ATLAS & CMS Calorimeters
examples
The CMS detector

Inner tracker
75M silicon pixels and strips

Electromagnetic calorimeter (ECAL)
76,000 PbWO₄ crystals

Hadronic calorimeter (HCAL)
brass / plastic scintillator

Superconducting solenoid
providing 3.8 T magnetic field

Muon chambers
embedded in the steel return yoke

outside the calorimeter
=> compact calorimeters!
Homogenous calorimeter made from 75848 PbWO₄ scintillating crystals

- Barrel (|\eta|<1.48), ~67 t
- 61200 crystals over 36 super-modules

- Endcaps (1.48<|\eta|<3), ~23 t
- 14648 crystals over 4 Dees (2 per endcap)
- Preceded by Pb/Si Pre-Shower
CMS crystals: PbWO$_4$

Excellent energy resolution
$X_0 = 0.89 \text{cm} \rightarrow$ compact calorimeter (23 cm for 26 $X_0$)
$R_M = 2.2 \text{ cm} \rightarrow$ compact shower development
Fast light emission (80% in less than 15 ns)
Radiation hard ($10^5 \text{Gy}$)

But
Low light yield (150 $\gamma$/MeV)
Response varies with dose
Response temperature dependence
CMS ECAL: monitoring

- Response of PbWO4 crystal change with irradiation
  - Loss of transparency

- Damage and recovery during LHC cycles tracked with a laser monitoring system

After laser correction
Before laser correction
CMS ECAL: performance

Stand-alone performance assessed during extensive test Beam campaigns at CERN...

Combined performance measured in-situ

\[ \sigma(E)/E(\%) \]

3x3 resolution
- no hodoscope cut
- hodoscope cut 4x4 mm²

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

(test beam)
Fermi Satellite with Large Area Telescope (LAT) instrument.

- Gamma-Ray Telescope
  - (200 MeV < \(\gamma\) < 300 GeV)
- Launched June 11 2008
- Consists of:
  - Tracker: Pb foils + Si strips
  - Calorimeter (see next slide)
  - Anticoincidence Detector: plastic scintillator tiles
Calorimeters in space: FERMI ECAL

- Homogenous calorimeter made from 1728 CsI(Tl) scintillating crystals

- 18 modules (400mmx400mmx250mm) ~100 kg each

- 1 module:
  - carbon-fiber alveolar structure +
  - 96 CsI(Tl) crystals (2.7 cm x 2.0 cm x 32.6 cm)
  - arranged in 8 layers of 12 crystals each

- Each module aligned 90° wrt its neighbors, forming x,y (hodoscopic) array

- Depth: 8.6 \(X_0\) (10.1 including tracker)
  \[\Rightarrow\] Need shower leakage correction

- Light read by 2 photo-diodes
Calorimeters in space: AMS-02

- **Alpha Magnetic Spectrometer (AMS):**
  - HEP-like detector operating as external module on ISS
  - Launched in 2011

- Search for Dark Matter, anti-matter, precise study of high energy cosmic ray (flux, composition), gamma rays.
AMS: A TeV precision, multipurpose, magnetic spectrometer

Transition Radiation Detector (TRD)
Identify $e^+$, $e^-$

Silicon Tracker
$Z$, $P$ or $R=P/Z$

Electromagnetic Calorimeter (ECAL)
$E$ of $e^+$, $e^-$

Time of Flight (TOF)
$Z$, $E$

Magnet
$\pm Z$

Ring Imaging Cherenkov (RICH)
$Z$, $E$

Z and $P$, $E$ or $R$ are measured independently by Tracker, ECAL, TOF and RICH
The AMS-02 ECAL

Sampling calorimeter made from Lead + Scintillating fibers

- **3-D imaging of shower development**
  - 9 Super-Layers (SL) alternatively oriented along X and Y axis (5 SL along X, 4 long Y)

- 1 Super-Layer (~18.5mm):
  - 11 grooved, Pb foils (1mm thick) interleaved with 10 layers of scintillating fibers (Ø~1mm) glued by epoxy-resin

- **Depth:** ~17 X0
- Fibers read by PMT

ECAL support structure

- ~10%/√E (test beam)

\[
\frac{\sigma(E)}{E} = \frac{10.4 \pm 0.2}{\sqrt{E}} \oplus (1.4 \pm 0.05) \% 
\]
ATLAS & CMS calorimeters
Solenoid: BEFORE the calorimeters
The ATLAS ECAL

Sampling Pb/LAr calorimeter with innovative “accordion” geometry

- Longitudinal dimension ~25 X0, 47 cm (vs 22 cm for CMS)
- 3 layers up to $|\eta|=2.5$ + presampler $|\eta|<1.8$
- 2 layers $2.5<|\eta|<3.2$
  - Layer 1 ($\gamma/n^0$ rej. + angular meas.)
    - $\Delta\eta \cdot \Delta\phi = 0.003 \times 0.1$
  - Layer 2 (shower max)
    - $\Delta\eta \cdot \Delta\phi = 0.025 \times 0.25$
  - Layer 3 (Hadronic leakage)
    - $\Delta\eta \cdot \Delta\phi = 0.05 \times 0.025$
- ~170 000 channels
- Usage of Liquid Argon
  - Radiation Hard
  - High number of electron-ion pair produced by ionization
    (1 GeV deposit -> $5 \times 10^6$ e-)
  - Stable vs time
  - BUT: • Need a cryostat (90K)
    • Slow time response (400 ns vs 25 ns LHC bunch crossing)
**ATLAS ECAL: accordion geometry (1)**

**Standard Liquid Argon**
- Slow response (long integration time)
- Electrodes \( \perp \) particles
- Long cables
  - To bring signal to pre-amplifiers
  - Regroup gaps
- Dead zones due to cables

**Accordion Liquid Argon**
- Accordion geometry: **fast**
- Electrodes \( \parallel \) to incident particles
  - Signal read out forward & backward
  - No long connection
- **No cracks (in azimuth)**
ATLAS ECAL: accordion geometry (2)
Stand-alone performance assessed during extensive test Beam campaigns at CERN...

Combined performance measured in-situ

**Linearity of the response**

\[
\frac{E_{\text{rec}}}{E_{\text{beam}}} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.3}{E} \oplus 0.7\%
\]

(test beam)
- **HCAL Barrel (HB):** $|\eta|<1.3$
- **HCAL Endcap (HE):** $1.3<|\eta|<3$
- **Forward HCAL (HF):** $3<|\eta|<5$, Fe+Quartz Fiber

See next
HB/HE: Sampling Brass/plastic scintillator calorimeter

**HB** (17 longitudinal layers)

- Segmentation: $\Delta \eta \times \Delta \phi = 0.087 \times 0.087$ (larger at high $\eta$)
- 18x20° “wedges” with alternate brass plates (5-8 cm) and “tiles” embedded with Wave Length Shifter (WLS).
  - Light from scintillator: blue-violet
  - WLS: absorb light then fluorescence in green
  - Green light read by Hybrid Photo Diode (HPD)

**HE** (19 longitudinal layers)
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
- At $|\eta|=0$, $\lambda_{\text{int}}$ from HB = 5.8! (7.2 with ECAL)
  - Large leakage…

- CMS adds HCAL Outer (HO):
  - Scintillator + WLS outside coil acting as “tail catcher”.

Poor Resolution: $\sim 100\% / \sqrt{E}$
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: $\sim 8 - 10 \lambda$

Use of different technics: cope with radiations in forward region
ATLAS TileCal

TileCal: Sampling Fe/plastic scintillator calorimeter

- Coverage: |\(\eta\)|<1.7
- 3 cylinders (1 barrel, 2 extended barrel)
- 3 longitudinal sampling
- Segmentation: \(\Delta \eta \times \Delta \phi = 0.1 \ (0.2) \times 0.1\)
- ~10 000 channels

- Key element: Tile
  - Perpendicular to beam axis
  - WLS carry light to PMT
ATLAS TileCal: Performance

**Linearity**

\[
\frac{\langle E \rangle}{E_{\text{nom}}} = (1.00 \pm 0.02) \quad \text{for} \quad E_{\text{beam}} \leq 100 \text{ GeV}
\]

**Resolution**

\[
\frac{\sigma}{E} = \left( \frac{52.9 \pm 0.9}{\sqrt{E_{\text{beam}}}} \right) \oplus (5.7 \pm 0.2) \%
\]

Resolution: \( \sim 50\% \sqrt{E} \)
### ATLAS/CMS ECAL Resolution

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology</strong></td>
<td>Lead/LAr accordion</td>
<td>PbWO₄ scintillating crystals</td>
</tr>
<tr>
<td><strong>Channels</strong></td>
<td>Barrel 110,208</td>
<td>Barrel 61,200</td>
</tr>
<tr>
<td></td>
<td>End caps 63,744</td>
<td>End caps 14,648</td>
</tr>
<tr>
<td><strong>Granularity</strong></td>
<td>$\Delta \eta \times \Delta \phi$</td>
<td>$\Delta \eta \times \Delta \phi$</td>
</tr>
<tr>
<td>Presampler</td>
<td>$0.025 \times 0.1$</td>
<td>$0.025 \times 0.1$</td>
</tr>
<tr>
<td>Strips/</td>
<td>$0.003 \times 0.1$</td>
<td>$0.006 \times 0.1$</td>
</tr>
<tr>
<td>Si-preshower</td>
<td>$0.003 \times 0.1$</td>
<td>$32 \times 32$ Si-strips per 4 crystals</td>
</tr>
<tr>
<td>Main sampling</td>
<td>$0.025 \times 0.025$</td>
<td>$0.017 \times 0.017$</td>
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<tr>
<td></td>
<td>$0.025 \times 0.025$</td>
<td>$0.018 \times 0.003$ to $0.088 \times 0.015$</td>
</tr>
<tr>
<td>Back</td>
<td>$0.05 \times 0.025$</td>
<td>$0.05 \times 0.025$</td>
</tr>
<tr>
<td>Depth</td>
<td>Barrel</td>
<td>Barrel</td>
</tr>
<tr>
<td>Presampler (LAr)</td>
<td>$10$ mm</td>
<td>$2 \times 2$ mm</td>
</tr>
<tr>
<td>Strips/</td>
<td>$\approx 4.3 X_0$</td>
<td>$\approx 4.0 X_0$</td>
</tr>
<tr>
<td>Si-preshower</td>
<td>$\approx 4.0 X_0$</td>
<td>$3 X_0$</td>
</tr>
<tr>
<td>Main sampling</td>
<td>$\approx 16 X_0$</td>
<td>$\approx 20 X_0$</td>
</tr>
<tr>
<td>Back</td>
<td>$\approx 2 X_0$</td>
<td>$\approx 2 X_0$</td>
</tr>
<tr>
<td>Noise per cluster</td>
<td>$250$ MeV</td>
<td>$200$ MeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$600$ MeV</td>
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<tr>
<td>Intrinsic</td>
<td></td>
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<tr>
<td>resolution</td>
<td></td>
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<tr>
<td>Stochastic term $a$</td>
<td>$10%$</td>
<td>$10$ to $12%$</td>
</tr>
<tr>
<td>Local constant</td>
<td>$0.2%$</td>
<td>$0.35%$</td>
</tr>
<tr>
<td>term $b$</td>
<td></td>
<td>$0.5%$</td>
</tr>
</tbody>
</table>

Note the presence of the silicon preshower detector in front of the CMS end-cap crystals, which have a variable granularity because of their fixed geometrical size of $29 \times 29$ mm². The intrinsic energy resolutions are quoted as parametrizations of the type $\sigma(E)/E = a/\sqrt{E} \oplus b$. For the ATLAS EM barrel and end-cap calorimeters and for the CMS barrel crystals, the numbers quoted are based on stand-alone test-beam measurements.
### How can CMS compete with ATLAS on the jet physics given these numbers?

=> **Particle Flow** (see next lecture)
ATLAS and CMS are NON-compensating calorimeters

- **Numbers (*)**:
  - ATLAS Tile Barrel e/h ~ 1.4
  - CMS ECAL: e/h ~ 2.4
  - CMS HCAL: e/h ~ 1.3
  - CMS HF: e/h ~ 4.7

- **Ex: CMS calibrates**:
  - ECAL for electrons/photons
  - HCAL with pions non-interacting in ECAL
  - But pions DO interact with ECAL. And thus get wrong calibration.
  - Degrades the resolution.

Again, **Particle Flow technics will help there** (by separating charged and neutral pions). See Lecture 3.

(*) to be verified…