Track Finding in CMS for the Level-1 Trigger at the HL-LHC

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High-Luminosity (HL) LHC

- Expected to collect ~ 3000/fb integrated luminosity @ $E_{CM} = 14$ TeV
- x10 more data than what previously collected by the LHC
- instantaneous luminosities $\sim 5-7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Operations from 2025 to 2035

**Goal: broaden the physics program**

- SM precision measurements
  - Higgs properties, PDF, QCD, TGCs, etc...
- New physics searches
  - Dark Matter, SUSY, BSM, extra dimensions, etc...

Summary of CMS SUSY Projections with SMS

Probe *up to* the quoted mass

- Mass scales [GeV]
- 5$\sigma$ discovery: 14 TeV, 3000 fb$^{-1}$
- 5$\sigma$ discovery: 14 TeV, 300 fb$^{-1}$
- 95% CL limits: 8 TeV

Figure 1.10: Observed and projected precision on Higgs boson couplings as a function of boson or fermion masses.
Why add a track-trigger @ L1?

**Expected improvements**
- charged lepton identification/transverse momentum ($P_T$) resolution

✓ Sharp turn-on efficiency curve

✓ Rate reduction allows for low object thresholds

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**CMS Phasell Simulation**

- $L1 p_T^{trig} > 20$ GeV
- $L1$ $p_T > 20$ GeV

- $L1$ $p_T$ (Run 1 configuration + METa unangled)
- $0 \leq |n| < 1.1$ (Q $\geq$ 4)
- $1.1 \leq |n| < 2.4$ (Q $\geq$ 4)

- $L1$ $p_T$ (Phasell: muon hits in $\geq$ 2 stations)
- $0 \leq |n| < 1.1$
- $1.1 \leq |n| < 2.4$

**Single Muon**

- $\mu$: 19 v. 50 GeV @ 285 kHz
Why add a track-trigger @ L1?

Expected improvements
- charged lepton identification/transverse momentum ($P_T$) resolution
- isolation of $e/\gamma$

Novelties
- vertex reconstruction from L1 tracks
  - reject PU jets
  - improve MET performances
  - ...

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Track matched to calorimeter cluster

Track used in MET calculation
Why add a track-trigger @ L1?

Expected improvements
- charged lepton identification/transverse momentum ($P_T$) resolution
- isolation of e/γ

Novelties
- vertex reconstruction from L1 tracks
  - reject PU jets
  - improve MET performances
  - ...

Great complements to current triggers
Track-trigger for HL-LHC: the challenge

• Want to reconstruct the trajectory of charged particles
  • in an extremely dense environment ($<\text{PU}>$ ~ 140-200)
    [$<\text{PU}>$ ~ 30 at highest instantaneous luminosities in LHC Run-1]
  • at an input rate of 40 MHz
  • Tracker data ~ 1K TB/sec
  • $O(10K)$ Tracks/Bunch crossing
  • with ~ 4 $\mu$s of latency
    [total allowed latency for L1 trigger ~ 12.5 $\mu$s]

• Never done before with such conditions
  ✓ a track-trigger was implemented at CDF (Tevatron)
    • tracks were reconstructed at L2
      [input ~ 30 KHz, latency 20 $\mu$s]
    • in a less dense environment
  ✓ a track-trigger will be part of the ATLAS Phase-I upgrade
    • will operate at lower input rates
      [after L1 (~ 1 KHz output rate)]
A track-trigger in two steps

1. Selection of high $P_T$ stubs

2. Track finding

@ 40 MHz – Bunch crossing
@ ~ 500 kHz – CMS Level-1 trigger
First step

- **Goal:** reduce the input rate to something bearable

- **Solution:** select only high-$P_T$ stubs
  - chosen (preliminary) threshold: 2-3 GeV/c
  - data reduction of one order of magnitude
  - sufficient for the purpose of L1 data transmission
  - Full efficiency at ~2.2 GeV/c
PT modules

Characteristics

• Two closely-spaced silicon sensors
• Read out by common front-end ASICs
  [different sensor spacing over the tracking volume (e.g., large spacing at large radii)]
• Radiation hard
  [need to survive 3000/fb]
• Less material
  [less electrical connectivity in the tracking volume]

2 Types under development:

2 Strip sensors
Strips: 5 cm x 90 μm
P = 2.7 W
~ 92 cm² active area
For r > 40 cm

Pixel + Strip sensors
Strips: 2.5 cm x 100 μm
Pixels: 1.5 mm x 100 μm
P = 5.0 W
~ 44 cm² active area
For r > 20 cm
Second step: track finding

Time/Regional Data Multiplexing *

Pattern Recognition

Track Fitting

Duplicate removal *

*: not in this talk
Two approaches being explored at CMS

• ASIC-assisted:
  1. Associative memory + FPGA
     • familiar from CDF/ATLAS
     • tackle combinatoric with AM, FPGA for parameter estimation

• Purely FPGA-based:
  2. Projective binning (Hough Transform)
  3. Combined Tracklet Builder & linearized track fit
     (not in this talk...will be covered by B. Winer)

Tuesday, October 11, 16
The Associative Memories+FPGA Approach

- Pattern recognition (PR) stage
  - look for coarse roads matching pre-loaded pattern
  - handled by Associative Memories
  - first estimate of track parameters

- Track Fitting (TF) Stage
  - Linearized $\chi^2$ fit on Kintex7 UltraScale FPGA by means of the Principal Component Analysis
  - $\sigma(\Phi) \sim 0.0003$, $\sigma(P_T)/P_T \sim 1\%$ for high $P_T$ tracks at central $\eta$

![Graphs showing CMS Preliminary Simulation, Phase-2 and L1 tracker reconstruction, $<PU>=140$.]
The Associative Memories+FPGA Approach

- **Work horses:**
  - ATCA shelves w/ full mesh backplane (40G+) and rear transceiver modules (RMT)
  - Pulsar 2b
  - INFN/FNAL Mezzanine
    - Associative Memories (AM)
    - Kintex7 Ultrascale FPGA

- **Multiplex:**
  - Regional: $8 \varphi \times 6 \eta$ segments
  - Time: 10 pulsar $\times$ 2 mezzanine
The Hough Transform (HT) Approach

- **PR/TF**
  - geometric processor (GP) sorts stubs in 36 subdivisions of the octant
  - coarse HT ran on the stubs
  - stubs from HT track candidates not consistent with the track in the r-z plane are filtered out
  - duplicates are removed
  - final TF is performed to accurately determine track parameters

(stubs belonging to a real track intersects in the track-paramter phase space)
The Hough Transform (HT) Approach

- **Work horses:**
  - μTCA crate
  - MP7

- **Multiplex:**
  - Regional: 8 φ octants
  - 1 TF processor (TFP) per octant
  - Time: 12-36
Conclusions

• Physics case established: a track-trigger for HL-LHC is something we “must have” for an optimal physics reach
  • PU mitigation, improved lepton ID for lower thresholds, etc...

• CMS tracking trigger R&D project is a pioneering effort which will pave the way for future hadron colliders
  • challenging project never attempted in the past for such conditions
  • pushing the limits of triggering in HEP

• Exploring two approaches in CMS
  • system demonstrations planned for the end of 2016
  • so far, promising results from both simulation and hardware across the board
• backup
Figure 1.3: Higgs couplings divided by SM prediction from the full dataset from the 2011 and 2012 runs
The CMS HL-LHC L1 Trigger

The addition of the tracking trigger along with a larger bandwidth and allowed latency are the main change for Phase 2
The Hough Transform (HT) Approach

Ref: CMS CR-2016/112

Fig. 6. Overview of the Hough Segment. Components are shown as boxes and data paths as lines, where arrows indicate the direction of communication.

Fig. 7. Overview of one Bin, the component corresponding to one $q/p_T$ column in the Hough Transform. All 32 Bins are daisy-chained together, starting and ending with the Book Keeper.