Long-lived particles as a key to the dark sector: Searches with CMS

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Dark Interactions Workshop

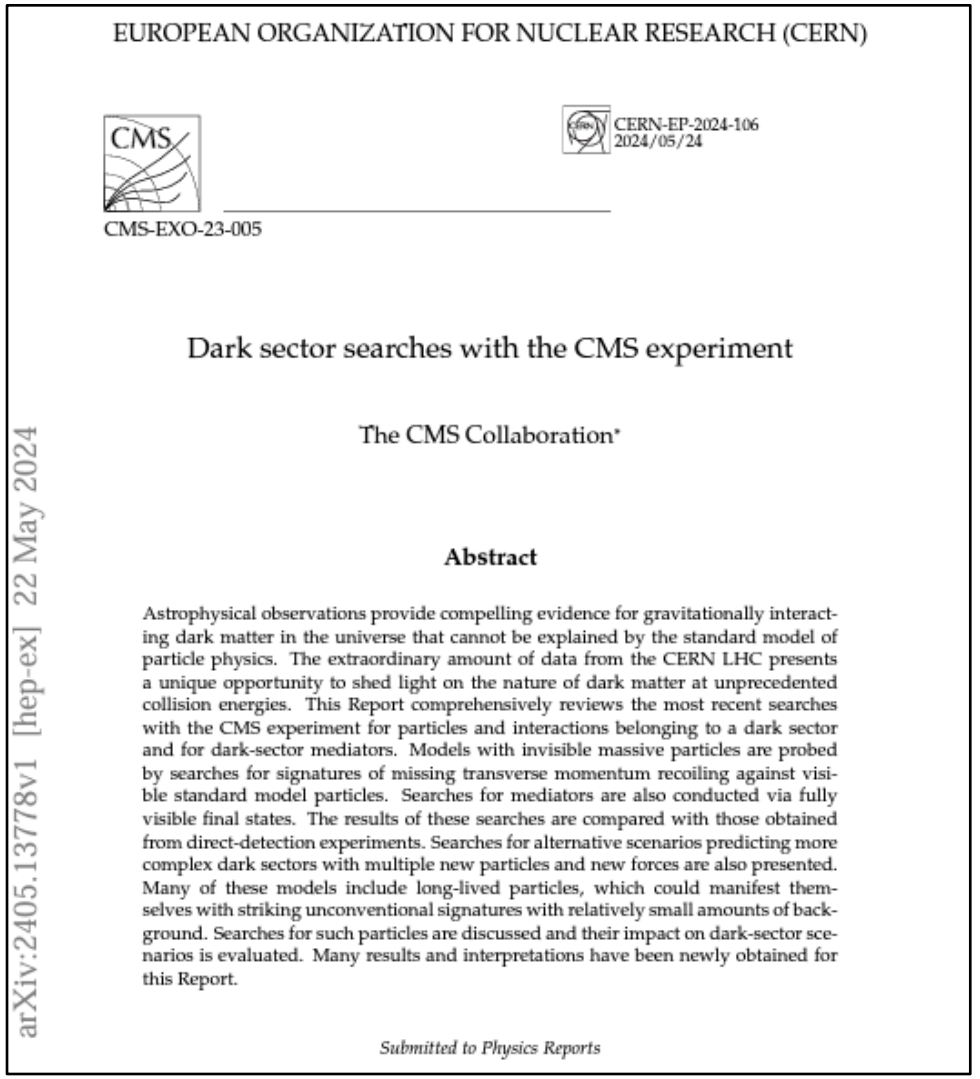
Simon Fraser University, Vancouver, BC, Canada

October 17, 2024

Timely Workshop…

CMS Dark Sectors Review Paper

- **CMS has a rich search program for particles and forces in dark sectors**
- Idea: Summarize this dark sector search program and draw overall conclusions in a **review paper**
- Now accepted by Phys. Rept. and on the arXiv (2405.13778)
- Will report today on the **long-lived particle searches** in the dark sector (~1/3 of analyses in this paper)



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2024-106
2024/05/24

CMS-EXO-23-005

Dark sector searches with the CMS experiment

The CMS Collaboration*

arXiv:2405.13778v1 [hep-ex] 22 May 2024

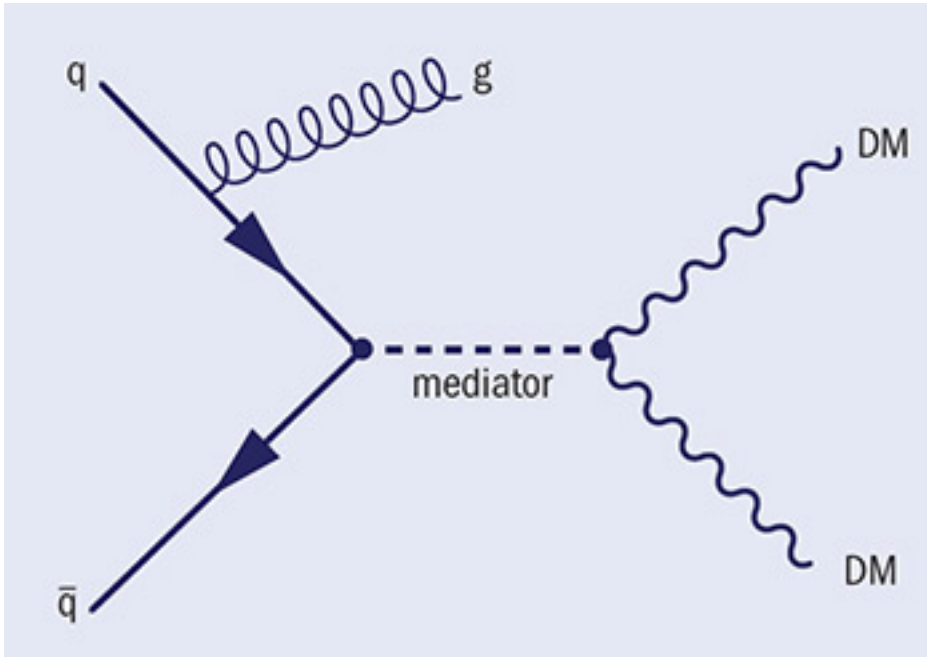
Abstract

Astrophysical observations provide compelling evidence for gravitationally interacting dark matter in the universe that cannot be explained by the standard model of particle physics. The extraordinary amount of data from the CERN LHC presents a unique opportunity to shed light on the nature of dark matter at unprecedented collision energies. This Report comprehensively reviews the most recent searches with the CMS experiment for particles and interactions belonging to a dark sector and for dark-sector mediators. Models with invisible massive particles are probed by searches for signatures of missing transverse momentum recoiling against visible standard model particles. Searches for mediators are also conducted via fully visible final states. The results of these searches are compared with those obtained from direct-detection experiments. Searches for alternative scenarios predicting more complex dark sectors with multiple new particles and new forces are also presented. Many of these models include long-lived particles, which could manifest themselves with striking unconventional signatures with relatively small amounts of background. Searches for such particles are discussed and their impact on dark-sector scenarios is evaluated. Many results and interpretations have been newly obtained for this Report.

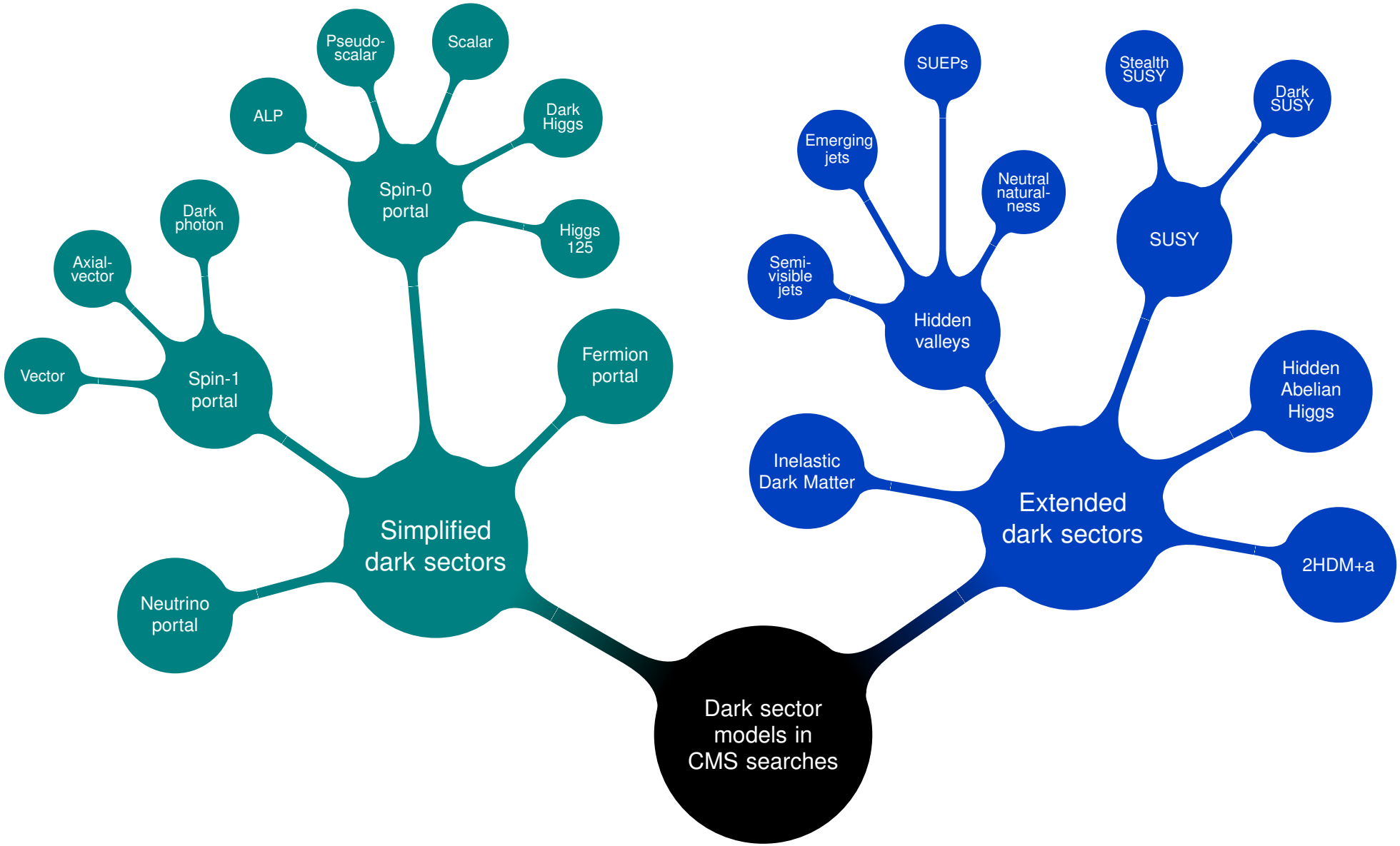
Submitted to Physics Reports

Dark Sectors

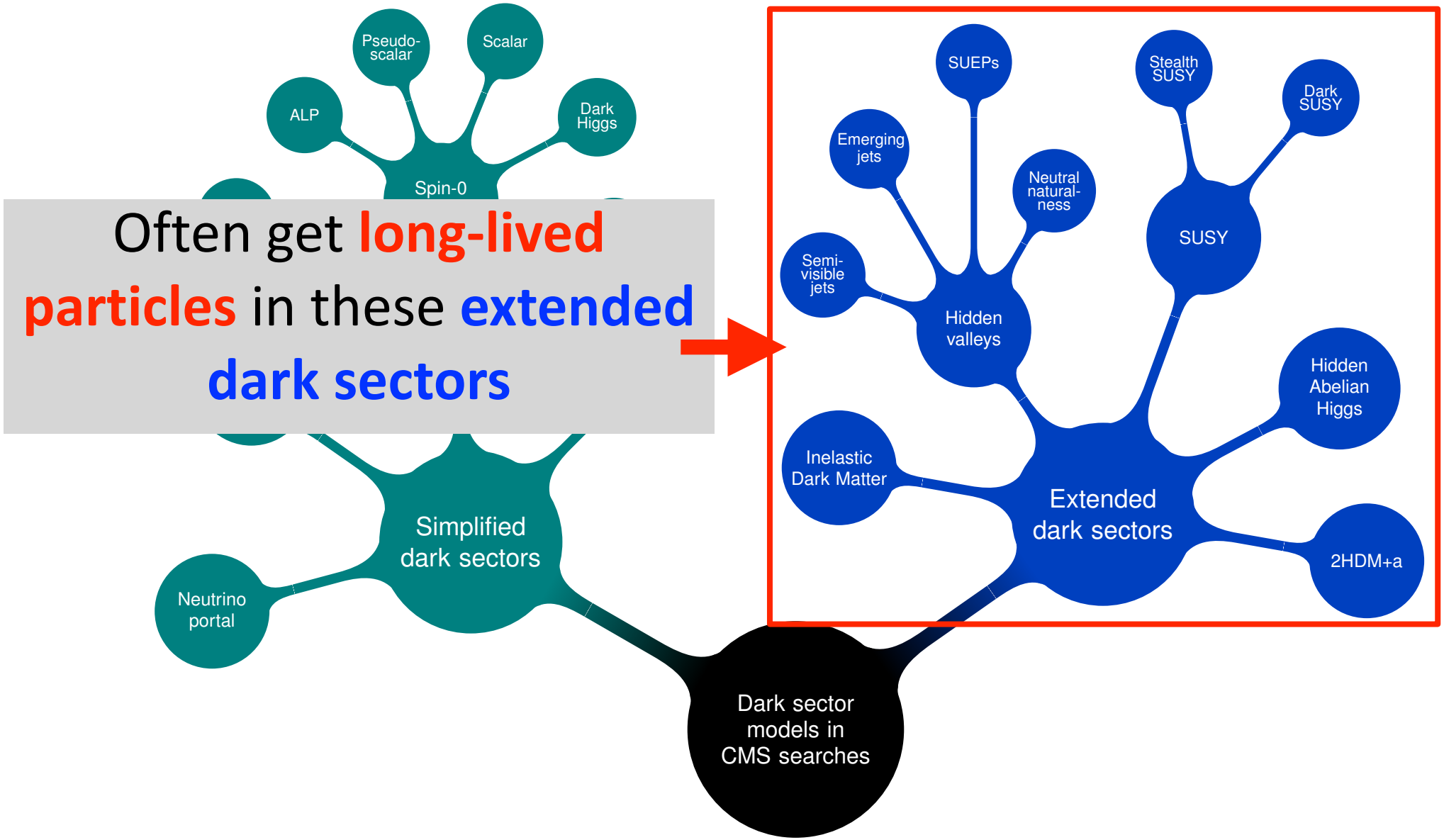
- **Pair-production of dark matter (DM) at colliders**
  - Signature: missing transverse energy recoiling against SM particle
- ***Simplified dark sectors***
  - Usually have a DM candidate + a mediator particle (could also be BSM)
- ***Extended dark sectors***
  - Could be more complicated dark scenarios with rich dynamics



Simplified and Extended Dark Sectors



Simplified and Extended Dark Sectors



Often get **long-lived particles** in these **extended dark sectors**

What's a New LLP?

- From an experimentalist's point of view, it's a particle beyond the standard model that:

  decays a reconstructable distance from the primary collision

  or

  is quasi-stable on the scale of the detector

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  - travel fast or slow
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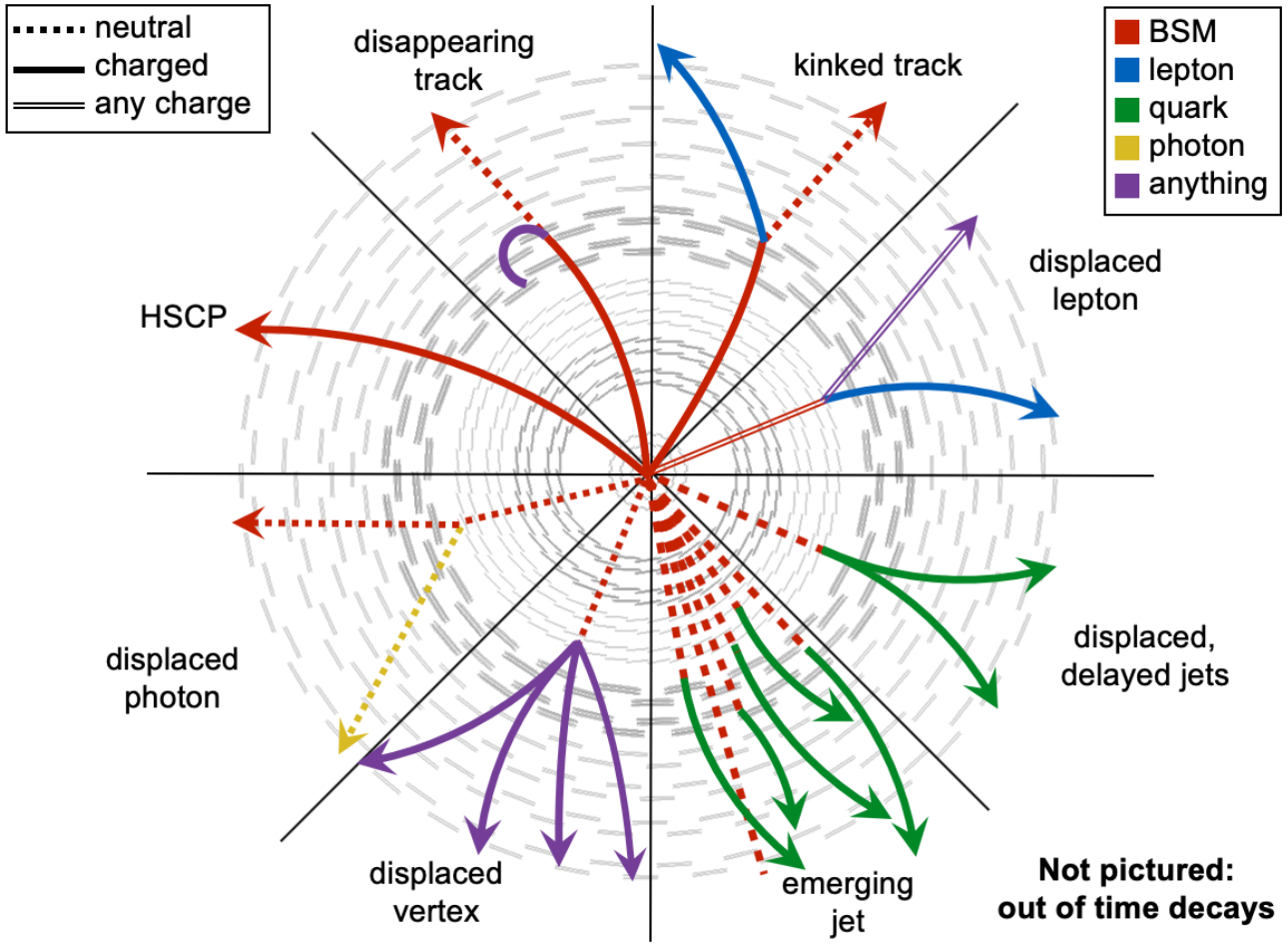
- They can:
  - be **charged,** neutral or have color
  - be light or heavy
  - travel fast or slow
  - decay to anything
- They often require dedicated searches or dedicated experiments

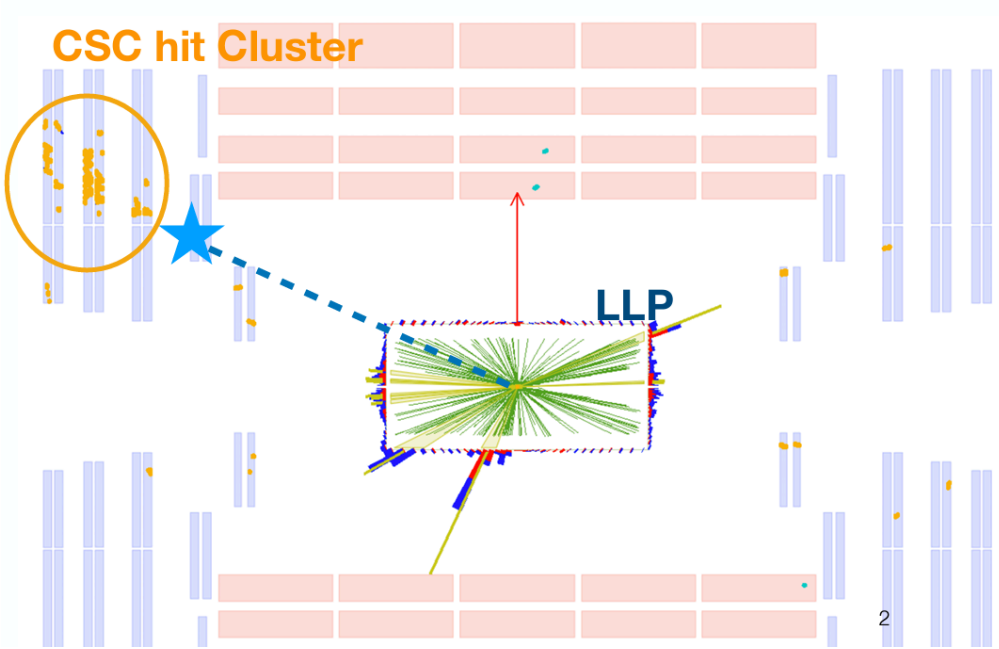
Long-Lived Particle Searches

- **Wide variety** of:
  - Charges
  - Final states
  - Decay locations
  - Lifetimes
- Design **signature-driven** searches
- Often interpret results with a **benchmark model**, but can expand to a **variety of scenarios**
- Jackson has already described many of these signatures already, so I won't repeat them, **except…**

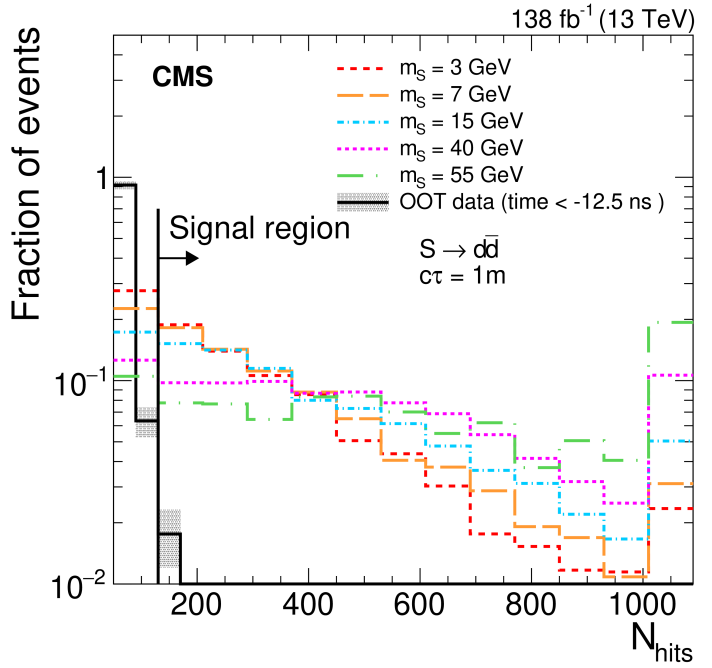


Special Mention: Muon Detector Showers

- **Neutral LLPs with ctau> 1m** could decay **beyond the calorimeter** with:
  - No tracks, no jets, **high-multiplicity shower (hundreds of hits per cluster)** in the muon system
- Essentially, we *use the muon system as a sampling calorimeter*
- **Unique signature** due to the presence of steel in the CMS muon system
- *Excellent background suppression from shielding material (background rejection of 1e6)*
- Sensitive to hadronic, tau, photon, and electron decays



arXiv:2402.01898



CMS Run 2 LLP Analyses in the Dark Sector

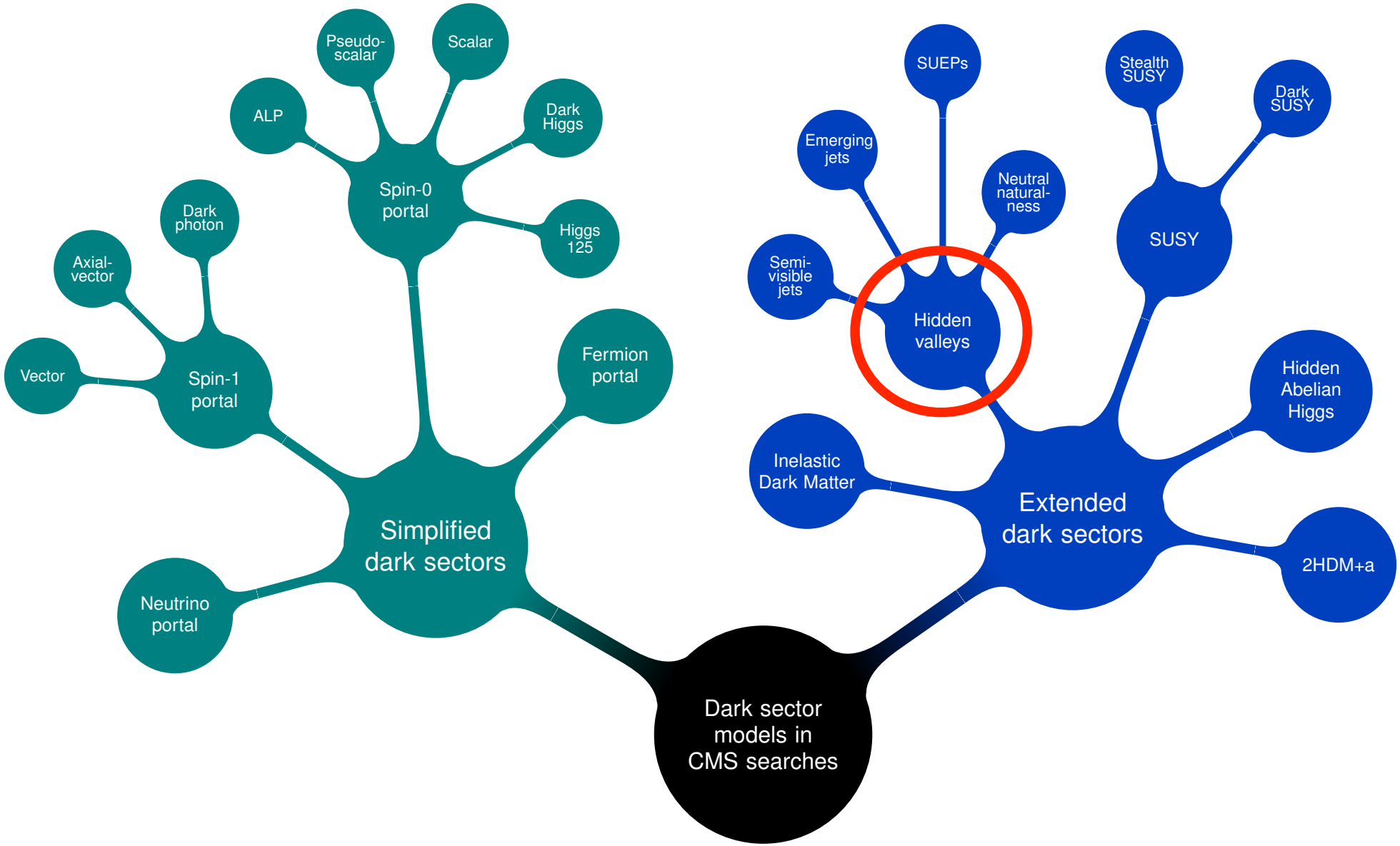
Displaced leptons
Displaced ee, emu, mumu (EXO-18-003)
Displaced dimuons (EXO-21-006, EXO-23-014)
H to aa to 4mu (HIG-18-003)
Displaced dimuon scouting (EXO-20-014)

Hadronic LLP decays
Displaced jets (EXO-19-021)
Displaced vertices (EXO-19-013)
Emerging jets (EXO-18-001, EXO-22-015)
Stopped particles (EXO-16-004)
Muon detector showers (EXO-20-015, EXO-21-008)

LLP + p_T^{miss}
Inelastic DM (EXO-20-010)
Delayed jets (EXO-19-001)
Trackless and OOT jets (EXO-21-014)
Displaced vertices + MET (EXO-22-020)

Rather than cover all models and results, I'll **pick a few models** and briefly describe the analyses and results for them

Hidden Valleys



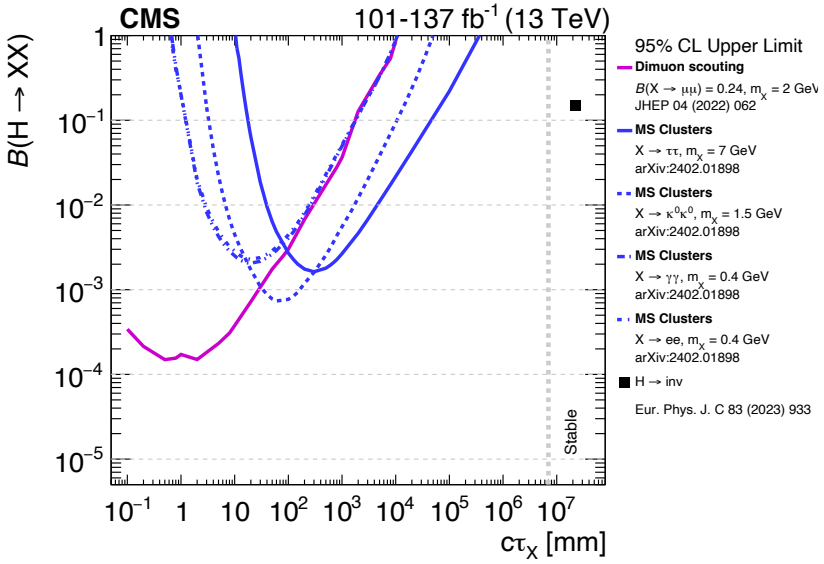
Extended dark sectors

Hidden valleys

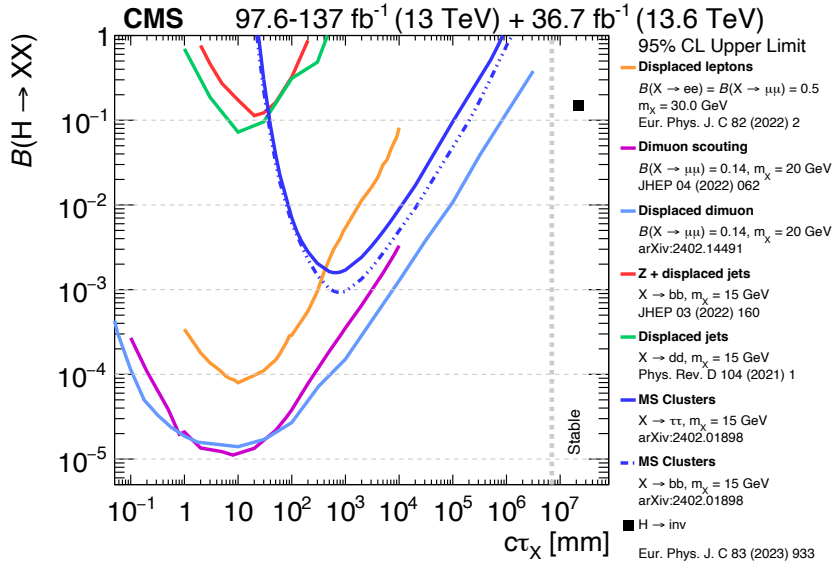
Higgs to long-lived particles (LLPs)

- **Hidden valleys:** dark sector model with rich dynamics at low energy scales, and accessible at colliders at high energy scales
- LLPs are well-motivated in dark sectors:
  - Heavy mediator connected to SM suppresses decay rates, produces long lifetimes
- Interpretations of LLP searches with hadronic and leptonic decays

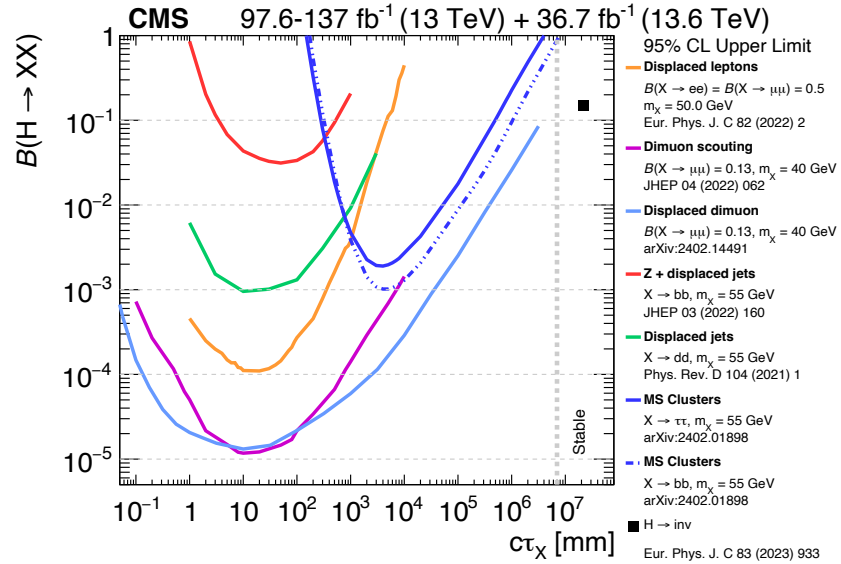
$0.4 < m_X < 2$ GeV



$5 < m_X < 30$ GeV



$40 < m_X < 55$ GeV



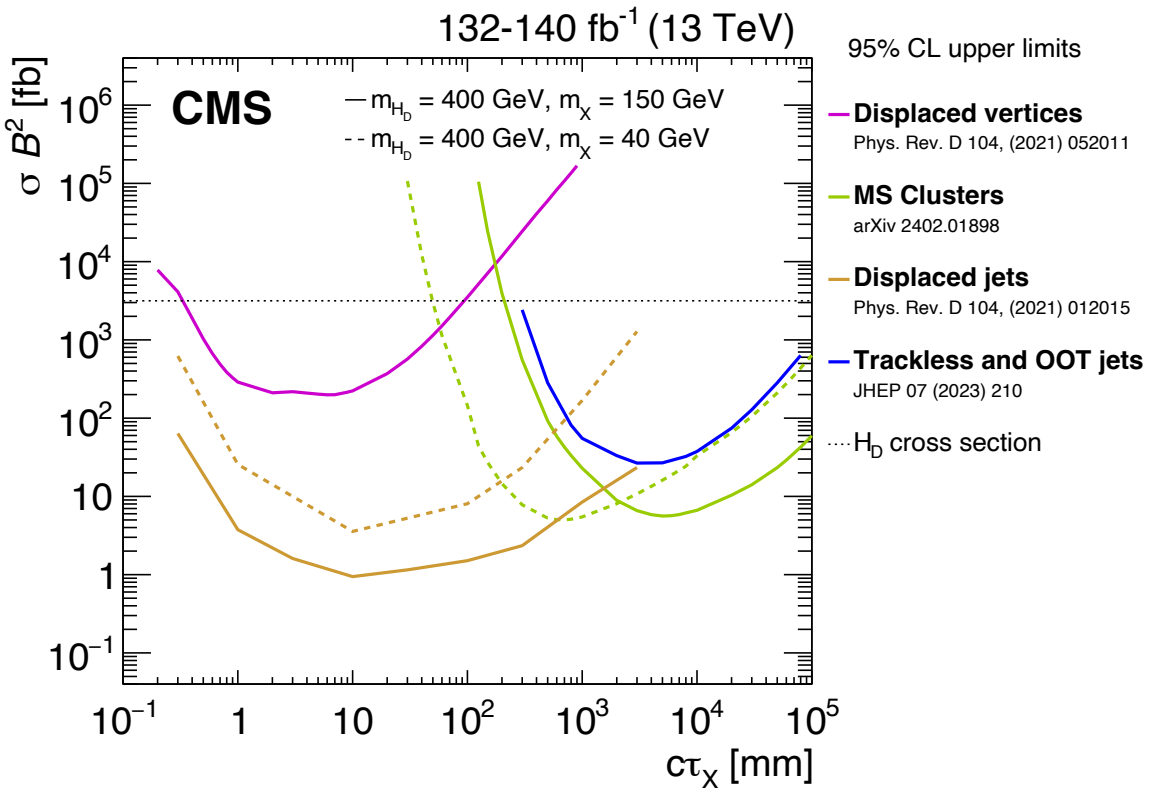
Extended dark sectors

Hidden valleys

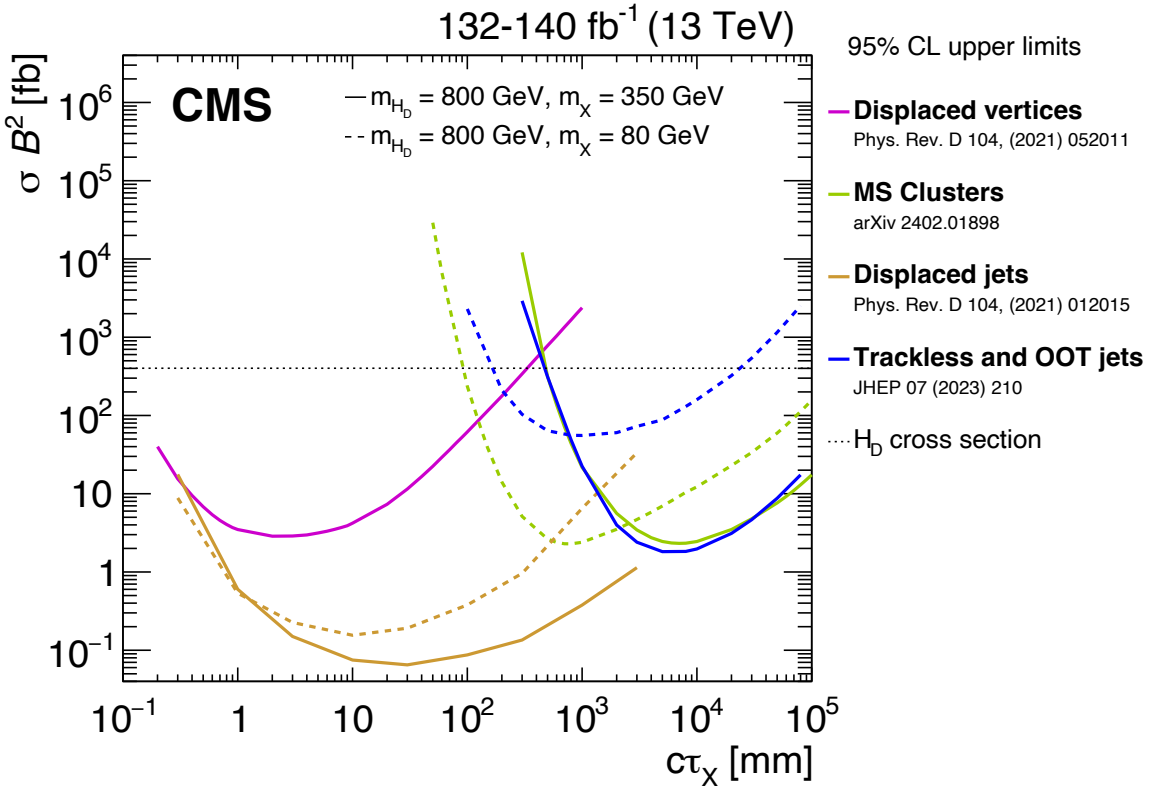
Dark Higgs to LLPs to 4b

- Reinterpretations of LLP searches with hadronic decays
- Dark Higgs mediator, fully hadronic final states
- Brand new reinterpretations for this paper

m_{HD} = 400 GeV



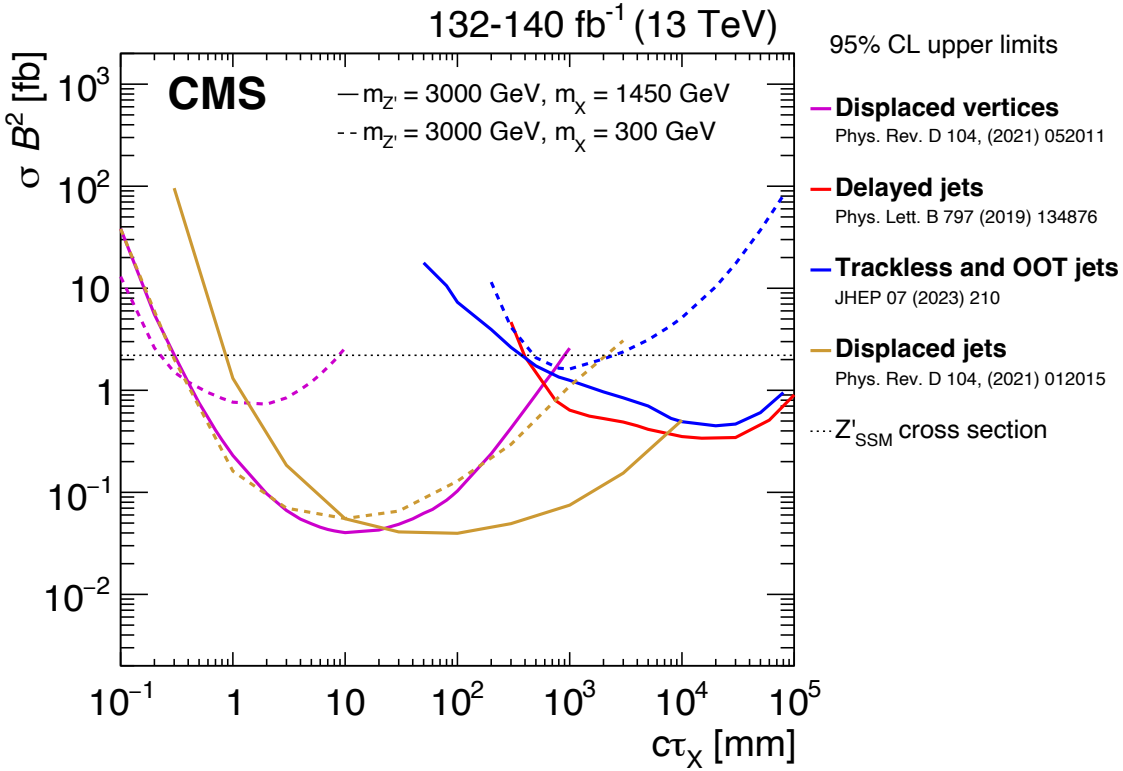
m_{HD} = 800 GeV



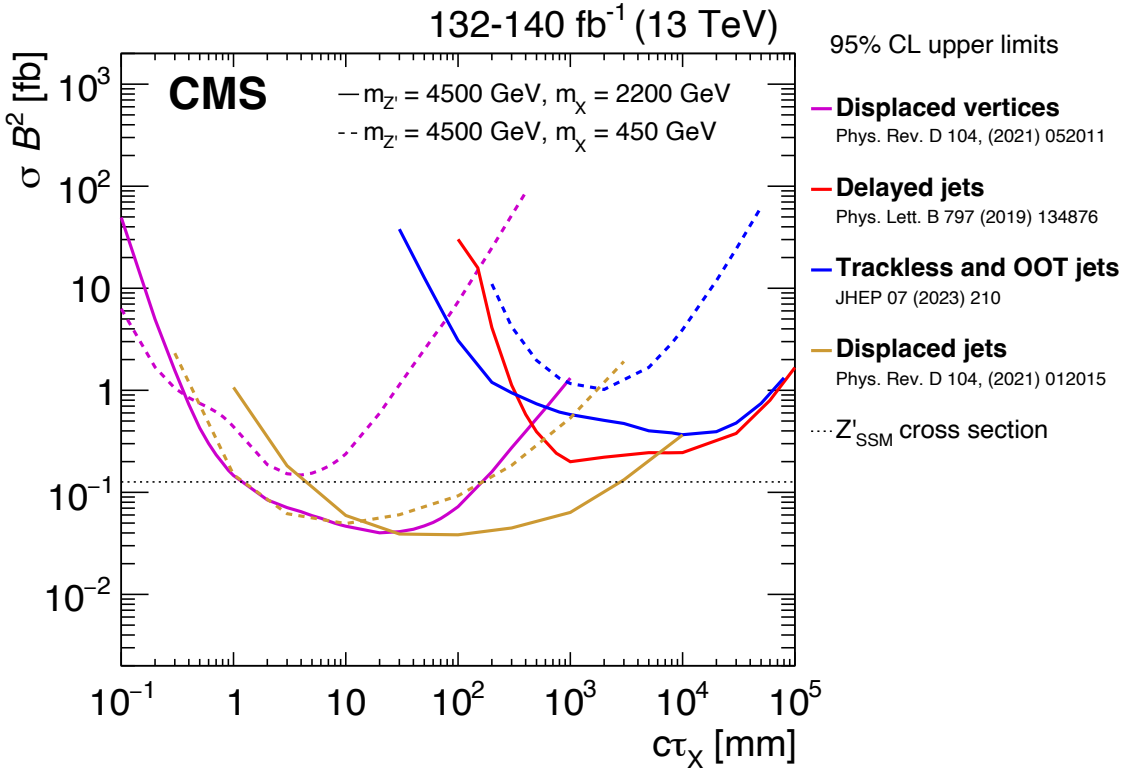
Z’ to LLPs to 4b

- Reinterpretations of LLP searches with hadronic decays
- Heavy Z’ mediator, fully hadronic final states
- Brand new reinterpretations for this paper

$m_{Z'}$ = 3000 GeV

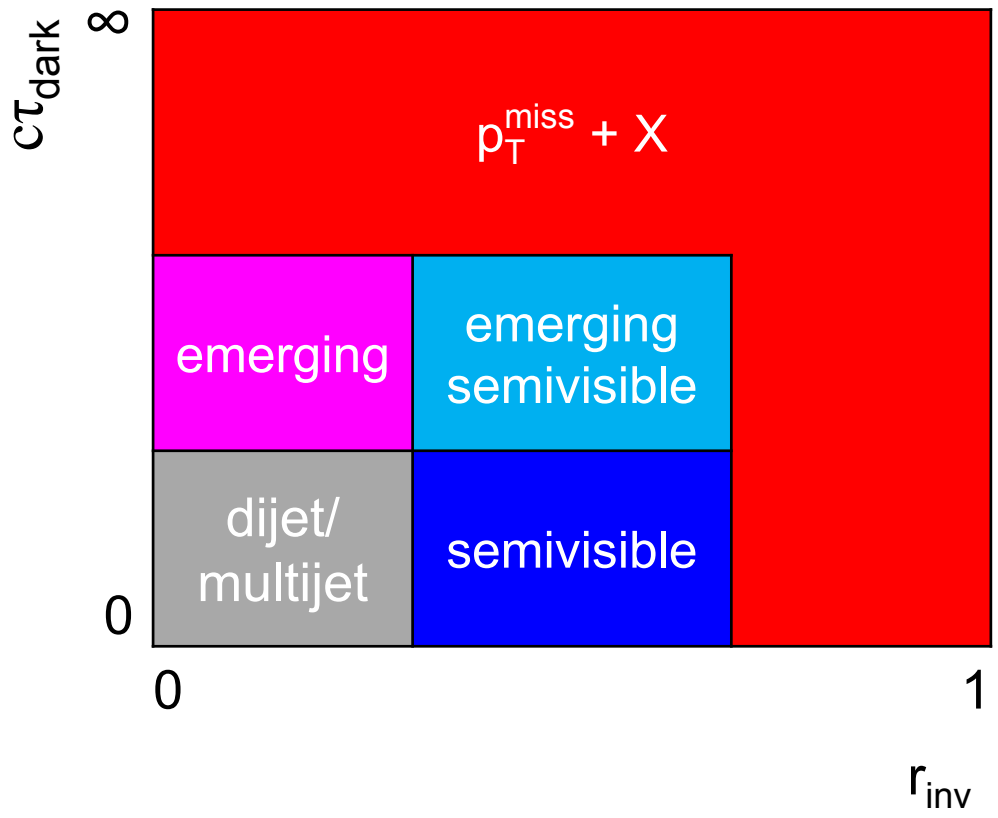


$m_{Z'}$ = 4500 GeV



Dark QCD

- **Hidden valleys**: dark sector model with rich dynamics at low energy scales, and accessible at colliders at high energy scales
- **Dark QCD**: Simple hidden valley scenario with an additional broken U'(1) gauge group
  - Dark photon can communicate with SM via kinetic mixing
  - Confined in the dark sector
- Rich phenomenology available: dijets, multijets, semivisible jets, emerging jets, etc.



Extended dark sectors

Hidden valleys

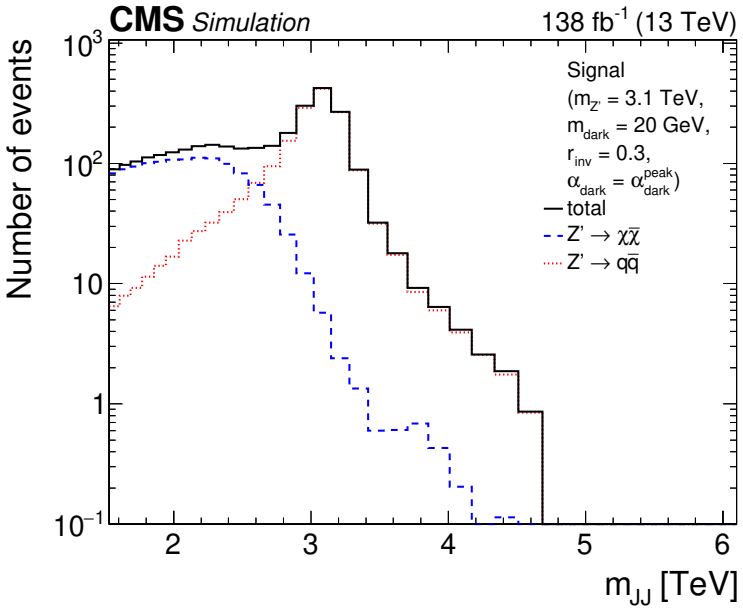
Semivisible Jets (I)

- Two new reinterpretations for this paper:
- Reinterpret dijets and monojet searches in semivisble jet signals
- **Dijet search (EXO-19-012)**: uses full combine datacards for fit & ratio methods
- **Mono jet search (EXO-20-004)**: uses MadAnalysis implementation

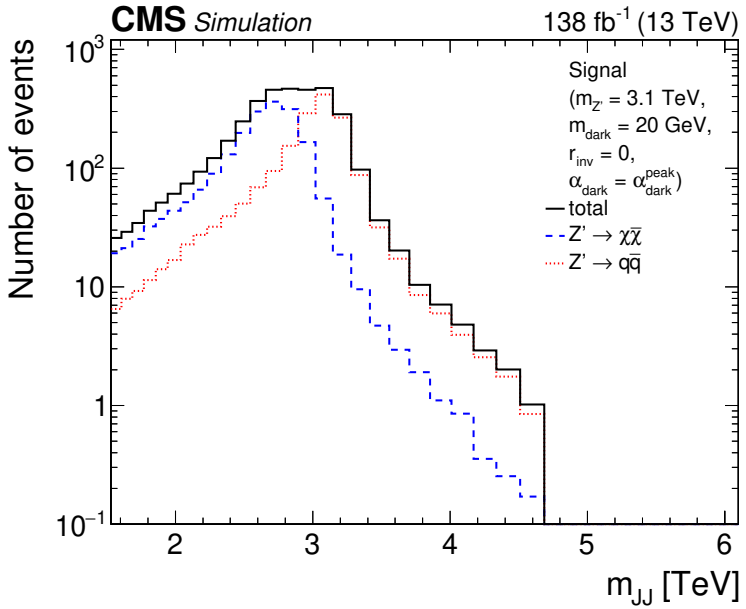
Reinterpretation of Dijet Search

$Z' \rightarrow qq$ and $Z' \rightarrow \chi\chi$

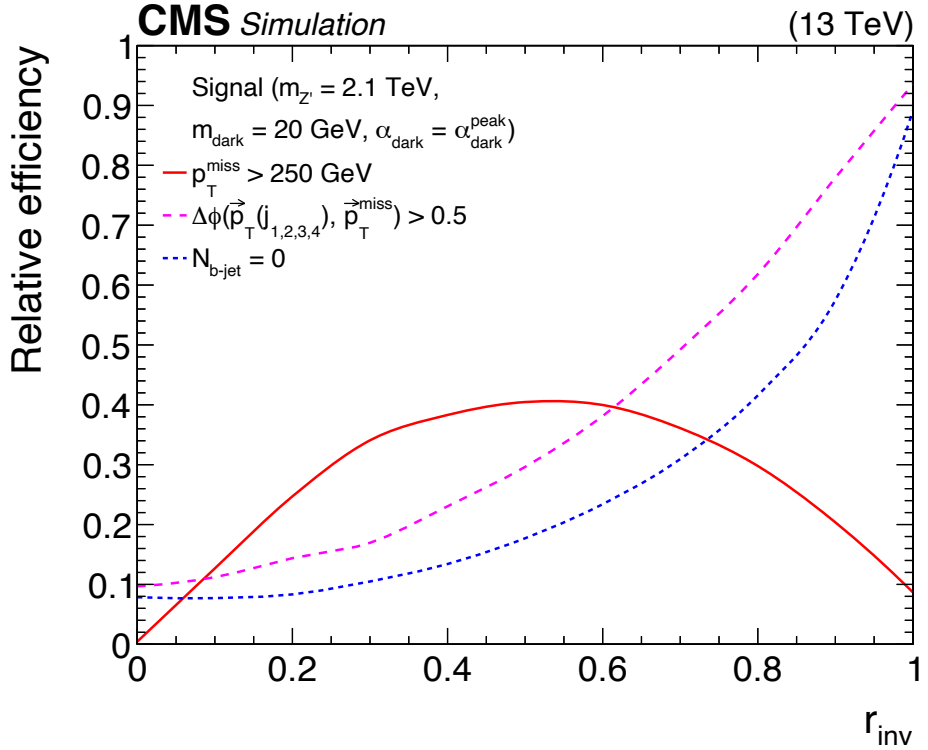
r_{inv} = 0.3



r_{inv} = 0



Reinterpretation of Monojet Search

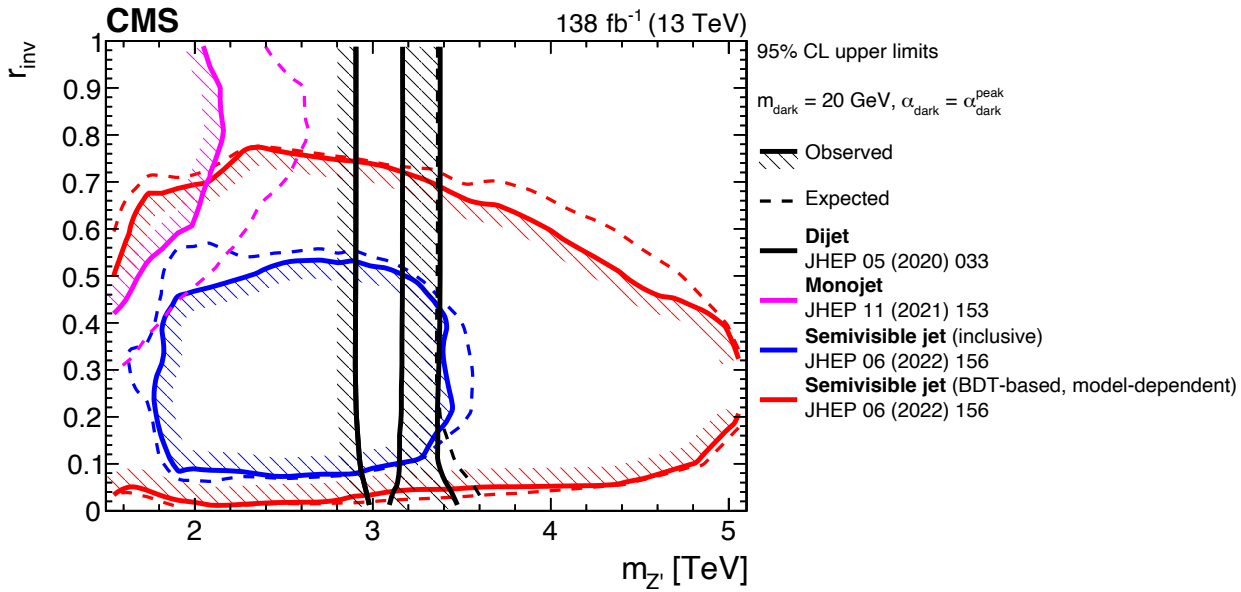


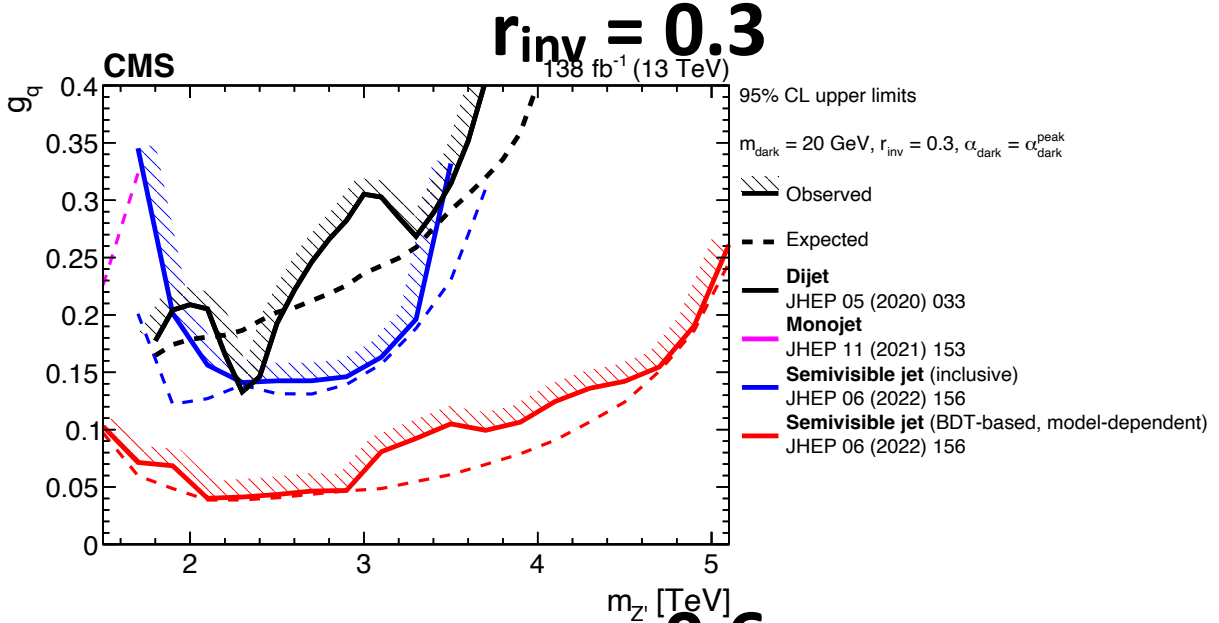
Extended dark sectors

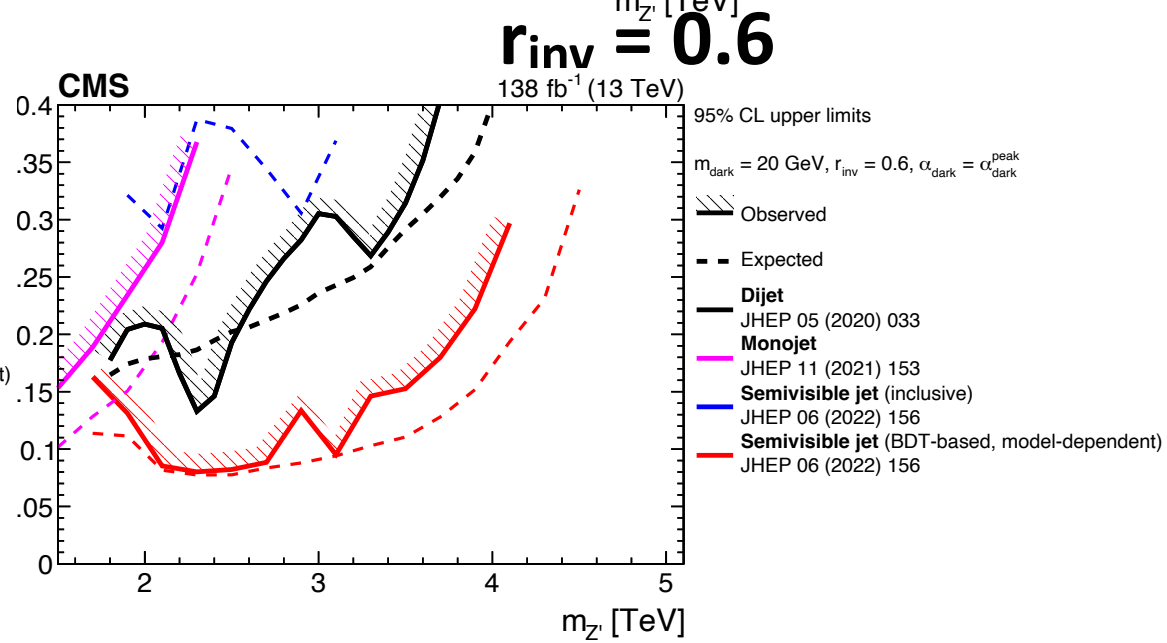
Hidden valleys

Semivisible Jets (II)

- Reinterpretations of the:
  - **Dijet search (EXO-19-012)**
  - **Mono jet search (EXO-20-004)**
  - **SVJ search** (**EXO-19-020**: cut-based and BDT-based, model-dependent)
- Brand new reinterpretations for this paper



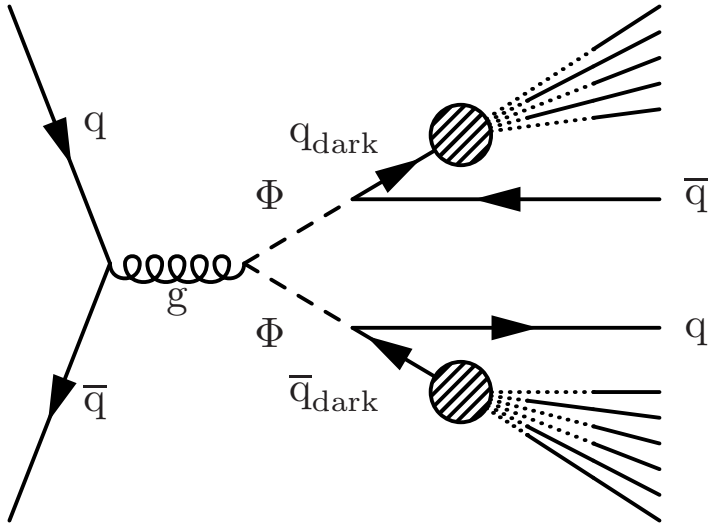


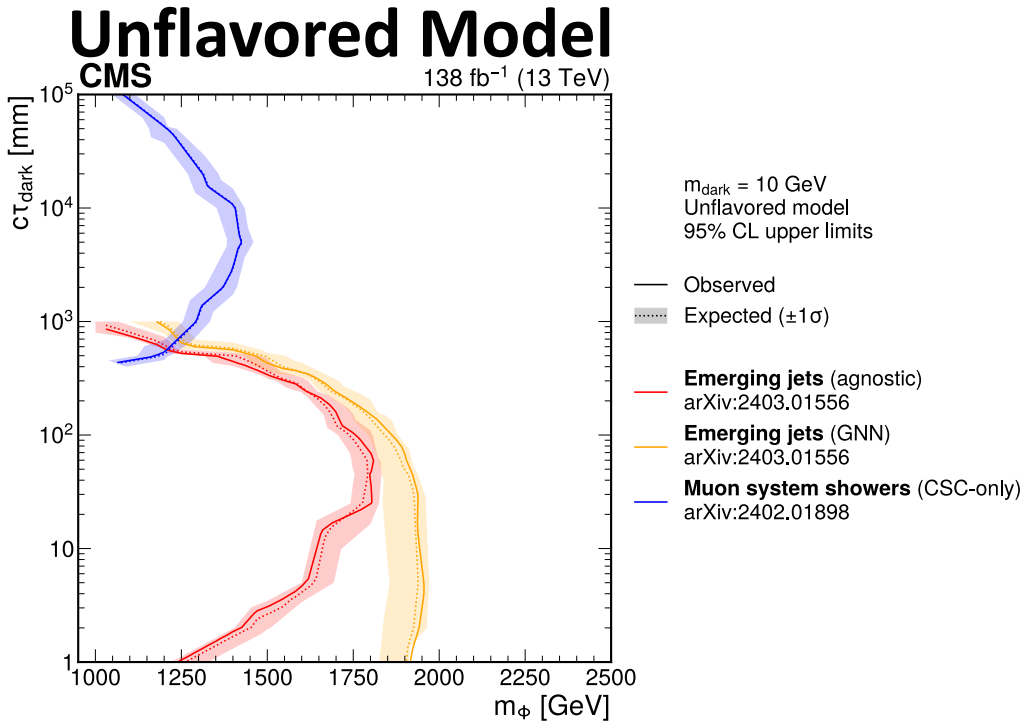


Extended dark sectors

Hidden valleys

Emerging Jets





- Bifundamental mediator (Φ) that decays to a jet and an emerging jet
- Reinterpretations of track-based emerging jets search (EXO-22-015: agnostic and GNN, model-dependent) and muon detector showers search (EXO-21-008)
- Brand new reinterpretation for this paper

Extended dark sectors

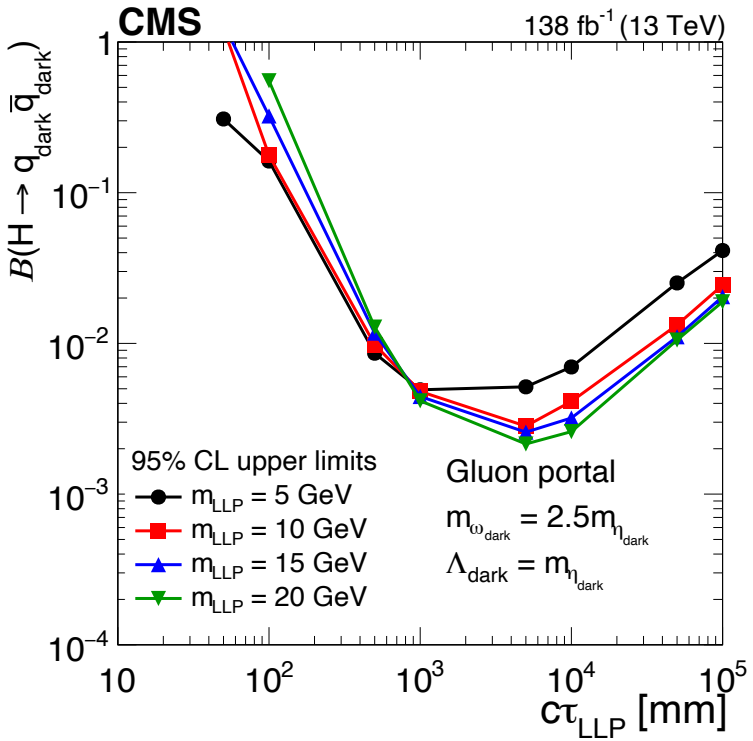
Dark QCD

Emerging Jets: SM Higgs Mediator

- Emerging jet signature: SM Higgs (mediator) decays to dark hadrons
- Muon detector shower search (EXO-21-008) reinterpreted in this emerging jets signature

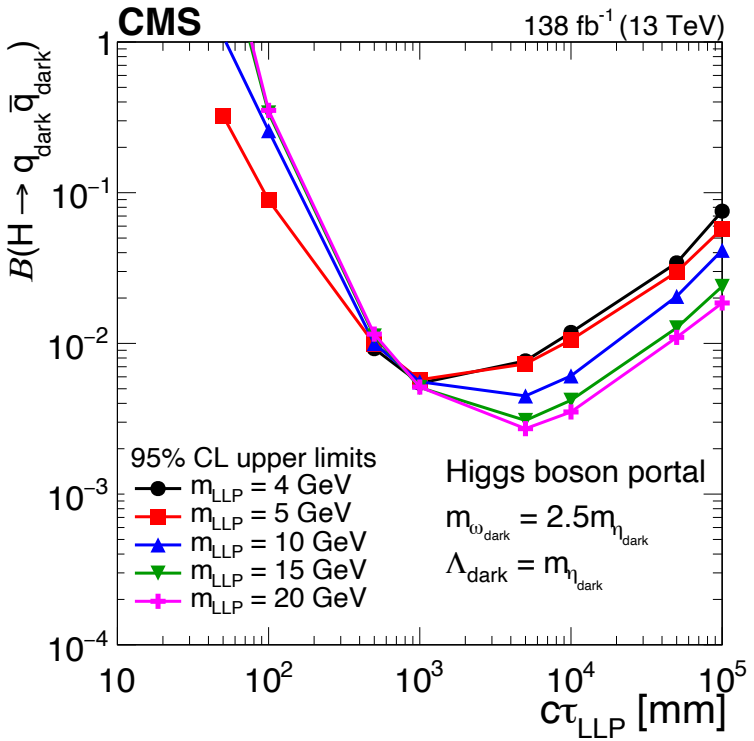
Gluon Portal

From EXO-21-008

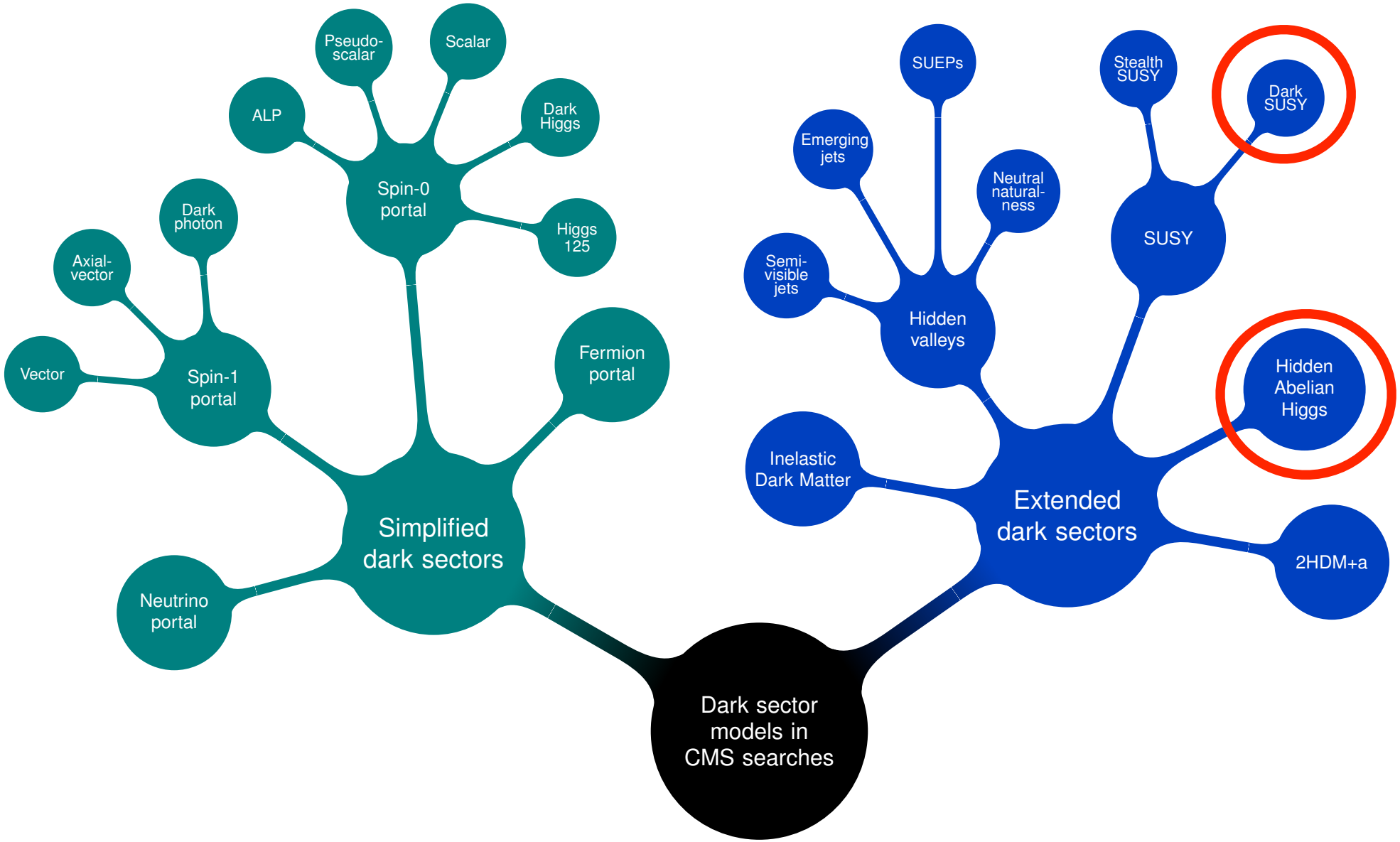


Higgs Boson Portal

From EXO-21-008

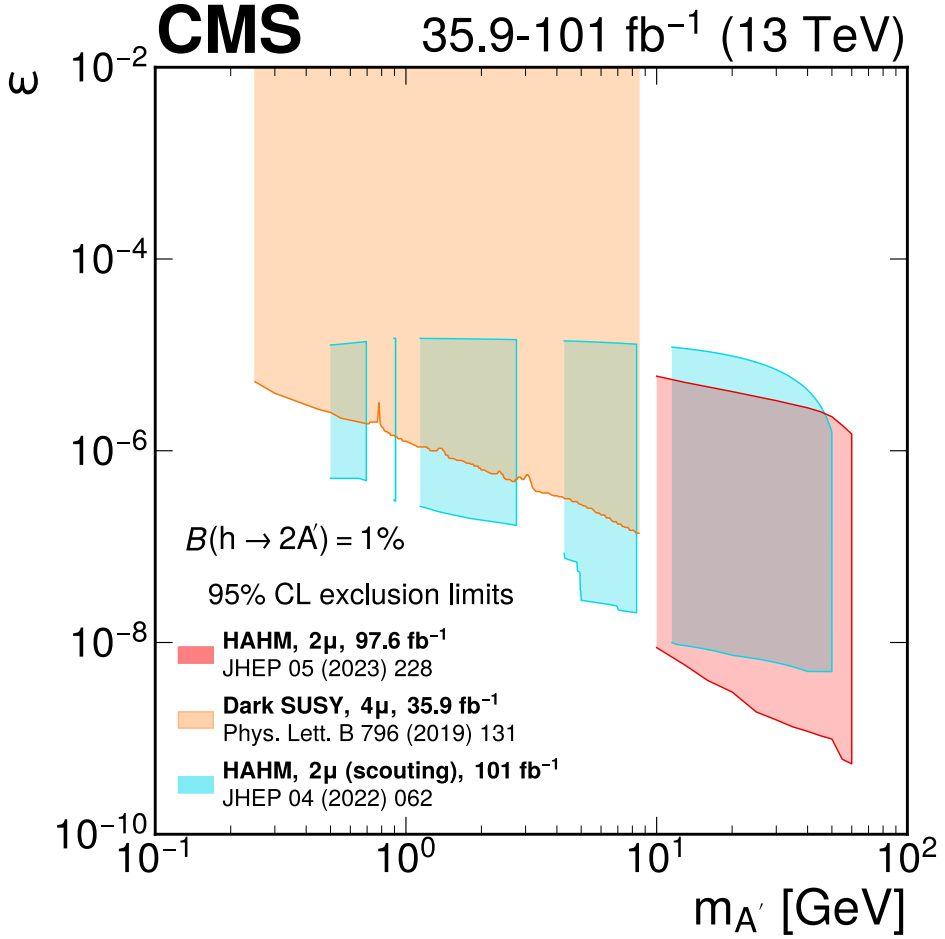


Dark SUSY and HAHM

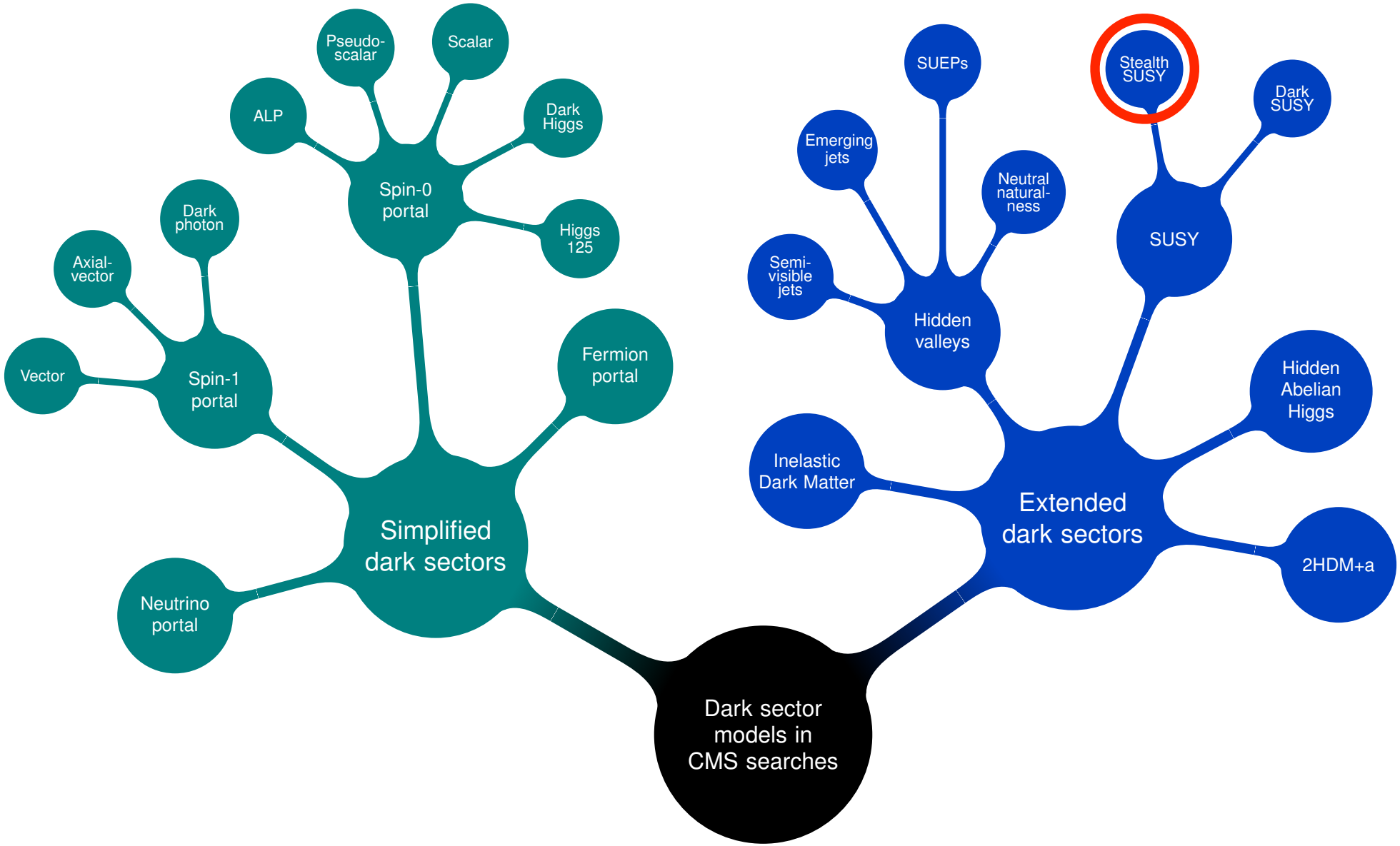


Dark SUSY and HAHM

- Summary plot for dark bosons, with LLP searches
- Includes searches involving displaced muons:
  - Displaced dimuons (EXO-21-006): HAHM
  - Displaced dimuons in scouting (EXO-20-014): HAHM
  - Displaced dimuons with 4mu (HIG-18-003): Dark SUSY model



Stealth SUSY

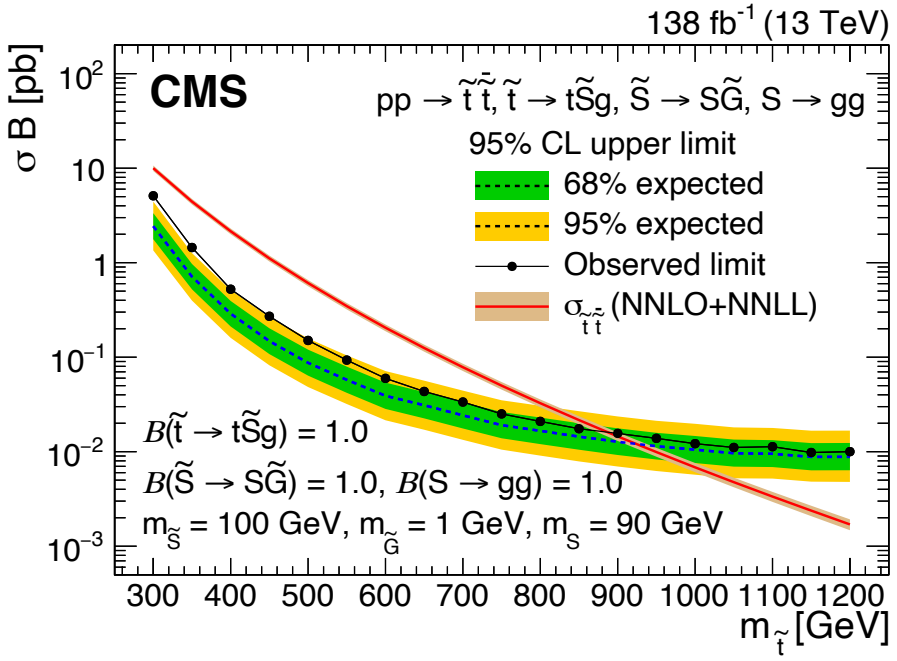


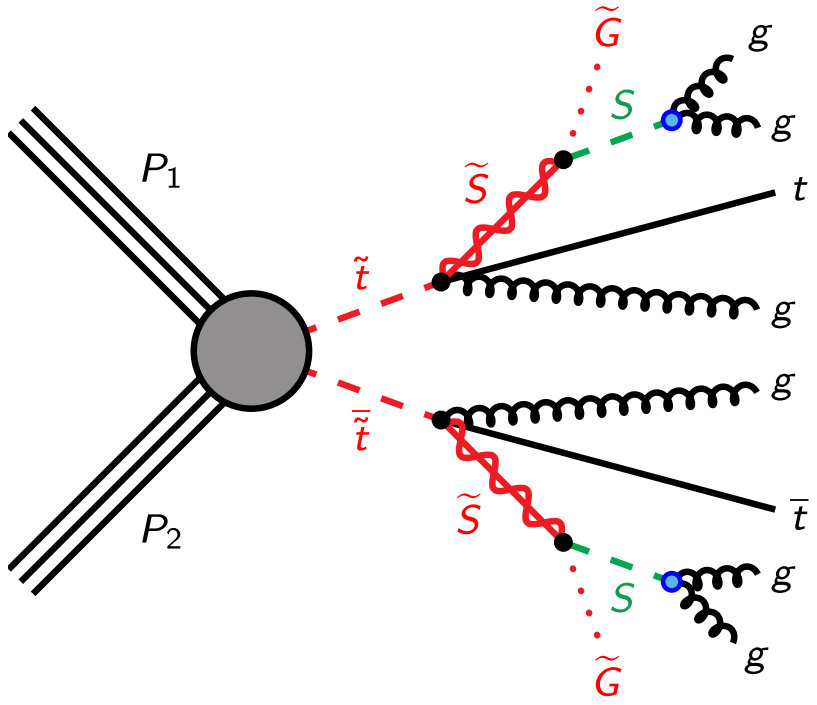
Stealth SUSY

- Stealth SUSY search originally optimized for vector portal (2t+6j)

Stealth SYY

(2t+6j)

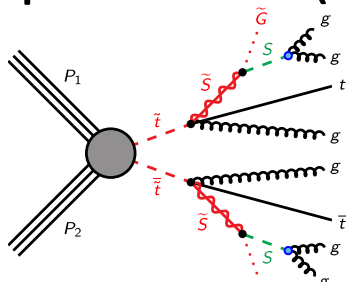


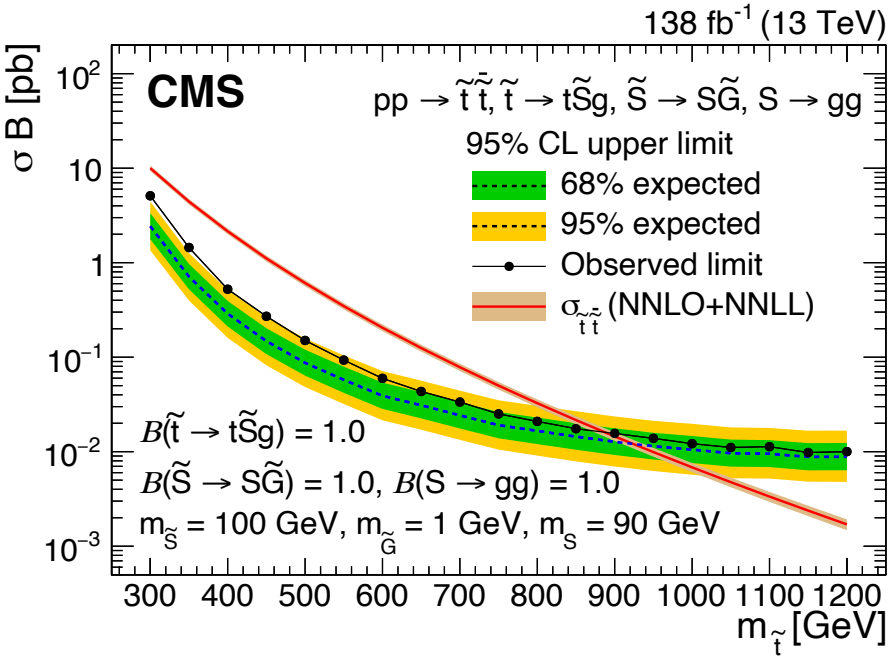


Stealth SUSY

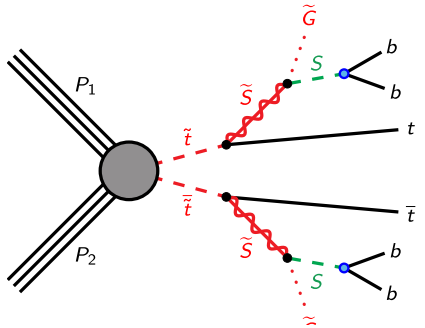
- Stealth SUSY search originally optimized for vector portal (2t+6j) but also sensitive to Higgs portal (2t+4b)
- Higgs portal reinterpretation (Stealth SHH) new for this paper

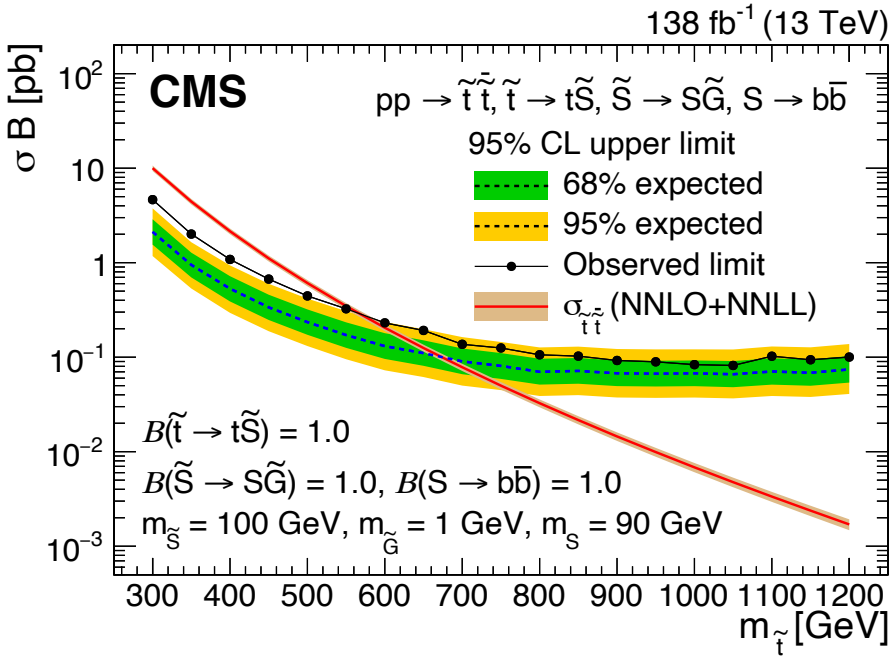
Stealth SYY (2t+6j)





Stealth SHH (2t+4b)

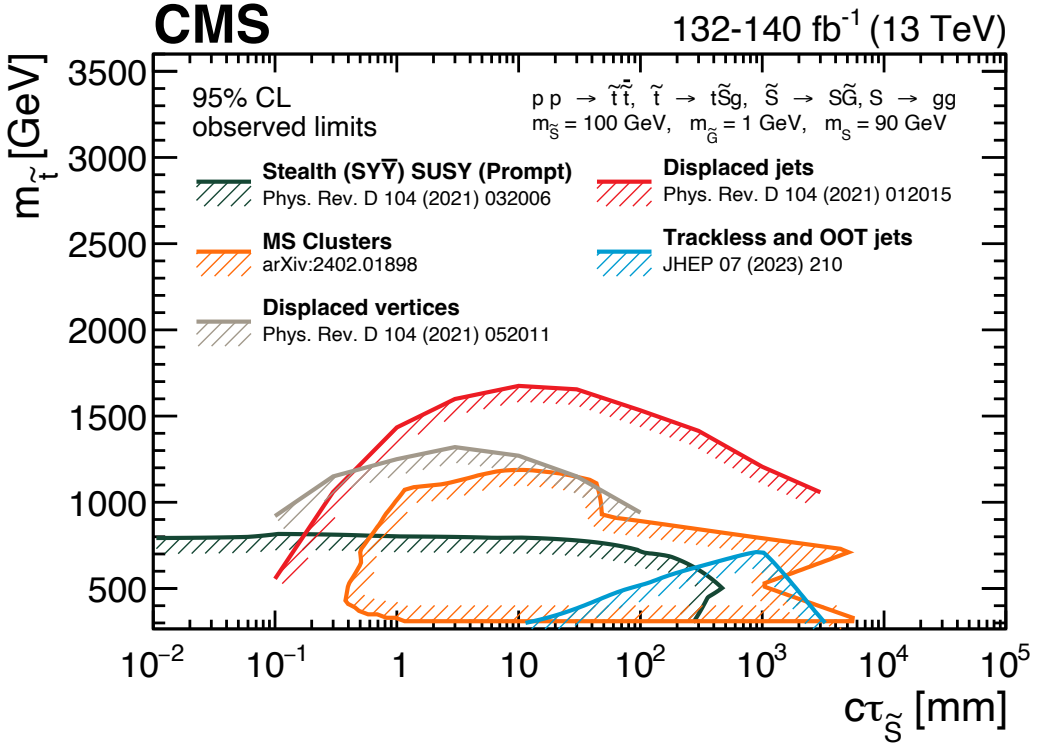




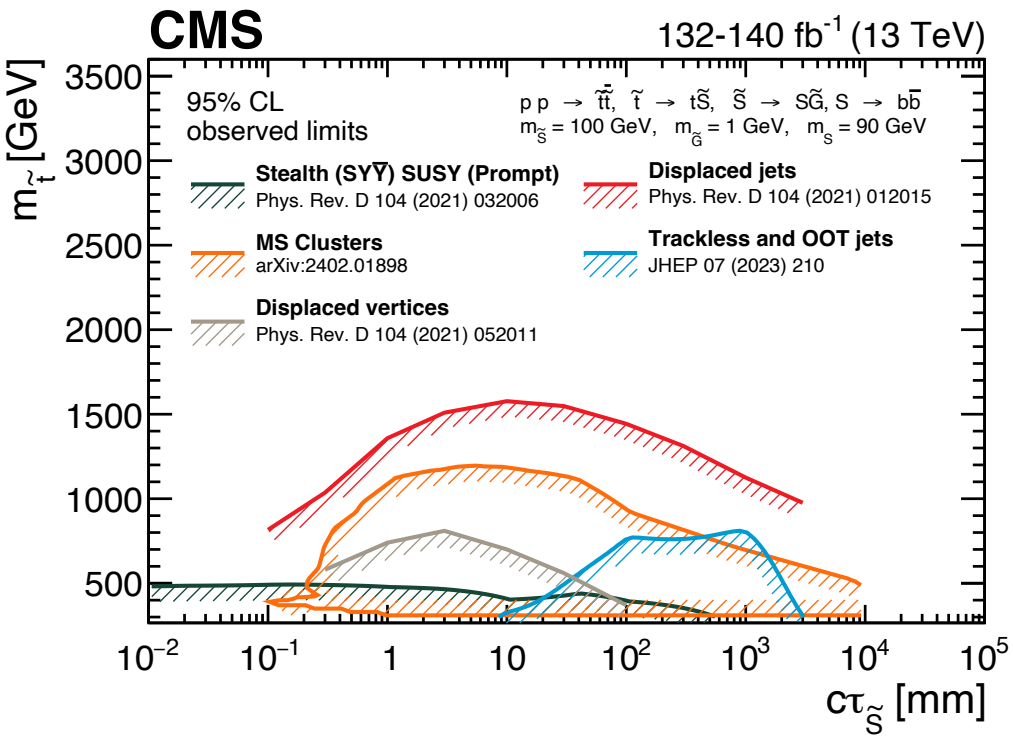
Stealth SUSY: LLP Reinterpretations

- Consider the case where singlino $\tilde{S}$ is long-lived
- Includes new reinterpretations of prompt stealth SUSY search and several LLP searches with hadronic decays
- $m_{\tilde{S}}$ **= 100 GeV**, $m_{\tilde{G}}$ = 1 GeV, m_S = 90 GeV

Stealth SYY (2t+6j)



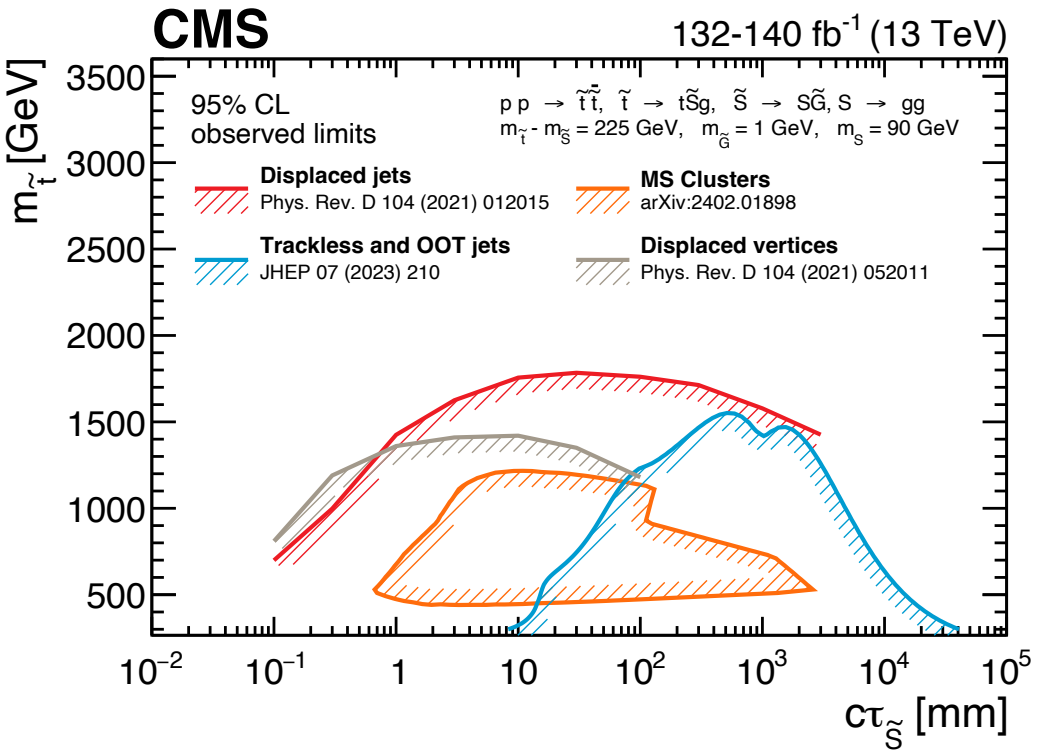
Stealth SHH (2t+4b)



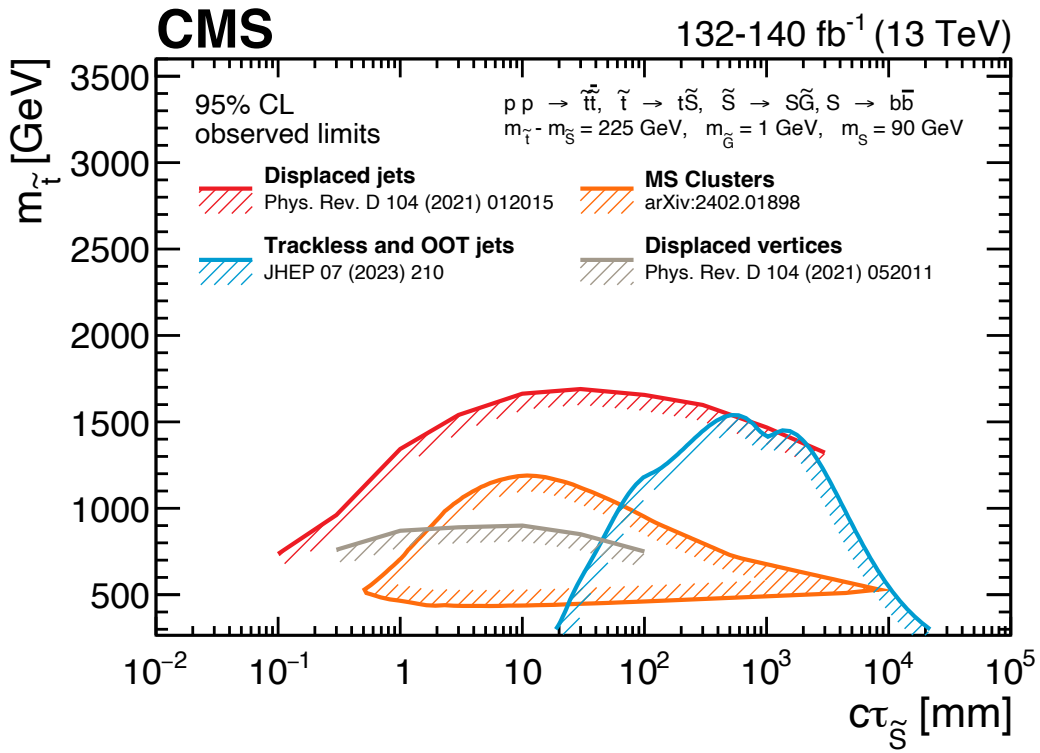
Stealth SUSY: LLP Reinterpretations

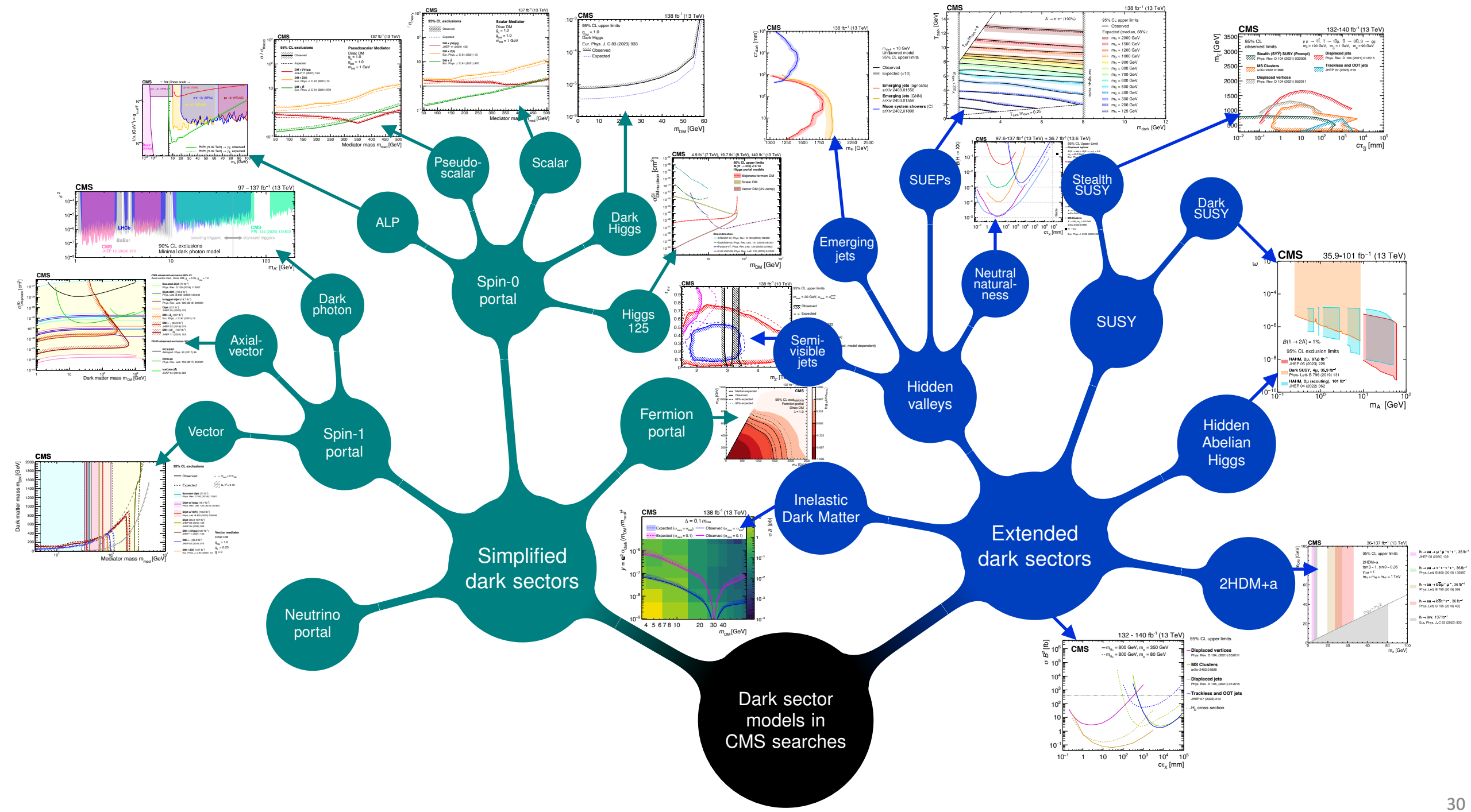
- Consider the case where singlino $\tilde{S}$ is long-lived
- Includes new reinterpretations of several LLP searches with hadronic decays
- $m_{\tilde{S}} - m_{\tilde{t}}$ **= 225 GeV**, $m_{\tilde{G}}$ = 1 GeV, m_S = 90 GeV

Stealth SYY (2t+6j)



Stealth SHH (2t+4b)



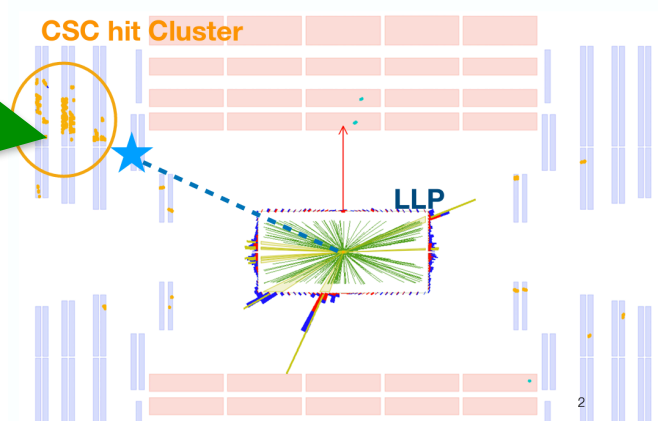

Dark sector models in CMS searches
Simplified dark sectors
Spin-0 portal
Pseudo-scalar
Scalar
ALP
Dark Higgs
Higgs 125
Spin-1 portal
Dark photon
Axial-vector
Vector
Fermion portal
Neutrino portal
Extended dark sectors
SUEPs
Emerging jets
Semi-visible jets
Hidden valleys
Neutral natural-ness
Stealth SUSY
Dark SUSY
SUSY
Hidden Abelian Higgs
2HDM+a
Inelastic Dark Matter

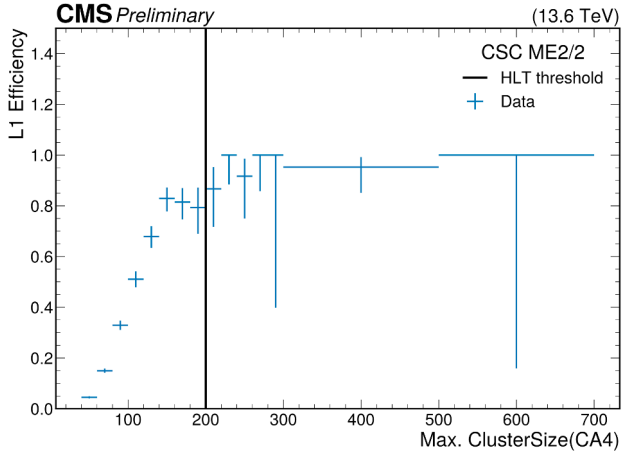
What’s next?

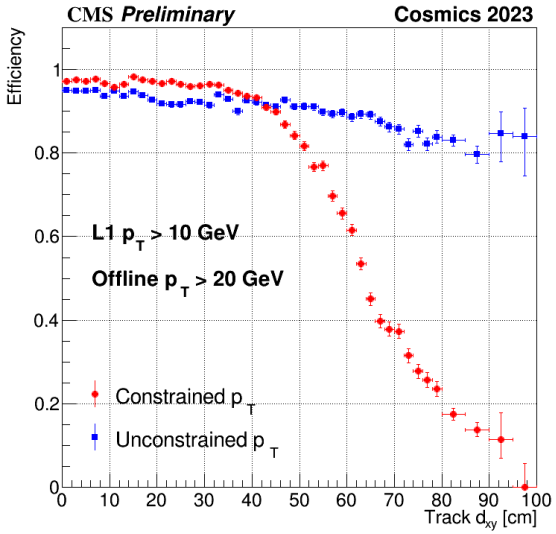
New LLP Triggers in CMS for Run 3

At both L1 (hardware) and HLT (software) levels

- New L1 & HLT triggers for **showers in the muon system**
- New triggers for **delayed jets:**
  - Using HCAL depth and timing (thanks to HCAL upgrade): L1 & HLT
  - Using ECAL timing: HLT
- New HLT triggers for **displaced taus**
- New L1 & HLT algorithms for **displaced muons**







CMS Phase 2 Upgrade & LLPs

Level 1 Trigger TDR

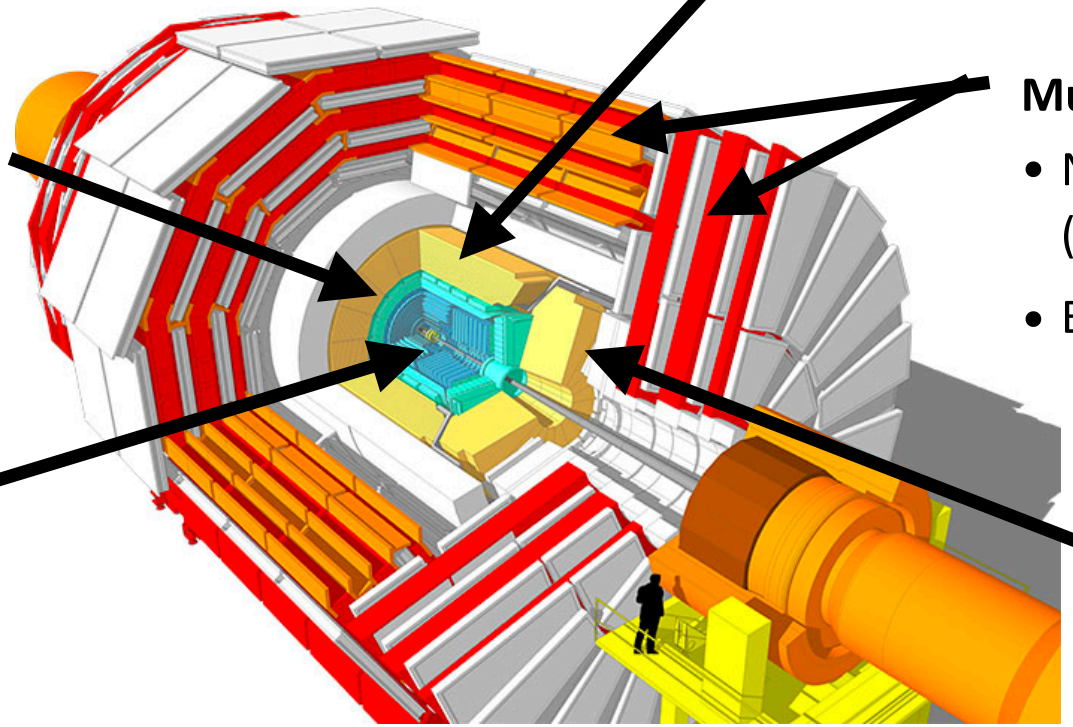
- New track trigger at 40 MHz
- 750 kHz L1 output
- 40 MHz data scouting (real time analysis)

DAQ & High Level Trigger (HLT) TDR

- Heterogeneous architecture
- 7.5 kHz HLT output

Barrel Calorimeter TDR

- ECAL crystal granularity readout at 40 MHz with precise timing for e/gamma at 30 GeV



New MIP timing detector (MTD) TDR

- 30 ps timing resolution

Muon System TDR

- New Gas Electron Multipliers (GEMs) & new iRPCs $1.6 < |\eta| < 2.4$
- Extended coverage to $|\eta| \sim 3$

Replaced Tracker TDR

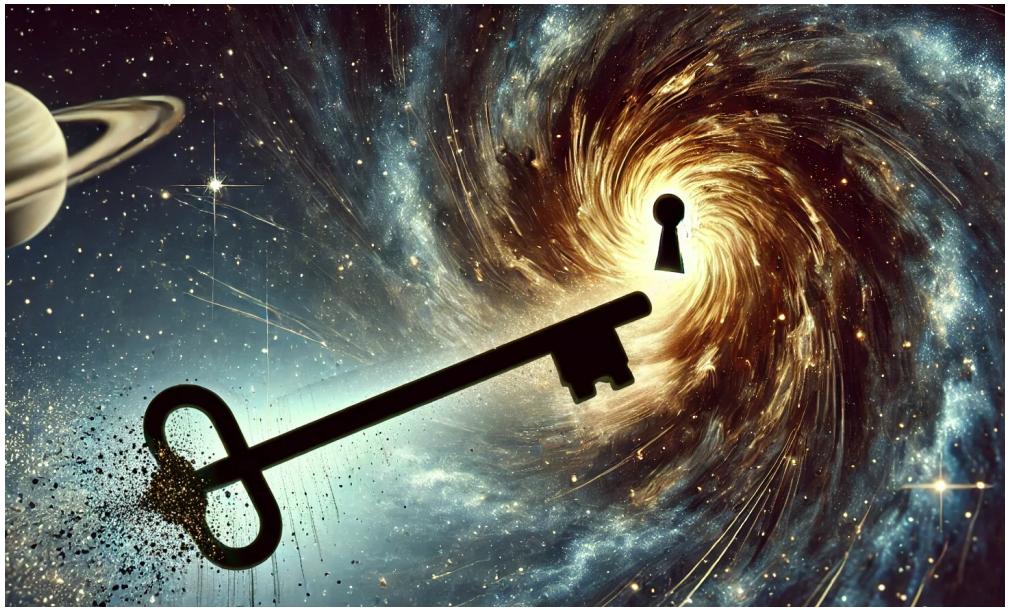
- Increased granularity
- Extended coverage to $|\eta| \sim 4$
- Designed for tracking in L1T

New High-Granularity Endcap Calorimeter (HGCAL) TDR

- Imaging calorimeter
- 3D showers and precise timing

Summary

- **Dark sectors paper reviews the impact of 40 CMS Run 2 analyses on the search for dark matter**
  - 16 LLP analyses with dark sector interpretations
- **Now public!**
  - arXiv 2405.13778, accepted by Phys. Rept.
  - CMS physics briefing for the public
- **Many new reinterpretations** for models with dark photons, 2HDM+a, semi visible jets, emerging jets, stealth SUSY, Higgs to LLP, Z' to LLP, dark Higgs to LLP
- **Long-lived particles:**
  - Appear in many dark sector models
  - Provide unconventional signatures
  - New triggers for Run 3 and new subdetectors at HL-LHC will increase our ability to look for LLPs
  - **A unique key to dark interactions**



Backup

Extended Dark Sectors

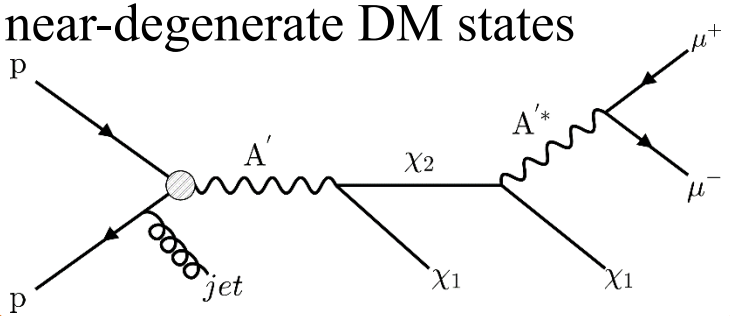
2HDM+a

- Benchmark values:

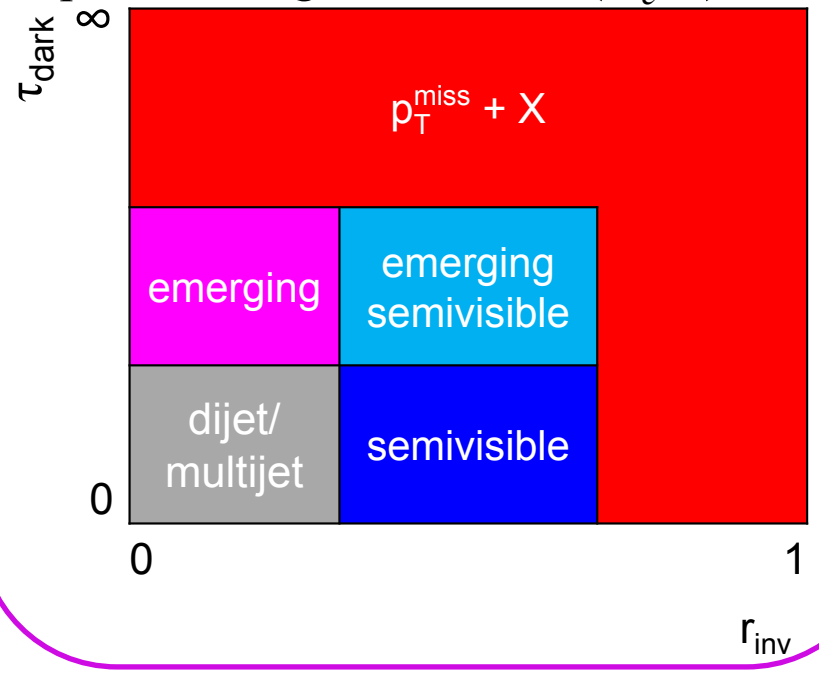
$$m_H = m_A = m_{H^\pm}, \quad m_\chi = 10\,\text{GeV},$$
$$\cos(\beta-\alpha) = 0, \quad \tan\beta = 1, \quad \sin\theta = 0.35,$$
$$\lambda_3 = \lambda_{P_1} = \lambda_{P_2} = 3, \quad y_\chi = 1.$$

- m_a floats; m_h, v fixed by SM

Inelastic DM: Multiple near-degenerate DM states



Hidden valleys (dark QCD): N_f^{dark} quarks charged under SU(N_c^{dark}) force



HAHM

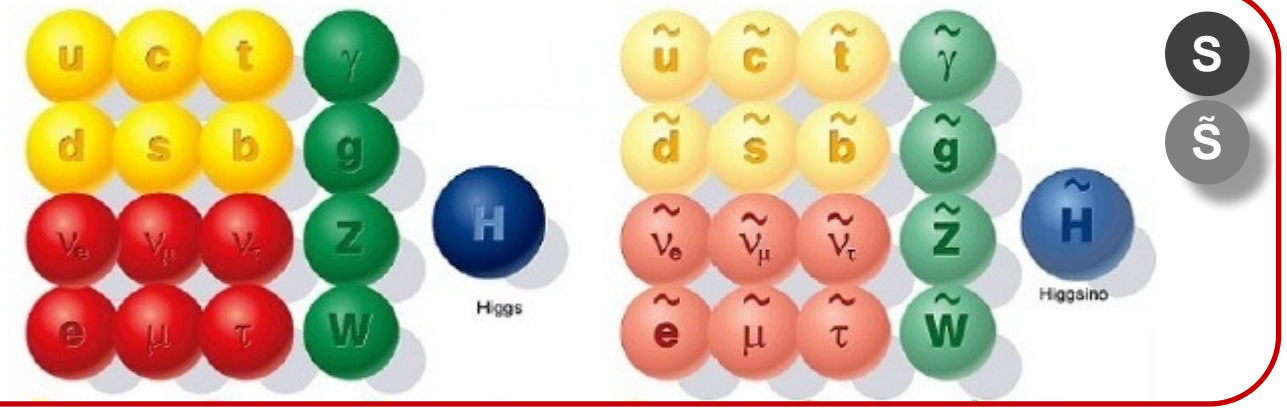
- Extra U(1) gauge group in addition to SM gauge
- Abelian hidden sector coupled to the SM
- Dark photons can be long-lived via the Higgs portal

Dark SUSY

- Hidden gauge $U(1)_D$ is broken near GeV scale, giving new dark vector bosons
- Dark photon can be prompt or long-lived, produce lepton-jets

Stealth SUSY:

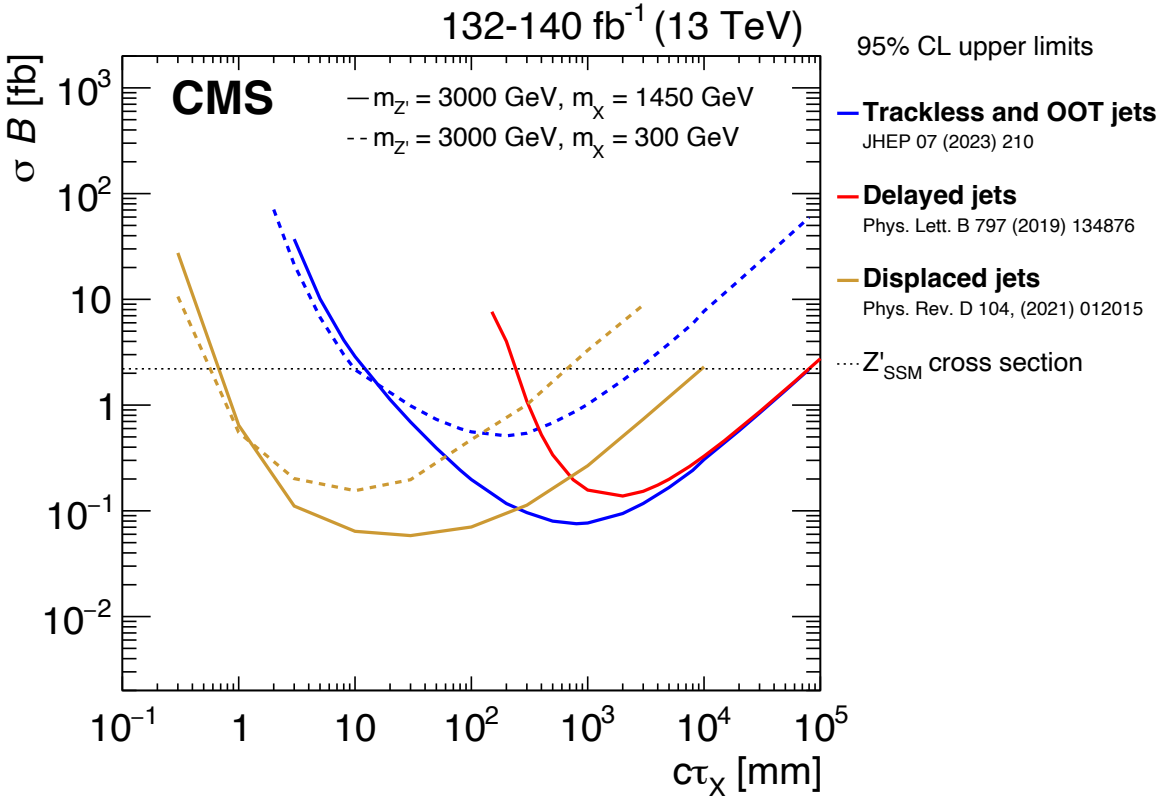
- Dark "stealth" sector w/ singlet & singlino
- DM particle: gravitino or axino, $m_{DM} \sim 1$ GeV



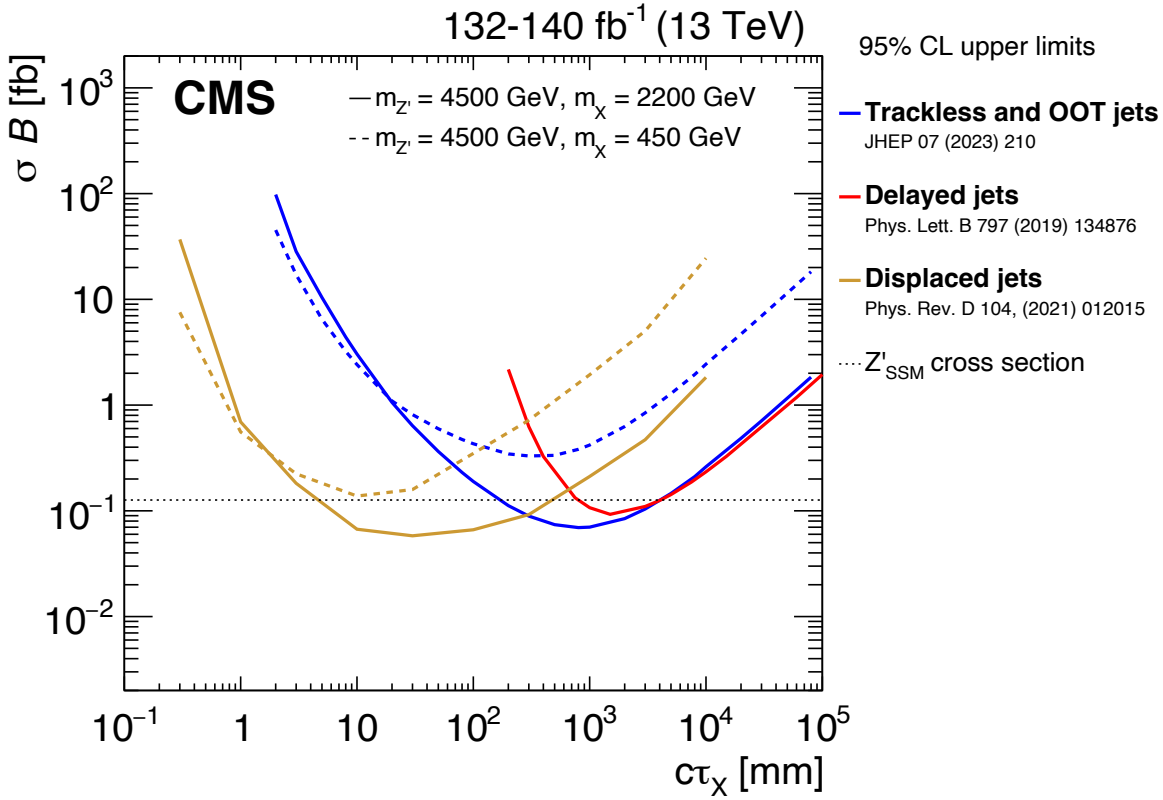
Z’ to LLPs to 2b+MET

- Reinterpretations of LLP searches with hadronic decays
- Heavy Z’ mediator, hadronic + p_T^{miss} final states
- Brand new reinterpretations for this paper

$m_{Z'}$ = 3000 GeV



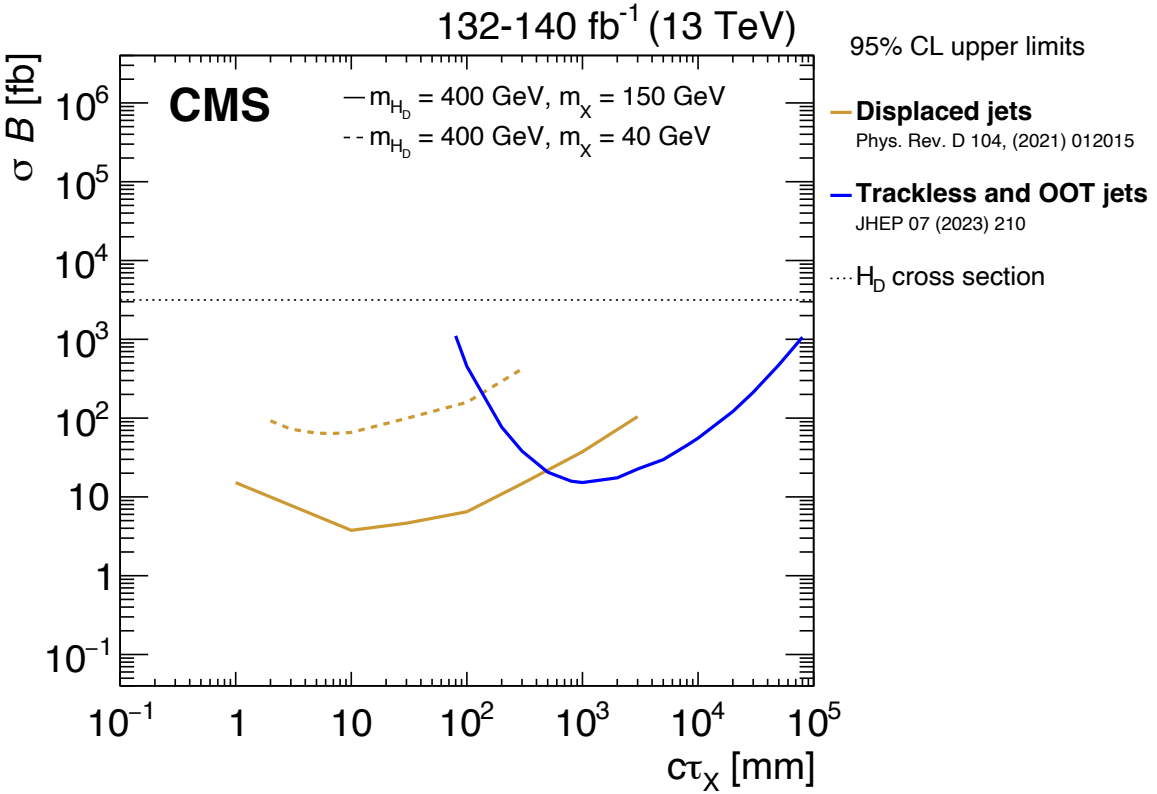
$m_{Z'}$ = 4500 GeV



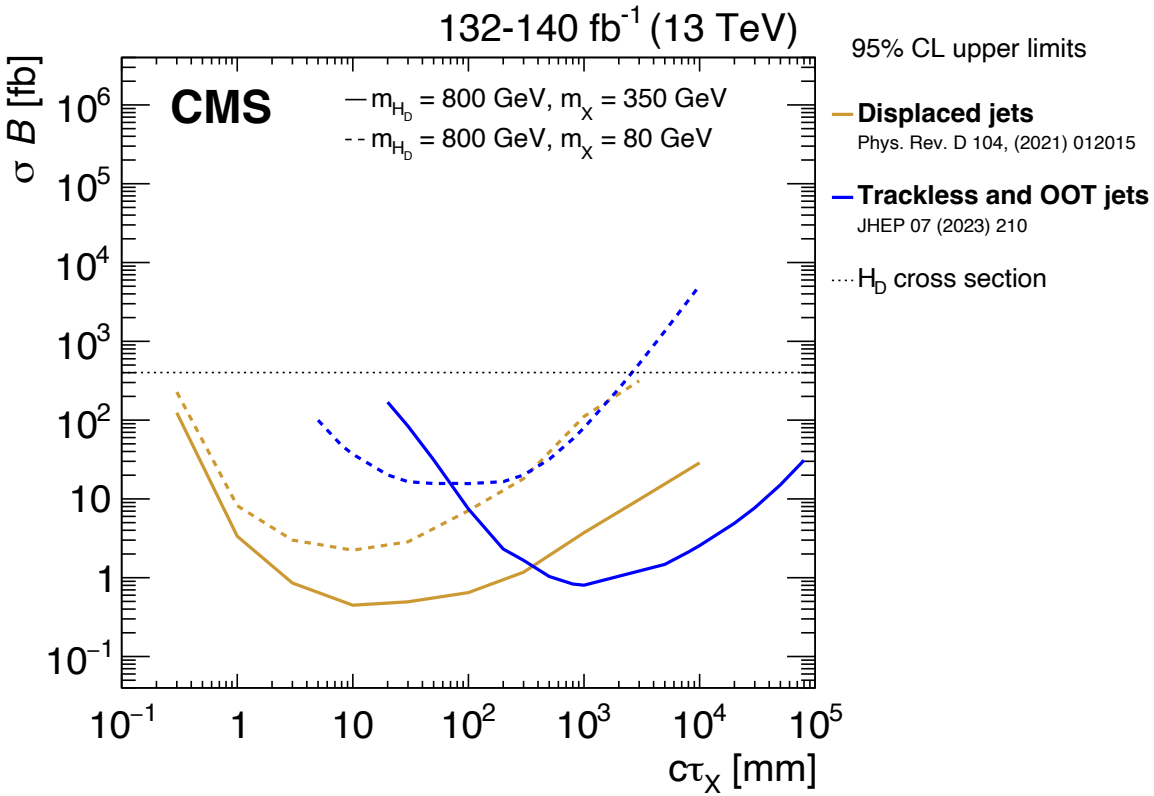
Dark Higgs to LLPs to 2b+MET

- Reinterpretations of LLP searches with hadronic decays
- Dark Higgs mediator, hadronic + p_T^{miss} final states
- Brand new reinterpretations for this paper

m_{HD} = 400 GeV



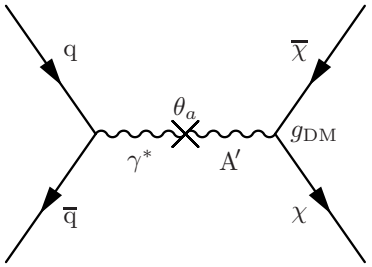
m_{HD} = 800 GeV



Simplified dark sectors

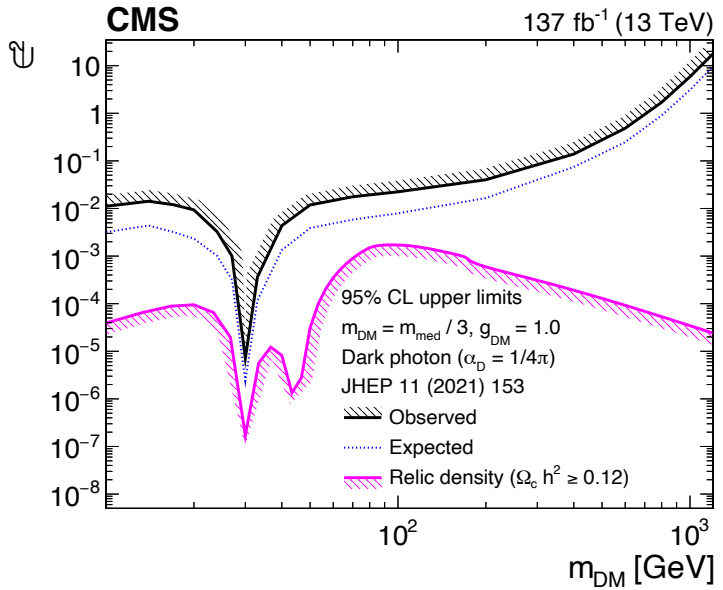
Spin 1

Dark Photons

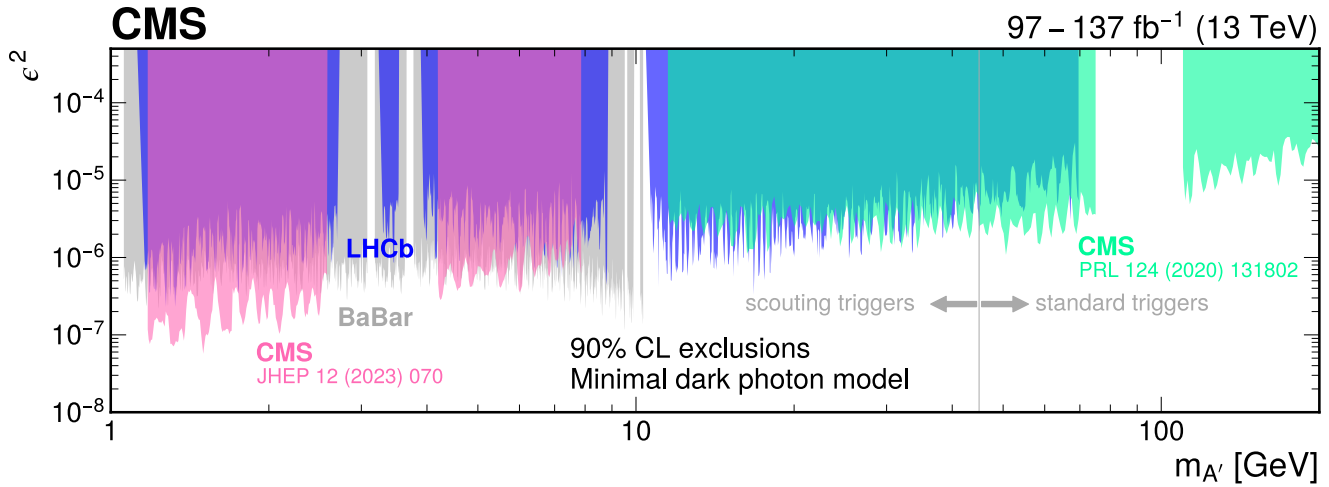


- Spin-1 mediator with pure vector coupling, mixes with SM photon and Z boson

- **Reinterpret monojet search (EXO-20-004) in dark photon model**
- Dark photon —> DM (invisible)
- Relic density constraints also shown
- Brand new reinterpretation for this paper



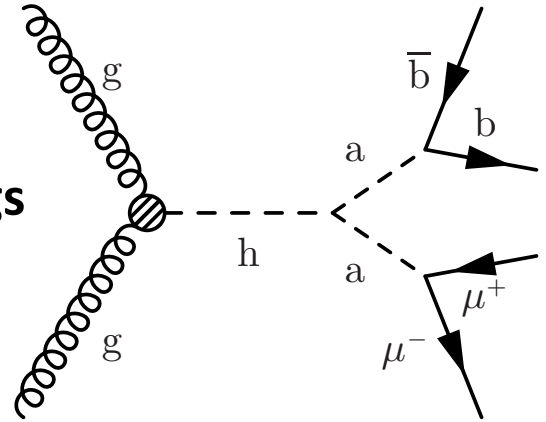
- **Summary plot in minimal dark photon model**
- Dark photon —> visible
- Includes two prompt dimuon analyses including scouting: EXO-21-005 and EXO-19-018

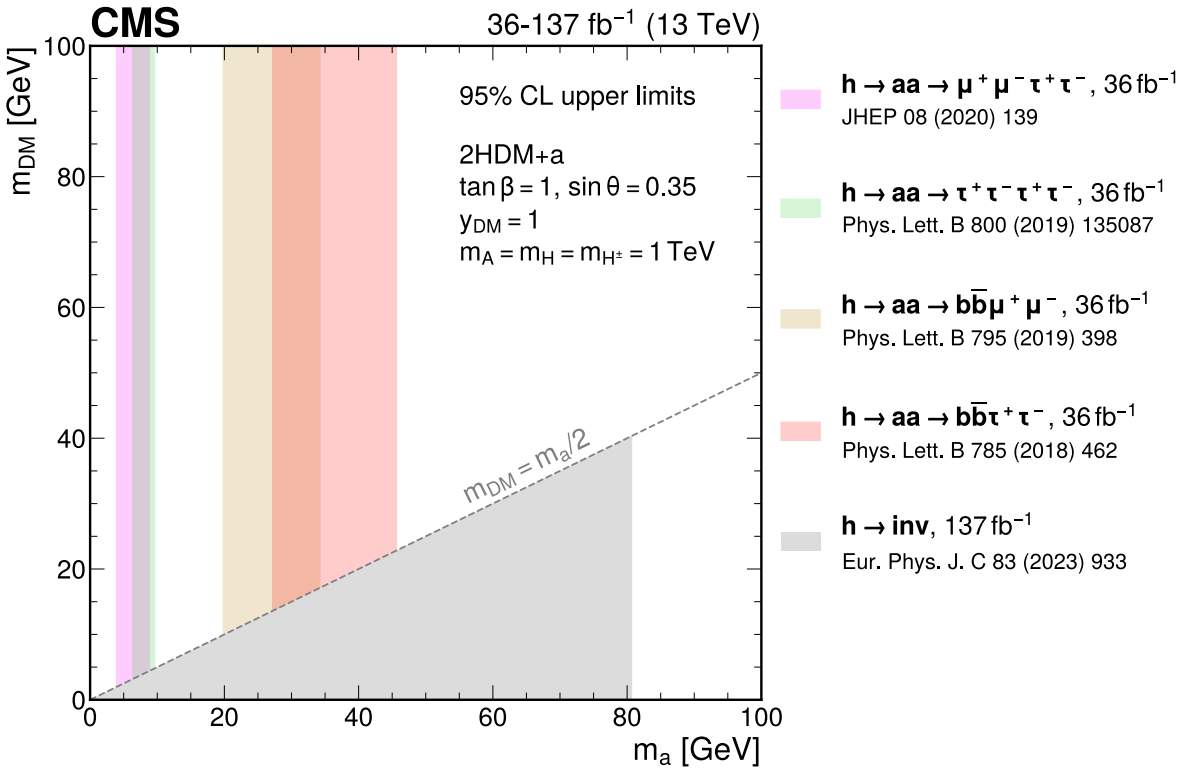


2HDM+a

- UV complete model
- Extension of two-Higgs-doublet models (2HDM): adds an additional pseudoscalar mediator (a)

- One example:
- **Exotic decays of SM Higgs**





- Includes h→aa and h→inv searches
- If a → $\chi\chi$ kinematically allowed, h→inv is most stringent
- Otherwise, visible decays of h are most stringent