Track-Based Triggers for Exotic Signatures

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**ABSTRACT:** Standard triggers at the Large Hadron Collider are designed to select events with high momentum Standard Model particles which originate from the proton-proton collision of interest. However, several Beyond the Standard Model scenarios predict signatures with displaced or extremely low momentum charged particles, and pose significant challenges for LHC triggers. This article presents a study of track-based triggers for long-lived particles and other unconventional exotic signatures at the upcoming High Luminosity LHC. Representative scenarios studied include soft-unclustered-energy-patterns resulting in large multiplicities of low momentum tracks, a GMSB Supersymmetry scenario with long-lived staus resulting in displaced leptons or anomalous prompt tracks, and a higgs portal scenario with long-lived scalars resulting in displaced hadronic tracks. Trigger efficiency is measured as a function of the baseline parameters of a track trigger, including transverse momentum and impact parameters. Recommendations for future hardware-based track triggers are presented.
1 Introduction

Many models of new physics predict unconventional track signatures at high energy colliders that could be observed by the general purpose detectors, ATLAS and CMS. For example, long-lived particles have a proper lifetime such that they travel a measurable distance before decaying, resulting in displaced, or anomalous prompt track signatures \cite{1}. Another scenario of interest includes models with a strongly coupled hidden valley, which can result in large multiplicities of soft charged particles \cite{2}. These unconventional signatures pose challenges for offline and trigger level data reconstruction.

Most Beyond the Standard Model (BSM) scenarios lead to jets, photons, or leptons originating from the collision point. These prompt signatures are easily identified in the first, hardware-based, stage of the trigger using a combination of calorimeter and muon spectrometer signals. Limited tracking information is only available at later stages in the trigger decision. This strategy is also sufficient to identify signatures characterised by high missing transverse momentum.
Unfortunately, standard triggers often result in low trigger efficiency for unconventional BSM signatures. If a BSM particle decays at a distance and produces jets or leptons, the decay products will not point back to the collision. Decay products can be mis-identified as pile-up or not identified at all if they do not pass standard quality criteria. If the particle travels a long distance before decaying, its interactions with the detector may look unlike those of a Standard Model particle, and the trigger may not identify this anomalous signature or select the event. Models with many soft charged particles often do not lead to an easily identifiable calorimeter or muon spectrometer signature.

When searching for these unconventional signatures, the most distinctive feature of the BSM event will be in the tracker. If track triggers can be developed that are fast enough to use on entire events at a high rate, they will provide a unique opportunity to trigger directly on these challenging signatures.

1.1 Current state of track triggering

The ability to use tracking in triggering decisions is limited by several factors. In ATLAS and CMS, tracking has only been used in the high-level trigger (HLT). In these cases, track reconstruction is performed in software, and the main limitation is the amount of CPU required to form tracks given the HLT latency. Because of this, fast algorithms are used, which often cover only small regions of the detectors, which are chosen based on signatures from calorimeter or muon systems. Full detector tracking is possible at a reduced rate, but typically with fast versions of tracking algorithms that are less efficient across wide ranges of track transverse momentum, $p_T$, and transverse impact parameter, $d_0$. A tracker participating in the Level 1 trigger (L1) decision would need to be implemented in hardware, and would be further limited by detector readout rates, the hardware-based tracking technology used, and output rate and latency constraints of the L1 system.

For the High Luminosity LHC (HL-LHC), both ATLAS and CMS plan to install new tracking detectors, and incorporate more tracking information into the trigger [3][4]. The possible coverage of a tracker depends on specific tracking algorithms. In general, increasing the maximum curvature, displacement, or target efficiency of a tracker increases complexity, rate, latency, or a combination of these. Put another way, in order to maintain a constant latency but extend its $d_0$ range, a tracker could increase its $p_T$ threshold or decrease its target efficiency. Depending on the tracker design, it may be possible to alter these requirements independently for prompt and displaced tracks, leaving a highly efficient prompt tracker with a low $p_T$ threshold, while also exploring a large range of displacements.

1.2 Expanding track triggering for future experiments

There has been a recent proliferation of studies on the efficacy of track-based triggers for long-lived particles and other exotic signatures, including rare Higgs decays [5], soft-unclustered-energy patterns (SUEPs) [2], and generic displaced signatures [6]. On ATLAS, it was demonstrated that a hardware-based track finder algorithm could extend its range to
include moderately displaced tracks [7]. However, because the signatures of these models are so varied, it is challenging to translate individual studies into an optimal design for a future trigger. In particular, for a realistic rate- and latency-limited trigger, it is unclear which efficiency trade-offs are most beneficial: is it better to expand $d_0$ coverage, reduce $p_T$ thresholds, or maximize overall tracking efficiency?

The answer to this question depends on the design of the trigger being considered, but it also depends on what kind of exotic signatures are being targeted. For hadronic decays, low $p_T$ thresholds are important, but high efficiency may not be needed. For leptonic decays the reverse is true.

The goal of this study is to provide a parameterization of trigger efficiencies for a variety of representative models, to be used as a guide for future trigger design. Specific tracking algorithms will not be discussed, but instead overall efficiency will be provided for a range of models as a function of several basic tracker coverage parameters.

2 Performance for benchmark models

Three Beyond the Standard Model scenarios are chosen in this work to represent several differing extreme cases of unconventional signatures (Figure 1): soft-unclustered-energy-patterns (SUEPs), long-lived scalars coupling to the Higgs boson, and the direct production of supersymmetric staus in a gauge-mediated symmetry breaking scenario.

The SUEP model explores one of the possible experimental signatures arising from a hidden valley with a dark SU(N) sector [2, 8]. The hidden valley is connected to the SM by a mediator whose mass is much greater than the mass splittings amongst the dark sector particles. Energy from the production of the mediator is distributed amongst a large multiplicity of these lighter particles. These light states could decay back to Standard Model particles either promptly or in a displaced way. The 't Hooft gauge coupling of the dark sector determines the emission angle of partons during showering. In the case that this coupling is large, the event energy will be distributed roughly equally among a large number.

Figure 1: Feynman diagrams for benchmark processes. From left to right: SUEPs, the Higgs portal, and long-lived staus.
of partons which in turn will be essentially isotropic. The model used here assumes large \( t \) Hooft coupling and prompt decay of the dark mesons to Standard Model particles. This creates a final state characterised by a high multiplicity of very low momentum charged particles, posing a unique triggering challenge and difficult to distinguish from pile-up unless the many soft tracks can be reconstructed.

The model which will be referred to generically as a “Higgs portal” in this paper explores the well-motivated possibility that the SM Higgs boson acts as a mediator to a hidden sector through mixing with a new neutral scalar \([9, 10, 11]\). If the only available decay channel for the dark scalar is via its (small) mixing with the Higgs, this process will be suppressed and the scalar will travel a macroscopic distance before decaying. The branching ratio for the decay of dark scalars follows those of the Higgs, restricted by their mass. The specific model implemented here introduces a dark U(1) gauge group with a dark Higgs potential, leading to a total of two new particles, but of which only the scalar is considered in practice. This model provides a good benchmark for a wide variety of Higgs portal scenarios, which will be a high priority target for the HL-LHC. The physical signature of this model is groups of displaced tracks arising from decay of the long-lived scalars into SM particles. These tracks generally have low \( p_T \) and while the kinematics arising from the multi-step decay are often quite complex, the light mass of the scalar means the tracks tend also to have modest impact parameters even when the scalar decays at quite a high radius.

The third model is direct production of staus in a gauge-mediated supersymmetry breaking (GMSB) SUSY model \([12, 13, 14]\). While some GMSB slepton models take the three sleptons to be mass-degenerate, here the stau alone is taken to be the next-to-lightest supersymmetric particle (NLSP). The gravitino is the lightest supersymmetric particle in GMSB models, with a negligible mass. The stau decays to a tau and a gravitino via a very small gravitational coupling, thereby gaining a significant lifetime. With the gravitino escaping undetected, this leaves the long-lived stau and a displaced tau to produce the visible signature. This model provides a useful benchmark for two key long-lived particle detection techniques: identification of anomalous prompt tracks in scenarios where sufficiently long lifetimes such that the stau can be directly detected, and reconstruction of displaced tracks from the decay of the tau in scenarios with a shorter stau lifetime. The displaced tracks from the tau decays in this second scenario tend to have a larger impact parameter than those in the Higgs portal model.

### 2.1 Simulation

All signals are generated assuming proton-proton collisions at a center of mass energy of \( \sqrt{s} = 14 \text{ TeV} \). The final state simulation is at truth level: particles considered for analysis are stable decay products of short-lived BSM or Standard Model particles with no simulation of detector or material interactions. Pile-up is not included in these samples.

SUEP events were generated in \textsc{Pythia8} using the custom plugin available alongside Ref. [2]. Events were generated with a range of scalar mediator masses: 125 GeV (that is, matching the Standard Model Higgs boson) and then 200 GeV to 1000 GeV in 200 GeV
intervals. The SUEP shower was assumed to have a temperature of 1 GeV and consisted of a large multiplicity of dark mesons with a mass of 1 GeV. Each dark meson was decayed, promptly, to a pair of light quarks, $d\bar{d}$.

A grid of Higgs portal events was generated using MadGraph5_aMC@NLO 2.9.3 and the SM + Dark Vector + Dark Higgs model described in Refs. [15, 16]. The Higgs mixing parameter was taken to be $1 \times 10^{-4}$ and the kinetic mixing parameter to be $1 \times 10^{-10}$. The dark Z mass is set to 1 TeV, essentially decoupling it. Thus in the generated scenario, there is only one relevant new particle, the dark scalar, and it decays only into Standard Model particles. The properties of the dark scalar were varied across the mass range $m_s = 5, 8, 15, 25, 40, \text{ and } 55 \text{ GeV}$ and lifetime range 0.01, 0.1, and 1 ns. Its branching ratios follow those of the Higgs, such that the scalars decay predominantly to $c\bar{c}$ and $\tau\bar{\tau}$ for $m_s = 5$ and 8 GeV and predominantly to $b\bar{b}$ for heavier $m_s$.

Long-lived GMSB staus are similarly generated and decayed with MadGraph5_aMC@NLO 2.9.3. A simplified model is used wherein the left-handed and right-handed staus are assumed to be mass-degenerate and have a mixing angle $\sin \theta = 0.95$ [17]. The gravitino is given a negligible mass of 1 GeV. Stau samples are generated for masses $m_{\tilde{\tau}} = 100, 200, 300, 400, 500, \text{ and } 600 \text{ GeV}$ and lifetimes 0.001, 0.01, 0.1, and 1 ns. Additionally, some heavy stau samples are generated with 10 ns and infinite lifetimes. These longer lifetime staus provide a sample of heavy stable charged particles whose tracks originate from the interaction point and can be directly reconstructed, and are studied separately from the staus with shorter lifetimes, which instead provide a sample of displaced tracks. The charged final state particles available for tracking in the sample of staus with finite lifetimes arise from tau decays and are therefore predominantly pions with a significant contribution from electrons and muons.

### 2.2 Analysis strategy

A common strategy is used for understanding the acceptance and efficiency of possible trigger selections for each model. First, baseline tracking criteria are defined based on potential detector specifications (e.g. $\eta$ coverage, radius of tracker) and only stable charged particles falling within these acceptance criteria are considered to be reconstructable. This geometric acceptance is independent of what could then be defined by a trigger selection and simply asks whether particles could be reconstructed by an offline tracking algorithm with the specified detector layout. Certain effects of adjusting the detector layout are explored for the heavy stable charged particle signature; for the other models these requirements are set once and kept fixed. The acceptance for a signal point is then the fraction of events with at least $n$ particles in the final state that meet the tracking criteria, where $n$ is also model dependent. For displaced signatures studying a $d_0$ threshold, only tracks with $d_0 > 1$ mm are counted in the acceptance criteria. This is to separate tracks which would be likely picked up by a prompt track reconstruction algorithm from those which would truly require a displaced tracking algorithm, and allows the efficiency of the displaced track trigger to be defined only relative to the events it is required to identify without prompt tracks.
Efficiency is then defined to capture the effects of track reconstruction criteria which could be set at the trigger level rather than enforced by the physical detector. The two most important criteria studied are the minimum $p_T$ and maximum $d_0$ of tracks which would be reconstructed at the trigger level. These factors have different effects in different BSM models, depending on whether the final state tracks are prompt or displaced, what the average decay angles of long-lived particles may be, and how much momentum the final state particles carry. To study the interplay of these effects, for a fixed acceptance, the $p_T$ and $d_0$ thresholds are varied and the fraction of surviving tracks measured. An event level efficiency is then defined, as for the acceptance, based on whether at least $n$ particles in the final state pass these thresholds.

In realistic tracking detectors, although the reconstruction efficiency for isolated tracks is very close to 1 for any track $p_T$, the efficiency even in offline algorithms tends to decrease with increasing $d_0$ [18]. To emulate this effect in the following studies, the likelihood of reconstructing a given track is set not as a binary by the $d_0$ threshold (e.g. all tracks up to $d_0 = 5$ mm are reconstructed; all above 5 mm are not reconstructed) but instead as a linearly decreasing function. The likelihood of reconstructing the track begins at unity for $d_0 = 1$ mm, where the displaced tracking algorithm is expected to begin, and decreases linearly with increasing $d_0$ until it reaches zero at the specified $d_0$ threshold.

Trigger selections in the following sections are designed such that negligible background contributions are expected in most cases. The one exception is the SUEP trigger, where background rates have not been studied but could be non-negligible due to the high pileup expected at the HL-LHC.

2.3 SUEPs

Soft-unclustered energy patterns are characterized by events with large multiplicities of diffusely distributed low momentum charged particles. Because final state particles are not collimated like Standard Model jets, and events often lack high momentum leptons or photons, SUEPs pose extreme challenges for the trigger.

Figure 2a shows charged particle transverse momenta for the benchmark models under consideration. Final state particles are spherically distributed in the mediator’s rest frame, with a momentum spectra described by a Maxwell Boltzman distribution determined by the dark meson mass, $m_{\pi_d}$ and temperature, $T$. Unlike most BSM scenarios, the $p_T$ spectrum does not depend on the mediator mass. Instead, all distributions in Figure 2a are similar in shape and all peak very sharply in the lowest $p_T$ bin.

The number of final state particles depends on mass of the scalar mediator and dark meson mass, $N \sim m_S/m_{\pi_d}$ (see Figure 2b). For a fixed mediator and dark meson mass, increasing the temperature reduces the number of final state particles and increases their mean momenta, as described in Ref. [19].

Dark mesons may decay to a variety of final state Standard Model particles. Possible decay modes include pairs of leptons, hadrons, photons, light or heavy flavor quarks. Decay
product may be also be displaced, or the final state may also include undetected dark matter particles.

For simplicity, this study focuses on prompt dark meson decays to light quarks, $d\bar{d}$, and counts the number of stable charged particles above a given $p_T$ threshold in pseudorapidity $|\eta| < 2.5$. It is assumed that the track-trigger would have sufficient longitudinal impact parameter resolution to associate tracks to the correct primary vertex, and neutral final state particles are neglected.

All tracks from SUEP decays in the model used here are prompt, and therefore the selection is relatively straightforward. Table 1 summarises the object-level acceptance and efficiency definitions used in the study of SUEPs. As for all models in this paper, only charged and stable particles are considered by this selection. Tracks within $|\eta| < 2.5$ are considered to be within the detector acceptance. The event level efficiency is 100% for SUEPs since in all cases there are many tracks meeting this acceptance requirement. The efficiency is defined as the fraction of events where at least $n_{\text{tracks}}$ tracks passing the acceptance requirement are reconstructed above the specified $p_T$ threshold.

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Table 1: Acceptance and efficiency requirements for a trigger on a high multiplicity of soft tracks

A prospective trigger would then rely on distinguishing an anomalously large number of soft
tracks to select SUEP events, where the key factor would be the $p_T$ threshold at which track reconstruction begins. For SUEP signatures, signal to background discrimination decreases with increasing track $p_T$ requirements. This study investigates a range of $p_T$ thresholds, ranging from $0.5 < p_T < 2$ GeV. The lowest threshold represents the minimum charged particle $p_T$ in most standard offline track reconstruction algorithms, aimed at charged particles that traverse a sufficient number of tracking detector layers [20, 21]. The highest $p_T$ threshold examined, $p_T = 2$ GeV, is based on the minimum L1 tracking threshold of 2 to 3 GeV estimated by CMS for their Phase 2 trigger upgrade [4]. Above $p_T = 2$ GeV, counting the $n_{\text{Tracks}}$ is no longer expected to be a powerful discriminator. See Figure 3 for number of reconstructed tracks in SUEP events above different track $p_T$ thresholds.

Figure 3: Number of events where at least $x$ charged particles pass the specified track $p_T$ threshold, for mediators of mass 200 GeV (a) and 800 GeV (b) out of 10,000 generated events.

Efficiencies for all simulated mediator masses are shown as a function of minimum $n_{\text{Tracks}}$ for the three tested minimum $p_T$ thresholds in Figure 4. The efficiency increases with mediator mass: although the track $p_T$ distribution, and therefore fraction of tracks passing the $p_T$ threshold, does not depend on mediator mass, the larger number of tracks in the case of a heavy mediator means a sufficient number are reconstructed more frequently. With a track reconstruction threshold of $p_T > 0.5$ GeV, efficiencies of 50% could be reached for all mediators over 200 GeV with a $n_{\text{Tracks}} > 100$ trigger, or all mediators over 400 GeV with a $n_{\text{Tracks}} > 150$ trigger. If the track reconstruction threshold increases to 1 GeV, 50% efficiency is only possible for masses over $\sim 600$ GeV, and with a reconstruction threshold of $p_T > 2$ GeV, there is negligible efficiency for all signals with any $n_{\text{Tracks}}$ threshold. For triggering on SUEPs, then, the most important parameter is the track $p_T$ threshold, and this must be kept as low as possible.

For a CMS-like tracker, where $p_T > 2$ GeV is the baseline, a trigger requiring a large track multiplicity is inefficient for most SUEP signal models. Other possible metrics for a SUEP trigger should be investigated, such as the scalar sum of jet energy, the scalar sum of track $p_T$ ($H_T$, shown in Figure 5), or event shapes such as isotropy or sphericity. At the LHC,
(a) Minimum track $p_T = 500$ MeV

(b) Minimum track $p_T = 1$ GeV

(c) Minimum track $p_T = 2$ GeV

Figure 4: Efficiency, defined as number of events for which at least $n_{\text{Tracks}}$ charged particle tracks within $\eta < 2.5$ pass the track reconstruction $p_T$ threshold, as a function of mediator mass for minimum track $p_T$ of 500 MeV (a), 1 GeV (b), and 2 GeV (c).

SUEP final state charged particles are expected to be isotropically distributed in $\phi$, but localized in $\eta$, resulting in a “belt of fire” the shape of which has been shown to be an efficient discriminator at HLT level [2]. The most optimal trigger available to the LHC experiments will likely use $H_T$ or event shape in combination with the number of reconstructed tracks.
2.4 Long-lived staus

Staus are electromagnetically charged, so they can be directly detected for large lifetimes, or identified via their decay products. The current most comprehensive limits are from the OPAL Experiment, which exclude staus less than about 90 GeV for all possible lifetimes [22]. Several LHC searches extend beyond that sensitivity, with searches for highly ionizing particles, disappearing tracks, and displaced leptons, but these searches are all trigger limited, and do not comprehensively cover the full lifetime space.

2.4.1 Displaced leptons

For lifetimes less than around 1 ns, long-lived staus can most easily be identified by their displaced decay products. In the GMSB model simulated, where the light gravitino does not interact with the detector, the only visible signature of the stau decays are the displaced taus that emerge from them. In the case of pair-produced staus, two taus are present in the final state, each the only visible product of its own displaced vertex. The taus then decay via their typical branching ratios, depicted in Figure 6. While relatively rare, the fully-leptonic scenario produces the distinctive signature of a pair of displaced, but otherwise high-quality leptons, and is thus the easiest to target from the reconstruction perspective. The fully leptonic decay mode is the only scenario that has currently been explored, with Run 2 results from both ATLAS [17] and CMS [23]. Triggering in these cases is also the most straightforward: photon triggers can be used to recover displaced electrons, and the relatively clean environment of the muon spectrometer allow for triggers without impact parameter requirements. In Run 2, both leptons were required to pass a relatively high $p_T$ threshold, upwards of 40 GeV. Because each lepton carries approximately 1/6 of the parent stau’s energy, these thresholds are prohibitively high for the identification of low-mass staus.

Figure 5: $H_T$ of charged particles passing the specified track $p_T$ threshold, for mediators of mass 200 GeV (a) and 800 GeV (b) out of 10,000 generated events.
Figure 6: Branching fraction of single taus (left) and pairs of taus (right). Left, labels indicate decays containing electrons ($e$), muons ($\mu$), and hadronic decays with one and three charged particles. Right, the leptonic and hadronic decays are grouped as $l$ and $h$ respectively.

Hadronic decays of these taus are harder to identify, requiring the adaptation of the already complex algorithms that are used for the identification of prompt taus. Approximately 15% of taus decay to multiple charged particles, and in this unique case, a visible displaced vertex is present. The remaining 50% of taus decay hadronically to a single charged particle. The total reconstructed energy fraction in these cases is larger than that of the leptonic decays due to the presence of only one neutrino, but this is due to the use of the calorimeter to measure neutral hadrons in the decay. The tracks themselves carry a smaller fraction of the overall energy.

In all scenarios, at least two displaced tracks are produced. For staus with masses larger than 100 GeV, these tracks typically have $p_T$ values well above the minimum thresholds for potential trackers. In this section, a baseline acceptance is used, described in Table 2. Events are considered to pass acceptance if they contain 2 tracks passing all the requirements. The resulting acceptance, for a range of masses and lifetimes, can be seen in Figure 7.

On top of this acceptance, efficiencies are defined based on requirements on individual tracks, and events are defined to have passed if at least two tracks in the event match these requirements. A range of minimum $p_T$ thresholds are explored, shown in Figure 8, which in this scenario have a minimal impact on overall efficiency, especially for higher masses. For the nominal CMS plan of a minimum $p_T$ of 2 GeV, there is no significant reduction of efficiency compared to lower values.

The event-level efficiency for this model is much more sensitive to changes in the track $d_0$ requirements. In this study, two parameterizations of efficiency are compared: a binary model in which all tracks with $d_0$ less than a given value were assumed to be identified, and a more realistic model in which a 100% identification efficiency was defined for prompt tracks, which fell off linearly until it reached zero at a tunable value. The two scenarios are compared in Figure 9, which shows event-level efficiency in both cases for a range of stau lifetimes. Though the binary model results in a higher efficiency, by definition, the
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**Table 2**: Details of the acceptance and efficiency definitions for displaced leptons. The $L_{x,y}$ parameter refers to the maximum production radius, while the $L$ variable refers the minimum length of the track.

**Figure 7**: Acceptance for displaced lepton signature requiring at least two tracks and passing the requirements listed in Table 2.

difference is modest ($< 30\%$) for most lifetimes.

Using this sloped $d_0$ parameterization, Figure 10 shows the efficiency to identify staus as a function of their mass and lifetime for a variety of endpoints. For endpoints less than 2 cm, efficiencies are small across the plane, but with endpoints at 10 cm (closer to typical offline efficiencies) efficiencies are high for the full range of lifetimes for which the displaced signature makes sense.
Figure 8: Efficiency as a function of stau mass for a range of minimum track $p_T$ values. Events are defined to have passed if they contain two tracks with a $p_T$ value larger than the minimum value, as well as a $d_0$ larger than 1 mm and smaller than 100 mm. The proper lifetime is $\tau = 0.1$ ns.

Figure 9: Event-level efficiency as a function of stau lifetime for a $m = 100$ GeV stau. Left is the case in which a binary efficiency is used, and tracks are assumed to be identified if their $d_0$ is less than a fixed value. Right, a parameterized version is used, in which prompt tracks have a 100% probability of being identified, which decreases linearly to zero up to a tunable endpoint. In both cases, a minimum track $p_T$ of 0.5 GeV and a minimum track $d_0$ of 1 mm are required.
Figure 10: Efficiencies for the stau decay model for a variety of minimum track $d_0$ values: 10 mm (top left), 20 mm (top right), 50 mm (bottom left), 100 mm (bottom right). Across a wide range of masses and lifetimes, efficiency increases as the minimum $d_0$. In all cases, a parameterized $d_0$ efficiency is used with an endpoint at 50 mm. In all cases, the five-track selection is used. (Top left) Efficiency as a function of stau mass and lifetime for a minimum $d_0$ of 10 mm and a $p_T$ of 2.0 GeV. (Top right) Efficiency as a function of stau mass and lifetime for a minimum $d_0$ of 20 mm and a $p_T$ of 2.0 GeV. (Bottom left) Efficiency as a function of stau mass and lifetime for a minimum $d_0$ of 50 mm and a $p_T$ of 2.0 GeV. (Bottom right) Efficiency as a function of stau mass and lifetime for a minimum $d_0$ of 100 mm and a $p_T$ of 2.0 GeV.
2.4.2 Direct detection

For long-lived staus with proper lifetimes of $\tau \geq 1$ ns, the charged stau will traverse a sufficient number of tracker layers such that its trajectory can be directly reconstructed as a prompt, high momentum, and isolated track. However, the stau will be slowly moving and highly ionizing with respect to the Standard Model charged particles produced at the LHC. Most Standard Model charged particles have mass $m < 1$ GeV, $\beta \sim 1$, and can be approximated as minimum ionizing particles. In contrast staus with masses $m \geq 100$ GeV, will most often be produced with $\beta\gamma \sim 1$ and be slowly moving, $\beta < 1$.

Long-lived staus with masses between $100 \leq m \leq 1000$ GeV, and proper lifetimes between $0.01 \leq \tau \leq 10$ ns, and a stable scenario are considered. Two possible trigger scenarios are studied. The first scenario looks for at least one high momentum and isolated track, and investigates the impact of geometric acceptance on the trigger efficiency. This scenario is meant to be as inclusive as possible to direct long-lived particle detection, and can serve as a baseline for triggers which incorporate delay or anomalous ionization measurements to reduce backgrounds. The second scenario assumes the outermost layer of the Inner Detector serves as a time of flight layer, and incorporates a timing measurement to further distinguish staus from Standard Model tracks.

The selections considered in the inclusive scenario are summarized in Table 3 and focus on if a stau decays within detector acceptance. The first geometric effect considered is the pseudorapidity range of the tracking detector or track-trigger. Typically the tracker is designed to emphasize efficiency and performance in the barrel. In contrast the endcap and further forward regions typically have degraded performance and higher background rates. The maximum pseudorapidity is varied from $|\eta| < 1.0, 2.5, 4.0$, to represent a barrel only scenario (if endcap rates are prohibatively high), a nominal scenario, and an extended scenario, respectively. An additional question to address is if the stau will traverse a sufficient number of tracker layers to be reconstructed. To investigate this effect, the minimum $L_{x,y}$ beyond which the stau must decay is varied from $600 < L_{x,y} < 1200$ mm. At the HL-LHC, this inclusive trigger will likely include a track-based isolation requirement. This study assumes sufficient tracker longitudinal impact parameter resolution such that any stau isolation requirement would be fully efficient.

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Table 3: Acceptance and efficiency requirements for an inclusive high $p_T$ charged particle trigger.
Figure 11: Stau acceptance for a variety of minimum tracker $|\eta|$ values. Acceptance is shown as a function of stau mass for proper lifetime $\tau = 10$ ns. The stau is required decay beyond $L_{x,y} = 1200$ mm.

Figure 11 shows event-level acceptance as a function of varying the track trigger maximum $|\eta|$ for a fixed minimum $L_{xy} = 1200$ mm. Varying the track trigger $|\eta|$ has a larger effect on the event-level acceptance for lower mass staus. Extending the track trigger to $|\eta| < 4.0$ would improve the acceptance for $m_{\tilde{\tau}} = 100$ GeV by 30% but provides negligible benefit for $m_{\tilde{\tau}} = 1$ TeV. Extending the track trigger acceptance to the far forward region would be extremely challenging from a technical perspective, and offer little benefit in terms of physics reach for meta-stable charged particles because these lower mass BSM particles also benefit from larger cross sections. In contrast, reducing the pseudorapidity coverage from $|\eta| < 2.5$ to the barrel only scenario, $|\eta| < 1.0$, would reduce the overall acceptance by 50% or more, and provides strong motivation for including the endcaps in any track trigger.

The impact of varying the minimum number of layers to reconstruct a track is shown in Figure 12. This studies assumes a fixed pseudorapidity requirement of $|\eta| < 2.5$. Reducing the minimum $L_{xy}$ from 1200 mm to 600 mm, or requiring fewer layers per track, improves the overall acceptance for stau lifetimes of $\tau = 1$ ns by roughly a factor of four. However, the efficiency for this lifetime never exceeds that of a displaced track trigger, as shown in Figure 9. Varying the number of layers required per track does not significantly improve the acceptance for lifetimes $\tau > 1$ ns, because most staus decay well beyond the tracker, $L_{x,y} \sim 1.2$ m.

Increasing the minimum $p_T$ required per track is a useful handle to reduce background rates with nearly full signal efficiency. The impact of varying the minimum track $p_T$ threshold on the event-level efficiency is shown in Figure 13. All $p_T$ thresholds considered are nearly fully efficient except for the lowest stau mass.

The second track-trigger scenario investigates using a time of flight detector as an additional
Figure 12: Stau acceptance for a variety of minimum tracker $L_{xy}$ values. Acceptance is shown as a function of stau lifetime for staus with mass $m = 100$ GeV (a) and $m = 500$ GeV (b). The track trigger covers $|\eta| < 2.5$.

Figure 13: Stau efficiency for a variety of minimum tracker $p_T$ values. Efficiency is shown as a function of stau mass for a stable lifetime and minimum $L_{x,y} = 1200$ mm.

handle to improve signal-background discrimination. A timing layer similar to the planned CMS MIP timing detector is considered [24]. The timing layer is assumed to be located at roughly $L_{x,y} = 1150$ mm, $Z = 3000$ mm, covering $|\eta| < 2.5$, and provides a 50 picosecond resolution timestamp for all charged particles passing through the detector. ATLAS also plans to incorporate precision timing at the HL-LHC, but only at larger pseudorapidity. For ATLAS, it may be more optimal to use calorimeter or muon spectrometer timing measurements to target the heavier staus targeted in this study.
The time of flight detector’s measurement is computed according to

\[ t_{\text{of}} = \frac{L(p_T, \eta)}{c p} \sqrt{p^2 + m^2} \]

An increase in path length, \( L \), due to the magnetic field is negligible for charged particles with \( p_T > 10 \text{ GeV} \) in a 4 Tesla solenoidal magnetic field, and therefore neglected by this study. The detector resolution is assumed to have a gaussian uncertainty with a width of \( \sigma = 50 \text{ ps} \). The spread of collisions in \( Z \) and the spread in collision time are assumed to follow gaussians with widths of \( \sigma = 50 \text{ mm} \) and \( \sigma = 200 \text{ ps} \), respectively. This study assumes the hardware track-trigger is able to measure the track’s longitudinal impact parameter, or origin in \( Z \), but not the primary vertex time. It is likely that computing the primary vertex time will only be possible in the high level trigger or offline, and that the uncertainty in the time-of-flight measurement will be dominated by the beamspot timespread. For simplicity, this study focuses on stable lifetimes, and the selections considered are summarized in Table 4.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Requirement</th>
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<tbody>
<tr>
<td>(</td>
<td>\eta</td>
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<tr>
<td>( L_{xy} )</td>
<td>&gt; 1000 mm</td>
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<tr>
<td>(</td>
<td>Z</td>
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<tr>
<td>Efficiency</td>
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</tr>
<tr>
<td>( p_T )</td>
<td>&gt; 10 GeV</td>
</tr>
<tr>
<td>delay</td>
<td>&gt; 0.25, 0.33, 0.50 ns</td>
</tr>
<tr>
<td>OR ( \beta )</td>
<td>&lt; 0.96, 0.95, 0.9</td>
</tr>
<tr>
<td>OR mass</td>
<td>&gt; 15, 30, 60 GeV</td>
</tr>
</tbody>
</table>

**Table 4**: Acceptance and efficiency requirements for a time of flight trigger.

Time-of-flight and delay distributions are shown in Figure 14 for different stau masses. For comparison, a “background” sample is simulated by looking at Standard Model particles in the event with \( p_T > 10 \text{ GeV} \) as a proxy. The time-of-flight measurements contain two peaks, at \( t_{\text{of}} \sim 3 \) and \( t_{\text{of}} \sim 10 \text{ ns} \) corresponding to the difference in path length for tracks which traverse the barrel or the endcaps, respectively. The delay is defined to be the time-of-flight measurement subtracted by the time it would take a particle traveling at the speed of light to reach the same region of the detector. Staus arrive noticeably later than background particles, and the measured delay in arrival increases with stau mass.

With the time-of-flight measurement it is also possible to extract the stau velocity, \( \beta \), and mass as shown in Figure 15. Computing \( \beta \) accounts for differences in path length, due to the stau \( \eta \) or the longitudinal position of the primary vertex \( Z \). As expected, background tracks peak at \( \beta = 1 \), while staus’ velocity decrease with increasing mass. Computing a charged particle’s mass requires a track momentum measurement, and the mass resolution...
can be described as

$$\frac{2}{\pi} rac{\Delta m}{m} = m^2 \left[ \left( \frac{\Delta p_T}{p_T} \right)^2 + \left( \frac{1}{1 - \beta^2} \frac{\sigma_{t_{of}}}{t_{of}} \right)^2 \right]$$

For simplicity, this study assumes a $p_T$ resolution of 1% which increases up to 10% for particles with $p_T$ of 1 TeV. This assumption is somewhat optimistic for the endcaps, but reasonable for the barrel [25, 26]. Measured masses are peaked at the actual stau mass, while background is peaked near zero, with long tails due to resolution effects.

The efficiency for staus to pass a variety of $\beta$ and mass requirements are shown in Figure 16. Event-level efficiencies are shown for stable staus with respect to having at least one track in geometric acceptance. The selections on $\beta < 0.96, 0.95, 0.90$ or mass > 15, 30, 60 GeV were chosen to provide comparable background efficiencies of 10%, 5%, and 1% per track,
respectively. In both cases, the event-level efficiency increases with stau mass. Requirements on the measured $\beta$ are less efficient than the measured mass.

![Graph](image1)

![Graph](image2)

**Figure 16**: Efficiency with respect to various requirements on measured track $\beta$ (a) and measured mass (b).

### 2.5 Higgs portal to long-lived scalars

The Higgs portal scenario can be targeted with a similar strategy to that discussed for staus in Section 2.4.1. However, this scenario presents an additional challenge due to the low energy of the displaced decay products. Fortunately, there is also a comparatively large number of displaced decay products, producing the distinctive signature of a displaced vertex, which makes triggering more feasible. Unlike the stau, the long-lived particle in this Higgs portal scenario is not electromagnetically charged, so no direct detection strategies are considered.

A baseline acceptance is defined using the same track requirements laid out in Table 2. However for this model a scenario with a minimum of five tracks as well as two is considered, due to the low momenta of the displaced tracks. The acceptances for these two definitions can be found in Figure 17. The acceptance requirement has the largest impact at low masses, where tracks are less likely to pass the minimum $p_T$ required.

The energy and multiplicity of the charged particles emerging from the long-lived scalar’s decay depend on the parents’ masses and number of decay products. In this model, the new scalar is assumed to have Higgs-like branching ratios. At very low masses, the scalar decays primarily to charm quarks and tau leptons, while at masses larger than twice the $b$ quark, $b\bar{b}$ becomes the dominant decay channel. This sudden change in decay modes creates discontinuities in acceptance and efficiency rates around $m = 10$ GeV.

The $p_T$ of individual displaced tracks is much smaller for the higgs portal scenario than the stau scenario. The overall energy scale is much lower, given the comparatively low Higgs
and scalar masses, and that energy is divided among a larger number of particles due to the predominantly hadronic decays.

Event-level efficiencies are defined based on the fraction of events entering the analysis acceptance where at least $N$ tracks pass additional reconstruction thresholds corresponding to potential online tracking configurations. These thresholds are a minimum $p_T$ requirement and a maximum $d_0$, where the exact values are varied to understand the impact each selection has on the efficiency. Two different values of $N$ are studied. The figures in this section largely correspond to $N = 5$, a likely realistic baseline for a trigger on a model with many tracks from hadronic decays of final state particles. An additional study is performed with $N = 2$ to allow for direct comparison to the stau model. Results for this two-track trigger are used in Section 3 and directly compared in Figure 18.

Unsurprisingly, the higgs portal efficiencies are very sensitive to the minimum $p_T$ requirement, as shown in Figure 18. A counter-intuitive trend is shown: the five-track case appears to be more efficient at low masses than the two-track case. This feature is due to the changing acceptance requirements in the two cases. Besides this, the overall trend is the same in each case. At a minimum $p_T$ of 2 GeV, efficiencies have dropped to around 50% of their original value, and values any higher make this strategy ineffectual.

The higgs portal’s efficiency dependence on the $d_0$ range, shown in Figure 19 is more modest: endpoints of 1 cm are at worst about 50% as efficient as endpoints of 10 cm. With the higher track multiplicity per event expected in this model, it’s easier to find tracks with small $d_0$, even for very displaced decays.

Figure 20 shows efficiency as a function of mass and lifetime for a variety of minimum $p_T$ values. The nominal CMS minimum of 2 GeV results in a peak efficiency of around 50% for the higher mass mediators, but markedly poorer efficiency for masses below 20 GeV.
Figure 18: Efficiency as a function of scalar mass for a range of minimum track $p_T$ values. Events are defined to have passed if they contain two (left) or five (right) tracks with a $p_T$ larger than the minimum value, and a linearly parameterized $d_0$ efficiency is used with an endpoint at 100 mm. Each of these efficiencies are defined after an acceptance requirement which also requires two or five tracks, respectively.

Figure 19: Efficiency as a function of scalar mass for a range of $d_0$ parameterization endpoints. Events are defined to have passed if they contain two (left) or five (right) tracks with a $p_T$ larger than 2 GeV, which also pass the parametrized $d_0$ requirement for a given endpoint.

3 Comparison of tracking parameters

The effect of varying primary tracking parameters is compared between different models in the following sections. The minimum $p_T$ threshold is relevant to some extent for all models, primarily affecting SUEP, Higg portals, and the stau decay products. Maximum reconstructed $d_0$ affects only the models with displaced tracks. The final factor considered is the detector layout, as studied through the HSCP model.
Figure 20: Efficiencies for the Higgs to long-lived scalar model for a variety of minimum track $p_T$ values: 0.5 GeV (top left), 1 GeV (top right), 2 GeV (bottom left), 5 GeV (bottom right). Across a wide range of masses and lifetimes, efficiency falls off steeply as the minimum $p_T$ increases over 2 GeV. In all cases, a parameterized $d_0$ efficiency is used with an endpoint at 50 mm. In all cases, the five-track selection is used.

3.1 Minimum transverse momentum

Event-level efficiencies as a function of the minimum track $p_T$ threshold and BSM parent mass is shown for several different models in Figure 21. The $p_T$ threshold has a small effect on the direct detection of stable charged particles, and is not considered here. For this comparison, the Higgs portal trigger selection is loosened to consider an event accepted if two, rather than five, tracks are successfully reconstructed: this adjustment makes the selection identical to the stau selection and the two plots are therefore directly comparable.

Displaced leptons, like heavy stable charged particles, are relatively robust to the $p_T$ threshold, though efficiencies would drop below 50% for the lightest staus with a $p_T > 10$ GeV requirement. The $p_T$ threshold has a much greater effect on the Higgs portal efficiencies, where the tracks from the hadronic decays of the LLP child particles are usually quite soft. Thresholds above 2 GeV would reduce the efficiency of even this two-track trigger to below 20% for all Higgs portal scalar masses. The largest impact of the $p_T$ threshold is on SUEPs, where all masses have negligible efficiency for $p_T \geq 2$ GeV.

Since the reconstruction for prompt and displaced tracks is likely to be controlled and parameterized separately in most systems, it may be possible to have a lower $p_T$ threshold for prompt track reconstruction than for displaced track reconstruction. This would enable
triggering for SUEP models, where this parameter is most necessary, with a lower threshold than a displaced track trigger would have access to. Nonetheless, the $p_T$ threshold for displaced tracks would still need to be on the order of 2 to 3 GeV to achieve significant efficiency for the Higgs portal model.

It should be noted that while the minimum track reconstruction $p_T$ threshold should be kept as low as possible within the balance of other factors, individual triggers tuned for particular BSM scenarios may benefit from using a much higher minimum $p_T$ requirement to suppress background. For example, the efficiency for detection of HSCPs was found to be nearly independent of minimum track $p_T$ for cut values up to 100 GeV.

**Figure 21:** Trigger efficiency as a function of BSM particle mass for staus (a), Higgs portals (b), and SUEPs (c) at a range of minimum track $p_T$ thresholds. The stau and Higgs portal samples both correspond to an LLP lifetime of 0.01 ns such that the tracks to be reconstructed are the decay products of the LLP. Effects of the $d_0$ cut are removed by setting the maximum $d_0$ selection to 100 mm, and for both long-lived models an event is considered to pass the trigger if 2 tracks are reconstructed. In the SUEP model all tracks are prompt.
3.2 Impact parameter dependence

Trigger efficiency dependence on the maximum reconstructed $d_0$ is shown as a function of LLP lifetime for the stau and Higgs portal models in Figure 22. As in the case of the $p_T$ comparison, these plots loosen the Higgs portal trigger selection to consider an event accepted if two, rather than five, tracks are successfully reconstructed. The requirements for an event to pass are therefore identical between these two LLP models. Two mass points in each of the two models are chosen to illustrate the full range of displaced track kinematics. For the staus, one low and one high mass point are chosen. For the Higgs portal, the mass points are chosen such that in one case the scalar decays primarily to $b$ quarks while in the other the decay products are $c$ quarks and taus.

![Figure 22](image_url)

**Figure 22**: Trigger efficiency as a function of lifetime at a range of maximum track $d_0$ values for staus with masses 100 GeV (c) and 600 GeV (b) and a Higgs portal with scalar masses 8 GeV (b) and 40 GeV (d). For all illustrated lifetimes, the tracks to be reconstructed are the decay products of the LLP. Effects of the $p_T$ cut are minimized by setting the minimum $p_T$ threshold to 0.5 GeV, and for both long-lived models an event is considered to pass the trigger if 2 tracks are reconstructed.
The trends in Figure 22 show that the greatest observable spread in efficiencies due to \(d_0\) threshold occurs at intermediate lifetimes for both models. While the average \(d_0\) value of the final state tracks increases steadily with lifetime, the overall efficiency also drops, so the greatest absolute differences occur at intermediate lifetimes. Thus to capture the effect of the \(d_0\) threshold at its most clear, Figure 23 shows the \(d_0\) threshold dependence as a function of mass at the 0.1 ns lifetime.

![Graph](a)

![Graph](b)

**Figure 23**: Trigger efficiency as a function of LLP mass at a range of maximum track \(d_0\) values for staus (a) and Higgs portal scalars (b) with lifetimes 0.1 ns. Varying \(d_0\) has a larger impact on the efficiency for the long-lived staus model than for the Higgs portal model.

The effects of \(d_0\) reconstruction threshold can be seen from Figure 23 to be significantly more important for the stau model than for the Higgs portal model. This is a consequence of the lightness of the Higgs portal scalars relative to the staus and the significant boost that they receive in the lab frame, causing their decay products to be much more collimated. This leads to a very different relationship between decay distance and \(d_0\) for the Higgs portal model, where the small opening angle in the decay of boosted LLPs means even those decaying far from the interaction point often have child particle momenta pointing quite close to the origin. It is therefore possible to achieve comparable efficiencies between loose and tight \(d_0\) thresholds in the Higgs portal model, while the significantly less boosted stau model suffers major efficiency losses from \(d_0\) thresholds at 10 or 20 mm.

### 3.3 Number of tracking detector layers

The minimum number of tracking detector layers required per track was studied for the HSCP scenario by requiring the stau to decay beyond a varying minimum \(L_{x,y}\). Reducing the minimum \(L_{x,y}\) from 1.2 to 0.6 m was not found to have a significant effect on the event-level acceptance for HSCP tracks. For staus with a lifetime of \(\tau = 1\) ns, the difference between the most compact and least compact tracking layer designs led to a factor four improvement in event-level acceptance. However, the acceptance remaining low in all cases.
For even longer lifetimes, most staus decay well beyond 1 m, and reducing the minimum number of layers required per track resulted in minimal acceptance improvements.

The effects of the number of tracking layers will still be significant, however, for displaced signatures. The radius at which an LLP decays will directly affect how many tracking layers are available to reconstruct the displaced track: e.g. if the particle decays after the first tracking layer, only $n-1$ will be included in the track reconstruction. This decay distance also correlates to $d_0$, to differing degrees for different models based on the boost of the parent particle, but with average decay distance longer than average $d_0$, since most particles will be produced with a decay angle < $90^\circ$. Then, if too few tracking layers remain to accurately reconstruct tracks for an LLP decay after a transverse radius of e.g. 100 mm, the efficiency for reconstructing tracks with $d_0$ of 100 mm would drop to zero.

As seen in the Section 3.2, access to high $d_0$ tracks significantly increases the efficiency for both stau and Higgs portal models. For staus, the efficiency of reconstructing high $d_0$ tracks is what allows the displaced track trigger to outperform the HSCP trigger at a lifetime of 1 ns. Staus with masses 100 GeV and 500 GeV at 1 ns lifetimes both show an efficiency < 0.2 for all tracker layer arrangements when triggered using the HSCP approach. When triggering on the displaced decay products, the efficiency is similarly under 0.2 for $m_\tau = 100$ GeV and $\sim 2.5$ for $m_\tau = 500$ if the maximum reconstructed $d_0$ is 20 mm. For the 500 GeV stau, increasing this maximum to 50 mm leads to an efficiency of $\sim 0.5$, and increasing it to 100 mm gives an efficiency of $\sim 0.68$. Reaching these $d_0$ values requires sufficient tracking layers after the decay of the stau, where a particle with $d_0$ 100 mm has a greater average decay distance than one with a smaller $d_0$. Any reconstruction efficiency for high $d_0$ tracks therefore does rely on having a higher number of tracking layers.

### 4 Recommendations

To tackle highly diffuse models like SUEPs, very low $p_T$ tracks are required, with the highest possible useful threshold at around 1 GeV for the models studied here. For experiments where this is not feasible at L1, alternate strategies which do not relying on track counting will be needed for the first stage of the trigger, and could be complemented with lower $p_T$ track requirements at HLT. In this case, overall efficiency is still likely to be low, because high-energy initial state radiation is required for any alternate trigger strategies. If the $p_T$ threshold could be kept at 1 GeV or pushed even lower for prompt tracks, it would be possible to drastically improve sensitivity to SUEPs.

For the other models considered here, a tracking threshold of $p_T > 2$ GeV is enough to provide useful sensitivity. However, in the case of the Higgs portal model, substantial improvement could still be gained from lower $p_T$ thresholds. To address models with light mediators, lower mass long-lived particles, and hadronic decays, the most useful design strategy is a track trigger that pushes the $p_T$ threshold as low as possible with modest $d_0$ coverage. To gain sensitivity to the decay products of more massive particles, like long-lived staus, a large $d_0$ range is more essential while the $p_T$ threshold is not.
To address all of these cases simultaneously while keeping resource usage to a minimum, the best design scenario is one that allows for increasingly large $d_0$ coverage as particle $p_T$ increases. In track trigger designs using pattern banks, this strategy is relatively easy to employ. An approximately constant number of patterns is required to cover a given area in the 2-dimensional space defined by maximum $d_0$ and $1/p_T$ values. An optimal pattern bank could be defined sampling from a triangle rather than a rectangle in that 2D space. A simpler alternative is to create a displaced tracking algorithm that is applied only to tracks passing a minimum $p_T$ threshold that is higher than the nominal prompt one. For example, a tracker with prompt tracking for tracks with $p_T > 1$ GeV and displaced tracking for $p_T > 2$ GeV would provide new sensitivity to all models considered here.

In general, for these unconventional signatures, perfect track reconstruction efficiency is rarely achievable. However, introducing even partial track reconstruction efficiency in a $p_T$ or $d_0$ range can make a substantial difference in sensitivity: triggering on 20% of events is infinitely better than triggering on none.

5 Conclusions

Current LHC triggers are designed to target prompt decays of heavy particles to high momentum Standard Model particles. However, many compelling BSM scenarios lead to decays which are significantly displaced from the interaction point or include low momentum decay products. For these unconventional scenarios, the anomalous charged particle trajectories are the most distinctive feature of the event. Track-triggers at the High Luminosity LHC will provide a unique opportunity to directly trigger on these challenging exotic scenarios for the first time.

This study presents a comprehensive overview of track-based triggers for unconventional exotic signatures, to be used as input to future trigger designs. BSM scenarios considered include dark QCD models with soft-unclustered-energy-patterns which result in large multiplicities of low momentum tracks, long-lived staus which may be directly detected as charged long-lived particles or indirectly detected via displaced tracks, and a higgs portal model which results in displaced hadronic decays. Event-level efficiencies are presented as a function of track-trigger parameters, with a particular emphasis on optimizing transverse momentum thresholds and transverse impact parameter range.

The impact of the track-trigger $p_T$ threshold on the overall efficiency depends strongly on the number of final state particles expected per event. To access SUEP signatures with many low momentum charged particles, it is essential to keep thresholds at $p_T > 1$ GeV or lower to employ track counting, otherwise additional handles are needed. In contrast, displaced hadronic and leptonic decays can still be accessed with $p_T > 2$ GeV thresholds, and directly detecting charged long-lived particles is nearly insensitive to the range of $p_T$ thresholds considered.

Extending the track-trigger $d_0$ range is also investigated. For decays occurring at the same position in the detector, massive long-lived particles considered in the stau scenario tend
to have larger $d_0$ than the decay products of the lighter long-lived scalars considered in the Higgs portal model. In both cases, extending the impact parameter range from $d_0 < 10$ mm to $< 100$ mm results in significantly improved efficiency for lifetimes between 0.1 and 10 ns. Recommendations for future High Luminosity LHC track-triggers are presented which will maximally access the range of models considered here. The optimal track-trigger design would keep the $p_T$ threshold as low as possible for prompt tracks, and for increasing $p_T$ values, the allowed $d_0$ range can be increased. The parameterized efficiencies presented in this result can also serve as a useful guide for developing specific triggers for unconventional exotic signatures.

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References


