ALEPH 88-87
EMCAL 88-4
M. Green et al.
26.7.1988

The ALEPH Calorimeter response to pion showers

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1. Introduction

The joint ECAL and HCAL tests of a production module of the Aleph End Cap electromagnetic calorimeter to pion beams of 5, 10, 20 and 30 GeV have been analysed and compared with Monte Carlo data. The analysis procedure was the same as that used for the 1985 tests of the prototype (ALEPH NOTE 169). The results show that the hybrid calorimeter responds to pions in an essentially identical way to the prototype; the small differences found are shown by the Monte Carlo results to be due to geometrical effects such as losses from the sides of the small prototype.

The present analysis includes comparison of the wire data with the pad data. Only a limited amount of electronics was available for the pad data and the readout was restricted to a region of 108 towers centred on the beam entry position. The pad data were unreliable in the prototype due to large coherent noise effects which have been reduced to insignificant levels in the production version of the readout electronics.

2. The Calibration factors

To determine the energy of hadron showers in ALEPH the pad tower information has to be used (the wire information will be readily useful only for showers isolated in a single module). This ECAL tower information will require calibration factors to compensate for the different response of stack III (with 4 mm Pb plates) to stacks I & II (with 2 mm Pb plates), and for the e/π response ratio. The first factor, S3, is approximately energy independent but the second increases with decreasing energy. These factors can be determined by fitting the test data to minimise the energy resolution and also by using the mean values of the signals of the test data. The former method is sensitive to fluctuations in the dispersion of the test data so the sample must be free of small contamination of small signals (e.g. muons) or large signals (e.g. electrons, multiple beam tracks). The latter method is insensitive to such contamination but depends on assumptions about the uniformity of the calorimeter; however it provides a valuable check that the sample used for the fitting method is free of contamination.

The extra calibration coefficients required for hadrons (stack III/II factor and e/π response ratio) depend on the development of the shower and thus on the starting point of the shower in the calorimeter. In practice the average values for showers starting in ECAL are probably the most useful so these have also been determined.

3. The Monte Carlo simulation

GEANT was used for the geometrical description, for tracking and electro-magnetic shower physics. GEISHA7 was used to simulate hadronic interactions. The detector described was a single ECAL endcap petal with 45 distinct planes each of Lead, Mylar, Xenon/C02 and Aluminium extrusion and there was a description of the pad-boundaries within the read-out area used. HCAL was not described beyond its front face position and its response was taken to be the Monte Carlo true energy entering smeared with the known effective HCAL resolution of $85\%/\sqrt{E}$.

Physics cuts (below which particle-tracking was stopped) were tested between 10 keV and 10 MeV and values selected which gave the greatest processing speed achievable without significant cut-dependence in the results: for photons and electrons, in the passive material, 1 MeV, and in the gas, 10 keV; for charged and neutral hadrons, 1 MeV (passive) and 100 keV (gas). A parameterization (a simplification of the Badier-Bardadin profile) was used for electron showers below 200 Mev, again securing speed without distortion. Even so, processing is quite slow, one event using about 1.5s per GeV of incident particle energy (IBM 168 units).

The Monte Carlo is calibrated directly in electron units by taking electrons as incident particles and recording the energy deposited in the gas; for Xe/CO_2 this is 0.228 MeV/GeV of incident energy (all the remaining incident energy appears in the passive material) as distinct from hadron showers where side losses etc can occur. This value arises very largely from the response of the first two stacks, but the relative response on stack III (found experimentally to be 1/1.93 for electrons) was verified by starting off the test electrons immediately in front of stack III.

The response of the detector to the heavily ionizing tracks of protons, deuterons, alphas etc, was limited by the imposition of a ceiling on the energy which can be deposited by one track in a single gas-plane; a 30 keV ceiling had been found to give the best results for the prototype, where the gas was Argon-Ethane, for which the absolute MC energy calibration was 0.091 Mev/Gev. Hence 75 keV (= 30 x 0.228/0.091) was tried initially, and confirmed by trials. It was easily verified that only the baryons exceed the limit. This ceiling lowers the e/π response by about 10% without affecting the stack III factor. At about 125 kev the effect of the ceiling would be less than 1%.

4 Features of the MC-true results.

4.1 Geometric Losses

There are energy losses caused by particles going to regions where they are not detected, such as crossing the backplane containing the HCAL without entering the area occupied by the calorimeter, or exiting through the sides of the ECAL. In addition, there is loss of signal from the pads, due to particles going beyond the limited readout area, whilst remaining in the ECAL. The sum of these losses varies slowly with incident energy, from about 7% at 5 GeV to 5% at 30 GeV, the majority (all but 2%) being recoverable from the wire-plane signal, as it arises from the small size of the pad-readout region. In the prototype, total losses varied between 17% and 10%; the wire-planes showed a similar loss as their area was the same as the pad area.

4.2 Invisible Energy

Even when full account is taken of geometric losses, it is clear that in hadronic showers, unlike electromagnetic showers, a significant proportion of the incident energy does not appear in any part of the detector, active or passive. In fact the hadronic interaction simulations of GHEISHA do not conserve energy or momentum, but model processes which yield the energy in undetectable form; about 30% of this effect is attributable to nuclear binding energy. The invisible energy in ECAL as a fraction of the incident energy, summing over all the interactions in ECAL, is given in the table.

Energy	Invisible fraction
5	0.48
10	0.40
20	0.25
30	0.18

This approximate log E dependence probably derives from the log E dependence of the average multiplicity in hadronic collisions, so the number of secondary interactions and hence binding-energy effects etc, have the same dependence.

The same effect was apparent in the prototype, but at a lesser rate, these fractions having scaled directly with path-length, ie with the number of secondary interactions in ECAL for each incident energy.

4.3 Neutrons

A significant amount of energy (330 MeV/shower average at 5 GeV), goes into neutrons, with a very wide angular distribution; being a mixture of an isotropic component (evaporation) and a weakly forward-collimated component (prompt). Only a small fraction interacts locally to produce a signal in the readout region, and most pass undetected out of the module. It is likely that most will interact in HCAL or in other ECAL modules, probably with a proton in hydrogenous material, and may give an isolated signal in the calorimeter.

4.4 Shower Structure

Compact segments arise from two causes, π^os (giving a local e/π ratio of 1.), and hadronic cascades, induced by soft charged pions, containing many protons and associated with large e/π values. For this reason the most compact showers (including the showers fully contained in ECAL) do not show significantly better resolution than the complete sample.

The long-range shower structure arises from fast charged pions, but forward collimation is quite weak, with a 1 GeV pion having a long path length and a significant probability of being emitted at an angle of more than 20^o to the incident particle.

5. Results

The pad data was extracted using the JULIA cluster finding algorithm which identifies clusters of contiguous pad towers above some threshold. The results depend on the way secondary clusters close to the primary (largest) cluster are treated. With hadron showers there is a tendency for the later stages of a shower to separate into secondary showers which are close to but disconnected from the primary shower; these arise when a linking minimum ionising signal from a few pads is below the cluster threshold, and when the linking particle is a fast neutron. Thus 50% of all hadron showers are accompanied by a secondary cluster with an energy above 100 MeV. These secondary clusters tend to develop in the later stages of a shower and in 75% of the cases do not have a contribution from stack I (a minimum ionising particle traversing three gaps would give a contribution above threshold). This feature enables secondary clusters close to the primary shower to be associated with it and included in the energy determination. A "sum of clusters" algorithm was used to overcome this effect and is compared with the results obtained if only the primary cluster is used. Another difficulty with pad information for pion showers is the contribution of the many isotropic slow neutrons associated with a shower that can give isolated signals from knock-on protons etc. These are very sensitive to pad thresholds and the cluster algorithm used and can cause several per cent differences in the apparent response of pads relative to wires.

The results of the 'sum of clusters' method is given in Table 1.

Table 1 Sum of Clusters: Pad Data

Energy	FITS e/π	FITS S3	MEANS e/π	MEANS S3	RESOLUTION %/√E	MONTE CARLO e/π	MONTE CARLO S3	MONTE CARLO %/√E
5	1.66	1.48	1.58	1.69	66.6	1.71	1.70	69.9
10	1.56	1.51	1.52	1.58	77.3	1.62	1.74	78.1
20	1.32	1.65	1.37	1.65	86.5	1.46	1.78	82.6
30	1.25	1.73	1.32	1.60	96.4	1.39	1.83	88.4

The errors on the e/π ratio, S3 and the resolution are typically ±0.05, ±0.05 and ±2% respectively for both data and Monte Carlo.

The results for both the e/π response ratio and the S3 factor from the fitting procedure and from the signal means are in good agreement, the Monte Carlo predictions are also in reasonable agreement with the data but show a smaller energy dependence of the resolution than the data. The S3 factor is essentially constant with energy (figure 1) at about 1.6 which is the ratio of the interaction lengths of the 4 mm and 2 mm calorimeter planes.

The e/π response ratio (figure 2) varies from about 1.3 at 30 GeV to about 1.7 at 5 GeV and the resolution from 67%/√E at 5 GeV to 96%/√E at 30 GeV.

Since the hybrid calorimeter resolution varies from 20% to 35% over this energy range a mean response of 1.5 would be adequate for many purposes and an iterative procedure only needed for analyses requiring maximum information from the calorimetry when wire information may also be used.

Table 2 shows the pad data using only the primary clusters.

Table 2 Primary Cluster: Pad Data

	FITS		MEANS		RESOLUTION	MONTE CARLO		
	e/π	S3	e/π	S3	%/√E	e/π	S3	%/√E
5	1.86	1.38	1.76	1.65	70.6	1.80	1.68	72.9
10	1.68	1.48	1.64	1.55	80.4	1.68	1.74	79.9
20	1.40	1.57	1.43	1.64	89.8	1.50	1.78	85.0
30	1.30	1.72	1.36	1.59	98.8	1.42	1.82	92.1

The response to pions is about 10% smaller than for the 'sum of clusters' due to the loss of secondary clusters, however the resolution is only a few per cent worse. Again the results from fitting and from the signal means are in good agreement, and there is reasonable agreement with the Monte Carlo predictions.

Table 3 shows these results for the wire data.

Table 3: Wire Data

Energy	FITS e/π	FITS S3	MEANS e/π	MEANS S3	RESOLUTION %/√E	MONTE CARLO e/π	MONTE CARLO S3	MONTE CARLO %/√E
5	1.55	1.59	1.49	1.75	62.4	1.53	1.75	64.5
10	1.47	1.67	1.47	1.65	72.7	1.43	1.77	71.9
20	1.31	1.77	1.36	1.74	82.6	1.32	1.83	77.3
30	1.23	1.83	1.31	1.69	92.2	1.28	1.86	84.6

The wire response to pions is several percent larger than the 'sum of clusters' data and the resolution is about 4% better (figure 3). The 'fit' and 'mean' results agree well and the Monte Carlo predictions are now in good agreement with the data. The Monte Carlo predictions for the pads involve pad thresholds and hence sensitivity to the accurate simulation of small signals so the slightly poorer agreement with pad data is not surprising. The overall agreement of the Monte Carlo predictions with the pad and wire data is remarkably good so the Monte Carlo information on side losses, invisible energy, neutron distributions etc which are not observed experimentally, can be taken seriously and provide valuable insight into the physics of the calorimetry.

At energies above 10 GeV the secondary pions in hadron collisions have a long mean free path and the showers are extended longitudinally. However at collision energies $\lesssim$ 5 GeV the secondary pions often have energies in the πN resonance region with a short mean free path between collisions so the showers become compact. This effect shows up in the data as a sharp increase in the fraction of hadron showers which are fully contained in ECAL at low energies (figure 4). The definition of

full containment in ECAL is arbitrary to some extent due to the neutron effects noted in 4.3. Full containment in ECAL was defined as a shower in ECAL and a signal less than 40 ADC counts in the first four planes of HCAL and a total energy in HCAL less than 1 GeV. The 40 counts is above the noise peak but below the minimum ionisation level (~ 120 counts) in the first four gaps and the 1 GeV total energy in HCAL allows the rejection of fast neutron interactions while accepting the full calorimeter noise and some contribution from slow neutron effects which would not be recognised as showers in HCAL.
The contained fraction so defined rises from 1.6% at 20 GeV to 33% at 5 GeV of all incident hadrons.

The resolution of the contained sample at 5 GeV for wire data is $56\%/\sqrt{E}$ compared to the $62.4\%/\sqrt{E}$ found in table 3. This improvement probably results from the finer sampling of these contained showers. The small containment at higher energies results in samples too small to give a significant determination of the resolution.

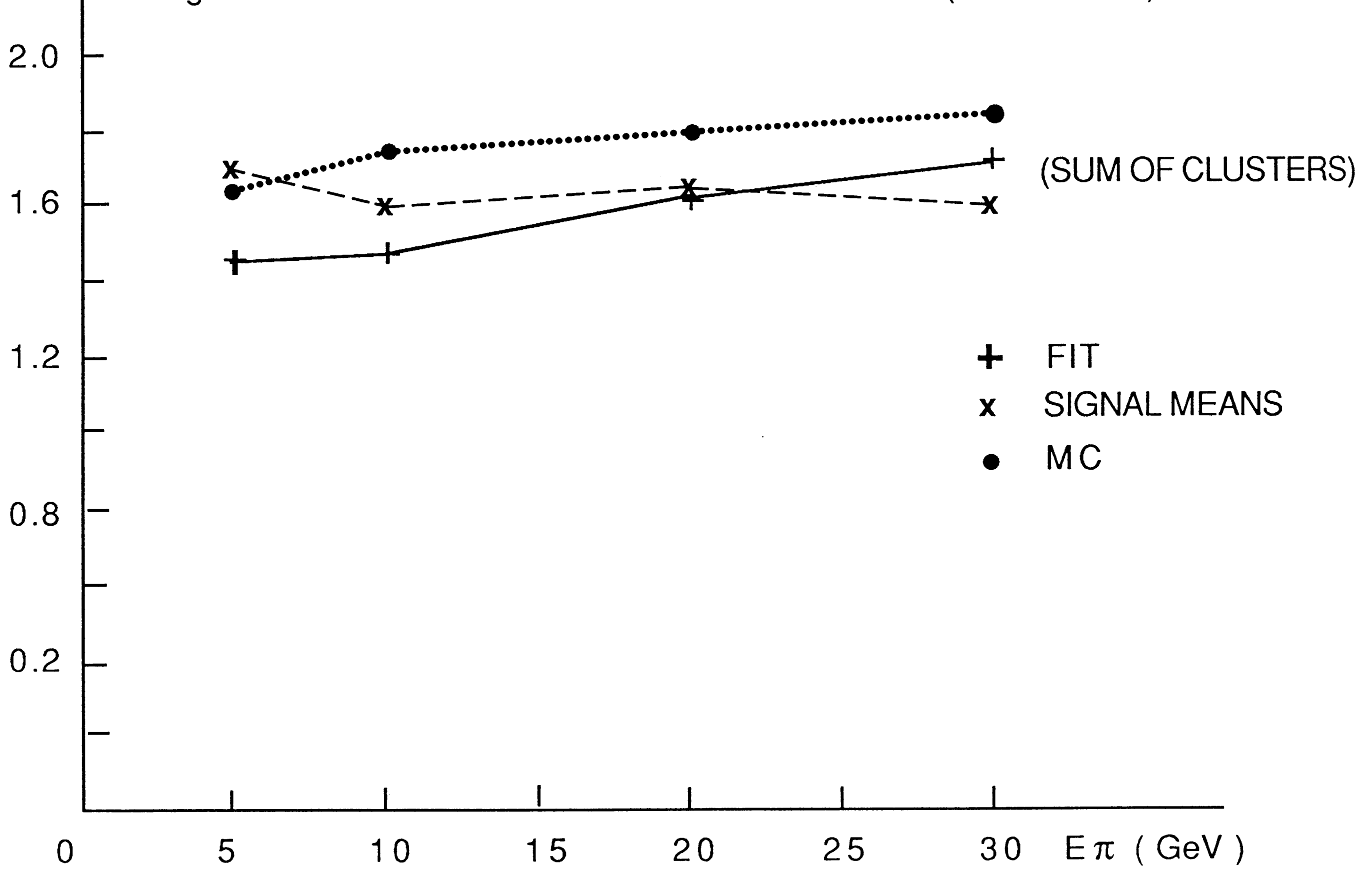
To obtain average parameters for events starting anywhere in ECAL, a two parameter (e/π and S3) fit was made to all events with signals greater than minimum ionisation in ECAL, the results for sums of clusters is given in table 4.

Table 4: Two parameter fit to ECAL sample (sum of clusters)

Energy	e/π	S3	Resolution ($\%/\sqrt{E}$)
5	1.63	1.50	65.5
10	1.52	1.53	74.3
20	1.42	1.53	86.2
30	1.36	1.49	96.3

This should be compared with table 1; the resolution obtained is essentially the same, the e/π ratio and S3 factors both show less variation with energy and agree well at 5 and 10 GeV where most of the ALEPH hadron data is likely to be.

Fig.1 STACK III / STACK II RESPONSE RATIO (S3 FACTOR)



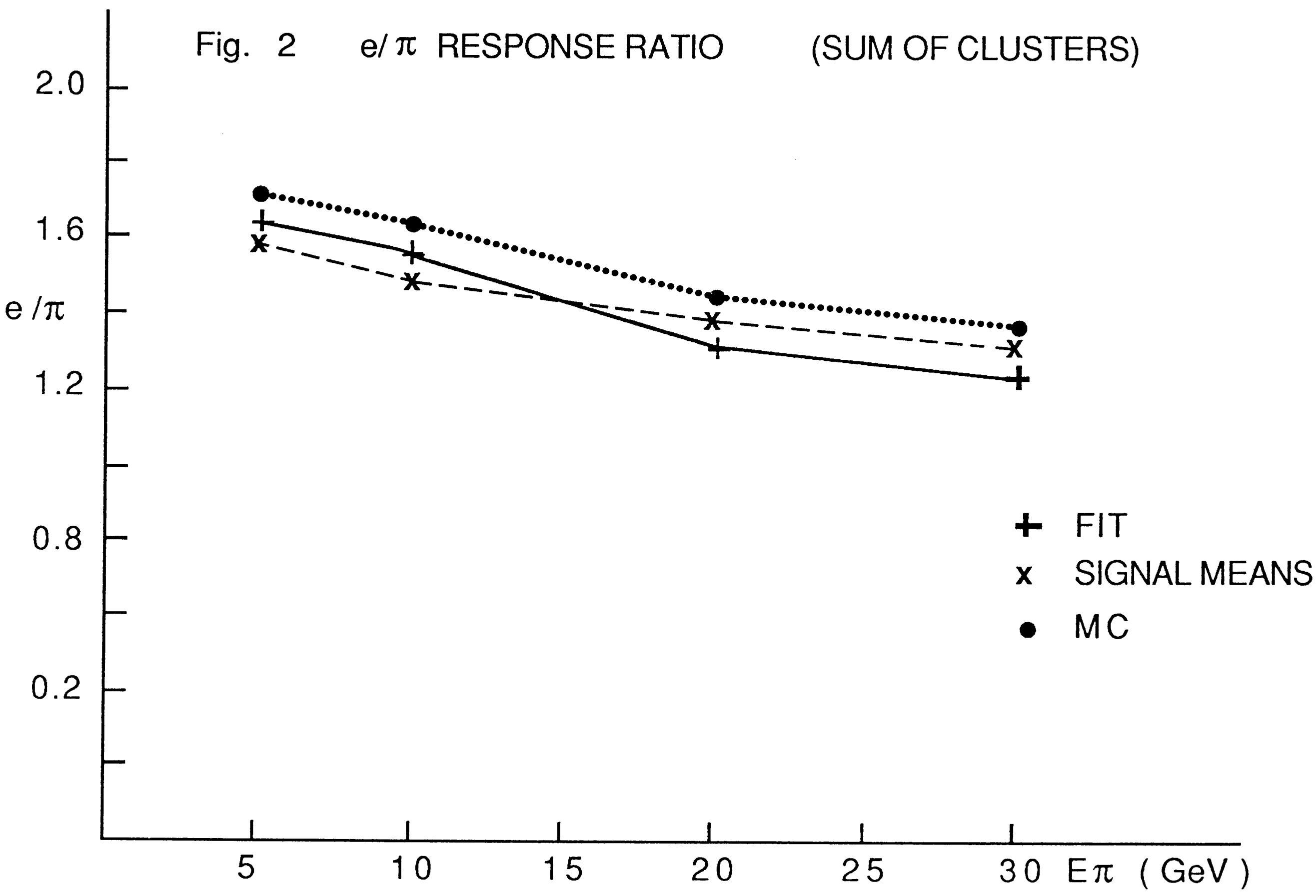


Fig. 2 e/π RESPONSE RATIO (SUM OF CLUSTERS)

Fig. 3 PION RESOLUTION (EVENTS STARTING IN ECAL)

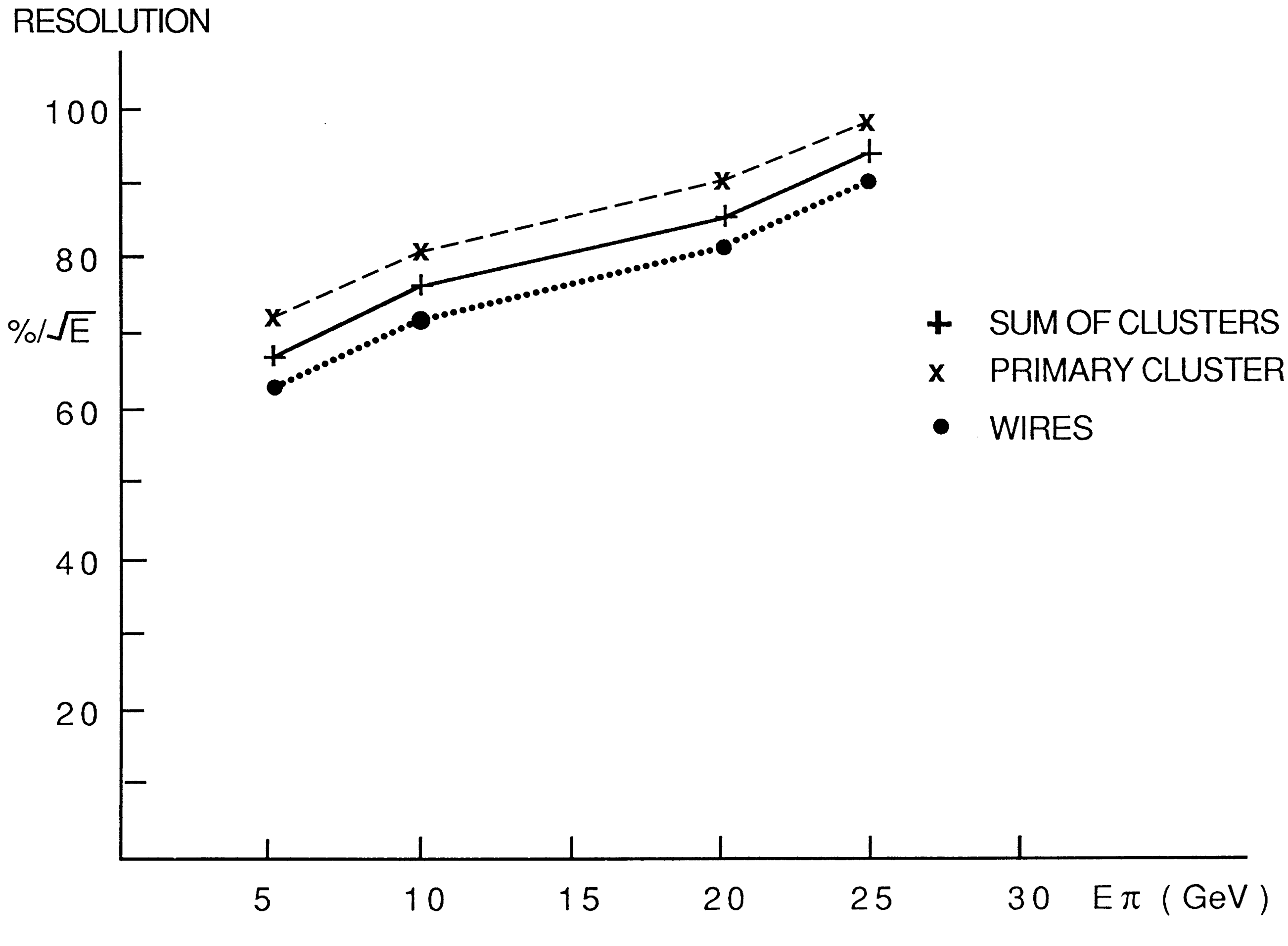


Fig. 4 EVENTS FULLY CONTAINED IN ECAL

(AS PERCENTAGE OF ALL INCIDENT HADRONS)