# Collider Searches, Scattering Interpretations

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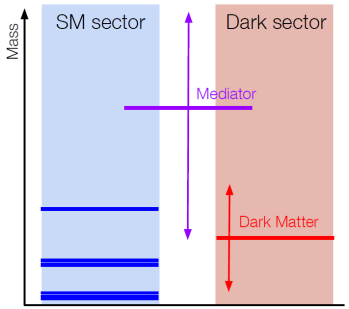
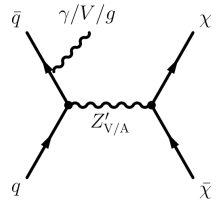
# Intro

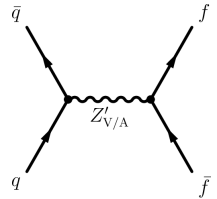
- Aim: provide overview of the standard collider interpretations in terms of scattering cross-section.
- Will not go into great detail on each one (refs provided).

# S-channel Mediator Simplified Models - V/AV mediators

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



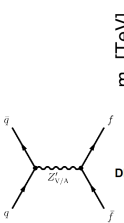



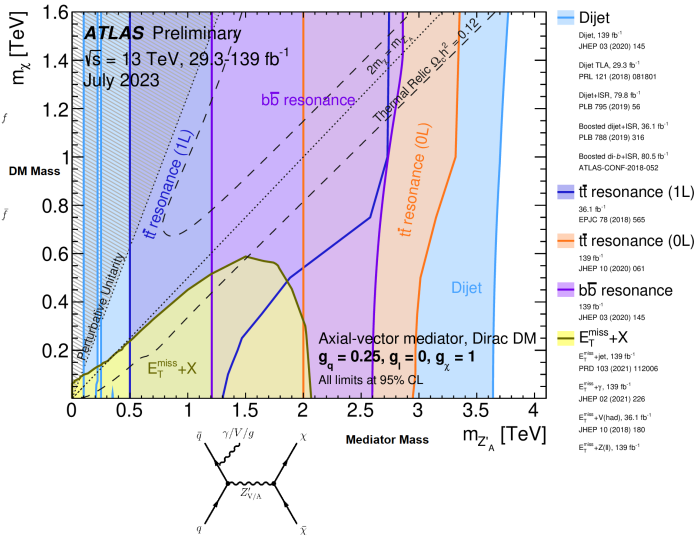

LHCDMWG White Paper (1507.00966)

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

# Putting it all together - Simplified Models I

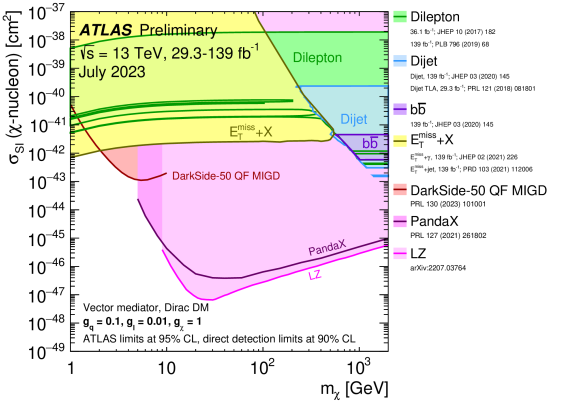
- ATLAS DM Summaries
- Illustrate complementarity between mediator and invisible searches.



# Comparisons with Detection Experiments

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



# Conversions to Scattering Cross-sections

Vector interactions

- SI DM-nucleon scattering takes form (p/n diff. negligible, flavour-blind):

$$\sigma_{\rm SI} = \frac{f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4}, \qquad f(g_q) = 3g_q,$$

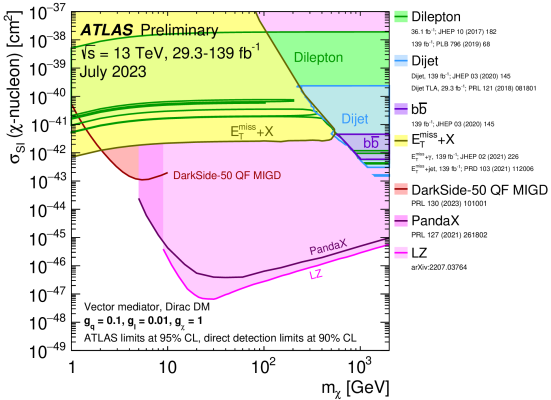
$$\sigma_{\rm SI} \simeq 6.9 \times 10^{-41}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,{\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2.$$

Axial-vector interactions

- Scattering is SD, $\sigma_{SD}$:

$$\sigma_{\rm SD} = \frac{3 f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4}. \qquad f(g_q) = 0.32 g_q,$$

$$\sigma^{\rm SD} \simeq 2.4 \times 10^{-42}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,{\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2.$$

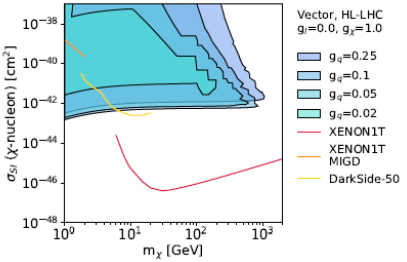


# Comparisons with Detection Experiments II 2206.03456

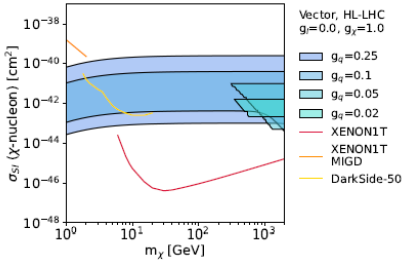
- Largely $m_\chi$-independent
- Low dependence on coupling

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

Product of couplings | Mediator mass | Reduced mass $\mu_{n\chi} = m_n m_{\rm DM}/(m_n + m_{\rm DM})$



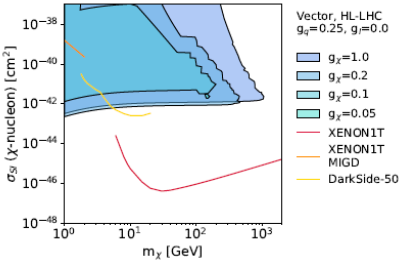

(a) Monojet analysis




(b) Dijet analysis

# Comparisons with Detection Experiments III 2206.03456

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

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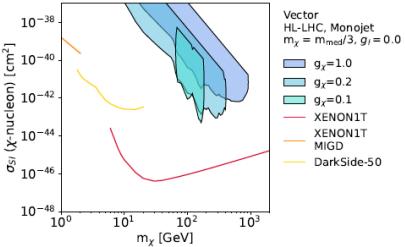


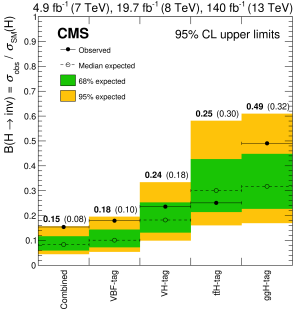

(a) Monojet analysis

# Invisible Higgs Searches - Combined

PLB 842 137963

- Run-2 combinations of 139 fb$^{-1}$ results, together with Run-1 analysis.
- VBF+$E_T^{miss}$ and Z+$E_T^{miss}$ most sensitive, Run-1 adds 4%.
- Already probing BR(H$\rightarrow$ *Inv*) at the 10% level!

| Analysis | Best fit $\mathcal{B}_{H\rightarrow \text{inv}}$ | Observed 95% U.L. | Expected 95% U.L. |
|---|---|---|---|
| Run 2 Comb. | $0.04 \pm 0.04$ | 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. | $0.04 \pm 0.04$ | 0.107 | $0.077^{+0.030}_{-0.022}$ |

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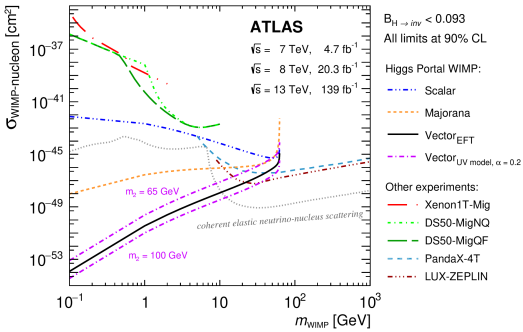
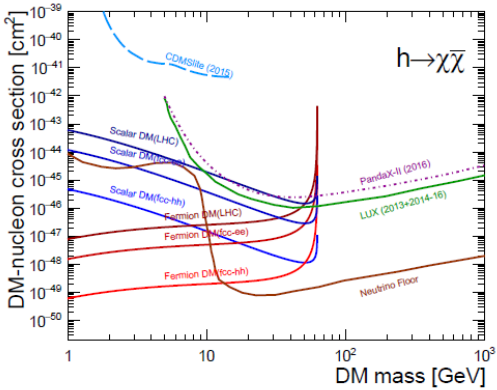
# Invisible Higgs Searches - Combined PLB 842 137963

- Conversions to scattering cross-section (2107.01252)

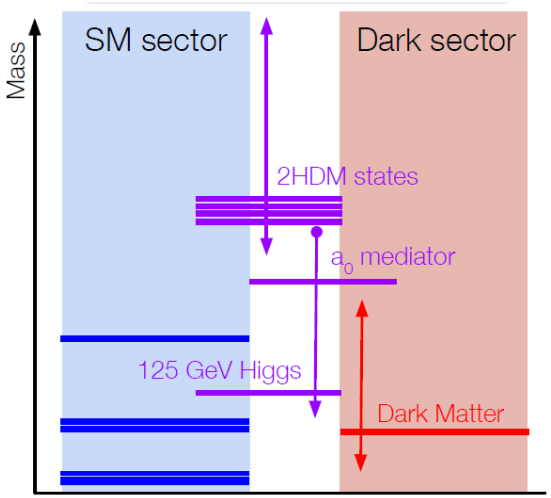



(b) Higgs portal model

# 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

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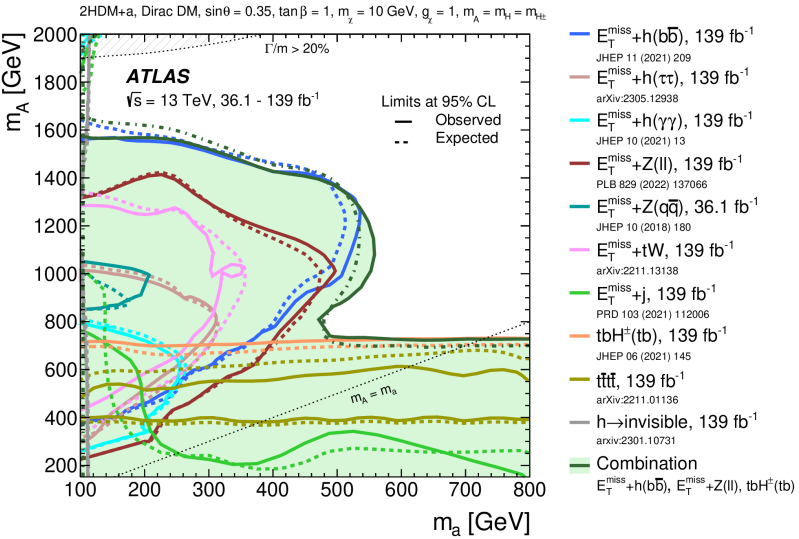
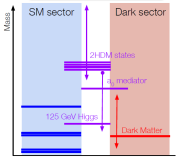
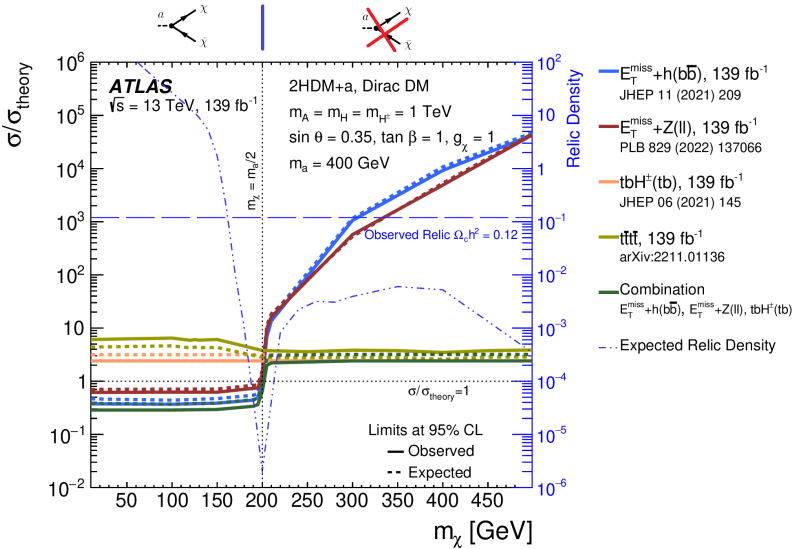


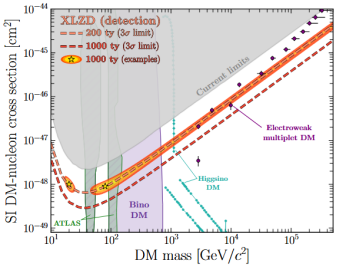
# 2HDM+a - Sensitivity to DM mass 2306.00641




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



- LHC has a full SUSY programme, (long-standing DM search).
- Cover all signatures - many final states and processes constrained.
- Also look to contextualise in model space. Difficult.
- e.g. ‘EWK pMSSM scan’ - assumes squarks/sleptons are decoupled (heavy), only EWKinos LHC-accessible.

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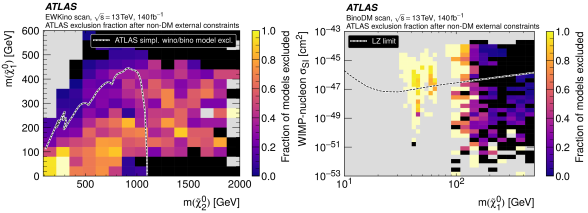
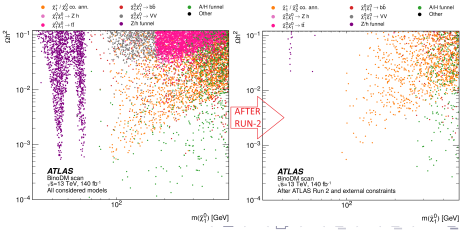
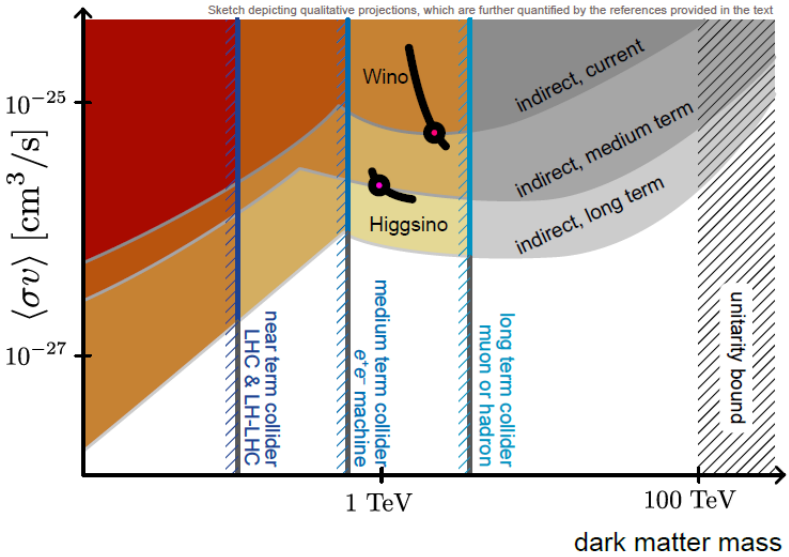


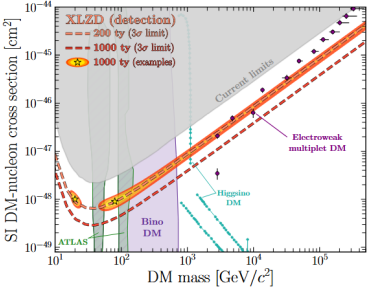
# Snowmass complementarity 2206.03456

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



# Complementarity II

- Lovely to see cross-fertilisation!

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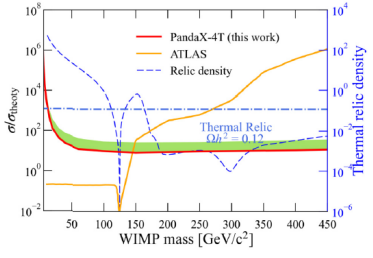


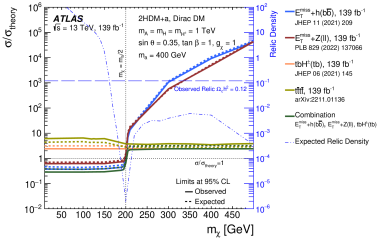


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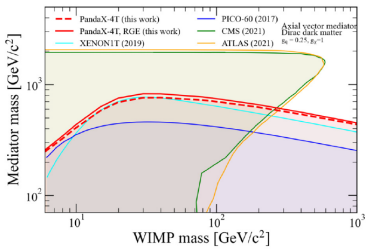


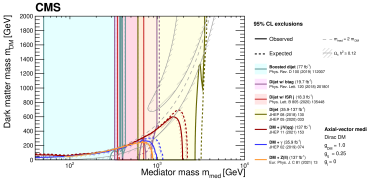


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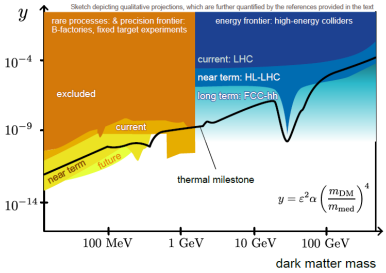
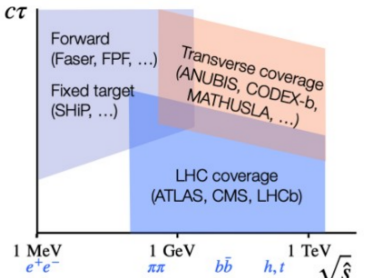
# New, light/weakly coupled DM experiments - Not Today

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

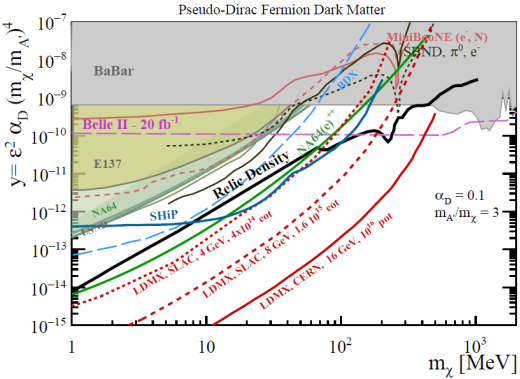


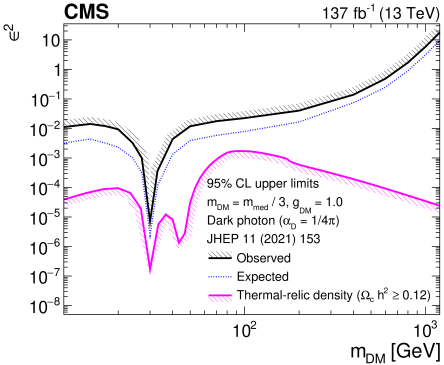



# Monojet and the dark photon portal

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

2102.12143

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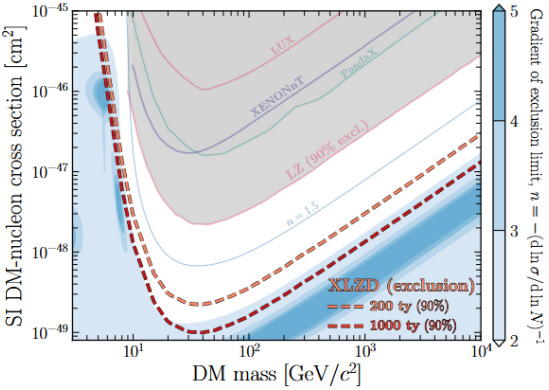
# Summary

- Hopefully a useful overview/resource - apologies for lack of polish.
- Will revise for discussing complementarity.
- Next meeting (19th May), Joe will discuss the DD side of the scattering plot.



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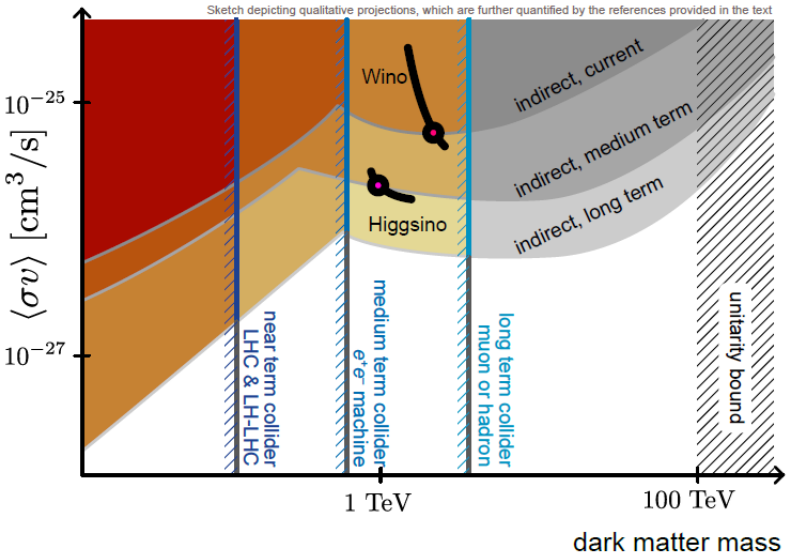
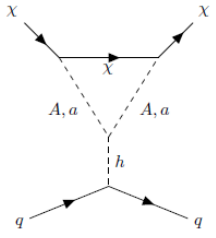
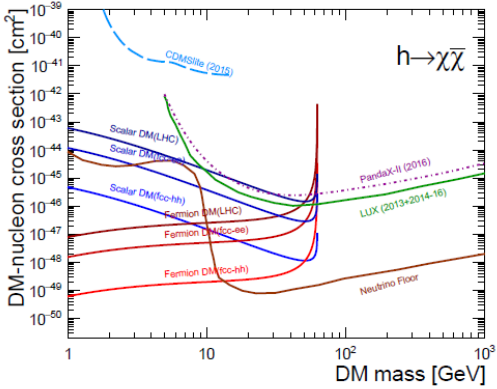


# Beyond Collider Reinterpretations / Colliders as data consumers

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




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




(b) Higgs portal model

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

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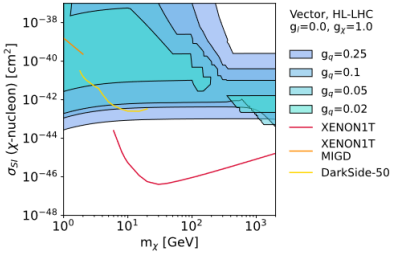
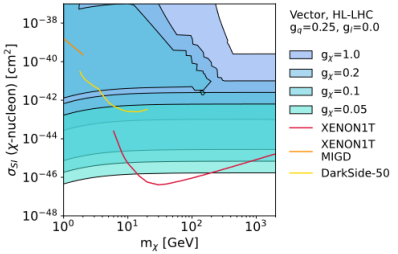
Product of couplings | Mediator mass | Reduced mass

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



# Spare slide