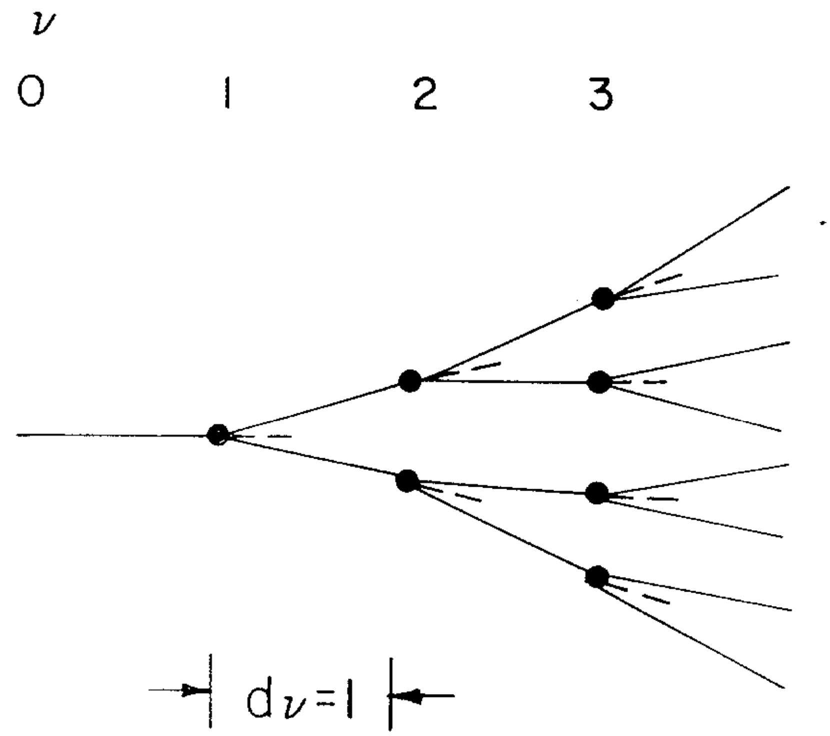


Figure 1. Schematic of a pionic cascade. At each generation, spaced by 1 interaction length, 3 pions are produced. The neutral pion causes an EM shower which dies away before the next hadronic generation.

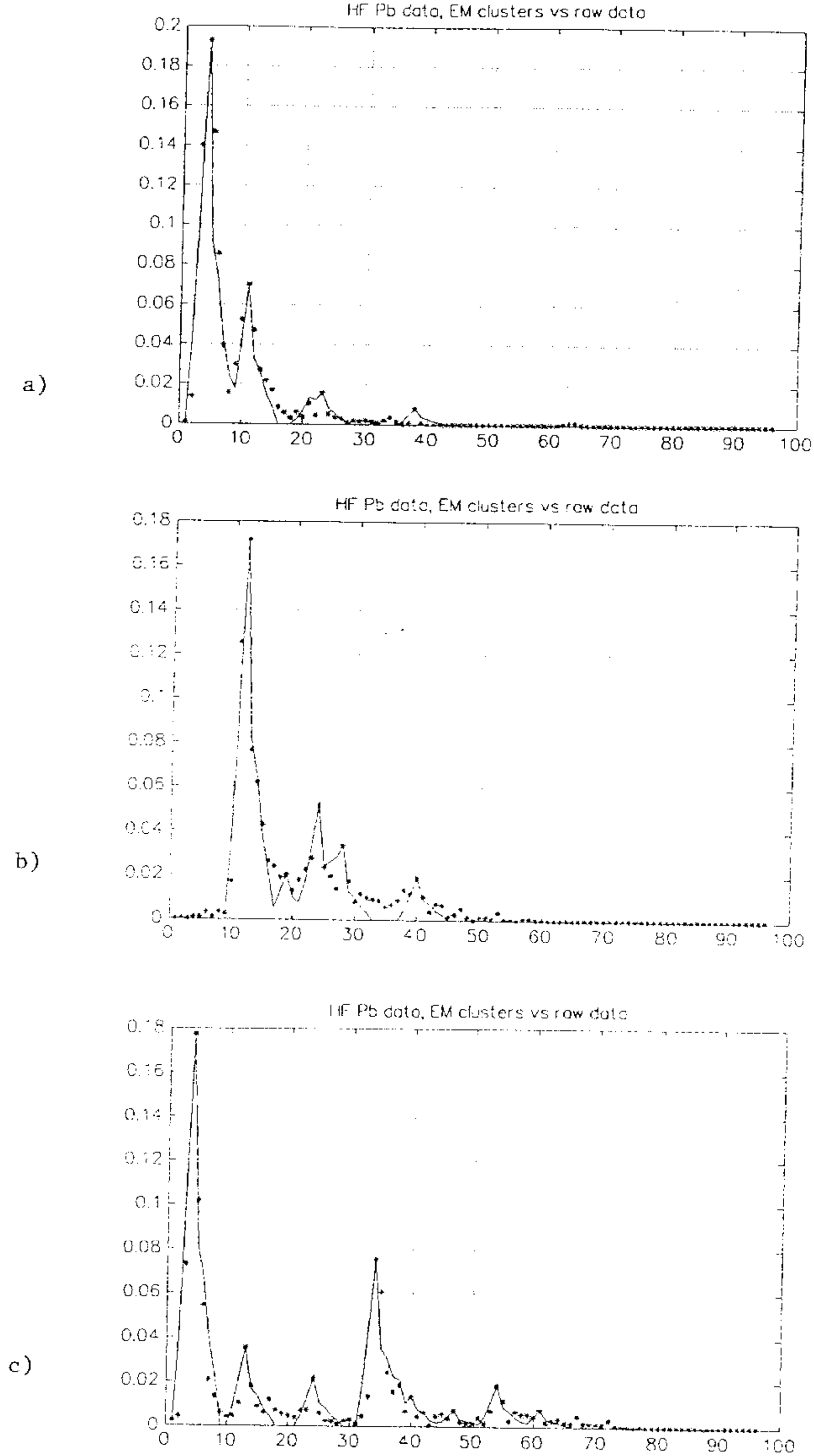
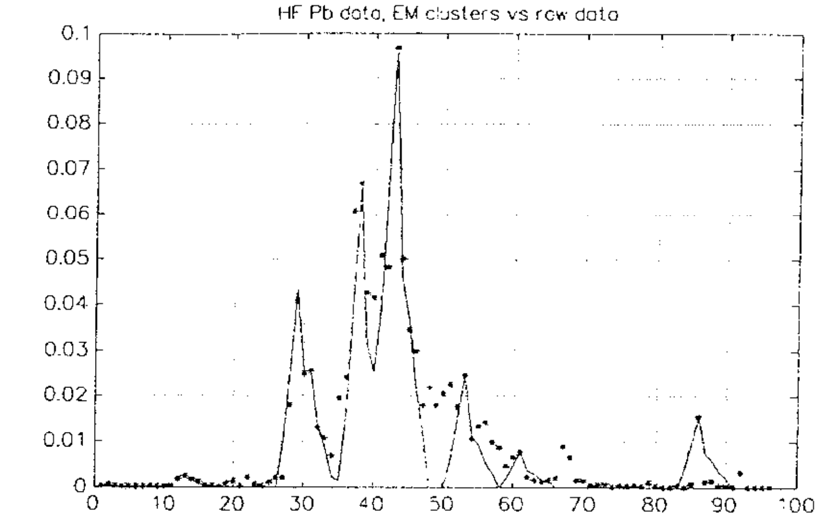


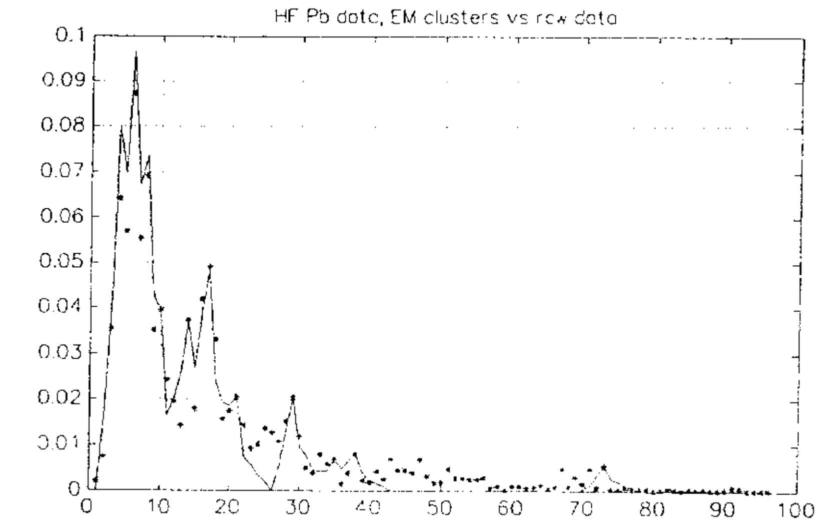
Figure 2. Longitudinal development for a single pion using the HF 250 GeV pion data incident on the homogeneous 3/4" Pb stack. The data points, *, are to be compared to the "model" indicated by the lines.
(a) - (f) - 6 typical events.
(a) - a minimal number of clusters, 4
(b),(c) - events with 5-6 clusters
(d) - a late developing 6 cluster event
(e),(f) - an event with 10, 11 clusters

(con't)

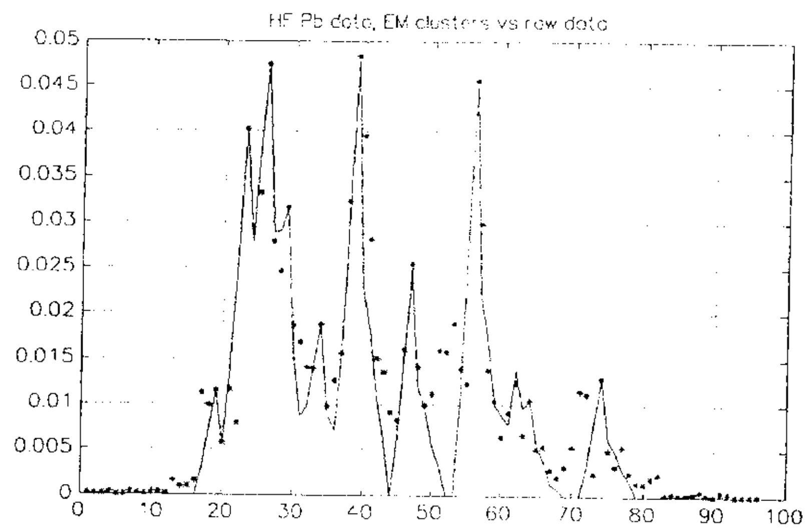
d)



e)



f)



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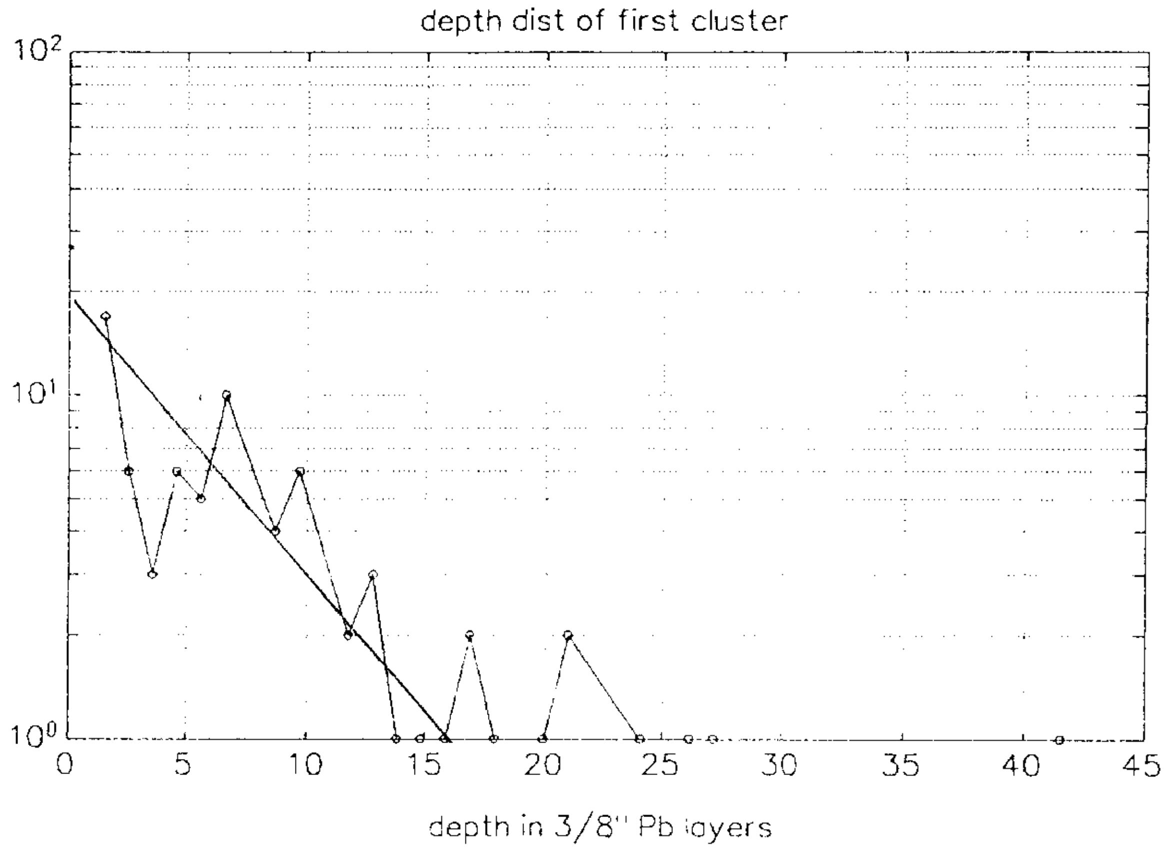

Figure 3. Distribution in depth (in units of 3/4" Pb plates) of the location of the first cluster. The straight line represents the expectation of an exponential distribution with length scale λo.

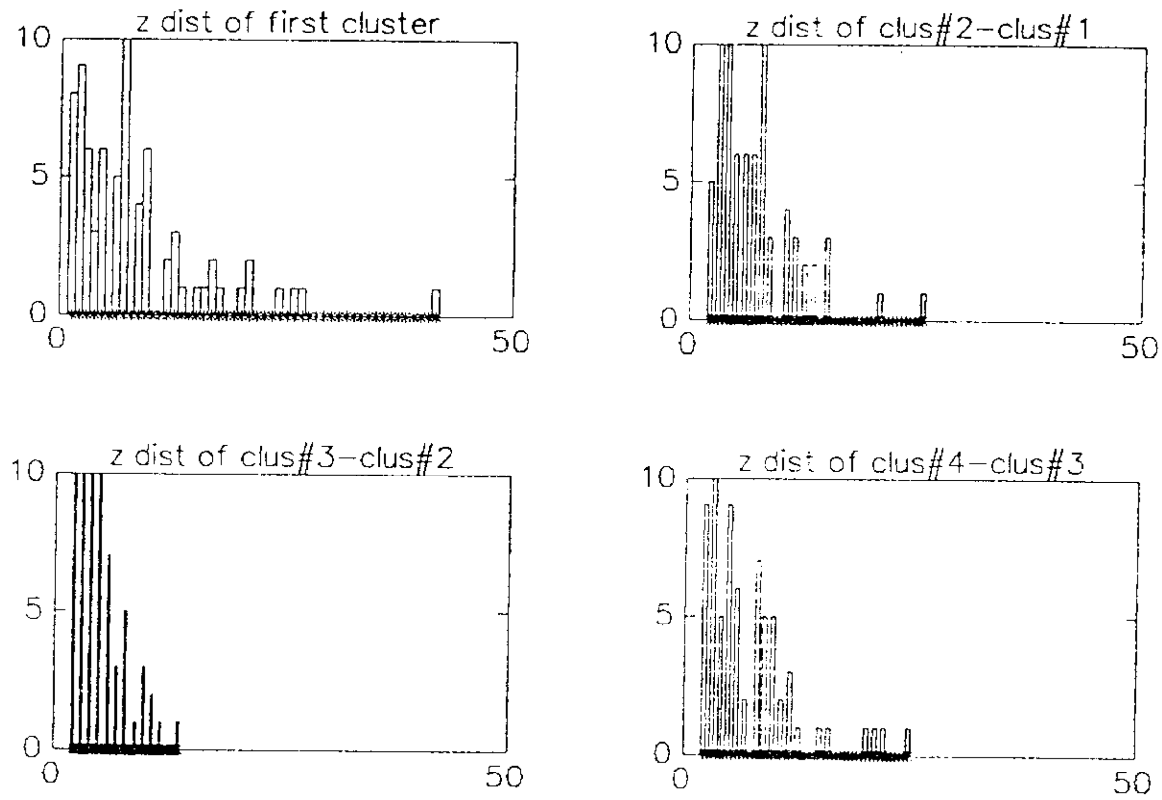

Figure 4. Distribution in depth of the location of the ith cluster minus the location of the (i-1)th cluster for i=1,2,3,4. The units are number of 3/4" Pb plates.

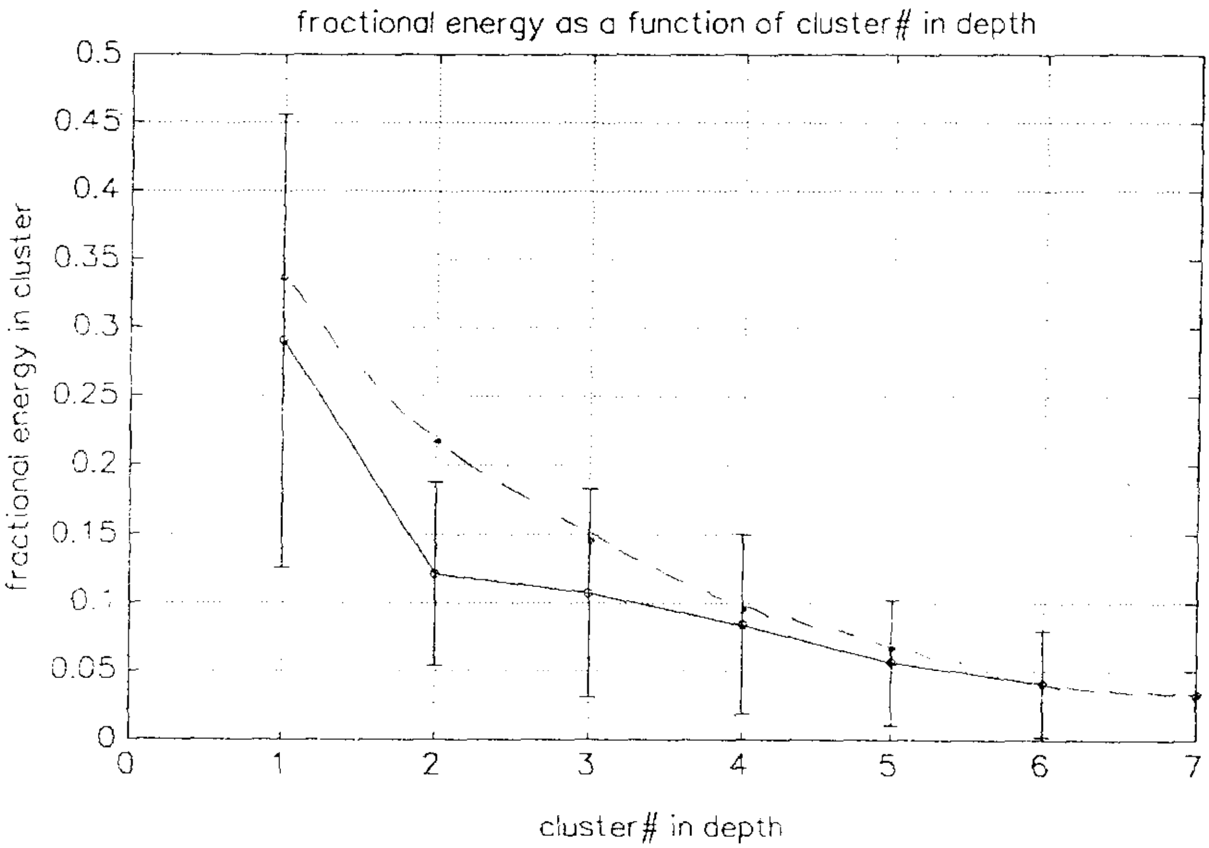

Figure 5. Mean and rms for fractional energy in a cluster as a function of the cluster number (ordered in depth). The dashed line represents the individual terms in the sum given in Eq. 2 .

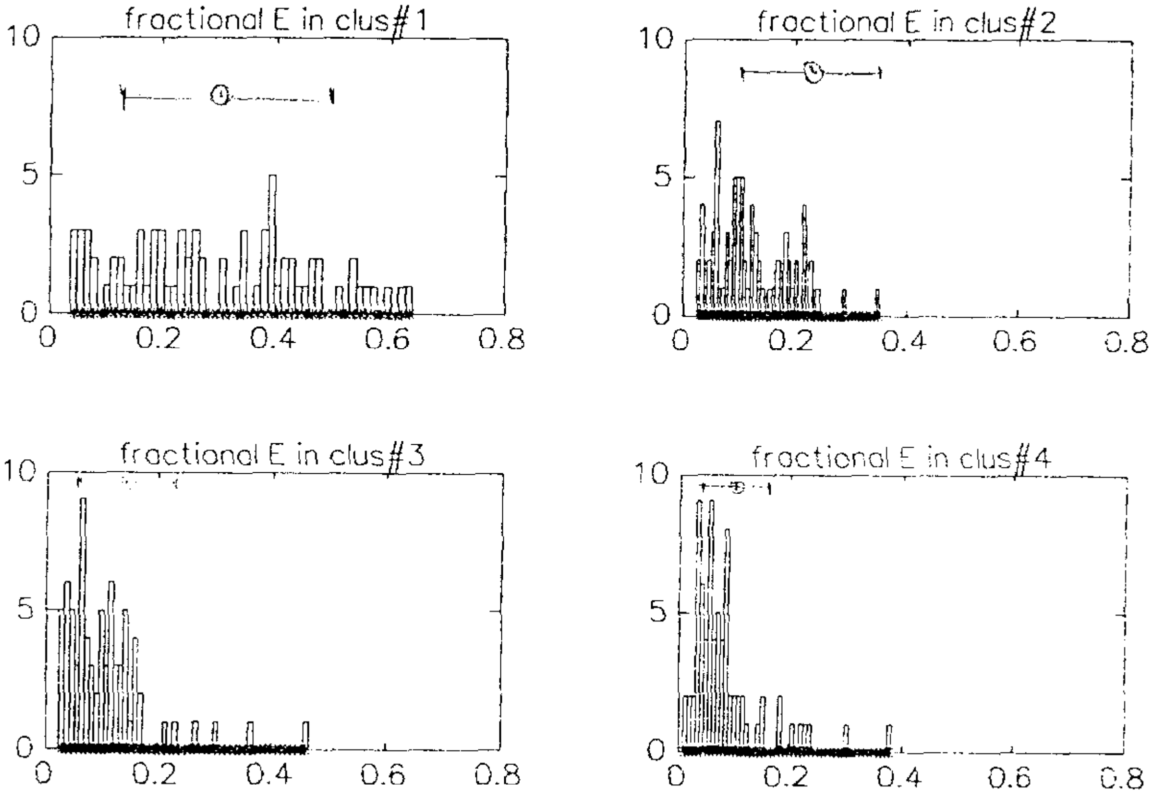

Figure 6. Distribution of fractional energy in a cluster for the first 4 clusters, ordered in depth. The symbols, I—0—I, indicate the expectation of Eq. 2, with $< n >_o$ = 3, independent of cluster depth.

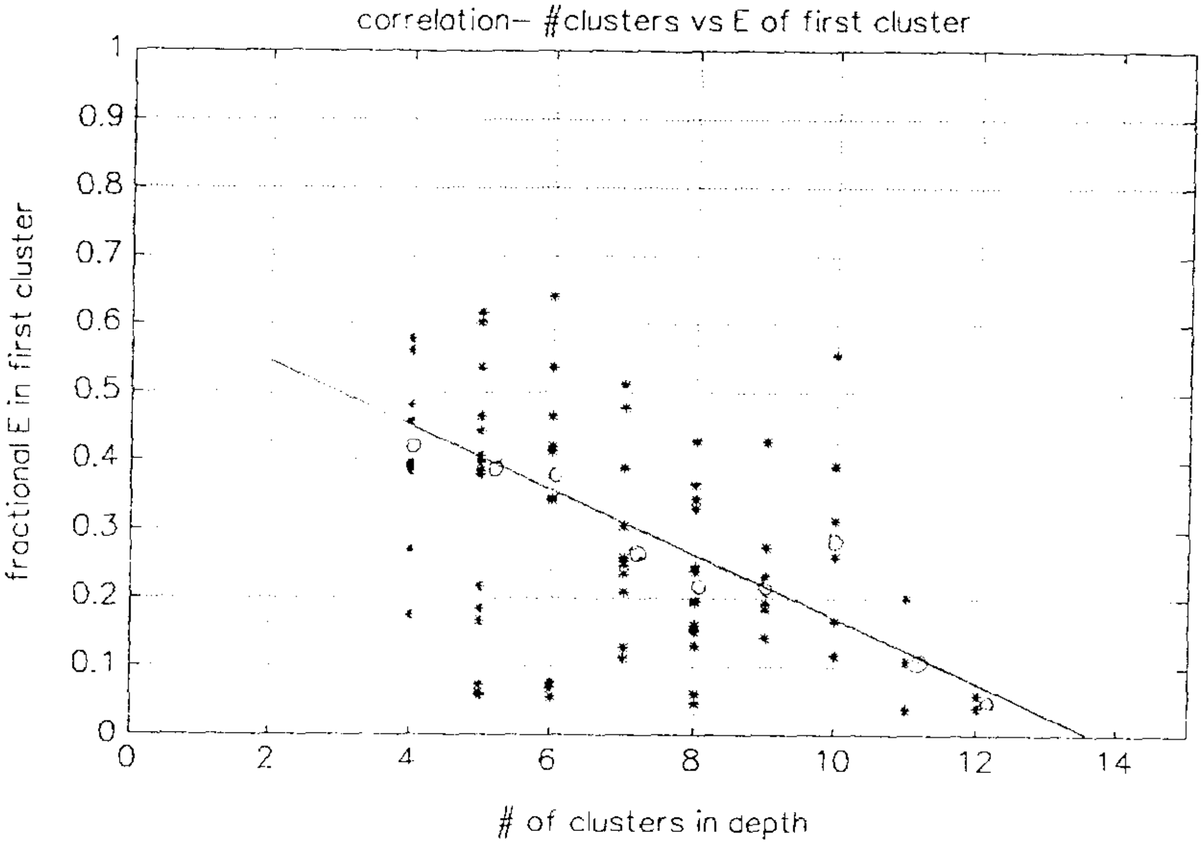

Figure 7. Fractional energy in the first cluster vs the found number of clusters, nclus. A correlation of large energy deposition in the first generation with few clusters is seen. The points , * , are individual events. The points, o, are the mean fractional energy, <e(ν)>, while the line represents the correlation.