Lecture 23
Types of calorimeters

**Homogeneous calorimeters:** (e.g., crystals)
  - Detector = absorber
  - Good energy resolution
  - Limited spatial resolution (particularly in longitudinal direction)
  - Only used for electromagnetic calorimetry

**Sampling calorimeters:**
  - Detectors and absorber separated → only part of the energy is sampled
  - Limited energy resolution
  - Good spatial resolution
  - Used both for electromagnetic and hadron calorimetry
Homogeneous calorimeters

Signal = photons (scintillation or Cherenkov radiation).
Readout via photomultiplier, -diode/triode….

- Scintillators (crystals)

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Density [g/cm$^3$]</th>
<th>$X_0$ [cm]</th>
<th>Light Yield γ/MeV (rel. yield)</th>
<th>$\tau_1$ [ns]</th>
<th>$\lambda_1$ [nm]</th>
<th>Rad. Dam. [Gy]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI (Tl)</td>
<td>3.67</td>
<td>2.59</td>
<td>$4 \times 10^4$</td>
<td>230</td>
<td>415</td>
<td>$\geq 10$</td>
<td>hydroscopic, fragile</td>
</tr>
<tr>
<td>CsI (Tl)</td>
<td>4.51</td>
<td>1.86</td>
<td>$5 \times 10^4$ (0.49)</td>
<td>1005</td>
<td>565</td>
<td>$\geq 10$</td>
<td>Slightly hygroscopic</td>
</tr>
<tr>
<td>CSI pure</td>
<td>4.51</td>
<td>1.86</td>
<td>$4 \times 10^4$ (0.04)</td>
<td>10</td>
<td>310</td>
<td>10$^3$</td>
<td>Slightly hygroscopic</td>
</tr>
<tr>
<td>BaF$_2$</td>
<td>4.87</td>
<td>2.03</td>
<td>$10^4$ (0.13)</td>
<td>0.6</td>
<td>220</td>
<td>10$^3$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>620</td>
<td>310</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BGO</td>
<td>7.13</td>
<td>1.13</td>
<td>$8 \times 10^3$</td>
<td>300</td>
<td>480</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>PbW0$_4$</td>
<td>8.28</td>
<td>0.89</td>
<td>$\approx 100$</td>
<td>10</td>
<td>$\approx 440$</td>
<td>10$^4$</td>
<td>light yield =f(T)</td>
</tr>
</tbody>
</table>

Light yield relative to NaI(Tl) readout with PM (bialkali photocathode)
Homogeneous calorimeters

Cherenkov radiators

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>SF-5 Lead glass</td>
<td>4.08</td>
<td>2.54</td>
<td>1.67</td>
<td>600 (1.5×10⁻⁴)</td>
<td>350</td>
<td>10²</td>
<td></td>
</tr>
<tr>
<td>SF-6 Lead glass</td>
<td>5.20</td>
<td>1.69</td>
<td>1.81</td>
<td>900 (2.3×10⁻⁴)</td>
<td>350</td>
<td>10²</td>
<td></td>
</tr>
<tr>
<td>PbF₂</td>
<td>7.66</td>
<td>0.95</td>
<td>1.82</td>
<td>2000 (5×10⁻⁴)</td>
<td>10³</td>
<td>Not available in quantity</td>
<td></td>
</tr>
</tbody>
</table>

Light yield relative to NaI(Tl) readout with PM (bialkali photocathode)
Sampling calorimeters

Absorber + detector separated $\rightarrow$ sampling fluctuations

$$N = \frac{T_{\text{det}}}{d}$$
$$= F(\xi) \frac{E}{E_c} X_0 \frac{1}{d}$$
$$\frac{\sigma(E)}{E} \propto \sqrt{\frac{N}{N}} \propto \sqrt{\frac{1}{E}} \sqrt{\frac{d}{X_0}}$$

MWPC, streamer tubes
warm liquids:
  - TMP = tetramethylpentane,
  - TMS = tetramethylsilane
cryogenic noble gases:
  - mainly LAr (LXe, LKr)
scintillators, scintillation fibres, silicon detectors
ATLAS LAr Calorimeter

Accordion geometry absorbers immersed in Liquid Argon

Liquid Argon (90K) + lead-steel absorbers (1-2 mm) + multilayer copper-polyimide readout boards
1 GeV E-deposit $\rightarrow 5 \times 10^6$ e$	ext{-}$

Accordion geometry minimizes dead zones.
Liquid Ar is intrinsically radiation hard.
Readout board allows fine segmentation (azimuth, pseudo-rapidity and longitudinal)

Spatial and angular uniformity $\approx 0.5\%$
Spatial resolution $\approx 5\text{mm} / E^{1/2}$

Pointing
CMS hadron calorimeter

Cu absorber + scintillator
2 \times 18 \text{ wedges (barrel)}
+ 2 \times 18 \text{ wedges (endcap)} \approx 1500 \text{ T absorber}

Scintillators fill slots and are read out via fibres by HPDs (hybrid photodiodes)

Test beam resolution for single hadrons

\[ \frac{\sigma_E}{E} = \frac{65\%}{\sqrt{E}} \oplus 5\% \]
Energy Measurement

How we determine the energy of a particle from the shower?
- Detector response must have linearity i.e., signal proportional to the energy deposit
  • The average calorimeter signal vs. the energy of the particle is different for homogenous and sampling calorimeters
  • Hadronic showers may include electromagnetic component from \( \pi^0 \)'s
- Detector resolution is controlled by fluctuations, i.e., event to event variations of the signal.

In general EM calorimeters have linear responses while hadronic calorimeters do not.

Sources of non-linearity:
- saturation of the medium (gas, crystal, scintillator)
- non-linearity of detectors (PMT, Photodiodes, electronics)
- leakage of the signal outside the detector
Homogeneous calorimeters - crystals or liquid Xe
Scintillation proportional to the total electron energy

Advantages:
- excellent energy resolution -> best statistical precision
  for mean energy $W$ required to produce a signal
  eg., visible photon in a crystal
  \[
  \frac{\sigma_E}{E} = \frac{1}{\sqrt{n}} = \frac{1}{\sqrt{E/W}}
  \]
- uniform response  -> good linearity

Disadvantages:
- limited segmentation
- high cost
CMS EM Calorimeter
barrel + endcaps 77,000 PbWO$_4$ crystals
Energy resolution – 1% at 30 GeV
Sampling calorimeters
Sandwich of dense material to induce showering interspaced with a detector (scintillator counting tracks, LAr counting ionization,..)

Advantage – good spatial segmentation, both lateral and in depth

Disadvantage – only see part of the shower

\[ f_{\text{sampling}} = \frac{E_{\text{visible}}}{E_{\text{deposited}}} \]
Energy resolution

\[ \sigma_E = a\sqrt{E} \oplus bE \oplus c \]

\[ \frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E} \]

a – stochastic term due to
  intrinsic statistical shower fluctuations
  sampling fluctuations
  signal quantum fluctuations (e.g., photo-electron statistics)

b – constant term due to
  inhomogeneities and imperfections
  non-linearity of electronics
  fluctuation of the energy lost in the absorber

c – noise term due to electronics noise, natural radioactivity, pile-up
Scintillators as active layer; signal readout via photo multipliers

Absorber  Scintillator

Light guide

Photo detector

Charge amplifier

Absorber as electrodes

HV

Argon

Active medium: LAr; absorber embedded in liquid serve as electrodes

Possible setups

Scintillators as active layer; wavelength shifter to convert light

Scintillator (blue light)

Wavelength shifter

Ionization chambers between absorber plates

Electrodes

Analogue signal
Hadron showers

Initiated by strong interactions
Characterized by hadronic interaction length
Contain electromagnetic components
Large complexity – requires simulation tools
Hadronic interactions cross sections

\[ \sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{inel}} \]

\[ \sigma_{\text{el}} \approx 10 \text{mb} \]

\[ \sigma_{\text{inel}} \approx A^{2/3} \]

\[ \sigma_{\text{tot}} (\text{nucl}) = \sigma_{\text{tot}} (\text{pp}) A^{2/3} \quad \sigma_{\text{tot}} (\text{pp}) \text{ increases with } s \]
Energy resolution of hadron showers

Hadronic energy resolution of non-compensating calorimeters does not scale with $1/\sqrt{E}$ but as

\[
\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \left( \frac{E}{E_0} \right) \approx \frac{a}{\sqrt{E}} \oplus b
\]