Homogeneous Calorimeter

- 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 ($27 X_0$)
- designed for γ's up to 80 GeV (eg. $K_L \to \pi^0 \pi^0 \to 4\gamma$)
- resolution quoted often as σ_E / E — fractional energy resolution

When $E_\gamma > 5$ GeV:

$$\boxed{\frac{\sigma_E}{E} < 1\%}$$

CMS Experiment

- electromagnetic calorimeter:
  - 80k lead-tungstate crystals ($PbWO_4$)
  - short X_0 (0.9 cm)
  - small R_M (2.2 cm)
  - fast scintillation
  - radiation-hard
  - problem: only 50 γ's/MeV emitted

Energy Resolution

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

- statistical fluctuations in active layers
- energy leakage (punchthrough)
- noise in active medium (eg. radioactivity)
- gain variations (eg. scintillation or photomultiplier tube gain)
- electronic noise
- events overlapping in time window (pileup)

General expression often used:

$$\frac{\sigma_E}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C$$

CMS:
$N = 155\,\mathrm{MeV}$
$S = 2.7\%$
$C = 0.55\%$

where $\oplus$ means sum in quadrature ($a \oplus b = \sqrt{a^2+b^2}$)

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

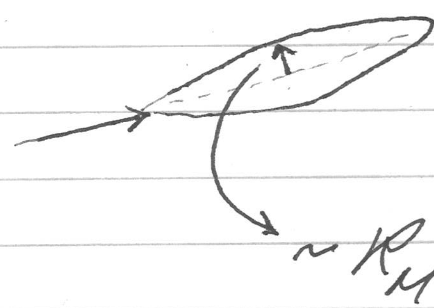
S ("sampling term"): statistical fluctuations in shower particle statistics (scintillation γ's or ionization e^-'s)

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

Position Resolution

Lateral shape of shower:

- independent of particle energy



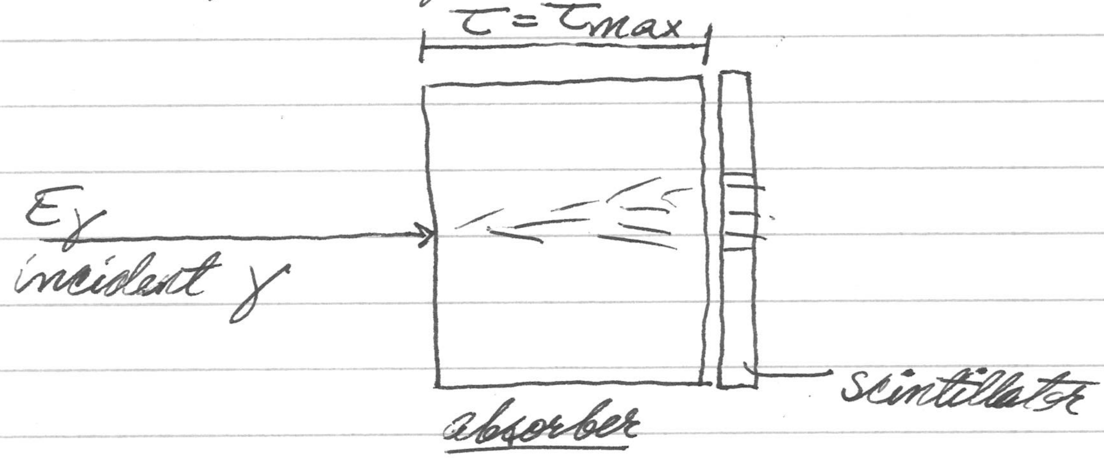
Width of shower ~ Molière radius

∴ position resolution a statistical matter
→ "error" on mean position of shower

$$\underline{\underline{\sigma_{xy}}} = \frac{R_M}{\sqrt{N_{shwr}}} = \boxed{\frac{R_M}{\sqrt{E/E_c}}}$$

Sampling Calorimeter

Consider simple setup:



The number of particles $= E_\gamma / E_c$

$$\therefore \quad N_{e^\pm} = \frac{2}{3} N_{tot} = \frac{2}{3} \frac{E_\gamma}{E_c}.$$

↳ observed in ionization detection medium

Fractional fluctuation on N_e

$$\frac{\sigma(N_e)}{N_e} = \frac{1}{\sqrt{N_e}}$$

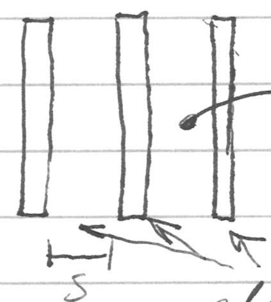
Since $N_e \propto E$, we have

$$\boxed{\frac{\sigma_E}{E} \simeq \frac{1}{\sqrt{N_e}}} \boxed{\simeq \frac{1}{\sqrt{2E_\gamma / 3E_c}}}$$

Sampling Fluctuations

A general form for sampling fluctuations in a sampling calorimeter

$$\frac{\sigma_s}{E} = \frac{2.7\%}{\sqrt{E\,[\mathrm{GeV}]}} \sqrt{\frac{s\,[\mathrm{mm}]}{f_{samp}}}$$



"gaps": active region with sensitive material

absorber

s = gap thickness

Sampling fraction: f_{samp}

- the ratio of energy loss $\left(\left.\frac{dE}{dx}\right|_{MIP}\right)$ in the active (sensitive) medium to the energy loss (MIP) in the absorber + active layer

Example: DØ EM calorimeter

$s = 2\,\mathrm{mm}$; $\langle f_{samp} \rangle \sim 10\%$

$\therefore\ \sigma_s/E = \frac{2.7\%}{\sqrt{E}}(5) \sim \frac{14\%}{\sqrt{E}}$ (actual value $15\%/\sqrt{E}$)

Choice of Materials

Absorber: Generally a dense material with moderate R_M ~~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's a magnetic field
  - move them outside