The CMS Level-1 Trigger for LHC Run II

Alex Tapper for the CMS collaboration
Outline

- System overview
- Upgraded processors and high-speed optical links
- Trigger algorithms and implementation
- Commissioning and performance with collision data
- Summary and outlook

Focus on calorimeter trigger, muons in backup
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The CMS Level-1 trigger

- The CMS trigger system consists of two levels, **Level-1 (L1)** and **High Level Trigger (HLT)**, designed to
  - select events of *potential physics interest*
  - achieve a $10^5$ rate reduction with no dead time

- **L1 trigger upgraded in 2016**
  - LHC Run II: increased luminosity and higher PU
  - Higher trigger rates but CMS detector electronics limited to L1 trigger rate of 100 kHz
  - Upgrade necessary to maintain sensitivity to electroweak scale physics and for TeV scale searches as in Run I
System overview

- **Key concepts**
  - Calorimeter system — remove boundaries by streaming data from single event into one FPGA
  - Muon system — use redundancy of three muon detector systems early to make a high resolution muon trigger
  - Global trigger — expandable to many more possible conditions and more sophisticated quantities, to give a richer menu ∼ à la Higher Level Trigger

- **Replaced EVERYTHING!**
  - All hardware, all software, databases… even the timing control system and DAQ interface…
System implementation

- Organised in two layers, implementing a **time-multiplexed** architecture

- Key technology changes
  - μTCA Standard (modern telecoms)
  - FPGAs: Xilinx Virtex® 7 XC7V690T
  - High Speed serial optical links: 10 Gb/s
  - Large optical patch panels: custom made commercial solution (Molex Flexplane™)
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Optical input links

- Replaced all parallel copper links by **serial optical links**
- Implementing patch panel modules **LC - MPO**

**Layer 1 input links**

576+504+72 links in total \( \text{(ECAL, HCAL, HF)} = 1152 \) links
CTP7 Calorimeter Trigger Processor

Layer 1 - Pre-processing
- Aggregates & time-multiplexes calorimeter data
- DAQ readout for monitoring

MP7 Master Processor

Layer 2 - Trigger Algorithms
- Hosts most of the algorithms
- DAQ readout for monitoring
System Integration

Layer 1:
3 Vadatech VT894 Crate, 18 CTP7 boards
6 bits ECAL+HCAL energy + veto & feature to Layer 2

Layer 2:
1 Vadatech VT894 Crate, 10 MP7 boards

Time multiplexing routed through 72 to 72 12-fibre MPO connectors

Global Trigger receives 12 electron/photon + 12 Tau iso/non-iso candidates + 12 Jets and sums.

8×10 Gb/s links

Molex Enclosure
Flexplane (commercial)
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**e/γ finder algorithm**

### Electrons in CMS

- Optimised clustering to recover energy loss due to tracker material
- Cluster shape used to remove pile-up induced candidate

### Cluster building

#### Cluster shapes
- Jet-like
- e/γ-like

#### Isolation

- Create isolation annuli (removing footprint) for ECAL and HCAL around cluster
- Isolation energy requirement fn. of PU and η
- Two working points

### Dynamic clustering

- Improved energy containment
- Showering electrons, photon conversions
- Minimise effect of pile-up
- Improved energy resolution

### Cluster shape veto

- Discriminate using cluster shape and EM energy fraction between e/γ and jets — 99.5% efficiency for e/γ

### Calibration

- e/γ cluster energy calibrated as fn. of $E_T$, η and cluster shape

### Energy weighted position

- Potential use in correlating objects e.g. invariant mass
Tau finder algorithm

- **Dedicated \( \tau \) trigger**
  - Based on e/\( \gamma \) clusters
  - Optimise reconstruction of multiple-prong object spread

### Clustering, shape and position

- Very similar to e/\( \gamma \) — optimised for \( \tau \)
- Cluster shape veto — under study

### Merging

- Merge neighbouring clusters (~15% of clusters)
- Recover multi-prong \( \tau \) decays

### Calibration

- \( \tau \) cluster energy calibrated as fn. of \( E_T, \eta, \) merging and EM fraction

### Isolation

- Very similar to e/\( \gamma \) — optimised for \( \tau \) including merging as input — also two working points
Jet finder algorithm

- Optimised cone size to match offline reconstruction algorithm
- Pile-up subtraction technique less sensitive to fluctuations.

### Input granularity
Access to higher granularity inputs than Run I

### Sliding window jet algorithm
- Search for seed energy above threshold
- Apply veto mask to remove duplicates
- Sum 9x9 trigger towers to approximate R=0.4 used offline

### Pile-up subtraction
- Consider four areas around jet window
- Subtract sum of energy in lowest three from jet energy

### Calibration
- Correct jet energies as a function of jet $E_T$ and $\eta$
## Inputs

Access to higher granularity inputs than Run I  
Tower-level non-uniformity calibration

## Energy sums algorithms

Scalar and vector sums of tower $E_T$ (and also jets)  
$\text{MET (MHT)}$ — vector sum of towers (jets)  
$E_T$ ($H_T$) — scalar sum of towers (jets)  
CORDIC algorithm used to convert $x$ and $y$ components to magnitude and angle

## Pile-up mitigation

Tower zero-suppression fn. of PU and $\eta$ as in lepton isolation

## Calibration

Option to calibrate $x$ and $y$ components — under study
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Commissioning

• Commissioned in parallel
  ‣ Calorimeter inputs duplicated in FPGAs (ECAL) and optically (HCAL)
  ‣ Run parasitically with CMS data taking (not triggering!)

• Steps to completion
  ‣ 2012-2014 interconnection tests ✓
  ‣ 2015 MC pattern test campaign ✓
  ‣ 2015 data taken in CMS global running ✓
    • Over 7 billion events in pp
  ‣ 2016 cosmic runs and beam splashes ✓
  ‣ 2016 first collisions ✓
  ‣ 2016 Started physics run ✓
  ‣ 2017 Optimised for high luminosity ✓
Performance results: e/\gamma and \tau

**L1 Electron Photon Finder**

- Large position resolution improvement

**L1 Tau Lepton Finder**

- Trigger efficiency for a single \( \tau \) with \( E_T > 26, 30 \) and 34 GeV vs offline \( \tau \) \( p_T \)
- Using tag and probe method on a dataset of \( Z \rightarrow \mu\tau \) events

Efficiency for a single e/\gamma with \( E_T > 38 \) GeV vs offline \( E_T \)

Using tag&probe method on \( Z \rightarrow ee \) dataset
Performance results: Jet and energy sums

**L1 Jet Finder**

- Match Level-1 Trigger jets to offline (anti-kt R = 0.4) jets using $\Delta R < 0.25$ in single muon data.

- Compare energies and calculate efficiencies as a function of offline jet quantities.

- Sharp efficiency turn-on with well calibrated $E_T$ scale.

**Missing Energy Triggers**

- $E_{T\text{miss}}$: Vector sum of trigger towers with PU dependent zero-suppression.

- Efficiency as a function of offline Missing $E_T$.

- PU mitigation gives lower rate (factor 2) at fixed efficiency, allowing lower thresholds.

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High level example: invariant mass

- Higher resolution objects - both $E_T$ and position - feed into..
- Global trigger allows large range of operations:
  - Simple thresholds, $P_T$ and $\eta$ for example, as in Run I
  - Combinations of objects, like correlations between positions and energies, even handling overlapping objects

- Example VBF Higgs to di-tau decays:
  - Two low $E_T$ jets, separated by large $\eta$ gap
  - Central high $p_T$ $\tau$-lepton pair from Higgs decay

Di-jet selection with jet $E_T > 35$ GeV & $m_{jj} > 620$ GeV

Di-$\tau$ selection with $|\eta| < 2.1$ & $P_T > 32$ GeV

Use of invariant mass allowed the jet threshold to be kept low

Combination of leptonic and hadronic selections adds $\sim 60\%$ efficiency for the Higgs signal
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Summary and outlook

- The CMS L1 trigger has successfully completed first years of operation in Run II
  - LHC Run II challenging environment, higher luminosity, centre-of-mass energy, increased PU
  - Excellent performance on single physics objects and sophisticated global quantities
- Development, installation and commissioning completed on a very tight schedule with parallel running
  - State-of-the-art, FPGA based, very high bandwidth processors with sophisticated, programmable algorithms
  - The system has successfully evolved with the changing LHC conditions.
- Exploit detector upgrades in shutdown in 2019-20
  - Improved HCAL information: longitudinal energy profile, improved timing information…
- Study the performance of this new trigger and learn from design and commissioning to begin designing Phase II trigger upgrade for HL-LHC
References

- CMS Level-1 Trigger TDR: https://cds.cern.ch/record/706847


- Phase 1 upgrade TDR: https://cds.cern.ch/record/1556311

- Performance notes for EPS 2017 and other conferences
  - $e/\gamma$: https://cds.cern.ch/record/2273270
  - $\tau$ and VBF with inv. mass: https://cds.cern.ch/record/2273268
  - Jets and sums: https://cds.cern.ch/record/2286149
  - $\mu$: https://cds.cern.ch/record/2286327
LHC: Future plans

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<th>Upgrades</th>
<th>Run 1 (PU)</th>
<th>Run 2 (PU)</th>
<th>Run 3 (PU)</th>
<th>Design (levelled)</th>
<th>HL-LHC</th>
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Bandwidth allocated per trigger object type

Note that fractions are inclusive → no attempt to correct for overlaps between different types of trigger
Challenges

- **Interesting** processes many orders of magnitude low cross sections than total pp cross section
- Cannot store all events (TB/s)
- Select interesting events without dead time
- Implemented as a two level system in CMS →

- Trigger rates are driven up in Run II by the increase in luminosity, the centre-of-mass energy, and by the higher PU (especially hadronic objects)
- CMS detector electronics are limited to a L1 trigger rate of 100 kHz
- Maintain sensitivity for electroweak scale physics and for TeV scale searches as in Run I
System implementation

• Key technology changes
  ‣ VME → μTCA (modern telecoms standard)
  ‣ System wide use of latest FPGAs → Xilinx Virtex® 7
  ‣ Parallel copper links → serial optical links
  ‣ Link speeds 1 Gb/s → 10 Gb/s
  ‣ Large optical patch panels → custom made commercial solution (Molex Flexplane™)
  ‣ Online software rewritten → more common code, modern libraries, more easily maintained

• Aim for flexible, maintainable system
  ‣ Adapt to evolving CMS physics programme
Time-multiplexing

**Time-multiplexed**

- Detector data ordering
- Self-contained event processing nodes
- MUX

**Conventional**

- Detector data ordering
- Globally laterally connected system
Each card spans 4 out of 72 towers in $\phi$ and all of $\eta$.

18 cards, each receiving 60 links at between 5.0 Gb/s & 6.4 Gb/s of Calorimeter data.

Layer 1 cards transmit 48 links @ 10G

Layer 1 Cards

72 input links per Layer-2 node

Layer-2 Cards

6 output links per MP card @ 10Gb/s

Flexible system:
Simple to upgrade from 16 bit towers to 24 bit towers or provide extra logic resources.

De-multiplexing node:
Separate card or firmware core in downstream system
• **Tower Level operations**
  ‣ **Calibration and Vetos** (H/E : ratio of the HCAL and ECAL energies, used in to discriminate electromagnetic and hadronic objects)
  ‣ **Mixed Link Speed MGT operations**
    4.8 and 6.4 Gb/s **synchronous** and 10 Gb/s **asynchronous**
**Time-multiplexed processing**

- **Calorimeter data** received in geometric order (increasing $\eta$) in one FPGA
- **Fully pipelined algorithms**: local processing, reduce signal fanout, eliminate register duplication and routing delays minimised.

- **240 MHz algorithm clock**
- **Compact, maintainable firmware**
  - rebuilt several times since the start of operations
Backup: resolutions etc.
e/γ reconstruction performance

CMS Preliminary 2016, √s=13 TeV, 8.2 fb⁻¹

CMS Preliminary 221 pb⁻¹ (2016) + 53 pb⁻¹ (2017) (13 TeV)

L1 e/γ candidates

2017 data

2016 data

Barrel

Endcaps

RMS/Std

CMS Preliminary 221 pb⁻¹ (2016) + 53 pb⁻¹ (2017) (13 TeV)

τ reconstruction performance

![Graphs showing τ reconstruction performance.](image)
τ reconstruction performance

CMS preliminary 2016

Barrel
Endcaps

Integrated Efficiency

RMS / $<E_T^\tau/L1 T^\tau_{offline}>/p_T^\tau_{ offline}$

CMS preliminary 2016

Barrel
Endcaps

$E_T^{\tau,L1} > 30$ GeV & $p_T^{\tau_{offline}} > 45$ GeV 35.9 fb$^{-1}$ (13 TeV)

$\tau$ reconstruction performance

CMS preliminary 2016

Barrel
Endcaps

35.9 fb$^{-1}$ (13 TeV)

CMS preliminary 2016

Barrel
Endcaps

35.9 fb$^{-1}$ (13 TeV)

CMS preliminary 2016

Barrel
Endcaps

35.9 fb$^{-1}$ (13 TeV)
Jet algorithm performance

PUS areas

Seed tower

Veto mask

Number of Interactions

Mean Energy Density (GeV)

Minimum Bias $\sqrt{s} = 13$ TeV $\mathrm{BX} = 50\text{ns} <\mathrm{PU}> = 40$

CMS Simulation Preliminary

Number Events / 7 GeV

Leading jet $p_T$ (GeV)

Leading jet $\eta$

Fourth leading jet $p_T$ (GeV)

Fourth leading jet $\eta$

CMS Simulation Preliminary

CMS Simulation Preliminary

CMS Simulation Preliminary

CMS Simulation Preliminary
Jet reconstruction performance
Jet trigger performance results

- Match Level-1 Trigger jets to offline (anti-\(k_t\) \(R = 0.4\)) jets using \(\Delta R < 0.25\) in single muon data
- Compare energies and calculate efficiencies as a function of offline jet quantities

- Sharp efficiency turn-on with well calibrated \(E_T\) scale
- Insensitive to pile-up
MET reconstruction performance

\[
\frac{\text{Offline } E_T^{\text{miss}}}{\text{Offline } E_T^{\text{miss}} - (L1 E_T^{\text{miss}} - \text{Offline } E_T^{\text{miss}})} \geq 40 \text{ GeV}
\]

PU \leq 14

PU \leq 22

2016 Data

CMS Preliminary 2016 Data 3.1fb\(^{-1}\) (13 TeV)

Online E_T^{\text{miss}} > 40 GeV
Energy sum trigger performance results

- Use jets to calculate scalar sum $H_T = \sum E_{Tj}$ for $E_{Tj} > 30$ GeV and $|\eta| < 3$ using single muon data.
- Vector sum of trigger towers with $|\eta| < 3$ to form $E_T^{\text{miss}}$.
Backup: muon trigger
Muon track finder algorithms

- **Muon track finding**
  - Segment into Barrel, Overlap, and Endcap regional processors
    - Complementary detector strengths e.g. RPC timing
    - Improve robustness in the case of dead channels/chambers and cracks
  - Pattern based track finding in endcap and overlap (with separate MVA LUT $p_T$ assignment in endcap)
  - Road search extrapolation track finding in barrel
  - Global muon trigger takes muon tracks from regional finders, sorts by $p_T$ and quality and cancels duplicates
  - Input from calorimeter trigger to apply isolation to muon candidates

![Diagram of CMS detector regions]

- **BMTF** $|\eta| < 0.83$
- **OMTF** $0.83 < |\eta| < 1.24$
- **EMTF** $|\eta| > 1.24$
Muon trigger performance results

- Trigger efficiency for a single muon with $p_T > 25$ GeV vs offline muon $p_T$ and $\eta$
- Using tag and probe method on a dataset of $Z \rightarrow \mu \mu$ events
Muon trigger performance results

- Trigger efficiency for a single muon with $p_T > 125$ GeV vs offline muon $p_T$
- Using tag and probe method on a dataset of $Z\rightarrow \mu\mu$ events