PROCEEDINGS OF SCIENCE

Searches for long-lived particles and other non-conventional signatures in CMS

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Many models beyond the standard model predict new particles with long lifetimes, such that the position of their decay vertex is measurably displaced from their production vertex. The decay of such feebly interacting particles gives rise to non-conventional experimental signatures. An overview of recent searches for long-lived particles is presented. The results are obtained with the data collected by the CMS experiment during Run 2 (2016-2018) and Run 3 (2022) of the CERN LHC. A discussion on the triggers operating during Run 3 and designed to target the signatures of the decay of long-lived particles is also provided.

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1. Introduction

A long-lived particle (LLP) is a particle whose decay length is such that it travels a macroscopic distance inside the detector before decaying, leaving unique and challenging experimental imprints. Predicted in many models of physics beyond the standard model (SM), the search for those particles has become an important part of the physics program of the CMS experiment [1] at the CERN LHC. In this paper, an overview of the most recent results on LLP searches is presented, with a particular highlight on the methods established to improve the experimental sensitivity on the associated non-conventional signatures. Searches exploiting Run 2 data (2016-2018, $\sqrt{s}$ = 13 TeV, 137 fb^{-1}) are discussed in Section 2, where scenarios in which the LLP decays in the tracker, in the electromagnetic calorimeter (ECAL), and in the muon chambers, are sequentially described. In Section 3, the first CMS search using Run 3 data (2022, $\sqrt{s}$ = 13.6 TeV, 36.7 fb^{-1}) is presented. Finally, an overview of the long-lived triggers designed for the Run 3 of data taking is given in Section 4, and the main results are summarised in Section 5.

2. Searches using Run 2 data

2.1 LLP decaying in the tracker

Two searches targeting LLPs that decay within the tracker volume are presented. The first search is designed to be sensitive to LLPs whose decay products produce a final state with at least one displaced vertex and missing transverse momentum $p_{\mathrm{T}}^{\mathrm{miss}}$ [2]. As events with exactly one displaced vertex are prone to originate from background processes, dedicated machine learning techniques are applied to improve the sensitivity of the analysis. The observed data is compatible with the SM background. The limits are set on split supersymmetry (SUSY) models, in which the pair-produced long-lived gluinos $\tilde{g}$ decay into quarks and a neutralino $\tilde{\chi}_1^0$. As shown in Fig. 1 (left), the search excludes at 95% confidence level (CL) long-lived $\tilde{g}$ with masses below 1800 GeV and mean proper decay lengths $1 < c\tau < 100$ mm, when the mass splitting between the $\tilde{g}$ and $\tilde{\chi}_1^0$ is 100 GeV. The obtained limits are the most stringent to date for the models considered.

The second search targets signatures of the production of inelastic dark matter [3]. In the model considered, a long-lived dark matter state decays into a pair of oppositely charged muons, originating from a displaced vertex, and a neutral dark matter state with nearly degenerate mass, which is undetected. The sensitivity on the long-lived signatures is enhanced thanks to a dedicated muon reconstruction algorithm. Its efficiency, shown in Fig. 1 (right), is improved at large displacement compared to the standard reconstruction algorithm. No significant excess over the predicted background is observed, and upper limits on the product of the cross section and branching fraction are set. It is the first search for inelastic dark matter at a hadron collider.

2.2 LLP decaying in the ECAL

A search for LLPs decaying in the outer regions of the tracker or in the ECAL has been performed in final states with jets and $p_{\mathrm{T}}^{\mathrm{miss}}$ [4]. The signatures of such decays are jets with low track multiplicity and delayed with respect to the collision time. The jet delay is measured using the ECAL timing information. A novel deep neural network discriminator has been designed to identify such LLP decays. No significant excess over the SM background is observed, and the results are

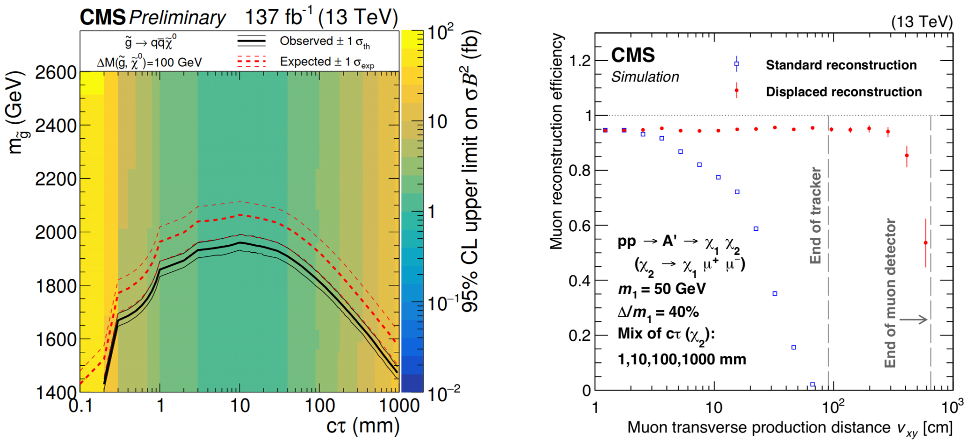

Figure 1: *(Left)* The 95% CL upper limits on the product of the cross section and branching fraction squared for the split SUSY model with a mass splitting between the $\tilde{g}$ and $\tilde{\chi}_1^0$ of 100 GeV, shown as a function of the gluino mass and $c\tau$. *(Right)* Muon reconstruction efficiency of the standard and displaced reconstruction algorithms as a function of the transverse vertex displacement.

interpreted in a simplified model of electroweak production of chargino-neutralino pairs, where the neutralino is long-lived. Neutralino masses up to 1.18 TeV are excluded at 95% CL, for a neutralino with $c\tau = 0.5$ m. The sensitivity to this benchmark model has been improved up to a factor 20 depending on the signal mass compared to previous searches considering prompt neutralino decays.

2.3 LLP decaying in the muon chambers

Searches for LLPs decaying inside the muon chambers are performed with a novel and unique reconstruction method [5, 6]. The technique consists in employing the muon detectors as a sampling calorimeter to reconstruct the particle showers originating from the decays of the feebly interacting particles. Such a strategy has the advantage to provide equal sensitivity to all LLP masses. In addition, the background level is significantly reduced by the shielding material placed in front of the muon detectors. The showers are reconstructed as clusters containing a hit multiplicity $\mathrm{N_{hits}}$. Figure 2 (left) shows the cluster reconstruction efficiency as a function of the radial and longitudinal LLP decay position, for a model in which the Higgs boson decays to a pair of long-lived scalars.

Based on the unique detector signature, the strategy offers sensitivity to a broad range of signal models, and two analyses have been conducted. The first analysis considers events produced with large $p_{\mathrm{T}}^{\mathrm{miss}}$ [5]. The distribution of $\mathrm{N_{hits}}$ in data is shown in Fig. 2 (right), where it is shown that the observed data is compatible with the background prediction. Limits are set on the branching fraction of the Higgs boson to LLPs with masses below 10 GeV, and are the most stringent LHC constraints to date. Additionally, the first LHC limits on models of dark showers produced via Higgs boson decay are provided. The second analysis is a search for heavy neutral leptons (HNLs) in the decays of W bosons [6]. It sets the best limits to date for HNL masses between approximately 2 and 3 GeV.

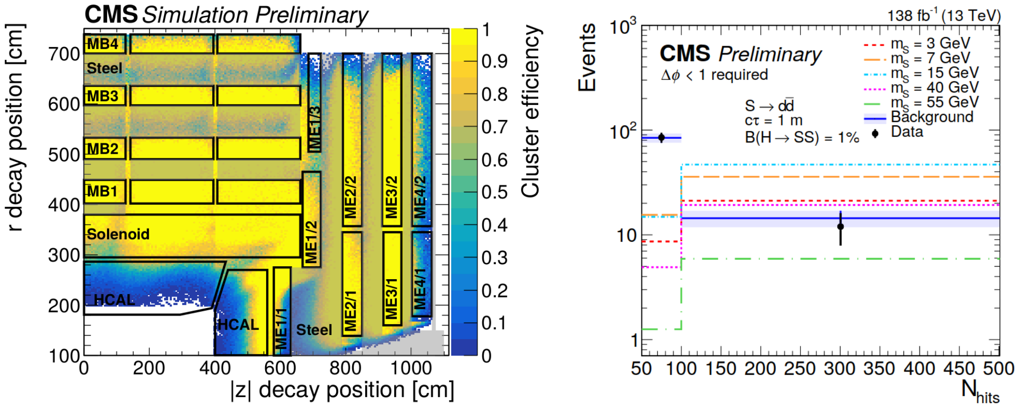

Figure 2: *(Left)* The cluster reconstruction efficiency as a function of the radial r and longitudinal $|z|$ decay positions for a simplified twin Higgs model, in which the Higgs boson decays to a pair of long-lived scalars. *(Right)* Distribution of $\mathrm{N_{hits}}$ in data. The background prediction and several signal hypotheses for the simplified twin Higgs model are also shown.

3. Search using Run 3 data

The first search performed with Run 3 data targets models in which the LLP decays to a pair of oppositely charged muons [7]. The decay happens within the tracker volume. To enhance the sensitivity of the search, events are collected with improved triggers on displaced dimuons. Two additional trigger paths were indeed designed for the Run 3 of data taking by lowering the thresholds on the transverse momentum p_T of the muons, and by imposing a minimum constraint on their transverse impact parameter. Compared to the triggers in Run 2, the efficiency with the new triggers is improved by up to a factor 4 at large $c\tau$ values, as shown in Fig. 3 (left) for a given signal model. To further improve the sensitivity of the search, both the standard and displaced muon reconstruction algorithms, reported in Fig. 1 (right), are employed.

The number of observed events in data is consistent with the SM background predictions. The results are interpreted in several benchmark models, among them the hidden Abelian Higgs model, in which the Higgs boson decays to a pair of long-lived dark photons. The upper limits on the production branching fraction of this process are shown in Fig. 3 (right). The results are substantially improved compared to the Run 2 analysis [8], particularly at low masses and long lifetimes. It is remarkable that such an improvement is obtained with a data sample that is about a factor 2.5 smaller than the one used in the Run 2 search. This shows the important impact of triggering events directly on the LLP decay signatures.

4. LLP triggers in Run 3

With the expertise on long-lived signatures developed with the Run 2 searches, a large effort has been invested in the design of new triggers directly targeting LLP decays, which will operate during the Run 3 of data taking. Besides the displaced dimuon triggers discussed in Section 3, a series of triggers has been designed to improve the sensitivity to LLPs, over a large variety of signal models [9]. They can be summarised in four families: triggers on clusters in the muon chambers,

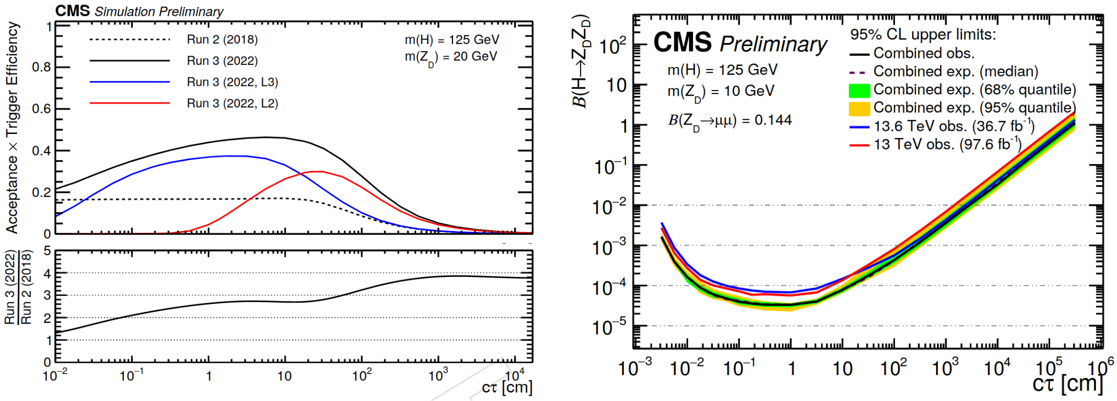

Figure 3: *(Left)* Efficiencies of the Run 2 and Run 3 triggers as a function of $c\tau$. The lower panel shows the ratio of the overall Run 3 efficiency to the Run 2 efficiency. *(Right)* The 95% CL upper limits on the branching fraction of the Higgs boson decaying to a pair of long-lived dark photons Z_D as a function of the dark photon $c\tau$, obtained in this analysis, the Run 2 analysis [8], and their combination.

triggers on delayed jets, triggers on displaced jets, and triggers on displaced and delayed jets. The triggers on clusters in the muon detectors were designed to select events with the signatures discussed in Section 2.3, while the triggers on delayed jets, whose performance is shown in Fig. 4 (left), exploit the ECAL timing information, as it is done in the search presented in Section 2.2. Concerning the triggers on displaced jets, their efficiency has been greatly improved compared to the corresponding triggers in Run 2, as can be seen in Fig. 4 (right). Finally, displaced and delayed triggers were designed to target signatures from LLPs decaying in the hadron calorimeter. The sensitivity to LLP decays is therefore expected to be significantly improved during Run 3.

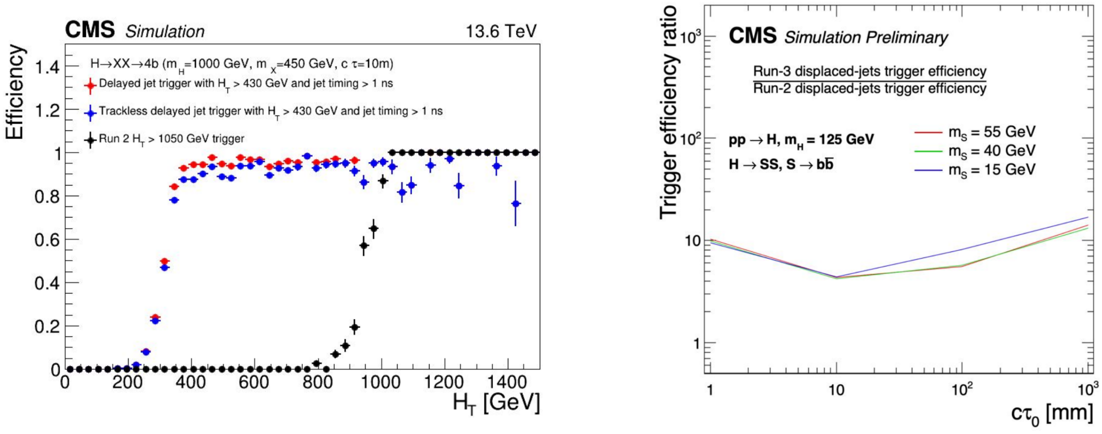

Figure 4: *(Left)* Efficiency of the Run 3 delayed jet triggers (red and blue) and the Run 2 trigger (black) shown as a function of scalar p_T sum of the jets. *(Right)* Ratio of the efficiency of the Run 3 and Run 2 displaced jet triggers as a function of $c\tau$, for a signal model in which the Higgs boson decays to a pair of long-lived scalars.

5. Summary

A vast physics program has been established in CMS to search for long-lived particles (LLPs). An overview of searches using Run 2 data, as well as the first search using Run 3 data, has been presented. A large variety of signal models has been explored, and scenarios in which the feebly interacting particle decays in the tracker, in the electromagnetic calorimeter, or in the muon chambers, have been studied. A wide range of new techniques has been designed to improve the sensitivity to the non-conventional signatures resulting from the decay of a LLP. Novel event reconstruction strategies, particle reconstruction algorithms, or advanced signal significance enhancement techniques based on machine learning, resulted in substantial improvements in the sensitivity to long-lived signatures. No significant deviation from the predicted background has been observed. In several instances, the best limits to date have been obtained for the signal models under scrutiny. The expertise gained with the Run 2 searches has been invested in the design of a series of triggers, targeting the signatures of LLP decays and operating during the Run 3 of data taking. The first search using Run 3 data collected with such triggers has shown the great potential of this strategy.

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