8. Electromagnetic Calorimeter

8.1 General considerations – calorimeter

energy- vs momentum measurement

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

e.g. at $E \simeq p = 100$ GeV

$\sigma_E/E \simeq 3.5\%$ (ZEUS) $\sigma_p/p \simeq 6\%$ (Aleph)

- at very high energies enventually have to switch to calorimeter because resolution improves with energy while magnetic sprectrometer res. decreases

- depth of shower $L \propto \ln E/E_0$

- magnetic spectrometer $\sigma_p/p \propto p/L^2$ -> 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 → trigger

- identification of hadronic vs. electromagnetic shower by segmentation in depth

8.2 Electromagnetic shower

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

for bremsstrahlung $\frac{dE}{dx} = -\frac{E}{X_0}$ with $X_0 \equiv$ radiation length

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

for sufficiently high energies:

since $(dE/dx)_{ion} \propto 1/\beta^2 \simeq 1$ at high energies and logarithmic rise is weak

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

critical energy E_C: $(\frac{dE}{dx}(E = E_c))_{ion} = (\frac{dE}{dx}(E = E_c))_{brems}$

and for $E > E_C$ bremsstrahlung dominates

:

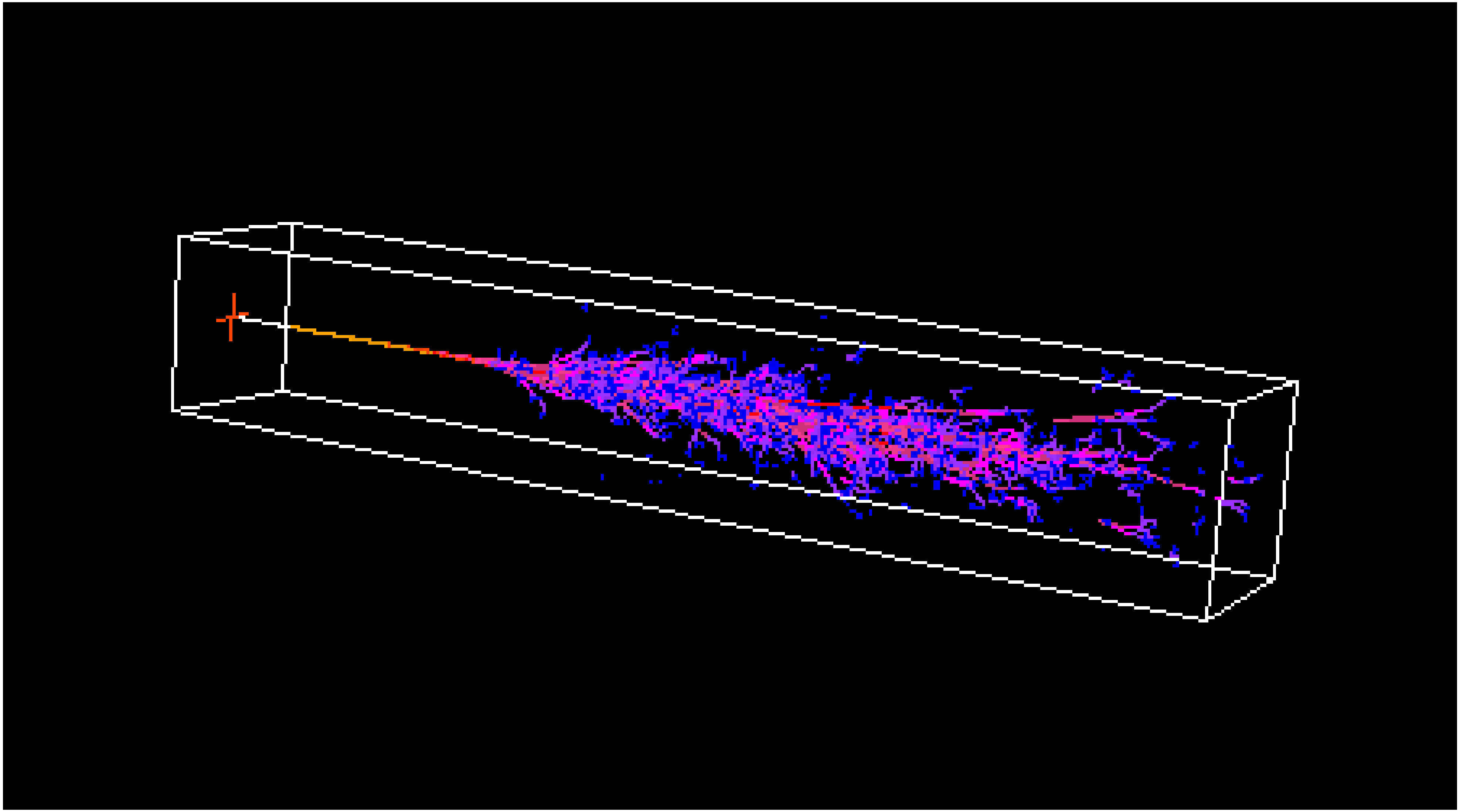
will see below that also transverse size is determined by radiation length via the Moliere radius

$$R_M = \frac{21 MeV}{E_c} X_0$$

examples:

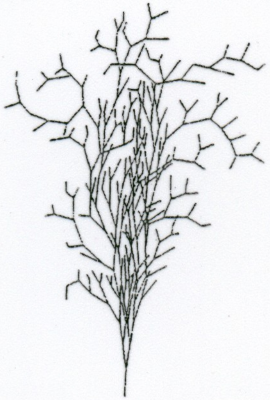
	X_0 (cm)	E_c (MeV)	R_M (cm)
Pb	0.56	7.4	1.6
plastic scint	34.7	80	9.1
Fe	1.76	21	1.8
Ar (liquid)	14	35	9.5
BGO	1.12	10.5	2.3
Pb glass (SF5)	2.4	11.8	4.3

Monte-Carlo simulation of an electromagnetic shower



analytic shower model:

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 looses via bremsstrahlung half of its energy $E_1 = E_0/2$
- photon materializes as $e^{+} e^{-}$ after X_0, energy of electron and positron $E_{\pm} \simeq E_0/2$

(precisely: $\mu_p = 7/9X_0$ or pair creation probability in X_0 -> $P = 1\text{-exp}(-7/9) = 0.54$

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 charakterize shower
  - number of particles in shower
  - location of shower maximum
  - longitudiual shower distribution
  - transverse shower distribution (width)

shower model (continued):

longitudiual variable t= x/X_0

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

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

total number of charged particles with energy E_1

$$N(E_0, E_1) = 2^{t_1} = 2^{\ln(E_0/E_1)/\ln 2} \approx E_0/E_1$$

number of particles at shower maximum $N(E_0, E_c) \approx E_0/E_c \propto E_0$

shower maximum located at $t_{max} \propto \ln(E_0/E_c)$

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

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

$$= (4 + t_0) \frac{E_0}{E_c} X_0 \propto E_0$$ proportional to E_0 !

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

for practical purposes: $T = \frac{E_0}{E_c} X_0 F \qquad (F < 1)$

Transverse shower develoment:

- emission of bremsstrahlung under angle $\langle \vartheta^2 \rangle \simeq 1/\gamma^2$

- multiple scattering of electron $\langle \vartheta^2 \rangle = \left(\frac{21\,\mathrm{MeV}}{E} \right)^2 t$

→ multiple scattering dominates tranverse shower development
described by Moliere radius

$$R_M = \frac{21\,\mathrm{MeV}}{E_c} \cdot X_0$$

useful relations:

$$X_0 = \frac{180 A}{Z^2} \quad (g/cm^2)$$

$$E_c = \frac{550\,\mathrm{MeV}}{Z}$$

$$t_{max} = \ln \frac{E}{E_c} - \begin{cases} 1 & \text{for electron induced shower} \\ 0.5 & \text{" gamma " "} \end{cases}$$

95% of energy within $L(95\%) = t_{max} + 0.08\,Z + 9.6 \quad (X_0)$

$$R(95\%) = 2 R_M$$

8.3 electromagnetic calorimeter

(i) homogeneous shower detector (absorbing material ≡ detection materials)
scintillating crystals (see chap.5)

	X_0 (cm)	R_M (cm)	σ_E/E
NaI	2.6	4.3	$1\%/\sqrt{E}$
CsI	1.8	3.8	$1.3\%/\sqrt{E}$
BGO	1.1	2.7	$1\%/\sqrt{E}$
$PbWO_4$	0.9	2.7	$2.5\%/\sqrt{E}$

contributions to the energy resolution:

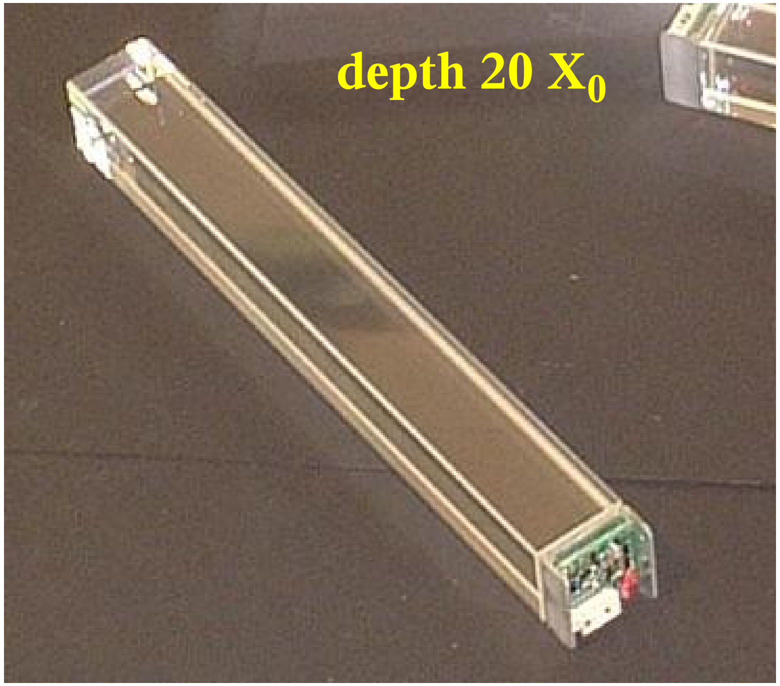
- shower fluctuations $\sigma_E/E \propto 1/\sqrt{E}$
- photon/electron statistics in detector "
- shower leakage $\sigma_E/E \simeq$ const.
- electronic noise $\sigma_E/E \propto 1/E$
- calibration $\sigma_E/E \simeq$ const.

total

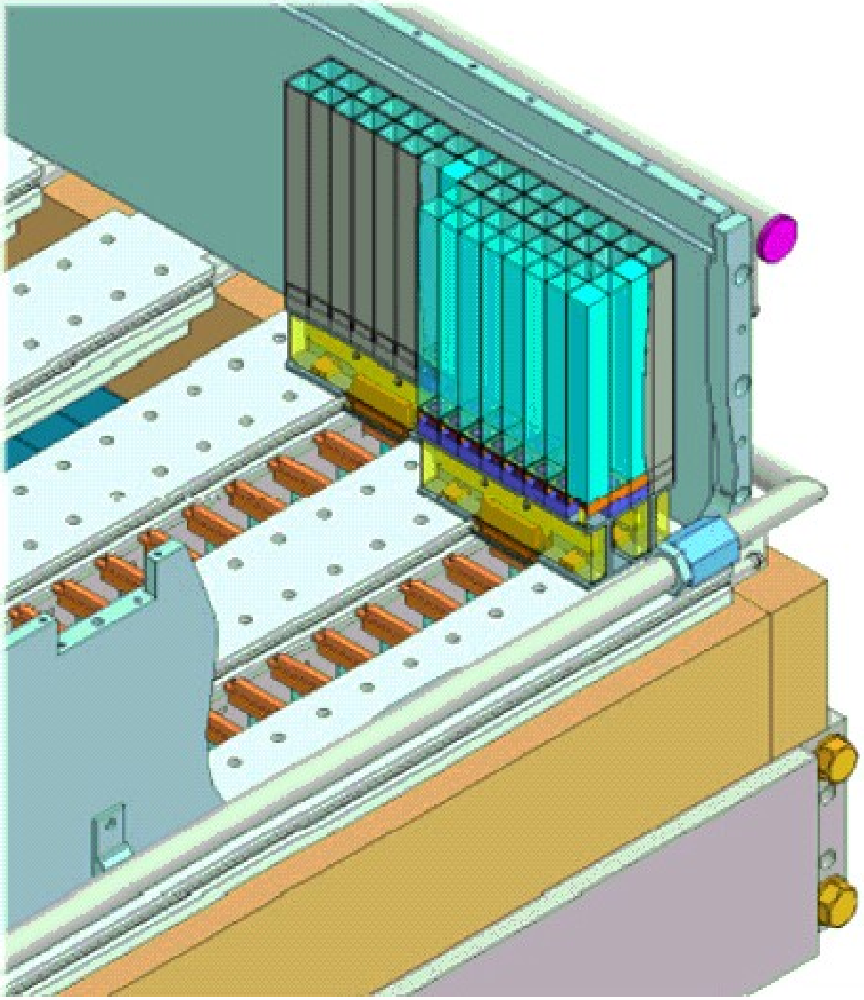
$$\frac{\sigma_E}{E} = \frac{A}{E} \oplus \frac{B}{\sqrt{E}} \oplus C$$

← energy resolution of em. calorimeter

example of modern crystal calorimeter: PHOton Spectrometer (PHOS) in ALICE:
array of 22 x 22 x 180 mm^3 $PbWO_4$ crystals - in total about 18 000 (same type as CMS)
dense, fast, relatively rad. hard, emission spectrum 420 – 550 nm
read out with 5 x 5 mm^2 avalanche photodiodes (see above, chapter scintillation detectors)
Q = 85%, charge sensitive preamplifier directly mounted on APD



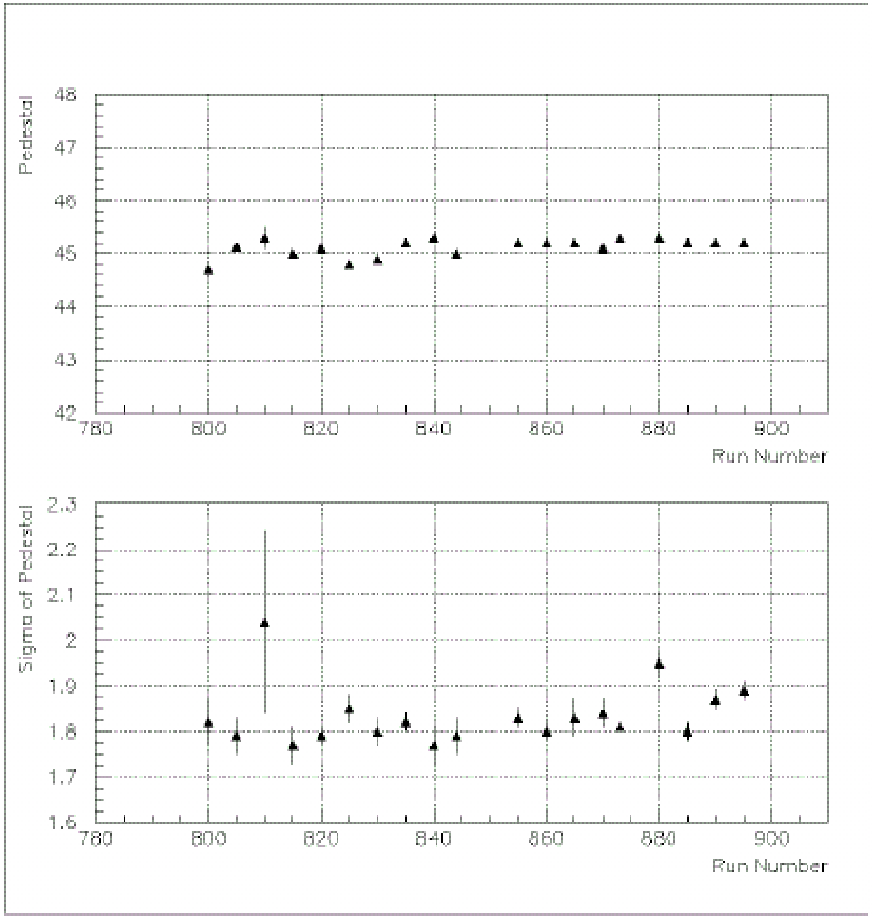
light yield of $PbWO_4$ relatively low and
strongly temperature dependent -> operate detector
at -25 deg C (triple light yield vs 20 deg C)
but need to stabilize to 0.3 deg C
(monitor with resistive temperature sensors)
crystals cold, electronics warm
(liquid coolant, hydrofluoroether)

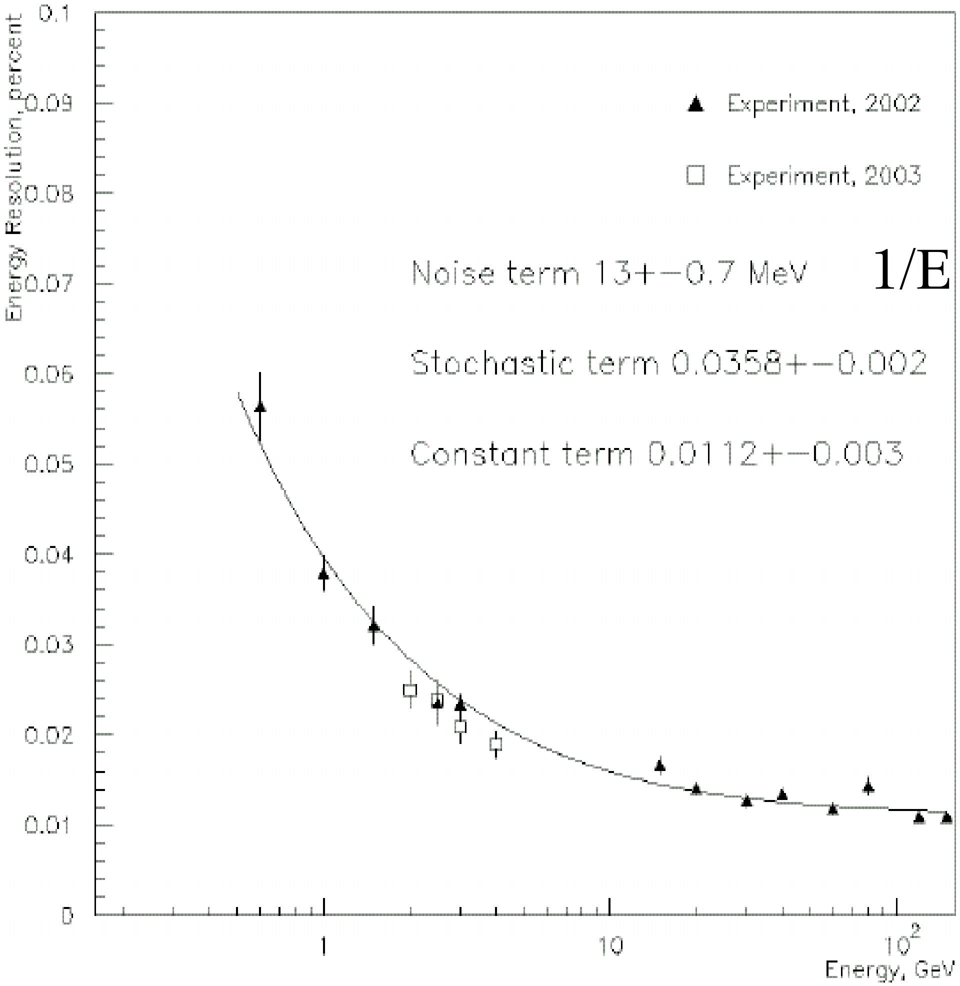


12.5 t of crystals covering 8 m^2 at 4 m from intersection point

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





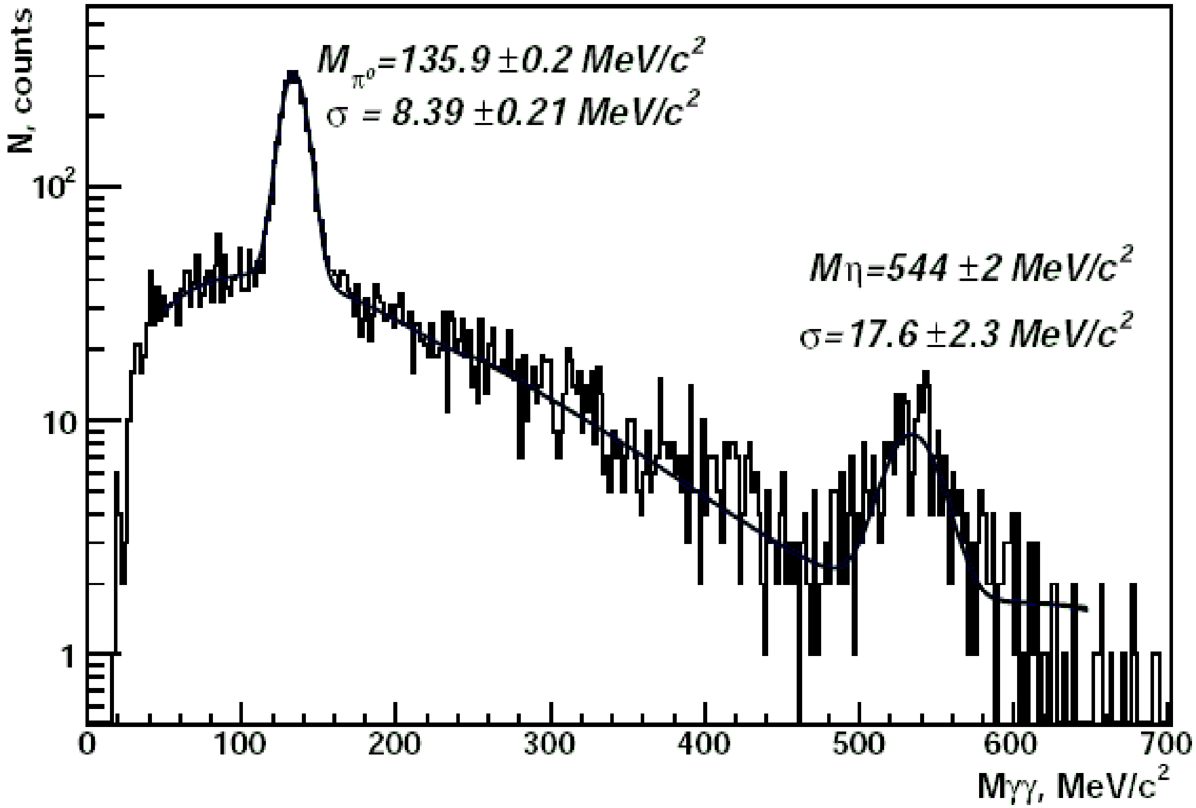
1/E term

1/√E term

electronic noise: 1 ch = 400 e

-> noise about 800 e

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



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

Alternative: instead of scintillating material use Cherenkov radiator

electrons and positrons of electromagnetic shower emit Cherenkov ligth
number of photons N_{ph} proportional to total path length T of electrons and positrons (see chapter 2)

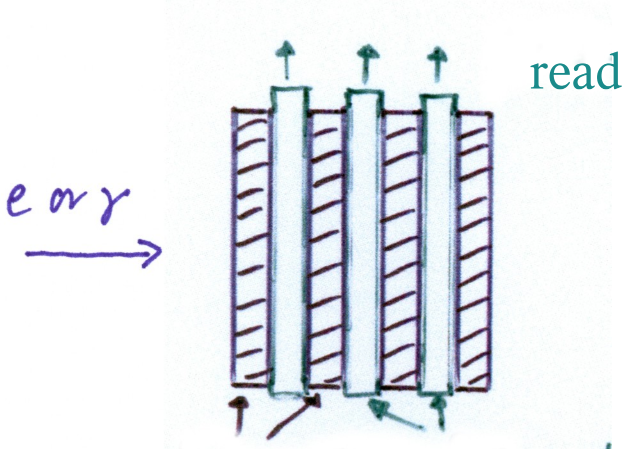
$$N_{ph} \propto T \propto E_0$$

remember: energy loss by Cherenkov radiation very small -> resolution limited by photoelectron statistics
typical:about 1000 photoelectrons 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 x 14 x 42 cm diamater 3.3 R_M and depth 17.5 X_0
read out with photomultipliers
typical performance: $\sigma_E / E = 0.01 + 0.05\sqrt{E}(GeV)$

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 ← energy loss
detection medium: scintillator, liquid Ar ← sampling of shower
often sandwich of absorber and detection medium



read-out

converter (absorber)

sampling elements

long. shower development: $t_{max} = t_{max}^{abs} \frac{x+y}{x}$

trans. shower development: $R(95\%) = 2 R_M \frac{x+y}{x}$

$x = \sum x_i$ absorber
$y = \sum y_i$ detection (sampling) elem.

energy loss in absorber and detection medium varies event -by- event
“sampling fluctuations” → 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

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

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

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

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

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

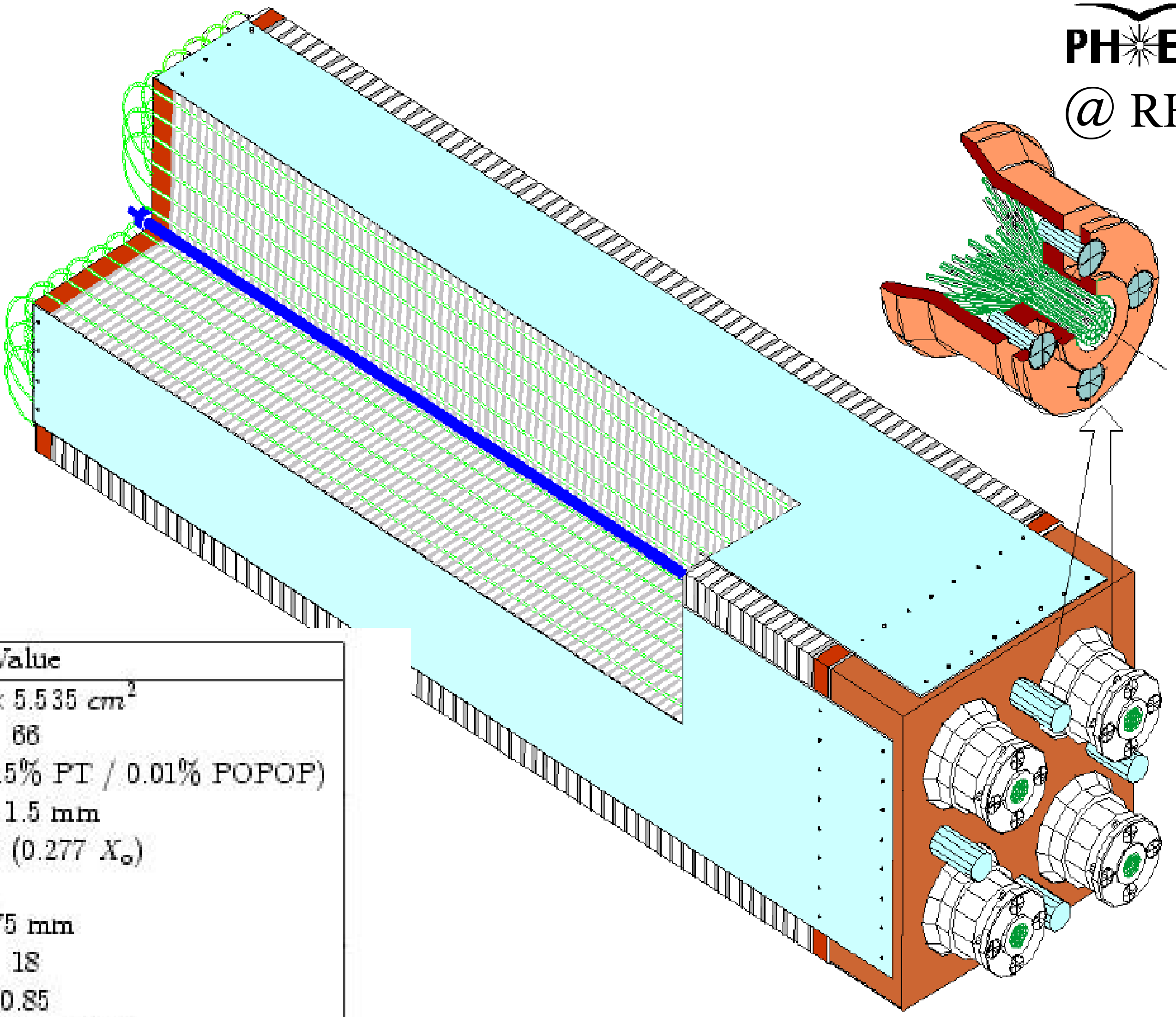
$$Pb: (1-\alpha) \ll \alpha \qquad \frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}} \sqrt{t_{conv}}$$

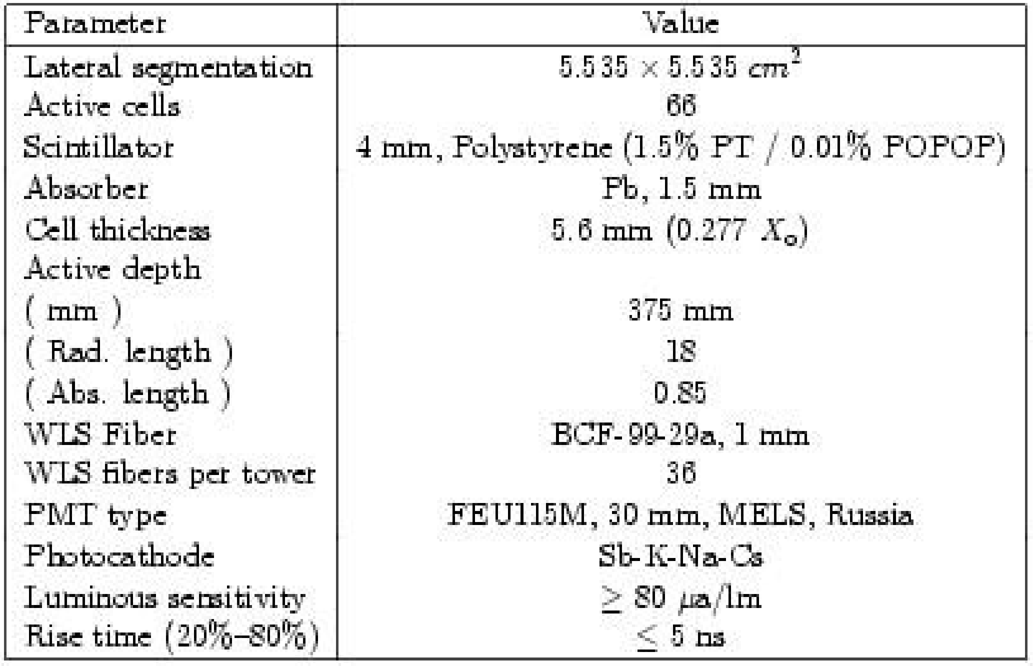
common parametrization: $\frac{\sigma_E}{E} = 3.2\% \sqrt{\frac{E_c(\mathrm{MeV})}{F}} \sqrt{\frac{t_{conv}}{E(\mathrm{GeV})}}$

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 x 5 cm2
38 cm deep (18 X_0) =
66 sampling cells
in total covering 48 m^2
in 15552 ind. towers

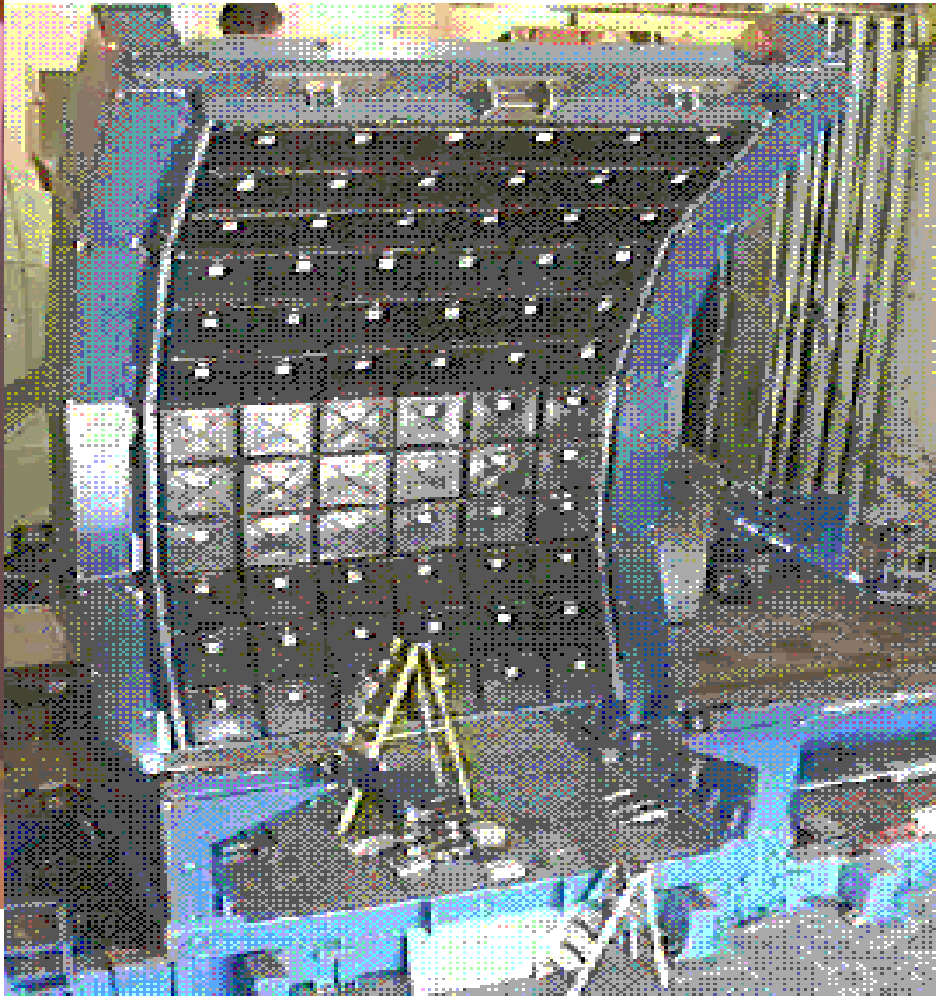
PHENIX
@ RHIC



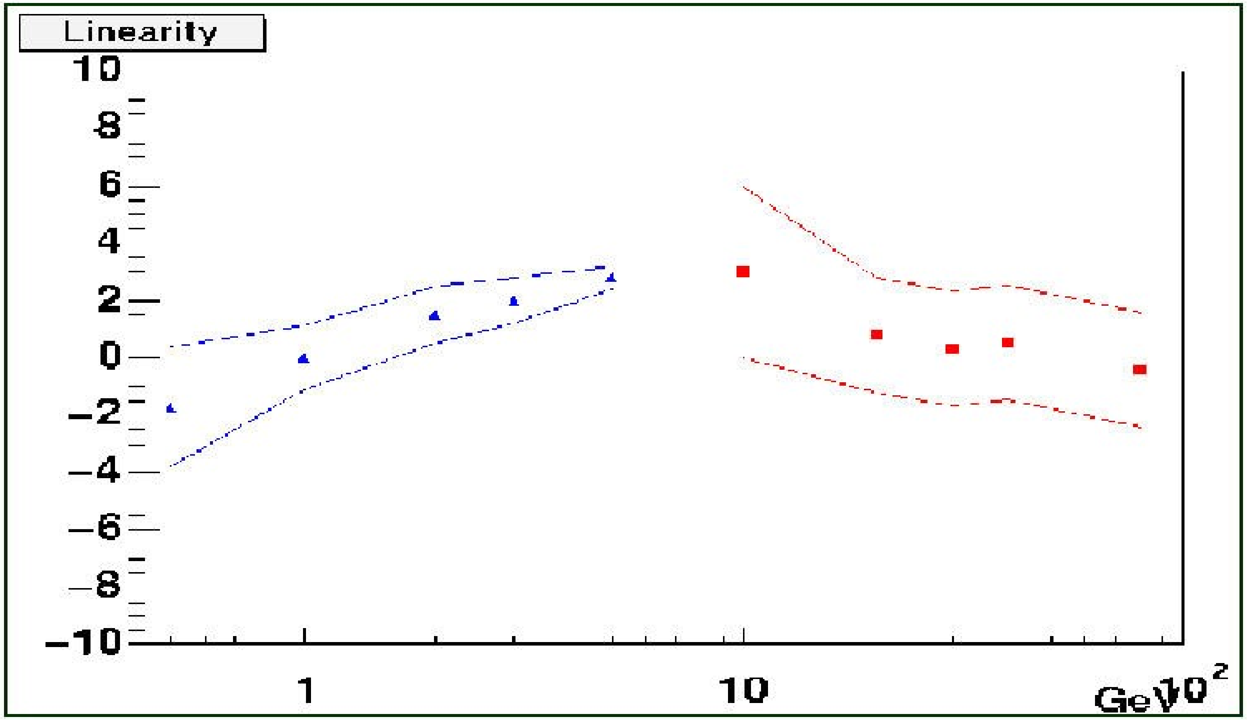


Parameter	Value
Lateral segmentation	5.535 × 5.535 cm^2
Active cells	66
Scintillator	4 mm, Polystyrene (1.5% PT / 0.01% POPOP)
Absorber	Pb, 1.5 mm
Cell thickness	5.6 mm (0.277 X_o)
Active depth	
(mm)	375 mm
(Rad. length)	18
(Abs. length)	0.85
WLS Fiber	BCF-99-29a, 1 mm
WLS fibers per tower	36
PMT type	FEU115M, 30 mm, MELS, Russia
Photocathode	Sb-K-Na-Cs
Luminous sensitivity	≥ 80 μa/lm
Rise time (20%–80%)	≤ 5 ns

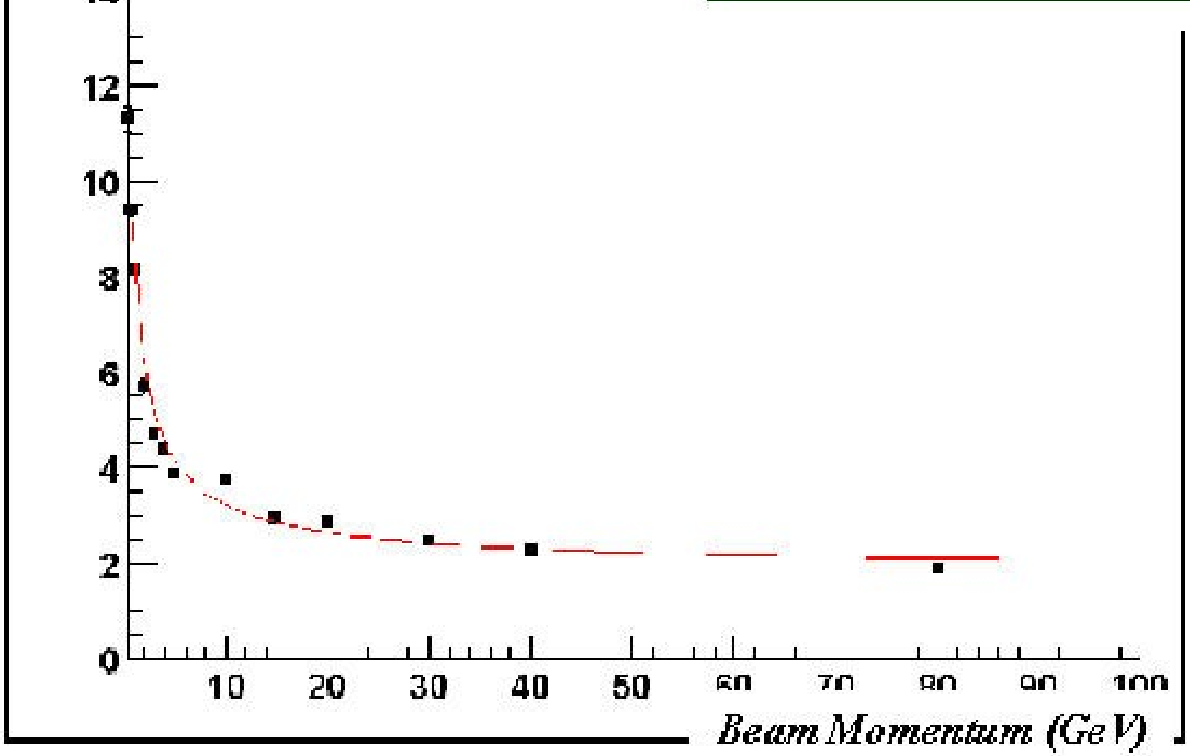

Pin 103
Split 34
67
ATTACHMENT A
SECTOR 4
SUPERMODULE 67

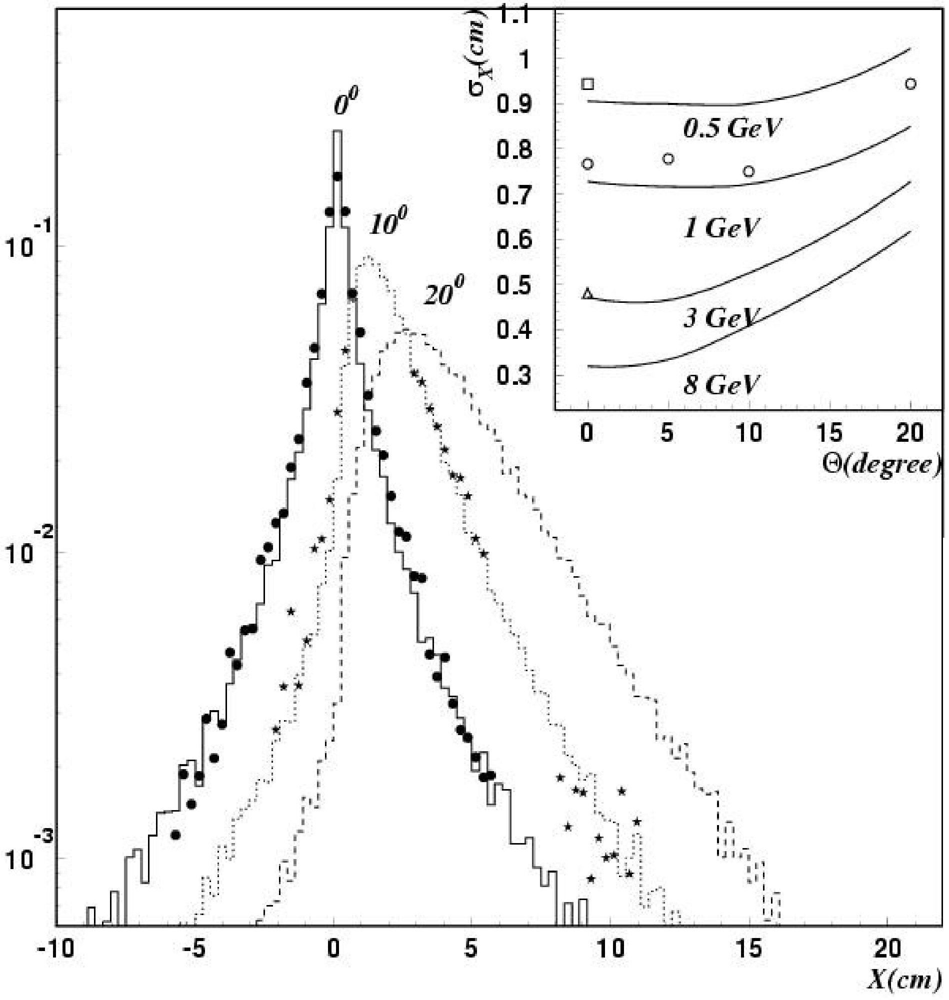


nominal energy resolution:
stochastic term 8%/sqrt(E)
constant term: 2%
time resolution: 200 ps

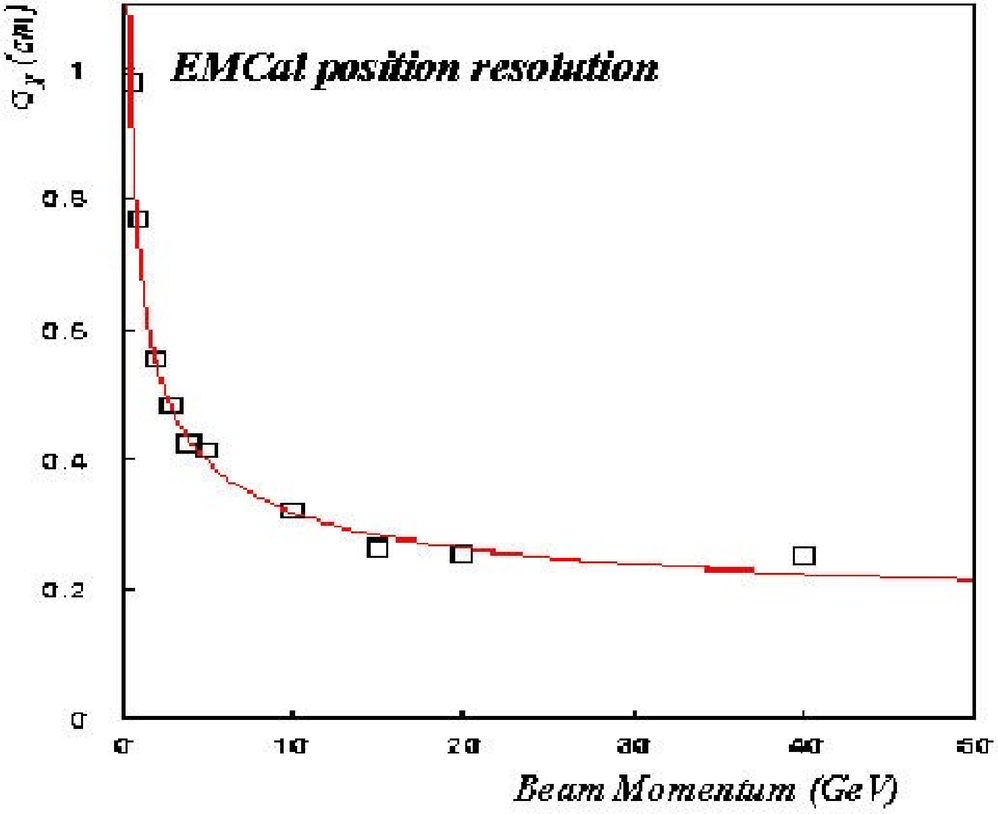


EMCal energy resolution

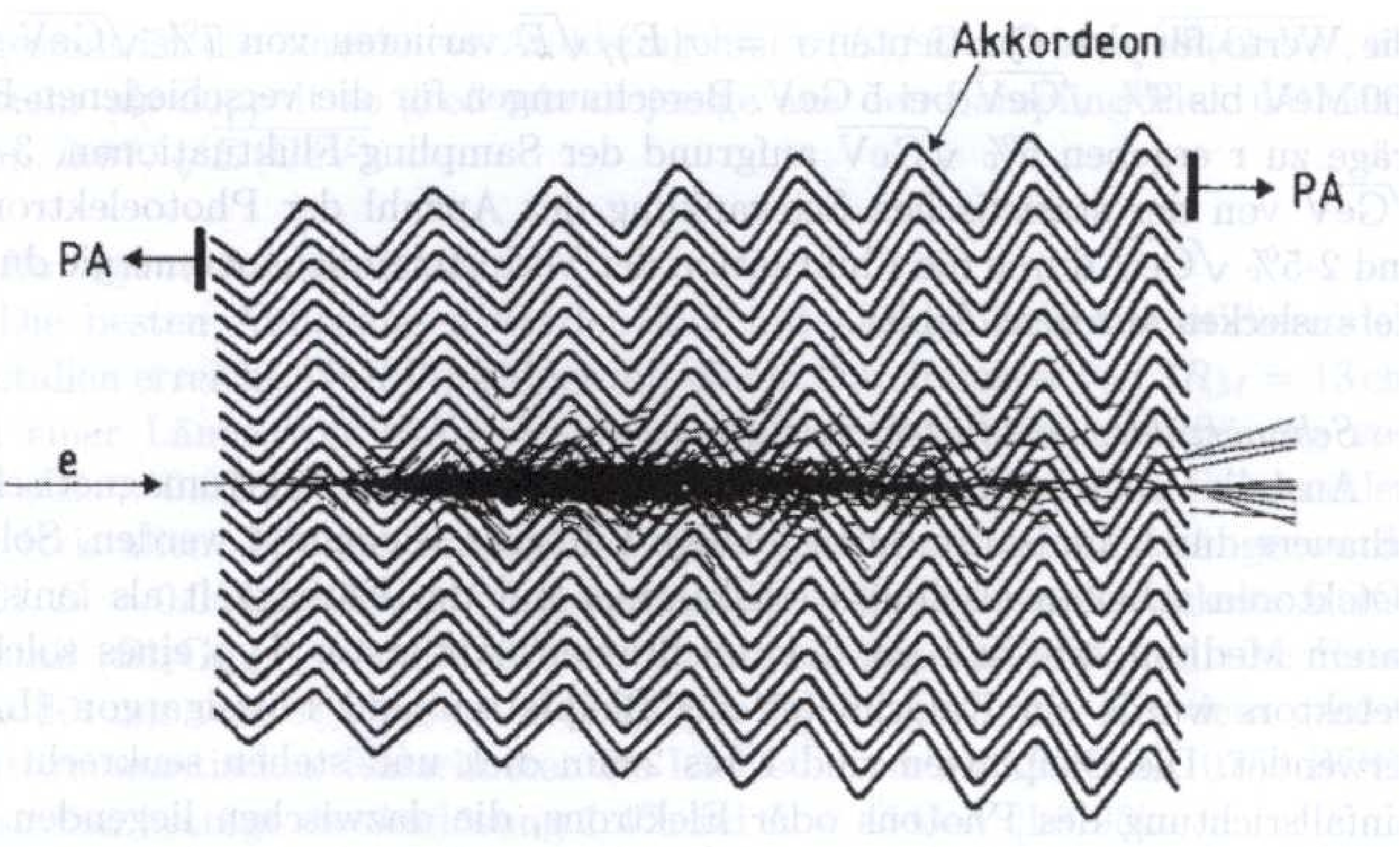




lateral shower profile well understood
-> position resolution in mm range



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



for faster read-out: interleave electrodes between metal plates and electronics directly on electrodes inside liquid

example: electromagnetic calorimeter of ATLAS