2.5 Important differences between the ATLAS and CMS detectors
The ATLAS detector concept
CMS Detector Concept

Key:
- Muon
- Electron
- Hadron (e.g., Pion)
- Photon

Transverse slice through CMS

Tracker Calorimeter Coil Muon Detector and iron return yoke
**CMS**

**CALORIMETERS**
- **ECAL**
  - 76k scintillating PbWO4 crystals

**HCAL**
- Plastic scintillator/brass sandwich

**Superconducting Coil, 4 Tesla**

**Tracker**
- Pixels
- Silicon Microstrips
- 210 m² of silicon sensors
- 9.6M channels

**Muon Barrel**
- Drift Tube Chambers (DT)
- Resistive Plate Chambers (RPC)

**Muon Endcaps**
- Cathode Strip Chambers (CSC)
- Resistive Plate Chambers (RPC)

**Iron Yoke**

**Total weight** 12500 t
**Overall diameter** 15 m
**Overall length** 21.6 m
How huge are ATLAS and CMS?

Size of detectors:

- Volume: 20 000 m³ for ATLAS
- Weight: 12 500 tons for CMS
- 66 to 80 million pixel readout channels near vertex
- 200 m² of active silicon for CMS tracker
- 175 000 readout channels for ATLAS LAr EM calorimeter
- 1 million channels and 10 000 m² area of muon chambers
- Very selective trigger/DAQ system
- Large-scale offline software and worldwide computing (GRID)

Time-scale:
More than 25 years from first conceptual studies (Lausanne 1984) to solid physics results in 2011 confirming that LHC has taken over the high-energy frontier from the Tevatron
<table>
<thead>
<tr>
<th></th>
<th><strong>ATLAS</strong></th>
<th><strong>CMS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field</td>
<td>2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)</td>
<td>4 T solenoid + return yoke</td>
</tr>
<tr>
<td>Tracker</td>
<td>Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$</td>
<td>Silicon pixels and strips (full silicon tracker) $\sigma/p_T \approx 1.5 \cdot 10^{-4} p_T + 0.005$</td>
</tr>
<tr>
<td>EM calorimeter</td>
<td>Liquid argon + Pb absorbers $\sigma/E \approx 10%/\sqrt{E} + 0.007$</td>
<td>PbWO$_4$ crystals $\sigma/E \approx 3%/\sqrt{E} + 0.003$</td>
</tr>
<tr>
<td>Hadronic</td>
<td>Fe + scintillator / Cu+LAr (10\lambda) $\sigma/E \approx 50%/\sqrt{E} + 0.03$ GeV</td>
<td>Brass + scintillator (7 \lambda + catcher) $\sigma/E \approx 100%/\sqrt{E} + 0.05$ GeV</td>
</tr>
<tr>
<td>calorimeter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon</td>
<td>$\sigma/p_T \approx 2%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)</td>
<td>$\sigma/p_T \approx 1%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)</td>
</tr>
<tr>
<td>Trigger</td>
<td>L1 + HLT (L2+EF)</td>
<td>L1 + HLT (L2 + L3)</td>
</tr>
</tbody>
</table>
**Important differences I:**

- In order to maximize the sensitivity for $H \rightarrow \gamma\gamma$ decays, the experiments need to have an excellent $e/\gamma$ identification and resolution

- CMS: has opted for a high resolution PbWO$_4$ crystal calorimeter
  - higher intrinsic resolution

- ATLAS: Liquid argon calorimeter
  - high granularity and longitudinally segmentation (better $e/\gamma$ ID)
  - electrical signals, high stability in calibration & radiation resistant
ATLAS/CMS: $e/\gamma$ resolutions

**Photons at 100 GeV**

ATLAS: 1-1.5% energy resol. (all $\gamma$)

CMS: 0.8% energy resol. ($\varepsilon_{\gamma} \sim 70\%$)

**Electrons at 50 GeV**

ATLAS: 1.3-2.3% energy resol. (use EM calo only)

CMS: ~ 2.0% energy resol. (combine EM calo and tracker)
Active sensors and mechanics account each only for ~ 10% of material budget

Need to bring 70 kW power into tracker and to remove similar amount of heat

Very distributed set of heat sources and power-hungry electronics inside volume: this has led to complex layout of services, most of which were not at all understood at the time of the TDRs
Important differences II:

• Inner detectors / tracker
  
  Both use solenoidal fields
  ATLAS: 2 Tesla
  CMS: 4 Tesla

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• CMS: full silicon strip and pixel detectors
  - high resolution, high granularity

• ATLAS: Silicon (strips and pixels)
  + Transition Radiation Tracker
  - high granularity and resolution close to interaction region
  - “continuous” tracking at large radii
## Main performance characteristics of the ATLAS and CMS trackers

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstruction efficiency for muons with $p_T = 1$ GeV</td>
<td>96.8%</td>
<td>97.0%</td>
</tr>
<tr>
<td>Reconstruction efficiency for pions with $p_T = 1$ GeV</td>
<td>84.0%</td>
<td>80.0%</td>
</tr>
<tr>
<td>Reconstruction efficiency for electrons with $p_T = 5$ GeV</td>
<td>90.0%</td>
<td>85.0%</td>
</tr>
<tr>
<td>Momentum resolution at $p_T = 1$ GeV and $\eta \approx 0$</td>
<td>1.3%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Momentum resolution at $p_T = 1$ GeV and $\eta \approx 2.5$</td>
<td>2.0%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Momentum resolution at $p_T = 100$ GeV and $\eta \approx 0$</td>
<td>3.8%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Momentum resolution at $p_T = 100$ GeV and $\eta \approx 2.5$</td>
<td>11%</td>
<td>7%</td>
</tr>
<tr>
<td>Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (µm)</td>
<td>75</td>
<td>90</td>
</tr>
<tr>
<td>Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (µm)</td>
<td>200</td>
<td>220</td>
</tr>
<tr>
<td>Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (µm)</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (µm)</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (µm)</td>
<td>150</td>
<td>125</td>
</tr>
<tr>
<td>Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (µm)</td>
<td>900</td>
<td>1060</td>
</tr>
</tbody>
</table>

- Performance of CMS tracker is undoubtedly superior to that of ATLAS in terms of momentum resolution.
- Vertexing and b-tagging performances are similar.
- However, impact of material and B-field already visible on efficiencies.
Important differences III:

- Coil / Hadron calorimeters

- CMS: electromagnetic calorimeter and part of the hadronic calorimeter inside the solenoidal coil + tail catcher, return yoke
  
  good for e/γ resolution
  bad for jet resolution

- ATLAS: calorimetry outside coil
Hadronic absorption length of the calorimeters

ATLAS

Material in front of Muon System

End of active hadronic

Tile barrel

Tile extended barrel

Hadronic endcap

Forward calorimeter

EM barrel

EM endcap

cryostat walls

Absorption Length

11\lambda

0 1 2 3 4 5

Pseudorapidity
Main performance parameters of the different hadronic calorimeter components of the ATLAS and CMS detectors, as measured in test beams using charged pions in both stand-alone and combined mode with the ECAL

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
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<tbody>
<tr>
<td></td>
<td>Barrel LAr/Tile</td>
<td>End-cap LAr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tile</td>
<td>HEC</td>
<td>Had. barrel</td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td>Combined</td>
<td>Combined</td>
</tr>
<tr>
<td>Electron/hadron ratio</td>
<td>1.36</td>
<td>1.49</td>
<td></td>
</tr>
<tr>
<td>Stochastic term</td>
<td>45%/√E</td>
<td>75%/√E</td>
<td>100%/√E</td>
</tr>
<tr>
<td>Constant term</td>
<td>1.3%</td>
<td>5.8%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Noise</td>
<td>Small</td>
<td>1.2 GeV</td>
<td>Small</td>
</tr>
<tr>
<td></td>
<td>3.2 GeV</td>
<td></td>
<td>1 GeV</td>
</tr>
</tbody>
</table>

The measured electron/hadron ratios are given separately for the hadronic stand-alone and combined calorimeters when available, and for the contributions (added quadratically except for the stand-alone ATLAS tile calorimeter) to the pion energy resolution from the stochastic term, the local constant term, and the noise are also shown, when available from published data.
Biggest difference in performance perhaps for hadronic calorimetry

**Jets at 1000 GeV**

**ATLAS:** $\sim 2\%$ energy resolution  
**CMS:** $\sim 5\%$ energy resolution,

But expect sizable improvement using tracks (especially at lower $E$)

$E_T^{\text{miss}}$ at $\Sigma E_T = 2000$ GeV

**ATLAS:** $\sigma \sim 20$ GeV  
**CMS:** $\sigma \sim 40$ GeV

This may be important for high mass $H/A \rightarrow \tau\tau$
Important differences IV:

• Muon spectrometer

• ATLAS: independent muon spectrometer; → excellent stand-alone capabilities

• CMS: superior combined momentum resolution in the central region; limited stand-alone resolution and trigger capabilities (multiple scattering in the iron)
Main parameters of the ATLAS and CMS muon measurement systems as well as a summary of the expected combined and stand-alone performance at two typical pseudorapidity values (averaged over azimuth)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudorapidity coverage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Muon measurement</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>-Triggering</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Dimensions (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Innermost (outermost) radius</td>
<td>5.0 (10.0)</td>
<td>3.9 (7.0)</td>
</tr>
<tr>
<td>-Innermost (outermost) disk (z-point)</td>
<td>7.0 (21–23)</td>
<td>6.0–7.0 (9–10)</td>
</tr>
<tr>
<td>Segments/superpoints per track for barrel (end caps)</td>
<td>3 (4)</td>
<td>4 (3–4)</td>
</tr>
<tr>
<td>Magnetic field B (T)</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>-Bending power (BL, in T·m) at $</td>
<td>\eta</td>
<td>\approx 0$</td>
</tr>
<tr>
<td>-Bending power (BL, in T·m) at $</td>
<td>\eta</td>
<td>\approx 2.5$</td>
</tr>
<tr>
<td>Combined (stand-alone) momentum resolution at $p$ = 10 GeV and $\eta \approx 0$</td>
<td>1.4% (3.9%)</td>
<td>0.8% (8%)</td>
</tr>
<tr>
<td></td>
<td>2.4% (6.4%)</td>
<td>2.0% (11%)</td>
</tr>
<tr>
<td></td>
<td>2.6% (3.1%)</td>
<td>1.2% (9%)</td>
</tr>
<tr>
<td></td>
<td>2.1% (3.1%)</td>
<td>1.7% (18%)</td>
</tr>
<tr>
<td></td>
<td>10.4% (10.5%)</td>
<td>4.5% (13%)</td>
</tr>
<tr>
<td></td>
<td>4.4% (4.6%)</td>
<td>7.0% (35%)</td>
</tr>
</tbody>
</table>

CMS muon performance driven by tracker: better than ATLAS at $\eta \sim 0$;
ATLAS muon stand-alone performance excellent over whole $\eta$ range
How to Select Interesting Events?

- Bunch crossing rate: 40 MHz, ~20 interactions per BX \((10^9 \text{ evts/s})\)
  - can only record ~200 event/s (1.5 MB each), still 300 MB/s data rate
- Need highly efficient and highly selective TRIGGER
  - raw event data (70 TB/s) are stored in pipeline until trigger decision

ATLAS trigger has 3 levels (CMS similar with 2 levels)
- Level-1: hardware, ~3 \(\mu\)s decision time, 40 MHz \(\rightarrow\) 100 kHz
- Level-2: software, ~40 ms decision time, 100 kHz \(\rightarrow\) 2 kHz
- Level-3: software, ~4 s decision time, 2 kHz \(\rightarrow\) 200 Hz
Trigger system selects ~200 “collisions” per sec.

LHC data volume per year: 10-15 Petabytes
= 10-15 $\cdot 10^{15}$ Byte

A typical Tier-2 GRID center (example: Tokyo University)
A few pictures from
the detector installation
ATLAS detector construction and installation
ATLAS detector construction: Calorimeters
Installation of one of the ATLAS Endcap Tracking Detectors (completed on 29. May 2007)
Installation of Inner Detector Services

~ 800 man-months of installation work over
~18 months, ~ 45 people involved/day
✓ ~ 9300 SCT cable-bundles
✓ ~ 3600 pixel cable-bundles
✓ ~ 30100 TRT cables
✓ ~ 2800 cooling & gas pipes

All tested and qualified
Muon detectors and endcap toroid magnets

Installation of the second (last) endcap toroid: 12. July 07
CMS Installation

Coil inserted, 14. September 2005

Cathode Strip chambers and yoke endcaps
Hadronic calorimeter, endcap
Tracker, outer barrel

K. Jakobs
Vorlesung Physik an Hadron-Collidern, Freiburg, SS 2011
CMS Tracker & ALICE TPC

(plus a LEP silicon detector!)
Installation of the CMS Electromagnetic Barrel Calorimeter
(1. half, completed on 22. May 2007)
CMS Detector closed for 10th Sep.