Dark Matter Searches at the LHC

James Frost
(james.frost@physics.ox.ac.uk)

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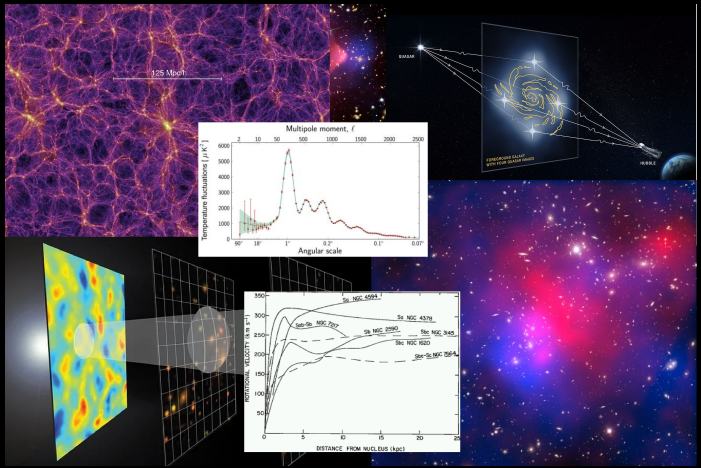
Outline

Why search for Dark matter?

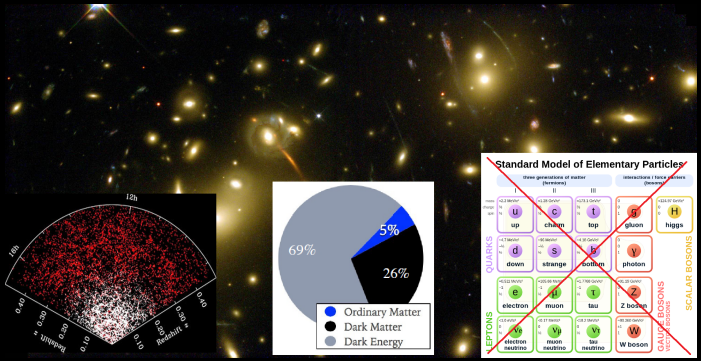
- Galactic rotation curves
- Dwarf galaxies
- Large scale structure
- Gravitational lensing
- Cluster collisions
- CMB + Baryogenesis



How to search for Dark matter?

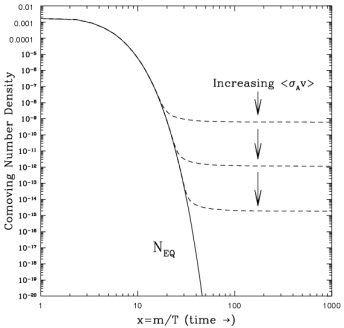
- Gravitationally interacting
- Dark
- Cosmologically stable
- 5x as much as SM

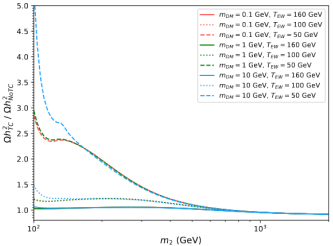
Properties inconsistent with any SM particle



Models of dark matter

- Dark matter must have very small effective SM couplings
  - Directly to SM particles?
  - Indirectly through BSM particles?
- Incorporate astrophysical knowledge
  - Relic density
  - Mechanism (freeze out, freeze-in)
  - DM nature (scalar, Dirac fermion, etc...)
- Candidates: WIMPs, dark γ axion/axion-like particles, dark sectors





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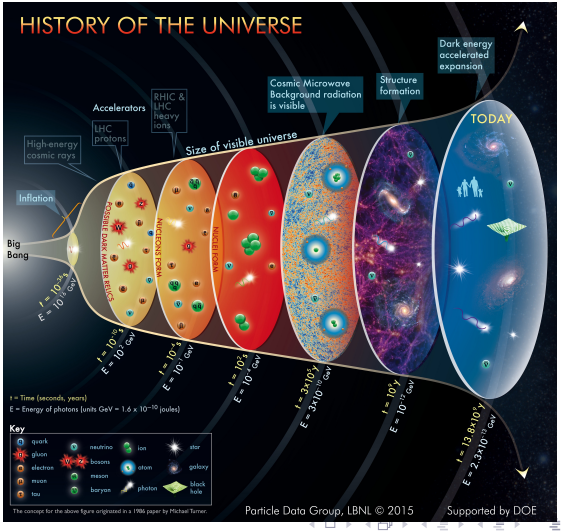
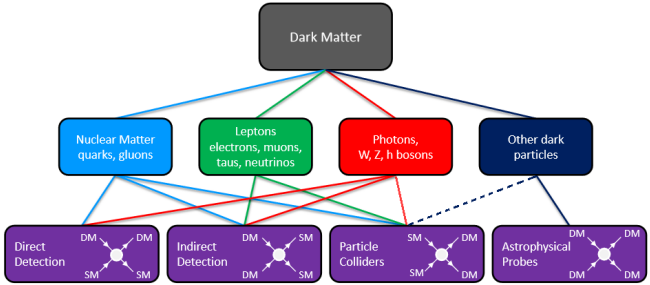


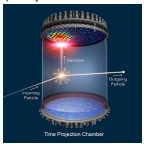
Complementarity, signatures

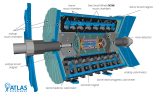
Assumptions

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

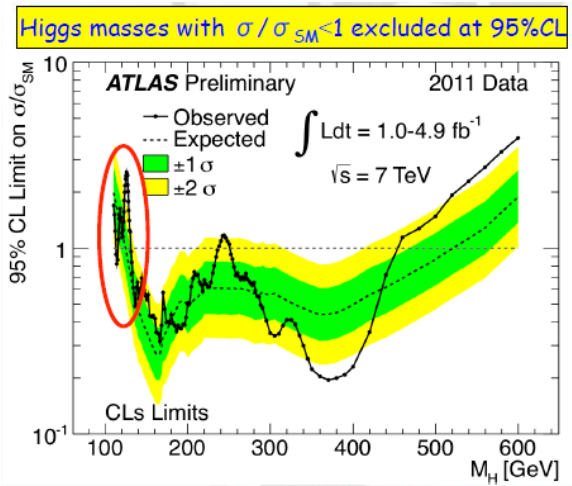


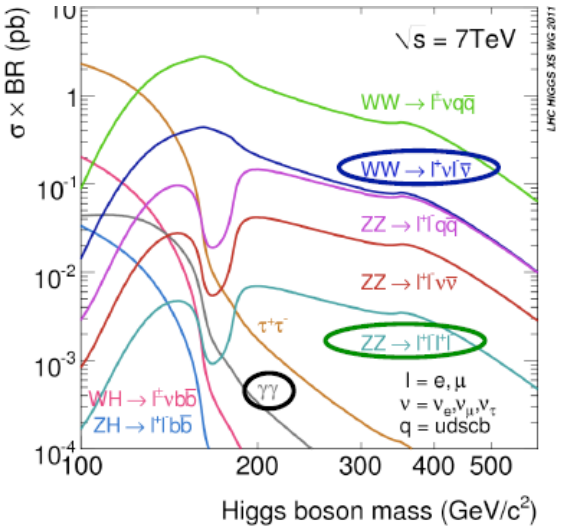
(adapted from 1305.1605)





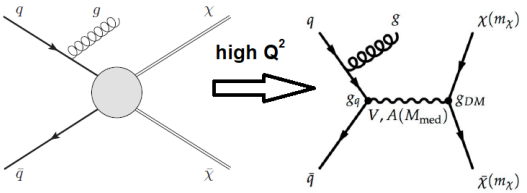
Intermezzo - Finding new particles is hard!





Anatomy of a collider DM signature

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

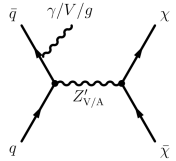


- DM pair-produced, non-interacting.
- Proton remnant & DM alone not triggered.
- Need to tag DM production event via visible radiation (ISR, assoc. production) $\rightarrow$ E_T^{miss}
- Resolving the DM interaction - 'mediator' particle - complementary approach, resonance signatures.
- Use simplified models (with mediator), and specific complete models to explore.
- Signature-driven approach - explore all DM signatures

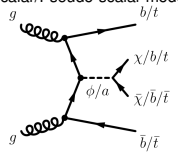
Introduction to Collider DM searches - Summary

- 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}.
- Dark Matter mediators need searches for new resonances. Complementary approaches.
- LHC can investigate and characterise the SM-DM interaction. Use simplified models (with mediator), and specific complete models to explore in LHC Run-2.

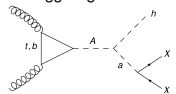
Vector model



Associated production:
Scalar/Pseudo-scalar model



Higgs signatures



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)
- Synergies: e.g.
  - invisible vs. mediator resonance
  - prompt vs LLP vs invisible
  - interplay with (in)direct detection

Models

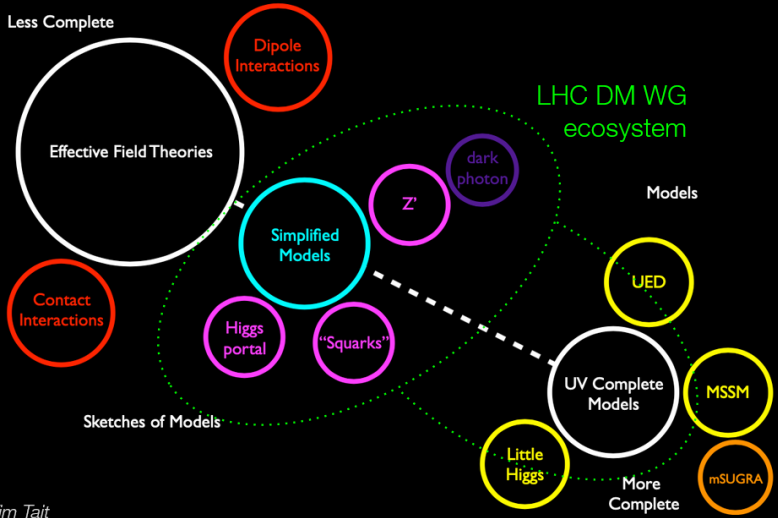
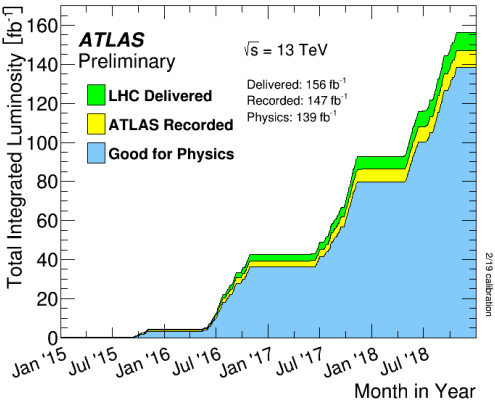


Figure: Tim Tait

ATLAS Datasets and Luminosity

- LHC Run-2 ended in late 2018.
- An unprecendentedly sensitive dataset.
- Many results already published, and more being released regularly.
- But just the beginning...
- LHC Run-3 at 13.6 TeV is progressing well since last summer.
  - Greater luminosity and greater collision energy
  - More than double our data ($\sim$ 400 fb^{-1}) by 2025.



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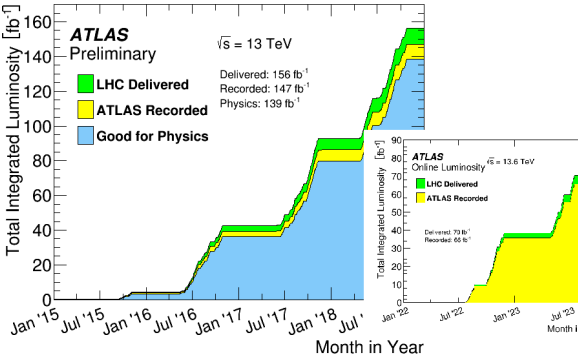
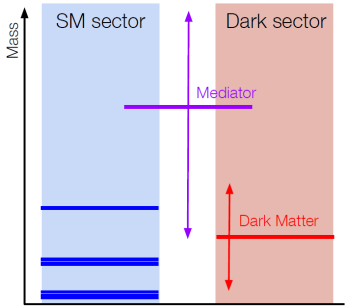


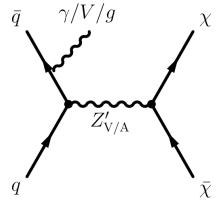
Outline

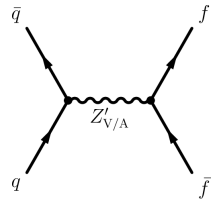
1. Dark Matter and Collider Searches
2. Monojet - Jet(s)+E_T^{miss}
3. Dijet/dilepton searches
4. Invisible Higgs decays
5. Extended Higgs Sectors (2hdm+a)
6. Dark Sectors, semi-visible jets and LLPs

S-channel Mediator Simplified Models

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





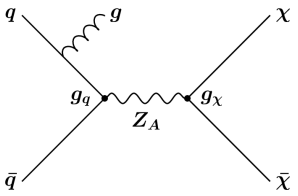


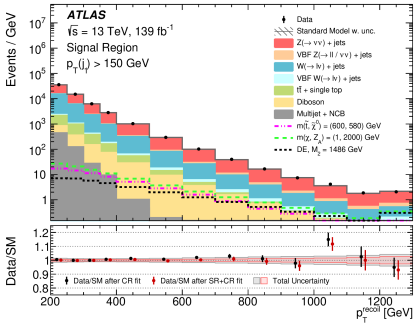
LHCDMWG White Paper (1507.00966)

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

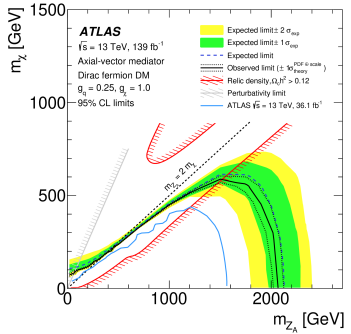
Monojet Search - Jet(s) + E_T^{miss} 2102.10874

- Very general DM search!
- Selections:
  - Energetic jet pT > 150 GeV
  - E_T^{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.





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



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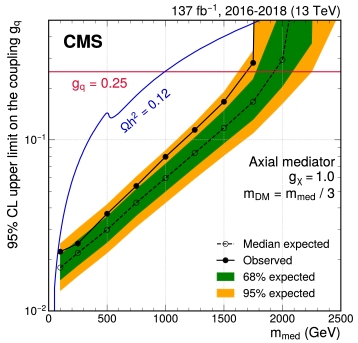

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Many interpretations

- Simplified Models
  - Fix coupling, exclude $m_{DM} - m_{med}$; fix ratio, exclude coupling
- T-channel models
- Generic sensitivity - e.g. SUSY, leptoquarks, extra dimensions

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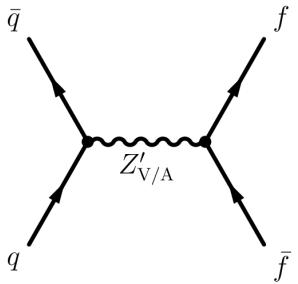
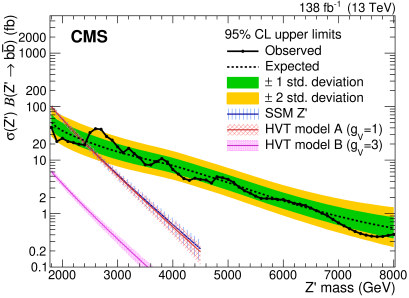
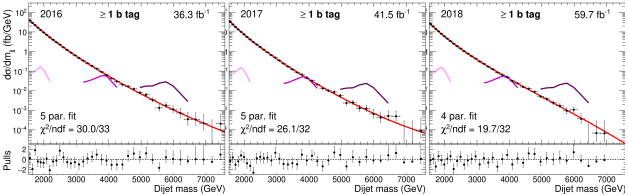


Mediator Resonance Searches - Dijets/dileptons

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

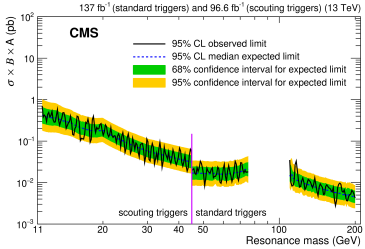


- Select 2+ jets, with b-tags
- Reduce QCD bkg: $|\Delta\eta| < 1.1$
- Search in m_{jj} spectrum
- 2205.01835

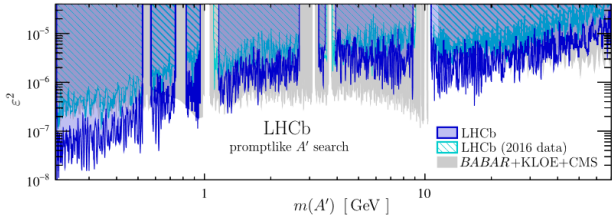


Low-mass di-lepton searches

- Search for dilepton resonances
- Data-scouting triggers extend low-mass reach.
- Phys. Rev. Lett. 124(2020)131802

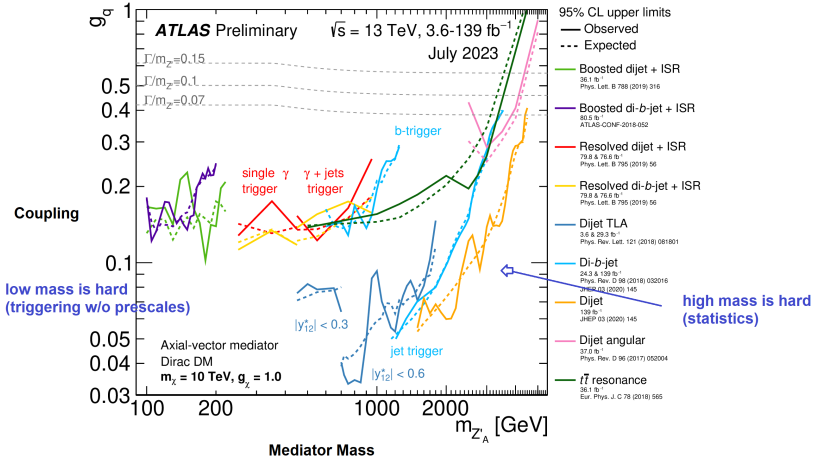


- Mediator decay to $\mu^+\mu^-$
- Drell-Yan main background
- Complements high-mass ATLAS & CMS
- Phys. Rev. Lett. 124, 041801



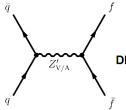
Putting it all together - Simplified Models I

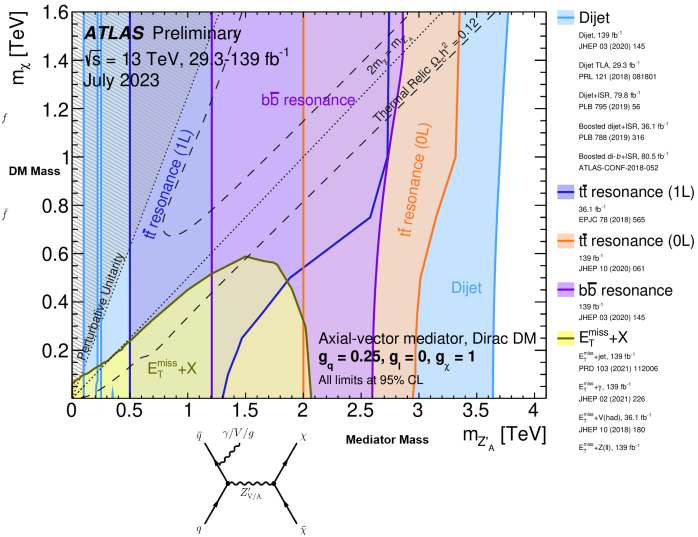
- ATLAS DM Summaries
- How do our mediator resonance searches do?



Putting it all together - Simplified Models II

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

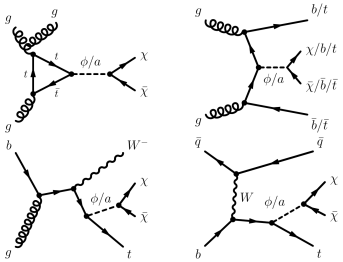




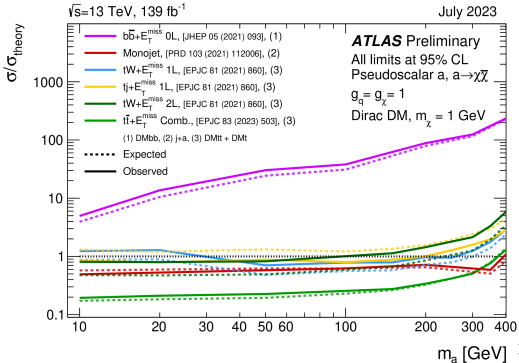
Spin-0 Simplified Models

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

Relevant Signatures:

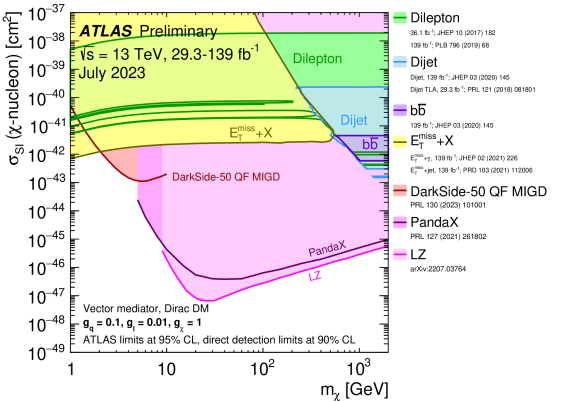


- $tt+E_T^{miss}$ combination
- $tW+E_T^{miss}$
- $bb+E_T^{miss}$
- monojet



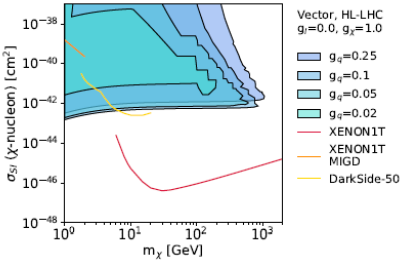
Comparisons with Detection Experiments

- **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.
- Ongoing work to illustrate variations (2203.12035, 2206.03456)

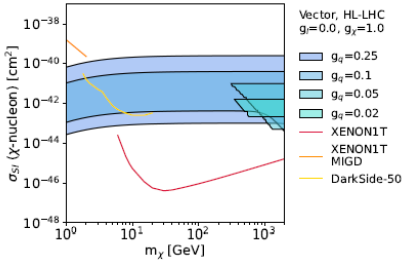


Comparisons with Detection Experiments II

- Largely m_χ-independent
- Low dependence on coupling



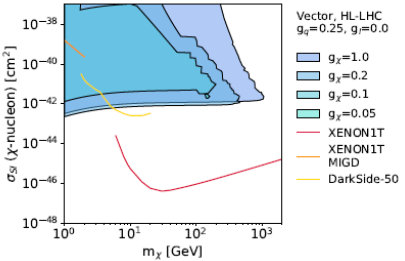
(a) Monojet analysis



(b) Dijet analysis

Comparisons with Detection Experiments III

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



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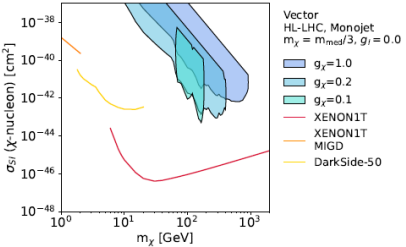

(a) Monojet analysis

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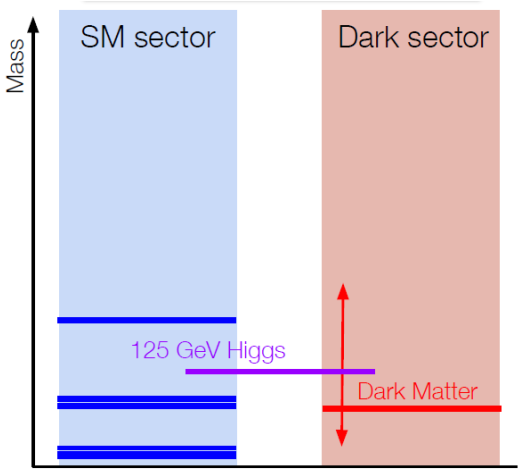
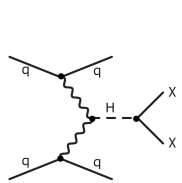


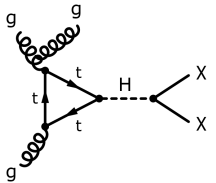
Invisible Higgs Searches

PLB 842 137963

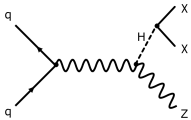
- 'Vanilla' Higgs portal
- Higgs boson mediates the interactions with DM, decays to DM
- 'Invisible Higgs' - anomalous BR (H→ inv = 0.12% in SM).
- Signatures: E_T^{miss}+ X, each Higgs production mode.
- Sensitivity led by VBF+E_T^{miss} and Mono-Z signatures.



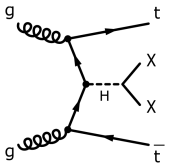
VBF+E_T^{miss}



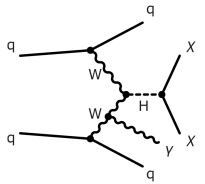
Monojet



$Z+E_T^{miss}$



$t\bar{t}+E_T^{miss}$



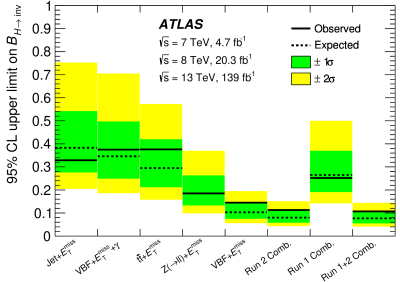
VBF+E_T^{miss}+γ

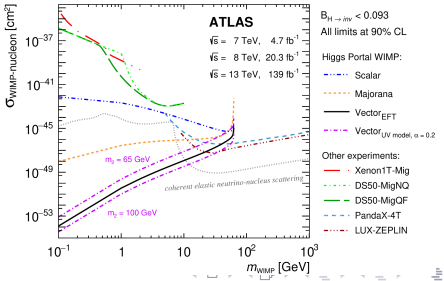
Invisible Higgs Searches - Combined

PLB 842 137963

- Recent combination 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%.
- W/Z+jet modelling (VBF+E_T^{miss}) largest uncertainty.
- Already probing BR(H$\rightarrow$ *Inv*) at the 10% level!

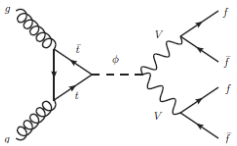
Analysis	Best fit $\mathcal{B}_{H\rightarrow \text{inv}}$	Observed 95% U.L.	Expected 95% U.L.
Run 2 Comb.	0.04 ± 0.04	0.113	$0.080^{+0.031}_{-0.022}$
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$	0.252	$0.265^{+0.105}_{-0.074}$
Run 1+2 Comb.	0.04 ± 0.04	0.107	$0.077^{+0.030}_{-0.022}$

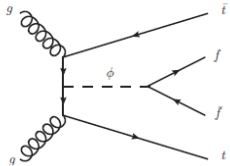


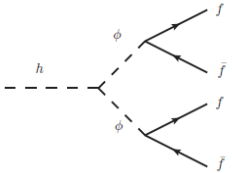


Aside: Dark Higgs models

- Good signature for models in which the Higgs boson properties are modified.
- e.g. models where a dark Higgs boson ϕ generates m_χ and mixes with h.
- SM-like dark Higgs production and decay, $\phi \to hh$ or $h \to \phi\phi$ are allowed.
- Constraints from precision Higgs, $h \to$inv, di-Higgs/diboson resonances
- If DM heavy, resonant $h \to \phi\phi \to 4f$ searches relevant







Models

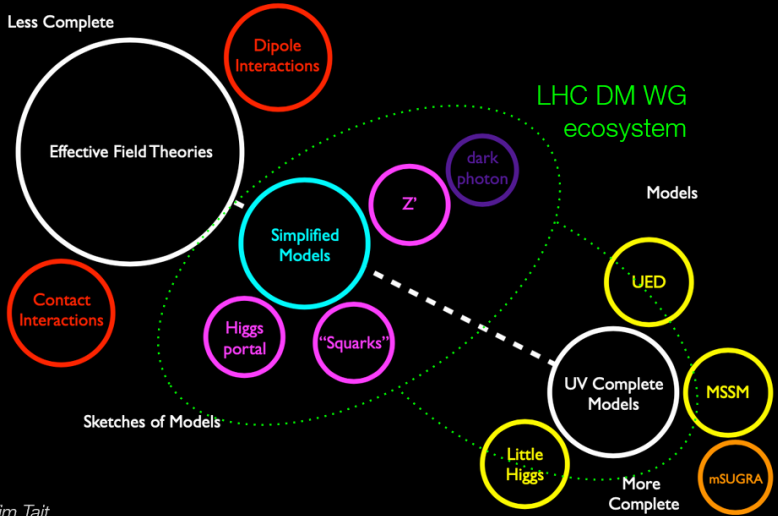


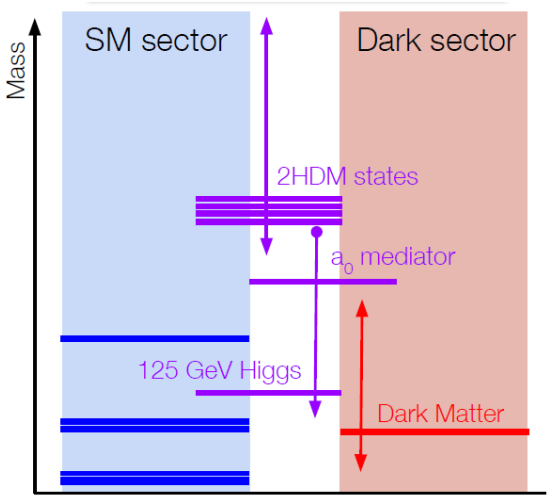
Figure: Tim Tait

Outline

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 (2hdm+a)
6. Dark Sectors, semi-visible jets and LLPs

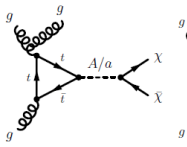
Extended Higgs sectors - 2hdm+a

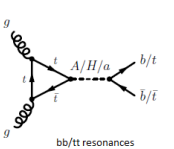
- Higgs sector unique and unexplored
- Natural portal to dark matter
- LHC DM WG benchmark white paper (1810.09420)
- Postulate two-Higgs doublet (ext. Higgs sector)
- Pseudoscalar (a) portal to DM. Reduced constraint from DD.
- For heavier m_{DM}, target scalar sector mediators.
- Interesting physics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

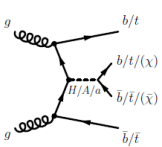


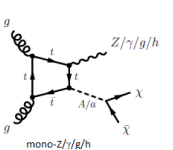
2HDM+a - Overview

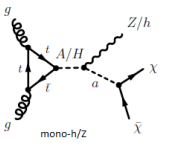
- UV complete model: pseudoscalar mediator with Extended Higgs sector.
- Rich phenomenology with great signature interplay.
- Complex model - LHC DM WG white paper defines several benchmarks.
- Incorporates analyses from across ATLAS search programme.
- New addition single top (tW/tq) $+E_T^{miss}$ search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

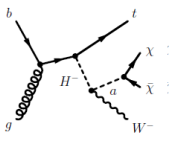


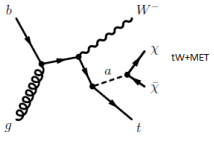




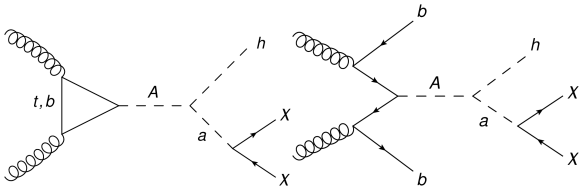


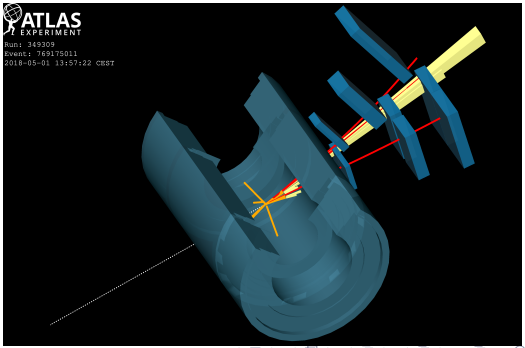






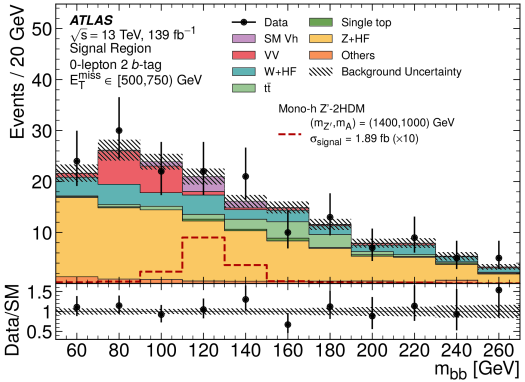
2HDM+a Analyses - I. Mono-Higgs



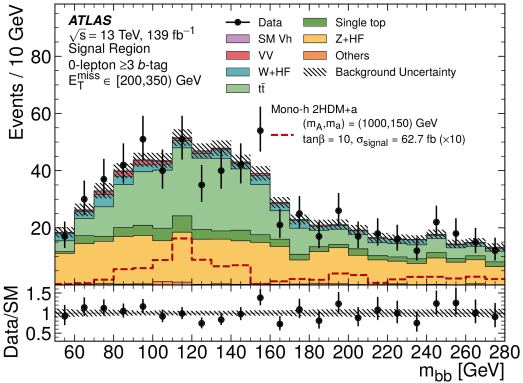


- Higgs boson recoiling against E_T^{miss}
- Sensitive to DM lighter than *a*, reasonable *A*-*a* mass splitting
- 2- and 3-b signal regions $\rightarrow$ sensitive to gg- and bb-induced production.

2HDM+a Analyses - I. Mono-Higgs



2b, merged channel



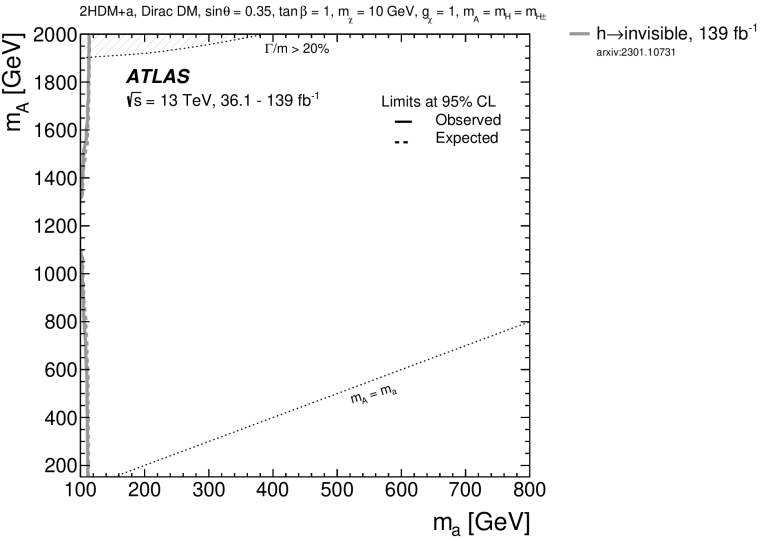
3b, resolved channel

Also: $h(\rightarrow \tau\tau) + E_T^{miss}$, $h(\rightarrow \gamma\gamma) + E_T^{miss}$

- Complete model - several parameters.
- Various benchmarks defined to illustrate/explore phenomenology
- Fix some parameters to satisfy theory constraints.
- Synergy of invisible/visible mediator signatures.

tan β - impacts gg- vs bb-production.
$m_A = m_H = m_{H^\pm}$ - avoid precision EW constraints.
sin θ - degree of *a*-*A* mixing.
m_χ - little direct experimental sensitivity, controls e.g *a* BRs.
g_χ - little mono-X sensitivity

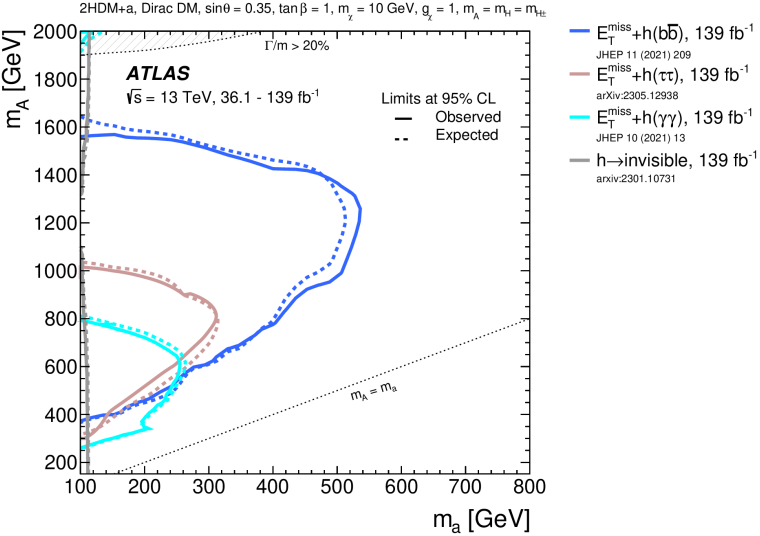
2HDM+a - Results 2306.00641



h→invisible, 139 fb^{-1}
arxiv:2301.10731

2HDM+a - Results

2306.00641

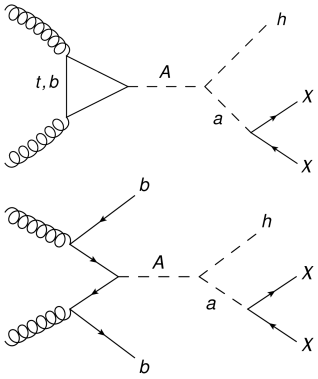


E_T^{miss}+h(bb̄), 139 fb^{-1}
JHEP 11 (2021) 209

E_T^{miss}+h(ττ), 139 fb^{-1}
arXiv:2305.12938

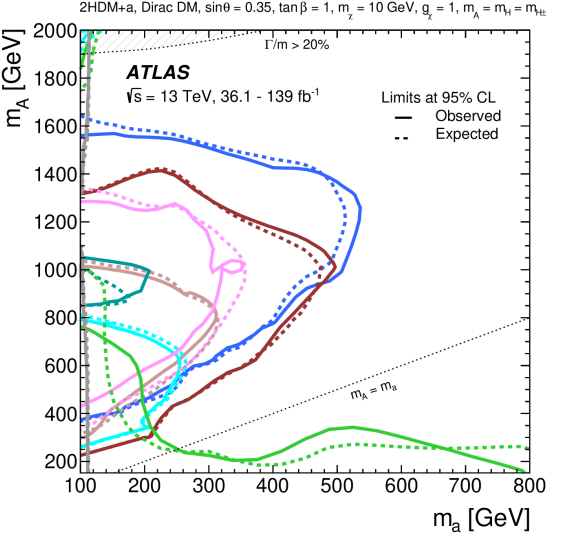
E_T^{miss}+h(γγ), 139 fb^{-1}
JHEP 10 (2021) 13

h→invisible, 139 fb^{-1}
arxiv:2301.10731



2HDM+a - Results

2306.00641



E_T^{miss}+h(bb̄), 139 fb^{-1}
JHEP 11 (2021) 209

E_T^{miss}+h(ττ), 139 fb^{-1}
arXiv:2305.12938

E_T^{miss}+h(γγ), 139 fb^{-1}
JHEP 10 (2021) 13

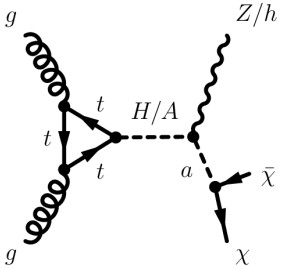
E_T^{miss}+Z(ll), 139 fb^{-1}
PLB 829 (2022) 137066

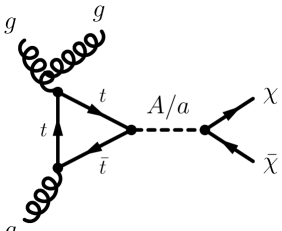
E_T^{miss}+Z(qq̄), 36.1 fb^{-1}
JHEP 10 (2018) 180

E_T^{miss}+tW, 139 fb^{-1}
arXiv:2211.13138

E_T^{miss}+j, 139 fb^{-1}
PRD 103 (2021) 112006

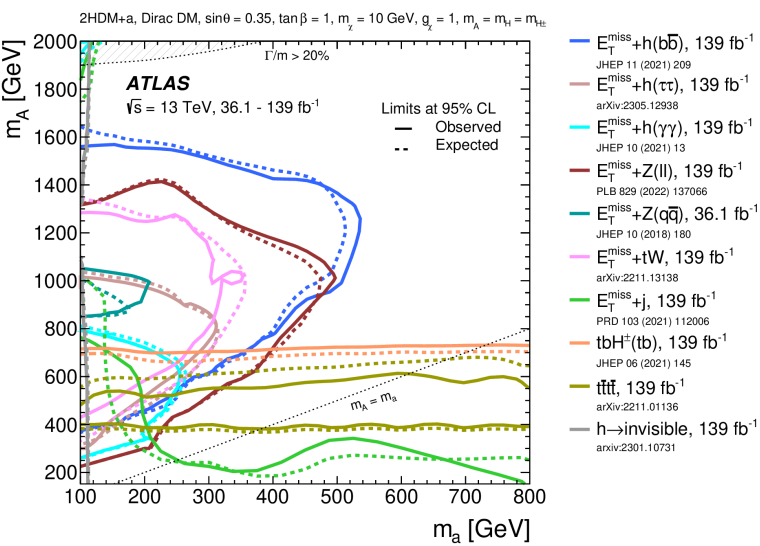
h→invisible, 139 fb^{-1}
arxiv:2301.10731





2HDM+a - Results

2306.00641



E_T^{miss}+h(bb̄), 139 fb^{-1}
JHEP 11 (2021) 209

E_T^{miss}+h(ττ), 139 fb^{-1}
arXiv:2305.12938

E_T^{miss}+h(γγ), 139 fb^{-1}
JHEP 10 (2021) 13

E_T^{miss}+Z(ll), 139 fb^{-1}
PLB 829 (2022) 137066

E_T^{miss}+Z(qq̄), 36.1 fb^{-1}
JHEP 10 (2018) 180

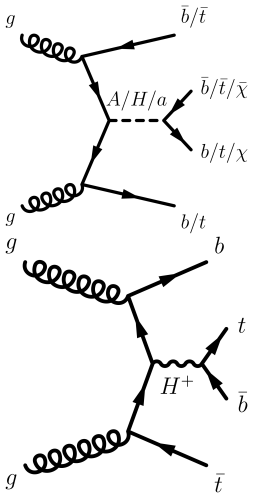
E_T^{miss}+tW, 139 fb^{-1}
arXiv:2211.13138

E_T^{miss}+j, 139 fb^{-1}
PRD 103 (2021) 112006

tbH$^{\pm}$(tb), 139 fb^{-1}
JHEP 06 (2021) 145

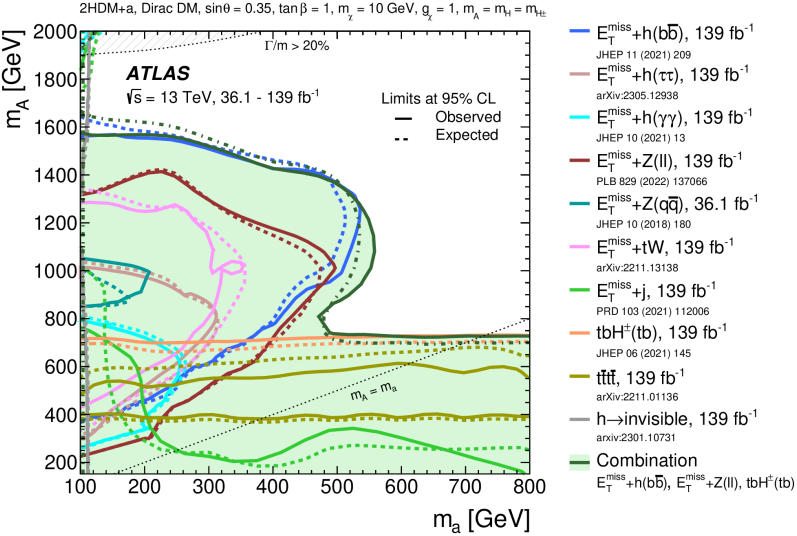
tt̄tt̄, 139 fb^{-1}
arXiv:2211.01136

h→invisible, 139 fb^{-1}
arxiv:2301.10731

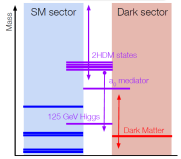


2HDM+a - Results

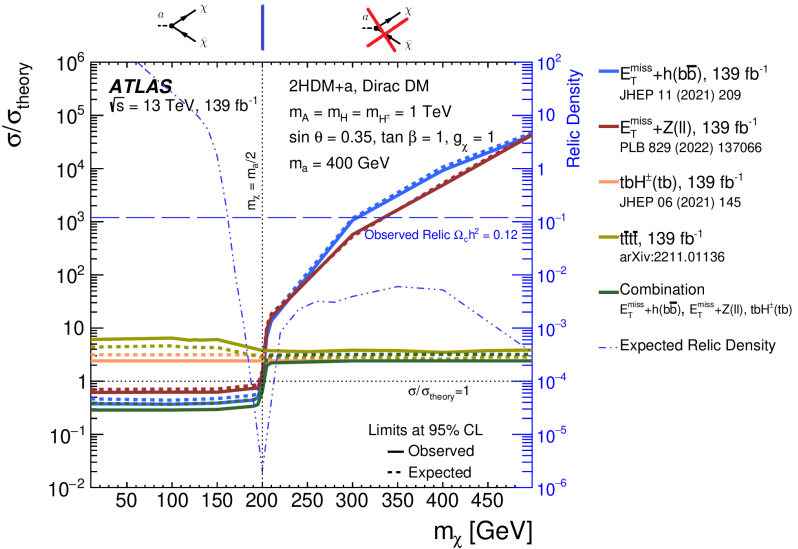
2306.00641



2HDM+a - Sensitivity to DM mass 2306.00641

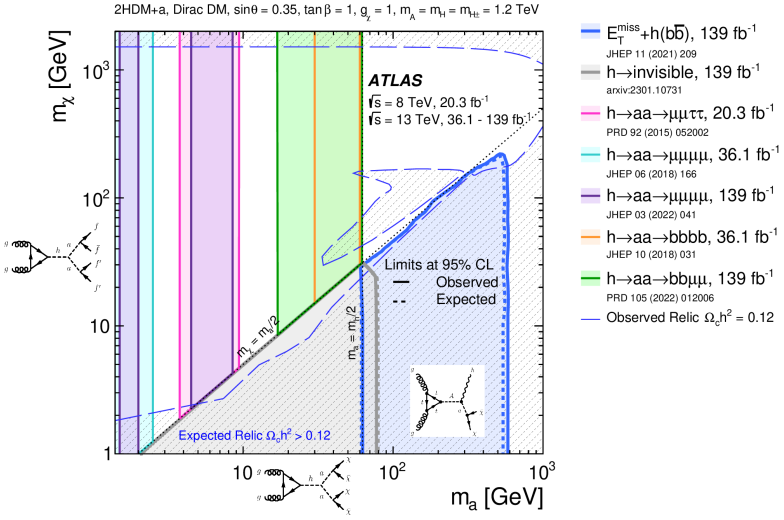


- Insensitivity to DM mass allows R.D. satisfaction.
- But can vary the DM mass to show dependence.
- Heavy Higgs/Mediator searches constrain higher m_χ.

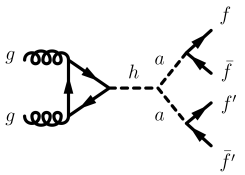


2HDM+a Light Pseudoscalars - What if *a* is light? 2306.00641

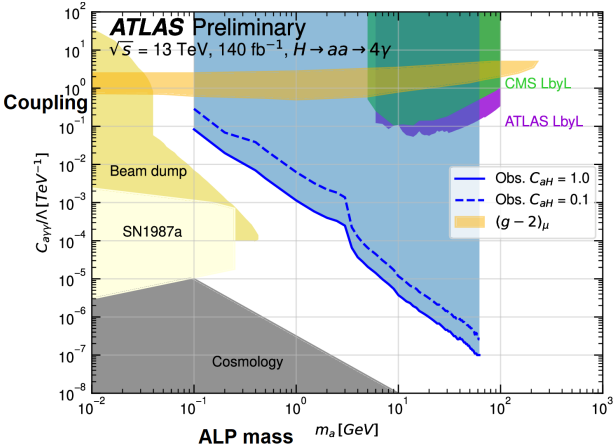
- Complementary with lower-mass ALP searches for pseudoscalars (2202.12631).
- Light resonant searches powerful when *a* cannot decay to DM.
- Invisible signatures kick in for lower DM masses.



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 $a \to \gamma\gamma$
- Non-resonant diboson production also relevant at LHC.



ATLAS-CONF-2023-040

Outline

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 (2hdm+a)
6. Dark Sectors, semi-visible jets and LLPs

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

PBC Report

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.

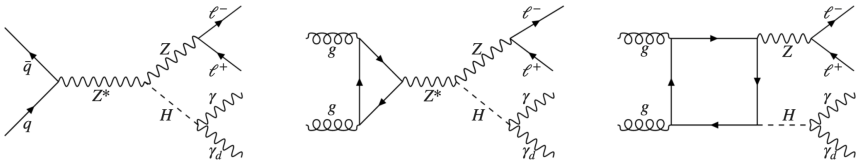
Dark Photon Searches - ZH

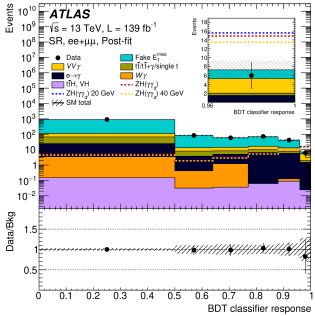
2212.09649

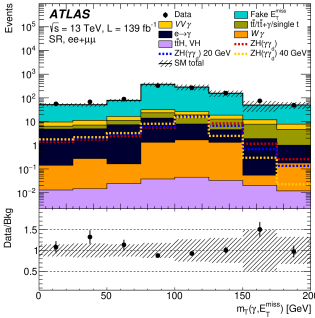
- Model: Higgs boson couples via dark sector
- Search for exotic decay
- Clean final state
- $Z \to \ell\ell$
- Cut on $m_{\ell\ell}$, $m_{\ell\ell\gamma}$, E_T^{miss}
- Train BDT and fit discriminant
- CRs for $e \to \gamma$, $VV\gamma$

$\mathcal{B}(h \to \gamma\gamma_D) < 2.3$ % at 95% CL.

cf. VBF+MET+γ Paper: 1.8 %

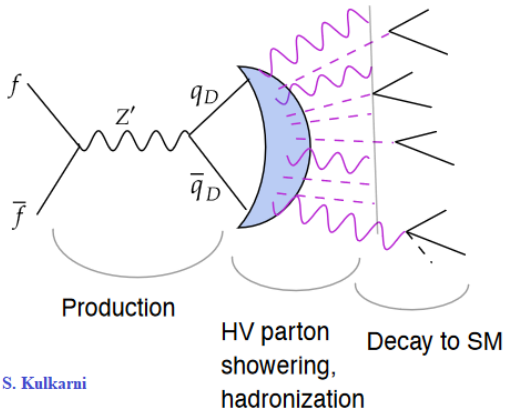






Strongly-interacting dark sectors - dark QCD/showers

- 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}.
- Unstable dark hadrons - dark jets; dark meson search



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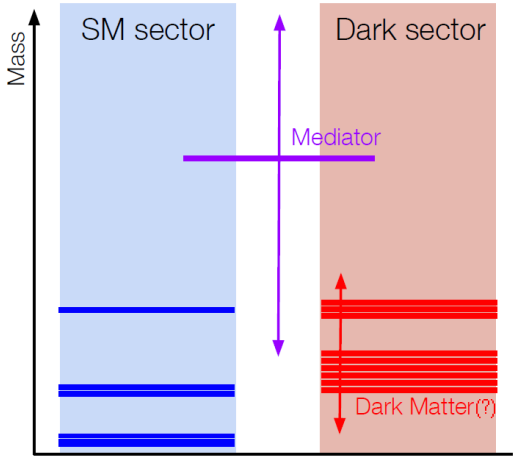
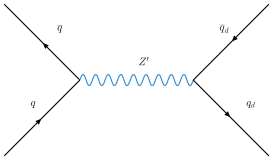
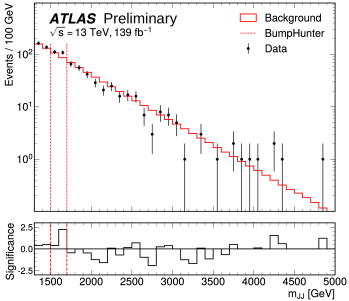


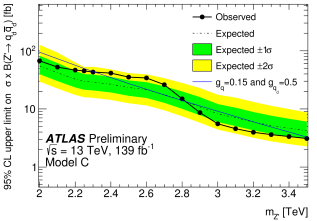
ATLAS-CONF-2023-047



- Recent first CONF search for dark jet resonance.
- Selects wide resonance signal through large-R jets of high track multiplicity.
- Bump hunt above a background shape CR template.

Model	n_f	Λ_d (GeV)	$\bar{m}_{q'}$ (GeV)	m_{π_d} (GeV)	m_{ρ_d} (GeV)	π_d decay mode
A	2	15	20	10	50	$\pi_d \to c\bar{c}$
B	6	2	2	2	4.67	$\pi_d \to s\bar{s}$
C	2	15	20	10	50	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 4.0$ GeV
D	6	2	2	2	4.67	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 0.7$ GeV

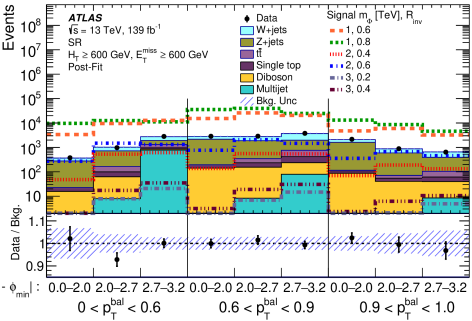


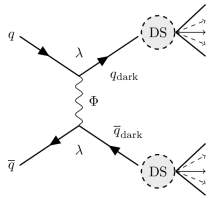


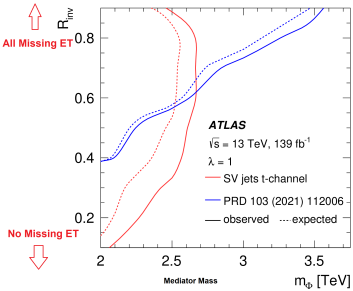
Semi-visible Jets - t-channel

2305.18037

- High E_T^{miss}, two high-p_T jets.
- Discriminating variables: p_T^{bal}, p_T jet balance, $|\Delta\phi|$.
- Use 1-lepton, 1-bjet and 2-lepton CRs.
- SR requires E_T^{miss}>600 GeV and H_T>600 GeV.
- Fit to 9 p_T^{bal}–$|\Delta\phi|$ ranges.



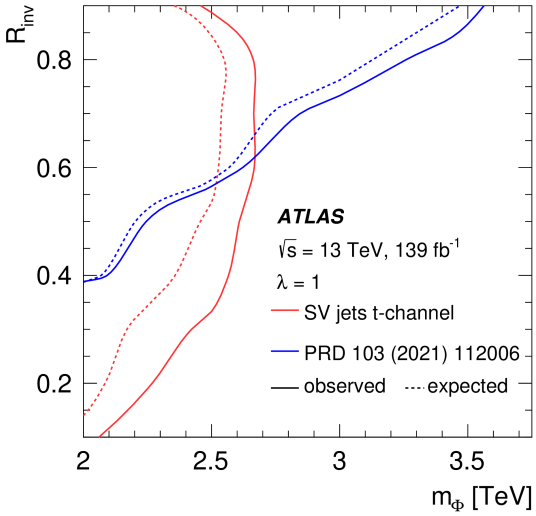




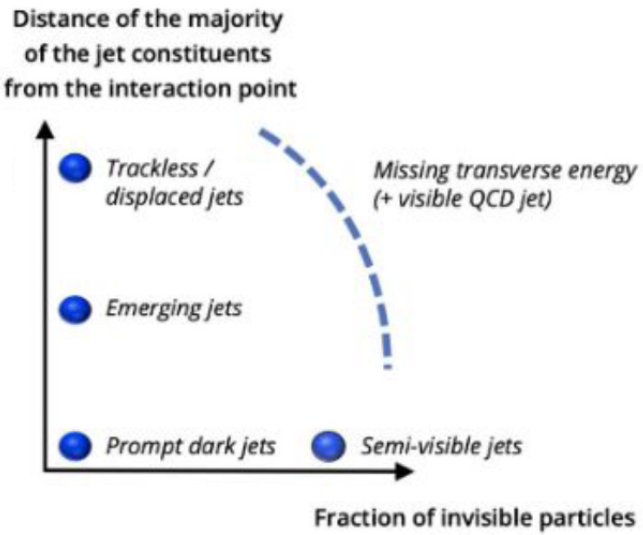
Semi-visible jets - thoughts

- Monojet complementarity shown. Dijet/darkjet to constraint low R_{inv}.
- S-channel also underway (CMS & ATLAS).

- Need to ensure we cover full signature range.
- More realistic dark-QCD model, or phenomenological 'E_T^{miss}-fraction' approach.
- Which variables/modelling are robust/trustable, theoretically?
- Discussions around an LHCDMWG white paper on concrete benchmarks.



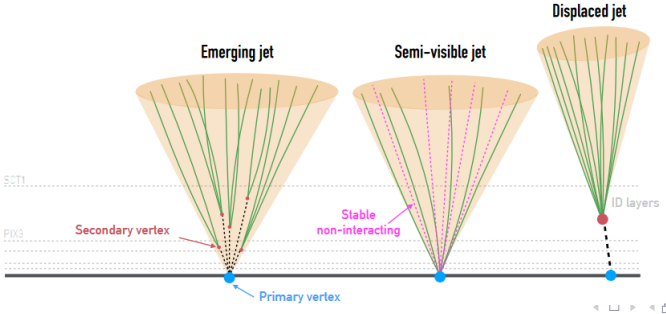
Strongly-interacting dark sector phenomenology



- Dark meson states with lifetimes?
- Generates long-lived signatures.
- Emergent or displaced jets (w/ E_T^{miss})

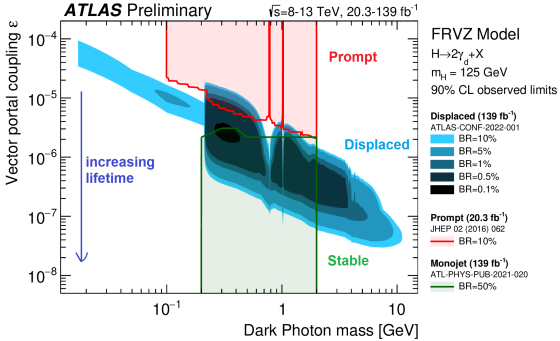
Emerging and Displaced Jets

- For dark hadron lifetimes O(10^{-3}–1), expect multiple displace vertices in a jet $\rightarrow$ emerging jet
- 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.



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→Inv (for e.g. h→ss).



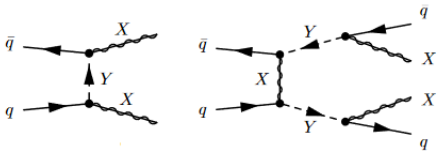
- Encountered for $h- > aa$, dark photon models. Will appear for darkjets, ALPs, 2hdm+a/dark higgs.

Run-2 Summary

- Wide ranging and successful collider search programme for dark matter.
- Initially focussed on WIMP hypotheses - still many options.
- Now also many results on other DM options - dark photons, ALPs, dark sectors.
- Often sophisticated analyses - precision bkgs, new/difficult signatures, broad combinations/summaries.
- Also combinations and legacy papers - some Run-2 results to come.
- Have focussed on ATLAS/CMS, but LHCb, FASER results coming in Run-3.

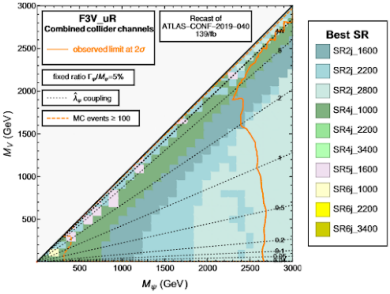
Ongoing Efforts - T-channel models

- 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)

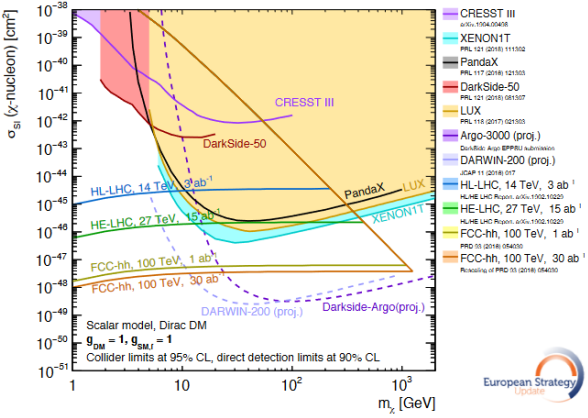
$$\mathcal{L}_{\text{F3S\_uR}} = \left[\hat{\lambda}_\psi \bar{\psi} u_R \tilde{S} + \text{h.c.}\right],$$
$$\mathcal{L}_{\text{S3M\_uR}} = \left[\lambda_\varphi \tilde{\chi} u_R \varphi^\dagger + \text{h.c.}\right],$$
$$\mathcal{L}_{\text{F3V\_uR}} = \left[\hat{\lambda}_\psi \bar{\psi} \vec{V} u_R + \text{h.c.}\right].$$



2010.07559 (using strong 0L)
White paper studies ongoing, incl. leptophilic and long-lived models.

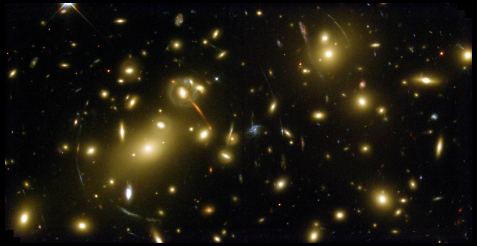
Outlook to Run-3 and HL-LHC

- Community Review
- LHCDMWG Workshop: Roadmap of Run-3 DM models, 13-17 May 2024
- Aims:
  - Review and update existing benchmarks in light of Run-2 results.
  - Ensure full signature coverage in Run-3 and beyond
- Huge sensitivity increase from dedicated triggers and improved techniques for difficult signatures (incl. LLP).



Conclusions

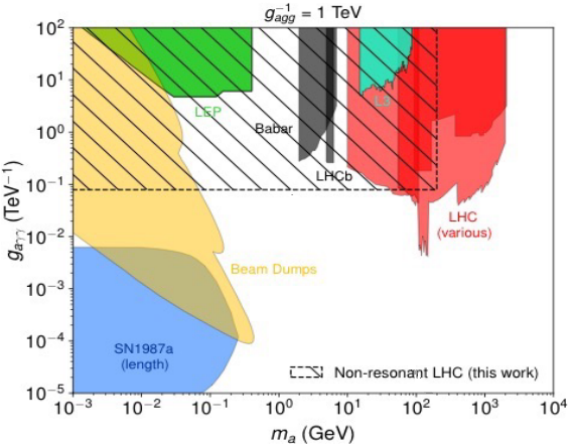
- Colliders are an interesting place to look for dark matter.
- Some unique advantages (high energy, probe interaction, DM candidate range).
- Some challenges (model guide, insensitivity to DM itself).
- Run-2 dataset powerful, huge broadening of programme.
- Run-3 and beyond: vital to continue to look widely, to ensure no missing opportunities.
- Investigate any hints from other sources (DD, lightDM, forward exp., LLP exp.).
- Still only 5-7% of the final HL-LHC dataset recorded, much yet unexplored!



Backup

Lighter DM - Non-resonant ALP searches

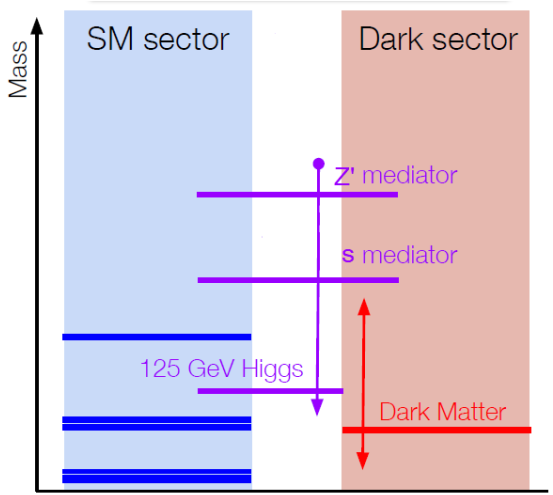
- Recent interest in non-resonant and loop-induced ALP searches at LHC.
- e.g. high mass tails of diboson production (paper)
- Also VBS VV of interest (indep. of gluon coupling).
- Electroweak ALPs accessible via $\bar{t}t$ resonances.
- Clear complementarity with other experiments
- Also with our light-by-light,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



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

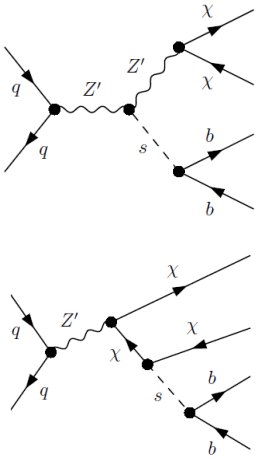
Outline

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 (2hdm+a)
6. Dark Higgs Boson Searches
7. Dark Sectors, semi-visible jets and LLPs



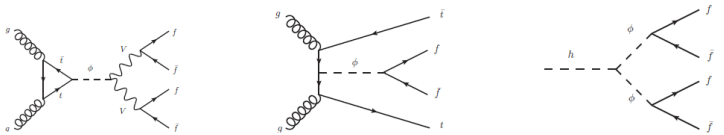
Dark Higgs Boson Models - Introduction

- Two-mediator model
- Assume dark matter acquires its mass through interaction with a dark higgs boson
- Also an extension of spin-1 simplified models
- Two mediators: massive Z' and a dark Higgs boson s

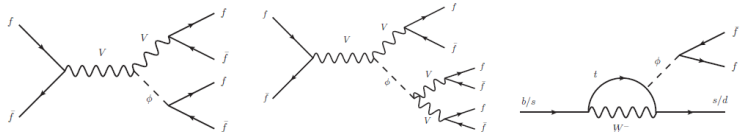


Dark Higgs + dark photon models

- Given a dark Higgs boson of mass m_s and mixing angle θ, production as SM h.
- SM-like dark Higgs decay, $s \to hh$ or $h \to ss$ are allowed.
- Constraints from precision Higgs, $h \to$inv, di-Higgs/diboson resonances

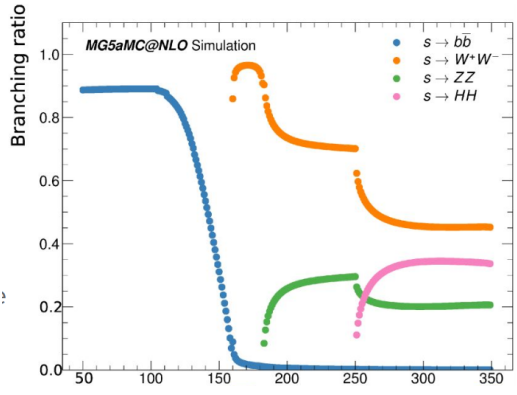


- Can extend to include additional interactions of the corresponding gauge boson.
- $\to$ dark photon, couplings either direct (Z' earlier) or via kinetic mixing (dark photon).



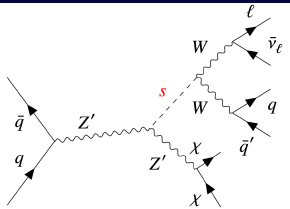
Dark Higgs Phenomenology

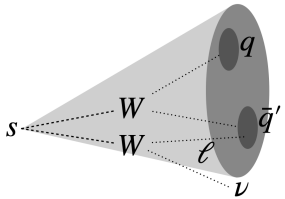
- Run-2 analysis benchmark assumed:
  - $g_\chi = 1.0$, $g_q = 0.25$, $\sin\theta = 0.01$
  - Standard simplified model choices, s unstable, even if lighter than DM.
  - Small mixing helps avoid constraints.
- $m_\chi = 200$ GeV.



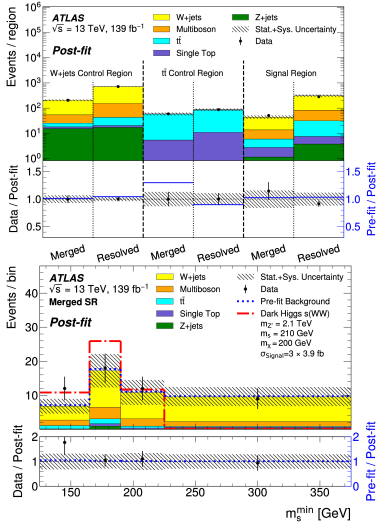
Dark Higgs Boson Searches I

2211.07175

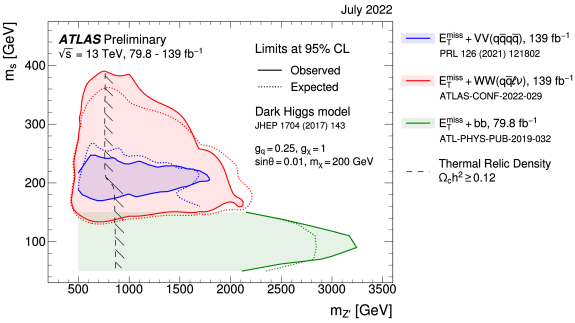


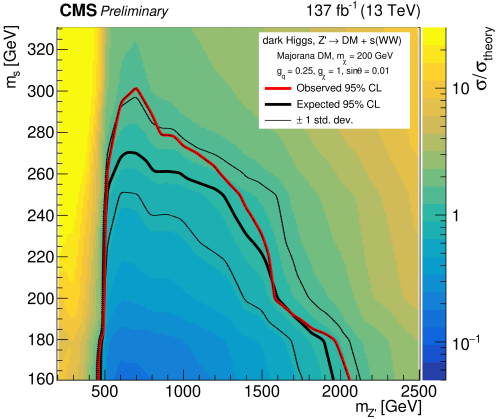


- Two mediator model (JHEP 04(2017)143) - Z' and dark Higgs (s).
- Search for W($l\nu$)W($q\bar{q}$) decay.
- E_T^{miss}>200 GeV, m_T>220 GeV
- Either one merged $W \to q\bar{q}$ merged TAR jet or two jets.
- W/Z+jets constrained using 1μ, 2-lepton CRs.
- Reconstruct m_s, search for excess.



Dark Higgs Boson Searches II





ATLAS DM Summary Plots

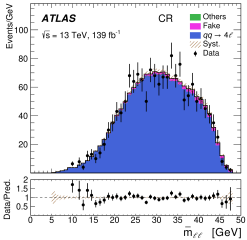
- Search complements earlier $s \rightarrow \mathrm{W}(q\bar{q})\mathrm{W}(q\bar{q})$ search, and $s \rightarrow b\bar{b}$ reinterpretation.

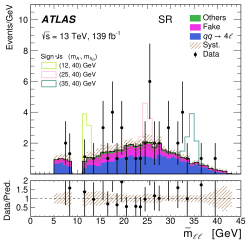
- CMS search for the dileptonic WW signature sets similar constraints.

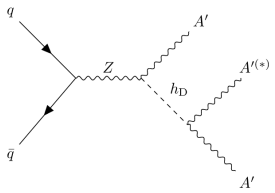
Dark Photon Searches - Exotic Z decays

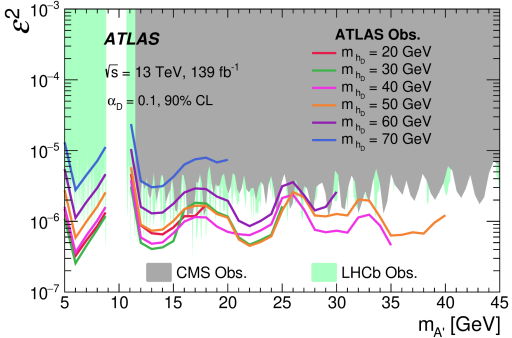
2306.07413

- Dark Abelian Higgs adds dark Higgs h_D for massive dark photon A'.
- A' decays into lepton pairs (or hadrons)
- For light A' masses, $Z \to h_D\, A'$
- At least 2 lepton pairs - similar masses.
- Fit to the average dilepton mass, $\bar{m}_{\ell\ell}$.
- $qq \to 4\ell$ dominant background.



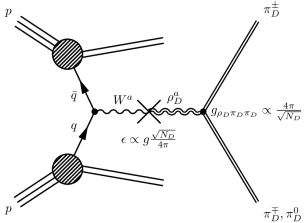


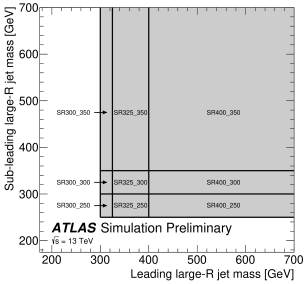


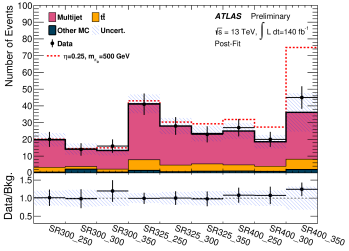


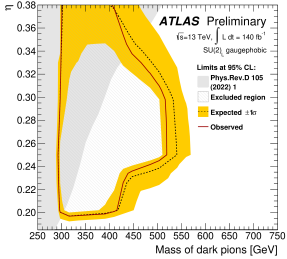
Dark Meson search

ATLAS-CONF-2023-021



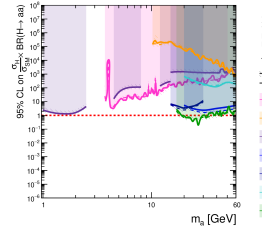


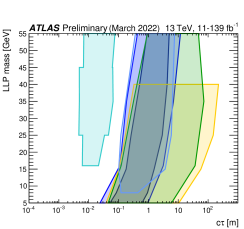


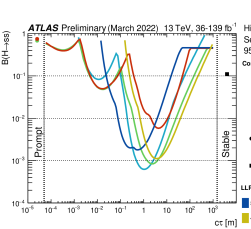


- Resonant production of dark ρ, dark π pair signature
- $\eta = m_{\pi_D}/m_{\rho_D}$
- Consider $\eta < 0.5$, thus $\rho_D^{\pm,0} \to \pi_D^{\pm}\pi_D^{\mp,0}$
- Gaugephobic $\to \pi_D^{0,+}$ decay to $t\bar{t}$, $t\bar{b}$
- 3t,1b or 2t,2b $\to$ 8-10 jets, 4 b-jets
- Fully hadronic signature, recluster into $R = 1.2$ jets.

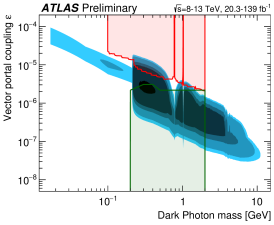
Summaries for prompt & LL signatures





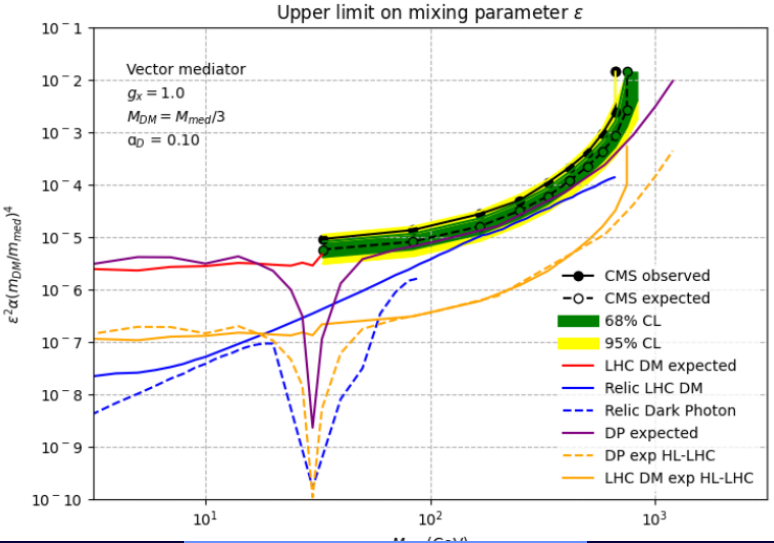


- LLP, or phase spaces with them, are ubiquitous in many DM models.
- Important complementarity with prompt searches. (Cf. visible/invisible, low-/high-mass).
- Also the *very* long-lived extreme e.g. monojet, h→Inv (for e.g. h→ss).

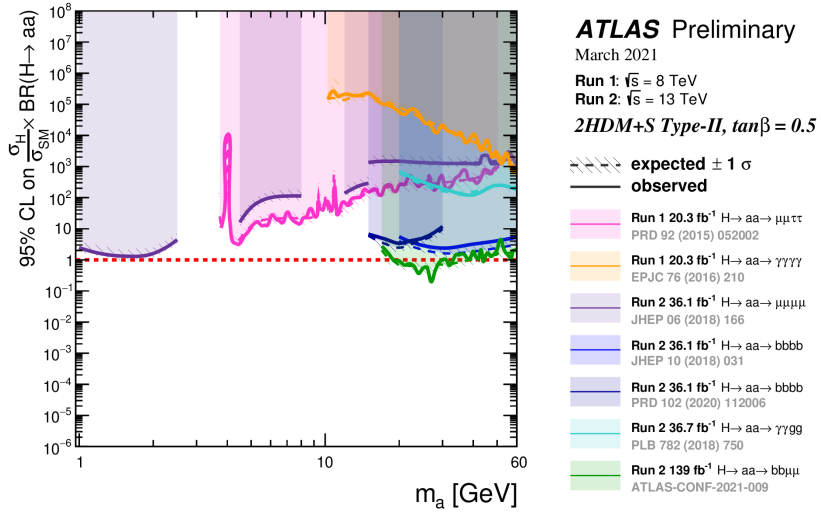


- Encountered for $h- > aa$, dark photon (FRVZ, but better HAHM). Will appear for darkjets, ALPs, 2hdm+a/dark higgs.

Monojet and the dark photon portal

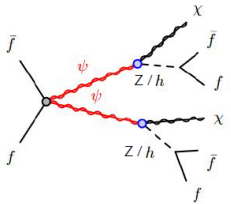


Low-mass resonance searches

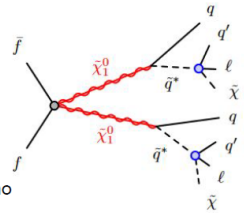


LLP Mechanisms I

- **Co-annihilation** (SUSY models, mass-degeneracy)
  - naturally makes the slightly heavier particle long-lived
  - e.g. wino-bino/wino-Higgsino co-annihilation -> long-lived neutralinos
    - displaced Higgs, target with (e.g.) displaced vertex + MET analysis, non-prompt photons, displaced dielectrons.



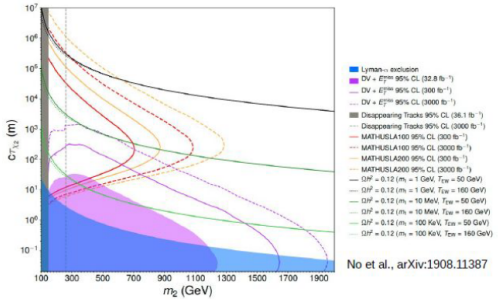
- **Asymmetric DM** (analogous to RPV SUSY)
  - connects DM abundance to baryon abundance via higher order B-L operator
  - importantly, allows LSP to decay into dark sector plus SM



Decay of a LL neutralino

LLP Mechanisms II

- **Freeze-in** (Feebly-interacting particle (FIP) models)
  - small couplings, long-lived
  - dark sector never in thermal contact, DM produced gradually from dark sector
  - e.g. Heavy particle decays to DM & SM, s.t. DM abundance follows production rate
  - stau NLSP -> SM & DM
  - $\tilde{\ell}^{\pm} \to \ell^{\pm}\tilde{G}$



No et al., arXiv:1908.11387

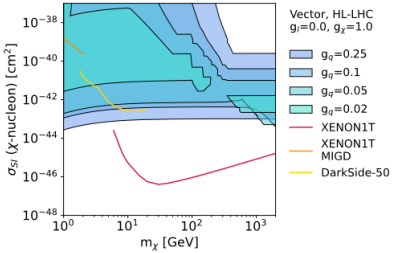
- Key feature is that the coupling is highly suppressed, thus a LL NLSP.
  - so LL sleptons: displaced leptons, disappearing track, dE/dx

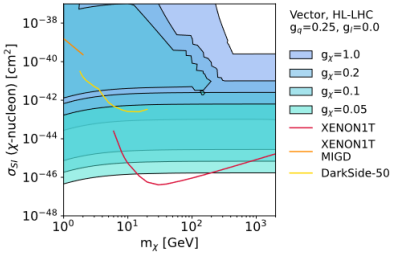
- Multi-D space.
- Usually we fix 2 of these, scan 1.

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

Product of couplings — Mediator mass — Reduced mass

$$\mu_{n\chi} = m_n m_{\rm DM}/(m_n + m_{\rm DM})$$





Spare slide