Detectors in Nuclear and Particle Physics

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8.1 General considerations - calorimeter

energy vs. momentum measurement

resolution: calorimeter: $\frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}}$ tracking detectors: $\frac{\sigma_p}{p} \propto p$

e.g.: at $E \simeq p = 100$ GeV: $\frac{\sigma_E}{E} \simeq 3.5\%$ (ZEUS), $\frac{\sigma_p}{p} \simeq 6\%$ (ALEPH)

- at very high energies eventually have to switch to calorimeter because resolution improves with energy, while magnetic spectrometer resolution decreases
- depth of shower $L \propto \ln \frac{E}{E_0}$
- magnetic spectrometer (see chapter 6) $\frac{\sigma_p}{p} \propto \frac{p}{L^2} \rightarrow$ length would have to grow quadratically to keep resolution const. at high momenta
- calorimeter can cover full solid angle, for tracking in magnetic field anisotropy
- fast timing signal from calorimeter $\rightarrow$ trigger
- identification of hadronic vs. electromagnetic shower by segmentation in depth

8.2 Electromagnetic shower

reminder: electrons loose energy by excitation/ionization of atoms and by bremsstrahlung

for bremsstrahlung:

$$\frac{dE}{dx} = -\frac{E}{X_0} \qquad \text{with } X_0 \equiv \text{ radiation length}$$

$$E = E_0 \exp(-x/X_0)$$

for sufficiently high energies: since $(dE/dx)_{ion} \propto 1/\beta^2$ falls until $\beta\gamma \approx 3$ towards high energies and the logarithmic rise is weak

$$\frac{\left(\frac{dE}{dx}\right)_{brems}}{\left(\frac{dE}{dx}\right)_{ion}} \approx \frac{ZE}{580 \text{ MeV}}$$

critical energy E_c:

$$\left(\frac{dE}{dx}(E = E_c)\right)_{ion} = \left(\frac{dE}{dx}(E = E_c)\right)_{brems}$$

and for $E > E_c$ bremsstrahlung dominates

will see below that also transverse size is determined by radiation length via the Moliere Radius R_M:

$$R_M = \frac{21.2 \; MeV}{E_c} \cdot X_0$$

Examples

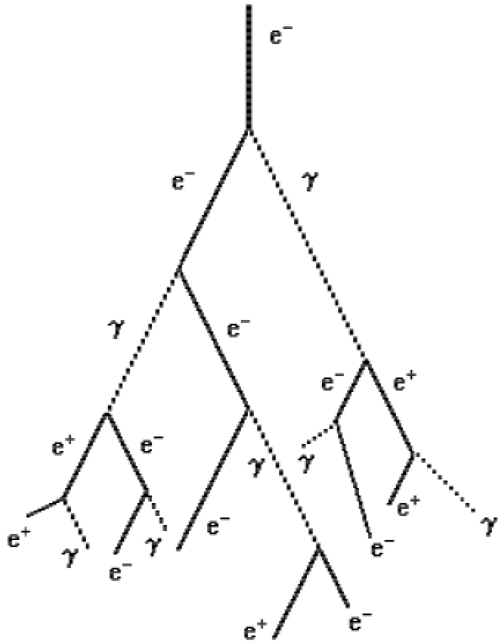
material	Z	X_0 [g cm^{-2}]	X_0 [cm]	E_c [MeV]	R_M [cm]
plastic scint.			34.7	80	9.1
Ar (liquid)	18	19.55	13.9	35	9.5
Fe	26	13.84	1.76	21	1.77
BGO		7.98	1.12	10	2.33
Pb	82	6.37	0.56	7.4	1.60
U	92	6.00	0.32	6.8	1.00
Pb glass (SF5)			2.4	11.8	4.3

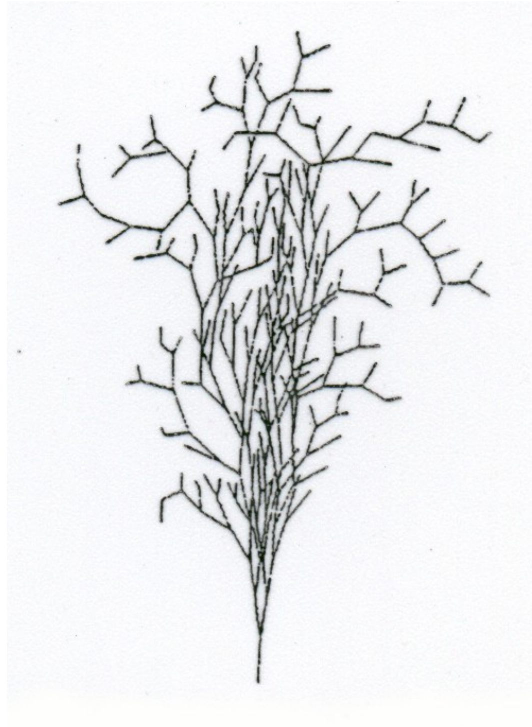
Analytic shower Model

a high energy electron enters matter

- electron looses energy by bremsstrahlung
- photon is absorbed by pair production

Monte-Carlo simulation of electromagnetic shower





$$\gamma + \text{ nucleus } \rightarrow e^+ + e^- + \text{ nucleus}$$
$$e + \text{ nucleus } \rightarrow e + \gamma + \text{ nucleus}$$

approximate model for electromagnetic shower

- over distance X_0 electron reduces via bremsstrahlung its energy to one half $E_1 = E_0/2$
- photon materializes as e^+e^- after X_0, energy of electron and positron $E_\pm \simeq E_0/2$ (precisely : $\mu_p = \frac{7}{9}X_0$ or pair creation probability in $X_0 \rightarrow P = 1 - \exp(-\frac{7}{9}) = 0.54$

assume:
– for $E > E_c$ no energy loss by ionization/excitation
– for $E < E_c$ electrons loose energy only via ionization/ excitation

- important quantities to characterize the em. shower

  number of particles in shower
  location of shower maximum
  longitudinal shower distribution
  transverse shower distribution (width)

introduce longitudinal variable $t = x/X_0$

number of shower particles after traversing depth t: $N(t) = 2^t$

each particle has energy $E(t) = \frac{E_0}{N(t)} = \frac{E_0}{2^t} \quad \rightarrow \quad t = \ln \frac{E_0}{E} / \ln 2$

total number of charged particles with energy E_1 $N(E_0, E_1) = 2^{t_1} = 2^{\ln(E_0/E_1)/\ln 2} \simeq E_0/E_1$

number of particles at shower maximum $N_{max}(E_0, E_c) \simeq E_0/E_c \propto E_0$

shower maximum located at $t_{max} \propto \ln \frac{E_0}{E_c}$

– numerical values: $t_{max} \simeq 3.5$ and $N_{max} \simeq 45$ for $E_0 = 1$ GeV

integrated track length of all charged particles in shower

$$T = X_0 \sum_{\mu=0}^{t_{max}-1} 2^{\mu} + t_0 X_0 N_{max}$$

with range t_0 of electron with energy E_c in units of X_0

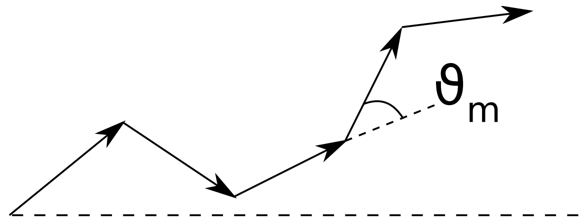
$$= (1 + t_0) \frac{E_0}{E_c} X_0 \propto E_0$$

proportional to E_0!

this was for all particles, for practical purposes for charged particles: $T = \frac{E_0}{E_c} X_0 F$ with $F < 1$

Transverse shower development

- emission of Bremsstrahlung under angle $\langle\theta^2\rangle \simeq \frac{m}{E} = \frac{1}{\gamma^2}$ small
- multiple scattering (3d) of electron in Moliere theory
$$\langle\theta^2\rangle = \left(\frac{21.2 MeV}{\beta\ pc}\right)^2 t$$



multiple scattering dominates transverse shower development
main contrib. from low energy electrons, assuming approximate range of electrons to be X_0

Moliere radius $\quad R_M = \sqrt{\langle\theta^2\rangle_{x=X_0}}X_0 \approx \frac{21\text{ MeV}}{E_c}X_0$

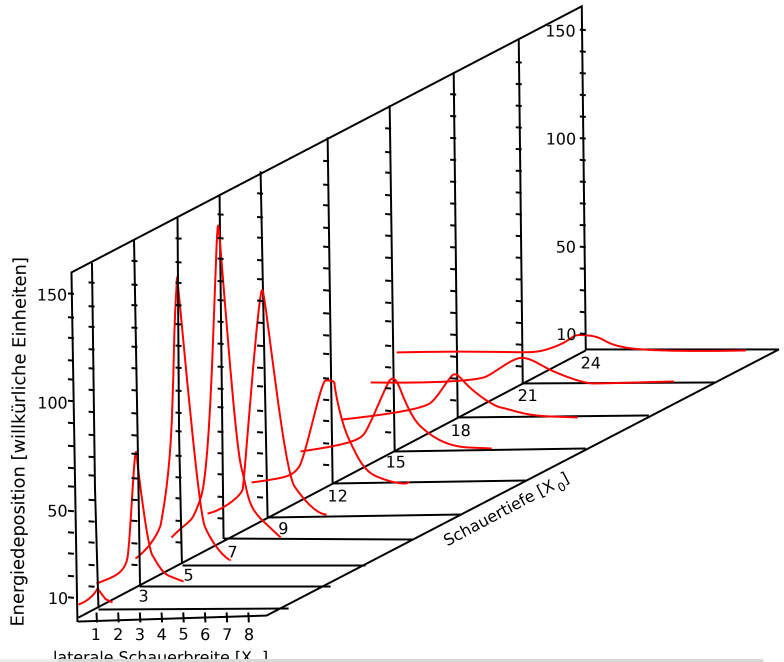
remember useful relations:

$$X_0 = \frac{180A}{Z^2}\ (\mathrm{g\ cm^{-2}})$$
$$E_c = \frac{580\ \mathrm{MeV}}{Z}$$
$$t_{max} = \ln\frac{E}{E_c} - \begin{cases} 1 & e \text{ induced shower} \\ 0.5 & \gamma \text{ induced shower} \end{cases}$$

95% of energy within

$$L(95\%) = t_{max} + 0.08\ Z + 9.6\ X_0$$
$$R(95\%) = 2\ R_M$$

a 6 GeV electron in lead

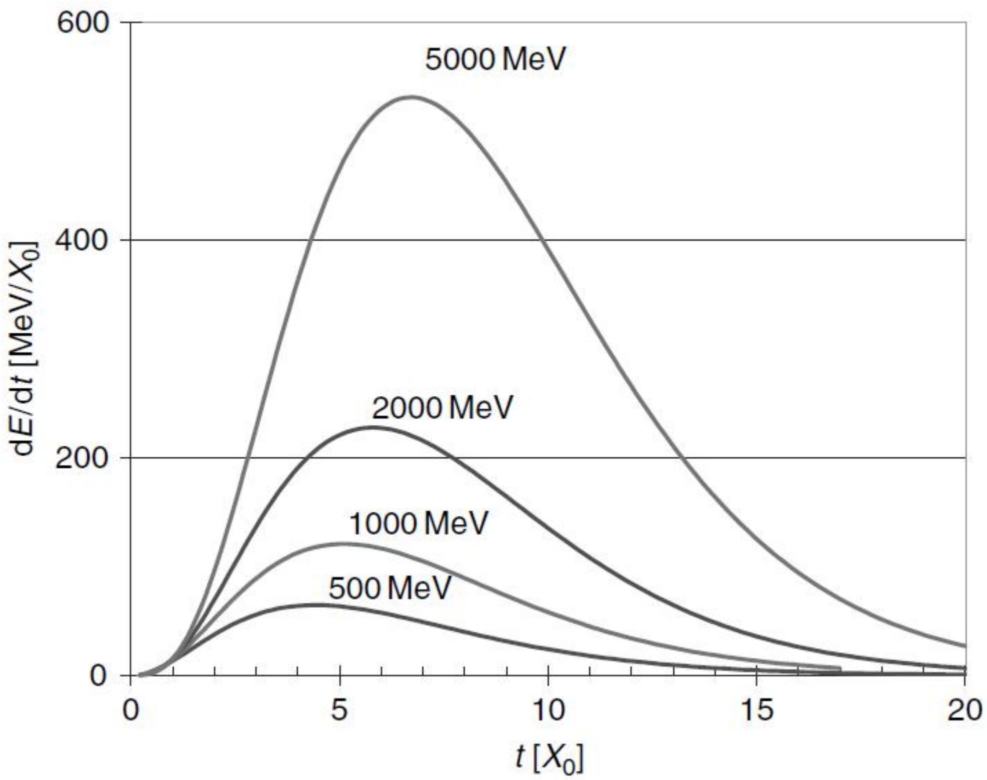


Longitudinal shower profile

parametrization (Longo 1975)

$$\frac{dE}{dt} = E_0 t^{\alpha} exp(-\beta t)$$

first secodaries increase
then absorption dominates

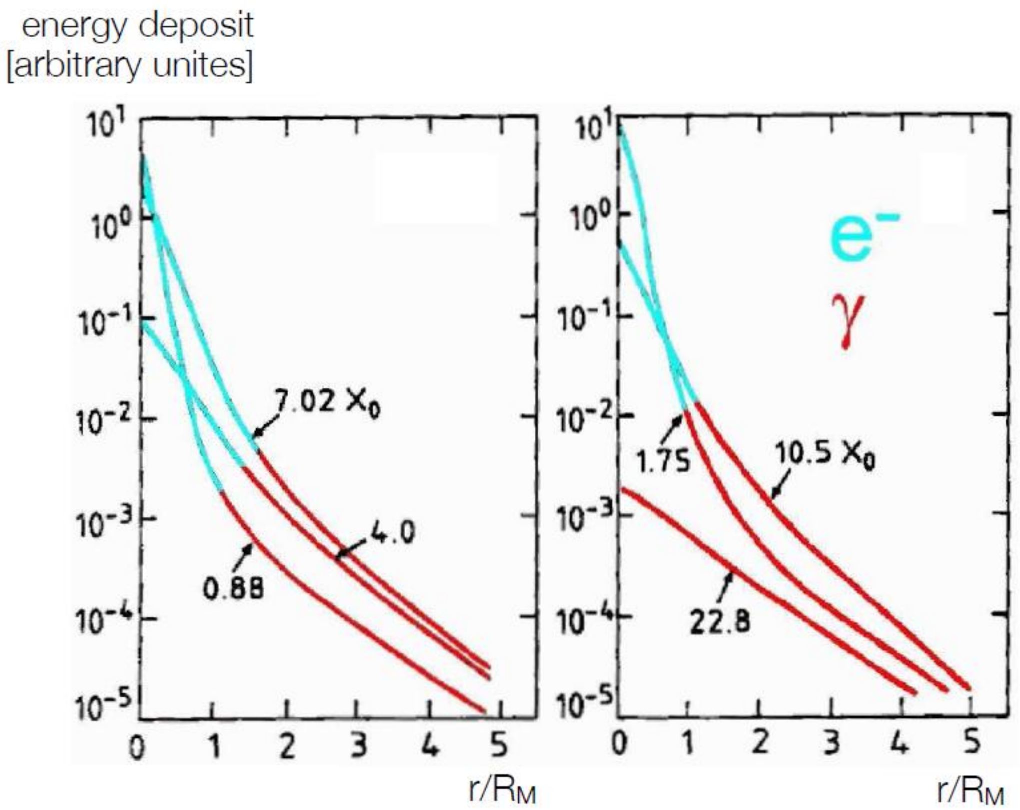


Transverse shower profile

parametrization as

$$\frac{dE}{dr} = E_0[\alpha exp(-r/R_M) + \beta exp(-r/\lambda_{min})]$$

with free parameters α, β
λ_{min} range of low energy photons
central part: multiple Coulomb scattering
tail: low energy photons (and electrons) produced in Compton scattering and photo effect



8.3 Electromagnetic calorimeter

(i) homogeneous shower detector

absorbing material ≡ detection material
scintillating crystals (see chapter 5)

	NaI(TI)	BGO	CsI(TI)	$PbWO_4$
density (g/cm^3)	3.67	7.13	4.53	8.28
X_0 (cm)	2.59	1.12	1.85	0.89
R_M (cm)	4.5	2.4	3.8	2.2
dE/dx_{mip} (MeV/cm)	4.8	9.2	5.6	13.0
light yield (photons/MeV)	$4 \cdot 10^4$	$8 \cdot 10^3$	$5 \cdot 10^4$	$3 \cdot 10^2$
energy resolution σ_E/E	$1\%/\sqrt{E}$	$1\%/\sqrt{E}$	$1.3\%/\sqrt{E}$	$2.5\%/\sqrt{E}$

Energy resolution of homogeneous calorimeters

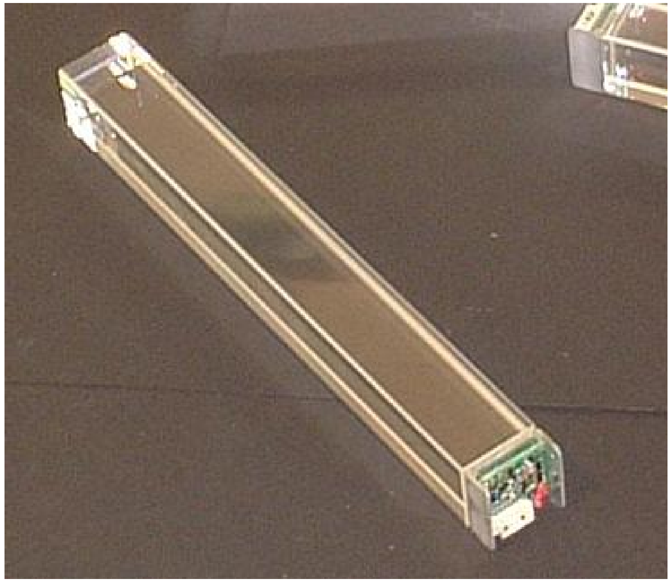
contributons to the energy resolution σ_E/E:

shower fluctuations (intrinsic)	$\propto \frac{1}{\sqrt{E}}$
photon/electron statistics in photon detector	$\propto \frac{1}{\sqrt{E}}$
electronic noise (noise)	$\propto \frac{1}{E}$
leakage, calibration	$\simeq const$

total energy resolution of electromagnetic calorimeter

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus X$$

PHOton Spectrometer (PHOS) in ALICE

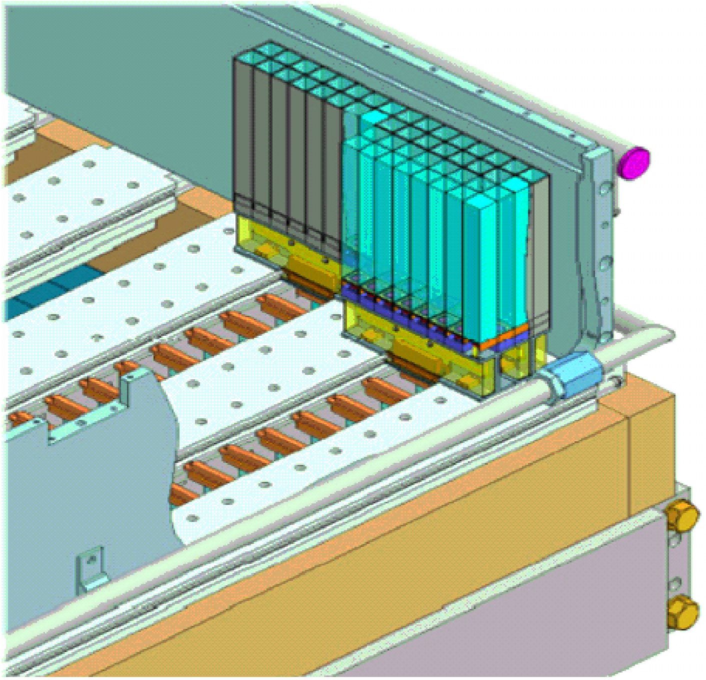


array of $22 \times 22 \times 180$ cm^3 $PbWO_4$ crystals, depth 20 X_0
in total about 18 000 (same type as CMS)

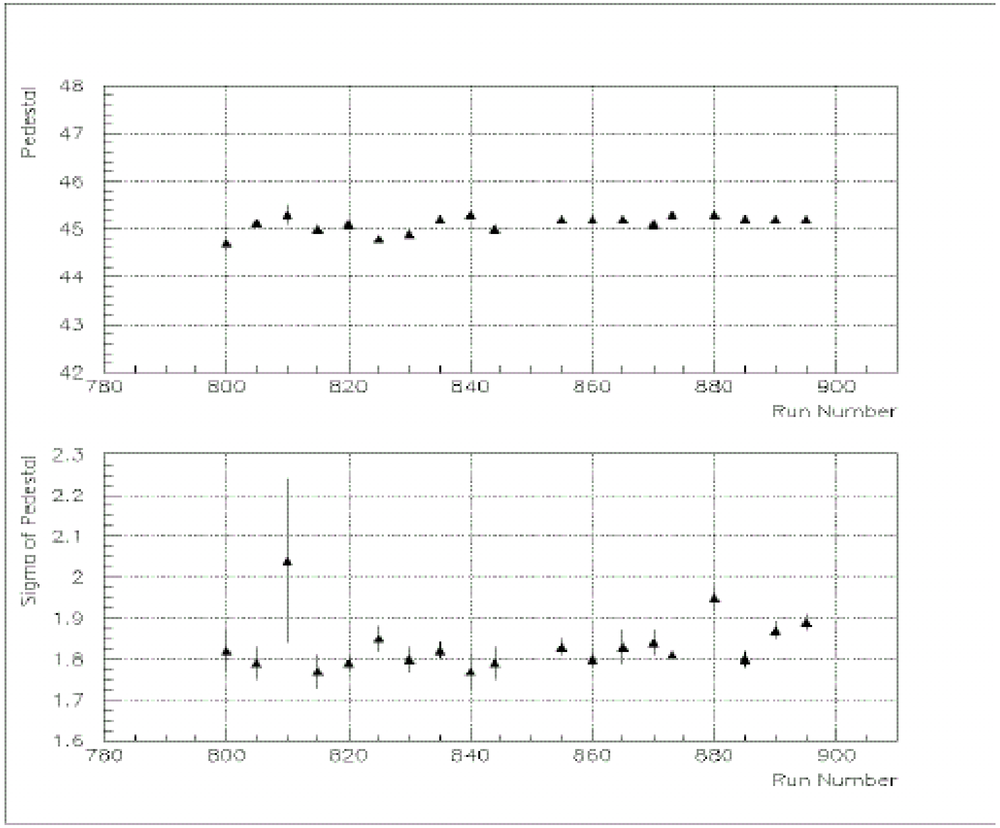
characteristics: dense, fast, relatively radiation hard

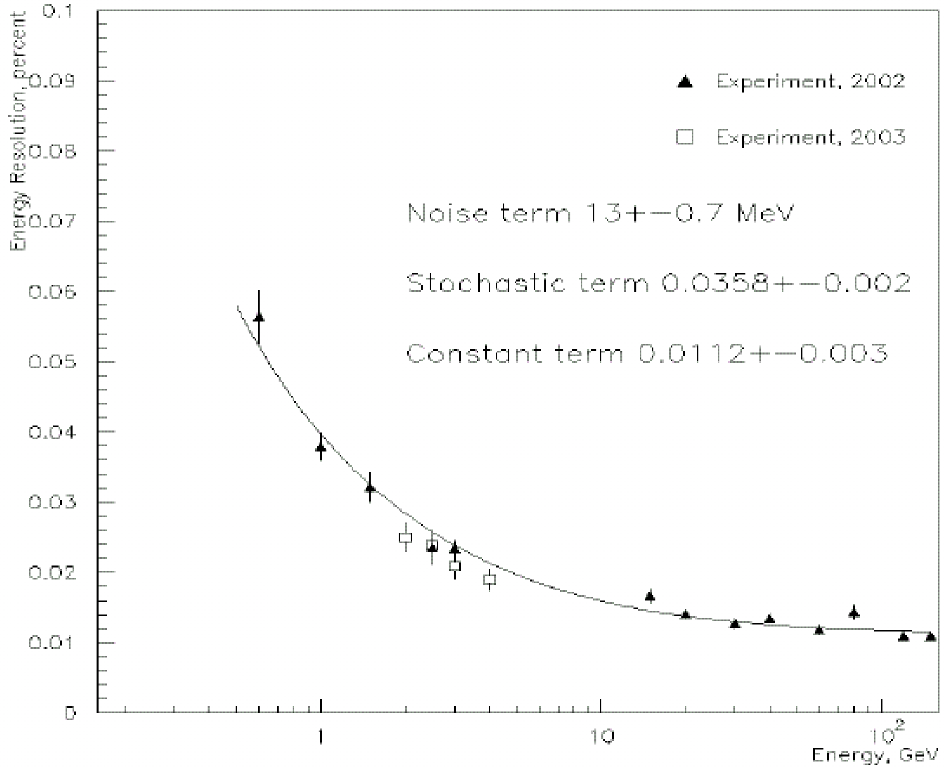
emission spectrum 420 – 550 nm
read out with 5×5 mm^2 avalanche photodiodes, $Q = 85\%$
charge-sensitive preamplifier directly mounted on APD

light yield of $PbWO_4$ relatively low and strongly temperature dependent → operate detector at -25° C
(triple light yield vs 20° C)
but need to stabilize to 0.3° C
(monitor with resistive temperature sensors)
crystals cold, electronics warm
(liquid coolant, hydrofluorether)



12.5 t of crystals covering 8 m^2 at 4 m from intersection point
in front: charged-particle veto (MWPC with cathode pad read-out)
test beams of pions and electrons at CERN PS and SPS: 0.6 – 150 GeV

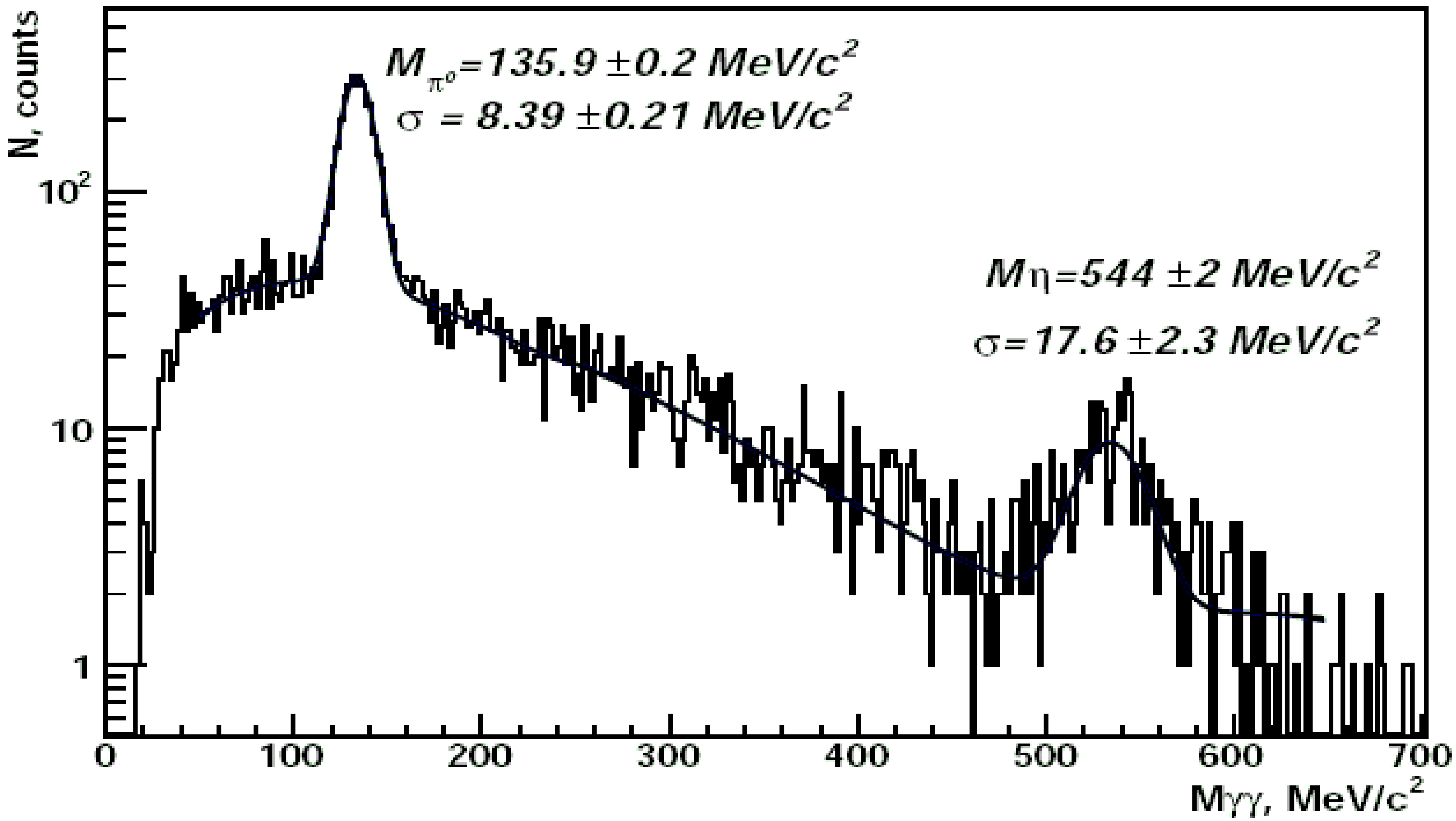




electronic noise:
1 ch = 400 e $\rightarrow$ noise about 700 e

$$\frac{\sigma_E}{E} = \frac{3.6\%}{\sqrt{E}} \oplus \frac{1.3\%}{E} \oplus 1.1\%$$

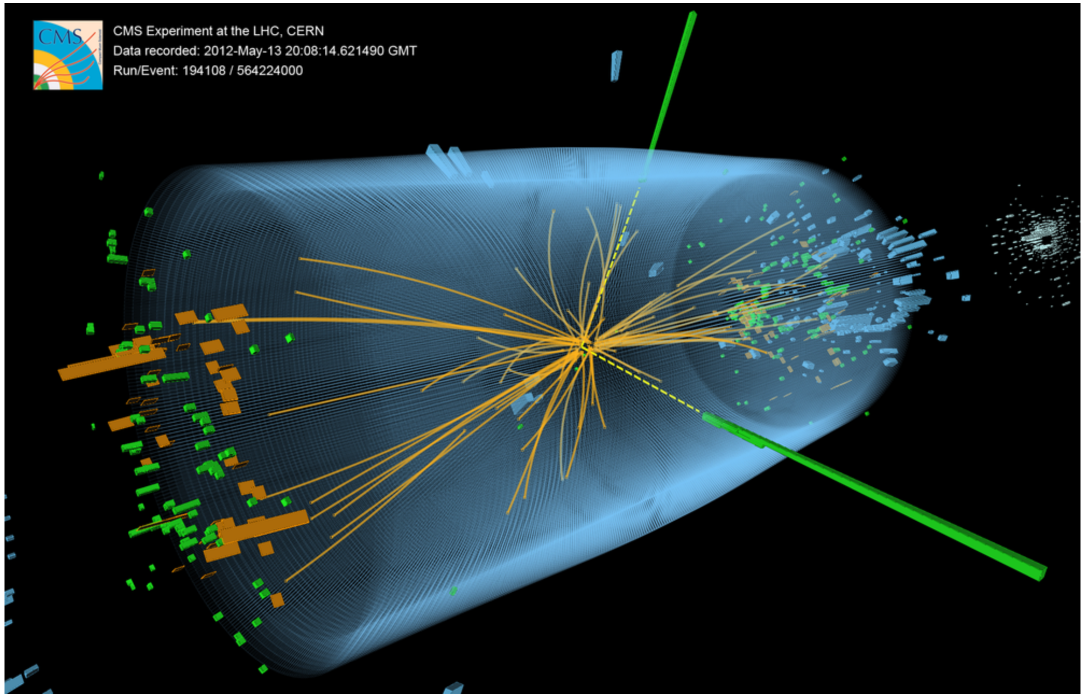
why does resolution matter so much?
peaks sit on combinatorial background, S/N strongly depends on resolution

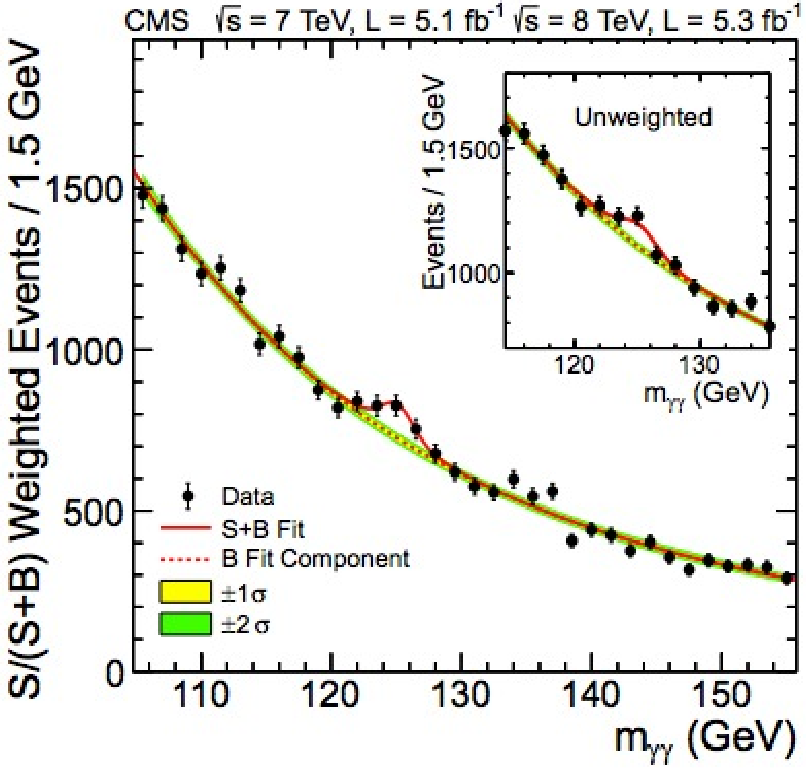


invariant-mass spectrum from the inclusive reaction 6 GeV/c $\pi^- + {}^{12}\mathrm{C} \rightarrow \pi^0 + X$, measured at a distance of 122 cm. The solid line is a fit of Gaussians plus 3^{rd} order polynomials.

Higgs – CMS crystal calorimeter ($PbWO_4$)

decay H $\to \gamma\gamma$ for CMS the most important discovery channel





Alternative: instead of scintillating material use Cherenkov radiator

electrons and positrons of electromagnetic shower emit Cherenkov light

number of photons N_{ph} proportional to total path length T of electrons and positrons (see Ch. 2)

$$N_{ph} \propto T \propto E_0$$

remember: energy loss by Cherenkov radiation very small

$\rightarrow$ resolution limited by photoelectron statistics

typical: about 1000 photo electrons per GeV shower energy

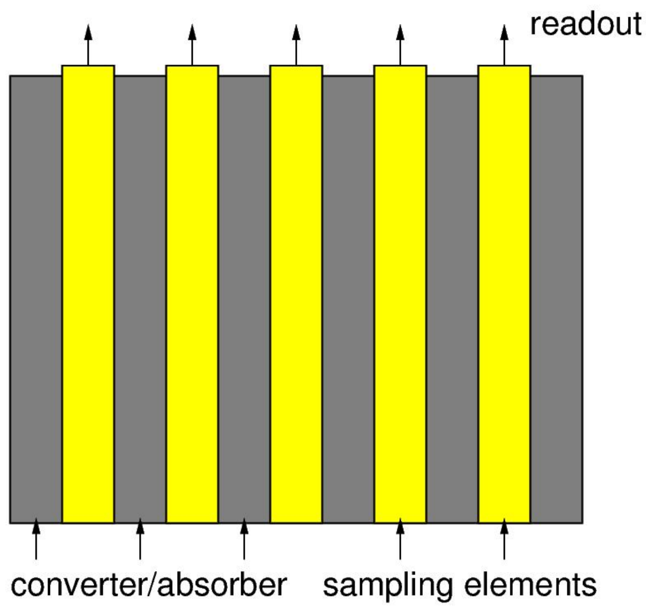
mostly used: lead glass, e.g. SF5: $n = 1.67$ $\beta_{thr} = 0.6$ or $E_{thr} = 0.62$ MeV for electrons

blocks of typical size $14 \times 14 \times 42$ cm
$\rightarrow$ diameter: 3.3 R_M and depth: 17.5 X_0

read out with photomultipliers

typical performance: $\sigma_E/E = 0.01 + 0.05\sqrt{E(\text{GeV})}$

(ii) Sampling calorimeter



signal generated in material different from material where (main) energy loss occurs

shower (energy loss) is only ‘sampled’

converter medium: Pb, W, U, Fe $\leftarrow$ energy loss

detection medium: scintillator, liquid Ar $\leftarrow$ sampling of shower

often sandwich of absorber and detection medium

longitudinal shower development $t_{max} = t_{max}^{abs} \dfrac{x+y}{x}$

transverse shower development $R(95\%) = 2R_M \dfrac{x+y}{x}$

$x = \sum x_i$ absorber

$y = \sum y_i$ detection element

energy loss in absorber and detection medium varies event-by-event

‘sampling fluctuations’ $\rightarrow$ additional contribution to energy resolution

Sampling fluctuations

energy deposition dominated by electrons at small energies
range of 1 MeV electron in U: $R \simeq 0.4$ mm
for thickness d of absorber layers ≥ 0.4 mm: only fraction f of these electrons reaches detection medium

$$f(e, \mathrm{conv} \to \mathrm{det}) \propto \frac{1}{d} \propto \frac{1}{t_{conv}}$$

fraction of electrons generated in detection medium $f(e, \mathrm{det}) \propto \frac{t_{det}}{t_{conv}}$

number of charged particles in shower: $N \simeq E_0/E_c$

fluctuations

$$\frac{\sigma_E}{E} \propto \frac{1}{\sqrt{N}} \propto \sqrt{\frac{E_c}{E}} \sqrt{\alpha t_{conv} + (1-\alpha)\frac{t_{conv}}{t_{det}}}$$

Fe: $(1-\alpha) \gg \alpha$ $\qquad \frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}} \sqrt{\frac{t_{conv}}{t_{det}}}$

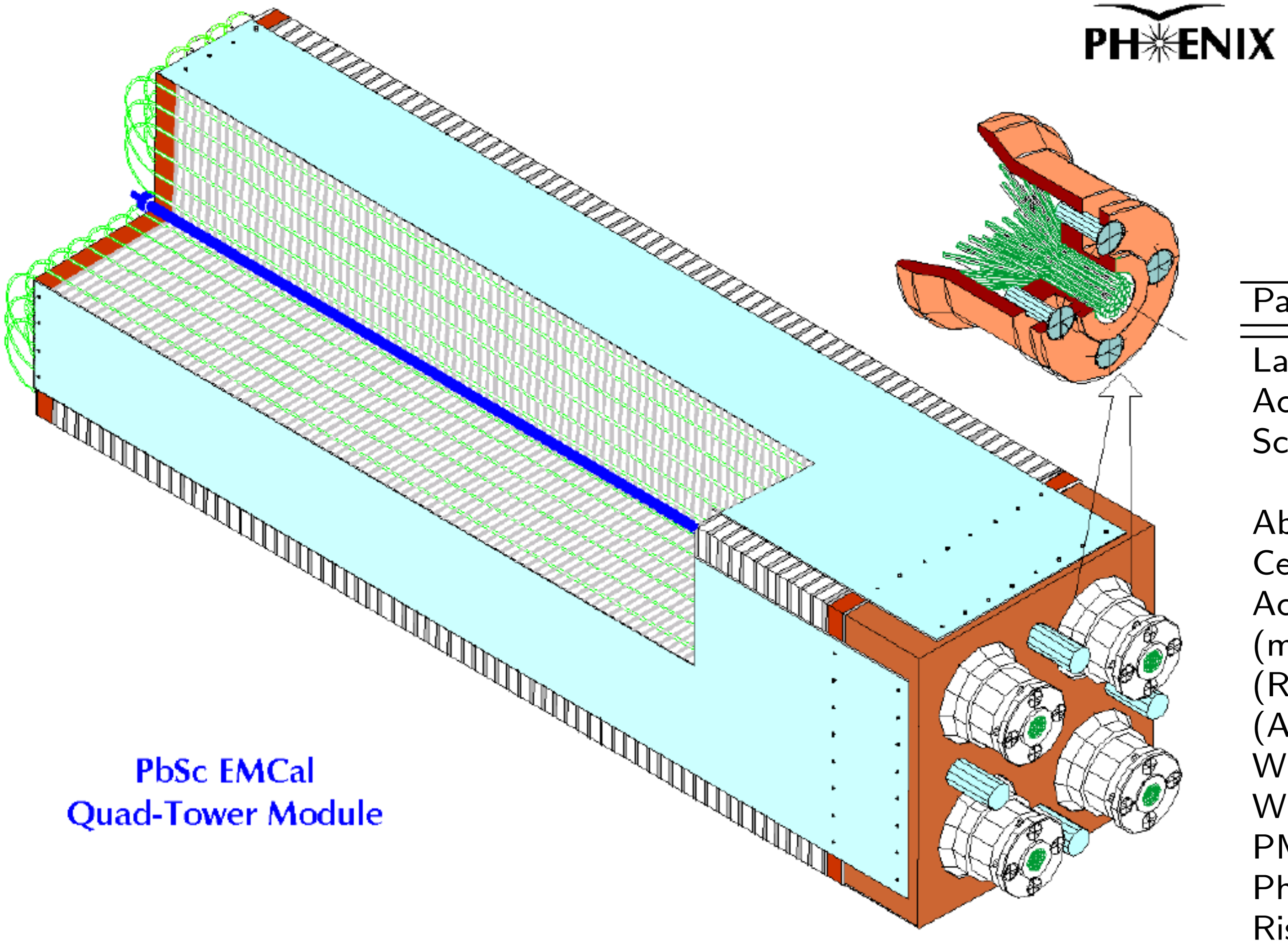
Pb: $(1-\alpha) \ll \alpha$ $\qquad \frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}} \sqrt{t_{conv}}$

common parametrization: $\frac{\sigma_E}{E} = 3.2\% \sqrt{\frac{E_c(MeV)}{F}} \sqrt{\frac{t_{conv}}{E(GeV)}}$

good energy resolution for

- E_c small (Z large)
- t_{conv} small ($x < X_0$, fine sampling)

example of modern electromagnetic sampling calorimeter: PHENIX PbScint Calorimeter
alternating layers of Pb sheets and plastic scintillator sheets connected to PMT via scintillating fibres



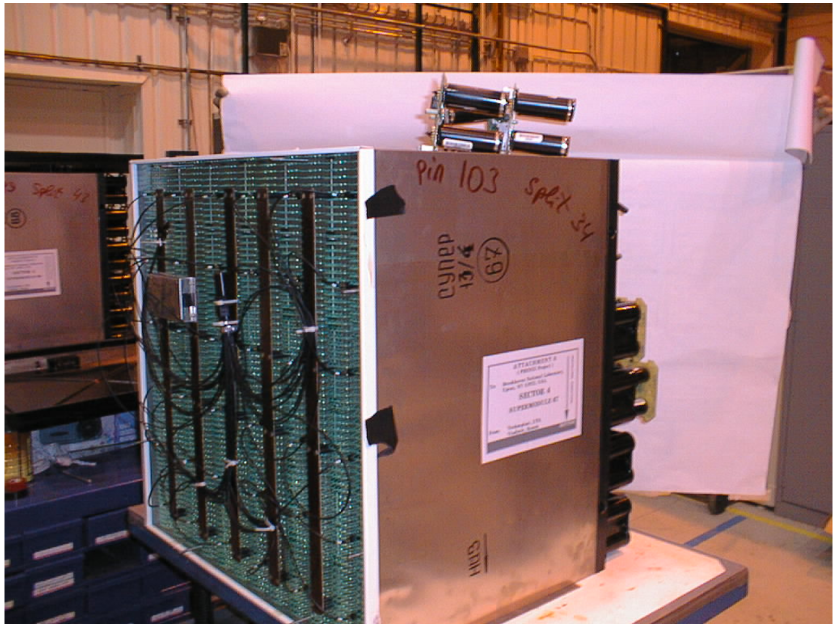
individual towers 5×5 cm^2

38 cm depth ($18 X_0$)
66 sampling cells

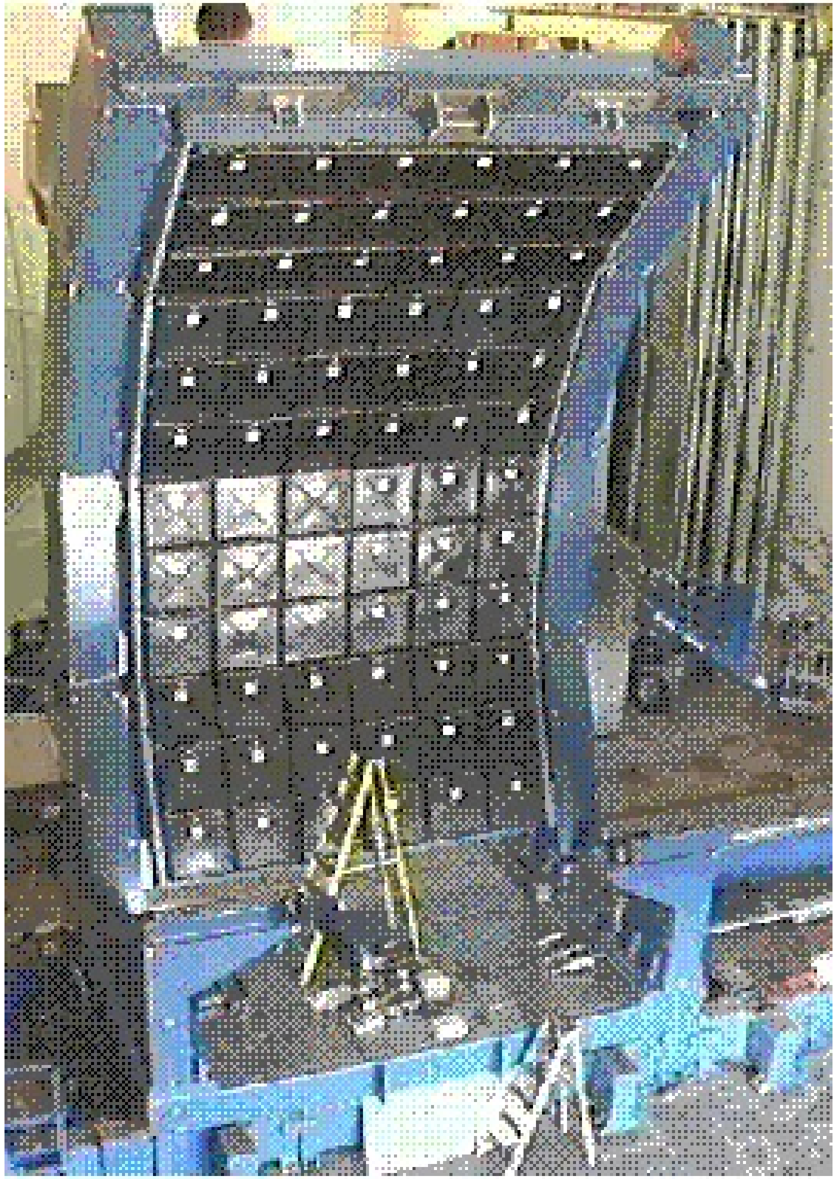
in total covering 48 m^2
in 15552 individual towers

Parameter	Value
Lateral segmentation	5.535 x 5.535 cm^2
Active cells	66
Scintillator	4 mm Polystyrene (1.5% PT/0.01% POPOP)
Absorber	1.5 mm Pb
Cell thickness	5.6 mm (0.277 X_0)
Active depth	
(mm)	375 mm
(Rad. length)	18
(Abs. length)	0.85
WLS Fiber	1mm, BCF-99-29a
WLS fibers per tower	36
PMT type	FEU115 M, 30 mm
Photocathode	Sb-K-Na-Cs
Rise time (25% - 80%)	$\leq$ 5 ns

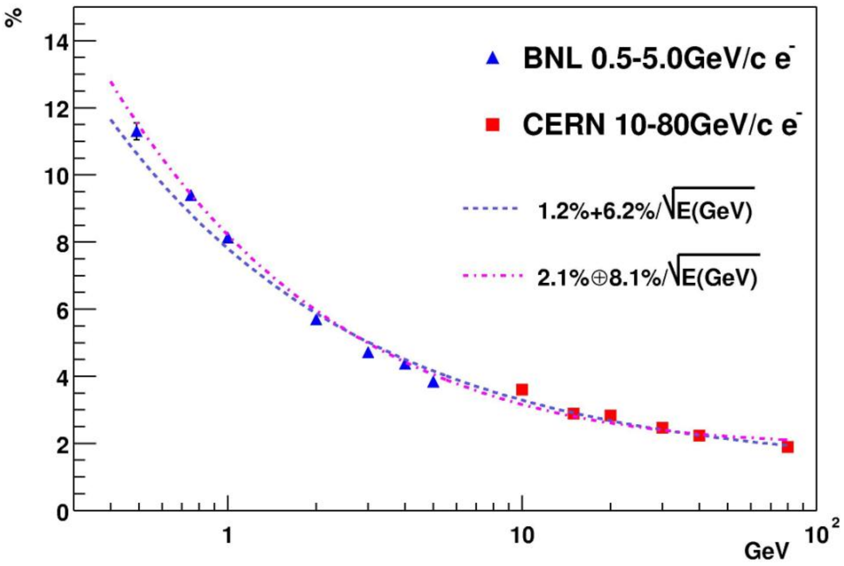
one module of PHENIX EMCal



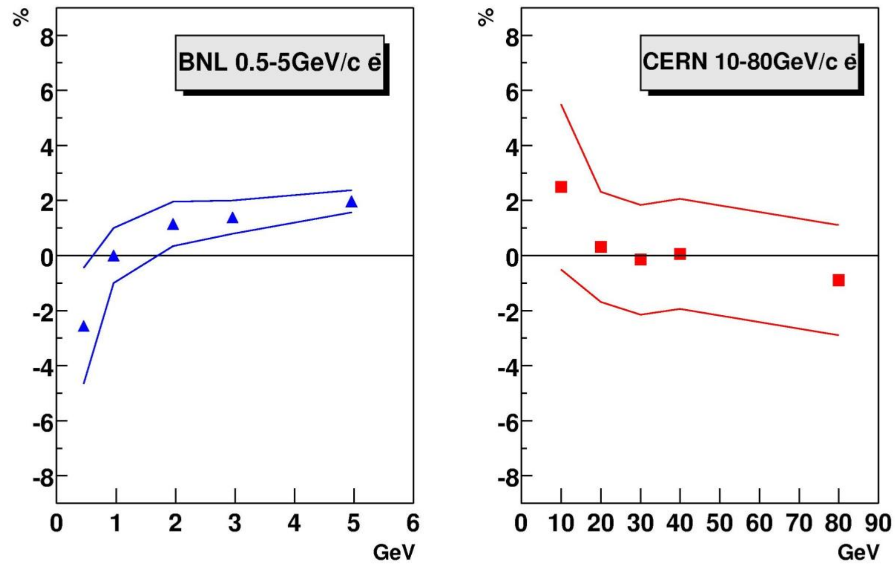
and entire WestArm



nominal energy resolution: stochastic term $8\%/\sqrt{E}$ and constant term: 2%
time resolution: 200 ps

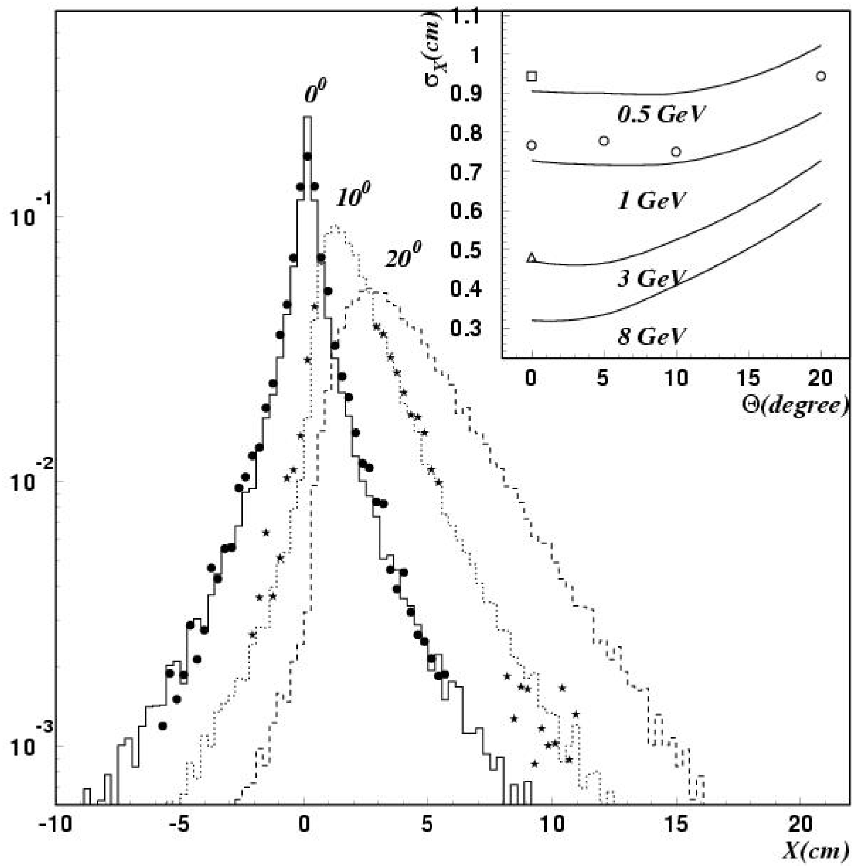


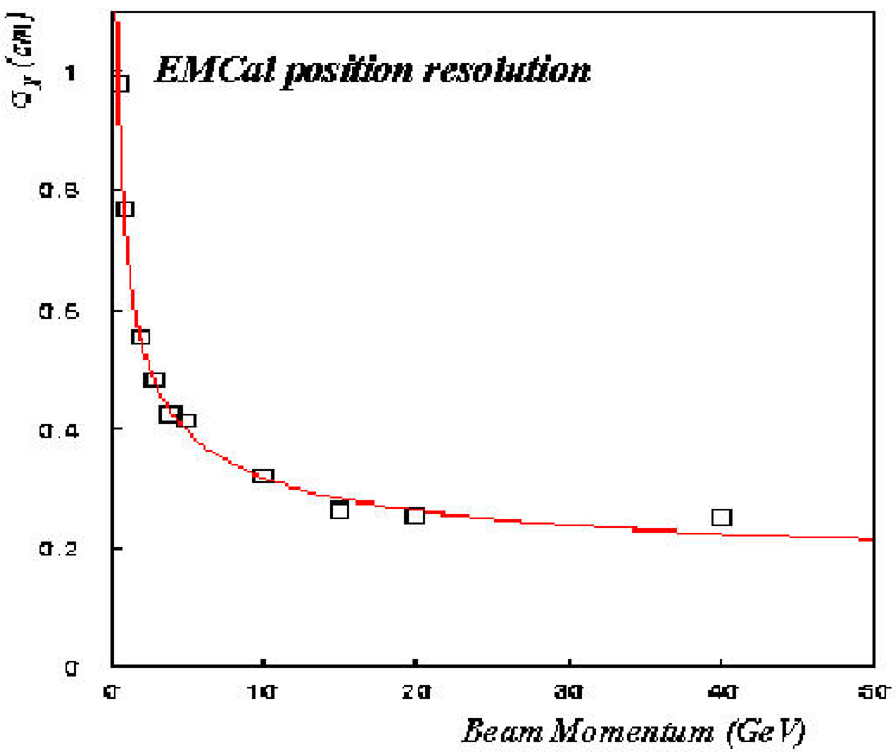
energy resolution



linearity of energy scale

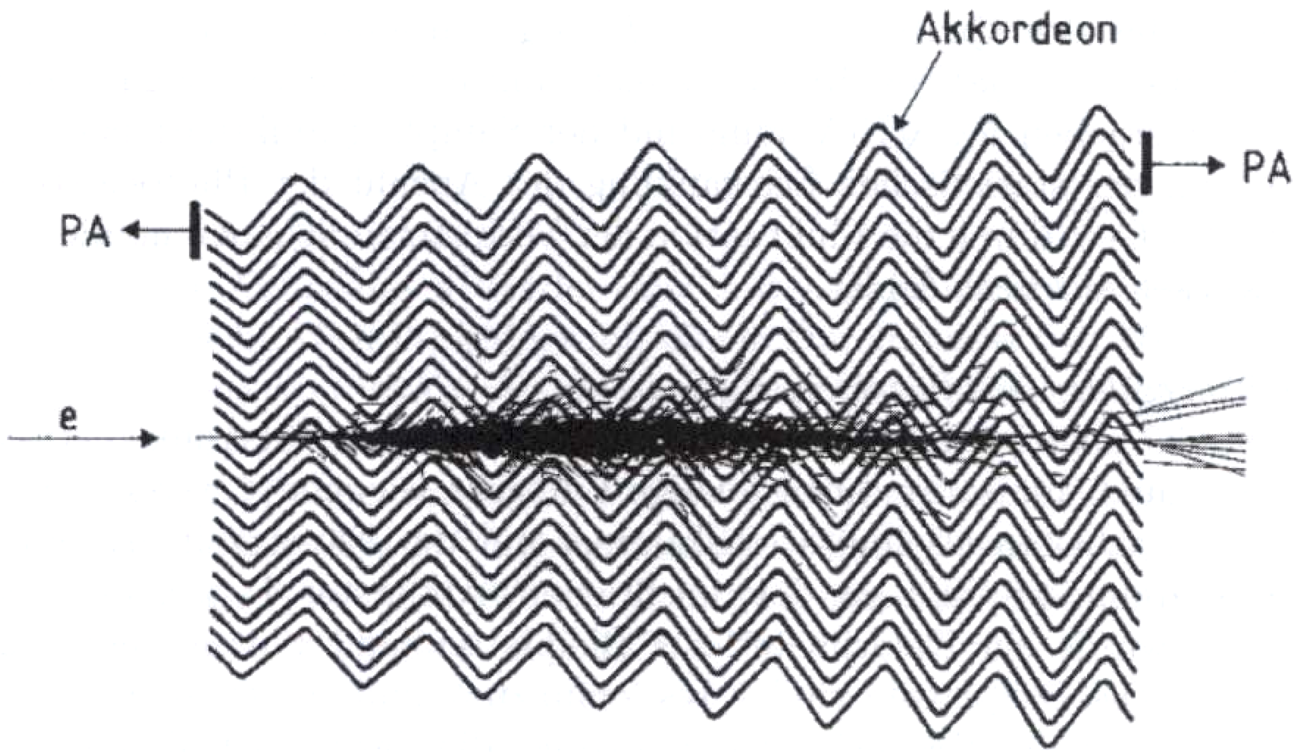
lateral shower profile well understood → position resolution in mm range





Liquid-Argon Sampling Calorimeter

instead of scintillator and optical readout: use of liquid noble gas and operation of sampling sections as ionization chamber



for faster readout: interleave electrodes between metal plates and electronics directly on electrodes inside liquid

example: electromagnetic calorimeter of ATLAS