DEUTSCHES ELEKTRONEN – SYNCHROTRON

DESY 90-103
December 1990

Length of Calorimeter and Effect of Absorbers in Front of Calorimeters

J. Krüger

II. Institut für Experimentalphysik, Universität Hamburg

ISSN 0418-9833

NOTKESTRASSE 85 · D-2000 HAMBURG 52

To be sure that your preprints are promptly included in the HIGH ENERGY PHYSICS INDEX , send them to the following address (if possible by air mail) :

DESY
Bibliothek
Notkestrasse 85
2 Hamburg 52
Germany

DESY 90 – 163
December 1990

LENGTH OF CALORIMETERS

AND

EFFECT OF ABSORBERS IN FRONT OF CALORIMETERS *

Jürgen Krüger

II. Institute for Experimental Physics, Hamburg University,
Luruper Chaussee 149, D–2000 Hamburg 50, Germany

for the ZEUS Calorimeter Group

ABSTRACT

A detailed analysis of the longitudinal hadron shower development was performed with the longitudinally finely segmented WA78 calorimeter at CERN (5–210GeV). The shower containment studies allow an optimization of the depth of hadron calorimeters and a reasonable extrapolation for particles and jets to very high energies (≈1TeV).

The effect of material in front of calorimeters for hadrons, electrons and jets was studied systematically with the ZEUS forward calorimeter prototype at CERN at energies from 0.5 to 100GeV.

* Talk given at the ECFA Large Hadron Collider Workshop, Aachen,
4 – 9 October 1990

1. LENGTH OF CALORIMETERS

1.1 INTRODUCTION

The optimum length of a hadron calorimeter is directly related to the longitudinal development of hadron showers.

Longitudinal shower profiles have been measured for single particles and jets with the WA78 hadron calorimeter at CERN in the energy range from 5GeV to 210GeV [1],[2].

A detailed analysis of shower containment and the influence of dead material (e.g. PM–boxes) inside the calorimeter was performed in particular with respect to the optimization of the depth of the high resolution ZEUS uranium scintillator calorimeter ($\sigma_h/\mathrm{E} \approx 35\%/\sqrt{E}$) and extrapolations to higher energies are performed.

1.2 THE WA78–H1–ZEUS CALORIMETER TEST

The WA78 hadron calorimeter (Fig. 1) consists of two parts with different absorber material, upstream uranium layers (60 x 60 x 1 cm^3) and downstream iron layers (60 x 60 x 2.5 cm^3). The 1st part (5.4λ) was operated with 12 modules of depleted uranium (10mm)/scintillator (5mm), 4 elements per module (0.45λ) and the 2nd part (8λ) with 13 modules of iron (25mm)/scintillator (5mm), also 4 elements per module (0.62λ).

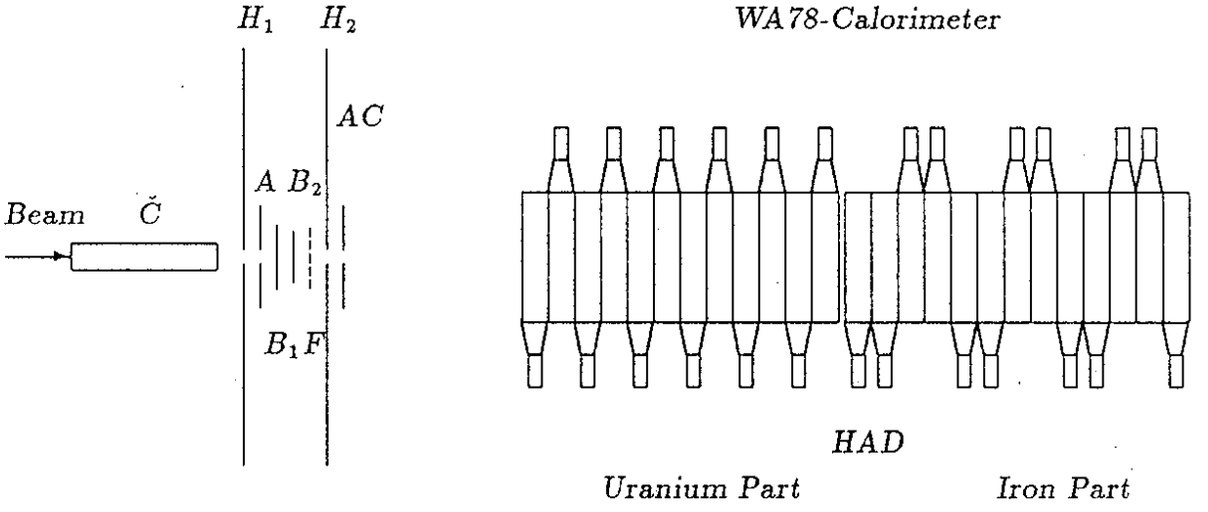

Fig. 1 The Experimental Set-Up of the WA78–H1–ZEUS Test

1.3 LONGITUDINAL HADRON SHOWER DEVELOPMENT AND SHOWER CONTAINMENT

The WA78 calorimeter has the advantage of a fine longitudinal readout segmentation (0.45λ). Data have been taken from 5GeV to 210GeV and thus allow an extrapolation to higher energies.

Figure 2 shows the longitudinal hadron shower profiles from 5 to 210GeV for all hadrons ($\equiv$ single hadrons) as function of the calorimeter depth in units of nominal interaction lengths λ. Figure 3 is similar to Fig. 2, but for events with shower vertices in the first module (0.45λ) of the calorimeter. These events are considered to behave like jet–like objects and are also called jets in the following.

There are some limitations of the data in particular at high energy (135GeV/ 210GeV), where the PMs have been run at reduced gain, due to pedestal problems and transverse shower containment.

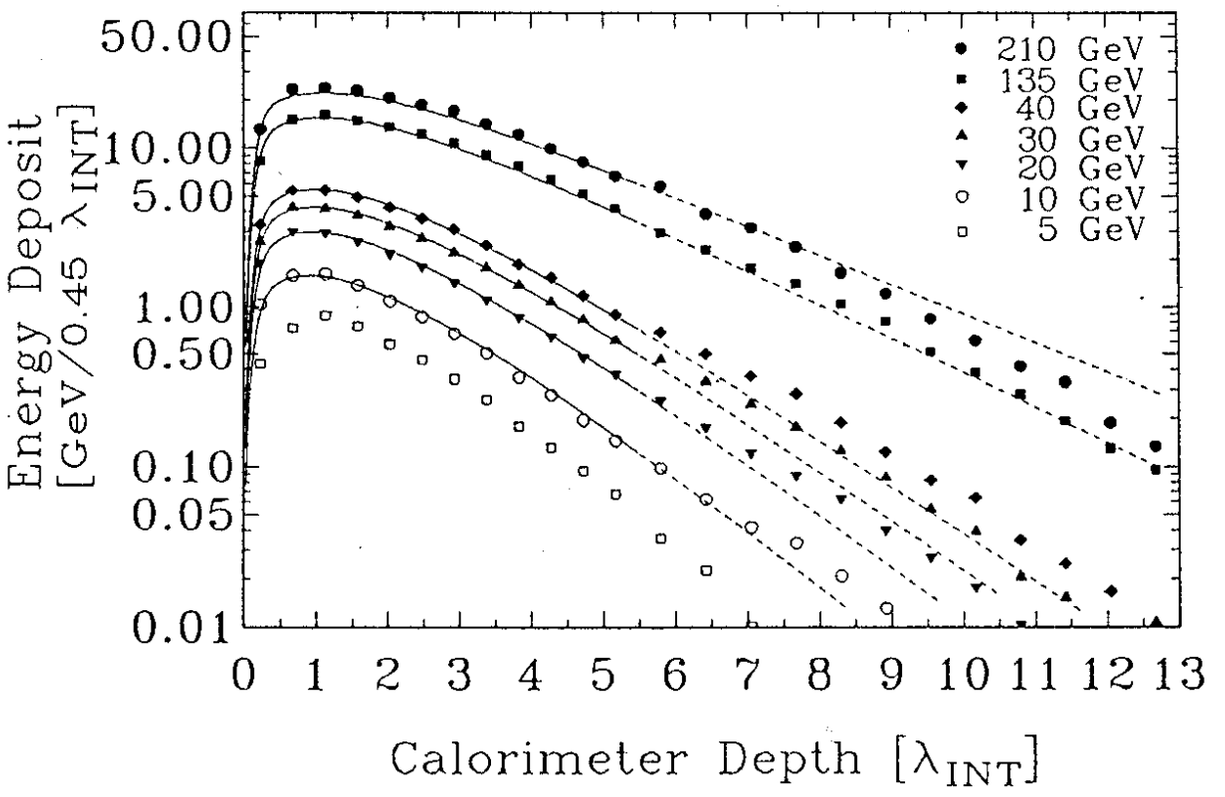

Fig. 2 Longitudinal Shower Profiles for Beam Momenta of 5 to 210 GeV for all Events

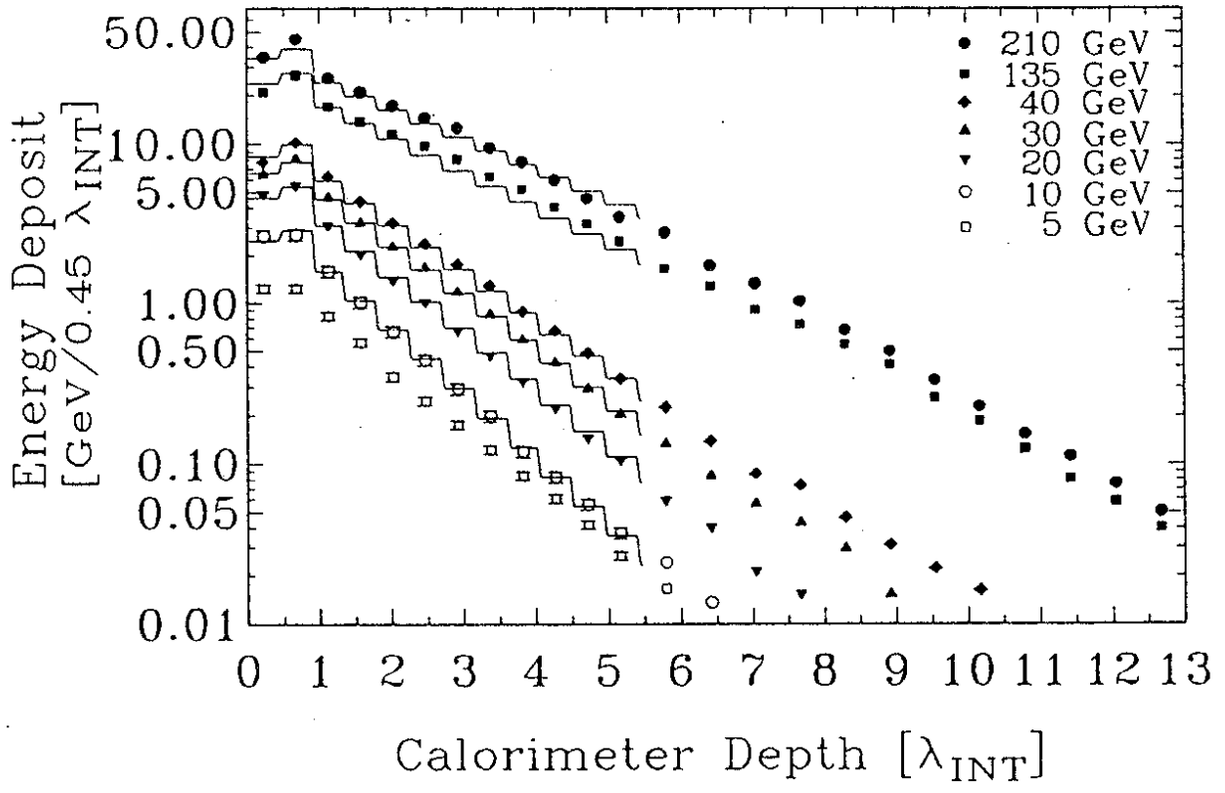

Fig. 3 Longitudinal Shower Profiles for Beam Momenta of 5 to 210 GeV for Events with Shower Vertices in the First Module

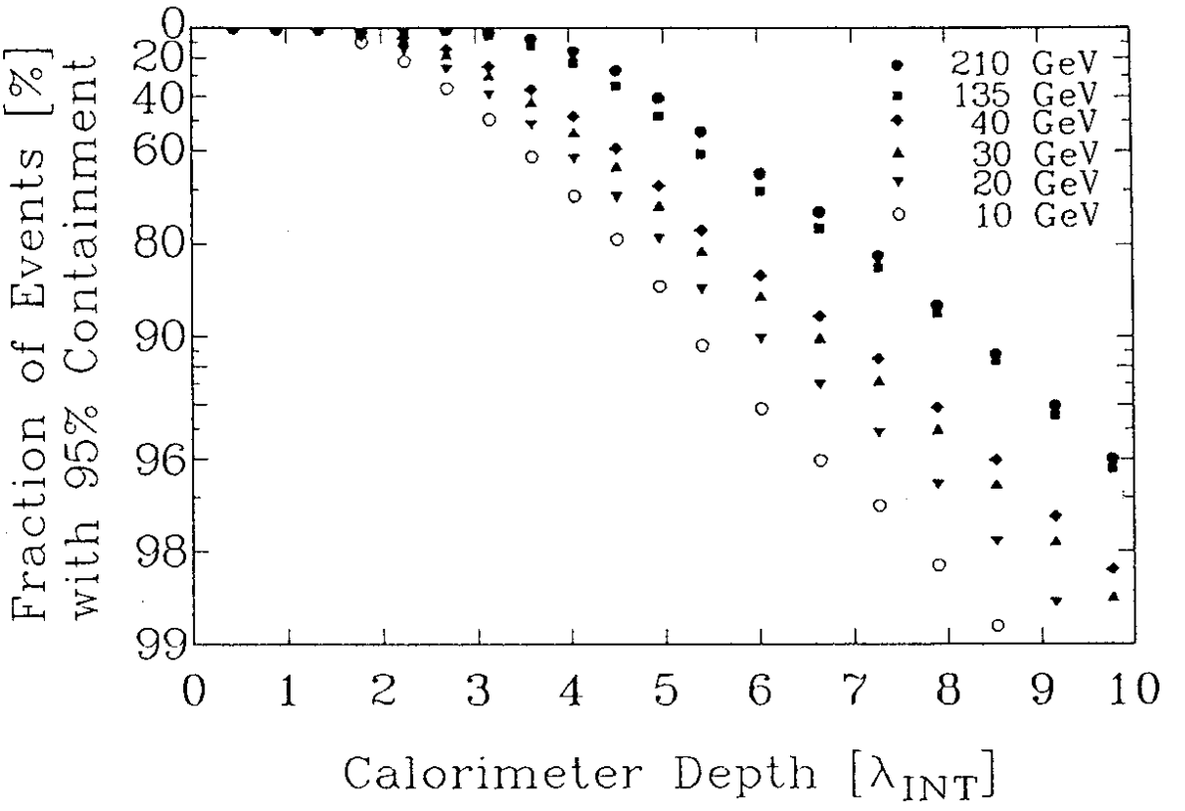

Fig. 4 Fraction of Events with 95% Energy Containment as a Function of the Calorimeter Depth for all Hadrons

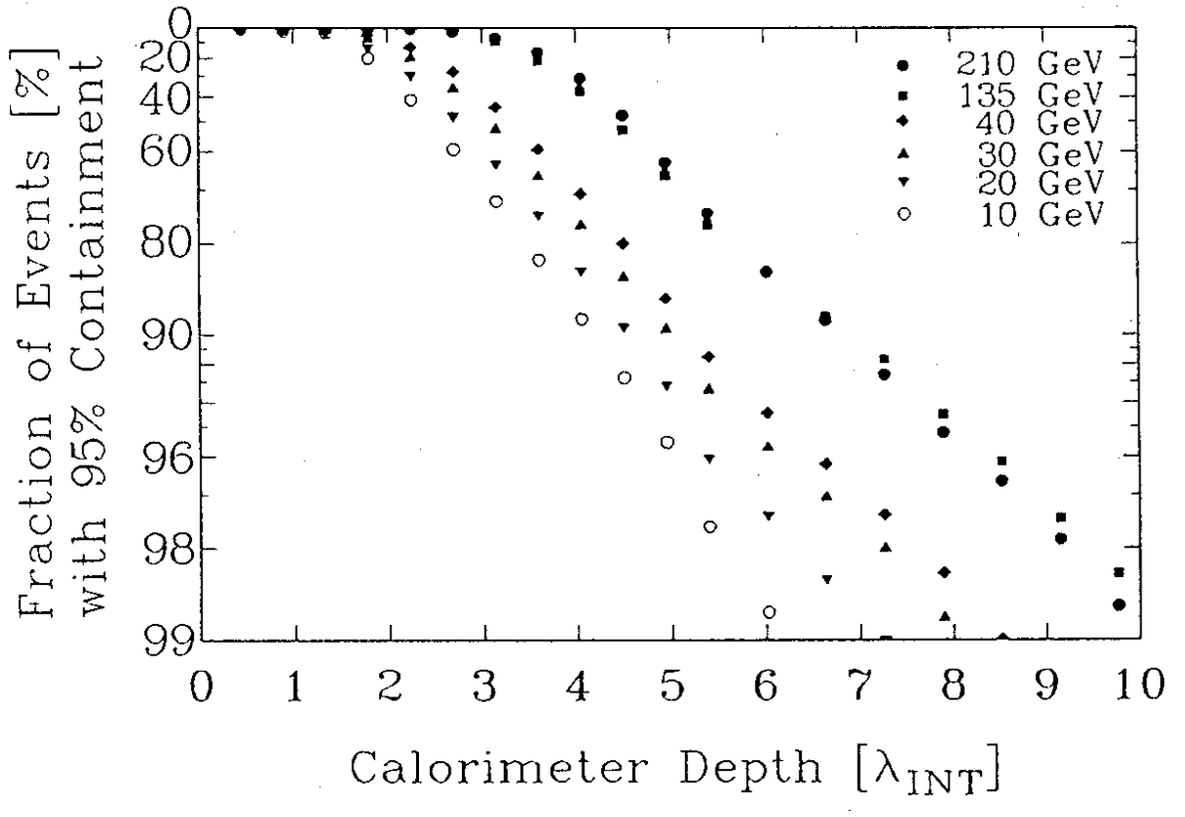

Fig. 5 Fraction of Events with 95% Energy Containment as a Function of the Calorimeter Depth for Events with Shower Vertices in the First Module

A phenomenological function has been fitted to the data. The parametrization of the energy deposit dE/dx(x) (Fig. 3) as a function of the distance x in interaction lengths from the shower vertex is:

$$\frac{dE}{dx}(x) = E_0 \left\{ \alpha \frac{b^{a+1}}{\Gamma(a+1)} x^a \, exp\,(-bx) + (1-\alpha)\, c \, exp\,(-cx) \right\}$$

where E_0 is the incident energy, a=3, $b[\lambda^{-1}]$=19.5, α=0.13±0.02 and $c[\lambda^{-1}]$=(0.67±0.03)-(0.166±0.003) ln(E_0[GeV]/50). The function describes well the data for energies above 10GeV (see Fig. 2, 3).

The shower distributions measured from the front end of the calorimeter (t) for all hadrons are given by the convolution of dE/dx(x) with the position of the first shower vertices:

$$\frac{dE}{dt} = \frac{1}{\lambda_\pi} \int_0^t exp\,(-\frac{x}{\lambda_\pi}) \frac{dE}{dx}\,(t-x)\,dx$$

where $\lambda_\pi = 1.11$ represents the interaction length of the incoming hadrons.

In order to determine the optimum length of a calorimeter the fraction of events with a certain shower containment has to be known. The fractions of all hadrons and jets with a shower containment of 95% in the calorimeter as function of the calorimeter depth are presented in Fig. 4 and 5. The criterium for the depth of the ZEUS calorimeter was for example that 90% of the jets of the maximum energy allowed by kinematics are contained in the uranium scintillator calorimeter with 95% of their energy [3]. This high resolution calorimeter is followed by a coarser backing calorimeter of 4 – 6 λ depth.

1.4 LEAKAGE DUE TO DEAD AREAS

The data offers also the possibility to investigate the influence of dead material, such as PM boxes, at various places inside the calorimeter [1].

The influence on the resolution due to the shower energy lost in the dead material of 0.6λ behind 5.4λ has been studied for 40GeV jets (start vertex of showers in the 1st module (0.45λ)) and behind 7.2λ for 135GeV jets. The information of the longitudinally finely segmented WA78 calorimeter has been combined to a calorimeter configuration as presented in Fig. 6 that corresponds to the ZEUS calorimeter system. It consists of a high resolution hadron calorimeter (a) plus veto readout section (necessary only for higher energies) (b), dead material (PM boxes, iron shielding) (c) and a coarser backing calorimeter (d).

The fraction of events contributing to a nongaussian tail due to the energy lost in the dead material (PM boxes) is measured in units of the calorimeter resolution for hadrons (σ_h/E=35%/$\sqrt{E} \equiv \sigma_{35}$) as function of the calorimeter depth. This is shown for jets in Fig. 7 and in Fig. 8 for the additional requirement that less than 2% of the shower energy are deposited in the backing calorimeter ($E_{BAC} < 2\%$, valid for about 90% of the events).

With a calorimeter depth of 5.4λ about 2.6% of 40GeV jets are found additionally outside 1σ_{35} and 0.6% outside 2σ_{35}.

A corresponding investigation with a calorimeter depth of 7.2λ and 135GeV jets shows that about 3% are additionally outside 1σ_{35} and 0.6% outside 2σ_{35}.

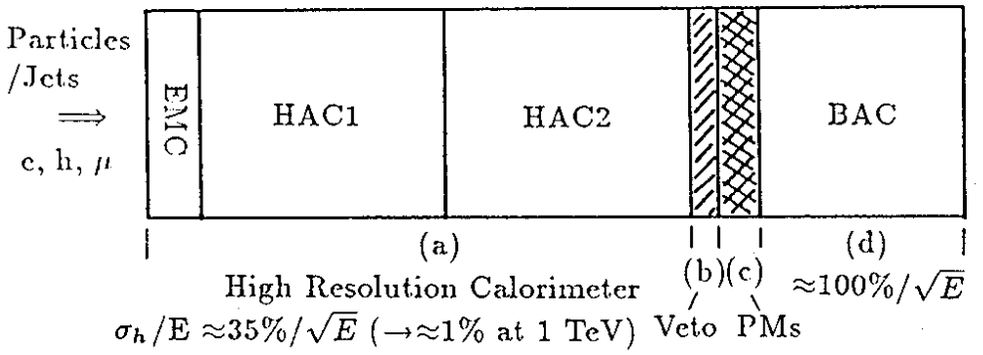

Fig. 6 Calorimeter Design of a High Resolution Calorimeter (a), (Veto Readout Section (b),) PM Boxes (c) and Backing Calorimeter (d)

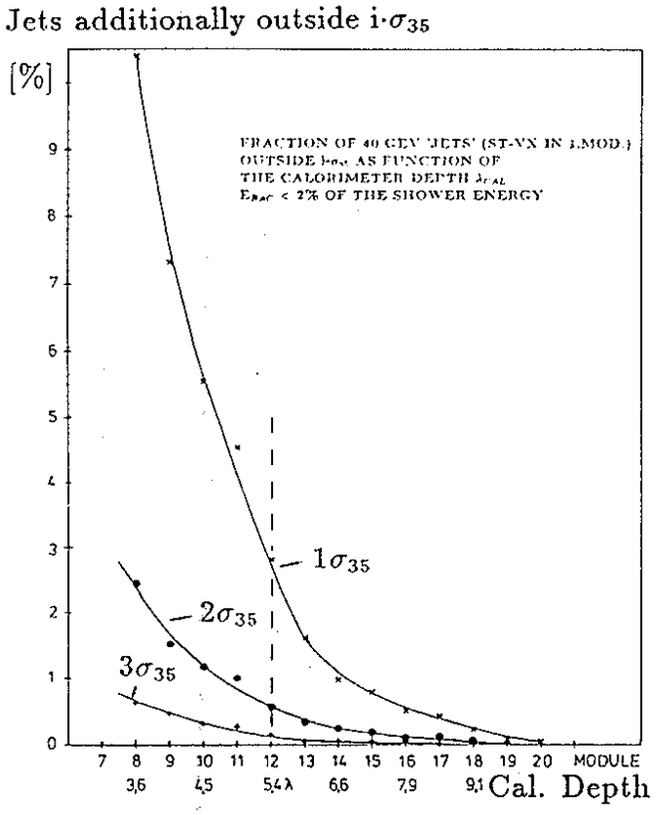

Fig. 7 Fraction of 40GeV 'Jets' outside i·σ_{35} as Fct. of the Calorimeter Depth and $E_{BAC} < 2\%$ of the Shower Energy

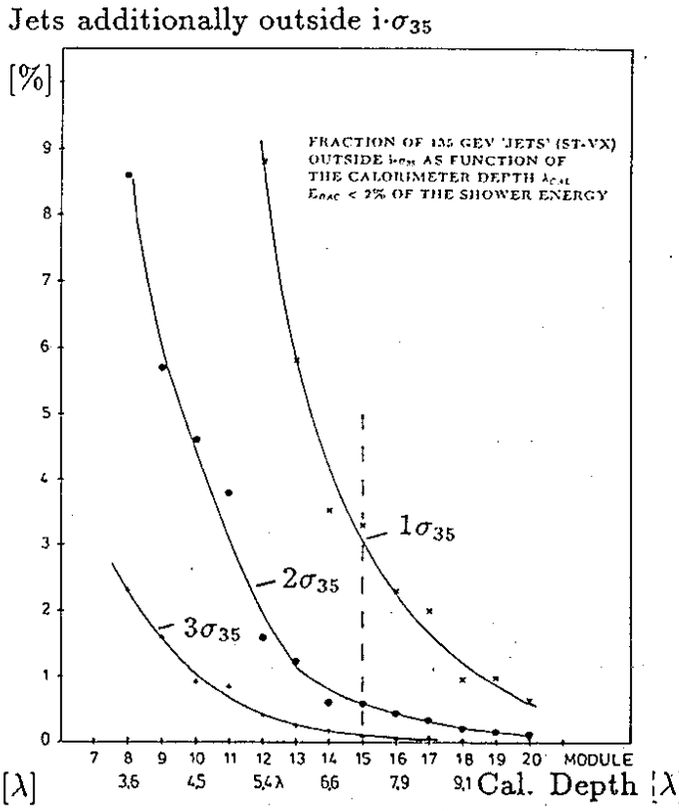

Fig. 8 Fraction of 135GeV 'Jets' outside i·σ_{35} as Fct. of the Calorimeter Depth and $E_{BAC} < 2\%$ of the Shower Energy

1.5 EXTRAPOLATION TO 1 TEV PARTICLES AND JETS

As already mentioned a reasonable extrapolation to higher energies is also possible with these data [4].

The calorimeter depth needed for a certain shower containment (90%, 92.5%, 95%, 97.5%) as function of the energy for 90% of single hadrons is presented in Fig. 9 and for 90% of jets in Fig. 10. An extrapolation to 1 TeV is also indicated.

The study of the calorimeter depth has been done with uranium (/iron) and uranium calorimeters. For other materials (Al and Pb) the necessary depths in units of λ may differ somewhat.

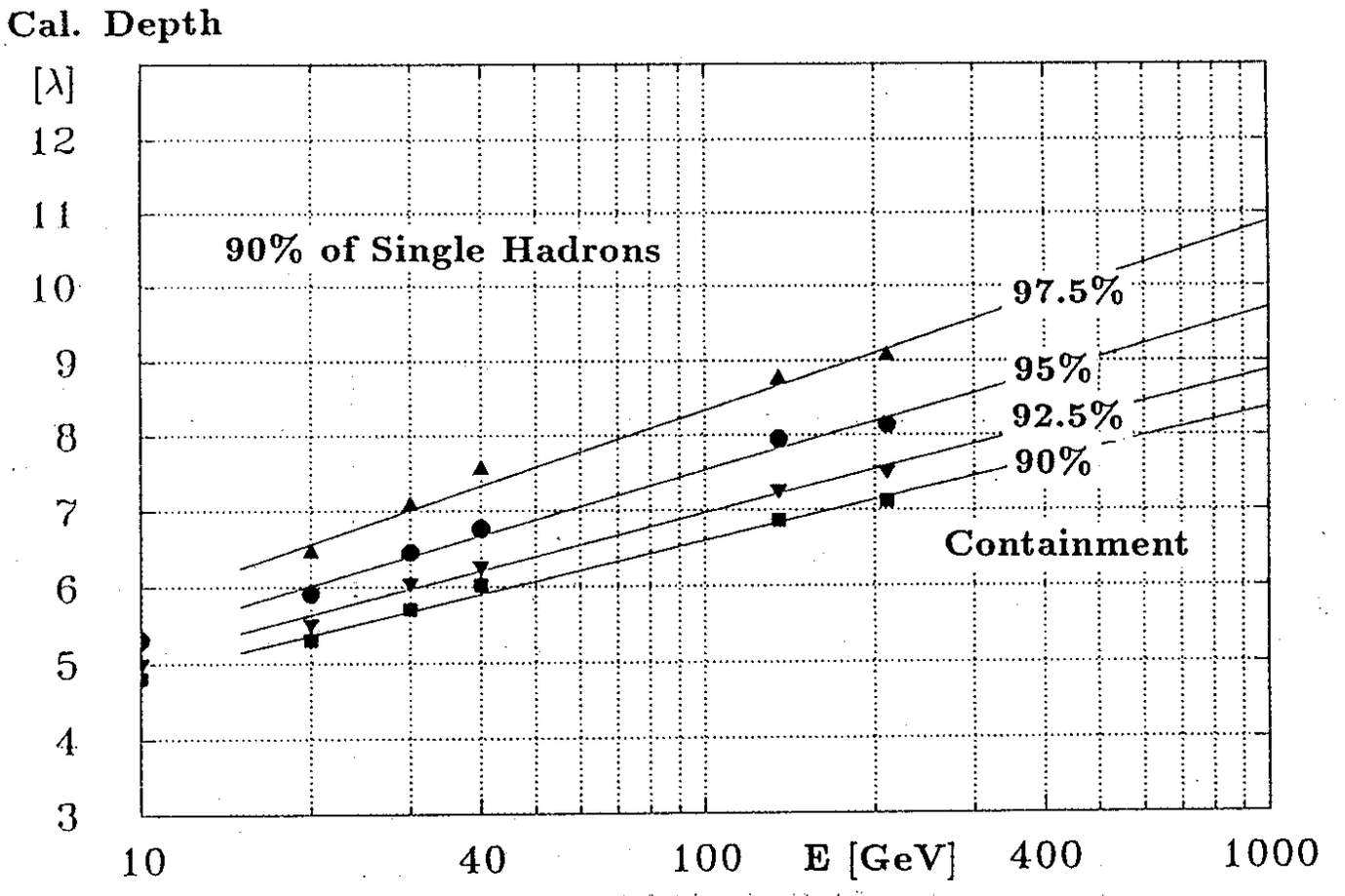

Fig. 9 Calorimeter Depth required for Different Fractions of Shower Containment for 90% of Single Hadrons as Function of the Energy

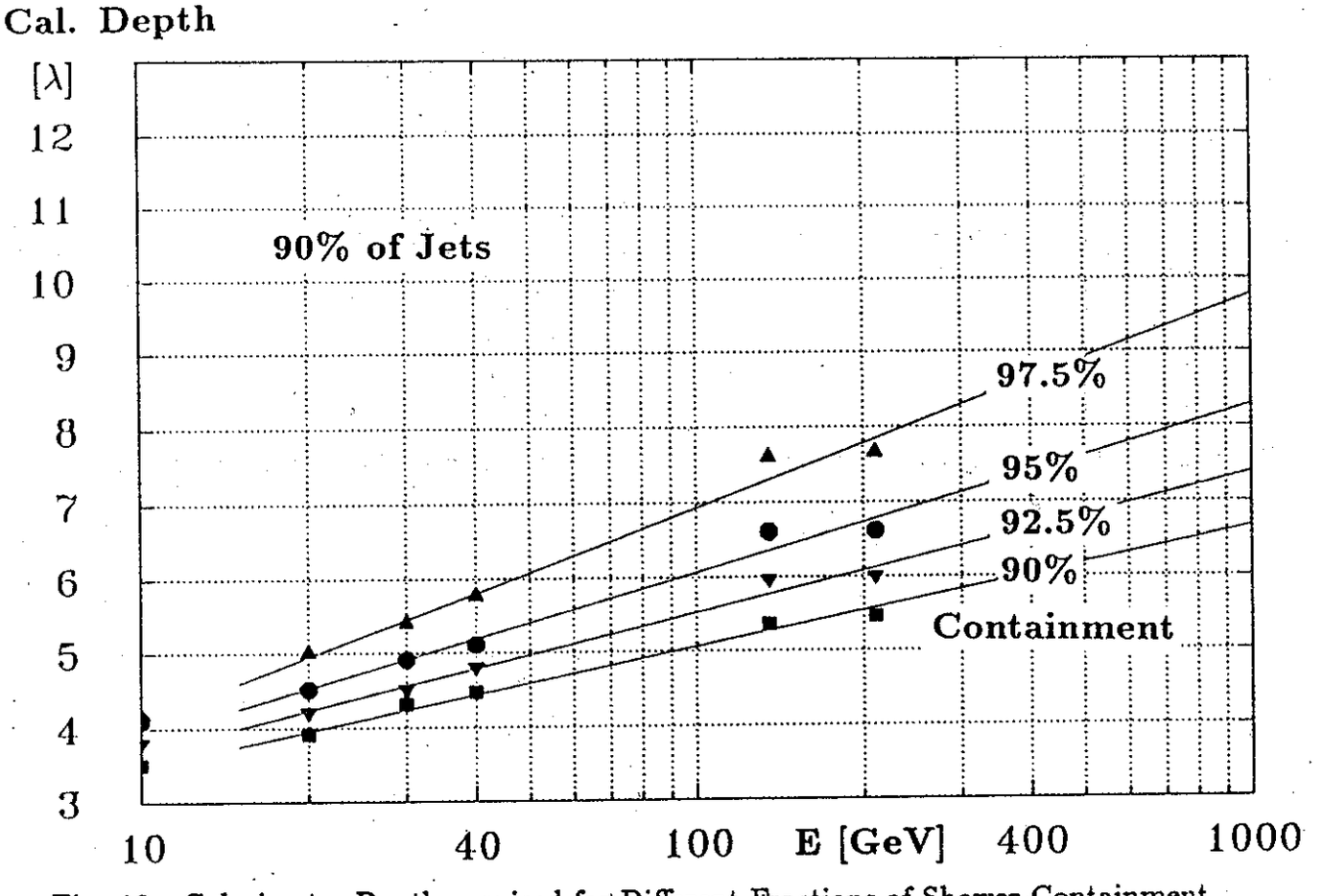

Fig. 10 Calorimeter Depth required for Different Fractions of Shower Containment for 90% of 'Jets' as Function of the Energy

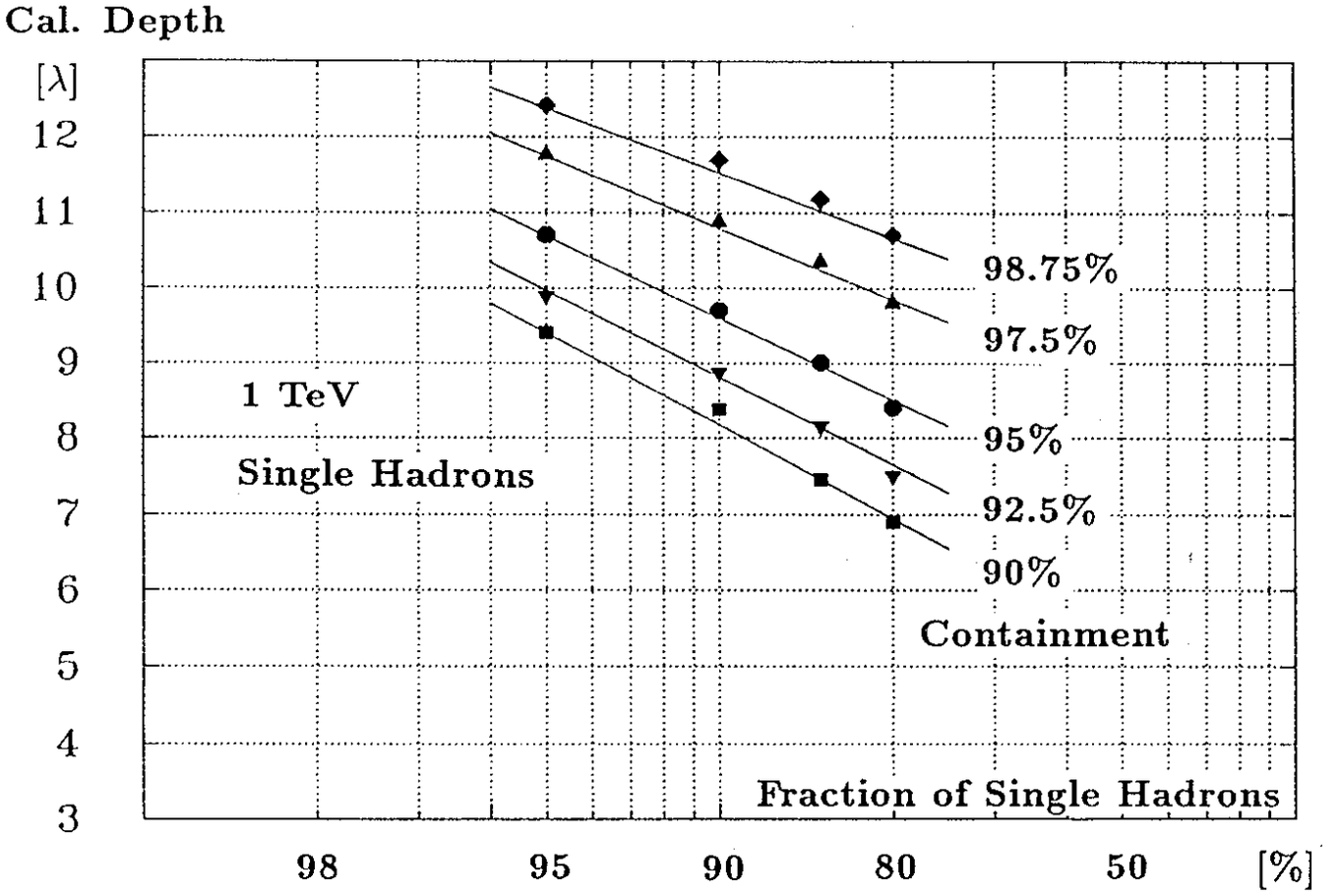

Fig. 11 Calorimeter Depth required for Different Fractions of Shower Containment for 1 TeV Single Hadrons [Extrapol.] as Fct. of the Fraction of Single Hadrons

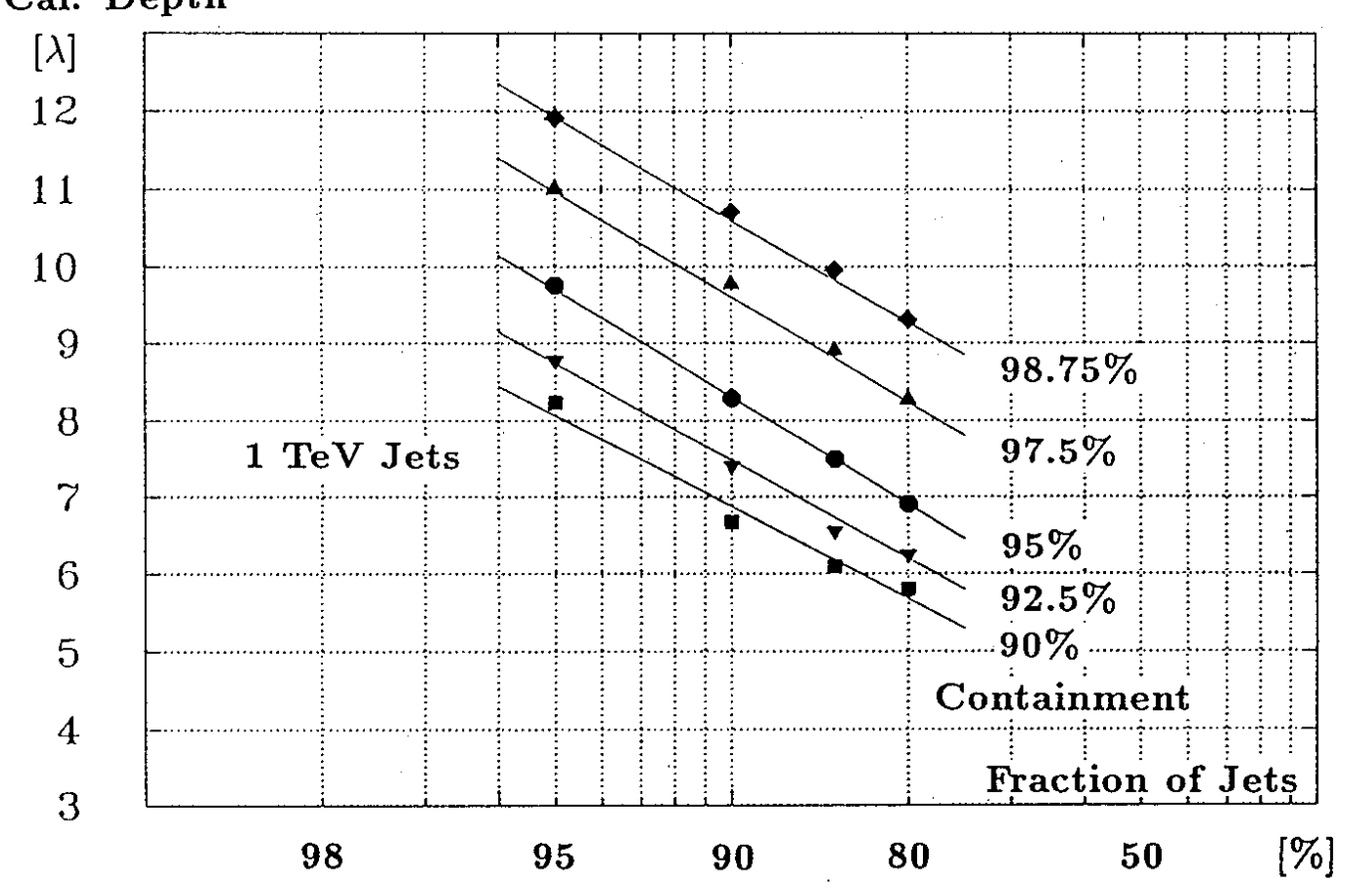

Fig. 12 Calorimeter Depth required for Different Fractions of Shower Containment for 1 TeV 'Jets' [Extrapolation] as Function of the Fraction of 'Jets'

Figure 11 and 12 show the calorimeter depth necessary for 1 TeV single hadrons and jets (extrapolations) with a certain shower containment as function of the fraction of single hadrons and jets.

For 85% – 90% of the 1 TeV jets with a shower containment of 98.75% a calorimeter depth of about $10\lambda - 10.5\lambda$ is needed. This is equivalent to about 95% of the 1 TeV jets having a shower containment of 95% at $9.5\lambda - 10\lambda$.

At 1 TeV the energy resolution of a high resolution hadron calorimeter with $\sigma_h/E \approx 35\%/\sqrt{E}$ approaches 1% . In order not to lose this excellent energy resolution at very high energies due to energy lost in the dead material of the PM boxes a very promising solution is to install an additional readout section in front of the dead material as veto counter to select events fully contained in the high resolution calorimeter as indicated in Fig. 6.

2. EFFECT OF ABSORBERS IN FRONT OF CALORIMETERS

2.1 INTRODUCTION

Very often tracking chambers, a magnet coil and various mechanical constructions are installed in front of a calorimeter. For example the material in front of the high resolution ZEUS uranium scintillator calorimeter is over a wide range about 1–1.5 radiation lengths X_0. But there are also narrow peaks up to 4 X_0 at a few small regions where mechanical support structures are necessary. This material degrades the measured signal and the energy resolution of the calorimeter.

2.2 MEASUREMENT PROGRAM WITH THE FCAL PROTOTYPE

Systematic measurements with various thicknesses of absorber (Al) directly in front of the ZEUS forward calorimeter (FCAL) prototype [5] have been performed at CERN in the momentum range from 0.5 to 100GeV/c to determine quantitatively the effect of absorbers [6], [4].

The FCAL prototype (Fig. 13) consists of four modules with a front area of 80cm x 80cm (4 x (20cm x 80cm)), a depth of 2m (7λ) and 192 PMs [5], [7].

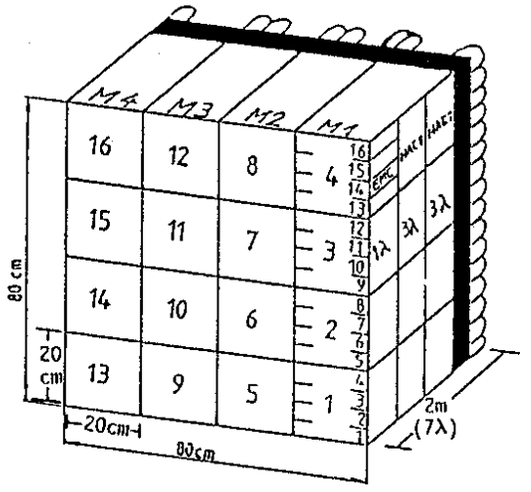

Fig. 13 The Module, Tower and Longitudinal Structure of the FCAL Prototype

The experimental set up used at CERN consisted of the scintillation beam counters B1, B2, B3 and B4 defining the beam, two Cherenkov counters C1 and C2 and the FCAL prototype calorimeter itself (Fig. 14).

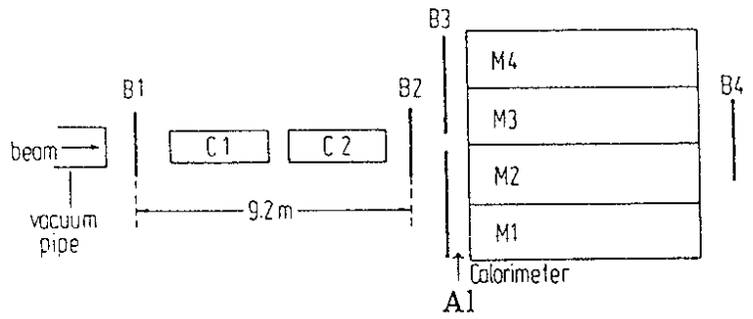

Fig. 14 The Experimental Set-Up with the FCAL Prototype at CERN

Without material in front of the prototype the energy resolution is $\sigma_h/\mathrm{E}=35\%/\sqrt{E}$ for hadrons and $\sigma_e/\mathrm{E}=18\%/\sqrt{E}$ for electrons and above 3GeV the ratio of electron to hadron response e/h is about 1 [5].

The main points of the measurement program are listed in the following:

Hadrons and Electrons

Absorber: Aluminium	Thickness:	0cm, 9cm, 18cm, 27cm (= 0, 1, 2, 3 X_0)
Momentum:	at CERN PS:	0.5, 1, 2, 3, 5 GeV/c
	at CERN SPS:	10, 20, 30, 75 GeV/c

Hadrons and Interaction Trigger – Jets

Absorber: Aluminium	Thickness:	0cm, 4cm, 10cm
Momentum:	at CERN SPS:	50, 100 GeV/c

2.3 EXPERIMENTAL RESULTS

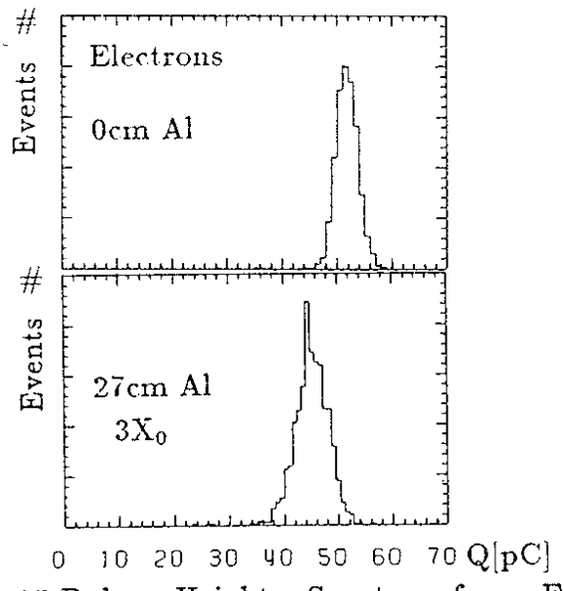

Fig. 15 Pulse Height Spectra for 30GeV Electrons without and with 27cm Al in Front of the Calorimeter

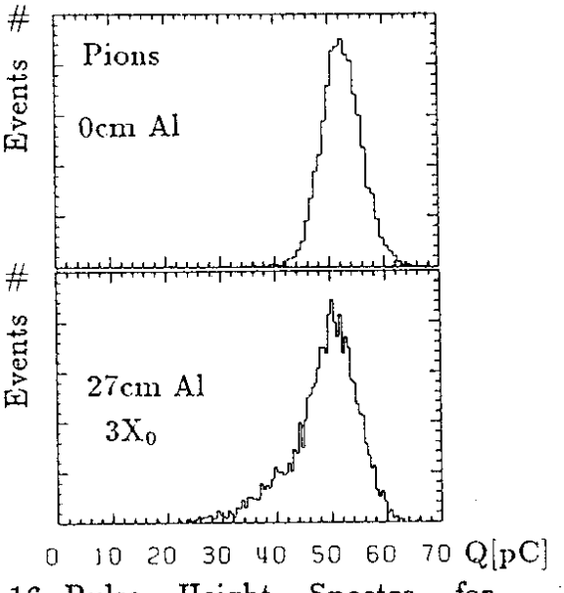

Fig. 16 Pulse Height Spectra for 30GeV Pions without and with 27cm Al in Front of the Calorimeter

Figure 15 and 16 show the pulse height spectra for electrons and pions at 30GeV without and with 27cm Aluminium absorber ($3X_0$) directly in front of the prototype. With absorber in front the mean values of the spectra are shifted significantly to lower values and the widths of the distributions increase. Whereas for electrons the shape remains approximately Gaussian, it becomes strongly asymmetric for hadrons with a tail to small pulse heights.

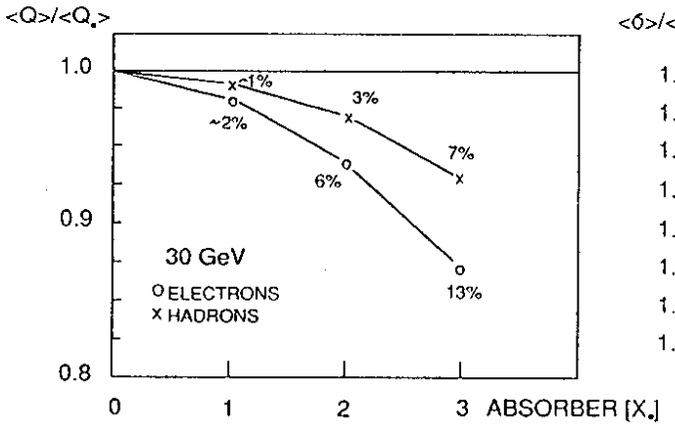

Fig. 17 Ratio of the Mean Signal Height with Absorber (<Q>) and without Absorber (<Q_0 >) as Function of the Absorber Thickness

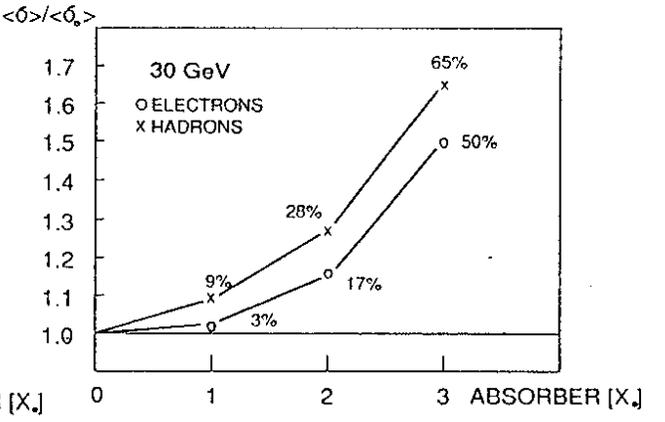

Fig. 18 Ratio of the Standard Deviation with Absorber (< σ >) and without Absorber (< σ_0 >) as Function of the Absorber Thickness

Figure 17 and 18 show for electrons and hadrons at 30GeV the ratio of the mean signal height and the standard deviation (3σ cut used) with material (< Q >, < σ >) and without material (< Q_0 >, < σ_0 >) as function of the absorber thickness in front of the calorimeter. For 1 X_0 material in front the mean value is reduced by about 1% for hadrons and 2% for electrons and decreases significantly in particular for electrons with increasing absorber thickness. The widths increase with absorber material in front and are for 1 X_0 by about 3% larger for electrons and 9% larger for hadrons.

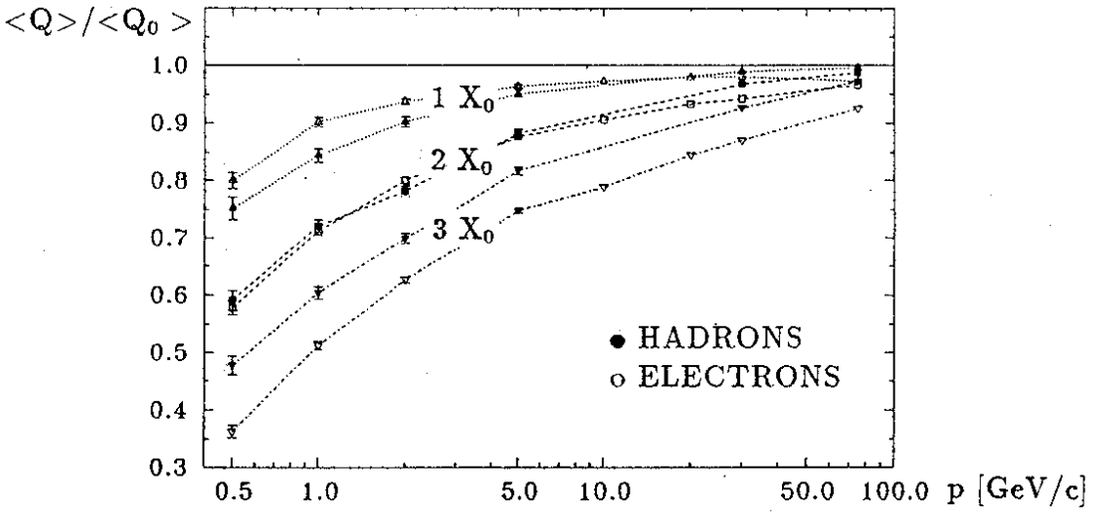

Fig. 19 Ratio of the Mean Signal Height with Absorber (<Q>) and without Absorber (<Q_0 >) as Function of the Momentum

The ratio <Q>/<Q_0 > for 9cm, 18cm and 27cm Aluminium absorber as function of the particle momentum is shown in Fig. 19. The deviation from 1 is large at low momenta and is decreasing with increasing momentum. Monte Carlo simulations have been performed and a similar behaviour has been found [6].

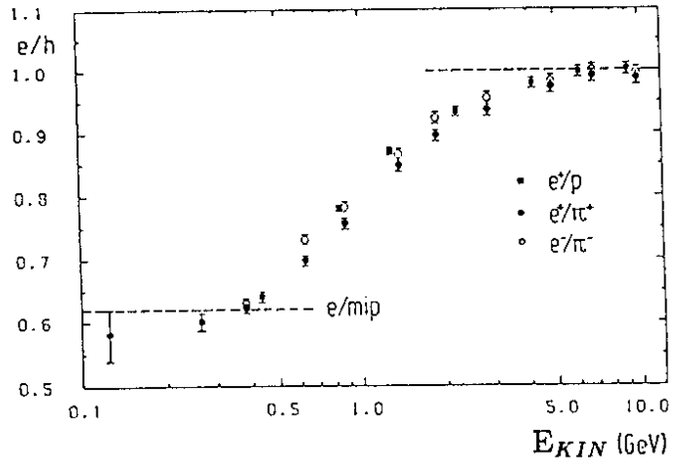

Fig. 20 e/h as Function of the Kinetic Energy E_{KIN} for p, π^+, π^-

Figure 20 shows the e/h ratios at equal kinetic energies E_{KIN} for π^+, $\pi^-$and p [5]. e/h is the same for π^+, π^- and p and depends in first approximation only on the kinetic energy E_{KIN}, the energy available for particle production and energy deposit in the calorimeter. At low energies hadrons lose more and more of their energy via dE/dx and approach the sampling fraction of a minimum ionizing particle (mip). Thus e/h approaches e/mip, which is 0.62 in the present calorimeter. As the electron response e is essentially linear with kinetic energy, the ratio $<Q>/E_{KIN}$ normalized to $<Q_0>/E_{KIN}$ at 75GeV ($(<Q_0>/E_{KIN})\,|_{75GeV}$) with absorber in front shows smaller deviations from 1.

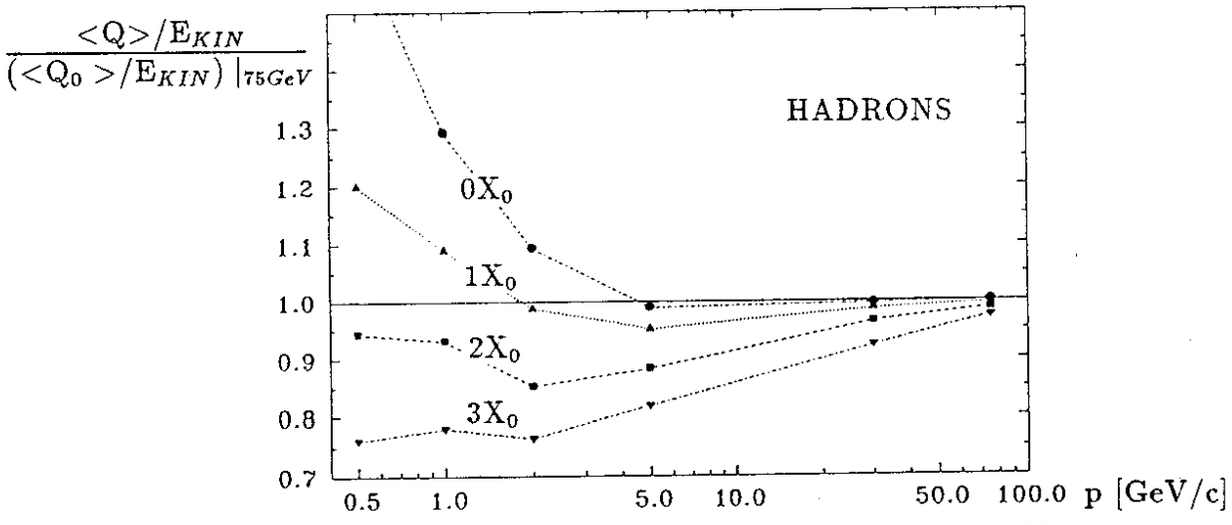

Fig. 21 Ratio of the Mean Signal Height ($<Q>$) and the Kinetic Energy E_{KIN} as Function of the Momentum

The normalized ratio $<Q>/E_{KIN}$ is shown in Fig. 21 for hadrons as function of the momentum. The different curves show the dependence on the absorber thickness. The deviation from 1 is significantly reduced compared to $<Q>/<Q_0>$.

The analysis of the data taken with the interaction trigger in front of the FCAL prototype and the study of methods to correct experimentally for energy lost in the absorber in front of the calorimeter via pulse height measurement are in progress [7].

ACKNOWLEDGEMENTS

I gratefully acknowledge the efficient cooperation of the participants of the various groups during the WA78–H1–ZEUS calorimeter test. I am also very grateful to my colleagues of the ZEUS calorimeter group for their excellent collaboration during the tests with the ZEUS FCAL prototype calorimeter. For the fruitful cooperation and numerous interesting discussions especially with respect to the ZEUS calorimeter R. Klanner, E. Lohrmann and G. Wolf are warmly acknowledged.

REFERENCES

1. Krüger, J., "Shower Development in a Uranium/Scintillator Calorimeter (WA78) and the Requirements for the Hadron Calorimeter of the ZEUS Detector", DESY, ZEUS Note 86–019 (1986)
2. Catanesi, M.G. et al., "Hadron, Electron and Muon Response of a Uranium–Scint. Calorimeter", Nucl. Instr. and Meth. A260 (1987) 43–54
3. The ZEUS Detector, Technical Proposal, DESY, March 1986
   The ZEUS Detector, Status Report 1987, DESY, September 1987
   The ZEUS Detector, Status Report 1989, DESY, March 1989
   Wolf, G., "HERA: Physics, Machine and Experiments", DESY 86–089
4. Krüger, J., "The ZEUS Uranium Scintillator Calorimeter ... ", Hamburg, DESY, in preparation
5. Behrens, U. et al., "Test of the ZEUS Forward Calorimeter Prototype", Nucl. Instr. and Meth. A289 (1990) 115
   Andresen, A. et al., "Response of a Uranium–Scintillator Calorimeter to Electrons, Pions and Protons in the Momentum Range 0.5 – 10 GeV/c", Nucl. Instr. and Meth. A290 (1990) 95
6. Fürtjes, A., Diploma Thesis, Münster (1990), DESY F35–90–02
7. Kröger, W. et al., "The Interaction Trigger ...", DESY, in preparation