Introduction to CMS

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Content

• I know that few in the audience are physicists
  – so I plan to give only an elementary introduction to the experiment
• Main objectives and experimental requirements
  – illustrations of some of the items built
• Brief history of development and construction
• Focus on objects which have been constructed and purchased
  – hope to provide some insight into opportunities for business
• To be supplemented later by a few more details on electronic procurements
  – in a separate session
What is the Large Hadron Collider?

- Latest CERN accelerator started operation 2010
  - very high intensity
    - $10^{15}$ collisions per year
  - very high rate
    - beams cross @ 40MHz
  - few “interesting” events
    - ~100 Higgs decays per year
  - Beams (from 2015)
    - 6.5 TeV protons
    - => 13 TeV energy
      - also ions, eg Pb
Where is the LHC?
What are we doing at the LHC?

- Colliding beams of protons
  - to maximise the energy available to create new particles

- Proton collisions are actually between their constituent parts...
  - $\lambda \sim 1/p \approx 1/E$
- Gluons
- Quarks ($\approx$ real and virtual)
- And the particles they exchange (Z, W,...)

(No more physics after this slide!)
The Compact Muon Solenoid experiment

• a general purpose detector for studying the full range of physics at the CERN Large Hadron Collider
  – designed to operate (nominally) for 10 years
  – high radiation levels throughout the experiment
  – they originate with flux of particles originating from the p-p collisions
    • so highest in centre and endcap regions
  – also operate with heavy ions: ~ 1 month annually

\[
\begin{array}{|c|c|c|c|}
\hline
R \text{ [cm]} & \text{Fast hadron fluence [cm}^{-2}] & \text{Dose [kGy]} & \text{Dose [Mrad]} \\
\hline
4.3 & 2.46 \times 10^{13} & 830 & 83 \\
22 & 1.6 \times 10^{13} & 67 & 6.7 \\
115 & 2 \times 10^{13} & 2 & 0.2 \\
\hline
\end{array}
\]

Suffice to say, these are very high and comparable with nuclear reactor interiors.
CMS: Compact Muon Solenoid

constructed as a series of layered sub-detectors, each with a specific purpose

- **CMS:** Compact Muon Solenoid
- **ECAL**
- **Tracker**
- **HCAL**
- **Muon chambers**
- **4T solenoid**

Total weight: 12,500 t
Overall diameter: 15 m
Overall length: 21.6 m
Magnetic field: 4 T
• Large solenoidal (4T) magnet
  • iron yoke - returns B field, absorbs particles

• Muon detection - penetration
  • the only particles we can measure which traverse the whole detector

• Calorimeters – absorb Energy
  • electromagnetic – electrons and gammas
  • hadronic – all other types of particle

• Tracking system – bend in B field
  • momentum measurements of charged particles
  • complex, multi-particle events
  • complement muon & ECAL measurements
From a hole in the ground
Assembly on the surface
ECAL crystal scintillators
Lowering endcap YE+3 Nov 2006
Lowering magnet and central YB0 Feb 2007
Endcap muon/forward calorimetry YE-1 Jan 2008
Services =
gas, optical fibres, power and signal cables, liquids for cooling, etc
Tracker installation Dec 2007

One of the final detector insertions
The detectors

• Would not exist without commercial procurements
• For illustration, I have chosen a couple of examples where there has been a strong UK involvement. Our detector activities have included
  – Custom integrated circuit electronics
  – Board-based digital electronics
  – Silicon sensors
  – Vacuum photodiodes
  – Scintillating crystals
  – Semi-custom optical links
  – Mechanical assemblies – some very large
  – Data acquisition and software development
  – ...
• In most cases in close collaboration with scientists and engineers from other countries
CMS Tracker and its sub-systems

- Two main sub-systems: Silicon Strip Tracker and Pixels
  - Pixels quickly removable for beam-pipe bake-out or replacement
  - SST not replaceable in reasonable time

<table>
<thead>
<tr>
<th>Microstrip tracker</th>
<th>Pixels</th>
</tr>
</thead>
<tbody>
<tr>
<td>~210 m² of silicon, 9.3M channels</td>
<td>~1 m² of silicon, 66M channels</td>
</tr>
<tr>
<td>73k APV25s, 38k optical links, 440 FEDs</td>
<td>16k ROCs, 2k olinks, 40 FEDs</td>
</tr>
<tr>
<td>27 module types</td>
<td>8 module types</td>
</tr>
<tr>
<td>~34kW</td>
<td>~3.6kW (post-rad)</td>
</tr>
</tbody>
</table>
Some milestones of a long project

- ~Jan 1990  R&D projects
- Apr 1992 CMS Letter of Intent
- Dec 1994 Technical Proposal
- Apr 1998 Tracker Technical Design Report
- Oct 1999 Front End Readout ASIC in 0.25µm CMOS
- Dec 1999 Decision to construct All Silicon Tracker
- Feb 2000 Tracker Technical Design Report Addendum
- Apr 2006 Module production completed
- Nov 2006 Tracker integration complete
- Dec 2007 Tracker inserted in CMS
- Mar 2008 Tracker connections completed
  - Sep 2008 small interlude
- Nov 2009 Tracker ON with LHC beam
- Mar 2010 Data taking at 7 TeV
Electromagnetic Calorimeter

• Measures electron and photon locations and energies
  – \(\sim 80,000\) PbWO\(_4\) scintillator crystals
  – Sensors
    • APD (barrel)
    • VPT (end cap)

Heavy mechanical engineering
Innovative crystals and photosensors
Demanding modern electronics
Off-detector electronics and services
ECAL modules

- **Main challenges** – as well as radiation tolerance
  - CMS ECAL designed for very high energy resolution
    - physics advantages for several specific discoveries
  - **very dense crystal material, with demanding specifications**
    - precise mechanical assembly and tolerances
    - final object very heavy
  - **electronics crucial**
    - large signal dynamic range
    - (~16bits) & high precision requirement
    - low noise
    - linearity
    - stability
  - **information vital to trigger**
    - selects data for readout
Tracker: APV25 custom integrated circuit

- Main features (many innovative, at the time)
  - Commercial 0.25µm CMOS
  - 128 programmable readout channels
  - amplifiers, memory, controls,…

- Designed and delivered by Imperial College and Rutherford Appleton Lab
  - manufacture via CERN contract
Optical links

• System developed for CMS Tracker mainly by CERN with industrial partners – later used for calorimeter, and other detectors
  – 1.3µm single mode FP laser transmitters, III-V semiconductor Tx & Rx
  • good linearity over wide range, good radiation & B-field tolerance
Tracker - Front End Driver

- Monolithic assembly (density/cost)
- ~ year 2005
- in UK with high yield
- opto-electric conversion
- data processing
- data transfer
- VME control and slow readout

- typical of many other CMS modules
TRACKER CONSTRUCTION
by worldwide effort

Austria, Belgium, Finland, France, Germany, Italy, CERN, Switzerland, UK, USA – 62 institutes
much movement of components and assemblies

Sensors, ASICs, hybrids procured and tested
some parts commercially: e.g. hybrids

Modules constructed in our dedicated centres, using automated assembly methods...
Modules and sub-system assembly

Inner barrel shells (Italy)

Endcap petals (Au, Ge, Be, Fr)

TOB modules and Rods (US, CERN) Hybrids (industry)
Sub-system integration
Integration at Tracker Integration Facility

• Dedicated clean room laboratory in CERN
  – assembled sub-systems, then added external cables, cooling, ...
Some of the challenges overcome

• Sensors: two major contracts with very different production quality

• Hybrids: flexible kapton-metal layer structure
  – subtle problems in through-via manufacture identified at late stage

• ASIC yield: variations after initial very good beginning
  – worked with company to understand and solve

• Cooling plant performance: manufacture weakness
  – failures in plant and components

• Many, many other issues
  – early attention to minor details is crucial to avoiding costly delays
  – most items are highly specialised with few, or no, second sources
Collision tracks: December 2009

Candidate multi-jet event at 2.36 TeV
4 particle-flow jets with ET > 7 GeV
tracks displayed with pT > 0.4 GeV
CMS ZZ → eeeμμ candidates
Discovery!

Yields for $m(4\ell) = 110\ldots 160$ GeV

<table>
<thead>
<tr>
<th>Channel</th>
<th>$4e$</th>
<th>$4\mu$</th>
<th>$2e2\mu$</th>
<th>$4\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ background</td>
<td>2.65 ±0.31</td>
<td>5.65 ±0.59</td>
<td>7.17 ±0.76</td>
<td>15.48 ±1.01</td>
</tr>
<tr>
<td>Z+X</td>
<td>1.20 ±1.08</td>
<td>0.92 ±0.65</td>
<td>2.29 ±1.81</td>
<td>4.41 ±2.21</td>
</tr>
<tr>
<td>All backgrounds</td>
<td>3.85 ±1.12</td>
<td>6.58 ±0.88</td>
<td>9.46 ±1.36</td>
<td>19.88 ±2.43</td>
</tr>
</tbody>
</table>

$m_H = 126$ GeV

164 events expected in [100, 800 GeV]
172 events observed in [100, 800 GeV]

Event-by-event errors
The future

- The experiments were demanding to design and build
  - the accelerator too...
  - but we succeeded in overcoming unprecedented challenges
  - a huge effort by many people and institutes, over many years

- Now we have set ourselves an even more difficult problem
  - upgrade the experiments to take data for a further 10-15 years
  - under even more demanding conditions
  - radiation tolerance, data volumes, reliability,..
  - while maintaining, or even improving, performance

- Replacing several major sub-detectors
  - and many other improvements
  - currently at R&D stage, prototyping, then construction from 2018?