Compact Muon Solenoid

- Extended Introduction to CMS
- Magnet
- Tracking System
- Electromagnetic Calorimeter
- Hadronic Calorimeter
- Muon System
- Trigger & Data Acquisition
- Summary

Ken Bell – Rutherford Appleton Laboratory
Physics Goals (as of 1994)

- **General Purpose Detector at LHC**: 14TeV pp, 40MHz
- **Standard Model Higgs Boson**
  - 85 – 160 GeV: Two photon channel
  - 130 – 700 GeV: Four lepton channel
  - 700 GeV – 1 TeV: $\ell\nu jj$ and $\ell\ell jj$ channels
  - $5\sigma$ discovery possible from LEP2 limit to 1 TeV ($10^5$pb$^{-1}$)
- **SUSY**
  - MSSM Higgs: Two photon and four lepton channels
  - Tau and $b$ tagging also important
  - Model-independent searches: high $E_t$ Jets and missing $E_t$
- **Heavy Ion Physics**
- **SM Higgs Boson used as performance benchmark**
Design Drivers

1) Efficient, hermetic muon triggering and identification
   - Low contamination & good momentum resolution over $|\eta| < 2.5$
   - Di-muon mass resolution <1% at 100 GeV/$c^2$
   - Charge determination for muons with momentum ~1 TeV/$c$
   - $\Delta p_T/p_T \sim 5\%$

2) High-granularity, hermetic electromagnetic calorimetry
   - Coverage over $|\eta| < 3.0$
   - Good energy resolution, ~0.5% at $E_T \sim 50$ GeV
   - Di-photon mass resolution <1% at 100 GeV/$c^2$

3) Powerful central tracking system
   - Good charged particle momentum resolution and reconstruction efficiency
   - Good reconstruction of secondary vertices (for $\tau$ and $b$-jets)

4) Hermetic combined calorimetry system
   - Coverage over $|\eta| < 5.0$
   - Good resolution for detecting and measuring “missing” $E_T$
     and for reconstructing the mass of jet-pairs

Criterion 1 drives overall physical design of the detector through magnet design
Criteria 2&3 need special technologies to cope with challenging LHC environment
• Single high field (4T) solenoid
  - Largest practicably constructible
  - Compact design, but large enough BL$^2$
  - Contains all barrel tracking and calorimetry
  - Therefore solenoid can be thick
• Flux return yoke accurately constructed and instrumented for muon detection with redundant measuring systems
  - 4 stations 32 $r$-$\phi$ measurements (barrel DT) & 24 $r$-$z$ measurements (endcap CSC)
  - Additional trigger from RPC layers
  - Sophisticated alignment system
• High-granularity electromagnetic calorimeter containing ~75k PbWO$_4$ crystals
  - >22$X_0$ in depth
• Tracking using 3-layer Si-pixel (66M channel) surrounded by 10-layer Si-strip (10M chans.) (210m$^2$ silicon: ~tennis court)
• Hermetic hadron calorimeter
  - Sampling type, brass/scintillator layers
Assembly Concept

- **Modular**
  - Ease of surface pre-assembly
  - Lower as 15 large pieces
  - Rapid access for maintenance

- **Surface (2000-2007)**
  - Assemble Barrel & Endcap yokes
  - Assemble & insert Coil
  - Assemble & install HCAL
  - Install Muon chambers
  - (Pre-)cable detectors
  - Start commissioning
  - Test of coil & “\(\phi\)-slice” of CMS

- **Underground (2006-2008)**
  - Install ECAL Barrel & Endcaps (preshower 2009)
  - Install Tracker and Beam-Pipe
  - Complete cabling
  - Close detector and finish commissioning
Performance Overview

Tracking

CMS ECAL

HCAL

Resolution in 3x3 crystal 704
S = 2.83 +/- 0.3 (\%)
N = 124 (MeV)
C = 0.26 +/- 0.04 (\%)
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>1984</td>
<td>Lausanne: Workshop on installing Large Hadron Collider in LEP tunnel</td>
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<tr>
<td>1987</td>
<td>CERN’s long-range planning committee recommends</td>
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<td>Large Hadron Collider as right choice for CERN’s future</td>
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<td>1989</td>
<td>LEP Collider starts operation</td>
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<tr>
<td>1990</td>
<td>Aachen: ECFA LHC Workshop</td>
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<td>1992</td>
<td>Evian les Bains: General Meeting on LHC Physics and Detectors</td>
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<tr>
<td>1993</td>
<td>Letters of Intent for LHC detectors submitted</td>
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<tr>
<td>1994</td>
<td><strong>LHC approved</strong></td>
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<tr>
<td>1995</td>
<td><strong>CMS Technical Proposal approved</strong></td>
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<tr>
<td>1998</td>
<td>LHC Construction begins</td>
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<tr>
<td>2000</td>
<td><strong>CMS assembly begins on the surface</strong></td>
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<tr>
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<td>LEP Collider closes</td>
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<td>2004</td>
<td>CMS experimental cavern completed</td>
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<tr>
<td>2008</td>
<td>10-Sep: First circulating beams</td>
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<td></td>
<td>Oct/Nov: CMS: 4-week, 300M cosmic-ray, data-taking at 3.8T: “CRAFT”</td>
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<td>2009</td>
<td>First proton-proton Collisions</td>
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<tr>
<td>2012</td>
<td>Reach design luminosity</td>
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<tr>
<td>2013</td>
<td>?? Upgrade LHC Phase 1: increase design luminosity by factor 2-4</td>
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<tr>
<td>2017</td>
<td>?? Upgrade LHC Phase 2: increase design luminosity by factor ~10</td>
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CMS Collaboration

### Number of Laboratories

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<td><strong>Total</strong></td>
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### Nr Scientists & Engineers

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<tr>
<td>USA</td>
<td>723</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>2310</strong></td>
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</tbody>
</table>

- **38 Countries**
- **175 Institutions**
- **2310 Scientists and Engineers**
UK groups in CMS Detector

- **UK is ~5% of CMS Collaboration**
- **Bristol University**
  - ECAL & Global Calorimeter Trigger (GCT)
- **Brunel University**
  - Strip Tracker & ECAL
- **Imperial College**
  - Strip Tracker, ECAL & GCT
  - CMS Spokesperson (T.S. Virdee)
- **Rutherford Appleton Laboratory**
  - Strip Tracker & ECAL
  - Electronic & Mechanical Engineering Support
- **Principal UK Strip Tracker involvement: Electronics & DAQ**
- **Principal UK ECAL involvement: Endcaps**
• Strong field (4T) with very large $B^2$
• Central tracking and calorimetry inside solenoid
• World’s largest SC solenoid
  ➢ 12.5m long, 6.3m diameter
  ➢ Many novel engineering aspects
  ➢ NbTi conductor embedded in pure Al
  ➢ Cold mass: 220 t
  ➢ Nominal current: 19.5 kA
  ➢ Stored energy at full field: 2.6 GJ

• Yoke
  ➢ 22m long, 15m diameter, 10000 t of iron
  ➢ 5 Barrel “wheels”, 3+3 Endcap “disks”

• Operate at B=3.8T
Map on Surface, before TK & ECAL installed
Rotary arm field-mapper: precision \(~7 \times 10^{-4}\)
Raw magnetic flux density measurements:

1st parameterisation:
12-fold symmetric model

Map good to 20G inside Tracking volume
Measured Endcap Deformation at 3.8T

3 Straight Line Monitor (SLM)
Laser Lines per Muon Endcap Station
10 optical CCD sensors per SLM

Measured ~15mm deformation agrees well with FEA prediction
All-Silicon Tracker: Pixels & Strips

- **TOB** - Tracker Outer Barrel
  - 6 layers, 5208 modules

- **TIB** - Tracker Inner Barrel
  - 4 layers, 2724 modules

- **TID** - Tracker Inner Disks
  - 2x3 disks, 816 modules

- **TEC** - Tracker EndCaps
  - 2x9 disks, 6400 modules

- **FPix** - Forward Pixels
  - 2x2 disks, 192 panels, 18Mpix

- **BPix** - Barrel Pixels
  - 3 layers, 768 modules, 48 Mpix
Pixel Tracker

- **Barrel Pixels**
  - 3 barrel layers at $r$ of 4.3, 7.3, 10.4 cm
  - 672 modules & 96 half modules
  - 11520 ROCs (48 million pixels)
- **Forward Pixels**
  - 2x2 disks at $z = \pm 34.5$ & $\pm 46.5$ cm
  - Extend from 6-15 cm in radius
  - 20° turbine geometry
  - 672 modules in 96 blades
  - 4320 ROCs (18 million pixels)
- **Design allows for three high precision tracking points up to $|\eta|$ of ~2.5**
- Active area: 0.78m² (BPIX), 0.28m² (FPIX)
- **Pixels 150$\mu$m x 100$\mu$m. Hit resolution of 10$\mu$m ($r-\phi$) & 20$\mu$m ($z$) expected due to charge sharing & $B=4T$**
- 66M readout channels
Silicon Strip Tracker

- **TIB**
  - 4 layers at $r$ of 25-50cm. Pitch 81/118µm
  - Hit resolution 23-34µm in $r$-$\phi$
- **TOB**
  - 6 layers at $r$ of 50-110cm. Pitch 118/183µm
  - Hit resolution 35-52µm in $r$-$\phi$
- **1st 2 layers of TIB/TOB**: 100mrad stereo angle
- **TID**
  - 2x3 disks at $|z|$ of 70-115cm
  - Pitch 97/128/143µm
- **TEC**
  - 2x9 disks at $|z|$ of 120-280cm
  - Pitch 96/126/128/143/158/183µm
- **1st 2 rings of TID, Rings 1,2,5 of TEC**: stereo
- **10 layer coverage in $|\eta|$ to ~2.4**
- **Active area**: ~210 m² Silicon
- **75k APV front-end chips**
- **9.6M readout channels**
Pixel commissioning in CRAFT

Pixel occupancy map

Barrel aligned at module level
(200-300 hits, 89% aligned)
SST commissioning in CRAFT

**Summary**

- **TOB** thick sensors: $S/N = 32$
- **TIB/TID** thin sensors: $S/N = 27/25$
- **TEC** (mixed thickness): $S/N = 30$
- **Conclude**: Signal/Noise as expected

**Graph 1**

- **Entries**: 81736
- **Mean**: 28.01
- **RMS**: 13
- $\chi^2 / \text{ndf}$: 108.8 / 62
- **Prob**: 0.0000211
- **Width**: 1.726 ± 0.021
- **MP**: 22.39 ± 0.04
- **Area**: $8.049e+04 \pm 378$
- **GSigma**: 3.95 ± 0.07

**Graph 2**

- **Distribution of the Mean of the Residuals for TOB**
  - **Unaligned**
  - **CRUZET4**: mean = 3 $\mu$m, RMS = 45 $\mu$m
  - **CRAFT-HIP**: mean = -1 $\mu$m, RMS = 28 $\mu$m
  - **CRAFT-MP**: mean = 0 $\mu$m, RMS = 24 $\mu$m

**Results**

- **TOB aligned**: rms = 26-40 $\mu$m
- **TOB aligned**: rms = 24-28 $\mu$m
ECAL

- Hermetic, homogeneous PbWO$_4$ calorimeter
  - Good energy resolution
- Why use PbWO$_4$ scintillating crystals?
  - Short radiation ($X_0 = 0.89$cm) & Moliere (2.2cm) length
  - Compact, fine granularity
  - Fast and radiation hard
  - Low light yield: compensate with high gain photodetectors which work in magnetic field
    - Avalanche Photodiodes (APDs) in barrel
    - Vacuum Phototriodes (VPTs) in endcaps

Extensive R&D needed:
~84 t of PbWO$_4$ (& APDs, VPTs)
[cf ~tens of g of PbWO$_4$ before CMS]
ECAL Barrel

- **Barrel**: 61200 crystals
  - $0 < |\eta| < 1.479$, inner radius 129cm
  - 36 identical “supermodules”
  - Crystal covers $1^\circ$ in $\eta$ & $\phi$
    - Front face $22\times22\text{mm}^2$, length = $230\text{mm} \rightarrow 25.8\ X_0$
    - Quasi-projective geometry
    - All channels pre-calibrated to 1.5% (cosmic rays)

$\sigma(E)/E = 0.42 \pm 0.01\%$
• **Endcaps:** 2 x 7324 crystals
  - $1.479 < |\eta| < 3.0$, $|z| \sim 314\text{cm}$
  - 2 “Dees” per endcap
  - Crystals arranged in $xy$ grid
    - Front face $28.6 \times 28.6\text{mm}^2$
    - Length $= 220\text{mm} \rightarrow 24.7\, X_0$
    - Quasi-projective geometry
ECAL Endcap Preshower

4300 sensor modules
20m² Silicon
138k channels

Final plane complete this month
Both endcaps installed & checked-out by Easter 2009

- Identifies $\pi^0$ over $1.653 < |\eta| < 2.6$
- Improves purity of electron ID
- High granularity $\rightarrow$ improved electron & $\gamma$ position determination
Energy Maps shown. Beam splash events also used to determine channel timings.

White areas to be recovered in 2008/09 shutdown.

Calibrations not yet applied in Endcaps (lower response VPTs nearer beam pipe)
ECAL Stopping Power (CRAFT cosmics)

Stopping power of cosmic rays traversing ECAL, as function of measured momentum (Tracker)

Dashed lines: contributions from collision loss (red) and bremsstrahlung (blue)

Errors: bin-width (x) & statistical (y)

Shows correctness of Tracker momentum scale & ECAL calibration from test beams
• Hermetic hadron calorimeter
  - Sampling type, brass/scintillator layers (HB, HO, HE). Hybrid Photo-Diodes
  - **Barrel**: $|\eta| < 1.4$, inside solenoid, single longitudinal sampling
  - **Outer**: barrel tail-catcher for $|\eta| < 1.26 \rightarrow >11\lambda_{int}$ in depth
  - **Endcap**: $1.3 < |\eta| < 3.0$
  - **Forward**: $3.0 < |\eta| < 5.0$: Iron/quartz-fibre
  - $\sigma/E$ (test beam): $\sim 97\% / \sqrt{E} \oplus 8\%$
ECAL & HCAL energy deposits highly correlated
Event selection:
Muon track matching in DT and Tracker
$20 \text{ GeV/c} < P_\mu < 1000 \text{ GeV/c}$
CRAFT: 200 k events
MC: 15 k events

HB energy: signal from HB towers corrected for muon path length in HB

Test Beam 2006
$P_\mu = 150 \text{ GeV/c}$
Mean signal = 2.8 GeV

CMS Preliminary
Muon System

Cathode Strip Chambers & Resistive Plate Chambers

Drift Tubes & Resistive Plate Chambers

Wires = anodes

Strips = cathodes

Endcap

Barrel

Resistive Plate Chambers

+ve anode

-ve cathode
Muon System

- Two independent & complementary systems
- At least 4 layers
- Drift Tube Chambers (Barrel)
  - 250 chambers, 180k channels
  - Good muon resolution: $r$-$_{\phi} \sim 100\mu m$, $Z \sim 150\mu m$, angle $\sim 1$ mrad
  - Slower response (up to 400 ns)
  - Economical for use in low rate region
- Resistive Plate Chambers (Barrel & Endcap)
  - 1020 chambers
  - Muon spatial resolution: $r$-$_{\phi} \sim 1.5$ cm
  - Fast response, <3ns timing resolution
  - Relatively inexpensive
    - Dedicated to first level trigger
- Cathode Strip Chambers (Endcaps)
  - 468 chambers, 450k channels
  - Good muon spatial resolution: $r$-$_{\phi} \sim 75$–$150\mu m$, <2mm at trigger level
  - Close wire spacing $\rightarrow$ fast response
    - 4ns timing resolution
    - Good for high rates
Beam Halo Hit Distribution in CSCs

Arrow indicates sequence beam traversed endcap disks: Iron progressively absorbs halo muons…
Run 62232, Event 1811006
DTs, HCAL & ECAL in Beam Splash Events

~$2 \times 10^9$ protons on collimator ~150m upstream of CMS

HCAL energy

ECAL energy

Debris

DT muon chamber hits

Inner tracking systems kept OFF
Muon DTs at CRAFT

- Chamber residuals:
  - Reasonable agreement between data & MC after fitting arrival time of cosmic muon
  - Sigma ~200-260µm
  - Sector 4 of wheel -2 shown here
  - B-field degrades MB1 resolution in wheels +/-2
• Already have Drift Velocity determination from CRAFT data
  ❖ Innermost stations on outer wheels have largest radial field (eg Wh-2 MB1)
  ❖ Highly suppressed zero on Y-axis: maximum difference in Drift Velocity is 3%
- Green: Tracker and Muon hits
- Magenta: ECAL
- Blue: HCAL
Trigger challenges at LHC

- Enormous data rate: $10^9$ Hz of collisions
  - More than 1TByte/s
- Minimum bias in-time pile-up
  - 22 events per bunch crossing
- Out-of-time pile-up
  - Events from different bunch crossings overlaid
- Tiny cross sections for Higgs and new physics
  - Selection $1:10^{11}$
- All online
  - Can’t go back and fix it. Events are lost forever!
- Level-1 (hardware): 40MHz $\rightarrow$ 100kHz
- Level-2 (software): 100kHz $\rightarrow$ ~100Hz
CMS Level-1 Trigger

- **Muons**
  - Three complementary detector systems
  - Share hits when available in overlap regions
  - Find best combination of information in Global Muon Trigger
- **Electrons, jets, energy sums etc.**
  - Combine ECAL and HCAL energies in Regional Calo Trigger and do local electron finding
  - Global energy sums and jets in the Global Calo Trigger
- All objects contribute to L1 accept
• High Level Trigger (HLT)
• Bandwidth/Timing constraints:
  - Each HLT trigger path is a sequence of filters
  - Progress from low- (Calo, Muon) to high- (Pixel, Strip) time-consuming algorithms
  - All algorithms regional (except jets)
    - Seeded by previous levels
  - Reco time is significantly improved by applying:
    - Regional data-unpacking
    - Local reconstruction (using one subdetector only)
• Runs on ~1000 Dual QuadCore CPUs at 2.6 GHz
• Major exercise in 2007 showed time/event OK
Data Acquisition Architecture
Underground Commissioning Progress

- First cosmic muon triggers underground
- Reached scale of 2006 Magnet Test & Cosmic Challenge
- Upgrade to final DAQ software architecture
- First µ coincidence of 2 subsystems
- Final DAQ hardware, final services

Sub-Detector + Trigger

- Pixels and EE added
- Muon Tracks in Si-Strip Tracker

May07 - Sep08
### Winter 2008/2009 Shutdown

- Install and commission preshower detector
- Tackle infant mortality in detectors installed prior to 2008
- Finalise commissioning of detectors installed in 2008
- Address issues arising from CRAFT running
- Schedule for restart in 2009:
  - Resume cosmic-ray data-taking at B=0T in April
  - Close detector by end of May
  - Extended CRAFT Run before 2009 LHC beams
Summary

- Construction of the CMS experiment is almost completed
- Commissioning work already carried out gives confidence that CMS detectors will operate with expected performance
- Integrated operation of subdetectors & central systems using cosmic-ray triggers is now routine, with near-final complexity and functionality
- Challenges conducted around the clock at 100% of 2008 load show that Computing, Software & Analysis tools are ready for early data
- Have already taken and analysed first beam-related data
- Preparations for rapid extraction of physics are well advanced
- Eagerly awaiting first LHC Physics during 2009
Back-Up
Cosmic Run at Four Tesla (CRAFT)

Aims:
- Run CMS for 4 weeks continuously to gain further operational experience this year
- Study effects of B field on detector components (since MTCC)
- Collect 300M cosmic events with tracking detectors and field
- Aim for 70% efficiency

Facts:
- Ran 4 weeks continuously from 13-Oct to 11-Nov
  - 19 days with B=3.8T
- 370M cosmic events collected in total
- 290M with B=3.8T and with strip tracker and DT in readout
  - 194M with all components in

Dataset: /Cosmics/Commissioning08-v1/RAW
Selection: DT,SIST,BFieldOn
Tot Events: 286825664

4 runs exceed 15h
Oct.21 VIP visit