Overview of the High-Luminosity Upgrade for the CMS Level-1 Trigger

R. Cavanaugh,
University of Illinois Chicago & Fermi National Accelerator Laboratory
Science Drivers
Science Drivers

• Weak scales, the *raison d’être* for the HL-LHC
  • Higgs, Flavour, Gauge Hierarchy, Supersymmetry, Dark Matter
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  - Higgs, Flavour, Gauge Hierarchy, Supersymmetry, Dark Matter
  - $O(100) \text{ GeV mass scales} \rightarrow O(50) \text{ GeV endpoints} \rightarrow O(20) \text{ GeV thresholds}$
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    - *PF* (carefully) pushed into HLT
    - Similar Offline vs HLT objects
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    - Final limitation: no tracking available
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    • Enable similar HLT vs L1 objects: better turn-on curves, better rates
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- Science potential of HL-LHC determined by datasets it collects
Upgraded Trigger Input Data
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- Increased data compared with Phase-1
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  - Barrel Calorimeter: 25x increase over current
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  • Match tracking info with fine grain calo info
  • Fit muon and track data together
  • More complex objects, conditions, & algorithms

CMS has good ability to discriminate between individual particles and between particle types.
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  - Match tracking info with fine grain calo info
  - Fit muon and track data together
  - More complex objects, conditions, & algorithms

- Input data and algorithm processing driving design & HW choices

CMS has good ability to discriminate between individual particles and between particle types
Current Level-1 Trigger
Current Level-1 Trigger

Calorimeter Trigger

ECAL

HCAL HB/HE µHTR

HCAL HF µHTR

Calo Trigger Layer-1

Calo Trigger Layer-2
Current Level-1 Trigger

Calorimeter Trigger

- ECAL
- HCAL HB/HE μHTR
- HCAL HF μHTR

- Calo Trigger Layer-1
- Calo Trigger Layer-2

Muon Trigger

- CSC
- Muon Port Card
- Splitters
- Link Board
- CPPF fan-out
- TwinMux fan-out

- Track Finder Layer
  - Endcap
  - Overlap
  - Barrel

- Sorting/Merging Layer
  - Endcap
  - Overlap
  - Barrel

- Global Muon Trigger
Current Level-1 Trigger

Calorimeter Trigger
- ECAL
- HCAL HB/HE µHTR
- HCAL HF µHTR
  - Calo Trigger Layer-1
  - Calo Trigger Layer-2

Muon Trigger
- CSC
- Muon Port Card
- Splitters
  - Link Board
  - CPPF fan-out
  - TwinMux fan-out
  - CPPF
  - TwinMux
  - DT
  - RPC
  - Link Board
  - Track Finder Layer
    - Endcap
    - Overlap
    - Barrel
  - Sorting/Merging Layer
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  - Global Muon Trigger
  - Global Trigger
Current Level-1 Trigger

Calorimeter Trigger
- ECAL
- HCAL
- HCAL HB/HE μHTR
- HCAL HF μHTR

Muon Trigger
- CSC
- RPC
- DT
- Link Board
- TwinMux fan-out
- CPPF fan-out

Calo Trigger Layer-1
- Muon Port Card
- Splitters

Calo Trigger Layer-2
- Track Finder Layer
  - Endcap
  - Overlap
  - Barrel

Sorting/Merging Layer
- Endcap
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- Barrel

Global Muon Trigger

Global Trigger
Current Level-1 Trigger

Calorimeter Trigger

- ECAL
- HCAL HB/HE µHTR
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Calo Trigger Layer-1

Calo Trigger Layer-2

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Track Finder Layer

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Global Muon Trigger

Global Trigger
Conceptual HL-LHC Trigger Design

Calorimeter Trigger
- ECAL
- HCAL HB
- HCAL HF

Muon Trigger
- CSC
- RPC
- DT

Muon Track Finding/Sorting/Merging
- Endcap
- Overlap
- Barrel

Barrel Calorimeter Trigger

Global Trigger

fan-out

Splitters

Link Board
Conceptual HL-LHC Trigger Design

Calorimeter Trigger
- ECAL
- HCAL HB
- HCAL HF

Muon Trigger
- CSC
- RPC
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Muon Track Finding/Sorting/Merging
- Link Board

Barrel Calorimeter Trigger

Endcap
Overlap
Barrel

Global Trigger

Max: 12.5μs
Conceptual HL-LHC Trigger Design

Calorimeter Trigger
- ECAL
- HCAL HB
- HCAL HF

Muon Trigger
- CSC
- GEM + iRPC
- RPC
- DT

Muon Track Finding/Sorting/Merging
- Link Board
- fan-out
- Endcap
- Overlap
- Barrel

Barrel Calorimeter Trigger

Global Trigger

Max: 12.5 μs
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Calorimeter Trigger
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Muon Trigger
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- DT

Muon Track Finding/Sorting/Merging
- Endcap
- Overlap
- Barrel

Barrel Calorimeter Trigger

Global Trigger

Max: 12.5 μs

CMS Phase-2 Simulation, <PU> = 0, Single muon
- muon $p_T = 7$ GeV

Preliminary
Conceptual HL-LHC Trigger Design

Calorimeter Trigger
- ECAL
- HCAL HB
- HCAL HF

Muon Trigger
- CSC
- GEM + iRPC
- RPC
- DT

Muon Track Finding/Sorting/Merging
- Link Board
- fan-out
- fan-out

Barrel Calorimeter Trigger

Endcap

Overlap

Barrel

Global Trigger

Max: 12.5 μs
Conceptual HL-LHC Trigger Design

Calorimeter Trigger
- ECAL (single xtal)
- HCAL HB
- HCAL HF

Barrel Calorimeter Trigger

Muon Trigger
- CSC
- GEM + iRPC
- RPC
- DT

Muon Track Finding/Sorting/Merging
- Link Board
- fan-out

Endcap

Overlap

Barrel

Global Trigger

Max: 12.5 μs

-40 Tbs
Conceptual HL-LHC Trigger Design

Calorimeter Trigger
- ECAL
- HCAL HB
- HCAL HF

Muon Trigger
- CSC
- GEM + iRPC
- RPC
- DT

Muon Track Finding/Sorting/Merging
- Muon Port Card
- Splitters
- Link Board
- fan-out

Barrel Calorimeter Trigger
- ~40 Tbs
- 3-4 Tbs
- small

CMS Phase-2 Simulation, <PU> = 200, Minbias
- Preliminary
- $E_T > 0.2$ GeV
- $E_T > 0.5$ GeV
- $E_T > 1$ GeV
- $E_T > 2$ GeV
- $E_T > 3$ GeV

Max: 12.5 μs
Conceptual HL-LHC Trigger Design

Calorimeter Trigger

- ECAL (single xtal)
- HCAL HB
- HCAL HF

Muon Trigger

- CSC
- GEM + iRPC
- RPC
- DT

Muon Track Finding/Sorting/Merging

- Endcap
- Overlap
- Barrel

Global Trigger

Max: 12.5 μs

3-4 Tbs

~40 Tbs

-40 Tbs
Conceptual HL-LHC Trigger Design

Calorimeter Trigger
- Endcap Calo
  - ECAL
    - single xtal
  - HCAL HB
  - HCAL HF
- Barrel Calorimeter Trigger
- Muon Trigger
  - CSC
  - GEM + iRPC
  - RPC
  - DT
  - Muon Port Card
  - Splitters
  - Link Board
  - fan-out

Muon Track Finding/Sorting/Merging
- Endcap
- Overlap
- Barrel

Global Trigger

Max: 12.5μs
-40 Tbs
-40 Tbs
3-4 Tbs
small
Conceptual HL-LHC Trigger Design

Calorimeter Trigger

Endcap Calo

ECAL

HCAL HB

HCAL HF

Barrel Calorimeter Trigger

Muon Trigger

CSC

GEM + iRPC

RPC

DT

Muon Port Card

Splitters

Link Board

fan-out

Muon Track Finding/Sorting/Merging

Endcap

Overlap

Barrel

CMS Phase-2 Simulation, $\sqrt{s} = 14$ TeV, $<\text{PU}> = 200$

Entries [a.u.]

Minbias

Preliminary

$E_T > 3.0$ GeV

$E_T > 2.0$ GeV

$E_T > 1.0$ GeV

$E_T > 0.5$ GeV

$N_{3D}$-Clusters

Max: 12.5 $\mu$s

-40 Tbs

-40 Tbs

-40 Tbs

3-4 Tbs

3-4 Tbs

small

$\sim 40$ Tbs

$\sim 40$ Tbs

~40 Tbs

-40 Tbs

~40 Tbs

$\sim 40$ Tbs
Conceptual HL-LHC Trigger Design

Calorimeter Trigger

- Endcap Calo
- ECAL (single xtal)
- HCAL HB
- HCAL HF

Barrel Calorimeter Trigger

- Endcap Calo Trigger Primitive Generator

Muon Trigger

- CSC
- GEM + iRPC
- RPC
- DT
- Muon Port Card
- Link Board
- Fan-out

Muon Track Finding/Sorting/Merging

- Endcap
- Overlap
- Barrel

Global Trigger

Max: 12.5 μs

- 3-4 Tbs
- 3-4 Tbs
- 3-4 Tbs
- 3-4 Tbs
- Fan-out
- Small
Conceptual HL-LHC Trigger Design

Track Trigger
- Outer Tracker
- Endcap Calo
  - Track Finder
  - Trigger Primitive Generator

Calorimeter Trigger
- ECAL
  - single xtal
- HCAL HB
- HCAL HF
- Barrel Calorimeter Trigger
  - Trigger Primitive Generator
  - Barrel Calorimeter Trigger

Muon Trigger
- CSC
- GEM + iRPC
- RPC
- DT
- Link Board
- Muon Port Card
- Splitters
- fan-out
- fan-out

Muon Track Finding/Sorting/Merging
- Endcap
- Overlap
- Barrel
- small

Global Trigger

Max: 12.5μs
Conceptual HL-LHC Trigger Design

Track Trigger
- Outer Tracker
- Endcap Calo

Calorimeter Trigger
- ECAL
- HCAL
- Track Finder Trigger Primitive Generator
- Endcap Calo Trigger Primitive Generator
- Barrel Calorimeter Trigger

Max: 12.5μs

Muon Trigger
- CSC
- GEM + iRPC
- RPC
- DT
- Link Board
- Muon Port Card
- Splitters
- fan-out

Muon Track Finding/Sorting/Merging
- Endcap
- Overlap
- Barrel

Global Trigger
- 3-4 Tbs
- small

Endcap Calo
- High transverse momentum Pas
- Low transverse momentum Fail
- Stub
Conceptual HL-LHC Trigger Design

Track Trigger
- Outer Tracker
- Endcap Calo

Calorimeter Trigger
- ECAL
- HCAL

Muon Trigger
- CSC
- GEM + iRPC
- RPC
- DT

Muon Track Finding/Sorting/Merging
- Link Board
- fan-out
- fan-out

CMS Phase-2 Simulation, <PU> = 200, Minbias

- 2 GeV with truncation
- 2 GeV w/o truncation
- 3 GeV with truncation
- 3 GeV w/o truncation

Entries [a.u.]

Preliminary
Conceptual HL-LHC Trigger Design

Track Trigger
- Outer Tracker
- Endcap Calo
- Track Finder
- Trigger Primitive Generator
- Endcap Calo
- Trigger Primitive Generator

Calorimeter Trigger
- ECAL
  - single xtal
- HCAL
  - HB
  - HF
- Barrel Calorimeter Trigger

Muon Trigger
- CSC
  - GEM + iRPC
- RPC
- DT
- Muon Port Card
- Splitters
- Link Board
- fan-out

Correlator Trigger
- 3-4 Tbs
  - small
- Global Trigger

Max: 12.5 µs
-40 Tbs
-40 Tbs
-40 Tbs
-40 Tbs
-40 Tbs
Conceptual HL-LHC Trigger Design

Track Trigger
- Outer Tracker
- Endcap Calo

Calorimeter Trigger
- ECAL
- HCAL HB
- HCAL HF

Muon Trigger
- CSC
- GEM + iRPC
- RPC
- DT

Muon Track Finding/Sorting/Merging
- Muon Port Card
- Splitters
- Link Board
- fan-out

Barrel Calorimeter Trigger
- Endcap
- Overlap
- Barrel

Track Finder
- Trigger Primitive Generator

Endcap Calo
- Trigger Primitive Generator

Correlator Trigger
- small
- small
- small

Global Trigger
- 3-4 Tbs
- 3-4 Tbs
- 3-4 Tbs
- 3-4 Tbs

Max: 12.5μs

~2.5μs

~5μs

-40 Tbs
-40 Tbs
-40 Tbs
-40 Tbs
-40 Tbs
-40 Tbs
-40 Tbs
-40 Tbs
-40 Tbs
Conceptual HL-LHC Trigger Design

Track Trigger
- Outer Tracker
- Endcap Calo
  - Track Finder
  - Trigger Primitive Generator

Calorimeter Trigger
- ECAL
  - single xtal
- HCAL HB
- HCAL HF

Muon Trigger
- CSC
- GEM + iRPC
- RPC
- DT

Muon Track Finding/Sorting/Merging
- Muon Port Card
- Splitters
- Link Board
- fan-out

Barrel Calorimeter Trigger
- Endcap Calo Trigger Primitive Generator
- Barrel Calorimeter Trigger

Correlator Trigger
- 3-4 Tbs

Global Trigger
- small 3-4 Tbs
- 3-4 Tbs

Max: 12.5μs
~5μs
~2.5μs
~1μs
Conceptual HL-LHC Trigger Design

Track Trigger
- Outer Tracker
- Endcap Calo
  - Max: 12.5μs
  - ~5μs
  - ~2.5μs
  - ~1μs

Calorimeter Trigger
- ECAL (single xtal)
- HCAL HB
- HCAL HF
  - -40 Tbs
  - -40 Tbs
  - -40 Tbs

Muon Trigger
- CSC
  - GEM + iRPC
- RPC
  - DT
  - Link Board
  - fan-out

Correlator Trigger
- 3-4 Tbs
  - 3-4 Tbs
  - small
  - small
  - small

Additional 1μs to propagate back to detector front ends and 30% safety factor
Hardware R&D: Electronic Boards

- **Key technologies:**
  - ATCA form factor
  - Ultrascale and Ultrascale+ class FPGAs
  - Multi-gigabit transceivers/optics: 16-25 Gb/s
  - Intelligent Platform Management Interface (IPMI) Controller for ATCA blades
  - Onboard Control running Embedded Linux
  - Onboard Bus: PCIE, AXI, IPBus
  - Large RAM

- **Key challenges:**
  - Power delivery and thermal management
  - System level integration & maintenance
Hardware R&D: Links and Memory

- **Samtec Firefly Optical links**
  - 14 Gbs and 28 Gbs tested
  - Error free TX all the way up to 28 G
  - Can also be used on RTMs

- **Molex Impel Connectors**
  - Can handle up to 40 Gbs

- **DDR4 as Large Memory Bank (tested 16 GB)**
  - Low cost, low power, huge memory
  - Fast, but some latency: 6-12 BX

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<table>
<thead>
<tr>
<th>PRBS-7</th>
<th>16G (CDR off)</th>
<th>26G</th>
<th>28G</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pseudorandom binary sequency pattern</td>
<td>CDR: Clock and Data Recovery</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>PRBS-31</th>
<th>16G (CDR off)</th>
<th>26G</th>
<th>28G</th>
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<tbody>
<tr>
<td></td>
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</table>

**DDR4 SODIMM**

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Fermilab

THE UNIVERSITY OF ILLINOIS AT CHICAGO
Example CMS studies of HL-LHC L1T Menu


### Table 4.1: L1 menu using algorithms that include track trigger capabilities.

<table>
<thead>
<tr>
<th>Trigger algorithm</th>
<th>Rate [kHz]</th>
<th>Offline threshold(s) [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle PU \rangle$</td>
<td>140 200</td>
<td></td>
</tr>
<tr>
<td>Single Mu (tk)</td>
<td>14 27</td>
<td>18</td>
</tr>
<tr>
<td>Double Mu (tk)</td>
<td>1.1 1.2</td>
<td>14 10</td>
</tr>
<tr>
<td>Ele* (iso tk) + Mu (tk)</td>
<td>0.7 0.2</td>
<td>19 10.5</td>
</tr>
<tr>
<td>Single Ele* (tk)</td>
<td>16 38</td>
<td>31</td>
</tr>
<tr>
<td>Single iso Ele* (tk)</td>
<td>13 27</td>
<td>27</td>
</tr>
<tr>
<td>Single $\gamma^*$ (tk-is0)</td>
<td>31 19</td>
<td>31</td>
</tr>
<tr>
<td>Ele* (iso tk) + e/$\gamma^*$</td>
<td>11 7.3</td>
<td>22 16</td>
</tr>
<tr>
<td>Double $\gamma^*$ (tk-is0)</td>
<td>17 5</td>
<td>22 16</td>
</tr>
<tr>
<td>Single Tau (tk)</td>
<td>13 38</td>
<td>88</td>
</tr>
<tr>
<td>Tau (tk) + Tau</td>
<td>32 55</td>
<td>56 56</td>
</tr>
<tr>
<td>Ele* (iso tk) + Tau</td>
<td>7.4 23</td>
<td>19 50</td>
</tr>
<tr>
<td>Tau (tk) + Mu (tk)</td>
<td>5.4 6</td>
<td>45 14</td>
</tr>
<tr>
<td>Single Jet</td>
<td>42 69</td>
<td>173</td>
</tr>
<tr>
<td>Double Jet (tk)</td>
<td>26 43</td>
<td>2@136</td>
</tr>
<tr>
<td>Quad Jet (tk)</td>
<td>12 45</td>
<td>4@72</td>
</tr>
<tr>
<td>Single ele* (tk) + Jet</td>
<td>15 15</td>
<td>23 66</td>
</tr>
<tr>
<td>Single Mu (tk) + Jet</td>
<td>8.8 12</td>
<td>16 66</td>
</tr>
<tr>
<td>Single ele* (tk) + $H_T^{miss}$ (tk)</td>
<td>10 45</td>
<td>23 95</td>
</tr>
<tr>
<td>Single Mu (tk) + $H_T^{miss}$ (tk)</td>
<td>2.7 8</td>
<td>16 95</td>
</tr>
<tr>
<td>$H_T$ (tk)</td>
<td>13 24</td>
<td>350</td>
</tr>
<tr>
<td>Rate for above triggers*</td>
<td>180 305</td>
<td></td>
</tr>
<tr>
<td>Est. rate (full EG eta range)</td>
<td>390</td>
<td></td>
</tr>
<tr>
<td>Est. total L1 menu rate ($\times 1.3$)</td>
<td>260 500</td>
<td></td>
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Example CMS studies of HL-LHC L1T Menu

  - Prototype L1 Menu inspired from Phase-1
- Desire pT thresholds to be O(20-40) GeV

### Table 4.1: L1 menu using algorithms that include track trigger capabilities. The beam conditions are \( p_s = 14 \text{ TeV} \) and \( L = 8.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \), \( \langle PU \rangle = 140 \),\( L = 5.6 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \), \( \langle PU \rangle = 200 \)

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Example CMS studies of HL-LHC L1T Menu

- Desire pT thresholds to be $O(20-40)$ GeV
- Phase-1 Experience
  - Sophisticated standalone trigger paths arose from improved response of objects
  - from need for pile-up resilience
- Relying on standalone triggers paths for Phase-2 will be tough at 200PU...combining triggers will be important
  - still being developed

| L = 5.6 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}, \langle PU \rangle = 140 |
| L = 8.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}, \langle PU \rangle = 200 |

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Example CMS studies of HL-LHC L1T Menu

- Desire pT thresholds to be O(20-40) GeV

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Rate for above triggers*             180 305
Est. rate (full EG eta range)        390

**Est. total L1 menu rate (× 1.3)**   **260 500**
Example CMS studies of HL-LHC L1T Menu

- Desire pT thresholds to be O(20-40) GeV
- HL-LHC 140 pile-up events per beam crossing:
  - No tracking at L1: rate \( \approx 1\,500\) kHz

### Table 4.1: L1 menu using algorithms that include track trigger capabilities.

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Example CMS studies of HL-LHC L1T Menu

- Desire pT thresholds to be O(20-40) GeV
- HL-LHC 140 pile-up events per beam crossing:
  - No tracking at L1: rate $\approx 1.500$ kHz
- HL-LHC 200 pile-up events per beam crossing
  - No tracking at L1: rate $\approx 4.000$ kHz

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Rate for above triggers* | 180 | 305 |
Est. rate (full EG eta range) | 390 |
Est. total L1 menu rate ($\times 1.3$) | 260 | 500 |

*L1 trigger with L1 tracks*
Example CMS studies of HL-LHC L1T Menu

- Desire pT thresholds to be O(20-40) GeV
- HL-LHC 140 pile-up events per beam crossing:
  - No tracking at L1: rate ≈ 1 500 kHz
- HL-LHC 200 pile-up events per beam crossing
  - No tracking at L1: rate ≈ 4 000 kHz
- Allow 50% margin (monitor trigs + uncertainty)
  - Max allowed design rate = 750 kHz
- Main Conclusions:

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Example CMS studies of HL-LHC L1T Menu

- Desire pT thresholds to be O(20-40) GeV
- HL-LHC 140 pile-up events per beam crossing:
  - No tracking at L1: rate ≈ 1 500 kHz
  - Tracking at L1: rate ≈ 260 kHz
- HL-LHC 200 pile-up events per beam crossing
  - No tracking at L1: rate ≈ 4 000 kHz
  - Tracking at L1: rate ≈ 500 kHz
- Allow 50% margin (monitor trigs + uncertainty)
  - Max allowed design rate = 750 kHz

Main Conclusions:

- Lepton, photon HL-LHC thresholds are comparable to Run-1, Phase-1
- Hadronic algorithms need more work to be comparable to Run-1, Phase-1

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<td>$H_T$ (tk)</td>
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<td>350</td>
</tr>
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</table>

Rate for above triggers* | 180 | 305 |
Est. rate (full EG eta range) | 390 |
Est. total L1 menu rate ($\times 1.3$) | 260 | 500 |
Example CMS studies of HL-LHC L1T Menu

- Desire pT thresholds to be O(20-40) GeV
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Main Conclusions:
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### Table 4.1: L1 menu using algorithms that include track trigger capabilities

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<tr>
<th></th>
<th>(\langle PU \rangle = 140)</th>
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<tbody>
<tr>
<td><strong>Trigger</strong></td>
<td><strong>Rate [kHz]</strong></td>
<td><strong>Offline threshold(s) [GeV]</strong></td>
</tr>
<tr>
<td>Single Mu (tk)</td>
<td>14 27 18</td>
<td></td>
</tr>
<tr>
<td>Double Mu (tk)</td>
<td>1.1 1.2</td>
<td>14 10</td>
</tr>
<tr>
<td>Ele* (iso tk) + Mu (tk)</td>
<td>0.7 0.2</td>
<td>19 10.5</td>
</tr>
<tr>
<td>Single Ele* (tk)</td>
<td>16 38</td>
<td>31</td>
</tr>
<tr>
<td>Single iso Ele* (tk)</td>
<td>13 27</td>
<td>27</td>
</tr>
<tr>
<td>Single (\gamma^*) (tk-isol)</td>
<td>31 19 31</td>
<td></td>
</tr>
<tr>
<td>Ele* (iso tk) + e/(\gamma^*)</td>
<td>11 7.3</td>
<td>22 16</td>
</tr>
<tr>
<td>Double (\gamma^*) (tk-isol)</td>
<td>17 5 22 16</td>
<td></td>
</tr>
<tr>
<td>Single Tau (tk)</td>
<td>13 38 88</td>
<td></td>
</tr>
<tr>
<td>Tau (tk) + Tau</td>
<td>32 55 56</td>
<td>56 56</td>
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<td>7.4 23</td>
<td>19 50</td>
</tr>
<tr>
<td>Tau (tk) + Mu (tk)</td>
<td>5.4 6</td>
<td>45 14</td>
</tr>
<tr>
<td>Single Jet</td>
<td>42 69 173</td>
<td></td>
</tr>
<tr>
<td>Double Jet (tk)</td>
<td>26 43 2@136</td>
<td></td>
</tr>
<tr>
<td>Quad Jet (tk)</td>
<td>12 45 4@72</td>
<td></td>
</tr>
<tr>
<td>Single ele* (tk) + Jet</td>
<td>15 15 23 66</td>
<td></td>
</tr>
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<td>Single Mu (tk) + Jet</td>
<td>8.8 12</td>
<td>16 66</td>
</tr>
<tr>
<td>Single ele* (tk) + (H_T^{miss}) (tk)</td>
<td>10 45</td>
<td>23 95</td>
</tr>
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<tr>
<td>( \langle PU \rangle = 140 )</td>
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</tr>
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<td>10.5</td>
</tr>
</tbody>
</table>

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<tr>
<th>Trigger algorithm</th>
<th>L1 tracks (pT &gt; 2 GeV) correlated with object</th>
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How to improve hadronic triggers?

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L1 tracks (pT > 2 GeV) correlated with object
Particle Flow + PUPPI @ L1

- Particle Flow: proven method to be effective in getting the best out of the CMS detectors — construct trigger objects from list of \{\mu, e, \gamma, h^\pm, h^0\}

- PUPPI (PileUp Per Particle Id): framework that determines, per particle, a weight for how likely a particle is from PU

See poster by Giovanni Petrucciani
Correlator Trigger R&D: Firmware with HLS

See poster by Giovanni Petrucciani
Basic PF+PUPPI Algorithm Steps

1. Vertexing done in parallel with PF & PU estimate
2. L1 PUPPI runs on global list of particle candidates from PF step
   (a) Sorted by most PV-like
3. Output vertex-filtered list used for reco/ID → prompt physics objects!
Correlator Trigger R&D: Firmware with HLS

- PF+PUPPI algorithms prototyped in firmware using Vivado High Level Synthesis

**See poster by Giovanni Petrucciani**
Correlator Trigger R&D: Firmware with HLS

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See poster by Giovanni Petrucciani
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latency: 62 cycles = 310 ns = 12.4 BX
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**Timeline for \(N(\text{EM}) = N(\text{Cal}) = N(\text{trk}) = 20\)**

- KU115 FPGA, 5ns clock cycle
  - Tk → Em link: 1 cycle
  - Tk → Em sum: 10 cycles
  - Em → Cal link: 5 cycles
  - Cal sub: 1 cycle
  - Cal sort & crop: 5 cycles
  - Em → Cal sum: 8 cycles
  - Cal → Cal Algo: 9+1 cycles
  - Charged Hadrons: 1 cycle
  - Photons: 1 cycle

Latency: 62 cycles = 310 ns = 12.4 BX

See poster by Giovanni Petrucciani

---

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<tr>
<th>Scheme</th>
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<tr>
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- PF+PUPPI algorithms prototyped in firmware using Vivado High Level Synthesis
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Algorithm Testing using Ultrascale+ Dev. Kit

- Very early look at VU9P FPGA
- Xilinx Development Kit includes
  - USB JTag Cable for Programming
  - Gigabit Ethernet
- Prototype PF Algorithm implemented using HLS
  - inputs reads from BRAM buffers

Early example:
10 EM-clusters
10 HAD-clusters
10 Tracks

output captured to BRAM buffers
Correlator Trigger R&D: Potential Gains

- **Missing Transverse Momentum**
  - About factor 2 (6) less rate, compared with track-based MET (CaloMET), for same trigger efficiency

- **Summed Jet Transverse Momenta**
  - About 15% (45%) lower trigger threshold, compared with track-based HT (CaloHT), for same efficiency and fixed trigger rate

See poster by Giovanni Petrucciani
Related contributions here at CHEP 2018

- "Particle Flow reconstruction in the Level-1 trigger at CMS for the HL-LHC"
  - Giovanni Petrucciani (CERN)
  - Poster 314

- "Synthesizing Machine Learning algorithms on FPGA"
  - Jennifer Ngadiuba (INFN, Milano)
  - Plenary, Tuesday Morning

- "Kalman Filter track reconstruction on FPGAs for acceleration of the High Level Trigger of the CMS experiment at the HL-LHC"
  - Sioni Paris Summers (Imperial College)
  - Parallel, T1 Online Computing, Tuesday Afternoon

- "Fast Boosted Decision Tree inference on FPGAs for triggering at the LHC"
  - Sioni Paris Summers (Imperial College)
  - Parallel, T1 Online Computing, Tuesday Afternoon

- "ATLAS and CMS Trigger and Data Acquisition Upgrades for the High Luminosity LHC"
  - Imma Riu (IFAE Barcelona)
  - Plenary, Tuesday Afternoon
Summary

- CMS Designing a L1 Trigger for HL-LHC that will enable unprecedented exploration weak-scale physics frontier
- L1 Trigger will exploit tracking, highly granular calorimetry, & efficient muon ID
- Hardware R&D program investigating
  - ATCA form factors
  - Ultrascale & Ultrascale+ FPGAs
  - High speed data links
  - Large DDR4 Memory Banks
- Algorithm R&D program investigating
  - Particle-flow and pile-up per particle ID
  - High-level Synthesis prototyping of FW