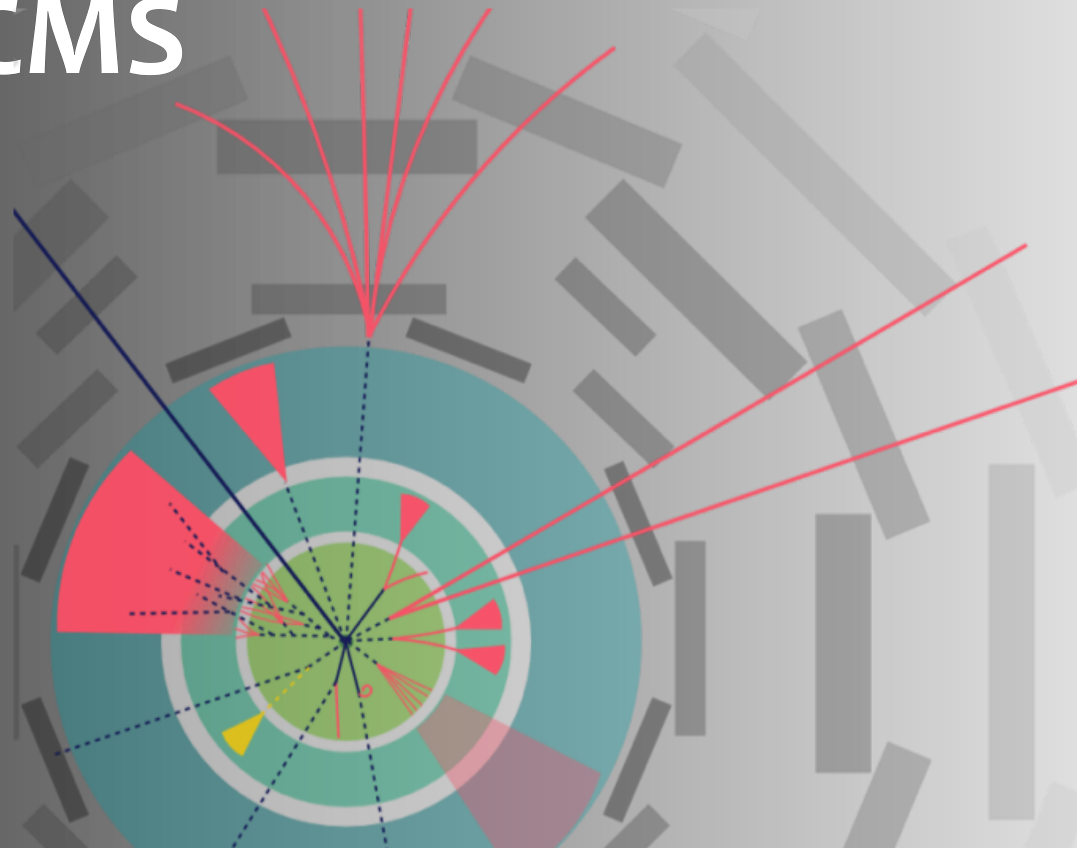
Searches for long-lived particles at CMS

Małgorzata Kazana
CMS Collaboration



Compact Muon Solenoid
experiment at the CERN's LHC

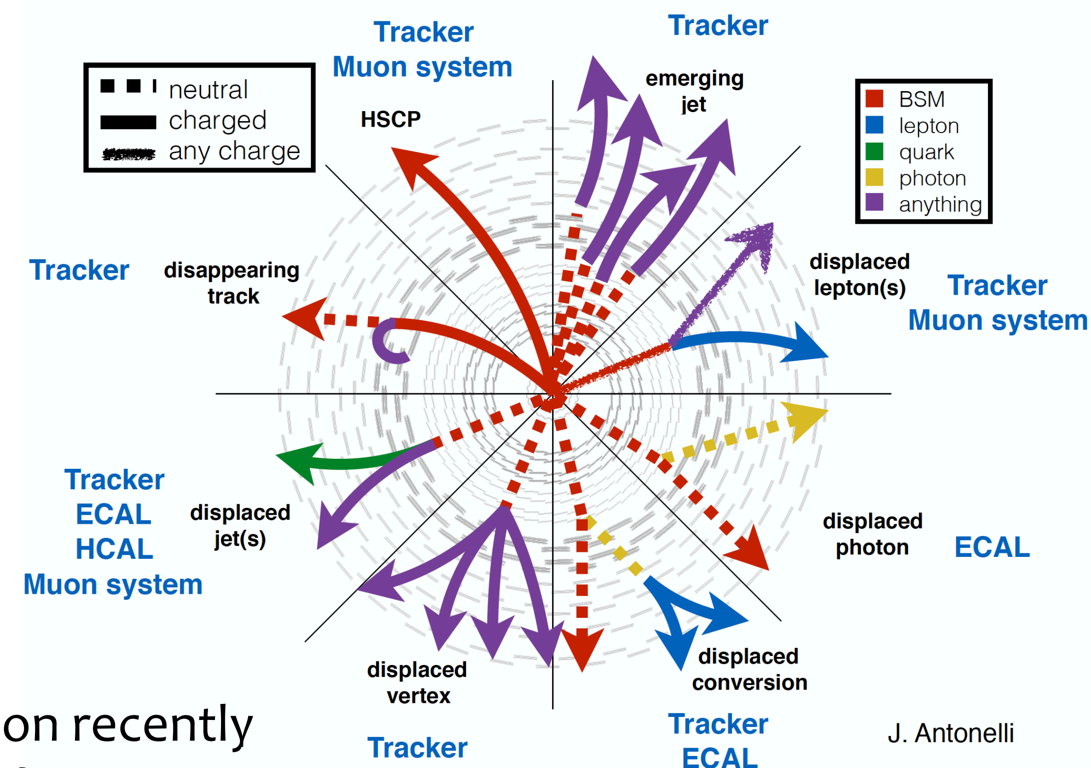
NCBJ National Centre
for Nuclear Research

Institute of Nuclear Physics
Polish Academy of Sciences
1st February 2022
(Virtual) Cracow, PL

Searches for long-lived particles

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

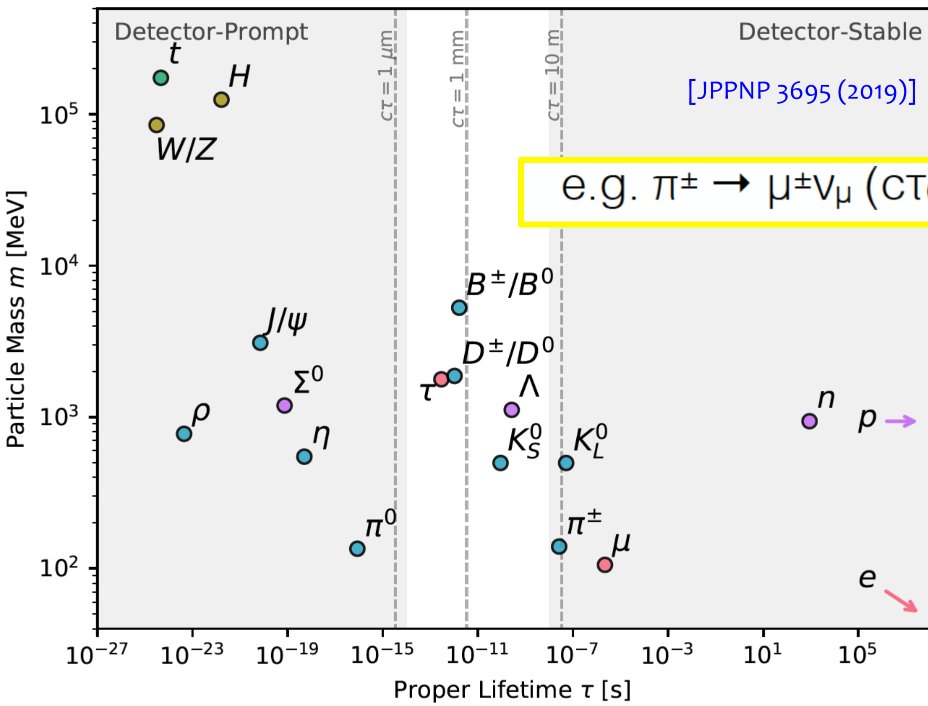
- Using the LHC data collected at 13 TeV in **Run II up to 138/fb:**
  - 2016 – 36/fb,
  - 2017 – 42/fb,
  - 2018 – 60/fb



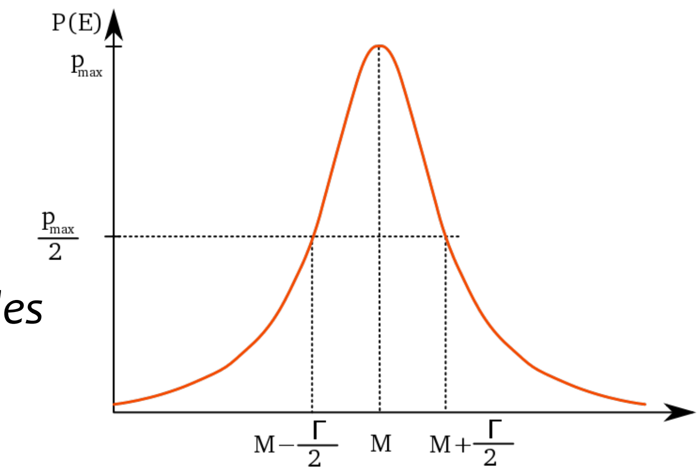
- In this talk, the focus is on recently published **by CMS** searches for **LLP**

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: $\boldsymbol{\tau \sim 1/\Gamma}$
  - Half time: $\boldsymbol{T_{1/2} = \ln 2\ \tau}$
- *The SM contains a large number of metastable particles*



e.g. $\pi^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$ ($c\tau_0 \sim 7.8$m)



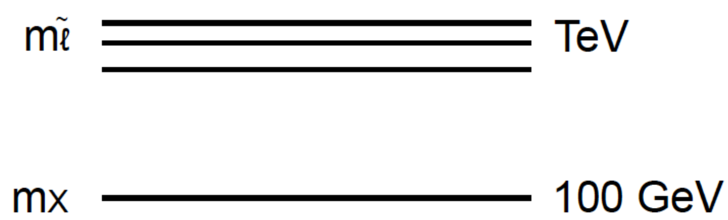
$$\Gamma \sim \varepsilon^2 \,(m/\Lambda)^{2n}\, \Phi$$

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*)

Why LLPs in BSM?

- **Small couplings (ε)** in **Supersymmetry**
- *Example*: R-parity Violating SUSY



additional terms in superpotential:

$$W_{\mathrm{RPV}} = \mu_i L_i H_u + \frac{1}{2}\lambda_{ijk} L_i L_j \bar{e}_k$$
$$+ \lambda'_{ijk} L_i Q_j \bar{d}_k + \frac{1}{2}\lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k,$$

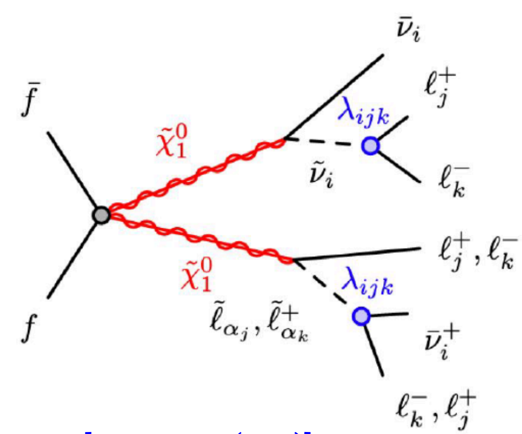
couplings need to be small to avoid proton decay and flavor violation

LSP long-lived:

$\Gamma(X^0 \rightarrow \ell\, \ell\, \nu) \sim \lambda^2\, m^5{}_X / m^4{}_{\tilde{\ell}}$

cτ ~ 1m

for $\lambda \sim 10^{-4}$, $m_X \sim 100$ GeV, $m_{\tilde{\ell}} \sim 1$ TeV



[JPPNP 3695 (2019)]

Why LLPs in BSM?

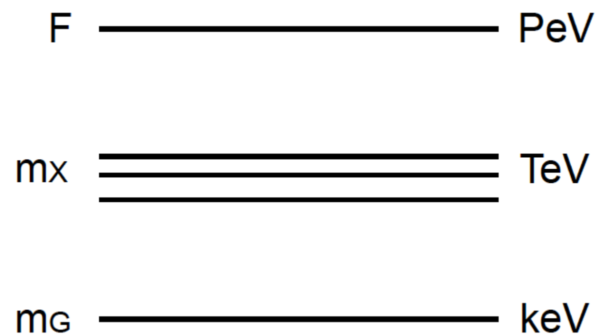
- **High scale operators (Λ) (*heavy mediator*)** in **Supersymmetry**
- *Example*: Gauge Mediated SUSY Breaking

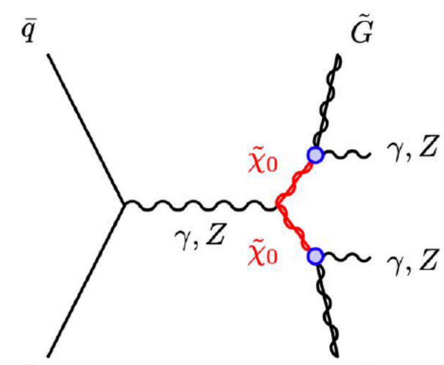
scale of SUSY breaking
F ~ 1 PeV

LSP is typically gravitino
$\mathbf{m_G} \sim F^2/M_{PL} \sim \mathbf{1\ keV}$

NLSP long-lived:
$\Gamma(X \rightarrow G + SM) \sim m^5_X/F^4$

cτ ~ 1m for $m_X \sim 100$ GeV





[JPPNP 3695 (2019)]

Why LLPs in BSM?

- **Small phase space (Φ)** (*compressed spectra*) in **Supersymmetry**
- *Example*: Anomaly Mediated SUSY Breaking

LSP is wino-like

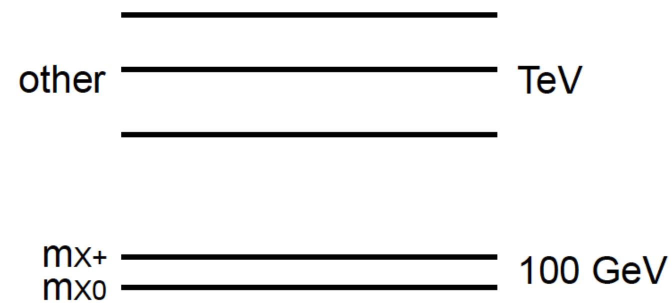
small chargino/neutralino mass difference

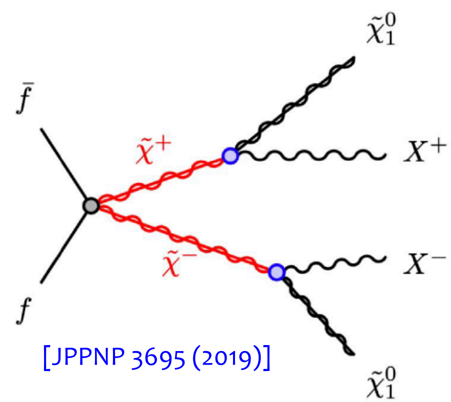
Δm ~ $m^4_W/\mu^3_{\text{(SUSY Higgs)}}$ ~ **100 MeV** for μ ~ 1 TeV

chargino long-lived:

$\Gamma(X^+ \longrightarrow X^0 + SM) \sim \Delta m^3/m^2$

cτ ~ 1m for m_X ~ 100GeV





[JPPNP 3695 (2019)]

Bunch of LLPs in BSM

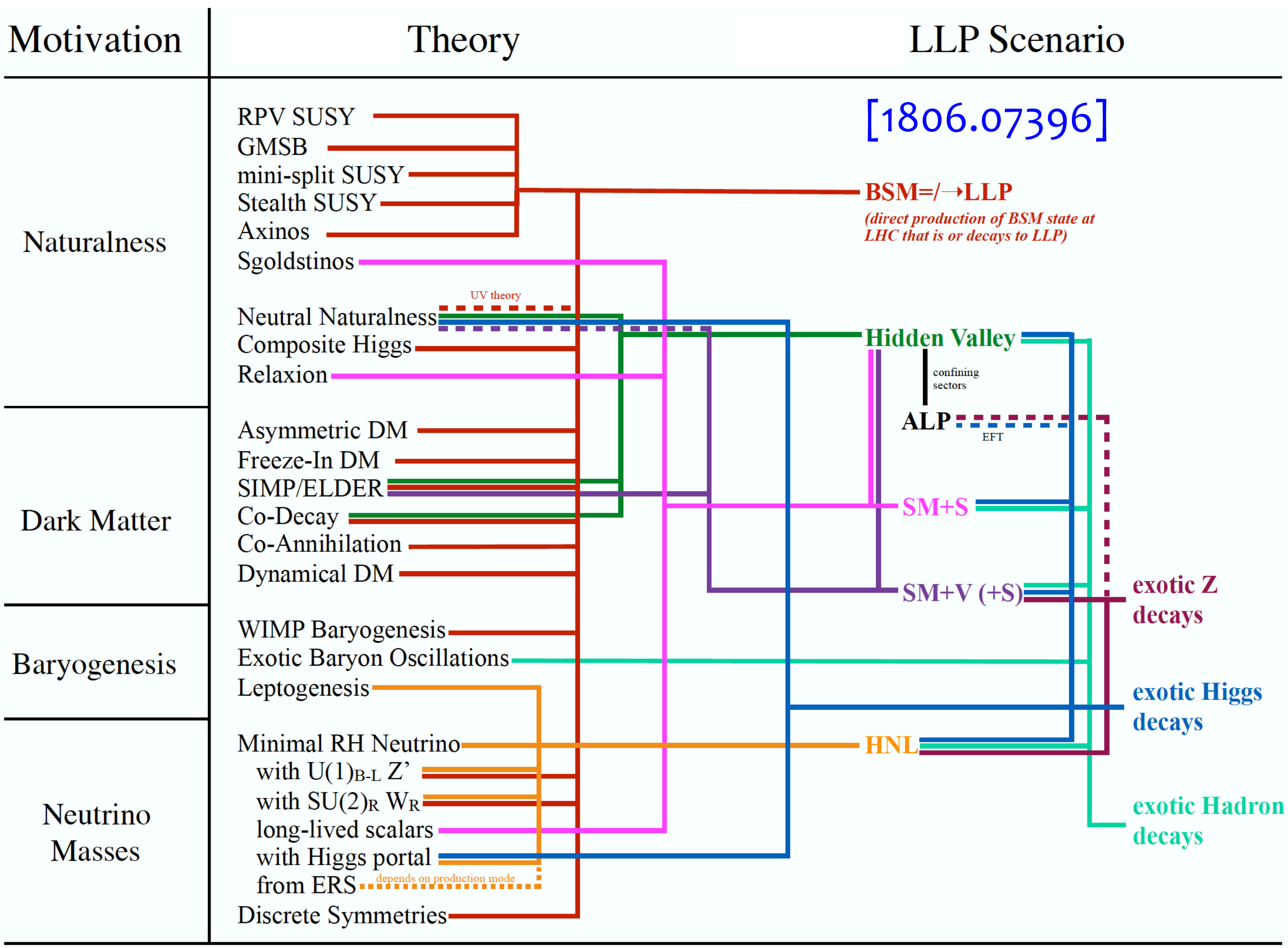
- The **long lifetime** is quite a common feature in new physics models

Discrete symmetry stabilizing Higgs mass

E.g. Freeze-in via decay requires LLPs with SM couplings

Out-of-equilibrium decay of WIMP-like LLP produces baryon asymmetry

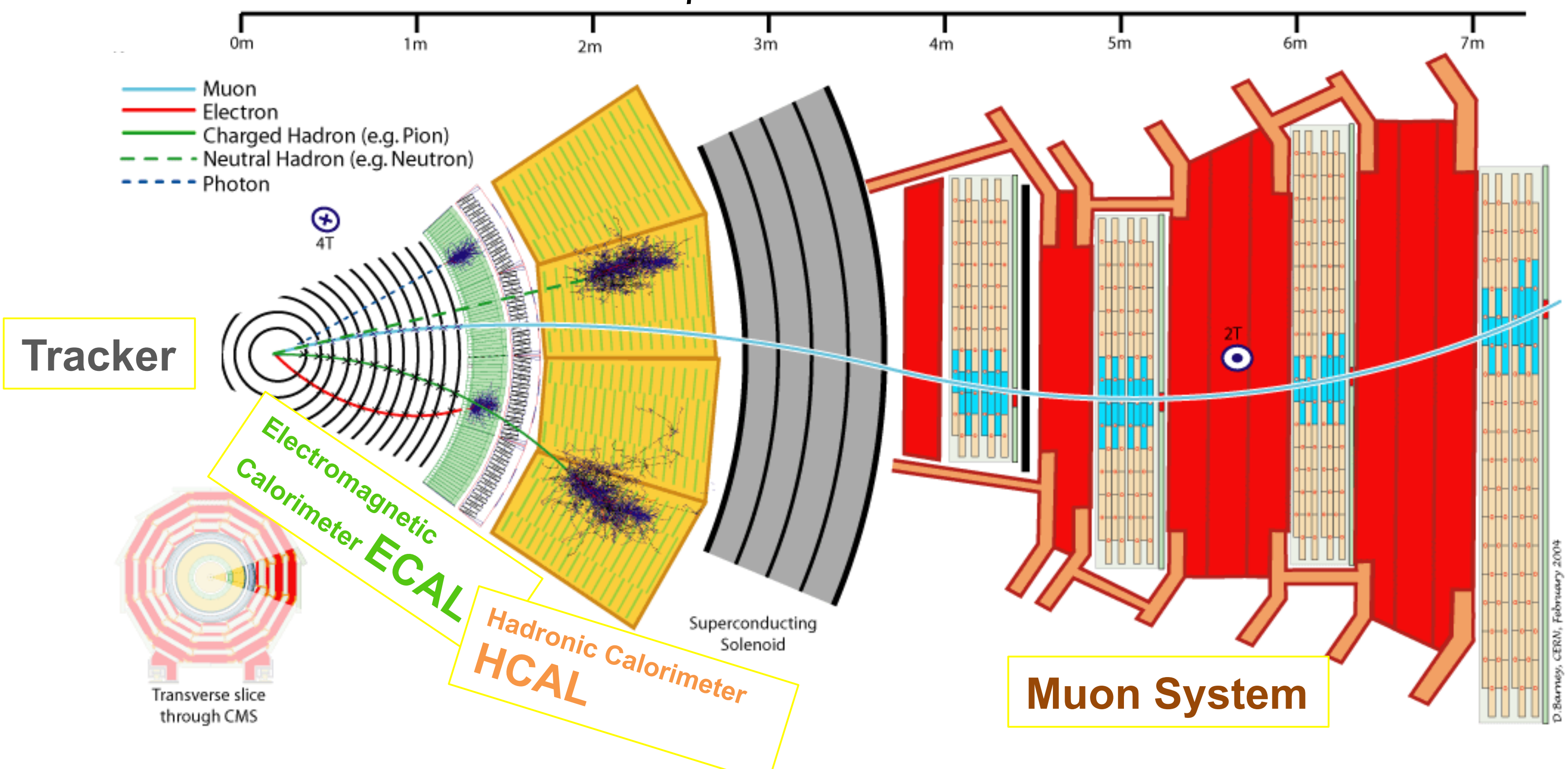
Tiny mixing between ν_LL and ν_R makes ν_R LLPs



Detector design vs LLPs

- **CMS: reconstruction** algorithms, cylindrical **geometry, trigger** all designed assuming ***particles emerge from the collision point***

- **LLPs signature** depend on the **lifetime $c\tau$:**
  - **Decay inside various regions of the detector**: *meta-stable LLP*
  - **Cross** the detector: *quasi-stable LLP*

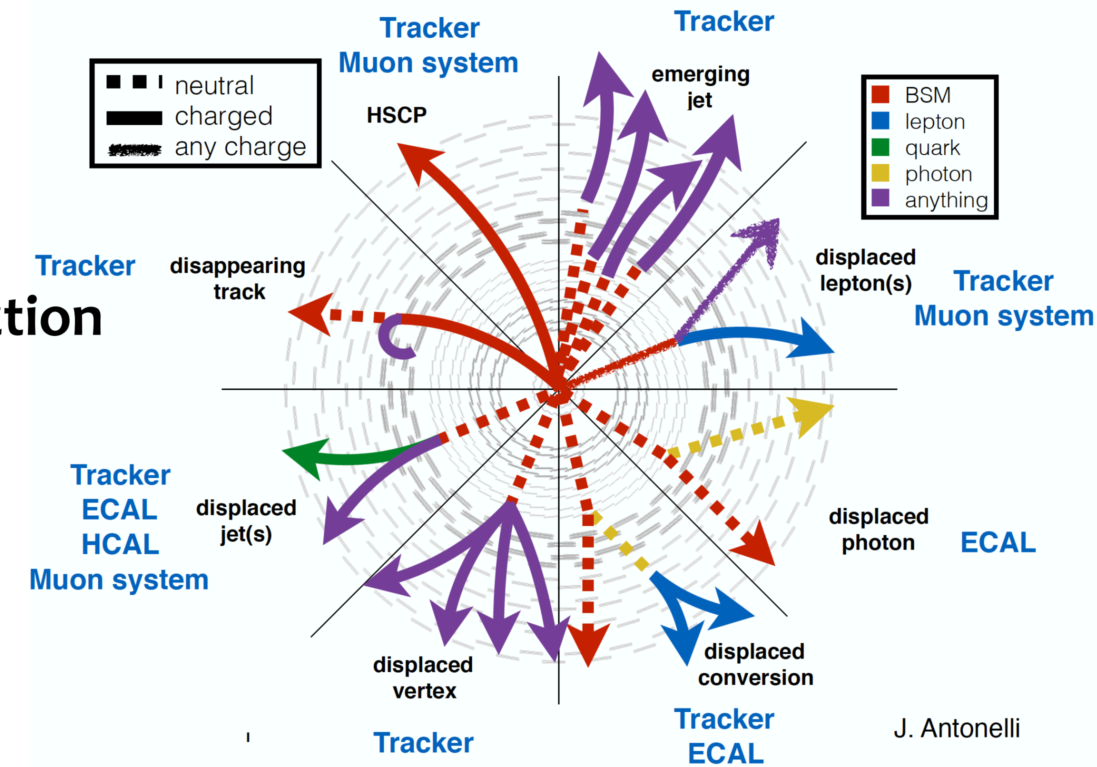


Signatures of LLPs

- **LLPs** have **unusual** final states that require **innovative** techniques

- **Challenging** from the experimental point of view

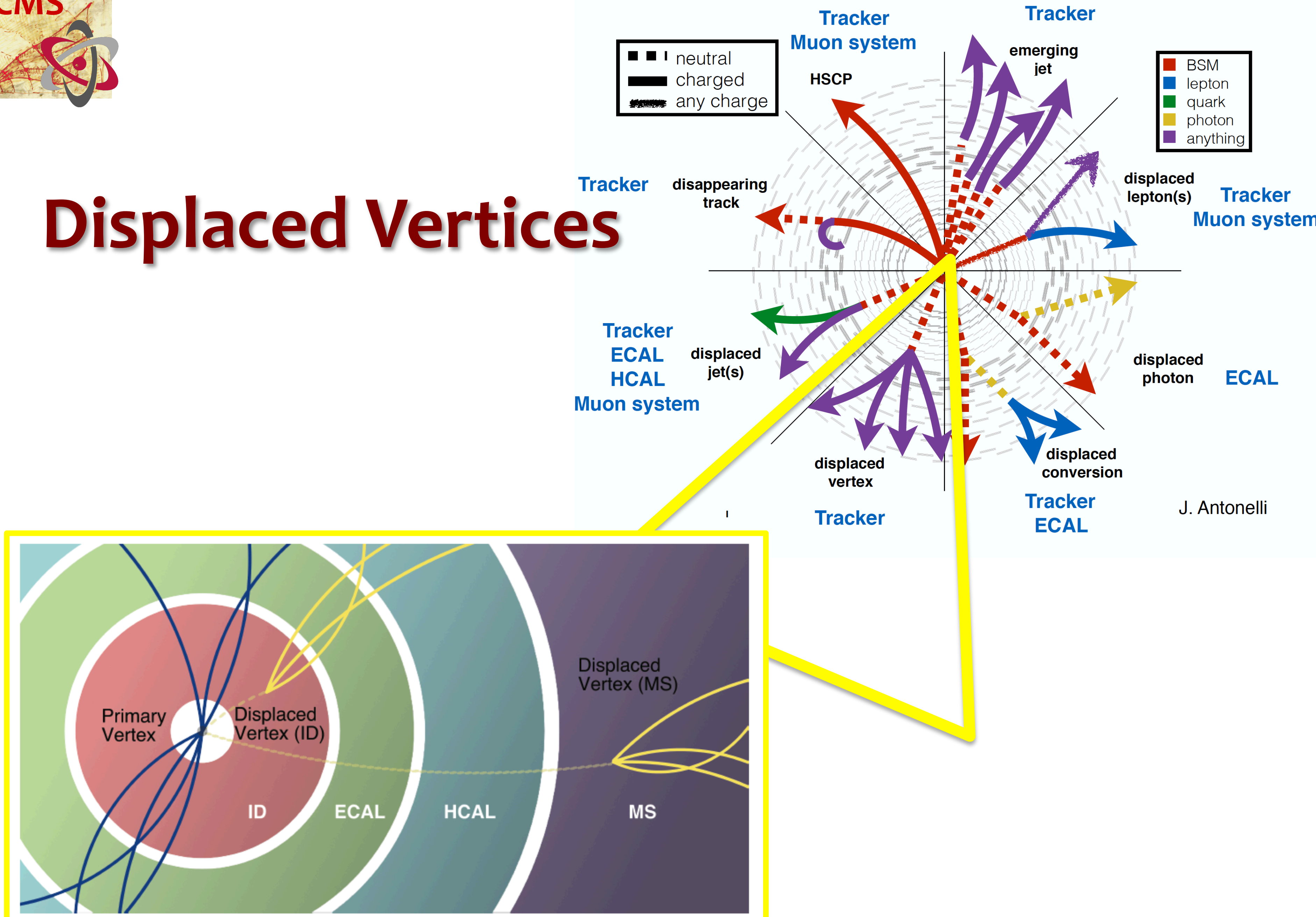
- **Dedicated** physics object **identification** and **reconstruction**
  - Displacements
  - Short tracks
  - Jet structure
  - Timing
  - Ionization
  - and more



- Triggering often weird/low energy signatures

- **Atypical** (non-collision) **backgrounds**
  detector noise, cosmic rays, reco failures – has to be estimated from data

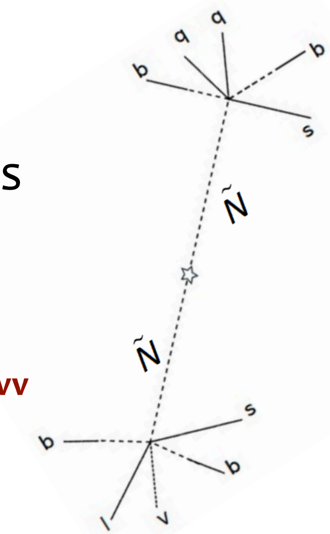
Displaced Vertices



EXO-19-013, Phys. Rev. D 104, 052011 (2021)

Displaced vertices in multijet events

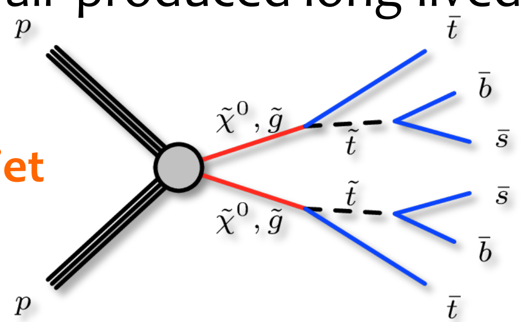
- **Signature:** **displaced jets** in the region of a beam pipe



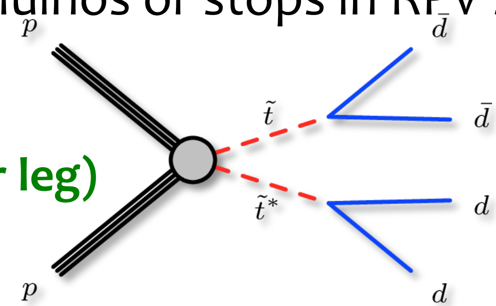
- **Analysis strategy:**
  - reconstruct displaced vertices from tracks in events with jets
  - focus on intermediate lifetimes **cτ** (100 μm to 10 cm)
    - first tracking (pixel) layer: 4.4 cm radius
  - distinguish **signal in two-vertex events** using **the distance d_{VV}** between vertices
  - SM background: prompt vertices in events with lots of jets
    misreconstructed tracks with non-negligible transverse impact parameters

- **Benchmark:**
  - Pair-produced long-lived neutralinos/gluinos or stops in RPV SUSY

Multijet



Dijet (per leg)

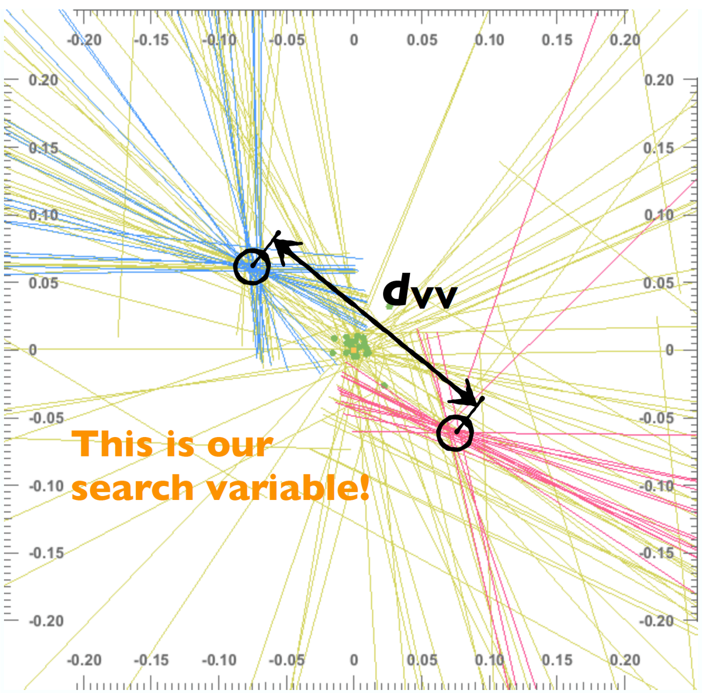


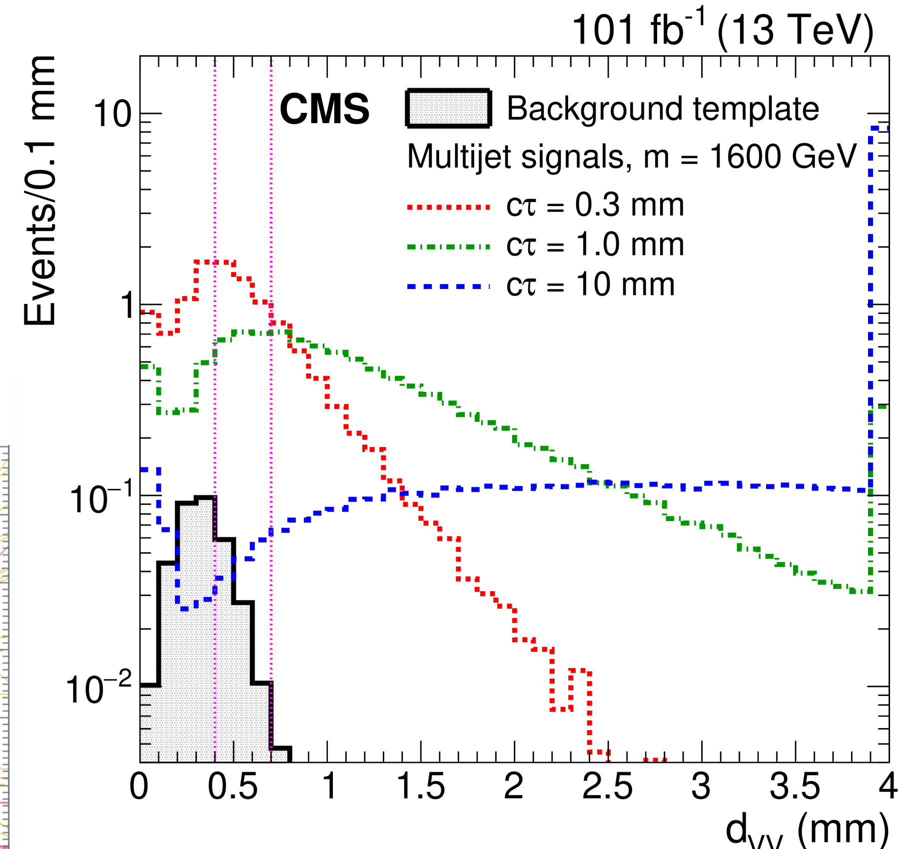
EXO-19-013, Phys. Rev. D 104, 052011 (2021)

Displaced vertices - variable

- **Search variable: d_{VV}** – xy distance between vertices
- **Search regions:** 3 bins
  - 0.0 – 0.4 mm
  - 0.4 – 0.7 mm
  - 0.7 – 40 mm

Signal MC Event Display

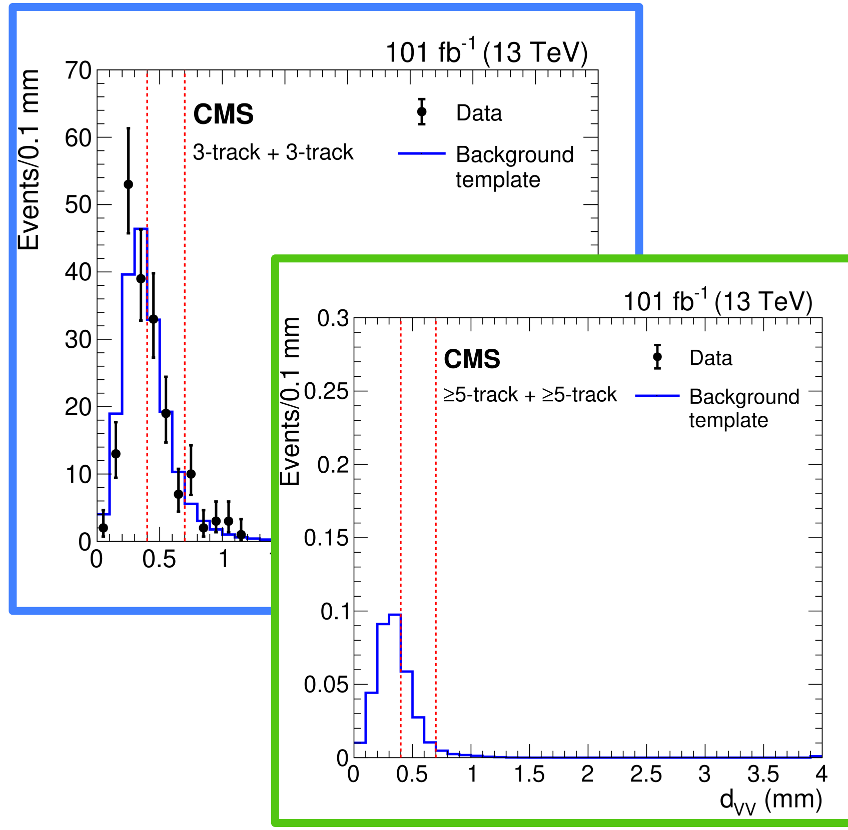




Displaced vertices - results

- **Trigger:** on events with large jet activity
  standard HT = $\Sigma^{\mathrm{Njets}} E_T$ > 1050 GeV
- **Selection:** ≥ 4 jets

- **Control samples:**
  - events with 3-track & 4-track vertices
- **Background:**
  - estimated from ≥5-track one-vertex
- **Signal region:**
  - ≥5-track two-vertex events



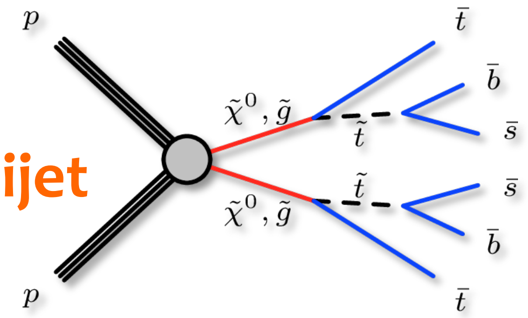
- **Results:** 0 event observed (≥5-track two-vertex)

		Predicted multijet signal yields			
d_{VV} range	Predicted background yield	0.3 mm	1.0 mm	10 mm	Observed
0–0.4 mm	0.243 ± 0.003 (stat) ± 0.061 (syst)	4.4 ± 0.5	1.5 ± 0.1	0.26 ± 0.02	0
0.4–0.7 mm	0.097 ± 0.003 (stat) ± 0.032 (syst)	4.1 ± 0.5	2.1 ± 0.2	0.14 ± 0.01	0
0.7–40 mm	0.012 ± 0.001 (stat) ± 0.006 (syst)	3.0 ± 0.3	7.6 ± 0.7	12 ± 1	0

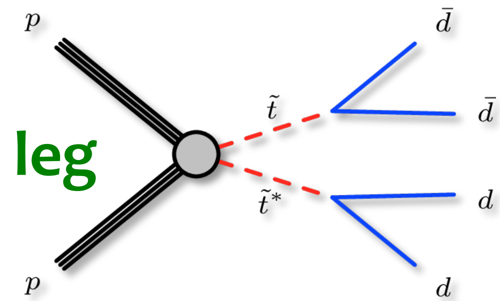
EXO-19-013, Phys. Rev. D 104, 052011 (2021)

Displaced vertices - intepretation

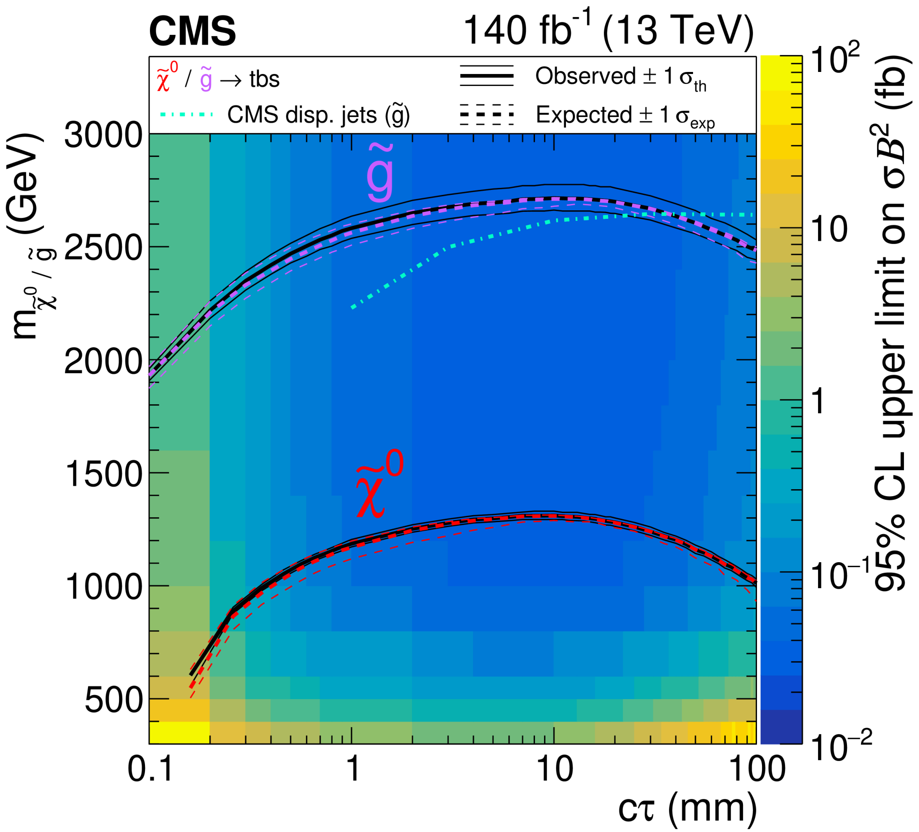
Multijet

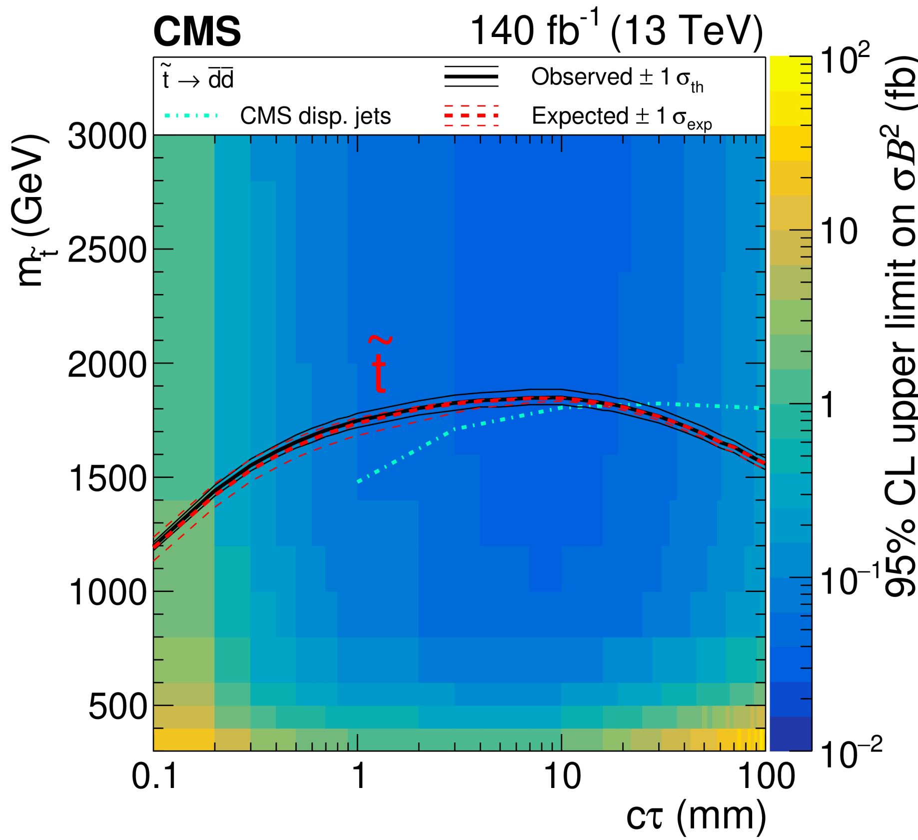


Dijet per leg



Full Run 2

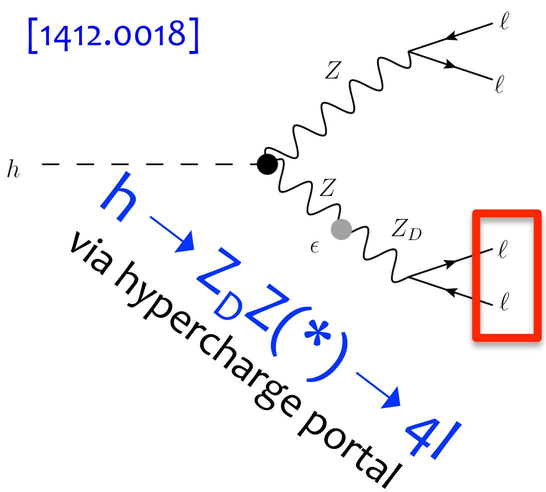




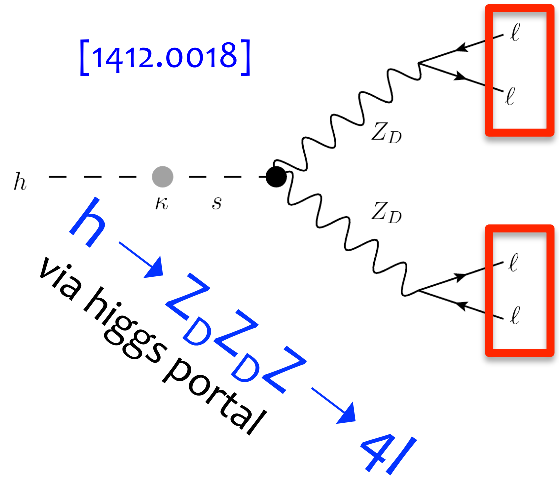
Displaced Vertices – low mass di-μ's

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

[1412.0018]

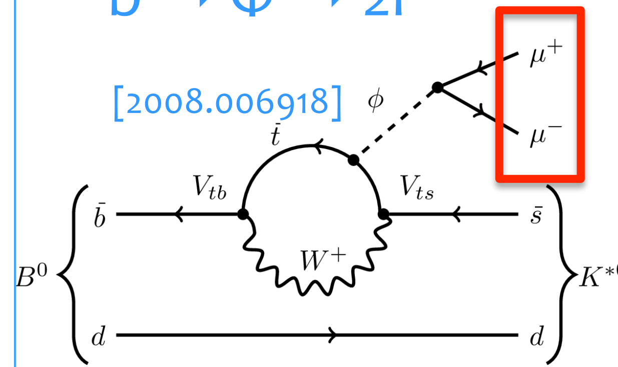


[1412.0018]



$b \to \Phi \to 2l$

[2008.006918]

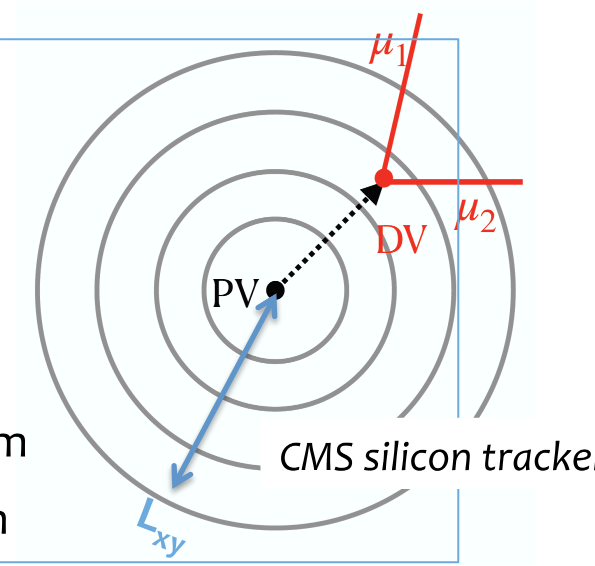


Long-lived scalar resonance arises from the decay of a B hadron

Very low mass search

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

- masses **down to ~2m$_\mu$** and **displacements** **L$_{xy}$** **up to 11 cm**



Benchmark models

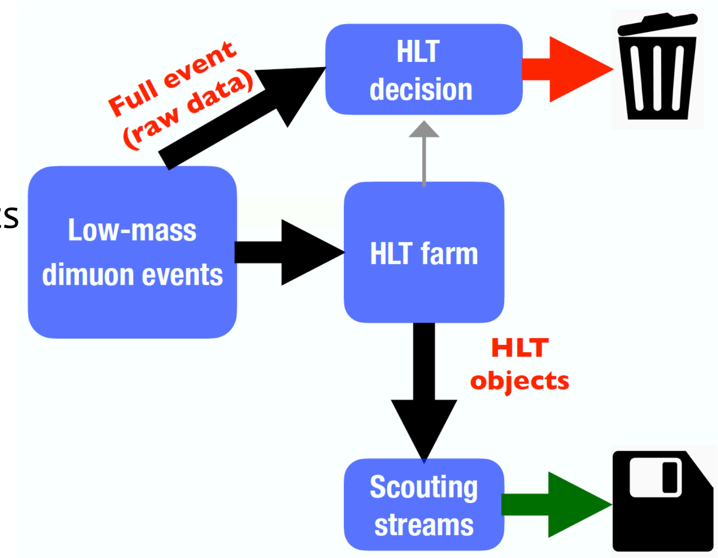
- **Z_D** : 0.5 GeV ≤ m(Z_D) ≤ **50 GeV** 0.1 mm ≤ cτ_0(Z_D) ≲ 1000 mm
- **Φ** : 0.3 GeV ≤ m(Φ) ≤ **5 GeV** 0.1 mm ≤ cτ_0(Φ) ≲ 100 mm

EXO-20-014, May 2021

Dimuon resonances w/scounting

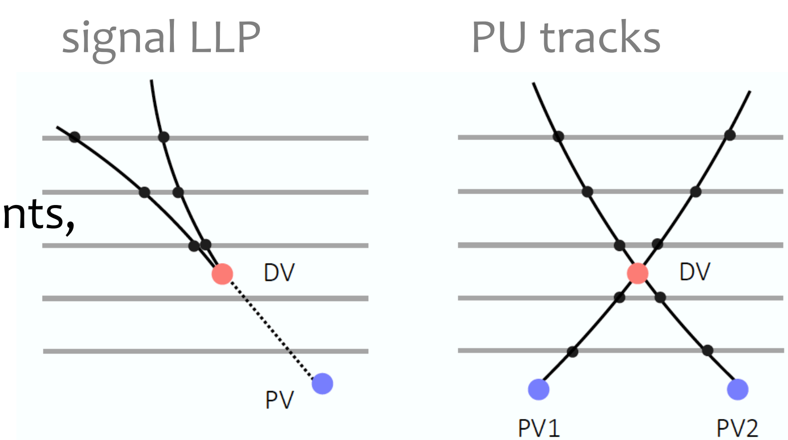
High rate triggers (*scouting*):

- 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



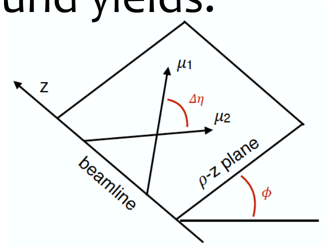
Signature :

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



Backgrounds:

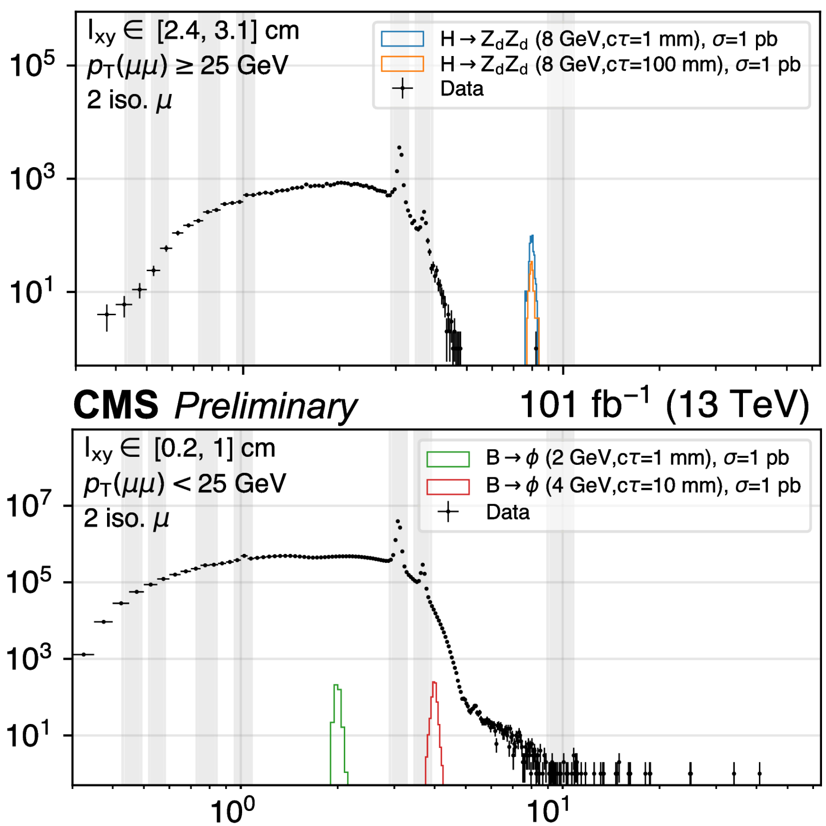
- Controlled with a set of kinematical cuts
- DV/dimuon kinematics & displacement requirements, material veto to reduce background yields:
  - Sophisticated cuts:
    - log10 ($\Delta\eta/\Delta\phi$) < 1.25
    - # excess pixel hits ≤ 0



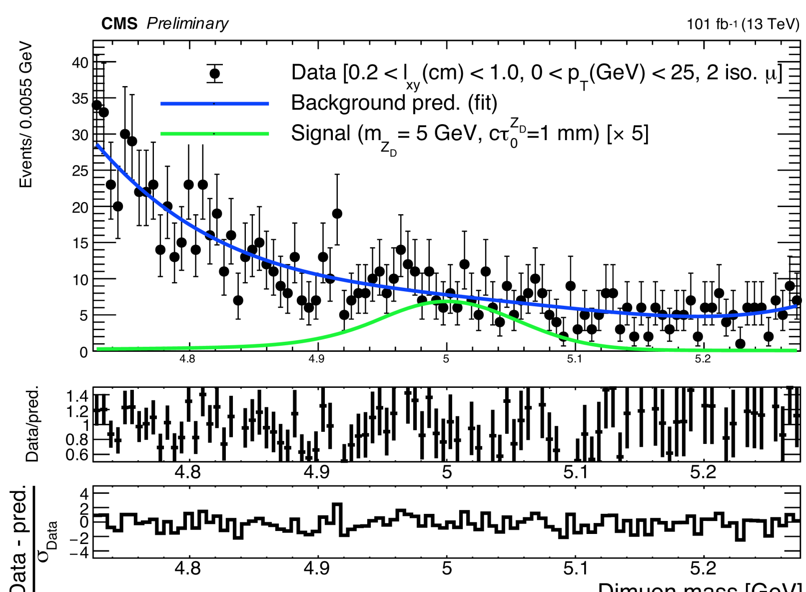
Dimuon resonances – results

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}



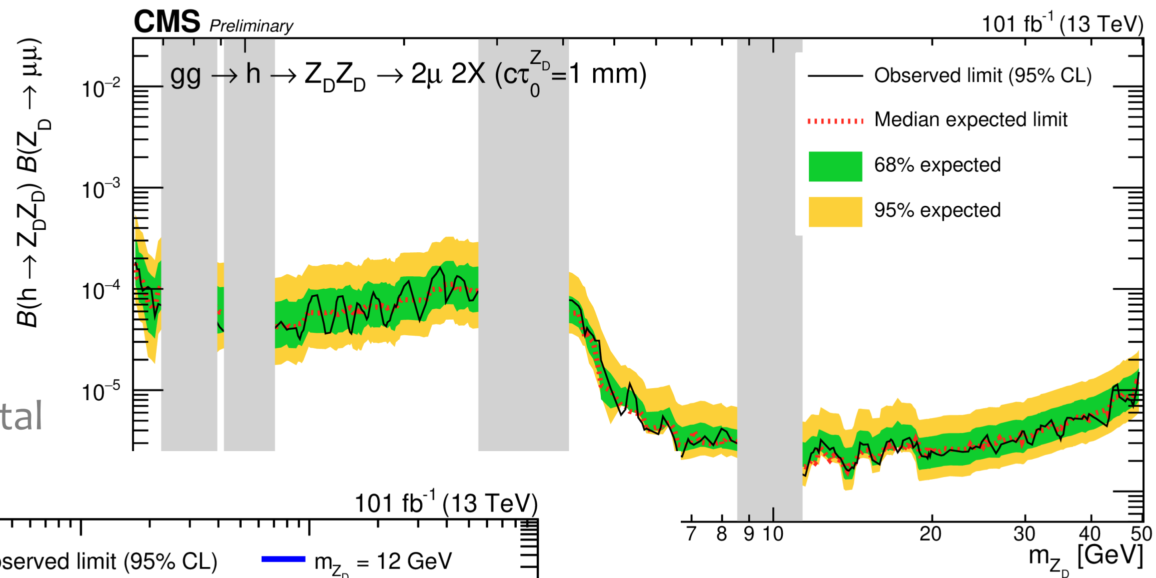
- **Simultaneous fit** in all search bins either bkg-only or bkg+signal hypotheses

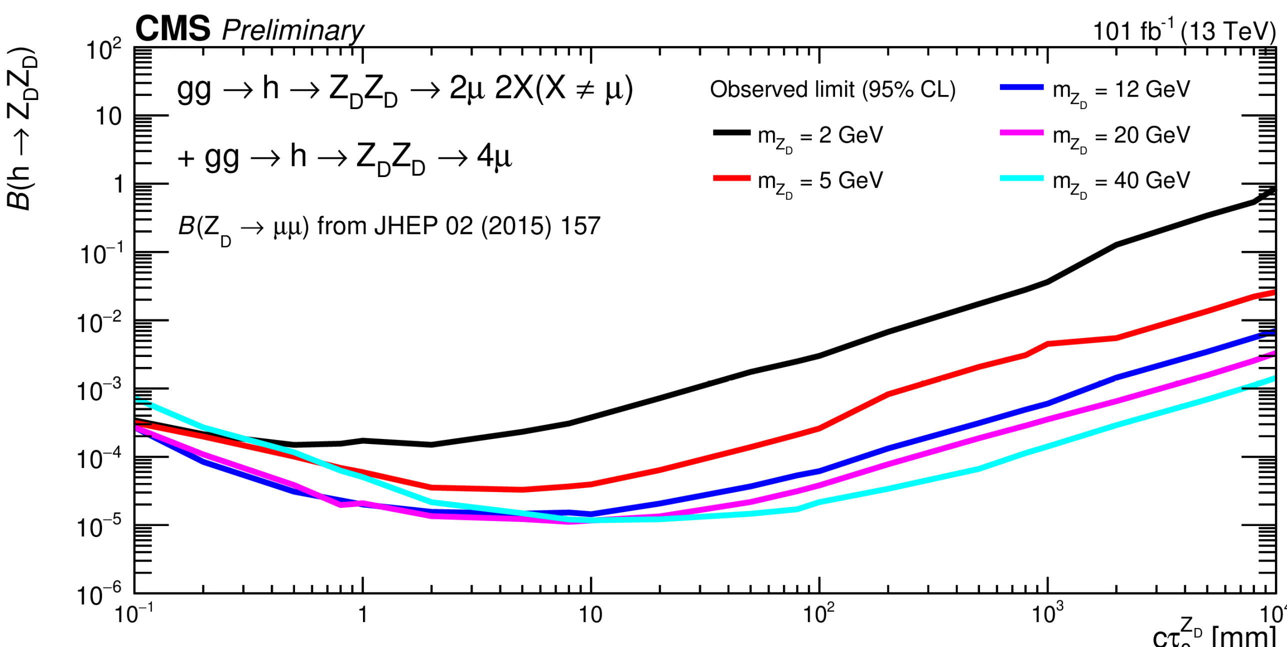


Dimuon resonances – limits

- **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

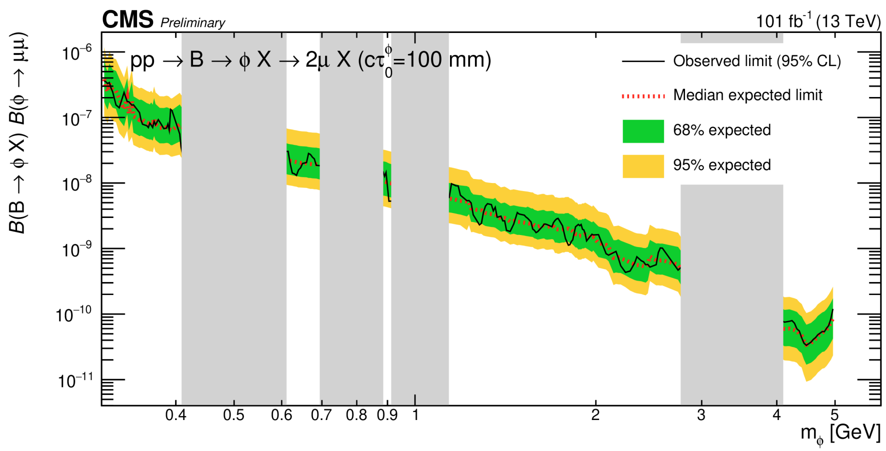


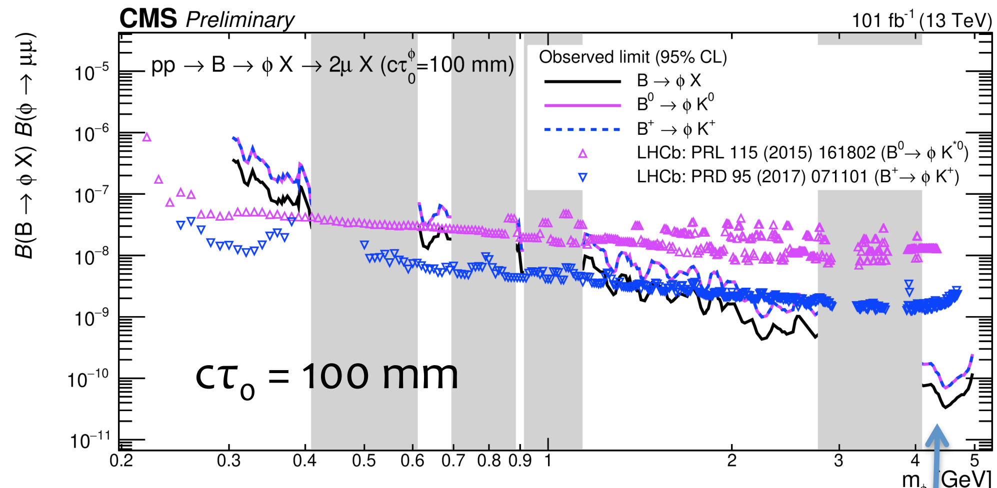


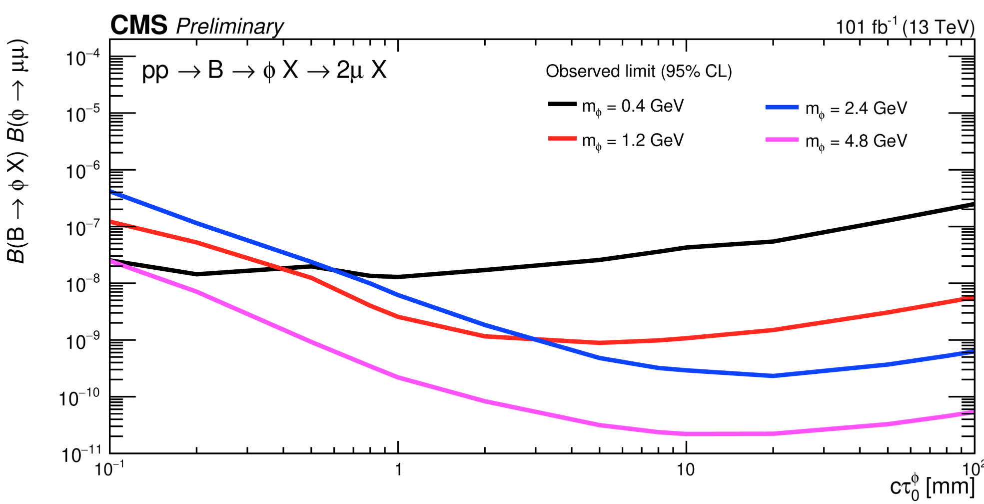
The most stringent constraints to date in a wide range of signal mass (2-40 GeV) and lifetime hypotheses

Dimuon resonances – limits

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

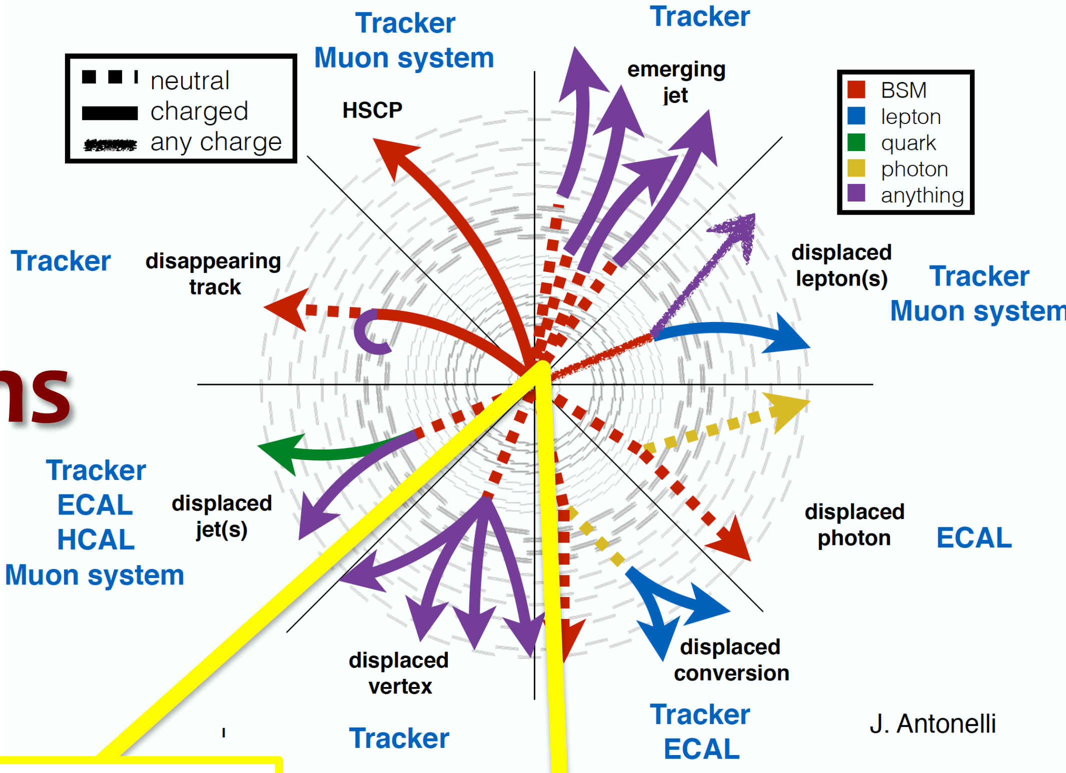


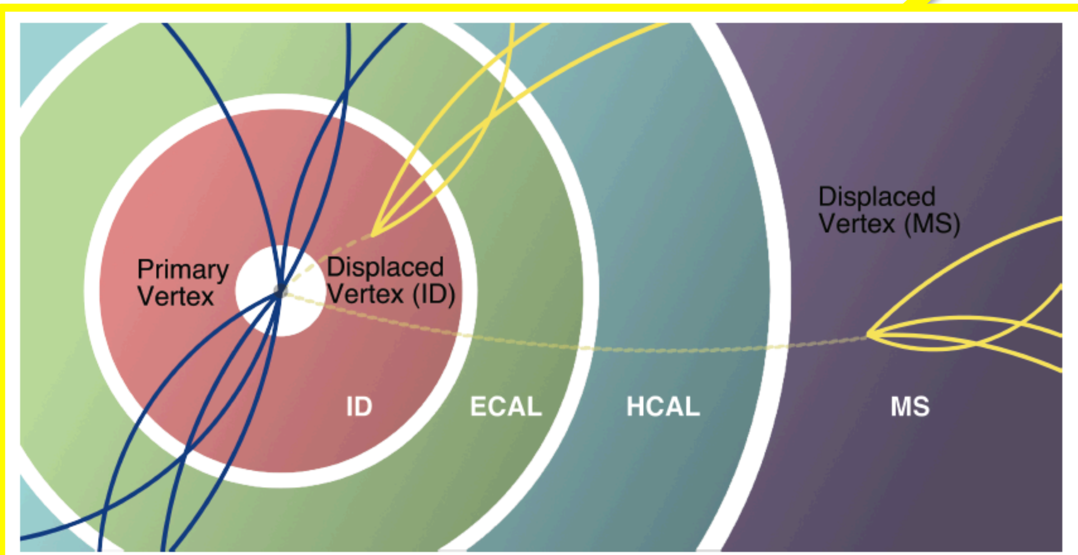




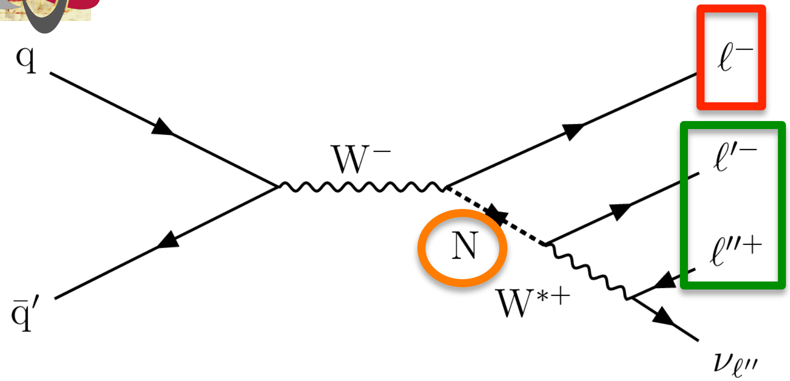
- Upper limits on $BR(B \to \phi X) \cdot BR(\phi \to \mu\mu)$
- **CMS reached sensitivity comparable with LHCb** especially at higher mass and higher lifetime

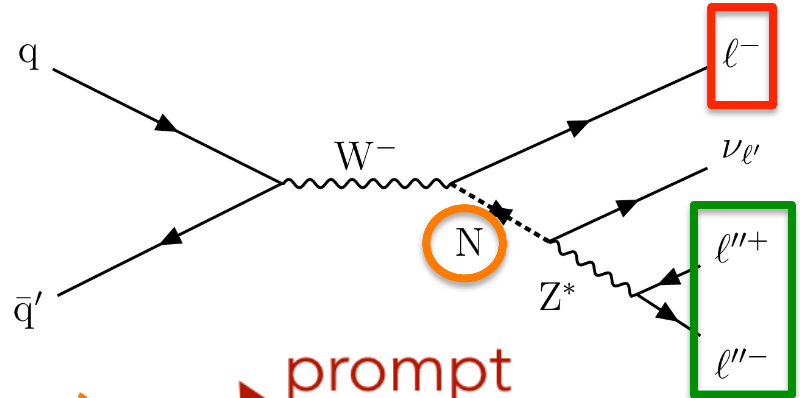
Displaced Leptons



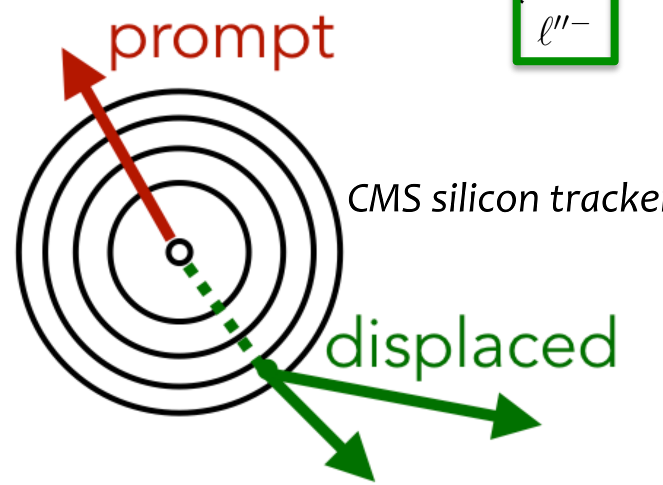


Heavy neutral leptons (HNL)





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**

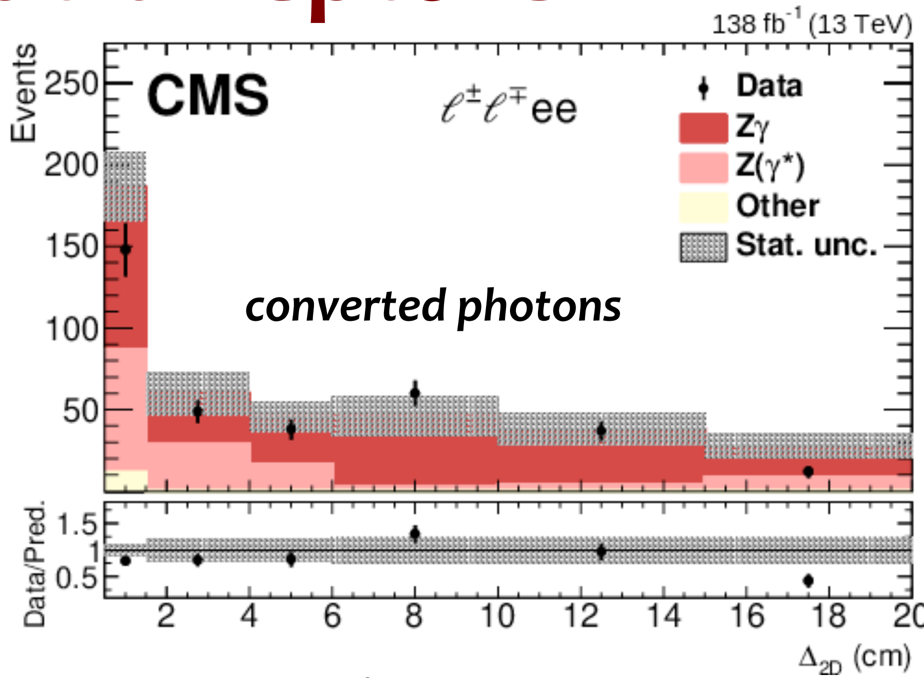
Signature: 3 lepton final state with:
- **2 displaced <u>soft</u> leptons** that form a **common vertex**
- **1 prompt lepton**
- Final states: **eeX** or **μμX** where X= {e, μ}

Run2: 138/fb

EXO-20-009, Jul 2021

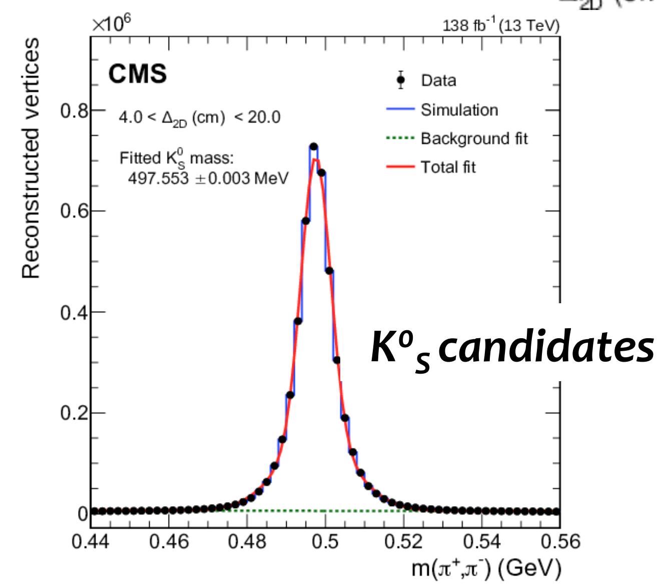
Heavy neutral leptons

- **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)

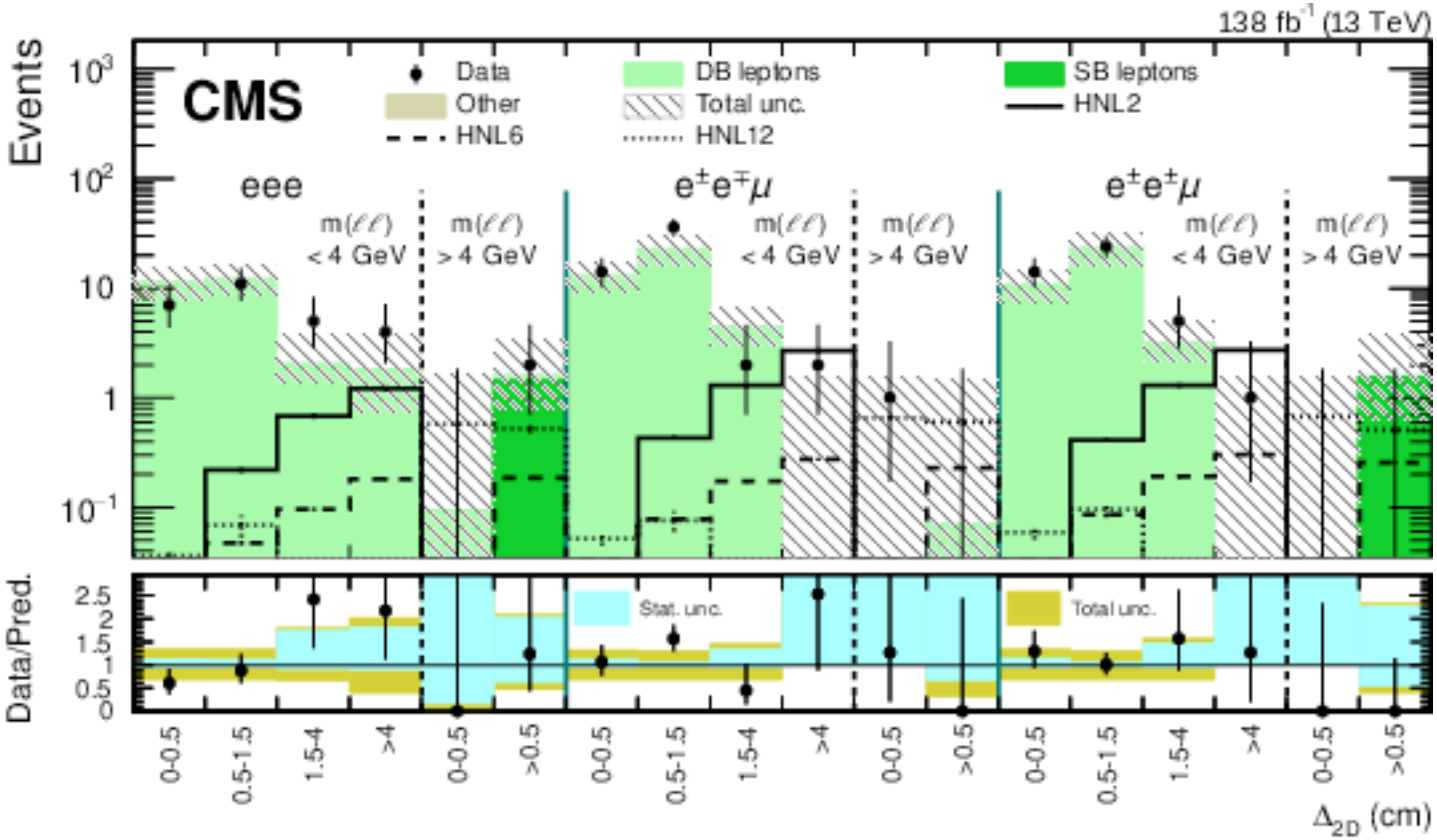


- **Data-driven estimation of background:**
  - "tight-to-loose" method in data control regions
  - Validate with closure tests in sideband regions

Heavy neutral leptons – eeX results

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

Majorana **HNL** interpretation



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).

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

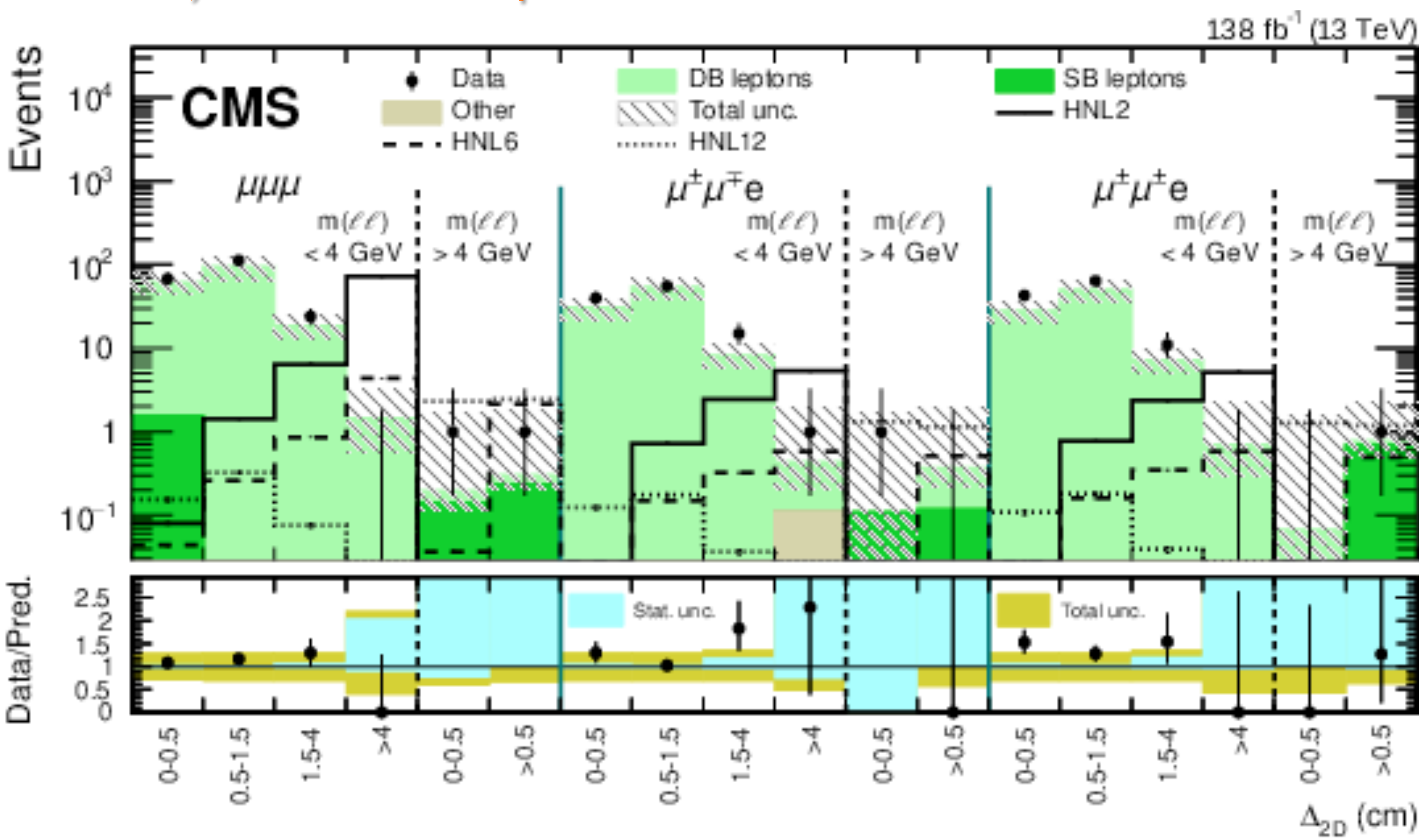
Run2: 138/fb

EXO-20-009, Jul 2021

Heavy neutral leptons – μμX results

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

Majorana **HNL** interpretation



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).

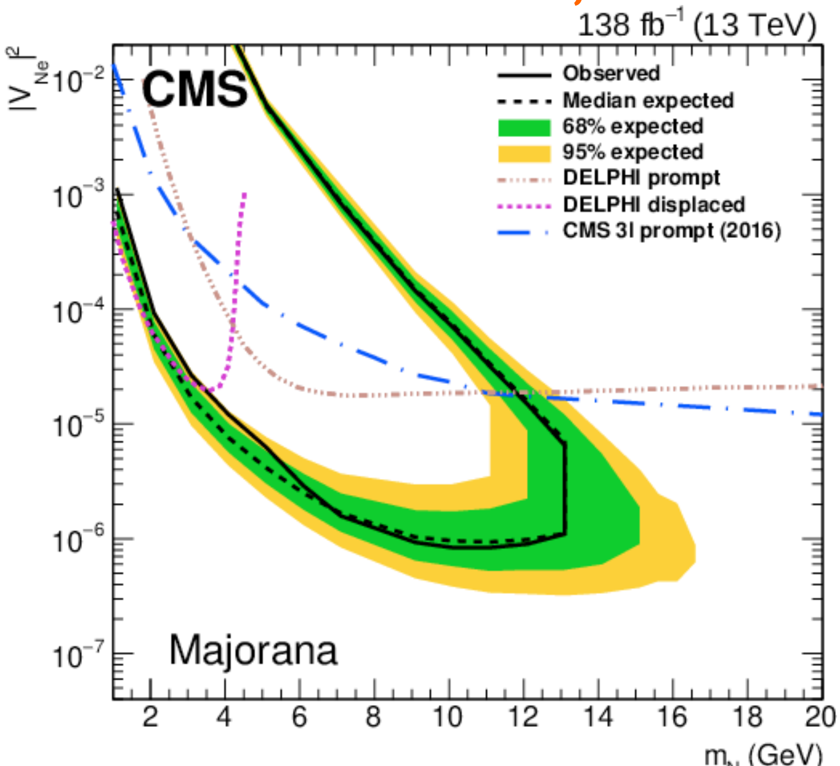
- No significant deviations from the SM expectations are observed for eeX and μμX final states

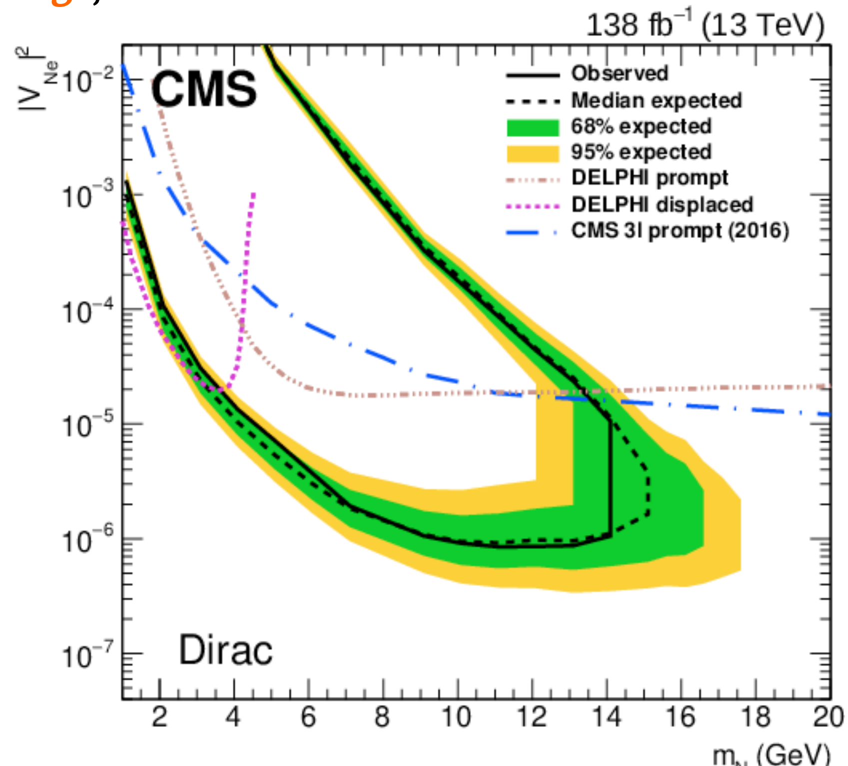
Heavy neutral leptons – limits

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*





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

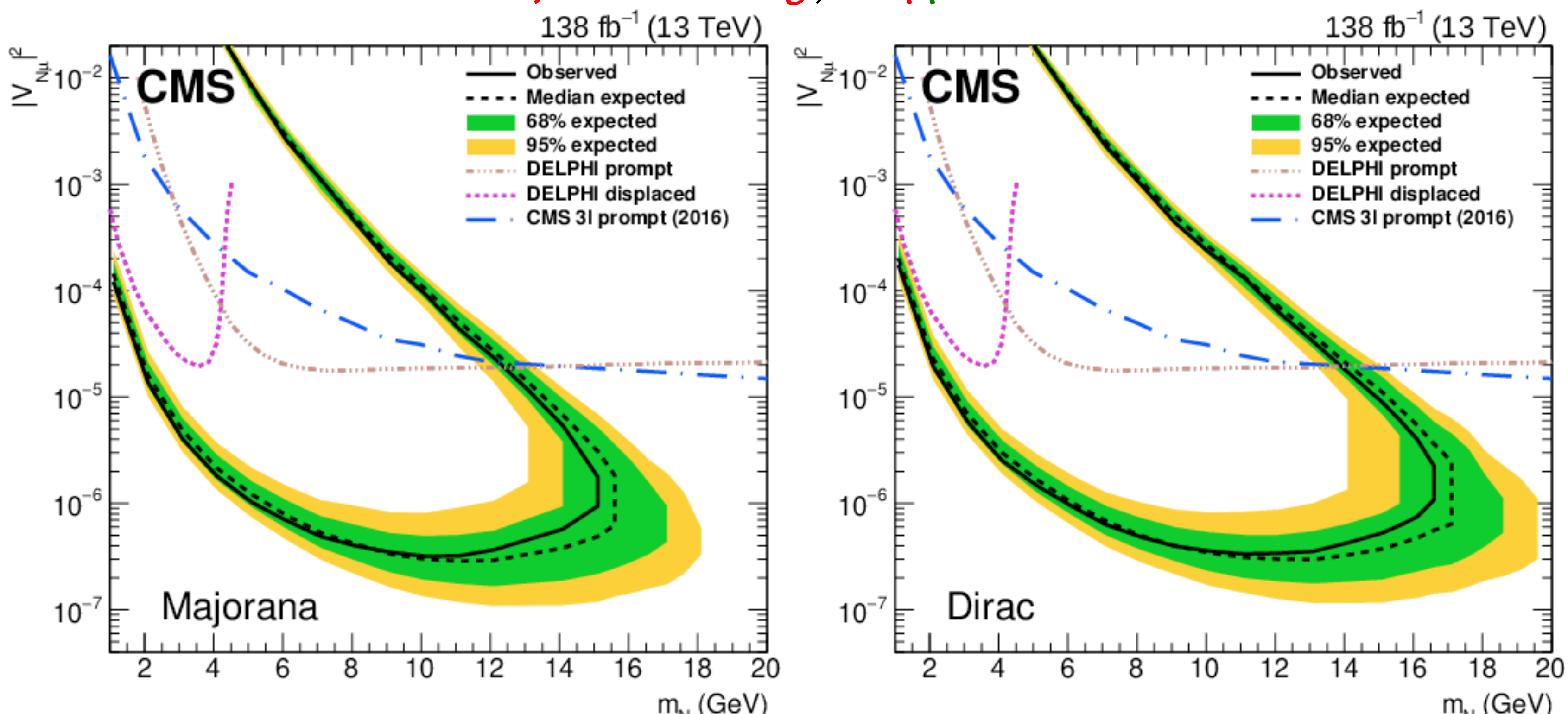
Results represent the *world best limits to date* on this type of processes in the explored parameter space of the *HNL production at the LHC*

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 muon mixing from μμX channels

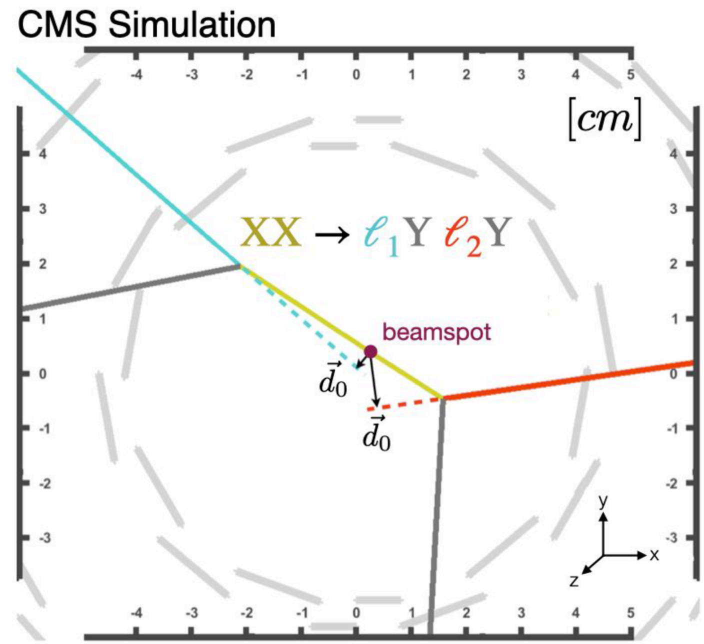


$$c\tau \propto \sum_i |V_{iN}|^{-2} m_N^{-5}$$

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*

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
  - **$|d_0|$ > ~100 μm** eliminates significantly the SM background

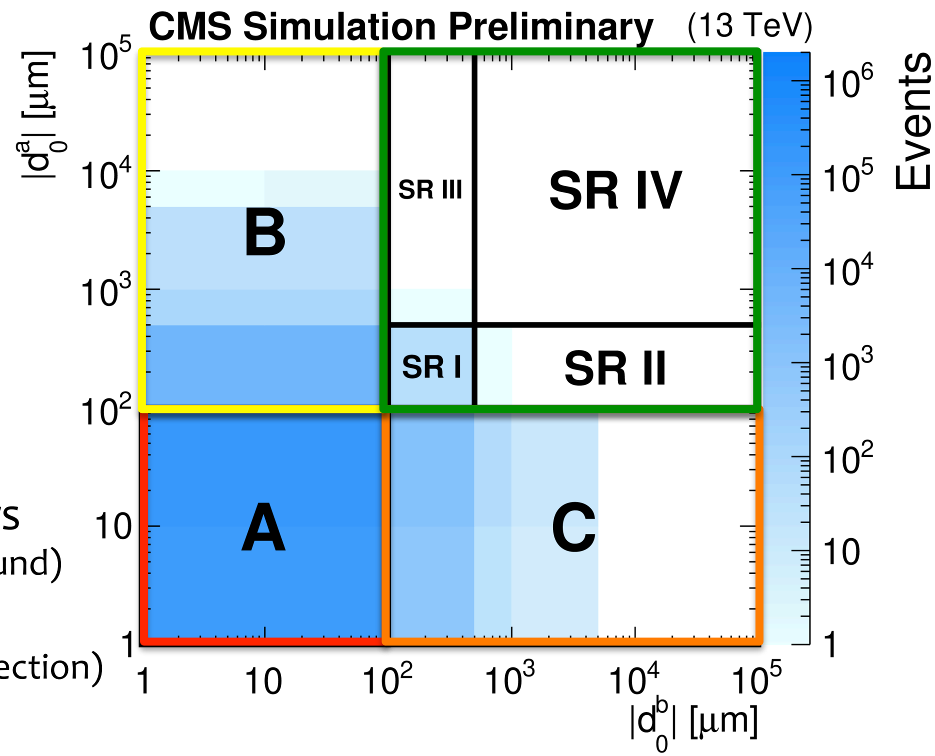


- **Analysis strategy:** VERY INCLUSIVE SEARCH for LLPs
  - Look for **eμ, ee, μμ final states** with both **large d_0**
  - No explicit constraints on non-lepton physics objects
    - Sensitivity to **large range of lifetimes cτ (10 mm to 1 m)**
  - Kinematical cuts to reject SM bkg that produce displaced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

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

Displaced leptons – inclusive search

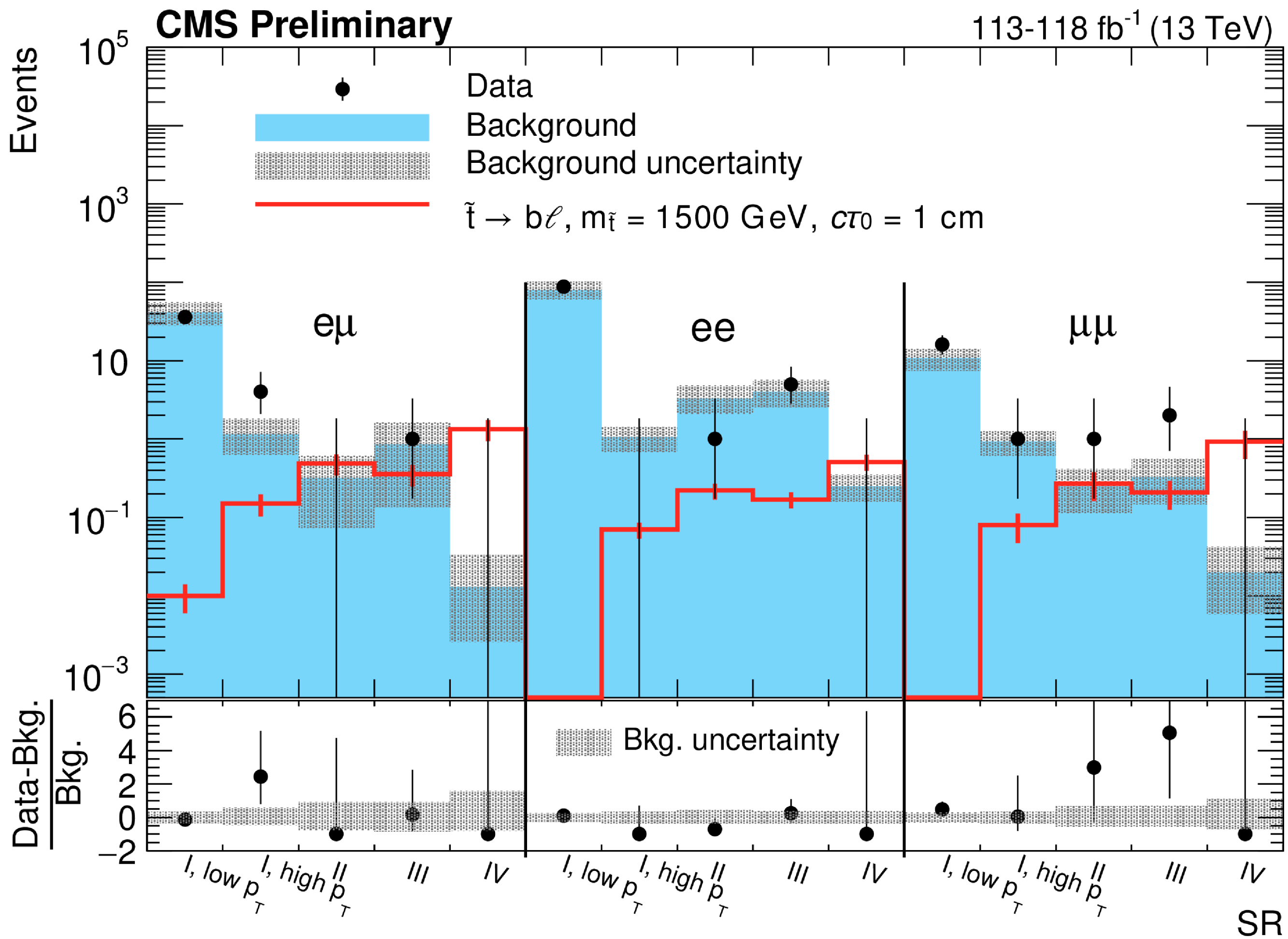
- Inclusive event selection:
  - ≥ 2 isolated, high-momentum, well-measured leptons
    - p_T set by trigger turn on (35–75 GeV depending on channel/year)
    - $|\eta| < 1.5$ (for $\mathbf{d_0}$ resolution)
  - No constraints on other event parameters such as missing energy, jets, etc
- Lepton $\mathbf{d_0}$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

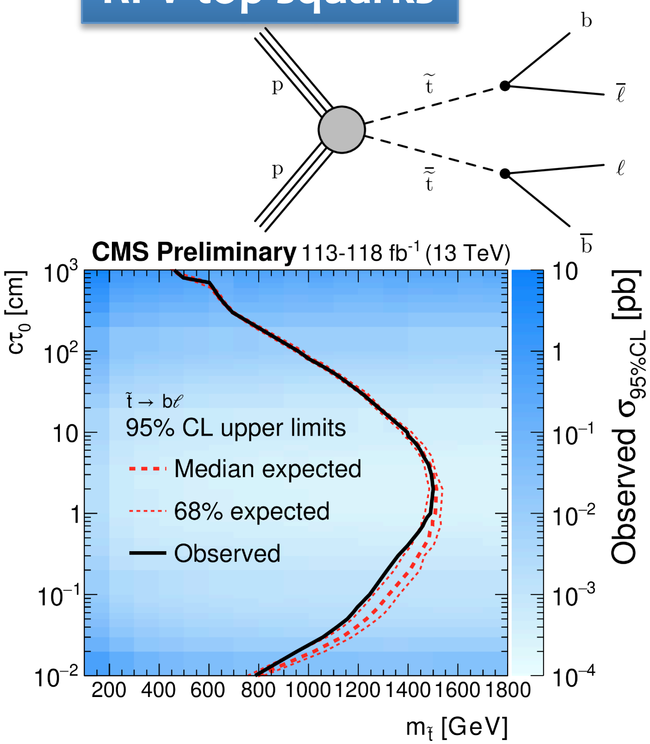


- Observation consistent with bg-only hypothesis

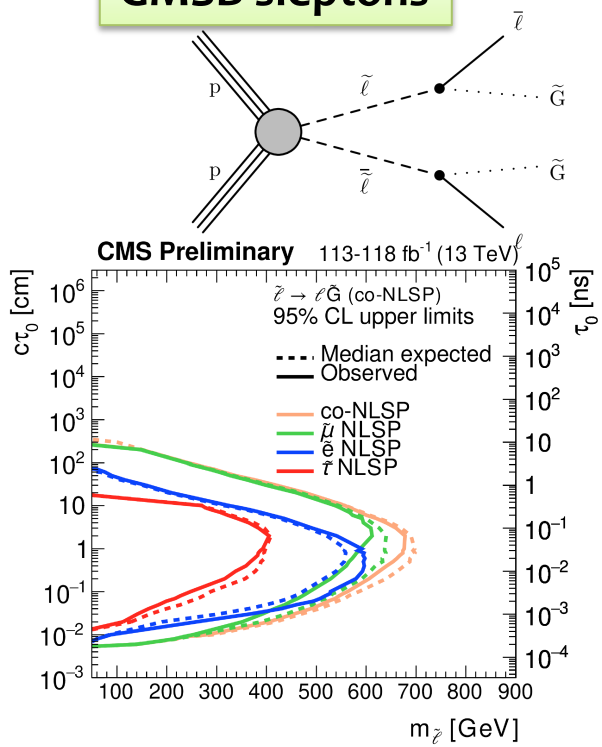
Displaced leptons – limits

- Mass and cross sections constrains over wide range of lifetimes

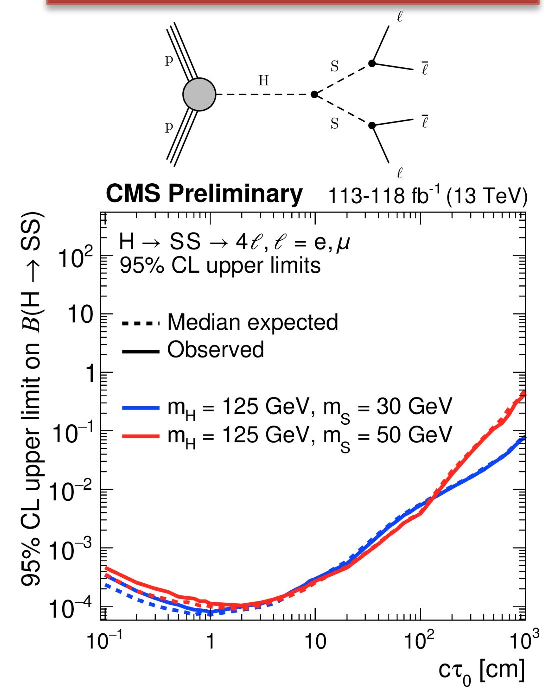
RPV top squarks



GMSB sleptons



Higgs boson decaying to long-lived scalars

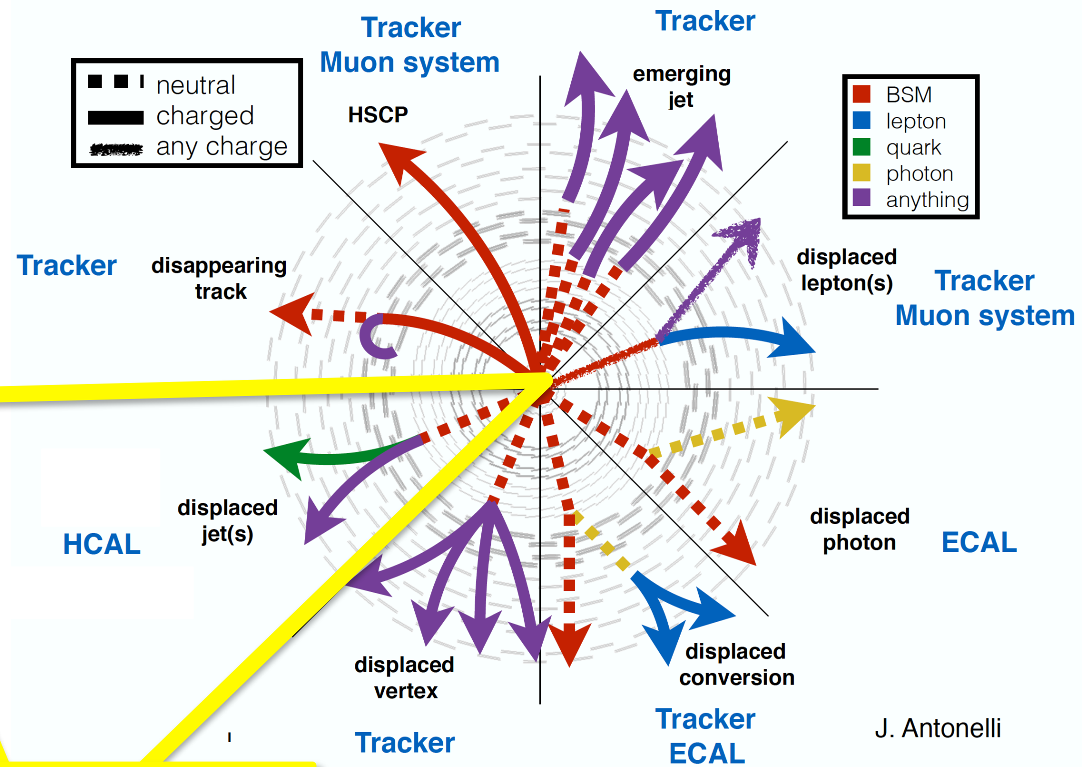


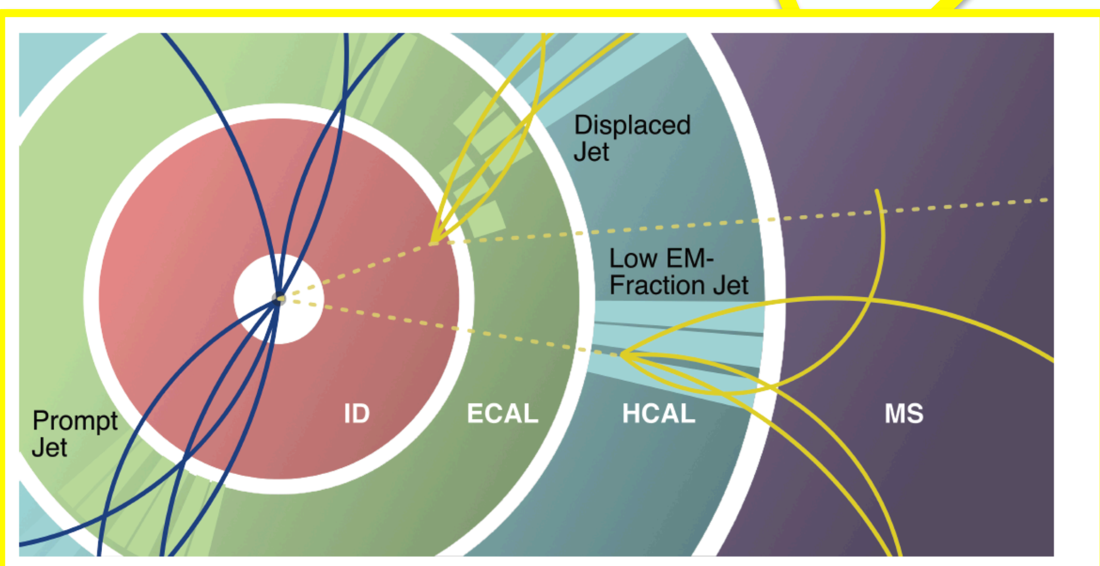
~600 GeV improvement wrt. previous displaced lepton limits

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

Most stringent limits to date for cτ ≲ 50 cm

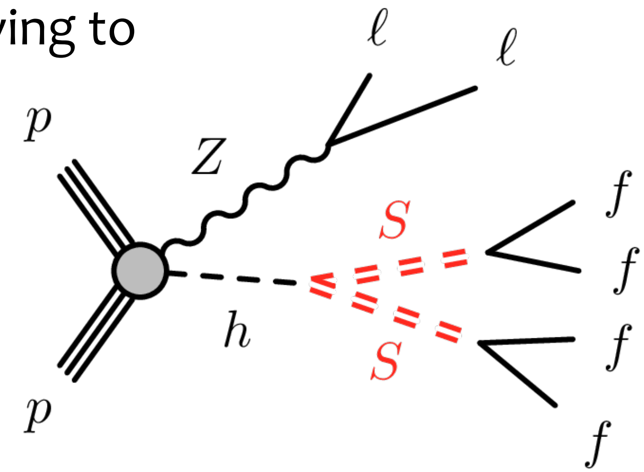
Displaced Jets





Displaced jets with Z boson

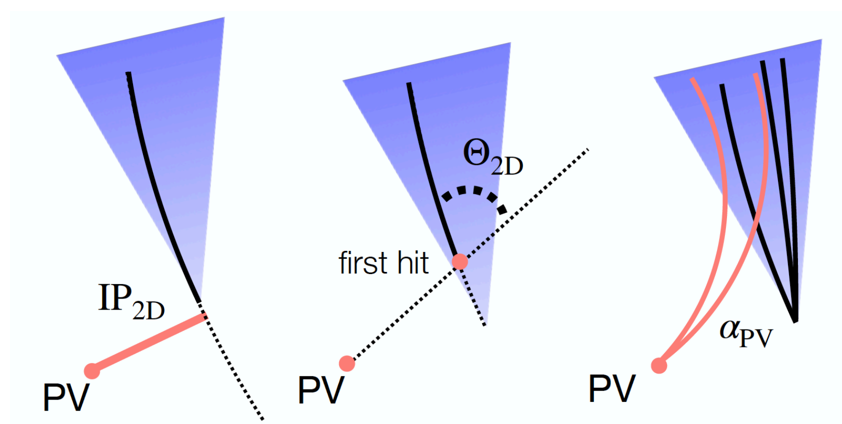
- **Search for:** SM-like (125GeV) **higgs** boson decaying to **light scalar LLPs** which **decay to b-jets** or **d-jets** and produced with **Z boson** association



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

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

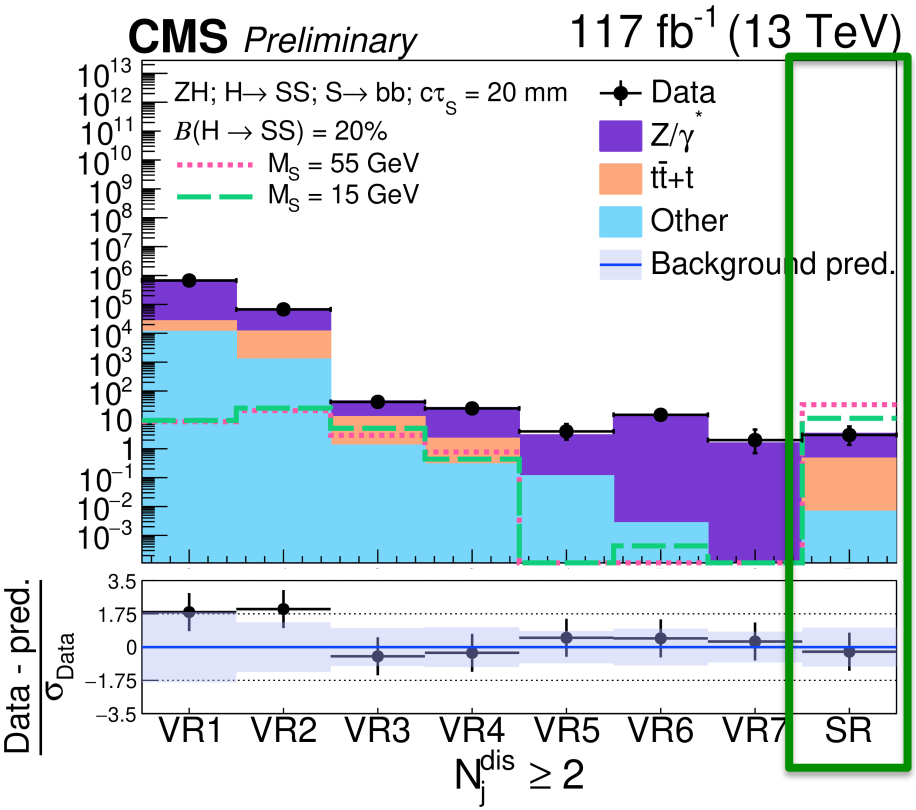
- **Selections:**
  - events with at least 2 displaced jets
  - no displaced vertex required

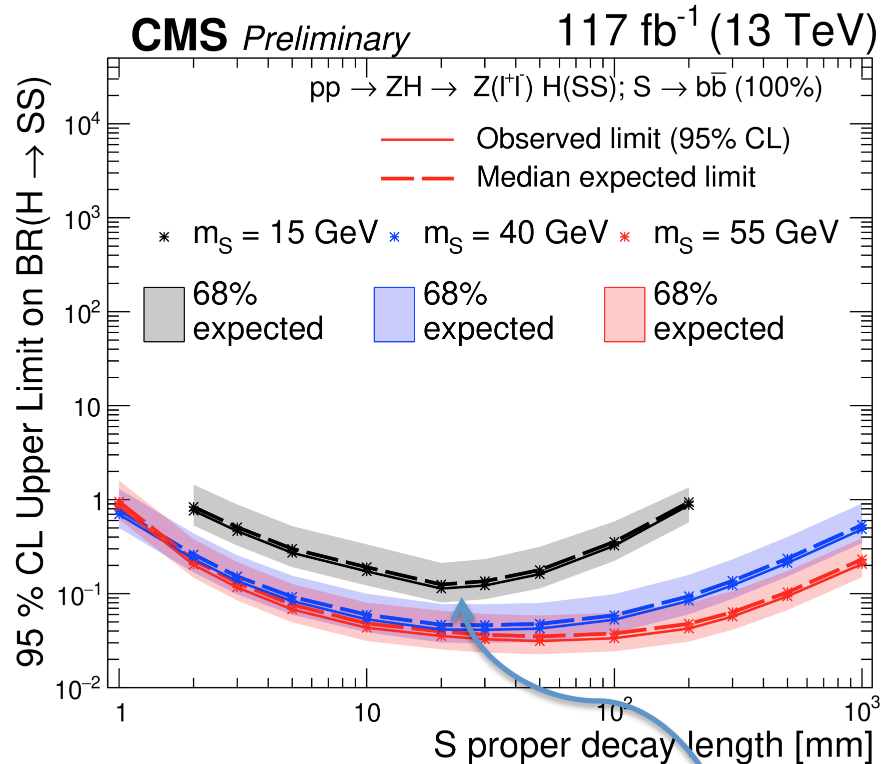


Displaced jets in the CMS silicon tracker

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





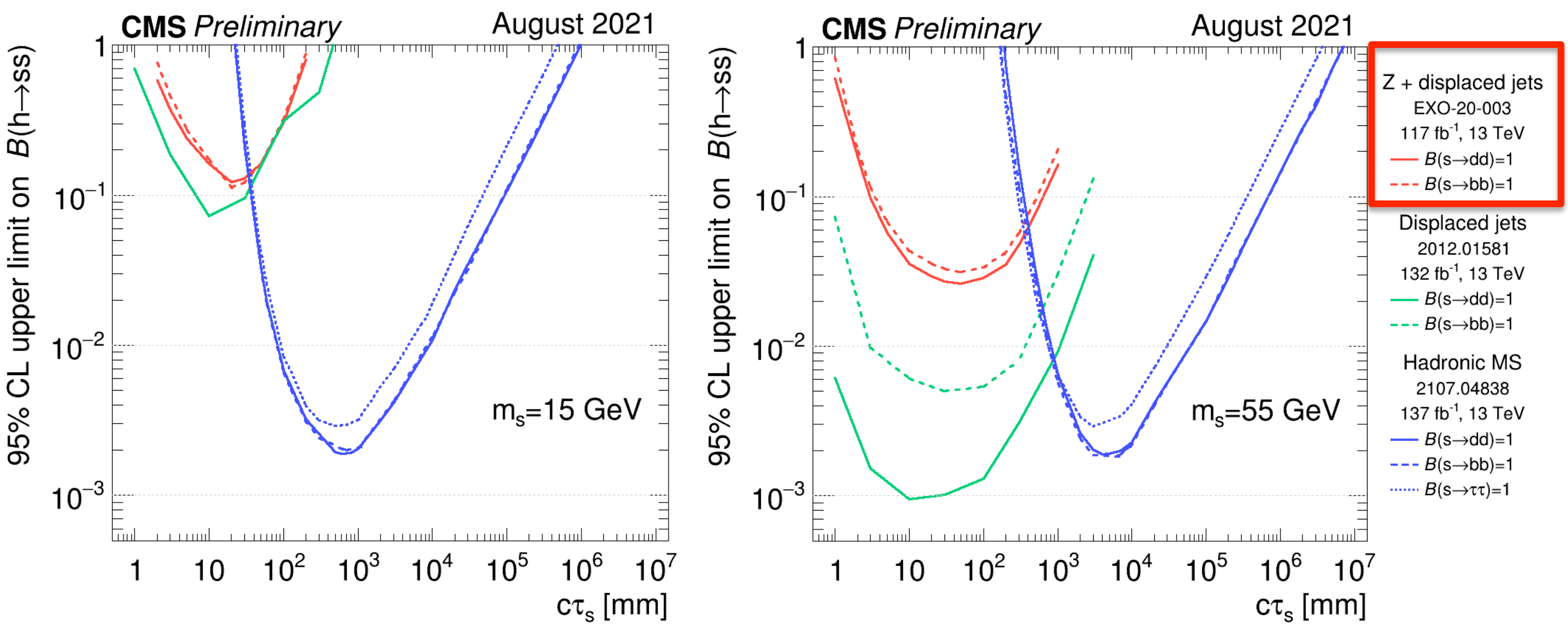
Most stringent CMS limits for the branching fractions (H→SS)
for low **mass scalars** of around **15 GeV** with mean proper decay lengths of **2-30 mm,**
where the scalars decay to a pair of **b quarks**

2016-18: 117/fb

EXO-20-003, May 2021

Displaced jet + Z vs other searches

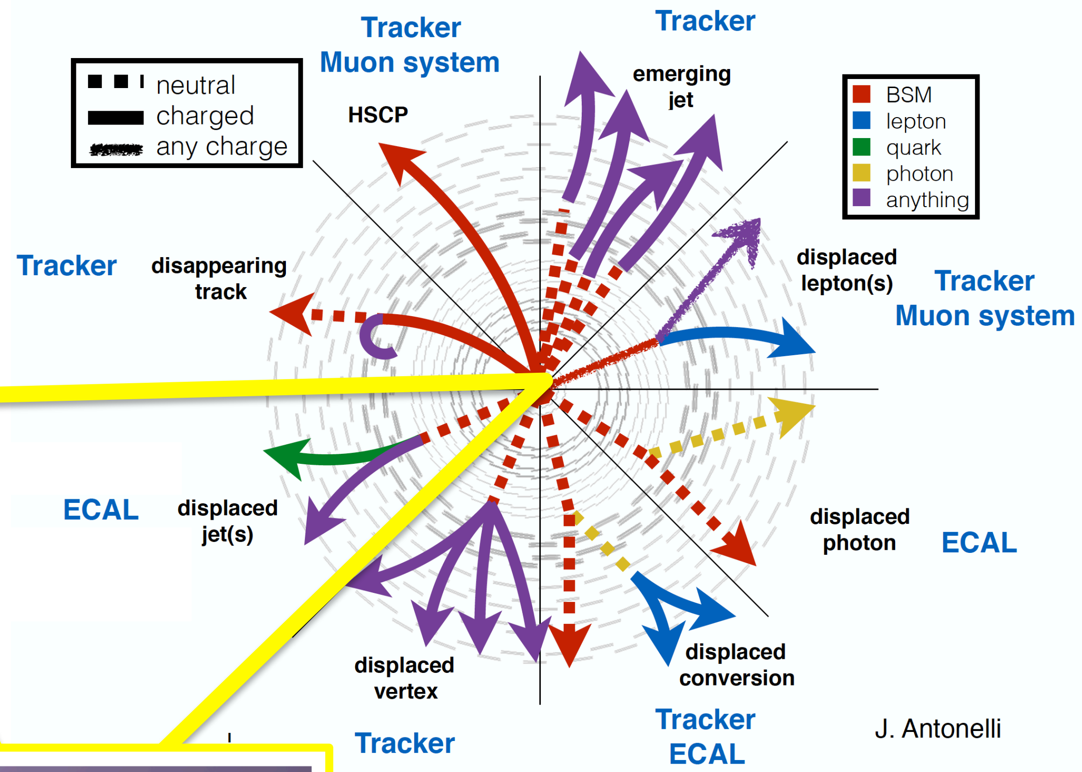
- Observed exclusion limit from different CMS hadronic long-lived particle analyses on the branching fraction of the SM- higgs boson to two neutral long-lived scalars

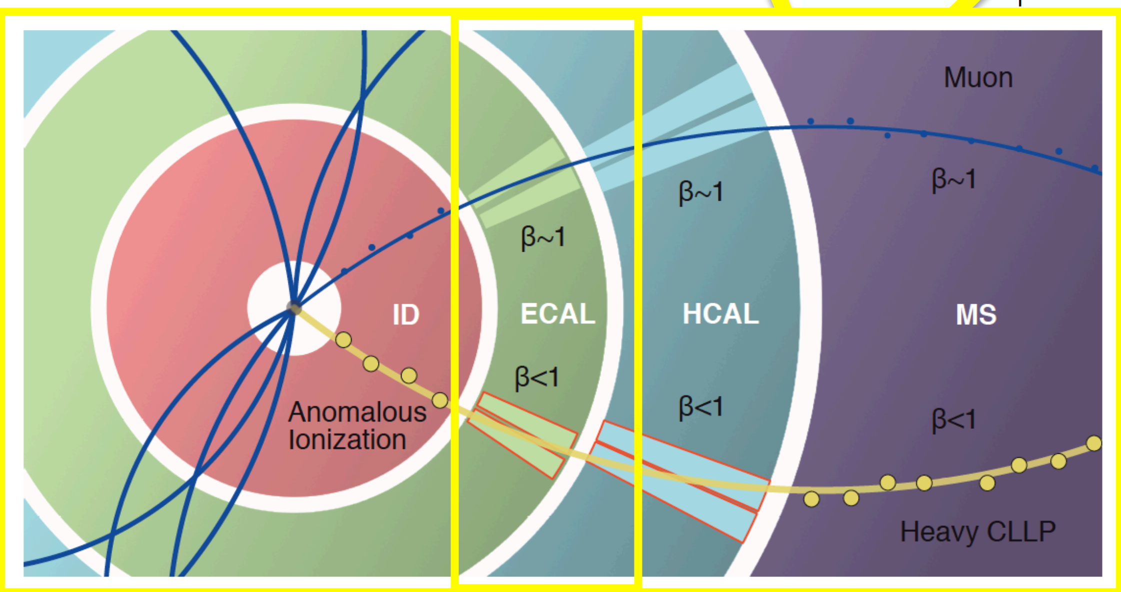


- Complementary results for CMS
  - Z+displaced jets: added a sensitivity to low mass LLP for 15 GeV, S→bb

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

Delayed Jets



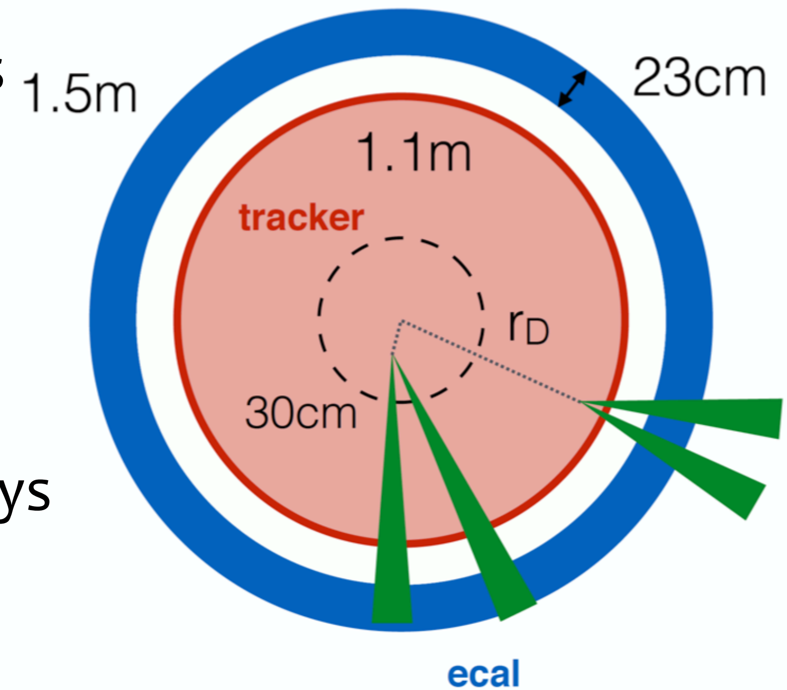


Phys. Lett. B 797 (2019) 134876, EXO-19-001

Delayed Jets

NEW! Usage of ECAL timing for calo jets

- **Signature:** Calorimeter deposits of displaced jets from massive LLPs are **delayed** wrt. jets from prompt decays



- **Strategy:**
  use ECAL timing to find ***displaced jets***

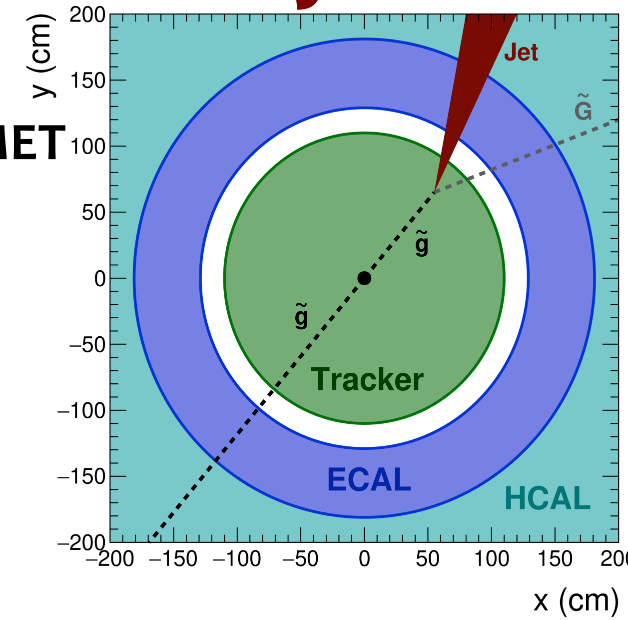
- **Profit:** increased acceptance for decays beyond tracker (0.3 - 1.5 m)

- **ECAL: jet time** is a median time of all ECAL cells in jet with energy > 0.5 GeV and |time| < 20ns, ΔR(cell, jet) < 0.4
- time resolution per cell (crystal+APD) ~200 ps

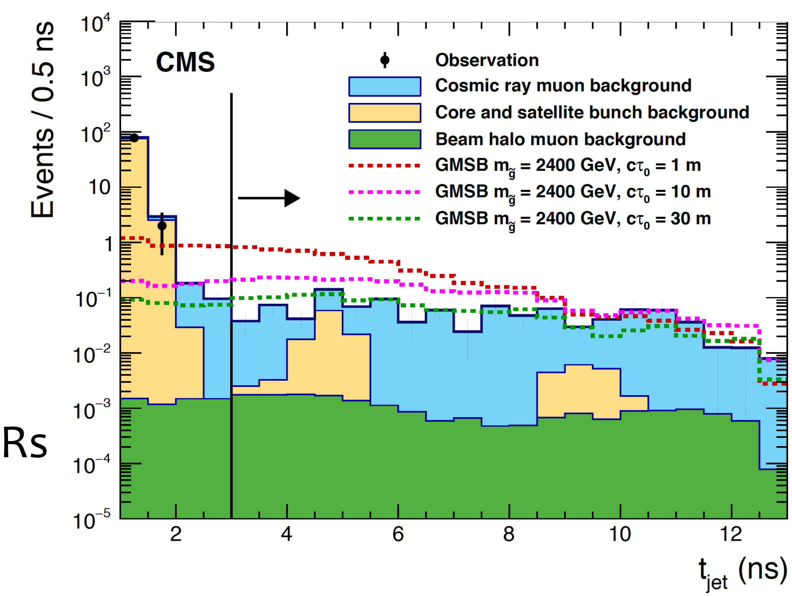
Phys. Lett. B 797 (2019) 134876, EXO-19-001

Delayed Jets – stratedy

- **Signal:** GMSB **long-lived gluinos** or Split SUSY **R-hadrons** decaying to **displaced jets + MET**



- **Selection:**
  - ≥ 1 delayed calo jet
    (t > 3ns, pT > 30 GeV, E > 70 GeV, |η| < 1.48)
  - MET > 300 GeV
- **Trigger:** MET > 120 GeV
- **Candidate event cleaning:**
  - beam halo rejected by muon CSC & HCAL
  - satellite bunches & mismeasurements veto
  - cosmics vetoed by muon DT and RPC
  - pileup & APD hits rejected by ECAL timing
- **Background:**
  Data-driven by invert cleaning cuts to form data CRs
- **Search region:** $N_{jet} \geq 1$, $t_{jet} > 3$ ns



Phys. Lett. B 797 (2019) 134876, EXO-19-001

Delayed Jets - results

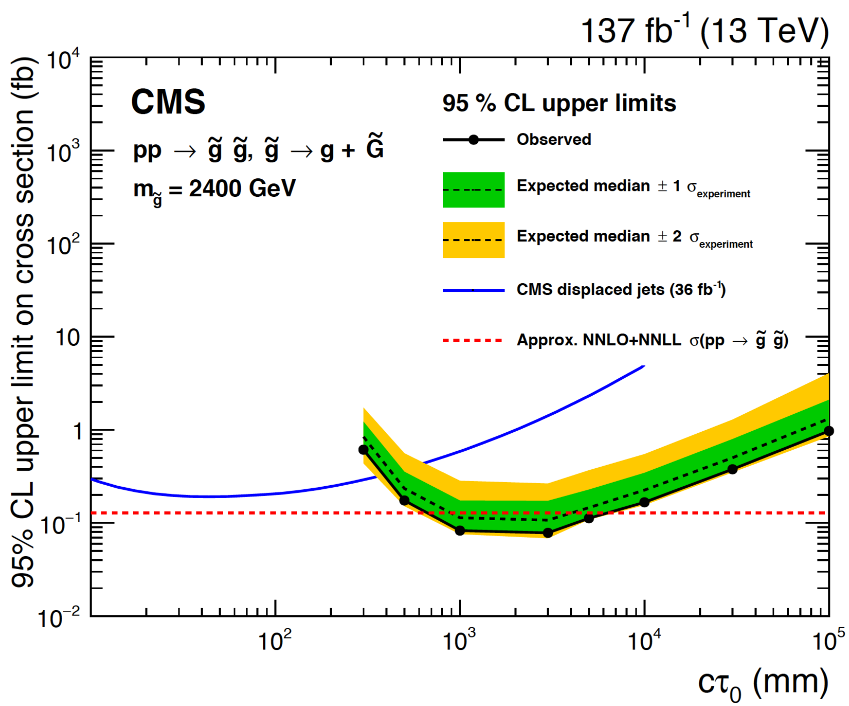
- **Observed: 0 events** in agreement with bckg. prediction of **1 evt**
- **Results (GMSB):**

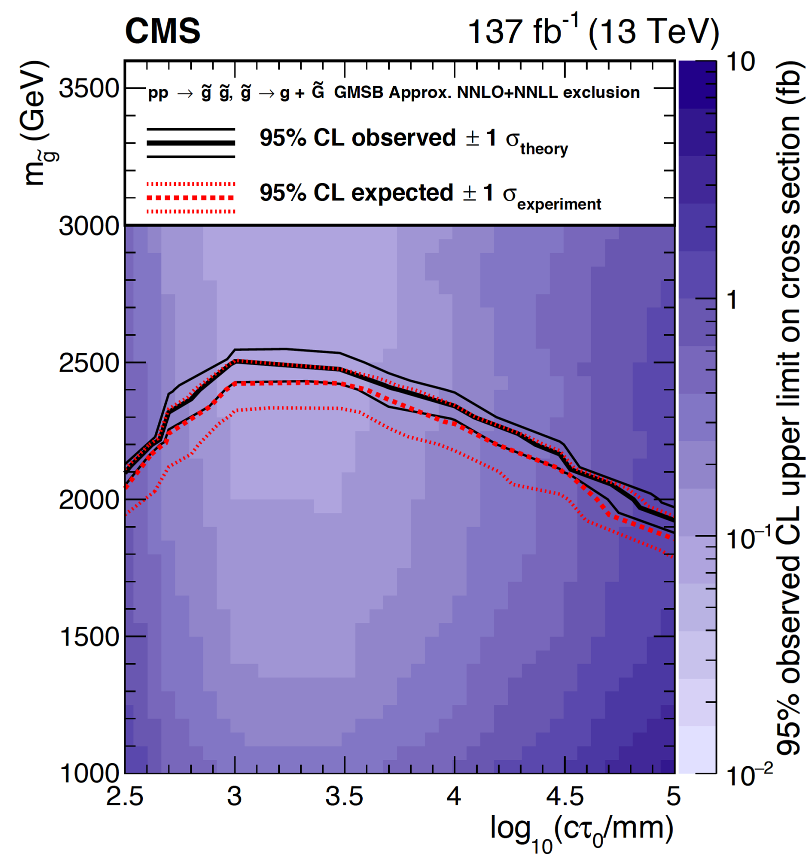
  Exclude $\mathbf{m_{\tilde{g}} < 2.50}$ **TeV for** $\mathbf{c\tau_0 \sim 1}$ **m**

  or $\mathbf{m_{\tilde{g}} < 2.15}$ **TeV for** $\mathbf{c\tau_0 \sim 30}$ **m**

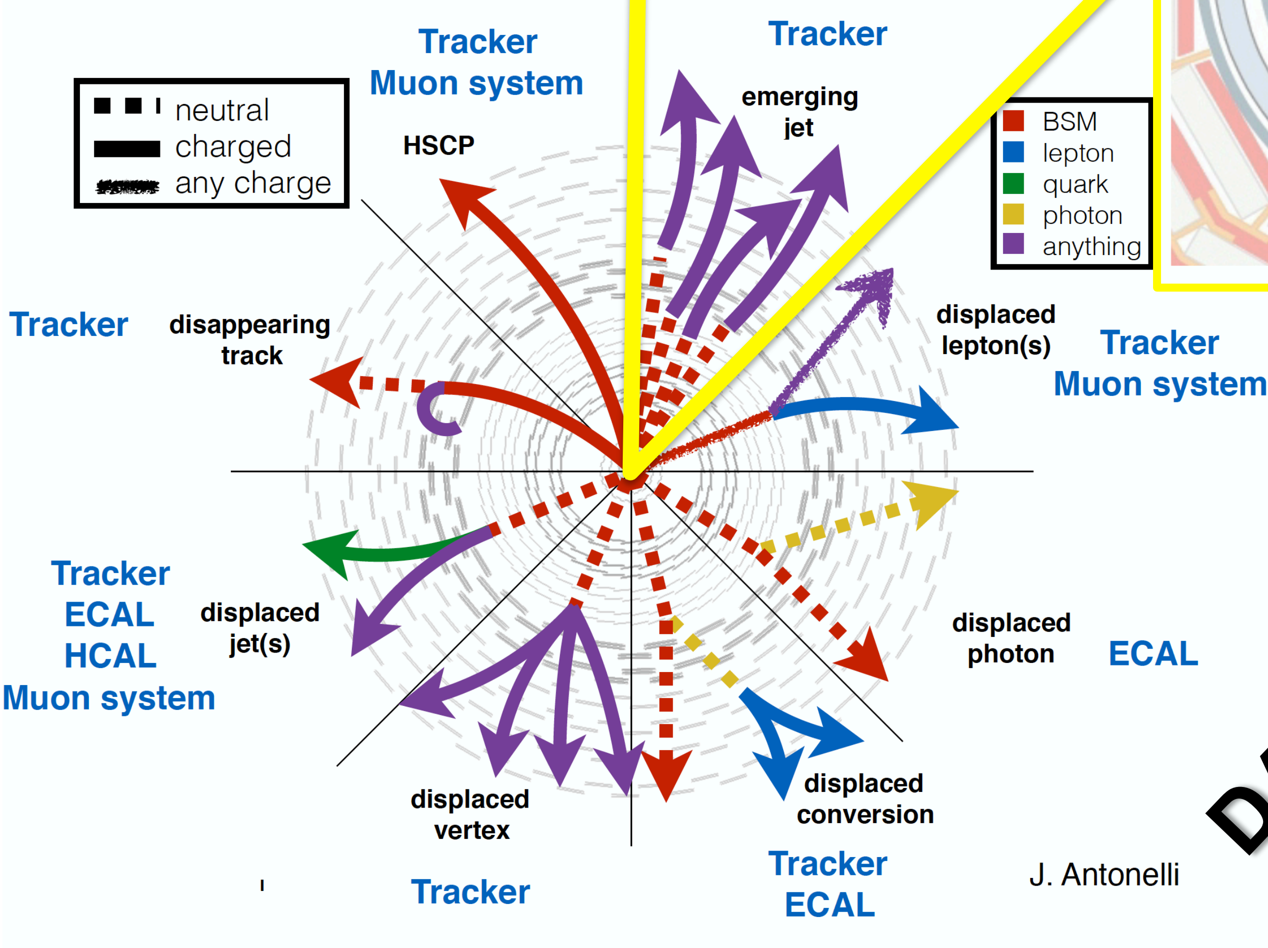
→ Significantly extends reach for $c\tau_0 \geq 1$ m (vs. tracker-based searches)

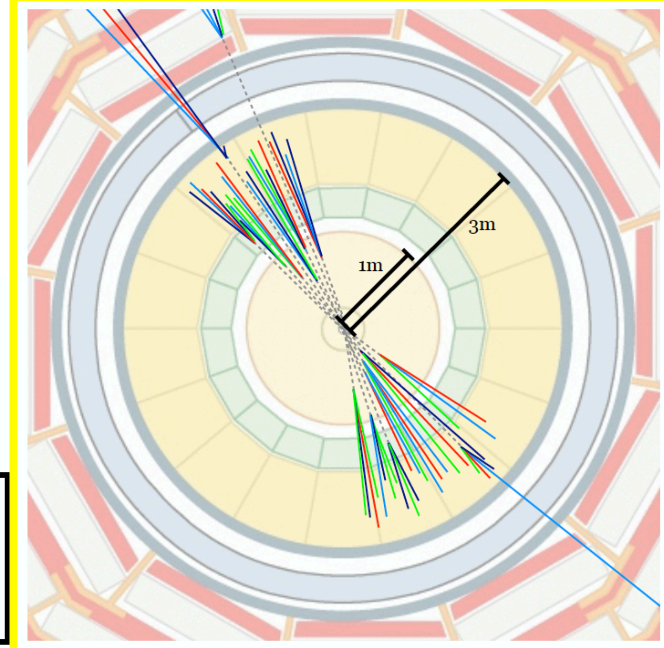
Background source	Events predicted
Beam halo muons	$0.02^{+0.06}_{-0.02}$ (stat) $^{+0.05}_{-0.01}$ (syst)
Core and satellite bunch collisions	$0.11^{+0.09}_{-0.05}$ (stat) $^{+0.02}_{-0.02}$ (syst)
Cosmic ray muons	$1.0^{+1.8}_{-1.0}$ (stat) $^{+1.8}_{-1.0}$ (syst)





Emerging Jets



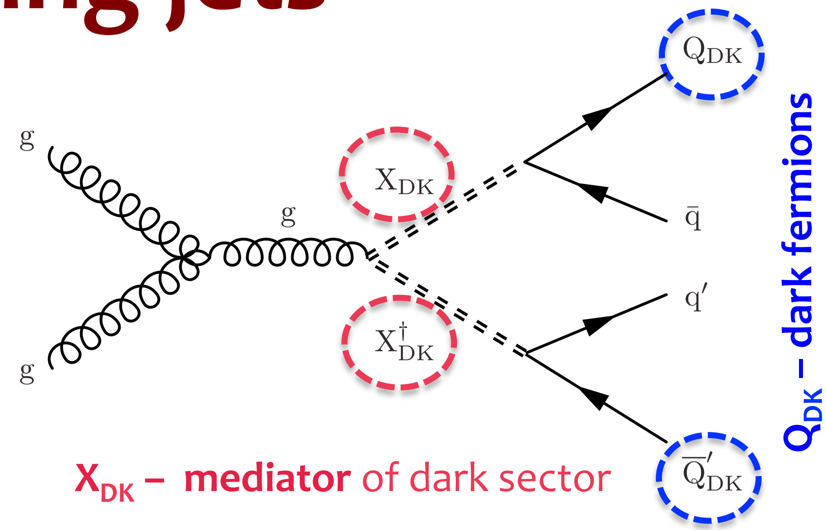


DARK SHOWERS
of Hidden Valley
[Knapen et al., arXiv:1612.00850]

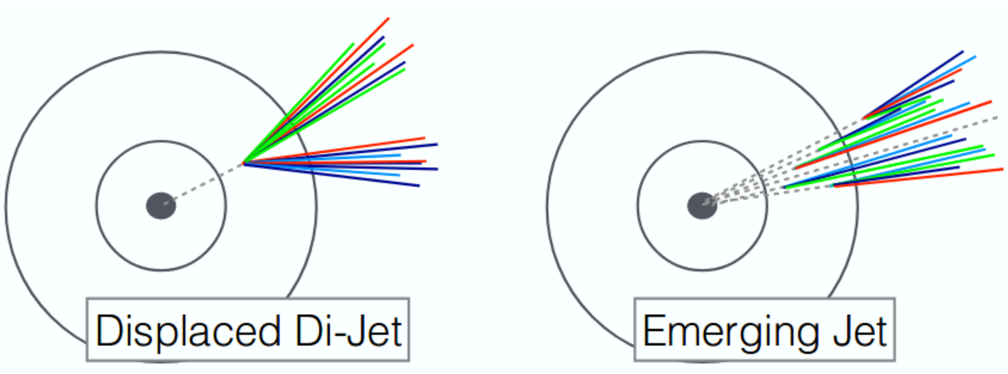
JHEP 02 (2019) 179, EXO-18-001

Emerging jets

- The **Dark QCD** model with long-lived dark-pions, which can decay to SM particles



- **Signal:**
  2 prompt jets and **2 emerging jets**



Emerging jets are produced in the hadronization of Q_{DK} to dark hadrons (π_{DK}) which form dark jets, and contain **multiple displaced vertices** from the **decay of dark-pions**

Signal model parameters	List of values
Dark mediator mass $m_{X_{DK}}$ [GeV]	400, 600, 800, 1000, 1250, 1500, 2000
Dark pion mass $m_{\pi_{DK}}$ [GeV]	1, 2, 5, 10
Dark pion decay length $c\tau_{\pi_{DK}}$ [mm]	1, 2, 5, 25, 45, 60, 100, 150, 225, 300, 500, 1000

focus on lifetimes of

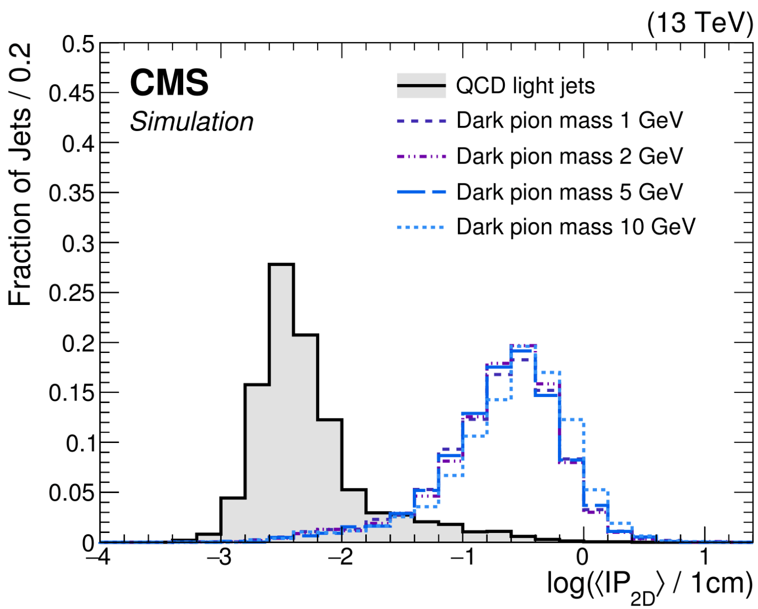
1 mm < $c\tau$ < 1 m

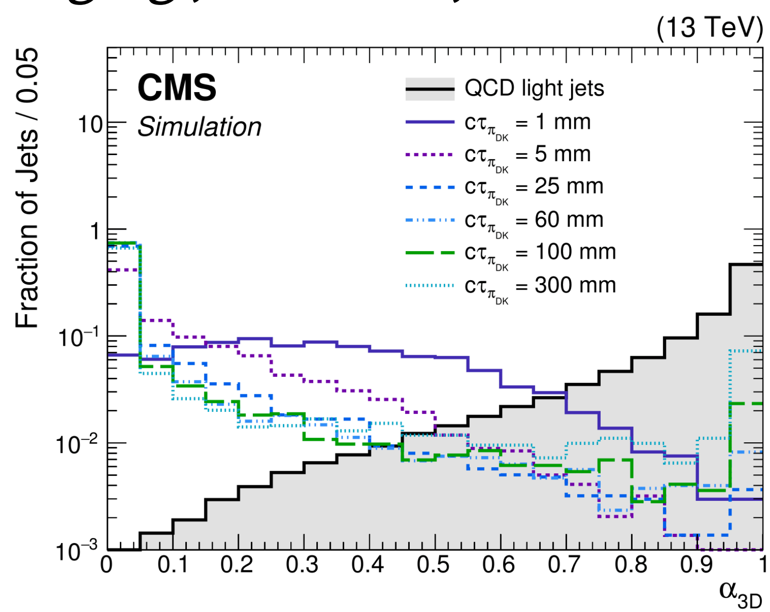
336 signal hypotheses

JHEP 02 (2019) 179, EXO-18-001

Emerging jets – stratedy

- **Data: 16/fb** – part of 2016
  due to saturation-induced dead time present in the readout of the silicon strip tracker
- **HLT Trigger: HT** > 900 GeV
- **Strategy:** extension of the displaced jet search
  and tagger for emerging jets – *emerging jets identification:*





- **7 Different selections sets** are used with:
  - optimized kinematic cuts on HT, p_T of jets, MET
  - optimized emerging jet tag cuts

2016: 16/fb

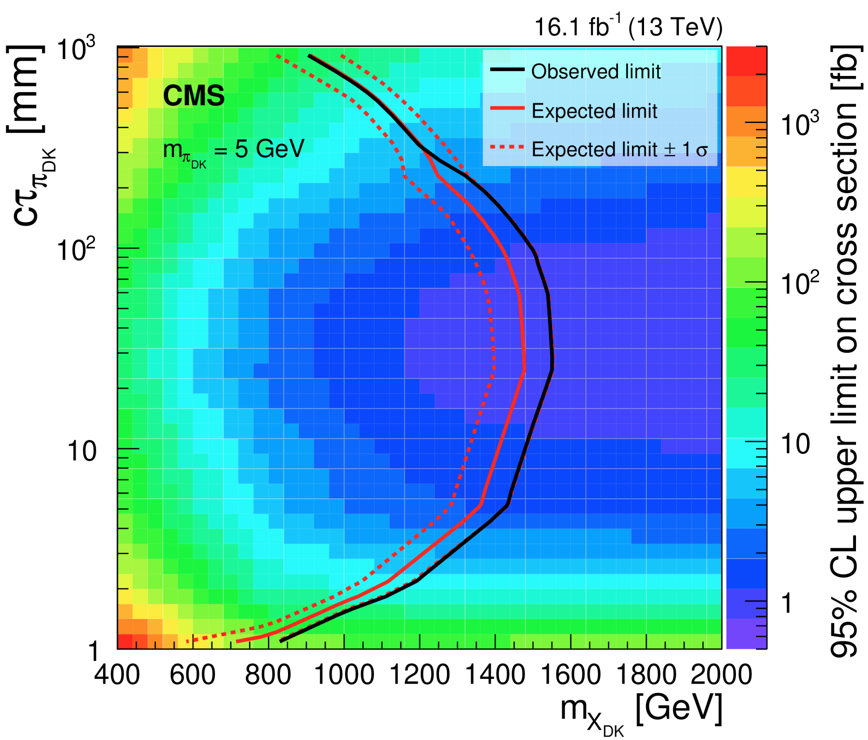
JHEP 02 (2019) 179, EXO-18-001

Emerging jets - limits

- **Results:** Observed events agree with bkg. expectation in all 7 selection sets

	Set number	Expected	Observed	Signal	Model parameters $m_{X_{DK}}$ [GeV]	$m_{\pi_{DK}}$ [GeV]	$c\tau_{\pi_{DK}}$ [mm]
Signal Regions	1	$168 \pm 15 \pm 5$	131	36.7 ± 4.0	600	5	1
	2	$31.8 \pm 5.0 \pm 1.4$	47	$(14.6 \pm 2.6) \times 10^2$	400	1	60
	3	$19.4 \pm 7.0 \pm 5.5$	20	15.6 ± 1.6	1250	1	150
	4	$22.5 \pm 2.5 \pm 1.5$	16	15.1 ± 2.0	1000	1	2
	5	$13.9 \pm 1.9 \pm 0.6$	14	35.3 ± 4.0	1000	2	150
	6	$9.4 \pm 2.0 \pm 0.3$	11	20.7 ± 2.5	1000	10	300
	7	$4.40 \pm 0.84 \pm 0.28$	2	5.61 ± 0.64	1250	5	225

Weaker constraints for cτ ≥ 10 cm due more decays outside pixel tracker



- **First emerging jets search at colliders!**
- **First Dark QCD results**
- Limits do not depend strongly on mass of dark pion π_{DK}
- Exclude dark-mass mediator X_{DK} mass between **400 and 1250 GeV** for $c\tau$ (π_{DK}) between **5 and 225 mm**

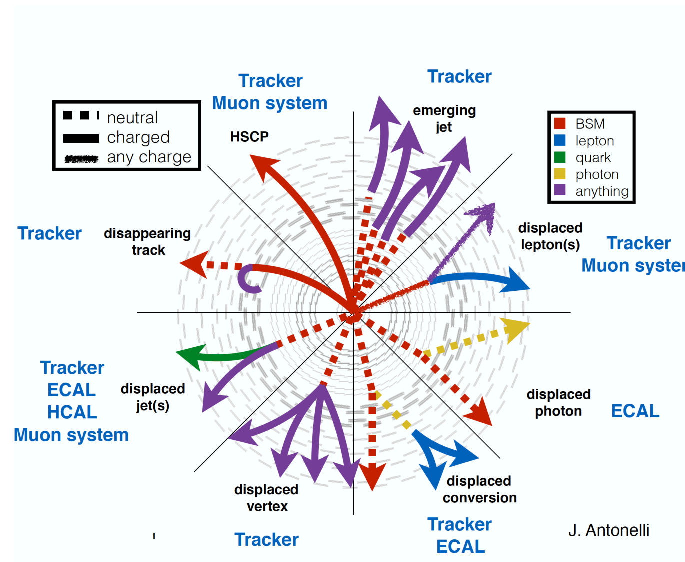
Future developments:
LLP triggering in Run3

L1 trigger

- **Hardware** based, information from **calorimeters and muon systems only** (regional triggers combined to global)
- First pattern recognition and raw measurements
- Fixed latency: 4 μs to accept/reject
- Skims rate to 100 kHz (in total)

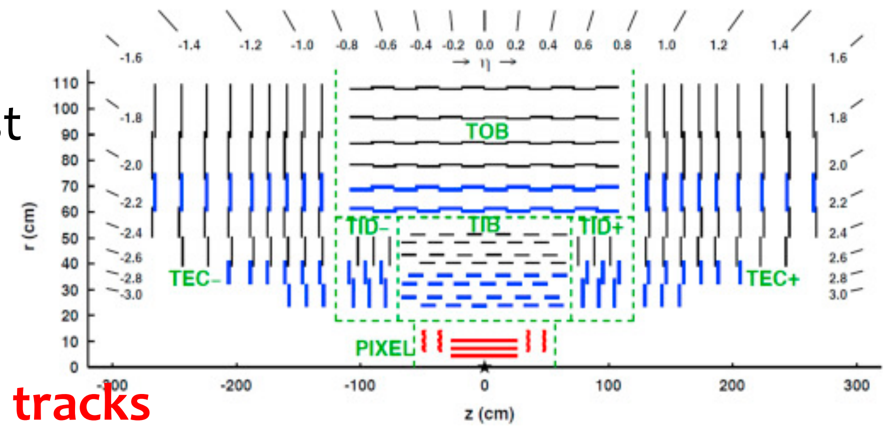
High level trigger (HLT)

- Fully **software,** includes **info from tracker**
- Similar algorithms as those applied offline
- Latency: 300 ms/events
- Skims rate to 1 kHz max (in total)



Displaced tracking for Run3

- CMS reconstruction designed for particles produced close to the collision point
  - Displacement → loss of efficiency
  - Displaced tracks and vertices are lost

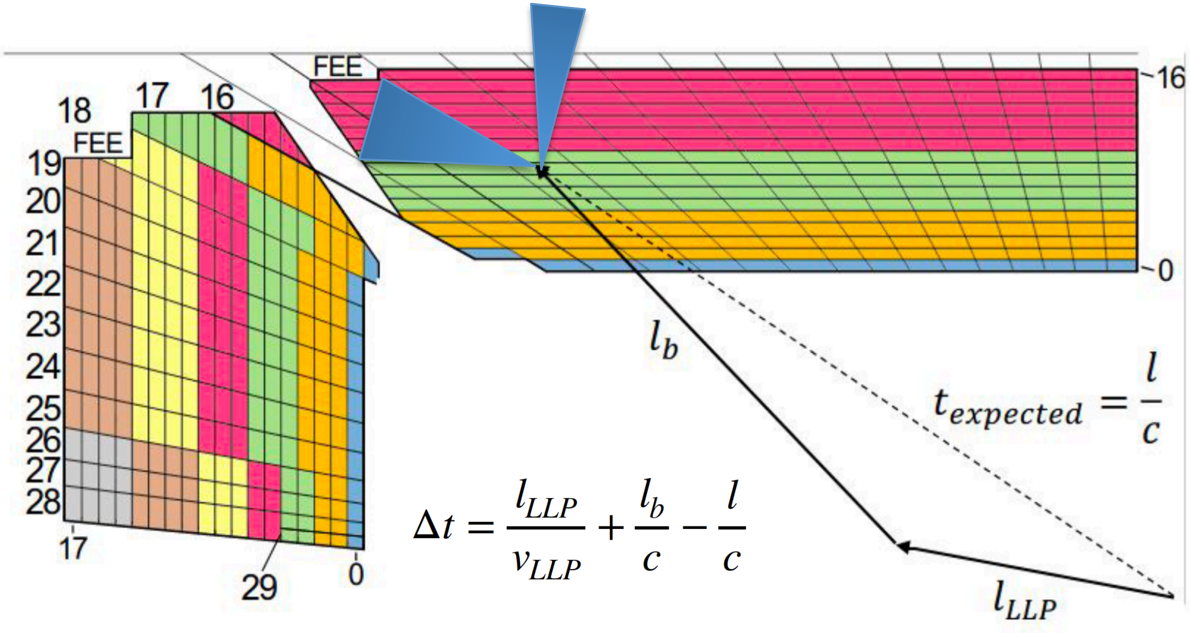


- **Tracking @ HLT**
  - *Current baseline:*
    - **single iteration seeded by pixel tracks**
  - *Developments:*
    - use **strip-seeded iteration** to recover efficiency for larger displacement
    - used in Run2 for dedicated HLT triggers (not standard tracking)

- **Tracking offline**
  - New iteration using predefined **Regions of Interest (ROI)**
    - pairwise tracks combined together into vertices
    - vertices clustered in spherical ROIs, radius 1 cm, tagged with an MVA
    - tagged ROIs used in tracking algorithm

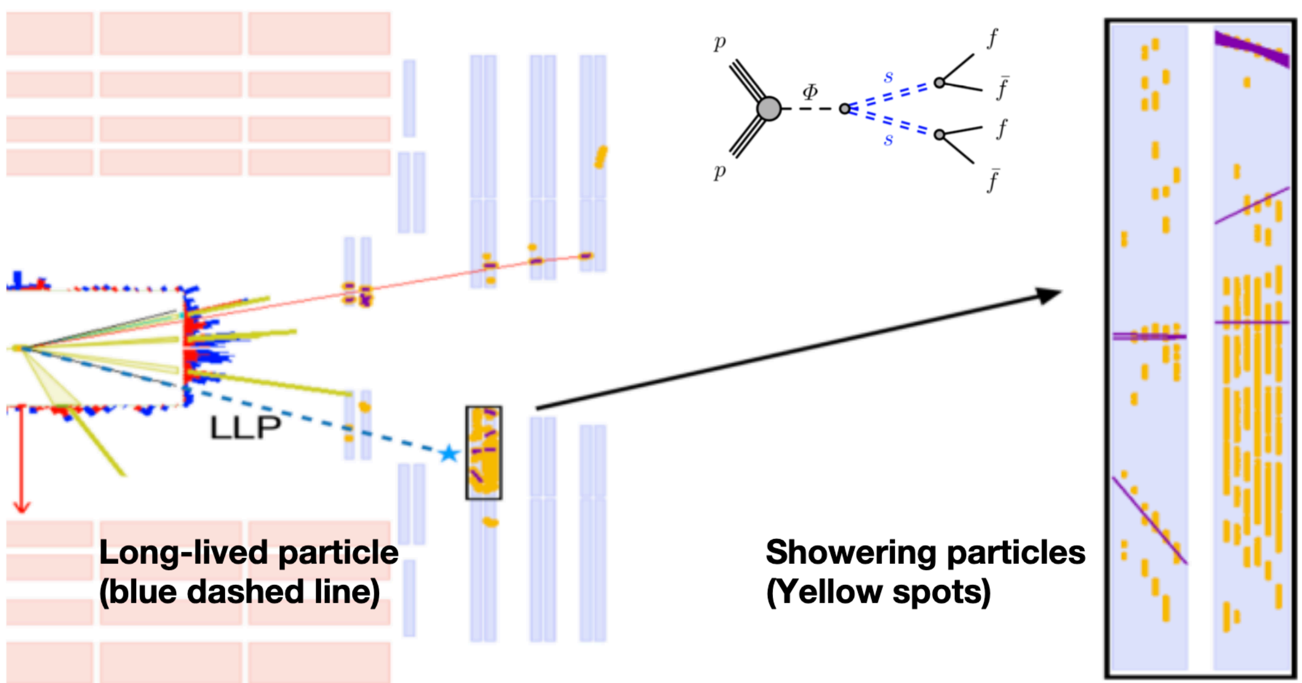
Trigger for LLPs in Calorimeters

- Hadronic sampling calorimeter **(HCAL)**: plastic scintillator and brass
- Some first level L1 trigger possibilities not fully exploited so far:
  - **Timing information** (resolution 0.5 ns)
    $\rightarrow$ **delay** due to kinks/heavy LLP mass
  - **Longitudinal depth** (4 layers in barrel, 7 layers in endcaps)
    $\rightarrow$ S/B discrimination (deeper showers)
- **Energy ratio** E_{HCAL}/E_{ECAL} $\rightarrow$ successful at **killing multi-jet background**, lower rate



Trigger for LLPs in Muon System

- Cathode Strip Chambers **(CSC)** in the endcaps: L1 triggering
- **Trigger on displaced muons**
  - Improved FPGAs → better resolution (x4) and bending (x3) wrt Run2
- **Trigger on showers (hit clusters from jets)**
  - **Count** cathode/anode **hits**
    → **threshold** optimised for S/B and for reasonable L1 trigger rates
  - Can be improved the missing energy approach of Run2 by a factor >10



LLP at CMS summary

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

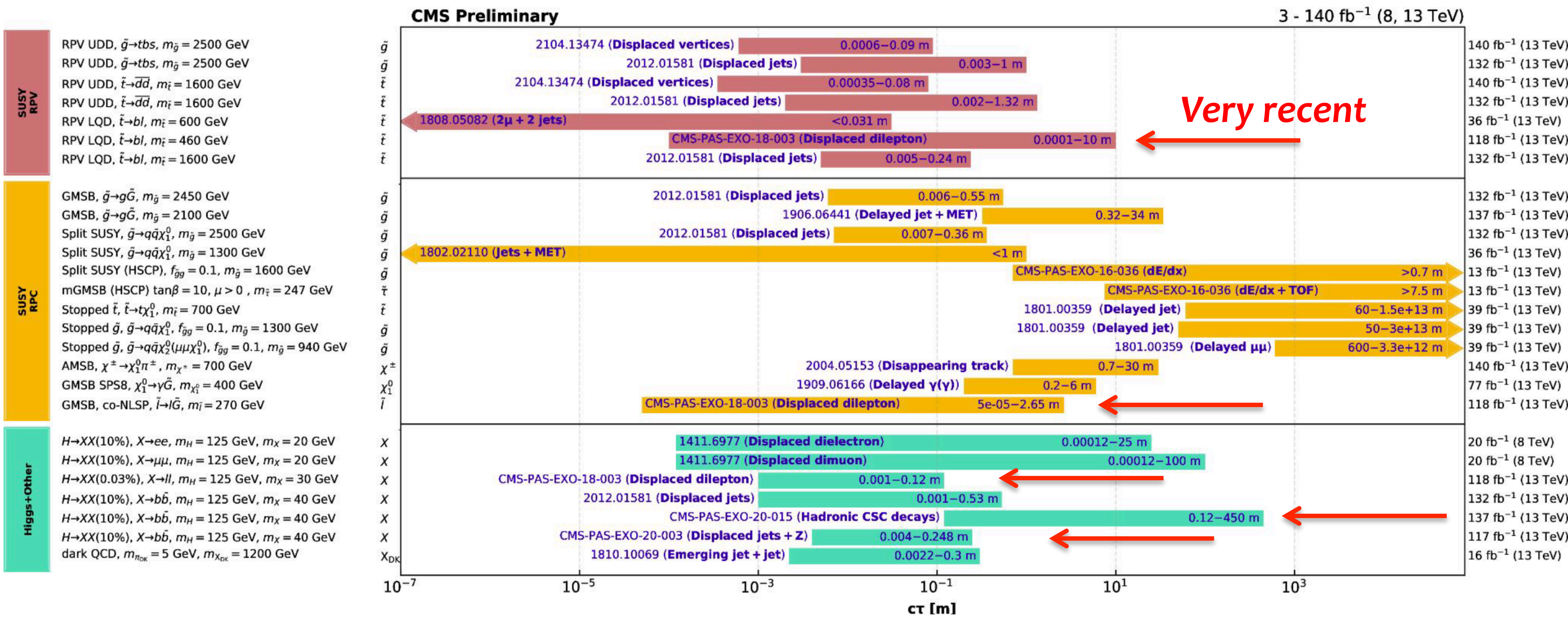
- **New results for full Run 2 data pushed limits on LLPs**
  - Explore challenging the **low mass LLPs**
  - Sensitive to **wide range of decay lengths**
  - Searches complement each other

- **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

Supported by grant: DIR/WK/2016/2019/15-1

Backup

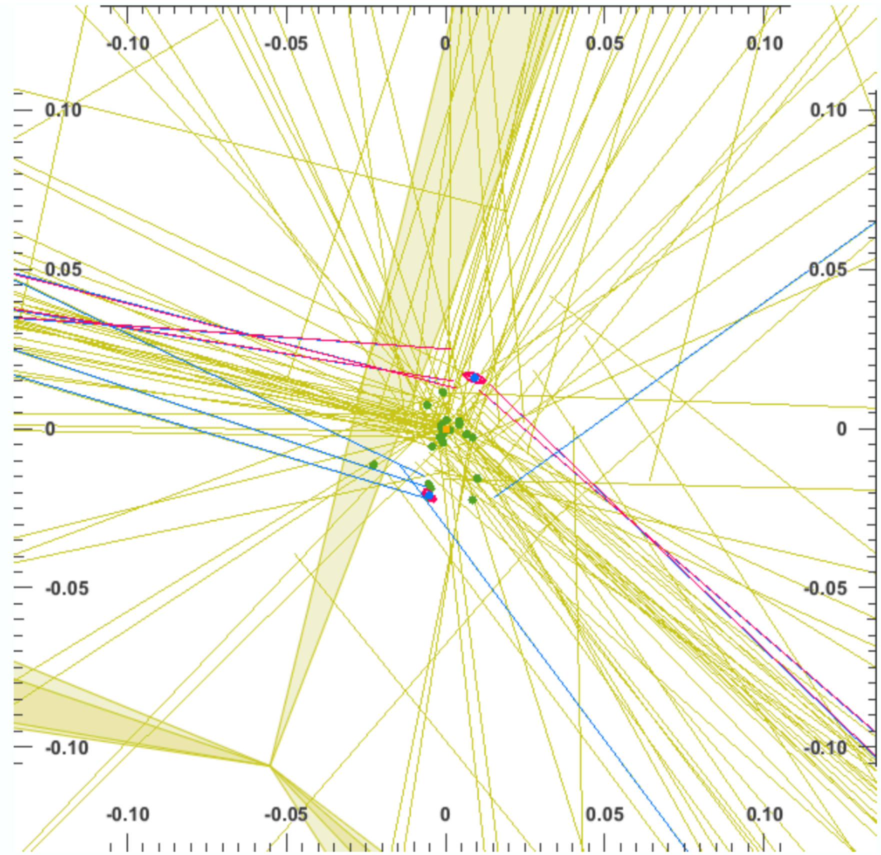
Displaced vertices - bkg

- **Background vertices** arise due to misreconstructed tracks with non-negligible transverse impact parameters

- Two-vertex background events are independent rare coincidences of two vertices from separate misreconstructions in one event

- No guarantee that MC can faithfully reproduce such effects

- **Use data-driven method**
to construct background template that models two-vertex background shape



Phys. Rev. D 98, 092011 (2018)

2016 DATA event observed

(≥5-track two-vertex) with d_{VV} = 396 μm