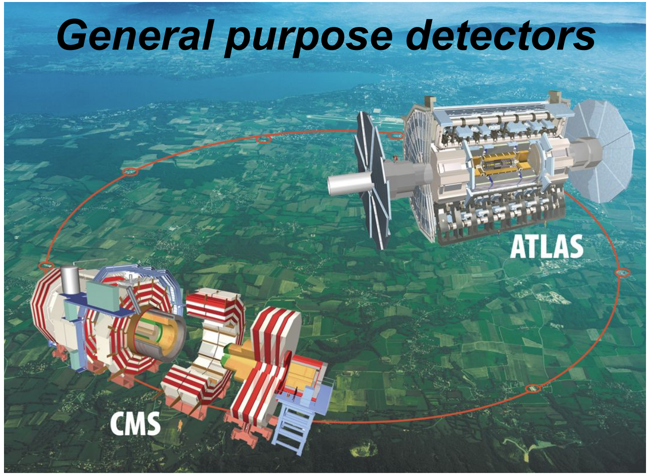
Recent highlights in BSM searches from the LHC

15th Conference on the Intersections of Particle and Nuclear Physics
12 June 2025

Shivani Lomte (UW-Madison)
On behalf of the ATLAS and CMS Collaborations

ATLAS & CMS experiments at the LHC



Complementary experiments, designed to independently explore wide range of physics phenomena

Together, provide cross-verification of results → core strength of LHC physics

Run-2 (2015–2018):
~140 fb^{-1} recorded per experiment at 13 TeV

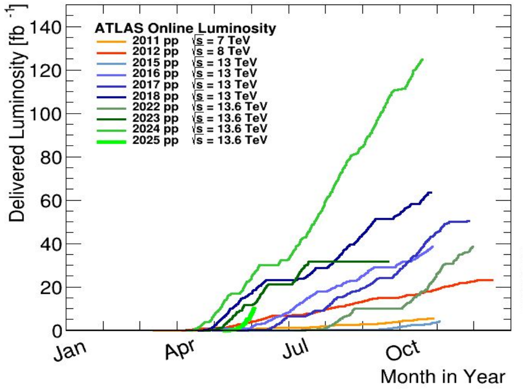
Run-3 (2022–2025):
Now running at 13.6 TeV, aiming for >250 fb^{-1}
Nearly doubling the Run-2 dataset

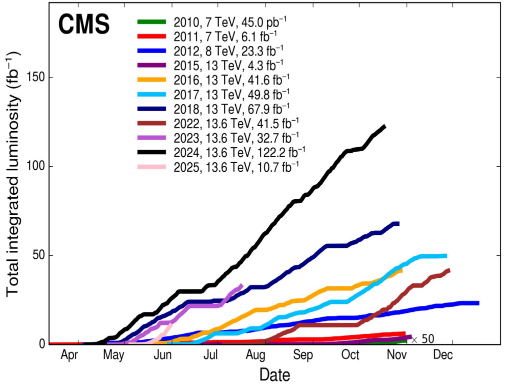
Combined total by end of Run-3:
~450 fb^{-1} per experiment (Run 1+2+3)

Expands reach for rare processes, heavier particles, and sensitivity to new physics signatures

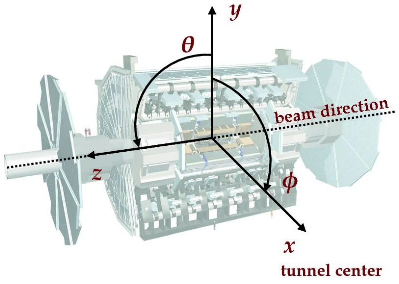
1 fb^{-1} corresponds to around
100 million million (potential) collisions

Growing total luminosity





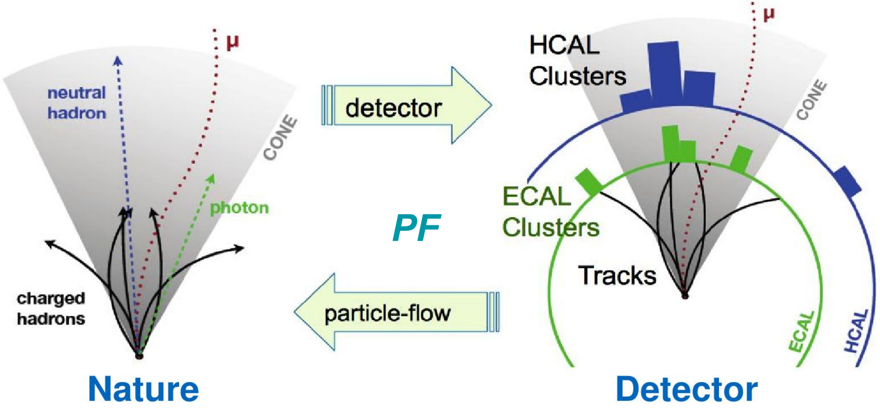
Reconstructed signatures



Layered sub-detector systems → allow precise particle identification and energy/momentum measurement

Standard objects:

- ***Electron***: inner tracks + EM calorimeter energy
- ***Photon***: EM clusters without associated tracks
- ***Muon***: tracks in tracker + muon system
- ***Jet***: anti-k_T algorithm to PF-like inputs
- ***b-jet***: identified using secondary vertex tagging
- ***Hadronic tau***: narrow jet with specific decay signature
- ***MET***: negative vector sum of transverse momentum (*hallmark of invisible particles escaping detector*)



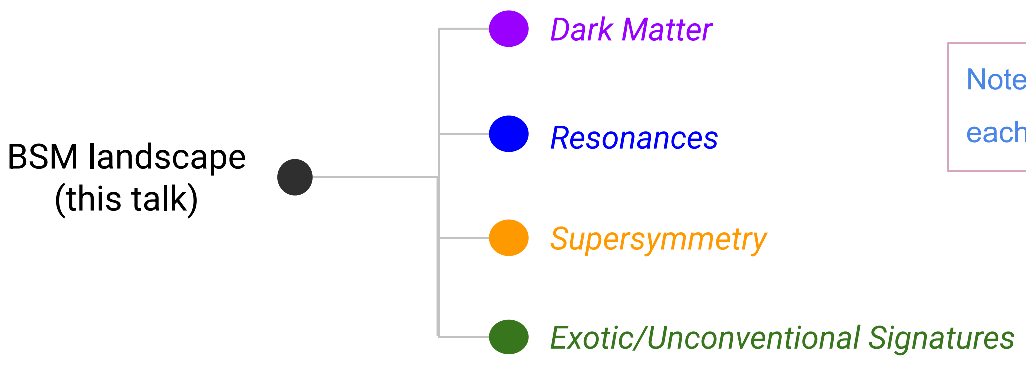
Beyond these, we go outside the box to look for *nonstandard objects and unusual signatures,* like displaced/trackless jets, secondary vertices, …

BSM program at the LHC

[ATLAS Public Results]

[CMS Public Results]

- We have measured SM with unprecedented precision
- But many open questions Beyond the Standard Model (BSM)
- LHC's BSM search program targets broad phase space for new physics
- The high energy and growing dataset provides powerful environment to explore new physics
  - produce new heavy particles
  - probe rare or exotic signatures
- Increasingly, novel techniques, like machine learning are used to enhance signal sensitivity



Note: only selective recent results from each category are showcased in this talk

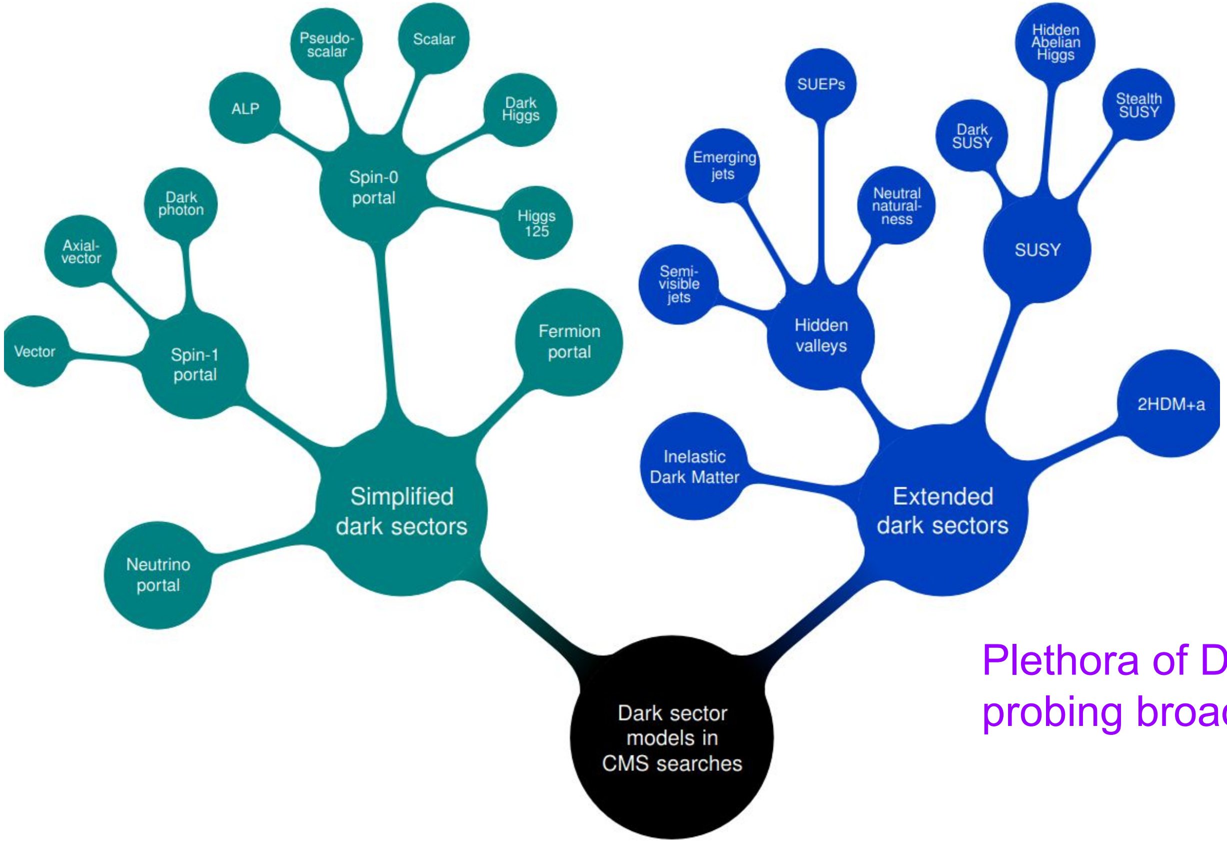
1. Dark Matter (DM) Searches

CMS-PAS-SUS-23-017

CMS-PAS-SUS-23-017

Phys.Rev.Lett. 134 (2025) 12, 121801

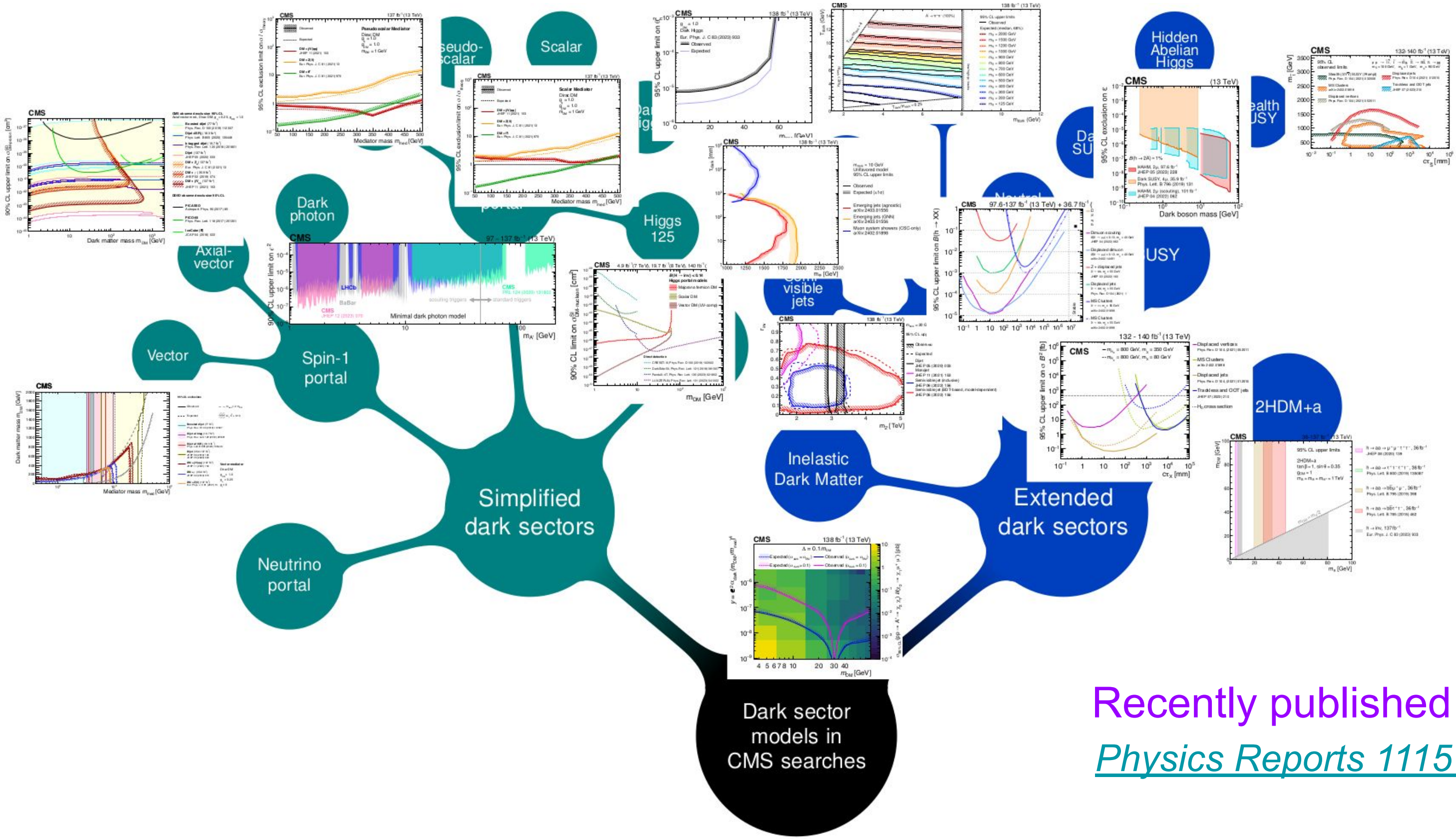
Dark sector map



Plethora of DM models,
probing broad phase space

Dark sector map

https://cms.cern/news/mapping-uncharted-territory-cms-reviews-searches-dark-matter



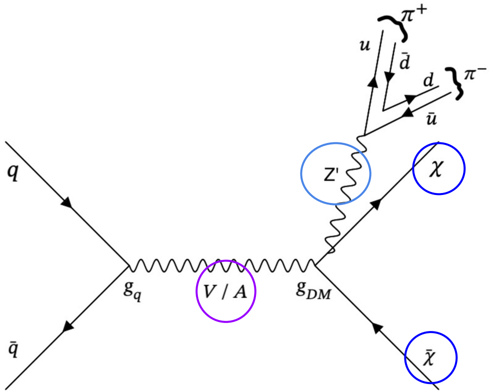
Recently published with CMS

Physics Reports 1115 (2025) 448

Search for DM+pencil jet

Dark Matter

CMS-PAS-SUS-23-017



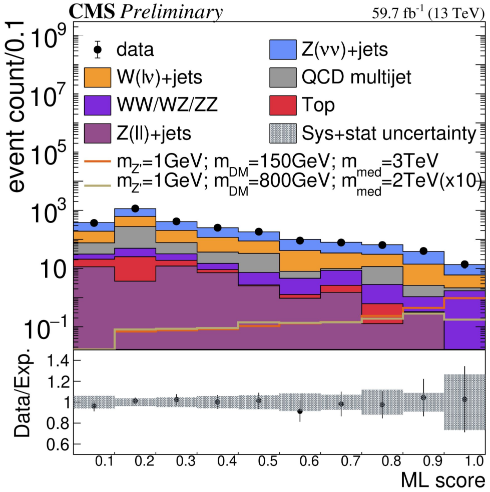
First search at LHC to use low-multiplicity jet signature and supervised machine learning to enhance signal sensitivity

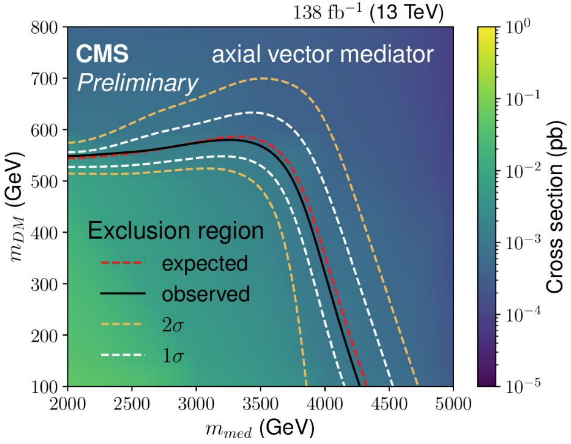
Mass range considered
DM candidate: 0.1 - 1 TeV
Mediator: 2- 5 TeV
Z' particle: 0.3 - 3 GeV

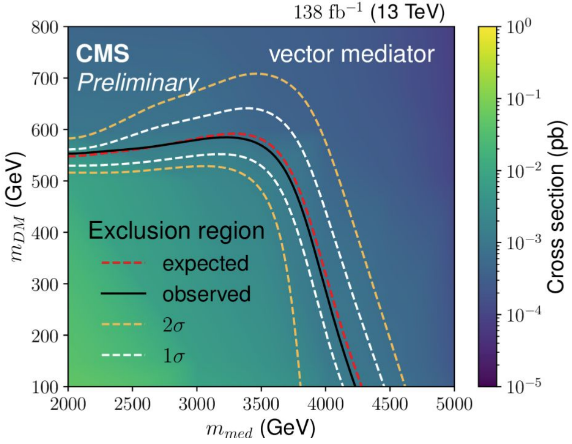
No significant excess observed.

Exclude mediator mass upto 4.25 TeV for DM mass 100 GeV at 95% CL

Expand sensitivity: 1.8 TeV → 4.2 TeV!





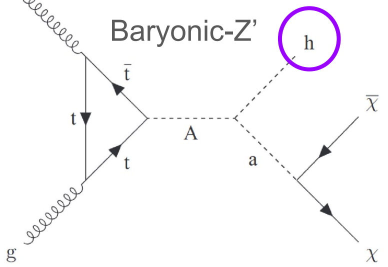


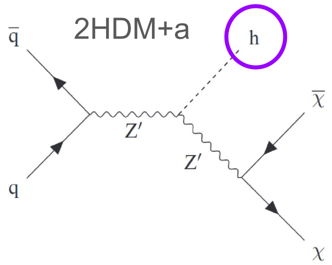
Search for mono-Higgs(bb)

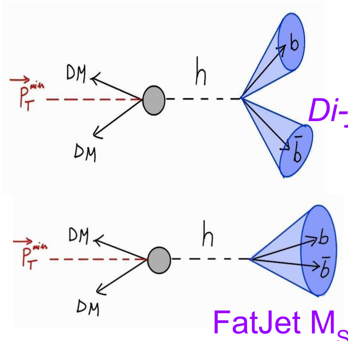
Dark Matter

CMS-PAS-SUS-24-007

Simplified DM models







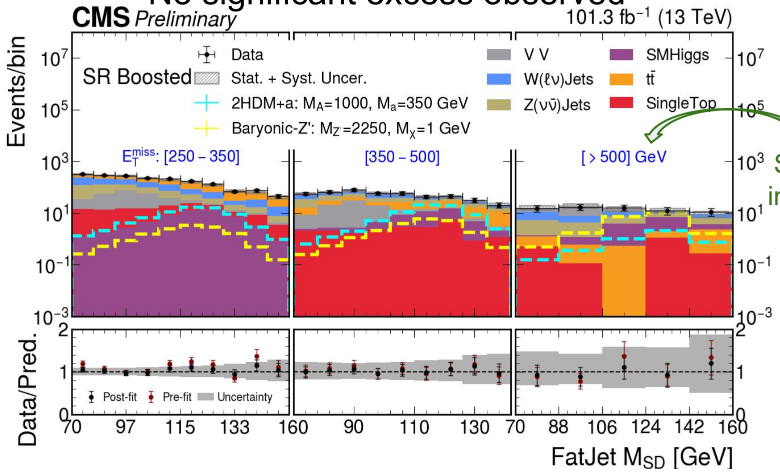
Di-jet M_{bb}

FatJet $M_{SoftDrop}$

Final state: MET + (H→bb)

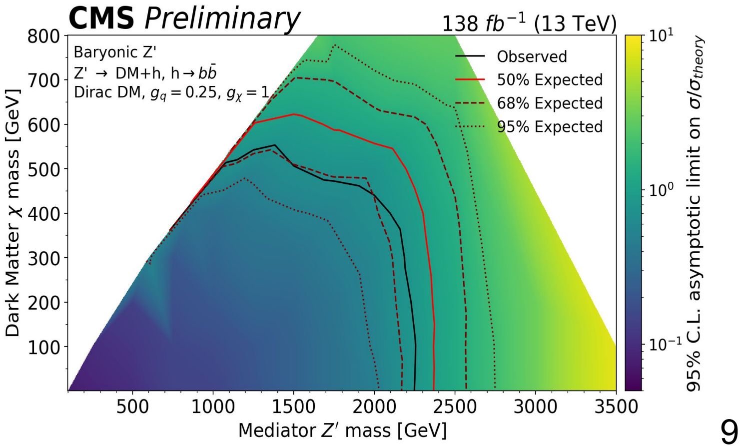
Enhanced S/B using graph neural network, ParticleNet tagger to identify H→bb vs QCD

No significant excess observed



Sliced in MET regions to increase signal sensitivity

Exclude Z' vector mediator upto 2.25 TeV for 1 GeV DM

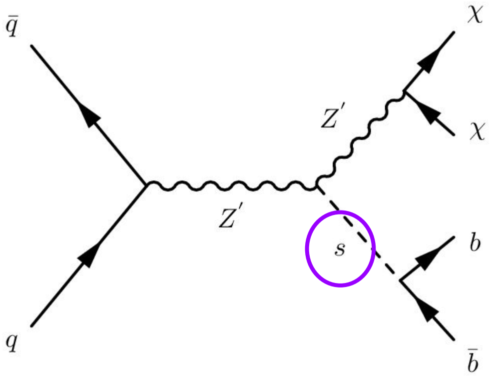


DM with dark Higgs → bb

Dark Matter

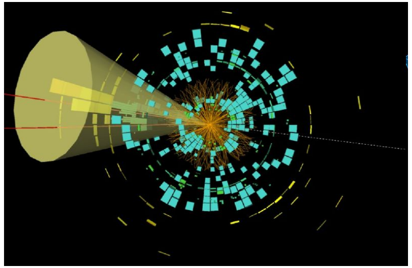
ATLAS-EXOT-2020-26

Phys.Rev.Lett. 134 (2025) 12, 121801

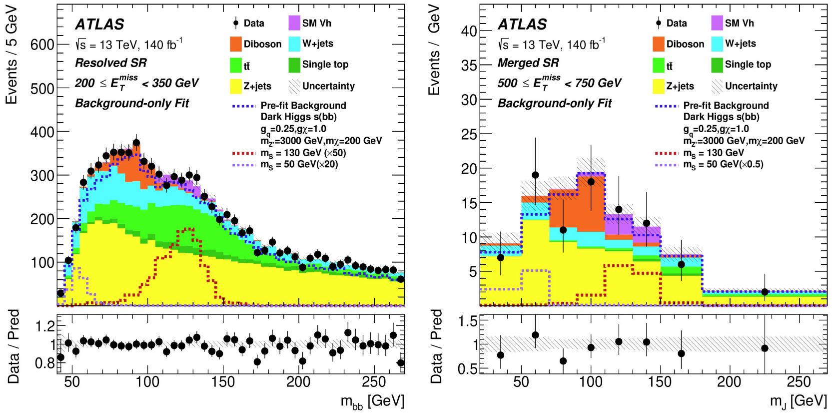


Dark Higgs scalar s → bb,
Z' → DM

Probe low m_s region

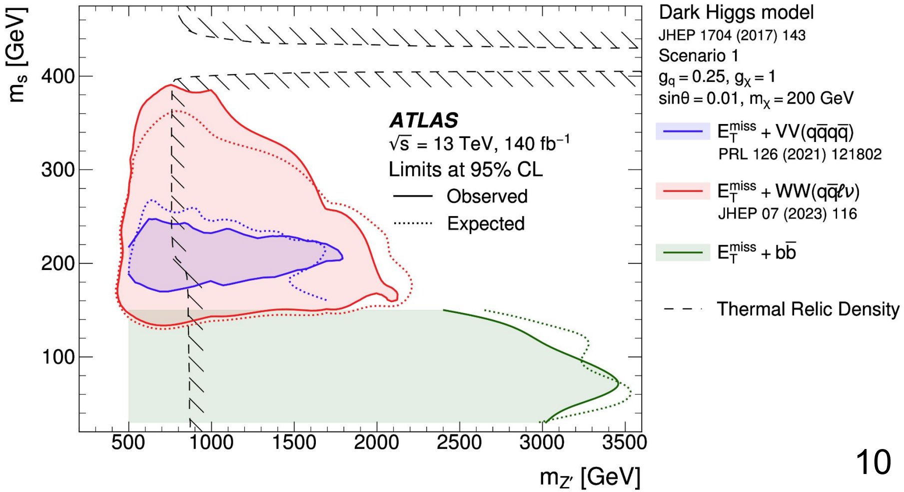


Resolved & Merged SR, sliced further in MET regions



Places stringent constraints

Exclude 30 < m_s < 150 GeV with Z' upto 4.8 TeV



2. Resonance Searches

CMS-PAS-B2G-24-007

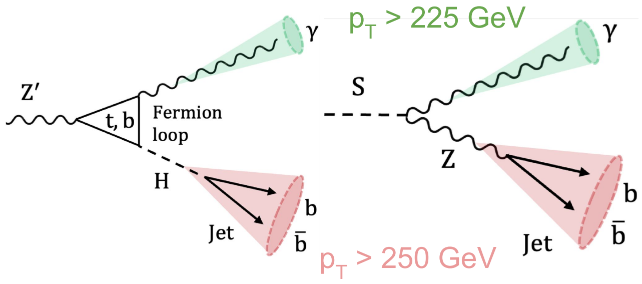
arXiv:2503.05463

arXiv:2502.09770

Heavy resonances γH and γZ with bb

Resonances

CMS-PAS-B2G-24-007



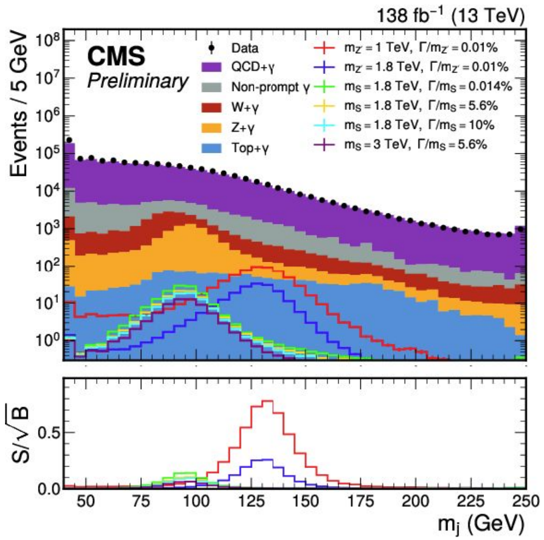
Target spin-1 Z’ → γH and spin-0 S → γZ

Boosted H/Z→bb decay

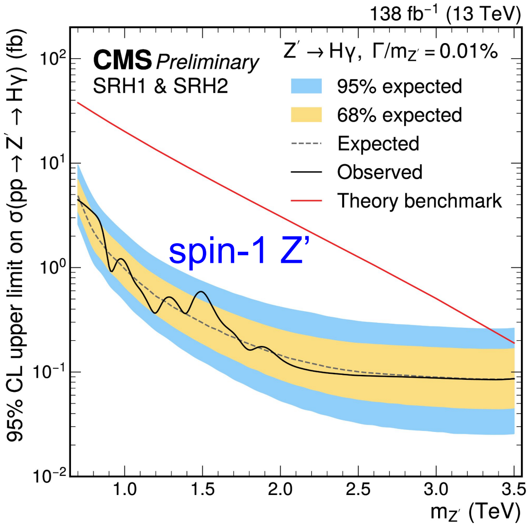
Jet substructure algorithm (ParticleTransformer)

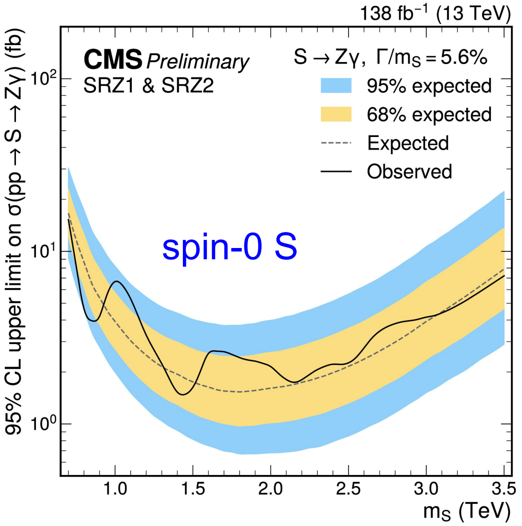
Jet mass regression (ParticleNet)

No significant excess observed



Most stringent limits to date





Exotic Higgs decay to 4 tau final state

Resonances

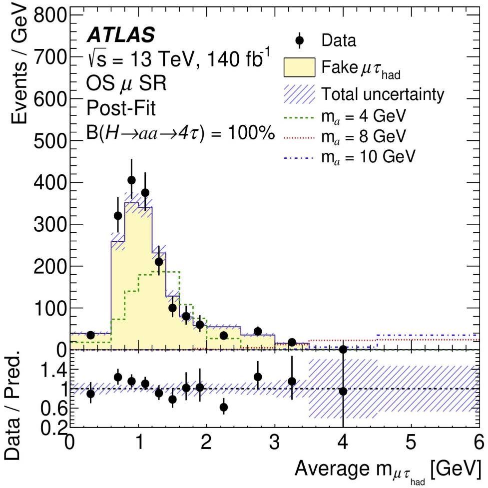
ATLAS-HMBS-2024-25
arXiv:2503.05463

$H \rightarrow aa \rightarrow 4\tau$ final state
Results presented: 4 GeV < m_a < 15 GeV
$a \rightarrow 2\tau \rightarrow \mu\tau_h$ boosted decay product

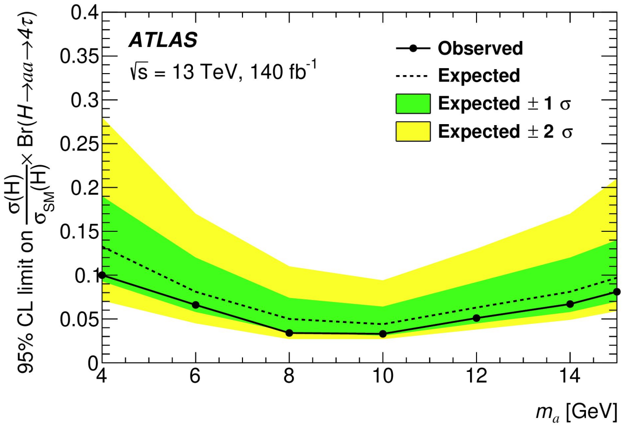
Exotic Higgs decays Summary from ATLAS

New tau identification technique improved ability to spot high p_T taus

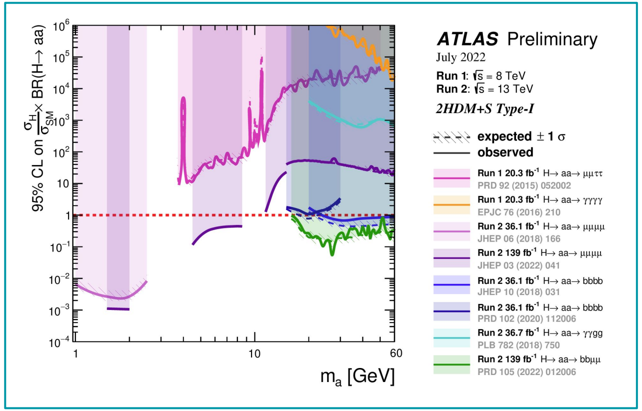
Average mass of the two $\mu\tau_{had}$



No significant excess observed



New limits set as low as 3% on the decay probability of Higgs bosons decaying into pairs of new particles.

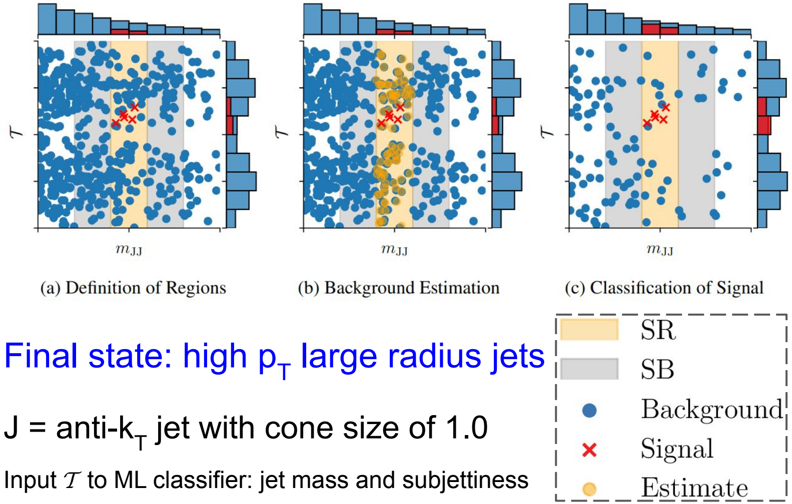


Anomaly detection for dijet resonance search

Resonances

ATLAS-HMBS-2024-34
arXiv:2502.09770

Weakly supervised ML to search for resonant signal, localized peak in m_{JJ}



(a) Definition of Regions (b) Background Estimation (c) Classification of Signal

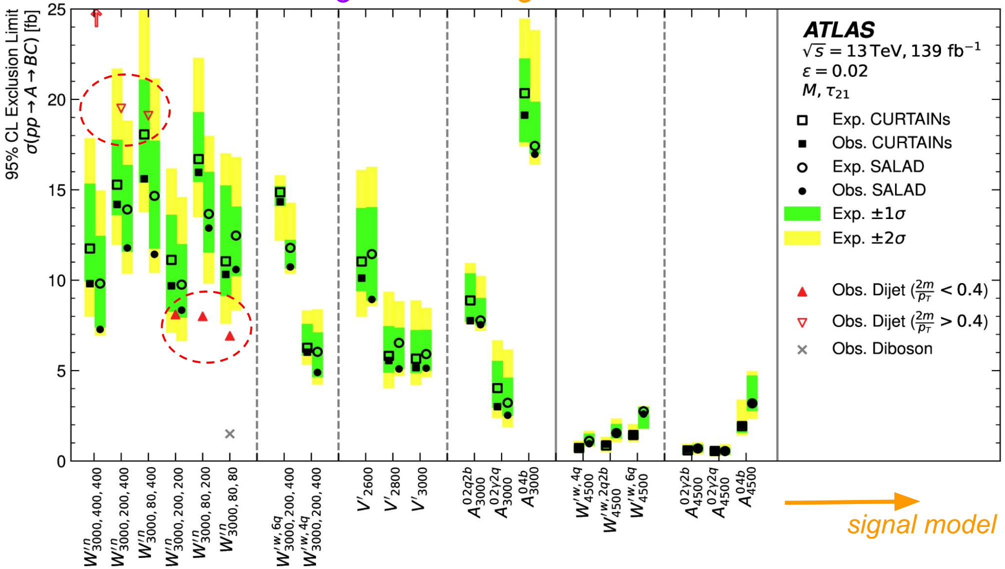
Optimized to be model-independent
Aims for sensitivity to broad range of new physics

Final state: high p_T large radius jets

J = anti-k_T jet with cone size of 1.0

Input $\mathcal{T}$ to ML classifier: jet mass and subjettiness

95% CL upper limits on σ(pp→A→BC) set by the 2 ML strategies for 20 signal models



Use 2 ML strategies to estimate backgrounds in different SRs. In each SR, search for local excess across various models

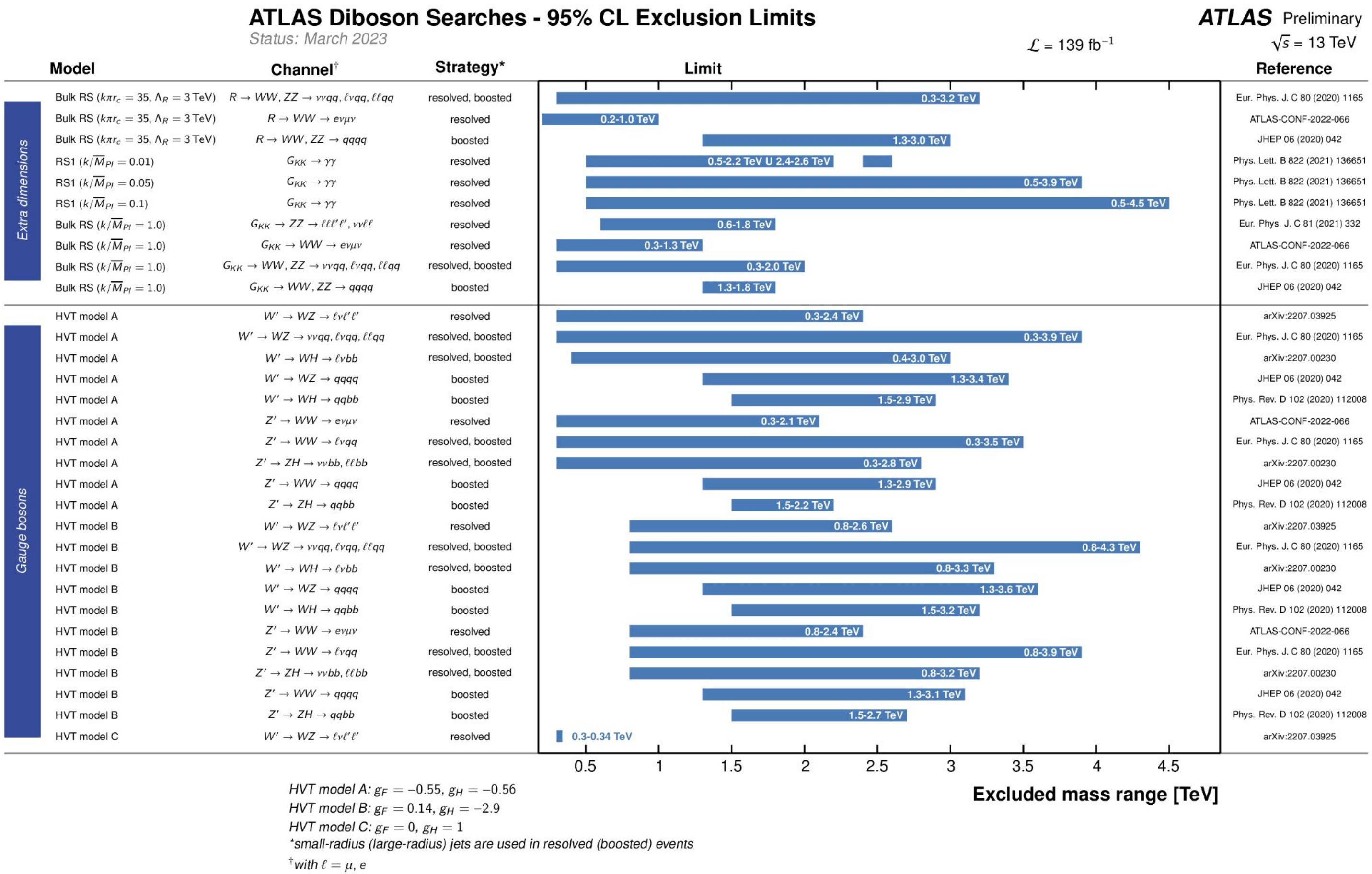
Similar performance, stronger limits for some models than existing di-jet searches

Summary of Diboson resonances

[Reference]

Extra dimensions

Gauge bosons



3. Supersymmetry

arXiv:2503.17186

CMS-PAS-SUS-24-003, *CMS-PAS-SUS-24-012*, *CMS-PAS-EXO-23-017*

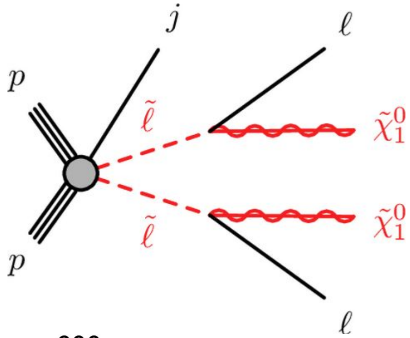
CMS-PAS-SUS-23-014

Search for direct slepton production

Supersymmetry

ATLAS EXPERIMENT

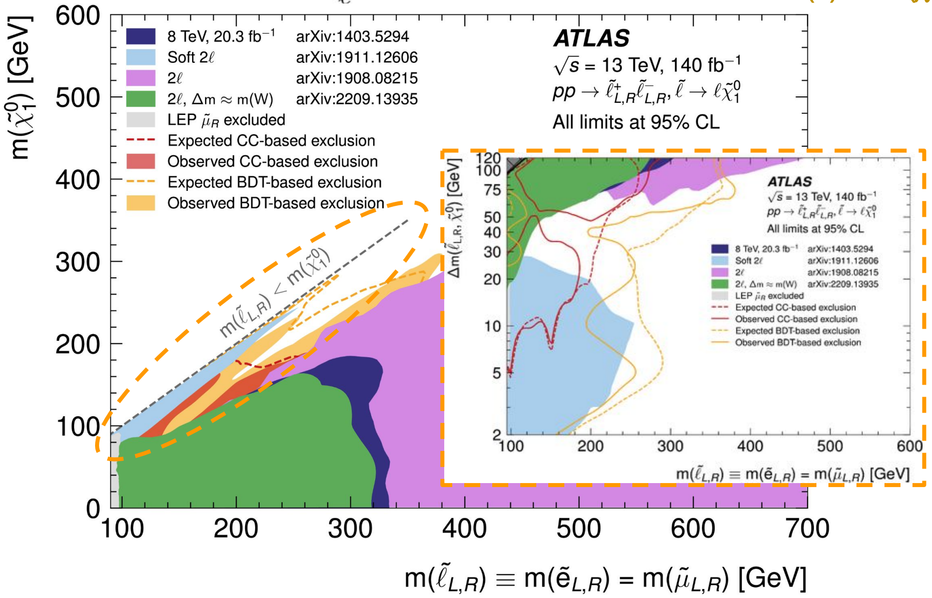
ATLAS-HMBS-2024-64
arXiv:2503.17186



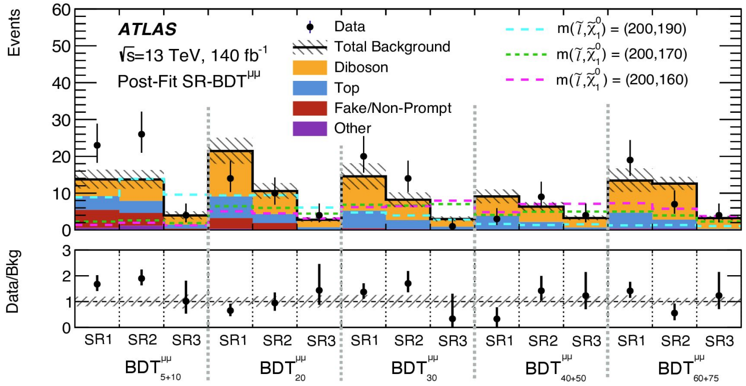
2 lepton + 1 jet + MET final state

Focus on challenging "corridor" region to close a persistent gap in sensitivity to models with $\Delta m < m_W$

$\Delta m = m(\tilde{\ell}) - m(\tilde{\chi}_1^0)$



Local excess of 2.4σ in smuon search



Uses cut-and-count & BDT methods, each optimized for different Δm splittings

For the first time, sensitivity across full Δm corridor

Search for Electroweakinos production

Supersymmetry

CMS-PAS-SUS-24-003
CMS-PAS-SUS-24-012
CMS-PAS-EXO-23-017

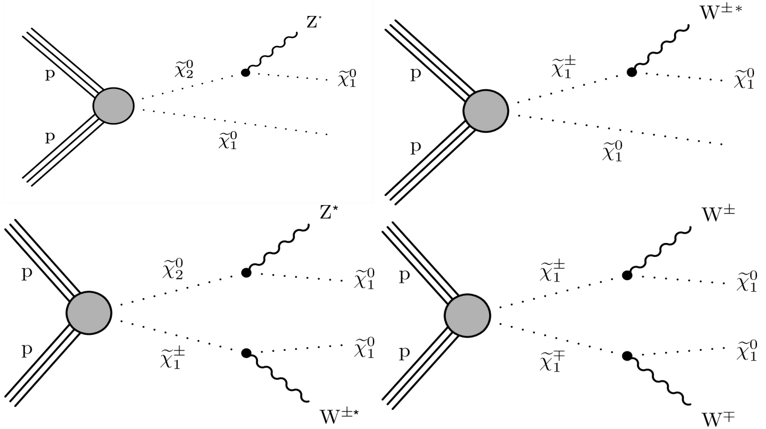
Probes previously unexplored soft regions

Compressed mass spectra $\rightarrow$ low p_T particles

$\Delta m(\chi_1^{\pm}, \chi_1^{0}) < 5$ GeV

Final state: 2 **soft** leptons + MET

OR 1 **soft** lepton + 1 isolated track + MET



for small Δm, soft leptons

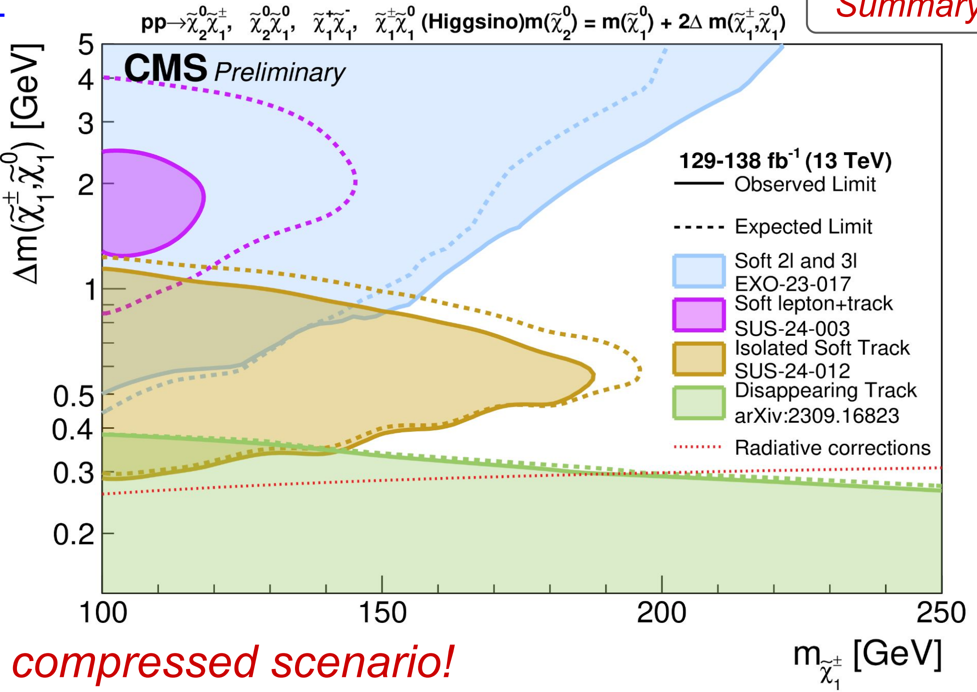
with ML reconstruction, p_T(e) as low as 1 GeV

for Δm<1 GeV, displaced track

Analyses featuring final states:

- soft opposite-sign electron pairs
- a soft lepton and isolated track
- a soft isolated track
- disappearing track

Summary



CMS covers full Δm spectrum in compressed scenario!

Comprehensive search with boosted objects

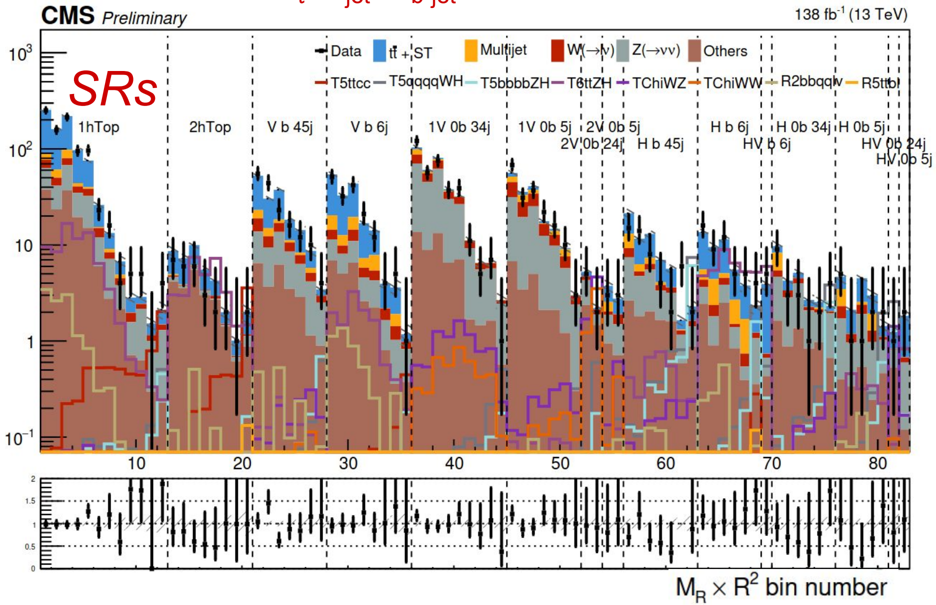
Supersymmetry

CMS-PAS-SUS-23-014

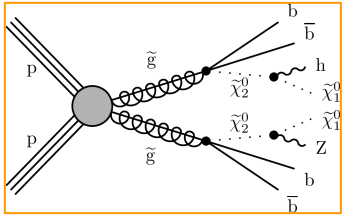
Search for SUSY in final states with highly Lorentz-boosted top quarks, W, Z, H, or leptonic jets

- Razor kinematic variables: signal-like localized peak, falling background
- Deep neural network, ParticleNet tagger for boosted object reconstruction

Categorized by N_ℓ, N_{jet}, $N_{b\text{-}jet}$ and type of boosted object

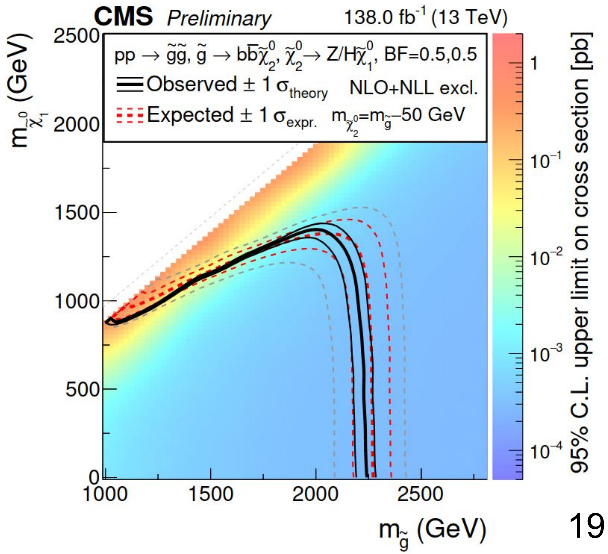


Gluino pair production T5bbbbZH



Exclude gluino mass up to 2.35 TeV

Comprehensive analysis with plethora of objects and interpretations



Summary of ATLAS SUSY searches

Reference

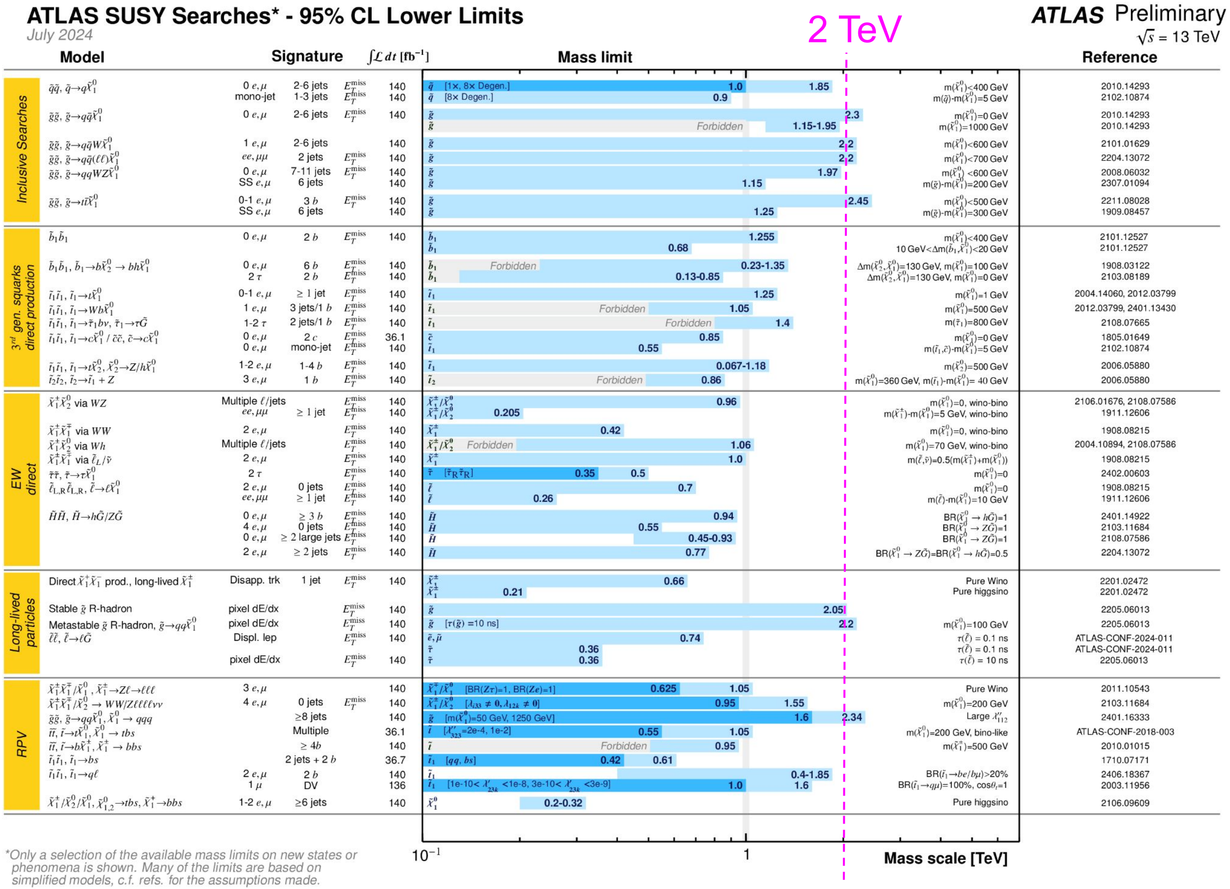
gluino

sbottom

electroweak

long-lived

RPV



4. Exotic/Unconventional Signatures

ATLAS EXPERIMENT arXiv:2505.01634

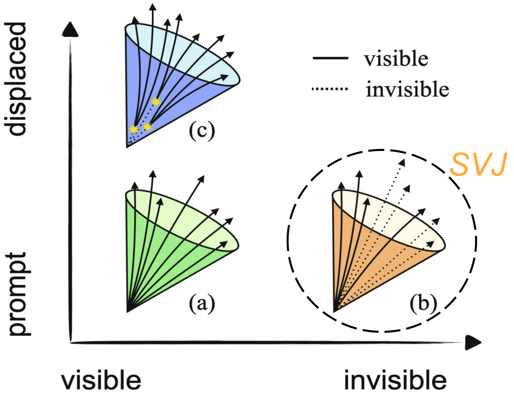
ATLAS EXPERIMENT arXiv:2505.02429

CMS *CMS-PAS-EXO-24-012*

Semi-visible jets or anomalous signature

Exotic Signatures

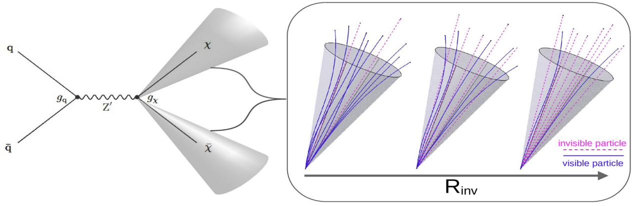
ATLAS-EXOT-2021-19
arXiv:2505.01634



Source: https://atlas.cern/Updates/Briefing/Shedding-Light-Dark-Sector

Dark QCD, Z' → q_D q_D
heavy resonance to dark quarks

R_{inv} = fraction of dark particles



Large R jets, hadronizes & decays to shower in **both** DM & SM particles

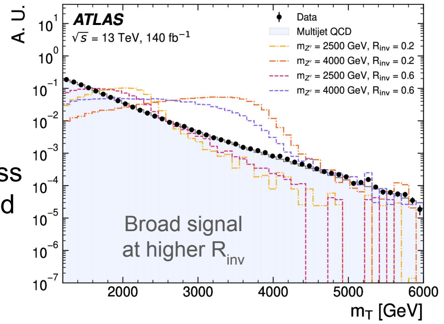
ATLAS' first s-channel dark-sector search

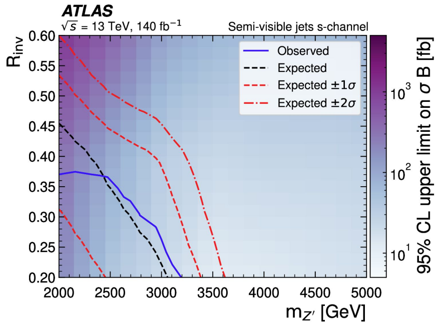
1. *Particle Flow Network (PFN)*

model-focused ML, uses charged particle track info + E_T^{miss} within jet shower

Transverse mass of two leading jets and E_T^{miss}

No excess observed

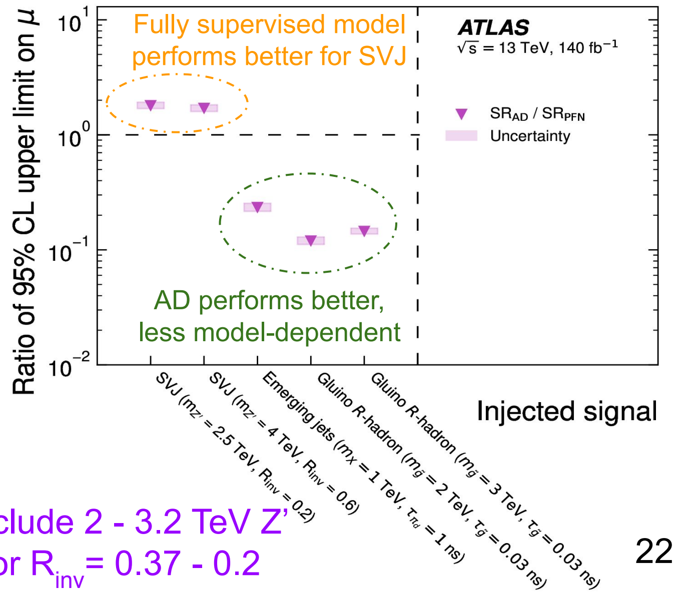




2. *Novel Anomaly Detection (AD)*

model-agnostic, semi-supervised ML, identify abnormalities wrt SM, enhances potential to **unexpected** new physics

Results quantified for few generic signals



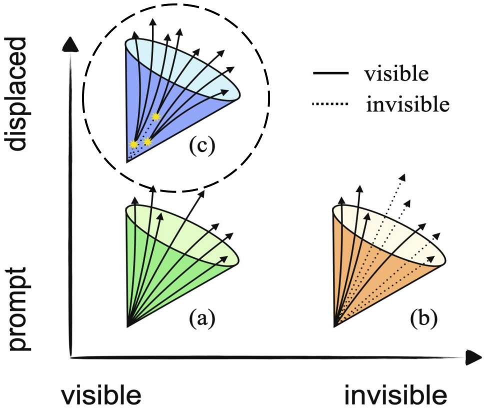
Exclude 2 - 3.2 TeV Z' for R_{inv} = 0.37 - 0.2

Search for emerging jets

Exotic Signatures

ATLAS' first Run-3 result!

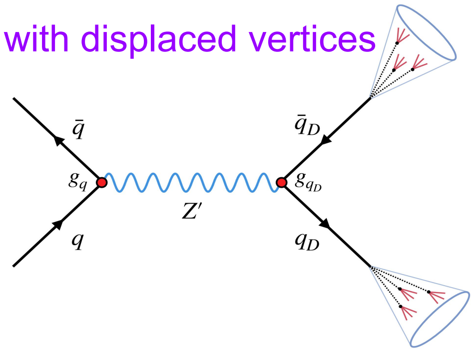
ATLAS-EXOT-2022-31
arXiv:2505.02429



Dark QCD, Z' → q_D q_D

heavy resonance to dark quarks

Jets with displaced vertices



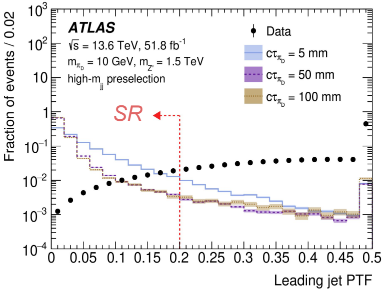
1. *Cut and count based strategy*

- Uses high-level jet observables: displaced tracks and secondary vertex info; jet substructure
- Re-interpretable and less model dependent

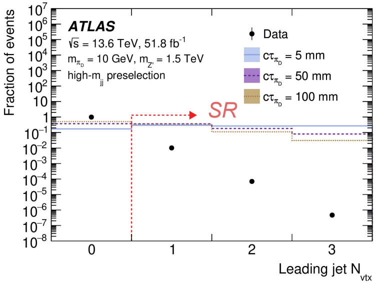
2. *ML based strategy*

- Uses per-jet transformer-based ML algorithm to differentiate emerging jets from SM jets
- Maximizes sensitivity to specific models

Prompt-Track-Fraction (PTF) measures
tracks starting near collision point

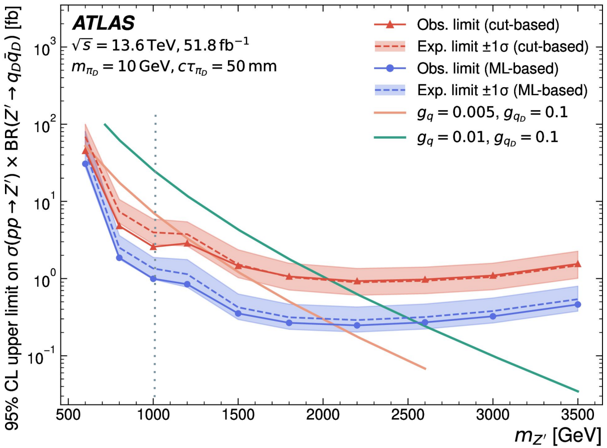


associated secondary vertices



Two categories: low and high dijet mass:

1. m_{jj} < 1 TeV → novel emerging jet trigger, trigger matched jets p_T > 250 GeV, PTF<0.04
2. m_{jj} > 1 TeV → high pT trigger, jet pT > 520 (300) GeV



First direct constraint on emerging jet pair production via s-channel mediator.

First application of a transformer-based algorithm for emerging jet tagging.

Cut-based: weaker limit, but more re-interpretable & less model-dependent

ML-based: stronger limit Z' upto 2.5 TeV excluded

Resonance search using Scouting data

Exotic Signatures

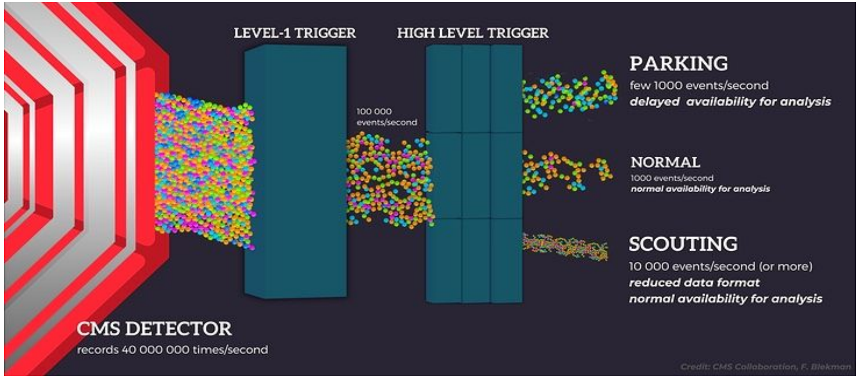
CMS-PAS-EXO-24-012

Physics Reports 1115 (2025) 678

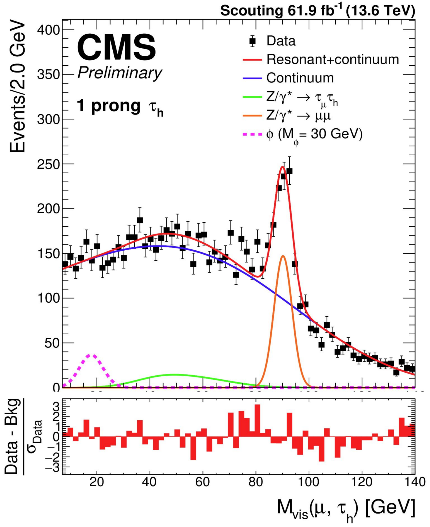
- Traditional triggers → high p_T thresholds, low efficiency for low mass resonance
- *Run-3 Scouting* dataset → lower p_T thresholds

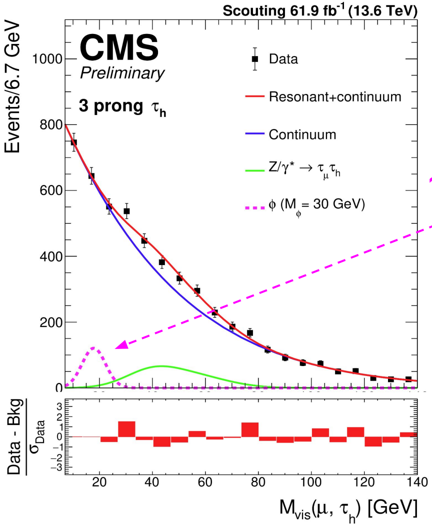
(records limited event info → allows high event rate)

- Search for low mass resonance ($\phi \to \tau\tau \to \mu\tau_h$)



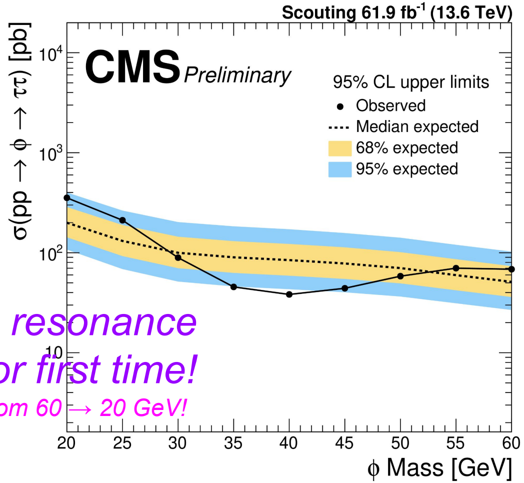
Novel ML algorithm to reconstruct low p_T τ_h decays





20-60 GeV M_ϕ

~ 10-40 GeV M_{vis}



Probe low mass resonance below 60 GeV for first time!

Brought sensitivity down from 60 → 20 GeV!

Summary of Exotic searches

Reference

other

contact-interactions

dark matter

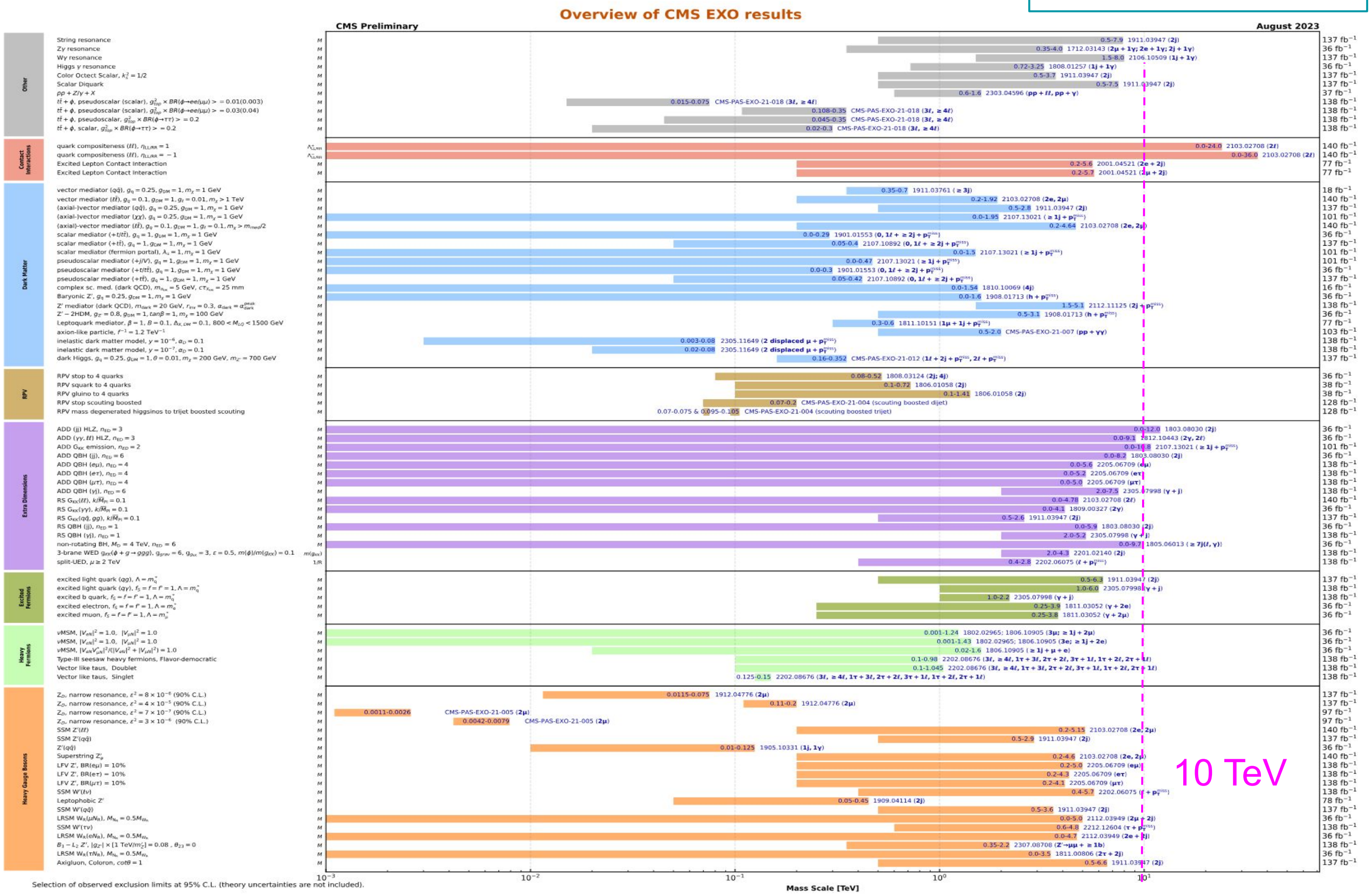
RPV

extra dimensions

excited ferminos

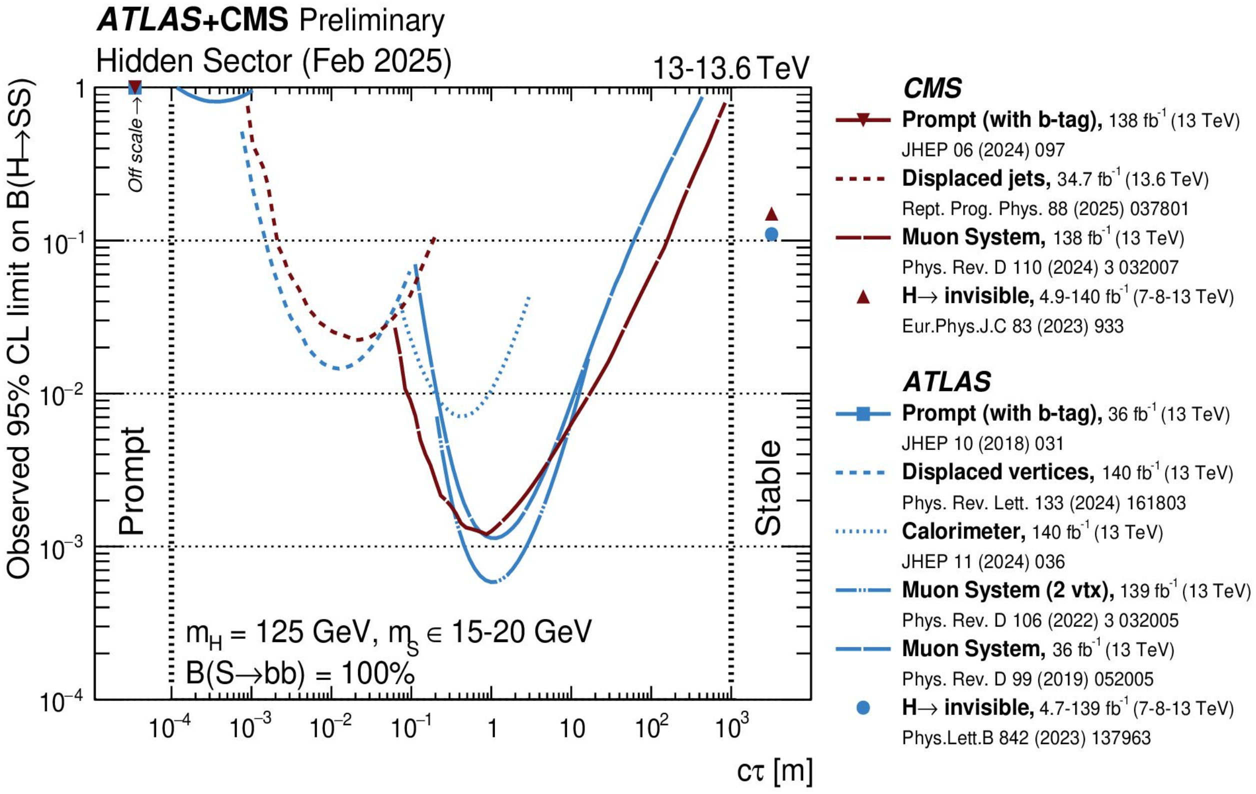
heavy fermions

heavy gauge bosons



Summary of LLP searches

Common ATLAS and CMS summary plots for Higgs boson mediated hidden sectors involving long-lived particles



Reference

Overview: selective list of recent BSM results at LHC

This talk

1. Heavy Hγ and Zγ resonances with bb — CMS-PAS-B2G-24-007
2. Exotic Higgs decay to 4 tau final state — ATLAS arXiv:2503.05463
3. Anomaly detection for di-jet resonance search — ATLAS arXiv:2502.09770
4. Direct slepton production — ATLAS arXiv:2503.17186
5. Electroweakinos production — CMS-PAS-SUS-24-003, CMS-PAS-SUS-24-012, CMS-PAS-EXO-23-017
6. Comprehensive search with boosted objects — CMS-PAS-SUS-23-014
7. DM+pencil jet — CMS-PAS-SUS-23-017
8. Mono-Higgs(bb) — CMS-PAS-SUS-23-017
9. DM with dark Higgs → bb — ATLAS Phys.Rev.Lett. 134 (2025) 12, 121801
10. Semi-visible jets — ATLAS arXiv:2505.01634
11. Emerging jets — ATLAS arXiv:2505.02429
12. Resonance search using Scouting data — CMS-PAS-EXO-24-012

Few more BSM results (not covered in this talk)

Vector-like T quark	CMS-PAS-B2G-23-009
New scalar resonance	CMS-PAS-B2G-24-001
Displaced dimuons	CMS-PAS-EXO-24-008
$H \to aa \to 4e$	CMS-PAS-EXO-24-031

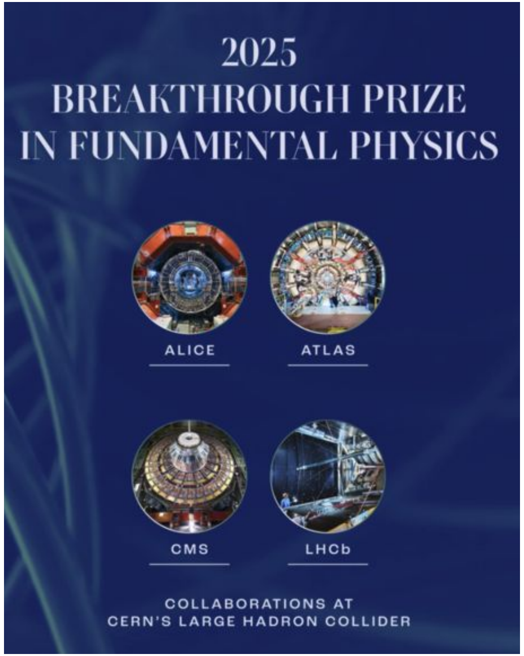
Vector-like leptons	2503.22581
Lepto-quarks	2503.19836
Heavy neutral leptons	2503.16213
Long-lived particles	2503.20445
New scalar with ttbar	2503.17254

More exciting BSM results this afternoon:

Exotics results from ATLAS by Michael Revering
Vector-like quarks at LHC by Elias Bernreuther
New pseudoscalar search with ATLAS by Sara Khaled

Summary & Outlook

- ★ Exciting and wide range of BSM landscape at the LHC.
- ★ Many results from 140 fb^{-1} of Run-2 dataset.
  Searches with Run-3 are ramping up.
- ★ Increasing the sensitivity to new physics with novel reconstruction techniques, and probing unexplored regimes, both at higher and lowest masses.
- ★ Highlighted only a selective sample of recent BSM results.



Stay tuned for many more results from the LHC!