PROCEEDINGS OF SCIENCE

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

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Many extensions of the standard model predict new particles with macroscopic lifetimes. Such particles produce different kinds of non-conventional signatures in the detector that often require specialized reconstruction and identification techniques. These proceedings will present new results that have been publicly released by the CMS Collaboration for the EPS-2025 conference.

The European Physical Society Conference on High Energy Physics (EPS-HEP2025)
7-11 July 2025
Marseille, France

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https://pos.sissa.it/

PoS(EPS-HEP2025)437

1. Introduction

As is the case for known particles such as pions, kaons, or muons, new resonances associated with phenomena beyond the standard model (BSM) could possess lifetimes long enough to travel measurable distances before decaying. Such long lifetimes may arise from scenarios involving nearly mass-degenerate spectra, heavy virtual mediators, or suppressed couplings. Depending on the particle's properties such as its mass, lifetime, and decay modes, this can give rise to a broad range of experimental signatures, many of which require dedicated search strategies.

While numerous results based on Run 2 data have been published in recent years, this proceeding focuses on the latest results of the CMS Collaboration [1] presented at the 2025 edition of the EPS-HEP conference.

2. New search using a soft displaced vertex

Many theoretical models beyond the standard model predict long-lived particles (LLPs) whose decays include an invisible particle, which could be dark matter candidate. Such models include the top squark coannihilation and bino-wino cohannilation models which have been considered as benchmarks in the analysis [2] presented in that section. The corresponding Feynman diagrams are shown in Fig. 1.

To enhance in scenarios with compressed spectra, where standard searches are typically limited, this novel search exploits a new strategy based on soft displaced vertices.

The event selection relies on three main elements: the presence of a soft displaced vertex reconstructed from the charged particles produced in the LLP decay, large missing transverse momentum (p_T^{miss}> 400 GeV) associated with the invisible particles, and an initial state radiation jet (p_T> 100 GeV) providing recoil. Events are collected using a p_T^{miss} trigger is used, and vetoes on selected leptons and photons, along with a set of additional topological cuts, are applied.

The reconstruction of displaced vertices is performed using the inclusive vertex finder (IVF) algorithm [3], applied to displaced tracks with p_T>0.5 GeV. The transverse displacement significance $|d_{xy}|/\sigma_{d_{xy}}$ is used as a key variable, while track quality criteria include requirements on the number of valid hits. The IVF parameters were specifically tuned to the LLP topology, characterized by large opening angle and vertex momemta not pointing to the primary vertex. With these optimizations, the vertex reconstruction efficiency improves from below 10% (default IVF) to 30-50% for LLP displacement of 1-100 mm.

Backgrounds from nuclear interactions of Standard Model particles with the tracker material are suppressed by applying a veto based on a material map derived from data.

Signal and control regions are defined based three variables: p_T^{miss}, the vertex significance $S_{xy}^{vtx} = |L_{xy}|/\sigma_{Lxy}$ and the number of good tracks associated with the vertex. Background estimates are obtained from data-driven methods

No significant excess above the expected background has been observed. Limits are set in the benchmark scenarios with small mass splittings (Δ_m < 25 GeV) between the next-to-lightest and the lightest particle. The search excludes top-squark masses in the range 400–1100 GeV and wino-like neutralino masses in the range 220–550 GeV, depending on the signal parameters. This constitutes the first LHC search explicitly targeting displaced vertices from hadronically decaying LLPs with

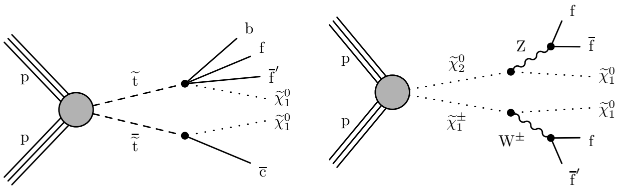

Figure 1: Feynman diagrams for top squark coannihilation model (left) and bino-wino coannihilation model (right) from Ref [2].

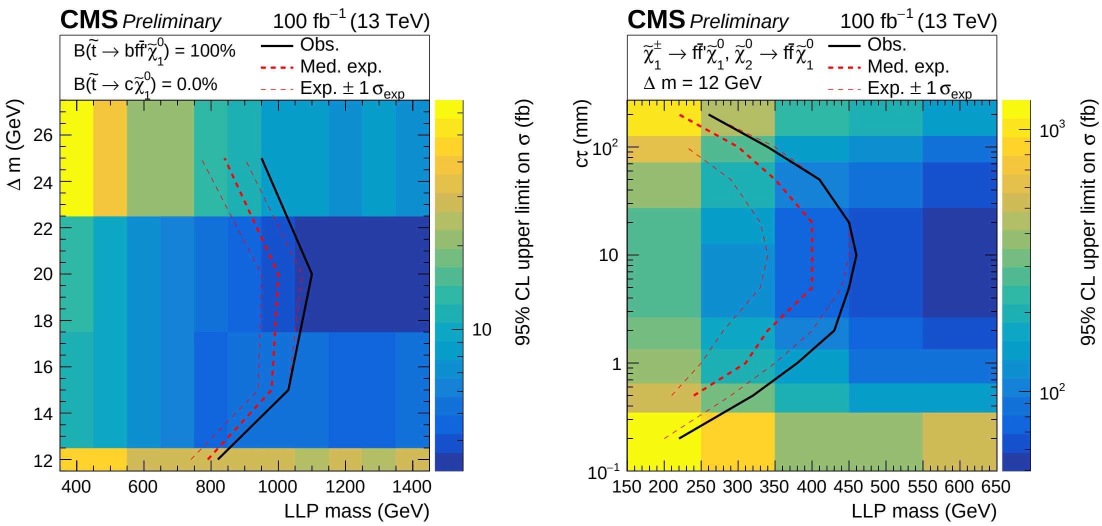

Figure 2: Observed and expected exclusion limits at 95% CL on the top squark production cross section as a function of m_t and Δm, for $B(\tilde{t} \to b f \bar{f}' \tilde{\chi}_0^1)$ of 100% on the left and on the production cross section for the bino-wino coannihilation model, as a function of LLP mass and $c\tau$, for Δm of 12 GeV on the right from Ref [2].

small mass splittings, and it sets the most stringent limits to date on the top-squark coannihilation and bino–wino coannihilation models. Selected results are shown in Fig. 2.

3. New search of long-lived staus using a dedicated displaced tagger

The search for pair-produced staus, the supersymmetric partners of the tau lepton, is an ongoing effort of the CMS collaboration. In gauge-mediated supersymmetry models (GMSB), the lighest supersymmetric particle (LSP) can be the gravitino, while the tau maybe be the next-to-lightest supersymmetric particle (NLSP), potentially long-lived. Different search strategies have developed to probe complementary lifetime ranges. Prompt decays are targeted with analyses relying on hadronically decaying taus and state-of-the art algorithm up [4]. Extremely long lifetimes, where the stau manifests as a highly ionizing, high p_T track, are covered by dedicated searches [5]. Intermediate lifetime have been explored through displaced electrons or muons from leptonic tau decays [6].

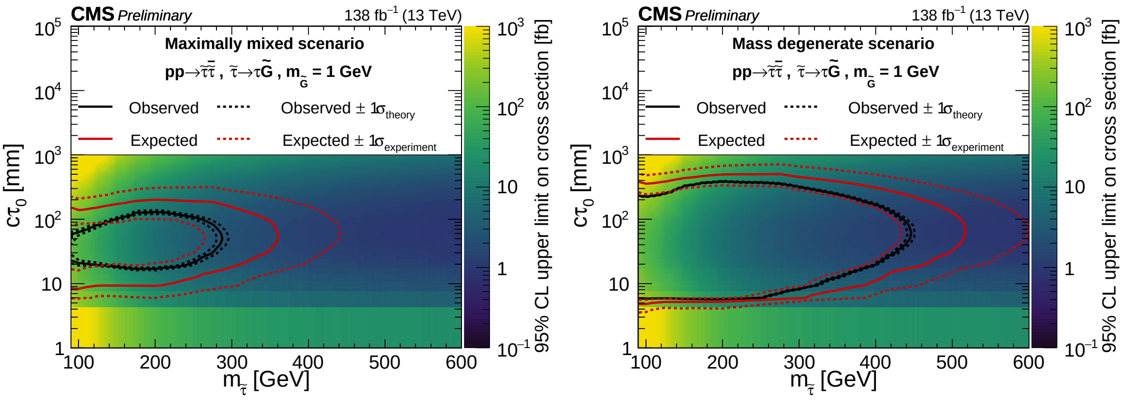

Figure 3: Observed and excluded exclusion limits at 95% CL for the pair production of long-lived staus, displayed in the plane of m_{τ} and $c\tau_0$ for the maximally mixed scenario on the left, and the mass degenerate scenario on the right from Ref [7].

A new strategy [7] extends the coverage to the case of displaced, hadronically decaying staus. It employs a dedicated tagger, DisTau, based on the ParticleNet graph convolutional neural network [8], specifically optimized for displaced taus identification. The event selection uses a p_T^{miss} trigger followed by an offline requirement p_T^{miss}> 120 GeV. Exactly two jets must pass the tight DisTau identification, with an additional requirement on the transverse displacement. Events containing electrons, muons and b-tagged jets are vetoed. The signal region is further binned in p_T^{miss}, the p_T of the subleading tau, and the stransverse mass M_{T2}.

No significant excess above the Standard Model expectation has been observed. Limits are set under different theoretical assumptions for the stau sector. The mass eigenstates $(\tilde{\tau}_1, \tilde{\tau}_2$ arise from mixing of the gauge eigenstates $(\tilde{\tau_L}, \tilde{\tau_R}$. Results are shown in Fig. 3 for two benchmark scenario: maximal mixing (mixing angle of $\pi/4$ for the $\tilde{\tau}_1$) and mass-degenerate case ($\tilde{\tau}_1 \approx \tilde{\tau}_2$). The production cross-section being almost five time larger for the mass-degenerate scenario, resulting in stronger exclusion limits accross lifetime and mass ranges.

The introduction of the DisTau algorithm significantly enhance the sensitivity to displaced hadronically decaying tau compare to previous searches. In the maximally mixed (mass degenerate) scenario, stau masses between 90–290 (90–450) GeV are excluded for $c\tau_0$ = 50 mm, and for $m_{\tilde{\tau}}$ = 200 GeV, stau proper lifetimes in the range 15–130 (5–390) mm are excluded. These results substantially extend the parameter space probed in supersymmetry searches at the LHC.

4. New search of long-lived ligh scalar from Higgs decay using hadrons

A recent analysis [9] has targeted the search for a new scalar particle S in the minimal Higgs-portal scenario. In this framework, the scalar S interacts with a dark sector containing new BSM particles and interactions that carry no Standard Model charges. A renormalizable mixing term between the Standard Model Higgs boson H and the scalar S induces the coupling responsible for production. A mixing between the SM Higgs boson H and the new scalar S originates from the renormalizable interactions.

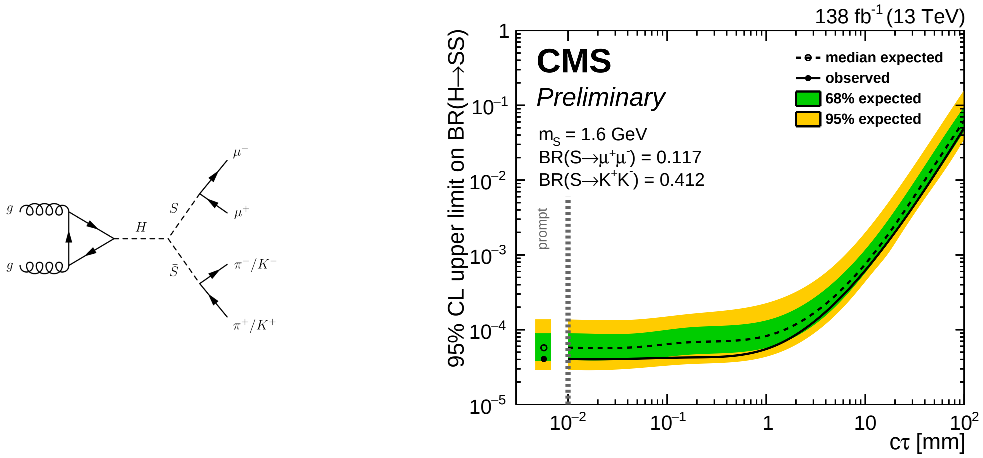

Figure 4: Left, diagram illustrating Higgs-mediated BSM light scalar production in gluon-gluon fusion processes in the final state of a pair of muons and a pair of charged hadrons. Right, observed and expected exclusion limits at 95% CL on the branching fraction B($H \to SS$) as function of signal proper lifetime $c\tau$ for m_S= 1.6 GeV for the most minimal extension of the SM Higgs sector. Figures are extracted from Ref [9].

The search explore the low-mass phase space where $m_S < 2$ GeV, where hadronic decays of S do not result in jets but instead yield exclusive two-body decay $S \to K^+K^-$ and $S \to \pi^+\pi^-$ decays, respectively above and below the $m_S = 2m_{K^\pm}$ kinematic threshold. These decays may occur with with a macroscopic lifetimes. To remain as model-independent as possible, the proper lifetime of S is treated a free parameter of the model. The signal searched is depicted on the left diagram of Fig. 4.

Event selection relies on a muon trigger and requires two pairs of oppositely charged particles with invariant masses compatible within the detector resolution. The four-body invariant mass must be consistent with the Higgs boson mass. The minimal p_T threshold for muons and hadrons is equal to 5 GeV, except for the leading muon associated with the trigger. For each candidate pair, the transverse displacement significance, $L_{xy}/\sigma_{L_{xy}}$ is computed, and events are classified into four categories according to the displacement significance of both pairs.

Limits are obtained by combining all categories and are reported as function of the scalar lifetime for different mass hypotheses. As shown in Fig. 4, for m_S=1.6 GeV, where kaon decays dominate, the search excludes at 95% CL branching fractions of the Higgs boson to light scalars greater than 10^{-4}. This analysis probes a largely unexplored region of parameter space for light long-lived particles.

5. Perspectives for Run 3 with dedicated triggers

Long-lived particles can produce unique signatures that often are not captured by standard triggers, and are therefore a crucial lever to enhance experimental sensitivity. During Run 3, a wide range of new or improved triggers has been deployed compared to Run 2. These include triggers for displaced objects such as jets, taus, photon with H_T, single and dimuons, muon plus photon, as well as delayed objects such as photons and jets identified using calorimeter timing information.

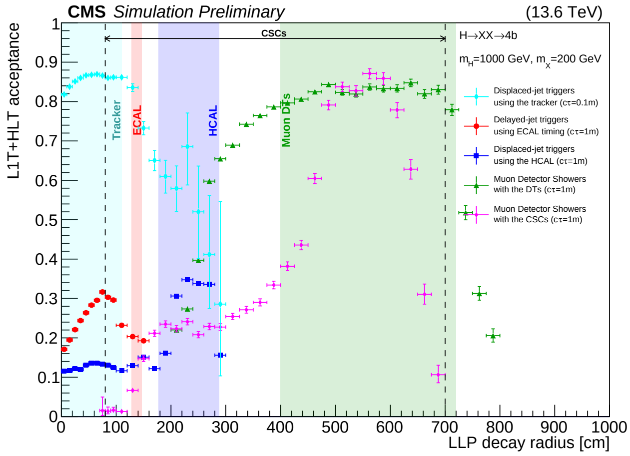

Figure 5: Acceptance for various LLP triggers using different subdetectors, as a function of LLP decay radius, for $H \to XX \to b\bar{b}b\bar{b}$ events in 2023 conditions from Ref [10].

In addition, specific triggers target muon detector showers, i.e. clusters of hundreds of hits in the muon chambers without associated tracks or jets in the same direction.

Beyond these dedicated LLP triggers, which save raw detector information for offline analysis, scouting techniques are also employed to lower thresholds and increase event rates by recording only high-level physics objects (jets, leptons, etc.) reconstructed at the High-Level Trigger. The dimuon scouting trigger, in particular, has been improved relative to Run 2: the pixel-hit requirement has been relaxed to increase the efficiency for displaced muons.

By exploiting information from different subdetectors, the CMS LLP trigger strategy covers a broad region of phase space. This is illustrated in Fig. 5 which shows the complementarity of dedicated hadronic LLP triggers for the Twin Higgs model where the signal is $H_{BSM} \to XX \to b\bar{b}b\bar{b}$. The combination of different trigger categories allows sensitivity across a wide range of lifetimes. The improvements implemented for Run 3 significantly extend trigger acceptance for LLP signatures and are expected to play a central role in upcoming searches. More results are available in a new released note [10].

6. Conclusion

The CMS long-lived particle (LLP) program remains highly active, with four new results presented for the first time at this EPS conference. By leveraging improved algorithms and innovative analysis strategies, CMS continues to probe unexplored regions of BSM parameter space. With the significant trigger upgrades implemented for Run 3, further advances in sensitivity are expected in the near future.

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PoS(EPS-HEP2025)437