A Level-1 Track Trigger for the CMS Phase 2 Upgrade

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The Ohio State University
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HL-LHC

- High-Luminosity LHC Running ~2026
  - Luminosity: \( \approx 5-8 \times 10^{34} \text{ cm}^2\text{s}^{-1} \)
  - “Pileup” (multiple interactions/crossing): 140 - 200
  - Integrated Luminosity: \( \approx 3000 \text{ fb}^{-1} \) (10 years)

- Upgrades to LHC Detectors
  - Need to handle challenging environment
  - Wide range of detector/trigger/DAQ upgrades proposed.

- CMS:
  - Central Tracker
  - End-cap Calorimetry
  - Muon Systems
  - Trigger/DAQ

Trigger Challenges

- **Current Level-1 Trigger**
  - No central tracking information
  - Electrons/Gammas (EG), Taus, Jets based solely on calorimeter deposits.
  - Muons reconstructed from tracks in muon chambers.
  - **Maximum Bandwidth: 100 kHz**

- **HL-LHC:**
  - Current Trigger System:
    - EG rate @25 GeV > 100 kHz
    - Muon rate plateaus
    - Overall Trigger Rate > 1000 kHz for ~2012 thresholds.
  - Upgraded System
    - Must increase total bandwidth
    - Must increase trigger capabilities

© Level-1 Tracking is a completely NEW handle.

<table>
<thead>
<tr>
<th>Trigger Algorithm</th>
<th>Rate [kHz]</th>
<th>Offline Threshold [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Mu (tk)</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>Double Mu (tk)</td>
<td>1.1</td>
<td>14 10.5</td>
</tr>
<tr>
<td>ele (iso tk) + Mu (tk)</td>
<td>0.7</td>
<td>19 10.5</td>
</tr>
<tr>
<td>Single Ele (tk)</td>
<td>16</td>
<td>31</td>
</tr>
<tr>
<td>Single iso Ele (tk)</td>
<td>13</td>
<td>27</td>
</tr>
<tr>
<td>Single γ (tk-iso)</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>ele (iso tk) + e/γ</td>
<td>11</td>
<td>22 16</td>
</tr>
<tr>
<td>Double γ (tk-iso)</td>
<td>17</td>
<td>22 16</td>
</tr>
<tr>
<td>Single Tau (tk)</td>
<td>13</td>
<td>88</td>
</tr>
<tr>
<td>Tau (tk) + Tau</td>
<td>32</td>
<td>56 56</td>
</tr>
<tr>
<td>ele (iso tk) + Tau</td>
<td>7.4</td>
<td>19 50</td>
</tr>
<tr>
<td>Tau (tk) + Mu (tk)</td>
<td>5.4</td>
<td>45 14</td>
</tr>
<tr>
<td>Single Jet</td>
<td>42</td>
<td>173</td>
</tr>
<tr>
<td>Double Jet (tk)</td>
<td>26</td>
<td>2@136</td>
</tr>
<tr>
<td>Quad Jet (tk)</td>
<td>12</td>
<td>4@72</td>
</tr>
<tr>
<td>Single ele (tk) + Jet</td>
<td>15</td>
<td>23 66</td>
</tr>
<tr>
<td>Single Mu (tk) + Jet</td>
<td>8.8</td>
<td>16 66</td>
</tr>
<tr>
<td>Single ele (tk) + HTmiss (tk)</td>
<td>10</td>
<td>23 95</td>
</tr>
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</tr>
<tr>
<td>HT (tk)</td>
<td>13</td>
<td>350</td>
</tr>
</tbody>
</table>

Rate for above Triggers 180
Est. Total Level-1 Menu Rate 260
Benefits of L1 Tracking

- **Electrons/Photons**
  - Extra measurement - Rate Reduction
  - Isolation

- **Muons**
  - Excellent $P_T$ Resolution
    - Rate Reduction
  - Isolation

- **Tau Triggers**
  - Multi-pronged

- **Separation of Interactions**
  - Hadronic/Multi-object Triggers
CMS Tracker

- Silicon pixel/strip Tracker
  - Inner Pixel Detector
  - Outer Pixel/Strip Detector
- Outer Tracker Geometry:
  - Barrel: 6 layers
  - Endcaps: 5 disks

Used for L1 Tracking

L1 Tracking is based on “stubs” found in the FE. Stub consists of pairs of hits on closely spaced layers.

Exact geometry still under optimization.
Basic Approach

**Note:** This is one of several approaches being explored by CMS. The remainder of the talk describes this “Tracklet” approach.
Basic Approach

• Form “Tracklets”
  ➡ Stubs from adjacent layers
  ➡ Find initial track parameters using beam constraint.

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  - Determine final track parameters

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• Remove duplicate tracks
  ➡ Seeding tracks on multiple layers leads to the same particle being found multiple times.

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Hardware Configuration

• Parallel Processing
  ➡ Divide tracking system into 28 sectors in $\phi$.
    ▶ Min $P_T$ 2 GeV
    ▶ Tracks contained within a sector and nearest neighbor, which simplifies communications.
  ➡ Each sector has a dedicated processor board.
  ➡ 4-8x time multiplexing
    ▶ @ 4x TM: each sector receives new event every 100 ns.
    ▶ Current spec: Latency < 4 $\mu$s.

• Sector Processors:
  ➡ Target large commercial FPGAs
  ➡ I/O:
    ▶ Stub Input: ~200 Gbits/s
    ▶ Neighbor Boards: 2 x 80 Gbits/s
    ▶ Track list: ~20 max trk/sec/event = ~20 Gbits/s

Downstream trigger systems will associate tracks with calorimeter and muon system objects to form L1 trigger objects.
Firmware Structure

- **Firmware:**
  - Pipelined: 13 steps each ~100 ns
  - Verilog Implementation (R&D target: Xilinx Vertex-7 chip)
  - Currently achieved a 1/4 barrel design with 320 MHz clocking.

```
INPUT DATA FROM FEDS
RECEIVE STUB DATA AND SORT BY MODULE
APPEND PHYSICAL COORDINATES
SEARCH STUBS FOR TRACKLETS
CALCULATE TRACK PARAMETERS
CALCULATE PROJECTION TO OTHER LAYERS
TRANSMIT TO OTHER LAYERS

STUBS
MATCHED STUBS FROM OTHER MODULES
TRACKLET DATA

MATCHED STUBS TO OTHER MODULES
TRANSMIT BACK TO TRACKLET

MATCHED STUBS FROM OTHER MODULES
RECEIVE HITS FROM OTHER LAYERS
FINAL TRACK FIT
TRANSMIT TRACKS

TRACKLET DATA

TRACKLETS
TO OTHER LAYERS

TRACK DATA TO MERGER

TRACKLIST TO GT
```

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Firmware Performance

• **C++ Firmware Emulation**
  ➡ Evaluate firmware performance
  ➡ Evaluate choices

• **Comparisons:**
  ➡ Integer vs floating point calculations
  ➡ Coverage based on tracklet seed
  ➡ duplicate track removal.

• **Single particle MC w/o pileup**
  ▶ High pileup performance (next page)

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**Tracks in Disks**
- **Floating Pt.**
- **Integer**

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**Muon Track Finding**
- Tracks in Disks

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**Tracking Efficiency**
- **p_T > 10 GeV**

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Algorithm Performance

Based on simulations with $<\text{PU}> = 140$. 

**Efficiency**

- Single muons
- Single pions
- Single electrons

**$p_T$ resolution / $p_T$**

- Single muons, $p_T < 5$ GeV/c
- Single muons, $5 < p_T < 15$ GeV/c
- Single muons, $15 < p_T < 100$ GeV/c

**$\eta$**

**$z_0$ resolution [cm]**

- Single muons, $p_T < 5$ GeV/c
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- Single muons, $15 < p_T < 100$ GeV/c

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Sector Demonstration

• Goal: Establish overall viability of tracklet approach.
  ➡ Firmware/Algorithm
  ➡ I/O Tests (input, neighbor, output)
  ➡ Latency
  ➡ Stress tests with data volumes

• Setup:
  ➡ Four μTCA cards
    ▶ Core sector board + 2 neighbors
    ▶ 4th acting as data source/sink.
  ➡ Firmware
    ▶ Developed for Xilinx Vertex 7
    ▶ 1/4 barrel
  ➡ Status:
    ▶ Test stand functional
    ▶ Basic track finding and neighbor communication has been established.
Summary

• High Luminosity Running of the LHC
  ➡ Outstanding physics potential
  ➡ Enormous challenges

• The CMS trigger system will require substantial upgrades
  ➡ More bandwidth
  ➡ New and improved object reconstruction

• Tracking at the Level-1 Trigger
  ➡ Added capability with substantial impact on trigger rates
  ➡ Complex pattern recognition problem with large data volumes

• R&D on a Track Trigger System
  ➡ Algorithms developed show excellent performance
  ➡ FPGA based system shows promise
  ➡ Efforts are ongoing to demonstrate full viability of design, identify and mitigate vulnerabilities
Backup Slides
Resolutions in Barrel

- Resolutions in Barrel
  - CMS Preliminary Simulation, Phase-2
    - Floating point
    - Integer emulation
  - 5<p_T<10 GeV
  - |η|<1.0

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