Introduction to Calorimetry
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Marie Curie, GSI  21 March 2012
Overview

• Introduction

• Electromagnetic Calorimetry
  * particle interactions
  * energy resolution

• Hadronic Calorimetry
  * particle interactions
  * energy resolution

• Jets and Particle Flow

• Homogeneous and Sampling calorimeters

• Future directions in calorimetry

• Calorimeters at work

• Summary
Calorimetry - one of the most important and powerful detector techniques in experimental particle physics

* Measurement of particle energy by total absorption in the calorimeter
* Measurement of the spatial location of the energy deposit, the angle (sometimes), and timing: important for triggers and collision tagging

* Convert energy $E$ of the incident particle into a detector response $S$

Basic mechanism: formation of electromagnetic or hadronic cascades/showers

* Compact detectors, cascade length increases only as $\log(E)$
* Energy resolution improves with increasing $E$, unlike spectrometers
* Can provide fast response, to avoid pileup, for triggering
Introduction

Calorimetry

The detectors fall into two main categories:

**Electromagnetic calorimeters** for the detection of $e^\pm$ and neutral particles $\gamma$ ($\pi^0$)

**Hadron calorimeters** for the detection of $\pi^\pm$, $p^\pm$, $K^\pm$ and neutral particles $n$, $K^0_L$

$\mu^\pm$ usually traverse the calorimeters, only losing small amounts of energy by ionisation.

* These 13 particles completely dominate the types of particles from high energy collisions likely to reach and interact with the calorimeters

* All other particles decay ~instantly, or in flight, usually within a few hundred microns from the collision, into one or more of the particles above

* Neutrinos, $\nu$, and neutralinos, $\chi^o$, undetected, but with hermetic calorimetry can be inferred from measurements of missing transverse energy in collider experiments.
Introduction

Look at a wedge of CMS, at the LHC, to show the typical layout of the Tracker, the Calorimeters and Muon detectors
Introduction

CMS: Particle identification from:
* Deposited energy location - in ECAL or HCAL
* Presence or absence of corresponding tracks in the Tracker

Sign of particle charge from the tracker

Tracker - minimum material to avoid losing particle energy before the calorimeters
Electromagnetic Calorimetry
Energy losses by electrons and photons

In matter, electrons and photons loose energy interacting with nuclei and atomic electrons

- electrons/positrons
  - bremsstrahlung (nucleus)
  - ionisation (atomic electrons)

- photons
  - pair production (nucleus), (above 1 GeV)
  - Compton scattering (atomic electrons)
  - Photoelectric effect (atomic electrons)

Above 1 GeV, radiative processes dominate energy loss by $e/\gamma$

The processes lead to an e.m. cascade or shower of particles eventually dissipating its energy in the calorimeter by ionisation and absorption

In the following, use the crystal PbWO$_4$, and/or Pb, to illustrate cascade properties.
Electrons

Bremsstrahlung, main loss for electrons/positrons above $O(10 \text{ MeV})$

Characterised by a ‘radiation length’, $X_0$, in the absorbing medium over which an electron loses, on average, 63.2% of its energy by bremsstrahlung.

$$E = E_0 e^{-x/X_0}$$

where

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln \frac{183}{Z^{1/3}}$$

$$-\frac{dE}{dx} = \frac{E}{X_0}$$

$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln \frac{183}{Z^{1/3}}}$$

Favours the use of high $Z$ materials for a compact e.m. calorimeter

$$X_0 \sim 180 \frac{A}{Z^2} \text{ [g cm}^{-2}] \quad \text{In Pb, } Z = 82, \ A = 207 \quad X_0 \sim 5.6 \text{ mm}$$

Electrons continuously lose energy by ionising the medium. Eventually, as they drop below $O(10 \text{ MeV})$, this becomes the main loss. This transition is at a critical energy, $E_c$. Finally, the electrons range out and stop.
Why don’t muons also loose all their energy in the calorimeters??

\[ \frac{dE}{dx} \propto \frac{Z^2 E}{m^2_{\mu}} \]

Bremstrahlung: \(1/m^2\) dependence

\(m_{\mu} = 210 \, m_e\)

Muons emit significant bremsstrahlung only above \(\sim 1\) TeV

Muons loose only (O) GeV in the calorimeters by ionisation, so high energy muons pass through the calorimeters.
Photons

Pair production, main loss for photons above 1 GeV
Characteristic mean free path before pair production, \( \lambda_{\text{pair}} = 9/7 \ X_0 \)

Intensity of a photon beam entering calorimeter reduced to \( 1/e \) of
the original intensity, \( I = I_0 \exp(-7/9 \ x/X_0) \). \( \lambda_{\text{pair}} = 7.2 \ \text{mm in Pb} \)

Below \( \sim 5 \ \text{MeV} \) in \( \text{PbWO}_4 \), Compton scattering dominates (blue line), with an
electron ejected at each scattering site.
Below \( \sim 0.5 \ \text{MeV} \) in \( \text{PbWO}_4 \), the photo-electric effect dominates (green dashed)
and the photon path finishes with the production of an electron.
Brem and pair production dominate the processes that degrade the incoming particle energy

50 GeV electron
Loses 32 GeV over $1X_0$ by bremsstrahlung

50 GeV photon
Pair production to $e^+ e^-$, 25 GeV to each particle
Energy regime degraded by 25 GeV

Minimum ionising particle (m.i.p)
In Pb, over $1X_0$, ionization loss $\sim O(10\text{s})$ of MeV
Factor of $\sim 1000$ less than the radiative losses.
Electromagnetic Cascades

Below a certain energy, defined as $E_c$, $e^\pm$ energy losses, via ionisation, greater than energy losses via bremsstrahlung.

Slow decrease in number of particles in the shower.

Photons progressively lose energy by
  * Compton scattering
  * Converting to electrons via the photo-electric effect, and absorption

Electrons/positrons range out/stop through
  * Ionization of the medium
  * Annihilation (positrons)

The multiplication process runs out.

\[
E_c \approx \frac{610 \text{MeV}}{Z + 1.24}
\]

For Pb, $Z=82$, $E_c = 7.3 \text{ MeV}$
Consider only Bremstrahlung and pair production
Assume $\lambda_{\text{pair}}$ and $X_0$ are equal and that, after each $X_0$, the number of particles increases by factor 2

After ‘t’ layers of $X_0$, number of particles:

$$N(t) = 2^t$$
$$E(t)/\text{particle} = E_0 \cdot 2^{-t}$$

Process continues until $E(t)/\text{particle} < E_c$
This layer contains the maximum number of particles:

$$t_{\max} = \frac{\ln E_0 / E_c}{\ln 2}$$

$$N^{\text{total}} = \sum_{t=0}^{t_{\max}} 2^t = 2^{(t_{\max}+1)} - 1 \approx 2 \cdot 2^{t_{\max}} = 2 \frac{E_0}{E_c}$$

For a 50 GeV electron on Pb
$N^{\text{total}} \sim 14000$ particles
$t_{\max}$ at $\sim 13 X_0$ (an overestimate)
Longitudinal Shower Development

Shower grows only logarithmically with $E_0$

Shower maximum, where most energy deposited,

$$t_{\text{max}} \sim \ln(E_0/E_c) - 0.5 \quad \text{for } e^\pm$$

$$t_{\text{max}} \sim \ln(E_0/E_c) + 0.5 \quad \text{for } \gamma$$

$$t_{\text{max}} \sim 5X_0, \ 4.6 \text{ cm, for } 10 \text{ GeV electrons in } \text{PbWO}_4$$

How many $X_0$ to adequately contain an em shower?

Rule of thumb:

RMS spread in energy leakage at the back of the calorimeter

$$= 0.5 \times \text{average energy leakage at the back}$$

CMS - want $< 0.3\%$ rms energy leakage

Require $< 0.65\%$ average energy leakage $\Rightarrow$ PbWO$_4$ 25$X_0$, 23 cm long
Transverse Shower Development

Mainly multiple Coulomb scattering by $e^\pm$ in shower

95% of shower cone located in cylinder of radius $2 R_M$ where $R_M =$ Moliere Radius

$$R_M = \frac{21 \text{ MeV}}{E_c} X_0 \ [g/cm^2]$$

$R_M = 2.19\text{ cm}$ in PbWO$_4$, $X_0 = 0.89\text{ cm}$, $E_c \sim 8.5\text{ MeV}$

How many $R_M$ to adequately contain an em shower?

Lateral leakage degrades the energy resolution
An additional contribution to the stochastic term (see later)

In CMS, keep contribution to $< 2%/\sqrt{E}$
Achieved by summing energy over $3\times3$ (or $5\times5$) arrays of PbWO$_4$ crystals
EM Cascade Profiles

EM shower development in Krypton (Z=36, A=84)

GEANT simulation of a 100 GeV electron shower in the NA48 liquid Krypton calorimeter
Electromagnetic Energy Resolution
Electromagnetic Energy Resolution

Assume energy released in the detector material (mainly ionisation, excitation) is proportional to the energy of incident particle

Mean energy required to produce a ‘visible’ photon in a crystal or an electron-ion pair in a noble liquid \( Q \)

Mean number of quanta produced \( <n> = E / Q \)

Energy resolution is given by the fluctuations on ‘n’

\[
\frac{\sigma_E}{E} = \frac{\sqrt{n}}{n} = \sqrt{\frac{Q}{E}}
\]

also applies for hadron calorimeters

Generally:

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

‘Stochastic term’

‘Noise term’

Electronics

Pile up

‘Constant term’

Imperfections in calorimeter construction (dimension variations)

Non-uniform detector response

Channel to channel intercalibration errors

Fluctuations in longitudinal energy containment

Energy lost in dead material, before in detector
Electromagnetic Energy Resolution

Energy resolution at high energy usually dominated by the constant term, \( c \)

Relative resolution improves with Energy

Goal of calorimeter design - find best compromise between the three contributions to the resolution

An example of the (very good) energy resolution for electrons measured using PbWO\(_4\) crystals, CMS ECAL, test beam

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

\( a \), stochastic term = 2.83%

\( b \), noise term = 124 MeV

\( c \), constant term = 0.26%
**Electromagnetic Energy Resolution**

**However, in certain cases:**
Energy of the incident particle is only transferred to making quanta, and to no other energy dissipating processes, for example in Ge.

Stochastic fluctuations much reduced
Now $\sigma_E / E = \sqrt{(FQ / E)}$ where $F$ is the ‘Fano’ factor.

**F ~ 0.1 in Germanium**
Detector resolution in AGATA 0.06% for 1332keV photons

**Conversely, photo-detectors can introduce more fluctuations:**
For CMS PbWO$_4$ crystals, scintillation emission small fraction of energy loss and $F \sim 1$

However - fluctuations in the avalanche process in the Avalanche Photodiodes used for the photo-detection gives rise to an excess noise factor in the gain of the device

This leads to **F ~ 2 for the PbWO$_4$ + APD combination**

$N_{pe} \sim 4500$ photo-electrons released by APD, per GeV of deposited energy

Coefficient of stochastic term $a_{pe} = \sqrt{F} / N_{pe} = \sqrt{2 / 4500} = 2.1\%$

Including lateral leakage fluctuations (2%)  Total estimated stochastic term 2.9%

2.8% measured
Electromagnetic Energy Resolution

An example of the ‘Fano’ factor in action: the AGATA Ge detector

Experiment with excited nuclei from a target

1382 keV line, width 4.8 keV (fwhm)

Resolution 0.15% (0.06% with source)
Hadron Calorimeters

Hadron calorimeters

* essential to detect jets, which are fragments of fundamental constituents such as quarks and gluons.

* Jets often comprise many $\pi^\pm$ (and $\pi^0$) and other hadrons.

* Sometimes they may contain just a single pion.

Each of the hadrons will generate its own hadronic cascade, which will often span both the ECAL and HCAL, and overlap with other cascades from the jet.

The story is far more complex than for em cascades.
Degradation of the hadron energy into a cascade proceeds through an increasing number of (mostly) strong complex interactions with the calorimeter material.

Two classes of effects:

* Energetic secondary hadrons are produced with a mean free path, $\lambda \sim 35 A^{1/3} \text{ g/cm}^2$ between interactions. Their momenta a ‘fair fraction’ of the primary hadron.

* A significant part of the primary energy consumed by nuclear processes: excitation, neutron evaporation, spallation involving particles of $O(\text{MeV})$ energies. Dominated by electrons, positrons, photons, and neutrons.
Hadronic Cascades

Collision with a nucleus

Multiplicity of secondary particles $\propto \ln(E)$

$n(\pi^0) \sim \ln E \ (GeV) - 4.6$
For a 100 GeV incoming pion, $n(\pi^0) \approx 18$

Further collisions and multiplication continue until energy of secondaries below the threshold for pion production

Electrons, photons -> em showers

$\pi^0 \rightarrow \gamma \gamma$ -> em showers

Charged hadrons 20%

Nuclear fragments, p 25%

Neutrons, soft $\gamma$ 15%

Breakup of nuclei 40%

Either not detected or too slow to be within detector time window

$= \text{invisible energy}$

Detector response to hadronic component smaller than it should be

Electron response > hadron response

$e/h > 1$
Signal, per GeV of hadron component (h) and signal per GeV of electromagnetic component (e) for a hadron calorimeter with $e/h = 1.8$.

2 dissimilar contributions to the total detector response
**Hadronic Cascades**

**Electromagnetic component fraction**
Fraction is large, varies wildly, event to event
Includes \( \pi^- p \rightarrow \pi^0 n \)
\( \pi^+ n \rightarrow \pi^0 p \)

The average e.m. fraction increases with incoming hadron energy:

These fluctuations in \( f_{em} \) give rise to
* non linearity, since \( e/h > 1 \)
* non gaussian response
* poor energy resolution
Hadronic Cascades

Unlike electromagnetic showers, hadron showers do not show a uniform deposition of energy throughout the detector medium.

Simulation of two hadron showers

Red - e.m. component  Blue – charged hadrons
Hadronic Cascades

The e.m. component more pronounced at start of the cascade than hadronic component

- peak close to the first interaction
- exponential fall off with scale $\lambda_I$

$t_{\text{max}}(\lambda_I) \approx 0.2 \ln E[GeV] + 0.7$

$t_{95\%}(cm) \approx a \ln E + b$

For Iron
$a = 9.4, b=39 \quad \lambda_I = 16.7 \text{ cm}$
For a pion of 100 GeV, $t_{95\%} \approx 80 \text{ cm}$

For adequate containment, need $\sim 10 \lambda_I$

Depth of Iron needed 1.67 m
Depth of Cu needed 1.35 m
Hadronic Cascades

Hadron lateral shower development

Lateral spread of shower from transverse energy of secondaries, \( <p_T> \sim 350 \text{ MeV/c} \)

Core + Halo

95% containment in a cylinder of radius \( \lambda_1 = 16.7 \text{cm in Fe} \)

Compare to 2.19 cm for an electromagnetic cascade in PbWO\(_4\)

Radial shower profile for a 150 GeV pion
Hadronic energy resolution
Consequences for $e/h \neq 1$

- response with energy is non-linear
- fluctuations on $F_{\pi^0}$ contribute to $\sigma_E/E$

Since the fluctuations are non-Gaussian,
- $\sigma_E/E$ scales more weakly than $1/\sqrt{E}$, more as $1/E$
- Deviations from $e/h = 1$ also contribute to the constant term

‘Compensating’ sampling hadron calorimeters

Retrieve $e/h = 1$ by compensating for the loss of invisible energy, several approaches:

- Weighting energy samples with depth
- Use large elastic cross section for MeV neutrons scattering off hydrogen in the organic scintillator
- Use $^{238}U$ as absorber. $^{238}U$ fission is exothermic. Release of additional neutrons

Neutrons liberate recoil protons in the active material
Ionising protons contribute directly to the signal
Tune absorber/scintillator thicknesses for $e/h = 1$

Example Zeus: $^{238}U$ plates (3.3mm)/scintillator plates (2.6mm), total depth 2m, $e/h = 1$

Stochastic term $0.35/\sqrt{E(\text{GeV})}$

- Dual readout, Cerenkov radiator to get only em part, scintillator – all parts
Compensated hadron calorimetry & high precision em calorimetry are usually incompatible

In CMS, hadron measurement combines HCAL (Brass/scint) and ECAL(PbWO$_4$) data

Effectively a hadron calorimeter divided in depth into two compartments

Neither compartment is ‘compensating’:
\[ e/h \approx 1.6 \text{ for ECAL} \]
\[ e/h \approx 1.4 \text{ for HCAL} \]

Hadron energy resolution is degraded and response is energy-dependent

**CMS:**
- **Stochastic term** \( a = 120\% \text{ (Zeus 35\%)} \)
- **Constant term** \( c = 5\% \)

CMS energy resolution for single pions up to 300GeV
### Cascades – a comparison

<table>
<thead>
<tr>
<th></th>
<th>Electromagnetic</th>
<th>Hadronic</th>
</tr>
</thead>
<tbody>
<tr>
<td>X₀</td>
<td>( \sim 180 , \text{A} / \text{Z}^2 )</td>
<td>(&lt; \lambda ≤ 35 , \text{A}^{1/3} )</td>
</tr>
<tr>
<td>23 cm deep</td>
<td>( \times ) 2.19 cm</td>
<td>80 cm deep</td>
</tr>
</tbody>
</table>

**Electromagnetic cascades:**
- well understood
- linear response with energy
- simulations successfully reproduce observed distributions

**Hadron cascades:**
- much harder to model
- large, non predictable, event to event variations
- non linear response

Hadron calorimeters much larger than em calorimeters
Jets and Particle Flow
At colliders, hadron calorimeters serve primarily to measure jets and missing $E_T$

Single hadron response (ie at test beams)
* indication of the level to be expected for jet energy resolution

Make combined use of
* Tracker information
* Fine grained information from the ECAL and HCAL detectors
* Measurement of jets can be significantly improved

This holistic approach is often referred to as ‘Particle Flow Event Reconstruction’
Jets in CMS at the LHC, pp collisions at 7TeV

Red - ECAL, Blue - HCAL energy deposits
Yellow – Jet energy vectors
Jets and Particle Flow

**Momenta of particles inside a jet**

**Example**
Quark/gluon jet with a total $p_T$ of 500 GeV/c

Average $p_T$ carried by the stable constituent particles of the jet $\sim 10$ GeV

Reduces to a ‘few’ GeV for the stable constituent particles for jets with $p_T < 100$ GeV

In a typical jet 65% of jet energy in charged hadrons
25% in photons (mainly from $\pi \rightarrow \gamma\gamma$)
10% in neutral hadrons

**For charged particles with ‘low’ momenta,**
**better to use momentum resolution of the tracker than the energy resolution of the calorimeters**
Only 10% of the jet energy (the neutral hadrons) left to be measured in the ‘poor’ HCAL

**Dramatic improvements for jet energy resolution**
Energy fraction carried by particle type in a jet
Particle Flow versus Calorimetry alone

CMS - large central magnetic field of 4T

Very good charged particle track momentum resolution

Good separation of charged particle energy deposits from others in the calorimeters

Good separation from other tracks

Large improvement in jet resolution at low $P_T$ using the resolution of the tracking system

Jet energy resolution as a function of $P_T$

Simulated QCD-multijet events, CMS barrel section: $|\eta| < 1.5$
Jets and Particle Flow

**CMS Preliminary 2010**

- **Simulation, PF**
- **7-TeV data, 7.5 nb⁻¹, PF**
- **Simulation, calo**
- **7-TeV data, 7.5 nb⁻¹, calo**

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**Missing \( E_T \) normalised to the total transverse energy for Di-jet events in CMS with and without particle flow**

- Particle Flow
- Calorimetry only

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D Cockerill, RAL, STFC, UK
Jets and Particle Flow

CMS missing $E_T$ resolution

$< 10$ GeV on whole $\Sigma E_T$ range up to $350$ GeV.

Factor 2 improvement using Particle Flow technique

![Missing $E_T$ resolution for Di-jet events](image_url)

- **Calorimetry only**
- **Particle Flow**
- **Di-jet events**

$\Sigma E_T$ [GeV]
Detectors for Electromagnetic and Hadronic Calorimetry
There are two general types of calorimeter design:

**Sampling calorimeters**
Layers of passive absorber (ie Pb or Cu) alternating with active detector layers such as Si, scintillator or liquid argon
→ Only part of the energy is sampled
→ Used for both electromagnetic and hadron calorimetry

**Homogeneous calorimeters**
Single medium, both absorber and detector, eg:
Liquified Xe or Kr organic liquid scintillators
Dense crystal scintillators: PbWO$_4$ CsI(Tl) BGO and many others
Lead loaded glass
Almost entirely for electromagnetic calorimetry
Lead tungstate crystals, CMS

- CMS Barrel crystal, tapered ~2.6x2.6 cm² at rear
  Avalanche PhotoDiode readout

- CMS Endcap crystal, tapered, 3x3 cm² at rear
  Vacuum Photo Triode readout

Reasons for PbWO₄
Homogeneous medium
Fast light emission ~80% of light in 25 ns
Short radiation length \( X_0 = 0.89 \text{ cm} \)
Small Molière radius \( R_M = 2.10 \text{ cm} \)
Emission peak 425 nm, matches to photo-detectors
Reasonable radiation resistance to very high doses

Downside
Only ~70 \( \gamma / \text{MeV} \)
(Csl, \( 5.10^4 \gamma / \text{MeV} \))
Temp dependence -2% / °C
Extremely brittle $$$/cc
A CMS PbWO₄ crystal ‘boule’ emerging from its 1123°C melt
Lead tungstate crystals, CMS

CMS at the LHC – scintillating PbWO₄ crystals

**Total of 75848 PbWO₄ crystals**

**Barrel:** 36 Supermodules (18 per half-barrel)
61200 Crystals (34 types) – total mass 67.4 t

**Endcaps:** 4 Dees (2 per Endcap)
14648 Crystals (1 type) – total mass 22.9 t

CMS Barrel, 61200 crystals

An endcap Dee, 3662 crystals awaiting transport
CMS PbWO$_4$ - photodetectors

**Barrel**

Avalanche photodiodes (APD)
- Two 5x5 mm$^2$ APDs/crystal
- Gain 50
- QE ~75%
- Temperature dependence -2.4%/°C

**Endcaps**

Vacuum phototriodes (VPT)
- More radiation resistant than Si diodes
- UV glass window
- Active area ~ 280 mm$^2$/crystal
- Gain 8 -10 (B=4T)
- Q.E. ~20% at 420nm
Lead tungstate crystals, ALICE

ALICE at the LHC – scintillating PbWO$_4$ crystals

Avalanche photo diode readout

Some of the 17,920 PbWO$_4$ crystals for ALICE (PHOS)
Energy resolution: the everyday challenges

Intercalibration of all the channels

Requires several steps before, during and after data taking

- test beam pre-calibration
- continuous monitoring during data taking (short term changes)
- Intercalibration by physics reactions during running: pi-zeros, etas, with specialized data-stream, phi symmetry

Currently intercalibrate to ~1.2% barrel, ~2-3% endcaps
Lead tungstate crystals, CMS in-situ

CMS Preliminary 2010

$\sqrt{s}=7$ TeV, $L_{\text{int}}=35$ pb$^{-1}$

CMS in-situ electromagnetic performance
Noble liquid calorimeters

Noble liquids for homogeneous calorimeters

<table>
<thead>
<tr>
<th></th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
</tr>
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<tbody>
<tr>
<td>Z</td>
<td>18</td>
<td>36</td>
<td>58</td>
</tr>
<tr>
<td>A</td>
<td>40</td>
<td>84</td>
<td>131</td>
</tr>
<tr>
<td>$X_0$ (cm)</td>
<td>14</td>
<td>4.7</td>
<td>2.8</td>
</tr>
<tr>
<td>$R_M$ (cm)</td>
<td>7.2</td>
<td>4.7</td>
<td>4.2</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>1.4</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Ionization energy (eV/pair)</td>
<td>23.3</td>
<td>20.5</td>
<td>15.6</td>
</tr>
<tr>
<td>Critical energy $\epsilon$ (MeV)</td>
<td>41.7</td>
<td>21.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Drift velocity at saturation (mm/$\mu$s)</td>
<td>10</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

When charged particle traverses these materials, half lost energy converted to ionisation, half to scintillation

Sometimes collected together – but difficult technically

Kr for most compact calorimeter: NA48, NA62 (from 2011)
Ar for low cost, high purity: ICARUS
Xe horribly expensive: Dark Matter searches

Liquid Argon
5 mm/$\mu$s at 1 kV/cm,
5 mm gap $\rightarrow$ 1 $\mu$s for all electrons to reach the electrode.

Ion velocity $10^3$ to $10^5$ times slower

$\rightarrow$ doesn’t contribute to the signal, for electronics with $\mu$s integration times.
NA48 liquid Kr electromagnetic calorimeter

NA48 Liquid Krypton Ionisation chamber (T = 120K)

No metal absorbers: quasi homogeneous

2 cm x 2 cm cells
$X_0 = 4.7\text{cm}$
125 cm length ($27X_0$)

1 cm drift space
3 µs drift time

photons from $\pi^0$s from $K^0$ decays
NA48 Liquid Krypton Ionisation chamber (T = 120K)

No metal absorbers: quasi homogeneous

Energy resolution, blue after unfolding spectrometer resolution
a = 3.2%  b = 9%/E  c = 0.42%
ATLAS sampling electromagnetic calorimeter

- LAr hadronic end-cap (HEC)
- LAr electromagnetic end-cap (EMEC)
- LAr electromagnetic barrel
  - Barrel em 114 t
  - Inner radius 1.4 m
  - Depth 53 cm, 22-30 X0
- LAr forward (FCal)

6.4 m

Barrel
Absorbers immersed in liquid argon (90K)
Multilayer Cu-polyimide readout boards
Electric field to collect ionisation
1 GeV energy deposit $\rightarrow 5 \times 10^6 \text{e}^-$

Accordion geometry minimises dead zones
Liquid argon intrinsically rad hard
Readout board allows fine segmentation (azimuth, rapidity, longitudinal)
ATLAS sampling electromagnetic calorimeter

Readout grouping into trigger towers

25 Xo total
4 Xo fine grain, pizero rejection
16 Xo shower core
2 Xo to evaluate late starters

170,000 channels
Energy resolution at test beam

Mean energy response at three eta locations
ATLAS sampling electromagnetic calorimeter

**ATLAS Preliminary**

Data $\int Ldt = 39 \text{ pb}^{-1}$

- Fit to data
- Bkg. from fit to data
- Pythia MC (direct J/\(\psi\))
- Fit to MC+data bkg.

$\mu_{\text{data}} = 3080 \pm 2 \text{ MeV}$

$\mu_{\text{MC}} = 3083 \pm 1 \text{ MeV}$

$\sigma_{\text{data}} = 132 \pm 2 \text{ MeV}$

$\sigma_{\text{MC}} = 134 \pm 1 \text{ MeV}$

$|\eta| < 2.47$

(1.37 < $|\eta|$ < 1.52 excluded)

**ATLAS Preliminary**

**ATLAS results for J/Psi and Z**
LHCb calorimeters

HCAL  ECAL  Presampling
LHCb (and ALICE) sampling electromagnetic calorimeters at the LHC

LHCb module

67 scintillator tiles, each 4 mm thick, interleaved with 66 lead plates, each 2 mm thick. Readout through wavelength shifting fibres running through plates to phototubes.
LHCb sampling electromagnetic calorimeter

Wall of 3312 modules
LHCb sampling electromagnetic calorimeter

LHCb test beam results

LHCb in-situ results, pi-zero and eta signals
CMS Hadron Sampling Calorimeter

CMS Hadron calorimeter at the LHC

Workers in Murmansk sitting on brass casings of decommissioned shells of the Russian Northern Fleet

Explosives previously removed!

Casings melted in St Petersburg and turned into raw brass plates

Machined in Minsk and mounted to become absorber plates for the CMS Endcap Hadron Calorimeter

Brass absorber preparation
Light produced in the scintillators is transported through optical fibres to Hybrid Photo Diode (HPD) detectors.

The CMS HCAL being inserted into the solenoid.

Scintillator tile inspection.
Wavelength shifter and fibre optic readout for the CMS scintillator tiles
**Borexino**
* Detect solar neutrinos ($^7$Be, 0.86 MeV)
* Acceptance ~ 200 keV to a few MeV
* **300 t of ultra pure organic liquid scintillator**
* Minimise background from radioactive contamination
* **500 photo-electrons/MeV**
* **5% resolution at 1 MeV**

**Kamland**
* Detect anti-neutrinos from power reactors above ~ 0.7 MeV
* **1000 t of ultra pure organic liquid scintillator**
* Minimise background from radioactive contamination
* **300 photo-electrons/MeV**
* **7.5% resolution at 1 MeV**

---

D Cockerill, RAL, STFC, UK

Introduction to Calorimetry

21.3.2012
Inside Borexino, before filling !!

PM tubes with Winston cone light collectors
Future directions in Calorimetry

The International Linear Collider (ILC)
Exploit Particle Flow techniques

**ECAL** \( \sim 1 \times 1 \text{ cm}^2 \)  **SiW** project – CALICE
**HCAL** \( \sim 3 \times 3 \text{ cm}^2 \)  **Steel/scintillator**

High longitudinal sampling, 30 layers ECAL and 40 layers HCAL

CALICE prototype, 1.4/2.8/4.2mm thick W plates (30\(X_0\)) interleaved with Silicon wafer, read out with 1x1cm\(^2\) pads.  Resolution \( a \sim 17\% \), \( c \sim 1.1\% \)
Calorimeters at work

No tracks towards large em deposits => photons

CMS, $pp \rightarrow 2$ photons + $X$, at 7 TeV in search for $H \rightarrow \gamma\gamma$, ECAL red, HCAL blue
CMS r-phi (end on) view
pp \rightarrow 2 \text{ electrons} + X, 7 \text{ TeV}

ECAL red, HCAL blue

Z' \rightarrow 2\text{e} search

Effective mass \( M_{ee} = 1309 \text{ GeV} \)

Track towards each large em deposit
\( \Rightarrow 2 \text{ electrons} \)

Rather quiet elsewhere

Effective mass \( M_{ee} = 1309 \text{ GeV} \)
**Calorimeters at work**

CMS side view

\[ pp \rightarrow 2 \text{ electrons} + X \]

7 TeV

ECAL red, HCAL blue

\[ Z' \rightarrow 2\text{e} \]

Effective mass

\[ M_{ee} = 1309 \text{ GeV} \]

Track towards each large em deposit

\[ \Rightarrow 2 \text{ electrons} \]

748 GeV

840 GeV

Rather quiet elsewhere
Calorimeters at work

CMS

Dijet event from pp collision at 7 TeV

Effective mass 4696.74 GeV

Hard scatter involving over 65% of the available collision energy

Effective mass 4696.74 GeV

Hard scatter involving over 65% of the available collision energy
Calorimeters at work

ECAL red
HCAL blue

CMS Event with 5 jets from pp collision at 7 TeV
Calorimeters at work

CMS Experiment at the LHC, CERN

Run / Event: 150431 / 541464

Heavy ion collision in CMS, Pb-Pb, Nov 2010, ECAL red, HCAL blue
Calorimeters at work

Heavy ion collision in CMS, Pb-Pb, Nov 2010, ECAL red, HCAL blue
Summary

Calorimetry is one of the most important detector techniques for particle physics.

Calorimeters playing a crucial role for physics at the LHC, e.g., $H \rightarrow \gamma\gamma$, $Z' \rightarrow ee$, SUSY (missing $E_T$).

Wide variety of mature and new technologies are available.

Calorimeter design is dictated by physics goals and experimental constraints.

Compromises often necessary, i.e., in choosing between high resolution e.m. calorimetry or high resolution hadron calorimetry.

References:
Backups
Homogeneous e.m. calorimeters

PbWO$_4$ - CMS ECAL energy resolution

**Electron energy resolution as a function of energy**

Electrons centrally (4mmx4mm) incident on crystal

Resolution 0.4% at 120 GeV

Energy resolution at 120 GeV

Electrons incident over full crystal face

Energy sum over 5x5 array wrt hit crystal.

Universal position ‘correction function’ for the reconstructed energy applied

Resolution 0.44%
## Homogeneous calorimeters

#### Three main types:
- Scintillating crystals
- Glass blocks (Cerenkov radiation)
- Noble liquids

### Crystals

<table>
<thead>
<tr>
<th></th>
<th>NaI(Tl)</th>
<th>CsI(Tl)</th>
<th>CsI</th>
<th>BGO</th>
<th>PbWO₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>3.67</td>
<td>4.53</td>
<td>4.53</td>
<td>7.13</td>
<td>8.28</td>
</tr>
<tr>
<td>$X_0$ (cm)</td>
<td>2.59</td>
<td>1.85</td>
<td>1.85</td>
<td>1.12</td>
<td>0.89</td>
</tr>
<tr>
<td>$R_M$ (cm)</td>
<td>4.5</td>
<td>3.8</td>
<td>3.8</td>
<td>2.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Decay time (ns)</td>
<td>250</td>
<td>1000</td>
<td>10</td>
<td>300</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>slow component</td>
<td>36</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission peak (nm)</td>
<td>410</td>
<td>565</td>
<td>305</td>
<td>410</td>
<td>440</td>
</tr>
<tr>
<td></td>
<td>slow component</td>
<td>480</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light yield γ/MeV</td>
<td>$4 \times 10^4$</td>
<td>$5 \times 10^4$</td>
<td>$4 \times 10^4$</td>
<td>$8 \times 10^3$</td>
<td>$1.5 \times 10^2$</td>
</tr>
<tr>
<td>Photoelectron yield</td>
<td>1</td>
<td>0.4</td>
<td>0.1</td>
<td>0.15</td>
<td>0.01</td>
</tr>
<tr>
<td>(relative to NaI)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rad. hardness (Gy)</td>
<td>1</td>
<td>10</td>
<td>$10^3$</td>
<td>1</td>
<td>$10^5$</td>
</tr>
</tbody>
</table>

### Lead glass, SF-6

- OPAL at LEP
- $X_0 = 1.69$cm,
- $\rho = 5.2$ g/cm³

### Barbar

- @PEPII
- 10ms inter’n rate
- good light yield, good S/N

### KTeV

- at Tevatron,
- High rate,
- Good resolution

### L3@LEP

- 25µs bunch crossing,
- Low rad’n dose

### CMS at LHC

- 25ns bunch crossing,
- high radiation dose

ALICE

PANDA
Variation in the lattice
(e.g. defects and impurities)

local electronic energy levels in the energy gap

If these levels are unoccupied electrons moving in the conduction band may enter these centres

The centres are of three main types:
• **Luminescence centres** in which the transition to the ground state is accompanied by photon emission
• **Quenching centres** in which radiationless thermal dissipation of excitation energy may occur
• **Traps** which have metastable levels from which the electrons may subsequently return to the conduction band by acquiring thermal energy from the lattice vibrations or fall to the valence band by a radiationless transition
Scintillating crystals

\[ \Delta \lambda = \lambda_{\text{em}} - \lambda_{\text{ex}} \]

\[ \Delta E_a \]

\[ h_{\nu_{\text{ex}}} \]

\[ h_{\nu_{\text{em}}} \]

\[ Q_0^g, Q_0^e \]

\[ \text{Stokes shift} \]

\[ \text{excitation} \]

\[ \text{radiative emission} \]

\[ \text{PbWO}_4: \lambda_{\text{excit}}=300\text{nm}; \lambda_{\text{emiss}}=500\text{nm} \]
Efficiency of transfer to luminescent centres

\[ \eta_\gamma = \frac{N_\gamma}{E_{dep}} = \frac{SQN_{eh}}{E_{dep}} = \frac{SQ}{\beta E_g} \]

- \( S, Q \approx 1 \), \( \beta E_g \) as small as possible
- medium transparent to \( \lambda_{\text{emiss}} \)

Conduction band

\[ E_{dep} \rightarrow \text{e-h} \]

\[ E_s = \beta E_g \]

\[ \beta > 1 \]

\[ N_{eh} = \frac{E_{dep}}{\beta E_g} \]

radiative efficiency of luminescent centres

\[ N_\gamma = SQN_{eh} \]

Scintillating crystals
CMS Barrel and Endcap Homogeneous ECAL

A CMS Supermodule with 1700 tungstate crystals

Installation of the last SM into the first half of the barrel

A CMS endcap ‘supercrystal’
25 crystals/VPTs
Electromagnetic shower

Big European Bubble Chamber filled with Ne:H₂ = 70%:30%, 3T Field, L=3.5 m, X₀≈34 cm, 50 GeV incident electron
Lead tungstate crystals, CMS in-situ

Measurement of the Z peak using Z->ee decays with the PbWO$_4$ crystals of the CMS ECAL at the LHC

CMS ECAL
Instrumental resolution:
1.0 GeV in ECAL Barrel
for the Z peak (91 GeV)

Events / 1 GeV

CMS Preliminary 2011, 7TeV
L = 4.7 fb$^{-1}$

ECAL Barrel

Note the hard work needed for various detector corrections