Searches for long-lived particles at CMS

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On behalf of the CMS Collaboration

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Why search for long-lived particles

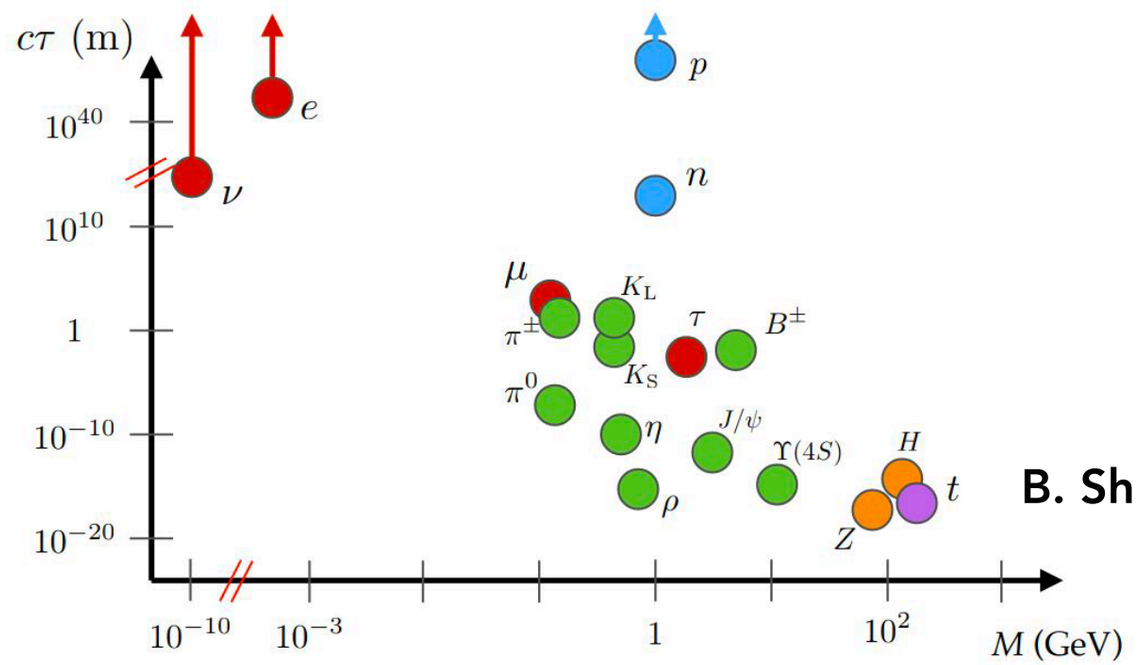
- The existence of long-lived particles (LLPs) is a common occurrence in both the standard model (SM) and beyond the SM scenarios

$$\tau_0^{-1} = \Gamma \sim \frac{1}{m} \int d\Pi_f \left| \mathcal{M}_{\text{decay}} \right|^2 ,$$

- A given particle is long-lived when:
  - The relevant coupling is small;
  - The decay is suppressed by some large scale;
  - The allowed final state phase space is small (i.e. with a nearly-degenerate mass spectrum)

- Many particles in the standard model are long-lived.

- LLPs in BSM scenarios are also well-motivated.



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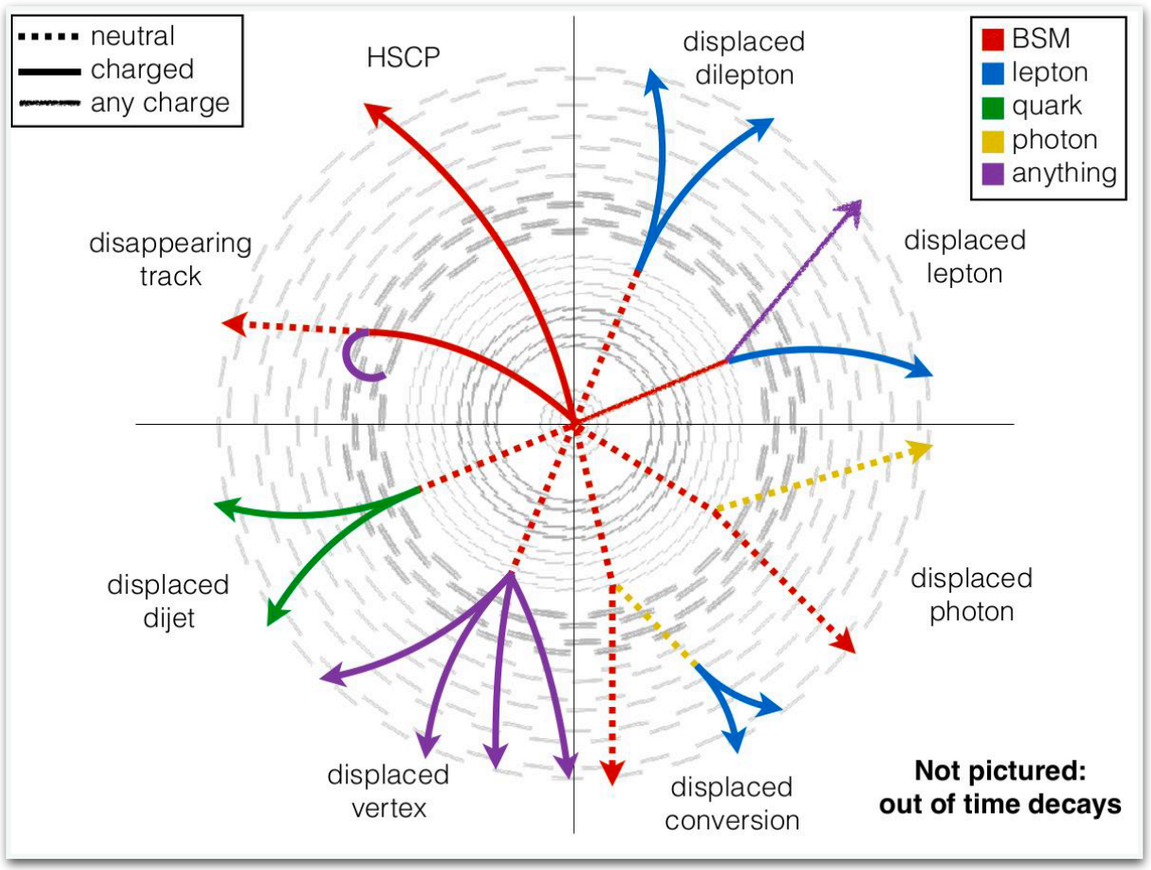
BSM LLP signatures

Rich signatures produced by BSM LLPs



Rich theoretical motivations for BSM LLPs

- **Split SUSY;**
- **SUSY with gauge mediation;**
- **SUSY with anomaly mediation;**
- **SUSY with R-parity violation;**
- **Asymmetric dark matter (DM) model;**
- **Freeze-in DM;**
- **Dynamical DM;**
- **Neutral naturalness;**
- **Heavy neutral leptons (HNLs);**

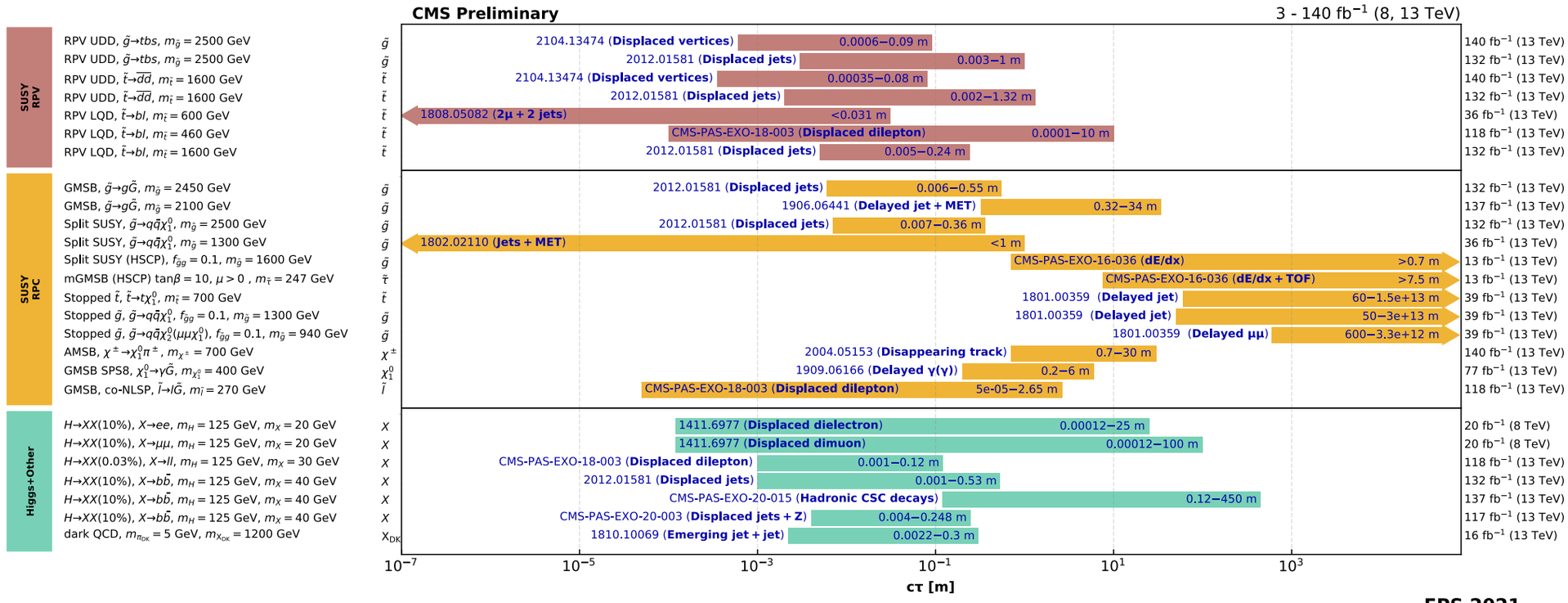
  ……

Unique experimental challenges

- **Standard techniques are usually tuned for prompt objects → inefficient for exotic LLPs;**
- **Calls for innovations in the multiple stages of the analyses:**
  - Specialized LLP triggers;
  - Special reconstruction;
  - Dedicated offline discrimination;
  - Estimation of non-standard background.

Overall landscape of the CMS LLP program

Overview of CMS long-lived particle searches



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

- **CMS LLP program has a wide coverage on a large variety of models/lifetimes with different final-state topologies (hadronic, leptonic, photonic, HSCP, disappearing tracks, etc.)**

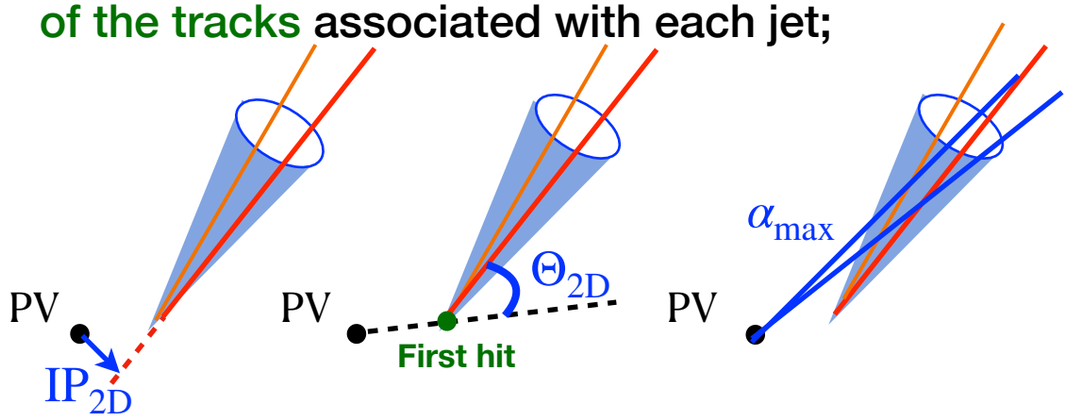
- **Recent full Run-2 results (public in 2021):**
  - CMS-EXO-20-003 **(Z+displaced jets)**
  - CMS-EXO-20-015 **(Hadronic CSC decays)**
  - CMS-EXO-20-014 **(displaced dimuon with scouting)**
  - CMS-EXO-18-003 **(inclusive displaced leptons)**
  - CMS-EXO-20-009 **(HNL with displaced leptons)**

Displaced jets accompanied with a Z boson

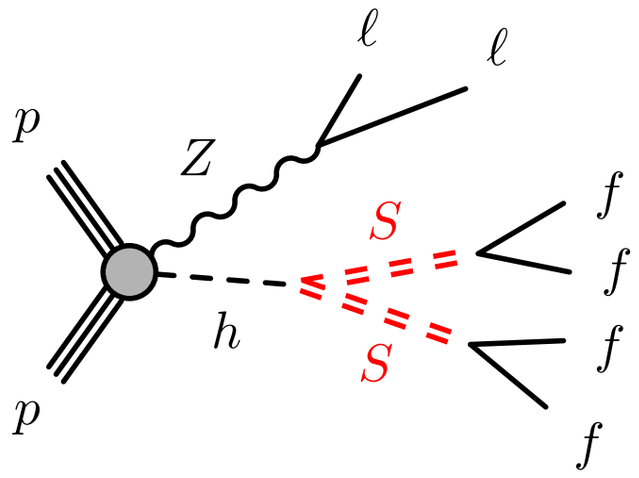
CMS-EXO-20-003

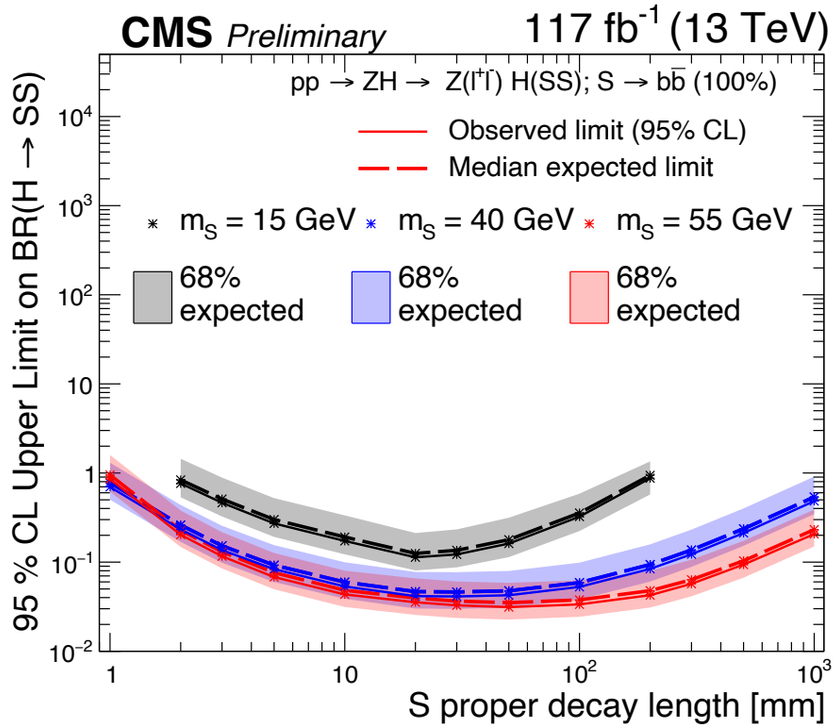
Search for SM-like (125GeV) Higgs boson decaying to LLP with ZH production

- Triggered with prompt leptons produced by the decaying Z boson;
- Cut-based displaced-jet tagging using the properties of the tracks associated with each jet;



- Look for events with ≥ 2 displaced jets;
- Expected 3.5 ± 1.8 background events, observed 3 events;
- Complementary to the CMS inclusive displaced jets search (CMS-EXO-19-021, PRD 104 012015) for low mass ($m_S < 20\text{GeV}$) heavy-flavor decays ($S \to bb$)





Hadronic decays in the endcap muon detector

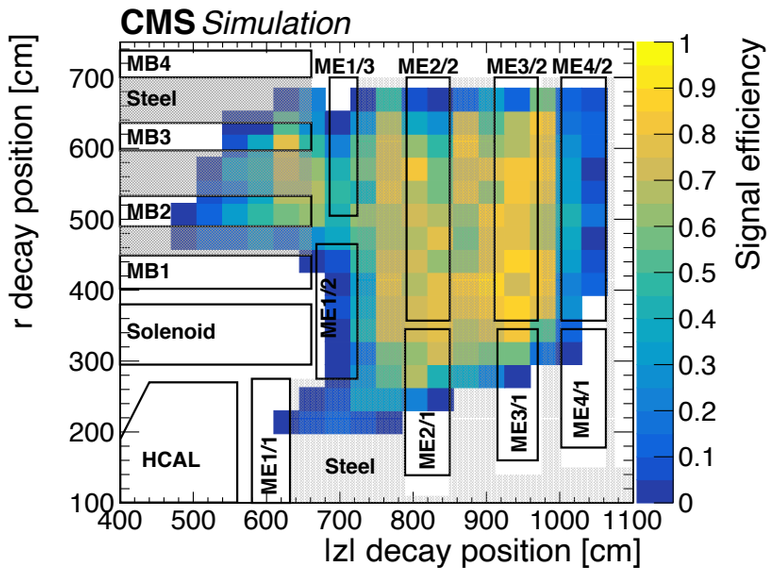
CMS-EXO-20-015

Search for hadronic decays of neutral LLPs inside the cathode strip chambers (CSCs) located at the endcaps

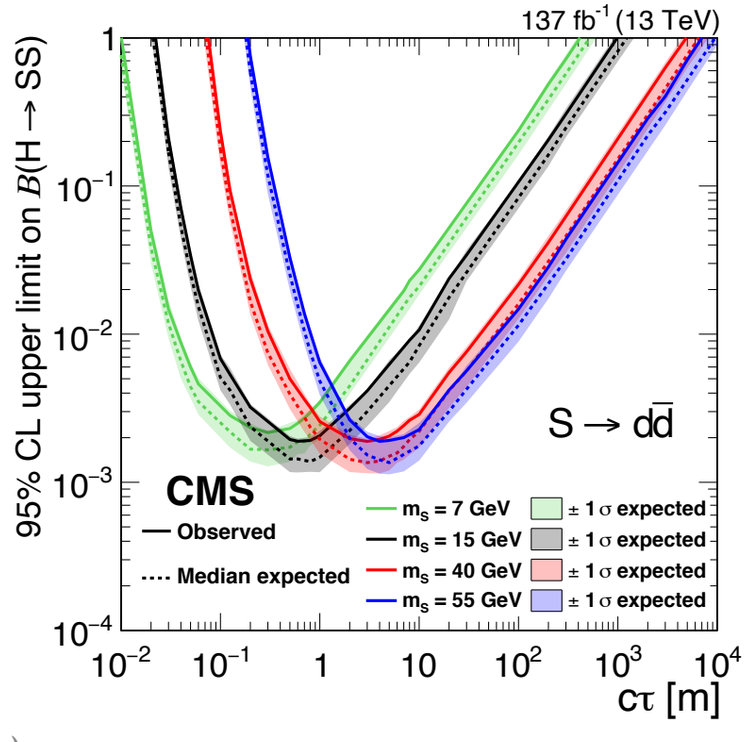
- CSC acts as a sampling calorimeter!
  - Hadronic decays of neutral LLPs produce clusters of large number of hits;
  - Low background due to the large interaction lengths before the muon endcaps

- Triggered with $p_{\mathrm{T}}^{\mathrm{miss}}$
  - Produced by ISR and LLPs decaying outside of the tracker and calorimeters.

- Dedicated cluster reconstruction using CSC hits
  - The LLPs are neutral→ veto clusters matched with jets or muons;
  - Number of hits in the cluster N_{hits} serves as the main discriminating variable.

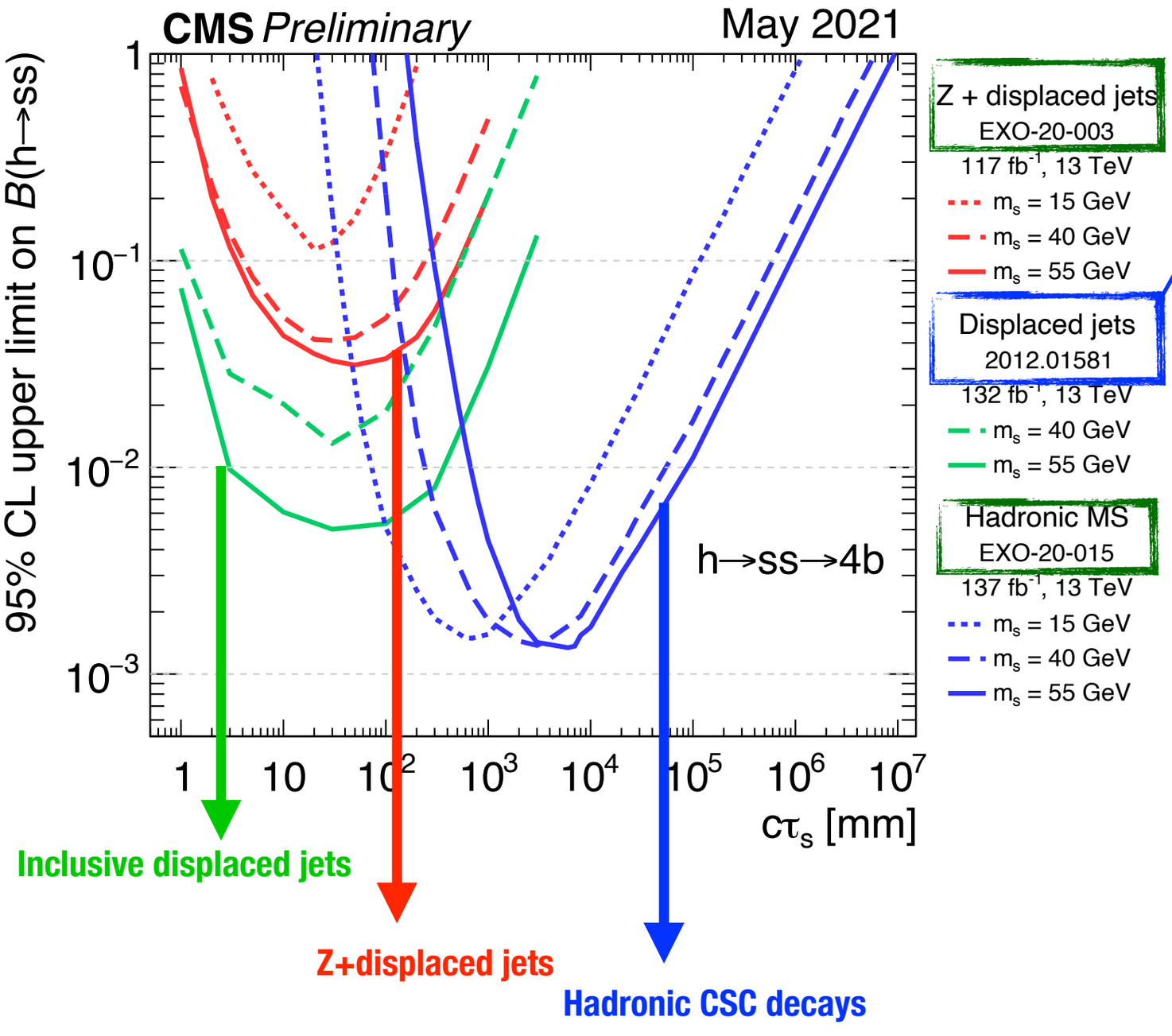


Interpreted with $pp \to \mathrm{H} \to \mathrm{SS}, \mathrm{S} \to \mathrm{dd}/\mathrm{bb}/\tau\tau$



CMS sensitivities to $H \rightarrow$ LLPs with hadronic decays

125 GeV $H \rightarrow SS \rightarrow bbbb$



Previous results obtained with the CMS inclusive displaced-jets search (PRD 104, 012015)

- Dedicated displaced-jets triggers allow sensitivities to ggH production with LLPs decaying in the tracker.

The three searches/approaches are complementary to each other, together they provide an excellent coverage over a large range of LLP lifetime (span ~7 orders of magnitude!)

Inclusive displaced-leptons search

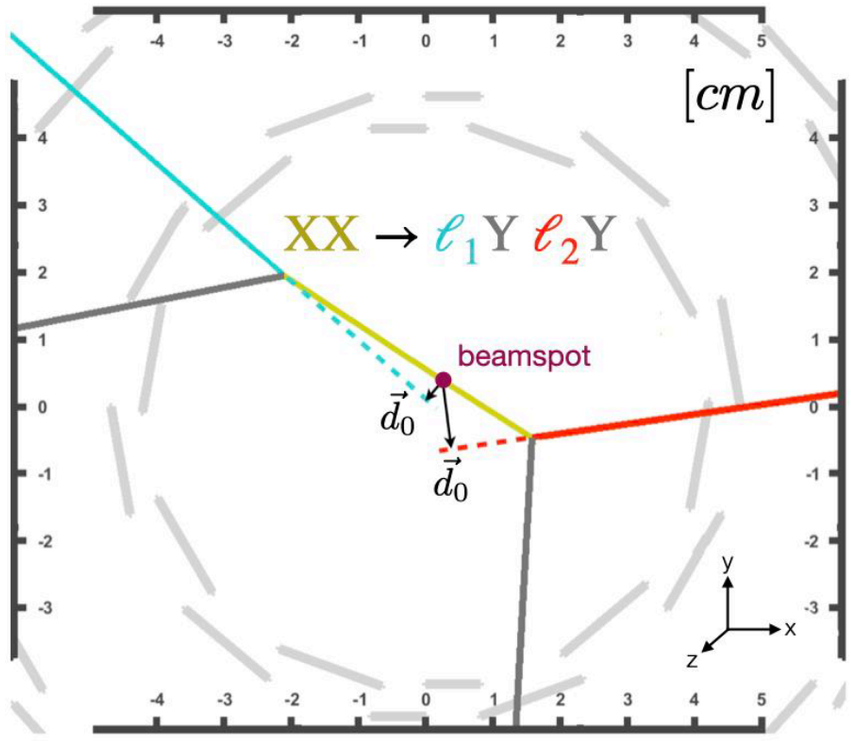
CMS-EXO-18-003

Inclusive search for displaced leptons ($e\mu, \mu\mu, ee$) with large impact parameters

- As model-independent as possible
  - No common-vertex requirement on the displaced-lepton pair → the two displaced leptons can originate from two separate displaced vertices;
  - No requirements on additional objects (jets, MET, lepton charge, etc.).

The search is sensitive to any model with displaced, isolated electrons or muons

- Transverse impact parameter d_0 serves as the main discriminating variable
  - **Signal region:** at least 2 leptons with $100\mu\text{m} < |d_0| < 10\text{cm}$



- Displaced muons triggered with special displaced-muon reconstruction (no PV constraint) at HLT.
- Displaced electrons triggered using photon reconstruction at HLT.

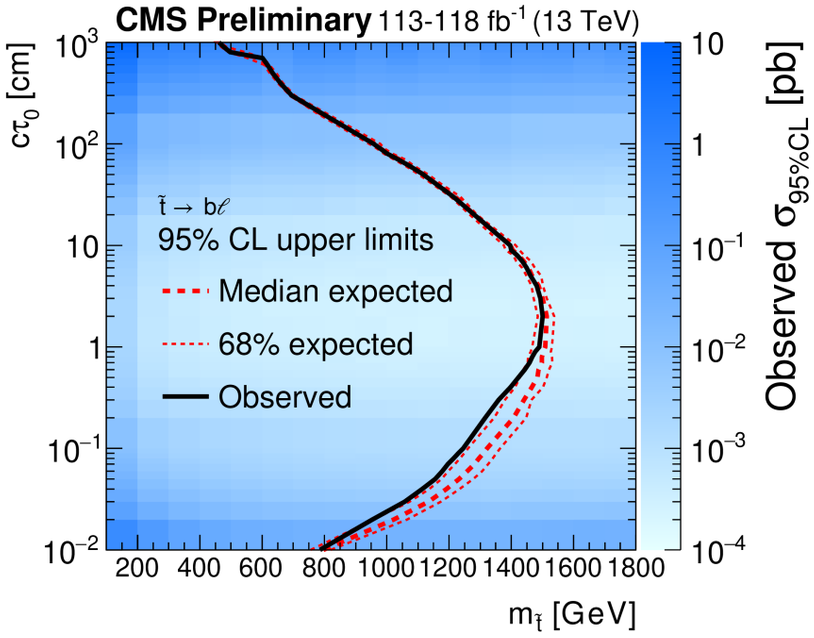
Offline lepton p_T thresholds are 35-75 GeV depending on the channel (constrained by HLT thresholds)

Inclusive displaced-leptons search

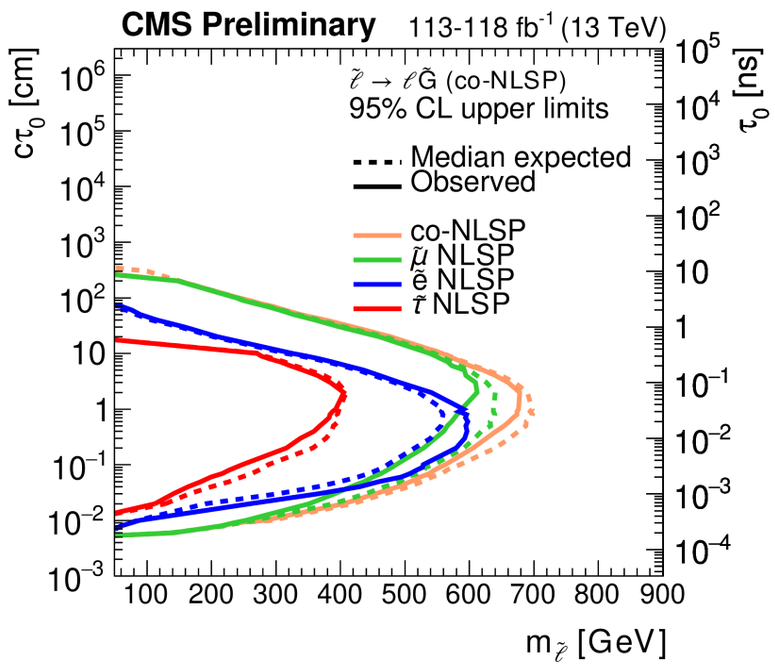
CMS-EXO-18-003

Placed limits on different models with displaced leptons

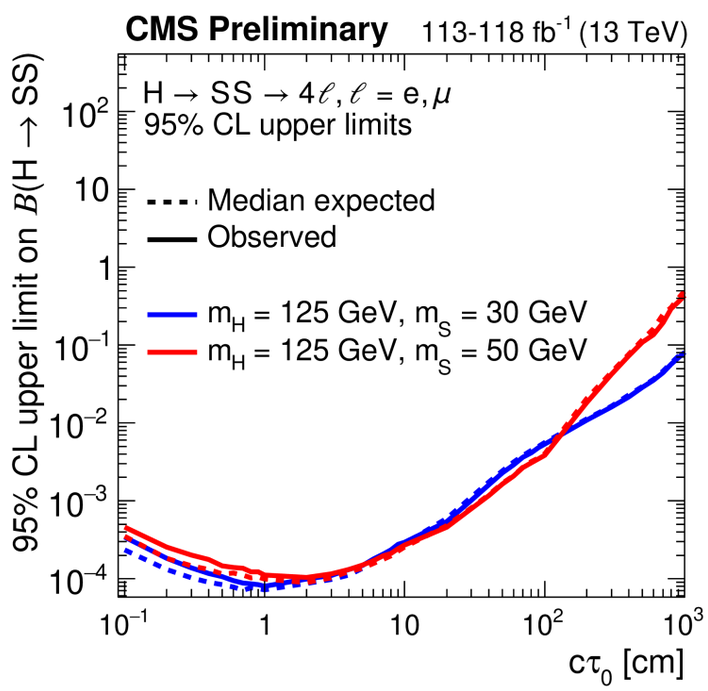
RPV SUSY ($\tilde{t} \to q\ell$)



GMSB ($\tilde{\ell} \to \ell\tilde{G}$)



exotic Higgs decays



Competitive limits on SUSY models, especially for small lifetime ($c\tau_0 < 1$ mm), due to looser selection on the lower bound of $|d_0|$ (100μm)

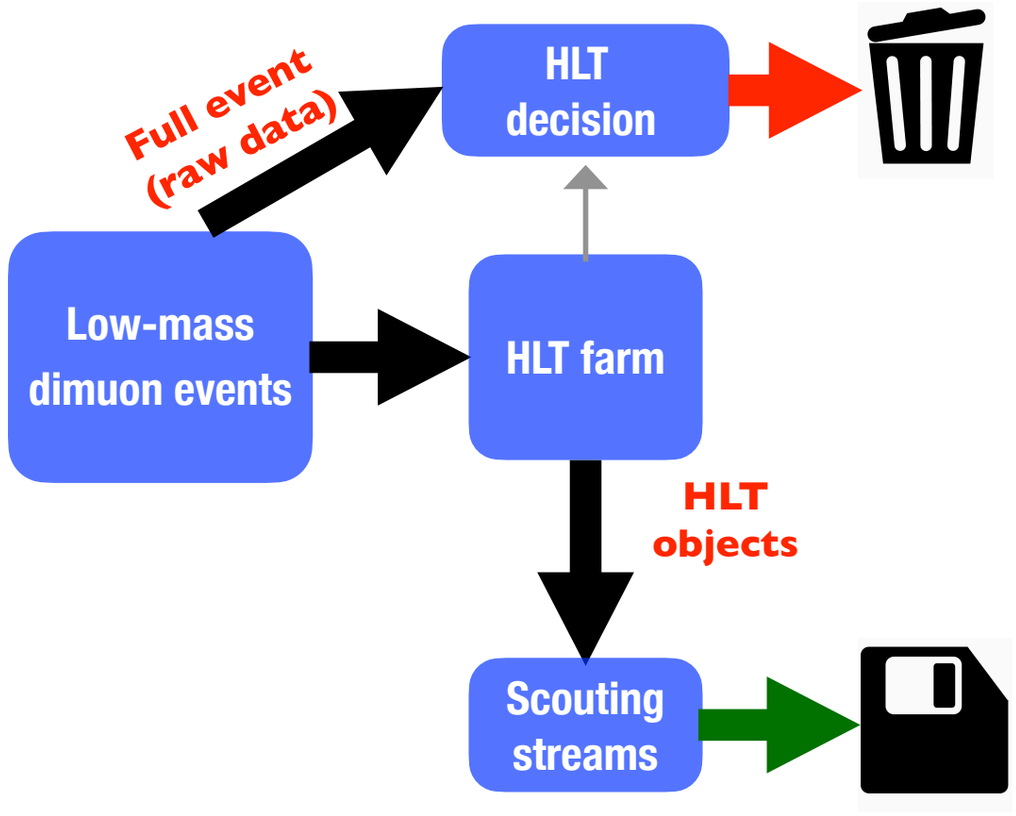
Currently most stringent limits for $c\tau_0 < 50$ cm

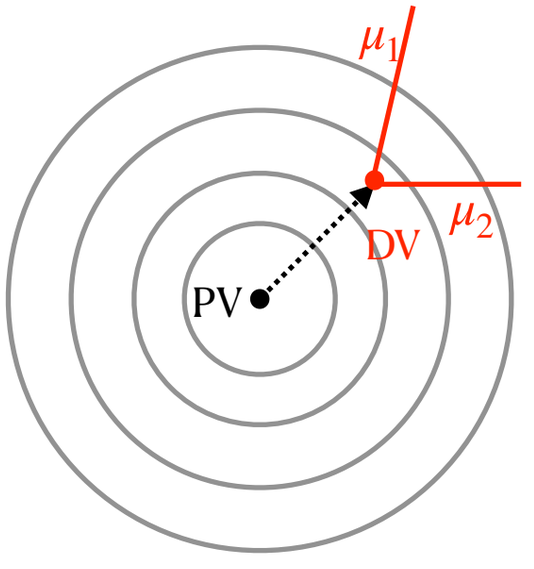
Displaced dimuon with scouting

CMS-EXO-20-014

Search for LLP decaying into displaced dimuon using data collected with high rate triggers ("scouting")

- Data scouting
  - Bypass the high-level trigger (HLT) thresholds by directly sending HLT objects to disk instead of saving raw data;
  - Reduced information compared to offline reconstructed objects;
  - Allow sensitivities to otherwise unaccessible low-mass events.
- Search for a narrow displaced dimuon resonance
  - Look for 2 opposite sign (OS) displaced muons ($p_T^{\mu} > 3$ GeV) originating from a common displaced vertex;
  - DV/dimuon kinematics & displacement requirements, material veto to reduce background yields.

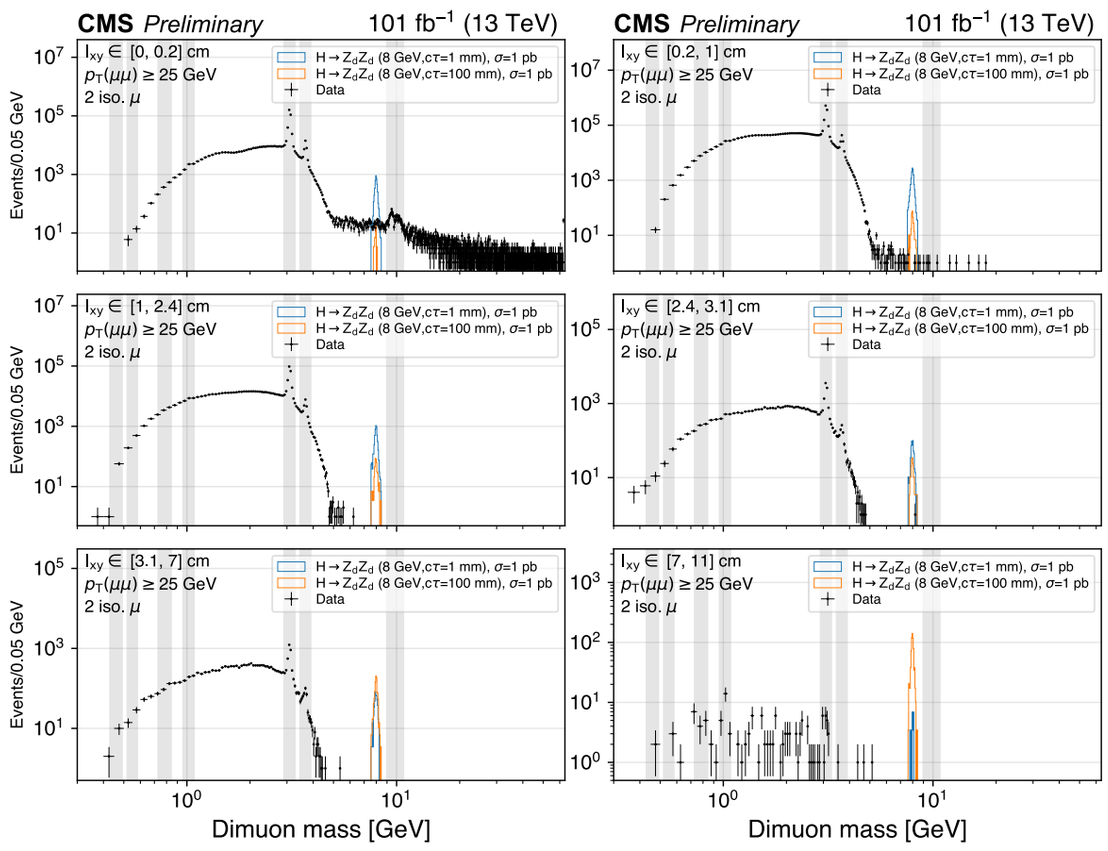




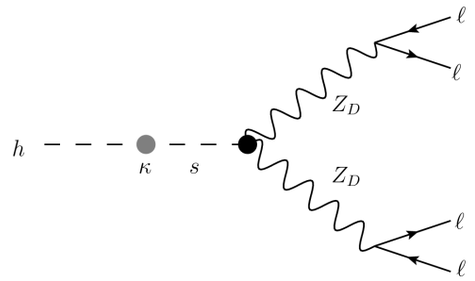
Displaced dimuon with scouting

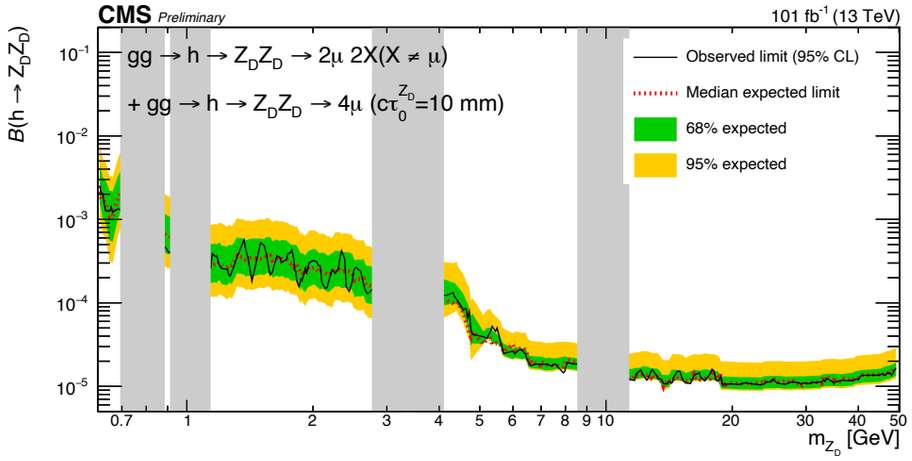
CMS-EXO-20-014

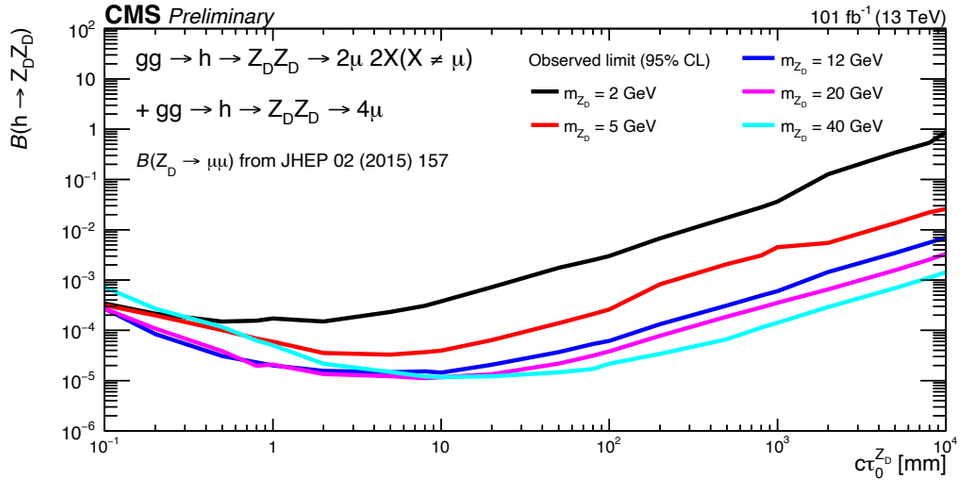
- Search for a narrow displaced dimuon resonance
  - Categorized in bins of L_{xy}, $p_T^{\mu\mu}$, and isolation
  - Simultaneous fit of the dimuon mass spectrum in all categories to extract the signal



Interpreted with dark photon Z_D decaying into displaced dimuon (as well as exotic B-meson decay)



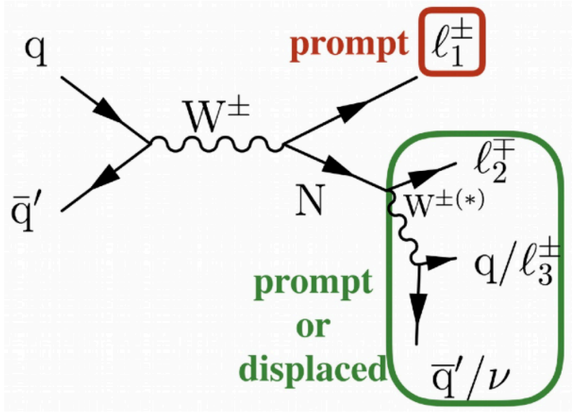




HNL search with displaced leptons

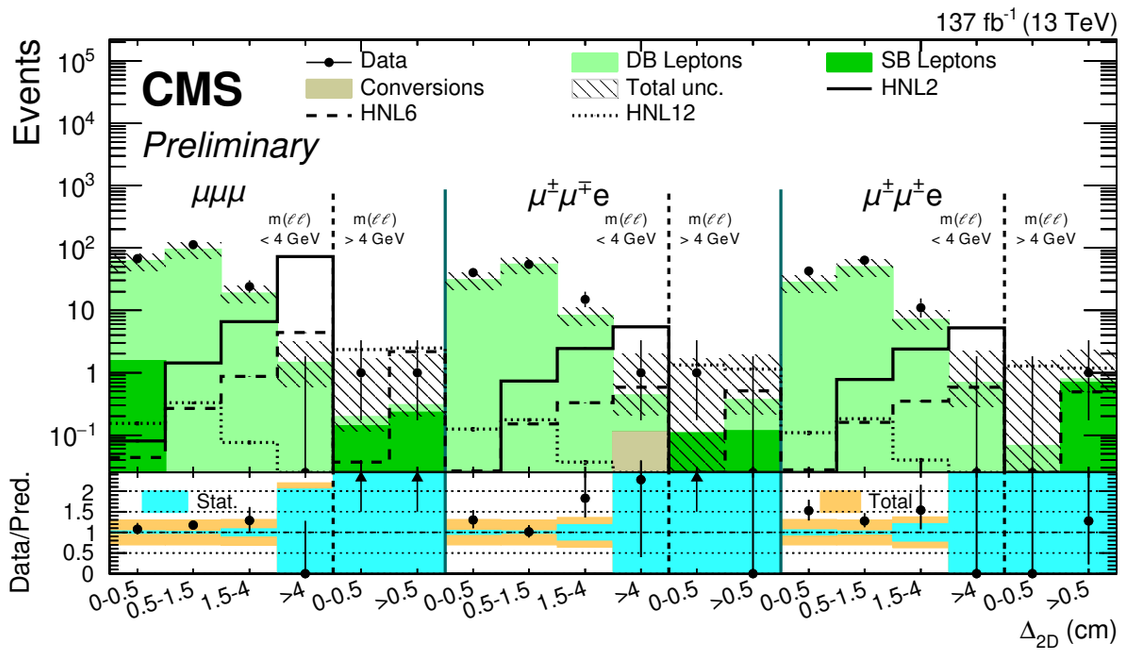
CMS-EXO-20-009

Search for Heavy neutral leptons (HNLs) with displaced leptonic decays



$\tau \propto \sum_i |V_{iN}|^{-2} m_N^{-5}$

- **HNL is long-lived when the mass or the mixing angle is small;**
  - When long-lived HNL decays leptonically, the final state consists of one prompt lepton and two displaced leptons
- **Search for two opposite-sign displaced leptons accompanied with on prompt lepton**
  - Events triggerd with the prompt lepton;
  - Reconstruct secondary vertex using the two displaced leptons;
  - Secondary vertex (SV) invariant mass and displacement serve as the main discriminating variables;
  - Other requirements on the SV quality, dilepton kinematics and trilepton kinematics to reduce the background.

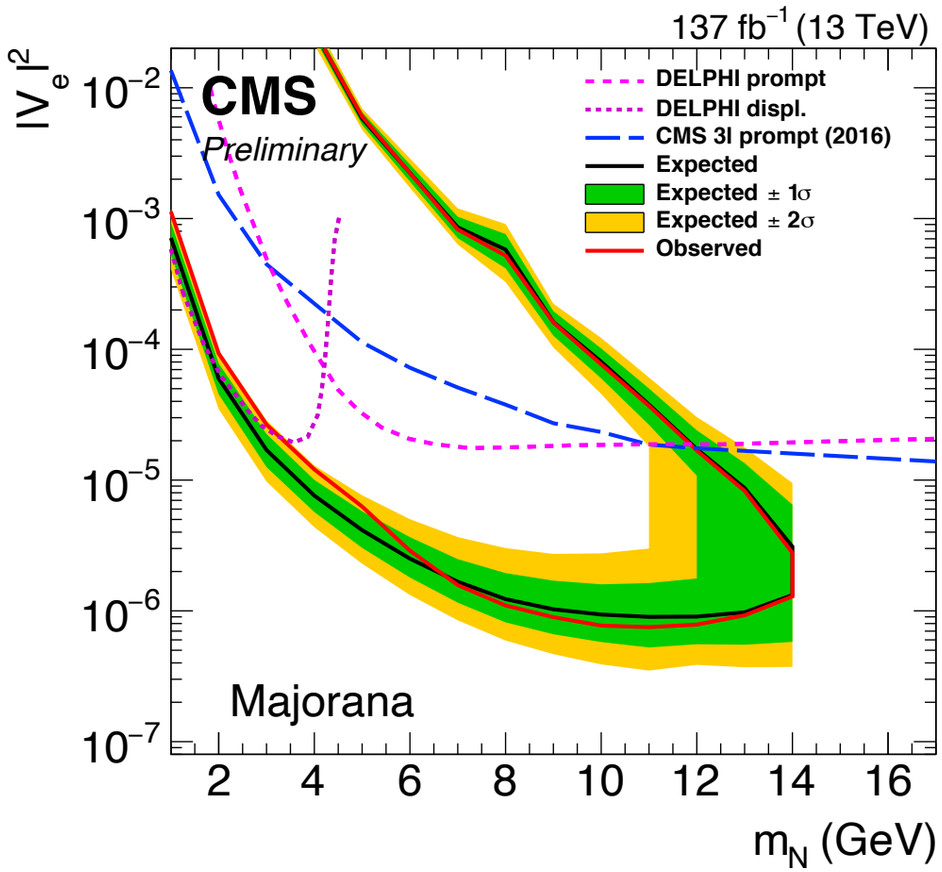


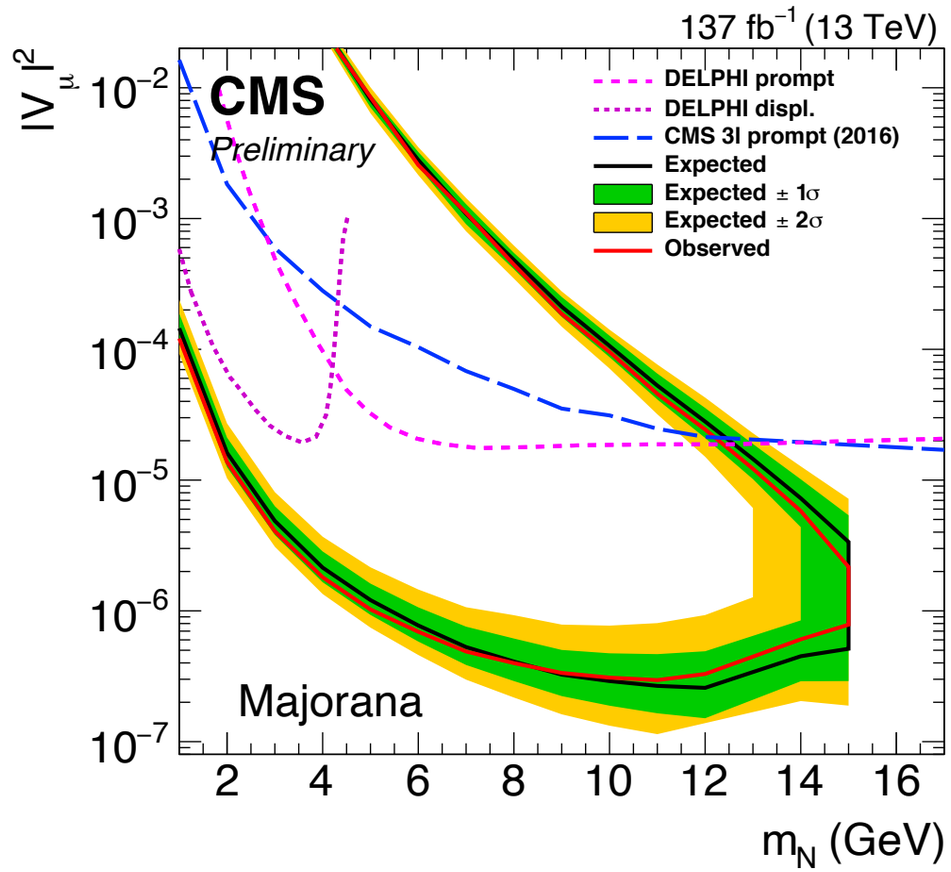
SV displacement

HNL search with displaced leptons

CMS-EXO-20-009

Observations consistent with background predictions
Placed limits on HNL mass and mixing angles





Greatly extended excluded phase space on top of previous searches.

Summary and outlook

- **CMS LLP program provides a wide coverage on a vast variety of BSM LLP signatures/models;**
  - Many more Run-2 searches in the pipeline → stay tuned!

- **At the same time, Run 3 will also be a great opportunity to further boost the capability of CMS to probe more challenging LLP signatures**

  - Novel level-1 and high level triggers dedicated to LLP signatures;
  - Improved reconstruction techniques utilizing and combining different information from different subdetectors (tracking, vertexing, timing, clusters in MS, etc.)
  - Advanced machine learning tools to help tackle some challenging and important LLP signatures (e.g. low-mass LLPs with hadronic decays)

Exciting times ahead!