Searches for dark matter with the ATLAS detector

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On behalf of the ATLAS collaboration

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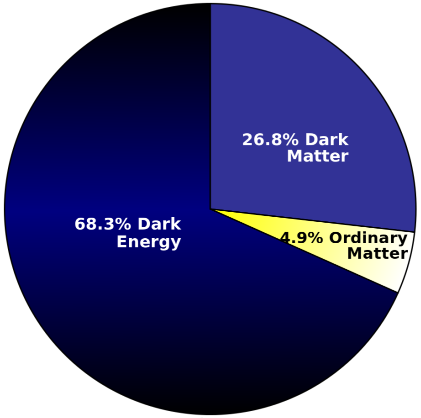
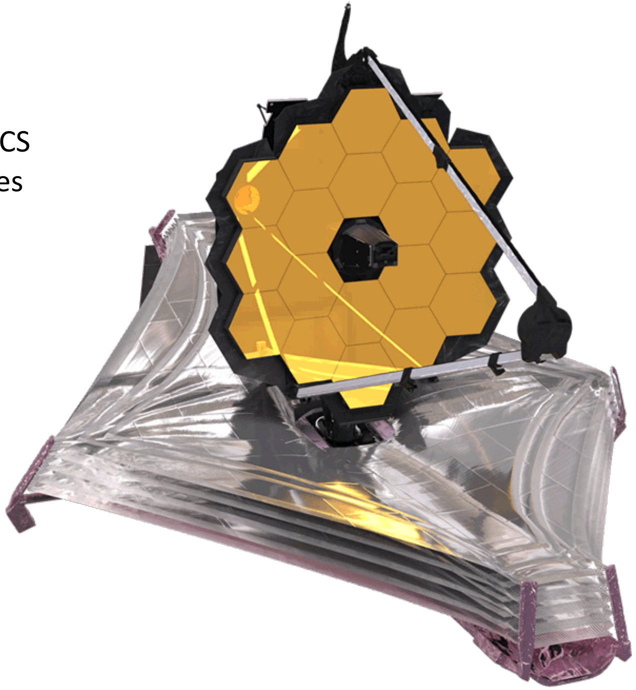
ICNFP 2022

Dark matter

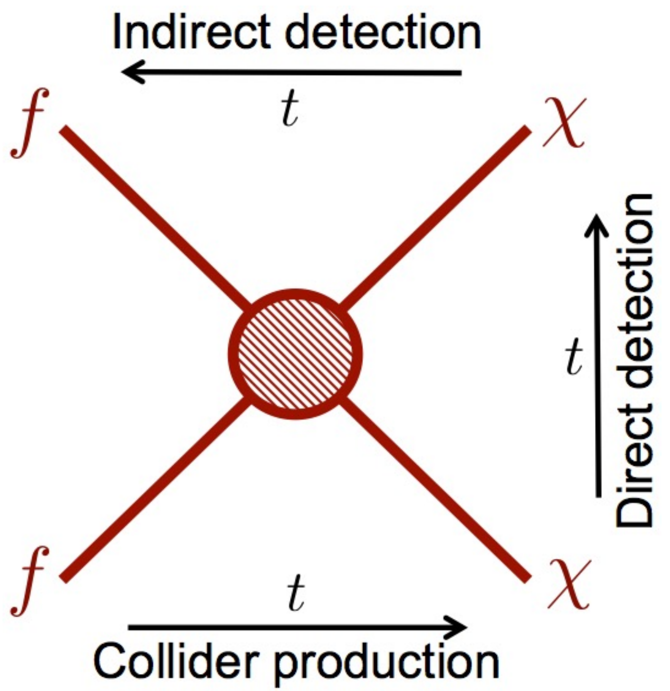
- 85% of matter in the universe!!
- Abundant cosmological evidence:
    - Galactic rotation curves
    - Cosmic Microwave Background anisotropies
    - Gravitational lensing
    - And more



Galaxy cluster SMACS 0723 from the James Webb telescope



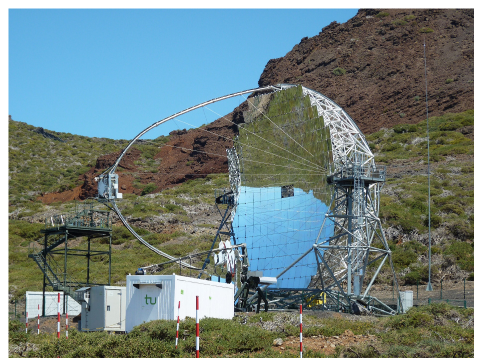
Detecting dark matter

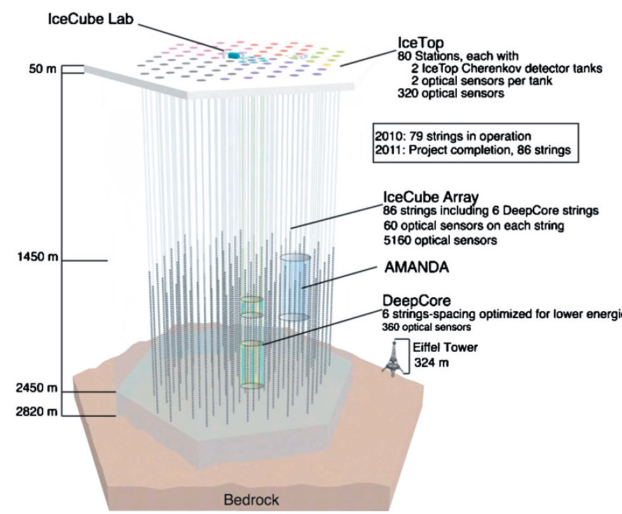


Indirect detection

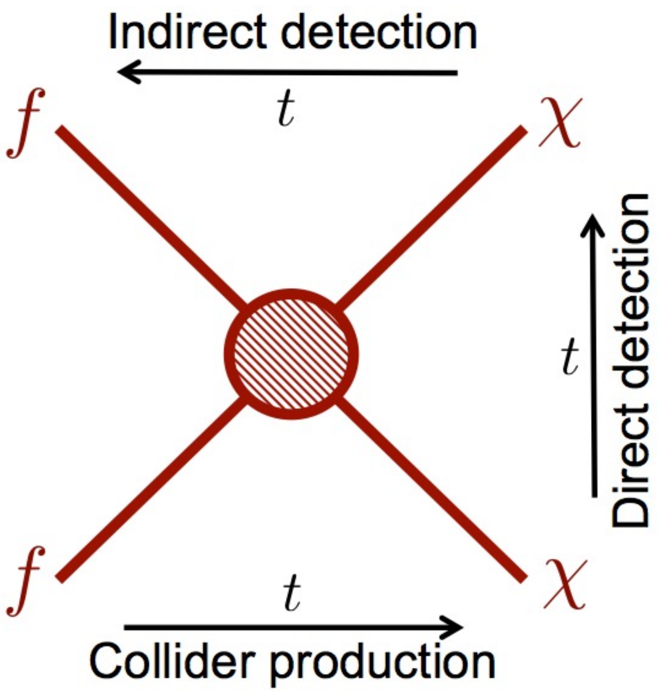
Detect ordinary matter resulting from decay/annihilation of dark matter

- IceCube
- MAGIC
- HESS





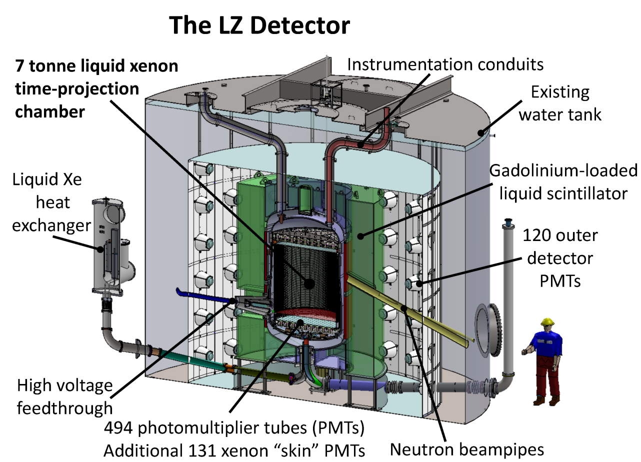
Detecting dark matter

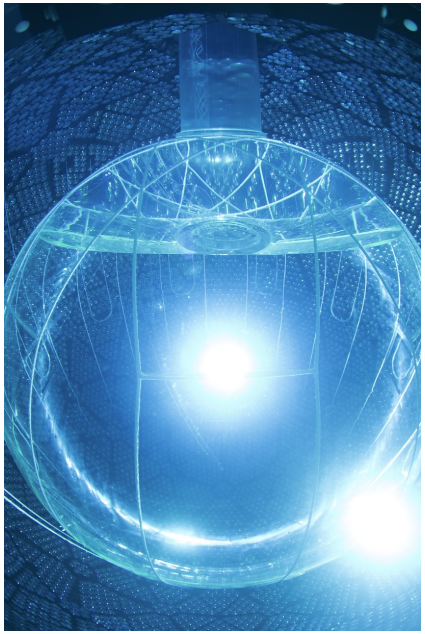


Direct detection

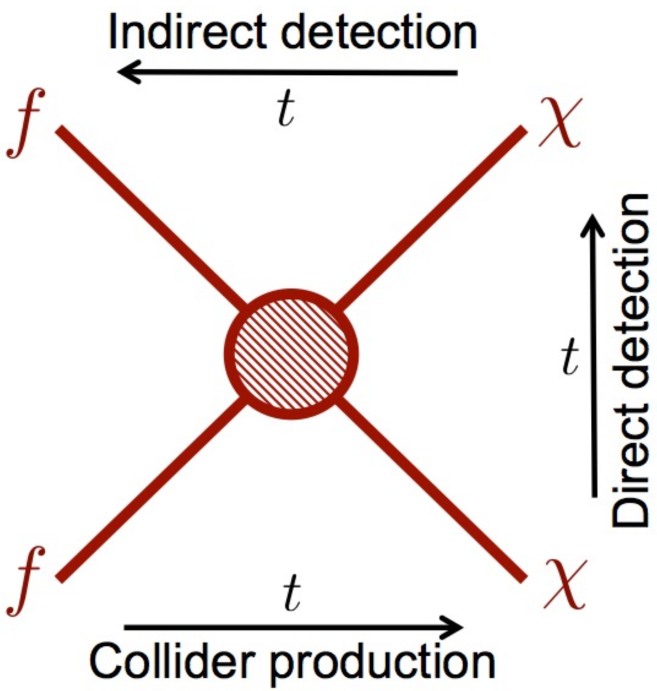
Detect interactions between dark matter and ordinary matter (e.g. nuclear recoils):

- LZ
- XENON
- SNOLAB





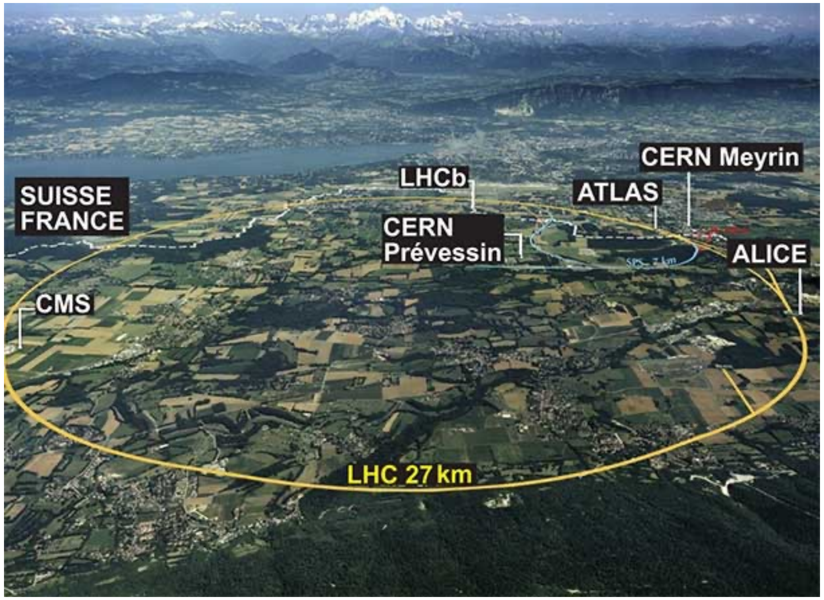
Detecting dark matter



Collider production

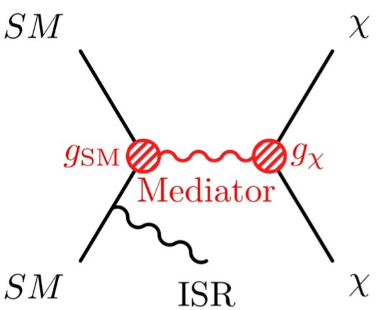
Why wait? Produce dark matter on demand!

- ATLAS
- CMS
- LEP



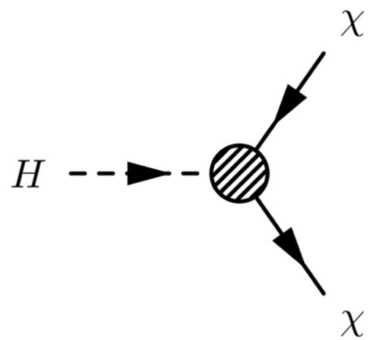
Dark matter models at ATLAS

Simplified models



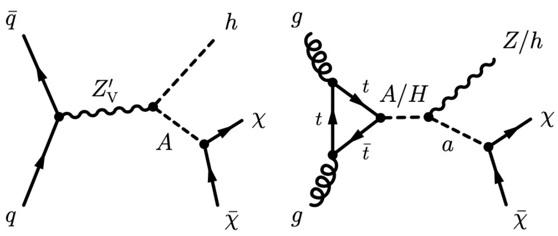
Introduce minimal number of new DOFs
Signatures: monoX, mediator resonance

Higgs portal



Higgs acting as a mediator to DM
e.g. $H \rightarrow inv$ decays

Extended Higgs sector

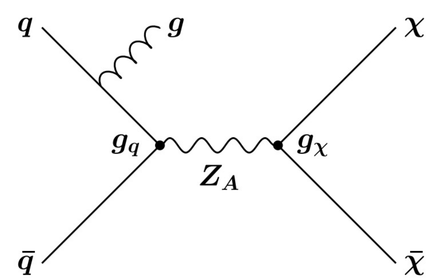


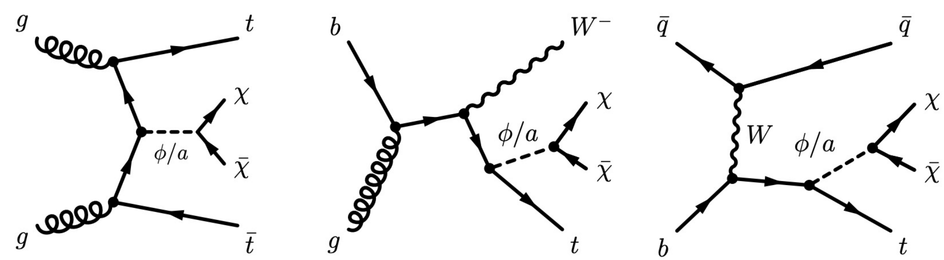
More complete models involving several Higgs-like (or scalar) bosons
e.g. 2HDMa, dark Higgs

+ others not covered here
e.g. SUSY, long-lived particles

- In this talk I will focus on a selection of recent analyses at ATLAS
- WIMP assumption – no direct interaction with detector
- Infer existence of dark matter through momentum imbalance $E_T^{miss} = |-\sum p_T|$

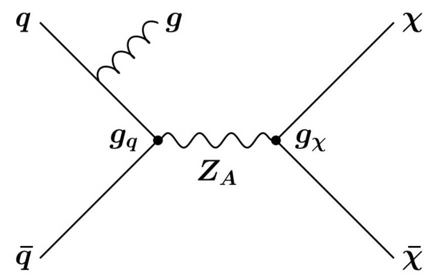
Simplified models





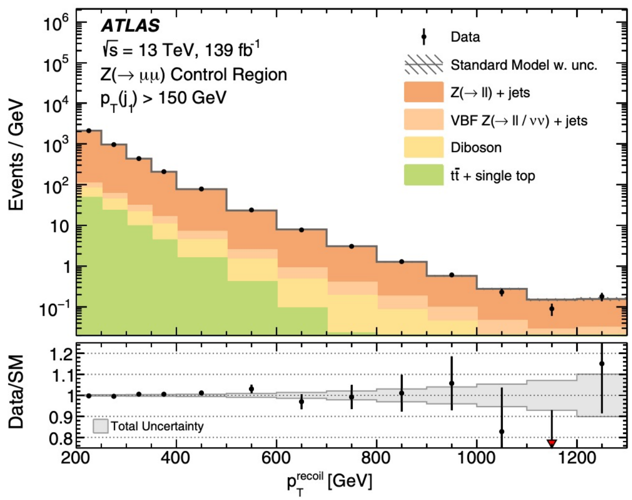
Jet + E_T^{miss} (Phys. Rev. D **103**, 112006)

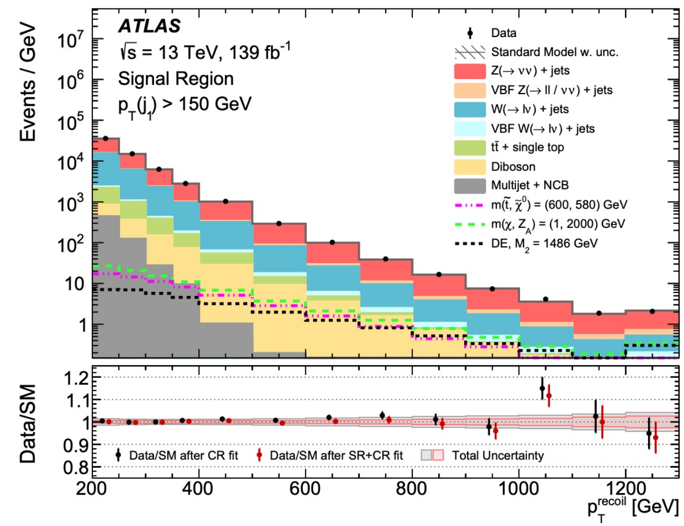
- Sensitive to both pseudoscalar and axial-vector mediators, $H \rightarrow inv$, as well as many other interesting models (SUSY, axion-like particles, etc)
- Selection:
  - $E_T^{miss} > 200$ GeV
  - Jet with $p_T > 150$ GeV, $|\eta| < 2.4$
  - No leptons
- Background estimation
  - V + jets, $t\bar{t}$, single t: (5 control regions)
  - Multijet: data driven jet smearing method



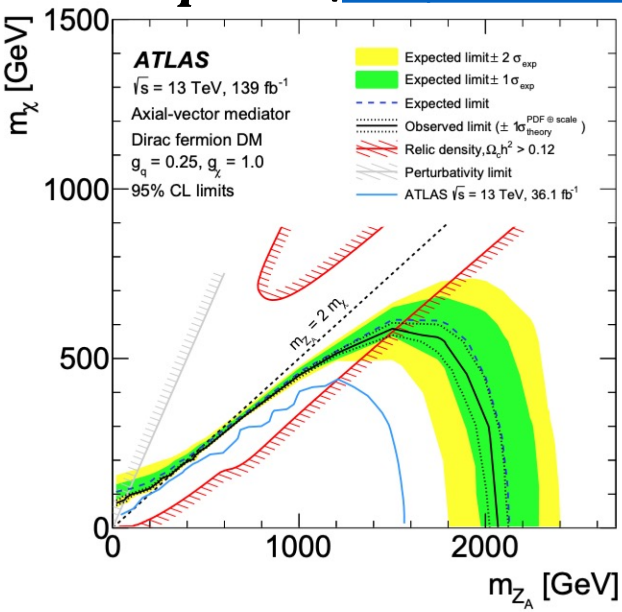
A-V couplings

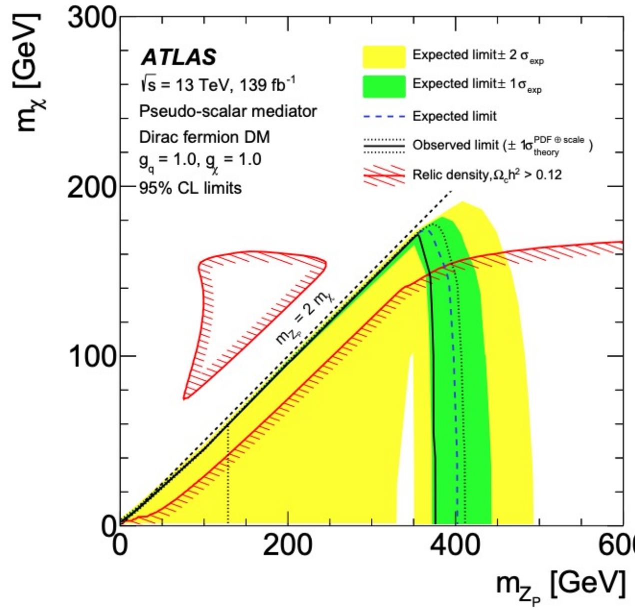
- Simultaneous fit to p_T^{recoil} (= E_T^{miss} in signal region) in signal + control regions



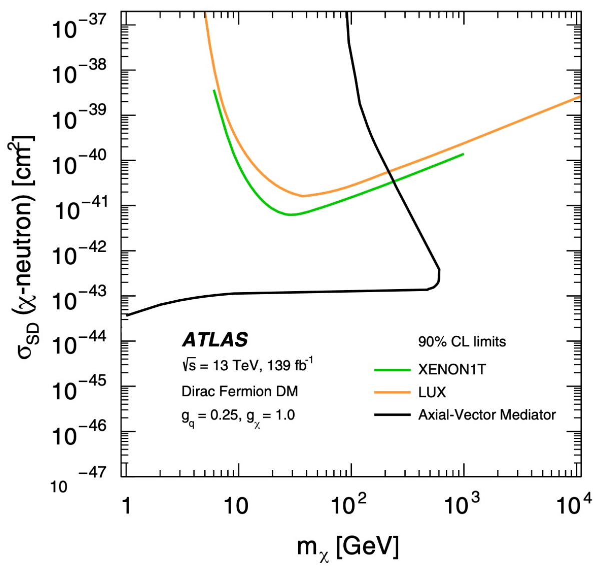


Jet + E_T^{miss} (Phys. Rev. D **103**, 112006)





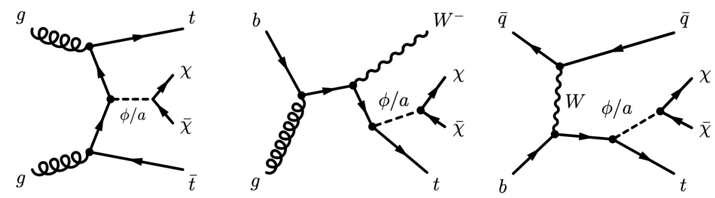
- 2D limits set on m_χ vs m_Z
- Excluded values up to $m_{Z_A} = 2.1$ TeV for A-V mediators
- Sensitivity to exclude very light pseudoscalar masses ($m_{Z_p} < 376$ GeV) for the first time in this final state
- Results compared with direct/indirect detection
- Limits also set on $H \to inv$ of 0.34 observed (0.39 expected)

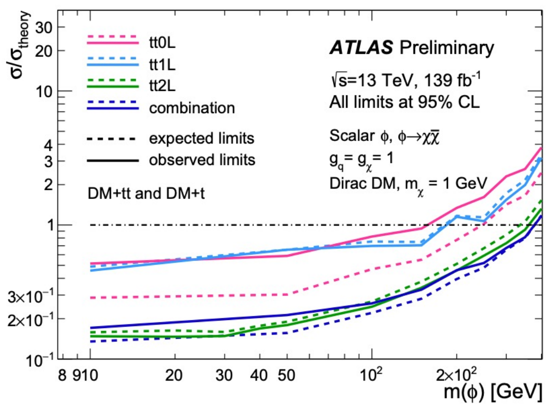


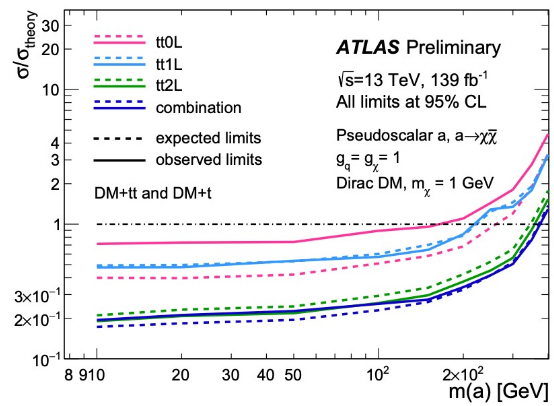
Individual $tt + E_T^{miss}$ results: Eur. Phys. J. C 80 (2020) 737 (0L), JHEP 04 (2020) 174 (1L), JHEP 04 (2021) 165 (2L)

$t\bar{t} + E_T^{miss}$ combination (ATLAS-CONF-2022-007)

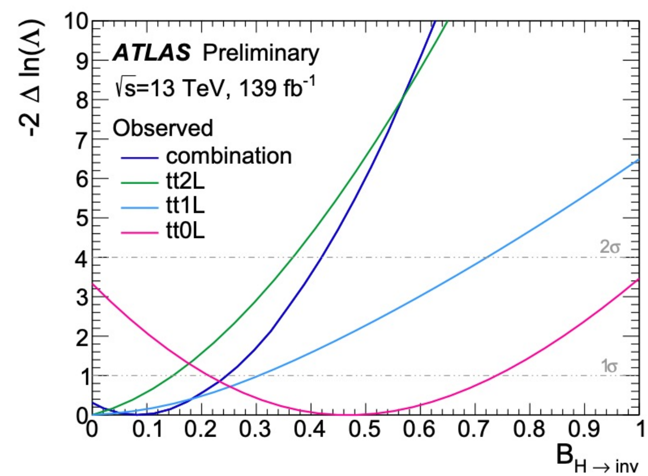
- Combination of $t\bar{t} + E_T^{miss}$ 0, 1, 2 lepton channels
- Targeting spin-0 simplified DM models
- Minimal flavour violation → Yukawa-like coupling between mediator and top quark
- Also interpreted as results on $H \to inv$







Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit	Reference
tt0L	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$	[27], this document
tt1L	$-0.04^{+0.35}_{-0.29}$	0.74	$0.80^{+0.40}_{-0.26}$	[28], this document
tt2L	$-0.09^{+0.22}_{-0.20}$	0.39	$0.42^{+0.18}_{-0.12}$	[29], this document
$t\bar{t}H$ comb.	$0.08^{+0.16}_{-0.15}$	0.40	$0.30^{+0.13}_{-0.09}$	This document

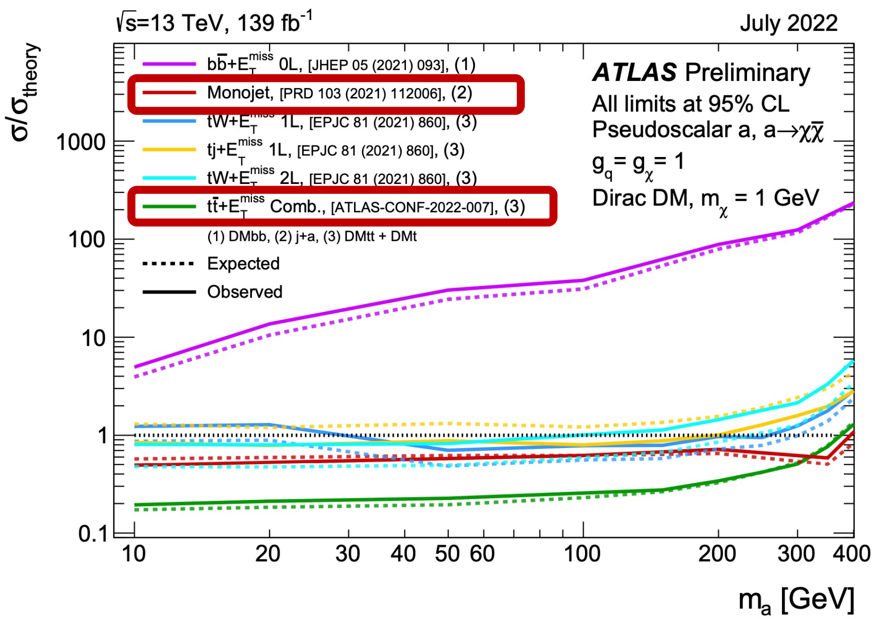


more on $H \to inv$ later

+ many more results

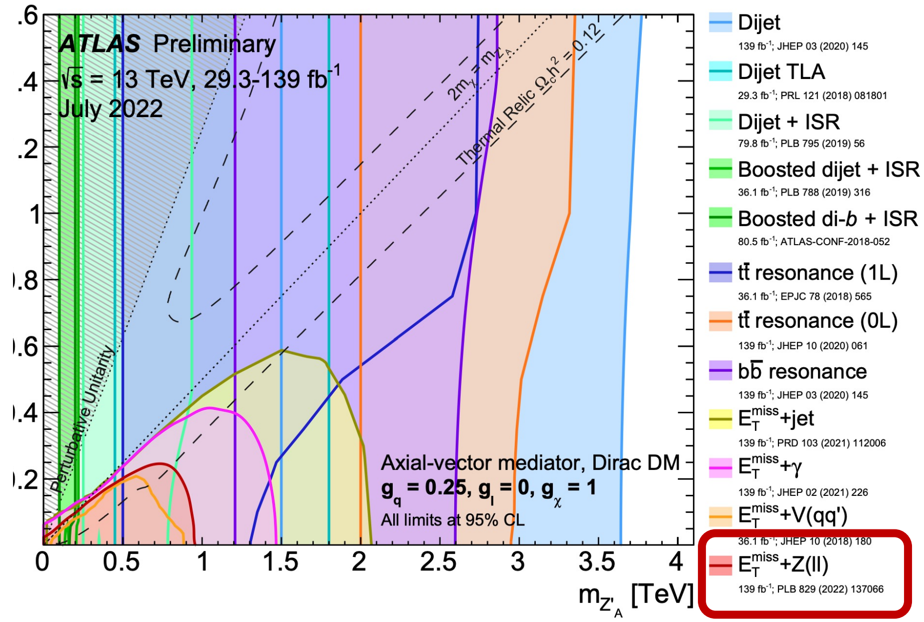
Simplified DM model summary (ATL-PHYS-PUB-2022-036)

Spin0 colour-neutral pseudoscalar mediator



Dominated by monojet, $t\bar{t} + E_T^{miss}$

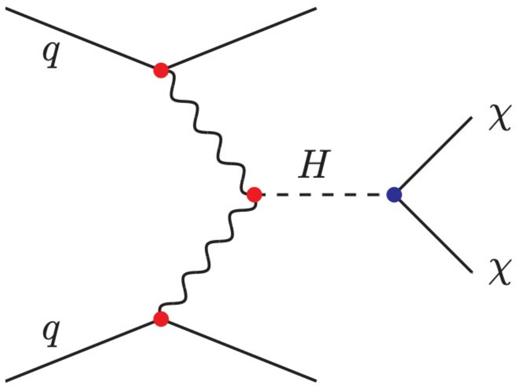
Spin 1 leptophobic axial-vector mediator



Interplay between the analysis sensitivity can drastically change as a function of the chosen coupling values

Discussed later

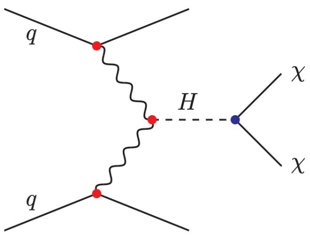
Higgs portal

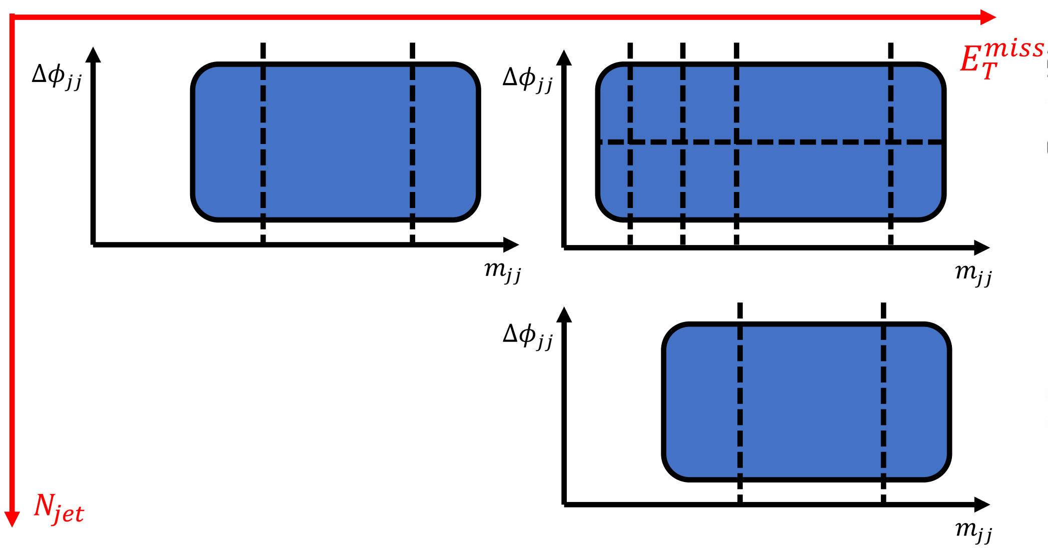


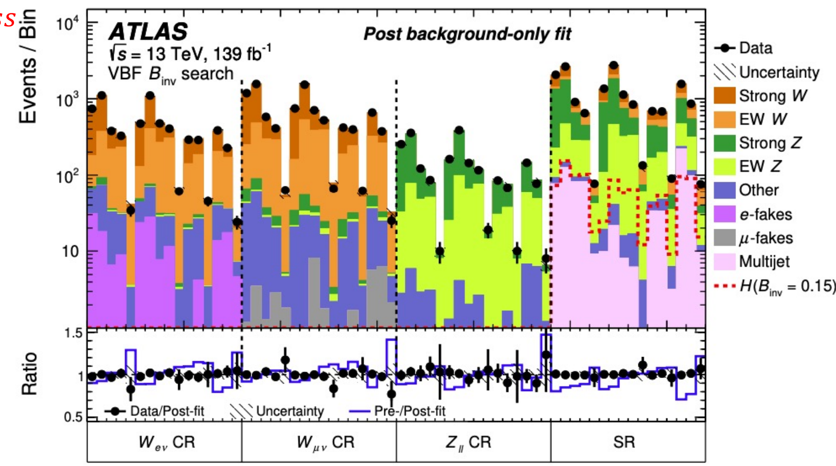
$H \rightarrow$ invisible

VBF Higgs + E_T^{miss} (JHEP 08 (2022) 104)

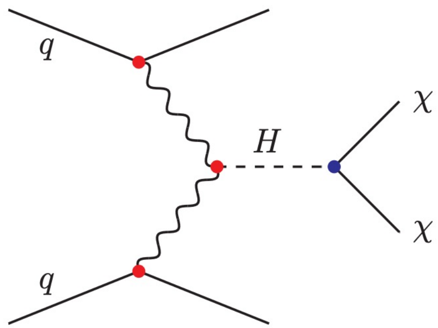
- SM B($H \rightarrow inv$) = 0.12%, from $H \rightarrow ZZ^* \rightarrow \nu\bar{\nu}\nu\bar{\nu}$
- Up to O(10%) modifications on B_{inv} from BSM physics
- VBF Higgs + E_T^{miss} signature provides the best limits on B_{inv}:
  - VBF topology (2 jets with large $\Delta\eta_{jj}, m_{jj}$, not back-to-back, opposite hemispheres)
  - E_T^{miss} > 160 GeV
  - Up to 2 additional ISR/FSR jets
  - 0 leptons/photons
- Background estimation: V+jets from lepton control regions
- 16 signal region bins defined by $n_{jet}, E_T^{miss}, m_{jj}, \Delta\phi_{jj}$



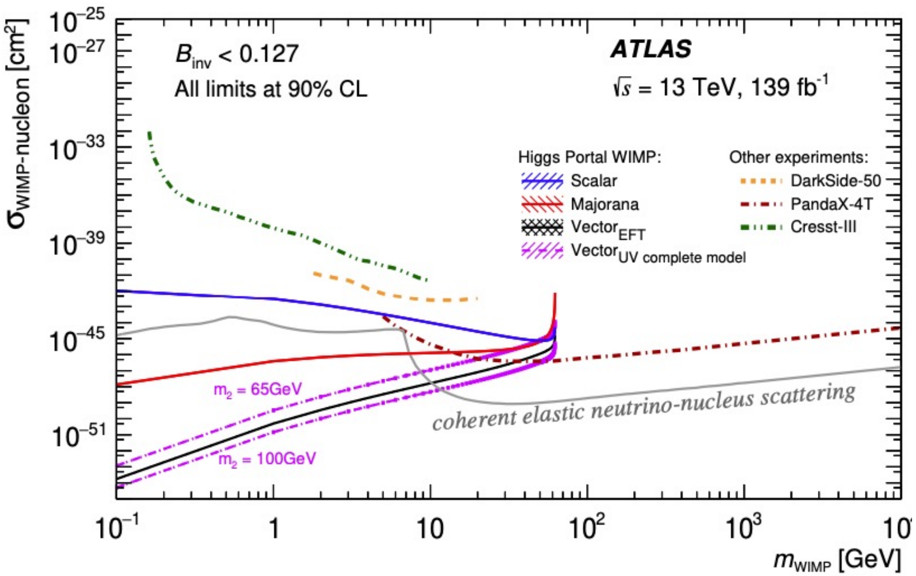


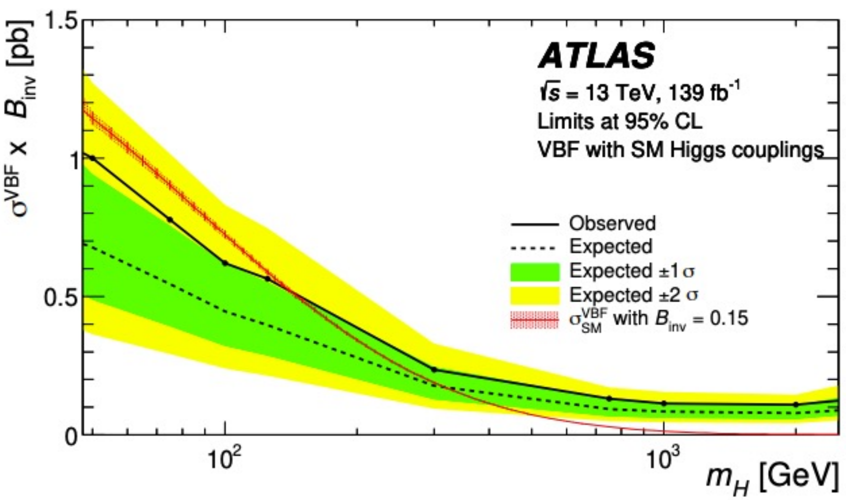


VBF Higgs + E_T^{miss} (JHEP 08 (2022) 104)



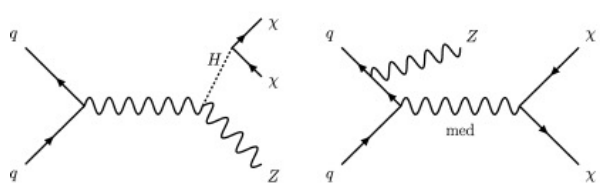
- 95% upper limit of 0.145 on B_{inv} (0.103 expected)
- B_{inv} limit reinterpreted with Higgs portal models:
  - limit on spin-independent WIMP nucleon XS,
  - invisible decays of new scalar particles with masses < 2TeV



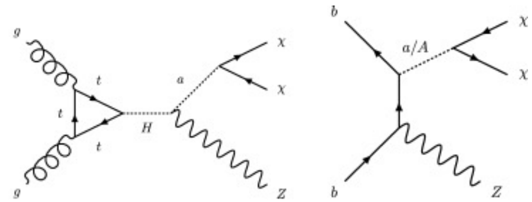


Highly complementary coverage with direct detection experiments for low DM masses

$Z(ll) + E_T^{miss}$, Phys. Lett. B 829 (2022) 137066



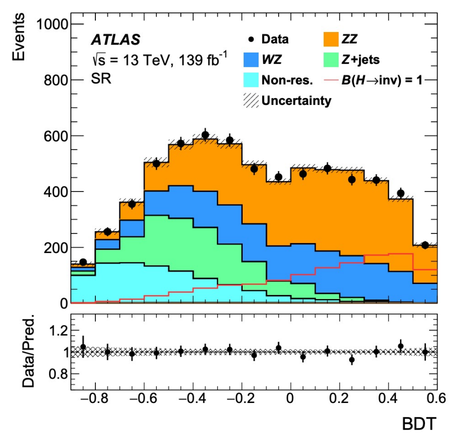
Simplified DM models

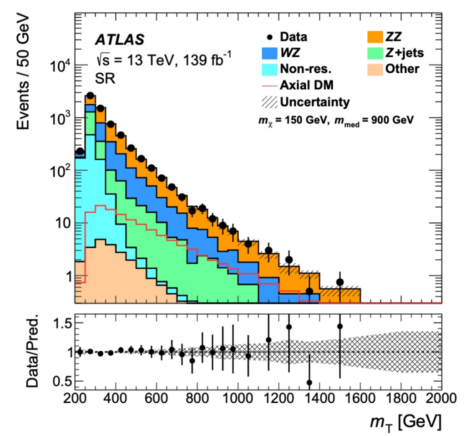


2HDMa

- Sensitive to many types of models; particularly competitive for $H \rightarrow inv$ and 2HDM+a
- Selection:
  - 2 oppositely charged leptons (e, μ), $m_{ll} \in [76, 106]$ GeV, $\Delta R_{ll} < 1.8$
  - $E_T^{miss} > 90$ GeV, E_T^{miss} significance > 9
- Background estimation: ZZ, WZ from 3 control regions
- Fit discriminant: BDT ($H \rightarrow inv$), transverse mass m_T (DM search)

$$m_{\mathrm{T}} = \sqrt{\left[\sqrt{m_Z^2 + (p_{\mathrm{T}}^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_{\mathrm{T}}^{\mathrm{miss}})^2}\right]^2 - \left[\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right]^2}$$

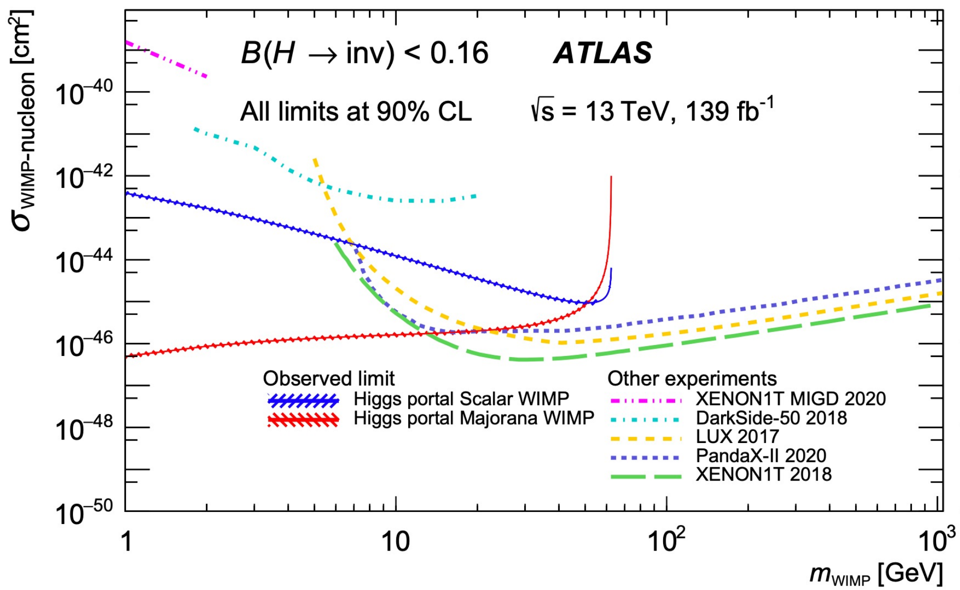




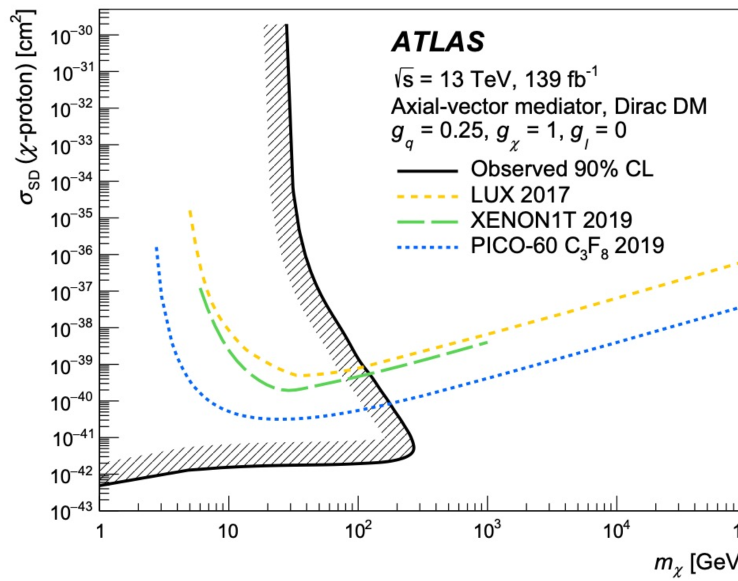
$Z(ll) + E_T^{miss}$, Phys. Lett. B 829 (2022) 137066

- 95% upper limit of 0.19 on $B(H \to inv)$ – competitive with VBF Higgs + E_T^{miss}
- Limit is 45% better than the previous analysis due to analysis improvements (e.g. use of BDT) and reduced systematic uncertainties
- Interpretations for simplified models and 2HDMa (next section) also provided

$H \to inv$

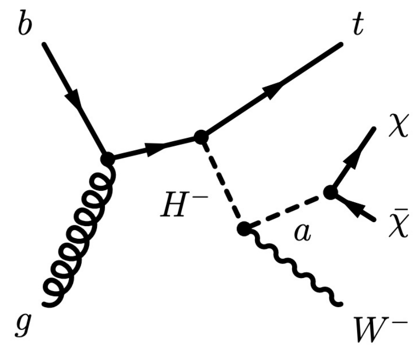


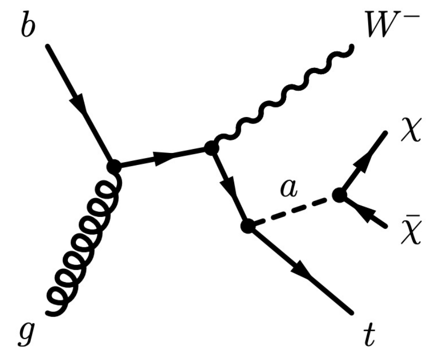
A-V mediator



Also see ATLAS-CONF-2020-052 for a preliminary $H \to inv$ combination involving the VBF and ttH production modes in Run 2 (95% limit on $B_{inv} = 0.13$)

2HDMa

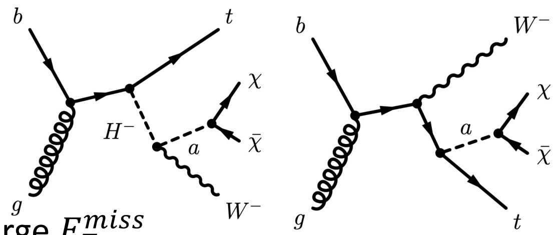


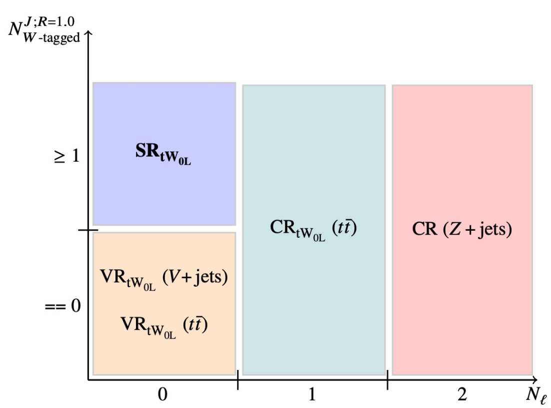


$tW + E_T^{miss}$ (ATLAS-CONF-2022-012)

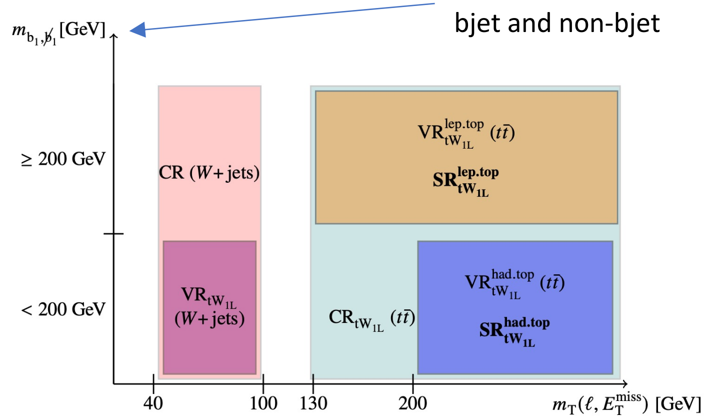
*Lepton = e, μ

- Extension of previous result for $t + E_T^{miss}$ (Eur. Phys. J. C 81 (2020) 860)
- $tW + E_T^{miss}$ is the dominant single top-quark final state for the 2HDM+a model, especially for lower values of $m_{H^\pm}$
- Target: $H \rightarrow$ boosted $W + a$, $t \rightarrow W +$ b
- 3 regions based on which Ws decay leptonically:
  - **tW0L**: 0 leptons*, ≥ 4 jets, ≥ 1 large-R jet (W-tagged), 1 b-jet, large E_T^{miss}
  - **tW1L**: exactly 1 lepton, 1 b-jet, high m_T, large E_T^{miss}
    - Further divide into **lep.top** and **had.top** channels
- Background estimation: V+ jets, $t\bar{t}$ from control + validation regions
- Additional split into E_T^{miss} bins for tW0L and tW1L had.top



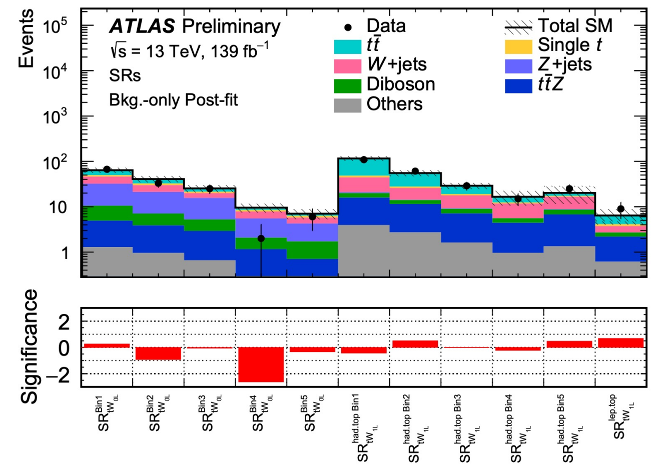


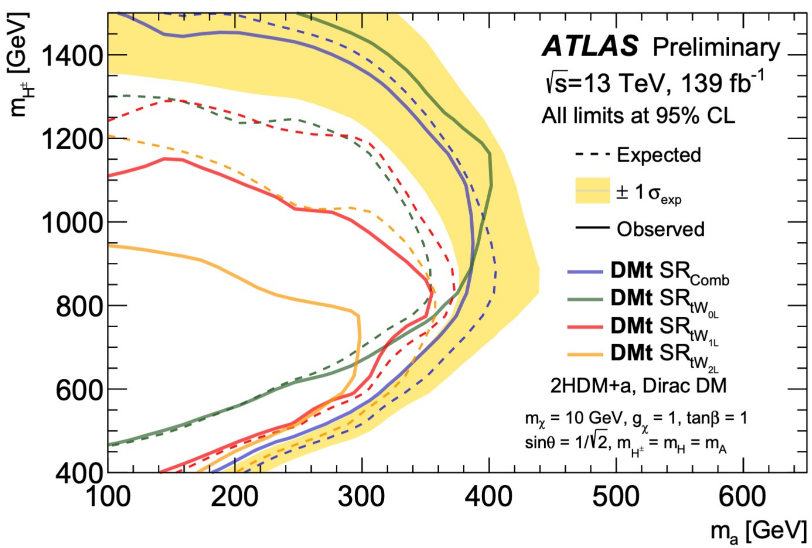
Invariant mass between bjet and non-bjet

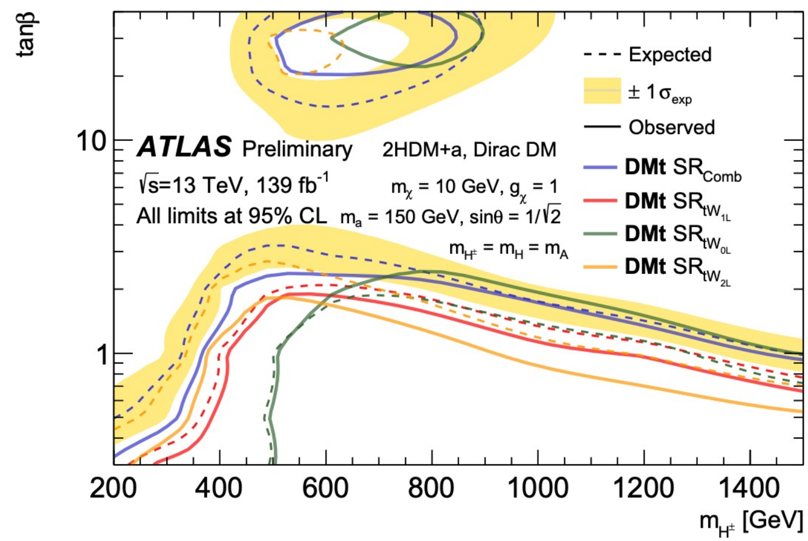


$tW + E_T^{miss}$ (ATLAS-CONF-2022-012)

- Combined with tW2L channel (Eur. Phys. J. C 81 (2020) 860)
- Excellent constraints on 2D scans of $m_{H^\pm} - m_a$, $\tan\beta - m_{H^\pm}$
- First time limits on high $\tan\beta$ parameter space in this final state

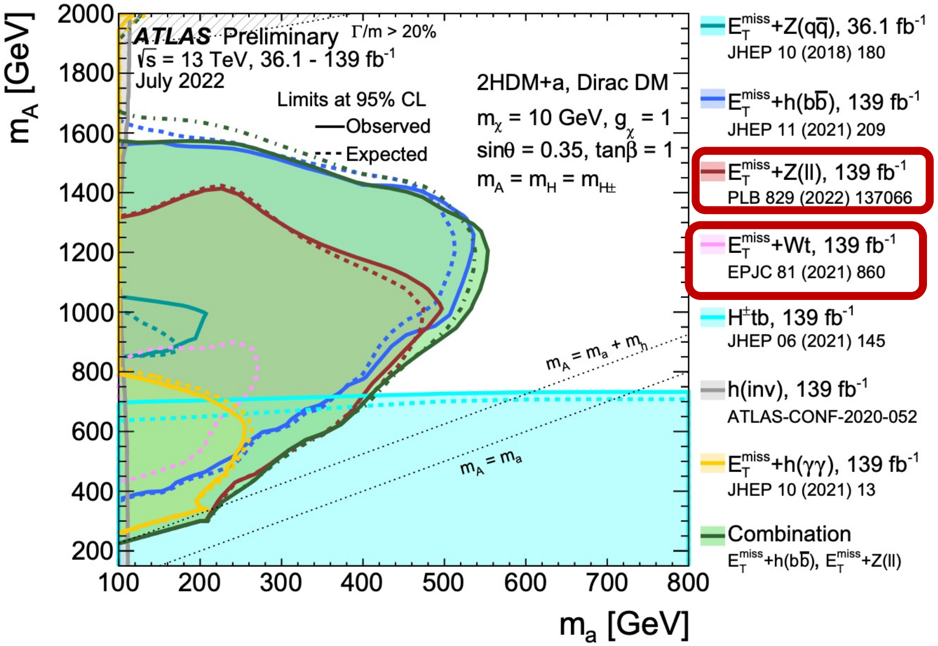


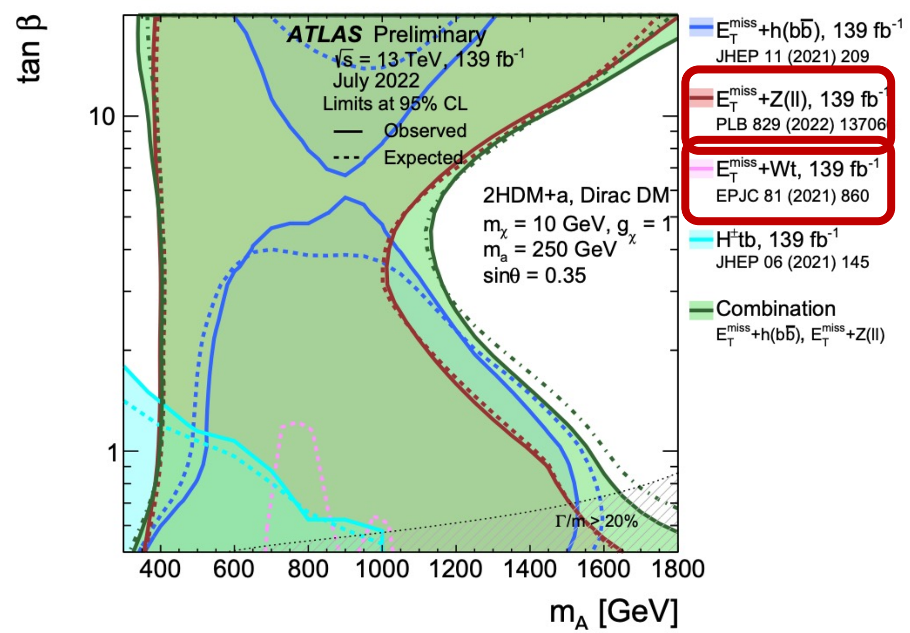




2HDM+a summary (ATL-PHYS-PUB-2022-036)

- Excellent complementarity covering a large part of the probed parameter space, especially between $E_T^{miss} + Z(ll)$ and $E_T^{miss} + h(b\bar{b})$ (JHEP 11 (2021) 209)
- Many more results available





Summary

- A wide variety of results from ATLAS shown today
  - Simplified models, Higgs portal, extended Higgs sector
- Complementarity of various approaches to dark matter
  - Not only between collider searches and direct/indirect detection
  - But even within different ATLAS analyses
- Many channels sensitive to more than one model

- No significant deviation from the SM seen so far, but stay tuned for new results!
  - Run 2 analyses are finishing up
  - Run 3 datasets starting to come in
  - Eventual 3000fb^{-1} (!) from the high luminosity LHC

- Other interesting recent results that were not covered in this talk:
  - Dark Matter in association with a dark Higgs decaying to W^+W^- in the one-lepton final state: ATLAS-CONF-2022-029
  - Invisible particles produced in association with single top quarks: ATLAS-CONF-2022-036
  - Non-resonant production of semi-visible jets: ATLAS-CONF-2022-038
  - All ATLAS public results

Acknowledgement

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Backup