Searches for Dark Matter with ATLAS at the LHC

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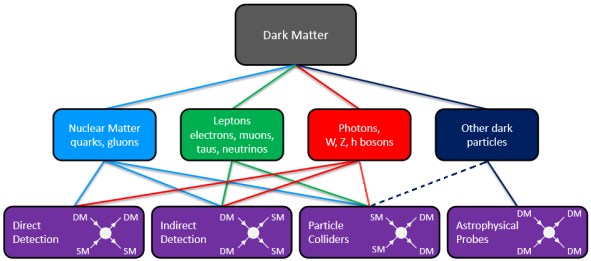
Collider Searches for Dark Matter

Though the presence of Dark Matter is well established, its nature is an open question.

- Dark Matter - explains wealth of astrophysical observations:



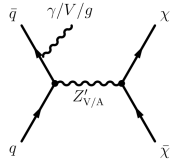
(adapted from 1305.1605)

- WIMP dark matter remains one attractive option.
  - Produced in early universe, now in thermal relic density.
  - Interaction with quarks via heavy mediator

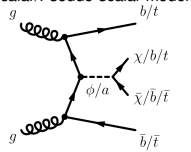
Introduction to Collider DM searches

- 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.

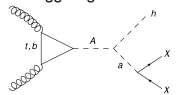
Vector model



Associated production:
Scalar/Pseudo-scalar model



Higgs signatures



Models

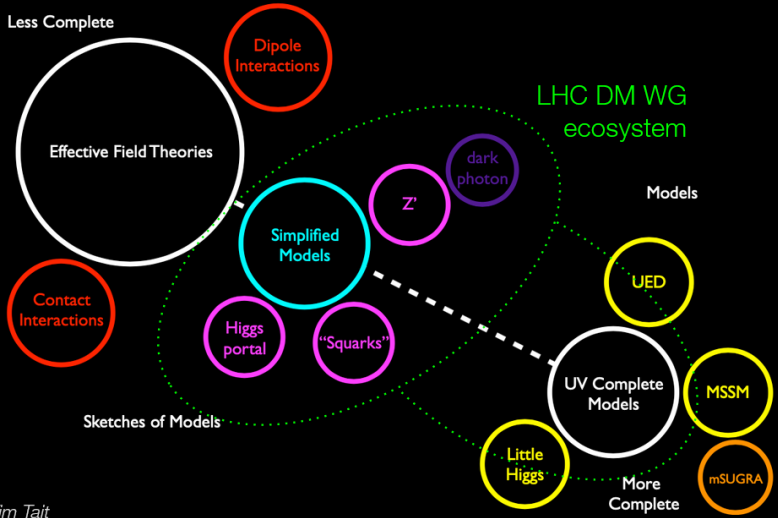
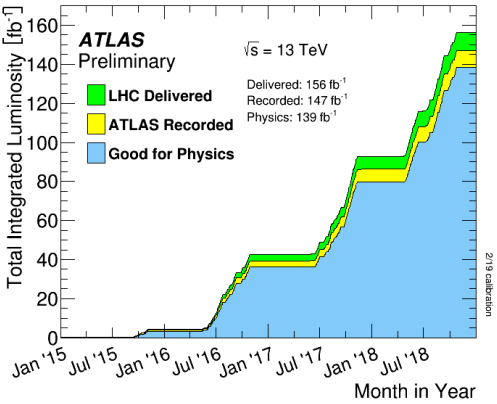


Figure: Tim Tait

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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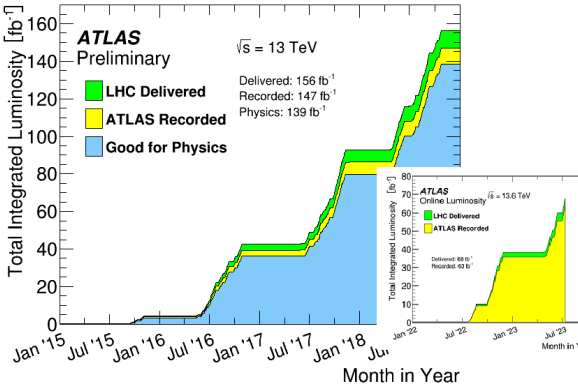
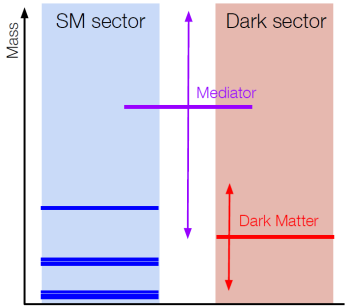
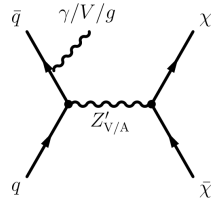
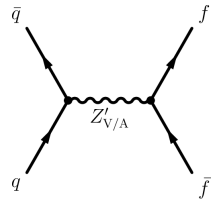


S-channel Mediator Simplified Models

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





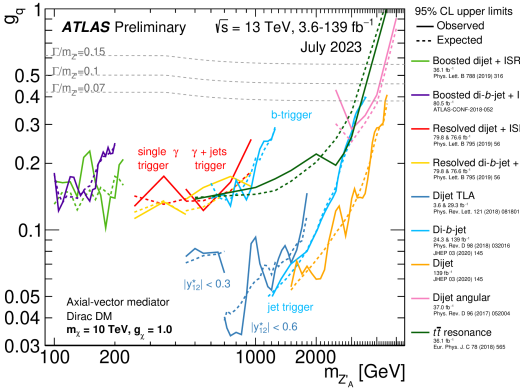


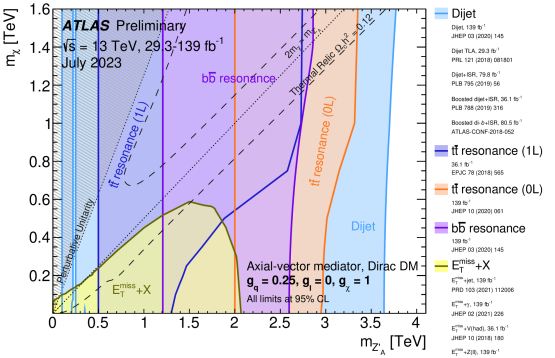
LHCDMWG White Paper (1507.00966)

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

Putting it all together - Simplified Models I

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



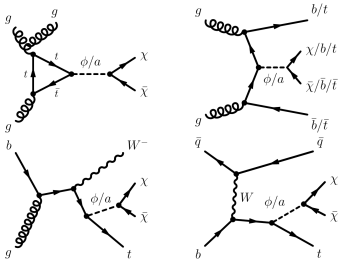


ATLAS Results and Summaries

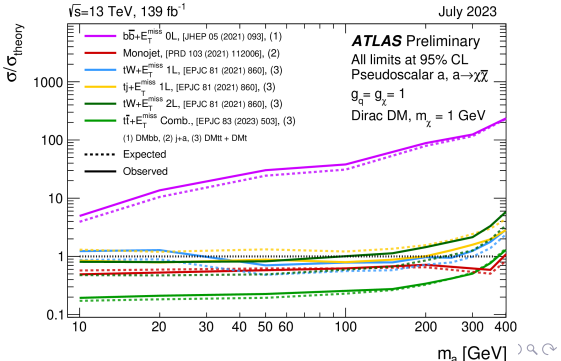
Spin-0 Simplified Models

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

Relevant Signatures:



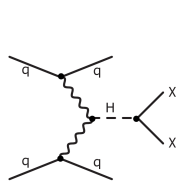
- tt+E_T^{miss}combination
- tW+E_T^{miss}
- bb+E_T^{miss}
- monojet



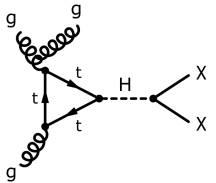
Invisible Higgs Searches

PLB 842 137963

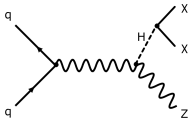
- 'Vanilla' Higgs portal
- Higgs boson mediates the interactions with DM, decays to DM
- 'Invisible Higgs' - anomalous BR (H→ inv = 0.12% in SM).
- Signatures: E_T^{miss}+ X, each Higgs production mode.
- Sensitivity led by VBF+E_T^{miss} and Mono-Z signatures.



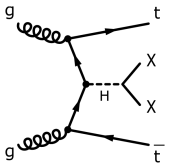
VBF+E_T^{miss}



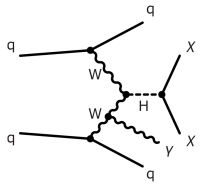
Monojet



$Z+E_T^{miss}$



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



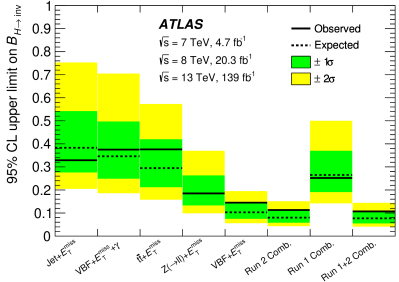
VBF+E_T^{miss}+γ

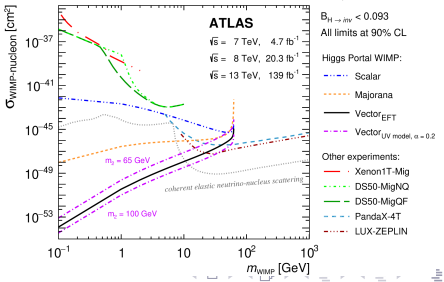
Invisible Higgs Searches - Combined

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	$0.077^{+0.030}_{-0.022}$





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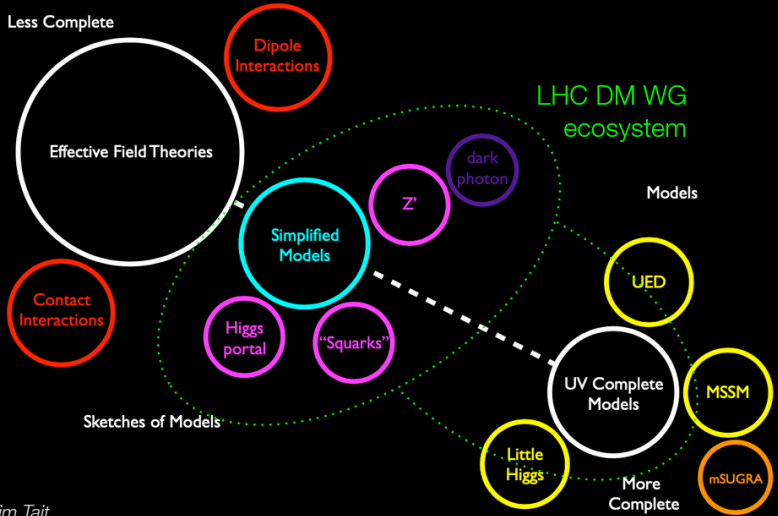
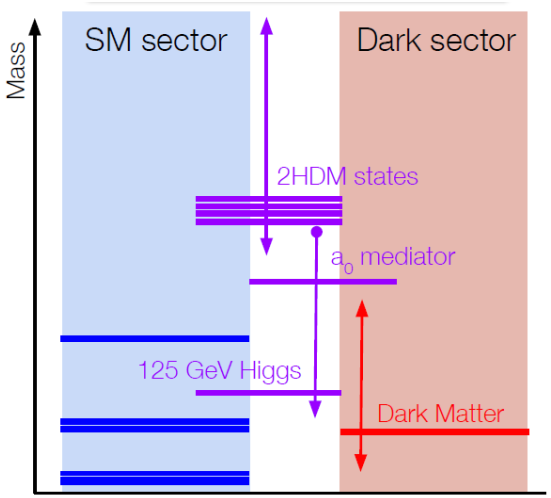


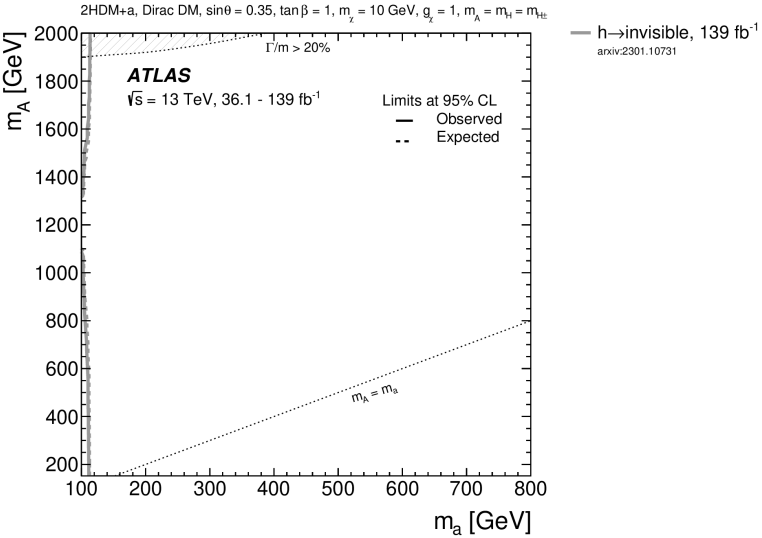
Figure: Tim Tait

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 - Results 2306.00641



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

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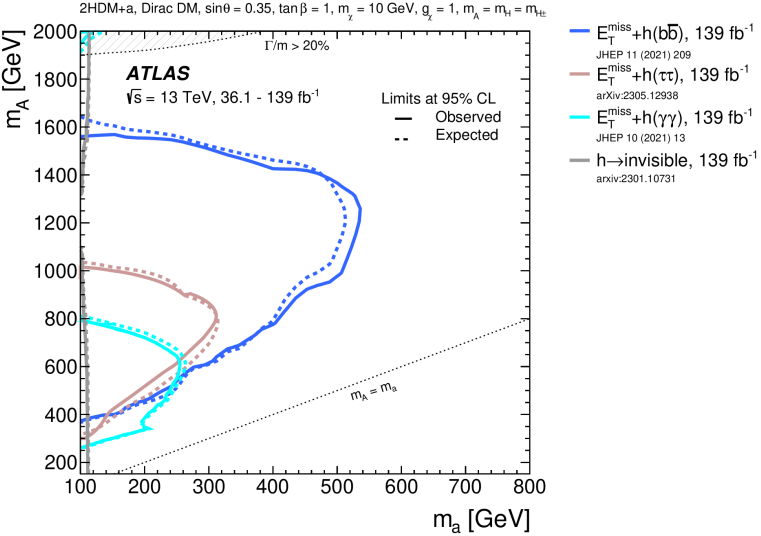
2306.00641



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}
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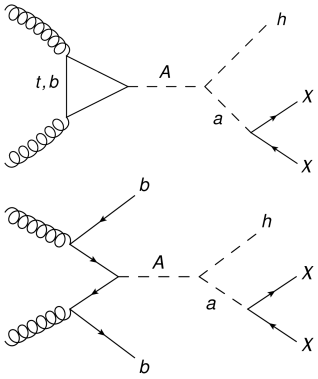

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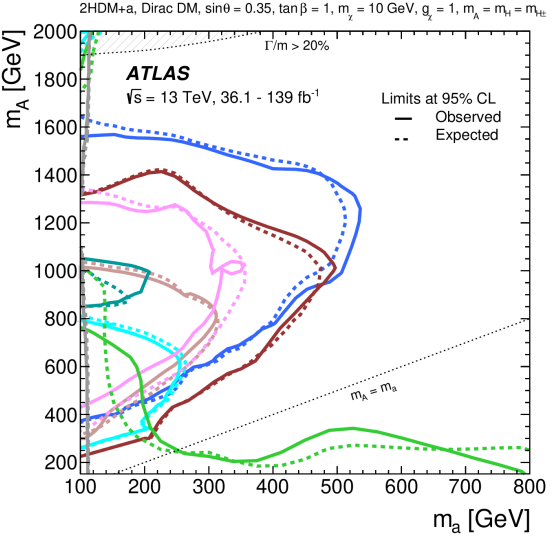

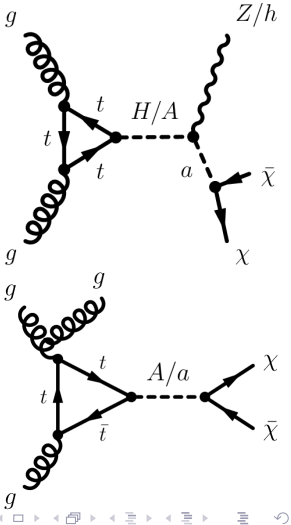

2HDM+a - Results

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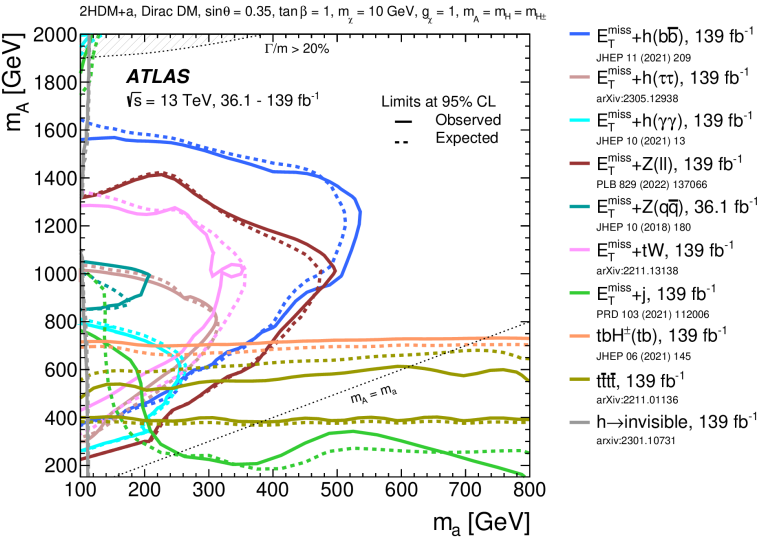

E_T^{miss}+h(bb̄), 139 fb^{-1}
JHEP 11 (2021) 209

E_T^{miss}+h(ττ), 139 fb^{-1}
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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

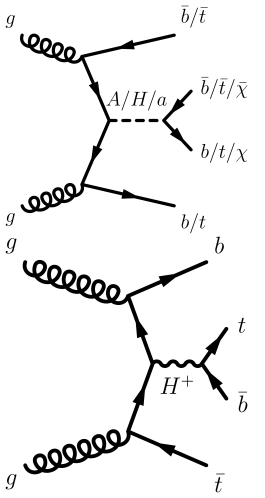
E_T^{miss}+tW, 139 fb^{-1}
arXiv:2211.13138

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

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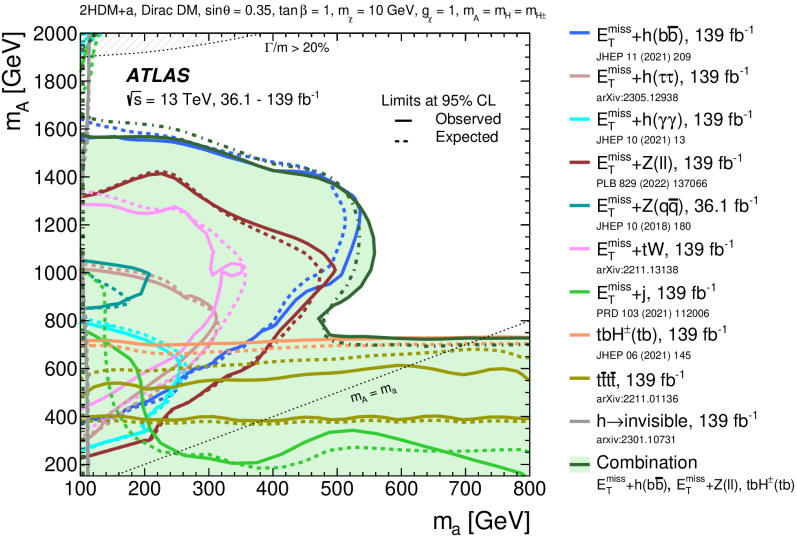
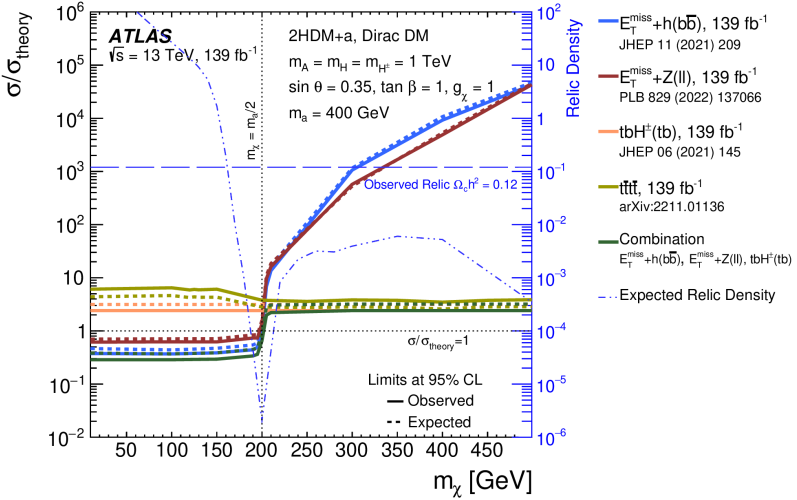


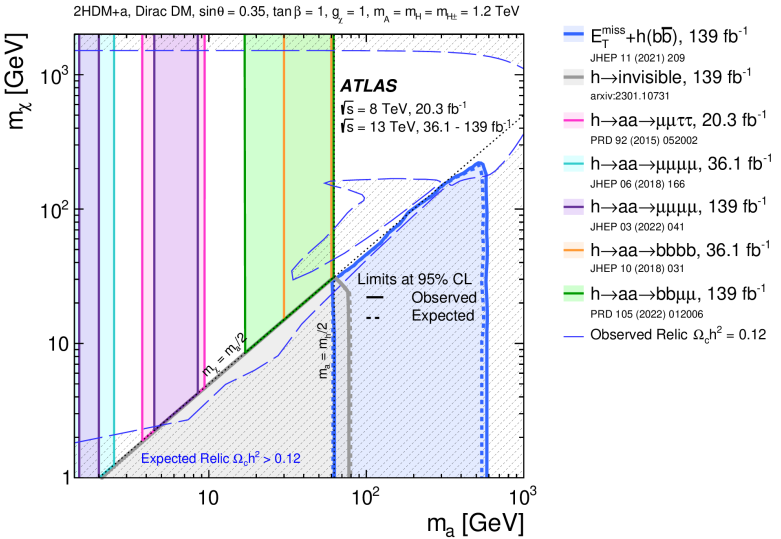
2HDM+a - Sensitivity to DM mass 2306.00641

- 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

- Also complementarity 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.



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

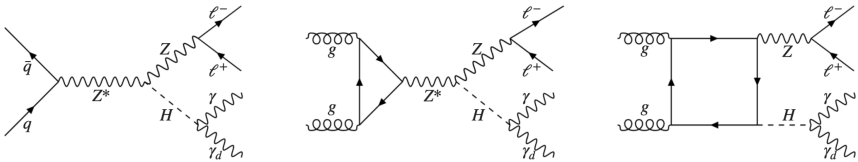
Dark Photons

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

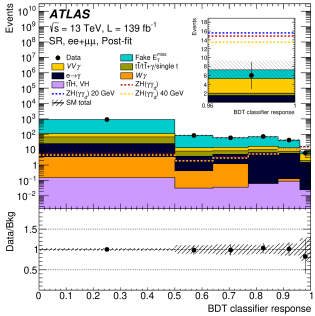
2212.09649

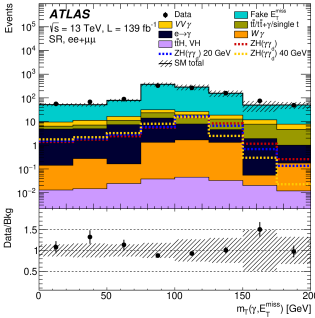
- Model: Higgs boson couples via dark sector
- Search for exotic decay
- Clean final state
- $Z \to \ell\ell$
- Cut on $m_{\ell\ell}$, $m_{\ell\ell\gamma}$, E_T^{miss}
- Train BDT and fit discriminant
- CRs for $e \to \gamma$, $VV\gamma$



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

cf. VBF+MET+γ Paper: 1.8 %

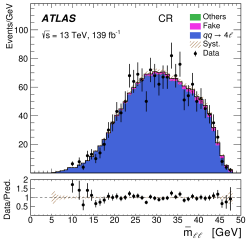


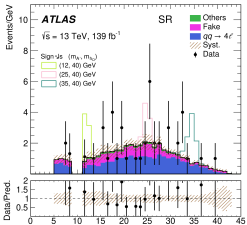


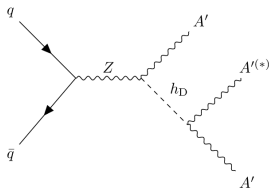
Dark Photon Searches - Exotic Z decays

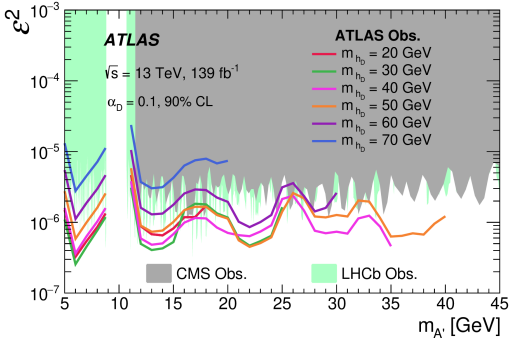
2306.07413

- 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.



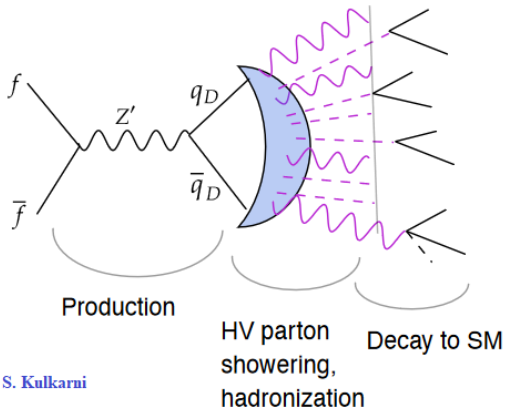






Strongly-interacting dark sectors - dark QCD/showers

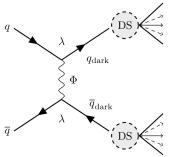
- What if dark sector confined?
- Simple mediator, but complex dark sector/matter phenomena.
- Generate dark quarks, hadronise into dark hadrons
- Dark hadrons: stable $\rightarrow E_T^{miss}$, unstable $\rightarrow$ decay to SM. Invisible fraction r_{inv}
- Unusual hadronic signatures.
- Prompt dark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

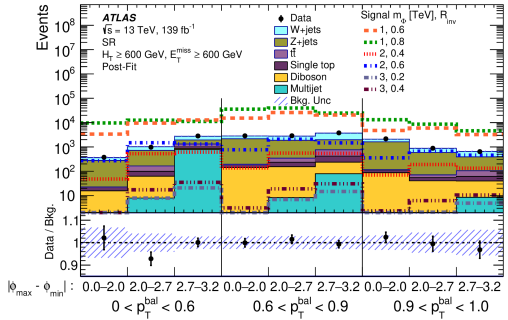


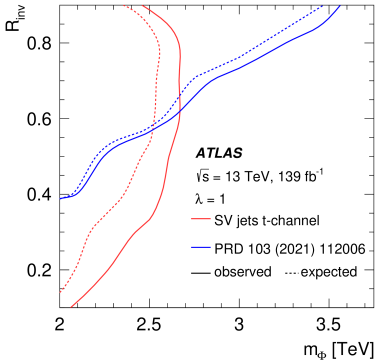
Semi-visible Jets - t-channel

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.







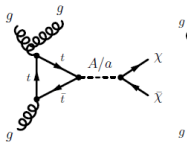
Conclusions and Outlook

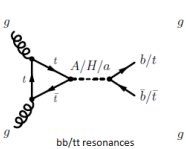
- ATLAS has a wide ranging and successful collider search programme.
- Includes range of WIMP hypotheses - still many options
- Now also many results on other options - dark photons, ALPs, dark sectors
- Often sophisticated analyses - LHC Run-2 results still coming
- Run-3 dataset growing fast!
- Many new ideas, both experimental (new techniques, new signatures) and theoretical (new models, anomalies)
- Stay tuned!

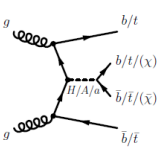
Backup

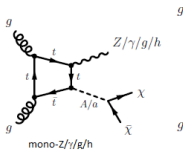
2HDM+a - Overview

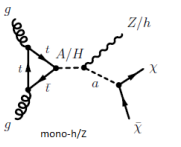
- UV complete model: pseudoscalar mediator with Extended Higgs sector.
- Rich phenomenology with great signature interplay.
- Complex model - LHC DM WG white paper defines several benchmarks.
- Incorporates analyses from across ATLAS search programme.
- New addition single top (tW/tq) +E_T^{miss} search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

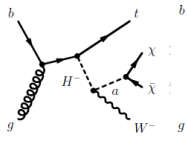


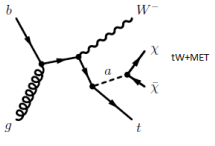




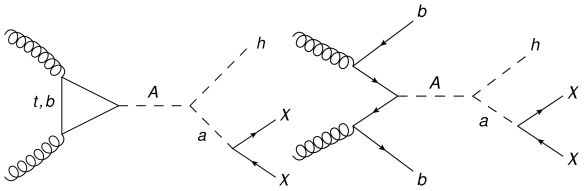


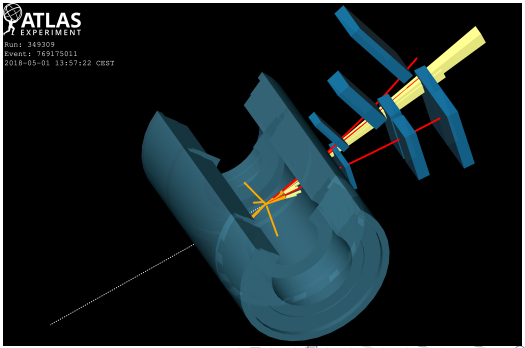






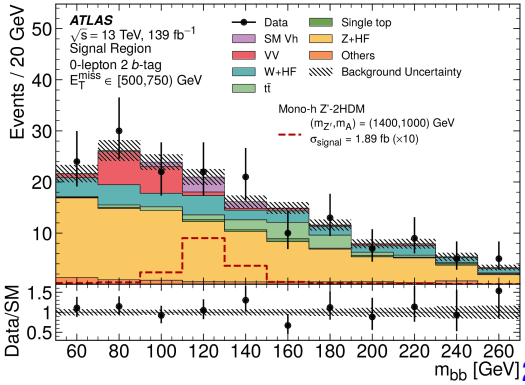
2HDM+a Analyses - I. Mono-Higgs



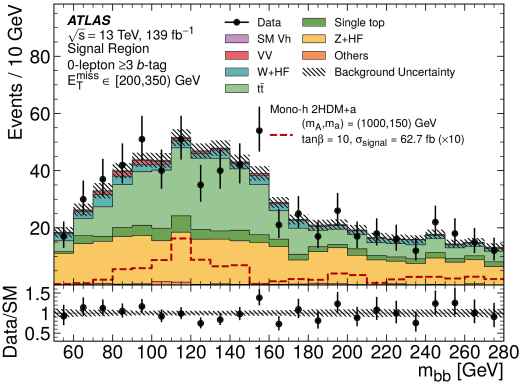


- Higgs boson recoiling against E_T^{miss}
- Sensitive to DM lighter than *a*, reasonable *A*-*a* mass splitting
- 2- and 3-b signal regions $\rightarrow$ sensitive to gg- and bb-induced production.

2HDM+a Analyses - I. Mono-Higgs



2b, merged channel

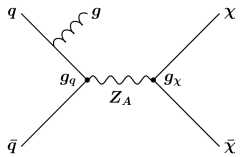


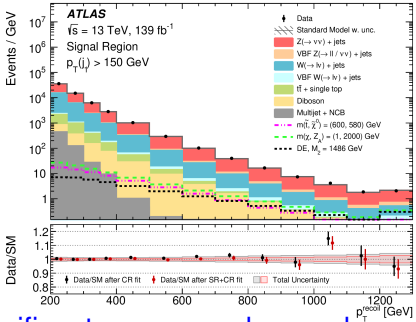
3b, resolved channel

New: $h(\rightarrow \tau\tau) + E_T^{miss}$

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

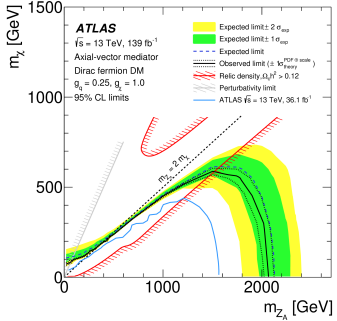
- Very general DM search!
- Selections:
  - Energetic jet pT > 150 GeV
  - E_T^{miss}> 200 GeV
  - Up to 3 extra jets
  - Search for excess in E_T^{miss}
- Shape fit in 13 E_T^{miss} bins (p_T^{recoil})
- Backgrounds: Z+jets, W+jets, Diboson, $t\bar{t}$
- Estimated in 1- and 2-lepton control regions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

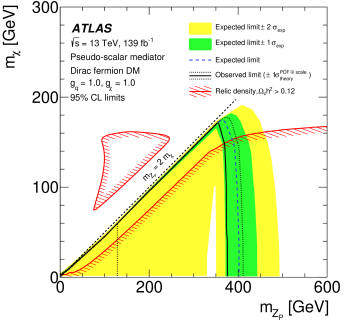


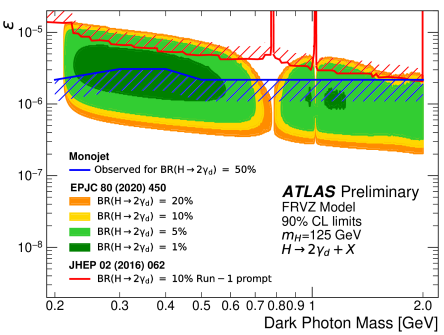


No significant excesses observed

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





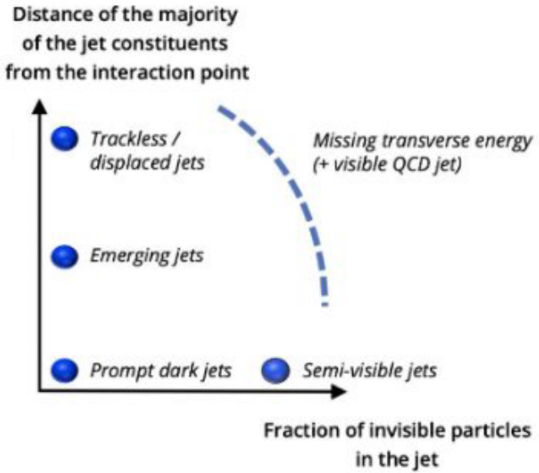


Many interpretations

- Simplified Models
- Long lifetime limit of LLP models. (Reinterpretation Note)
- Generic sensitivity - e.g. SUSY, leptoquarks, extra dimensions

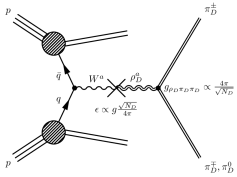
Strongly interacting dark sector signatures

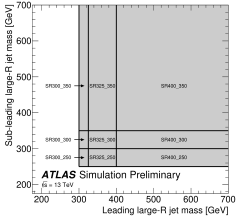
- Signature depends upon lifetime and balance of visible/invisible dark meson decays.
-

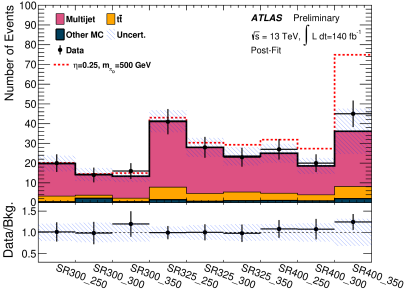


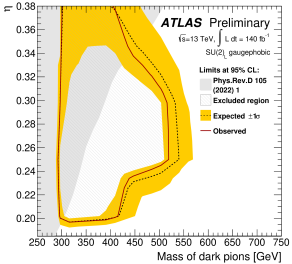
Dark Meson search

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.

Spare slide