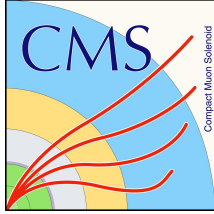


Searches for new physics with long-lived and unconventional signatures in CMS

Bryan Cardwell (UVA)
on behalf of the CMS collaboration

EPS-HEP 2021
27.07.2021

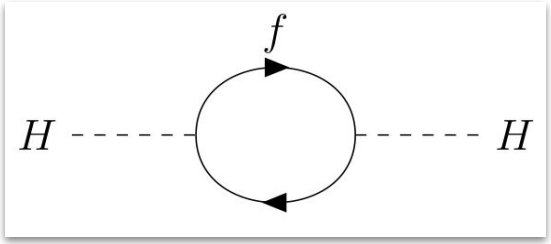
The Standard Model (SM)

Describes nearly all known particles and their non-gravitational interactions

Experimentally verified

Incomplete:

Unnatural:



$\propto$ (highest allowed SM energy)^2

mass / charge / spin	≃2.2 MeV/c² / ⅔ / ½ u up	≃1.28 GeV/c² / ⅔ / ½ c charm	≃173.1 GeV/c² / ⅔ / ½ t top	0 / 0 / 1 g gluon	≃124.97 GeV/c² / 0 / 0 H higgs
QUARKS	≃4.7 MeV/c² / −⅓ / ½ d down	≃96 MeV/c² / −⅓ / ½ s strange	≃4.18 GeV/c² / −⅓ / ½ b bottom	0 / 0 / 1 γ photon	SCALAR BOSONS
LEPTONS	≃0.511 MeV/c² / −1 / ½ e electron	≃105.66 MeV/c² / −1 / ½ μ muon	≃1.7768 GeV/c² / −1 / ½ τ tau	≃91.19 GeV/c² / 0 / 1 Z Z boson	GAUGE BOSONS VECTOR BOSONS
	<1.0 eV/c² / 0 / ½ νe electron neutrino	<0.17 MeV/c² / 0 / ½ νμ muon neutrino	<18.2 MeV/c² / 0 / ½ ντ tau neutrino	≃80.39 GeV/c² / ±1 / 1 W W boson	

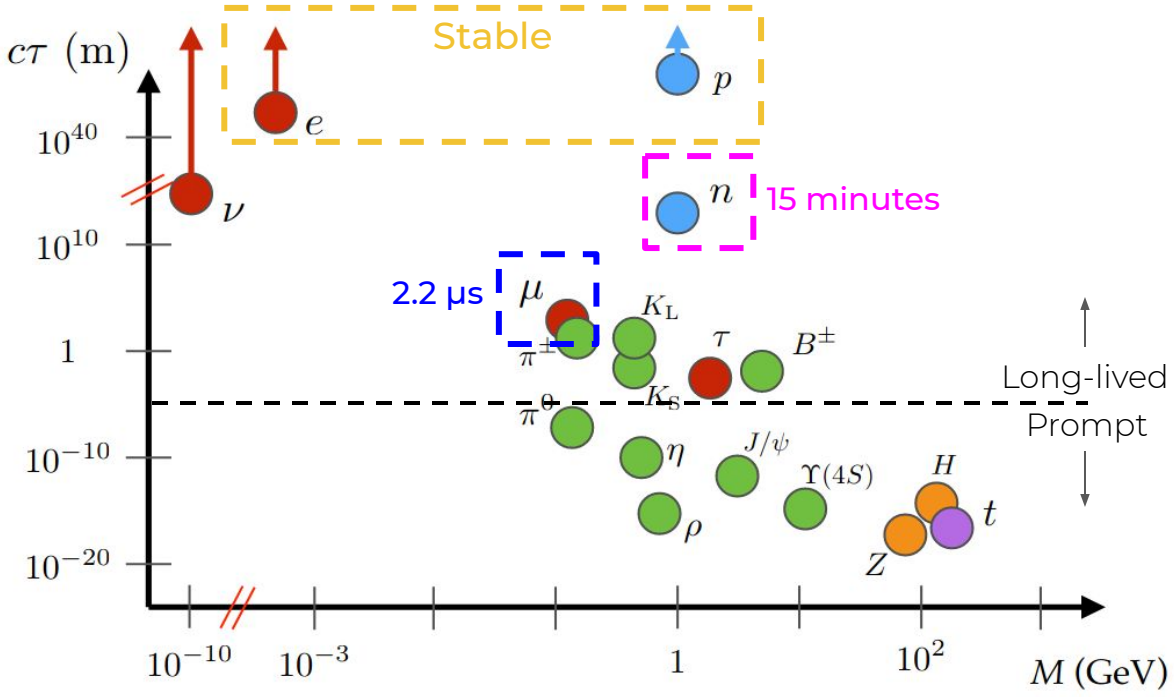
Long-lived particles (LLPs)

SM particle lifetimes vary across tens of orders of magnitude

Long lifetimes result from a few simple physical mechanisms:

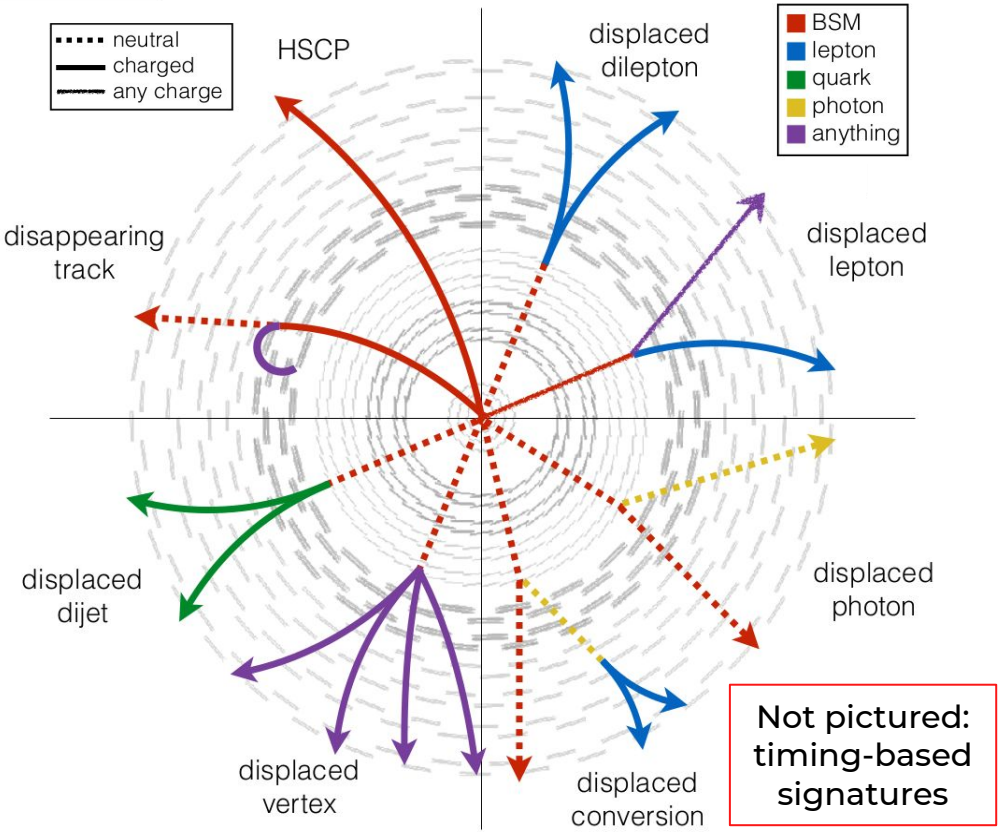
- Conserved quantities
- Limited phase space
- Heavy intermediate states
- Small couplings

These same mechanisms frequently occur in Beyond-the-SM (BSM) theories



We should generically expect that BSM particles may be long lived!

BSM LLPs in CMS



BSM LLPs could produce striking signatures in CMS

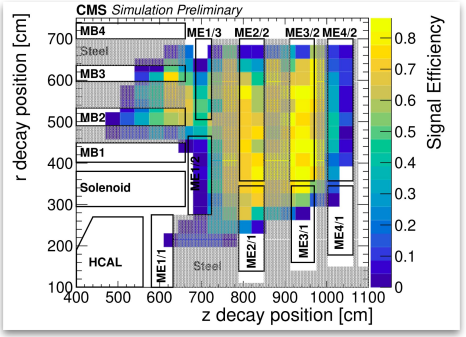
↓

Standard methods render most analyses insensitive

↓

Dedicated BSM LLP searches are necessary to understand whether new physics exists at the TeV scale

BSM LLP searches at CMS

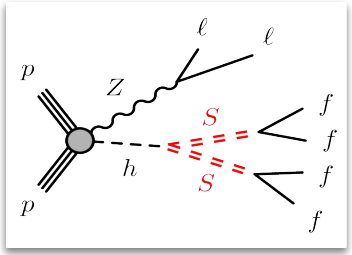


Rich, ongoing program of BSM LLP searches at CMS

- Full Run 2 results include searches for BSM LLPs that produce **displaced vertices, displaced jets, disappearing tracks,** and **delayed photons**

Results from just the past few months include:

- Neutral LLPs decaying in the endcap muon system 2107.04838
- Displaced jets in association with a Z CMS-PAS-EXO-20-003



- Displaced muons with high-rate triggers CMS-PAS-EXO-20-014 (see Annapaola's talk)

BRAND NEW! Displaced leptons CMS-PAS-EXO-18-003

BRAND NEW! Heavy neutral leptons CMS-PAS-EXO-20-009

} Today's talk

Displaced leptons

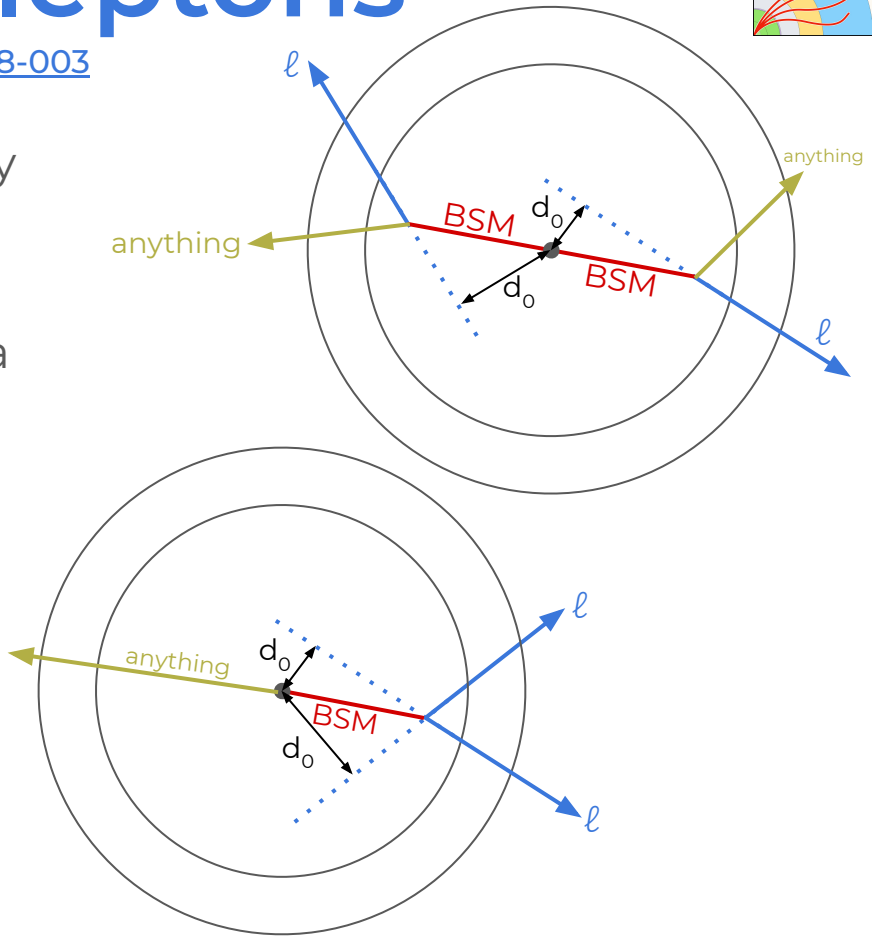
CMS-PAS-EXO-18-003

Very inclusive search for **BSM LLPs** that decay to leptons (ℓ) in 2016-18 data

Look for **ee**, **μμ**, or **eμ** pairs where each ℓ has a large transverse impact parameter (d_0)

d_0 is a powerful discriminating variable:

- d_0 > ~100 μm removes nearly all SM bg
- Set **no explicit constraints** on non-lepton physics objects
- Identify displaced decays **without** requiring that ℓ form a common vertex

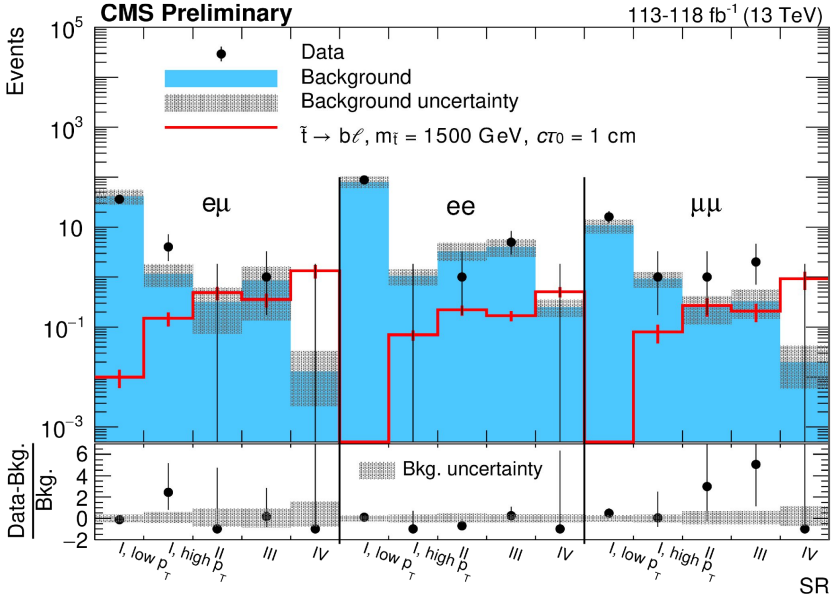


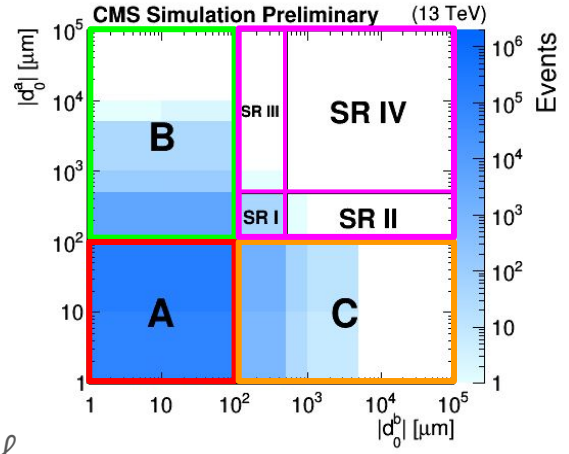
Displaced leptons

CMS-PAS-EXO-18-003

Very inclusive event selection:
- ≥ 2 isolated, high-momentum, well-measured ℓ
- no constraints on missing energy, jets, ℓ charge product, etc

Signal region: ≥ 2 ℓ with $100\mu m < |d_0| \leq 10cm$





Backgrounds:
- poorly measured ℓ
- tau lepton and heavy-flavor meson decays

Estimate bg from data in prompt-ℓ regions
- $N_{SR} \approx (N_B \times N_C) / N_A$

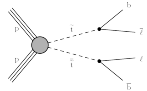
Categorize SR events by ℓ d_0 and momentum

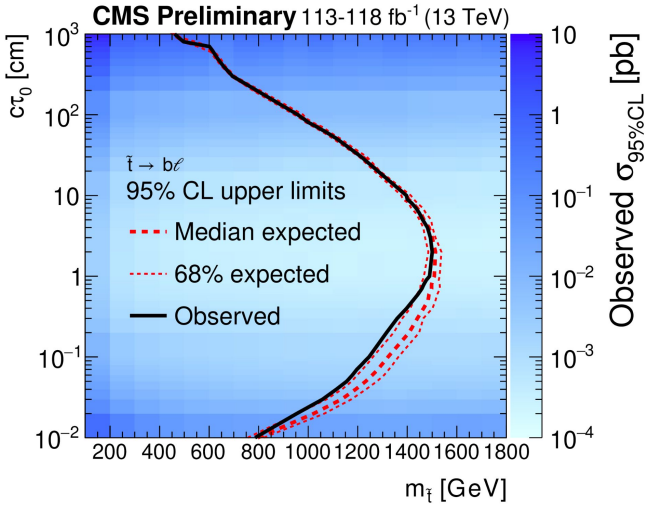
Observation consistent with bg-only hypothesis

Displaced leptons

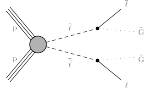
CMS-PAS-EXO-18-003

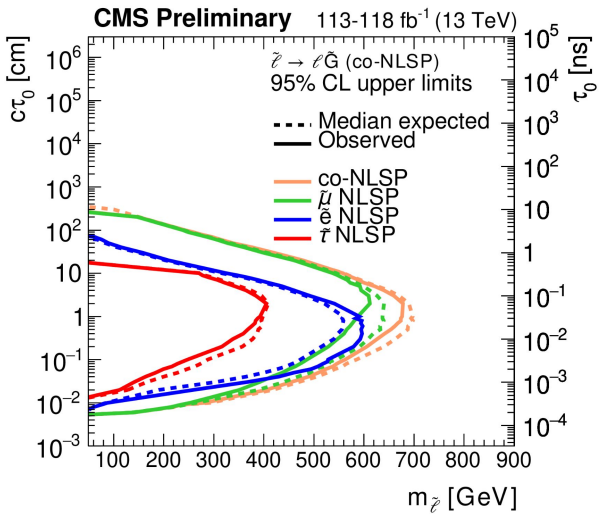
Constrain production of RPV top squarks and GMSB sleptons and the BR of Higgs bosons to long-lived scalars across wide range of new-particle lifetimes



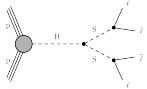


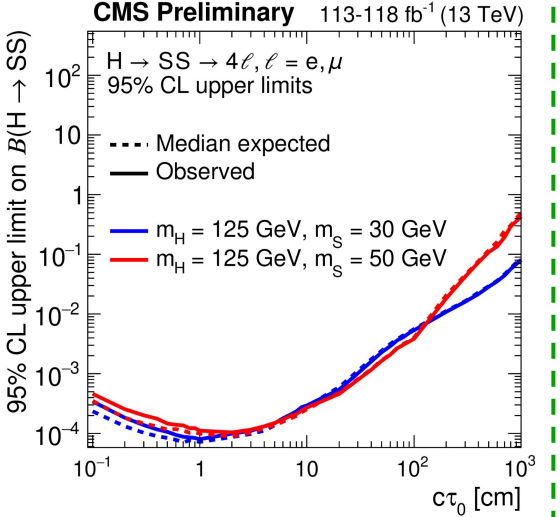
~600 GeV improvement over previous displaced ℓ exclusion





Similar reach as 2011.07812; exclusive sensitivity $\lesssim 10^{-1}$ cm





Most stringent limits to date for $c\tau \lesssim 50$ cm

Heavy neutral leptons

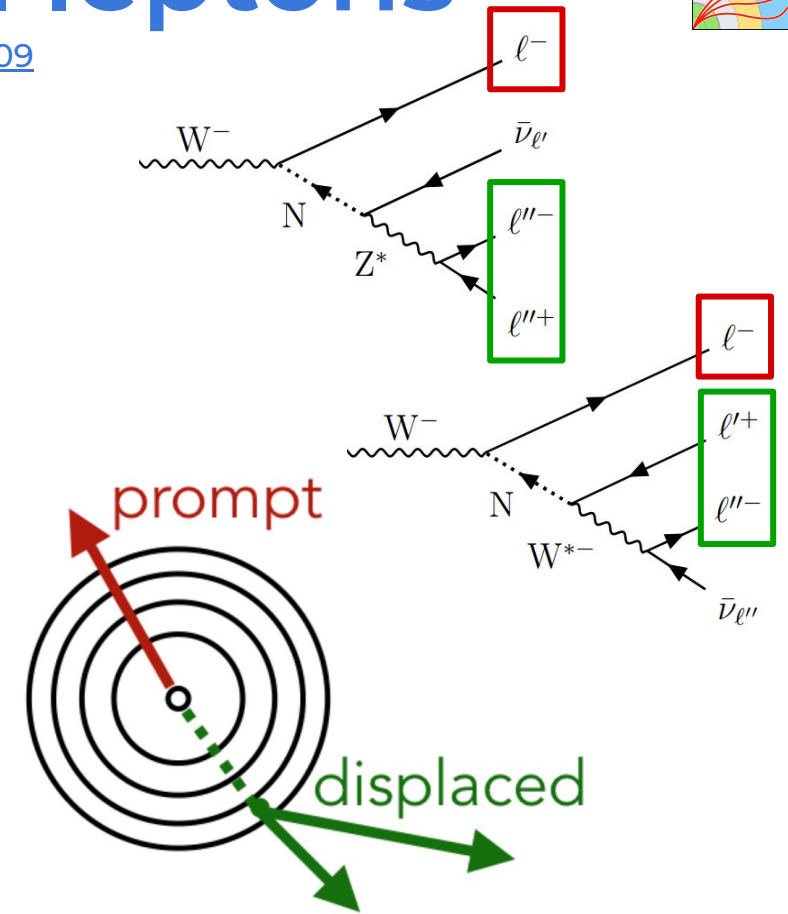
CMS-PAS-EXO-20-009

Search for heavy neutral leptons (**HNL**) that mix with SM neutrinos

Target difficult region of parameter space
- small **HNL** masses + small neutrino mixing
- → long-lived **HNL**

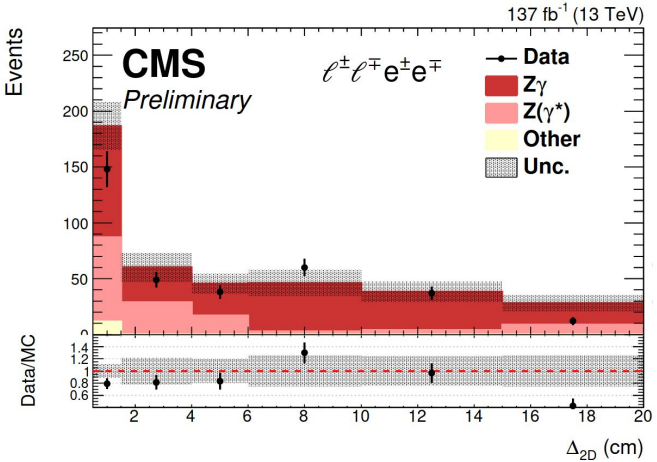
Look for **HNL** from W decays that decay to W or Z bosons, producing:
- 1 prompt ℓ
- 2 displaced ℓ that form a **common vertex**

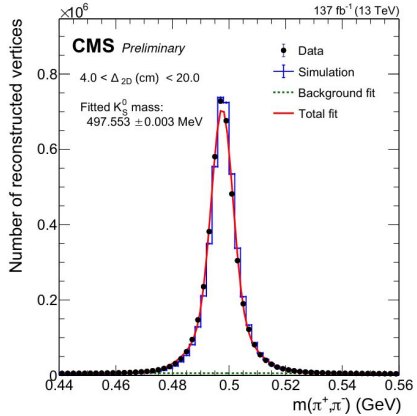
Trigger on prompt ℓ to enable sensitivity to low-momentum displaced ℓ
- Sensitive to **HNL** masses < 20 GeV



Heavy neutral leptons

CMS-PAS-EXO-20-009





Take advantage of **HNL** decay kinematics

- Distance between primary and secondary vertices (Δ_{2D})
- Displaced di-ℓ invariant mass
- Angular distributions of prompt and displaced ℓ

Backgrounds

- SM hadron decays
- misidentified hadrons
- unidentified photon conversions

Estimate background from data

- “tight-to-loose” method in data control regions
- validate with closure tests in sideband regions

Heavy neutral leptons

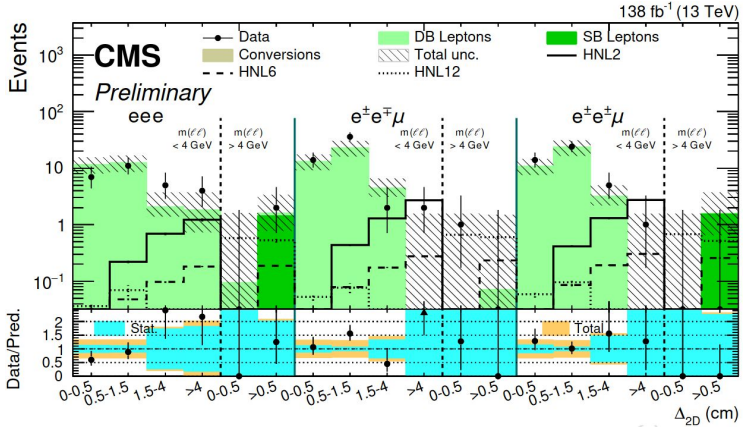
[CMS-PAS-EXO-20-009]

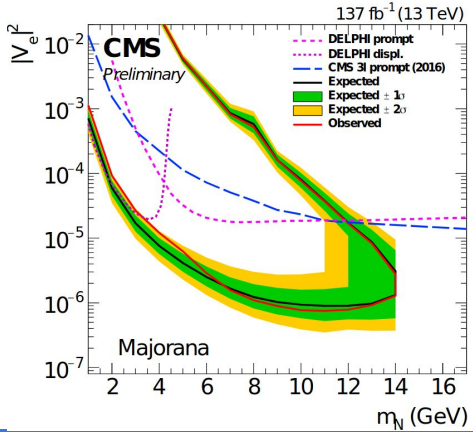
Categorize SR events by invariant mass, vertex displacement, and lepton flavor

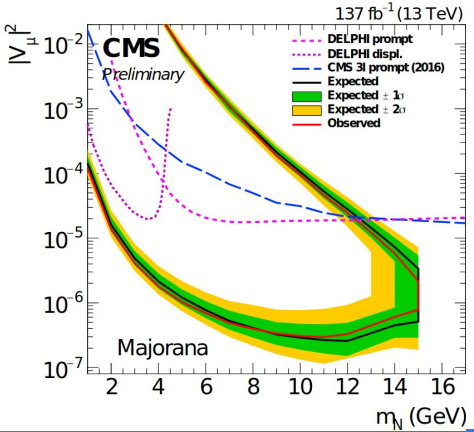
Observation consistent with background-only hypothesis

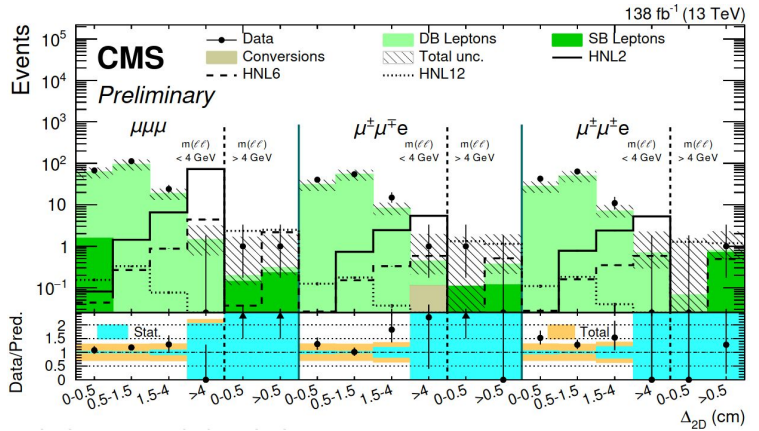
Constrain **HNL** neutrino mixing parameter values as a function of **HNL** mass

- **More than an order of magnitude improvement** over existing limits for many **HNL** masses!

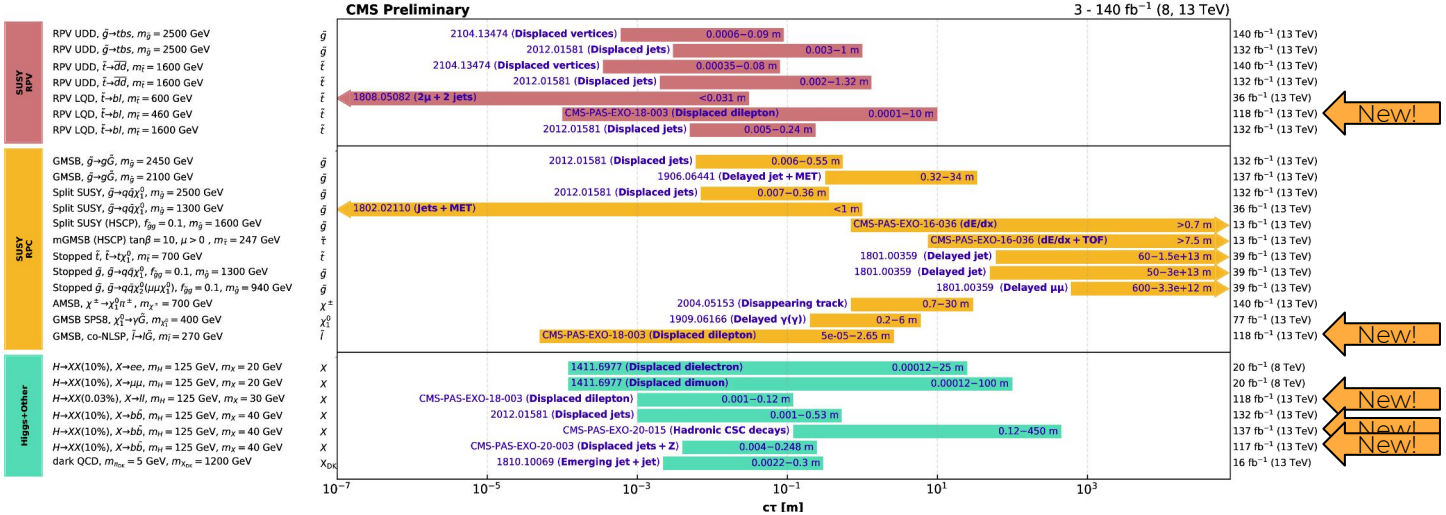








Conclusion



CMS is engaged in a rich, ongoing program of BSM LLP searches

Several recent results achieve complementary goals and test new regions of parameter space

- **Lower masses** with innovative triggering (EXO-20-003, EXO-20-014, EXO-20-009)
- **Longer lifetimes** with muon system decays (2107.04838)
- **Wide applicability** with model-independent, signature-based analysis design (EXO-18-003)

CMS will continue to explore the lifetime frontier in LHC Run 3 and beyond

- New triggers, techniques, and ideas
- New timing detector will open new possibilities

Additional material

LLPs in the endcap muon system

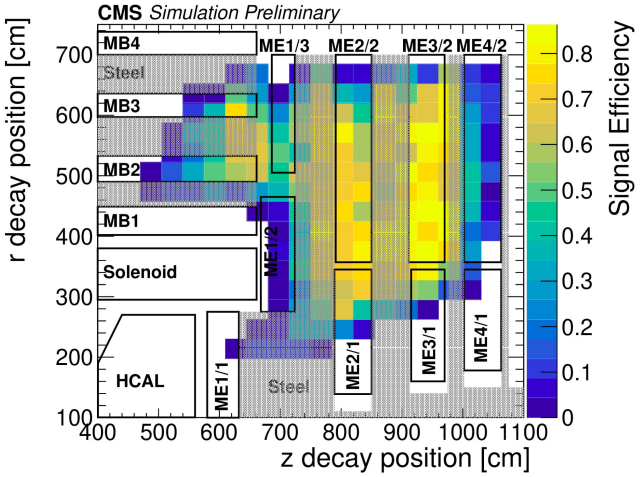
2107.04838

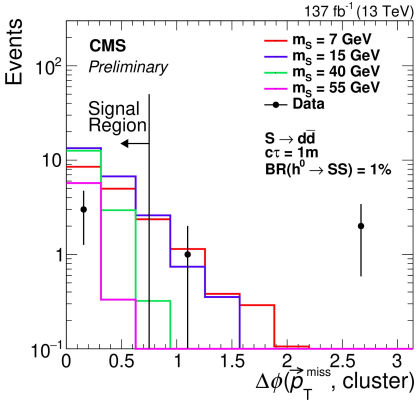
Neutral LLP decays could produce particle shower in CMS muon system
- Large radius → sensitive to large new particle lifetimes
- Steel in muon system provides excellent bg shielding

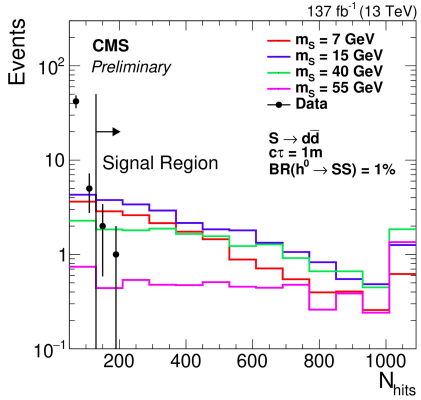
Trigger on missing energy, reject punch-through jets and μ-induced showers, and use number of CSC hits to separate signal and bg

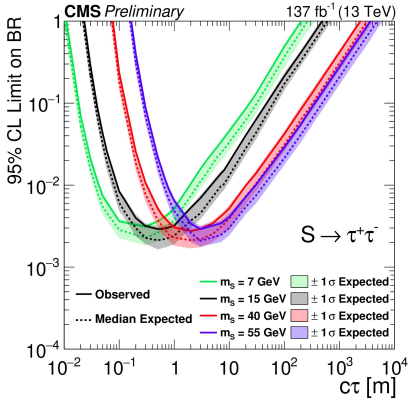
Current best LHC limits for LLP lifetimes above 6, 20, and 40 m assuming LLP masses of 7, 15, and 40 GeV, respectively

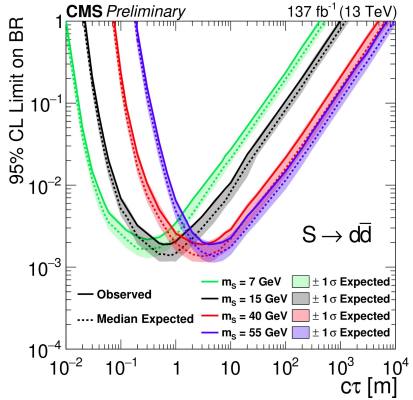
Dedicated trigger will improve performance in Run 3





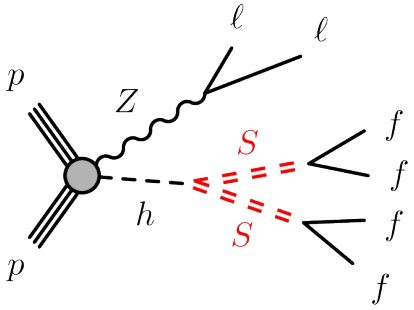


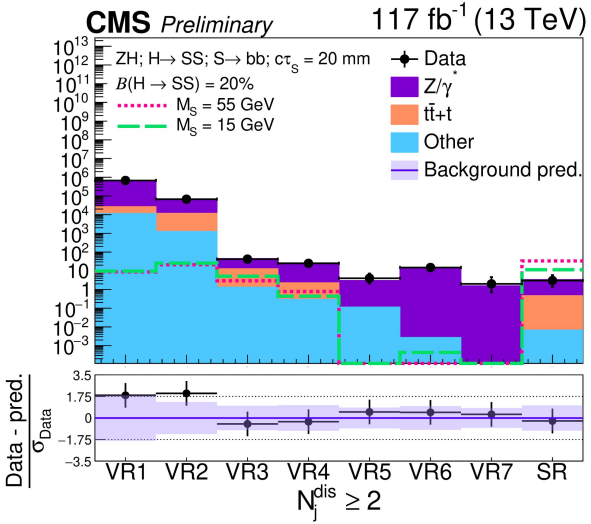




Displaced jets with a Z

CMS-PAS-EXO-20-014





Collect ZH associated production events with di-lepton triggers

Search for displaced jets from Higgs boson decays to long-lived scalars

Trigger strategy provides sensitivity to low-momentum displaced jets

Exclude H → SS → dd (bb) branching ratios above ~14% (~13%) for proper decay lengths of 1-5 cm