Calorimetry in Particle Physics

Lecture III

Electromagnetic Calorimeters

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Homogeneous Calorimeters: Basics

Converter and detection material identical

Shower detected via

- Čerenkov light $Pb - glass,\ PbF_2$
- Scintillation light $NaJ(Tl),\ CsJ\,(Tl),\ BGO,\ PbWO_4$
- Ionization $L\,Ar,\ L\,Kr$

Most important question:

Which processes determine energy resolution achievable with an electromagnetic calorimeter :

- Shower fluctuations

$$N_{Shower} \sim E$$

Assuming Poisson statistics

$$\boxed{\frac{\sigma}{E} \approx \frac{a}{\sqrt{E}}}$$

- Photoelectron statistics in detector (photomultiplier, diode, ...)

$$N_e \sim N_\gamma \sim N_{Shower} \sim E$$

Again assuming Poisson statistics

$$\frac{\sigma}{E} = \frac{b}{\sqrt{E}}$$

Homogeneous Calorimeters: Basics

b derived from

$$\Delta E = \text{energy deposited in material}$$

Effective number n_γ of photons produced

$$n_\gamma = \frac{n_{pe}}{\varepsilon_{pe} \cdot \varepsilon_{col}}$$

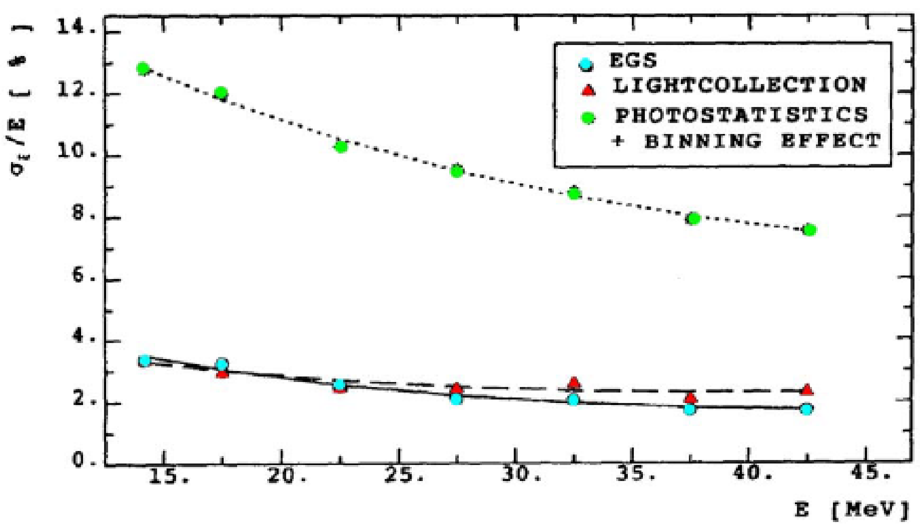
ε_{pe} photocathode efficiency (producer)

ε_{col} light collection efficiency (simulation)

n_{pe} number of photoelectrons observed (measured)

$$\frac{\Delta E}{n_\gamma} = \text{MeV/photon produced} \rightsquigarrow b$$

$$\left(\frac{\sigma}{E}\right)_{measured}, \qquad b \longrightarrow a \ \text{ derived}$$

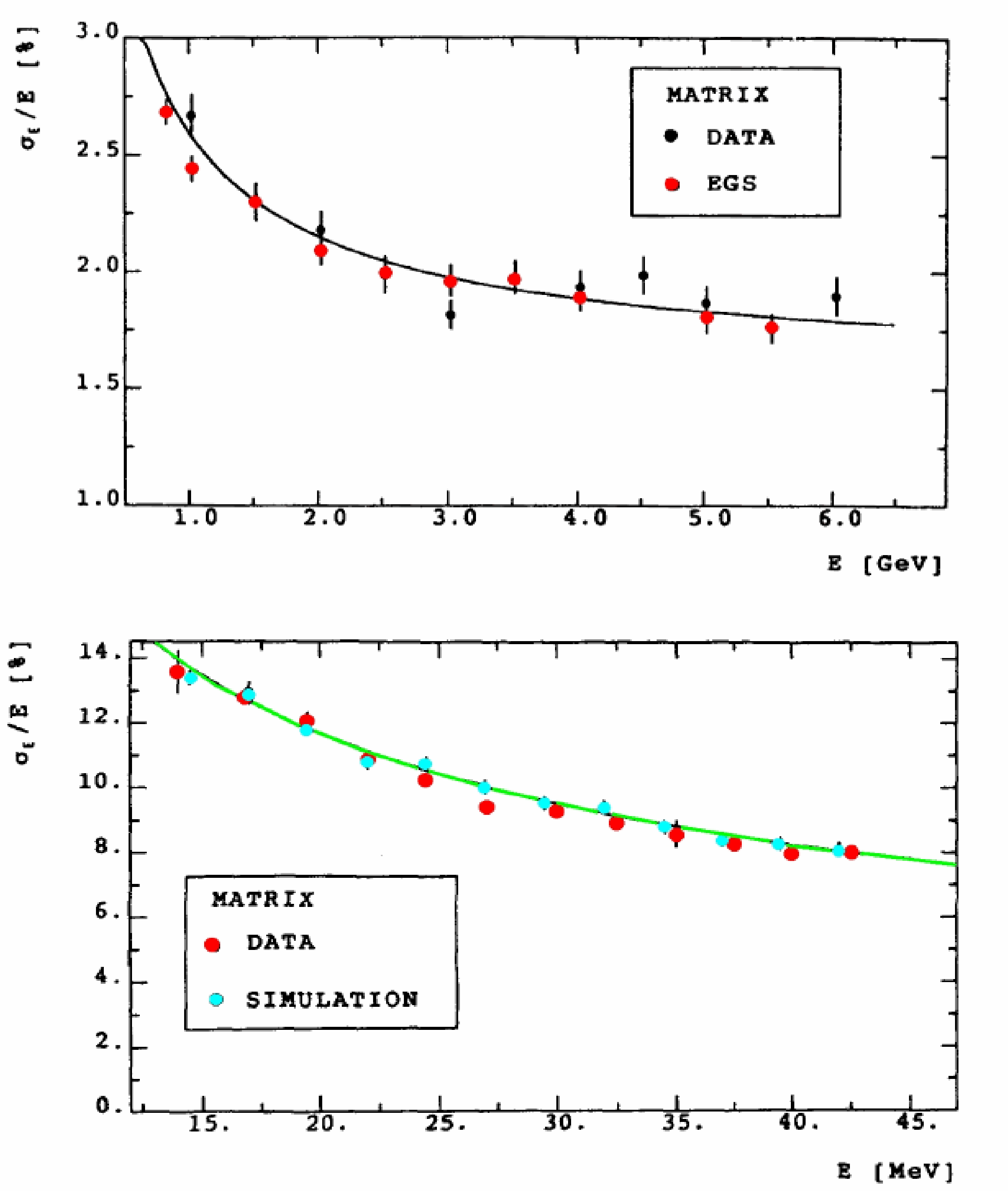


- Electronic noise

For Si–diodes or silicon avalanche photodiodes (APD) noise nonnegligible: $\sigma_{noise} = c$

$$\boxed{\frac{\sigma}{E} = \frac{c}{E}}$$

Homogeneous Calorimeters: Basics

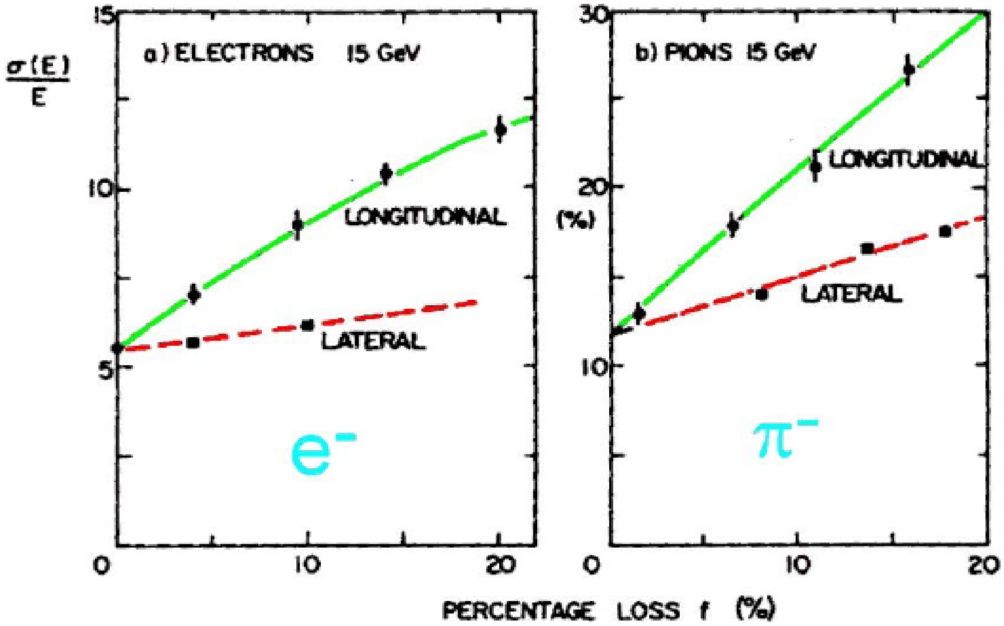


Homogeneous Calorimeters: Basics

- LEAKAGE

  Detector has finite dimensions, shower energy not deposited fully in detector.

  Lost energy fluctuates



Longitudinal losses more dangerous than transversal!

Simple model :

Energy loss through leakage at rear end of counter

$$\Delta E \;\approx\; \Delta t \cdot (\frac{dE}{dt})_{t_e}$$

$(\frac{dE}{dt})_{t_e}$ energy loss at end of counter

$\Delta t \;\approx\; 1$ positional fluctuation of shower max.

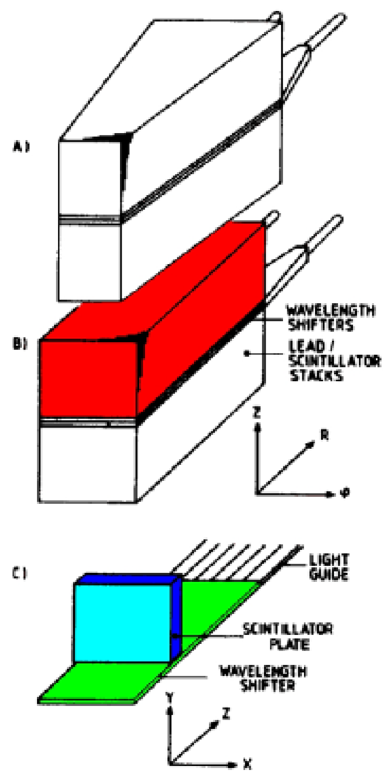
(depends on fluctuation of first conversion point)

$$(\frac{dE}{dt})_{t_{MAX}} \;\sim\; E\,, \quad (\frac{\sigma}{E})_{Leak} \;=\; d$$

Homogeneous Calorimeters: Basics

- **Efficiency of light transport**

  Efficiency of photon collection varies with the shower position especially for wedge–shaped counters



Simple model

$$\frac{d\,N_{pe}}{N_{pe}} = \frac{1}{<\varepsilon>} < \frac{d\varepsilon}{dt} > \Delta t$$

$< \frac{d\varepsilon}{dt} >$ average at t_{MAX}

$$(\frac{\sigma}{E})_{LT} = e$$

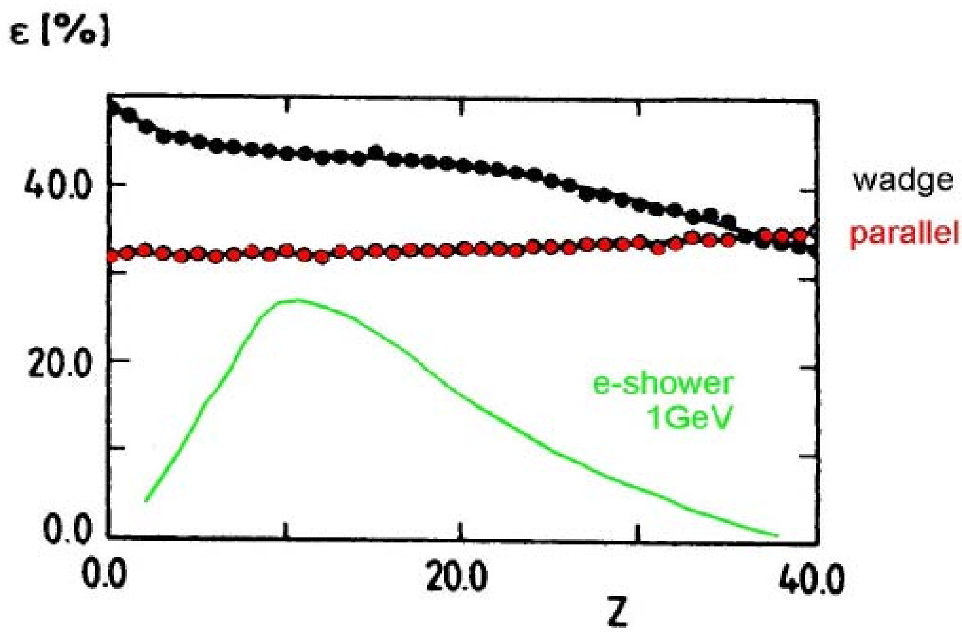
Can be separated from leakage contribution investigating differently shaped counters

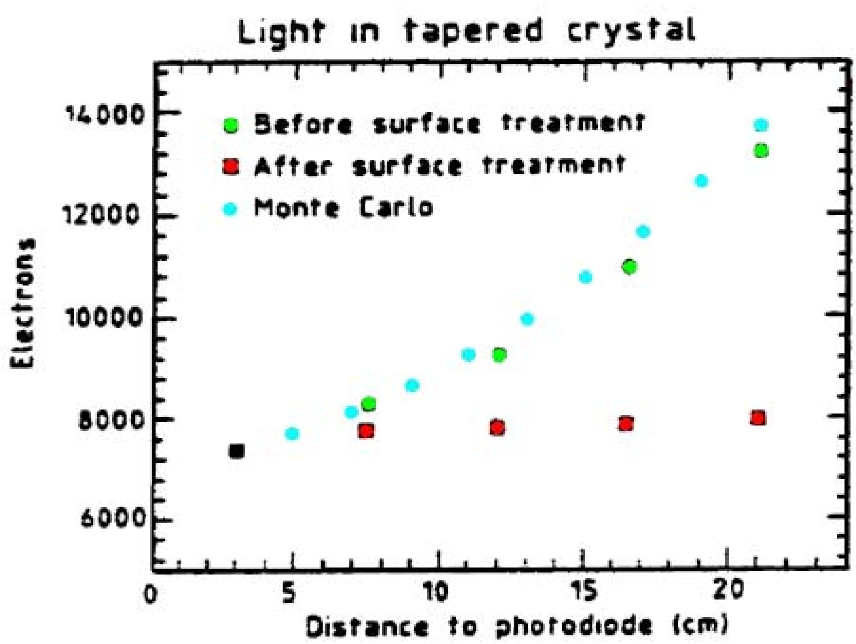
Homogeneous Calorimeters: Basics

Remarks

Light collection efficiency depends on geometry and homogenity of material :

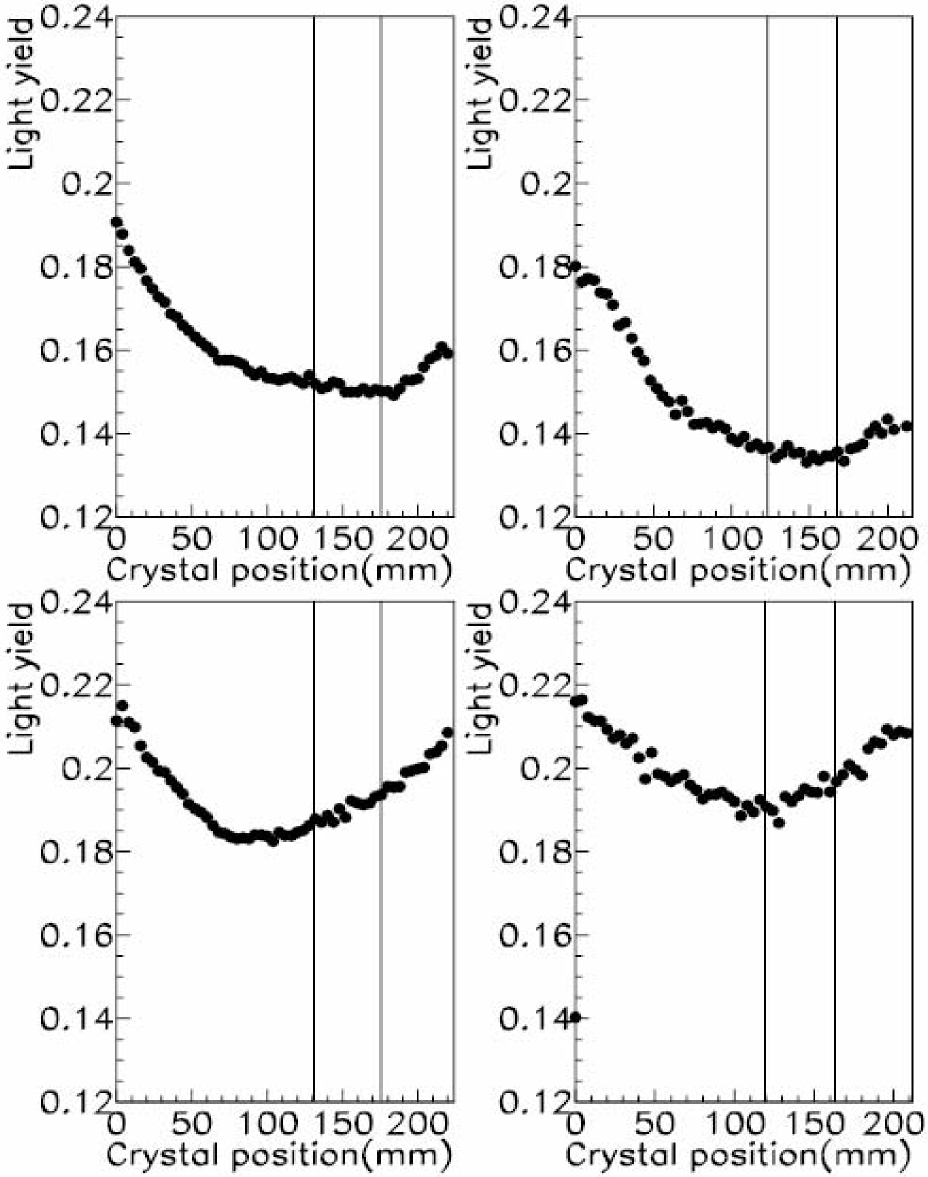
- geometry





Homogeneous Calorimeters: Basics

- inhomogeneous absorption : $PbWO_4$



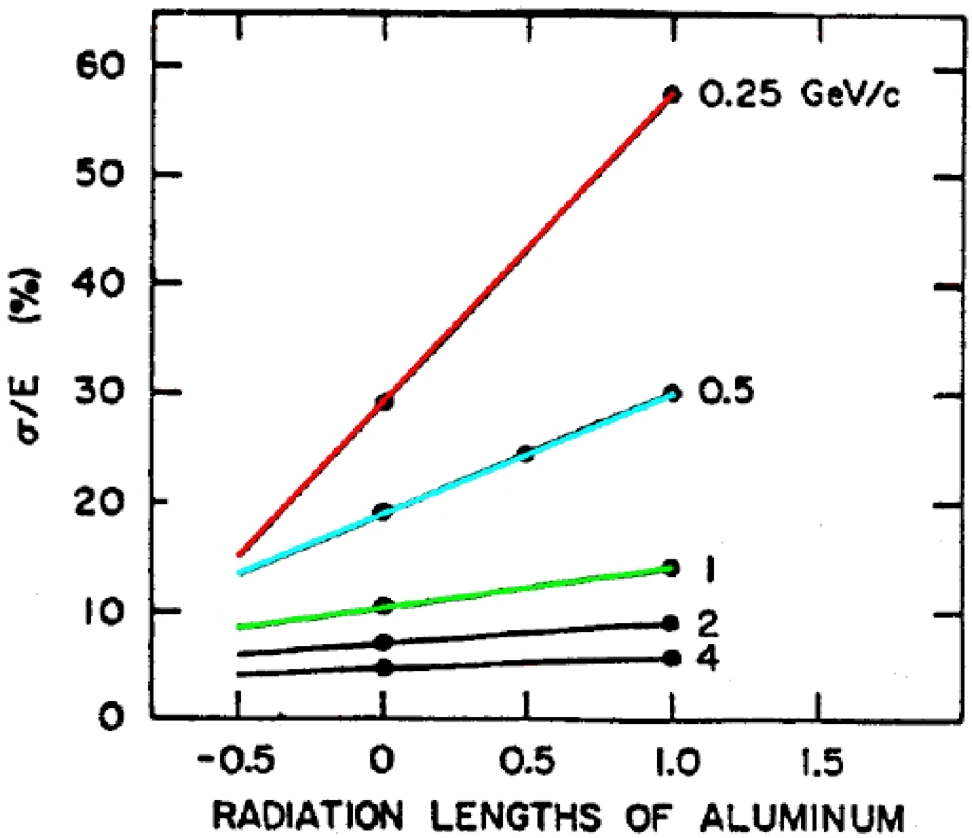
Crystal Ball : $NaJ\,(Tl)$

$$\frac{\sigma}{E} \sim E^{-\frac{1}{4}}$$

Homogeneous Calorimeters: Basics

- Material in front of counter

  Degradation of energy resolution due to energy loss in front of calorimeter



Effect most pronounced at low energy

Partial recovery by presampler

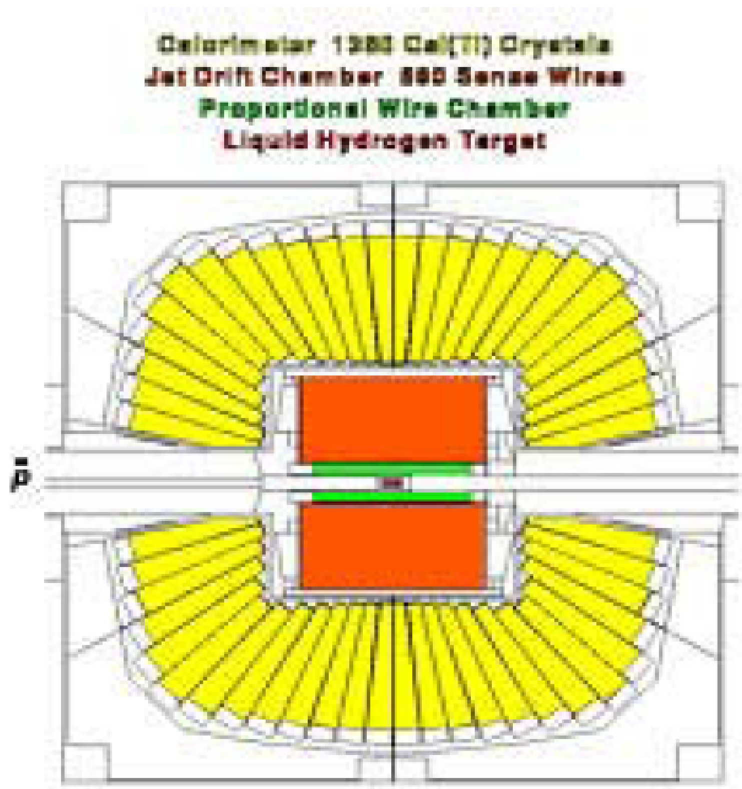
Homogeneous Calorimeters: Systems

- CRYSTAL BARREL DETECTOR $CsJ\,(Tl)$

$\rho\,[\mathrm{g/cm^3}]$	X_0[cm]	R_M[cm]	$\#pe$	τ[ns]
4.53	1.86	3.8	1900/MeV	900

Physics program: $p\overline{p}$ annihilation with $p\overline{p} \leq 2$ GeV

Optimized for 20 MeV $\leq E_\gamma \leq$ 2 GeV

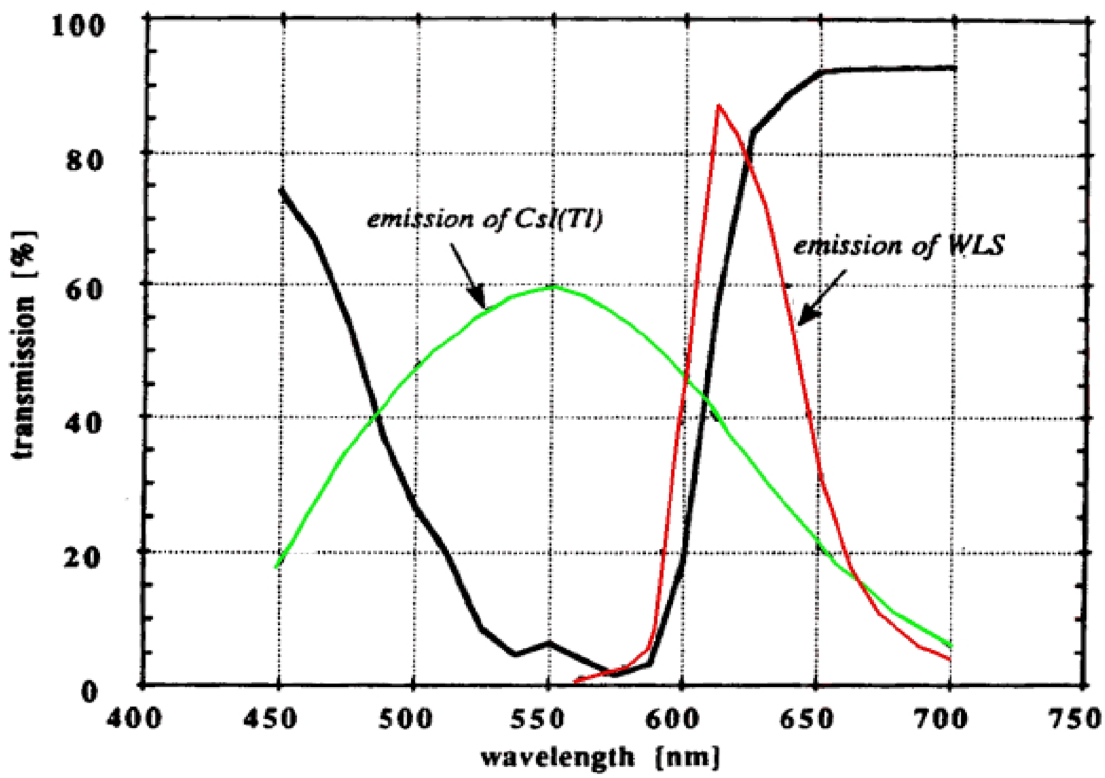


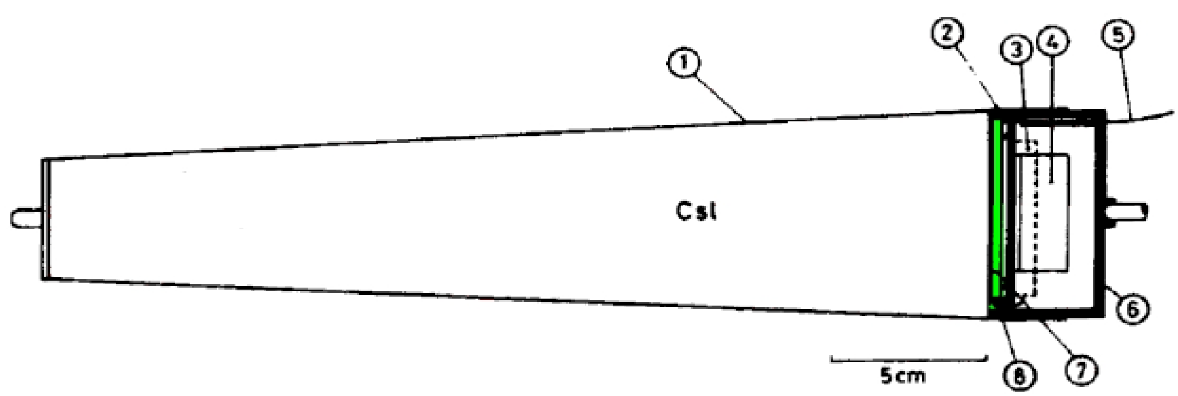
System: 1380 modules covering $\Delta\Omega/4\pi = 0.95$

Module extensions: longitudinal 16.7 X_0 (1% leakage)
lateral 1.5 R_M

Homogeneous Calorimeters: Systems

Read–out: via wavelength shifter by Si–diode

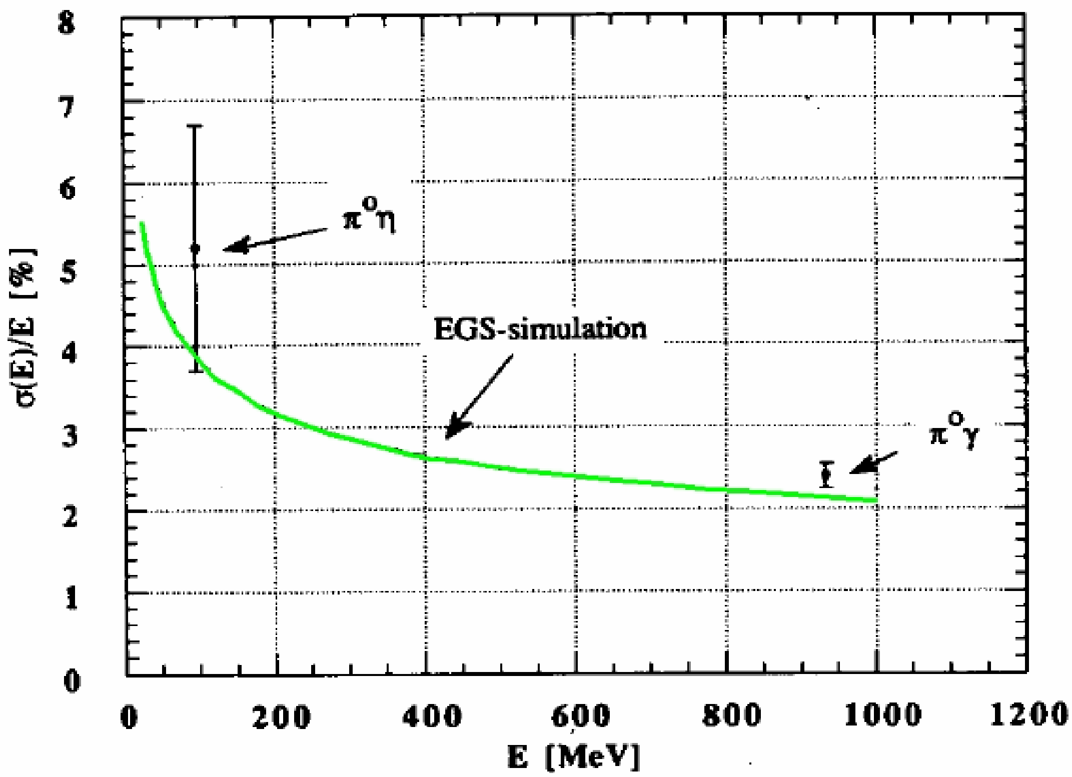




Homogeneous Calorimeters: Systems

Performance

Energy resolution : $\frac{\sigma}{E} \sim E^{-1/4}$



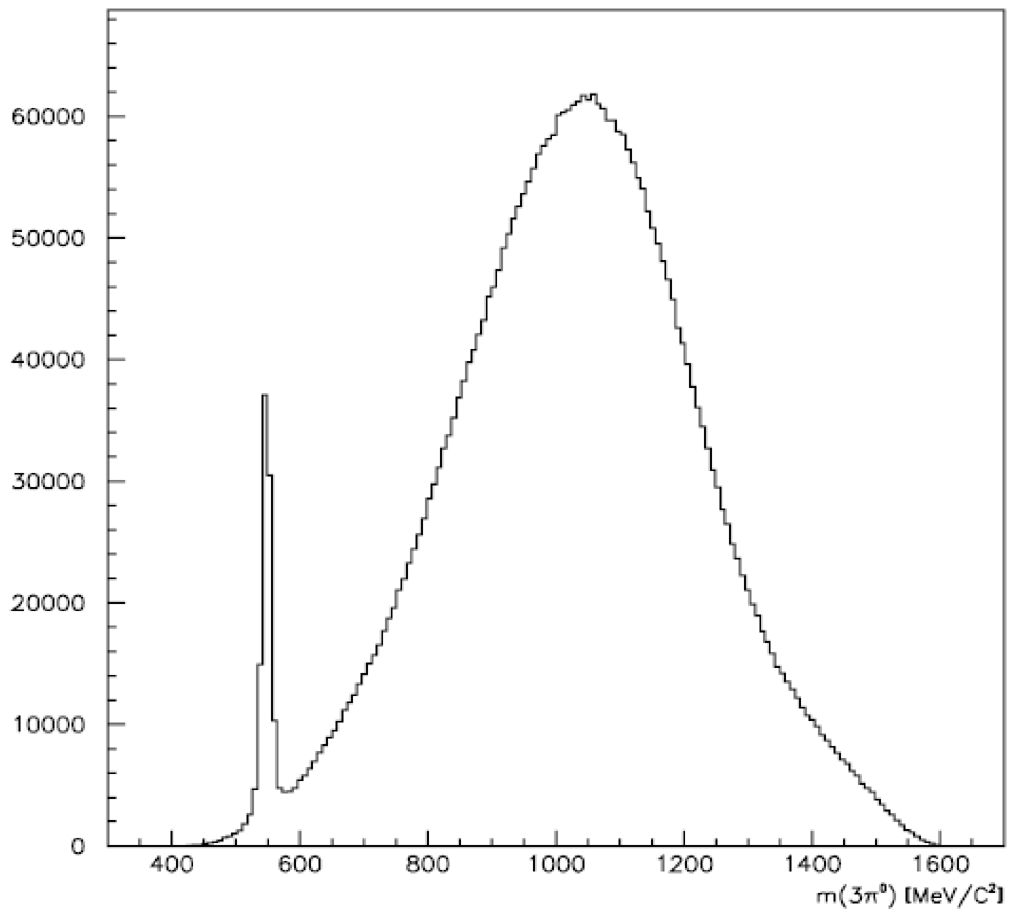
Intrinsic nonuniformity
stochastic noise (220 keV/channel)
Coherent noise (60 keV/channel)

Homogeneous Calorimeters: Systems

Angular resolution: $\sigma_\theta = 1.5^0 \quad (\sigma_r = 1.5 \text{ cm})$

Excellent mass resolution achieved:

Decay: $\eta \rightarrow \pi^0 \; \pi^0 \; \pi^0$
$\hookrightarrow 2\gamma \;\; \hookrightarrow 2\gamma \;\; \hookrightarrow 2\gamma$



Other detectors using $CsJ\,(Tl)$:

CLEO 2, BABAR, BELLE

Homogeneous Calorimeters: Systems

- CMS ELECTROMAGNETIC CALORIMETER

$PbWO_4$: radiation hardness

ρ [g/cm^3]	X_0[cm]	R_M[cm]	#photons/MeV	τ[ns]
8.28	0.89	2	80	10

Physics program : $H^0 \longrightarrow \gamma\gamma, \ \ldots$

$$\frac{\sigma_M}{M} = \frac{1}{2}\left\{\frac{\sigma_1}{E_1} \oplus \frac{\sigma_2}{E_2} \oplus \frac{\sigma_\theta}{tg\,\theta/2}\right\}$$

Goal: Stochastic $\leq 2\,\%/\sqrt{E}$

Constant term $\leq 0.5\,\%$

Noise term ~ 150 MeV

$$\sigma_\theta \leq \frac{50\ mr}{\sqrt{E}} \quad \text{for} \quad |\,\eta\,| \leq 1$$

System : $n_\theta * n_\eta = 432 * 216$ for $|\,\eta\,| \leq 1.56$

Module extensions: longitudinal 25.8 X_0

lateral 1 R_M

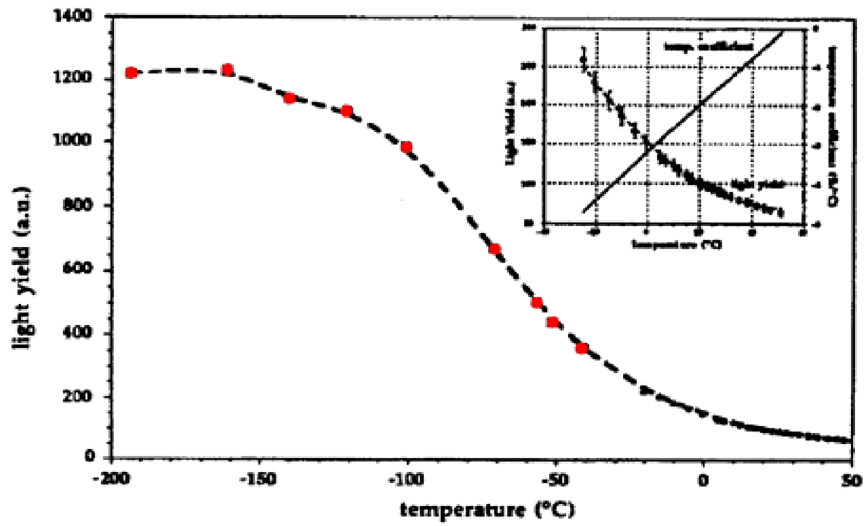
Read–out: Silicon avalanche photodiode (APD)

Preshower detector ($3X_0$ Pb+Si-strip detector)

Design has to consider properties of $PbWO_4$ luminescence :

Light yield and decay time depend on temperature

Homogeneous Calorimeters: Systems

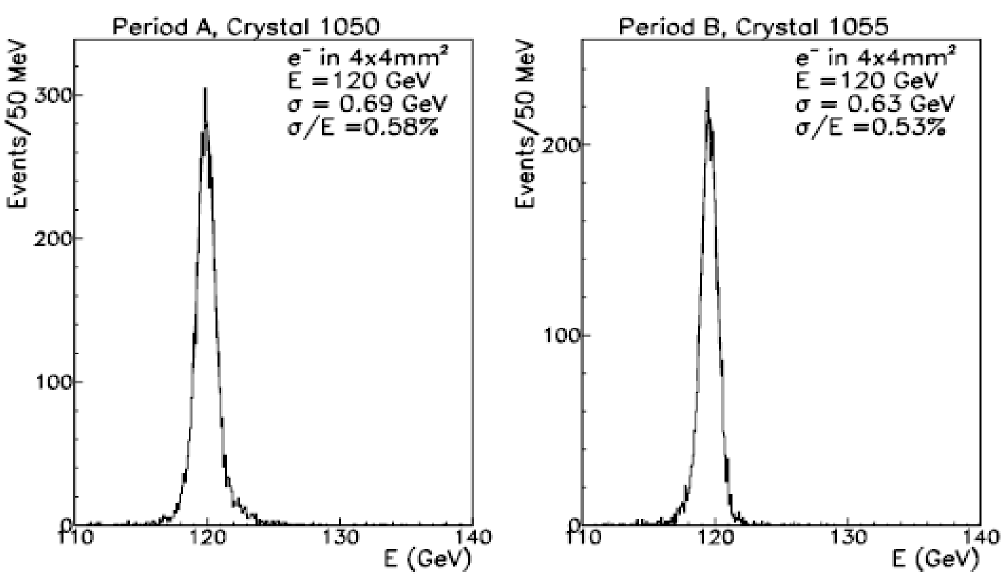


Temperature stabilization $\pm 0.05\ K$ and monitoring necessary

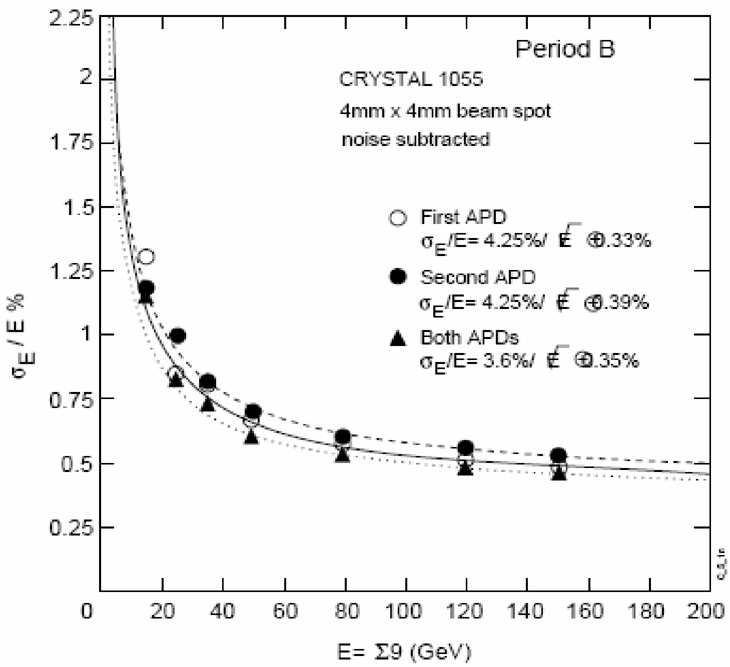
<u>Performance</u> : test beam results

- Energy resolution

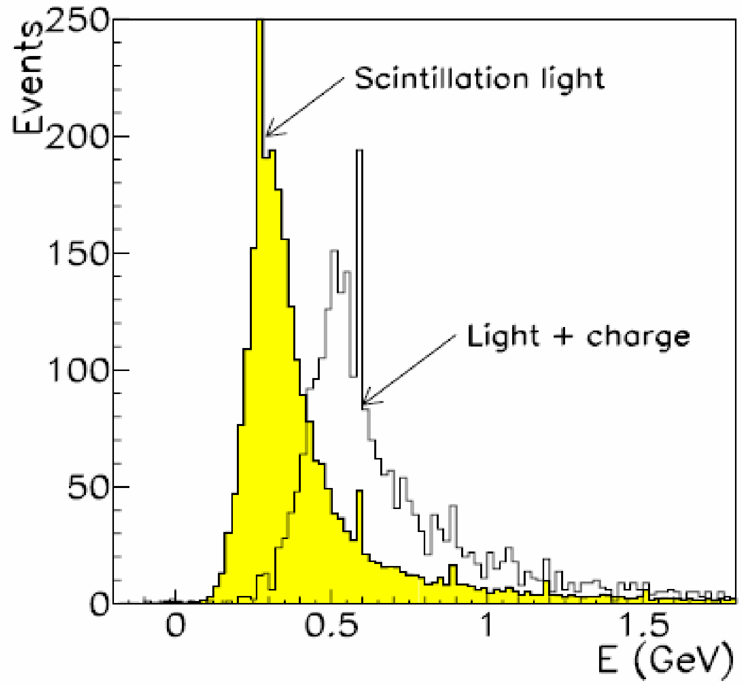
$$\frac{\sigma}{E} = \frac{0.036}{\sqrt{E}} \oplus 0.0035$$



Homogeneous Calorimeters: Systems



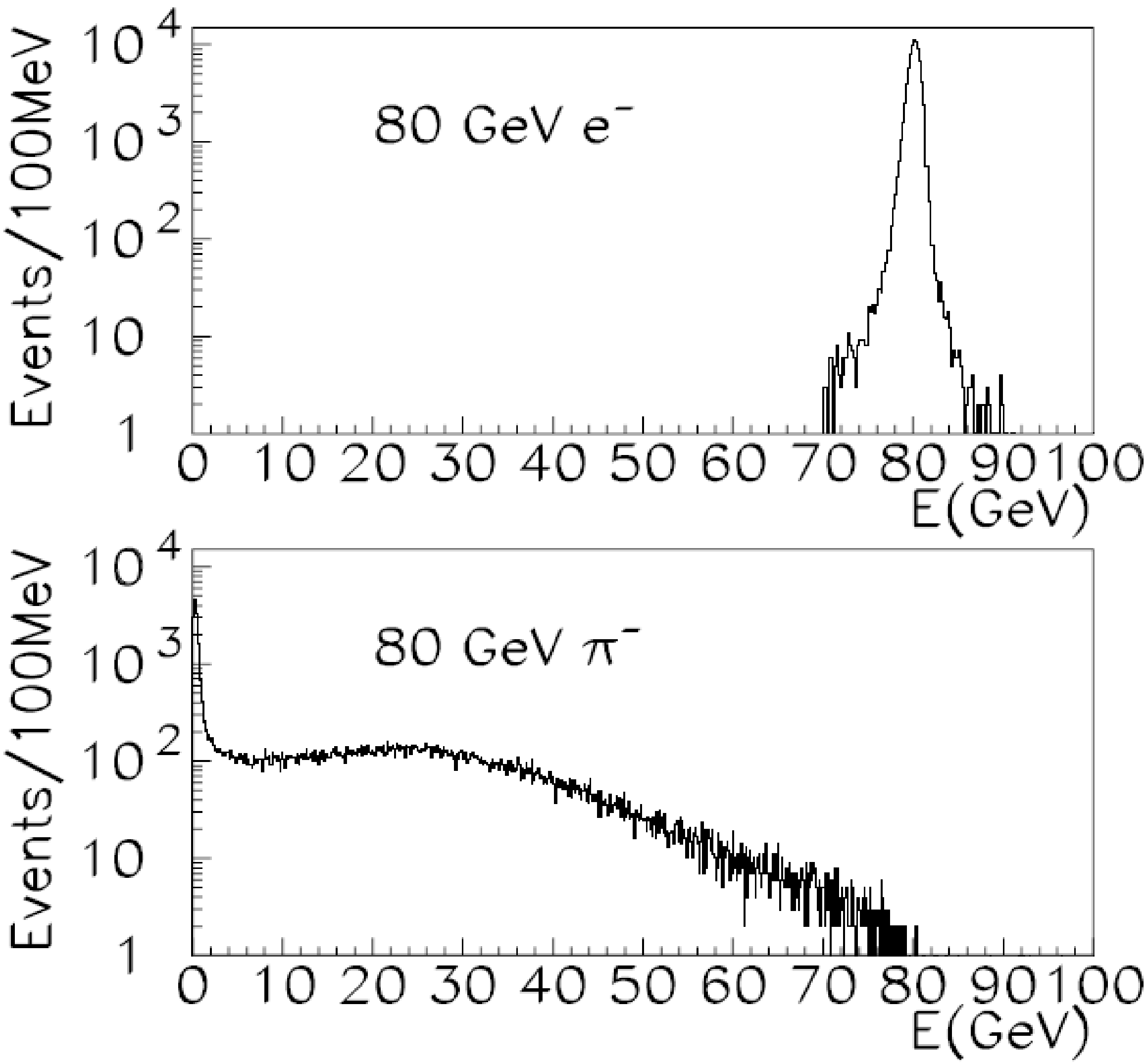
Improvement : longitudinal leakage
nuclear counter effect



Increase of light output necessary

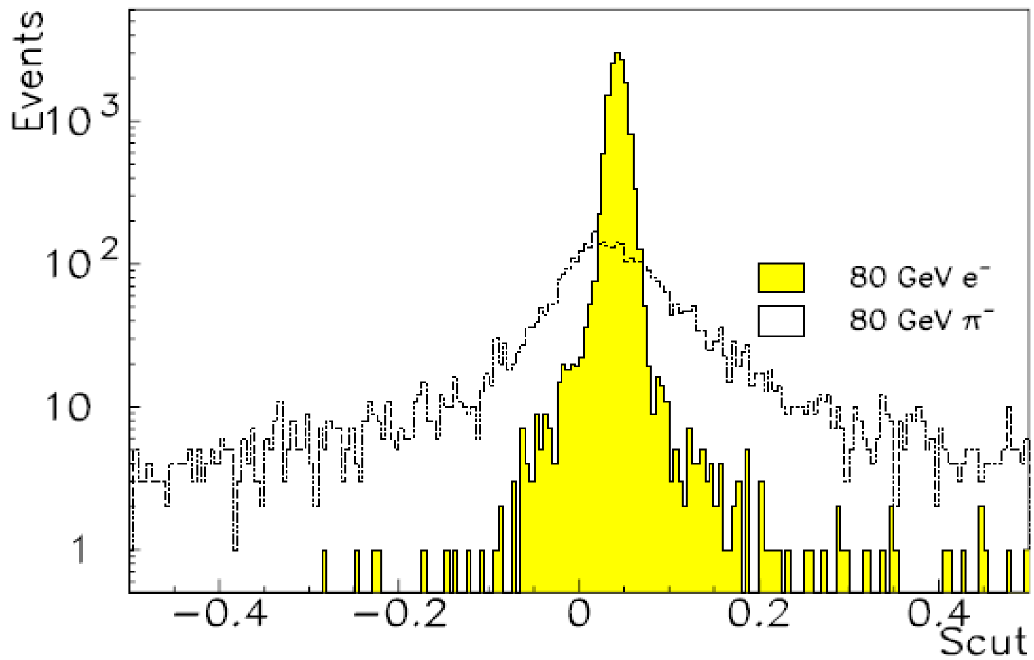
Homogeneous Calorimeters: Systems

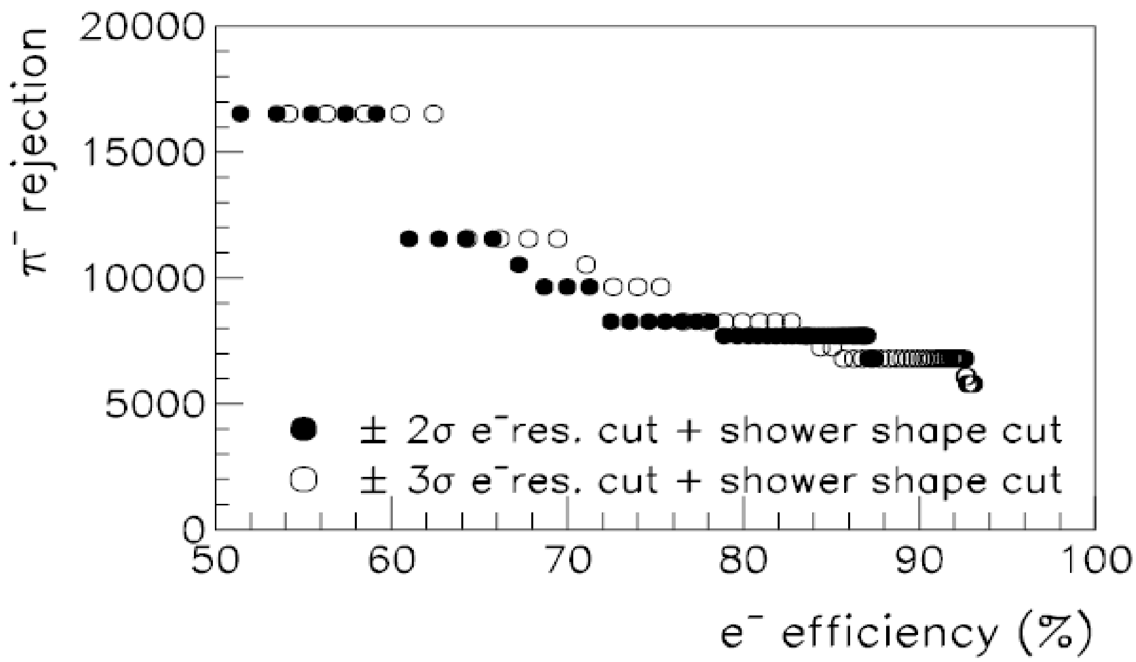
- e/π separation : Longitudinal



Homogeneous Calorimeters: Systems

Transverse :





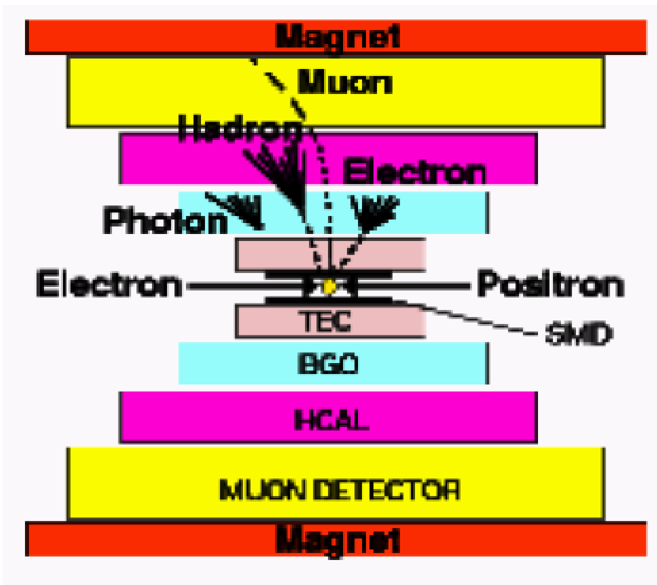
- 50–80 photons/MeV

Homogeneous Calorimeters: Systems

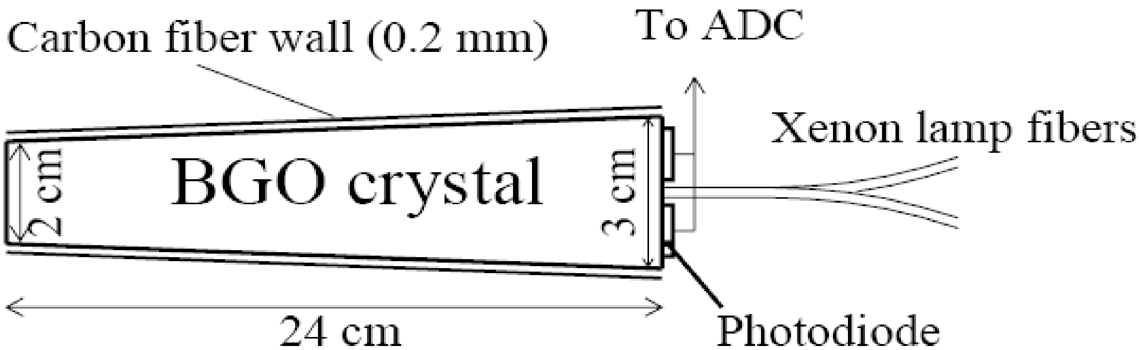
- L3 ELECTROMAGNETIC CALORIMETER *BGO*

$\rho\,[\text{g/cm}^3]$	X_0[cm]	R_M[cm]	#photons/MeV	τ[ns]
7.13	1.12	2.7	15 % of $NaJ(Tl)$	300

Physics goals : Z–decays, B–physics, W^+W^-, Higgs



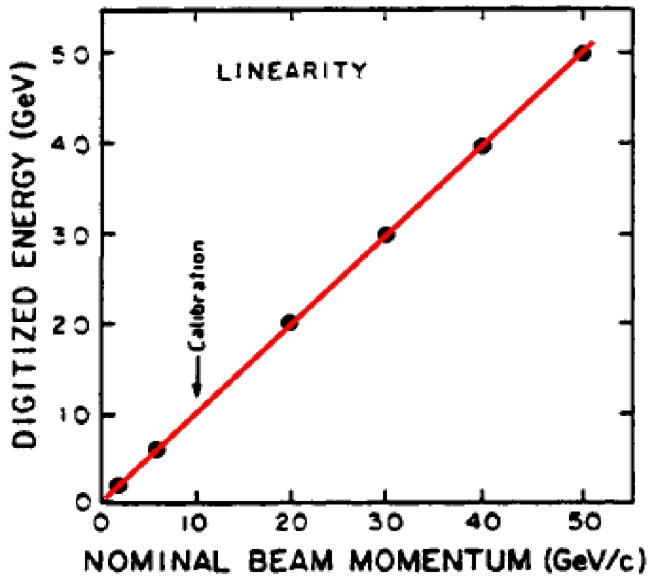
System: 12 000 crystals
$L = 22\ X_0,\ \ d_T \approx 0.75\ R_M$
Read–out photodiode



Homogeneous Calorimeters: Systems

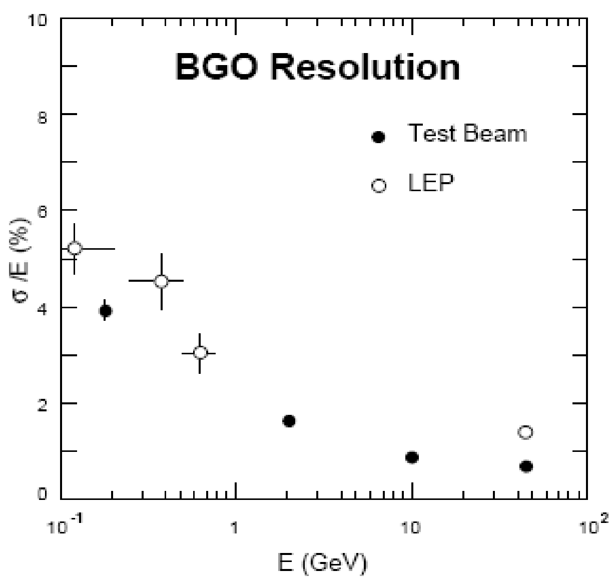
Performance:

Linearity



Influence of inhomogeneous light collection

Energy resolution



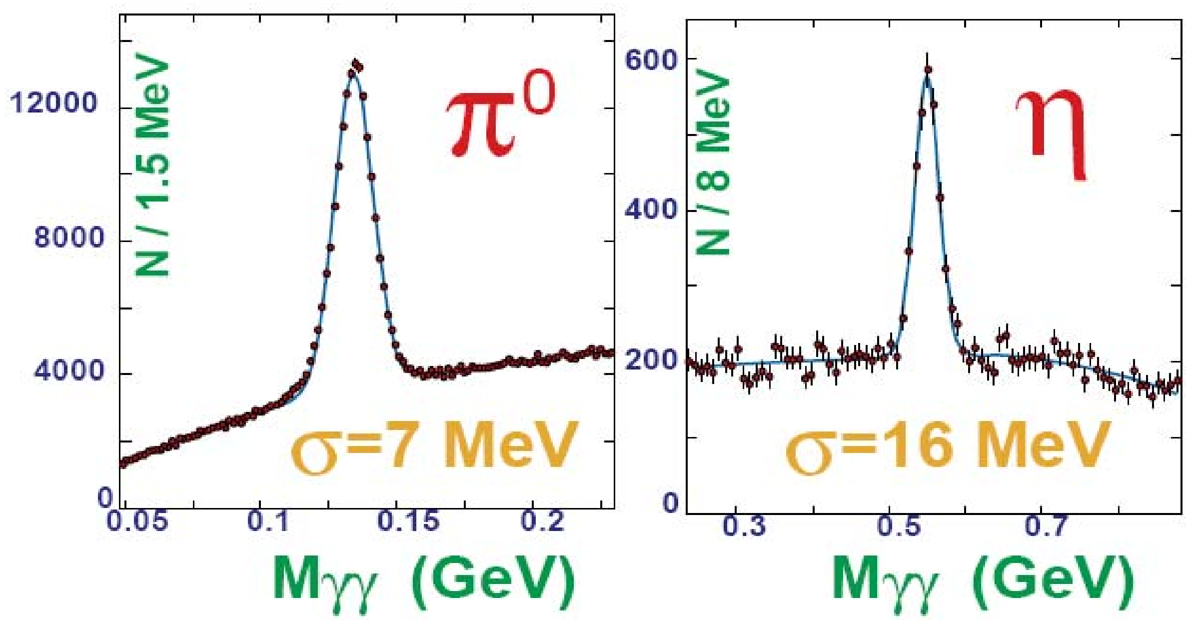
Intrinsic resolution and noise

Influence of nonscintillating material

$$E_\gamma > 6\ GeV \quad : \quad \frac{\sigma}{E} < 1\,\%\ !$$

Homogeneous Calorimeters: Systems

Excellent mass resolution achieved



Homogeneous Calorimeters: Systems

- NA48 ELECTROMAGNETIC CALORIMETER LKr

Physics goal: CP–violation $K_L^0 \to \pi^0\,\pi^0$

$$\frac{\sigma}{E} \leq \frac{0.04}{\sqrt{E}}$$

$$\sigma_x = 1 \text{ mm}$$

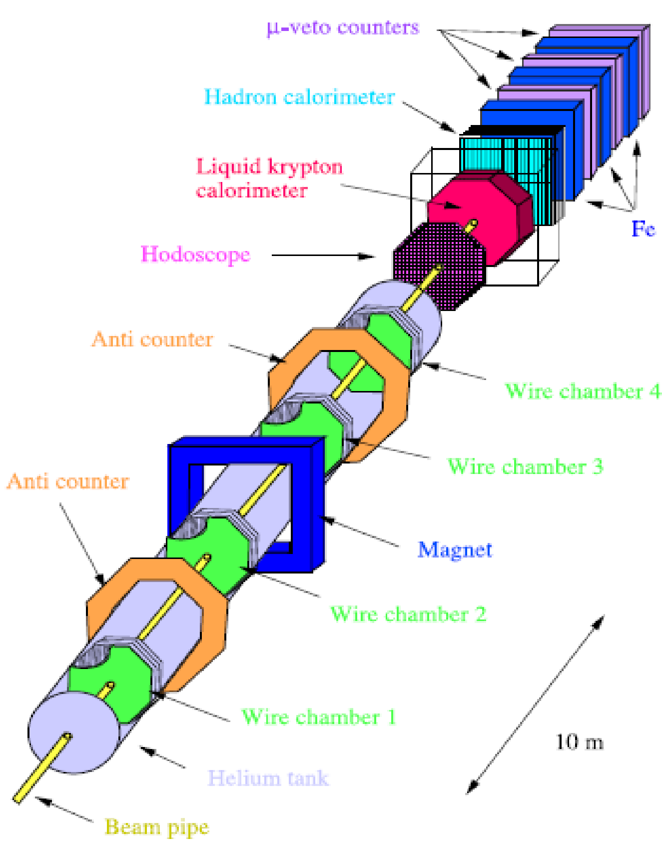
good time resolution (< 1 ns)

good 2γ resolution (4 cm)

Liquid Krypton

ρ [g/cm^3]	X_0[cm]	R_M[cm]
2.45	4.76	4.7

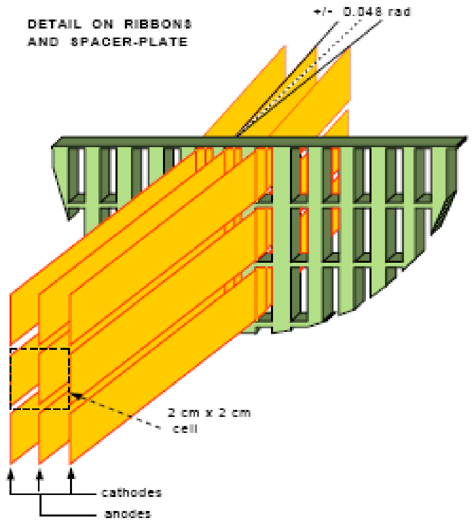
The NA48 Detector



Homogeneous Calorimeters: Systems

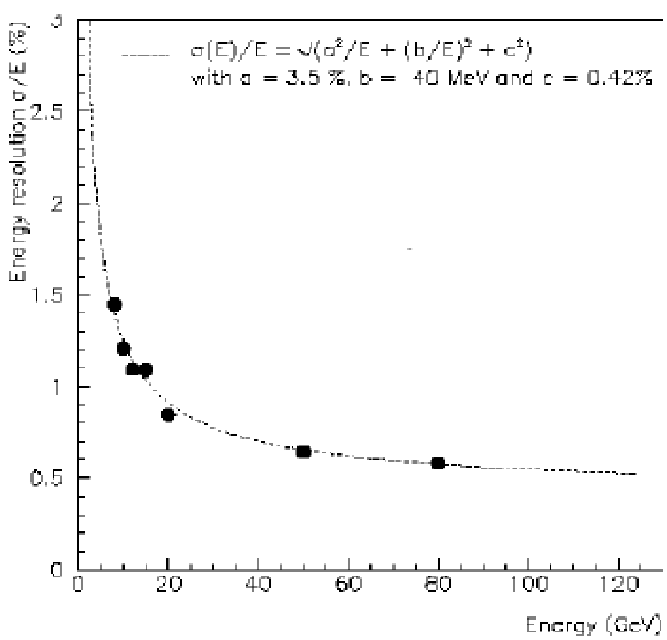
System : Zig–Zag (± 50 mr) electrodes parallel to beam direction. Material negligible

Current measured



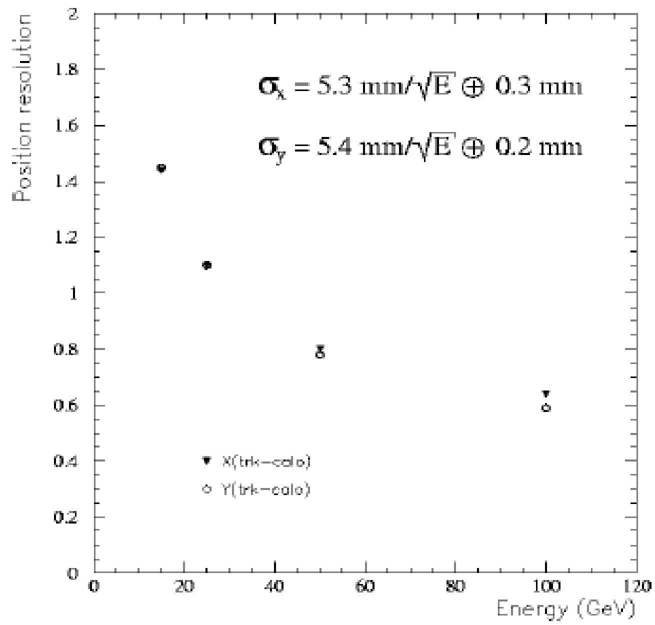
Performance : Energy resolution

$$\frac{\sigma}{E} = \frac{3.5\%}{\sqrt{E}} \oplus \frac{4.0\%}{E} \oplus 0.42\%$$

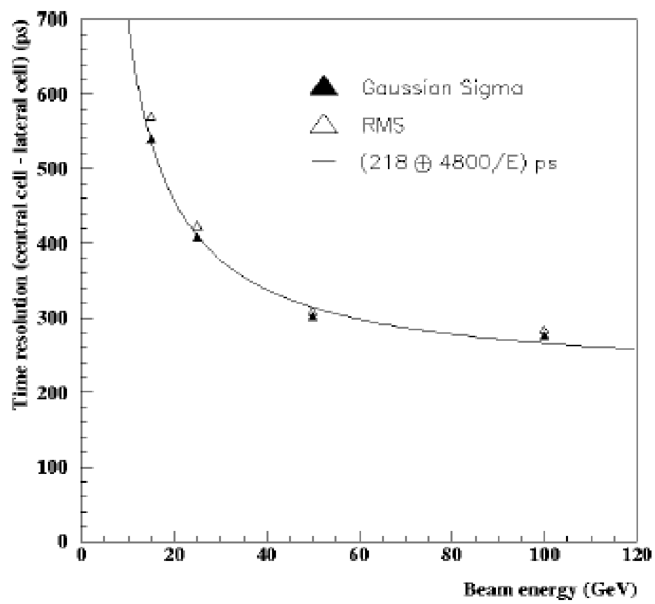


Homogeneous Calorimeters: Systems

Spatial resolution $E > 20\ GeV,\ \sigma_x < 1\ mm$



Time resolution $\tau < 0.5$ ns



Remark: Since current is measured less sensitive to electronegative admixtures.

Sampling Calorimeters: Fluctuations

Detector and converter material separated

Examples :	Pb – Scintillator	ARGUS, H1–SPACAL
	U–Scintillator	ZEUS
	Pb–L Ar	H1, SLD
	U–L Ar	DO
	Pb–Gas	DELPHI, ALEPH
	Pb/Fe–Scintillator	CDF

Sampling fluctuations dominate energy resolution !

Monte Carlo simulation :
Energy deposition in material dominated by low energy electrons

$$R_U\,(T_e = 1\ MeV) = 0.4\ mm$$

for $$d_U\,(3\ mm) = 3\ mm \quad \rightsquigarrow$$

only a minor fraction in LAr (Scintillator) observable

Fraction
$$f(e^-, U \to Sc) \;\sim\; \frac{1}{d(U)} \;\sim\; \frac{1}{t_{abs}}$$

Fraction of low energy e^- produced in detector material
$$f(e^-,\ \gamma \to e^- \text{ in } Sc/L\,Ar) \;\sim\; \frac{t_{act}}{t_{abs}}$$

Since
$$N \;\sim\; \frac{E}{\varepsilon_c}$$

$$\frac{\sigma}{E} \;\sim\; \frac{1}{\sqrt{N}} \;\sim\; \sqrt{\frac{\varepsilon_c}{E}}\;\sqrt{\alpha\ t_{abs} + (1-\alpha)\ \frac{t_{abs}}{t_{act}}}$$

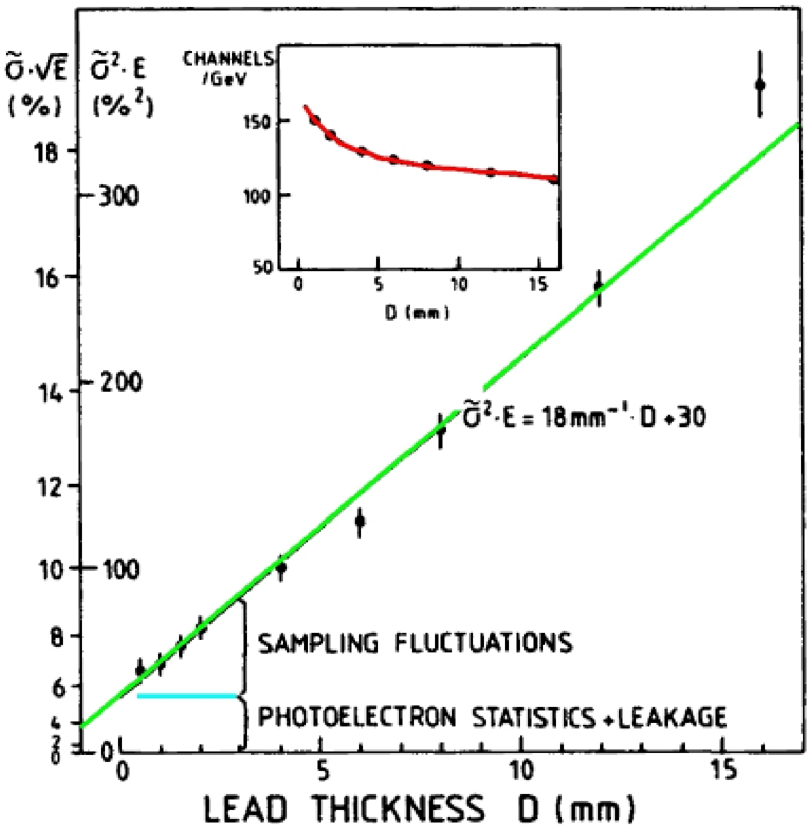
Sampling Calorimeters: Fluctuations

Z_{abs} small (Fe) : $(1-\alpha) \gg \alpha$ $\frac{\sigma}{E} \sim \frac{1}{\sqrt{E}} \sqrt{t_{abs}}$

Z_{abs} large (Pb) : $\alpha \gg (1-\alpha)$ $\frac{\sigma}{E} \sim \frac{1}{\sqrt{E}} \sqrt{t_{abs}}$

Good parametrization :

$$\tilde{\sigma} = \frac{\sigma}{E} = 3.2\,\% \sqrt{\frac{\varepsilon_c\ [MeV]}{F}} \sqrt{\frac{t_{abs}}{E\ [GeV]}}$$



Good resolution achieved, if

ε_c small (Z converter large)

t_{abs} small ($\Delta x < X_0$, fine sampling)

Sampling Calorimeters: Systems

- ARGUS shower counters

  Pb–Scintillation sandwich with WLS read–out

Physics program: $e^+e^- \rightarrow \Upsilon\,(ns)$

B–decays, charm spectroscopy, $\Upsilon\,(2S) \rightarrow^3 P_J + \gamma$

τ–physics, $\gamma\gamma$–physics

30 MeV $\leq E_\gamma \leq$ 5 GeV, e–identification

System:

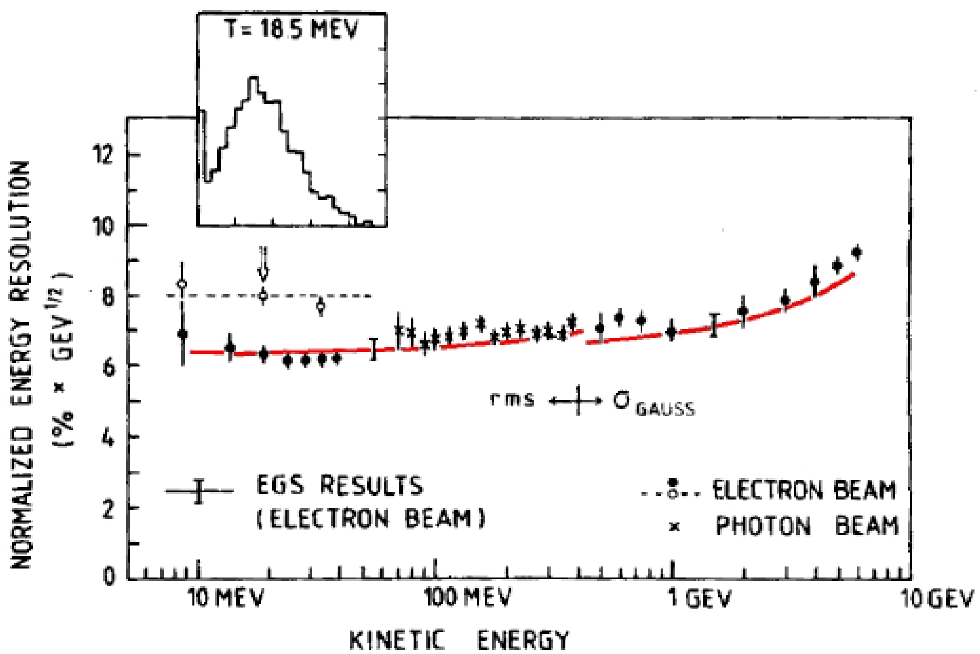
fig.67 $\longrightarrow$

1280 barrel counters L = 12.5 X_0, r = 0.5 R_M

2 $*$ 240 end cap counters L = 10.6 X_0, r = 0.5 R_M

Performance:

Energy resolution $\frac{\sigma}{E} = \frac{7\,\%}{\sqrt{E}}$

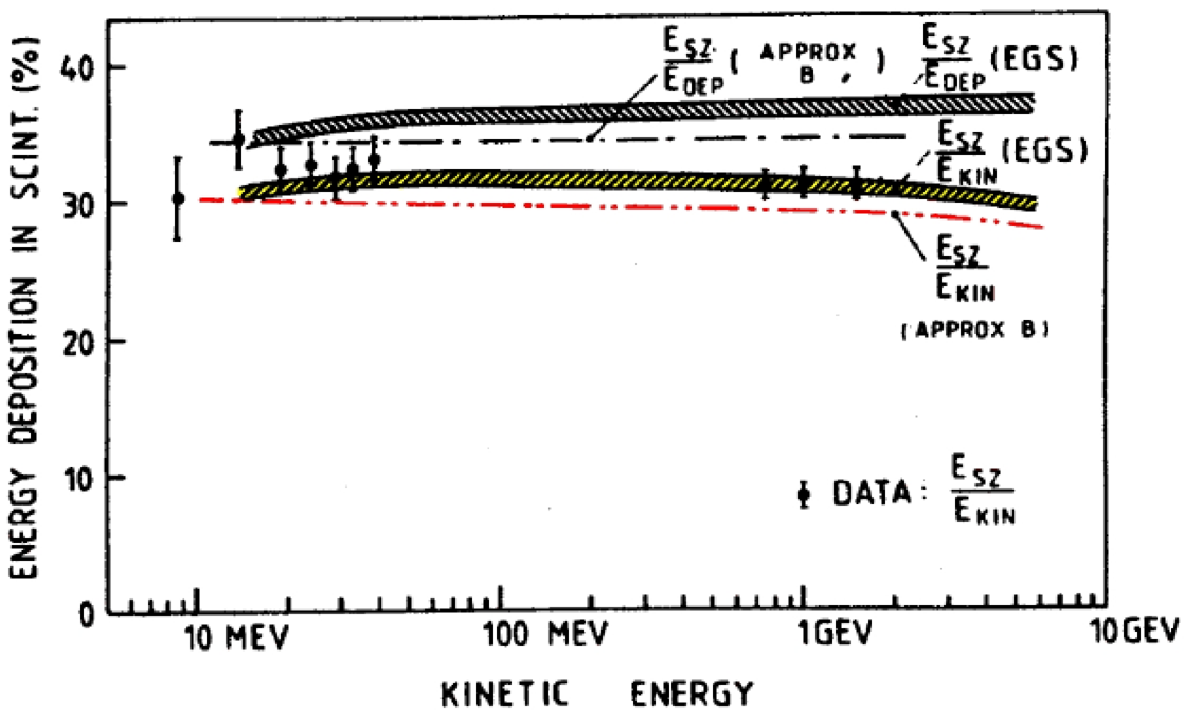


Sampling Calorimeters: Systems

$$\frac{E_{Sc}}{E_{Kin}} = \frac{(\frac{dE}{dx})_s \ D_{Sc}}{(\frac{dE}{dx})_s \ D_{Sc} + (\frac{dE}{dx})_{Pb} \ D_{Pb}} \quad < \frac{E_{Sc}}{E_{Dep}}$$

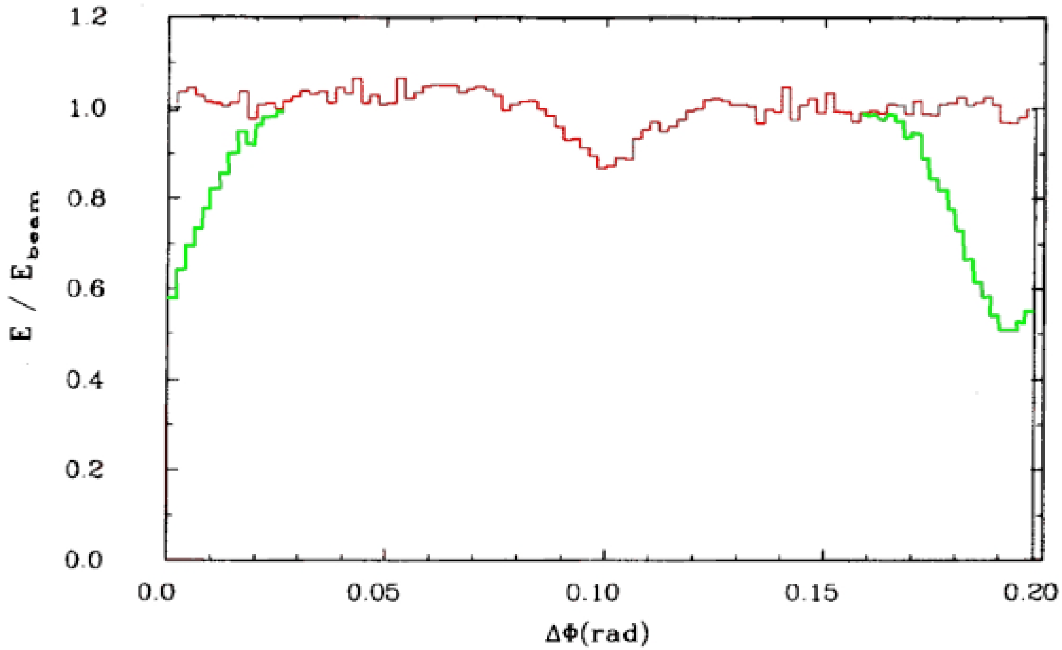
Since not all e^- produced in Pb pass also through scintillator

$$D_{Sc} \longrightarrow D_{Sc} \cdot F\,(E_{cut}, \varepsilon_c), \quad F < 1$$

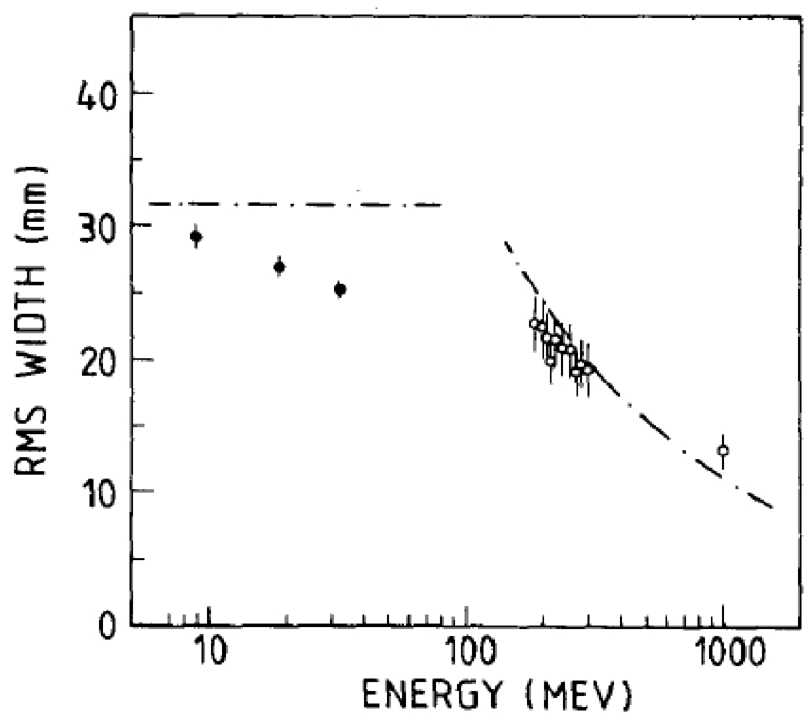


Sampling Calorimeters: Systems

Homogenity



Spatial resolution < 20 mm



Sampling Calorimeters: Systems

Other detectors: BEMC of H1

- H1 SpaCal Pb–scintillating fiber

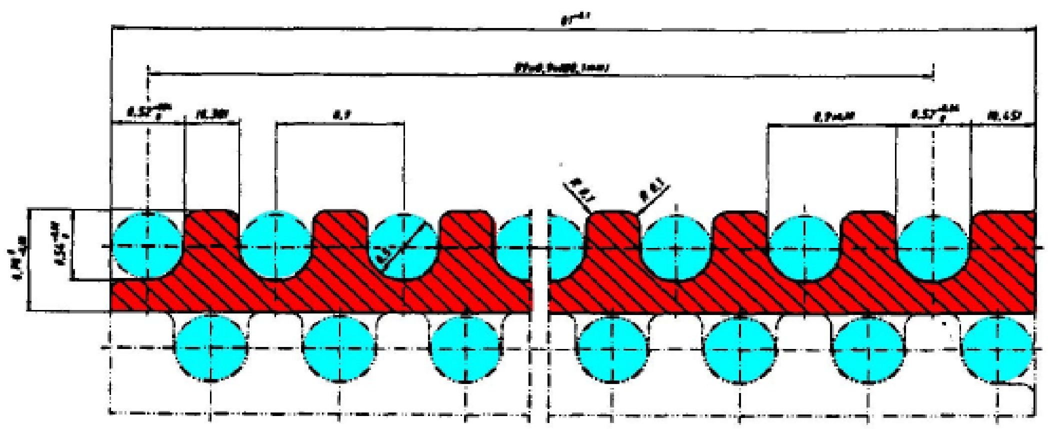
ρ [g/cm^3]	X_0[cm]	R_M[cm]	#photons/MeV	τ[ns]
7.89	0.91	2.5	20	< 1

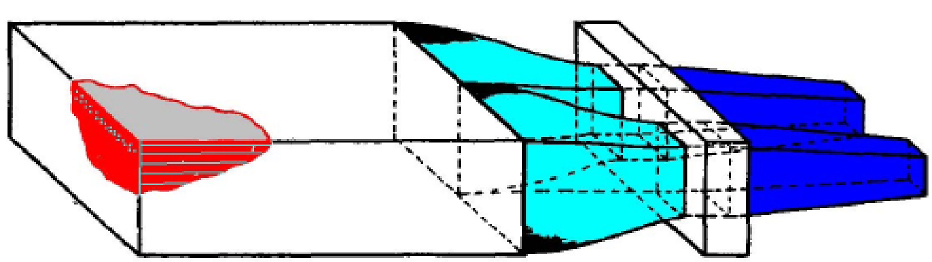
Physics program: $e^- p \to e^- X$

good e/π–separation
acceptance down to low Q^2
good time resolution
good energy and space resolution

System: 1192 modules

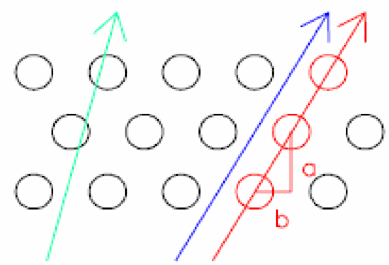
$L = 27.5 \;\; 0 ; \;\; d_T = 1.6 \; R_M$





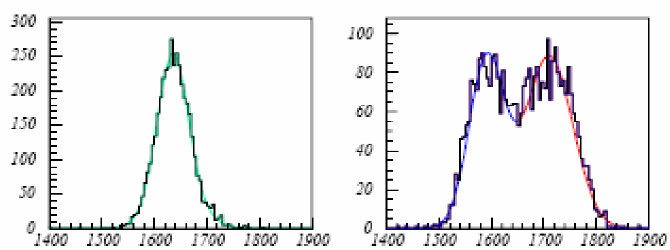
Sampling Calorimeters: Systems

Module orientation chosen to minimize channeling



$a/b = \sqrt{3} = \alpha/\beta \rightarrow \alpha=3^o, \beta=1.7^o$

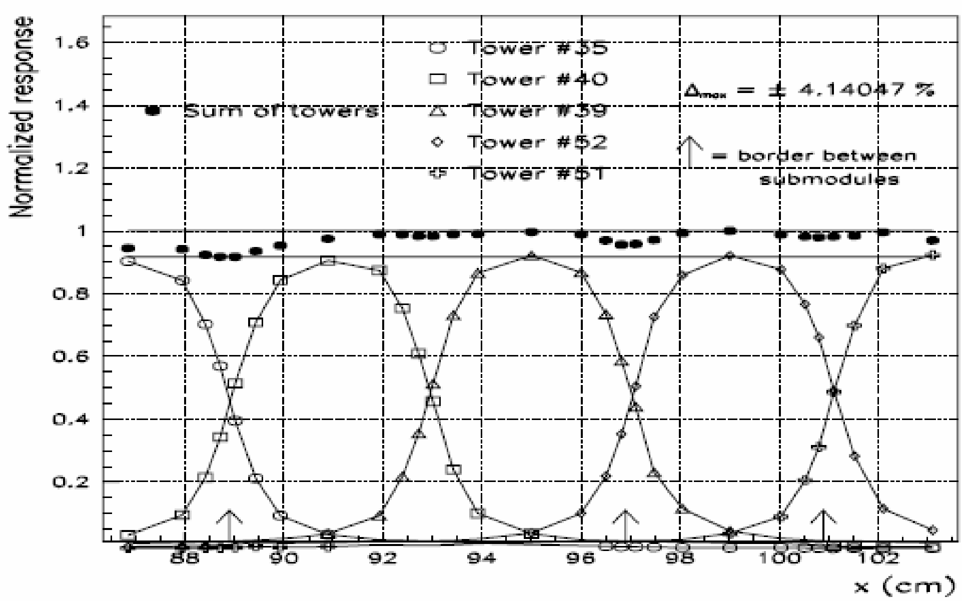
40 GeV, $\alpha = 3.0^\circ$



$\beta = 3.0^\circ$ $\beta = 1.9^\circ$

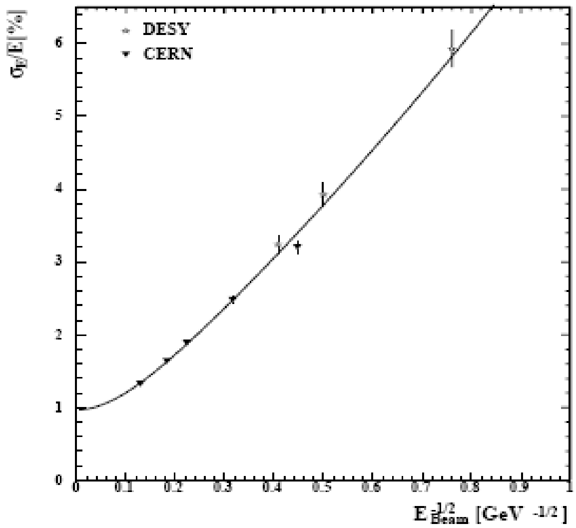
Performance:

Homogenity



Sampling Calorimeters: Systems

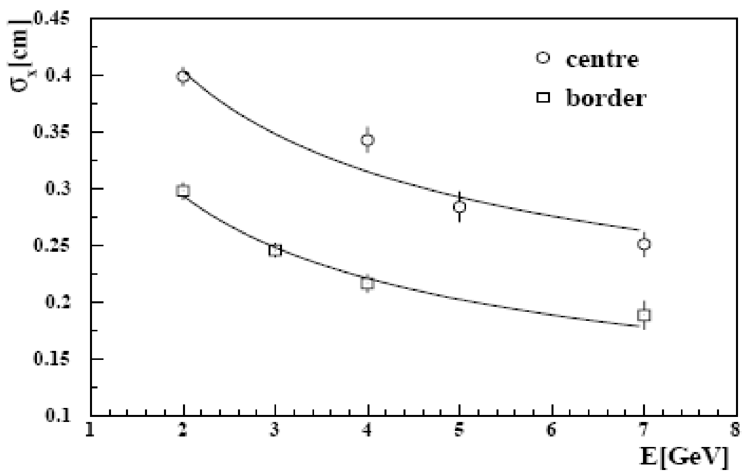
Energy resolution



$$\frac{\sigma}{E} = \frac{0.071\ GeV^{1/2}}{\sqrt{E}} \oplus 0.01$$

Energy dependence as expected from sampling fluctuations, 0.005 of constant term due to light–yield–fluctuations

Spatial resolution



$$\sigma = \frac{3.8\ mm\ GeV^{1/2}}{\sqrt{E}} + 0.3\ mm$$

Sampling Calorimeters: Systems

- ATLAS electromagnetic calorimeter

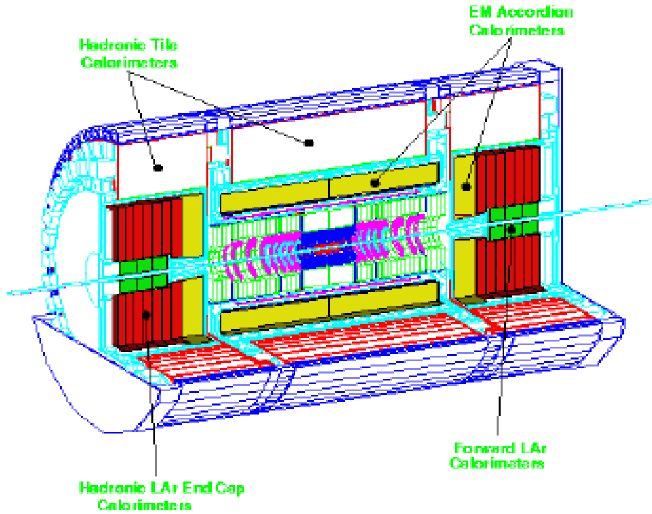
  $L\,Ar$ accordeon shaped sampling calorimeter

  Physics goal: $H \to \gamma\gamma$

  good energy and angular resolution

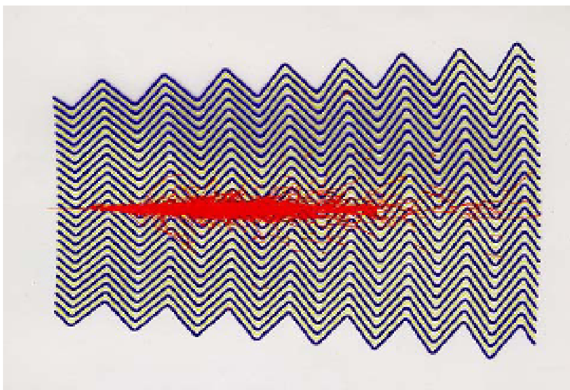
  radiation resistant

  barrel ECAL : 1 k Gy/year



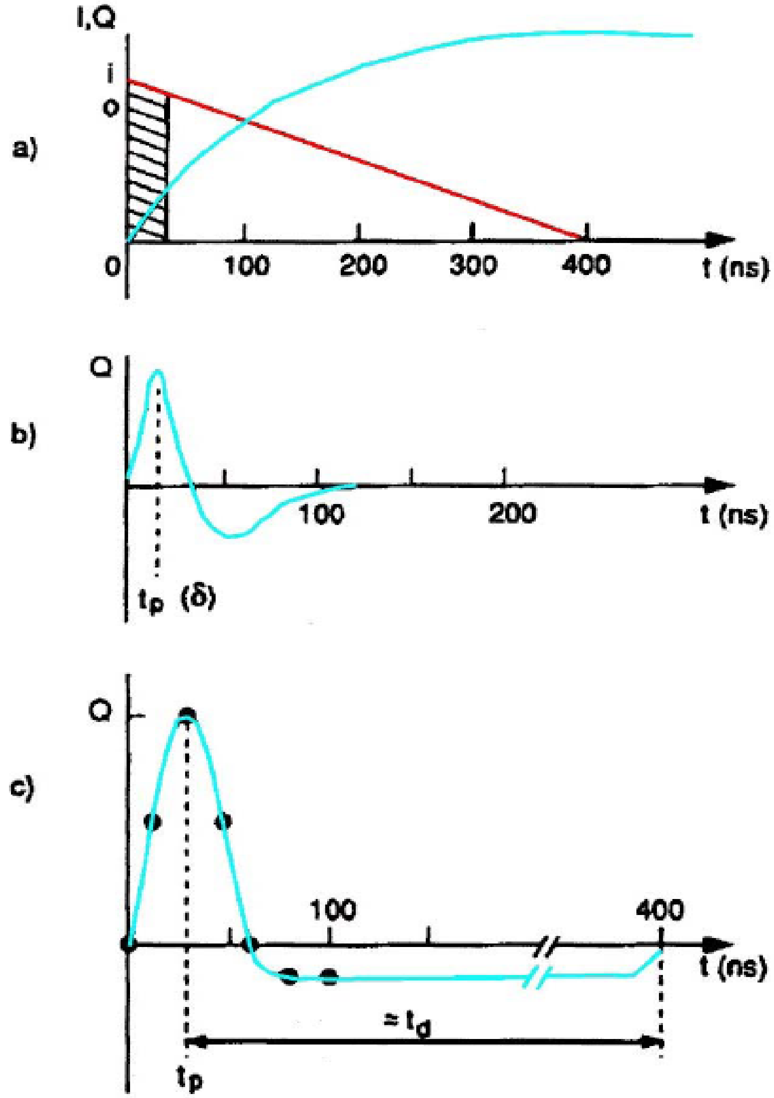
System (prototypes) :

Accordeon geometry



Sampling Calorimeters: Systems

Current measured (fast, insensitive to impurities)



Longitudinal segmentation : $9X_0,\ 9X_0,\ 7X_0$

Preshower $X,\ Y$ coordinate

$\Delta\,\phi = 0.020, \quad \Delta\,\eta = 0.018$

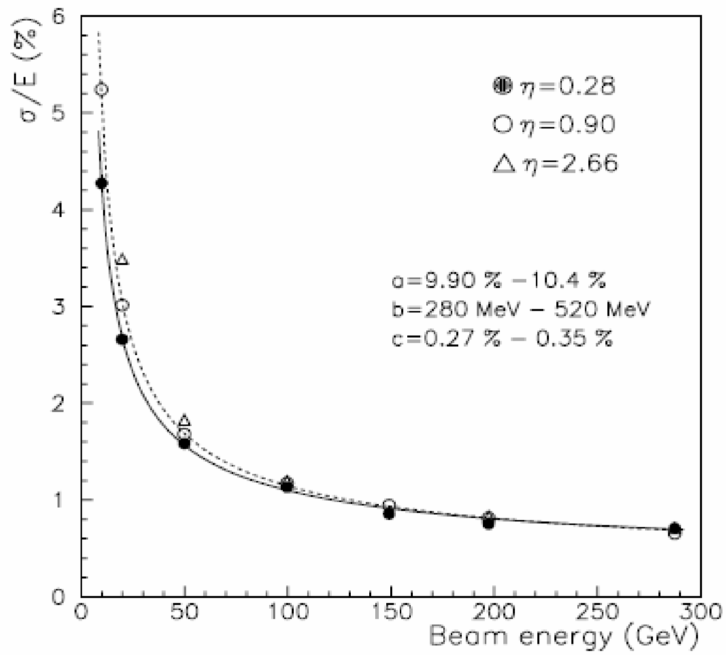
Performance:

Energy resolution

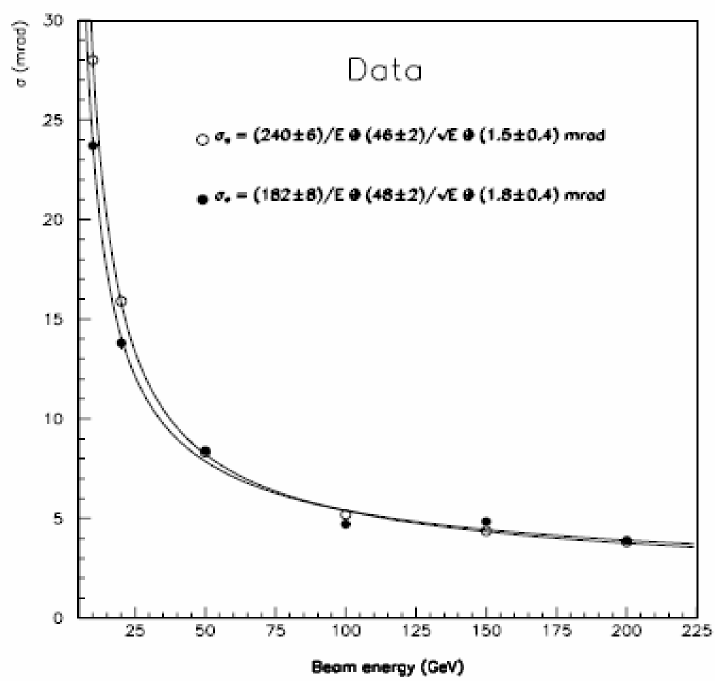
$$\frac{\sigma}{E} = \frac{0.10\ GeV^{1/2}}{\sqrt{E}} \oplus \frac{0.28\ GeV}{E} \oplus 0.0035$$

Sampling Calorimeters: Systems

Improvement with presampler



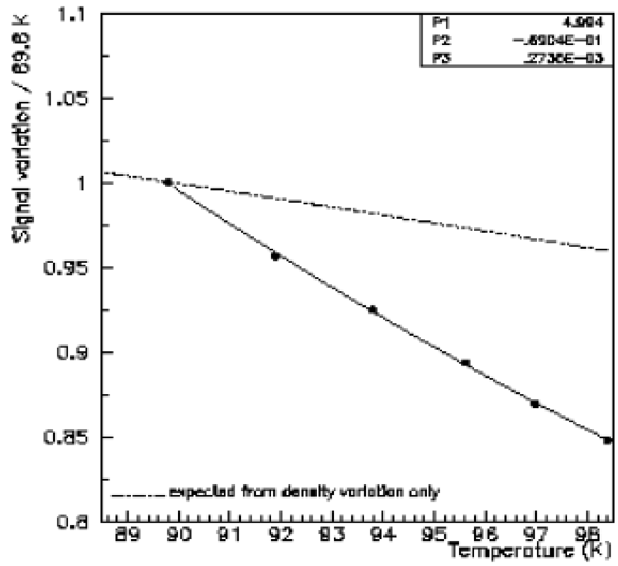
Spatial resolution



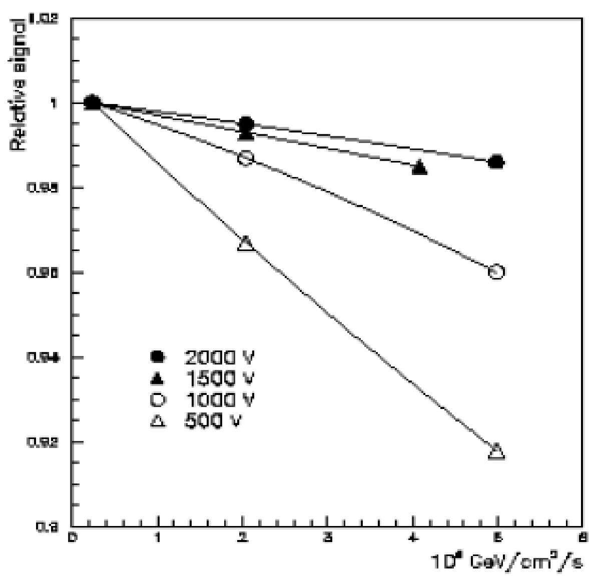
Influence of temperature (density, v_D)

Sampling Calorimeters: Systems

Temperature dependence (density and Onsager)



Flux dependence (density of ions)



Experiment :

$5 \cdot 10^5$ GeV/cm$^2/s$ at $\eta = 2.5$ expected

factor 5 higher $\eta = 3.2$

Electromagnetic Calorimeters: Overview

Comparison of electromagnetic calorimeters