Long-lived Particles at the LHC

Todd Adams
Florida State University

MoEDAL

FASER

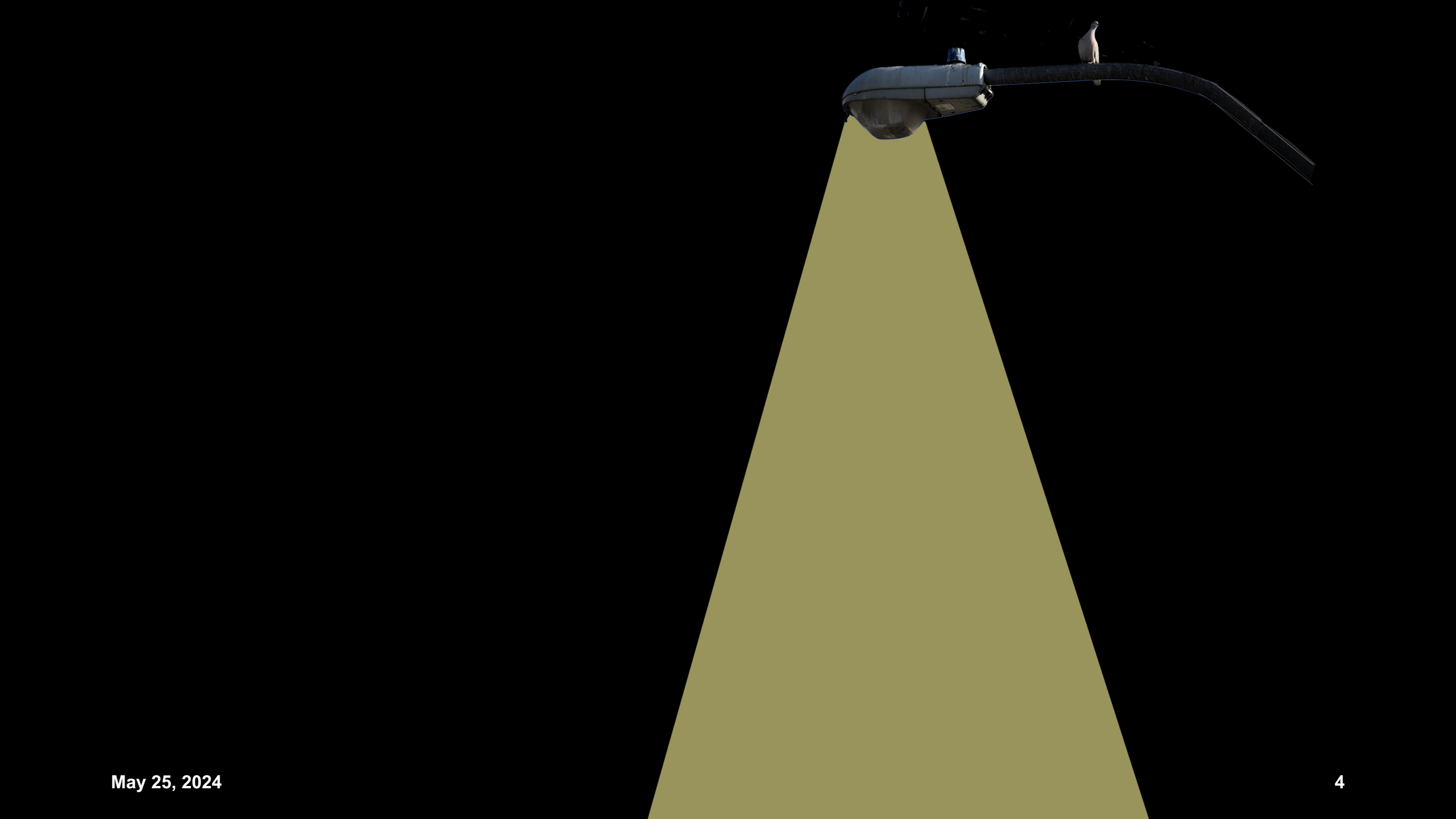
Collider, Dark Matter, and Neutrino Physics 2024

May 25, 2024

Why search for long-lived particles at the LHC?

Why search for long-lived particles at the LHC?

Because we can!



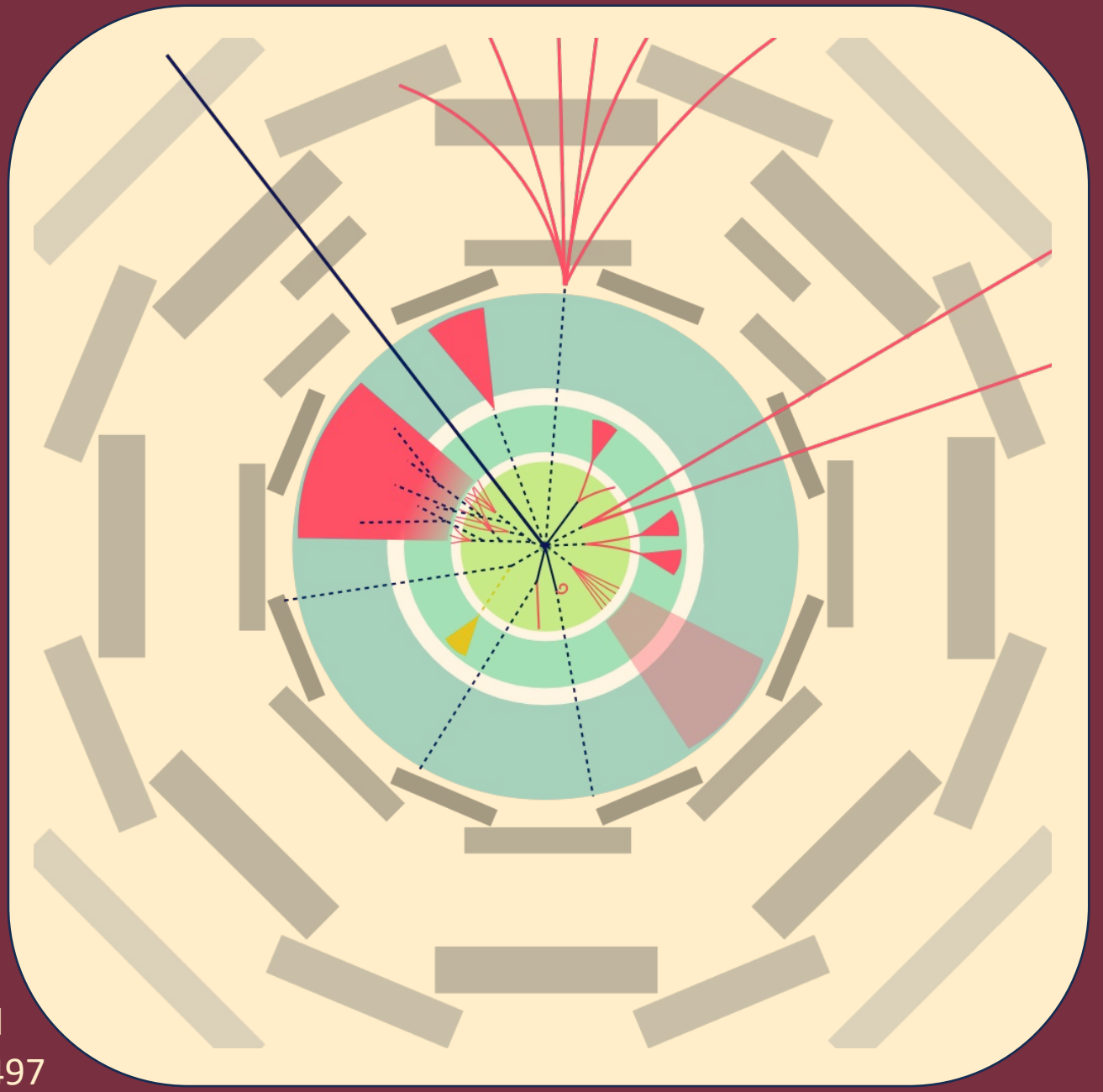
Many reasons to "expect" long-lived particles

- Standard model has lots of long-lived particles
  - muons, charged pions, kaons, neutrons, lambdas , b-hadrons
- Several mechanisms
  - small mass splittings → long lifetime: ex. n → p e- nu
  - small couplings → long lifetime
  - hidden valleys/dark sectors

- Earlier searches may have missed BSM LLPs

Rich LHC program

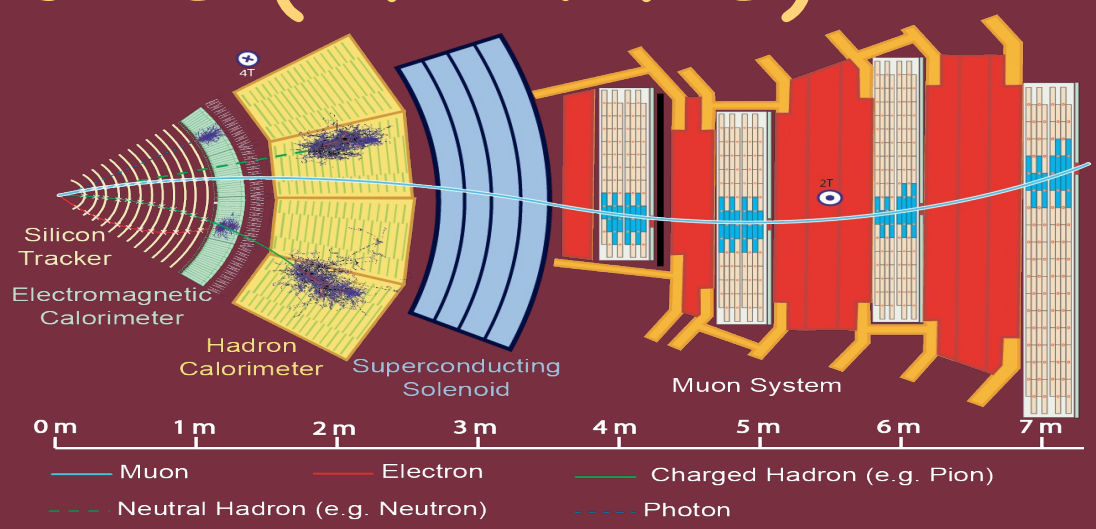
- Example searches
  - displaced vertices
  - late arriving particles
  - highly ionizing
  - non-pointing photons/jets
  - displaced jets
  - …

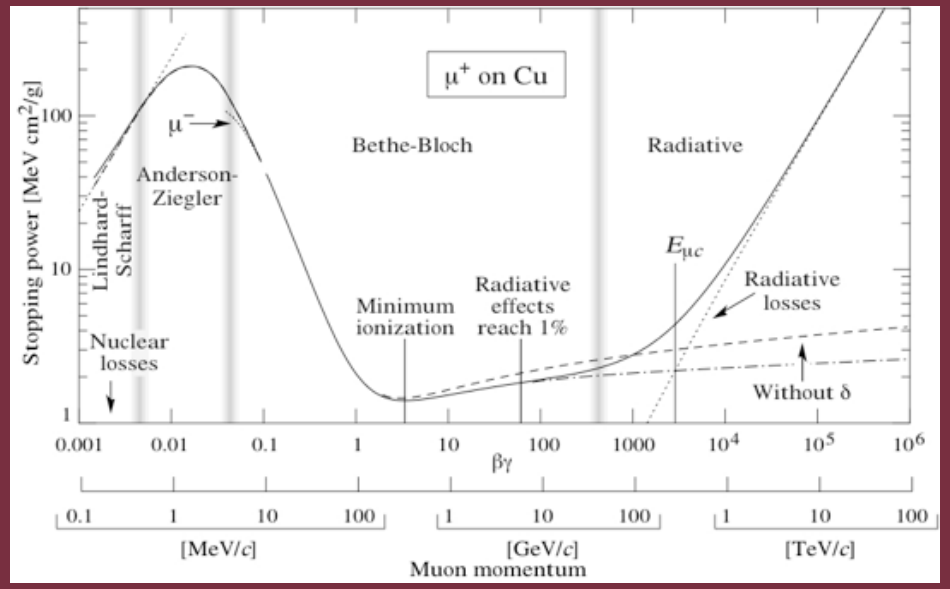


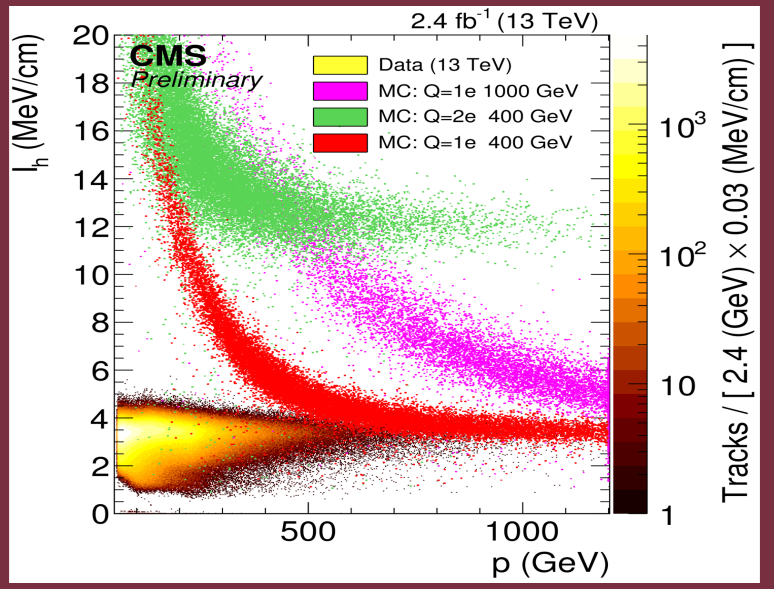
Heather Russell
[hep-ex] 1903.04497

CHArged Massive Particles (CHAMPs)

- Key – SLOW-MOVING
  - longer time-of-flight + highly ionizing
- Interpretations
  - lepton-like
  - hadron-like
  - lifetime
  - Z′





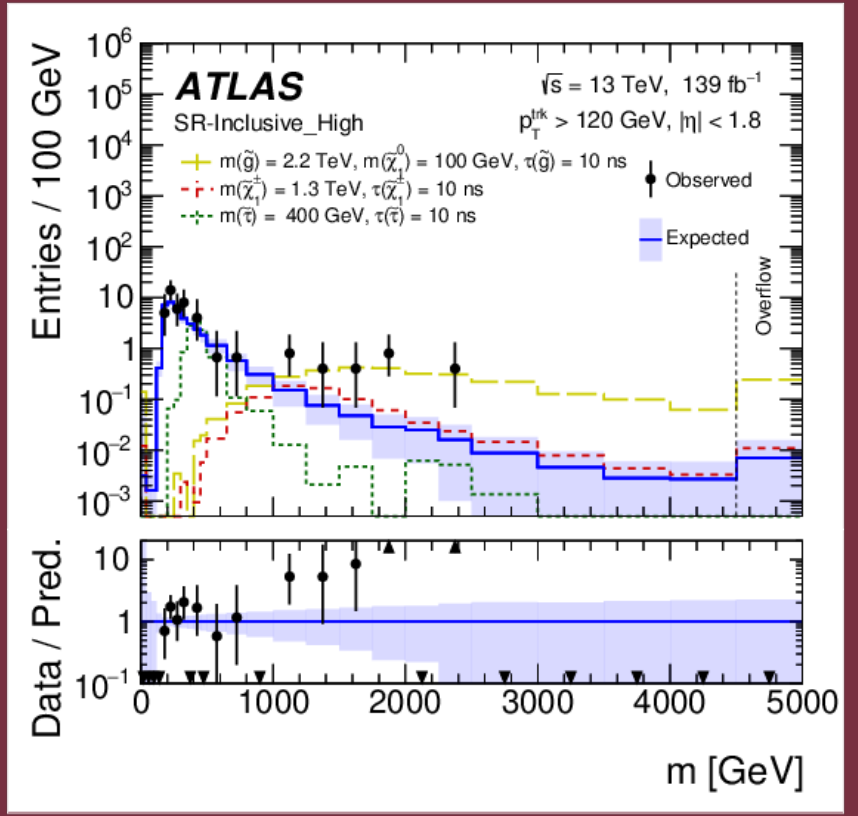


Previous ATLAS Result

Published: **JHEP 06 (2023) 158**

- Search based on large dE/dx in pixel detection
- Reconstruct mass based on dE/dx and p
- Excess in high-dE/dx + high mass (m>1 TeV)
- Observed 7 events at high mass
- Expected 0.7 ± 0.4 events
- 3.6σ(3.3σ) local(global) excess of events
- Directly measured time-of-flight is generally consistent with $\beta = 1$

???



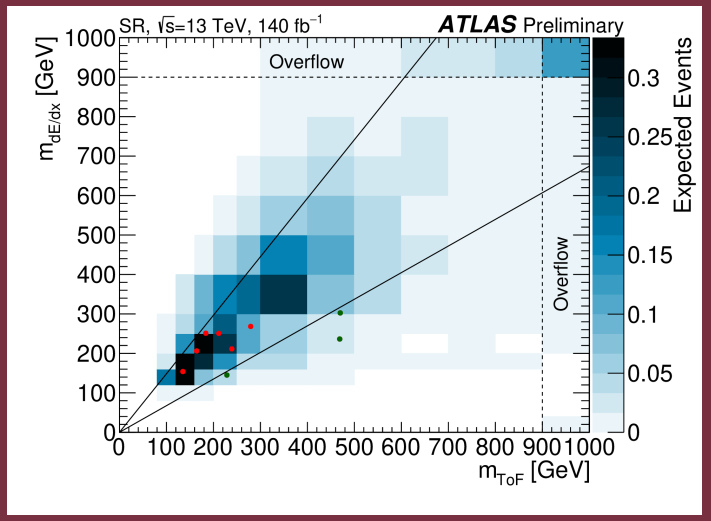
New ATLAS CHAMPs Result

ATLAS-CONF-2023-044

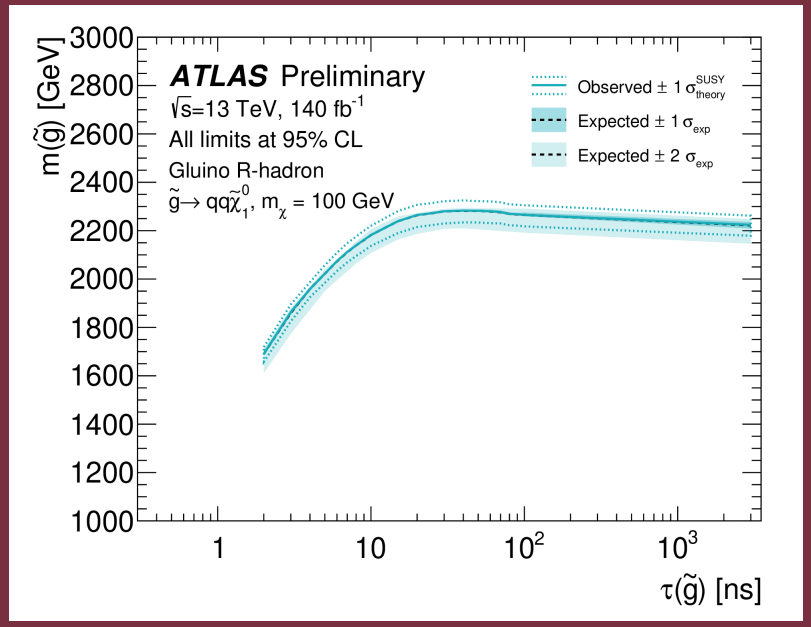
- Determine $\beta\gamma$ two ways
  - dE/dx in silicon pixel detector
  - time-of-flight to hadron calorimeter
- Use $\beta\gamma$ to calculate two masses
- Interpretation in terms of lifetime

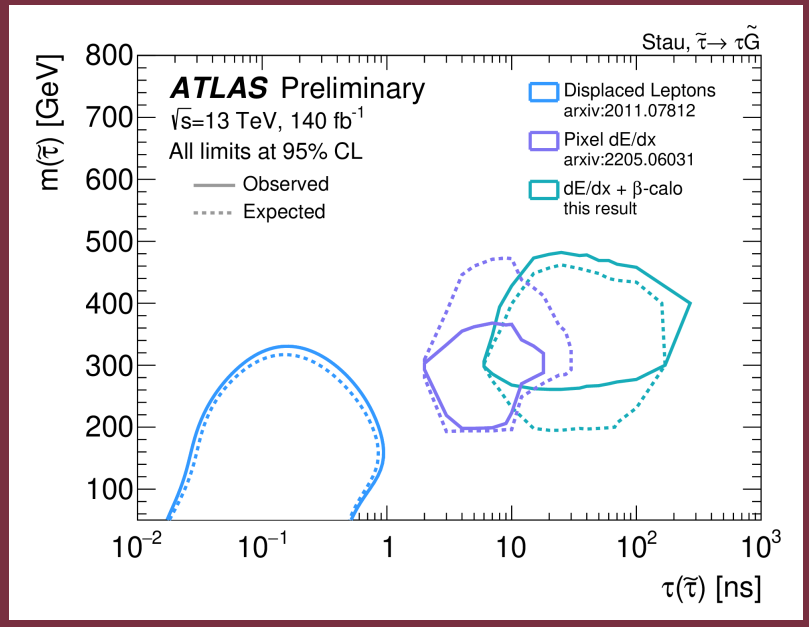
Observed: 6 events

3.7 +/- 0.4 expected



Inconsistent with previous excess being from slow-moving CHAMPs

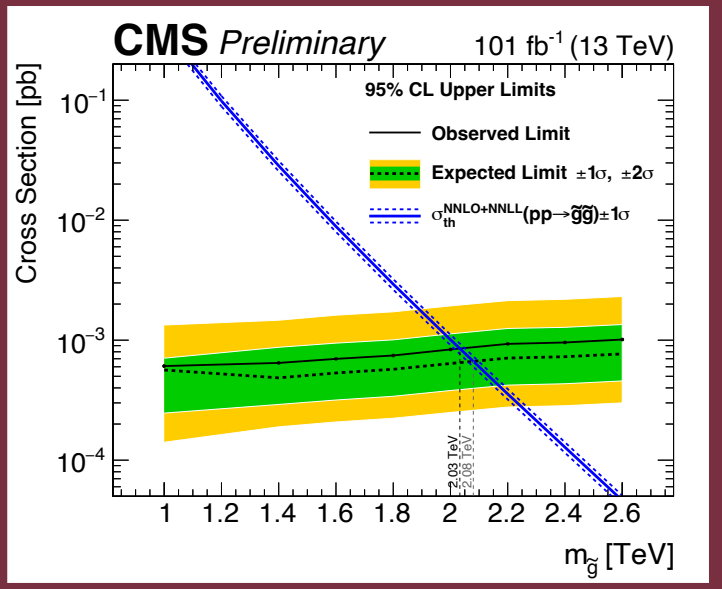


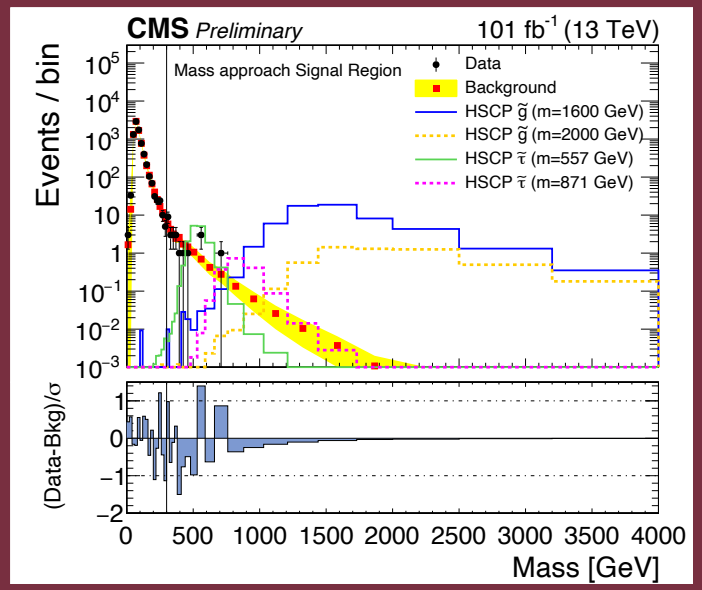


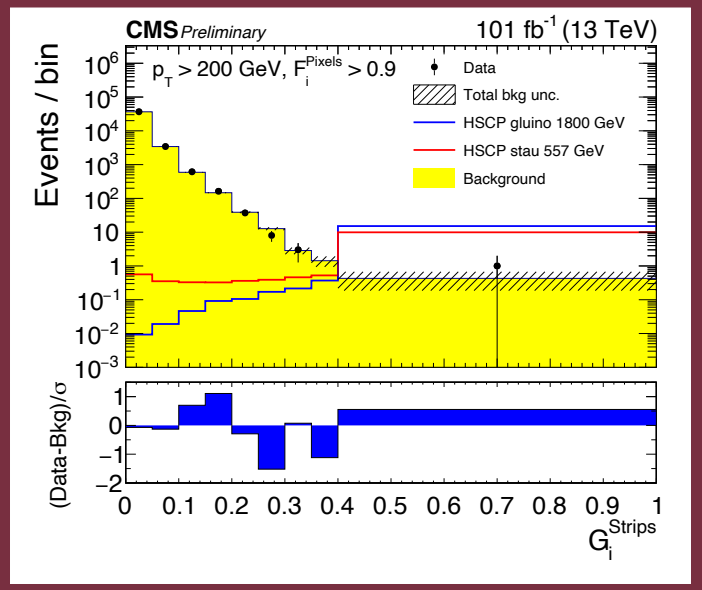
CMS CHAMPs Result

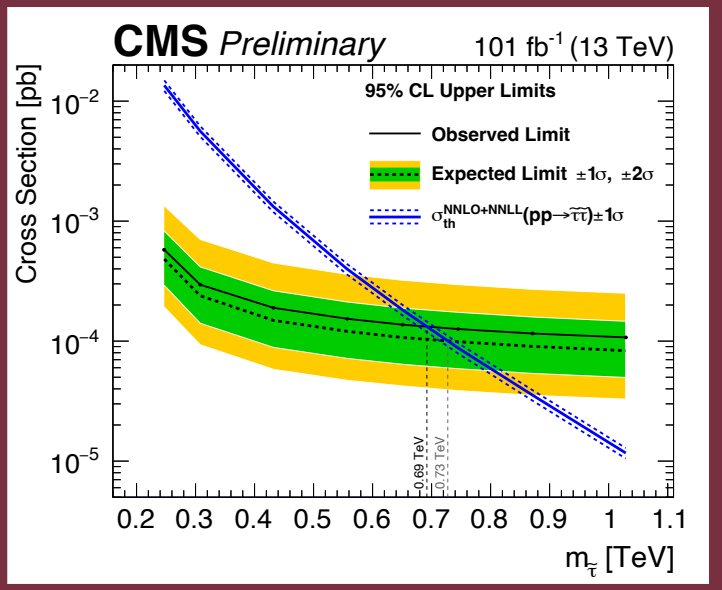
- Two analyses:
  - pixel dE/dx vs. strip dE/dx
  - mass calculation
- No excess observed in either analysis
- Assume "stable"

CMS-PAS-EXO-18-002





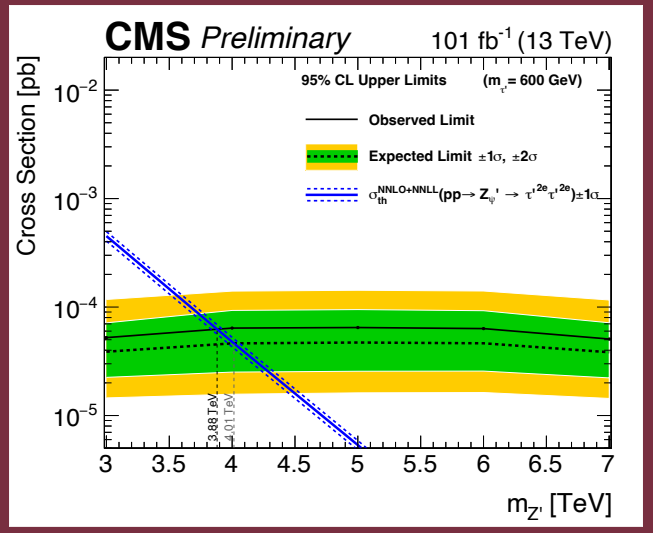


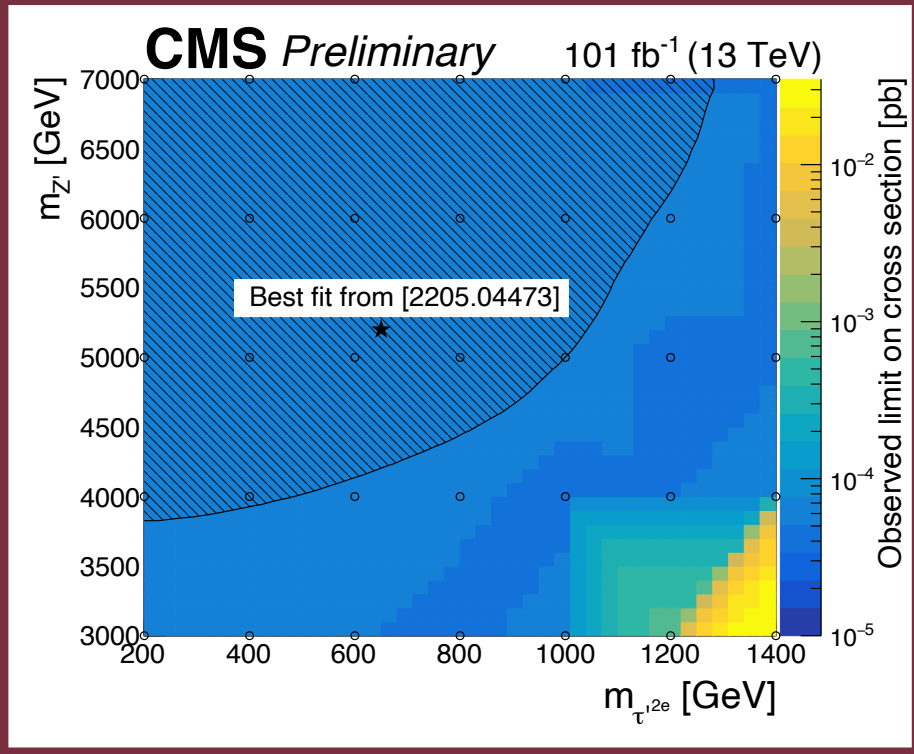


New Interpretation

CMS-PAS-EXO-18-002

- Giudice, G.F., McCullough, M. & Teresi, D., dE/dx from boosted long-lived particles. JHEP 2022, 12 (2022). [link]
  - Suggested previous ATLAS excess could be explained by *fast-moving, multiply charged* particles
    - large dE/dx with beta ~ 1
- $Z' \rightarrow X^{++}X^{--}$ ("stable" X)

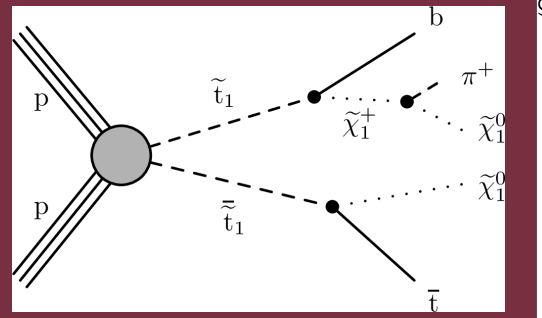


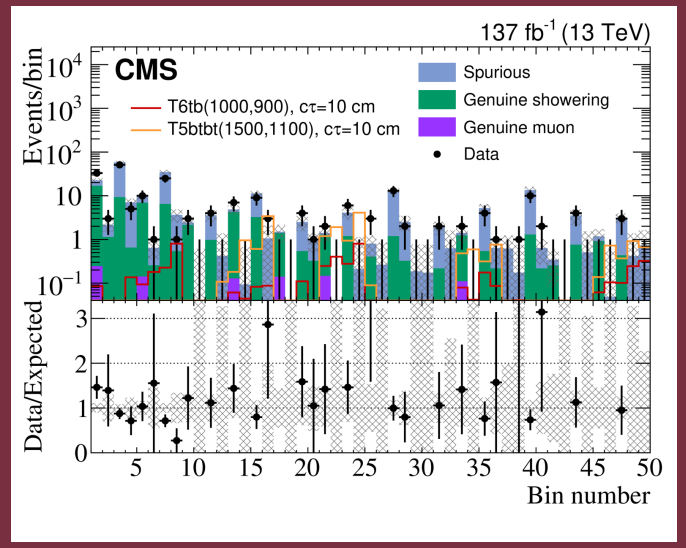


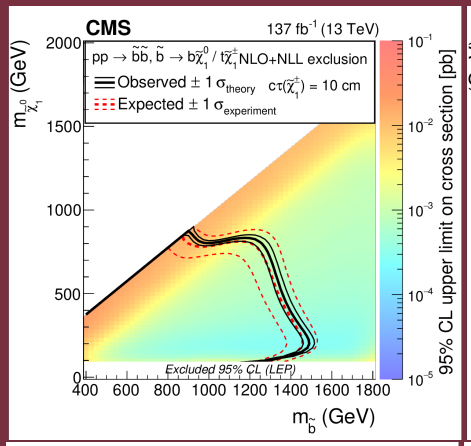
Disappearing Tracks

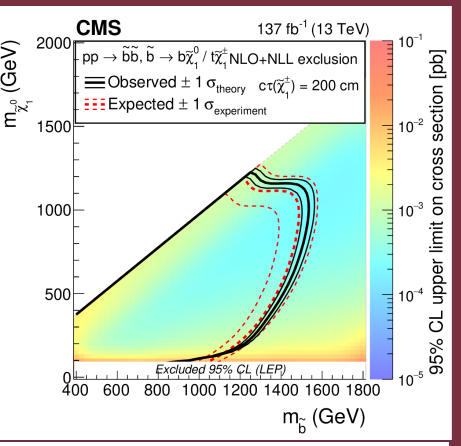
[hep-ex] 2309.16829
CMS

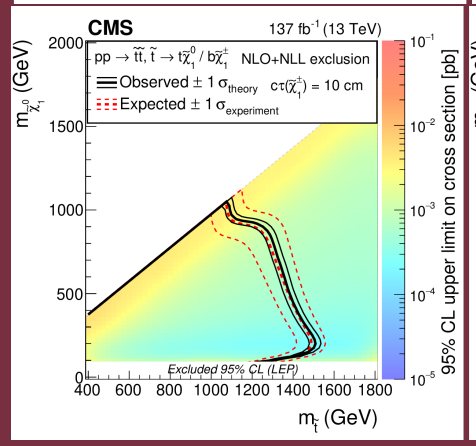
- Similar to CHAMPs search, but look for decay
- Charged track "disappears"
- Use high dE/dx
- Divide into 50 regions
- No excess observed
- Future work needed to combine "stable" and "disappearing" analyses
  - ATLAS already allows both together

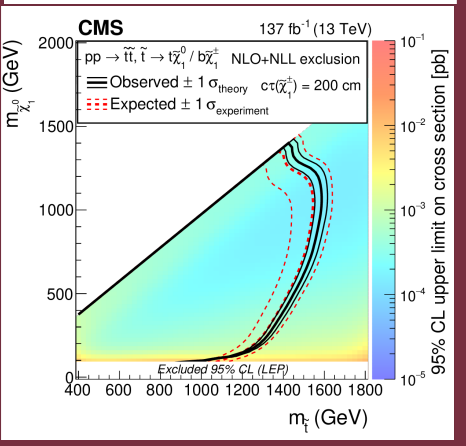




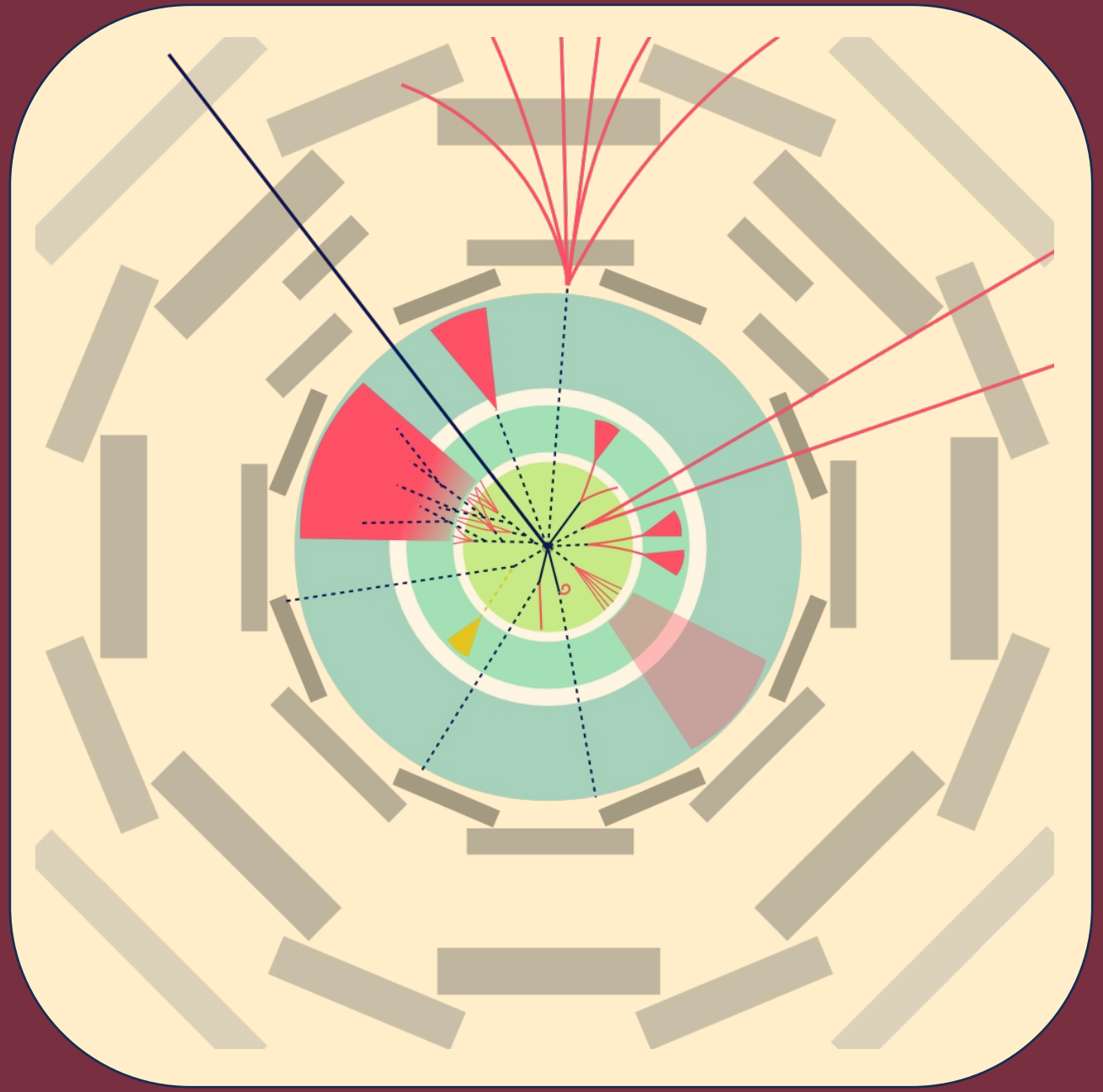








Now consider neutral particles decaying in flight

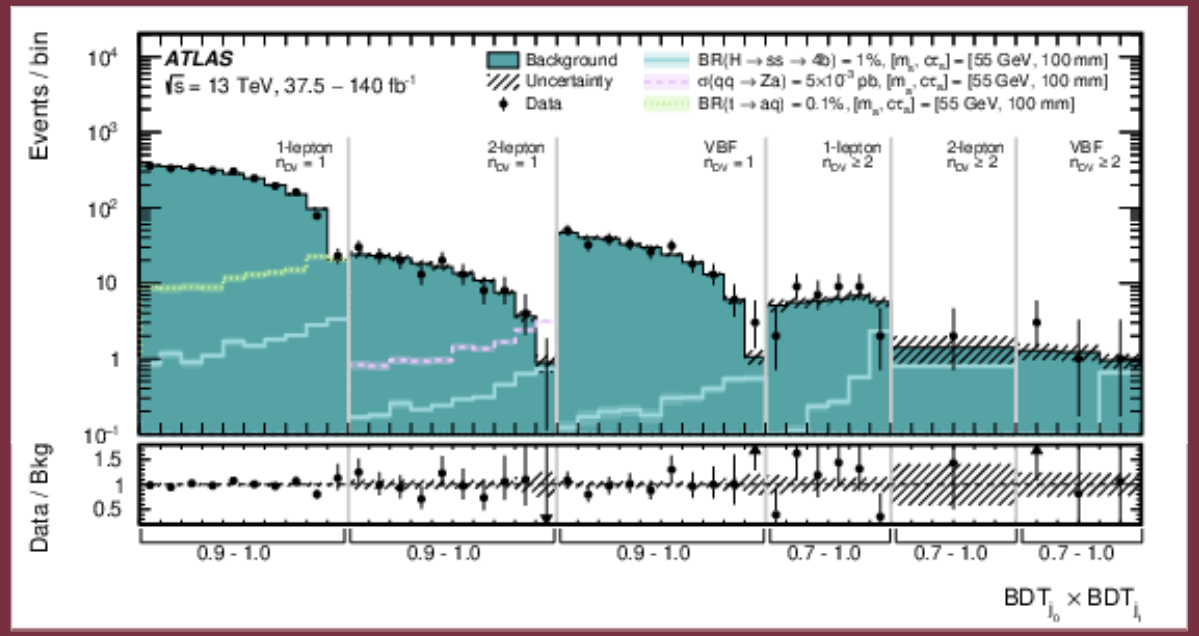


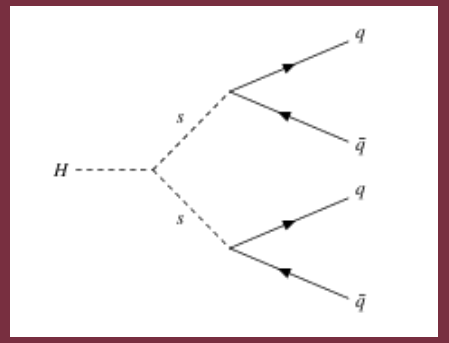
Light, long-lived particles

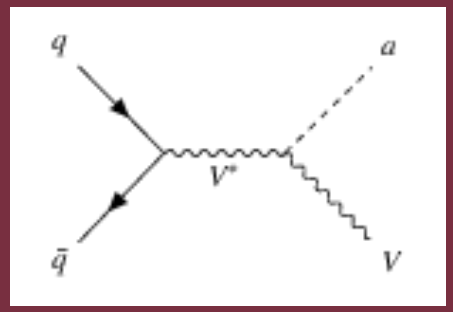
[hep-ex] 2403.15332

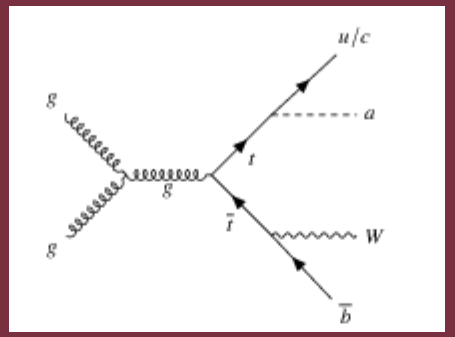
ATLAS

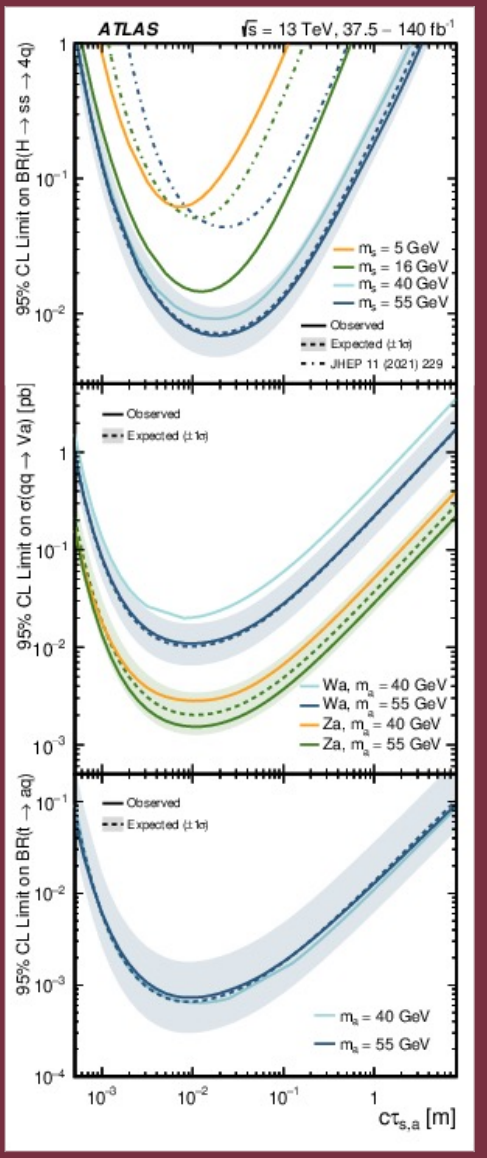
- light particles decaying to hadrons
- boosted decision tree (≥2 displaced jets)
- six signal regions







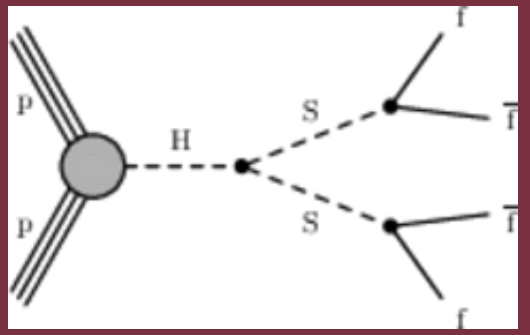


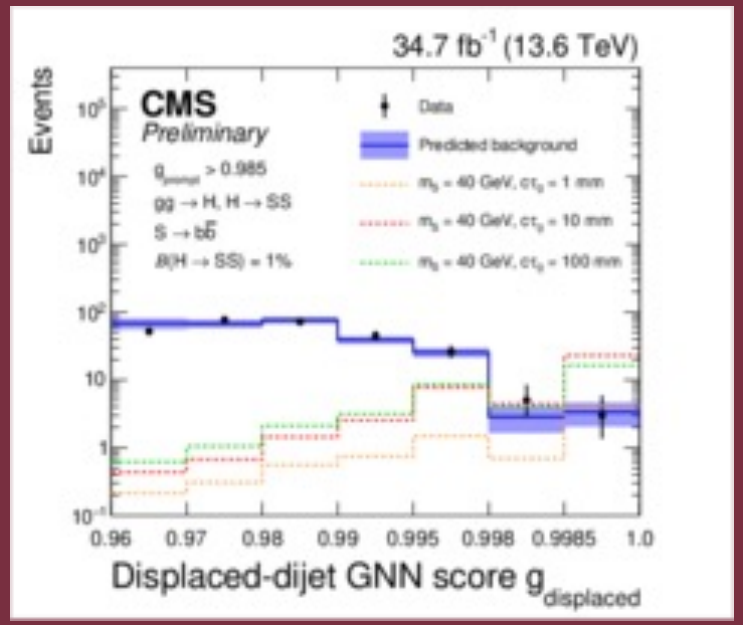


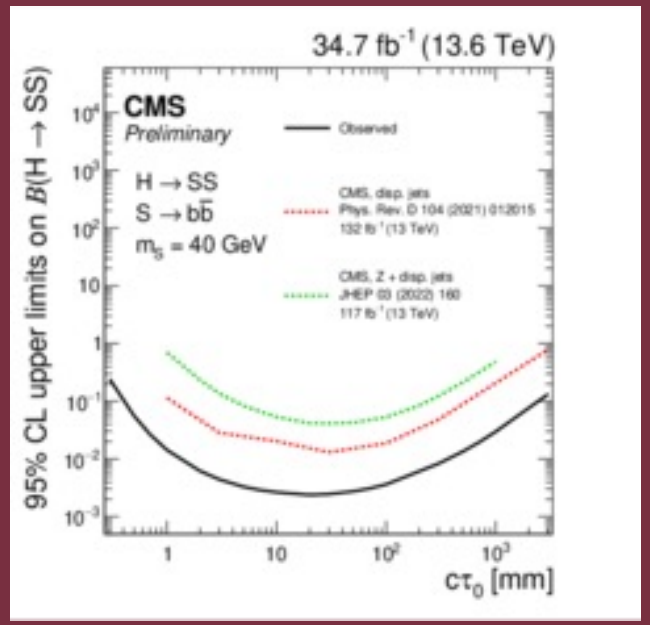
Light, long-lived particles (II)

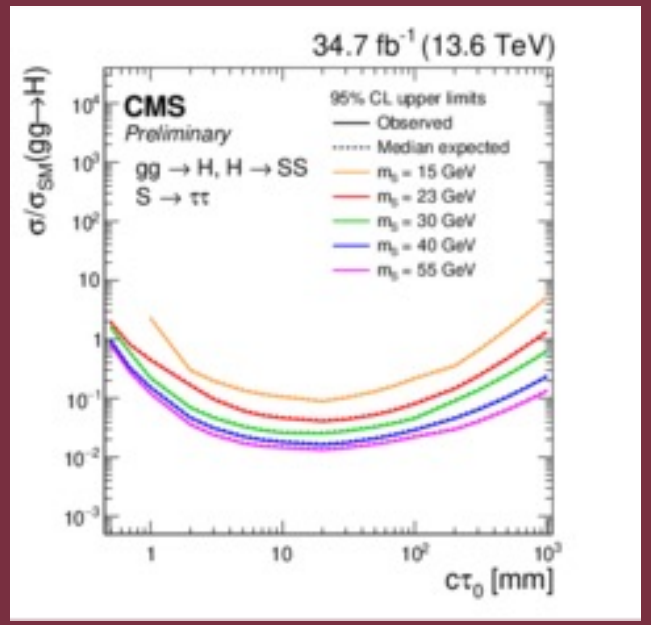
CMS-PAS-EXO-23-013
CMS

- Light particle (S) decaying to (displaced) jets or taus
- No excess
- First tracker-based displaced tau result
- S→bb limits outperform previous CMS results







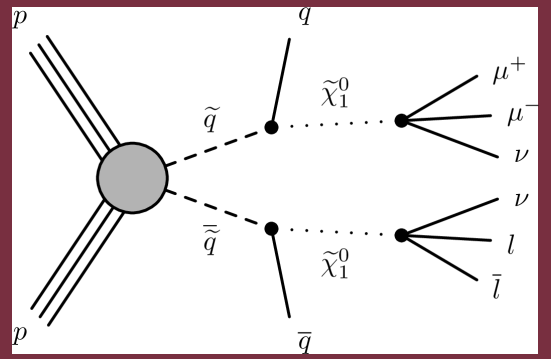


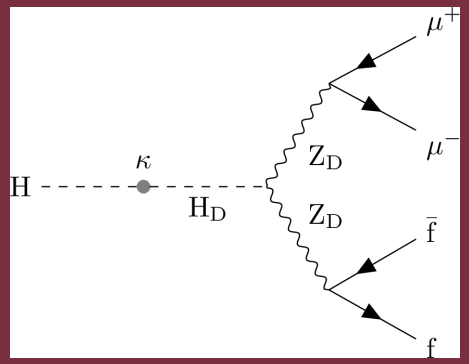
Run 3 analysis

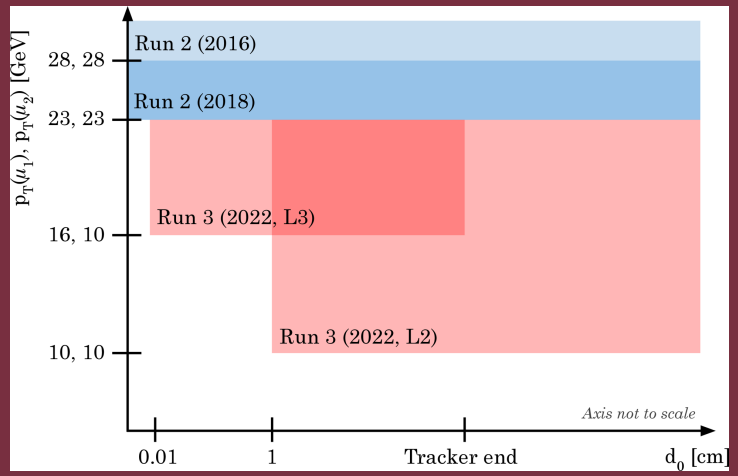
LLPs → two muons

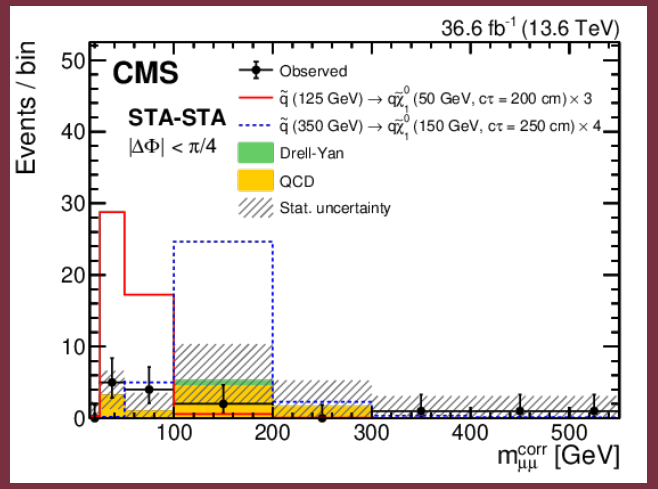
[hep-ex] 2402.14491
CMS

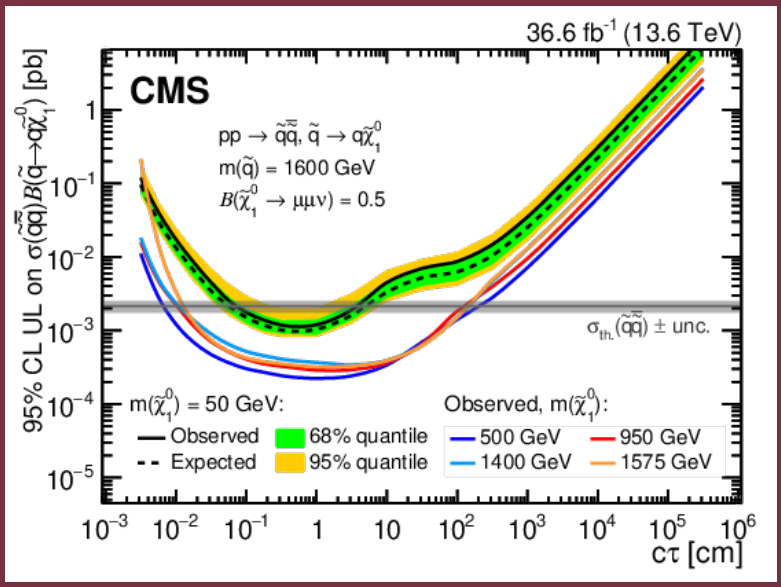
- ≥1 displaced muon with pT > 10 GeV
- New trigger developed for Run 3
- Multiple signal regions
- Smaller dataset outperforms previous result due to improved trigger







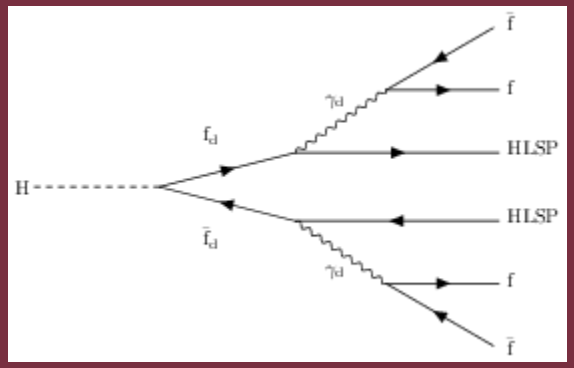




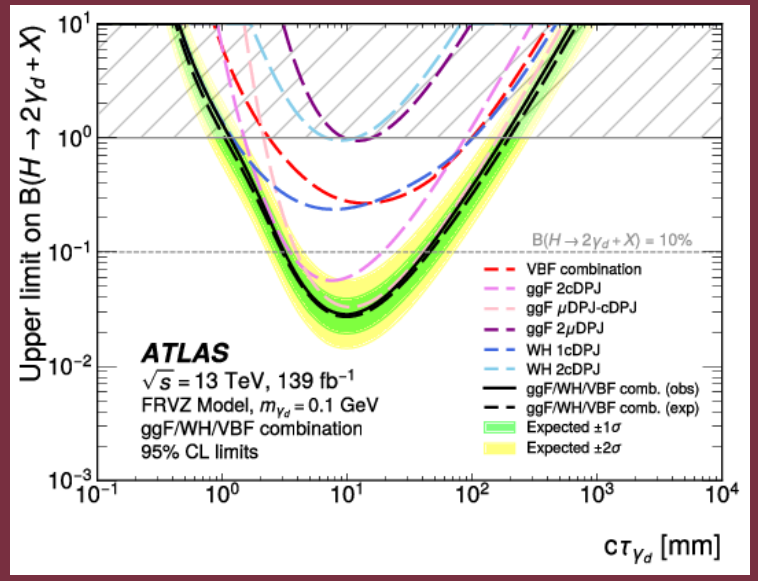
Dark photons – Higgs via VBF

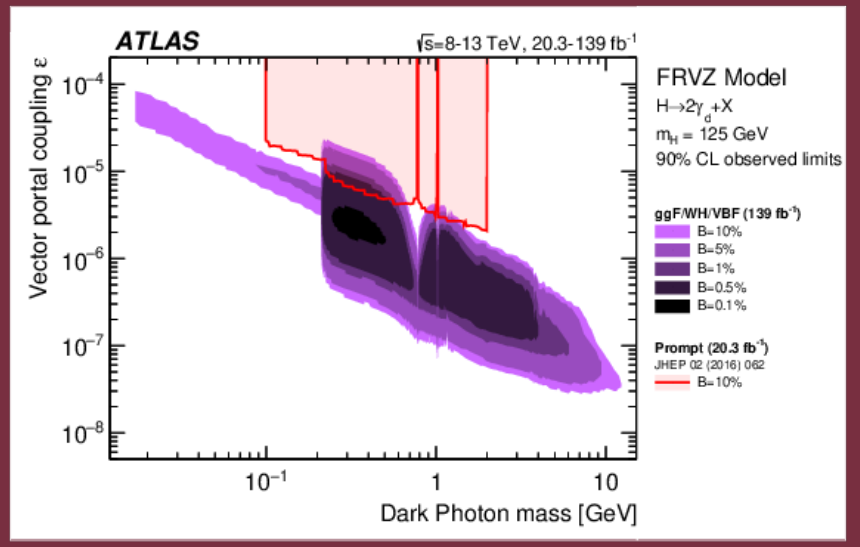
[hep-ex] 2311.18298
ATLAS

- Vector boson fusion (VBF) production of Higgs which decays via dark sector
- Dark photon jet (DPJ) → collimated fermions
- Three signal regions
  - muon-jet + calo-jet/low MET + calo-jet/high MET
- No significant excess observed



See talk by Luca Lavezzo from earlier today Sat May 25

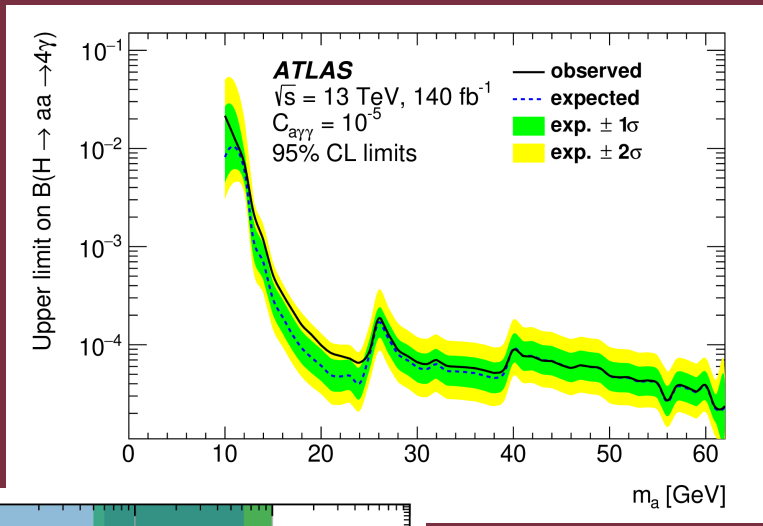


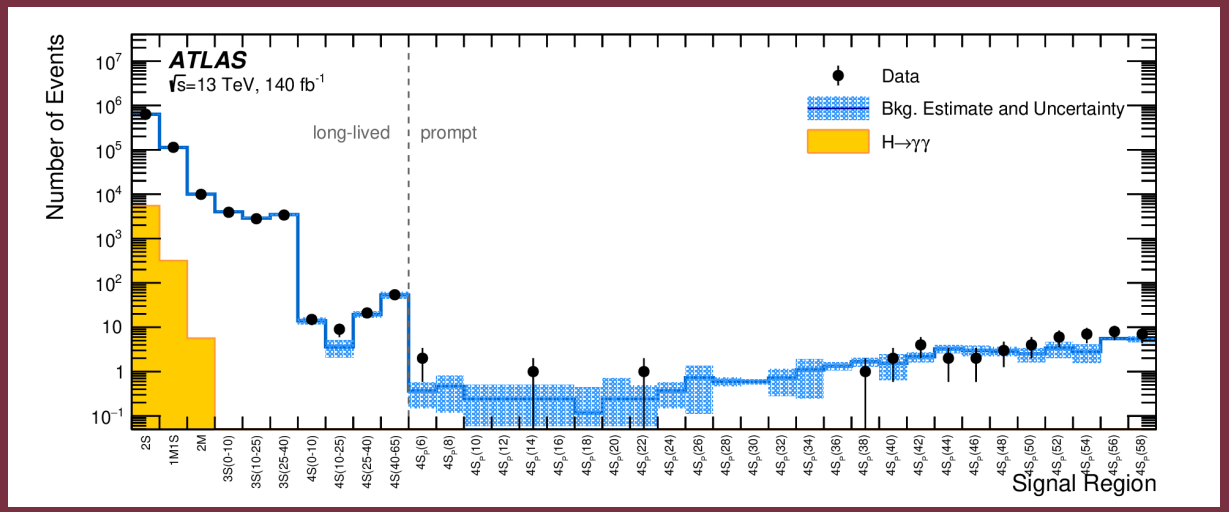


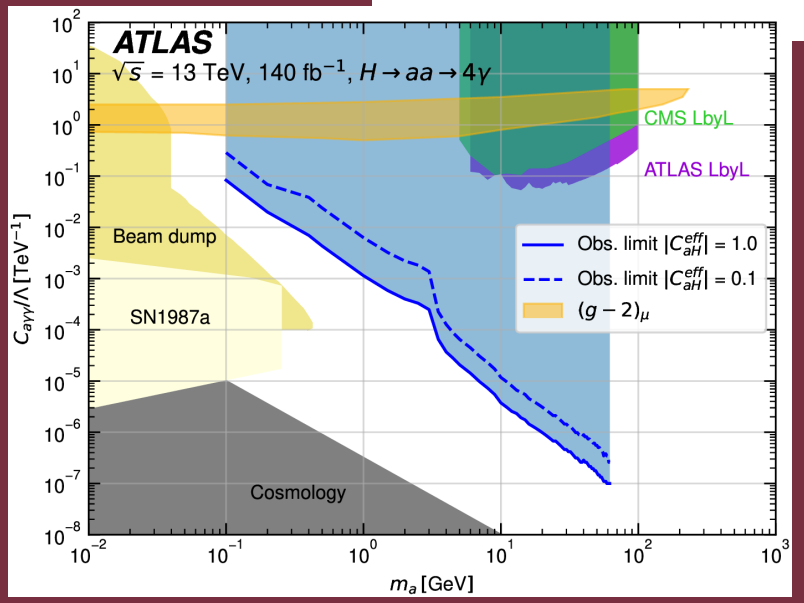
H→aa→4γ

- a = axion-like particles
- Small coupling → long lifetime
- a → γ + γ (may be collimated)
- Long-lived and prompt
- No excess observed

[hep-ex] 2312.03306
ATLAS



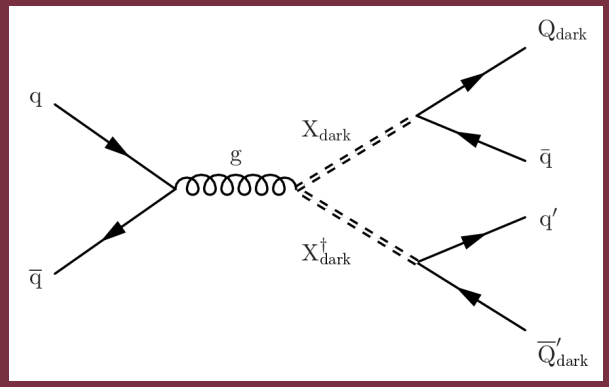




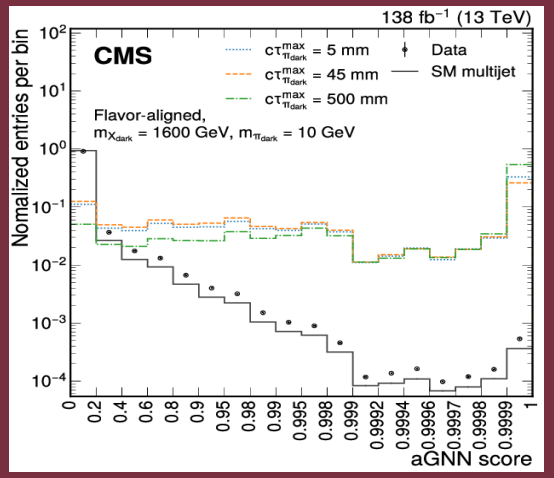
Emerging Jets

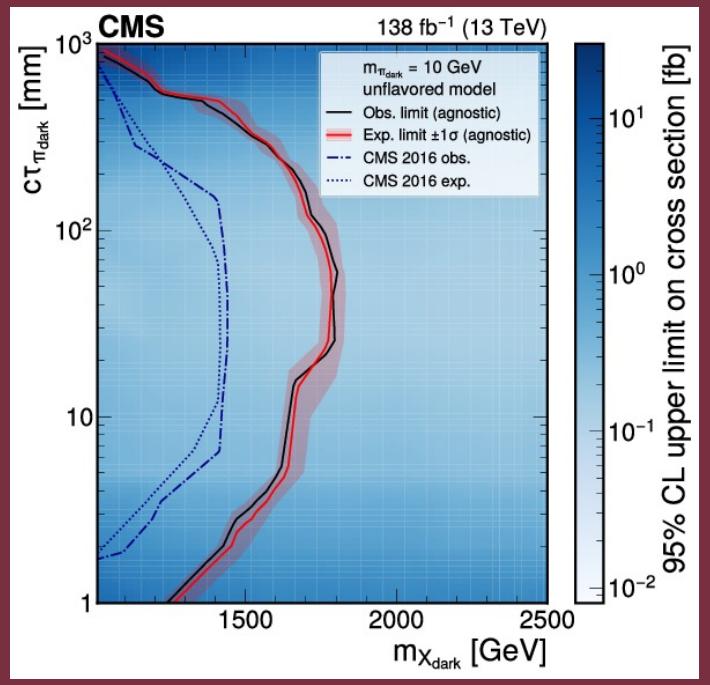
[hep-ex] 2403.01556
CMS

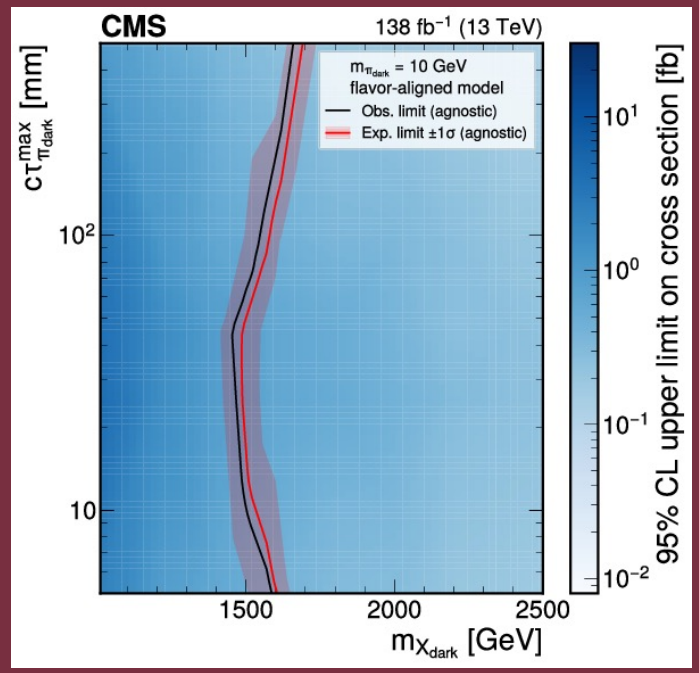
- Emerging jet (EJs) → jet with displaced vertex
- Use neural networks to identify EJs
- Require at least 2 EJs
- 16 signal regions used
- No significant excess observed



See talk by Kevin Pedro from Thurs May 23



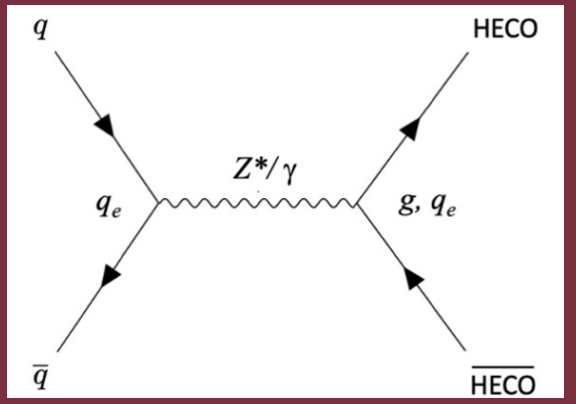


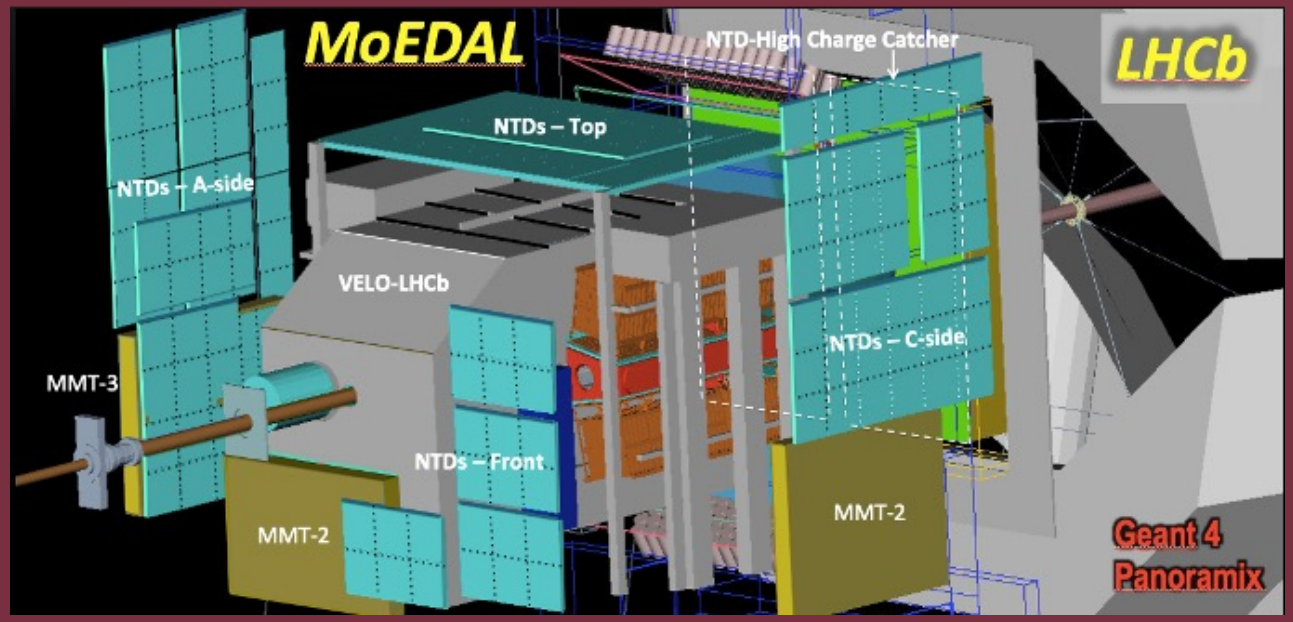


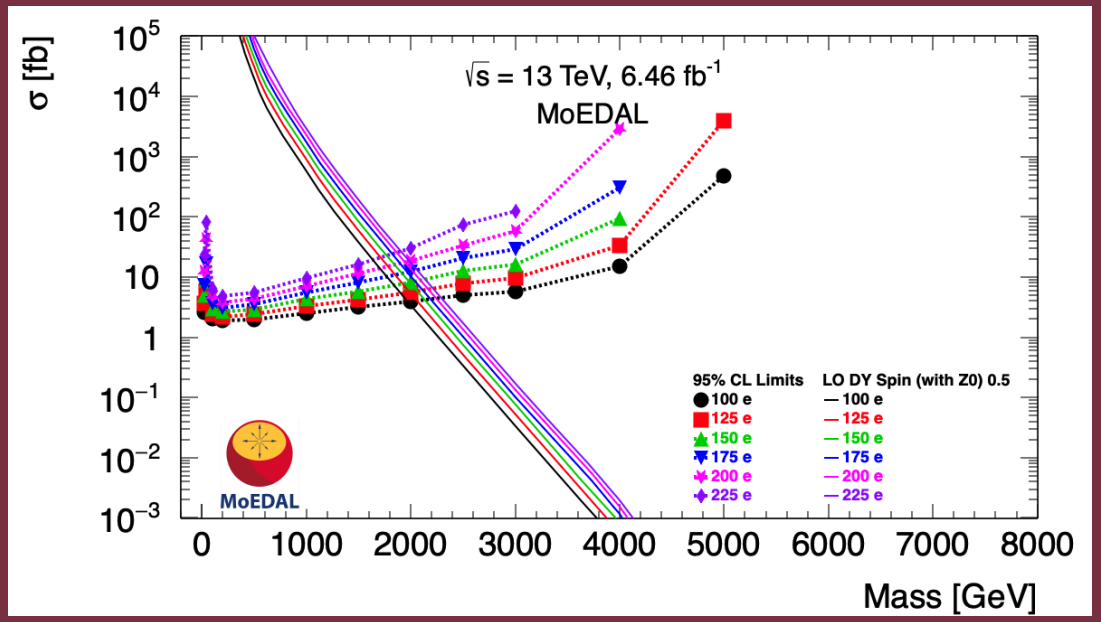
MoEDAL Results

[hep-ex] 2311.06509
MoEDAL

- Detector located near LHCb
- Studies of High Electric Charge Objects (HECOs) and magnetic monopoles
- Two papers so far – no excess





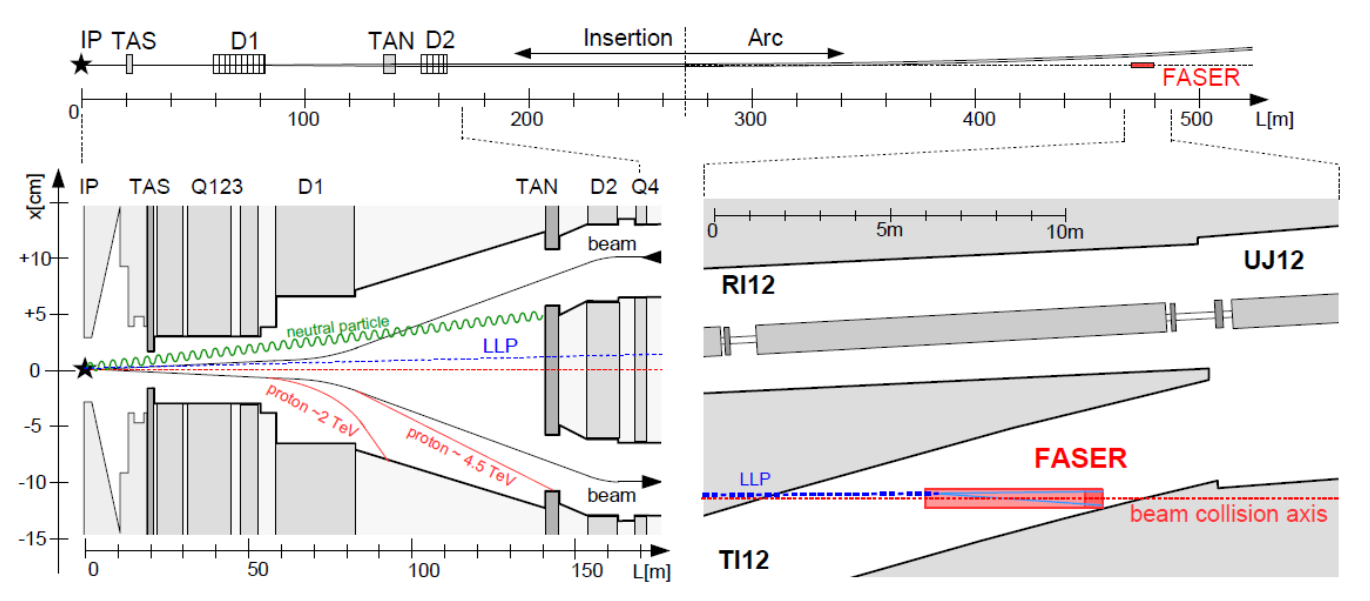


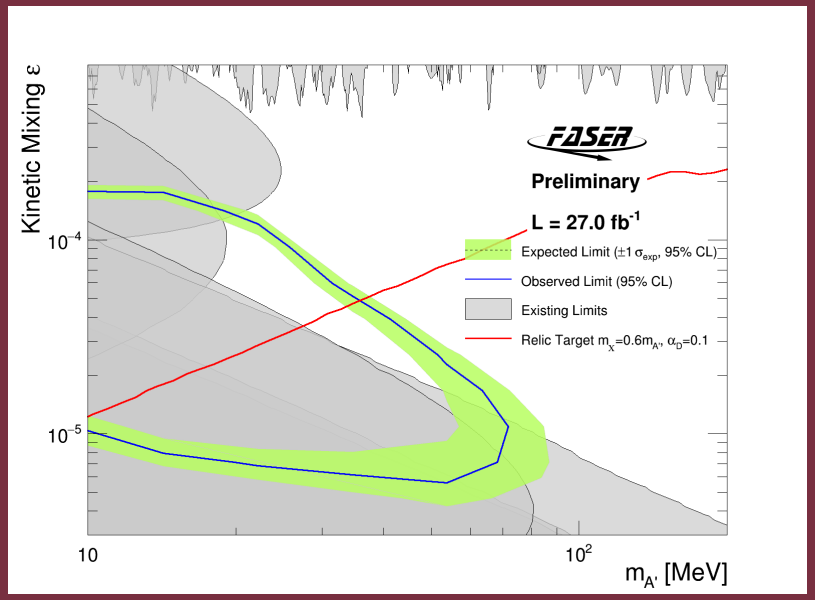
FASER Dark Photons

FASER-CONF-2023-001
FASER

- Forward Search Experiment
- 480 m downstream of ATLAS
- Started data taking in July 2022
- First results on searches for dark photons

See talk by
Roshan Mammen Abraham
from Thursday May 23





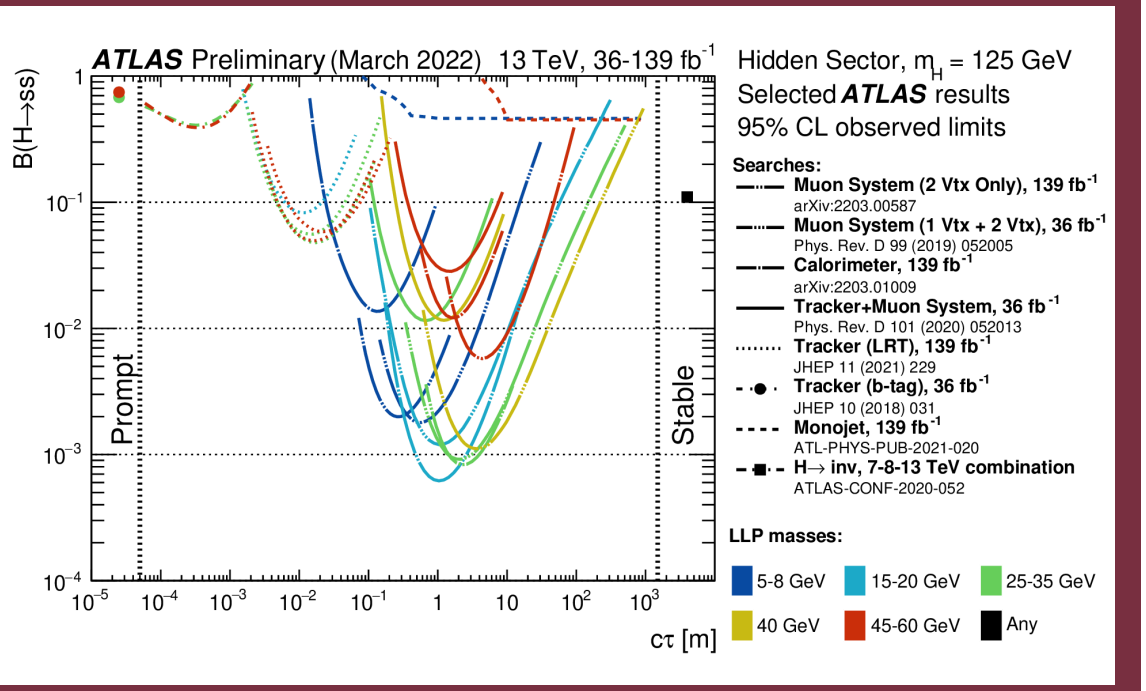
ATLAS SUSY Searches* - 95% CL Lower Limits

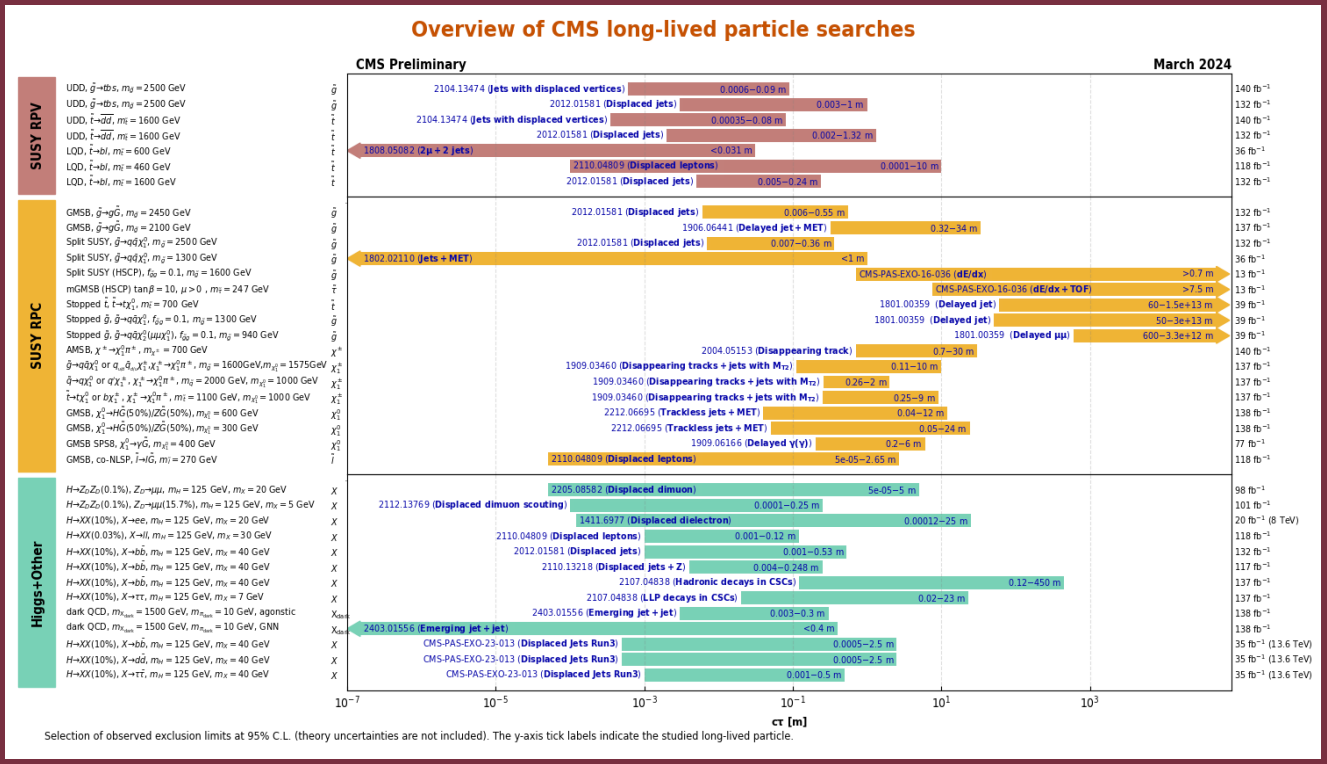
August 2023

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

	Model	Signature		$\int \mathcal{L}\,dt$ [fb^{-1}]	Mass limit		Reference
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	140	$\tilde{\chi}_1^\pm$ 0.66	Pure Wino	2201.02472
					$\tilde{\chi}_1^\pm$ 0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		140	$\tilde{g}$ 2.05		2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$	pixel dE/dx		140	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns] 2.2	m($\tilde{\chi}_1^0$)=100 GeV	2205.06013
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		140	$\tilde{e},\tilde{\mu}$ 0.7	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
					$\tilde{\tau}$ 0.34	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
		pixel dE/dx		140	$\tilde{\tau}$ 0.36	$\tau(\tilde{\ell})$ = 10 ns	2205.06013





Summary

Summary

- Expand LHC searches through long-lived particles
- New triggers + new algorithms
- Sophisticated analysis strategies
- More analyses than time to present
- More to come