CMS: from commissioning to first beams
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for the CMS Collaboration

- Commissioning in 2008
- The first LHC beams
  - Beam splashes
  - Beam halo
- Cosmic run at 4 Tesla
- Readiness for 2009
About *real magic* and magic that is real

6/17/87 (Delhi)

“I’m writing a book on magic,” I explain, and I’m asked, “Real magic?” By *real magic* people mean miracles, thaumaturgical acts, and supernatural powers.

“No,” I answer: “Conjuring tricks, not real magic.”

*Real magic*, in other words, refers to the magic that is not real, while the magic that is real, that can actually be done, is not *real magic*.

Lee Siegel, Net of Magic (p. 425)
About *real data* and data that is real

6/01/09 (Geneva)

“I’m writing slides on data,” I explain, and I’m asked, “Real data?” By *real data* people mean high-energy collisions, SM physics and BSM physics.

“No,” I answer: “Cosmic muon data.”

*Real data*, in other words, refers to the *data* that is not yet real, while the *data* that is real, that can actually be analyzed, is not *real data*.

This talk offers *data that is real*, not yet *real data*. 
**Tracker**
66M Si pixels & 10M Si strips

**Superconducting Solenoid**
Very large, 6m x 13m
4 T, 2.7 GJ stored

**Hadronic calorimeter: HCAL**
Brass & scintillator
Barrel (HB), Endcap (HE), Outer (HO)

**EM calorimeter: ECAL**
PbWO4 crystals
High resolution
High granularity > 80k crystals
Barrel (EB) & Endcap (EE)

**Muon System**
Barrel: Drift Tubes (DT)
Endcap: Cathode Strip Chambers (CSC)
Both: Resistive Plate Chambers (RPC)

**Trigger/DAQ**
Hardware Level-1 (100 kHz)
76/s Event Builder @ L-1 rate
Software High Level Trigger (300 kHz)
From the CMS Album

Dance of the endcaps

Barrel pixel insertion

YE-1 lowering
2006 - First system-wide test

Pieces still in the surface
Scaled-down infrastructure
Slice of nearly all final components and DAQ

Parasitic to B field mapping at 5 values for physics
2007/8 – Putting the pieces together

- Integration of subdetectors and trigger
  - considered separately: 19 items, each equally weighted

- All CMS systems ready for LHC in August 2008
  - except some parts of RPC

- Reached scale of 2006 tests
- First $\mu$ coincidence of two subsystems
- Upgrade to final DAQ software
- First cosmic muon triggers underground
- Start of full week exercises (CRUZET 1)
- Final DAQ hardware, final services
2008 – Waiting for the beam

• Operate CMS as a single detector
  – Integration of new sub-detectors
  – Increase complexity, maximize stability
  – Coordinate with installation schedule

• Infrastructure
  – DAQ and Trigger
  – DQM, DCS, DSS
  – Control Room
  – Magnet off,
    ZEro Tesla Runs

Sep 10th
First LHC Beam
CRUZET3 – first global muon tracks

- Dimuon trigger
  - Top-bottom coincidence
  - \( \geq 2 \) station segments

- Muon signals found in
  - Muon chambers
  - HCAL
  - ECAL
  - Tracker TOB + TIB

- Global track fits
  - First alignment data
CRUZET4 – Welcoming the ECAL Endcaps

Muon Chambers

Barrel ECAL

Endcap ECAL

HCAL
Cosmic Showers at zero tesla

- \( O(100) \) muons
  - 0.02% cosmic events at 0 T
- Event-by-event spread in \( \phi \) compatible with multiple scattering
- All events compatible with parallel (atmospheric) muon shower

\[
\frac{1}{2} \Delta \phi \approx \tan \frac{1}{2} \Delta \phi = \frac{r_{\text{CMS}}}{h}
\]

\[
\Delta \phi \approx 0.01\pi
\]

\[
\Rightarrow \quad h \gtrsim 500 \text{ m}
\]
Last year beams in the LHC

- **September 7**
  - Beam 1 on collimators (upstream of CMS)

- **September 10 (D-day)**
  - Beam 1, then Beam 2 circulating (hundreds of turns)

- **September 11**
  - RF capture (millions of orbits)
  - Beam halo through CMS
  - Beam-gas events

- **About 40 hours of beam at or through CMS**
  - All systems ON except Tracker and Solenoid

- CMS Trigger and DAQ fully functional: millions of beam events recorded
Beam Splash Event Display

HCAL energy

ECAL energy

Muon chamber hits

LHC Tunnel Profile
Beam Splashes – energy in CMS

ECAL energy vs Beam Loss Monitors

- TCTH: position of beam interaction
- TCTV: 2.1 m downstream
- TAN: 6.8 m downstream
- TCLP: 4.3 m upstream
- XRP MBRC: 5.3 m upstream

# of digits in the DT MB3 stations

- Muon hits vs ECAL

- HCAL energy vs ECAL

- BLM measurement (normalized to average)

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SUSY09
Splash synchronization of calorimeters

- In splash events all channels fire
- synchronize in one go all the calorimeters
- time of arrival follows geometry

ECAL

\[ \text{beam} \quad 1 \text{ ns} \]

HCAL

Sep 10

Before Delay Tuning
- Depth 1
- Depth 2
- Depth 3
- Depth 4.4R
- Depth 4L

Sep 18

After Delay Tuning (Beam Splash Run #63198)
- Depth 1
- Depth 2
- Depth 3
- Depth 4.4R
- Depth 4L
Cometh September 10
Circulating beams

Multiple orbits detected in the CMS beam monitoring system (BPTX)
First RF capture

BPTX – CSC halo

Lower cosmic rate due to backpressure

Large debunched signal in CSC

Initial timing difference of BPTX & CSC trigger

Phase drifting

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Bx wrt. orbit signal

SUSY09 20
From the CMS Album

Halo muons in couples...

...and singles.

Halo muon crossing both endcap and barrel chambers
Beam Halo Muons

**Beam Halo**: muons outside of beam-pipe, arising from decays of pions created when off-axis protons scrape collimators or other beamline elements.

CSC Hit Distribution from Beam Halo Events
Beam Halo muon features

θ – muon angle w.r.t. the beam line for different distances from the beam line

• As expected:
  • Away from beam line: cosmic rays
  • Close to the beam line: beam halo
Beam Halo - comparison with simulation

beam ON data: combination of
• beam halo
• cosmic rays

angle w.r.t. the beam line (radians)
Cosmics Run at 4 Tesla – CRAFT

• Four weeks of continuous running
  – target 70% efficiency
  – **19 days with B = 3.8 T**
  – gain operational experience in 24/7 operation
  – identify areas of concern, understand efficiency

• 370 M cosmic events
  – **290 M events at B = 3.8 T**
  – 87% events with muons
  – 3% also have Si strip hits
  – 0.03% have Si pixel hits

• Data Operations
  – 600 TB transferred
  – Prompt reconstruction within hours
  – Reconstructed 10+ times
    • Increasing understanding

4 runs exceed 15h

Oct 21 VIP visit
From the CMS Album

Nice muon through tracker

Opposite charge...

Cosmic through barrel and endcap
From the CMS Album

Muon through tracker...

...including pixel hits
The path of least resistance

- Reconstructed angles of cosmic rays indicate increased acceptance through the access shafts of CMS
Tracker Barrel Alignment

- Mean of residual distributions (cm)
  - Sensitive to module displacements
- Only modules with 30+ hits considered
  - 96 % TIB, 98 % TID, 98 % TOB, 94 % TEC
- HIP algorithm: TIB RMS = 26 µm, TOB RMS = 28 µm
Pixel Barrel Alignment

- Barrel aligned at module level
  - 200-300 hits, 89% considered
- Endcap aligned at half-disk level (8)
- HIP algorithm: \textbf{PIX RMS} = 47 \, \mu m
Cosmic Tracking using Tracker

- Momentum distribution for high quality tracks
  - 8 hits, 1 hit in TIB Layer 1 or 2, 1 hit in TOB Layer 5 or 6
  - ~70 k tracks expected with $p_T > 100$ GeV

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ECAL Timing and occupancy

**Timing** – bottom is late ✔

**Occupancy** – top is busier ✔ (shaft side)

- $E_{\text{seed}} > 100$ MeV
ECAL energy spectrum
Muon stopping power in PbWO4

Collision loss
Bremsstrahlung

Not a fit!
After the cosmic campaign

3% of muon chambers repaired
Cooling system maintenance

ECAL Preshower installed
63% of forward pixels repaired
What has been keeping us busy

• Since November 2008…
  – Installation of ECAL Preshower
  – Interventions on problematic channels O(1%)
    • 6 % forward pixels, 4% DT chambers, 2% CSC chambers, 1% ECAL
  – CMS cooling system maintenance

• … while running the experiment as a whole...
  – Weekly global runs since April
  – 1-week at zero Tesla just last week (45 M cosmics)
  – Start 4 Tesla running in July

• ...even while things move
  – Last week the minus endcap was closed
  – The plus endcap is being closed as we speak

• Continue global data-taking with cosmics before beam this fall
Conclusions

• CMS is commissioned and has taken first data with the LHC
  – It’s only been 3 out of O(20) years
• After the LHC hiccup, we have been touching-up

• CMS is ready for **real data** in September
  – Until then we will be exploiting **data that is real**
  – Stay tuned for early physics searches and (re)discoveries!

• Until then we should all discover Boston’s lobster rolls
FOR DISCUSSION
Prospects for 2009-2010 Run

• 10 pb\(^{-1}\)
  – Standard candles: W, Z, top cross-sections at 10 TeV
  – Jet energy corrections
  – Searches using high-Et jets

• 100 pb\(^{-1}\)
  – Precision measurements of SM
  – W', Z'
  – JES from top
  – Heavy stable charged particles
  – SUSY searches
  – ...

• 200–300 pb\(^{-1}\) at 10 TeV
  – head-to-head with Tevatron for Higgs mass \(\sim\)160 GeV
Strip and Pixel Tracker: Status

• Strip Tracker
  – TOB: 98.2% (0.6% recoverable)
  – TIB/TID: 96.9 % (1% recoverable)
  – TEC+: 99.2%
  – TEC-: 97.8 % (1.7% recoverable)

• Pixels
  – Barrel pixels: 99.1%
  – Forward pixels: 94.0%
    • Dominated by some readout chips without bias voltage and others without low voltage
    • Repairs finished
HCAL Barrel Muon Response

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
Triggering on the beam

- **BPTX technical trigger**
  - Most reliable source of trigger, to be synchronized with other trigger sources
  - Rate = beam revolution frequency = 11.223 kHz
  - Efficiency diminishes as the beam weakens

- **CSC beam halo trigger (special muon bit)**
  - Very clean, noiseless trigger.
  - Rate without beam ~2% due to cosmic muons
  - Signals from the endcap facing the beam delayed by 2 BX to keep the 2 endcaps in synch
  - Used also for beam splash, but chambers not in the read-out (gigantic events)

- **Forward HCAL technical trigger**
  - clean trigger, but typically beam halo too weak

- **Non-filtering HLT**
  - Though streaming events accordingly to L1 bit and performing basic reco
Beam Detectors

BCM1 L/F diamonds
Z=± 1.9m, r=4.3cm

BSC1: scintillators
Z=± 10.9 m, r=4.3cm

BCM2 diamonds &
BSC2 scintillators
Z=± 14.4m, r=29cm

BCM1 L/F and BCM2
PROTECTION of CMS

BPTX beam pickup
Z=± 175m
First Circulating Beam Through CMS

Beam1 arrives at +z monitor ~15ns before -z monitor (TOF)
Triggering on the beam

RF capture tests

Response matrix measurements

Tests with circulating beam

BPTX –

BPTX +

CSC halo

Bx wrt. orbit signal

0 5 10 15 20 25 30 35 40

time CEST - hours wrt. Sep 12 0:00

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Beam timing jitter?

Circulating beam – BX jitter

Bx wrt. orbit signal

2615
2610
2605
2600
2595
2590

21.4 21.45 21.5 21.55 21.6

BPTX trigger
BPTX trigger
me HALO trigger

time CEST - hours wrt. Sep 12 0:00
First RF capture

Monte Carlo (both beams)

before capture

Energy in forward HCAL

before capture

after capture

after capture

difference of number of fired CSC chambers

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"Synchronization" tests, 5-9 Sept

- Collimators placed at 146 m away from the IP on each side of CMS to stop the beam
- Beam 1 at injection energy (450 GeV) shot towards CMS from z+
- Beam 2 tried the first time on Sept 10
“Beam Splash” Events

- Single beam shots of $2 \times 10^9$ protons onto closed collimators ~150m upstream of CMS
  - Hundreds of thousands of muons pass through CMS per event
  - Enormous amount of energy deposited in calorimeters
- Allowed synchronization of triggers (previously with cosmic muons)
  - Muon end caps, BPTX beam pick up, etc
- Internal synchronization of sub-detectors
CSC alignment

- tracks crossing overlapping muon chambers can be used for alignment
- 11,000 beam halo events (out of a total of ~500 k) useful for alignment collected in 9 min of LHC running
- 300 microns accuracy achieved
Average of single DT cell efficiency per SuperLayer

Lower values correspond to Superlayers with some group of disconnected (temporary) channels.

- Average of single DT cell efficiency per SuperLayer
- Mean: 98.54
- RMS: 0.888

Entries = 654
Measured Endcap Deformation at 3.8T

3 Straight Line Monitor (SLM) Laser Lines per Muon Endcap Station
10 optical CCD sensors per SLM
DT Drift Velocity Along Z, Field On/Off

- Innermost stations on outer wheels have largest radial field
- Maximum difference in drift velocity is 3%
Pixel Signal

Barrel Pixel cluster charge corrected for the track angle
Tracker Signal/Noise

- TOB thick sensors: S/N = 32
- TIB/TID thin sensors: S/N = 27/25
- TEC (mixed thickness): S/N = 30

On track Strip clusters S/N ratio in peak mode of the read-out chip, corrected for the track angle

Track hit finding efficiency of TIB and TOB layers, excluding modules not in operation
Tracker Alignment

$\chi^2/\text{ndof}$

- **Unaligned**
  - Mean = 5.46
- **CRUZET**
  - Mean = 3.39
- **CRAFTHIP**
  - Mean = 2.49
- **CRAFTMP**
  - Mean = 2.82
Pixel Occupancy Maps

Pixel hits in cosmics, B=3.8 T

Pixel barrel hits in cosmics, B=3.8 T
Beam splash timing

So, in a splash event or beam-halo event, we expect a completely timed in ECAL if we correct each time by
\[ \frac{\sqrt{R^2 + Z^2}}{c} + \frac{Z}{c} + t_0 \]