Level-1 Track Quality Evaluation at CMS for the HL-LHC

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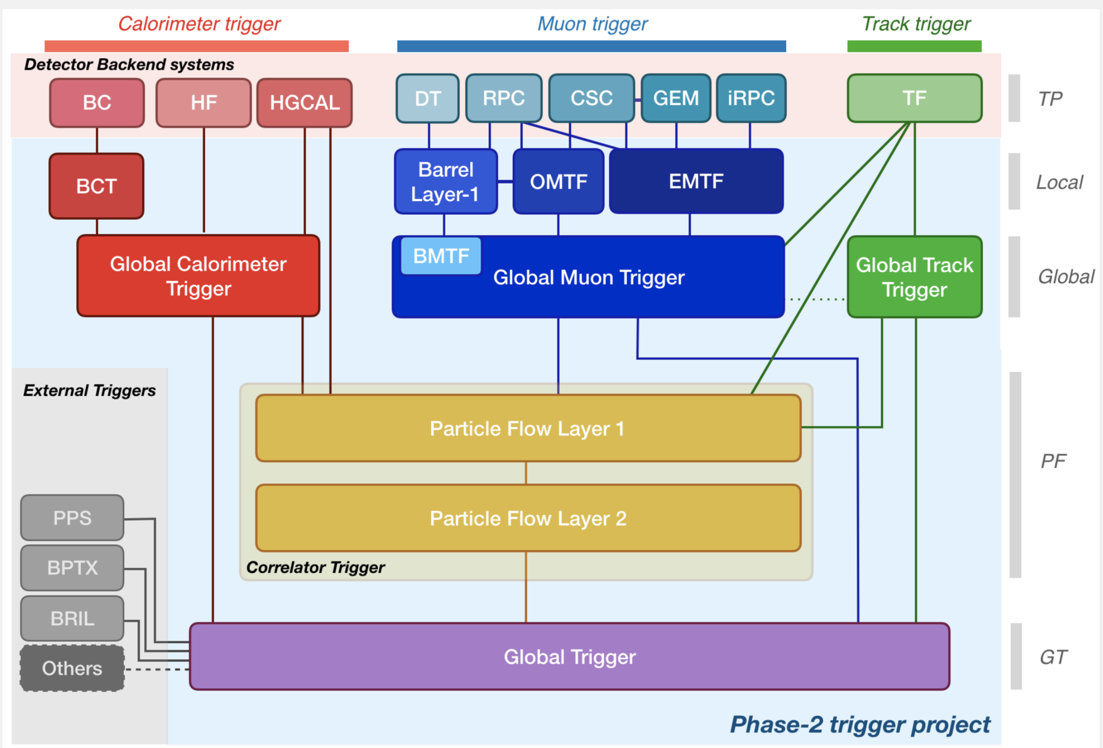
Introduction

The upcoming High-Luminosity LHC will provide 200 proton-proton collisions per bunch crossing on average, thus creating highly complex events demanding efficient data reconstruction and processing. In order to meet these requirements, the Compact Muon Solenoid (CMS) experiment is upgrading its Level-1 trigger system. Among these updates will be the reconstruction of charged particle tracks in the silicon tracker, enabling more precise track selection further down the pipeline. In this work, we will present the development of a **track quality** variable which combines many of the reconstructed track properties into one feature that describes whether the track is real or fake, or whether the reconstruction represents a genuine particle or not. Using machine learning techniques, track quality can be evaluated and used to select tracks efficiently and quickly while fitting within the tight computational resource constraints in the hardware. This track quality variable has immense value to beyond standard model searches requiring exact reconstruction such as missing energy analyses.

Level-1 Track Trigger

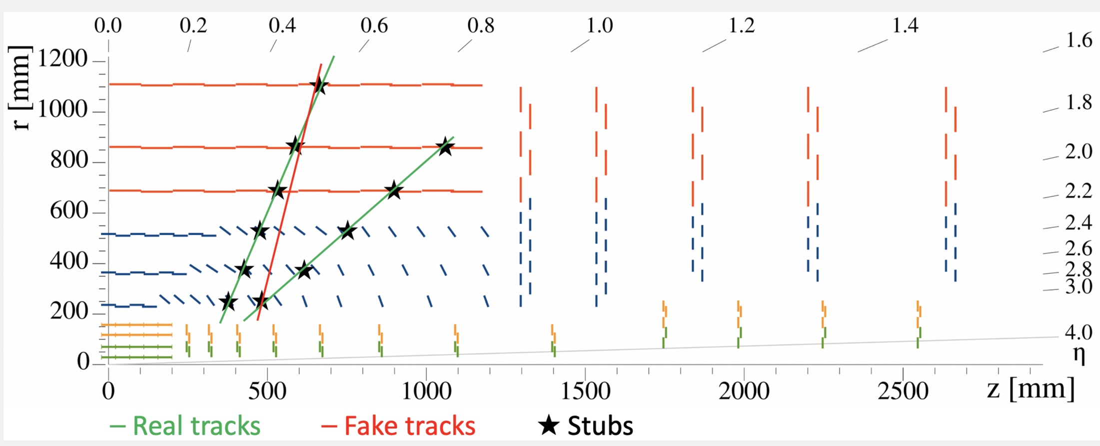
- Particle tracks from CMS Outer Tracker reconstructed in Track Finder (TF) [1]
- Reconstructed track parameters and quality flags passed to Trigger system to help other physics object
- FPGAs run Track Trigger algorithms
- Track Finder addition maximizes trigger efficiency while maintaining trigger rate below allotted rate



CMS L1 Phase-2 upgraded Trigger design, Track Trigger consists of the TF and global track trigger.

Track Quality

- Particles pass through CMS Outer Tracker and interact to create stubs
- Stub information used to reconstruct particle tracks



Track quality is a measure of how real a reconstructed track is.

Track quality is important for removing fake tracks because:

- Result of error in reconstruction
- Mask real physics occurring
- Hurtful for analyses that rely on combination of reconstructed tracks
  - Vertexing, missing transverse energy, jets, etc.

Definitions

Real tracks = tracks from a single, physical particle
Fake tracks = tracks not from a single, physical particle
Prompt tracks = tracks from pp collision point
Displaced tracks = track not from pp collision point $\mathcal{O}(cm)$
True positive rate = % of real tracks correctly classified
False positive rate = % of fake tracks incorrectly classified

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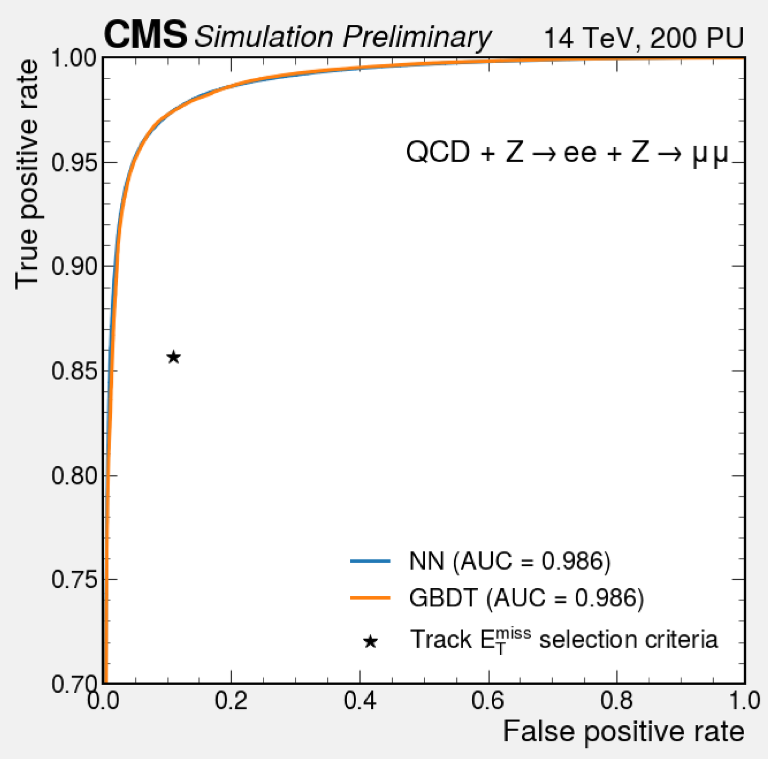
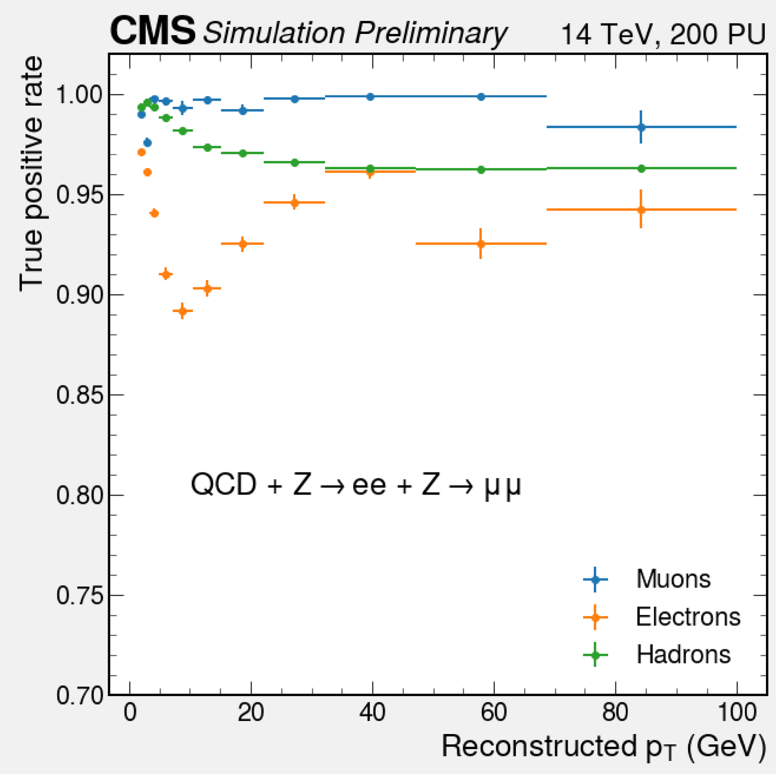
Prompt Track Quality Classifier

Gradient boosted decision tree (GBDT) for classifying real/fake tracks [2]:

- 60 trees, max depth of 3
- Features from reconstructed track parameters: $\{\phi,\, \eta,\, z_0,\, n_{stub},\, n_{misslayer},\, \chi^2_{bend},\, \chi^2_{rz},\, \chi^2_{r\phi}\}$
- Trained and tested on prompt tracks





Left: GBDT versus two other methods of classifying real and fake tracks

Right: GBDT performance on reconstructed p_T spectrum for 3 particle types, average false positive rate is 0.3

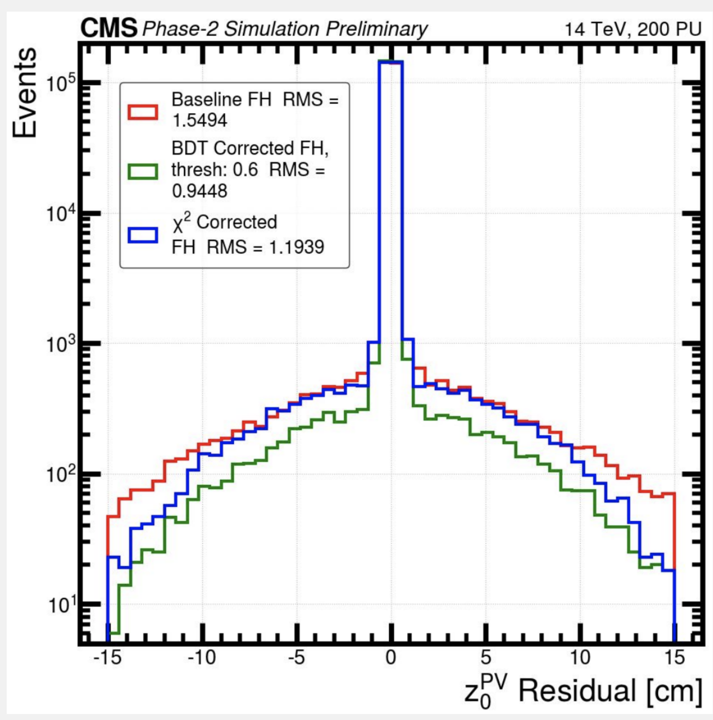
Performance and resource use for Xilinx VU9P FPGA [3,4]:

Model	Python AUC	HLS AUC	Latency (clk)	LUT %	FF %	DSP %
NN	0.985	0.982	8	0.104	0.029	0.292
GBDT	0.986	0.981	3	0.140	0.027	0.0

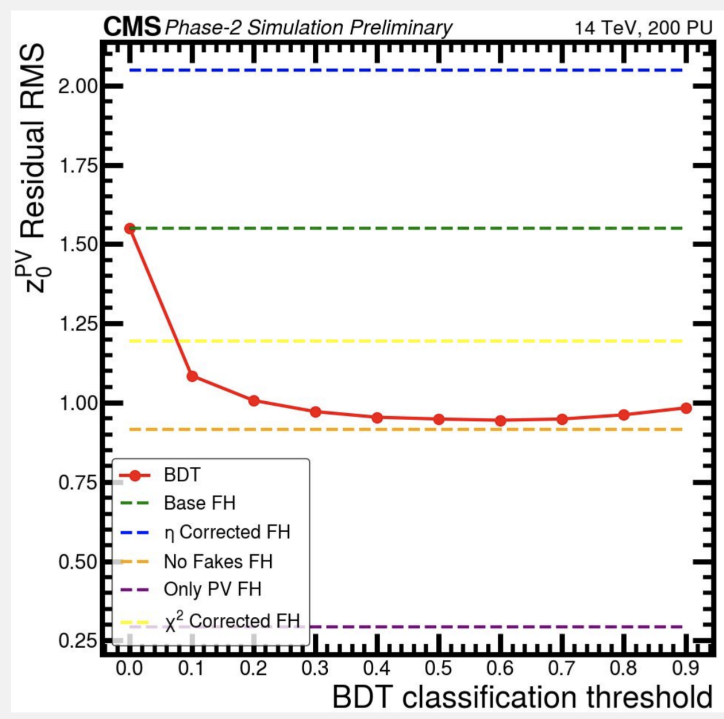
Track Quality Application: Primary Vertex Reconstruction

Vertexing chain: Track reconstruction → Track quality evaluation → Vertex reconstruction

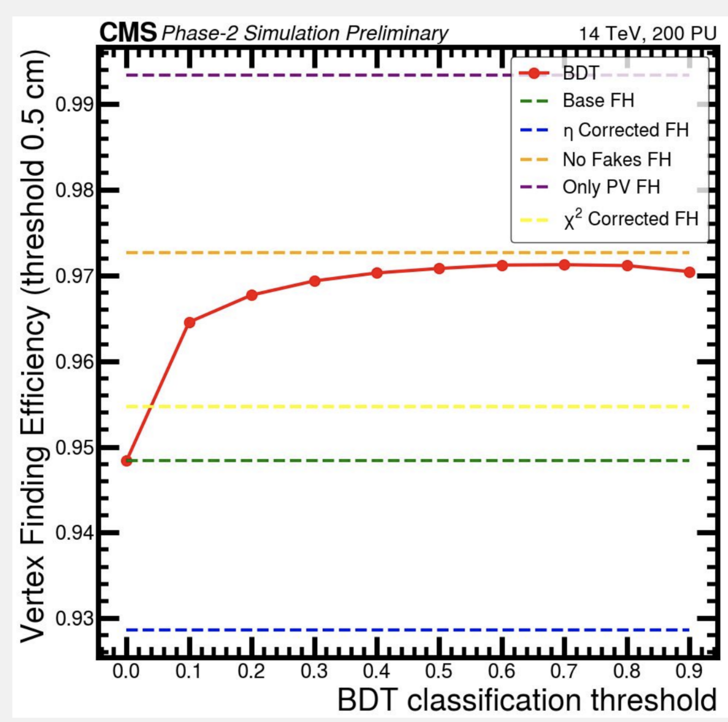
Using track quality to remove fake tracks compared to no removal (baseline) or χ^2 cuts improves vertex reconstruction [1,5].



Difference between the reconstructed and simulated primary vertex z_0



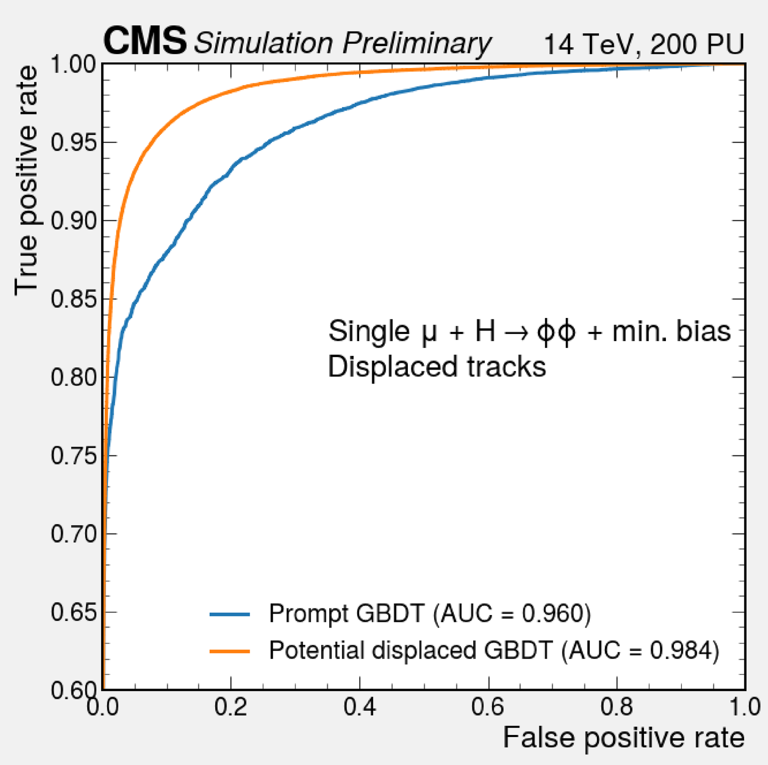
Root-mean square of the residual z_0^{PV} (left plot)

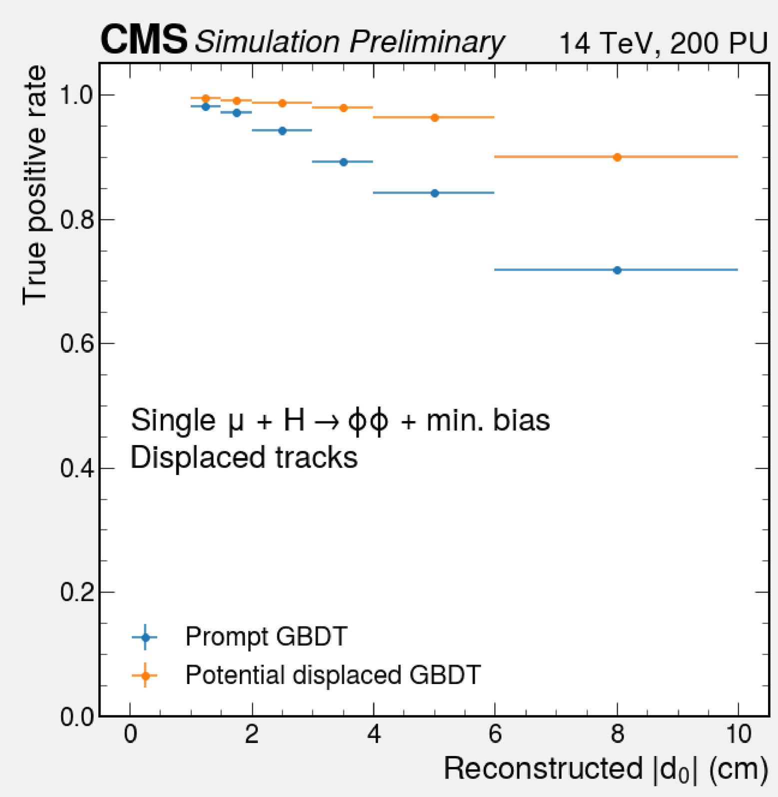


% of vertices reconstructed within 0.5 cm of the simulated vertex

Displaced Track Quality Classifier

Motivation: Displaced tracks arise from long-lived particles and have immense value for beyond standard model searches (dark matter candidates, etc.) but the prompt classifier performance degrades greatly for more displaced tracks





Potential displaced GBDT:

- 150 trees, max depth of 4
- Addition of displaced d_0 feature
- Trained on $|d_0| > 1$ cm tracks
- Sample weight $\propto d_0$

Left: Performance improvement using displaced GBDT

Right: Performance along $|d_0|$, average false positive rate = 0.15

[1] CMS Collaboration, "The Phase-2 Upgrade of the CMS Level-1 Trigger", **CERN-LHCC-2020-004 ; CMS-TDR-021**.
[2] Savard, C. "Level 1 trigger track quality machine learning models on FPGAs for the Phase 2 upgrade of the CMS experiment", Fast Machine Learning for Science Workshop 2020, **https://indi.to/WmWZm**
[3] J. Duarte *et al.*, "Fast inference of deep neural networks in FPGAs for particle physics", **JINST 13 P07027 (2018), arXiv:1804.06913**
[4] S. Summers *et al.*, "Fast inference of boosted decision trees in FPGAs for particle physics", **arXiv:2002.02534**
[5] Brown, C.E. "Track Finding and Neural Network-Based Primary Vertex Reconstruction with FPGAs for the Upgrade of the CMS Level-1 Trigger System", Connecting the Dots 2022, **https://indi.to/nwMBJ**