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Displaced Vertex Track Trigger for the CMS Phase-2 Upgrade

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Abstract

As part of the CMS Phase-2 upgrade, track information from the outer tracker will be available at the Level-1 trigger and with this comes the expanded opportunity to trigger on physics objects such as long-lived particles. Presented here is a feasibility study in calculating displaced vertex information using an extended version of the Level-1 tracking that identifies displaced tracks. Combinations of tracks are used to form vertex candidates and a gradient-boosted decision tree is used to distinguish between misidentified and genuine displaced vertices. A simulated sample of an exotic Higgs boson decay to dark photons is used as the benchmark signal. Using this method, vertices with transverse distances from the beamline ranging from 0.02 to 20.0 cm can be reconstructed. This study is based on simulation only and therefore does not account for hardware limitations.

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Displaced Vertex Track Trigger for the CMS Phase-2 Level-1 Trigger Upgrade

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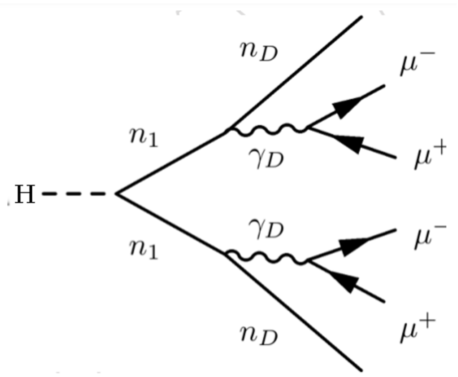

Figure 1: Dark photon pair production in four-muon channel. The Higgs boson decays to neutralinos, denoted by n_1, which have a mass of 50 GeV. These further decay into dark photons, γ_D,and dark neutralinos, n_D, with masses of 20 GeV, and 1 GeV, respectively. The dark photon lifetime is 1 cm.

1. Introduction

Once the High-Luminosity LHC (HL-LHC) begins operations in 2030, an average of 200 simultaneous proton-proton interactions will occur in the CMS detector [1] [2] every 25ns. CMS employs a two-tier trigger system to select events and bring the rate of events down to a level that can be stored. The first tier of the trigger system, the Level-1 Trigger (L1T), will have a new addition during the HL-LHC era, namely track information describing the trajectory of charged particles traversing the silicon tracker. Intersections of these tracks at a point far from the primary interaction vertex can indicate the presence of "secondary vertices" that arise from the decays of long-lived particles (LLPs) like those predicted by many beyond-Standard Model theories [3]. In these proceedings, a feasibility study [4] using track information to trigger on LLPs producing displaced vertices as part of the L1T is presented.

2. Algorithm description and performance

The displaced vertexing algorithm is intentionally kept simple to allow it to meet the timing and resource constraints of the L1T. Tracks that pass quality and kinematic cuts are selected and then checked pairwise for intersections in the plane transverse to the beam direction. Several kinematic quantities, such as the vertex displacement and momentum direction, are calculated for each intersection, which then constitute the input to a gradient-boosted decision tree (GBDT), which assigns to each intersection a probability of being genuine. The event passes the trigger if any intersection scores above a predetermined cutoff value.

2.1 Track preselection

For this study, several samples are used to determine general track selections for a wide range of potential signal models. A dark photon model [5] of an exotic Higgs boson decay, $H \to \gamma_D\gamma_D \to 4\mu$, depicted in Figure 1, is used as the signal benchmark. A displaced muon sample with a flat distribution of track transverse momentum, p_T, and transverse displacement is used to provide a set of high-quality displaced tracks. A minimum bias sample containing an

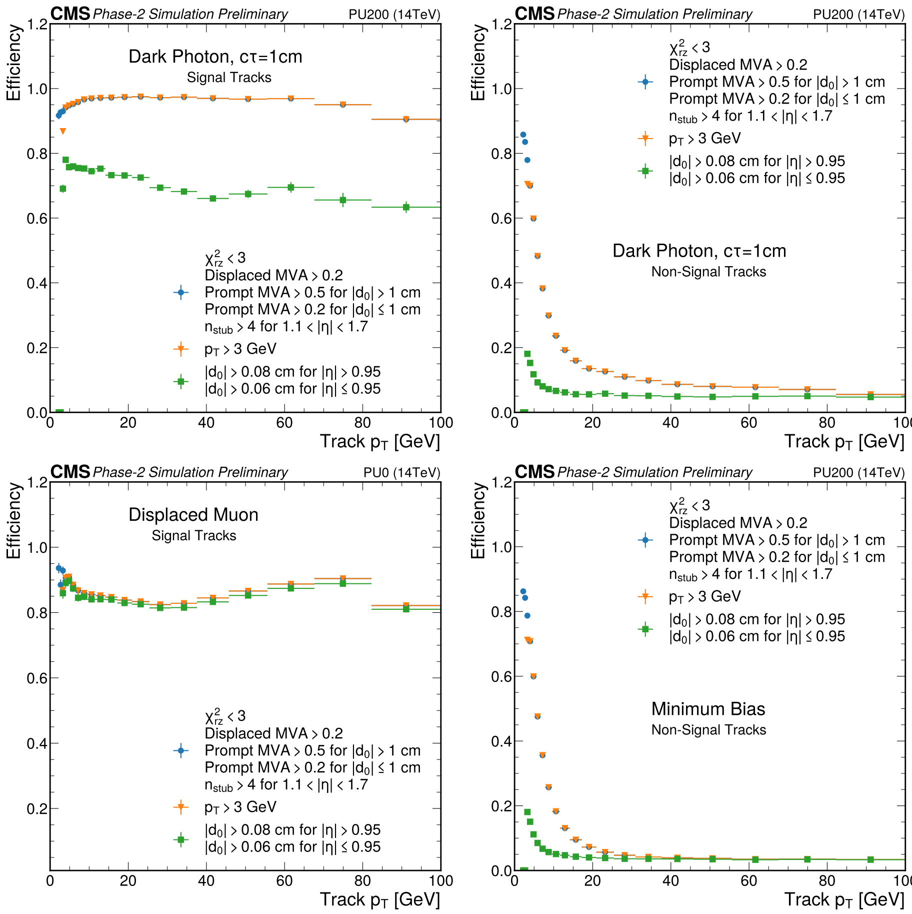

Figure 2: Track cutflow efficiencies for signal (left) and non-signal (right) tracks after quality and kinematic cuts [6]. n_{stub} denotes the number of "stubs" [7], correlated pairs of hits, in the silicon tracker while "Displaced MVA" and "Prompt MVA" refer to two BDTs trained to distinguish misidentified from genuine tracks for displaced and prompt tracks, respectively.

average of 200 pileup (PU) interactions is used to simulate background events. Dark photon tracks associated with a truth level μ^+ or μ^- from the dark photon decay are considered signal tracks and all others are non-signal. All displaced muon tracks are considered signal tracks and all minimum bias tracks are non-signal. Many of the track quality variables are summarized into a single score by a dedicated track quality GBDT, but a cut on χ^2_{rz}, the goodness-of-fit in the r-z plane, and removing tracks with few hits in the tracker in the overlap region between barrel and disk serve to further reduce the amount of fake tracks. The track transverse impact parameter, d_0, and p_T have good separation of signal and background but the cut values are kept loose to keep the selection general. Cutflow efficiencies for these samples are shown in Figure 2.

2.2 Vertex calculation

Tracks that pass the selection are considered pairwise in order of descending p_T. For each pair, the helical tracks are projected as circles in the transverse plane and checked for intersections. In the case of two intersections, if only one lies within the trajectory of both tracks, it is chosen.

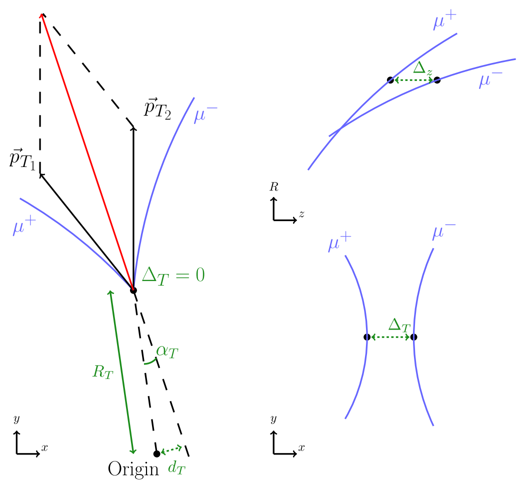

Figure 3: Vertex parameters calculated for each selected intersection between tracks.

Otherwise, the intersection where the tracks are closest in the beam direction, z, is chosen. The following vertex parameters [8], illustrated by Figure 3, are then calculated for the intersection: the transverse distance of the vertex from the beamline, R_T; the angle between the parent particle's momentum vector and the position vector of the vertex, α_T, and its cosine, $\cos\alpha_T$; the impact parameter of the parent particle, d_T; the distance in z between tracks at the vertex, Δz; and the distance in the transverse plane between tracks at the vertex, Δ_T (which for now is always zero as only direct intersections are considered).

2.3 GBDT training and structure

Using the xgboost library [9], a GBDT consisting of 150 trees of depth 4 was trained on half the genuine displaced vertices from 23,538 dark photon events and half the misidentified displaced vertices from 195,950 minimum bias events. The second half of the vertices from both samples were used to test the model. The input features include the vertex parameters previously defined and the following track features: p_T; d_0; track momentum polar and azimuthal angles, ϕ and η; z-coordinate at point of closest approach, z_0; track goodness-of-fit parameters, χ^2_{bend} and χ^2_{rz}; displaced MVA score; and prompt MVA score. After training, the area under the curve of the ROC curve was calculated to be 0.738 and the performance is shown in Figure 4.

2.4 Algorithm performance

To define the working points for this algorithm, a series of increasingly tight cuts are applied to the vertex candidates from each event. If one or more vertices pass the cuts, the event is considered triggered on. The background rate and signal efficiency after each cut can be seen in Figure 5. Four working points for the GBDT score are proposed: a tight cut of >0.994, which has a 20% signal efficiency and zero misidentification rate, a medium cut of >0.95 with a 41% signal efficiency and 0.1 kHz background rate, a loose cut of >0.9, which has a 47% signal efficiency and 1.6 kHz background rate, and a very loose cut of >0.72, which has a 57% signal efficiency and 10 kHz background rate. At each working point, the percentage of truth-level vertices that are matched to reconstructed vertices is computed and the results are compiled in Figure 6.

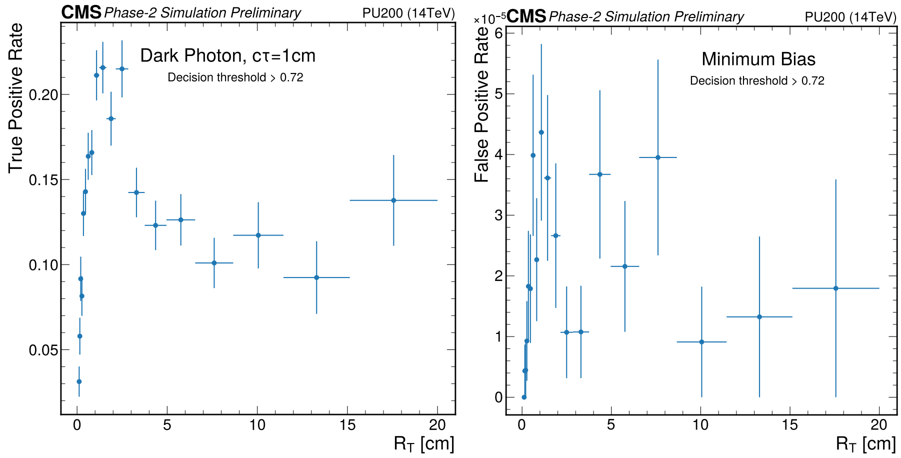

Figure 4: True positive rate and false positive rate versus vertex displacement at a cutoff of 0.72 on output score.

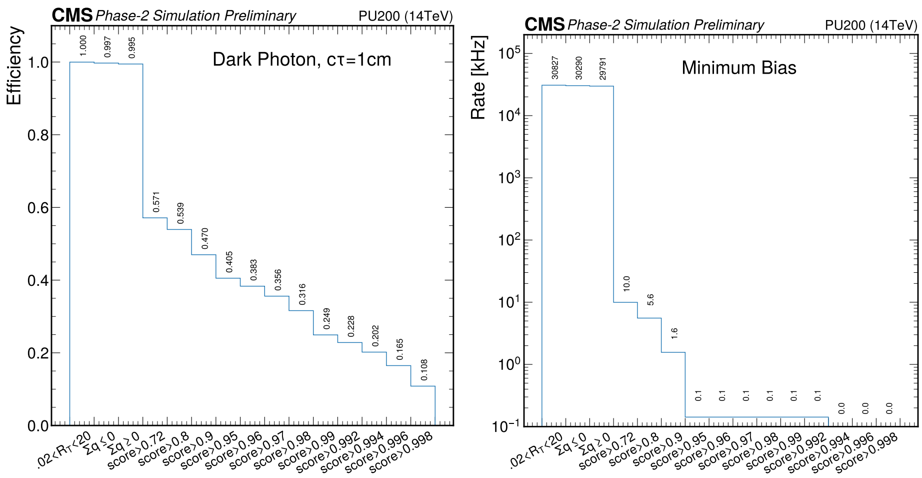

Figure 5: Percentage of events triggered for a dark photon sample (left) and the corresponding background trigger rate for the minimum bias sample (right). Going left to right, each cut on the horizontal axis is applied cumulatively. Σq is the sum of charges of both tracks associated to a vertex, so requiring $\Sigma q = 0$ is equivalent to requiring the tracks be oppositely charged. The background rate is determined by multiplying the misidentification rate in the 200 PU minimum bias sample by the number of bunches, 2760, and the revolution frequency, 11246 Hz.

3. Summary

Using only L1T track information and a simple intersection finding algorithm, displaced vertices up to 20 cm away from the beamline can be reconstructed. A signal efficiency of 57% for a dark photon sample is achieved with 10 kHz of background. A lightweight GBDT is able to effectively distinguish between genuine and misidentified displaced vertices to keep the background to acceptable levels. Future work will be done to see the effects of digitization on GBDT performance and to recreate this algorithm in firmware for a field-programmable gate array.

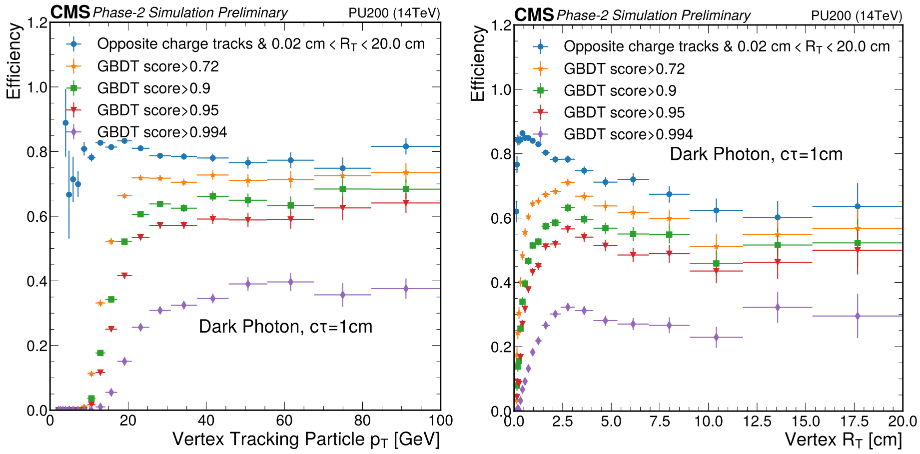

Figure 6: Fraction of true vertices matched to a track vertex as a function of the highest-p_T truth-level particle associated with the true vertex (left) and the vertex transverse displacement (right).

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