

# Searches for Dark Matter with the ATLAS Detector

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On behalf of the ATLAS collaboration

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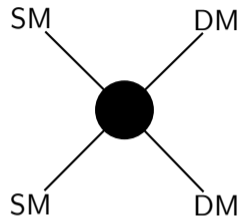


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# Introduction

- Collider searches for dark matter:
  - Look for DM production from Standard Model particles.
  - Complementary with direct, indirect detection experiments.
  - Can detect DM as "invisible" particles through  $E_T^{\text{miss}}$ .
  - Can also look for visible decays of new DM/SM mediators.
- This talk: latest ATLAS DM searches with full run 2 dataset:
  - Summary of different dark matter models under consideration.
  - Quick overview of four recent analyses and their DM interpretations:
    - $VBF + E_T^{\text{miss}}$ : [EXOT-2020-11](#)
    - $Z(\ell) + E_T^{\text{miss}}$ : [HIGG-2018-26](#)
    - $t\bar{t} + E_T^{\text{miss}}$ : [ATLAS-CONF-2022-007](#)
    - $tW + E_T^{\text{miss}}$ : [ATLAS-CONF-2022-012](#)
    - More detail can be found at the linked public results pages.
  - Comparison of limits from different channels through benchmark DM model(s).

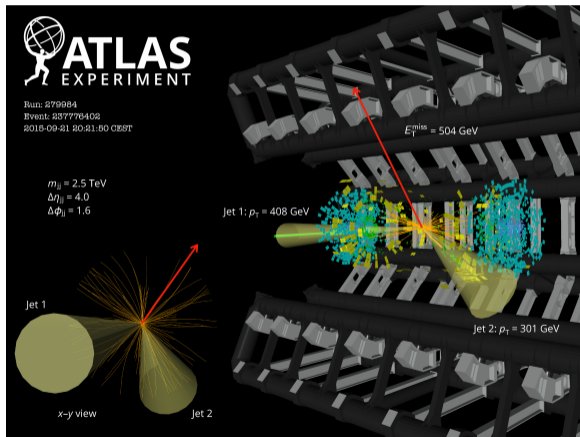


# Dark Matter Collider Searches

- Three classes of dark matter models being constrained by these analyses:
- Simplified models of **new mediators** (scalar or vector) which couple to SM and DM fermions.
  - Limits depend on the mediator mass and coupling strengths  $(g_l, g_q, g_\chi)$ .
- **2HDM+ $a$** : UV-complete model with two Higgs doublets, extra pseudoscalar mediator  $a$ :
  - Benchmark model for the LHC DM Working Group: [Phys. Dark Univ. 27 \(2020\) 100351](#).
  - Five main parameters: mediator  $m_a$ , DM fermion  $m_\chi$ , heavy Higgs  $m_A = m_H = m_{H^\pm}$ .
  - Also depends on  $a/A$  CP-odd mixing angle  $\sin(\theta)$ ; ratio of Higgs doublet VEV  $\tan(\beta)$ .
- **Higgs portal**: mediator is the 125 GeV Higgs boson, can couple to scalar, fermion, or vector DM.
  - DM may get mass through Higgs mechanism; detectable if  $m_{\text{DM}} < \frac{1}{2}m_h$ .
  - Set limits on Higgs branching ratio to invisible particles.

# Search for VBF Higgs + $E_T^{\text{miss}}$

- Search for invisible decay of Higgs boson produced via vector boson fusion.



[arXiv:2202.07953](https://arxiv.org/abs/2202.07953)

- **Most sensitive**  $h \rightarrow \text{inv}$  channel: distinct jet signature.

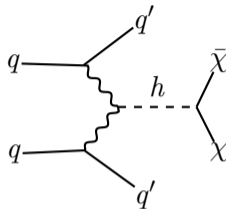
- Require jet pair with large rapidity gap,  $m_{jj} > 0.8 \text{ TeV}$ .

- Large  $E_T^{\text{miss}} > 160 \text{ GeV}$ .

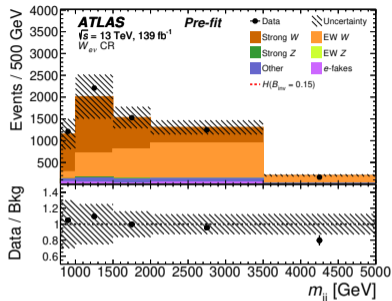
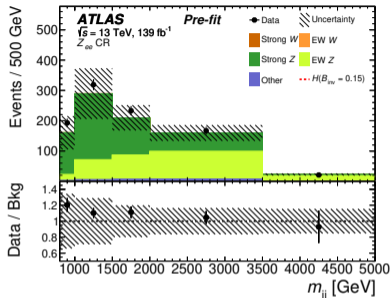
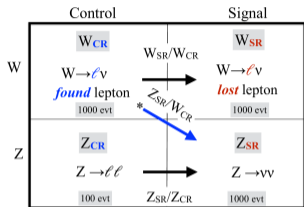
- Fully reoptimized since  $36.1 \text{ fb}^{-1}$  result.

- Main background:

- $Z(\nu\nu) + \text{jets}$ ,  $W(l\nu) + \text{jets}$  lost lepton.
- Suppressed by high  $m_{jj}$  requirement.
- Partially data-driven estimate from 1 ( $W$ ), 2 ( $Z$ ) lepton control regions.
- Additional small multijet background with fake  $E_T^{\text{miss}}$ .



# VBF + $E_T^{\text{miss}}$ Background Estimation

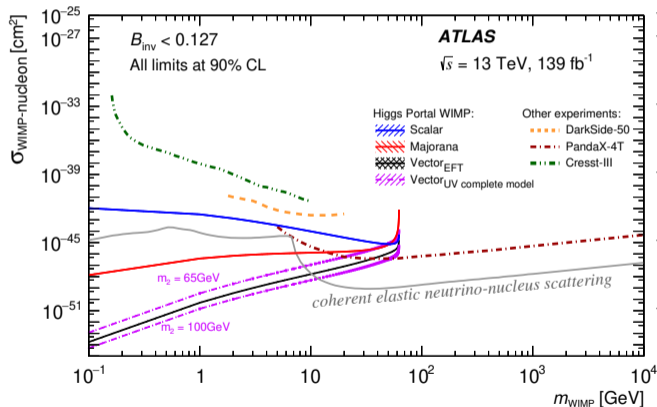


- Monte Carlo background predictions corrected with data from control regions.
- Major background estimation improvements from collaboration with J. Lindert et al.
  - $Z(\ell\ell)$  statistics much lower than  $W(\ell\nu)$  due to lower cross section, branching ratio.
  - Theorists provided **analytic reweighting** from  $Z/W$  as 1D function of  $m_{jj}$ .
  - Details on calculation and associated uncertainties available in their paper: [arXiv:2204.07652](https://arxiv.org/abs/2204.07652).
  - Z background **now constrained using W**: leads to improvement in expected limit.

# Higgs Portal Dark Matter Interpretation

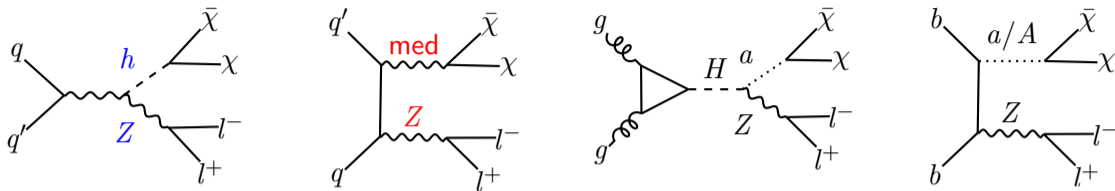
- Set 95% CL limits on  $h \rightarrow \text{inv.}$ :
  - $\mathcal{B}_{h \rightarrow \text{inv.}} = 0.145$  ( $0.103^{+0.041}_{-0.028}$ ).
  - Significant improvement from  $36.1 \text{ fb}^{-1}$ :  $0.37$  ( $0.28^{+0.11}_{-0.08}$ ).
- Interpret as spin-independent WIMP-nucleon elastic scattering cross section in Higgs portal:
  - New **scalar** boson
  - New Majorana **fermion**
  - New **vector** boson (EFT)
  - Renormalizable **vector** model; dark Higgs with mass  $m_2$ . (LHEP-270, 2022).
- Complementary to direct detection for  $m_{\text{WIMP}} < 10 \text{ GeV}$ ; probing **below neutrino floor**.

| Observed | Expected | +1 $\sigma$ | -1 $\sigma$ | +2 $\sigma$ | -2 $\sigma$ |
|----------|----------|-------------|-------------|-------------|-------------|
| 0.145    | 0.103    | 0.144       | 0.075       | 0.196       | 0.055       |



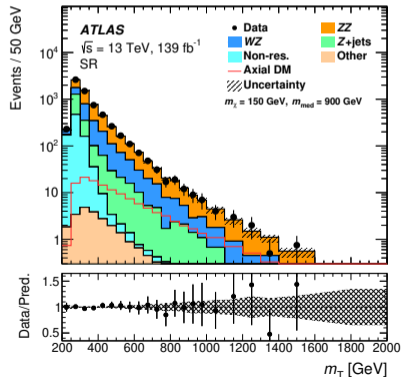
arXiv:2202.07953

# Searches for $Z(l\bar{l}) + E_T^{\text{miss}}$



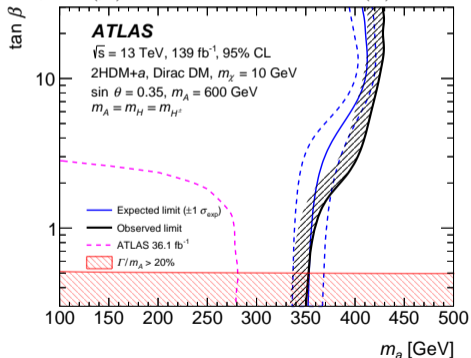
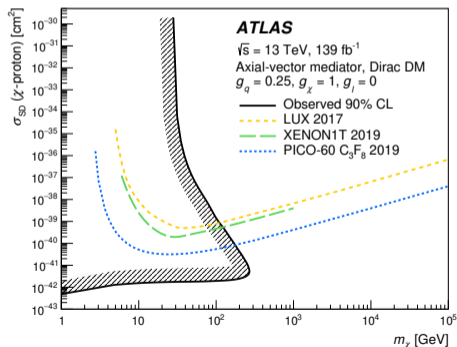
- Search for  $Z$  decay to  $l^+l^-$  plus  $E_T^{\text{miss}} > 90$  GeV.
- Most sensitive **2HDM**+ $a$  channel; also sensitive to **Higgs portal**, **(axial) vector** mediator signals.
- Main backgrounds:  $ZZ$ ,  $ZW$ ;  $Z$ +jets with fake  $E_T^{\text{miss}}$ :
  - Select  $ee, \mu\mu$  with  $76 < m_{ll} < 106$  GeV,  $\Delta R_{ll} < 1.8$ .
  - Separate fit for each signal: BDT used for  $h \rightarrow \text{inv.}$
  - Other signals fit using  $m_T$  for each mass point.
  - Main systematics:  $ZZ$  background, jets and  $E_T^{\text{miss}}$ .

Phys. Lett. B 829 (2022) 137066



# $Z(\ell) + E_{\tau}^{\text{miss}}$ Dark Matter Interpretations

- Set 95% limit on  $\mathcal{B}_{h \rightarrow \text{inv.}} = 0.19$  (0.19), improved from 0.67 (0.39) in  $36.1 \text{ fb}^{-1}$  analysis.
- Set model-dependent limits on vector, axial-vector models: compare to direct detection.
  - Mediators up to 950; DM up to 250 (350) GeV **now excluded**.
- Set 2HDM+ $a$  limits: **significant improvements** due to inclusion of  $bb$  signals.
  - Probe eight models: six 2D scans in  $m_a, m_A, \tan(\beta)$ ; two 1D scans in  $\sin(\theta)$ .

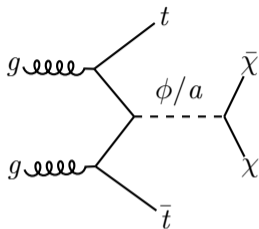


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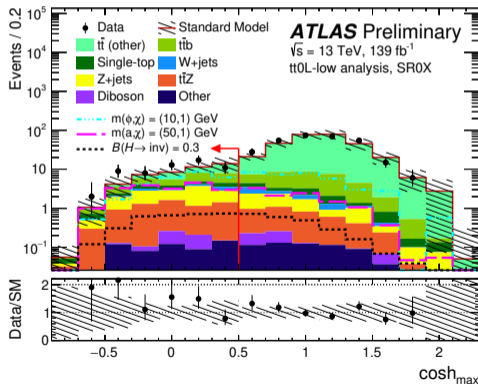


# Searches for $t\bar{t} + E_T^{\text{miss}}$

- Search for DM in association with top quark(s).
- Sensitive to new (pseudo) scalar DM mediators.
- Combination of existing ATLAS  $t\bar{t} + E_T^{\text{miss}}$  searches (for DM, stop squarks):
  - **tt2L**: JHEP 04 (2021) 165
  - **tt1L**: JHEP 04 (2021) 174
  - **tt0L**: Eur. Phys. J. C 80 (2020) 737
  - **tt0L-low**: ATLAS-CONF-2022-007: **new extension** with increased sensitivity to low mediator masses.



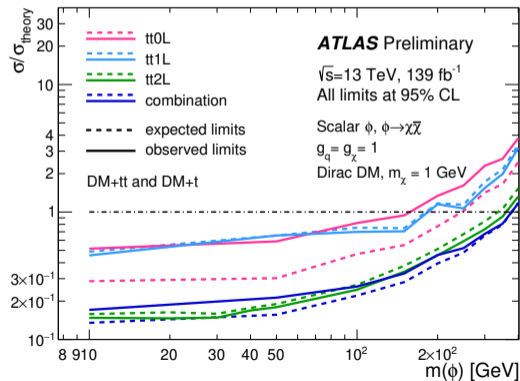
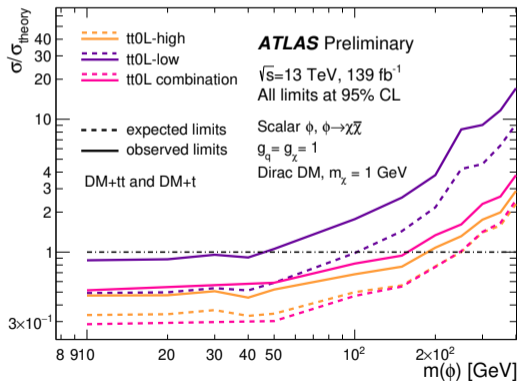
- **tt0L-low**: Lower  $E_T^{\text{miss}}$  or  $E_T^{\text{miss}}$  significance (160-250 GeV,  $S < 14$ ).
- New mix of  $E_T^{\text{miss}}$  and  $b$ -jet triggers.
- New variables to suppress  $t\bar{t}$  with fake  $E_T^{\text{miss}}$ .



$$\cosh_{\text{max}} = \max(\cosh(\eta_W - \eta_{b_1}), \cosh(\eta_W - \eta_{b_2}))$$

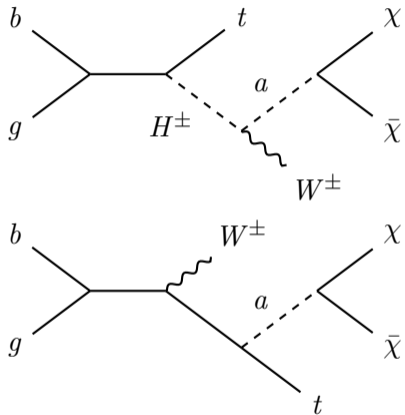
# $t\bar{t} + E_T^{\text{miss}}$ Limits on New Mediators

- Combination of all four channels excludes (pseudo)scalar mediator masses up to 370 GeV.
- Expected limits improved by 14% (24%) for low mass scalar (pseudoscalar) couplings.
- Also interpret in  $t\bar{t}H$  channel as observed (expected) limit on  $\mathcal{B}_h \rightarrow \text{inv.} = 0.40$  ( $0.30_{-0.09}^{+0.13}$ ).



ATLAS-CONF-2022-007

# Searches for $tW + E_T^{\text{miss}}$

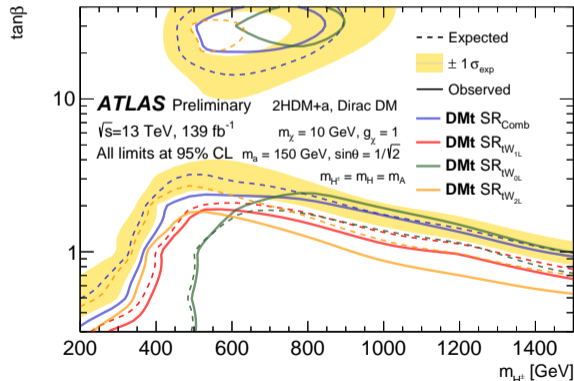
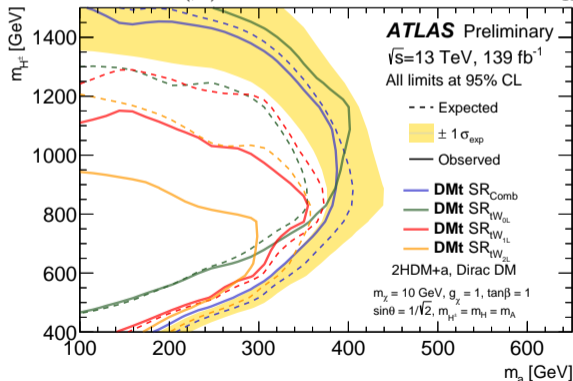


ATLAS-CONF-2022-012

- Dedicated search for  $tW + \text{DM}$  final states:
  - Dominant 2HDM+ $a$  mode for single- $t$  final states.
  - On-shell production of charged Higgs bosons with masses  $\sim$  a few hundred GeV.
- Three target search regions with  $E_T^{\text{miss}} > 250$  GeV:
  - 0L: hadronic  $t$ , hadronic  $W$
  - 1L: leptonic  $t$ , hadronic  $W$
  - 1L: hadronic  $t$ , leptonic  $W$
  - Hadronic  $W$  identified as tagged boosted  $R = 1.0$  jet with  $p_T > 200$  GeV.
  - Combined with 2L channel from older ATLAS analysis ([Eur. Phys. J. C 81 \(2021\) 860](#)).
- Main backgrounds:  $Z$ +jets,  $W$ +jets, tops ( $t, t\bar{t}, t\bar{t}Z$ ).

# $tW + E_T^{\text{miss}}$ Limits on 2HDM+a

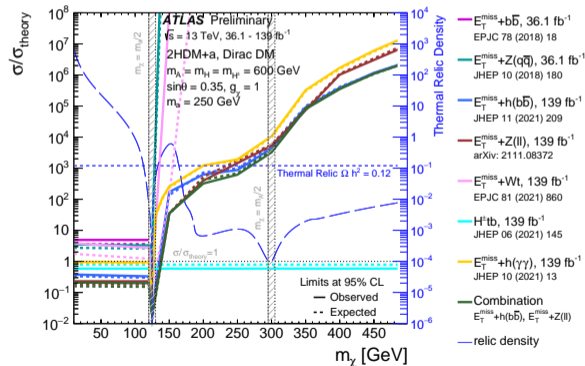
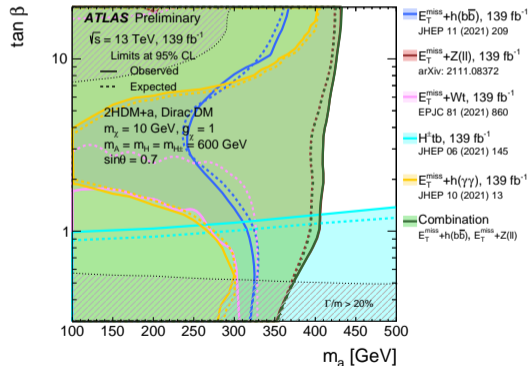
- No significant excess observed; set improved limits at large  $m_{H^\pm}$ , high  $\tan(\beta)$ .
- Models with  $\tan(\beta) = 1$ ,  $m_{H^\pm} < 1.5$  TeV,  $m_a < 350$  GeV excluded.
- $\tan(\beta) < 2$ ,  $m_a = 150$  (250) GeV excluded for  $200$  (400)  $< m_{H^\pm} < 1500$  GeV.
- $20 < \tan(\beta) < 30$  excluded for  $500 < m_{H^\pm} < 800$  GeV.



ATLAS-CONF-2022-012

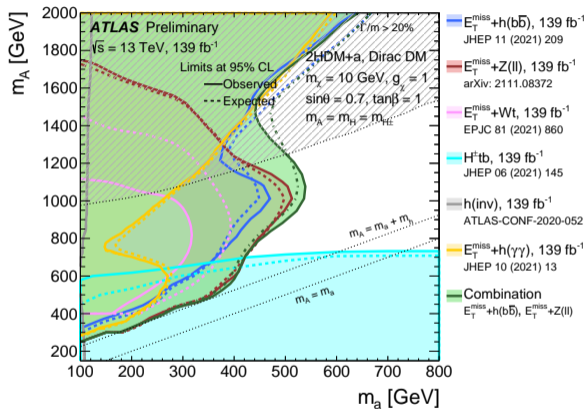
# Combined Limits on 2HDM+ $a$ Model

- Statistical combination performed of most sensitive channels  $Z(\ell\ell) + E_T^{\text{miss}}$ ,  $H(bb) + E_T^{\text{miss}}$ .
- **Increasingly large areas of phase space excluded** by all 2DHM+ $a$  analyses:
  - Additional full run 2 results from  $h(\gamma\gamma) + E_T^{\text{miss}}$ ,  $H^\pm tb$  searches included.
  - Limits presented as various parameter scans, including 1D scan over DM mass  $m_\chi$ .
  - Scans are **model dependent**, with remaining parameters fixed to arbitrary values.



ATLAS-CONF-2021-036, ATLAS-PHYS-PUB-2021-045

# Conclusion



- Presented latest ATLAS results in several searches for dark matter.
- Set new limits on multiple DM models:
  - Strong limits on invisible Higgs branching ratio:  $0.145 (0.103^{+0.041}_{-0.028})$  from  $\text{VBF} + E_T^{\text{miss}}$ ; can combine with other channels for further improvement.
  - Continuing to exclude large sections of 2HDM+a parameter space.
- Thank you for your attention!

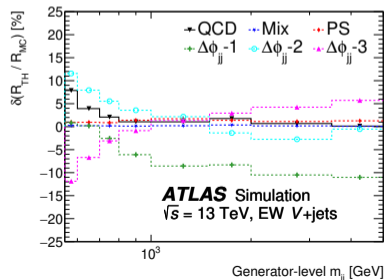
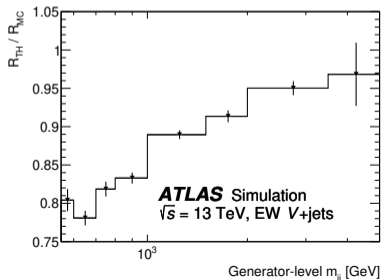
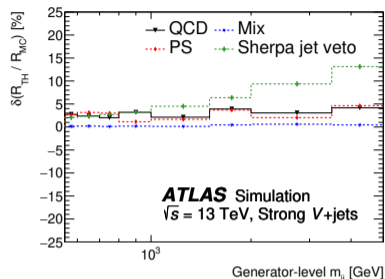
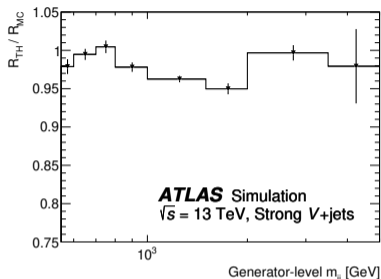
ATLAS-PHYS-PUB-2021-045

# Backup

# VBF+MET: Z/W Reweighting Results

- Theorists provided inputs for reweighting.
- Left: ratios; right: frac. uncertainties:
  - QCD, QCD/EW mixing uncertainties calculated by theorists.
  - Parton shower: vary PS model.
  - QCD reweighting: impact of jet veto.
  - EWK reweighting: diboson interference as function of  $\Delta\phi_{jj}$ .

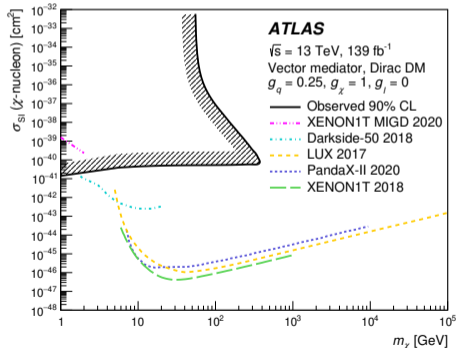
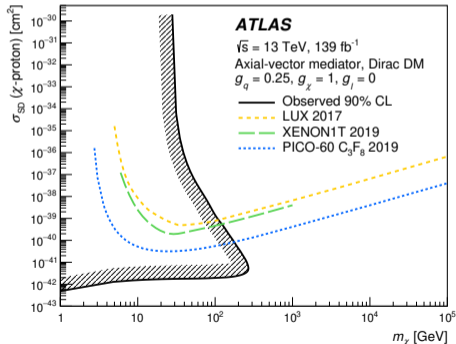
[arXiv:2202.07953](https://arxiv.org/abs/2202.07953)





# $Z(\ell) + E_{\text{T}}^{\text{miss}}$ Dark Matter Interpretations

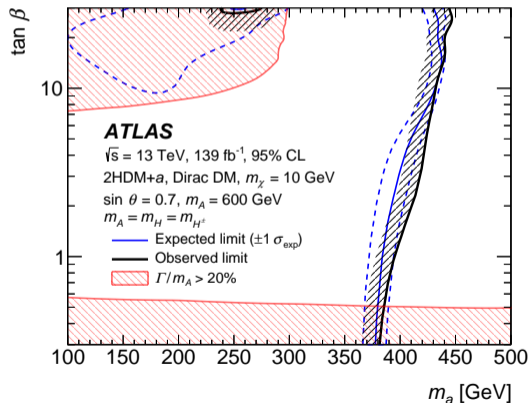
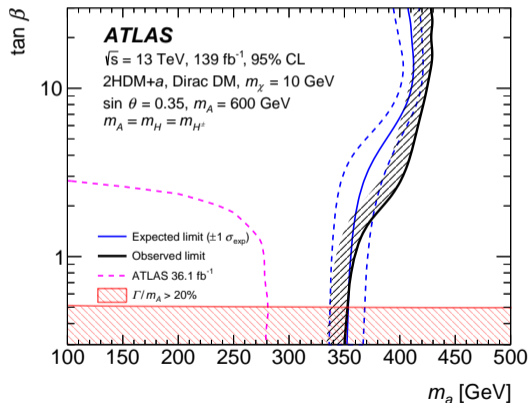
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- Set model-dependent limits on vector and axial-vector mediator models:
  - Mediator masses up to 950 GeV **now excluded** for  $g_q = 0.25$ ,  $g_\chi = 1$ ,  $g_l = 0$ .
  - DM masses up to 250 (350) GeV excluded for axial vector (vector) case.
  - Interpret as WIMP-nucleon cross section limits: complementary for low WIMP masses.



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# 2HDM+ $a$ Limits from $Z(l) + E_T^{\text{miss}}$

- Set 2HDM+ $a$  limits from **eight scans**, holding different parameters fixed:
  - 2D scans in  $(m_a, m_A)$ ,  $(m_a, \tan(\beta))$ ,  $(m_A, \tan(\beta))$  (**new**) for  $\sin(\theta) = 0.35$  and **0.7 (new)**.
  - 1D scan in  $\sin(\theta)$  at low, high  $m_A$ ,  $m_a = (0.6, 200)$ ,  $(1, 350)$  (GeV, TeV).
- **Significant improvement** from  $36.1 \text{ fb}^{-1}$  analyses due to inclusion of  $bb$  signals.



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