PROCEEDINGS OF SCIENCE

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

Claire Savard[†a,*]

[a] *University of Colorado-Boulder,*
390 UCB, Boulder, U.S.A.

E-mail: claire.savard@colorado.edu

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 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 the standard model searches requiring exact reconstruction such as analyses using missing energy.

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[†] on behalf of the CMS Collaboration
[*] Speaker

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1. Introduction

The CMS Phase-2 Level-1 Trigger will include the reconstruction of charged particle tracks which will be used by other trigger algorithms to calculate physics objects precisely, such as primary vertices. The inclusion of reconstructed tracks in the upgraded trigger increases the information capable of being used by trigger algorithms for a more rigorous event selection process. When the charged particle tracks are reconstructed, there is some non-negligible error that consequently allows some reconstruction of tracks that do not actually correspond to real particles traveling through the CMS detector [1]. These problematic tracks can decrease the performance of Level-1 Trigger algorithms using track properties as input. Thus, we developed a track quality variable that determines whether a track is a result of error in the reconstruction algorithm.

2. Level-1 Track Finder

The Phase-2 Level-1 Trigger will consist of different modules each assigned different triggering tasks. The Track Finder is one of the first modules to run and is in charge of reconstructing charged particle tracks using information collected from the CMS Outer Tracker within a 4 μs latency on FPGA-based hardware [2]. Each reconstructed track is represented by a 96-bit track word that holds information about certain properties of the track, such as its location in the detector and transverse momentum. This track information is then sent through fiber optical links to other parts of the trigger system that plan to use this information for their triggering algorithms (Figure 1).

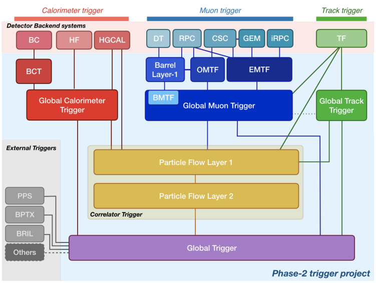

Figure 1: CMS L1 Phase-2 upgraded trigger design [2]

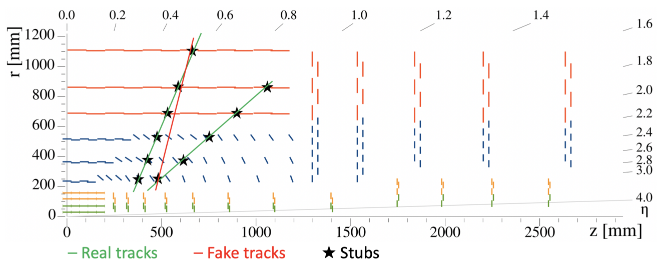

Figure 2: Stub information from the CMS Outer Tracker (blue and red modules) is used to reconstruct particle tracks [2]

3. Track Quality

After charged particle tracks are reconstructed in the Level-1 Track Finder, we want to determine whether the reconstruction was good or not. Poor reconstruction results in *fake tracks*, which are defined as tracks that do not represent a single, physical particle and are instead a result of error in the reconstruction process. *Real tracks* are therefore tracks that do represent a single, physical particle interacting with the CMS Outer Tracker. Figure 2 shows an example of real and fake tracks.

Track quality is defined as a measure of how likely a reconstructed track is real. The quality of the track is calculated using the reconstructed track properties and then added as an additional track property in the track word for further trigger algorithms to use. In general, the use of track quality to remove fake tracks is important because these troublesome tracks mask real physics occurring and cause issues when using track collections to reconstruct physics objects like primary vertices.

4. Prompt Track Quality Classifier

We developed a gradient boosted decision tree (GBDT) to calculate the quality of each reconstructed track.This classifier was chosen because it is an intuitive model that is continuous and categorical data friendly and is easy to tune. Decision trees also use simple logic which is beneficial for its implementation on the Track Finder FPGA boards. The classifier has 8 input features derived from the track properties stored in the track word. The features consist of 3 coordinates (ϕ, η, and z_0), 2 variables that describes the detector hits associated with each track (n_{stub} and $n_{misslayer}$), and 3 goodness-of-fit variables (χ^2_{bend}, χ^2_{rz}, and $\chi^2_{r\phi}$). The model only has 60 trees and a maximum depth of 3 as minimization of resource usage on the FPGA boards is a priority.

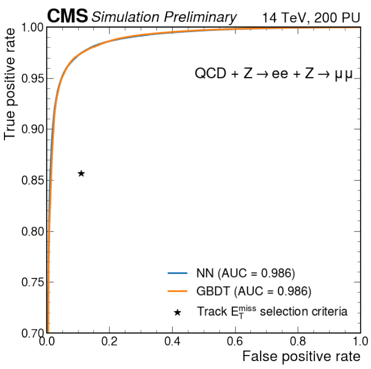

Figure 3: GBDT versus two other methods of classifying real and fake tracks

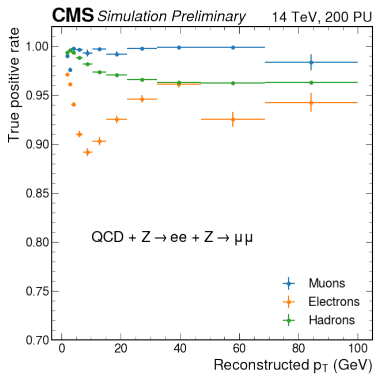

Figure 4: GBDT performance vs. reconstructed p_T for 3 particle types, false positive rate = 0.3

In Figure 3, we see that the GBDT outperforms an old selection criterion used for calculating track quality, but has about the same performance as a neural network (NN) approach that was developed. However, the GBDT was chosen over the NN because of its lower FPGA resource usage (3 clock cycle latency, 0.14% of LUT usage, and 0.027% of FF usage) estimated using the Conifer tools [3]. The GBDT performs better in general on muons and hadrons than on electrons which are harder tracks to reconstruct correctly due to their more complicated Bremsstrahlung interactions within the detector (Figure 4).

4.1 Application: Primary Vertex Reconstruction

Primary vertex reconstruction in the Global Track Trigger uses the charged particle track collection in its algorithm. When fake tracks populate the track collection, the reconstructed primary vertices become less accurate. By using the track quality variable to remove fake tracks, we can increase the primary vertex reconstruction performance compared to removing no fake tracks or if we were to remove fake tracks using an older selection criterion based only on track goodness-of-fit χ^2 variables (Figures 5, 6, and 7) [4].

5. Displaced Track Quality Classifier

Displaced tracks, i.e. tracks that do not originate from the proton-proton collision point, arise from long-lived particles and have immense value for beyond standard model searches, such as dark matter. Because the overwhelming majority of particles in CMS are not displaced (i.e. prompt), the GBDT in Section 4 focused solely on prompt tracks and does not classify displaced tracks well

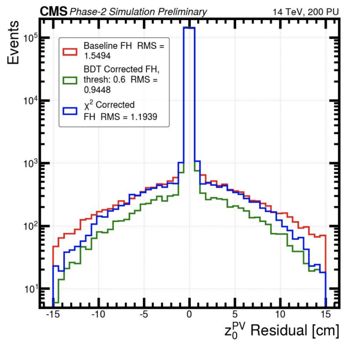

Figure 5: Difference between the reconstructed and simulated primary vertex z_0 [4]

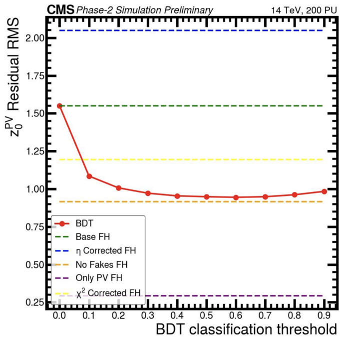

Figure 6: Root-mean square of the z_0^{PV} residual [4]

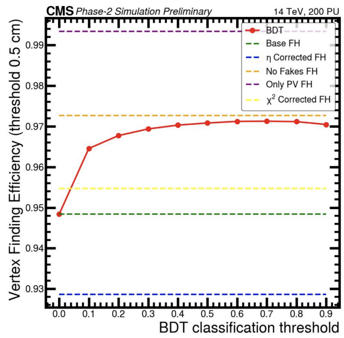

Figure 7: Vertex reconstruction efficiency within 0.5 cm of the simulated vertex [4]

(Figures 8 and 9). To increase the performance on displaced tracks, we developed a preliminary GBDT with 150 trees and a maximum depth of 4 that is only trained on displaced tracks. This GBDT has the same features as the classifier in Section 4 with the addition of a displacement variable d_0. Initial results show great improvement using a displaced-specific classifier.

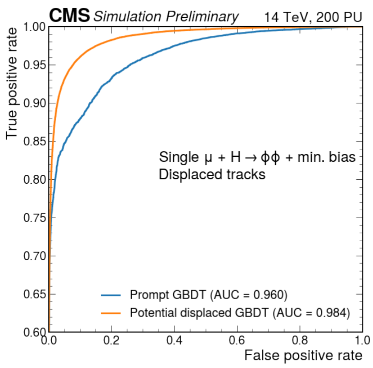

Figure 8: Performance improvement classifying displaced tracks using a displaced-specific GBDT

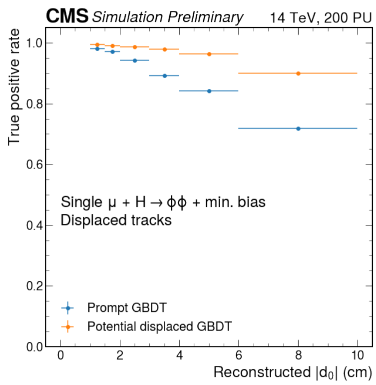

Figure 9: Performance of displaced-specific GBDT along d_0 with an average false positive rate = 0.15

6. Conclusion

In summary, the GBDT developed for determining the quality of the Level-1 Track Finder tracks outperforms an older method and has been shown to improve the reconstruction of primary vertices. Another GBDT specifically for displaced tracks has merit in long-lived particle analyses and is seen to improve performance greatly over its prompt counterpart.

References

[1] CMS Collaboration, “The CMS experiment at the CERN LHC”, JINST 3 S08004 (2008), doi:10.1088/1748-0221/3/08/S08004

[2] CMS Collaboration, “The Phase-2 Upgrade of the CMS Level-1 Trigger”, CERN-LHCC-2020-004 ; CMS-TDR-021.

[3] S. Summers et al., “Fast inference of boosted decision trees in FPGAs for particle physics”, JINST 15 P05026 (2020)

[4] Brown, C.E. “Track Finding and Neural Network-Based Primary Vertex Reconstruction with FPGAs for the Upgrade of the CMS Level-1 Trigger System”, CMS-CR-2022-100