

Dark Matter Searches at LHC

James Frost

(james.frost@stfc.ac.uk)



Science and
Technology
Facilities Council



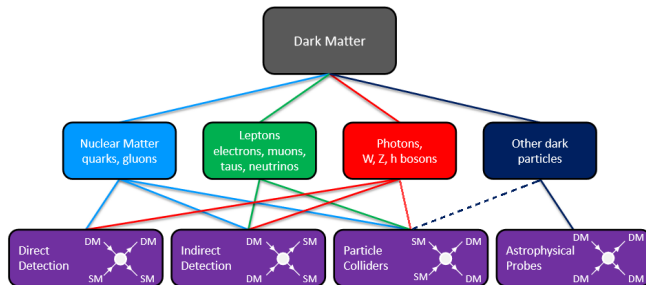
Wednesday 22nd October 2025

- 1 Dark Matter and Collider Searches
- 2 Monojet - Jet(s) + E_T^{miss}
- 3 Dijet/dilepton searches
- 4 Invisible Higgs decays
- 5 Extended Higgs Sectors
- 6 Dark sectors & light DM

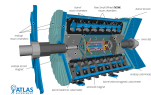
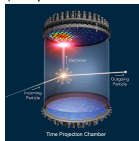
Complementarity, signatures

Assumptions

- DM interacts non-gravitationally
- Has some effective hadron coupling
- Complementarity
- Direct/indirect detection, accelerators, light DM
- For what collider signatures to search?

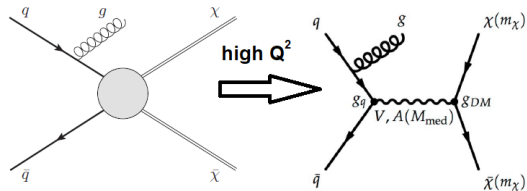


(adapted from 1305.1605)



Anatomy of a collider DM signature

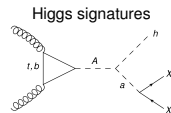
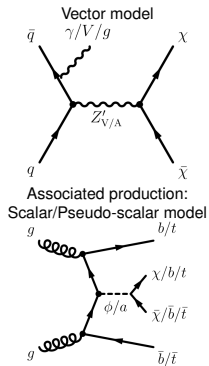
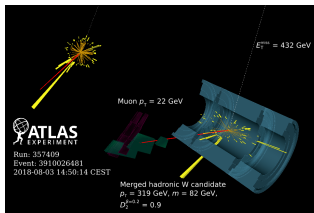
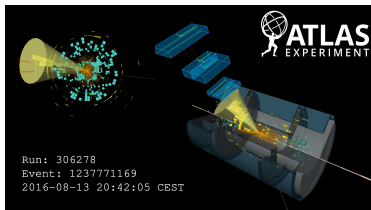
- LHC high-energy probe
- Allows characterisation of DM interaction
- Use/need model to guide phenomenology



- DM pair-produced, non-interacting (in detector - heavy neutrino-like).
- Include the DM interaction - 'mediator' particle, critical sensitivity.
- Mediator searches - complementary approach, resonance signatures.
- Use simplified models (with mediator), and specific complete models to explore.
- **Signature-driven approach - explore all DM signatures**
- Sensitivity across wide range of DM mass: heavy/WIMP DM, dark sectors (ALPs, dark photons, dark showers).

Introduction to Collider DM searches - Summary

- Any WIMP DM produced at collider experiments will interact weakly and pass invisibly through detectors.
- Inferred through 'Missing E_T ' (E_T^{miss}) when event does not balance in plane transverse to beam.
- Visible radiation (photons, jets, vector bosons) from ISR or associated production can tag DM pair production.
- Consequently, collider searches focus on production of a SM particle(s) (X) with large E_T^{miss} .



What makes a good simplified/concrete DM model?

Necessary

- Compelling dark matter candidate, ability to satisfy relic density
- Tractable no. of parameters
- Evades existing constraints
- Important, generic signatures

Desirable

- Interesting phenomenology
- Wide range of possible signatures (illustrate breadth of programme w/o 100s of models)
- Synergies: e.g.
 - ▶ invisible vs. mediator resonance
 - ▶ prompt vs LLP vs invisible
 - ▶ interplay with (in)direct detection

Models

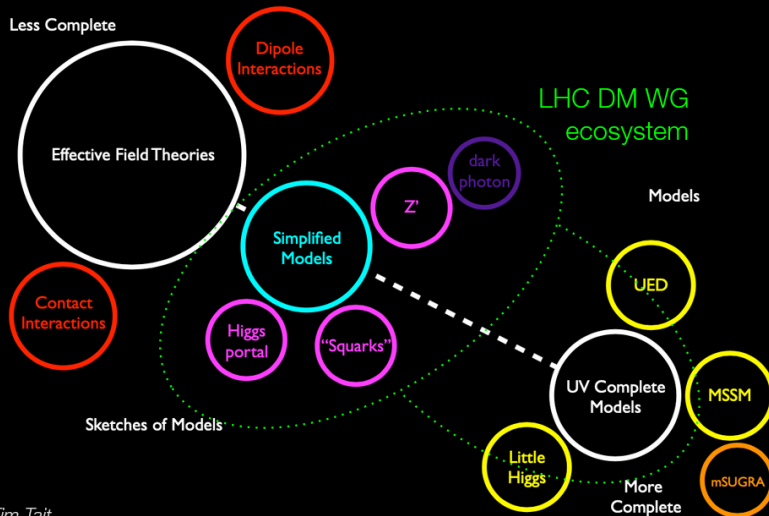
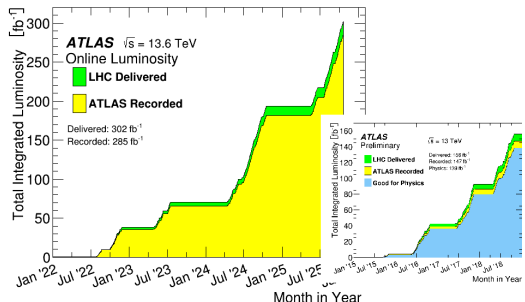


Figure: Tim Tait

LHC Datasets and Luminosity

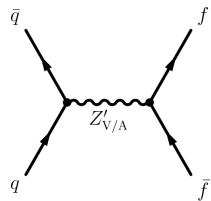
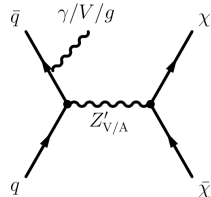
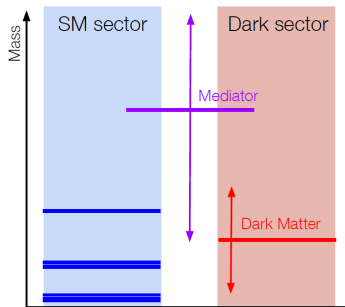
- LHC Run-2 ended in late 2018.
- An unprecedentedly sensitive dataset.
- Many **ATLAS** and **CMS** results (~ 600 each) already published, and more being released regularly.
- **And just the beginning...**
- LHC Run-3 at 13.6 TeV has been progressing steadily since summer '22. Run 3 results coming soon!
 - ▶ Greater luminosity and greater collision energy
 - ▶ Already tripled our data ($> 400 \text{ fb}^{-1}$) - more until mid-2026.



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S-channel Mediator Simplified Models - V/AV mediators

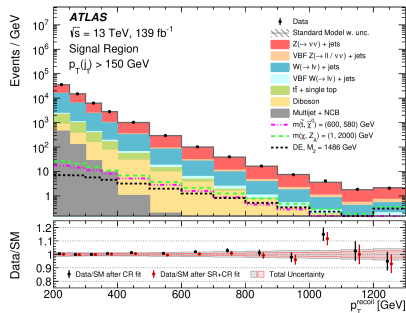
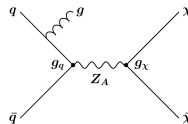
- Introduce mediator, talks to DM and SM sectors.
- Two complementary approaches:
 - ▶ Look for DM - mono-X signature
 - ▶ Look for mediator - resonance search



LHCDMWG White Paper (1507.00966)

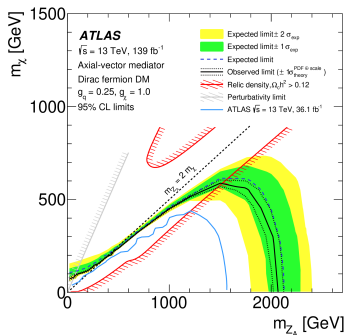
- Relic density: use to *guide* searches (simplified model useful, but incomplete)

- Very general DM search!
- Selections:
 - ▶ Energetic jet $p_T > 150$ GeV
 - ▶ $E_T^{\text{miss}} > 200$ GeV
 - ▶ Up to 3 extra jets
 - ▶ Search for excess in E_T^{miss}
- Shape fit in 13 E_T^{miss} bins (p_T^{recoil})
- Backgrounds: Z+jets, W+jets, Diboson, $t\bar{t}$
- Estimated in 1- and 2-lepton CRs
- High precision calculation ([paper](#)) of Z+jets/W+jets.
- O(1-2%) uncertainty on predicted background.

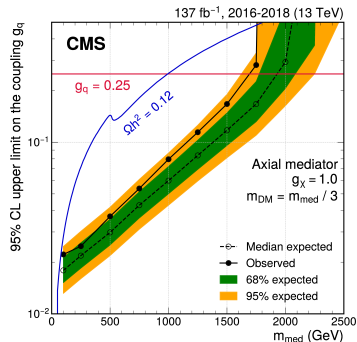


No significant excesses observed

Monojet Search - $\text{Jet}(s) + E_T^{\text{miss}}$ - Model Interpretations



2102.10874



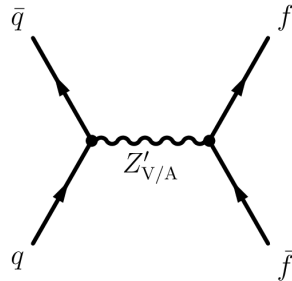
JHEP 11(2021)153

Many interpretations

- Simplified Models
 - Fix coupling, exclude $m_{\text{DM}} - m_{\text{med}}$; fix ratio, exclude coupling
- T-channel models (LHCDMWG White Paper 2504.10597)
- Generic sensitivity - e.g. SUSY, leptoquarks, extra dimensions

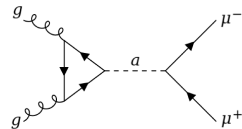
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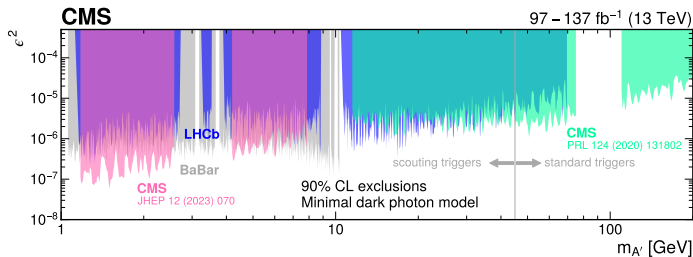
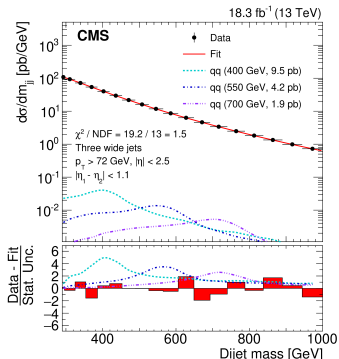


Mediator Resonance Searches - Dijets/dileptons

- General signature, dijet/dilepton resonances.
- Signal peak on falling background
- Dileptons if mediator couples
- Many techniques for low mass.

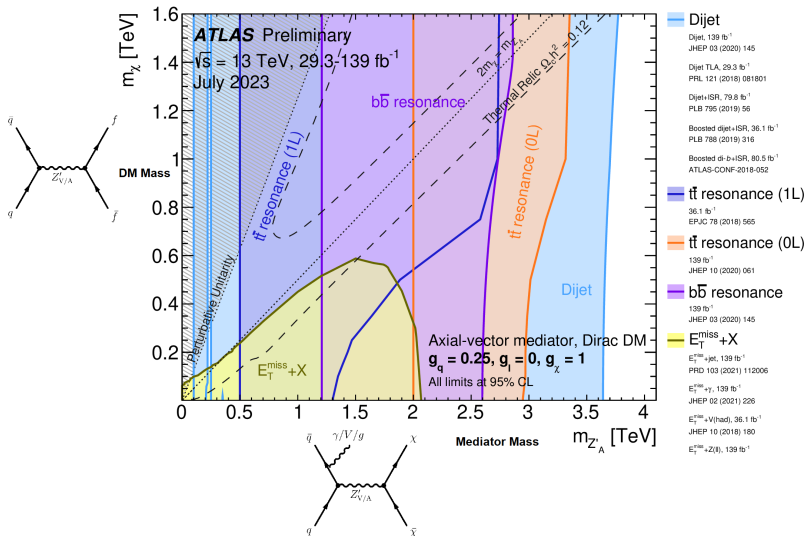


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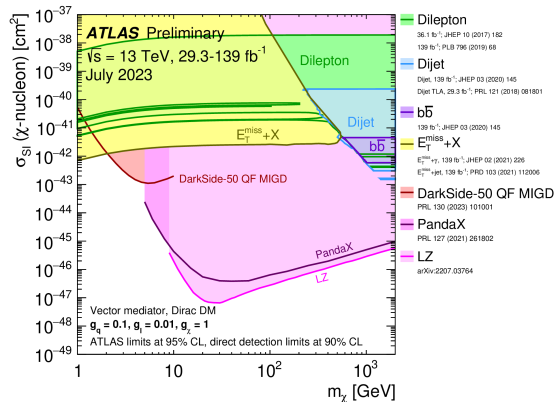
Putting it all together - Simplified Models I

- **ATLAS DM Summaries**
- Illustrate complementarity between mediator and invisible searches.

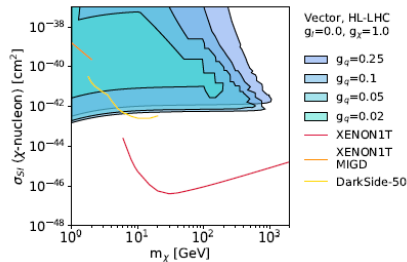


Comparisons with Detection Experiments

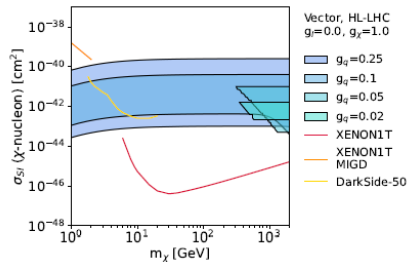
- **Key message: complementarity**
- LHCDMWG white paper on presentation ([1603.04156](#))
- Assumptions: WIMP, local DM density, interaction type (model-dependence).
- Colliders insensitive to DM mass (all is E_T^{miss}), mediator more important.
- Explore couplings to illustrate variations ([2203.12035](#), [2206.03456](#))



- Largely m_χ -independent
- Low dependence on coupling

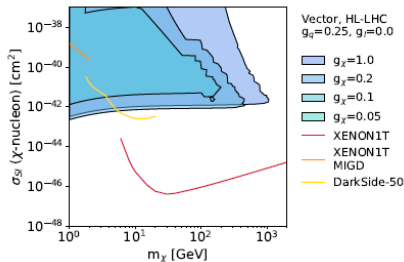


(a) Monojet analysis

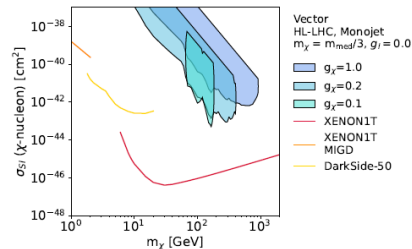


(b) Dijet analysis

- Mediator mass important
- Connect to light DM experiments
- LHC unique for larger m_{med}/m_χ



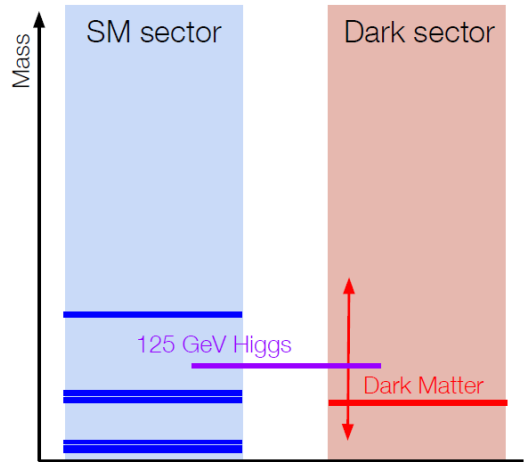
(a) Monojet analysis



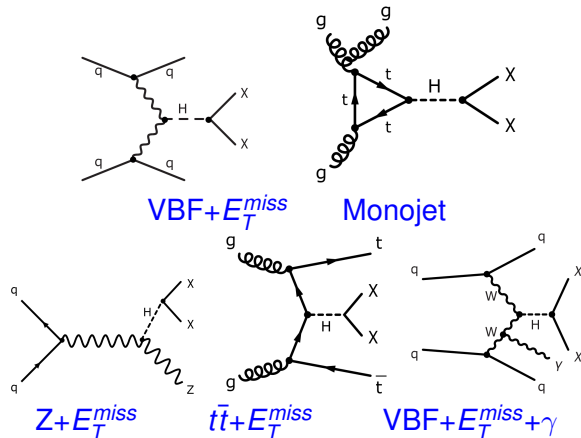
(a) Monojet analysis

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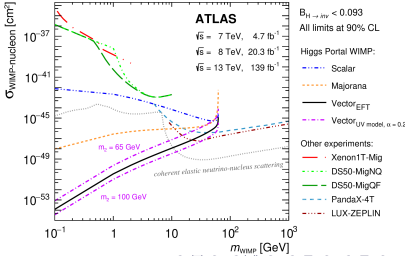
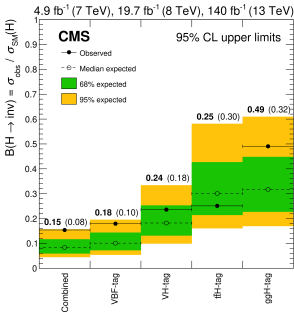


- ‘Vanilla’ Higgs portal
- Higgs boson mediates the interactions with DM, decays to DM
- ‘Invisible Higgs’ - anomalous BR ($H \rightarrow \text{inv} = 0.12\%$ in SM).
- Signatures: $E_T^{\text{miss}} + X$, each Higgs production mode.
- Sensitivity led by $\text{VBF} + E_T^{\text{miss}}$ and Mono-Z signatures.



- Run-2 combinations of 139 fb⁻¹ results, together with Run-1 analysis.
- $VBF+E_T^{miss}$ and $Z+E_T^{miss}$ most sensitive, Run-1 adds 4%.
- Already probing BR($H \rightarrow Inv$) at the 10% level!
- Conversions to scattering cross-section ([2107.01252](#))

Analysis	Best fit $\mathcal{B}_{H \rightarrow inv}$	Observed 95% U.L.	Expected 95% U.L.
Run 2 Comb.	0.04 ± 0.04	0.113	$0.080^{+0.031}_{-0.022}$
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$	0.252	$0.265^{+0.105}_{-0.074}$
Run 1+2 Comb.	0.04 ± 0.04	0.107	$0.077^{+0.036}_{-0.022}$

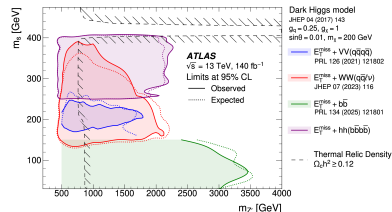
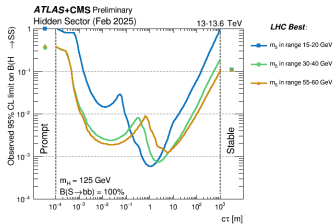
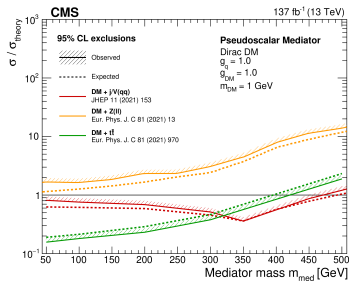


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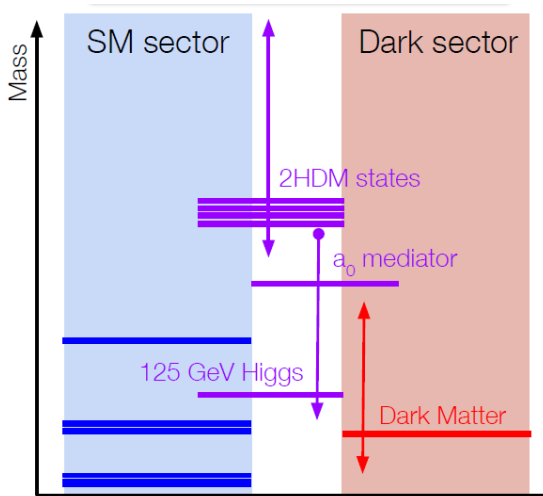
Scalar mediator models

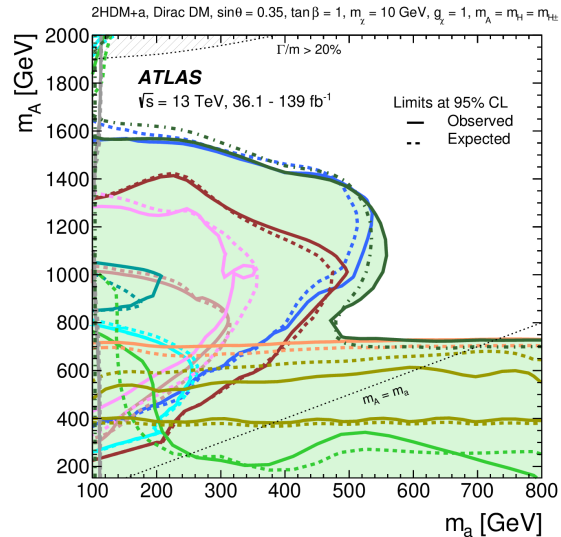
- Wide range of models, increasing complexity: simplified scalar mediator/extended Higgs sector/SUSY (many others).
- Complementary to (in)direct detection at high-masses; lower masses/couplings connect to lightDM and LLP programmes.
- Simplified models: dominant signatures $t\bar{t}$ with E_T^{miss} , also $t+E_T^{miss}$, monojet. 4-top (resonance) at higher mass.
- More complete models - broader/different signatures
- Dark higgs/scalar models: scalar S mixes with SM Higgs.
 - Colliders sensitive at high mass/mixing ($h\bar{h}$ resonance or $h \rightarrow ss$, or low mixing plus second mediator).
 - Active LLP target (dark Higgs portal).



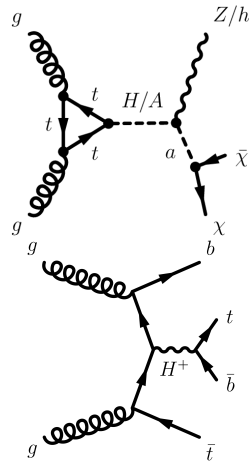
Extended Higgs sectors - 2hdm+a

- Higgs sector unique and unexplored
- Natural portal to dark matter
- LHC DM WG benchmark white paper ([1810.09420](#))
- Postulate two-Higgs doublet (ext. Higgs sector)
- Pseudoscalar (a) portal to DM. Reduced constraint from DD.
- For heavier m_{DM} , target scalar sector mediators.
- Interesting physics from wide range of signatures and A-a mixing.

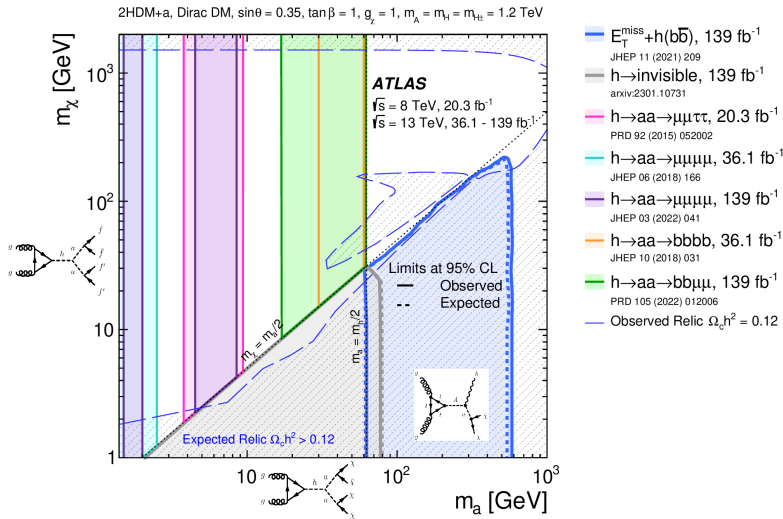




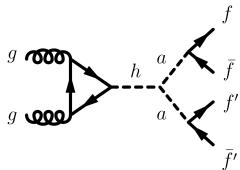
- $E_T^{\text{miss}} + h(b\bar{b})$, 139 fb $^{-1}$
 JHEP 11 (2021) 209
- $E_T^{\text{miss}} + h(\tau\tau)$, 139 fb $^{-1}$
 arXiv:2305.12938
- $E_T^{\text{miss}} + h(\gamma\gamma)$, 139 fb $^{-1}$
 JHEP 10 (2021) 13
- $E_T^{\text{miss}} + Z(\ell\ell)$, 139 fb $^{-1}$
 PLB 829 (2022) 137066
- $E_T^{\text{miss}} + Z(q\bar{q})$, 36.1 fb $^{-1}$
 JHEP 10 (2018) 180
- $E_T^{\text{miss}} + tW$, 139 fb $^{-1}$
 arXiv:2211.13138
- $E_T^{\text{miss}} + j$, 139 fb $^{-1}$
 PRD 103 (2021) 112006
- $tbH^\pm(tb)$, 139 fb $^{-1}$
 JHEP 06 (2021) 145
- $t\bar{t}t\bar{t}$, 139 fb $^{-1}$
 arXiv:2211.01136
- $h \rightarrow \text{invisible}$, 139 fb $^{-1}$
 arxiv:2301.10731
- **Combination**
 $E_T^{\text{miss}} + h(b\bar{b})$, $E_T^{\text{miss}} + Z(\ell\ell)$, $tbH^\pm(tb)$



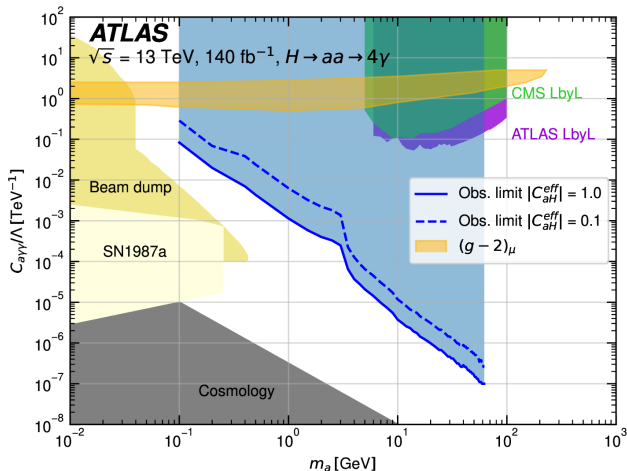
- Golden channel is $h \rightarrow aa \rightarrow 4f/4\chi$
- Complementary with lower-mass ALP searches for pseudoscalars (2202.12631).
- Light resonant searches powerful when a cannot decay to DM.
- Invisible signatures kick in for lower DM masses.



Aside: Axion-like particle (ALP) searches

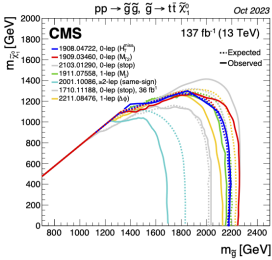


- ALP searches for light pseudo-scalars (from U(1) SSB).
- Several final states, depending upon mass.
- Lowest masses probed by $a \rightarrow \gamma\gamma$
- Non-resonant diboson production also relevant at LHC.

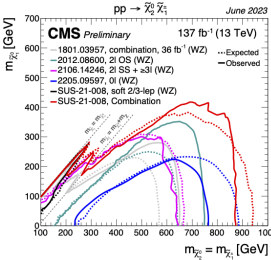


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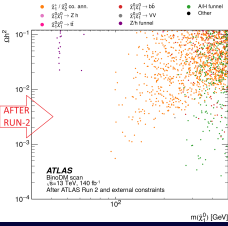
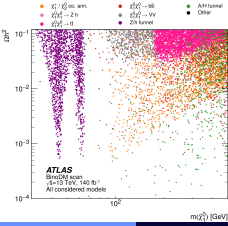
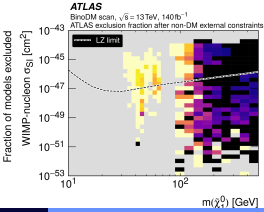
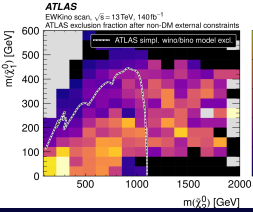
- Also a full SUSY programme, (long-standing DM search).
- Cover all signatures - many final states and processes constrained.
- Also look to contextualise in model space.



Stop searches

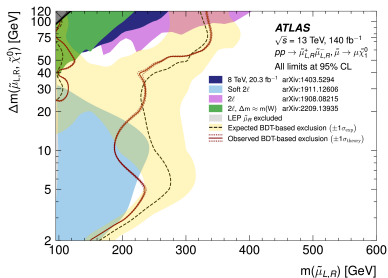


Electroweakinos



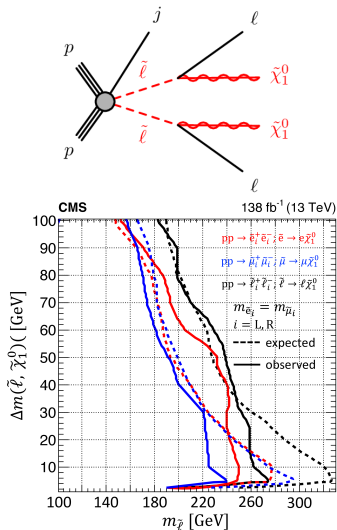
SUSY Strikes Back?

- Recent interest in results looking for different (and thus less well constrained) 'compressed EWK scenarios'.
- Small δ mass between SUSY partners of electroweak bosons, low p_T signatures.
- Multiple ($\sim 2\sigma$) excesses - Run-3 data needed!



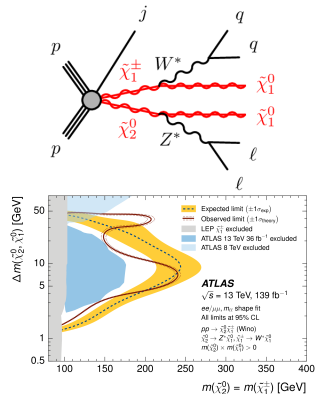
2106.01676

James Frost (Rutherford Appleton Laboratory)



2508.13900

HEP Forum, 2025

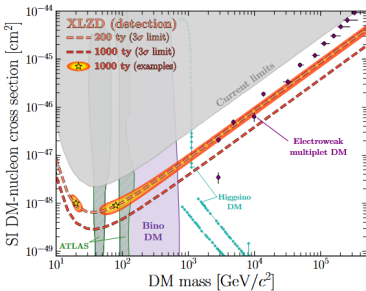


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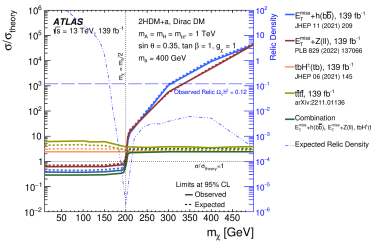
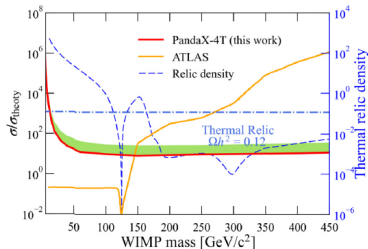
Also CMS: 2111.06296

Complementarity II

- Lovely to see cross-fertilisation!

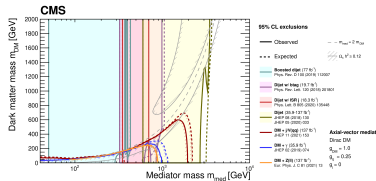
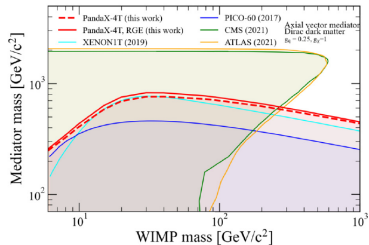


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2208.03626



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Light DM and Dark Sectors

- Have some hidden sector which (usually) includes a DM candidate
- Postulate a portal that communicates between SM and dark sectors, i.e. have some dark sector states decay back to SM with small coupling.
- Common in very weakly/feebly interacting models
- Dark sector need not be thermal - freeze-in via heavy particle decays.

Portal

Dark Photon, A_μ

Dark Higgs, S

Axion, a

Sterile Neutrino, N

Dark Photons

Massive new dark gauge boson γ_D from U(1) extension

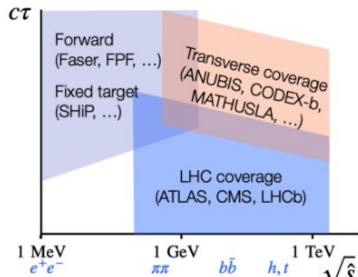
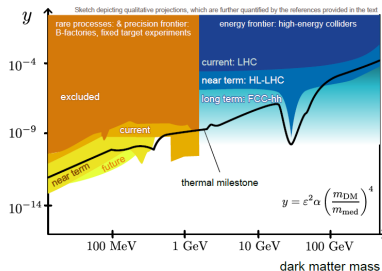
Mixes with SM photon (ϵ parameter)

Strategies for prompt and LLP signatures.

PBC Report

New, light/weakly coupled DM experiments

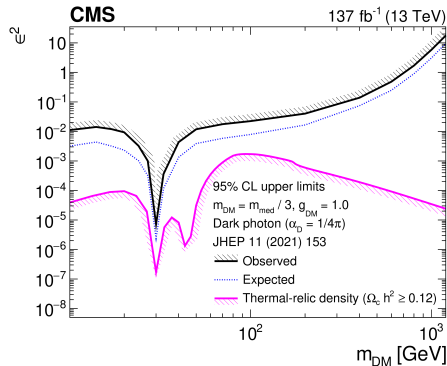
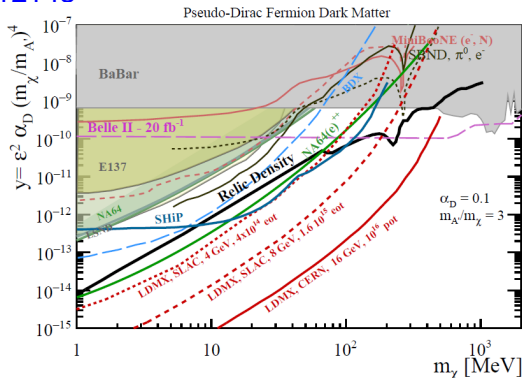
- New generation of experiments designed which complement existing LHC experiments.
 - ▶ Forward experiments
 - ▶ Transverse coverage
 - ▶ Fixed target
- Cover very weakly interacting light particles, may exploit LHC as source (e.g. neutrino beam).
- Focussing on DM - but motivations are much wider than this!
 - ▶ collider neutrino physics, low-x QCD, astro-/cosmic ray physics, [dark matter](#), new exotica,



Monojet and the dark photon portal

- Can also recast limits into PBC portals to connect to light DM.
- Full m_{DM} picture.
- Note colliders cover full m_{DM}/m_{med} range.

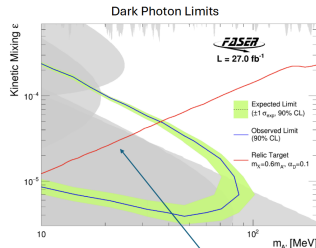
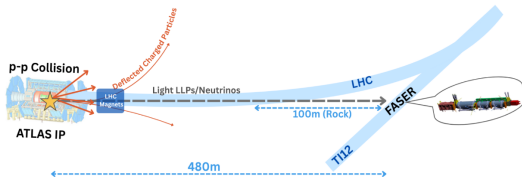
2102.12143



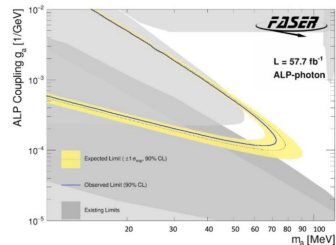
2405.13778

FASER

- Detector far forward of ATLAS - sensitive to light LLP (e.g. dark sector mediators) and collider neutrinos.
- Sensitive to dark photons with small couplings, and esp. $2m_e < m_{A'} < 2m_\mu$.
- Also ALPs, with $a \rightarrow \gamma\gamma$.
- All FASER papers, e.g. first observation of collider ν
- New for 2025: Preshower detector (near-by $\gamma\gamma$)
- Over 200 fb^{-1} of data, 5-10x existing results. Run-4 approved = $\sim 680 \text{ fb}^{-1}$.

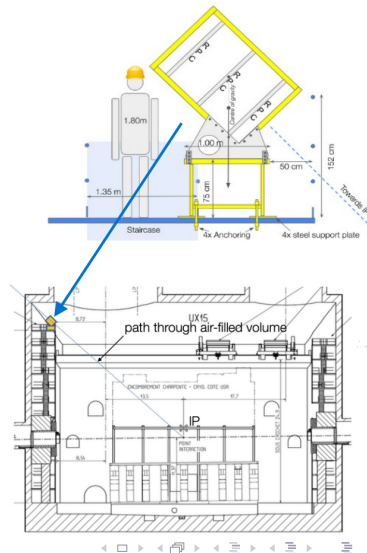
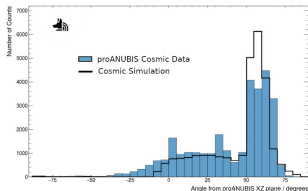


Red line is region motivated by DM thermal relic density



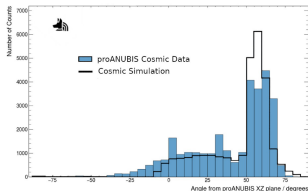
ANUBIS

- Transverse detector - heavy FIPs at $\geq$ EWK scale.
- Sensitivity to LLPs (>1 GeV) with $c\tau > O(10^2 m)$.
- Use ATLAS cavern as particle decay volume.
- Exploit ATLAS detector to veto collision products.
- Current focus: proANUBIS prototype detector.
- Installed March '23 - 160 fb^{-1} recorded to date.
- Validate detector tech., ATLAS synth., reco

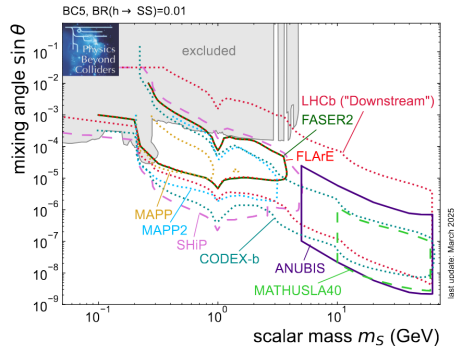


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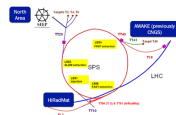
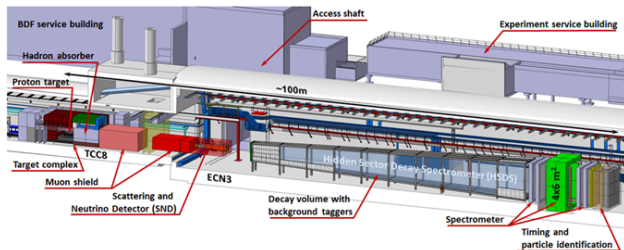


ANUBIS complementary to FASER/FPF & SHiP



PBC report 2025 for ESPPU

- Great sensitivity for feebly-interacting particles in hidden sector models, SM neutrino measurements.
- UK leadership/initiation.
- Beam dump experiment approved for construction in the North Area ECN3 facility - SPS 400 GeV proton beam.
- Data-taking to start prior to LS4 (2033, const. 2029) - upgrades for Run-5, operation throughout 2040s.



Accelerator schedule	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
LHC	Run 3		LS3				Run 4		LS4			
SPS (North Area)	Run 3		LS3				Run 4		LS4			
BDF / SHiP	Design and prototyping		Production / Construction / Installation				Operation		Complete detector / consolidation			
Milestones BDF	TDR studies		PRR		PRR		SwB					
Milestones SHiP	TDR studies		PRR		PRR		SwB					

Approval for TDR

Facility TDR submission

Experiment TDRs submission

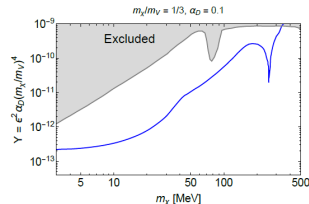
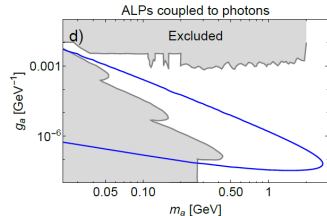
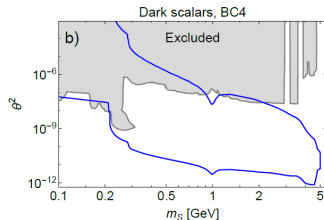
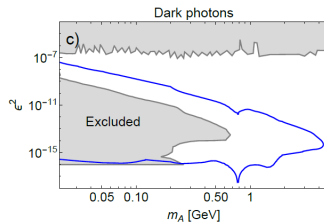
Start of detector installation

Facility commissioning

Experiment commissioning & start of data taking

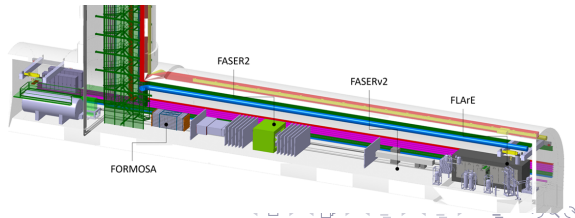
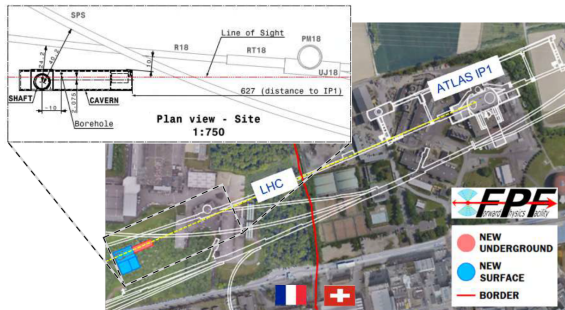
SHiP Physics

- Intense SPS proton beam (400 GeV) onto a heavy target produces FIPs.
- Identify decays in isolated volume, isolated vertex from target.
- SPS delivery of 4×10^{19} PoT annually.
- Design for < 1 background event up to lifetime 6×10^{20} PoT.
- 90% CL exclusions shown - leading sensitivity to many models
- Also other aims: neutrino programme (esp. HNLs, ν_τ).



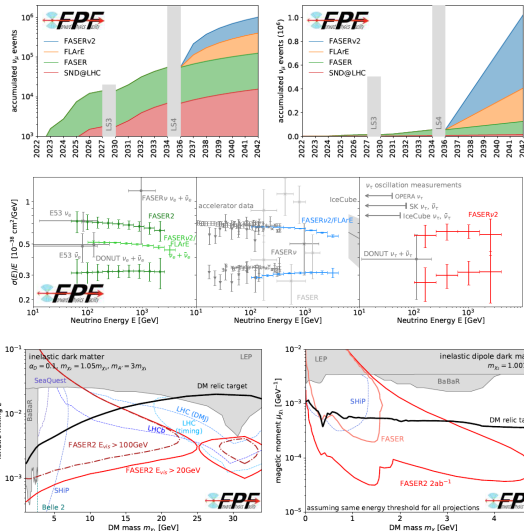
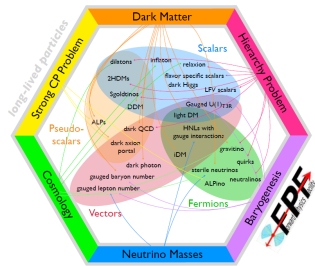
Forward Physics Facility

- Rich physics potential motivates dedicated forward facility for HL-LHC
- Exploit lumi with longer/wider detectors (target volume, flavour production) and new detectors (complementary physics)
- FPF LoI submitted to CERN last week
- Site selected west of ATLAS, investigations complete.
- Four experiments designed for FPF - layout under optimisation
 - ▶ FORMOSA (milli-charged particles), FASER2 & FASER ν 2 (both enlarged), FLArE (LAr TPC for DM & ν)



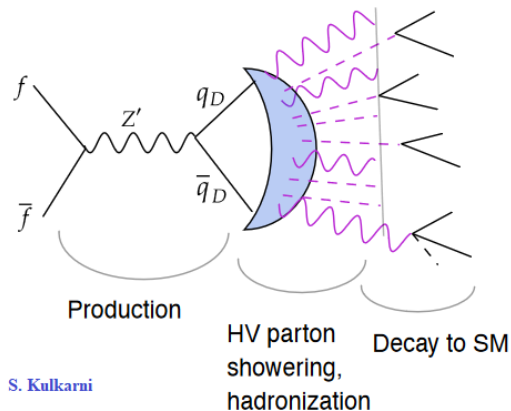
FPF Physics

- Physics sensitivity from huge collider neutrino production
- Strong sensitivity across dark sectors.
- Particular strengths: LLPs from compressed spectra (soft photons), heavy exotica (LHC energies)



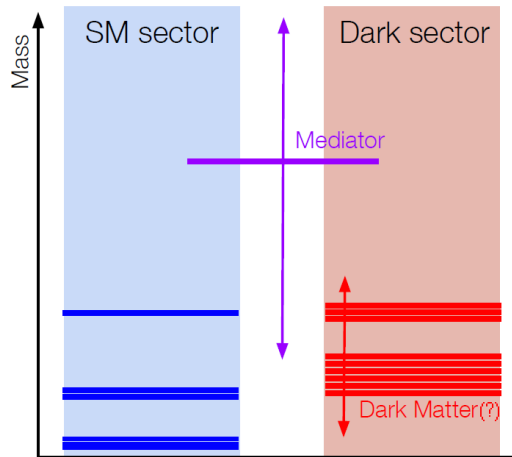
Strongly-interacting dark sectors - dark QCD/showers

- What if dark sector confined?
- Simple mediator, but complex dark sector/matter phenomena.
- Generate dark quarks, hadronise into dark hadrons
- Dark hadrons: stable $\rightarrow E_T^{miss}$, unstable $\rightarrow$ decay to SM. Invisible fraction r_{inv}
- Unusual hadronic signatures.
- Prompt dark hadron decay $\rightarrow$
Semi-visible jet signature: SM jet aligned with E_T^{miss} (ATLAS, CMS).
- Unstable dark hadrons - dark jets; dark meson search



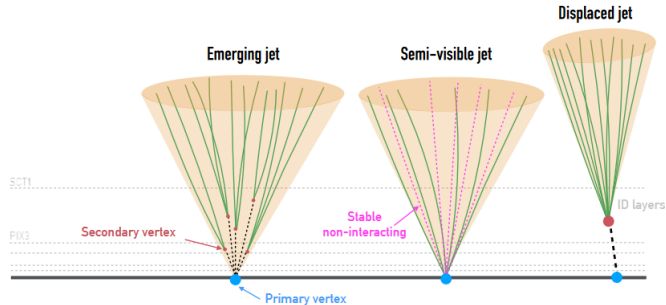
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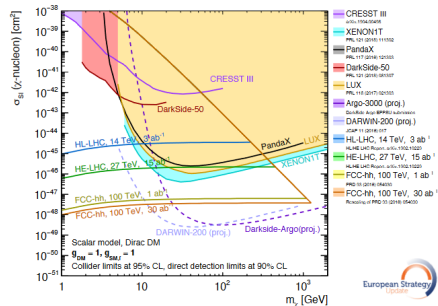


Semi-Visible, Emerging and Displaced Jets

- For dark hadron lifetimes $O(10^{-3}-1)$, expect multiple displaced vertices in a jet $\rightarrow$ emerging jet ([ATLAS](#), [ATLAS R3](#), [CMS](#))
- Greater lifetimes yield a displaced jet, with jet constituents pointing to a common displaced/secondary vertex.
- Important to cover the signature space, not leave holes between topologies.
- Theoretical modelling questions also pertinent (benchmark effort + [workshop](#)).



- Community Review [LHCDMWG WS, May '24](#)
- Run-3: New sensitivity - dedicated triggers, improved techniques (incl. LLP), all signatures.
- HL-LHC (2030-) will bring ultimate sensitivity (3 ab^{-1})
- Current and future DD experiments strengthening.
- Good time to ask complementary questions:
 - ▶ If ID/DD sees something, can we target it at colliders? If we see something?
 - ▶ Do we have model coverage? That translate between areas?
 - ▶ What counts as gold-standard DM discovery?



[CMS DM Summary Paper](#)
[ATLAS Simplified Model Paper](#)
[ATLAS 2hdm+a Paper](#)
Web portals: [ATLAS Searches](#)
[CMS Publications](#)

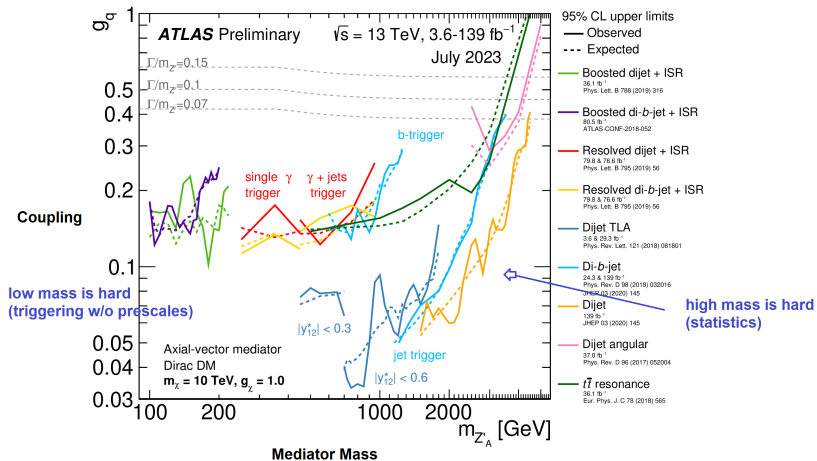
Conclusions

- Colliders are an interesting place to look for dark matter.
- Some unique advantages (high energy, probe interaction, DM candidate range).
- Some challenges (model guide, insensitivity to DM itself).
- LHC Run-2 dataset powerful, huge broadening of programme.
- WIMP hypotheses $\rightarrow$ + dark photons, ALPs, dark sectors.
- Run-3 and beyond: vital to continue to look widely, to ensure no missing opportunities.
- Investigate any hints from other sources (DD, lightDM, forward exp., LLP exp.). Smooth interfacing/translation critical.
- (Me) v. interested in developing this for HL-LHC/XLZD era!
- Still only $\sim 10\%$ of the final HL-LHC dataset recorded, much yet unexplored!



Putting it all together - Simplified Models I

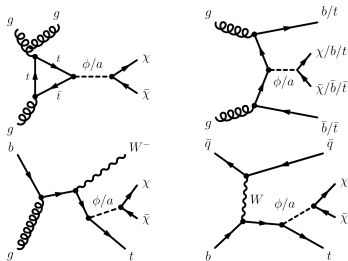
- ATLAS DM Summaries
- How do our mediator resonance searches do?



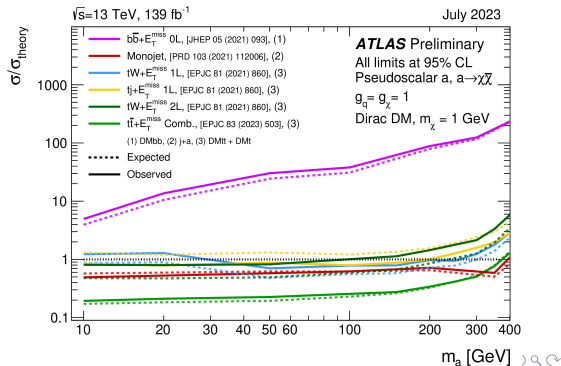
Spin-0 Simplified Models

- Consider scalar/pseudo-scalar mediators
- Yukawa-type couplings $\rightarrow$ heavy quark (b/t)-associated searches dominate.

Relevant Signatures:

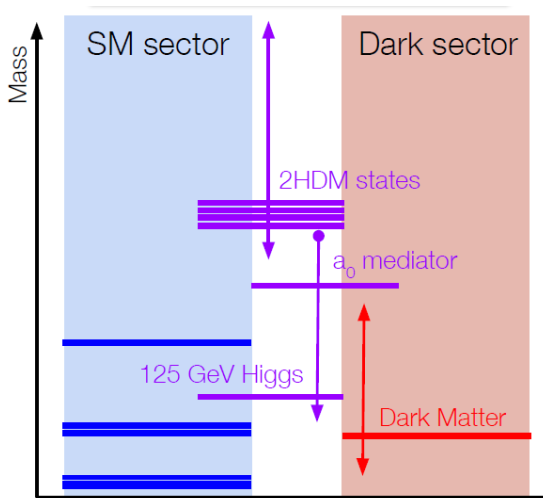


- $t\bar{t} + E_T^{\text{miss}}$ combination
- $tW + E_T^{\text{miss}}$
- $b\bar{b} + E_T^{\text{miss}}$
- monojet



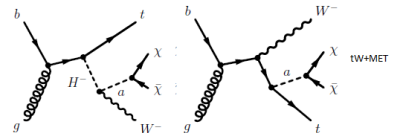
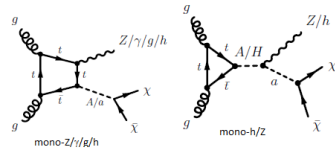
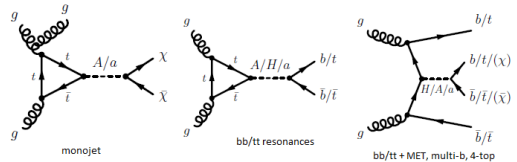
Extended Higgs sectors - 2hdm+a

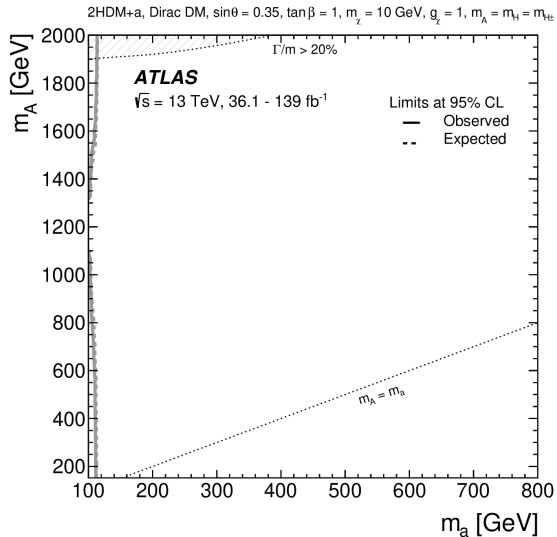
- Higgs sector unique and unexplored
- Natural portal to dark matter
- LHC DM WG benchmark white paper ([1810.09420](#))
- Postulate two-Higgs doublet (ext. Higgs sector)
- Pseudoscalar (a) portal to DM. Reduced constraint from DD.
- For heavier m_{DM} , target scalar sector mediators.
- Interesting physics from wide range of signatures and A-a mixing.



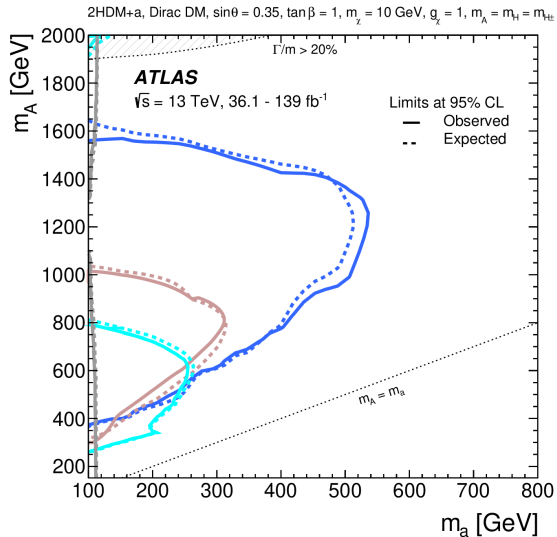
2HDM+a - Overview

- UV complete model: pseudoscalar mediator with Extended Higgs sector.
- Rich phenomenology with great signature interplay.
- Complex model - [LHC DM WG white paper](#) defines several benchmarks.
- Incorporates analyses from across ATLAS search programme.
- New addition single top (tW/tq) + E_T^{miss} search ([2211.13138](#)).

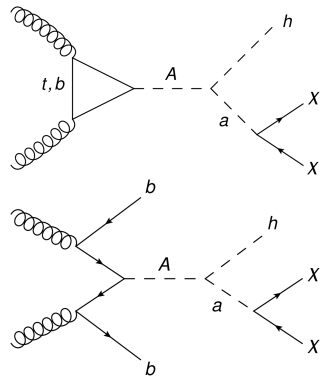


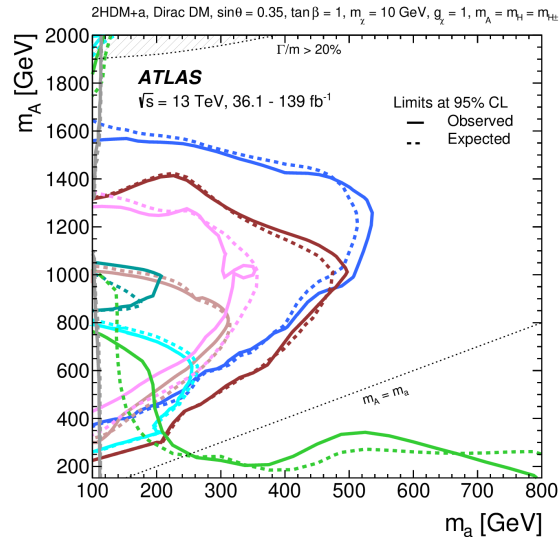


— $h \rightarrow \text{invisible}$, 139 fb $^{-1}$
 arxiv:2301.10731

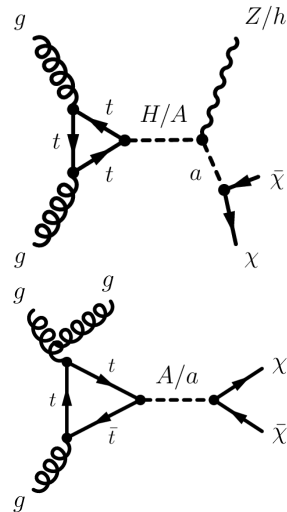


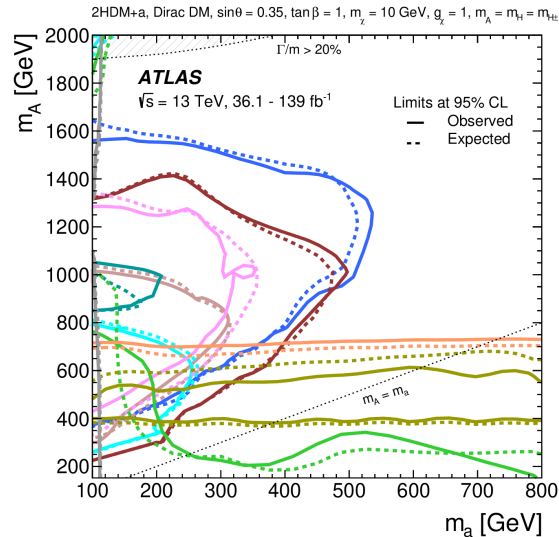
- $E_T^{\text{miss}} + h(b\bar{b})$, 139 fb $^{-1}$
 JHEP 11 (2021) 209
- $E_T^{\text{miss}} + h(\tau\tau)$, 139 fb $^{-1}$
 arXiv:2305.12938
- $E_T^{\text{miss}} + h(\gamma\gamma)$, 139 fb $^{-1}$
 JHEP 10 (2021) 13
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 arxiv:2301.10731



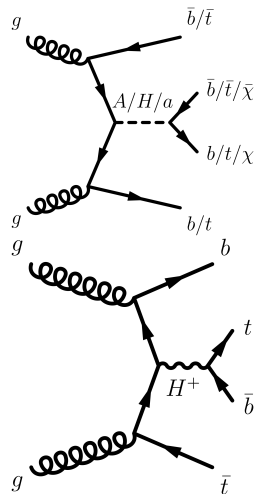


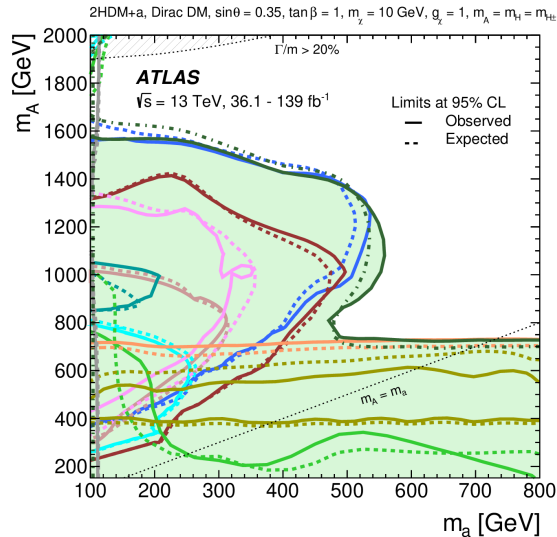
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- $E_T^{\text{miss}} + Z(\ell\ell)$, 139 fb $^{-1}$
 PLB 829 (2022) 137066
- $E_T^{\text{miss}} + Z(q\bar{q})$, 36.1 fb $^{-1}$
 JHEP 10 (2018) 180
- $E_T^{\text{miss}} + tW$, 139 fb $^{-1}$
 arXiv:2211.13138
- $E_T^{\text{miss}} + j$, 139 fb $^{-1}$
 PRD 103 (2021) 112006
- $h \rightarrow \text{invisible}$, 139 fb $^{-1}$
 arxiv:2301.10731



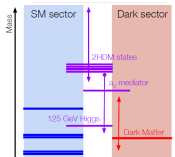


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- $E_T^{\text{miss}} + j$, 139 fb $^{-1}$
 PRD 103 (2021) 112006
- $t\bar{b}H^\pm(tb)$, 139 fb $^{-1}$
 JHEP 06 (2021) 145
- $t\bar{t}t\bar{t}$, 139 fb $^{-1}$
 arXiv:2211.01136
- $h \rightarrow \text{invisible}$, 139 fb $^{-1}$
 arxiv:2301.10731

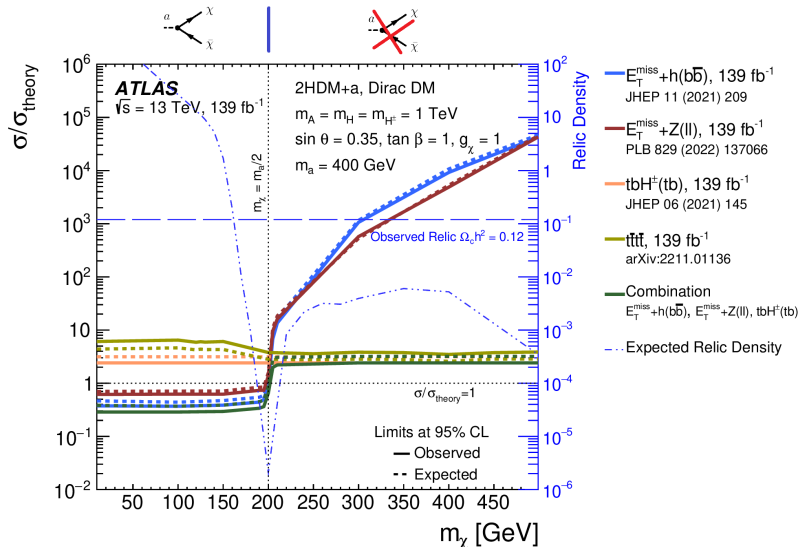




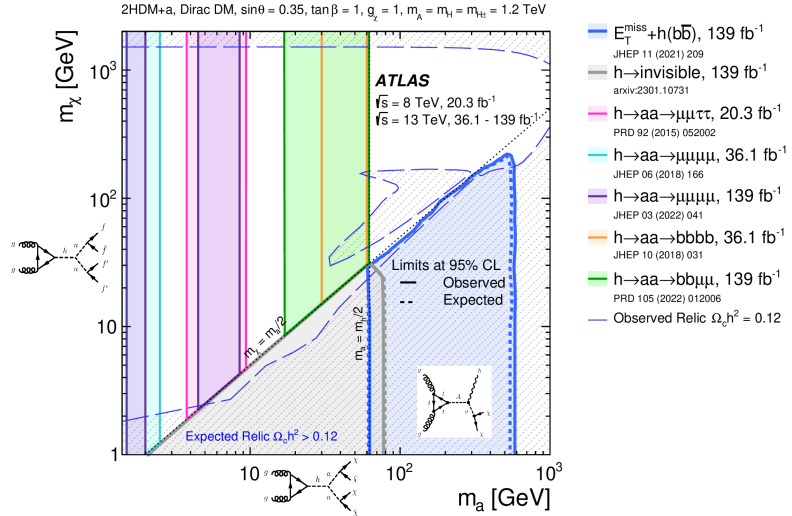
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 PRD 103 (2021) 112006
- $tbH^\pm(tb)$, 139 fb $^{-1}$
 JHEP 06 (2021) 145
- $t\bar{t}t\bar{t}$, 139 fb $^{-1}$
 arXiv:2211.01136
- $h \rightarrow \text{invisible}$, 139 fb $^{-1}$
 arxiv:2301.10731
- **Combination**
 $E_T^{\text{miss}} + h(b\bar{b})$, $E_T^{\text{miss}} + Z(\ell\ell)$, $tbH^\pm(tb)$



- Insensitivity to DM mass allows R.D. satisfaction.
- But can vary the DM mass to show dependence.
- Heavy Higgs/Mediator searches constrain higher m_χ .

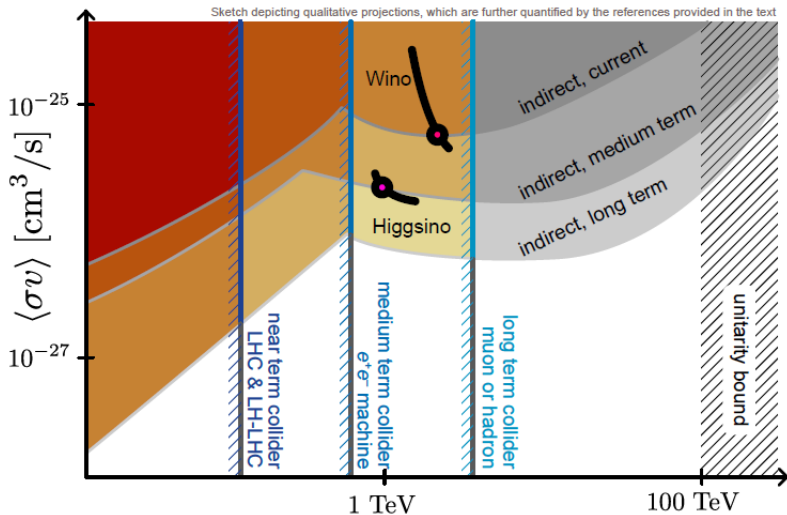


- Complementary with lower-mass ALP searches for pseudoscalars (2202.12631).
- Light resonant searches powerful when a cannot decay to DM.
- Invisible signatures kick in for lower DM masses.



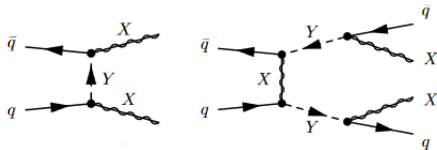
Snowmass complementarity 2206.03456

- DM in Dirac fermion doublet (Higgsino) or of a Majorana fermion triplet (Wino)
- Very minimal/predictive model
- RD + cosmology + freezeout gives mass.
- Wino at edge of ν fog, Higgsino foggy.



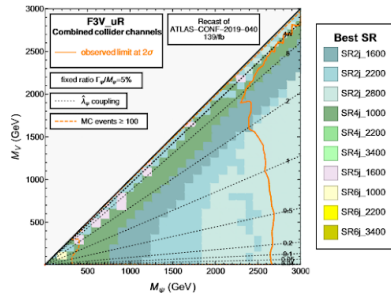
Ongoing Efforts - T-channel models

- T-channel process often exists in DM models.
- Often same final state as e.g. SUSY searches
- e.g. disquark/monojet signatures



- LHCDMWG-inspired UFO with range of t-channel models
- Extend SM with DM (X) and mediator (Y)

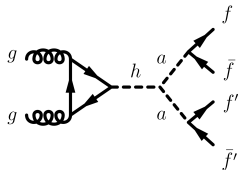
$$\mathcal{L}_{F3S_uR} = \left[\hat{\lambda}_\psi \bar{\psi} u_R \tilde{S} + \text{h.c.} \right],$$
$$\mathcal{L}_{S3M_uR} = \left[\lambda_\varphi \tilde{\chi} u_R \varphi^\dagger + \text{h.c.} \right],$$
$$\mathcal{L}_{F3V_uR} = \left[\hat{\lambda}_\psi \bar{\psi} \tilde{V} u_R + \text{h.c.} \right].$$



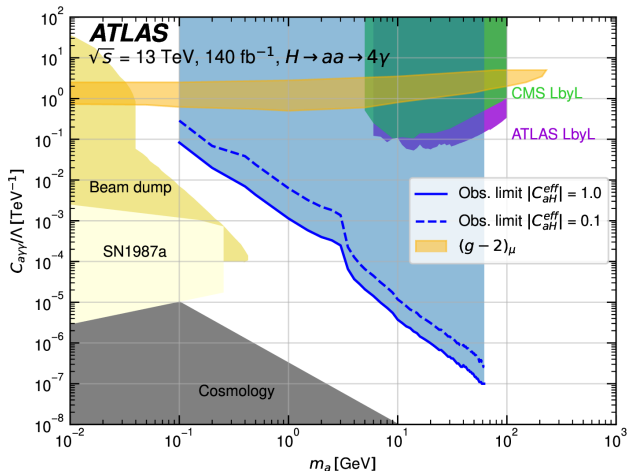
[2010.07559](#) (using strong 0L)

White paper studies ongoing, incl. leptophilic and long-lived models.

Aside: Axion-like particle (ALP) searches



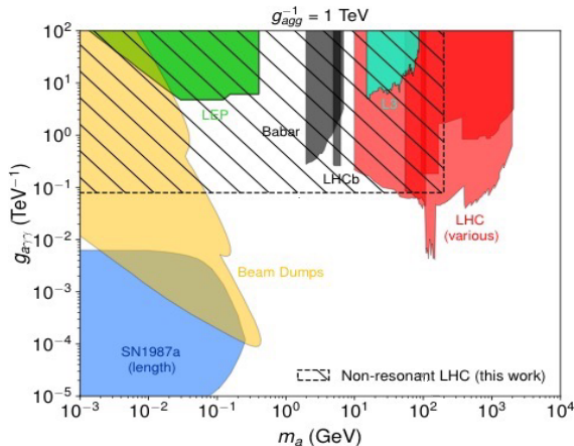
- ALP searches for light pseudo-scalars (from U(1) SSB).
- Several final states, depending upon mass.
- Lowest masses probed by $a \rightarrow \gamma\gamma$
- Non-resonant diboson production also relevant at LHC.



EPJC 84(2024)742

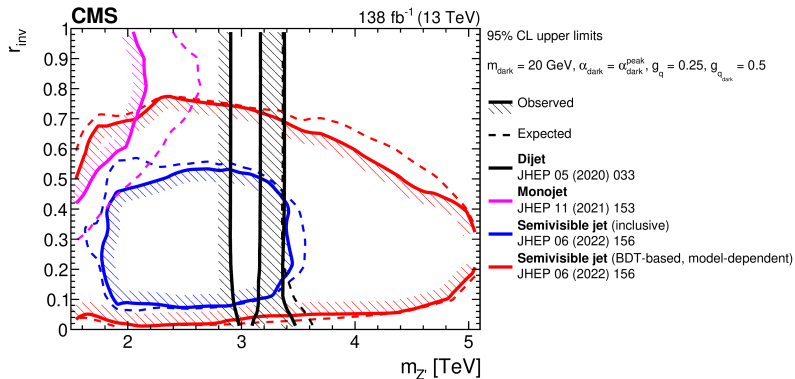
Lighter DM - Non-resonant ALP searches

- Recent interest in non-resonant and loop-induced ALP searches at LHC.
- e.g. high mass tails of diboson production ([paper](#))
- Also VBS VV of interest (indep. of gluon coupling).
- Electroweak ALPs accessible via $t\bar{t}$ resonances.
- Clear complementarity with other experiments
- Also with our light-by-light, $h \rightarrow aa \rightarrow 4\gamma$



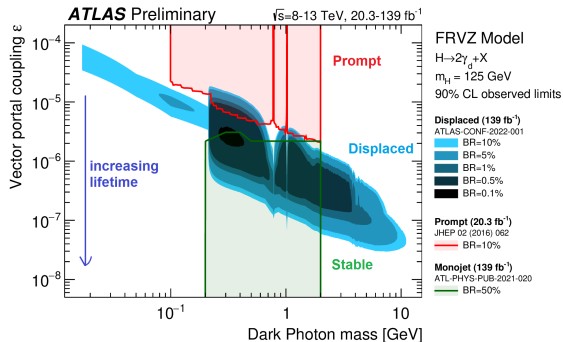
1905.12953, re-interpreting CMS $ZZ/\gamma\gamma$ searches

Snowmass complementarity 2206.03456



Summaries for prompt & LL signatures

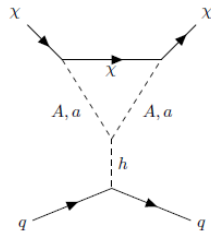
- LLP, or phase spaces with them, are ubiquitous in many DM models.
- Important complementarity with prompt searches. (Cf. visible/invisible, low-/high-mass).
- Also the *very* long-lived extreme e.g. monojet, $h \rightarrow \text{Inv}$ (for e.g. $h \rightarrow ss$).



- Encountered for $h \rightarrow aa$, dark photon models. Will appear for darkjets, ALPs, $2\text{hdm}+a/\text{dark higgs}$.

Beyond Collider Reinterpretations / Colliders as data consumers

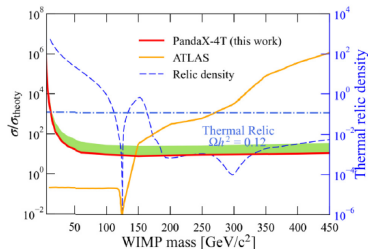
- Great to increase interaction with detection results.
- **Challenges**
 - ▶ We have varied models, interactions not necessarily pure SI/SD.
 - ▶ Would our events always show up in the WIMP search region?
 - ▶ Sensitivity to DM is indirect (once mediator decays invisibly) - m_{DM} /couplings set as benchmark or left to allow R.D. satisfaction.
- **Wishlist for moving to more complete models, or exploration of wider model spaces (e.g. pMSSM, 2hdm+a)**
 - ▶ would like translation from HEP model set (masses, interactions) to DD/ID cross-section and constraints? (MadDM)
 - ▶ or translation from detection limit to limits on a given interaction/set of effective interactions.
 - ▶ e.g. DD not sensitive to our 2hdm+a benchmarks ($m_{DM} = 10$ GeV). But enforcing R.D. may require $m_{DM} \sim m_a/2$ - then is DD important? Or if we scan m_{DM} ?
 - ▶ e.g. We scan pMSSM (20-D) space, imposing R.D. not exceeded, where do these lie on WIMP exclusion curve?



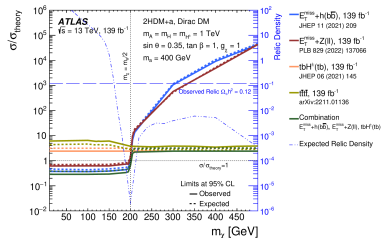
SI detection signal from loop-level in 2hdm+a

Interfacing/Translation

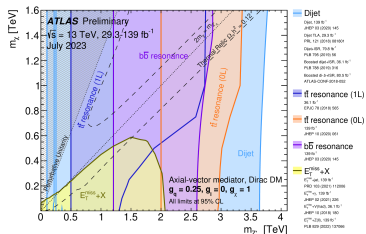
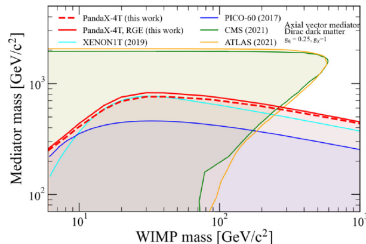
- If we or DD saw a signal, how could the other focus/confirm it?

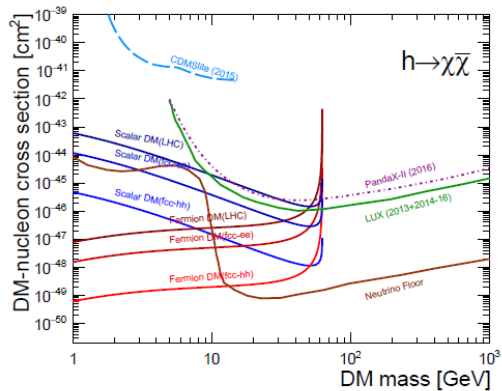


2208.03626



2306.00641



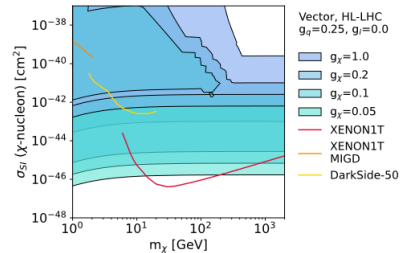
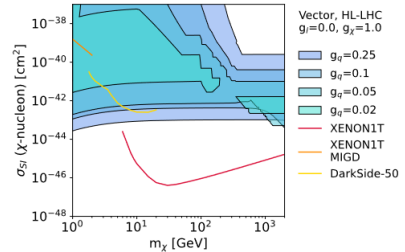


(b) Higgs portal model

- Multi-D space.
- Usually we fix 2 of these, scan 1.

$$\sigma_{\text{SI}} \simeq 6.9 \times 10^{-41} \text{ cm}^2 \cdot \left(\frac{g_q g_{\text{DM}}}{0.25} \right)^2 \left(\frac{1 \text{ TeV}}{M_{\text{med}}} \right)^4 \left(\frac{\mu_{n\chi}}{1 \text{ GeV}} \right)^2$$

$\frac{g_q g_{\text{DM}}}{0.25}$ → Product of couplings
 $\frac{1 \text{ TeV}}{M_{\text{med}}}$ → Mediator mass
 $\frac{\mu_{n\chi}}{1 \text{ GeV}}$ → Reduced mass
 $\mu_{n\chi} = m_n m_{\text{DM}} / (m_n + m_{\text{DM}})$



Spare slide