CMS Trigger System

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Cross-Sections and Rates

- Formidable task: Trigger Rejection $4 \times 10^5$
- Bunch crossing rate 40MHz $\rightarrow$ permanent storage rate $O(10^2)$Hz

Cross sections for different processes vary by many orders of magnitude:

- inelastic: $10^9$ Hz
- $W \rightarrow \ell v$: 100 Hz
- $tt$: 10 Hz
- Higgs (100 GeV): 0.1 Hz
- Higgs (600 GeV): 0.01 Hz

Required selectivity:

$1 : 10^{10 - 11}$

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**Principle of Trigger**

Event accepted?  
\[ T(\ldots) \]

Successive steps

Depends on

- Event type
- Properties of the measured trigger objects

Since the detector data are not promptly available and the function is highly complex, \( T(\ldots) \) is evaluated by successive approximations.

**Trigger objects (candidates):**
- e, g, m, hadronic jets, t-Jets,
- missing energy, total energy

**Trigger conditions:** according to physics and technical priorities

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Trigger Levels in CMS

**Level-1 Trigger**
- Only calorimeters and muon system involved
- Reason: no complex pattern recognition as in tracker required (appr. 1000 tracks at 1034 cm-2s-1 luminosity), lower data volume
- Trigger is based on:
  - Cluster search in the calorimeters
  - Track search in muon system
- Latency: 3.2 μs
- Input rate: 40 MHz
- Output rate: up to 100 kHz
- Custom designed electronics system

**High Level Trigger (several steps)**
- More precise information from calorimeters, muon system, pixel detector and tracker
- Threshold, topology, mass, … criteria possible as well as matching with other detectors
- Latency: between 10 ms and 1 s
- Input rate: up to 100 kHz
- Output (data acquisition) rate: approx. 100 Hz
- Industrial processors and switching network

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Level-1 Trigger Dataflow

Calorimeter Trigger
- Regional Calorimeter Trigger
- Global Calorimeter Trigger

Muon Trigger
- RPC
- CSC
- DT
  - Local CSC Trigger
  - Local DT Trigger
  - DT Track Finder
  - CSC Track Finder

Global Muon Trigger

Global Trigger
- 4+4 μ
- 4 μ
- 4 μ

Global Muon Trigger
- e, J, E_T, H_T, E_T miss

40 MHz pipeline, latency < 3.2 μs

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**L1 Muon Trigger Overview**

- **DT hits**: $|\eta| < 1.2$
- **CSC hits**: $0.8 < |\eta| < 2.4$
- **RPC hits**: $|\eta| < 2.1$

1. **Local trigger**
   - **Barrel Track Finder**
     - $\leq 4$ muon candidates ($p_T$, $\eta$, $\phi$, quality)
   - **Endcap Track Finder**
     - $\leq 4$ muon candidates ($p_T$, $\eta$, $\phi$, quality)

2. **Regional trigger**
   - $\leq 4$ barrel + $\leq 4$ endcap muon candidates ($p_T$, $\eta$, $\phi$, quality)

3. **Global Muon Trigger**
   - $\leq 4$ muons ($p_T$, $\eta$, $\phi$, quality)

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RPC Trigger: Idea

B Filed map in CMS
RPC Trigger: Idea

RPC-Trigger is based on strip hits matched to precalculated patterns according to $p_T$ and charge.

For improved noise reduction algorithm requiring coincidence of at least 4/6 hit planes has been designed. Number of patterns is high. FPGA solution (previously ASICs) seems feasible, but currently expensive. Solutions to reduce number of patterns under study.
RPC Trigger: Role of Strips

- Track Bending and Strip Width

\[ r [m], B [T], p_t [GeV] \]
\[ r = p_t / 0.3 B \]
\[ \sin \alpha = R/2 / r \]
\[ \sin \alpha = 0.3 B R / 2 p_t \]

For CMS:
\[ B=4T, R=3m \]
\[ \alpha \approx 2 \text{ GeV} / p_t \]
\[ \sigma_1/p = \sigma_\alpha / 2 \]
\[ \sigma_\alpha = \Delta x / \sqrt{2 \Delta R} \]

For RPCs at MS1 and MS2:
\[ \Delta x = 2.4 \text{ cm} \text{ (i.e. } \Delta \phi = 1/3^\circ) \]
\[ \Delta R = 80 \text{ cm} \]
\[ \sigma_1/p = 1 / 100 \text{ GeV} \]
RPC Trigger: Role of Strips

- Track Bending and strip Length
- Time of flight and signal propagation
- Random coincidence and background hits

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Level 1 Calorimeter Trigger

Major Elements
- Trigger Primitive Generator (TPG)
- Regional Calorimeter Trigger (RCT)
- Global Calorimeter Trigger (GCT)

0.3 $\eta$ x 0.3 $\phi$
**L1 Electron/Photon Trigger**

**Issue is rejection of huge jet background**

- Electromagnetic trigger based on 3x3 trigger towers
  - Each tower is 5x5 crystals in ECAL (barrel; varies in end-cap)
  - Each tower is single readout tower in HCAL

**Non-isolated**
- FG ECAL crystal energy profile
- HCAL to ECAL energy comparison \( H/E < 5\% \)

**Isolation**
- FG+HAC
- At least one quiet corner

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Typical Level-1 Rates and Efficiencies

- Single isolated $e/\gamma$ rate at 25 GeV threshold: 1.9 kHz
- 95% efficiency at 31 GeV

Low Luminosity $e/\gamma$ trigger rates

Single $e/\gamma$ Efficiency

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L1 Jet and \( \tau \) Triggers

Issues are jet energy resolution and tau identification

**Sliding window:**
- granularity is 4x4 towers = trigger region
- jet \( E_T \) summed in 3x3 regions \( \Delta \eta, \Delta \phi = 1.04 \)

“\( \tau \)-like” shapes identified for \( \tau \) trigger

- Single, double, triple and quad thresholds possible
- Possible also to cut on jet multiplicities
- Also \( E_T^{\text{miss}} \), \( \Sigma E_T \) and \( \Sigma E_T(\text{jets}) \) triggers
Typical Level-1 Jet Rates and Efficiencies

- Single jet rate at 120 GeV threshold: 2.2 kHz, 95% efficiency at 143 GeV
- Dijet rate at 90 GeV: 2.1 kHz 95% efficiency at 113 GeV
- Single t-jet rate at 80 GeV threshold: 6.1 kHz
Muons at LHC

Issue is $p_T$ measurement of real muons

![Graph showing rate vs. $p_T$ threshold for different decay modes with $|\eta| < 2.1$ and $L = 10^{34}$ cm$^{-2}$s$^{-1}$]
Drift Tube Trigger

- Bunch and track identifier
- Tracker Correlator
- Trigger Server
- Drift Tube Track Finder
CSC Muon Trigger

- CSC Track Finder (TF)
- CSC Local Charged Tracks (LCT)
- CSC Anode Trigger Electronics (ATE)
- CSC Cathode Trigger Electronics (CTE)
- CSC Track Finder Electronics (TFE)
- CSC Muon Sorter (MS)
Curves show individual DT, RPC & CSC & 3 Global Muon Trigger Combinations:
OR, AND, & optimized selection based on track quality & $p_T$ information
Single muon trigger rate is 8.1 kHz for a threshold of 25 GeV (90% efficient)
Dimuon muon trigger rate is 2.8 kHz for thresholds of 8, 5 GeV (90% efficient)
Logic combinations of trigger objects sent by the Global Calorimeter and the Global Muon Trigger

- Best 4 isolated electrons/photons: $E_T, \eta, \phi$
- Best 4 non-isolated electrons/photons: $E_T, \eta, \phi$
- Best 4 jets in forward regions: $E_T, \eta, \phi$
- Best 4 jets in central region: $E_T, \eta, \phi$
- Best 4 t-Jets: $E_T, \eta, \phi$
- Total $E_T$: $\sum E_T$
- Total $E_T$ of all jets above threshold: $H_T$
- Missing $E_T$: $E_T^{\text{missing}}, f(E_T^{\text{missing}})$
- 12 jet multiplicities: $N_{\text{jets}}$ (different $E_T$ thresholds and h-regions)
- Best 4 muons: $p_T$, charge, $f$, $h$, quality, MIP, isolation

- Thresholds: ($p_T$, $E_T$, $N_{\text{jets}}$)
- Optional topological and other conditions: (geometry, isolation, charge, quality)
- 128 algorithms running in parallel
## Level-1 Trigger table \((10^{34})\)

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Threshold (GeV)</th>
<th>Rate (kHz)</th>
<th>Cumulative Rate (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated e/g</td>
<td>34</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Di-e/g</td>
<td>19</td>
<td>3.3</td>
<td>9.4</td>
</tr>
<tr>
<td>Isolated muon</td>
<td>20</td>
<td>6.2</td>
<td>15.6</td>
</tr>
<tr>
<td>Di-muon</td>
<td>5</td>
<td>1.7</td>
<td>17.3</td>
</tr>
<tr>
<td>Single tau-jet</td>
<td>101</td>
<td>5.3</td>
<td>22.6</td>
</tr>
<tr>
<td>Di-tau-jet</td>
<td>67</td>
<td>3.6</td>
<td>25.0</td>
</tr>
<tr>
<td>1-jet, 3-jet, 4-jet</td>
<td>250, 110, 95</td>
<td>3.0</td>
<td>26.7</td>
</tr>
<tr>
<td>Jet(\star)E_{T}^{miss}\</td>
<td>113*70</td>
<td>4.5</td>
<td>30.4</td>
</tr>
<tr>
<td>Electron\star jet</td>
<td>25*52</td>
<td>1.3</td>
<td>31.7</td>
</tr>
<tr>
<td>Muon\star jet</td>
<td>15*40</td>
<td>0.8</td>
<td>32.5</td>
</tr>
<tr>
<td>Min-bias</td>
<td></td>
<td>1.0</td>
<td>33.5</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>33.5</td>
</tr>
</tbody>
</table>
High-Level Trigger

• Runs on large CPU farm
• Code as close as possible to offline reconstruction
• Selection must meet CMS physics goals
  – Output rate to permanent storage limited to $O(10^2)$Hz
• Reconstruction on demand
  – Reject as soon as possible
  – Trigger “Levels”:
    • Level-2: use calorimeter and muon detectors
    • Level-2.5: also use tracker pixel detectors
    • Level-3: includes use of full information, including tracker
  – “Regional reconstruction”: e.g. tracks in a given road or region
High Level trigger Goals

- Validate Level-1 decision
- Refine $E_T/p_T$ thresholds
- Refine measurement of position and other parameters
- Reject backgrounds
- Perform first physics selection
HLT selection: $\mu$, $\tau$, jets and $E_T^{\text{miss}}$

- **Muons**
  - Successive refinement of momentum measurement; + isolation
    - Level-2: reconstructed in muon system; must have valid extrapolation to collision vertex; + calorimeter isolation
    - Level-3: reconstructed in inner tracker; + tracker isolation

- **$\tau$-leptons**
  - Level-2: calorimetric reconstruction and isolation
  - Level-3: tracker isolation.

- **Jets and $E_T^{\text{miss}}$**
  - Jet reconstruction with iterative cone algorithm
  - $E_T^{\text{miss}}$ reconstruction (vector sum of towers above threshold).
HLT selection: electrons and photons

- Issue is electron reconstruction and rejection
  - Higher $E_T$ threshold on photons

- **Electron reconstruction**
  - key is recovery of radiated energy

- **Electron rejection**
  - key tool is pixel detector

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### HLT Summary: $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Threshold (GeV)</th>
<th>Rate (Hz)</th>
<th>Cuml. rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive electron</td>
<td>29</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Di-electron</td>
<td>17</td>
<td>1</td>
<td>34</td>
</tr>
<tr>
<td>Inclusive photon</td>
<td>80</td>
<td>4</td>
<td>38</td>
</tr>
<tr>
<td>Di-photon</td>
<td>40, 25</td>
<td>5</td>
<td>43</td>
</tr>
<tr>
<td>Inclusive muon</td>
<td>19</td>
<td>25</td>
<td>68</td>
</tr>
<tr>
<td>Di-muon</td>
<td>7</td>
<td>4</td>
<td>72</td>
</tr>
<tr>
<td>Inclusive tau-jet</td>
<td>86</td>
<td>3</td>
<td>75</td>
</tr>
<tr>
<td>Di-tau-jet</td>
<td>59</td>
<td>1</td>
<td>76</td>
</tr>
<tr>
<td>1-jet * $E_{T}^{miss}$</td>
<td>180 * 123</td>
<td>5</td>
<td>81</td>
</tr>
<tr>
<td>1-jet OR 3-jet OR 4-jet</td>
<td>657, 247, 113</td>
<td>9</td>
<td>89</td>
</tr>
<tr>
<td>Electron * jet</td>
<td>19 * 45</td>
<td>2</td>
<td>90</td>
</tr>
<tr>
<td>Inclusive b-jet</td>
<td>237</td>
<td>5</td>
<td>95</td>
</tr>
<tr>
<td>Calibration etc</td>
<td></td>
<td>10</td>
<td>105</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>105</strong></td>
<td></td>
</tr>
</tbody>
</table>

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**HLT performance — signal efficiency**

- **With previous selection cuts**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Efficiency (for fiducial objects)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(115 GeV)$\rightarrow$gg</td>
<td>77%</td>
</tr>
<tr>
<td>H(160 GeV)$\rightarrow$WW$^*$ $\rightarrow$2m</td>
<td>92%</td>
</tr>
<tr>
<td>H(150 GeV)$\rightarrow$ZZ$\rightarrow$4m</td>
<td>98%</td>
</tr>
<tr>
<td>A/H(200 GeV)$\rightarrow$2t</td>
<td>45%</td>
</tr>
<tr>
<td>SUSY ($\sim$0.5 TeV sparticles)</td>
<td>$\sim$60%</td>
</tr>
<tr>
<td>With $R_p$-violation</td>
<td>$\sim$20%</td>
</tr>
<tr>
<td>W$\rightarrow$en</td>
<td>67% (fid: 60%)</td>
</tr>
<tr>
<td>W$\rightarrow$mn</td>
<td>69% (fid: 50%)</td>
</tr>
<tr>
<td>Top$\rightarrow$m X</td>
<td>72%</td>
</tr>
</tbody>
</table>
Summary

The CMS Trigger System is close to become reality after a long period of simulation studies, hardware prototyping and system construction.

The CMS trigger design meets the challenging LHC requirements:

- Large rate reduction
- High efficiency for signal events
- Wide inclusive selection (open to the unexpected)
- Huge flexibility allowing future adaptation to the unknown

CMS Trigger system reduces the rate by an overall factor of roughly 10^6 while maintaining good efficiency.

• **Level-1:**
  - First factor of 1000
  - Hadronic \(\tau\) trigger implemented
  - Sliding window jet triggers
  - Isolated and non-isolated lepton triggers (without central tracking)
  - 128 trigger lines available

• **HLT:**
  - Second factor of 1000
  - Access to full event information
  - Partial reconstruction based on the calorimeter and muon systems initially (verify and improve Level-1 decision), followed by pixel + tracker information for final rejection
Conventional Concept with 3 Steps

- **LEVEL-1 Trigger 40 MHz**
  - Hardwired processors (ASIC, FPGA)
  - Pipeline logic systems

- **SECOND LEVEL TRIGGER 100 kHz**
  - SPECIALIZED processors

- **HIGH LEVEL TRIGGERS 1kHz**
  - Commercial processor farms

**Processing time (s):**
- 1 μs
- 1 ms
- 0.1 - 1 s

**Rate (Hz):**
- 10^8
- 10^6
- 10^4
- 10^2
- 10^0
- 10^{-2}
- 10^{-4}
- 25 ns
Local / Regional Electron/Photon Trigger

Trigger primitive generator (local)
Flag max of 4 combinations ("Fine Grain Bit")

Regional calorimeter trigger
$E_T$ cut

Longitudinal cut hadr./electromagn. $E_T$

Hadronic and electromagnetic isolation

Electron / photon on LHC Physics, 12-30 October 2009
Level-1 Trigger

- Information from Calorimeters and Muon detectors
  - Electron/photon triggers
  - Jet and missing $E_T$ triggers
  - Muon triggers

- Backgrounds are huge
  - Sophisticated trigger algorithms
  - Steep functions of thresholds

- Synchronous and pipelined
  - Bunch crossing time = 25 ns
  - Time needed for decision (+its propagation) $\approx 3 \mu s$

- Highly complex
  - Trigger primitives: ~5000 electronics boards of 7 types
  - Regional/Global: 45 crates, 630 boards, 32 board types

- Large flexibility
  - Large number of electronics programmable parameters
  - Most algorithms implemented in re-programmable FPGAs