Calorimetry

for Hadron Colliders

(mainly LHC)
A few points

Why build calorimeters?
  Calorimeters important properties

Electromagnetic processes involved

EM shower developments

Experimental techniques
  Homogeneous calorimeters
  Sampling calorimeters

Hadronic Showers

Tevatron and LHC calorimeters
  CDF, D0, CMS, LHCb, ALICE, ATLAS
  Structure
  Performance

Calorimeters for Linear Colliders
Hadronic Showers: EM fraction

Large fluctuation of the EM component from one shower to the other
Varies with energy

Energy resolution is degraded w.r.t. EM showers
50-100%/√E ± a few %
Jets

At Hadronic Colliders, quarks & gluons produced, evolves (parton shower, hadronisation) to become jets

In a cone around the initial parton:
  high density of hadrons
LHC calorimeters cannot separate all the incoming hadrons
  Use dedicated calibration schemes (based on simulation in ATLAS)
  Use tracking system to identify charged hadrons (Particle Flow in CMS)
Tevatron: 25 years ago!
Tevatron: 25 years ago

EM Calorimeter: Pb-Scintillator

CEM $|\eta| < 1.1$ - $18 \times \chi_0$

$\Delta \eta \Delta \phi = 0.1 \times 0.26$

$\sigma(E)/E = 13.5%/\sqrt{E} \oplus 1.5%$

PEM $1.1 < |\eta| < 3.6$ - $23.2 \times \chi_0$

$\Delta \eta \Delta \phi = 0.26 \times 0.26$ & $0.13 \times 0.13$

$\sigma(E)/E = 16%/\sqrt{E} \oplus 1.\%$

HAD Calorimeter: Fe-Scintillator

CHA+WHA $|\eta| < 1.1$ - $4.7 \lambda$

$\Delta \eta \Delta \phi = 0.1 \times 0.26$

$\sigma(E_T)/E_T = 50%/\sqrt{E_T} \oplus 3\%$

PHA $1.1 < |\eta| < 3.6$ - $23.2 \times \chi_0$

$\Delta \eta \Delta \phi = 0.26 \times 0.26$ & $0.13 \times 0.13$

$\sigma(E)/E = 80%/\sqrt{E} \oplus 5\%$
Tevatron: 25 years ago and still taking data

Fig. 31. Schematic view of a portion of the DØ calorimeters showing the transverse and longitudinal segmentation pattern. The shading pattern indicates groups of cells ganged together for signal readout. The rays indicate pseudorapidity intervals from the center of the detector.

The temperature at approximately 90 K. Different absorber plates are used in different locations. The electromagnetic sections (EM) use thin plates (3 or 4 mm in the CC and EC, respectively), made from nearly pure depleted uranium. The fine hadronic sections are made from 6-mm-thick uranium-niobium (2%) alloy. The coarse hadronic modules contain relatively thick (46.5 mm) plates of copper (in the CC) or stainless steel (EC).

A typical calorimeter cell is shown in Figure 32. The electric field is established by grounding the metal absorber plates and connecting the resistive surfaces of the signal boards to positive high voltage (typically 2.0 kV). The electron drift time across the 2.3 mm liquid argon gap is approximately 450 ns. Signal boards for all but the EM and small-angle hadronic modules in the EC are made from two 0.5 mm G-10 sheets. The surfaces of the sheets facing the liquid argon gap are coated with carbon-loaded epoxy [79] with a typical sheet resistivity of 40 MΩ; these surfaces serve as the high voltage electrodes for the gap. For one sheet, the other surface is bare G-10; the facing inner surface of the second sheet, originally copper-coated, is milled into the pattern necessary for segmented readout. Several such pads at approximately the same η and φ are...

**EM Calorimeter: U/LAr**

4 layers: ~1.4, 2.0, 6.8, 9.8 X₀

Δη×Δφ = 0.1×0.1

σ(E)/E = 13.5%/√E ± 1.5%

**HAD Calorimeter: U-Cu-Fe/LAr**

3 layers: ~1.3, 1.0, 0.76 λ

Δη×Δφ = 0.1×0.1
CMS calorimeter
The CMS calorimeter

The CMS choices
Solenoidal Magnetic Field: 4T
Outside the calorimeter
“Compact” calorimeter
Very precise EM calorimeter
PbWO crystal (very dense)
“Thin” HAD calorimeter
ECAL @ CMS

Precision electromagnetic calorimetry: 75848 PWO crystals

PWO: PbWO$_4$ about 10 m$^3$, 90 ton

Previous Crystal calorimeters: max 1 m$^3$

Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals (2x2x23 cm$^3$)

EndCaps: 1.48 < $|\eta|$ < 3.0
4 Dees
14648 crystals (3x3x22 cm$^3$)
CMS crystals: PbWO₄

Excellent energy resolution

\[ X_0 = 0.89\text{cm} \rightarrow \text{compact calorimeter (23cm for 26 X}_0\text{)} \]

\[ R_M = 2.2\text{ cm} \rightarrow \text{compact shower development} \]

Fast light emission (80% in less than 15 ns)

Radiation hard \((10^5\text{Gy})\)

But

Low light yield \((150\ \gamma/\text{MeV})\)

Response varies with dose

Response temperature dependance
Fast light emission: ~80% in 25 ns
Peak emission ~500 nm (visible region)
Radiation resistant to very high doses
Light Collection: APD & VPT

APD: ECAL barrel
- Photo-electrons from THIN 6µm p-layer induce avalanche in p-n junction
- Electrons from ionising particles traversing the bulk are NOT amplified

Vacuum Phototriodes: ECAL Endcaps
- Single stage PM tube with fine metal grid anode (insensitive to axial magnetic fields)
- Favourable for EC-ECAL
- Q.E. ~20% at 420nm
CMS ECAL Construction

Submodule
2x5 crystals

Module
400 crystals

Supermodule
1700 crystals

Total 36 Supermodules
CMS ECAL: Performance in testbeam

Excellent performance obtained in testbeam

\[
\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\text{GeV})}} \oplus \frac{125}{E(\text{MeV})} \oplus 0.3\%
\]

1/4 of barrel modules

How to preserve it at LHC

CERN, 8-9 Feb 2011

M. Diemoz, INFN-Roma
Sensitive to radiation dose

Large effect which needs to be corrected for
Laser system which sends light to each crystal during beam (LHC abort gap)
Crystal calibration in CMS

Inter-calibration: several steps
- testbeam (1/4 of barrel ECAL)
- cosmic muons in situ
- Laser pulsing: tracks variations during data taking
- Temperature stability: $\Delta E/E = -2\%/{}^0C$
- Using particles: $\pi^0$, $\eta^0$
Performance in-situ CMS

CMS Preliminary 2010
$\sqrt{s}=7 \, \text{TeV}$, $L_{\text{int}}=35 \, \text{pb}^{-1}$
CMS Hadronic calorimeter

Central: $|\eta| < 1.7$ Cu/scintillator + WLS
2 + 1 (HO) layers
5.9 + 3.9 $\lambda$ ($|\eta| = 0$)

Endcap $1.3 < |\eta| < 3$ Cu/scintillator + WLS
2/3 layers

Forward $2.85 < |\eta| < 5.19$
Fe/quartz fibers (radiations)

Copper: non magnetic material
CMS Hadronic Response

CMS is using a Particle Flow Technic to reconstruct Jets and Missing Transverse Energy

use the best measurement for each component

Tracker for charged hadron

ECAL for electrons & photons

HCAL for neutral hadrons
CMS-Particle Flow Jet Reconstruction Performance

**CMS Preliminary**

Jet Response vs. $p_T$ (GeV/c)

Jet-Energy Resolution vs. $p_T$ (GeV/c)

CMS Preliminary 2010

$|\eta| < 1.1$

$\sqrt{s} = 7$ TeV, $L = 34$ pb$^{-1}$

**MC**

Corrected Calo-Jets

Particle-Flow Jets

$0 < |\eta| < 1.5$

Jet Resolution vs. Transverse Momentum (GeV/c)

Anti-$k_T$ 0.5 PFJets

(See slide 103)
ATLAS calorimeter
ATLAS EM calorimeter

Accordion Pb/LAr $|\eta|<3.2 \sim 170k$ channels

Precision measurement $|\eta|<2.5$

3 layers up to $|\eta|=2.5$ + presampler $|\eta|<1.8$

2 layers $2.5<|\eta|<3.2$

- Layer 1 ($\gamma/\pi^0$ rej. + angular meas.)
  $\Delta\eta.\Delta\phi = 0.003 \times 0.1$

- Layer 2 (shower max)
  $\Delta\eta.\Delta\phi = 0.025 \times 0.0.25$

- Layer 3 (Hadronic leakage)
  $\Delta\eta.\Delta\phi = 0.05 \times 0.0.025$

Energy Resolution: design for $\eta\sim0$

$\Delta E/E \sim 10%/\sqrt{E} \oplus 150 \text{ MeV}/E \oplus 0.7%$

Angular Resolution

$50\text{ mrad}/\sqrt{E(\text{GeV})}$
The cryostat structure

- Superconducting solenoid coil
- Al cryostat warm wall
- Al cryostat cold wall (tapered)
- Presampler
- ID services + cables
- Scintillator
- Al cryostat walls warm
- Cold
- BARREL
  - Pb(1.5mm) 2.10cm/X0
  - Pb(1.1mm) 2.65cm/X0

ENDCAP
- Pb(1.7mm)
- OUTER WHEEL
- B = 2 T
- η = 1.375
- η = 1.475
- η = 1.68
- η = 1.8
Accordion: collecting the signal

The ionization signal is sampled every 25 ns by a 12 bits ADC in 3 gains. 5 samples are recorded at ATLAS.

The shaper output of the ionisation and calibration signal is different!

- Injected signal shape
- Different Injection point

NEED CORRECTIONS

The equalization of the electronic readout. Requires to know the shaping function of each cell at few percent level → equalization with an electronic control signal
Obtaining a fast response

Integrate the current over time $t_p << t_D$ ($t_p \sim 40$ ns)

S/N is smaller than in the case $t_p = t_D$

$S \sim t_p$, $N \sim \frac{1}{\sqrt{t_p}} \Rightarrow \frac{S}{N} \sim t_p^{3/2}$

$\sim$30 smaller for 40 ns than for 400 ns

Bipolar shaper response to triangular signal

$\rightarrow$ detector response time is not $t_d$ but $t_p$
The segmentation
Electrons $E = 245$ GeV

550 $\mu$m at $\eta = 0$

250 $\mu$m at $\eta = 0$
## Energy Resolution CMS vs ATLAS

<table>
<thead>
<tr>
<th></th>
<th>CMS (PbW0₄) / ATLAS (Pb/LAr)</th>
<th>10 GeV</th>
<th>100 GeV</th>
<th>1000 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stochastic (GeV)</strong></td>
<td></td>
<td>0.095 / 0.32</td>
<td>0.3 / 1</td>
<td>0.949 / 3.2</td>
</tr>
<tr>
<td><strong>Noise (GeV)</strong></td>
<td></td>
<td>0.3 / 0.3</td>
<td>0.3 / 0.3</td>
<td>0.3 / 0.3</td>
</tr>
<tr>
<td><strong>Constant (GeV)</strong></td>
<td></td>
<td>0.05 / 0.07</td>
<td>0.5 / 0.7</td>
<td>5 / 7</td>
</tr>
<tr>
<td><strong>σ(E) (GeV)</strong></td>
<td></td>
<td>0.30 / 0.44</td>
<td>0.65 / 1.26</td>
<td>5.1 / 7.7</td>
</tr>
<tr>
<td><strong>σ(E)/E (%)</strong></td>
<td></td>
<td>3 / 4.4</td>
<td>0.65 / 1.26</td>
<td>0.51 / 0.77</td>
</tr>
</tbody>
</table>

\[
\frac{\sigma(E)}{E} = \frac{0.03}{\sqrt{E\text{(GeV)}}} \oplus \frac{0.3}{E\text{(GeV)}} \oplus 0.005
\]

\[
\frac{\sigma(E)}{E} = \frac{0.1}{\sqrt{E\text{(GeV)}}} \oplus \frac{0.3}{E\text{(GeV)}} \oplus 0.007
\]
ATLAS LAr cell calibration

Cell to cell calibration from electronics calibration system

Inject a known signal amplitude
Correct for the difference between calibration signal and ionisation signal shapes
Correct for the sampling fraction
Apply calibration factor
ATLAS cluster correction

Make use of simulation
compare energy deposited in the calorimeter to the one reconstructed
takes into account un-detected energies in
dead region of the detector
energy deposited outside the cluster
parametrize corrections as a function of energy and \( \eta \)
dedicated correction factors for electrons, photons, jets

In situ, use precise knowledge of \( M_Z \) to set absolute energy scale (correct to \( \sim \%) \) from testbeam)

Method developed during testbeam campaigns and now applied in ATLAS

![Graph showing the ratio of reconstructed electron energy to the beam energy as a function of the electron beam energy.](image)
Cluster Energy Reconstruction

- $E_{\text{rec}}$: Need to correct $E_{\text{acc}}$ for losses
  - in matter in front of calorimeter (ID1 + cryostat)
  - Between Crysotat & Accordion
  - Loss outside the cluster $E_{\text{outcluster}}$
  - Rear leakage $E_{\text{leak}}$

- Use MC

![Diagram showing energy reconstruction process with variables $E_{\text{rec}}$, $E_{\text{outcluster}}$, $E_{\text{leak}}$, $E_{\text{acc}}$, and $E_{\text{ps}}$.](image-url)
ATLAS Linearity with data
ATLAS Hadronic calorimeters

Tiles Calorimeter $|\eta| < 1.7$
- Fe / Scintillator
- 3 layers in depth

LAr/Cu $1.7 < |\eta| < 3.2$
- 4 layers in depth

Forward: 1 layer EM, 2 HAD
- LAr/Cu or W $3.2 < |\eta| < 4.9$

Total thickness: ~ 8 -10 $\lambda$
Use of different technics: cope with radiations in forward region
ATLAS Hadronic Tiles calorimeter
HEC Cu/LAr
1.5 < |\eta| < 3.2 ~5600 channels
4 layers \( \Delta \eta \cdot \Delta \varphi = 0.1 \times 0.1 \) & 0.2x0.2

FCal Cu-W/LAr
3.1 < |\eta| < 4.9 ~3500 channels
3 layers \( \Delta x \cdot \Delta y \) 3x2.6 cm\(^2\) - 5.4x4.7 cm\(^2\)
Electromagnetic end-cap calorimeter

Forward calorimeter

Hadronic end-cap calorimeter

Feed-throughs and front-end crates

Endcap cryostat view

5.4.2 Signal feed-throughs

The signal feed-throughs bring all the signal, monitoring, calibration and spare lines through the insulating vacuum from the liquid-argon cold volume to the front-end crates located at room temperature around and on the outside of the barrel and end-cap cryostats. A total of 64 feed-throughs serve the \( \times 10 \) lines of the barrel electromagnetic calorimeter, whereas a total of \( 5 \times 10 \) feed-throughs serve the \( 4 \times 10 \), lines of the two end-caps. In each end-cap, 4 feed-throughs are used by the EMEC, 4 by the HEC and 1 by the FCal. The EMEC uses also part of the four HEC feed-throughs.

A feed-through consists primarily of a warm flange and a cold flange, with a flexible bellows welded between them. The volume between the two flanges is under vacuum. Each flange houses four gold-plated pin carriers, providing a total of \( (9) \) signal connections per feed-through.
ATLAS Jets Performance

\[ \sigma(E)/E \ (50 \text{ GeV}) \sim 15 \% \]
Fractional JES systematic uncertainty

Anti-$k_t$, $R=0.6$, EM+JES, $0.3 \leq |\eta| < 0.8$, Data 2010 + Monte Carlo QCD jets

- ALPGEN + Herwig + Jimmy
- JES calibration non-closure
- Single particle (calorimeter)
- Total JES uncertainty

- Noise Thresholds
- PYTHIA Perugia2010
- Additional dead material

ATLAS Preliminary
LHCb calorimeter
<table>
<thead>
<tr>
<th>sub-detector</th>
<th>SPD/PS</th>
<th>ECAL</th>
<th>HCAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of channels</td>
<td>$2 \times 5952$</td>
<td>5952</td>
<td>1468</td>
</tr>
<tr>
<td>overall lateral dimension in x,y</td>
<td>$6.2 \text{ m} \times 7.8 \text{ m}$</td>
<td>$6.8 \text{ m} \times 7.8 \text{ m}$</td>
<td>$6.8 \text{ m} \times 8.4 \text{ m}$</td>
</tr>
<tr>
<td>depth in z</td>
<td>$180 \text{ mm}$, $2X_C$, $0.1 \lambda_j$</td>
<td>$835 \text{ mm}$, $25X_C$, $1.1 \lambda_j$</td>
<td>$1656 \text{ mm}$, $5.6 \lambda_j$</td>
</tr>
<tr>
<td>basic requirements</td>
<td>20-30 photoelectrons per MIP</td>
<td>$\sigma(E)/E = 10% / \sqrt{E} \oplus 1.5%$</td>
<td>$\sigma(E)/E = 80% / \sqrt{E} \oplus 10%$</td>
</tr>
<tr>
<td>dynamic range</td>
<td>0-100 MIPs, 10 bits (PS), 1 bit (SPD)</td>
<td>0-10 GeV $E_x$, 12 bits</td>
<td>0-10 GeV $E_x$, 12 bits</td>
</tr>
</tbody>
</table>
LHCb segmentation

Lateral segmentation
(showing 1/4 of the detectors front face)

ECAL (SPD/PS)  HCAL

Outer section: 262.6 mm cells
Inner section: 131.3 mm cells
2688 channels
860 channels

Outer section: 121.2 mm cells
Middle section: 60.6 mm cells
Inner section: 40.4 mm cells
2688 channels
1792 channels
1472 channels
Module structure: Pb/Scintillator

Engineering design and assembly of modules:

Weight of one module ~28 kg

Assembly of scintillator, lead, fibers and the readout part for inner section modules
Shower identification of triggering

- Shower identification of triggering
- Pb
- Pb/Scintillator
- Fe/Scintillator
- e±
- π±
- π0
- SPD (scintillator)
- PS (scintillator)
- 12mm
Module performance (testbeam)

**Module performance**

**Uniformity**
Lateral scan of ECAL module with 50 GeV e⁻ beam

- Uniformity parameters:
  - $A_{\text{global}} = (0.46 \pm 0.03)\%$
  - $A_{\text{local}} = (0.39 \pm 0.01)\%$

- ±1.3% for e-beam parallel to module axis
- ±0.6% for e-beam at 200 mrad

**Energy resolution**
ECAL module energy resolution: e⁻ beam

- Required energy resolution:
  - $10\% / \sqrt{E} \oplus 1\%$

![Graph showing uniformity and energy resolution data](image-url)
ALICE calorimeter
Complete since 2008:
ITS, TPC, TOF, HMPID, FMD, T0, V0, ZDC,Muon arm, Acorde 
PMD, DAQ

Partial installation (2010):
4/10 EMCAL* (approved 2009)
7/18 TRD* (approved 2002)
3/5 PHOS (funding)

~ 60% HLT (High Level Trigger)

2011
10/10 EMCAL
10/18 TRD

TRD to be completed end 2011
Elements of the ALICE calorimeter

- StructureSupport
- 12 Modules
- 4 Towers
  - Pb-Scint
- 24 Strip Modules
- Sampling calorimeter (20 $X_0$)
  - 1 module = 4 towers
    - $(\Delta \eta \Delta \phi \sim 0.014 \times 0.014)$
  - 1 tower = 77 layers of
    - 1.76 mm scint./ 1.44 mm Pb

StrongBack
Dual readout for hadronic showers DREAM
Intermezzo: DREAM (ongoing R&D)

- Quartz sensitive to em only (Cerenkov light)
- Scintillator sensitive to visible energy only

Some characteristics of the DREAM detector:
- Depth 200 cm (10.0 \( \lambda_{int} \))
- Effective radius 16.2 cm (0.81 \( \lambda_{int} \), 8.0 \( \rho_M \))
- Mass instrumented volume 1030 kg
- Number of fibers 35910, diameter 0.8 mm, total length \( \approx 90 \text{ km} \)
- Hexagonal towers (19), each read out by 2 PMTs
DREAM: The principle

DREAM: The (energy-independent) Q/S method

\[ S = E \left[ f_{em} + \frac{1}{(e/h)_S} (1 - f_{em}) \right] \]

\[ Q = E \left[ f_{em} + \frac{1}{(e/h)_Q} (1 - f_{em}) \right] \]

\[ e/h = 1.3 \text{ (S)}, \quad 5 \text{ (Q)} \]

\[ \frac{Q}{S} = \frac{f_{em} + 0.20 (1 - f_{em})}{f_{em} + 0.77 (1 - f_{em})} \]
DREAM: some results

![Energy resolution vs. 1/√E plot](image1)

- Scintillator: $94\% / √E + 7\%$
- Quartz: $81\% / √E + 2.2\%$
- Q/S corrected: $64\% / √E + 0.6\%$

![Calorimeter response vs. Energy plot](image2)

- Jets (raw data)
- Jets (after Q/S)
- Pions (raw data)
- Pions (after Q/S)
- Calibration (e⁻)

±3% variation
Back to LHC: Taking data
Signal Readout: ATLAS LAr example
Trigger
ATLAS Trigger chain

Interaction rate 
~1 GHz

Bunch crossing rate 40 MHz

LEVEL 1 TRIGGER
< 75 (100) kHz

Regions of Interest

LEVEL 2 TRIGGER
~ 1 kHz

EVENT FILTER
~ 100 Hz

CALO MUON TRACKING

Pipeline memories

Derandomizers

Readout drivers (RODs)

Readout buffers (ROBs)

Event builder

Full-event buffers and processor sub-farms

Data recording
Level 1 calorimeter trigger

Trigger towers \((\Delta \eta \times \Delta \phi = 0.1 \times 0.1)\)

Electromagnetic calorimeter

Hadronic calorimeter

Vertical Sums

Horizontal Sums

Electromagnetic isolation ring

& 

Hadronic isolation ring and core

LAr - Barrel

ATLAS preliminary

Calorimeter cell energy [GeV]

L1Calo ADC energy [GeV]
Trigger performance and “menus” are a key element towards physics results. Balance between the various channels are regularly adjusted vs instantaneous luminosity. For calorimetry:

- Get calibrated energy for L1
- Use “final” energy calibration (à la offline) for HLT
ATLAS $E_{T}^{\text{miss}}$ calibration

![Graph showing $E_{T}^{\text{miss}}$ calibration with data and MC comparison.](image)
Calorimeters: behind the Inner Detector
Material in front of calorimeters

Electron Brem
Photon conversions

Proper description of material (ID weighting during construction)

Taken into account for event reconstruction
Understanding material in front of calorimeter
Calorimeters R&D for Linear Colliders
Some ideas for future calorimeters (Linear Colliders)

Boson-Boson scattering
Hadronic Decay of W & Z
Needs improved energy resolution
Highly granular calorimeters optimized for particle flow

$\Delta(M_Z, M_W) \sim 10$ GeV

c.f. R. Pöschl for the CALICE collaboration - SPSC January 2011
Calorimeters developed for Linear colliders

- VXD tag b,c jets
- Tracking system
- EM Cal
- HAD Cal
- Muon system
Calorimeter requirements

- Extreme high granularity
- Hermetic
- Compact
  Inside the coil of the solenoid
Many ongoing testbeams (e.g. CALICE)

Linear Collider Calorimeters Development:
Fine segmentation (also for HAD)
Both longitudinal and lateral
Self-supporting calorimeter
Minimize dead zones
Semi-digital readout
Electronics embedded inside the calorimeter
Development of Power Pulsing

Example: DHCAL
Some conclusions

Calorimeters are playing a critical role in the interpretation of events at LHC

- Electron/Photon - Jet - $E_T^{miss}$ reconstruction
- Background rejection $e^\pm$/jets - $\gamma/\pi^0$

Triggering

Detector design & construction have (obviously) a direct impact onto the physics

- Cell segmentation 0.1x0.1 at Tevatron, 0.025(0.003)x0.025 at LHC, semi-digital R/O for Linear Collider

More and more precise simulation (interaction with matter, detector geometry) allows to understand quickly and very efficiently the detector performance

LHC detectors and calorimeters in particular are performing already very close to designed specifications