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Search for new physics with long-lived and unconventional signatures in CMS

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Many extensions of the standard model predict new particles with long lifetimes or other properties, that give rise to non-conventional signatures in the detector. This talk discusses new techniques to detect such signatures in the CMS detector, and presents recent results from such searches in CMS using the full Run-II data-set of the LHC.

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1. Introduction

The Standard Model of particle physics (SM) is a remarkably successful theory whose predictions are consistent with the results of every high-energy collider experiment to date. At the same time, the SM cannot be the whole story. It fails to describe several known phenomena such as gravity, neutrino mass, and dark matter, and there are compelling theoretical reasons to suspect that beyond-the-Standard-Model (BSM) physics may manifest at currently accessible energy scales.

Conserved quantities, limited decay phase space, heavy intermediate states, and small coupling constants cause SM particle lifetimes to vary by more than thirty orders of magnitude. Because these same mechanisms are ubiquitous in BSM theories, it is reasonable to expect BSM particle lifetimes to vary in a similar manner.

In the context of LHC physics, a particle whose lifetime is such that it decays a measurable distance away from the proton-proton collision is known as a long-lived particle (LLP). In a detector such as CMS [1], BSM LLPs could produce striking, exotic signatures such as charged particle tracks that disappear mid-flight or physics objects whose trajectories do not point back to the proton-proton interaction point.

Any significant observation of such a signature would be a sure sign of new physics, but standard triggering, reconstruction, identification, and analysis techniques render the vast majority of analyses insensitive to BSM LLPs. Dedicated BSM LLP searches are therefore a critical component of the quest to understand whether BSM physics manifests at currently accessible energy scales.

2. Searching for new long-lived particles with CMS

The CMS collaboration is engaged in a rich program of dedicated BSM LLP searches. Full Run-II results target signatures such as displaced vertices, displaced jets, and disappearing tracks [2–4]. In just the past few months, CMS has made public the results of several new BSM LLP analyses, including searches for neutral BSM LLPs that decay in the endcap muon system [5], displaced jets

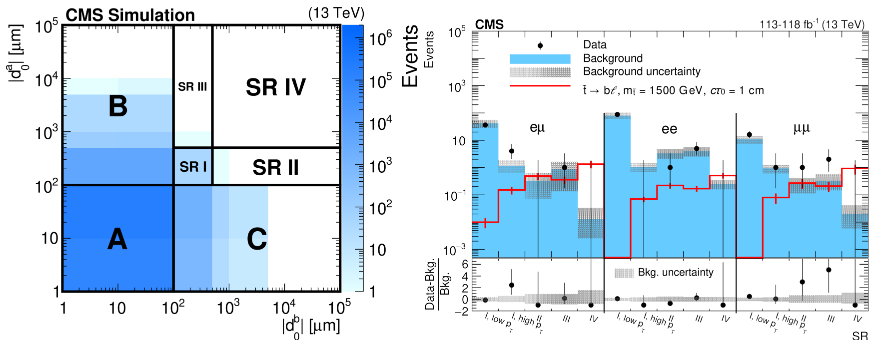

Figure 1: Definition of control regions (A, B, and C) and signal regions (SR I–IV) used in the displaced leptons analysis (left). Signal region yields of the predicted background, data observation, and a representative signal model in the displaced leptons analysis (right). [8]

resulting from exotic Higgs boson decays in association with a Z boson [6], and displaced muon pairs in events collected with high-rate triggers [7].

Two such analyses were unveiled in the days preceding EPS 2021: a very inclusive, signature-based search for BSM LLPs that decay to at least one lepton [8] and a targeted search for heavy neutral leptons (HNLs) that explores the particularly difficult low-mass, long-lifetime region of the HNL parameter space [9]. The following sections describe these recent results.

3. Search for displaced leptons

The CMS collaboration has performed a search for BSM LLPs in a final state with two or more leptons whose trajectories are displaced from the proton-proton interaction point. By focusing on the displaced lepton signature, the analysts enable sensitivity to leptons produced in separate BSM LLP decays as well as those that share a common displaced vertex, all without reconstructing displaced vertices or setting explicit constraints on the presence or absence of other potential BSM LLP decay products.

This analysis specifically targets events with at least two leptons (two electrons, two muons, or an electron and a muon) with transverse impact parameters between 100 μm and 10 cm. The leptons are required to have transverse momenta above a few tens of GeV, be well measured, and be isolated from other detector activity. These simple lepton quality and displacement criteria are sufficient to dramatically reduce the SM background without setting requirements om the lepton charge product or any non-lepton physics object.

Potential SM backgrounds come from leptons from prompt processes with poorly measured displacement values as well as leptons from displaced tau lepton and heavy-flavor meson decays. After subdividing the signal region by lepton displacement and transverse momentum to maximize sensitivity to a wide range of BSM LLP lifetimes and masses, the analysts use data events with zero or one displaced lepton to estimate the signal region contribution of such backgrounds. The left-hand side of Fig. 1 shows how the plane defined by the displacement of two leptons is divided into signal regions and control regions.

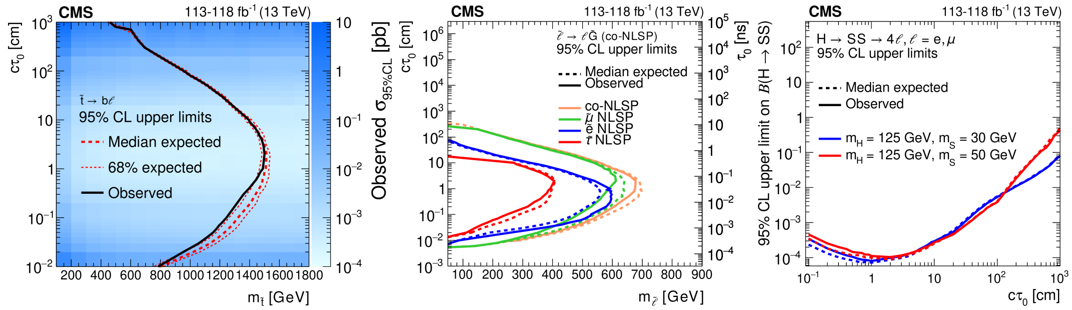

Figure 2: Limits on three BSM scenarios set by the displaced leptons analysis. Results are presented in the mass-lifetime plane of the superpartner of the top quark (left), superpartners of the electron, muon, and tau leptons (center), and scaler lifetime-Higgs boson to long-lived scaler branching fraction (right). [8].

As shown in the right-hand side of Fig. 1, the observed number of signal region events is consistent with the background-only hypothesis, so the results are used to constrain several well-motivated BSM models. Figure 2 shows excluded regions of parameter space for long-lived superpartners of the top quark in an R-parity-violating supersymmetric model, long-lived superpartners of the electron, muon, and tau leptons in a gauge-mediated supersymmetry breaking model, and long-lived scalar particles produced in Higgs boson decays. Thanks to its model-independent, signature-based approach, this analysis is able to constrain many possible BSM models across a wide range of BSM LLP masses and lifetimes.

4. Search for heavy neutral leptons

The second analysis presented here is a search for long-lived heavy neutral leptons (HNLs) that mix with standard model neutrinos. By targeting HNLs with appreciable lifetimes, this search gains sensitivity to the previously unexplored region of parameter space in which HNL masses and neutrino mixing parameters are simultaneously small.

To enable sensitivity to this difficult region of parameter space, the analysts consider the scenario in which the HNL is produced in the decay of a W boson and itself decays to a W or Z boson. If the W or Z boson then decays leptonically, the final state will include one prompt lepton from the initial W boson decay and two displaced leptons that form a common, displaced vertex. Triggering on the prompt lepton allows the analysts to study low-momentum displaced leptons, which in turn enables sensitivity to HNL masses below 20 GeV.

The analysts exploit HNL decay kinematics to identify potential signal events. Specifically, they use the distance between the primary and secondary vertices and the invariant mass and angular distributions of the prompt and displaced leptons to separate signal from background. The signal-region contribution of background processes is estimated using data events that pass less stringent selection criteria, and the identification efficiencies of displaced leptons and vertices are evaluated using data events with either a Z boson and a photon, a J/ψ meson, or a K^0_S meson.

The potential signal events are then categorized by di-lepton invariant mass, vertex displacement, and lepton flavor. As shown in Fig. 3, the observed signal-region yields are consistent with the expected background contributions, so the results are used to constrain the available parameter

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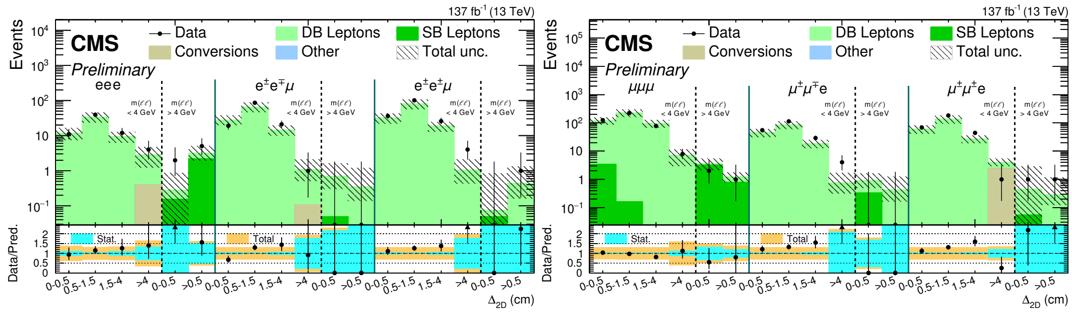

Figure 3: Signal region yields of the predicted background and data observation in the heavy neutral leptons analysis [9].

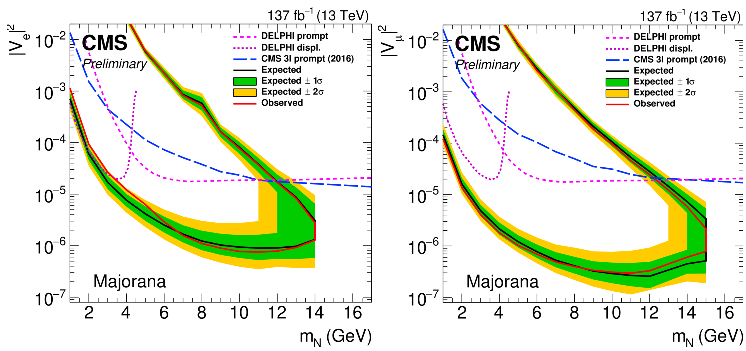

Figure 4: Limits on the electron (left) and muon (right) neutrino mixing parameters as a function of HNL mass for Majorana HNL. A similar range of mixing parameter values are excluded in the Dirac HNL scenario [9].

space of Dirac and Majorana HNLs. The resulting limits, such as those shown in Fig. 4, exclude neutrino mixing parameter values that are frequently more than an order of magnitude lower than existing limits in the low-mass region.

5. Summary

The CMS collaboration is engaged in a rich, ongoing program of BSM LLP searches that are critical to understanding whether new physics exists at currently accessible energy scales. As shown in Fig. 5, these analyses cover a wide range of final states and new particle masses and lifetimes, but there are still many stones unturned.

Several recent CMS BSM LLP searches achieve complementary goals and test new regions of parameter space. In particular, these analyses probe lower BSM LLP masses with innovative triggering strategies, longer lifetimes by considering novel signatures, and achieve wide applicability with model-independent, signature-based design.

CMS will continue to explore the lifetime frontier in Run 3 of the LHC and beyond. The work to develop new triggers, new analysis techniques, and new ideas is ongoing, and the upgraded CMS detector, especially the new timing detector, will open entirely new opportunities for BSM LLP searches.

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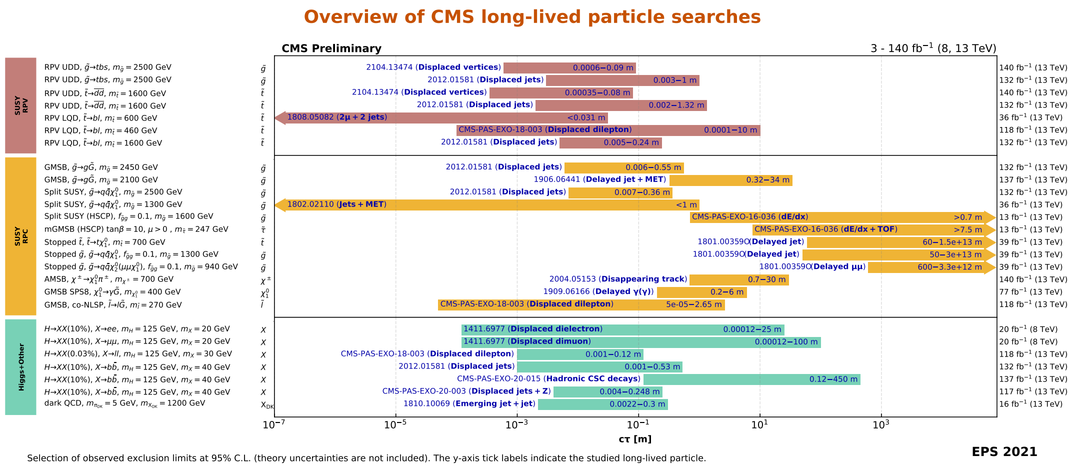

Figure 5: A bar chart representing the lifetime reach of CMS long-lived particle analyses for a selected set of new physics phenomena [10].

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