

# Dark Matter at Colliders

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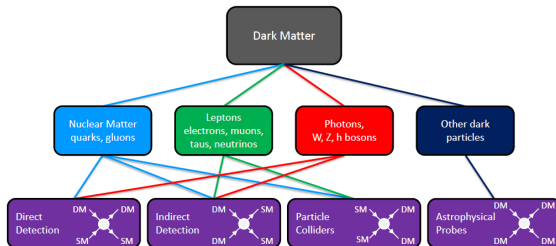


Thursday 5th May 2022

# Collider Searches for Dark Matter

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

- **Dark Matter** - explains wealth of astrophysical observations:

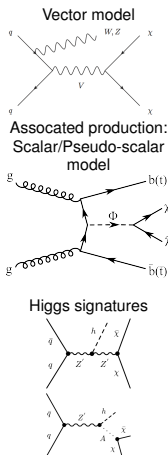


(from 1305.1605)

- **WIMP dark matter remains an attractive option.**
  - ▶ Produced in early universe, now in thermal relic density.
  - ▶ Interaction with quarks via heavy mediator pair-production.
  - ▶ Search for signatures of Dark Matter at the LHC through tagging ISR, or searching for production of new mediator particles.

# 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.
- Initial state radiation (photons, jet, vector bosons) 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) to explore this in LHC Run-2.



# Models

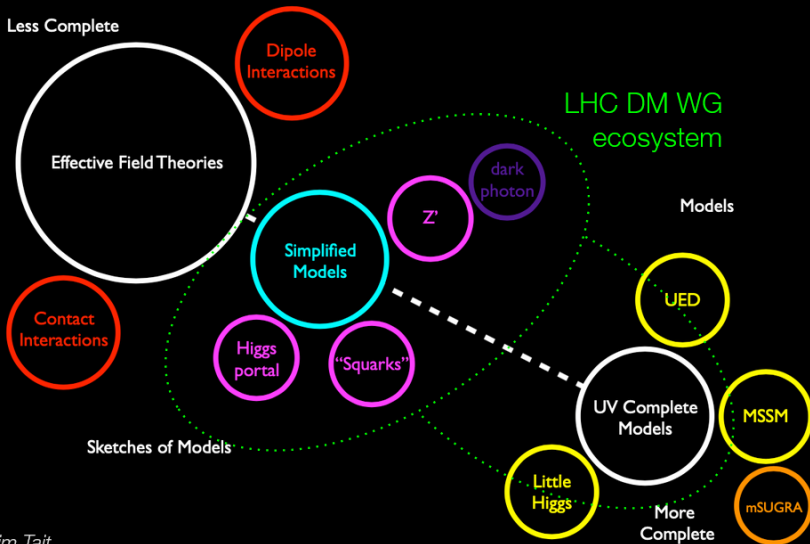
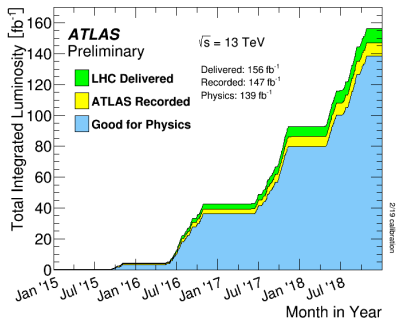


Figure: Tim Tait

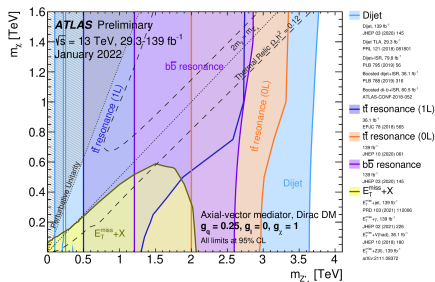
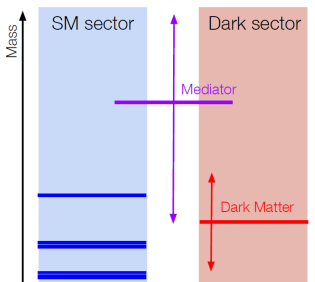
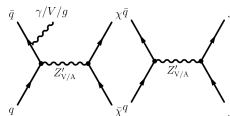
# Where are we up to?

- LHC Run-2 ended in late 2018.
- An unprecedentedly sensitive dataset.
- Many results already published, and more being released regularly.
- **But just the beginning...**
- LHC Run-3 is just around the corner
  - ▶ Greater luminosity and greater collision energy
  - ▶ More than double our data ( $\sim 400 \text{ fb}^{-1}$ ) by 2025.



# 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



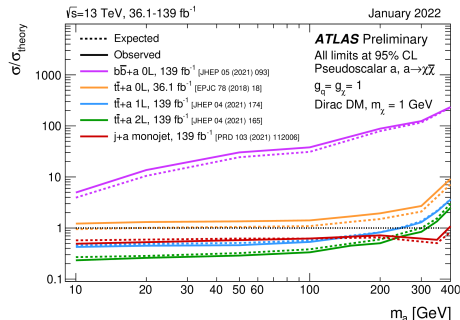
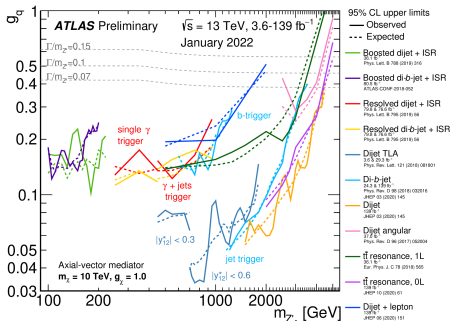
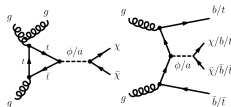
- Relic density: use to *guide* searches (simplified model incomplete)

# S-channel Mediator Simplified Models II

- Or focus on mediator searches, quantify coupling constraints.
- Much work to extend constraints to lower masses.

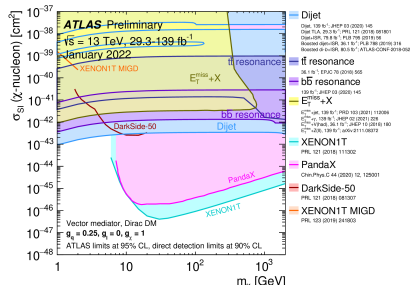
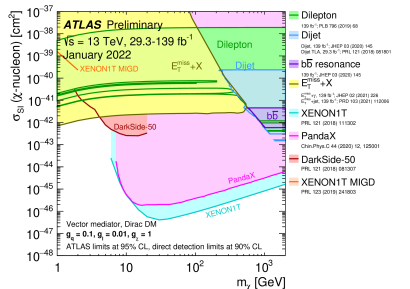
Also consider scalar/pseudo-scalar mediators...

Heavy quark (b/t)-associated searches dominate



# Comparisons with Detection Experiments

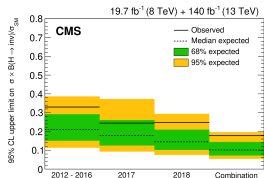
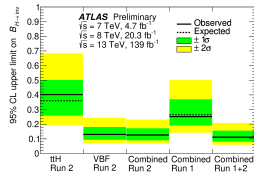
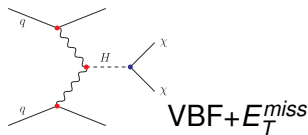
- **Key message: complementarity**
- LHCDMWG white paper on presentation (1603.04156)
- Assumptions: WIMP, local DM density, interaction type (model-dependence).
- Colliders insensitive to DM mass (all is  $E_T^{miss}$ ), mediator more important.
- Ongoing work to illustrate variations (2203.12035)





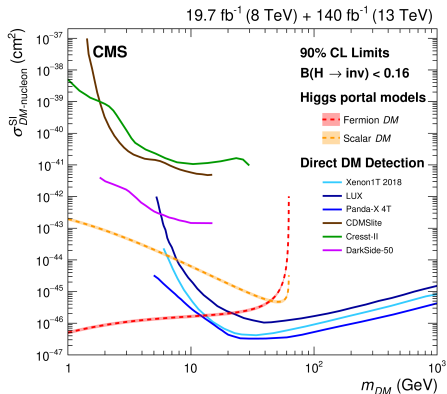
# Invisible Higgs Searches

- ‘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.
  - ▶  $\text{VBF} + E_T^{\text{miss}}$ ,  $Z + E_T^{\text{miss}}$ ,  $\text{tt} + E_T^{\text{miss}}$ ,  
monojet/mono-V(had),  $\text{VBF} + E_T^{\text{miss}} + \gamma$
- Already probing Higgs BR down to below 10% level.



# Invisible Higgs Searches

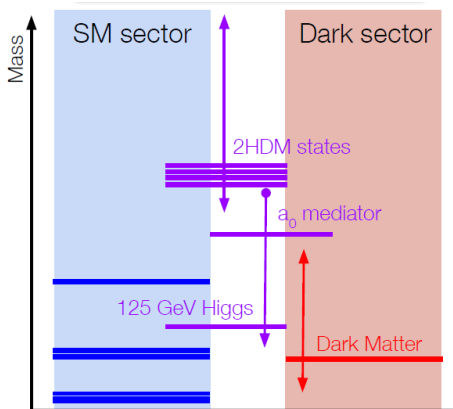
- Also can be reinterpreted.
- Sensitivity starts at  $m_H/2$ .
- Mediator more fixed, but dependence on the WIMP type.



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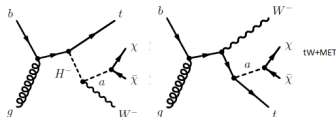
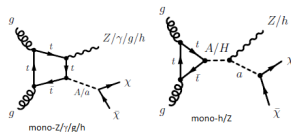
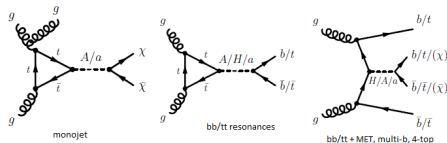
# Extended Higgs sectors

- 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.
- *Interesting physics from wide range of signatures and  $A$ - $a$  mixing.*

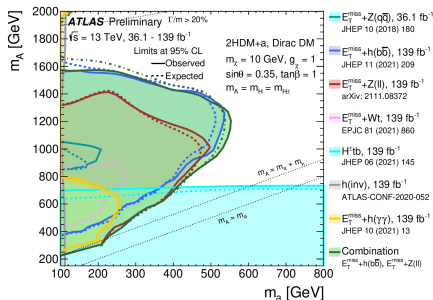


# 2HDM+a - Overview

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

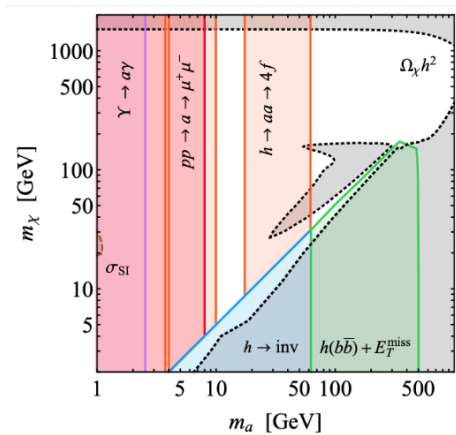


- Various benchmarks to illustrate varied phenomenology.
- Preliminary combination
- Sensitivity dominated by mono-H(bb) and mono-Z(II) searches.
- But also new signatures - e.g. top+ $E_T^{miss}$
- Synergy of invisible/visible signatures - can also target the heavier Higgs states.
- Structure of the Higgs sector (is there only one Higgs boson?) of wide interest.



# 2HDM+a Light Pseudoscalars

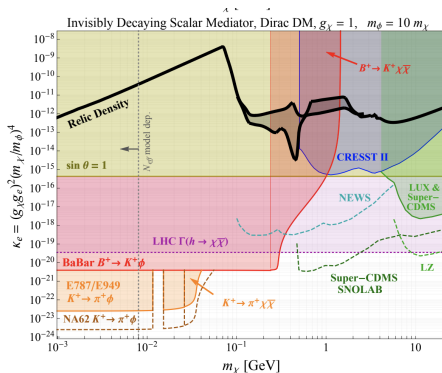
- Also complementarity with lower-mass searches for pseudoscalars.
- Under active exploration.
- Light resonant searches powerful when  $a$  cannot decay to DM.
- Invisible signatures kick in for lower DM masses.



2202.12631

# Benchmarks for lighter DM models (MeV-10 GeV)

- Interaction beginning with FPC (FIP Physics Centre) on light DM benchmarks.
- Much interplay between LHC, DD and beamdump/light DM experiments (and many subtleties).
- Intention to agree on a set of benchmarks, (simplified models) to compare the different communities' results coherently.



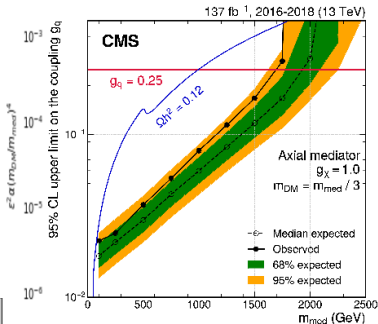
Singlet Mixing Model (1512.04119)

# Benchmarks for lighter DM models (MeV-10 GeV) II

In practice, conversion/rescaling between LHC Spin-1 results and PBC dark photon models is relatively straightforward. Need to speak the same language though!

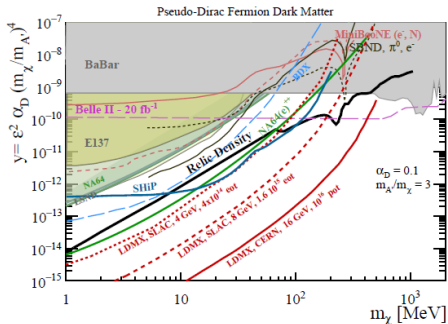
CMS already provided interpretation in term of DM mass fraction in their monojet paper

Caveats: allowing coupling to vary needs care outside of narrow-width regime. Independent work ongoing to enable this more straight-forwardly.



Some care needed on the balance of complementarity - the range of DM/mediator mass ratios covered is a strength of LHC searches.

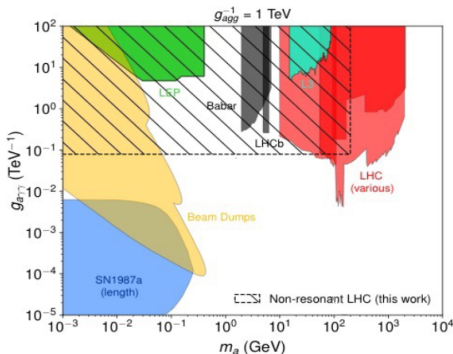
The LHC provides unique sensitivity above 10 GeV.





# Lighter DM III

- Also 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

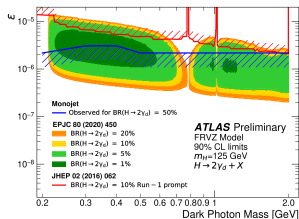


1905.12953, re-interpreting CMS  
 $ZZ/\gamma\gamma$  searches

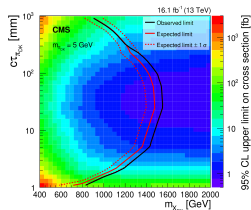
# New directions

## Dark sectors and Long-Lived Particles

- Much interest in the interplay between DM and LLP, and strongly-interacting dark sectors.
- Under exploration in several areas (semi-visible jets in LLP and Snowmass), can also reinterpret standard DM searches (e.g. monojet)).
- Are there DM-specific LLP features?
  - ▶ e.g. light, jets (anti-)aligning with  $E_T^{miss}$ , spread of decay lengths/boosts
- Clear complementarity with DM programme.



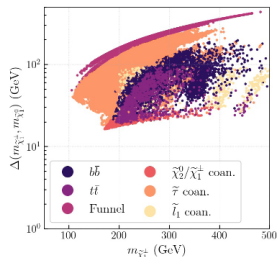
ATL-PHYS-PUB-2021-020



1810.10069 (CMS emerging jets  
16 fb<sup>-1</sup>)

## Anomalies

- Impact of current anomalies on the dark matter landscape.
- Theoretical focus, particularly w.r.t.  $(g - 2)_\mu$  mostly on pMSSM at the moment, but developing ... e.g.
  - ▶ Light DM
  - ▶ 2HDM models
- Flavour anomalies and dark matter - signatures and models vary widely - e.g. large extended sector on top of leptoquarks (e.g. 4321 models), or a singlet portal.



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# Conclusions and Outlook

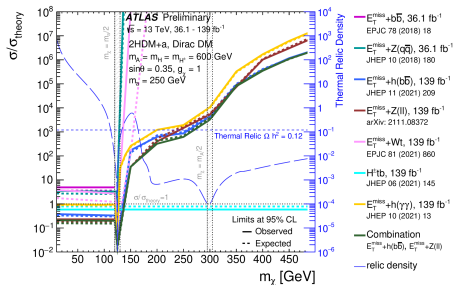
- Wide ranging and successful collider search programme.
- Initially focussed on WIMP hypotheses - still many options
- Now also many results on other DM options - dark photons, ALPs, dark sectors
- Often sophisticated analyses - LHC Run-2 results to come
- Also combinations and summary papers.
- Have focussed on ATLAS/CMS, but also LHCb, FASER/FPF experiments coming during Run-3.



- Many ideas, both experimental (techniques, signatures) and theoretical (new models, anomalies) - [stay tuned!](#)



# 2HDM+a and DM



# Spare slide