Homogeneous Calorimeters

- composed of uniform material permitting function of absorber and detector

- typical example: crystal calorimeter
  - heavy scintillating crystals
  - can have very good energy resolution

KTeV calorimeter (CP violation @ Fermilab)

- CsI crystals: 50 cm deep (27 X₀)
- designed for y^+ up to 80 GeV
  (e.g., K^+ \rightarrow \mu^+ \mu^- \rightarrow \gamma \gamma)
- resolution quoted after as \( \frac{\sigma_E}{E} \)

When \( E_y > 5 \) GeV:

\[
\frac{\sigma_E}{E} < 1\%
\]

CMS Experiment

- electromagnetic calorimeter:
  - 80k lead-tungstate crystals (PbWO₄)
  - short X₀ (0.9 cm)
  - small X₀ (2.2 cm)
  - fast scintillation
  - radiation hard
- problem: only 50\% s/MeV emitted
Energy Resolution

Even if energy calibration is correct on average, several effects alter measured energy:

- Statistical fluctuations in active layers
- Energy leakage (punchthrough)
- Noise in active medium (e.g., radioactivity)
- Gain variations (e.g., scintillation or photon multiplicator tube gain)
- Electronic noise
- Events overlapping in time window (cross-talk)

General expression often used:

$$\frac{\sigma_{E}}{E} = \frac{S}{E} \oplus \frac{N}{E} \oplus C$$

CMS:
N = 155 MeV
S = 2.7%
C = 0.55%

where $\oplus$ means sum in quadrature

$$\sigma \oplus \beta = \sqrt{\sigma^2 + \beta^2}$$

N ("noise term"): fluctuation from electronic noise.
This noise is same regardless of energy ($\sigma_N = N$).

S ("sampling term"): statistical fluctuations in shower particle statistics (scintillation or ionization)

C ("constant term"): calibration uncertainty due to detector non-uniformity / variation
Position Resolution

Lateral shape of shower:
- independent of particle energy

Width of shower ~ Molière radius

\[ \sigma_p = \frac{R_m}{\sqrt{N_{\text{shower}}}} = \frac{R_m}{\sqrt{E/E_c}} \]
Sampling Calorimeter

Consider simple setup:

\[ E_y \quad \text{incident} \quad \text{scintillator} \]

\[ L = L_{\text{max}} \]

The number of particles = \( E_y / E_c \)

\[ N_e = \frac{2}{3} N_{\text{esc}} = \frac{2}{3} \frac{E_y}{E_c} \]

\( \text{observed in ionization detector medium} \)

Fractional fluctuation on \( N_e \)

\[ \sigma (N_e) = \frac{1}{N_e} \]

Since \( N_e \propto E_y \), we have

\[ \frac{\sigma_e}{\frac{E}{E_c}} = \frac{1}{\sqrt{N_e}} \approx \frac{1}{\sqrt{2E_y / 3E_c}} \]
**Sampling Fluctuations**

A general form for sampling fluctuations in a sampling calorimeter

\[
\frac{\Delta E}{E} = \frac{2.7\%}{\sqrt{E\ [\text{GeV}]}} \sqrt{\frac{S\ [\text{mm}]}{f_{\text{amp}}}}
\]

"gap": active region with sensitive material

absorber \( S = \text{gap thickness} \)

**Sampling fraction**: \( f_{\text{amp}} \)

- the ratio of energy loss \( \frac{dE}{dx} \) in the active (sensitive) medium to the energy loss \( \mu_{\text{ip}} \) in the absorber + active layer

**Example**: DØ EM calorimeter

\( S = 2\text{mm}; \quad <f_{\text{amp}}> \sim 10\% \)

\[
\therefore \frac{\Delta E}{E} = \frac{2.7\%}{\sqrt{5}} \sim \frac{14\%}{\sqrt{5}} \quad \text{(actual value)}
\]
Choice of Materials

Absorber: Generally a dense material with moderate X-ray good

Active Medium: Material providing observable which is correlated with particle energy
  - ionization
  - scintillation

- Liquid Argon and scintillators provide better resolution than gaseous active media
  - latter have larger Landau fluctuations

Scintillators
- might be alternating layers of absorber and plastic scintillator
- light sensitive device has large gain
- charged particles in shower produce light in scintillating medium
- fast signals, large amplitude
  - if "read out" with photomultiplier tubes
  - difficulty if there is a magnetic field
  - move them outside