The new Global Muon Trigger of the CMS experiment

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On behalf of the CMS Collaboration

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Large Hadron Collider

- 27 km circumference
- ~100 m underground
- 7 TeV nominal beam energy
- 40 MHz bunch crossing rate
- ~1 billion collisions / s
- 4 experiments
Large Hadron Collider

- LHC run 2:
  - 13 TeV pp centre-of-mass energy
  - Target ~100 fb\(^{-1}\) delivered luminosity
  - Increasing instantaneous luminosity
  - Increasing pileup

Pileup:
Several proton-proton collisions per bunch crossing (BX)
All created particles overlaid in the detector

Many interesting processes are rare.
(currently ~1 Higgs boson produced / min, but few decay to golden channels)

Require a lot of data to be studied.
CMS Collaboration

~3500 scientists, engineers, administrative staff and students
193 institutes
43 countries
Compact Muon Solenoid

CMS DETECTOR
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE
- 12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm) ~16m² ~66M channels
- Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
- Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
- Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
- Brass + Plastic scintillator ~7,000 channels
CMS - subdetectors

- **Electromagnetic calorimeter (ECAL)**
- **Silicon tracker**
- **Hadron calorimeter (HCAL)**
- **Superconducting magnet**
- **Iron yoke**
- **Muon chambers**

- Neutrinos: no signal in detector
- Radius 7.5 m
- Particles from previous collision are still in the detector when protons from the next bunch collide
Only a small fraction of the 40 MHz LHC collision rate can be analysed

CMS uses a 2-level trigger system to select interesting events for analysis

**L1 trigger**
- **Custom HW** in μTCA standard
- 3.8 μs latency
- High granularity data kept in readout buffer until L1 decision
- **100 kHz output rate**
- Trigger control and distribution system (TCDS) delivers trigger signal to front end electronics
  - Can throttle the trigger
- Silicon tracker not used at L1
  - Presentation by T. Schuh
  - Poster by L. Calligaris

**High Level Trigger (HLT)**
- Entirely in software
- Processor farm with ~20000 cores
- Working on full events built by DAQ
- File based (On RAM disks)
  - Decouple online SW from HLT SW
- **1 kHz output rate**
- HLT farm used for cloud computing during technical stops of the LHC
  - Ongoing work to also use it between collision runs

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Data Acquisition

- DAQ2 operating since 2015 run
  - Dedicated talk by J. Hegeman
- Readout and build events at L1 trigger rate (100 kHz)
- Event size $O(1\ MB)$
- High throughput system (200 GB/s)
- Lossless system
  - Backpressure is generated if event building cannot keep up
  - Throttles trigger if needed
CMS status

- LHC start up very fast, despite problems in accelerator chain and incidents with local fauna
- **Data taking efficiency** by luminosity greater *91%*

![CMS Integrated Luminosity, pp, 2016, \( \sqrt{s} = 13 \text{ TeV} \)](image)

Data included from 2016-04-22 22:48 to 2016-06-03 02:47 UTC

- **LHC Delivered**: 2078.33 pb\(^{-1}\)
- **CMS Recorded**: 1901.52 pb\(^{-1}\)

Delivered 2015: 4220 pb\(^{-1}\)
Upgraded Global Muon Trigger
Why upgrade the trigger?

• Higher LHC performance in run 2
  ▪ Higher centre-of-mass energy of 13 TeV (7/8 TeV in run 1)
  ▪ Increased luminosity
  ▪ Higher pileup
  ▪ Increased trigger output rate would require major detector upgrades

• A more selective trigger is needed
  ▪ Making use of capabilities of new FPGAs and fast serial links
    - Higher precision in particle parameter measurements
    - Implement more sophisticated algorithms

• More trigger algorithms in the menu
  ▪ Previously limited to 128 algorithms
  ▪ Now max. 512 algorithms

• Several components showed signs of ageing

• Move to common HW for different subsystems
Upgraded muon trigger

2015 legacy

- CSC Hits
- DT Hits
- RPC Hits

- MPC
- SC
- LB

- CSC Track Finder
- DT Track Finder
- PACT

- CSC Sorters
- DT Sorters
- RPC Sorters

- 4 muons
- 4 muons
- 4+4 muons

- Global Muon Trigger
- Global Trigger

2016 upgrade

- CSC Hits
- RPC Hits
- DT Hits
- HO HTR

- MPC
- Mezz
- LB

- CPPF
- TwinMux

- Barrels
- 36 muons
- 36 muons
- 36 muons

- Global Muon Trigger
- Calo Layer 2

- 8 muons

Moving from a subdetector centred concept to a geometry centred concept

Based on common HW designs

3 muon track finders (TF) for different $\eta$ regions

- Barrel muon TF (BMTF)
- Overlap muon TF (OMTF)
- Endcap muon TF (EMTF)

Global Muon Trigger performs sorting, duplicate removal and calculates muon isolation

Best 8 muon candidates are sent to the upgraded Global Trigger
Hardware

• Trigger processor: **Master Processor 7 (MP7)**
  - Advanced mezzanine card (AMC) in μTCA standard
  - **Generic design** for stream data processor
    - Used by several other CMS systems as well
      - e.g. GT, BMTF, Calorimeter trigger
  - Based on Xilinx **Virtex-7 690 FPGA**
  - 72 optical Rx & 72 optical Tx links at 10 Gb/s

• DAQ link: **AMC13**
  - A 13\textsuperscript{th} AMC in the second μTCA carrier hub (MCH) slot of the crate
  - 10 Gb/s optical links to central DAQ
  - **Distributes LHC clock, timing and control signals** to MP7 over backplane
GMT installation

Global muon trigger installation in the CMS service cavern

- 36 I/O links on each cable
- Fibres to DAQ
- Fibres from TCDS
- Patch panel at back of the rack
- AMC13
- MP7
- MCH
- Power
Track finders

- **Barrel Track Finder**
  - DT and RPC
  - $|\eta| < 0.83$
  - 2D track finding
  - 12 wedges in $\phi$

- **Overlap Track Finder**
  - DT, CSC and RPC
  - $0.83 < |\eta| < 1.24$
  - Pattern finding
  - 6 sectors in $\phi$ on each detector side

- **Endcap Track Finder**
  - CSC and RPC
  - $|\eta| > 1.24$
  - 3D track finding
  - 6 sectors in $\phi$ on each detector side
Upgraded Global Muon Trigger

- One MP7 board
- One AMC13

### Bit Widths

<table>
<thead>
<tr>
<th>Bit Width</th>
<th>Legacy</th>
<th>Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>$\eta$</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>$\phi$</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Charge</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Quality</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Track Address</td>
<td>n/a</td>
<td>29</td>
</tr>
</tbody>
</table>

- $\pm 2$ BX ($\pm 1$ BX) around trigger arrival time for outputs (inputs)
- Working on zero suppression
- 100 ns (4 BX) algo latency + 5 BX for (de-)serialisation
- 1008 energy sums
- up to 6 boards

DAQ readout via AMC13

Barrel Track Finder: 36 muons
Overlap Track Finder: 36 muons
Endcap Track Finder: 36 muons

Global Muon Trigger
- Muon sorting
- Duplicate cancellation
- Abs / rel isolation
- 8 muons

Calo Layer 2
Global Muon Trigger algorithm

1st sorting stage
- sorting stage 0 neg. end-cap
- sorting stage 0 neg. overlap
- sorting stage 0 barrel
- sorting stage 0 pos. overlap
- sorting stage 0 pos. end-cap

With duplicate cancellation

2nd sorting stage
- sorting stage 1 global sort

Isolation unit
- select 5x5 sums
- isolation check

Muon sorting
- energy deposits
- coordinates at vertex
- calorimeter indices
- isolation bits
- cancel signal
- barrel muons
- overlap muons
- end-cap muons
- final muons

Duplicate removal between wedges/sectors and between TF (LUTs)

Ranking by $p_T$ and quality (LUT)

CERN
Duplicate muon removal

• The **same muon can be found twice** (~1% of the muons)
  ▶ Due to overlap of adjacent track finder wedges/sectors or adjacent TF
  ▶ This **would increase the trigger rate for double muon triggers**

• Two methods of cancelling duplicates
  ▶ **Track address based** (Track Address: Track segments used to build the muon)
    - Used to **cancel duplicates between BMTF wedges**
    - A tracks are marked as duplicates if they **share one common segment**
    - Plan to used address based cancel out also for EMTF muons
  ▶ **Muon coordinate based**
    - Different address schemes between TF require duplicate cancel out by muon track coordinates
    - Tracks within the cancel out window are marked as duplicates
    - Cancel out window $\Delta R^2 = f_1 \Delta \eta^2 + f_2 \Delta \phi^2$
    - Window shape tunable by factors $f_1$ and $f_2$

• If a duplicate is found the **muon with higher quality is kept**
• **Tuning needed to keep real close-by di-muons**
• Cancel out unit catches ~80% of duplicate muons while keeping ~70% efficiency for di-muons
Isolation

- The GMT receives **1008 energy sums from the calorimeter trigger** on 28 optical links
  - 36 (φ) * 28 (η)
  - 5 bit per sum
  - Sums over 5x5 calo regions

- Muon coordinates are extrapolated to the vertex (LUTs)
- Muons are matched to corresponding energy sum index (LUTs)
- For each muon two isolations are calculated (LUTs)
  - Absolute isolation
  - Relative isolation
    - Energy sum relative to muon $p_T$
- Isolation bits are merged with output muons

- Algorithm in FW but not commissioned yet
- Other isolation algorithms are under study
Firmware

- **Virtex-7 690 T**
- **Pipelined logic** at 240 MHz and 40 MHz

**Resource utilisation**
- Logic: 51%
- Block RAM: 32%
- Inputs 10 Gb/s: 64/72
- Outputs 10 Gb/s: 36/72

- **Links, readout, IPbus**
- **Muon deserialisation / serialisation**
- **Cancel out**
- **Sorting**
- **Isolation**
Firmware

• Initially developed with Xilinx ISE
  ‣ Needed SmartXplorer for parallel implementation runs on a cluster of 5 machines
  ‣ Took at least 13h for the implementation
  ‣ Needed to floor plan entire design to achieve timing closure
• Change to Vivado reduced implementation time to 2h
  ‣ Still need some floor planing constraining several functional blocks to clock regions

- Links, readout, IPbus
- Muon deserialisation / serialisation
- Cancel out
- Isolation
- Sorting (Partly constrained)
Trigger emulation

- Trigger emulator software within the CMS software framework
  - Use cases:
    - Rate and efficiency studies
    - Production of Monte Carlo simulated samples
    - Algorithm studies
    - Creating test patterns for firmware validation on test bench
    - Calculating LUTs for duplicate cancel out and sorting
    - Planned: Online DQM comparisons with FW
  - 100% agreement between HW output and emulator
    - Verified with test patterns from simulated samples
    - Compared unpacked data from collision events with emulator output

- Written in C++
- Emulator configuration
  - Automated from offline conditions synchronized to online DB configuration
    - O2O: Online to offline DB configuration transfer
  - Manually from configuration file for studies
Control and monitoring software

- **Common control and monitoring software** (SWATCH) is used to configure and monitor the system (Dedicated presentation by T. Williams)

- Centrally controlled **run control** state machine
  - Load configuration and LUTs from online DB at configure

- **Monitoring** status registers from MP7 and AMC13
  - Muon counters at input, after first and second sorting stages
  - Bunch counter mismatches
  - Disabled inputs
  - Input/Output link status
  - DAQ readout status

![Diagram](image-url)
Summary

• CMS L1 trigger was upgraded to μTCA based system

• New global muon trigger uses generic, FPGA based, trigger processor board with 144 optical inputs and outputs at 10 Gb/s
  • Sorting of muons from regional muon track finders including regional sorting previously done on independent boards
  • Removal of duplicate muons from overlap areas
  • Absolute and relative isolation bits assignment for muons sent to global trigger
  • Firmware implemented and 100% compatible with software emulation

• New global muon trigger has been commissioned and is used for data taking since March 2016
  • Preliminary studies show lower rates while maintaining similar efficiencies as in 2015