Introduction to Calorimeters

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Southampton Lecture
4 Dec 2014
Overview

- Introduction
- Electromagnetic Calorimetry
- Hadron Calorimetry
- Jets and Particle Flow
- Future directions in Calorimetry
- Summary
Introduction

Calorimetry

One of the most important and powerful detector techniques in experimental particle physics

Two main categories of Calorimeter:

Electromagnetic calorimeters for the detection of $e^\pm$ and neutral particles $\gamma$

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 losing small amounts of energy by ionisation

The 13 particle types above completely dominate the particles from high energy collisions reaching and interacting 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, and neutralinos, $\chi^0$, undetected but with hermetic calorimetry can be inferred from measurements of missing transverse energy in collider experiments
Calorimeters

Calorimeters designed to stop and fully contain their respective particles
‘End of the road’ for the incoming particle

Measure - energy of incoming particle(s) by total absorption in the calorimeter
- spatial location of the energy deposit
- (sometimes) direction of the incoming particle

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

Detector response \( S \propto E \)
Calorimetry: basic mechanism

Energy lost by the formation of electromagnetic or hadronic cascades/showers in the material of the calorimeter

Many charged particles in the shower

The charged particles ionize or excite the calorimeter medium

The ionisation or excitation can give rise to:

- The emission of visible photons, O(eV), via scintillation
- The release of ionisation electrons, O(eV)

Photo-detectors or anodes/dynodes then detect these “quanta”
Introduction

Where you STOP is what you ARE !!!

2 metres

A ‘wedge’ end on view of the CMS experiment at the LHC

Magnetic field, 4T

Get sign of charged particles from the Tracker

Tracker to be of minimum material to avoid losing particle energy before the calorimeters.

Key:
- Muon
- Electron
- Charged Hadron (e.g. Pion)
- Neutral Hadron (e.g. Neutron)
- Photon

Tracker em calorim had calorim

\[ e^\pm \]
\[ \gamma \]
\[ p, \pi^\pm, K^\pm \]
\[ n, K^0 \]
\[ \mu^\pm \]
There are two general types of calorimeter design:

1) Sampling calorimeters

Layers of passive absorber (ie Pb or Cu) alternating with active detector layers such as plastic scintillator, liquid argon or silicon

→ Only part of the energy is sampled
→ Used for both electromagnetic and hadron calorimetry
→ Cost effective

ATLAS   ECAL & HCAL
ALICE   EMCAL
CMS    HCAL
LHCb   ECAL
2) Homogeneous calorimeters

Single medium, both absorber and detector
- Liquified Ar/Xe/Kr
- Organic liquid scintillators, large volumes, Kamland, Borexino, Daya Bay
- Dense crystal scintillators: PbWO$_4$, CsI(Tl), BGO and many others
- Lead loaded glass

**Almost entirely for electromagnetic calorimetry**

![Diagram of a crystal calorimeter with particle paths and detector types listed: Babar ECAL CsI(Tl), ALICE ECAL (PbWO$_4$), CMS ECAL (PbWO$_4$), Si photodiode or PMT.]}
Electromagnetic Calorimetry
Electromagnetic Cascades

Electromagnetic cascades
• $e^\pm$ bremsstrahlung and photon pair production
  By far the most important processes for energy loss by electrons/positrons/photons with energies above 1 GeV
  Leads to an e.m. cascade or shower of particles

• Bremsstrahlung
  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.

$$E = E_0 \, e^{-x/X_0} \quad \text{where} \quad -\frac{dE}{dx} = 4\alpha N_A Z^2 A^2 r_e^2 E \ln \frac{183}{Z^{1/3}}$$

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

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

$X_0 \sim 180 \frac{A}{Z^2} \text{ [g cm}^{-2}\text{]}$

In Pb (Z=82) $X_0 \sim 5.6 \text{ mm}$

Due to the $1/m^2$ dependence for bremsstrahlung, muons only emit significant bremsstrahlung above ~1 TeV ($m_\mu \sim 210 m_e$).

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

Pair production
Characteristic mean free path before pair production, \( \lambda_{\text{pair}} = \frac{9}{7} X_0 \)

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

Brem and pair production dominate the processes that degrade the incoming particle energy

50 GeV electron
Losers 32 GeV over \( 1 X_0 \) 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 \( 1 X_0 \), ionization loss \( \sim O(10) \) of MeV
Factor of \( \sim 1000 \) less than the above
Below a certain critical energy, $E_c$:

$e^\pm$ energy losses are greater through ionisation than bremsstrahlung

The multiplication process runs out

- Slow decrease in number of particles in the shower
- Electrons/positrons are stopped

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

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

\[ \text{Pb (Z=82), } E_c = 7.3 \text{ MeV} \]

Liquids and solids
Consider only Bremstrahlung and pair production
Assume: Incident energy = $E_0$, $\lambda_{pair}$ and $X_0$ are equal
Assume: after each $X_0$, the number of particles increases by factor 2

After ‘t’ layers, each of thickness $X_0$:
Number of particles = $N(t) = 2^t$
Average energy per particle = $E(t) = E_0 / 2^t$

Process continues until $E(t) < E_c$
This layer contains the maximum number of particles:

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

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

**For a 50 GeV electron on Pb**

$N_{total} \sim 14000$ particles

$t_{max}$ at $\sim 13X_0$ (an overestimate)
EM Cascade Profiles

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

GEANT simulation: 100 GeV electron shower in the NA48 liquid Krypton calorimeter
**Longitudinal Shower Development**

Shower only grows logarithmically with $E_o$.

Shower maximum, where most energy deposited,

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

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

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

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

Rule of thumb: RMS spread in shower leakage at the back $\sim 0.5 \times$ average leakage at the back

CMS Require the rms spread on energy measurement to be $< 0.3\%$
Therefore require leakage $< 0.65\%$

**Require crystals 25 $X_0$ / 23 cm long**

Amount of shower containment as a function of $t_{\text{max}}$ - see additional slides
EM Cascade Profiles

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

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

\(R_M = 2.19 \text{ cm in PbWO}_4 \) (\(X_0 = 0.89\text{cm}, E_c \approx 8.5\text{MeV}\))

How many \(R_M\) to adequately measure 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 3x3 (or 5x5) arrays of PbWO\(_4\) crystals
Detectors for Electromagnetic Calorimetry
PbWO$_4$ crystals: CMS and ALICE

Vital properties for use at LHC:

**Compact and radiation tolerant**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>8 g/cc</td>
</tr>
<tr>
<td>$X_0$</td>
<td>0.89 cm</td>
</tr>
<tr>
<td>$R_M$</td>
<td>2.2 cm</td>
</tr>
<tr>
<td>Sum over 3x3 or</td>
<td></td>
</tr>
<tr>
<td>5x5 crystals</td>
<td></td>
</tr>
</tbody>
</table>

**Fast scintillation**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission</td>
<td>~80% in 25 ns</td>
</tr>
<tr>
<td>Wavelength</td>
<td>425 nm</td>
</tr>
<tr>
<td>Output</td>
<td>150 photons / MeV (low, only 1% wrt NaI)</td>
</tr>
</tbody>
</table>

(See backup slide to compare to other crystals/liquids)
Homogeneous calorimeters

A CMS PbWO$_4$ crystal ‘boule’ emerging from its 1123°C melt
Homogeneous electromagnetic calorimeters

CMS at the LHC – scintillating PbWO_4 crystals

**Total of 75848 PbWO_4 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
Sampling electromagnetic calorimeters

ATLAS ‘Accordion’ sampling liquid argon calorimeter at the LHC

Corrugated stainless steel clad Pb absorber sheets, 1-2 mm thick

**Immersed in liquid argon (90K)**

Multilayer Cu-polyimide readout boards

**Collect ionisation electrons** with an electric field across 2.1 mm liquid Argon drift gap

1 GeV energy deposit $\rightarrow$ collect $5.10^6$ e$^-$

Accordion geometry minimises dead zones

Liquid argon intrinsically radiation hard

Readout board allows fine segmentation (azimuth, rapidity, longitudinal)
Sampling electromagnetic calorimeters

The LHCb sampling electromagnetic calorimeter 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 Avalanche Photodiodes

Wall of 3312 modules

3 types of modules
Borexino
Detect 0.862 MeV neutrinos from $^7$Be decays in the sun

300 t ultra pure organic liquid scintillator. Less than $10^{-16}$ g/g of $^{238}$U and $^{232}$Th

$10^4$ photons / MeV at 360 nm
3 ns decay time
Photon mean free path 8 m

Readout
2,212 photo-multiplier 8 inch tubes

Timing 1 ns
Cluster position resolution 16 cm
Liquid Scintillator Calorimeters

Borexino

**Top:** Internal surface of stainless steel support sphere + PMTs + their optical concentrators.

**Bottom:** Preparation of outer vessel + close-up of an optical concentrator.
Energy Resolution
Energy resolution of a calorimeter where $E$ is energy of incoming particle:

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

$a$, stochastic term

Fluctuations in the number of signal generating processes, ie on the number of photo-electrons generated

$b$, noise term

Noise in readout electronics

‘pile-up’ due to other particles from other collision events arriving close in time
Energy Resolution

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

\(c\), 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 or in detector

**Crucial to have small constant term for good energy resolution at the highest particle energies**
Consider a physics search for a 2 TeV $Z' \rightarrow e^+e^-$

Each electron has energy, $E = 1\text{ TeV} = 1000\text{ GeV}$

For stochastic term: Typical CMS $3\% / \sqrt{E(\text{GeV})} \rightarrow \sim 0$

Noise term: Typical CMS $0.25\text{ GeV} / E(\text{GeV}) \sim 0$

Only left with Constant term $\sigma/E \sim 0.5\%$

$Z'$ mass will be measured to a precision of $\sim \sqrt{2} \times 0.5\% \sim 0.7\% = 14\text{ GeV}$

**Calorimetry:**
The relative resolution, $\sigma/E$, **improves** with increasing particle energy $E$

**Goal of calorimeter design** - find best compromise between the three contributions - at a price you can afford!
Intrinsic resolution of homogeneous e.m. calorimeters

Energy released in the detector material mainly ionisation and excitation

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

Mean number of quanta produced

The intrinsic energy resolution is given by the fluctuations on ‘n’

\[ \sigma_E / E = \sqrt{n / n} = \sqrt{(Q / E)} \]

Typically obtain  \( \sigma_E / E \ 1\% - 3\% / \sqrt{E} \text{ (GeV)} \)

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 Germanium.

Fluctuations much reduced:

\[ \sigma_E / E = \sqrt{(FQ / E)} \] where F is the ‘Fano’ factor.

\( F \sim 0.1 \text{ in Ge} \)

Detector resolution in AGATA 0.06% (rms) for 1332 keV photons
Intrinsic em energy resolution for homogeneous calorimeters

The AGATA Germanium detector

Experiment with excited nucleii from a target
1382 keV line width 4.8 keV (fwhm)
Resolution 0.15%
Resolution 0.06% with a source
Energy resolution for crystal em calorimeters

Energy resolution - the CMS PbWO₄ crystal calorimeter

Scintillation emission only small fraction of energy loss in crystal, so $F \sim 1$

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

$F \sim 2$ for the crystal + APD combination

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

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

This assumes total lateral shower containment

In practice energy summed over limited 3x3 or 5x5 arrays of crystals, to minimise added noise

Expect $a_{\text{leak}} = 2\%$ from an energy sum over a 3x3 array of crystals

Expect a stochastic term of $a = a_{pe} \oplus a_{\text{leak}} = 2.9\%$

Measured value $2.8\%$
Energy resolution in homogeneous em calorimeters

Energy resolution

CMS ECAL, 3x3 array of PbWO$_4$ crystals
Test beam electrons

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

- $a$, stochastic term = 2.83%
- $c$, constant term = 0.26%

Borexino
Photoelectron yield \( \sim 500 \) per MeV

Expect \( \sqrt{500} / 500 = 4.4\% \)
Measured \( \sim 5\% \) at 1 MeV
Prior to installation: modules taken to test beams at CERN and elsewhere

In situ in CMS: trigger, record and use known resonances to calibrate the crystals

$\pi^0 \rightarrow \gamma \gamma$

$\eta \rightarrow \gamma \gamma$

$Z \rightarrow ee$

peak at 91 GeV

width of Gaussian 1.01 GeV

Crucial input for resolution estimates for $H \rightarrow \gamma \gamma$ at 125 GeV
In situ in CMS also use:

$W$ decays, $W \rightarrow e^\pm \nu$

Electron energy, $E$, measured in the ECAL
Electron momentum, $p$, measured in the Tracker
Optimize the $E/p$ distributions ($E/p = 1$ ideally)

Phi symmetry (gives quick initial values)
The transverse energy flow, summed over many “minimum bias” collisions, should be the same towards any phi angle

Use this symmetry to calibrate rings of individual crystals sitting at the same pseudorapidity
Getting excellent energy resolution – in a real detector !!

![Graph showing energy resolution](image)

**Instrumental resolution of 1.01 GeV from Z -> ee decays in the CMS ECAL Barrel**

- **CMS Preliminary 2011, 7TeV**
- **L = 4.7 fb⁻¹**
- **ECAL Barrel**

**Note the crucial work needed for the various corrections**

**Values**
- Instrumental resolution of 1.01 GeV
- Events / 1 GeV
- Mₑₑ (GeV/c²)

**Legend**
- No corrections
- Intercalibrations (IC)
- IC + transparency
Intrinsic resolution of sampling electromagnetic calorimeters

Sampling fluctuations arise due to variations in the number of charged particles crossing the active layers

\[ n_{\text{charged}} \propto E_0 / t \quad (t = \text{thickness of each absorber layer}) \]

If each sampling is independent

\[ \sigma_{\text{samp}} / E = 1 / \sqrt{n_{\text{charged}}} \propto \sqrt{(t / E)} \]

Need ~100 sampling layers to compete with homogeneous devices.

Typically \( \sigma_{\text{samp}/E} \sim 10\% / \sqrt{E} \)
Intrinsic energy resolution for sampling e.m. calorimeters

Intrinsic resolution of sampling electromagnetic calorimeters

ATLAS  stochastic term  ~10%
constant term  0.3%

Thickness of the 1-2 mm thick absorber sheets controlled to 6.6 µm to achieve a constant term of 0.3%

LHCb  stochastic term  9.4%
constant term  0.83%

Also: ATLAS spatial resolution ~5mm / √E (GeV)
Hadronic Calorimetry
Hadronic cascades much more complex than e.m. cascades

Shower development determined by the mean free path, $\lambda_I$, between inelastic collisions

The nuclear interaction length is given by $\lambda_I = A / (N_A \sigma_{inel})$, $\sigma_{inel} \approx \sigma_0 A^{0.7}$, $\sigma_0 \approx 35 \text{ mb}$

Expect $\sigma_I \propto A^{2/3}$ and thus $\lambda_I \propto A^{1/3}$.

In practice $\lambda_I \sim 35 A^{1/3}$

High energy hadrons interact with nuclei producing secondary particles, mostly $\pi^\pm$ and $\pi^0$

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

Collision with a nucleus
Multiplicity of secondary particles $\propto \ln(E)$
$n(\pi^0) \sim \ln E (\text{GeV}) - 4.6$

For a 100 GeV incoming hadron, $n(\pi^0) \approx 18$

~ 1/3 of the pions produced are $\pi^0$ with $\pi^0 \rightarrow \gamma\gamma$ in $\sim 10^{-16}$ s

Thus the cascades have two distinct components: hadronic and electromagnetic
Hadronic Cascades

Simulations of hadron showers

Red - e.m. component    Blue – charged hadrons

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

**Hadronic longitudinal shower development**

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

Shower profile characterised by a peak close to the first interaction, then, an 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**: $a = 9.4, b = 39, \lambda_I = 16.7 \text{ cm}$

$E = 100 \text{ GeV}, t_{95\%} \approx 80 \text{ cm}$

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

- Iron 1.67m
- Copper 1.35m

**Hadronic lateral shower development**

The shower consists of core + halo

**95% containment**: cylinder of radius $\lambda_I = 16.7 \text{ cm in iron}$

Compare to a radius of 2.19 cm for an e.m cascade in PbWO$_4$
Electromagnetic versus hadronic scale for calorimetry

\[ X_0 \sim 180 \frac{A}{Z^2} \ll \lambda_I \sim 35 A^{1/3} \]

E.M shower size in PbWO4  
23 cm deep \times 2.19 cm radius

Hadron shower size in Iron  
80 cm deep \times 16.7 cm radius

Hadron cascades much longer and broader than electromagnetic cascades

Hadron calorimeters much larger than em calorimeters
The hardware - electromagnetic and hadronic calorimeters

Detectors for Hadronic Calorimetry
Hadron Sampling Calorimeters

CMS Hadron calorimeter at the LHC

Brass absorber preparation

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
The CMS HCAL being inserted into the solenoid

Light produced in the scintillators is transported through optical fibres to Hybrid Photo Diode (HPD) detectors
Light emission from the scintillator tiles blue-violet, $\lambda = 410-425$ nm.

This light is absorbed by wavelength shifting fibers which fluoresce in the green, $\lambda = 490$ nm.

The green light is conveyed via clear fiber waveguides to connectors at the ends of the scintillator megatiles.
Energy resolution of hadronic calorimeters

Hadron calorimetry resolution
Strongly affected by the energy lost as ‘invisible energy’:
- nuclear excitation followed by delayed photons
  (by up to to ~1μsec, so usually undetected)
- soft neutrons
- nuclear binding energy

Fluctuations in the ‘invisible energy’ play an important part in the degradation of the intrinsic energy resolution

Further degradation
If the calorimeter responds differently as a function of energy to the em component of the cascade ($\pi^0 \rightarrow \gamma\gamma$)

$F_{\pi^0} \sim 1/3$ at low energies
$F_{\pi^0} \sim a \log(E)$ (the em part increases or ‘freezes out’ with energy)

In general, hadronic component of hadron shower produces smaller signal than the em component, so $e/h > 1$

Hadron energy dissipation in Pb
Nuclear break-up (invisible) 42%
Charged particle ionisation 43%
Neutrons with $T_N \sim 1$ MeV 12%
Photons with $E_\gamma \sim 1$ MeV 3%

EM fraction for 20GeV and 200GeV pions on lead
Consequences for $e/h \neq 1$

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

Since the fluctuations are non-Gaussian
  - $\sigma_E/E$ scales more weakly than $1/\sqrt{E}$, more as $1/E$

‘Compensating’ sampling hadron calorimeters seek to restore $e/h = 1$ (see backup slide) and achieve higher resolution and linearity
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’:
\[ e/h \sim 1.6 \text{ for ECAL} \]
\[ e/h \sim 1.4 \text{ for HCAL} \]

Hadron energy resolution is degraded and response is energy-dependent

Stochastic term \[ a = 120\% \]
Constant term \[ c = 5\% \]

CMS energy resolution for single pions up to 300GeV
Jets and Particle Flow
At colliders, hadron calorimeters serve primarily to measure jets and missing $E_T$.

Single hadron response gives an 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

Jets from a simulated event in CMS
**Traditional approach**
Components of jet energy only measured in ECAL and HCAL

In a typical jet 65% of jet energy in **charged** hadrons  
25% in **photons** (mainly from $\pi^0 \rightarrow \gamma\gamma$)  
10% in **neutral hadrons**

**Particle Flow Calorimetry**

- Charged particles measured with tracker when better  
- Photons measured in ECAL  
- Leaves only neutral hadrons in HCAL (+ECAL)

Only 10% of the jet energy (the neutral hadrons) left to be measured in the poorer resolution HCAL

Dramatic improvements for overall jet energy resolution
Jet measurements with Particle Flow

Momenta of particles inside a jet

Consider a quark/gluon jet, total $p_T = 500$ GeV/c

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

Jets with $p_T < 100$ GeV, constituents $O\ (GeV)$

For charged particles with momenta $O\ (GeV)$:
Better to use momentum resolution of the Tracker
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 combined resolution of the Calorimetry and Tracking systems

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

Jet energy resolution as a function of $P_T$
Event recorded with the CMS detector in 2012
Characteristic of Higgs boson decay to 2 photons

No charged track present, so must be a photon

<table>
<thead>
<tr>
<th>EM calorimetry</th>
<th>Hadronic calorimeter</th>
<th>Tracker</th>
<th>Muon detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>E.m. energy proportional to green tower heights</td>
<td>Hadron energy proportional to orange tower heights</td>
<td>Charged tracks Orange curves</td>
<td>Muon detector hits Blue towers</td>
</tr>
</tbody>
</table>
Can **YOU** calculate the **Effective mass** for the 2 high energy photons in the event??

**Photon 1**

<table>
<thead>
<tr>
<th>ECAL Energy (GeV)</th>
<th>Angle Phi ** (radians)**</th>
<th>Pseudo-rapidity ** (η)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon 1</td>
<td>90.0264</td>
<td>0.719</td>
</tr>
<tr>
<td>Photon 2</td>
<td>62.3762</td>
<td>2.800</td>
</tr>
</tbody>
</table>

**see definitions in next slide**

**You can also ask Professor Moretti for his estimate!**
CMS Event – angle definitions

Transverse view
Angle of the photons in the r-phi plane, $\Phi_1$ and $\Phi_2$

$\Phi_1 = 0.719$ radians
$\Phi_2 = 2.800$ radians

Longitudinal view
Angle of the photons wrt the +ve direction of the beam axis, $\theta_1$ and $\theta_2$

$\theta$ related to pseudo-rapidity ($\eta$) by

$$\eta = - \ln \left[ \tan \left( \frac{\theta}{2} \right) \right]$$

$\eta_1 = 0.0623$
$\eta_2 = -0.8110$
The crowning glory of CMS (and ATLAS) calorimetry!

$19.7 \, \text{fb}^{-1} (8 \, \text{TeV}) + 5.1 \, \text{fb}^{-1} (7 \, \text{TeV})$

$\bar{\mu} = 1.14^{+0.26}_{-0.23}$

$\bar{m}_h = 124.70 \pm 0.34 \, \text{GeV}$
Calorimetry a key detector technique for particle physics

In this talk, calorimetry for photons/electrons from ~1 MeV, to O(50 GeV) for Z decays, to O(1 TeV) for jets

Calorimeters playing a crucial role for physics at the LHC, eg H → γγ, Z’ → ee, SUSY (missing E_T)

Calorimeters indispensible for neutrino physics

Wide variety of technologies available. Calorimeter design is dictated by physics goals, experimental constraints and cost. Compromises necessary.

References:
Backups
Future directions in Calorimetry

The International Linear Collider (ILC)

Use Particle Flow, aided by finely segmented calorimetry

Very high transverse segmentation
ECAL ~1x1 cm² SiW cells – CALICE
HCAL ~3x3 cm² Steel/scintillator

High longitudinal sampling
30 layers ECAL and 40 layers HCAL

CALICE prototype
1.4/2.8/4.2 mm thick W plates (30X₀)
Interleaved with Silicon wafers
Read out at level of 1x1 cm² pads

Resolution for electrons
Stochastic term  a ~17%
Constant term  c ~ 1.1%
**Particle Flow Calorimetry in CMS**

Missing $E_T$ normalised to the total transverse energy for Di-jet events in CMS

CMS missing $E_T$ resolution < 10 GeV over whole $\Sigma E_T$ range up to 350 GeV
Factor 2 improvement on calorimetry by using Particle Flow technique
Energy resolution of hadronic calorimeters

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 $0.35/\sqrt{E}$(GeV)

Additional degradation to resolution, calorimeter imperfections:
- Inter-calibration errors, response non-uniformity (laterally and in depth), energy leakage, cracks
Homogeneous electromagnetic calorimeters

ALICE at the LHC – scintillating PbWO$_4$ crystals

Avalanche photo diode readout

Some of the 17,920 PbWO$_4$ crystals for ALICE (PHOS)
Homogeneous calorimeters

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

<table>
<thead>
<tr>
<th>Crystals</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>
</tbody>
</table>
  - slow component | 36 | 15 |
| Emission peak (nm) | 410 | 565 | 305 | 410 | 440 |
  - slow component | 480 |
| Light yield γ/MeV | $4 \times 10^4$ | $5 \times 10^4$ | $4 \times 10^4$ | $8 \times 10^3$ | $1.5 \times 10^2$ |
| Photoelectron yield | 1 | 0.4 | 0.1 | 0.15 | 0.01 |
  (relative to NaI) |
| Rad. hardness (Gy) | 1 | 10 | $10^3$ | 1 | $10^5$ |

**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
The Power of Calorimetry
A high energy DiJet event in CMS

A high mass dijet event in the first 120nb$^{-1}$ of data, at 2.13 TeV taken in CMS with pp collisions at 7 TeV, July 2010

Run: 138919
Event: 32253996
Dijet Mass: 2.130 TeV

Calorimeter energy deposits on $\eta \times \phi$ map
ECAL red, HCAL blue

Jet 1 $P_T$: 585 GeV
Jet 2 $P_T$: 557 GeV

D Cockerill, RAL, STFC, UK
Extra info – em shower depth

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

Rule of thumb

RMS spread in shower leakage at the back $\sim 0.5 \times$ average leakage at the back

CMS - keep rms spread $< 0.3\% \Rightarrow$ leakage $< 0.65\% \Rightarrow$ crystals $25X_0$ (23cm) long

Other relations

$$<t_{95\%}> \sim t_{max} + 0.08Z + 9.6$$
$$<t_{98\%}> \sim 2.5 \ t_{max}$$
$$<t_{98\%}> \sim t_{max} + 4 \ \lambda_{att}$$

Tail of cascade - photons of a few MeV $\sim$ at the min in the mass attenuation coefficient

$\lambda_{att} \sim 3.4X_0 \sim$ photon mean free path.

$\lambda_{att}$ is associated with the exponential decrease of the shower after $t_{max}$
Comment, em longitudinal profile, Pb versus Cu:

The coulomb field in Pb, Z=82 with $E_c = 7.3$ MeV means that bremstrahlung dominates over ionisation to much lower shower particle energies than for example in Cu, Z=29 with $E_c = 20.2$ MeV.

As a consequence the depth ($X_0$) of a shower proceeds further in Pb than in Cu.
Homogeneous liquid Kr electromagnetic calorimeters

NA48 Liquid Krypton Ionisation chamber (T = 120K)

No metal absorbers: quasi homogeneous

NA48 Liquid Krypton
2cmx2cm cells
$X_0 = 4.7$cm
125cm length ($27X_0$)
$\rho = 5.5$cm

Cu-Be ribbon electrode

a ~ 3.3%
b ~ 40 MeV
c ~ 0.2

full device (prel.)
Homogeneous calorimetry

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
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%
Central core: multiple scattering

Peripheral halo: propagation of less attenuated photons, widens with depth of the shower
EM showers, logitudinal profile

Shower parametrization

\[ \frac{dE}{dt} \propto t^\alpha e^{\beta t} \]

Longitudinal development

EM showers (EGS4, 10 GeV e⁻)

<table>
<thead>
<tr>
<th>Material</th>
<th>Z</th>
<th>A</th>
<th>( \rho ) [g/cm³]</th>
<th>( X_0 ) [g/cm²]</th>
<th>( \lambda_a ) [g/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen (gas)</td>
<td>1</td>
<td>1.01</td>
<td>0.0899 (g/l)</td>
<td>63</td>
<td>50.8</td>
</tr>
<tr>
<td>Helium (gas)</td>
<td>2</td>
<td>4.00</td>
<td>0.1786 (g/l)</td>
<td>94</td>
<td>65.1</td>
</tr>
<tr>
<td>Beryllium</td>
<td>4</td>
<td>9.01</td>
<td>1.848</td>
<td>65.19</td>
<td>75.2</td>
</tr>
<tr>
<td>Carbon</td>
<td>6</td>
<td>12.01</td>
<td>2.285</td>
<td>43</td>
<td>86.3</td>
</tr>
<tr>
<td>Nitrogen (gas)</td>
<td>7</td>
<td>14.01</td>
<td>1.25 (g/l)</td>
<td>38</td>
<td>87.8</td>
</tr>
<tr>
<td>Oxygen (gas)</td>
<td>8</td>
<td>16.00</td>
<td>1.428 (g/l)</td>
<td>34</td>
<td>91.0</td>
</tr>
<tr>
<td>Aluminium</td>
<td>13</td>
<td>26.98</td>
<td>2.7</td>
<td>24</td>
<td>106.4</td>
</tr>
<tr>
<td>Silicon</td>
<td>14</td>
<td>28.09</td>
<td>2.33</td>
<td>22</td>
<td>106.0</td>
</tr>
<tr>
<td>Iron</td>
<td>26</td>
<td>55.85</td>
<td>7.87</td>
<td>13.9</td>
<td>131.9</td>
</tr>
<tr>
<td>Copper</td>
<td>29</td>
<td>63.55</td>
<td>8.96</td>
<td>12.9</td>
<td>134.9</td>
</tr>
<tr>
<td>Tungsten</td>
<td>74</td>
<td>183.85</td>
<td>19.3</td>
<td>6.8</td>
<td>185.0</td>
</tr>
<tr>
<td>Lead</td>
<td>82</td>
<td>207.19</td>
<td>11.35</td>
<td>6.4</td>
<td>194.0</td>
</tr>
<tr>
<td>Uranium</td>
<td>92</td>
<td>238.03</td>
<td>18.95</td>
<td>6.0</td>
<td>199.0</td>
</tr>
</tbody>
</table>

For \( Z > 6 \): \( \lambda_a > X_0 \)
Crystals: building blocks

These crystals make light!

Crystals are basic components of electromagnetic calorimeters aiming at precision
Scintillation: a three step process

Scintillator + Photo Detector = Detector

PMT, PD, APD

How does it works

absorption e.g. $\gamma$

conversion

emission

$I(E) = I_0(E)e^{-\mu d}$

Energy $\rightarrow$ Excitation

Conduction band

Valence band

Conduction band

Valence band

Rad. emission

$E_g$

$\gamma$

Excitation
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

\[ \text{PbWO}_4: \lambda_{\text{excit}} = 300 \text{ nm} ; \lambda_{\text{emiss}} = 500 \text{ nm} \]

**Excitation**

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

**Radiative Emission**

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

**Stokes Shift**

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

**Energy Levels**

- **Ground State**
- **Excited State**

**Configurational Coordinates**

\[ Q_0^g, Q_0^e \]

\[ \Delta E_a \]
**Scintillating crystals**

\[ E_{\text{dep}} \rightarrow e-h \]
\[ E_s = \beta E_g \quad \beta > 1 \]
\[ N_{eh} = \frac{E_{\text{dep}}}{\beta E_g} \]

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

Efficiency of transfer to luminescent centres

Radiative efficiency of luminescent centres

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

- \( S, Q \approx 1 \), \( \beta E_g \) as small as possible
- medium transparent to \( \lambda_{\text{emiss}} \)
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
Copper has been selected as the absorber material because of its density. The HB is constructed of two half-barrels each of 4.3 meter length. The HE consists of two large structures, situated at each end of the barrel detector and within the region of high magnetic field. Because the barrel HCAL inside the coil is not sufficiently thick to contain all the energy of high energy showers, additional scintillation layers (HOB) are placed just outside the magnet coil. The full depth of the combined HB and HOB detectors is approximately 11 absorption lengths.

The hadron barrel (HB) and hadron endcap (HE) calorimeters are sampling calorimeters with 50 mm thick copper absorber plates which are interleaved with 4 mm thick scintillator sheets.
CMS Hadron sampling calorimetry
Electromagnetic shower

Big European Bubble Chamber filled with Ne:H₂ = 70%:30%, 3T Field, L=3.5 m, \( X_0 \approx 34 \) cm, 50 GeV incident electron
We study the inclusive dijet final state using the **dijet mass spectrum** and the **dijet centrality ratio** observables. Together the Dijet Mass and Ratio provide a **test of QCD** and a **sensitive search** for new physics beyond the Standard Model.

- **QCD**

  - Dijet mass distribution is a simple check of rate vs dijet mass from QCD and PDFs.
  - Dijet centrality ratio is a detailed measure of QCD dynamics from angular distribution.

- **Dijet Resonance**

  - Dijet mass provides most sensitive “*bump*” hunt for new particles decaying to dijets.
  - Dijet centrality ratio can confirm that a “*bump*” is not QCD fluctuation.

- **Contact Interaction**

  - Dijet centrality ratio is more sensitive than the dijet mass to contact interactions from quark compositeness.
  - when all experimental uncertainties are considered.
Jet Energy Resolution with stand alone calorimetry

For a single hadronic particle: $\frac{\sigma_E}{E} = a / \sqrt{E} \oplus c$ (neglect electronic noise)

Jet with low particle energies, resolution is dominated by $a$, and at high particle energies by $c$

If the stochastic term, $a$, dominates:
- error on Jet energy ~ same as for a single particle of the same energy

If the constant term dominates:
- error on Jet energy is less than for a single particle of the same energy

For example:
1 TeV jet composed of four hadrons of equal energy
Calorimeter with $\frac{\sigma_E}{E} = 0.3 / \sqrt{E} \oplus 0.05$

$\delta E_{\text{Jet}} = 25 \text{ GeV}$,
compared to $\delta E = 50 \text{ GeV}$, for a single 1 TeV hadron
Jet s in CMS at the LHC, pp collisions at 7TeV

Red - ECAL, Blue - HCAL energy deposits
Yellow – Jet energy vectors