CMS tracker & track-trigger impact

Workshop on the physics of the HL-LHC & perspectives at HE-LHC

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on behalf of the CMS Collaboration
HL-LHC opportunities & challenges

• **Physics potential -- 3000 fb\(^{-1}\)**
  ‣ Extend discovery reach in searches for new physics & rare SM processes
  ‣ Higgs boson precision measurements
  ‣ Improved SM measurements
  ‣ Precision measurement in **flavor sector**
    • *CP violation, rare B decays, top FCNC, ...*

• **Experimental challenges -- extreme conditions!**
  ‣ Expected average pileup of 200 with resulting increase in particle density
  ‣ Radiation damages

• *Physics goals rely on continued excellent detector performance & triggering!*
CMS detector upgrades

• HL-LHC conditions requires upgrade or replacement of several sub-systems

• **Lifetime of detectors** => replace inner tracker & forward calorimeter

• **Increased readout bandwidth**
  ‣ Accommodate higher data rates
  ‣ Requires replacing much of FE/BE electronics
    • Also to improve radiation tolerance

• **PU mitigation**
  ‣ Higher detector granularity to reduce occupancy
  ‣ Improved trigger capabilities
  ‣ Precision timing
**Trigger**
- Track information @ L1
- L1: 12.5 µs latency, 750 kHz output rate
- HLT: 7.5 kHz output rate

**Barrel EM calorimeter**
- Replace FE/BE electronics
- Lower operating temperature

**Muon systems**
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage (1.5<η<2.4)
- Muon tagging (2.4<η<3)

**Tracker**
- Completely new inner+outer tracker (OT)
- 40 MHz readout (pT>2 GeV) in OT
- Extend coverage to η~4

**Endcap calorimeter**
- Replace endcap calorimeters => HGCal
- Radiation tolerant, high granularity
- 3D capability
Muon upgrades

- New DT+CSC electronics for increased radiation tolerance & readout speed
- New forward detectors
  - Gas Electron Multipliers & (improved) RPC stations
  - Forward extension (GEM) to $|\eta| < 2.8$
- Maintain standalone muon trigger efficiency

**Figure 1.4:** An $R$-$z$ cross section of a quadrant of the CMS detector, including the Phase-2 upgrades (RE3/1, RE4/1, GE1/1, GE2/1, ME0). The acronym iRPCs in the legend refers to the new improved RPC chambers RE3/1 and RE4/1. The interaction point is at the lower left corner. The locations of the various muon stations are shown in color (MB = DT = Drift Tubes, ME = CSC = Cathode Strip Chambers, RB and RE = RPC = Resistive Plate Chambers, GE and ME0 = GEM = Gas Electron Multiplier). M denotes Muon, B stands for Barrel and E for Endcap. Labelling details are given in Section 1.2.2. The magnet yoke is represented by the dark gray areas.

Near the interaction region a silicon tracker, composed of an inner pixel detector surrounded by a silicon strip detector, measures vertices and momenta of charged particles. The electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL) are located inside the solenoid, measuring electromagnetic and hadronic showers with lead tungstate crystals and a scintillator-brass sampling detector, respectively.

The current silicon tracker must be replaced before the start of Phase-2, since it will suffer significant radiation damage by the end of Run 3. To maintain excellent track reconstruction at high pileup, the granularity of both the inner pixel tracker and the outer tracker will be increased, by decreasing the pixel size and by shortening the strip lengths. For the first time at CMS a momentum measurement will become possible within a few microseconds, and this information can be used in the Level-1 (L1) trigger. The track trigger will greatly sharpen the L1 $p_T$ resolution, which will reduce the trigger rate at a given transverse momentum. Thus by combining input from the tracker and muon systems the $p_T$ threshold for the single muon trigger can be kept low despite the high rate at HL-LHC.

The endcap calorimeters will also suffer significant radiation damage. The replacement planned for Phase-2, the High Granularity Calorimeter (HGCAL), will have an electromagnetic and a hadronic component.

**Figure 2:** Graph showing L1 trigger rate vs. $p_T$ threshold for different configurations. The orange line represents the CMS Phase-2 Simulation Preliminary results for $\sqrt{s}=14$ TeV, $<\text{PU}>=200$. The graph indicates that the combinatorial performance of the Phase-2 (CSC+GE11+GE21+ME0) configuration is superior to the Phase-1 detector (CSC) configuration, particularly in the $2.10<|\eta|<2.40$ region, which enhances the trigger performance and reduces trigger rates compared to the Phase-1 configuration.
Precision timing

- ECAL barrel + HGCal upgrades => 30-50 ps timing resolution for moderate-energy photons & high-energy hadrons

- Dedicated precision timing layer
  - Thin LYSO + SiPM, outside tracker barrel support tube
  - Precision timing for charged particles => useful for flavor analyses?

[Diagram showing CMS Simulation <μ> = 200 with simulated vertices, 3D reconstructed vertices, 4D reconstructed vertices, and 4D tracks plotted against z (cm) and t (ns).]
Tracker system

**PS modules** (pixel-strip)
- Top sensor: 2x2.5 cm strips, 100 µm pitch
- Bottom sensor: 1.5 mm x 100 µm pixels

**2S modules** (strip-strip)
- Strip sensors 10x10 cm²
- 2x5 cm long strips, 90 µm pitch

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Figure 2.3: Sketch of one quarter of the tracker layout in $r$-$z$ view. In the Inner Tracker the green lines correspond to pixel modules made of two readout chips and the yellow lines to pixel modules with four readout chips. In the Outer Tracker the blue and red lines represent the two types of modules described in the text.

Figure 2.4: Average number of module layers traversed by particles, including both the Inner Tracker (red) and the Outer Tracker (blue) modules, as well as the complete tracker (black). Particle trajectories are approximated by straight lines, using a flat distribution of primary vertices within $|z| < 70$ mm, and multiple scattering is not included.
Tracker system

- Requirements driving design
  - Radiation tolerance
  - Increased granularity to cope with PU=200
  - Extended coverage at high $|\eta|$\n  - Reduced amount of material => improved momentum resolution (combined with better hit resolution)
  - Track finding @ 40 MHz
Tracking performance

- Iterative track finding: seeding - track finding - track fitting - track selection
  - At PU=200, about 6000 charged particles per event!
- High efficiency & low fake rates
- Improved two-track separation in high-p_T jets
Tracking performance

- Excellent track resolutions with even improved performance beyond current tracker system

- Very high vertex efficiency (~93% at PU=200) & precise vertex resolutions
Tracking performance

• Further optimization under study
  ‣ Using “vector hits” -- hit pairs that provide both position & direction
  ‣ Additional dedicated iteration targeting displaced tracks

• Promising results
  ‣ Improved efficiency with reduced fake rate
  ‣ Computational consumption under study
Track trigger concept

- **Self-seeded L1 track trigger**
  - Local $p_T$ reconstruction
  - Reconstruct tracks with $p_T > 2$ GeV & identify $z_0$ with $\sim 1$mm precision

- **Outer tracker modules** provide $p_T$ discrimination in FE electronics through hit correlations between closely spaced sensors

- **Stubs**: Correlated pairs of clusters, consistent with $\geq 2$ GeV track
  - Data reduction at trigger readout (by a factor 10-20)
  - *Stubs form input to track finding*
Tracking @ L1

• HL-LHC conditions
  ‣ 6-7K charged particles/BX at PU=200
  ‣ ~200 tracks with $p_T > 2$ GeV

• Resulting challenges
  ‣ Combinatorics => 15-20K input stubs/BX
  ‣ Data volumes => up to ~50 Tbits/s
  ‣ L1 trigger decision within 12.5 µs => time available for track finding ~4 µs

• Benefits
  ‣ Improved lepton identification and $p_T$ measurements
  ‣ Track isolation
  ‣ Vertex determination
  ‣ Large rate reductions possible!
Track trigger strategy

- Parallelization
  - Divide tracker in segments in $\phi / z$
  - Time-multiplexed systems -- process several BX simultaneously

- Several approaches studied to attack combinatorics & occupancies
  - CMS baseline a fully FPGA-based system
    - *Off-the-shelf hardware*
    - *Programmable* $\Rightarrow$ *flexibility*
  - Tracklet road search algorithm with full hit precision
  - Hough transform with large time-multiplexing
L1 tracking performance

- Stub finding performance
  - Sharp turn-on & high efficiency

- L1 tracking efficiency
  - Very high & flat tracking efficiency
  - Low-$p_T$ electrons challenging
  - Here shown for $p_T > 3$ GeV
    - Benchmark studied for TDR

\[ \text{CMS Phase-2 Simulation Preliminary} \]

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L1 tracking performance

- Precise track parameter resolutions
- Note: Plots assume an earlier ("flat") version of tracker geometry
  - Current geometry => slightly worse $z_0$ resolution at intermediate/forward $\eta$
  - Necessary to avoid inefficiencies from lack of communication between PS module halves

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**Figure 6.8: Relative resolutions**

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Physics examples

Extended muon coverage
=> improved signal acceptance e.g. in LFV
$D_s \rightarrow \tau \nu$, $\tau \rightarrow \mu \mu \mu$ search

Improved $\mu \mu$ mass resolution => 25% gain in separation significance

L1 tracking enables $B_s \rightarrow \phi \phi \rightarrow 4K$ search
Conclusions

• Achieving full physics potential of HL-LHC requires significant upgrades to CMS detector systems

• Of particular relevance to flavor physics
  ‣ New inner pixel + outer tracker system
    • Higher granularity & improved momentum resolutions
    • Capability of tracking @ 40 MHz => can enable signatures otherwise unattainable
  ‣ Improvements also from...
    • Upgraded muon system => reduced trigger rates & extended η acceptance
    • Potential to benefit from precision timing (under study)?

• Preliminary studies show excellent offline & L1 tracking performance
backup
Tracker FE / BE system overview

- Data from front-ends received at Data, Trigger Control Board (DTC)
- Likely an ATCA form factor, 50-70 modules per DTC
- FPGA emulation of GBT links to the front-ends
- Approximately 4x100Gpbs outputs to L1Tk system
- L1Tk system builds and delivers track primitive to the L1 trigger
- On-going R&D for this system is the focus of this talk... (see talk from F. Vasey on Wednesday for more details on the Tk FE / BE)
Phase-2 trigger system

• Current L1 trigger uses information from calorimeters & muon system

• Planned upgrades
  ‣ Replace ECAL barrel + endcap front-end electronics
  ‣ Increased latency & L1 accept rate
  ‣ L1 tracking + global track-trigger correlator
Tracklet-based method

- **Seed** by forming tracklets
  - Pairs of stubs in adjacent layers/disks
  - Initial tracklet parameters from stubs + beamspot constraint
- **Project** to other layers/disks & match with stubs
  - Inside-out & outside-in
  - Calculate residuals used in fit
- **Fit** stubs matched to trajectory
  - Linearized $X^2$ fit
- Remove **duplicate** tracks based on shared stubs
Time-multiplexed + Hough transform

• Fully time-multiplexed architecture where all module data for given BX send to a single track finder processor board

• Pattern recognition using Hough transform + track fitting (all in FPGA)
**Associative memory (AM) approach**

- Tackle combinatorics through massive parallel processing using ASIC
  - Filters out ~80% of stubs not associated with high-\(p_T\) particles
- Pattern Recognition Associate Memory = content addressable memory (CAM) + majority logic (ML)
- Pattern recognition with narrow roads, match preloaded patterns in AM chip
  - Time roughly proportional to \# stubs
  - (1) **Find roads** -- low-resolution track candidates
  - (2) **Fit tracks** (linearized \(X^2\)) inside roads using FPGA