LLP searches

Red LHC
9 – 11 May, 2022 Madrid (Spain)

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Our motivation at IFCA-UC

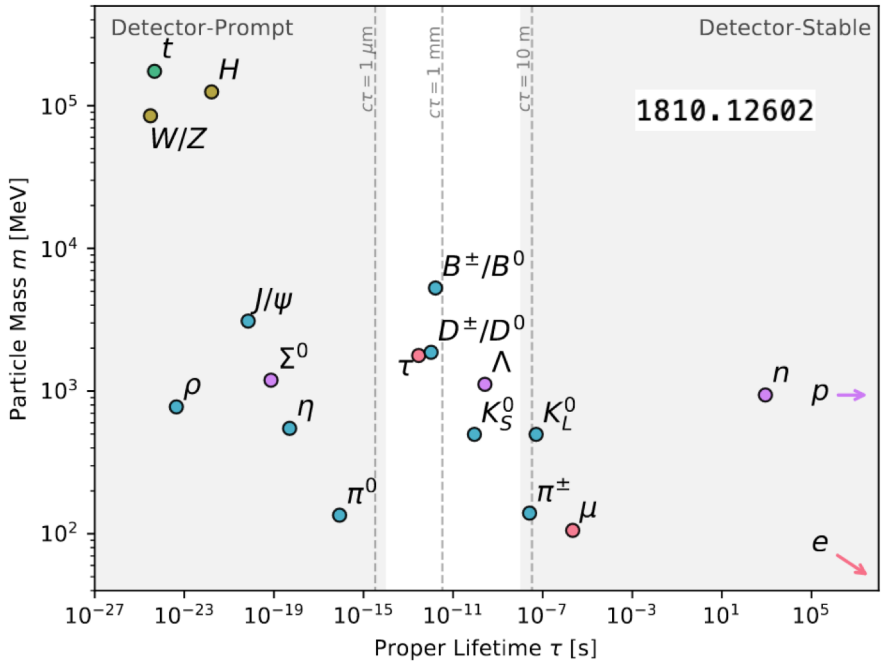
- IFCA-CSIC/Universidad de Cantabria like other Spanish groups is dedicating more interest at the end of Run2 to enlarge include Long-Lived Particles in their BSM program

- In the last few years we have been working on a full Run 2 analysis (ongoing) for **displaced leptons coming from a common vertex**
  - PhD: thesis of Celia Fernandez (supervisors: Pablo Martínez Ruíz del Árbol and Celso Martínez Rivero)
  - Expertise within the group with of muons (displaced reconstructions etc)

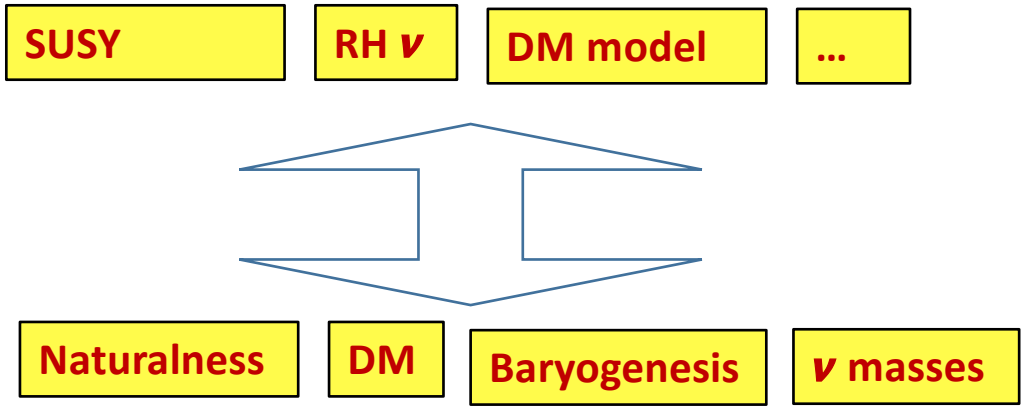
- Few comments of this analysis later

Motivation

- No clear hints of BSM physics so far in LHC Run 2 data
- **LLPs are common in the SM**



Our favorite BSM models at LHC to address the shortcomings of SM:

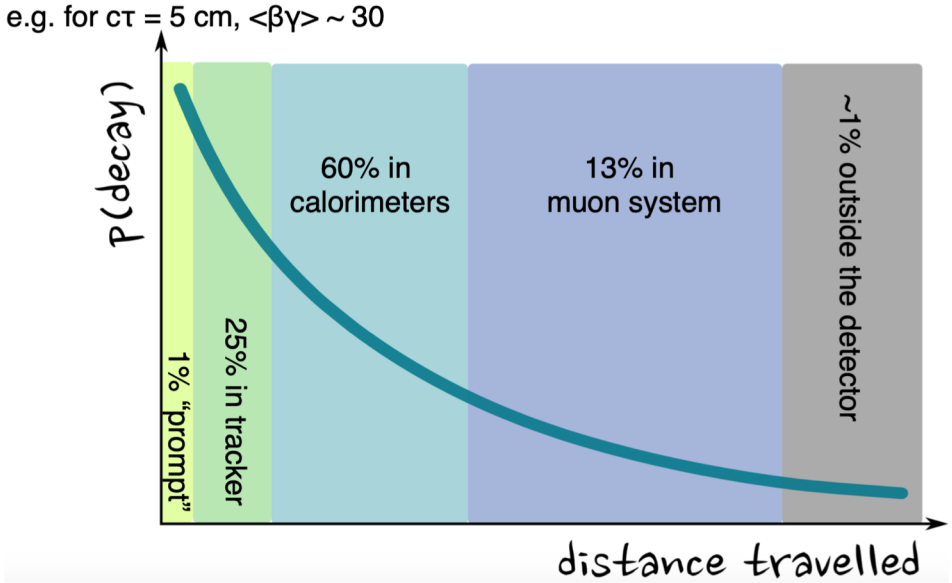


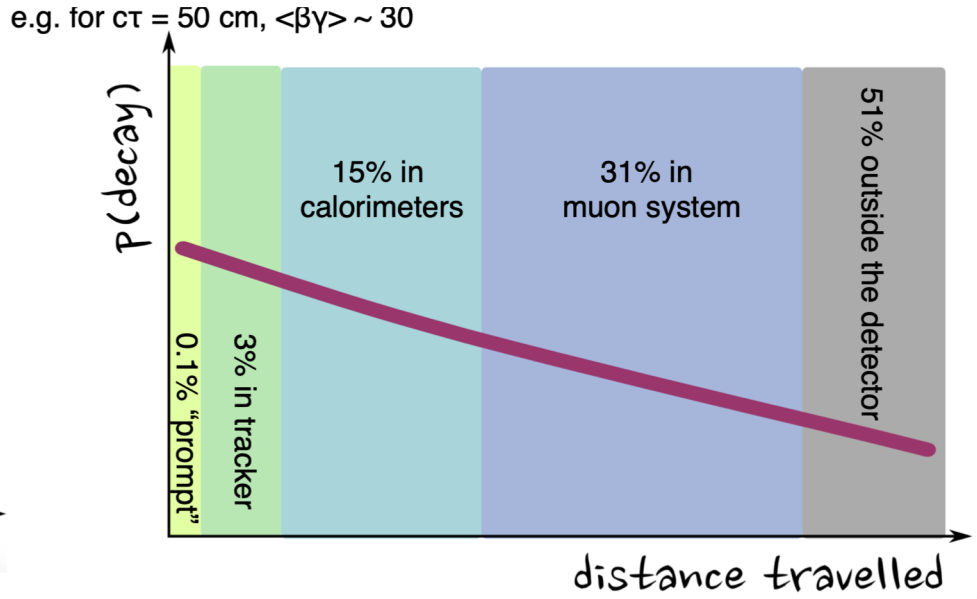
Can give rise to **Long-Lived Particles (LLP)**

- **Small couplings, scale suppression, small phase space**

Signatures

- Signature depends on model, cτ, $\beta^*\gamma$ (mass hierarchy,….)
- Flight distance can involve different subdetectors





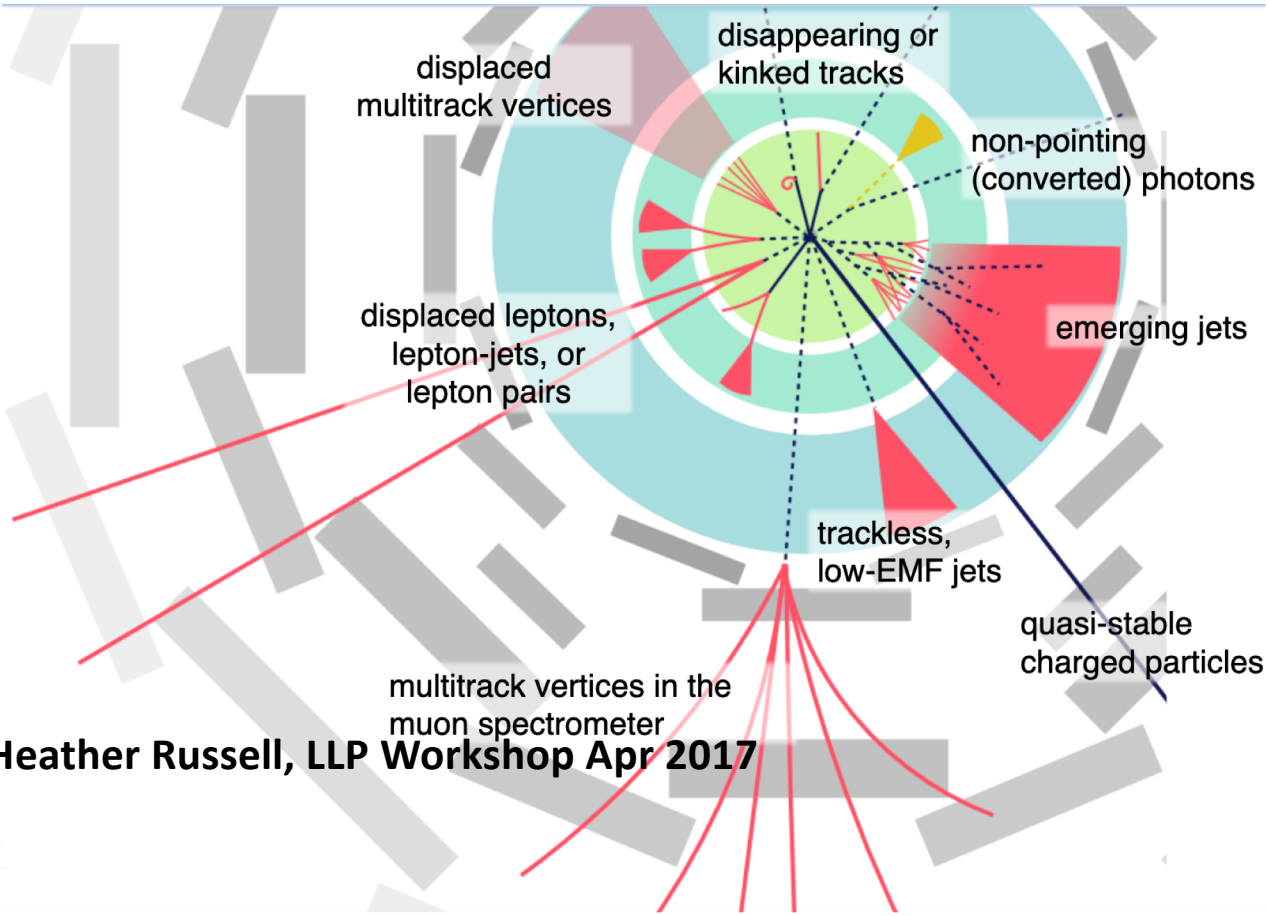
from Heather Russell, LLP Workshop Apr 2017

- Or be more suitable for other detectors (more details by Vasiliki)

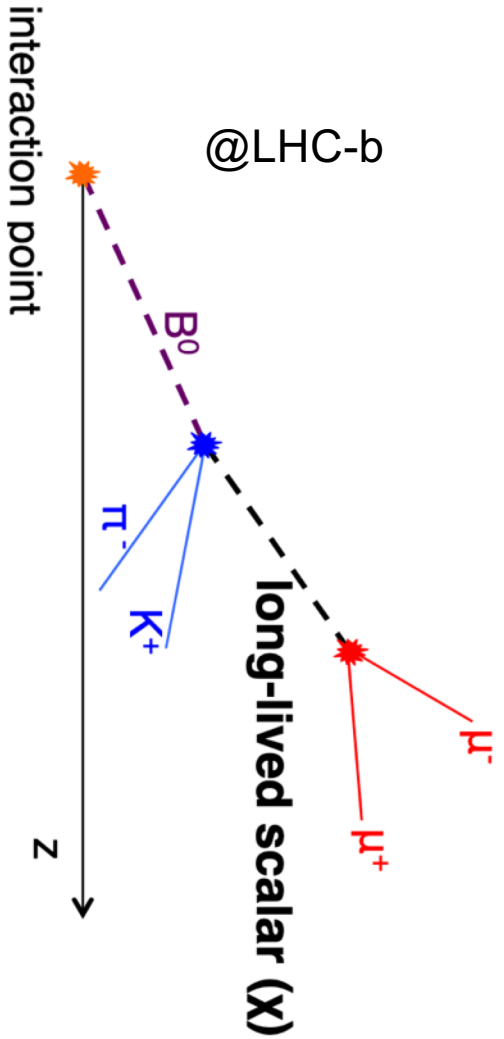
MATHUSLA MILLIQAN FASER …

LHC signatures in a nutshell

- It can be indirect detection: **displaced, leptons, jets, vertices** …
- Or direct: charged LLPs **with abnormal energy loss**
- May involve very particular signatures: **stopped particles, disappearing tracks**…
- LHC-B gives access to **forward regions** and special signatures: **B-meson with long lived decays** etc



from Heather Russell, LLP Workshop Apr 2017

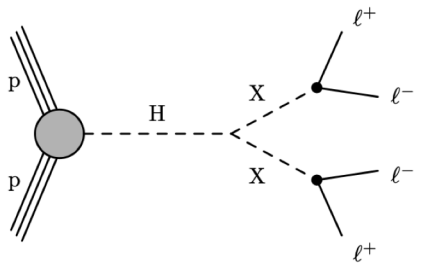


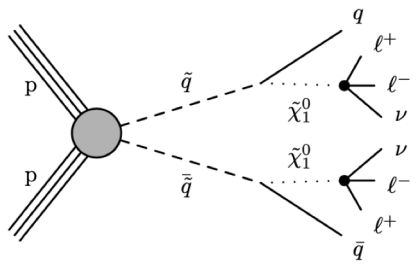
LLP analyses

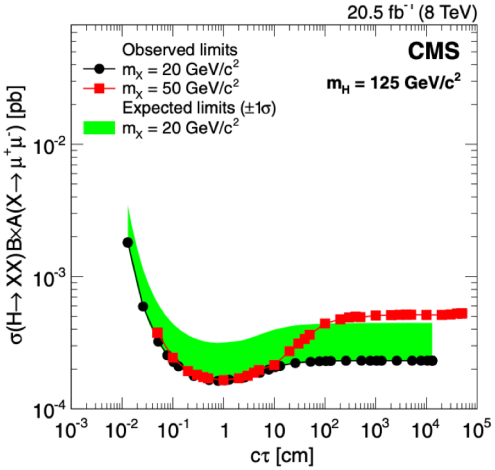
- Typically involve new non-usual signatures
  - Trigger important role
  - New reconstruction techniques
- But usually very low backgrounds
  - Unusual backgrounds: Cosmic rays, beam halo, material interactions,…
  - Estimated with data-driven methods
  - Now analysis pushing to lower pT: background can increase
- During Run 2 effort to cover extensively the different potential signatures
  - Tracker, calorimeter, muon system based searches
- And converge to a use of a coherent set of simplified models
  - As usual you have to be careful to interpret results

One example: our ongoing Dilepton vertex search

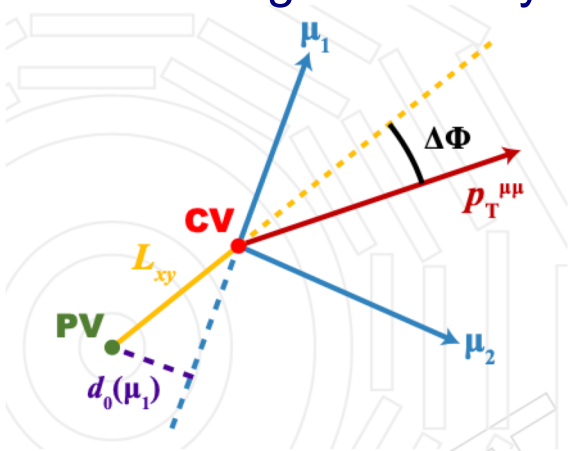
- Inspired in Run 1 search: PRD 91, 052012 (2015)
- Indirect LLP search to **Dimuon or Dielectron vertices**
- Search for muon (tracker + muon system: new approach) or electron track (new in Run 2)
- Interpretations: H → SS RPV







- Very low backgrounds: Estimated based on *collinearity* variable. Exploits that backgrounds do not have a preference for Δϕ between $\overrightarrow{PV-DV}$ and $\overrightarrow{P_T^{ll}}$
  - This background is symmetric and signal free → Background from CR



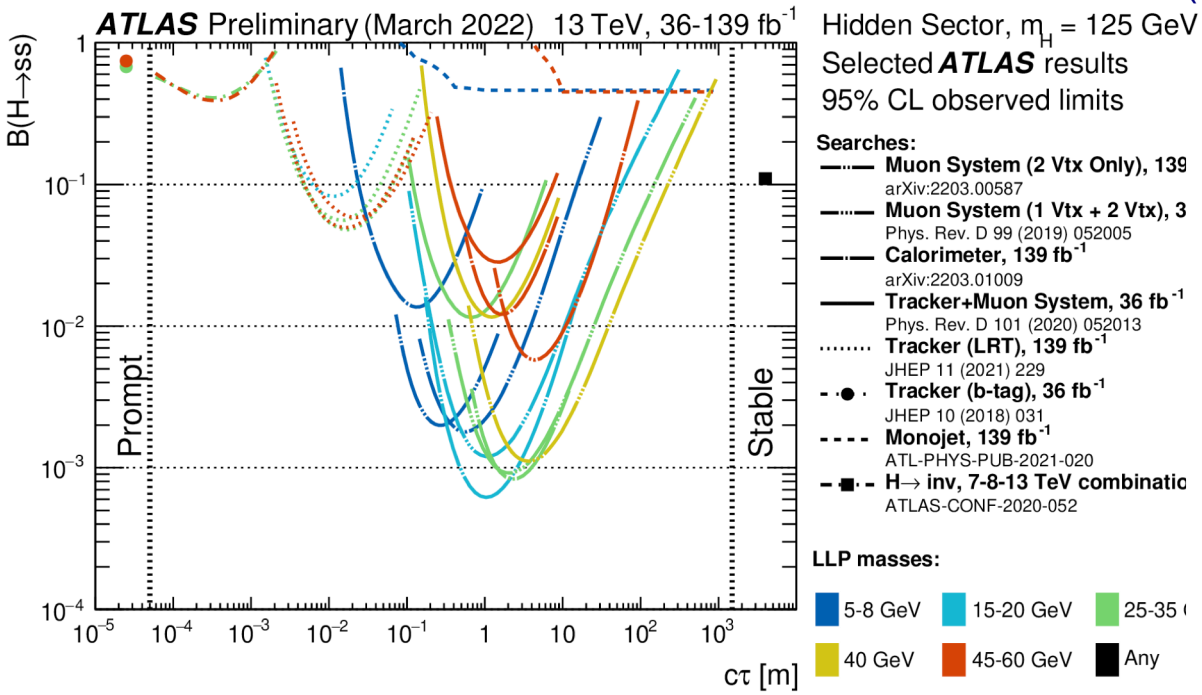
- ▲Backgrounds as cosmic rays negligible after angular cuts
- ▲But cosmic rays excellent handle to calibrate our lepton displaced reconstruction efficiencies

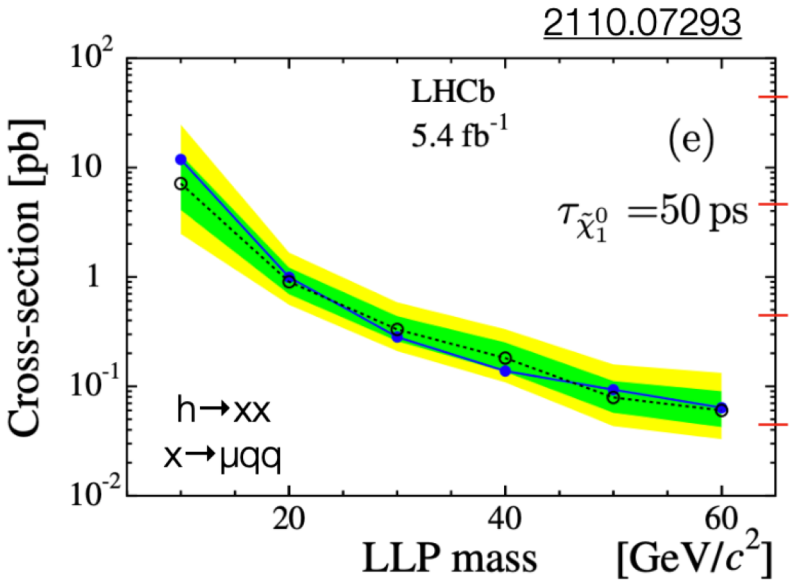
- Good sensitivity for cτ~ 0.1 cm – 1 m

Lots of searches already finalized for Run 2

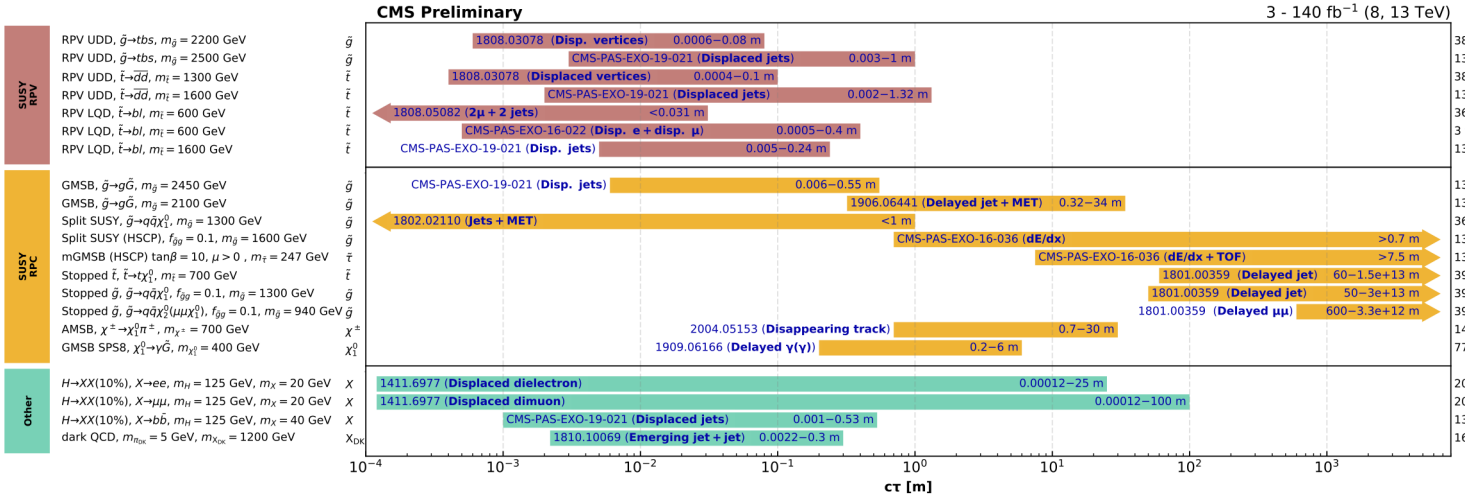
(more comprehensive list in the back up)

- And some are on the pipeline





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.

LHCP 2020

- Still an area at LHC with a lot of **room for improvement beyond luminosity for Run 3** and further

Thank you

Run 2 so far at LHC

- **Full Run 2 results**
- **11 from ATLAS 14 from CMS**
- **4 from LHCb 3 from MoEDAL**
- **~2 from far detectors**

ATLAS

- Pixel dE/dx [La Thuille Talk]
- Disappearing track [2201.02472]
- Stopped particles [2104.03050]
- Heavy Neutral Leptons [ATLAS-EXOT-2019-29]
- Displaced lepton jets [ATLAS-CONF-2022-001]
- Displaced leptons (no vertex) [2011.07812]
- Displaced vertex + μ [2003.11956]
- Z + Displaced Vertices [2107.06092]
- Decays in Calorimeter [2203.01009]
- Decays in Muon Spectrometer [2203.00587]
- Non-pointing photons (TBA)

LHCb

- semi-leptonic [2110.07293]
- e±μ∓ν [2012.02696]
- dimuon [2007.03923]
- Dark photon [1910.06926]

CMS

- Disappearing track [2004.05153]
- 0 Lepton + Short tracks [1909.03460]
- Dimuon Displaced Vertices [EXO-21-006]
- Dimuons in Scouting data [2112.13769]
- Displaced leptons (no vertex) [2110.04809]
- Heavy Neutral Leptons [2201.05578]
- Long-lived staus [SUS-21-001]
- Displaced Vertices [2104.13474]
- Displaced Jets [2012.01581]
- Z+Displaced Jets [2110.13218]
- Delayed jets [1906.06441]
- Trackless Jets [2105.09178]
- Decays in Muon Endcaps [2107.04838]
- Delayed Photons [1909.06166]

Some Useful links

- Long-Live LHC working group Web
- Long-Lived particle group has hold 10 meetings since its inception kickoff in 2017
  - Full list of meetings in this link
- Next one (11th) at the end of the month (still open for registration)

- ATLAS Public Results (Exotica)
- CMS Public Results (Exotica)
- LHCb Public Results

- Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case

- Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider (LHC LLP whitepaper)

Material for back-up

Summary Plots

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Searches ATLAS

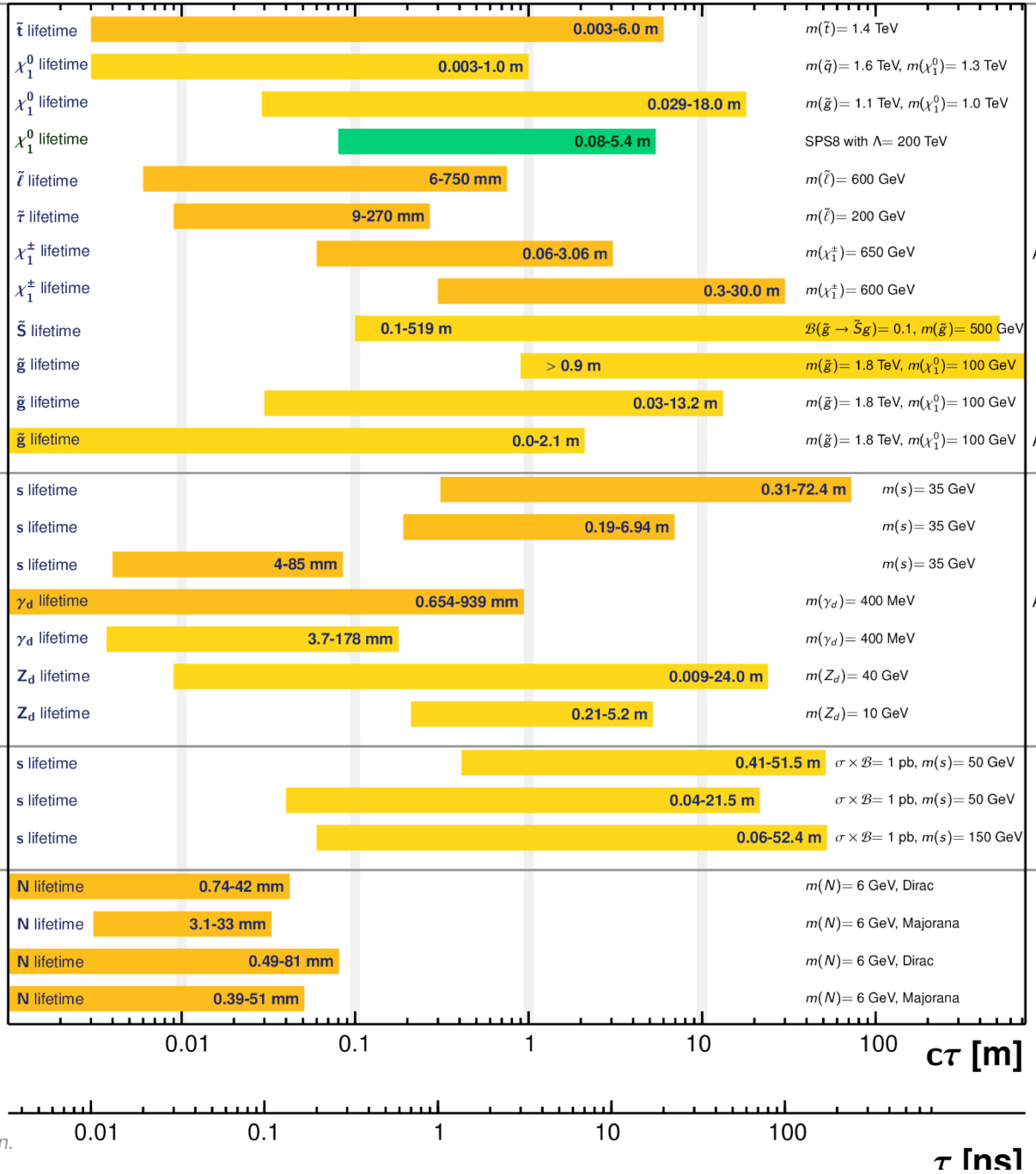
Status: March 2022

ATLAS Preliminary

$\int \mathcal{L}\,dt$ = (20.3 – 139) fb^{-1}

$\sqrt{s}$ = 8, 13 TeV

	Model	Signature	$\int \mathcal{L}\,dt$ [fb^{-1}]	Lifetime limit		Reference
SUSY	RPV $\tilde{t} \to \mu q$	displaced vtx + muon	136	$\tilde{t}$ lifetime	0.003-6.0 m	$m(\tilde{t})$= 1.4 TeV	2003.11956
	RPV $\chi_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$	displaced lepton pair	32.8	χ_1^0 lifetime	0.003-1.0 m	$m(\tilde{q})$= 1.6 TeV, $m(\chi_1^0)$= 1.3 TeV	1907.10037
	GGM $\chi_1^0 \to Z\tilde{G}$	displaced dimuon	32.9	χ_1^0 lifetime	0.029-18.0 m	$m(\tilde{g})$= 1.1 TeV, $m(\chi_1^0)$= 1.0 TeV	1808.03057
	GMSB	non-pointing or delayed γ	20.3	χ_1^0 lifetime	0.08-5.4 m	SPS8 with Λ= 200 TeV	1409.5542
	GMSB $\tilde{\ell} \to \ell\tilde{G}$	displaced lepton	139	$\tilde{\ell}$ lifetime	6-750 mm	$m(\tilde{\ell})$= 600 GeV	2011.07812
	GMSB $\tilde{\tau} \to \tau\tilde{G}$	displaced lepton	139	$\tilde{\tau}$ lifetime	9-270 mm	$m(\tilde{\ell})$= 200 GeV	2011.07812
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	disappearing track	136	$\chi_1^\pm$ lifetime	0.06-3.06 m	$m(\chi_1^\pm)$= 650 GeV	ATLAS-CONF-2021-015
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	large pixel dE/dx	139	$\chi_1^\pm$ lifetime	0.3-30.0 m	$m(\chi_1^\pm)$= 600 GeV	CERN-EP-2022-029
	Stealth SUSY	2 MS vertices	36.1	$\tilde{S}$ lifetime	0.1-519 m	$\mathcal{B}(\tilde{g} \to \tilde{S}g)$= 0.1, $m(\tilde{g})$= 500 GeV	1811.07370
	Split SUSY	large pixel dE/dx	36.1	$\tilde{g}$ lifetime	> 0.9 m	$m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV	1808.04095
	Split SUSY	displaced vtx + E_T^{miss}	32.8	$\tilde{g}$ lifetime	0.03-13.2 m	$m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV	1710.04901
	Split SUSY	0 ℓ, 2 – 6 jets + E_T^{miss}	36.1	$\tilde{g}$ lifetime	0.0-2.1 m	$m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV	ATLAS-CONF-2018-003
Higgs BR = 10%	$H \to ss$	2 MS vertices	139	s lifetime	0.31-72.4 m	$m(s)$= 35 GeV	2203.00587
	$H \to ss$	2 low-EMF trackless jets	139	s lifetime	0.19-6.94 m	$m(s)$= 35 GeV	2203.01009
	VH with $H \to ss \to bbbb$	2ℓ + 2 displ. vertices	139	s lifetime	4-85 mm	$m(s)$= 35 GeV	2107.06092
	FRVZ $H \to 2\gamma_d + X$	2 μ–jets	139	γ_d lifetime	0.654-939 mm	$m(\gamma_d)$= 400 MeV	ATLAS-CONF-2022-007
	FRVZ $H \to 4\gamma_d + X$	2 μ–jets	36.1	γ_d lifetime	3.7-178 mm	$m(\gamma_d)$= 400 MeV	1909.01246
	$H \to Z_dZ_d$	displaced dimuon	32.9	Z_d lifetime	0.009-24.0 m	$m(Z_d)$= 40 GeV	1808.03057
	$H \to ZZ_d$	2 e,μ + low-EMF trackless jet	36.1	Z_d lifetime	0.21-5.2 m	$m(Z_d)$= 10 GeV	1811.02542
Scalar	Φ(200 GeV) $\to ss$	low-EMF trk-less jets, MS vtx	36.1	s lifetime	0.41-51.5 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1902.03094
	Φ(600 GeV) $\to ss$	low-EMF trk-less jets, MS vtx	36.1	s lifetime	0.04-21.5 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1902.03094
	Φ(1 TeV) $\to ss$	low-EMF trk-less jets, MS vtx	36.1	s lifetime	0.06-52.4 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 150 GeV	1902.03094
HNL	$W \to N\ell$, $N \to \ell\ell\nu$	displaced vtx ($\mu\mu$,μe, ee) + μ	139	N lifetime	0.74-42 mm	$m(N)$= 6 GeV, Dirac	CERN-EP-2022-017
	$W \to N\ell$, $N \to \ell\ell\nu$	displaced vtx ($\mu\mu$,μe, ee) + μ	139	N lifetime	3.1-33 mm	$m(N)$= 6 GeV, Majorana	CERN-EP-2022-017
	$W \to N\ell$, $N \to \ell\ell\nu$	displaced vtx ($\mu\mu$,μe, ee) + e	139	N lifetime	0.49-81 mm	$m(N)$= 6 GeV, Dirac	CERN-EP-2022-017
	$W \to N\ell$, $N \to \ell\ell\nu$	displaced vtx ($\mu\mu$,μe, ee) + e	139	N lifetime	0.39-51 mm	$m(N)$= 6 GeV, Majorana	CERN-EP-2022-017



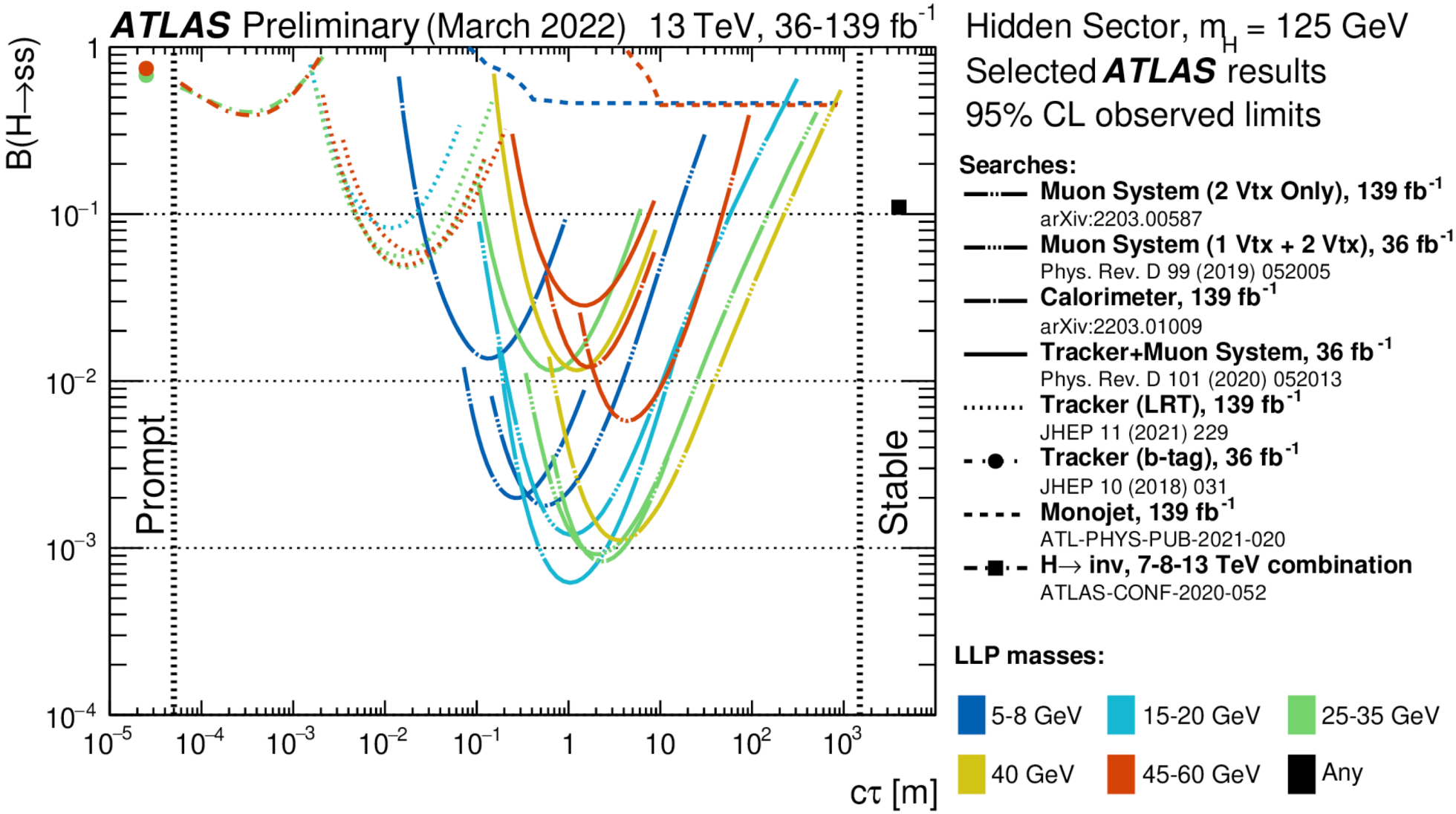
$\sqrt{s}$ = 8 TeV

$\sqrt{s}$ = 13 TeV partial data

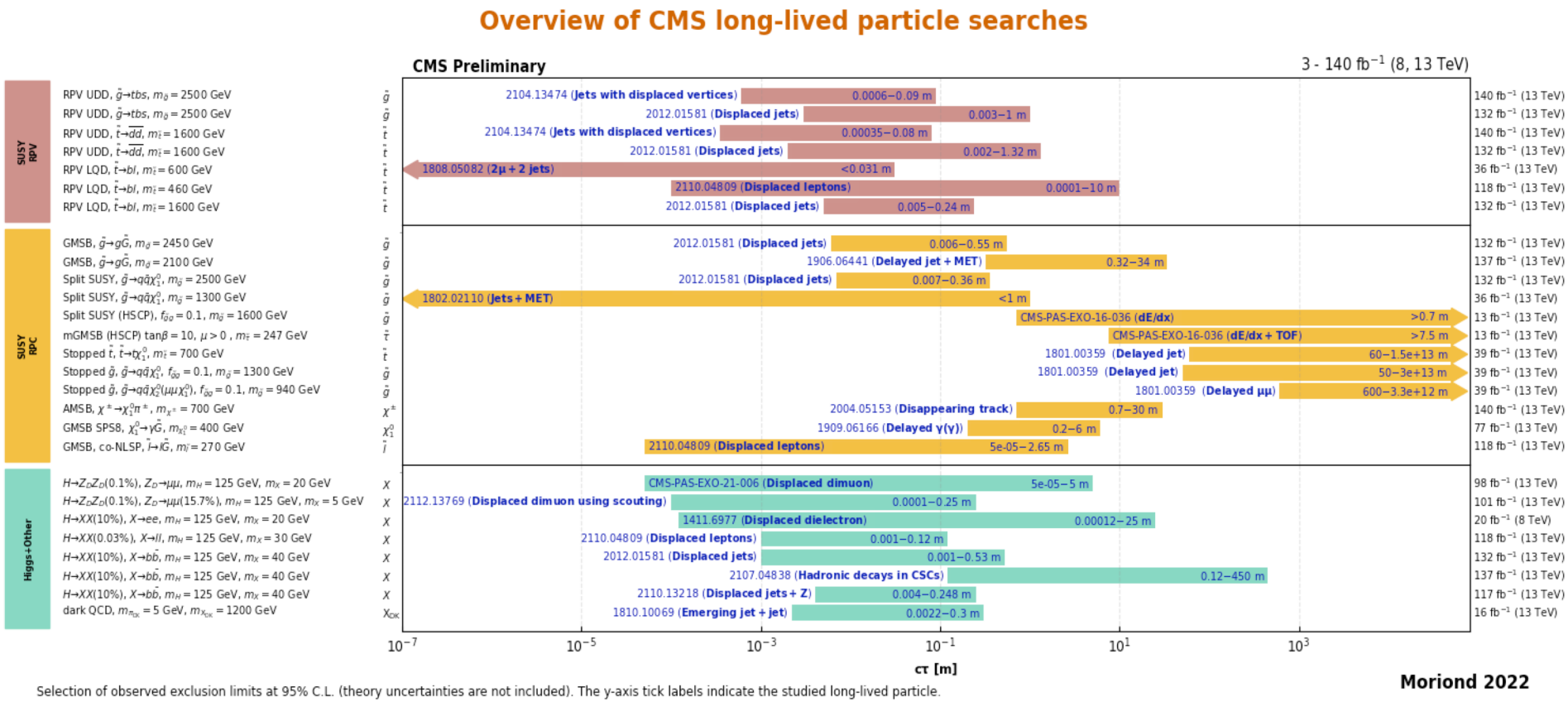
$\sqrt{s}$ = 13 TeV full data

*Only a selection of the available lifetime limits is shown.

Searches ATLAS

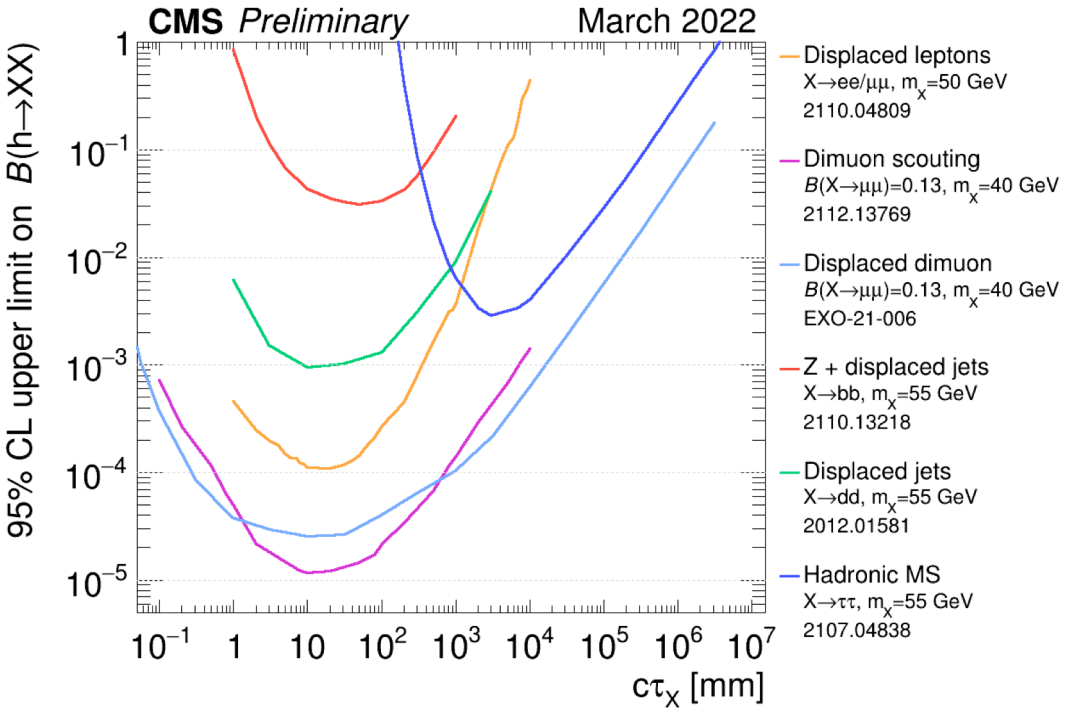


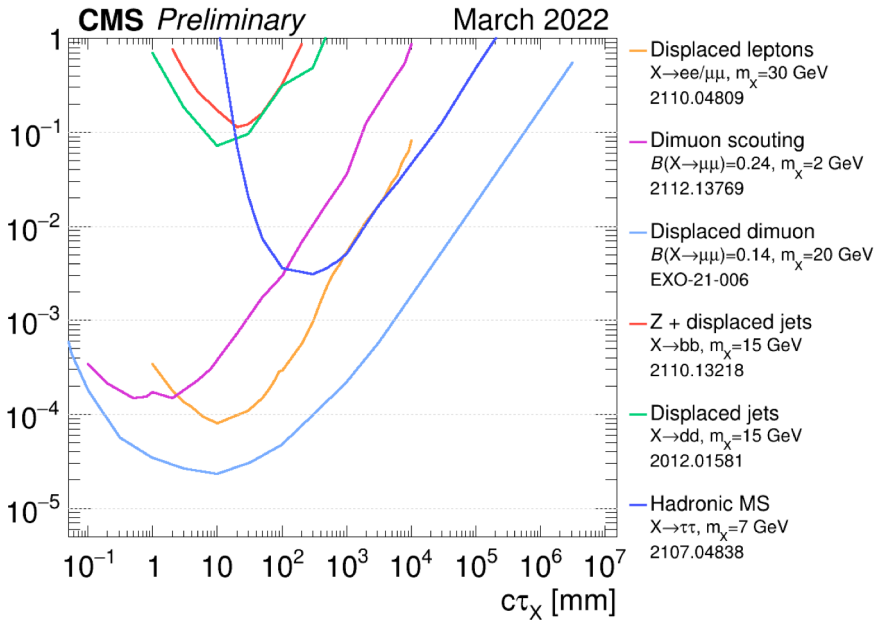
Searches CMS



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 H→XX





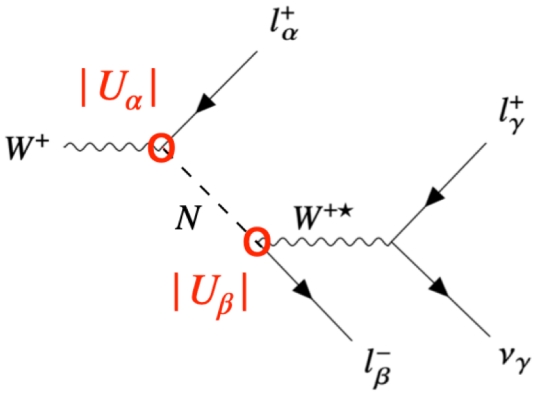
The 95% CL observed exclusion limit from different CMS hadronic long-lived particle analyses on the branching fraction of the standard model higgs boson, h, to two neutral long-lived particles, X, shown as a function of the long-lived particle's proper lifetime. The **Dimuon scouting and Displaced dimuon exclusions assume X decays according to JHEP 02 (2015) 157, while the Displaced leptons analysis assumes X->ee or μμ with a 50%** branching fraction for each decay mode. The exclusions shown for Z+displaced jets, Displaced jets, and Hadronic MS analyses assume X decays with 100% branching fraction to bb, dd, tautau, respectively.

Material for back-up

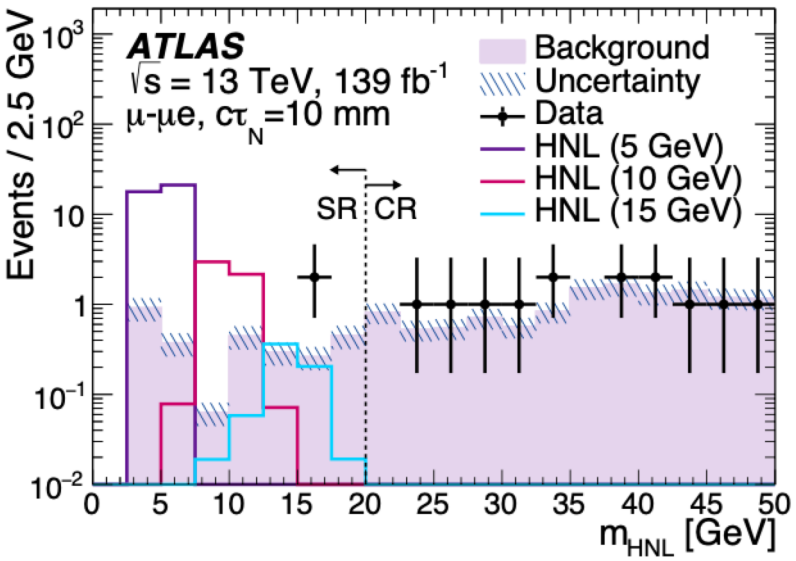
Selected Latest Results from LHC

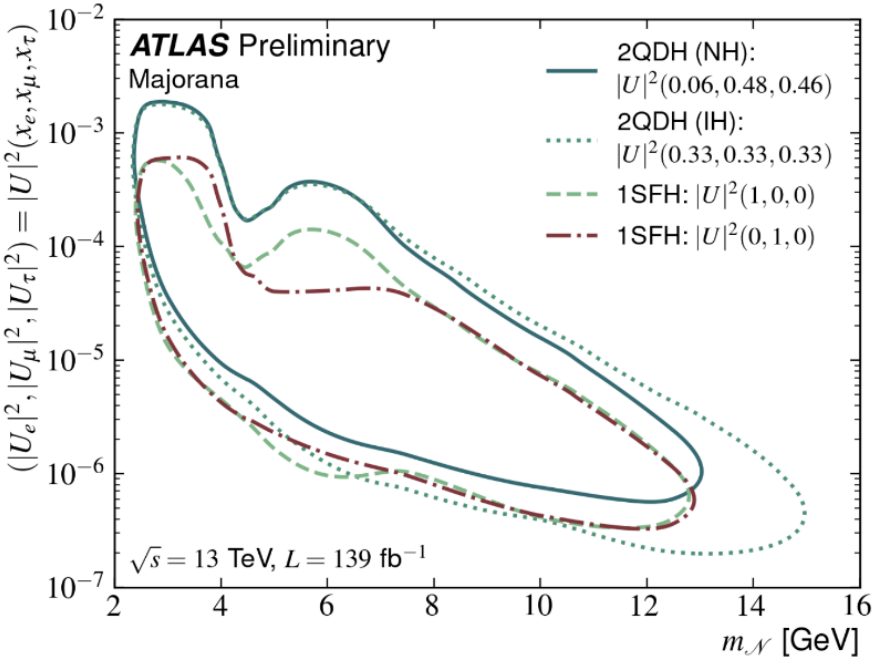
ATLAS (new): Displaced HNLs EXOT-2019-29

- Signature: prompt l_α(trigger) + DV with 2 OS lepton (l_β-l_γ)
- Long-Lived particle group has hold 10 meetings since its inception kickoff in 2017
  - HNLs undergo weak-like interactions controlled by dimensionless mixing angles ($|U\alpha|^2$) between SM ν and HLN



- 6 categories depending on lepton flavors (e or μ)
- m_N reconstructed via energy-momentum conservation
- Events with $20 < m_N < 50$ GeV used to constrain background in the SR
- Background from random lepton crossings. Measured with object shuffling method: mix leptons from different CR's

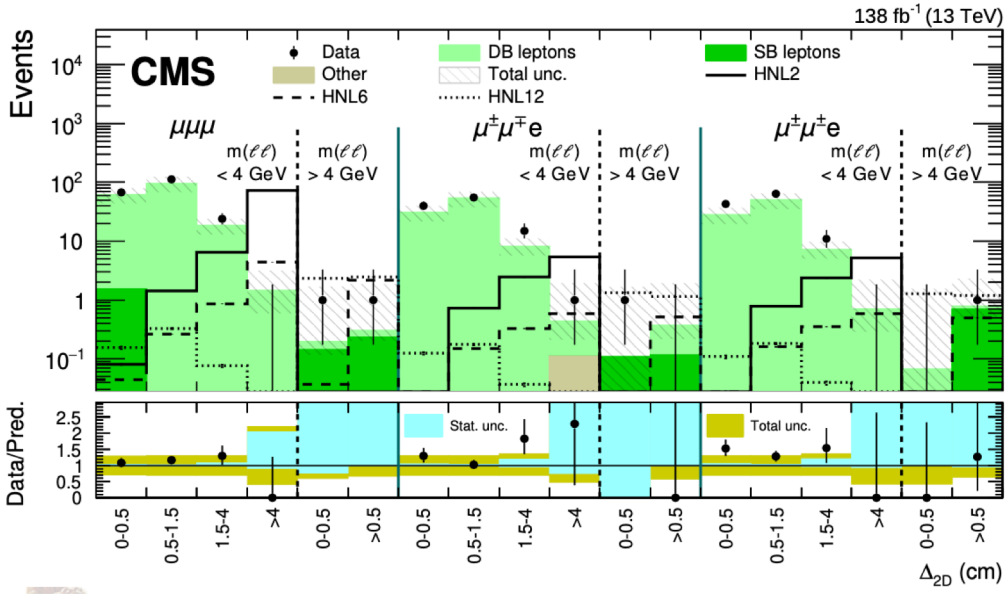


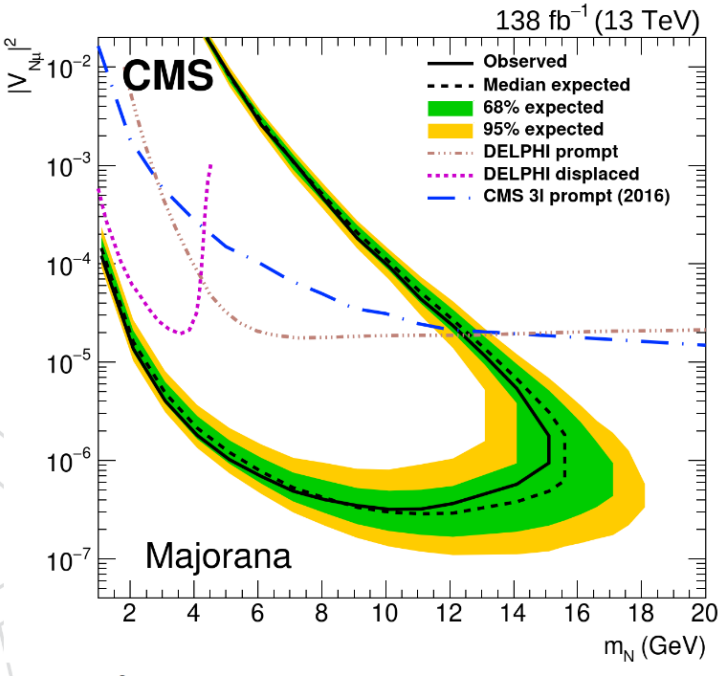


CMS: Displaced HNLs

EXO-20-009

- 3 lepton categories
- Background from CRs
- Categories based on: mll, b-jet veto, transverse displacement of displaced lepton pair

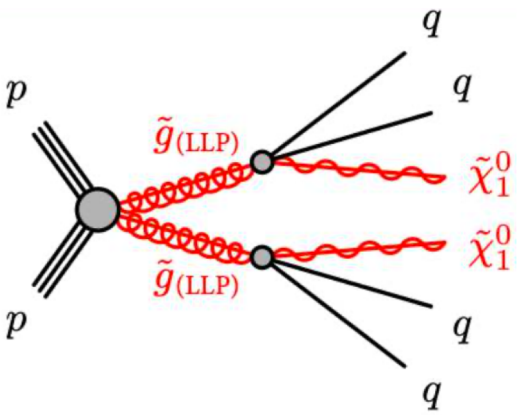




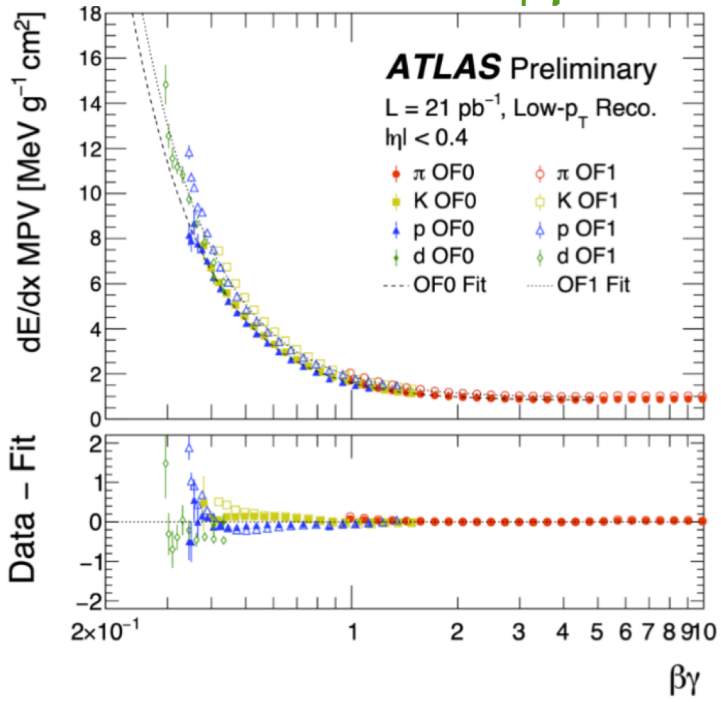
ATLAS (new): Heavy Charged Long-Lived particle SUSY-2018-42

(not yet available)

- Signature: high pT track with anomalously high dE/dx
- Select isolated high-pT (> 120 GeV) tracks in high-MET events (trigger)
- Sensitive to gluinos, charginos, staus with m = 200 - 2500
  - m = 200 - 2500 GeV
  - τ = O (0.1 ns)



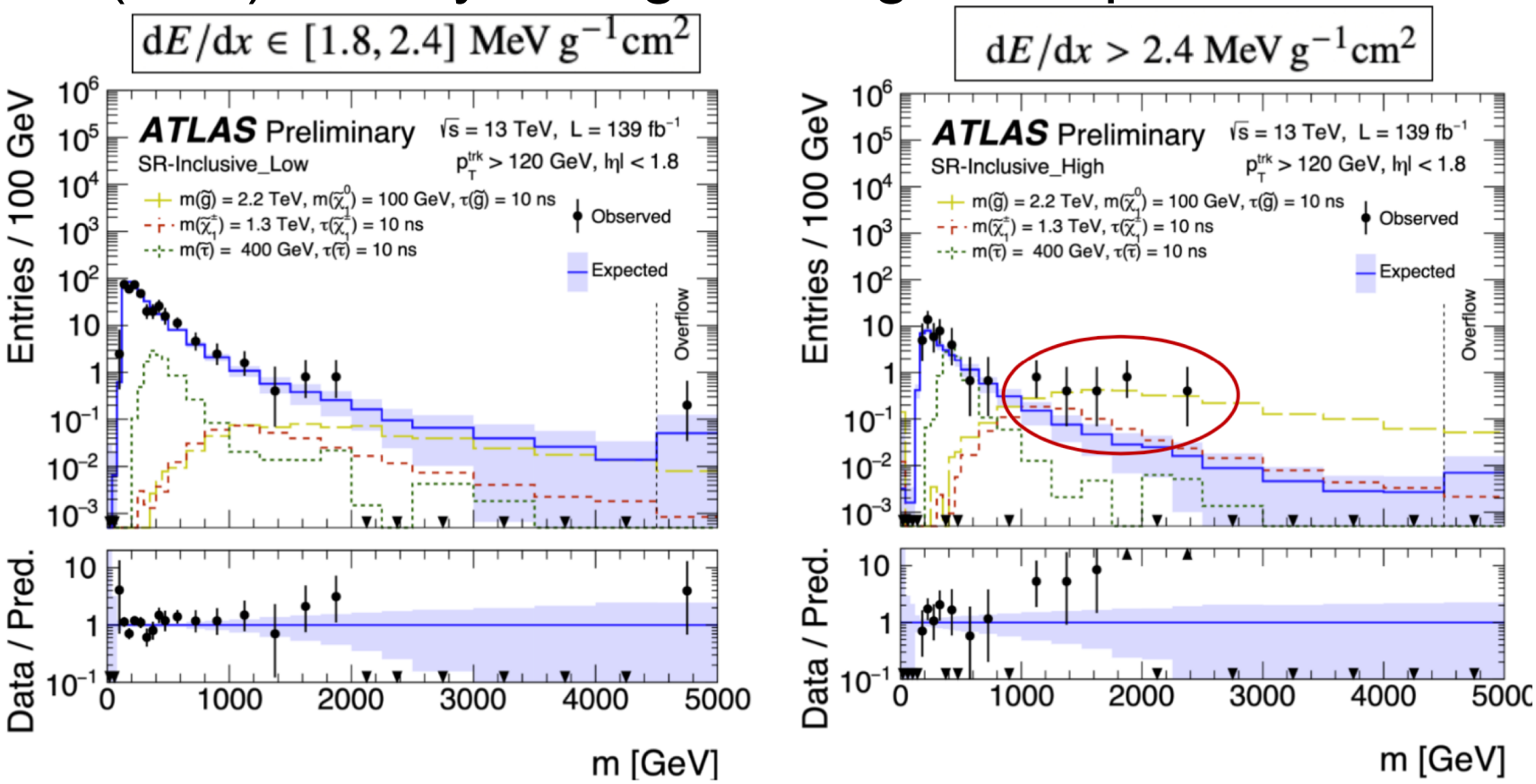
- Obtain mass spectrum:
  - Extract and parametrize relation between <dE/dx> and $\beta\gamma$



- Compute <dE/dx>trunc averaging individual clusters associated with the tracks
- (η, condition dependent) → <dE/dx>corr
- Evaluate mass m using m = p/[βγ(<dE/dx>corr)]

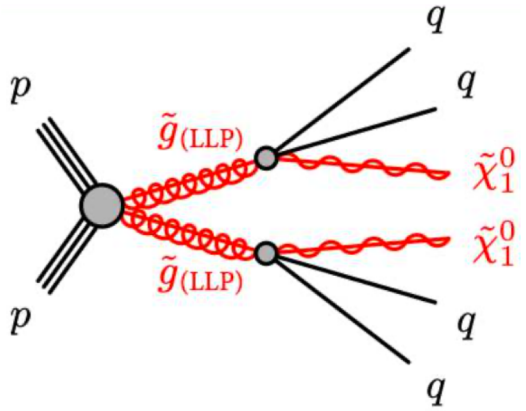
- Background mass spectrum from random toy tracks derived from CRs inverting cuts
  - Kinematic región for (pT, η)
  - dE/dX CR (binned in η)

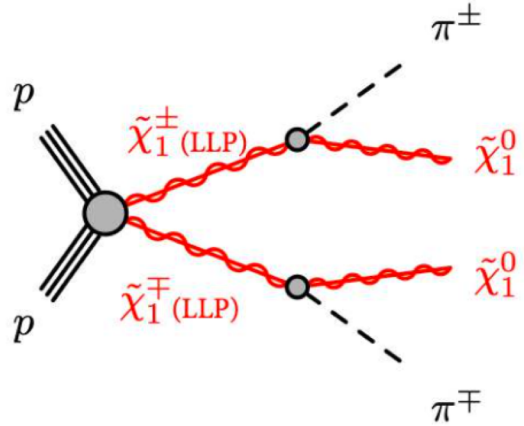
ATLAS (new): Heavy Charged Long-Lived particle: Results

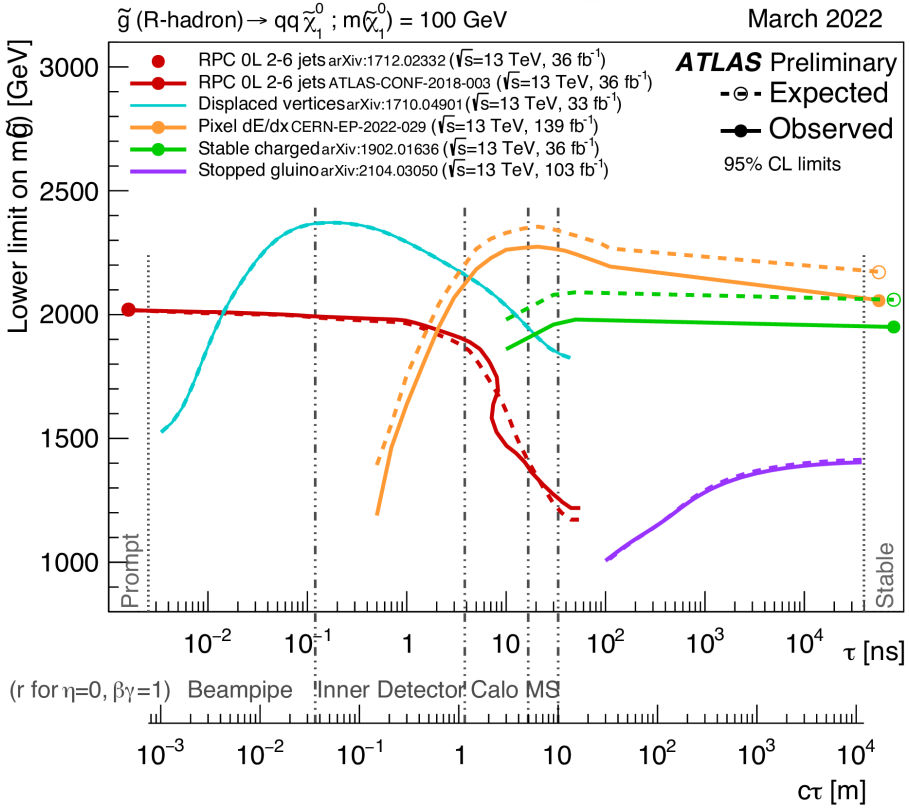


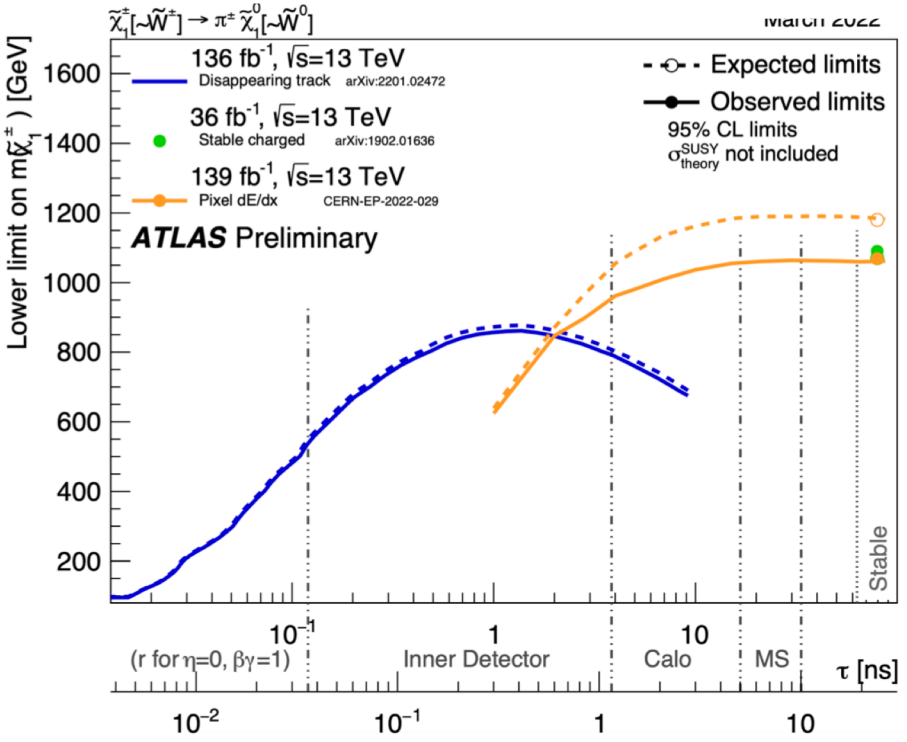
- Excess in high-dE/dx signal region (dE/dx > 2.4 MeV/(g/cm2)) at m > 1 TeV
  - 3.6σ local (3.3σ global) for 1.4 TeV mass hypothesis
- Checked timing of 7 tracks responsible for an excess in the calorimeters and in the muon spectrometer
  - Found however that ToF consistent with β ≈ 1

ATLAS (new): Heavy Charged Long-Lived particle: Exclusions



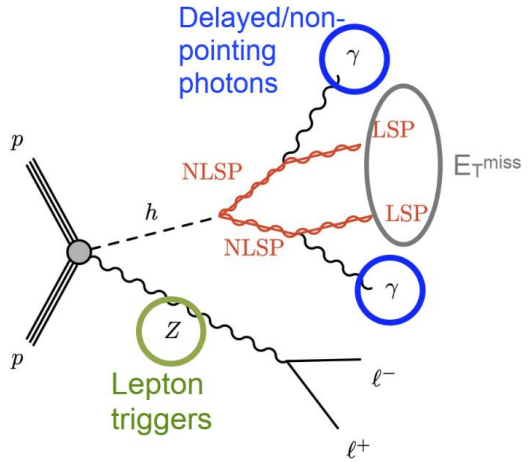


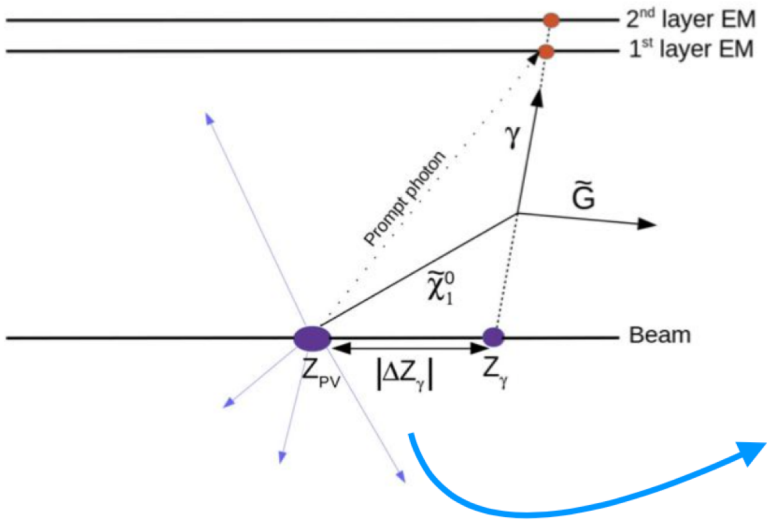


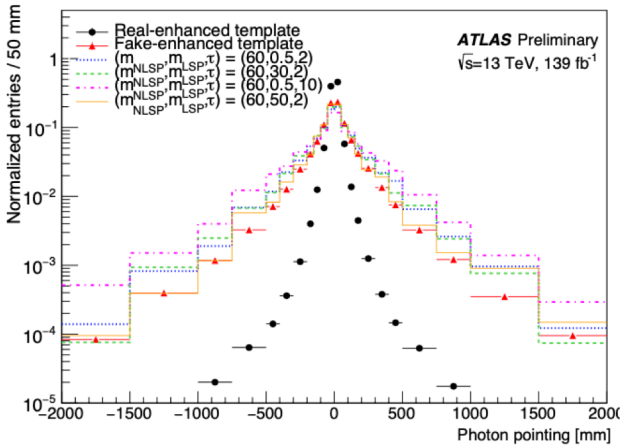


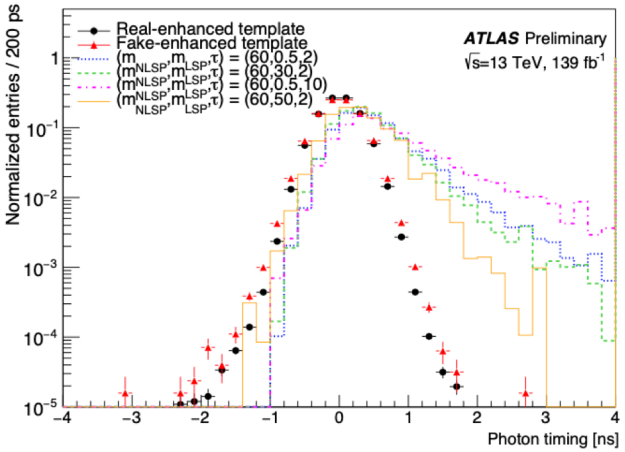
ATLAS (new): Non-pointing delayed photons [ATLAS-CONF-2022-017]

- Signature: late γ wrt bunch crossing not pointing to PV
- Sensitive to H to BSM signal with GMSB decay
  - 3.6 m(NLSP) = 30-60 GeV
  - τ(NLSP) ≈ 0.1-100 ns
- Strategy: fit to pointing (Zγ) and timing (tγ) templates for real and fake photons



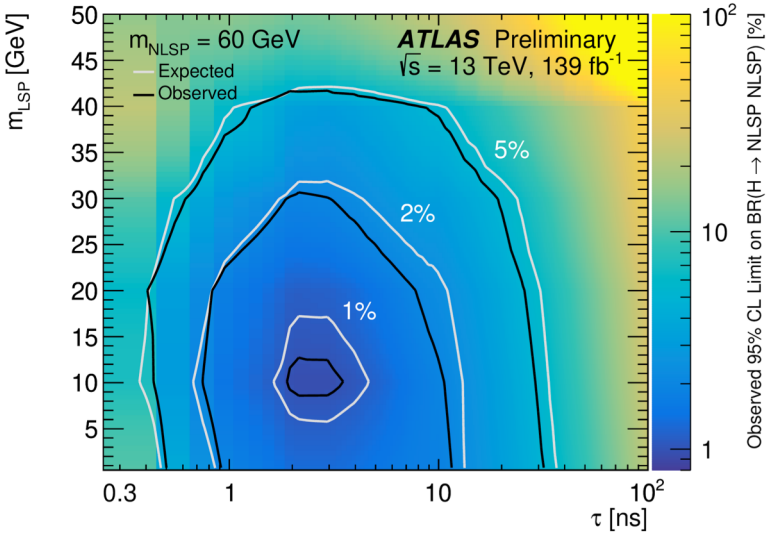






Figures from Julia Gonski,Moriond QCD 2022

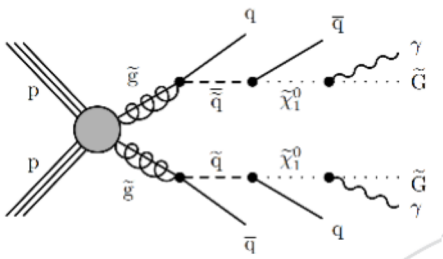
ATLAS (new): Non-pointing delayed photons: Results

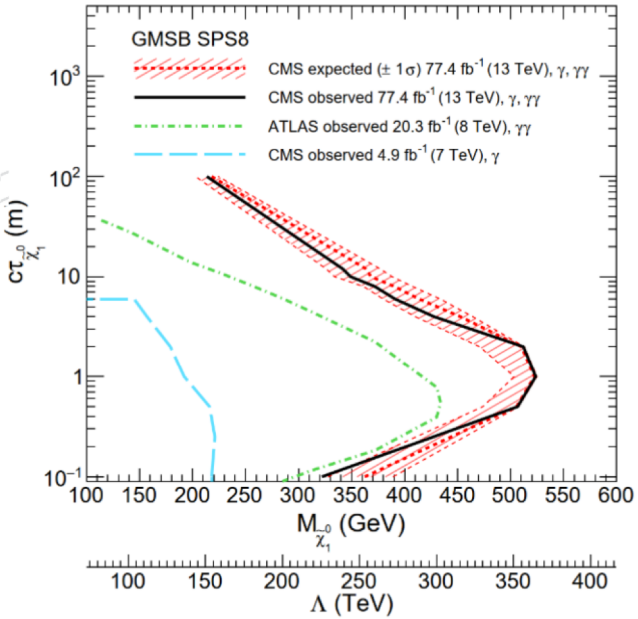


Interpolated 95% CL limits on BR(H → NLSP NLSP) in the plane of LSP mass versus NLSP lifetime. Within each plot, the NLSP mass is held fixed, with values of 60 GeV (top left), 50 GeV (top right), 40 GeV (bottom left), and 30 GeV (bottom right). A smoothing function is used to continuously fill the plane, interpolating between the results for the discrete signal models which were simulated on a grid with 10 GeV spacing. **For visualization purposes, contours are superimposed indicating where the expected and observed 95% CL limits on BR(H → NLSP NLSP) reach values of 1%, 2%, and 5%.**

- Model not yet covered by CMS. Similar search

EXO-19-005

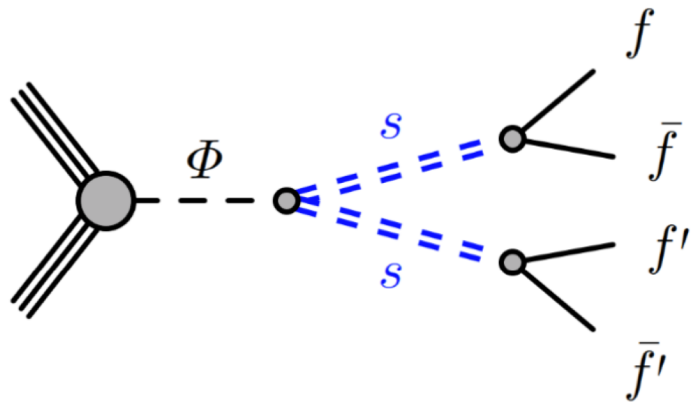


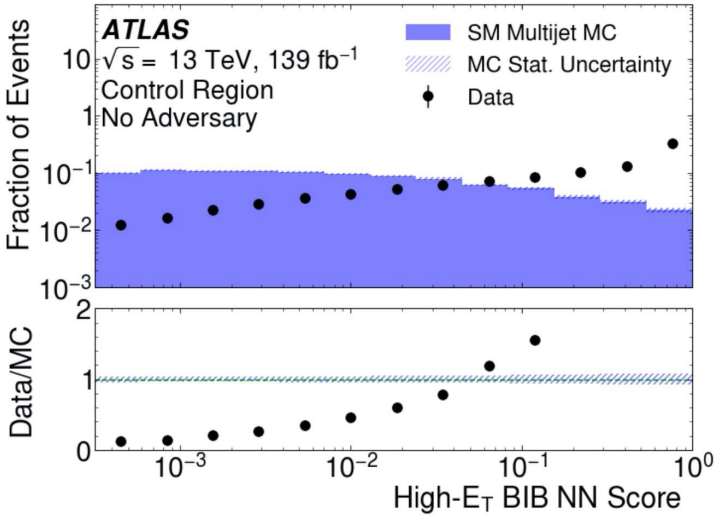


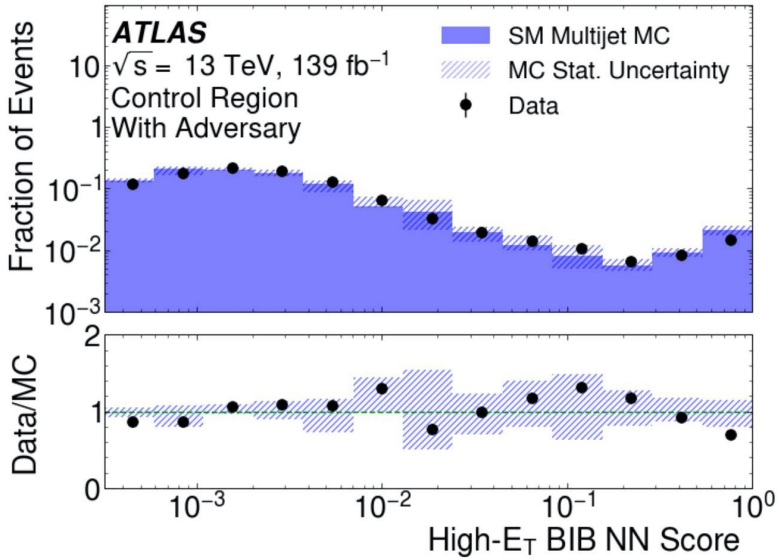
ATLAS (new): Hadronic jets in HCAL

arXiv:2203.01009

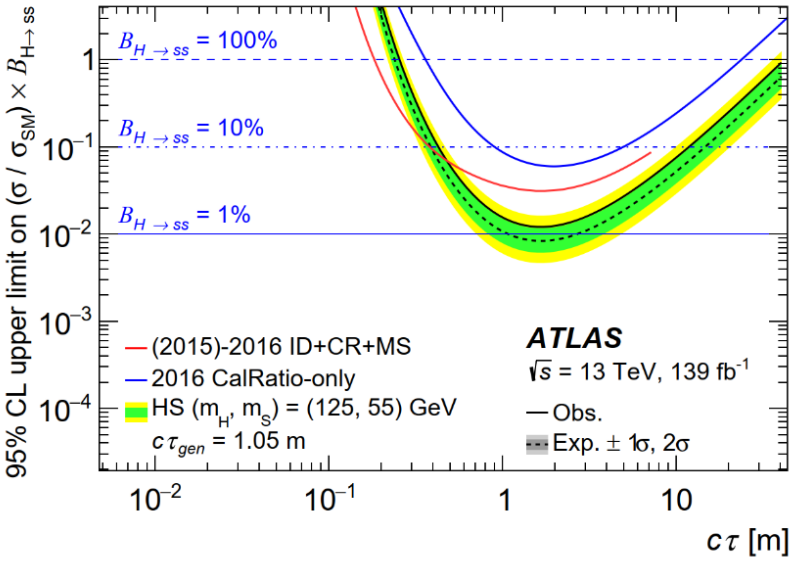
- Signature: narrow trackless jets with large H/E from LLP decays in HCAL
- Sensitivity: m(LLP) = 5-500 GeV, cτ(LLP) ≈ 1 cm - 10 m
- Strategy involves sophisticate bkg modeling
  - **'CalRatio' trigger** (large H/E→low jet pT)
  - **Displaced-jet NN tagger:** DeepNN with adversarial network to mitigate mismodeling of QCD MC events.
  - **Event level BDT**: Displaced-jet NN outputs + other event variables



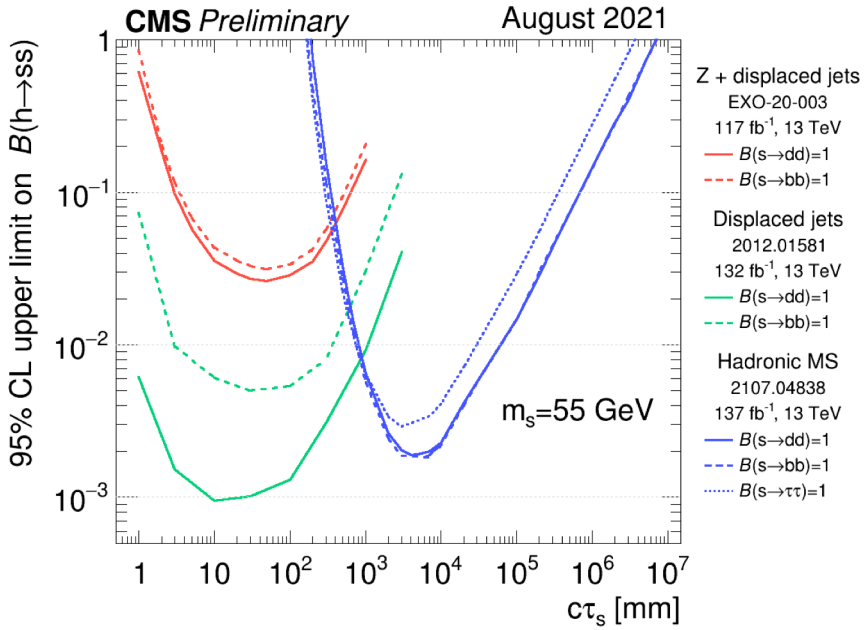




ATLAS (new): Hadronic jets in HCAL: Results



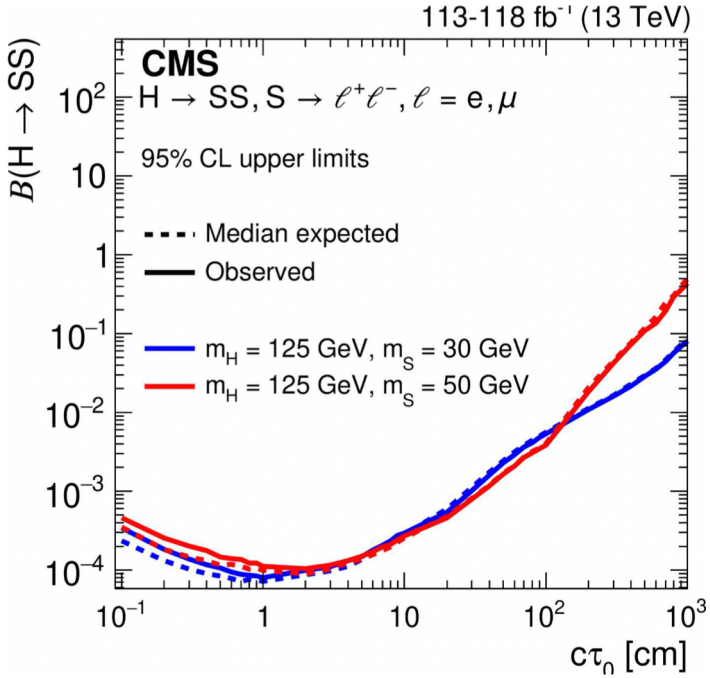
- Lies on less sensitive region CMS for similar searches
- Lack of CalRatio trigger (specific displaced–jet triggers will be available ror Run 3)



CMS: Displaced lepton and muon searches

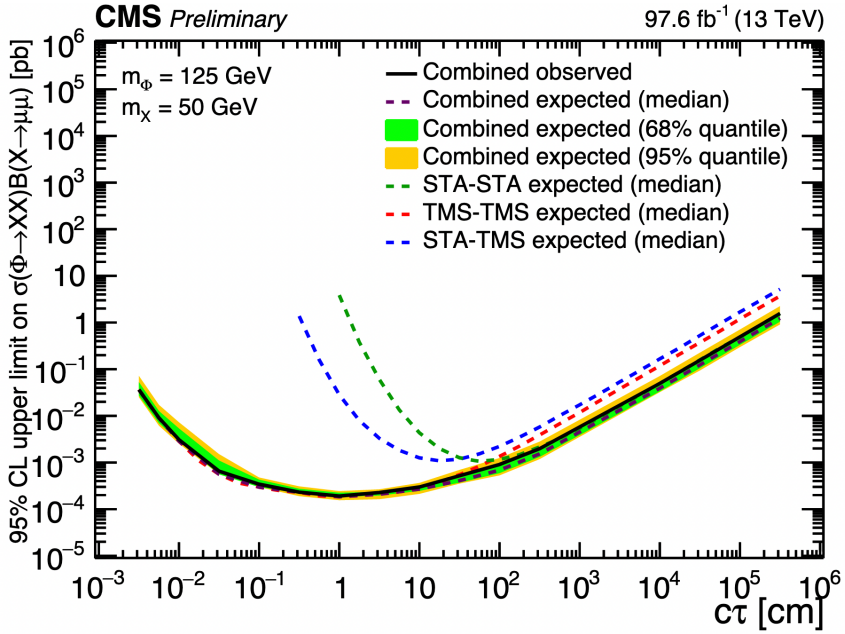
EXO-18-003

- Inclusive search for displaced leptons
  - As model independent as possible
  - Interpreted with SUSY model and hidden sector



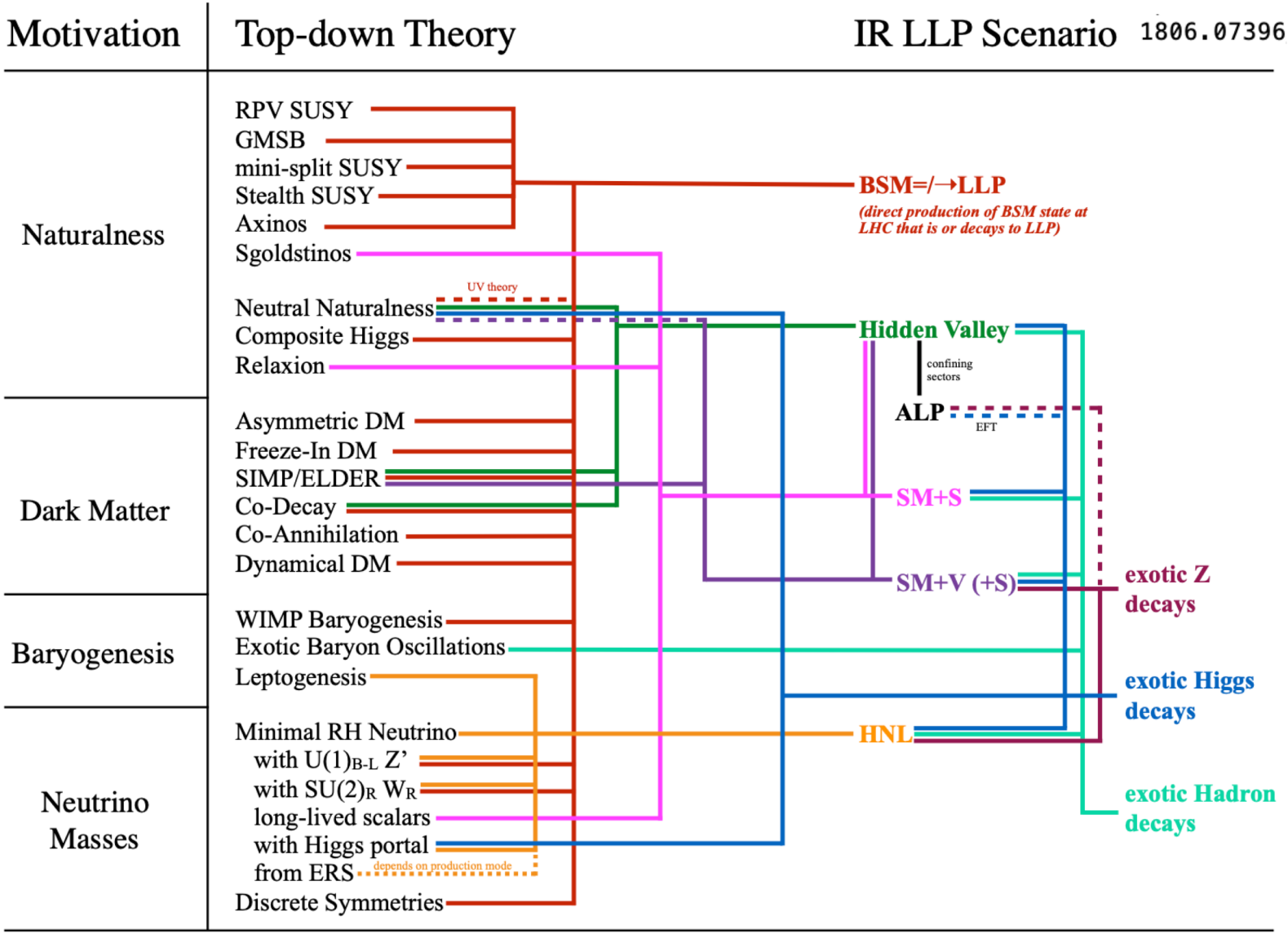
EXO-21-006

- Inclusive search for displaced leptons
  - As model independent as possible
  - Use of Standalone (MS-only) muons to extend reach to large cτ

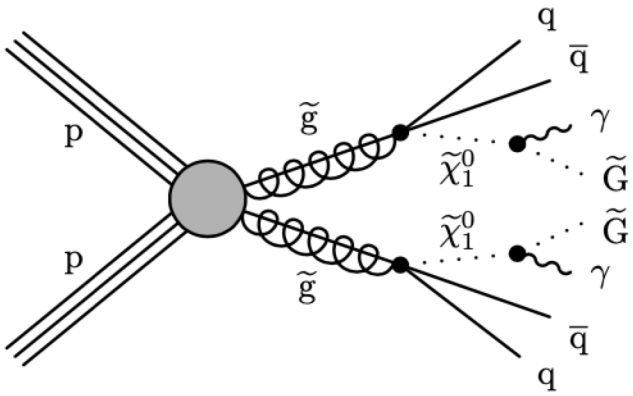


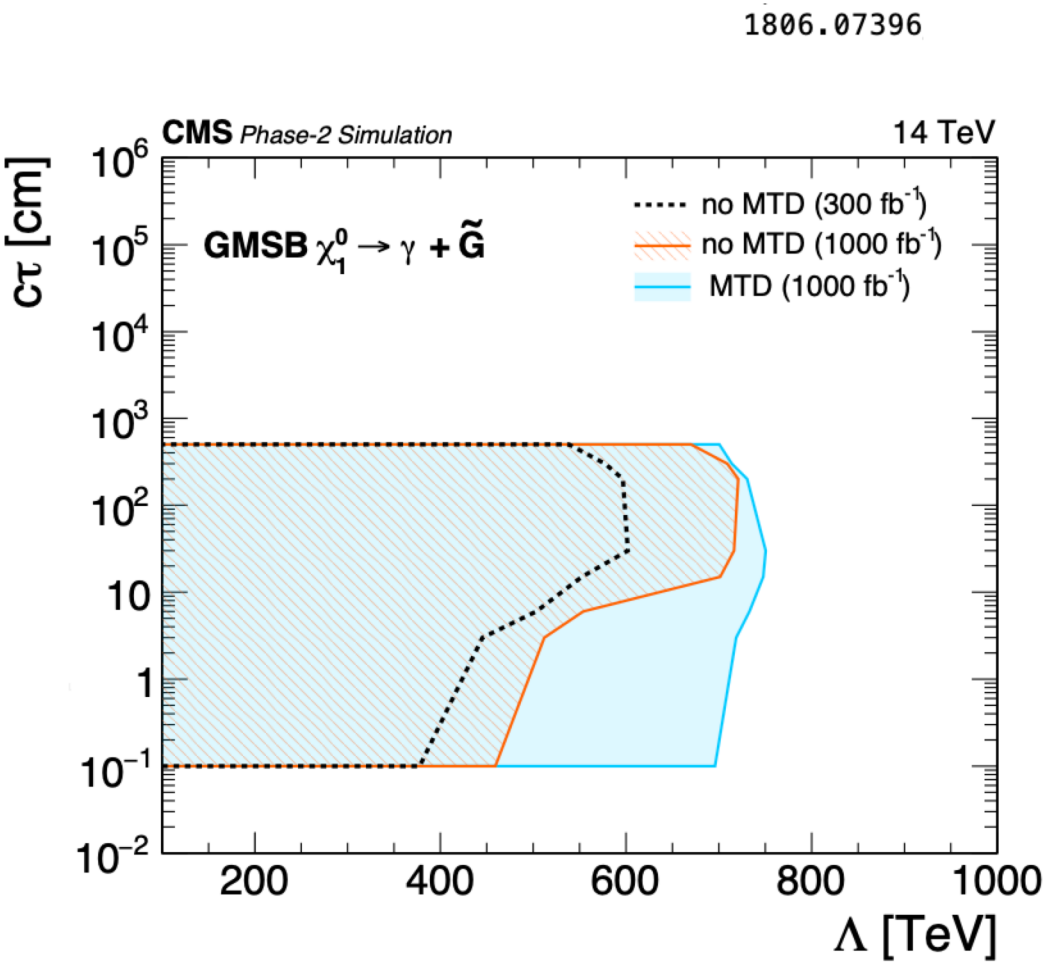
BSM models

- Many BSM models predict or are compatible with LLP

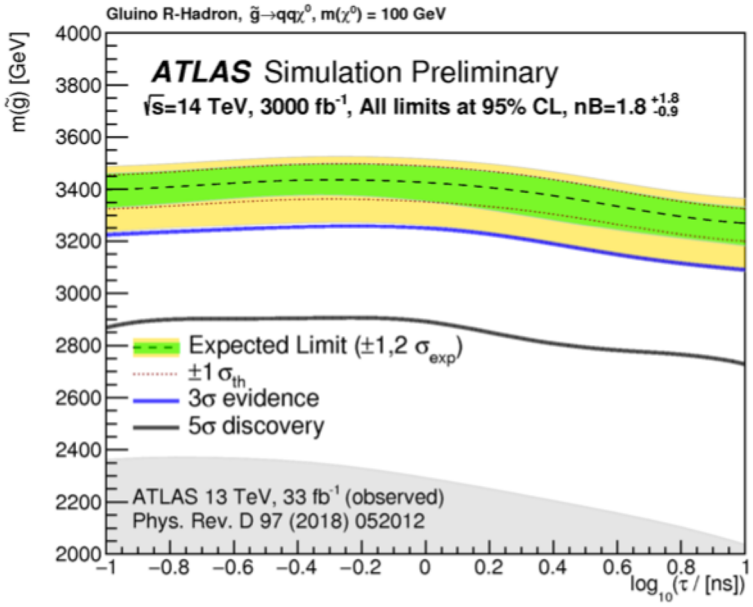


CMS MTD


p
p
$\tilde{g}$
$\tilde{g}$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
q
$\bar{q}$
$\bar{q}$
q
γ
γ
$\tilde{G}$
$\tilde{G}$


1806.07396
CMS Phase-2 Simulation
14 TeV
GMSB $\chi_1^0 \rightarrow \gamma + \tilde{G}$
no MTD (300 fb^{-1})
no MTD (1000 fb^{-1})
MTD (1000 fb^{-1})
$c\tau$ [cm]
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
200
400
600
800
1000
Λ [TeV]

Example HL-HLC projections



- Displaced vertex + MET signature
  - Important role of new ATLAS tracker detector
  - Based on simulation of upgraded detector