Searches for long-lived particles at CMS

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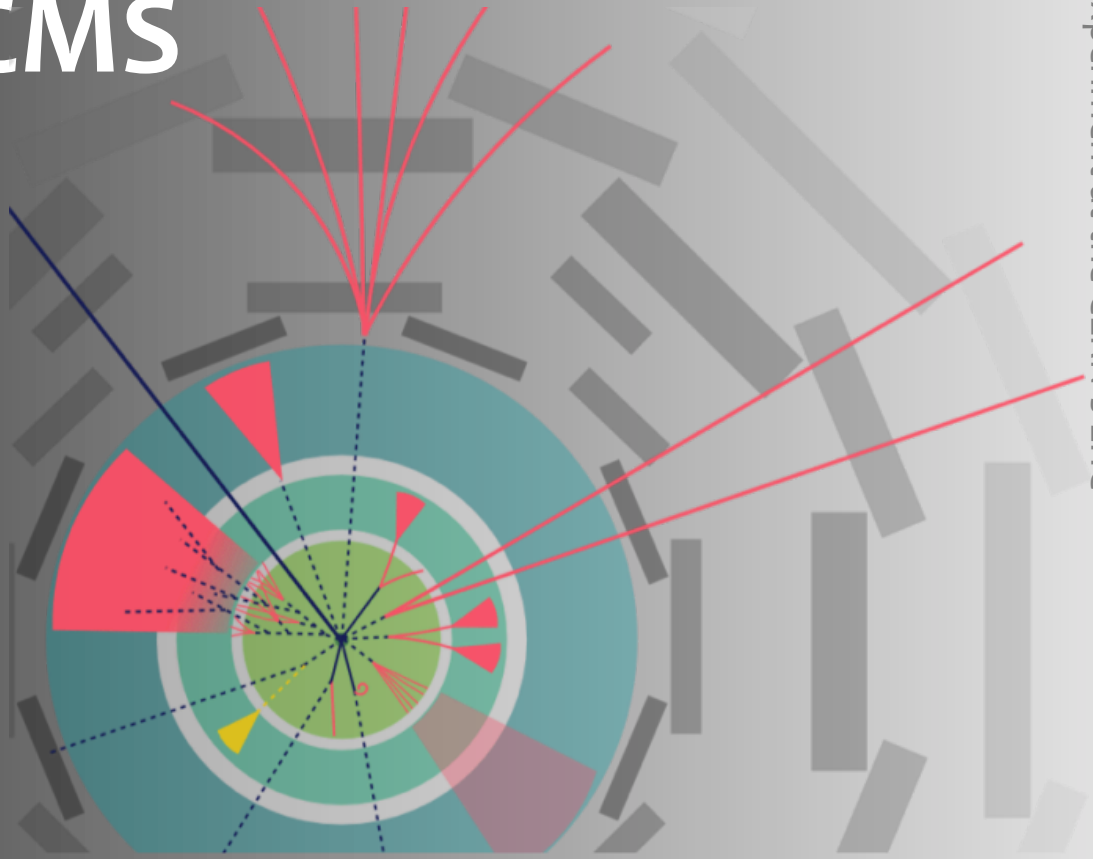


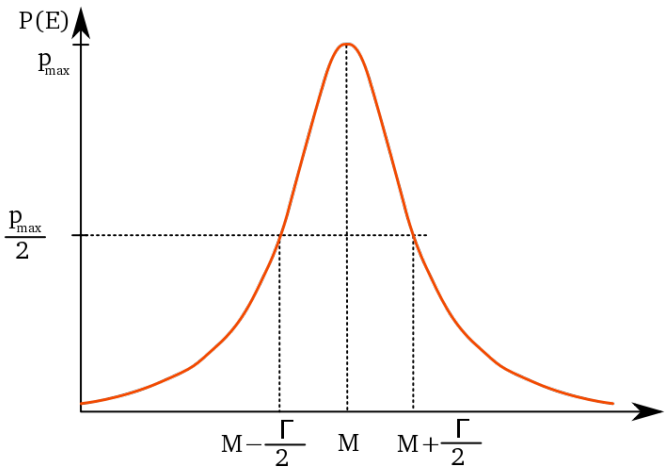
Compact Muon Solenoid experiment at the CERN's LHC

22th PANIC
Particles and Nuclei International Conference
5-10 September 2021
(Virtual) Lisbon, PT

Long Lived Particles (LLPs)

- Particles with a **macroscopic lifetime, $c\tau \gtrsim 1$ mm**

- Particles have: **mass (M)** and **width (Γ)**
- **Γ** is determined by how the particle decays
  - proper lifetime: **$\tau \sim 1/\Gamma$**



- Particles can gain a large lifetime (small **Γ**) whenever a particle decays via:
  - small couplings (**ε**),
  - high scale operators (**Λ**) (*heavy mediator*)
  - small phase space (**Φ**) (*compressed spectra*)

$$\Gamma \sim \varepsilon^2 \left(m/\Lambda\right)^{2n} \Phi$$

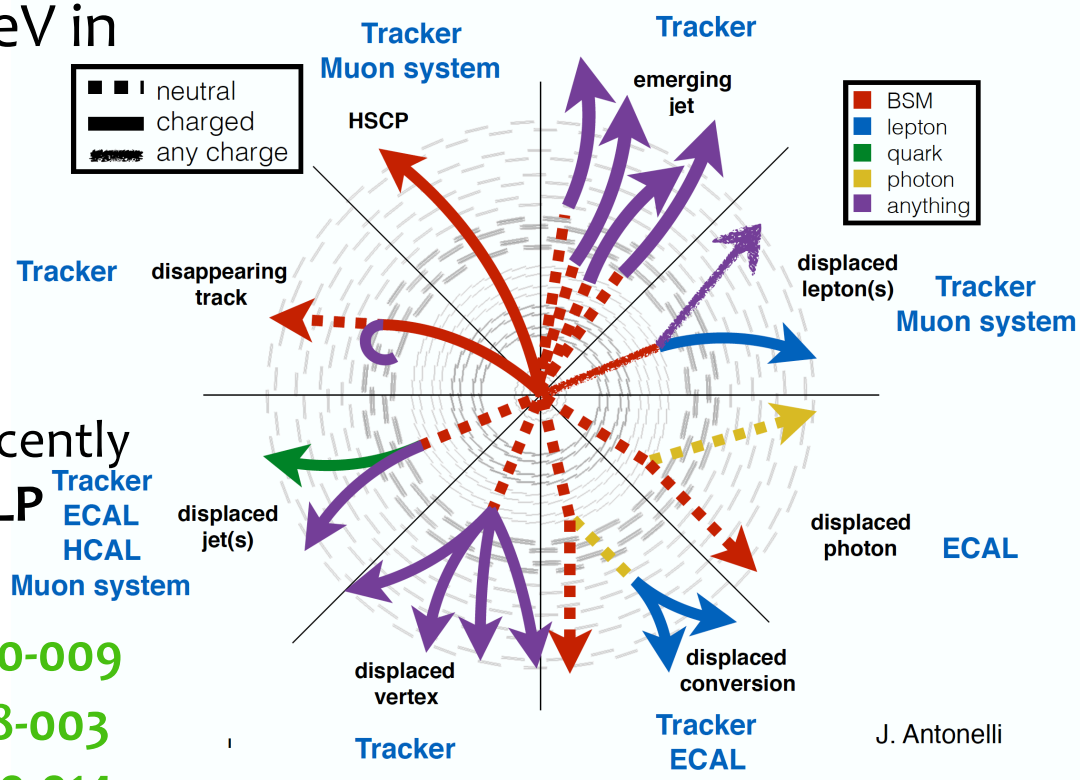
- Many BSM (SUSY, RPV, Hidden Sectors, etc.) models predict **LLPs**
- **LLPs** have **unusual** final states that require **innovative** techniques
- **Challenging** from the experimental point of view
- Difficult to simulate **background –** have to be estimated from data

Searches for long lived particles

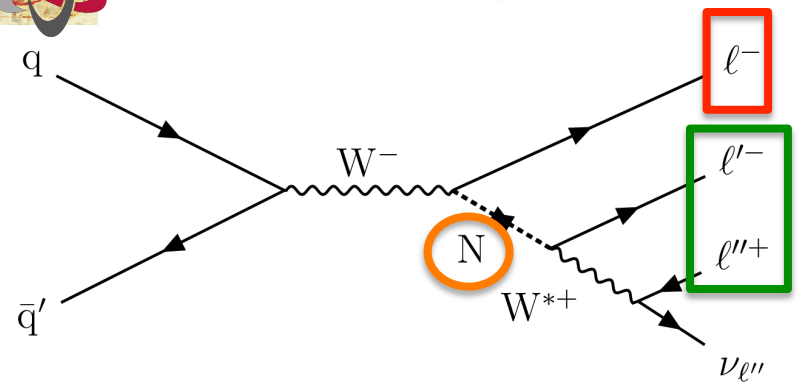
- LLPs have many possible exotic **signatures** (model independent analyses) studied by the CMS detector and more challenging ones are under consideration

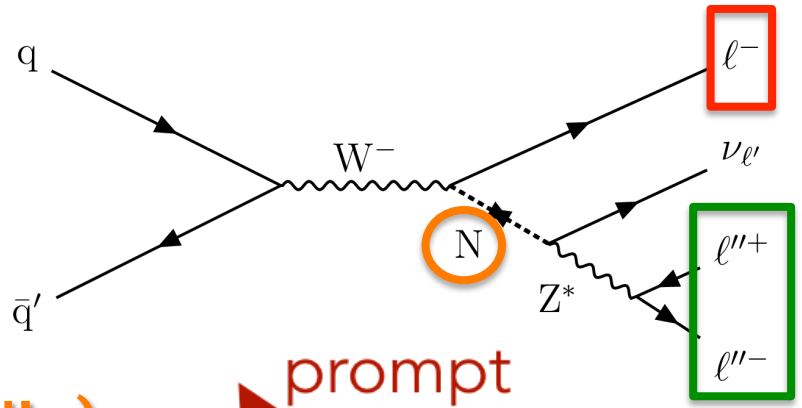
- Using data collected at 13 TeV in **Run II up to 137/fb:**
  - 2016 – 36/fb,
  - 2017 – 41/fb,
  - 2018 – 60/fb

- In this talk, the focus is on recently published **by CMS** searches for **LLP** decaying in the tracker:
  - Heavy neutral leptons **EXO-20-009**
  - Displaced leptons **EXO-18-003**
  - Di-μ displaced vertex **EXO-20-014**
  - Displaced jets + Z **EXO-20-003**

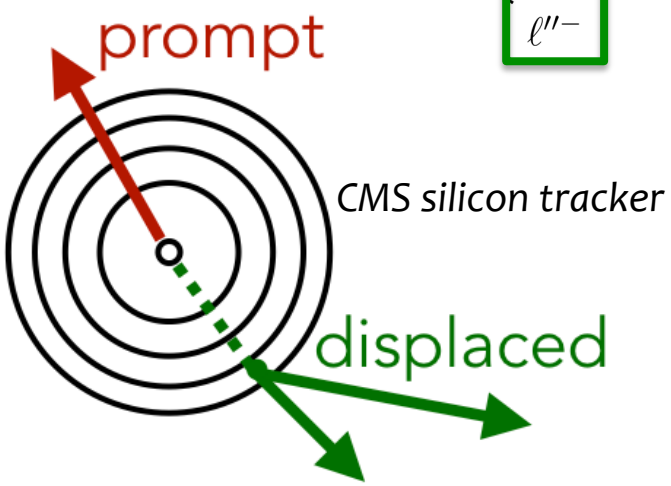


Heavy neutral leptons (HNL)





Majorana or right-handed Dirac neutrinos **(HNLs)**
interact only with SM neutrinos
HNL $(M_N, |V_\ell|^2)$



Difficult region of parameter space:

- HNL **production:** in decays of W bosons
- HNL **decays:** N→Wl, N→Zν
- HNL **lifetime:** smaller is the mass (**< 20 GeV**) or neutrino-mixing (**V~ 10^{-7} - 10^{-2}**)

→ **long-lived HNL**

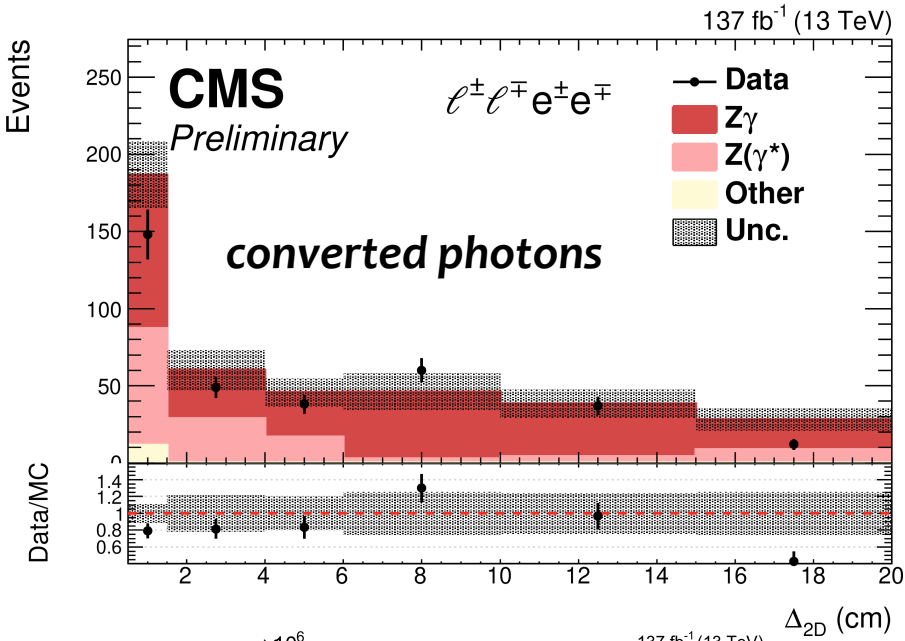
Signature: 3 lepton final state with:
- **2 displaced soft leptons** that form a **common vertex**
- **1 prompt lepton**
- Final states: **eeX** or **μμX** where X= {e, μ}

EXO-20-009, Jul 2021

Heavy neutral leptons

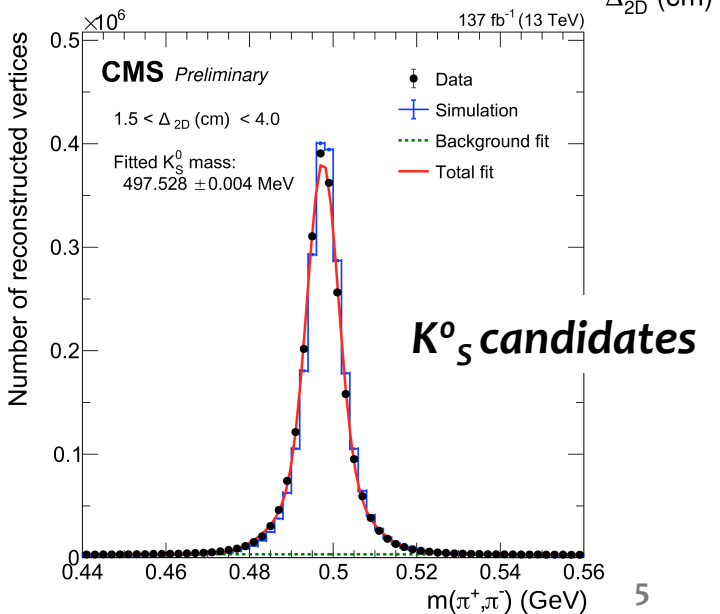
- **Trigger:**
  - **Single (or double) lepton** trigger on prompt lepton to enable sensitivity to low-pT displaced leptons

- **Discriminating variables:**
  design to reflect HNL decay kinematics:
  - **Distance** between **primary and secondary vertices** (Δ_{2D} < 20 cm)
  - Displaced **di-ℓ invariant mass**



- **Backgrounds:**
  - Unidentified **photon conversions**
  - Misidentified hadrons (K^0_S)

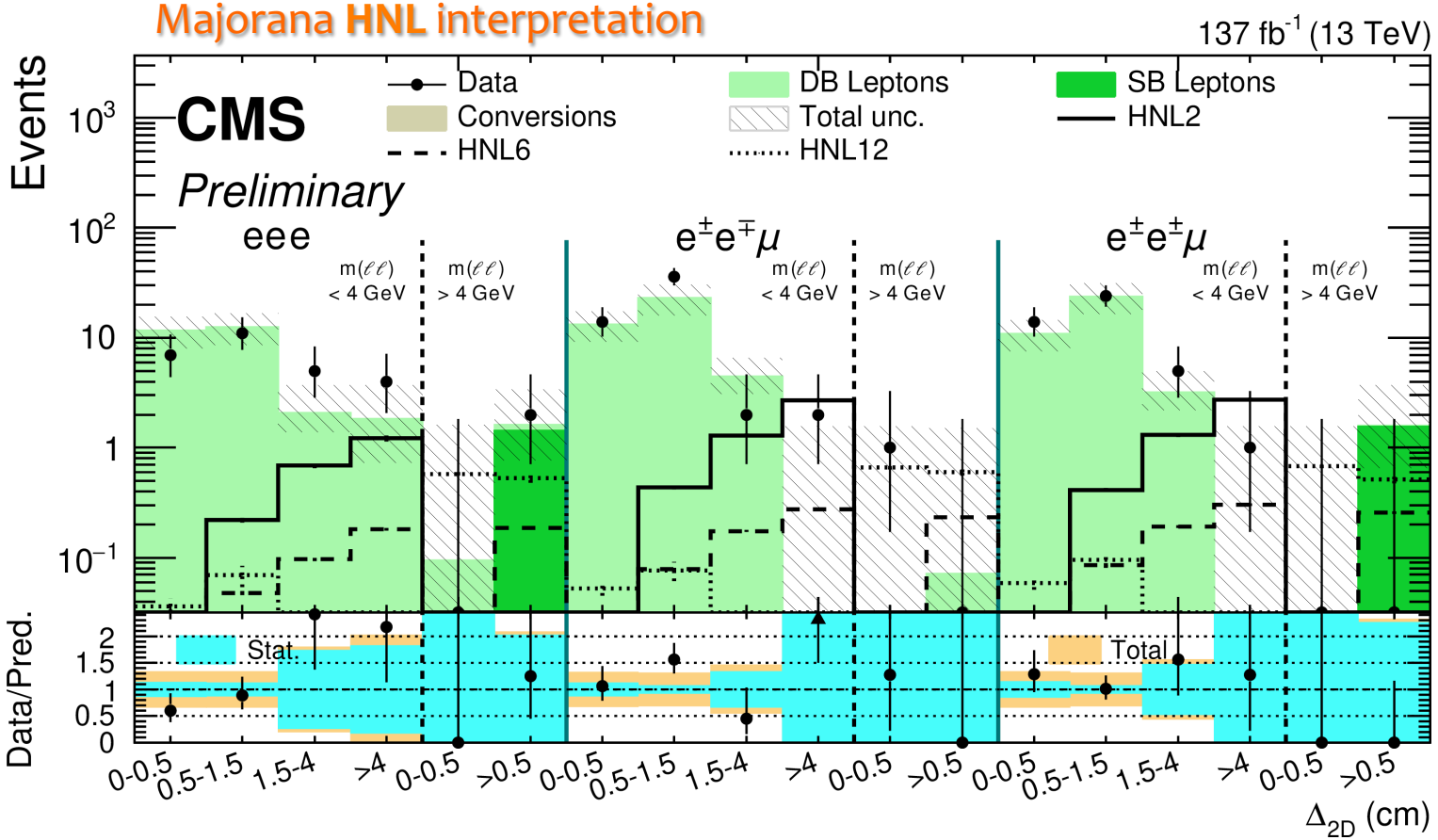
- **Data-driven estimation of background:**
  - "tight-to-loose" method in data control regions
  - Validate with closure tests in sideband regions



EXO-20-009, Jul 2021

Heavy neutral leptons – eeX results

- Events are categorized in SRs by lepton flavor, invariant mass and vertex displacement



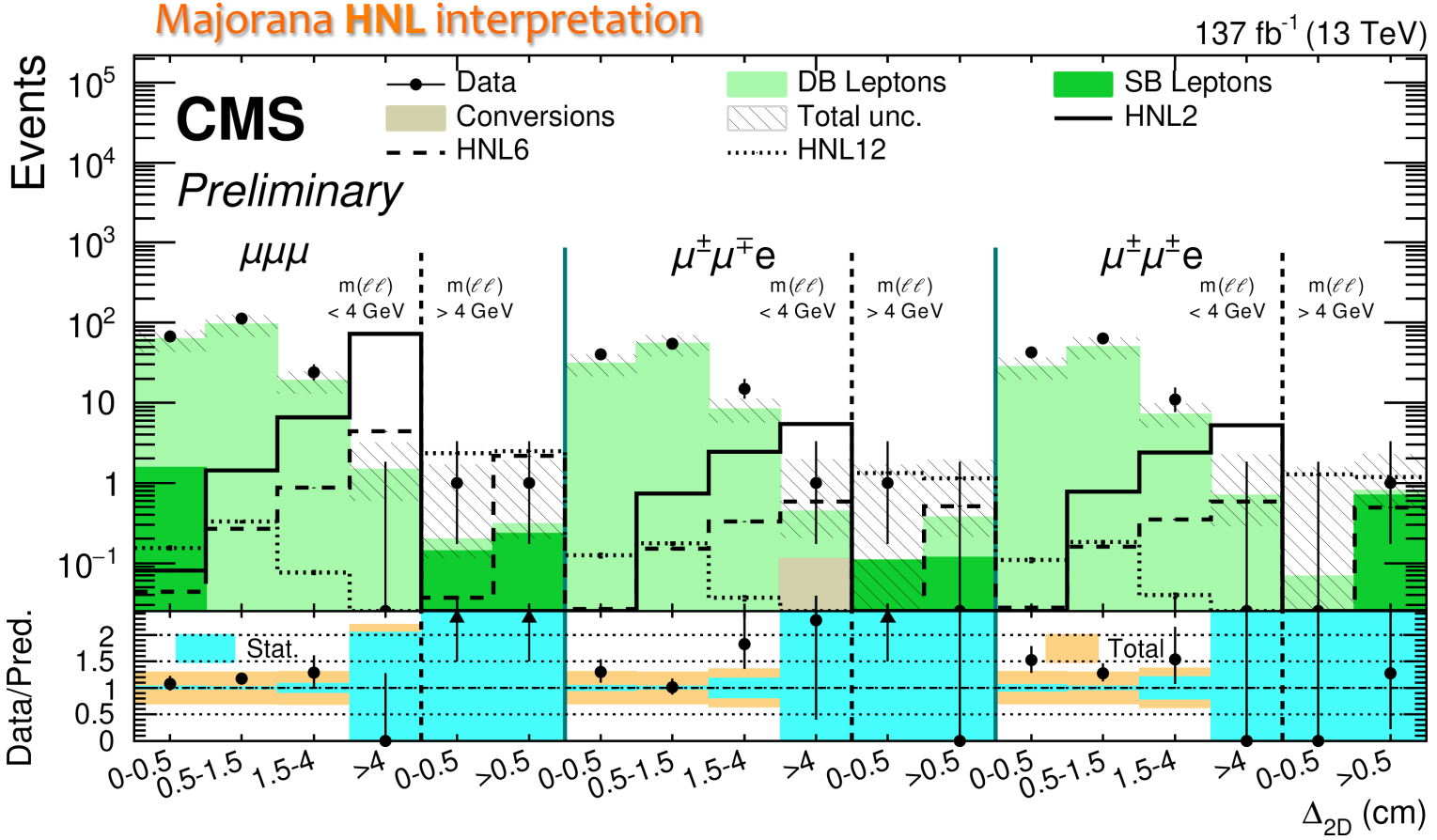
- No significant deviations from the SM expectations are observed for eeX and μμX final states

Majorana HNL: $m_N = 2$ GeV and $|V_{N\ell}|^2 = 0.8 \times 10^{-4}$ (HNL2), $m_N = 6$ GeV and $|V_{N\ell}|^2 = 1.3 \times 10^{-6}$ (HNL6), $m_N = 12$ GeV and $|V_{N\ell}|^2 = 1.0 \times 10^{-6}$ (HNL12).

EXO-20-009, Jul 2021

Heavy neutral leptons – μμX results

- Events are categorized in SRs by lepton flavor, invariant mass and vertex displacement



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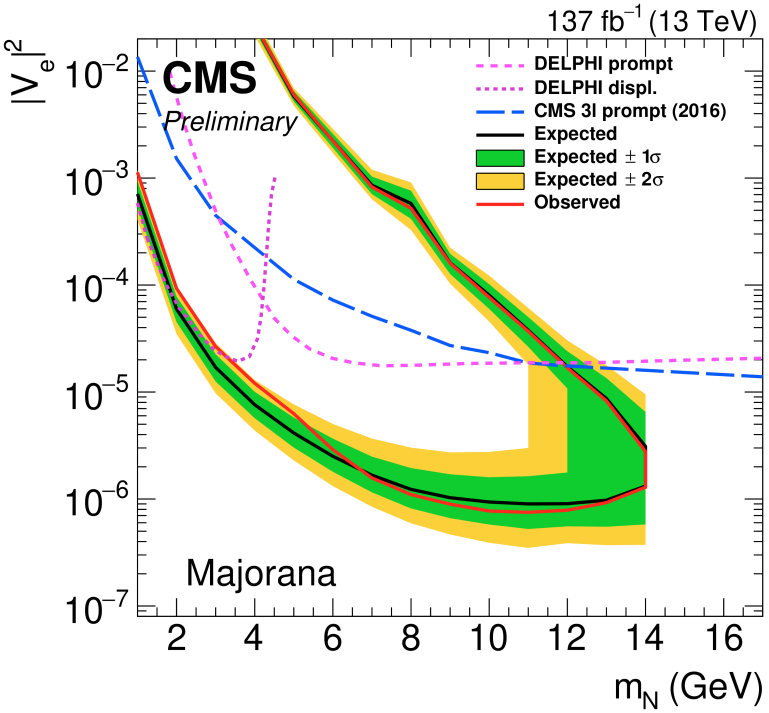
EXO-20-009, Jul 2021

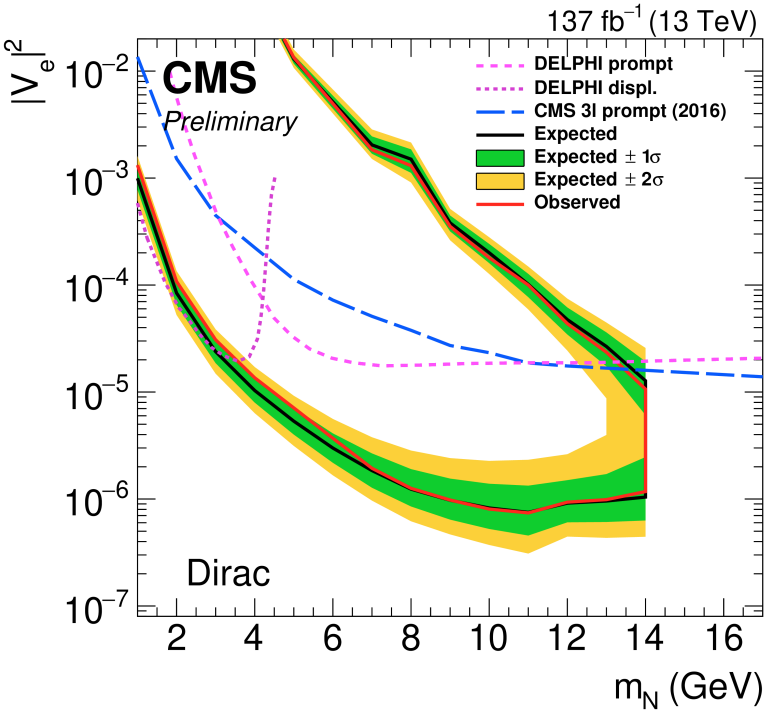
Heavy neutral leptons – limits

Constraints are obtained for HNL Majorana and right-handed Dirac neutrinos

- on the mass and coupling strength parameters (*for electrons and muon*)
- extending the exclusion limits from previous searches (back to **Delphi LEP times**)
- and (extending) **mixing parameter** values in the range of $10^{-7} - 10^{-5}$

for electron mixing *from* **eeX** *channels*





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

- Results represent the *world best limits to date* on this type of processes in the explored parameter space of the HNL production at the LHC

EXO-20-009, Jul 2021

Heavy neutral leptons – limits

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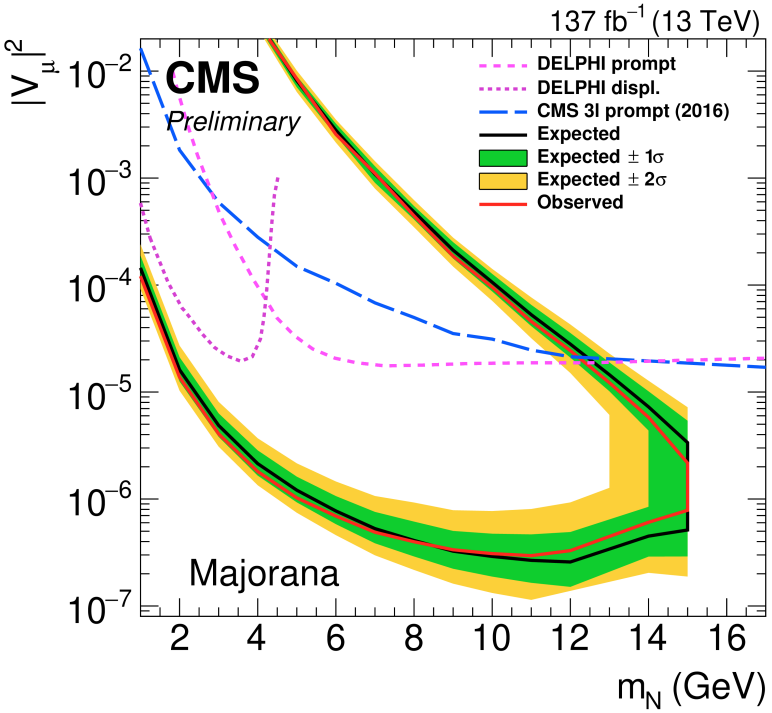
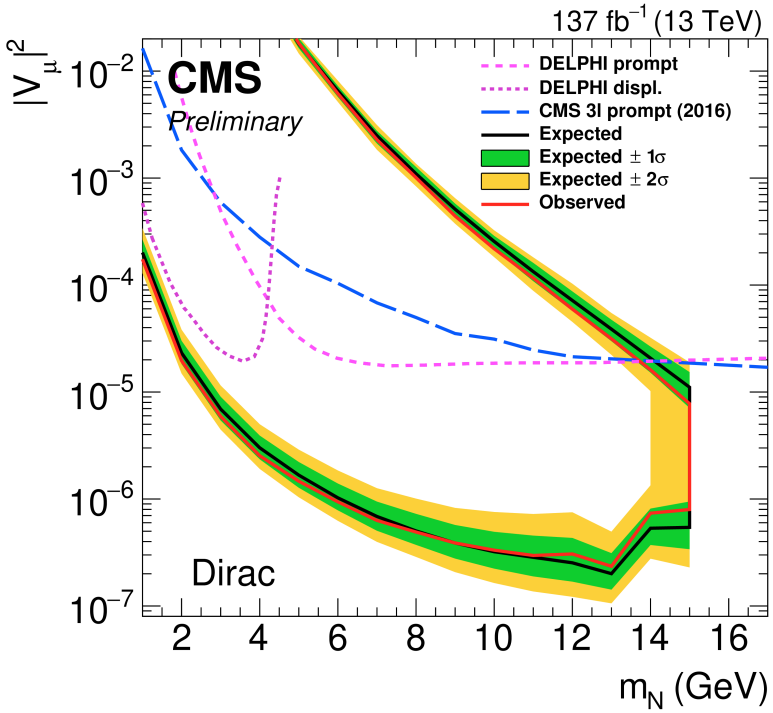
for muon mixing *from* **μμX** *channels*





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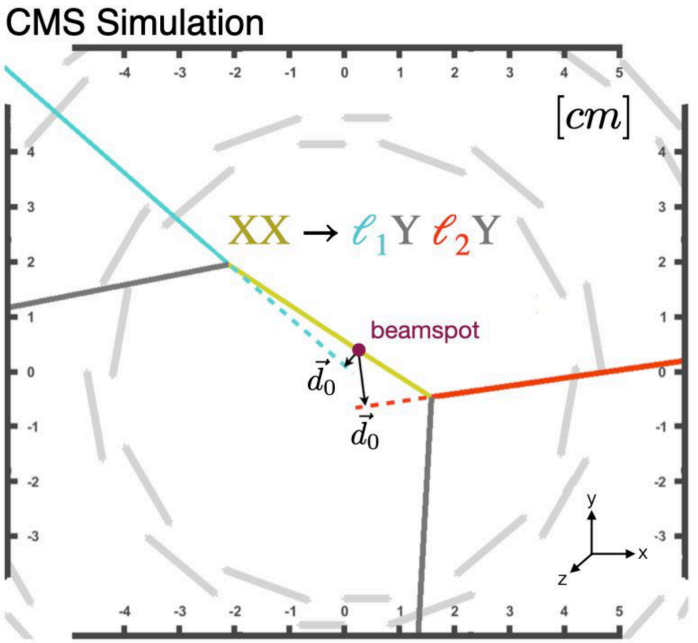
Displaced leptons

- **Signature: displaced lepton pair** where both leptons have a **large transverse impact parameter (d_0)**
  - **d_0** is an effective discriminating variable:
  - Leptons are expected to come from **different secondary vertices**, but no such explicit requirement is introduced
  - **$|d_0| > \sim 100\ \mu m$** eliminates significantly the SM background



- **Analysis strategy:** VERY INCLUSIVE SEARCH for LLPs
  - Look for **eμ, ee, μμ final states** with both **large d_0**
  - No explicit constraints on non-lepton physics objects
    - Sensitivity to **large range of lifetimes cτ (10 mm to 1 m)**
  - Kinematical cuts to reject SM bkg that produce displaced leptons

- **Triggering:**
  - Muon and photon (sensitive to displaced electrons) double triggers (no cuts on vrt)

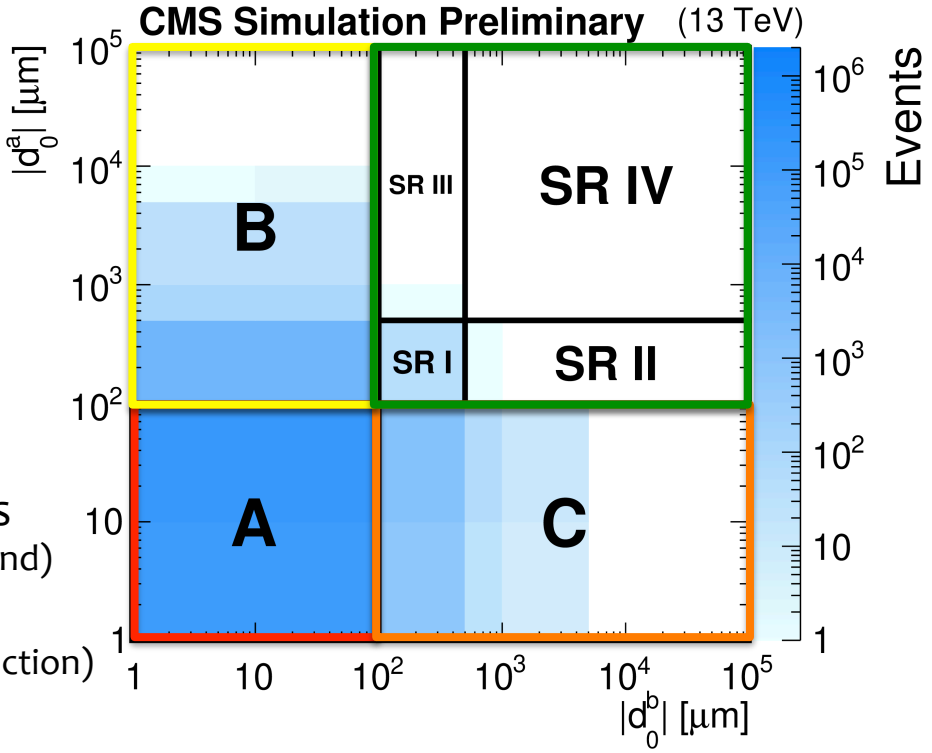
EXO-18-003, Jul 2021

Displaced leptons

- Inclusive event selection:
  - ≥ 2 isolated, high-momentum, well-measured leptons
    - p_T set by trigger turn on (35–75 GeV depending on channel/year)
    - $|\eta| < 1.5$ (for $\mathbf{d_0}$ resolution)
  - No constraints on other event parameters such as missing energy, jets, etc

- Lepton $\mathbf{d_0}$ is used to define the **signal regions** (SRs)
  - **SR: 100μm < $|d_0|$ ≤ 10cm** for both leptons

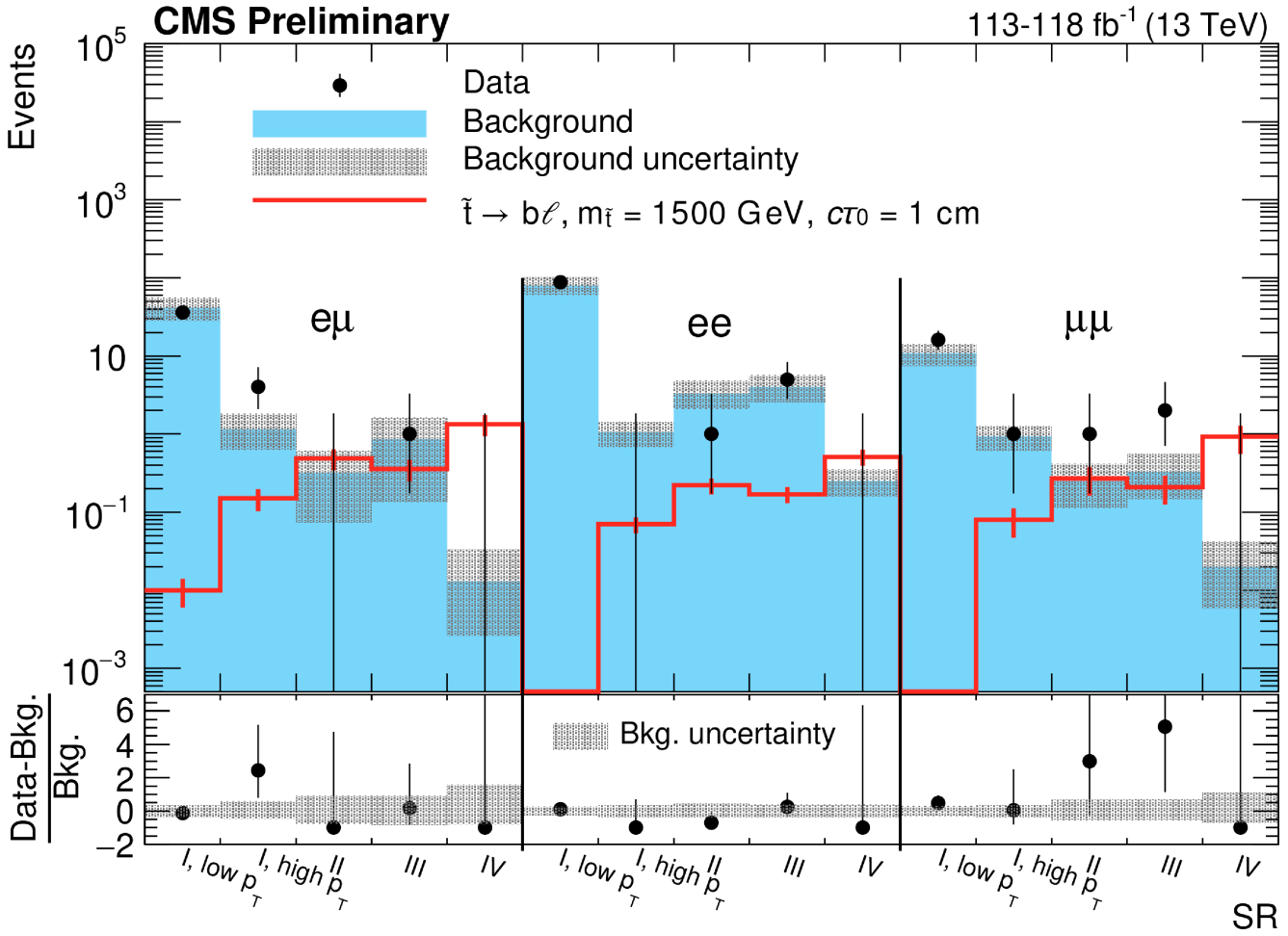
- Main backgrounds:
  - Poorly measured leptons
  - Semileptonic decays of tau leptons pairs (correction to account for irreducible tau background)
  - Heavy-flavor hadron decays (negligible due to isolation requirements at preselection)



- Data-driven estimate of background
  - $N_{SR\_i} \approx (N_{B\_i} \times N_{C\_i}) / N_{A\_i}$ for $i \in \{I, II, II, IV\}$

Displaced leptons – results

- Events are categorized in SRs by lepton flavor and $\mathbf{d_0}$ and momentum p_T



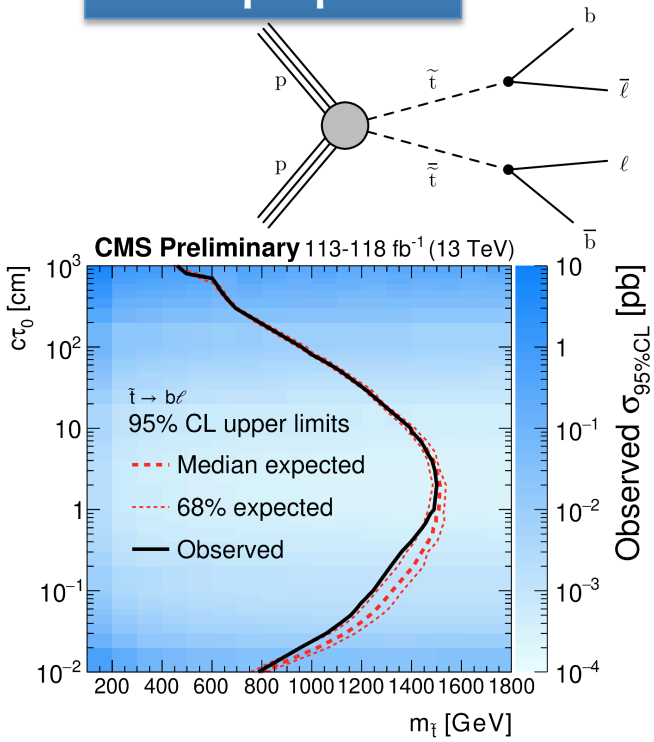
- Observation consistent with bg-only hypothesis

EXO-18-003, Jul 2021

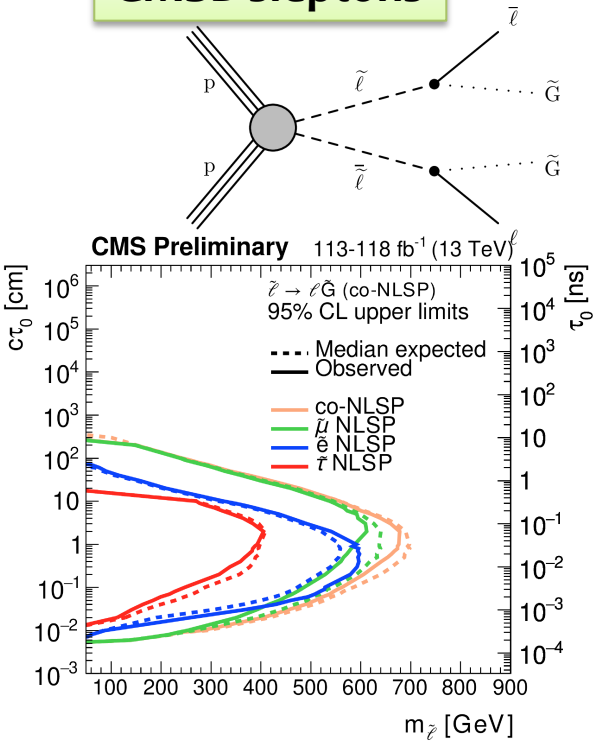
Displaced leptons – limits

- Mass and cross sections constrains over wide range of lifetimes

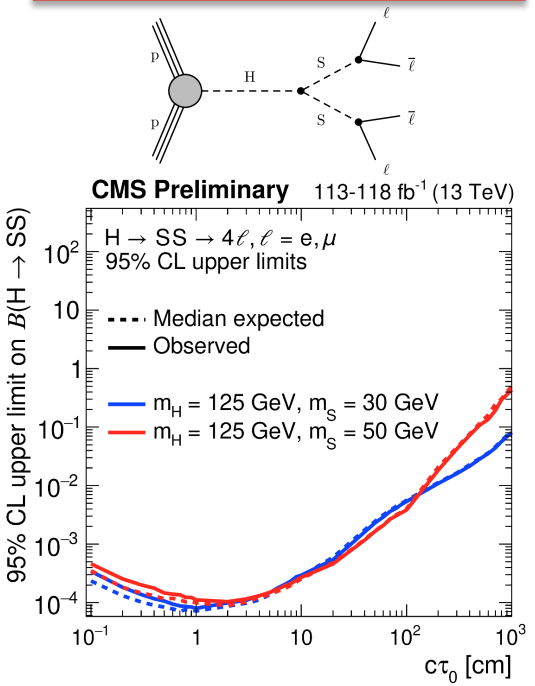
RPV top squarks



GMSB sleptons



Higgs boson decaying to long-lived scalars



~600 GeV improvement wrt. previous displaced lepton limits

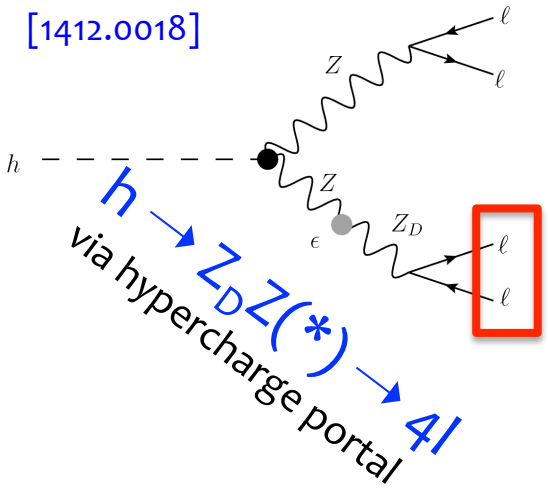
Similar reach as ATLAS-2011.07812 exclusive sensitivity ≲ 10^{-1} cm

Most stringent limits to date for cτ ≲ 50 cm

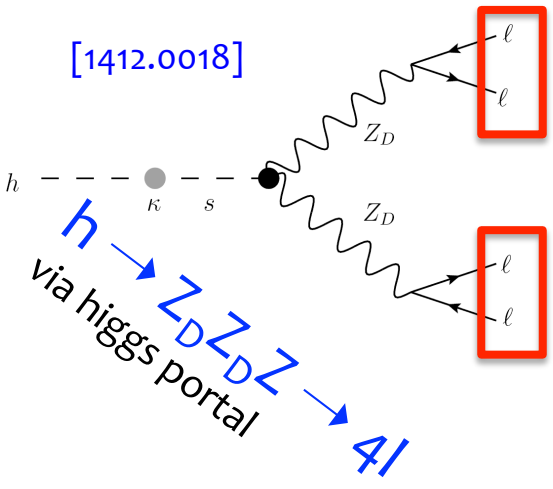
Dimuon resonances

Higgs boson decays to a pair of long-lived dark photons

[1412.0018]

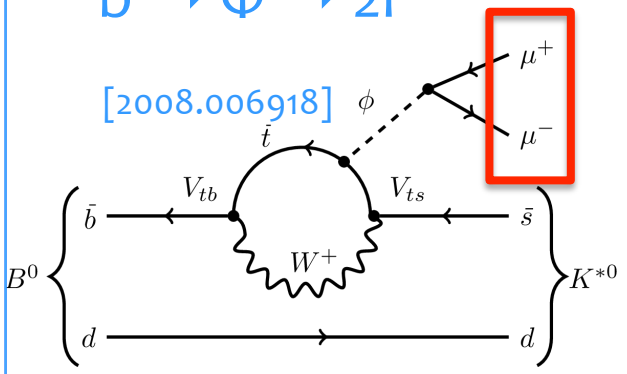


[1412.0018]



$b \to \Phi \to 2l$

[2008.006918]

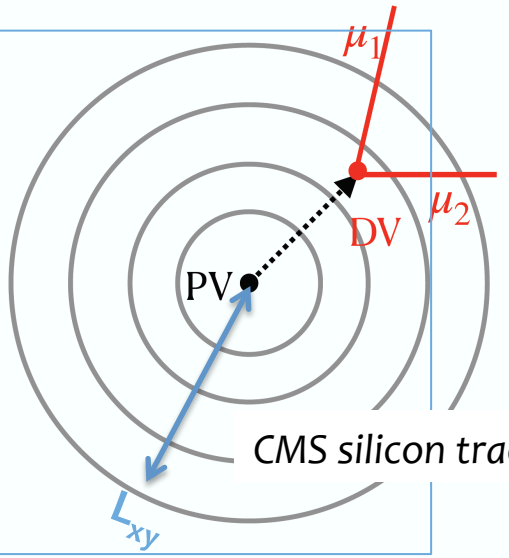


Long-lived scalar resonance arises from the decay of a B hadron

Very low mass search

for a muon pair with **displaces vertex** (DV)

- masses **down to ~2m_μ** and **displacements L_{xy} up to 11 cm**



Benchmark models

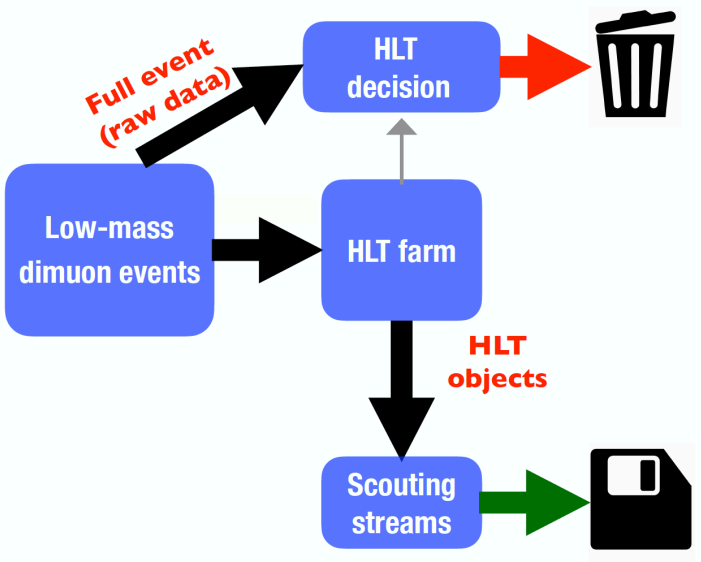
- Z_D : 0.5 GeV ≤ m(Z_D) ≤ **50 GeV** 0.1 mm ≤ $c\tau_0$(Z_D) ≤ 1000 mm
- Φ : 0.3 GeV ≤ m(Φ) ≤ **5 GeV** 0.1 mm ≤ $c\tau_0$(Φ) ≤ 100 mm

EXO-20-014, May 2021

Dimuon resonances w/scounting

High rate triggers (*scouting*):

- Bypass the high-level trigger (HLT) thresholds by directly sending HLT objects to disk instead of saving raw data
- Reduced event info compared to offline reconstructed objects
- **DoubleMu trigger path** allow sensitivities to **otherwise inaccessible low-mass** events

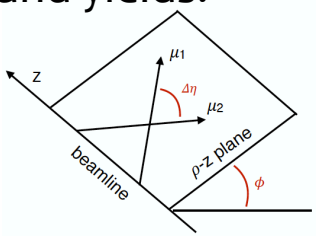


Signature :

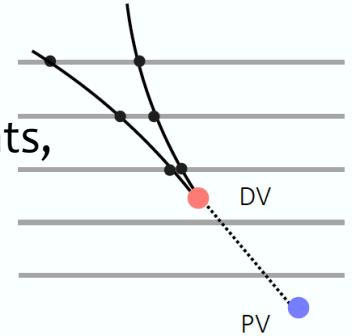
- At least 2 opposite sign muons ($p_T > 3$ GeV, $|\eta| < 2.4$) and **1 displaced vertex**

Backgrounds:

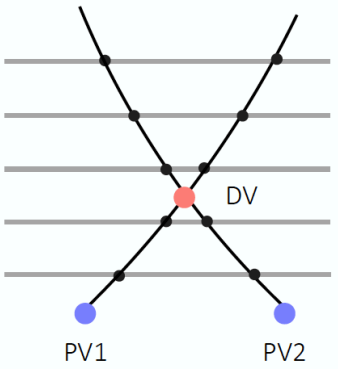
- Controlled with a set of kinematical cuts
- DV/dimuon kinematics & displacement requirements, material veto to reduce background yields:
  - Sophisticated cuts:
    - log10 ($\Delta\eta/\Delta\phi$) < 1.25
    - # excess pixel hits ≤ 0



signal LLP



PU tracks

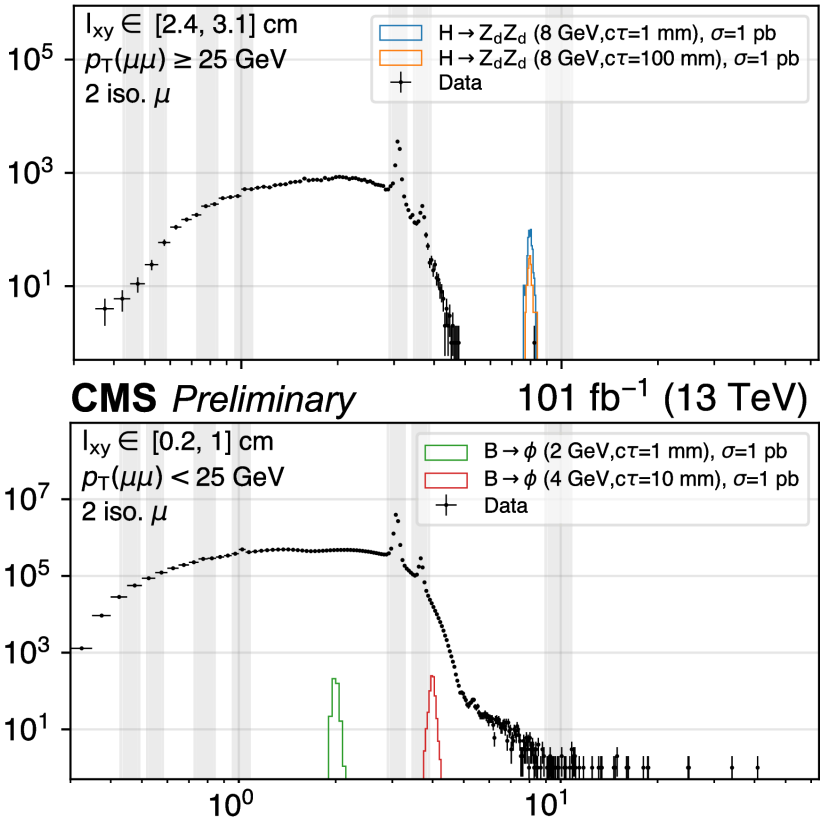


EXO-20-014, May 2021

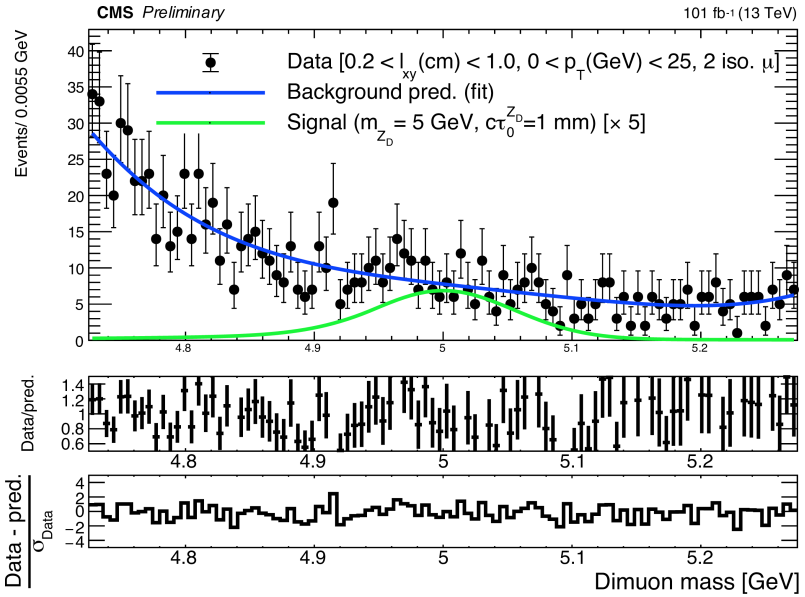
Dimuon resonances – results

Strategy:

- Search for a **narrow peak** in dimuon invariant mass spectrum
- SM bkg estimated directly from data can be parameterized by analytical functions
  - SM resonances are masked ($\pm 5\sigma_{res.}$ window) for the result
- Events are **categorized in bins** of muon isolation (2,1,0 iso-mu), di-mu momentum $p_T(\mu\mu)$ and displacement L_{xy}



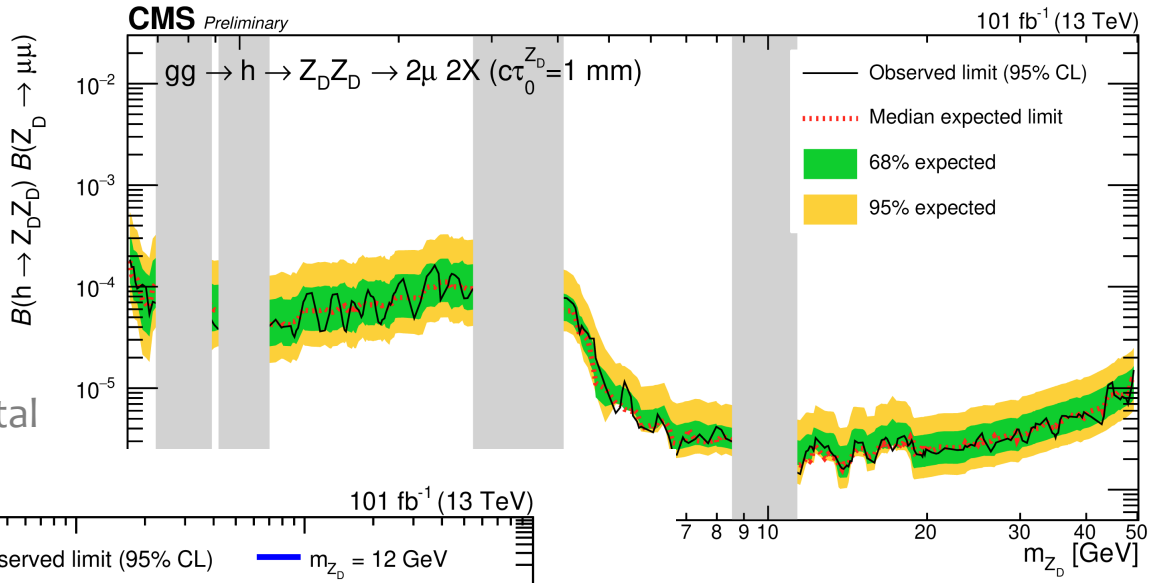
- **Simultaneous fit** in all search bins either bkg-only or bkg+signal hypotheses

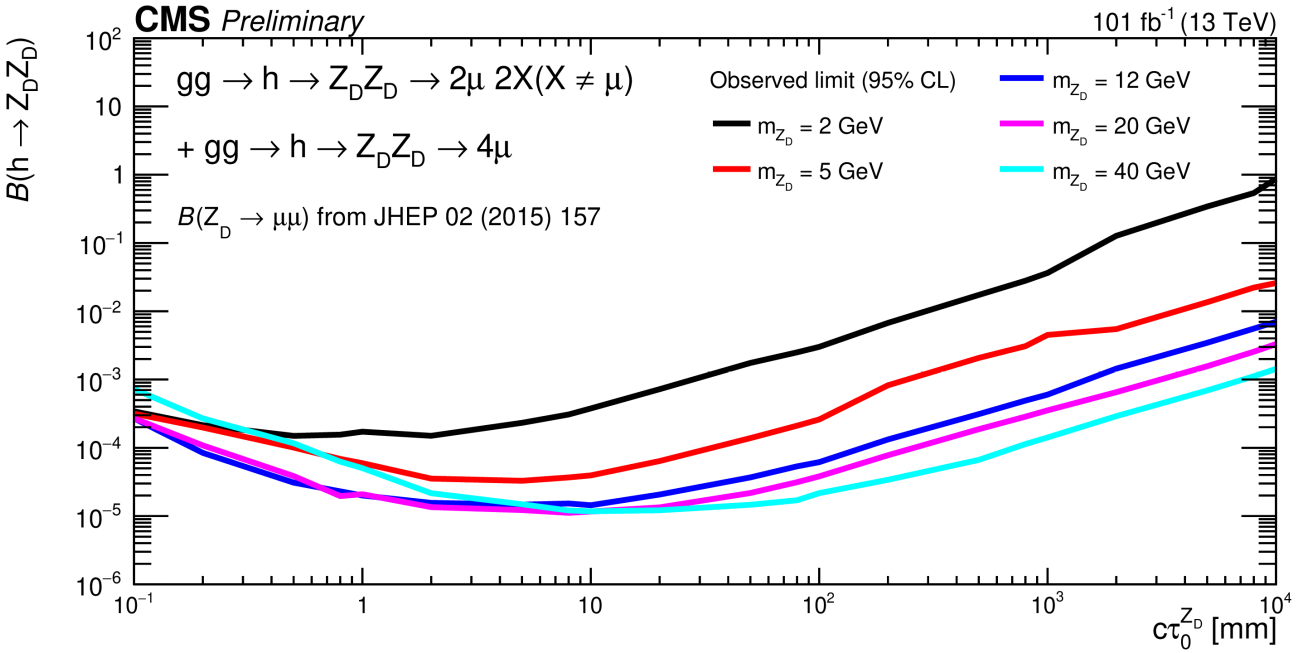


Dimuon resonances – limits

- **No significant excess is observed**
- Bkg+signal fits are used to set limits signal models

SM-like Higgs boson decay to leptons via one or two intermediate Z_D through the hypercharge or Higgs portal





The most stringent constraints to date in a wide range of signal mass (2-40 GeV) and lifetime hypotheses

EXO-20-014, May 2021

Dimuon resonances – limits

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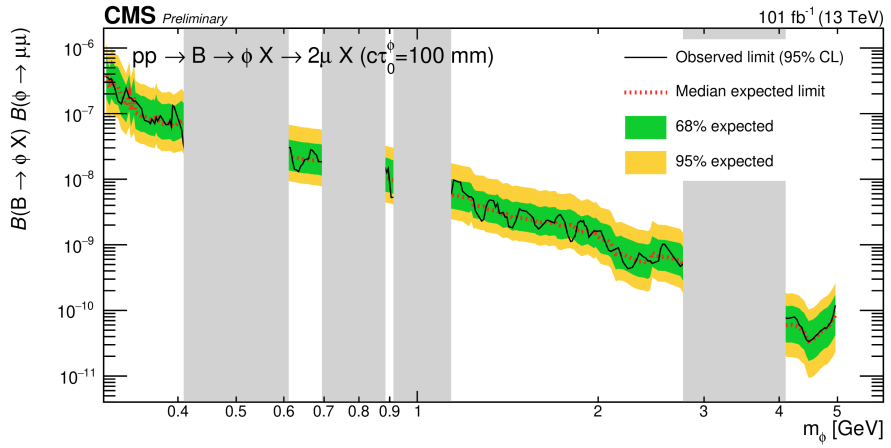
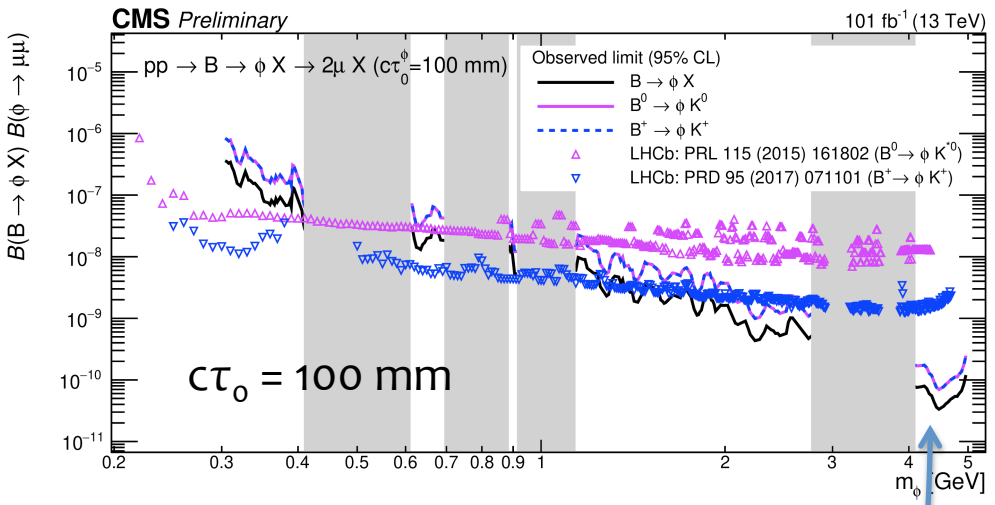
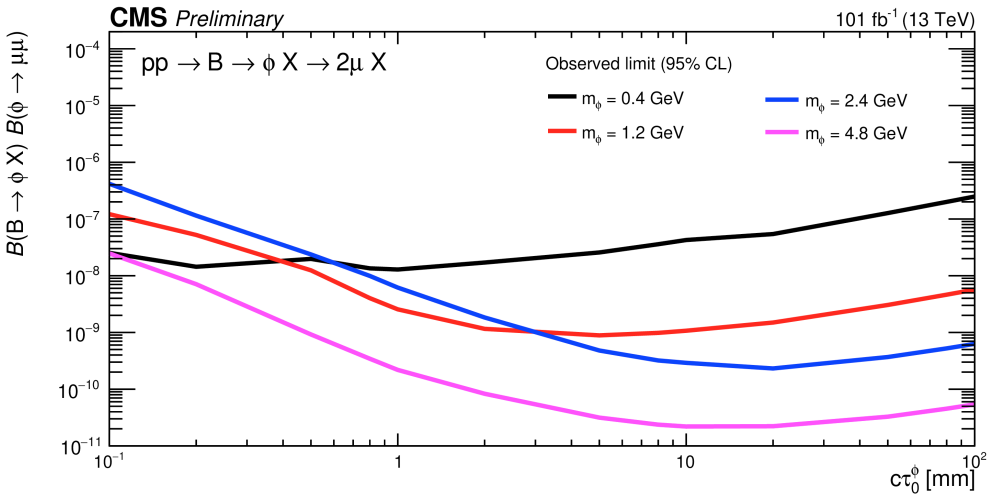


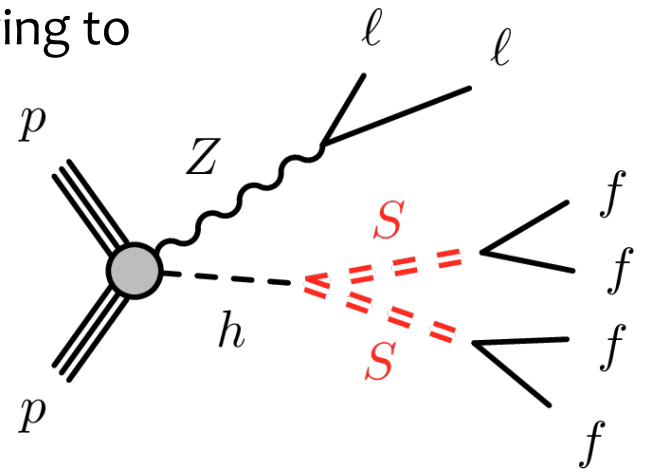




- Upper limits on $BR(B \rightarrow \phi X) \cdot BR(\phi \rightarrow \mu\mu)$
- **CMS reached sensitivity comparable with LHCb** especially at higher mass and higher lifetime

Displaced jets with Z boson

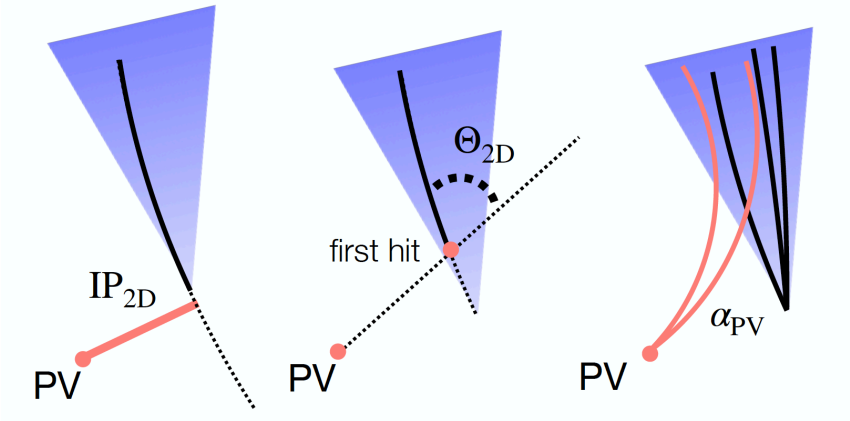
- **Search for**: SM-like (125GeV) **higgs** boson decaying to **light scalar LLPs** which **decay to b-jets** or **d-jets** and produced with **Z boson** association



- **Trigger** and selections based on **Z boson** decays to **electron or muon** pairs provide sensitivity to **light (15 GeV or less) LLPs,** which have up to now been difficult to access

- Cut-based **displaced-jet tagging** using the properties of the tracks associated with each jet

- **Selections:**
  - events with at least 2 displaced jets
  - no displaced vertex required

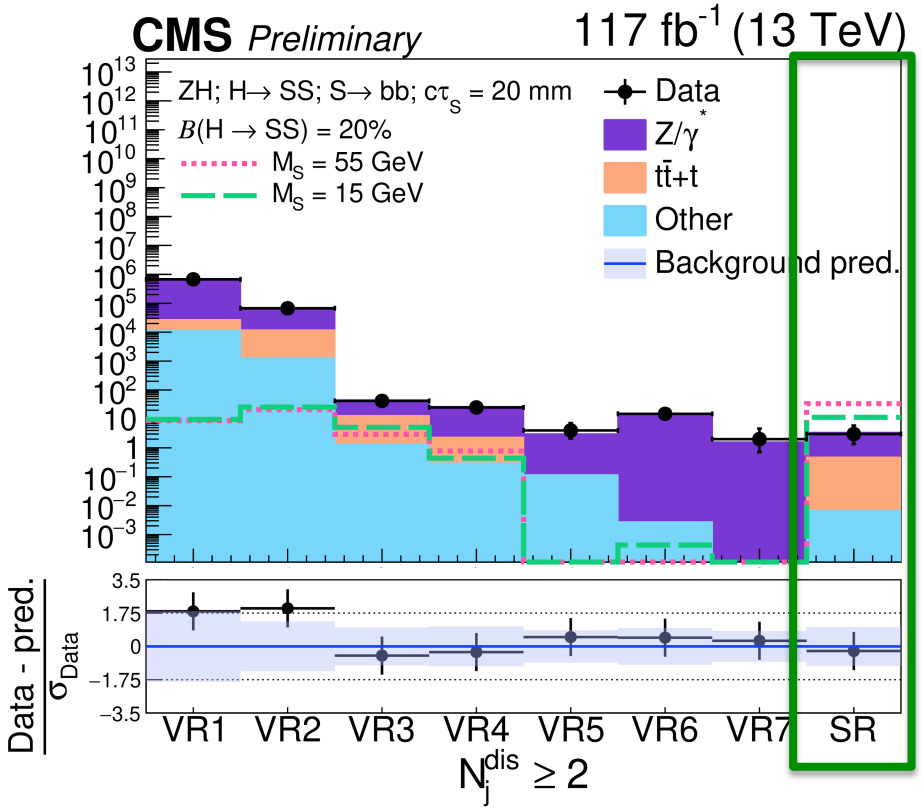


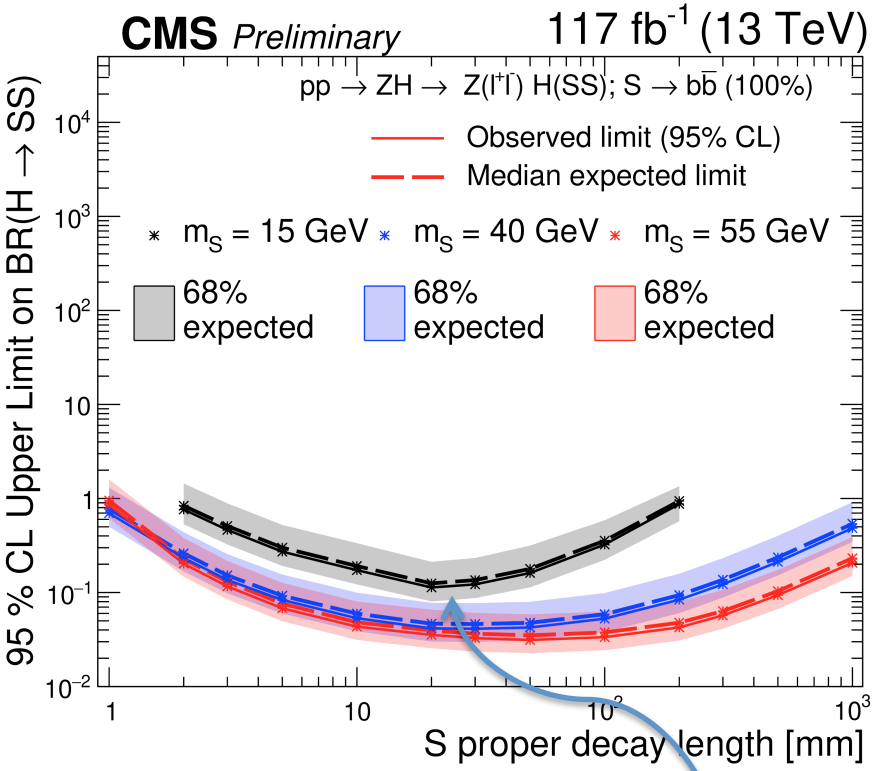
Displaced jets in the CMS silicon tracker

EXO-20-003, May 2021

Displaced jet + Z – results & limits

- Events categorized to validate bkg estimate and define a SR region
- **Results:** **3 events** observed wrt **3.5 ± 1.8 events** expected



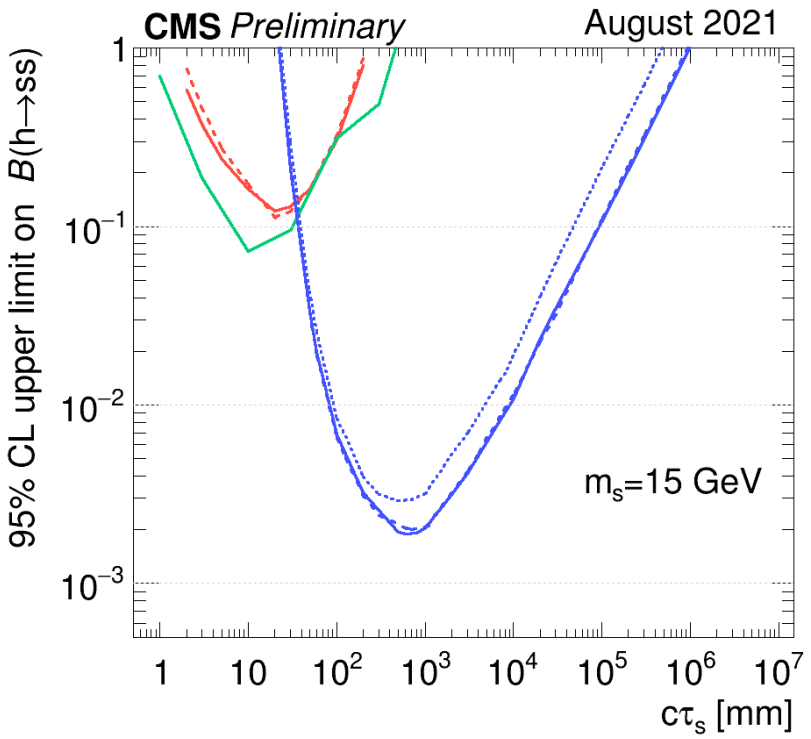


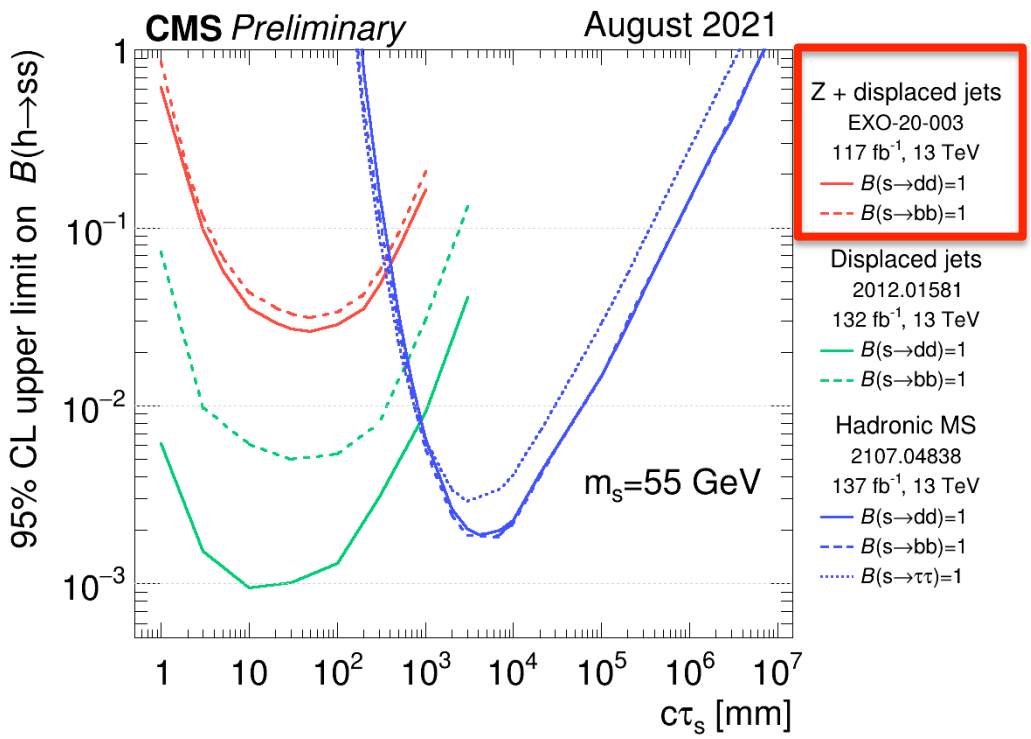
Most stringent CMS limits for the branching fractions (H→SS)
for low **mass scalars** of around **15 GeV** with mean proper decay lengths of **2-30 mm,**
where the scalars decay to a pair of **b quarks**

EXO-20-003, May 2021

Displaced jet + Z vs other searches

- Observed exclusion limit from different CMS hadronic long-lived particle analyses on the branching fraction of the SM- higgs boson to two neutral long-lived scalars





- Complementary results for CMS
  - Z+displaced jets: added a sensitivity to low mass LLP for 15 GeV, S→bb

https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

LLP at CMS summary

- Unconventional signatures of displaced leptons or jets are powerful tools in searches for different LLPs in *a model independent way*

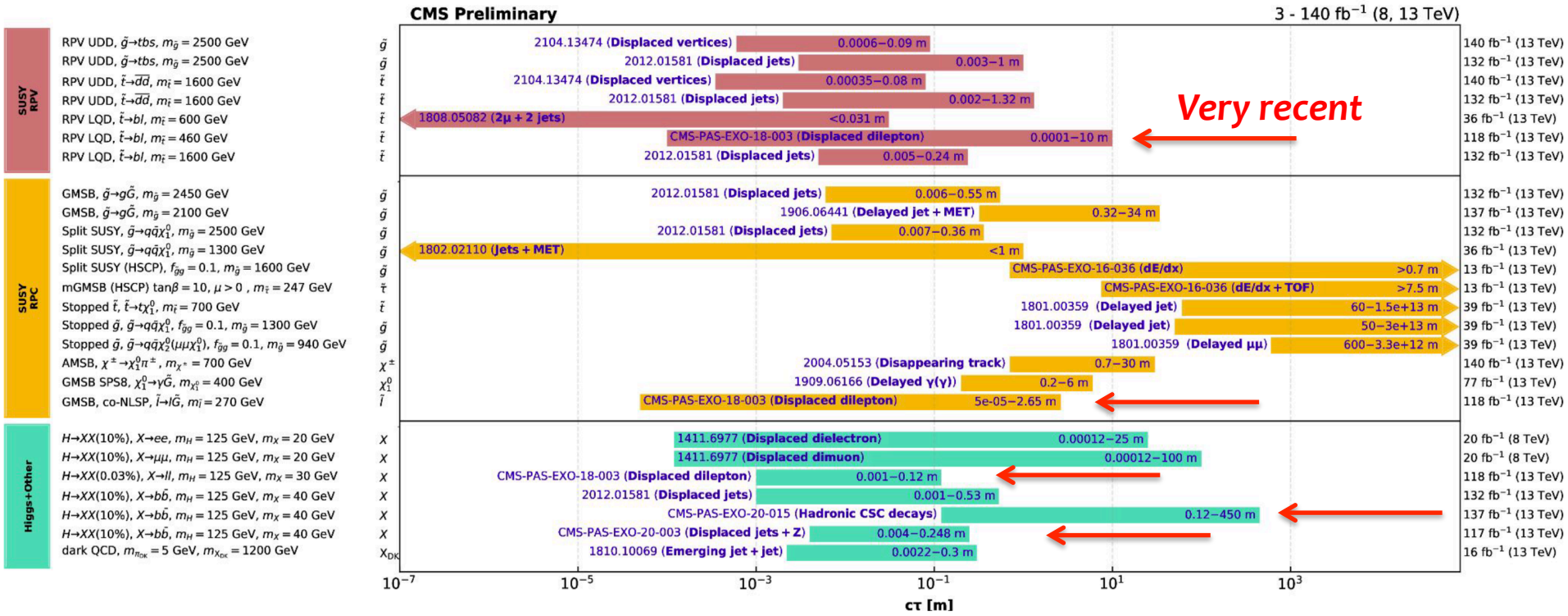
- **New results for full Run 2 data pushed limits on LLPs**
  - Explore challenging the low mass LLPs
  - Sensitive to wide range of decay lengths
  - Searches complement each other

- Any detected signal of LLP would be a clear indication of a new physics
  - Therefore, the CMS experiment make an effort for LHC Run 3
    to enhance his sensitivity to cached the LLPs
    by **new algorithms of reco** and **triggering especially at the L1**

- EXO CMS public results:
  http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/LLP.html

Thank you!

Selection of LLP searches at CMS



https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

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