Dark Sector at ATLAS

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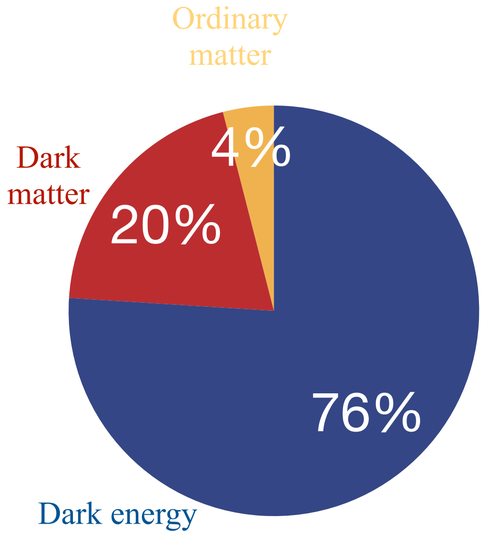
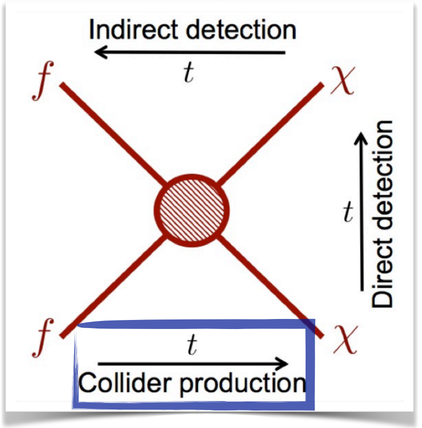
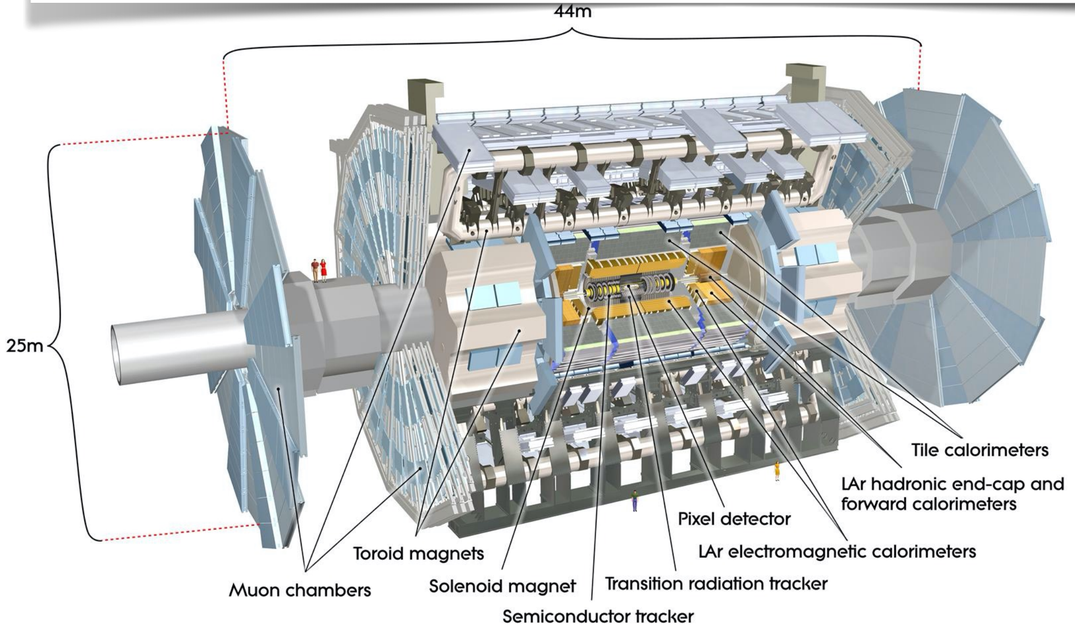
Exploring the Dark Sector at Accelerators

- Ordinary matter is just ~5% of the Universe
- Dark matter and dark energy account for ~95% of the Universe
- Many cosmological evidences of dark matter:
  - Galactic rotation curves
  - Cosmic Microwave Background anisotropies
  - Gravitational lensing
- Collider production of dark matter at accelerators
- Dark matter could be composed of particles which don't undergo SM gauge interactions





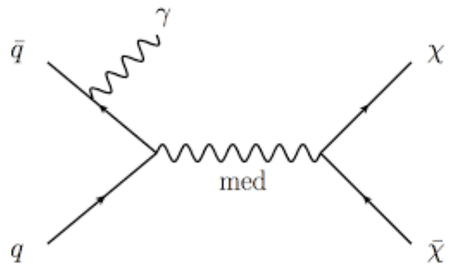


- ATLAS is a general purpose detector at the LHC
- ATLAS has collected 139 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data from Run 2 + more to come in the future —> LHC Run 3 just started!
- Assume no direct interaction of dark matter with detector
- Infer existence of dark matter through momentum imbalance $E_{\mathrm{T}}^{\mathrm{Miss}} = |-\sum p_{\mathrm{T}}|$

Dark Matter Models at ATLAS Experiment

Results discussed in this talk will cover:

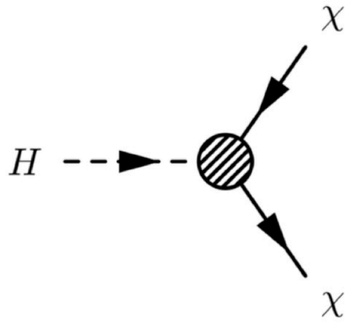
Simplified models



Introduce minimal number of new degrees of freedom
Signatures: monoX, mediator resonance

LHC DM WG white paper
arXiv:1507.00966

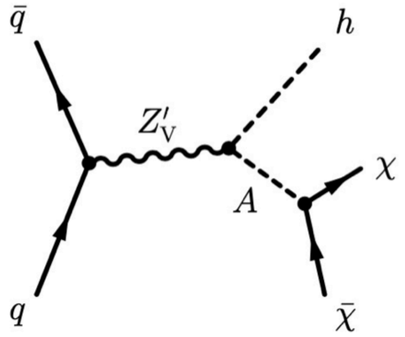
Higgs Portal



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

Higgs to invisible decays searches

Extended Higgs Sector



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

2HDM+a model:
JHEP 05 (2017) 138

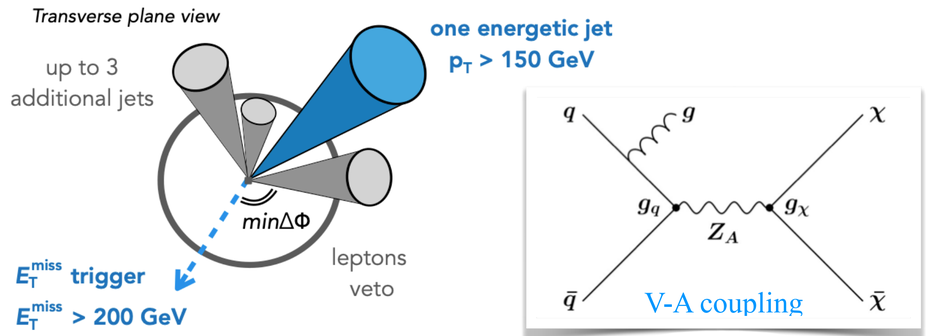
Dark Higgs model:
JHEP 04(2017)143

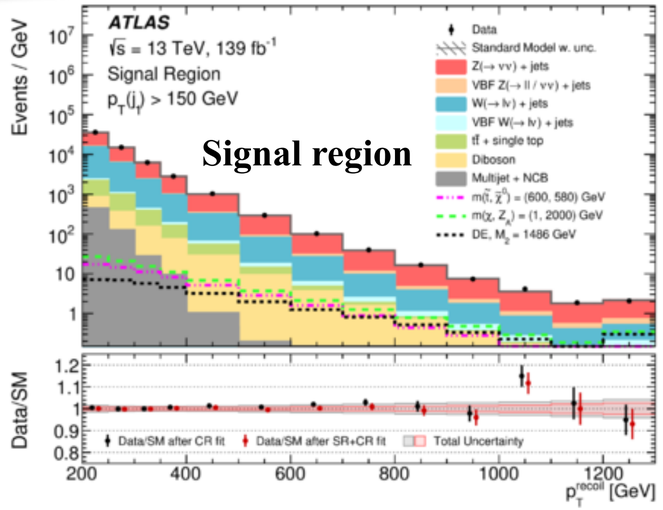
Simplified Models

Searches in the Jets + E_T^{Miss} final state

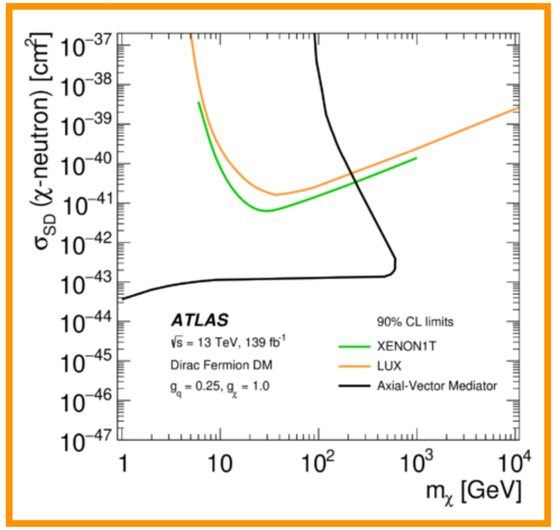
[Phys. Rev. D 103, 112006]

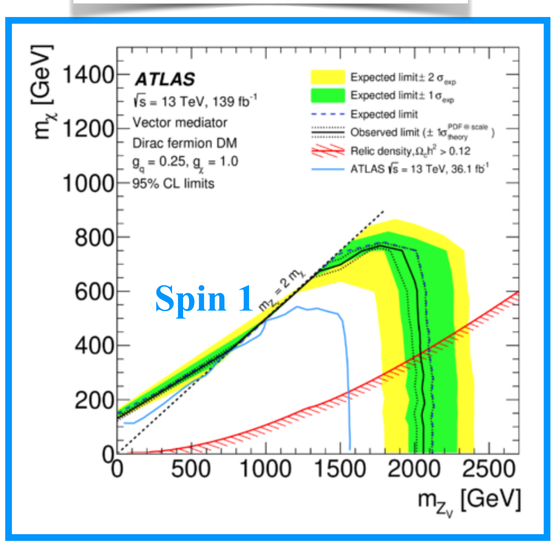
- Sensitive to both spin 0 pseudoscalar and spin 1 axial-vector mediators, $H \rightarrow inv$, and many other interesting models (SUSY, axion-like particles, etc)
- Selection:
  - $E_T^{Miss} > 200$ GeV
  - Up to 3 additional jets, one jet with $p_T > 150$ GeV, $|\eta| < 2.4$
  - Lepton and photon veto
- Background estimation
  - V+ jets, $t\bar{t}$, single t: (5 control regions)
  - Multijet: data driven jet smearing method
- Simultaneous fit to p_T^{recoil} (E_T^{Miss} = in signal region) in signal + control regions





- Comparison with direct/indirect detection results are provided





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

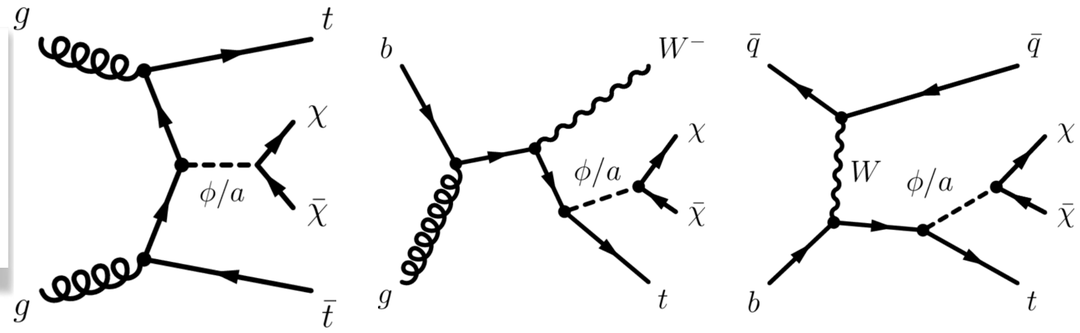
Multiple dark sector re-interpretations of the mono-jet analysis: [ATL-PHYS-PUB-2021-020]

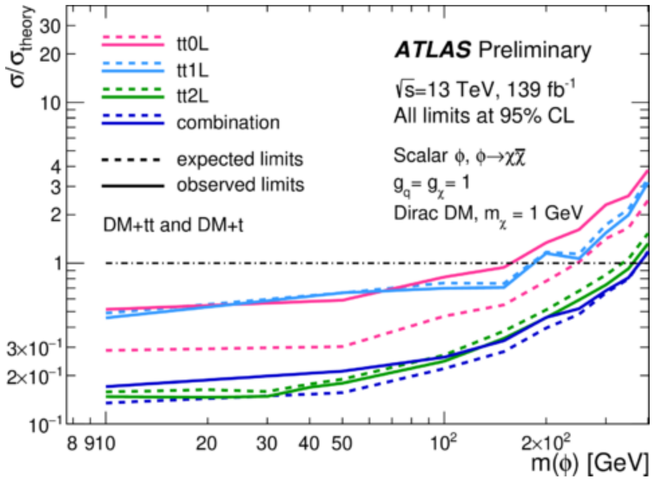
Dark Sector at ATLAS - LHCDays 2022

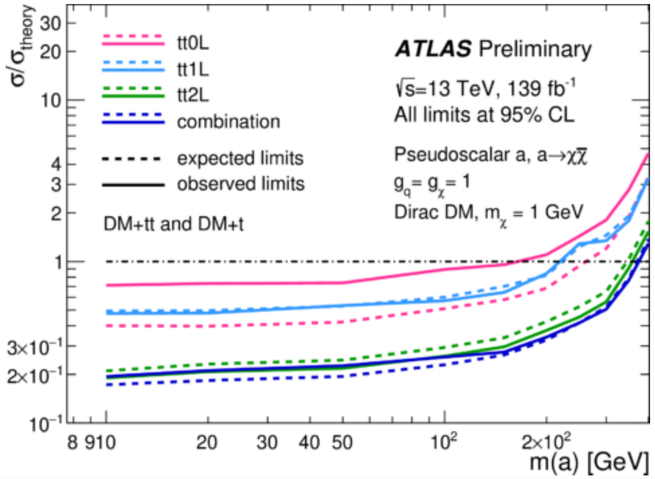
Combination of the $t\bar{t} + E_T^{Miss}$ searches

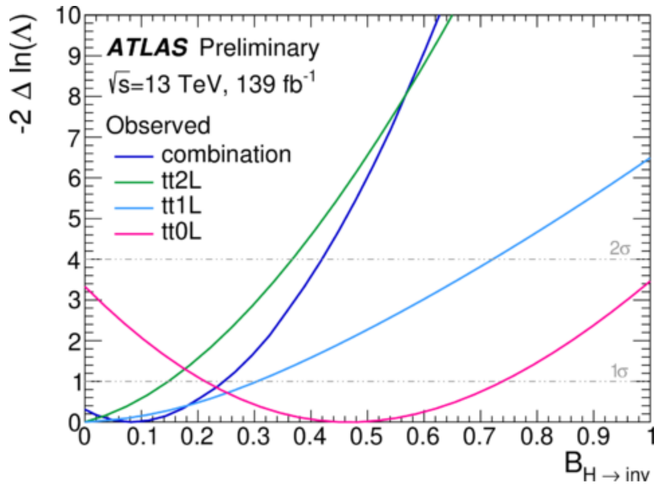
ATLAS-CONF-2022-007

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









- More references…..

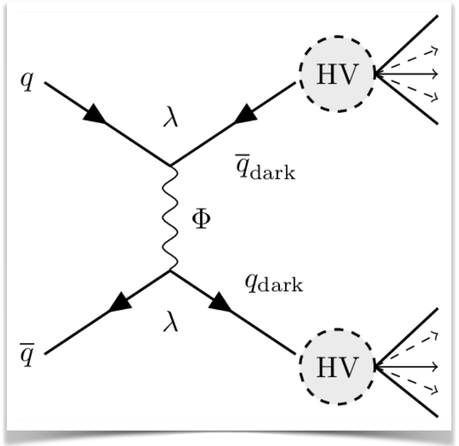
Eur. Phys. J. C 80 (2020) 737
JHEP 04 (2020) 174
JHEP 04 (2021) 165

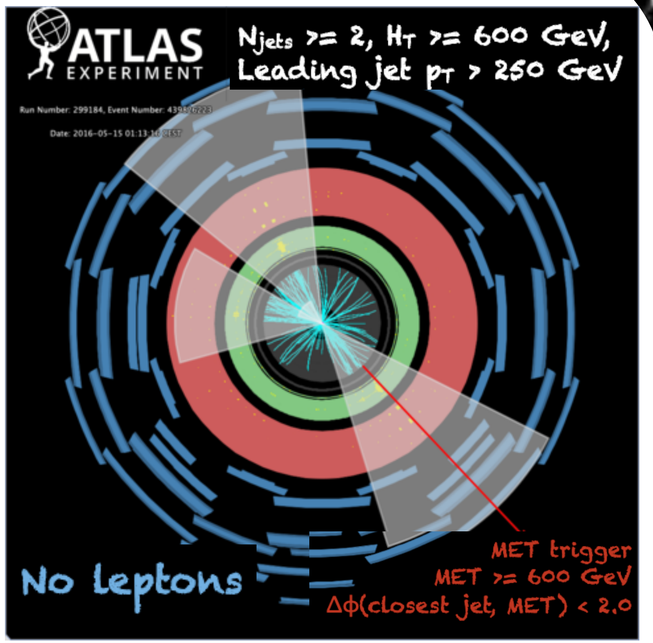
Analysis	Best fit $\mathcal{B}_{H\to inv}$	Observed upper limit	Expected upper limit	Reference
tt0L	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$	[27], this document
tt1L	$-0.04^{+0.35}_{-0.29}$	0.74	$0.80^{+0.40}_{-0.26}$	[28], this document
tt2L	$-0.09^{+0.22}_{-0.20}$	0.39	$0.42^{+0.18}_{-0.12}$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

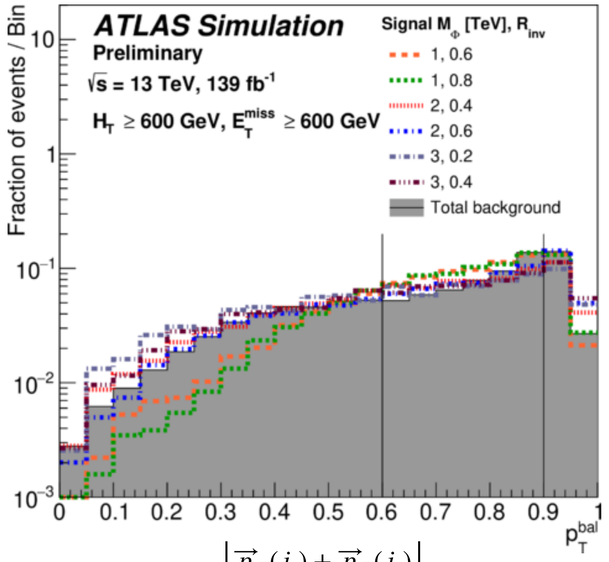
Search for semi-visible jets in non-resonant production mode [ATLAS-CONF-2022-038]

- Jets interpreted with dark hadrons, with E_T^{Miss} direction aligned with one of the semi-visible jets in leading order
- 9-bin grid using the two observables below, identically in SR and CRs
- Defined SR, 1L, 1L1B and 2L CRs with muon and *b*-tag requirements
- Limits on the mediator mass, for different R_{inv} values

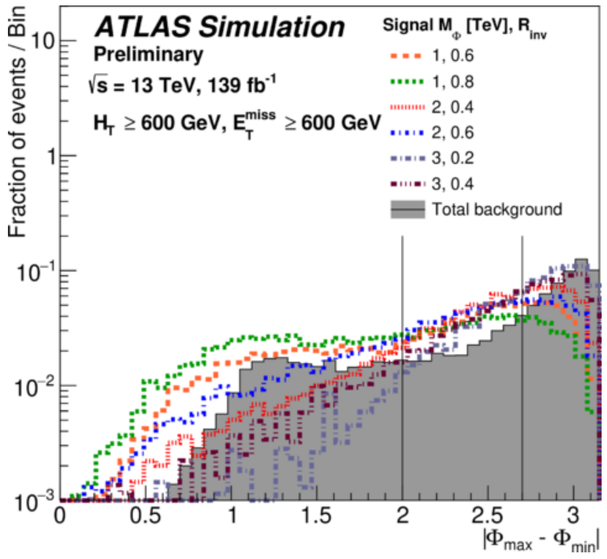
$$R_{inv} = \frac{N \text{ stable dark hadrons}}{N \text{ total hadrons}}$$

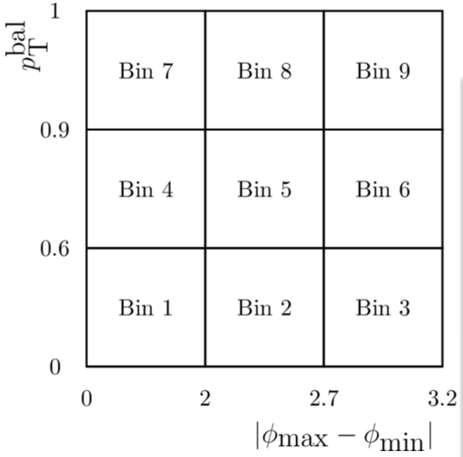


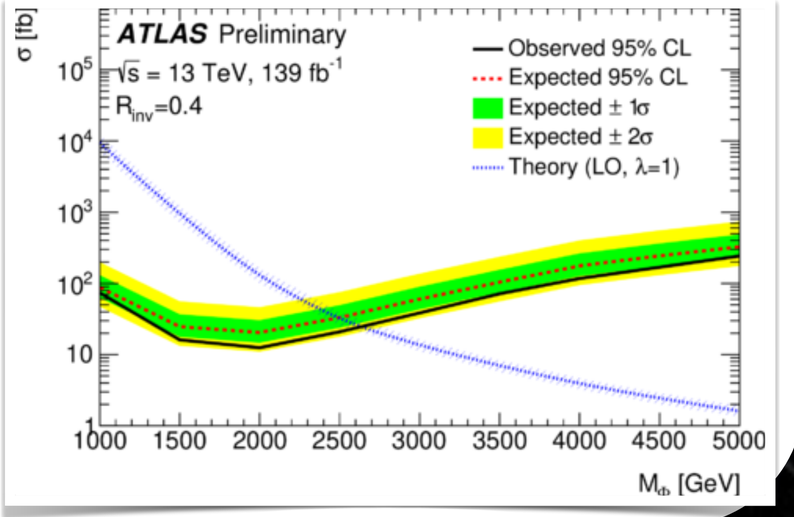




$$p_T^{\text{bal}} = \frac{\left|\vec{p}_T(j_1) + \vec{p}_T(j_2)\right|}{\left|\vec{p}_T(j_1)\right| + \left|\vec{p}_T(j_2)\right|}$$



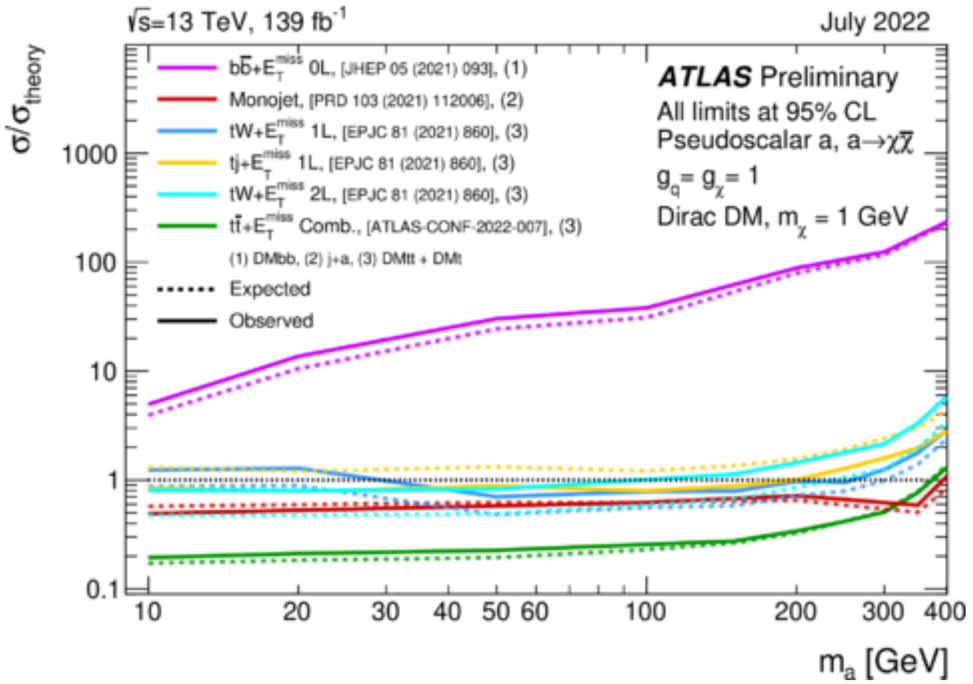




Simplified Dark Matter Model Summary

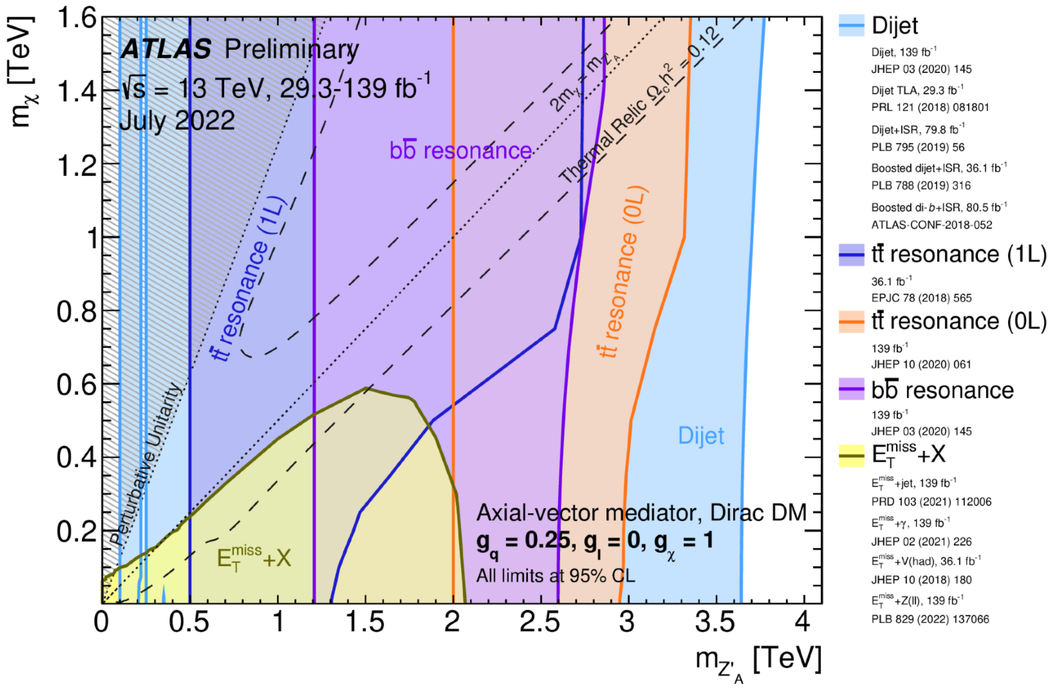
[ATL-PHYS-PUB-2022-036]

Spin 0 mediator searches



- Many complementary channels explored
- Sensitivity driven by $t\bar{t} + E_T^{Miss}$ in 0+1+2 lepton channel combination

Spin 1 mediator searches



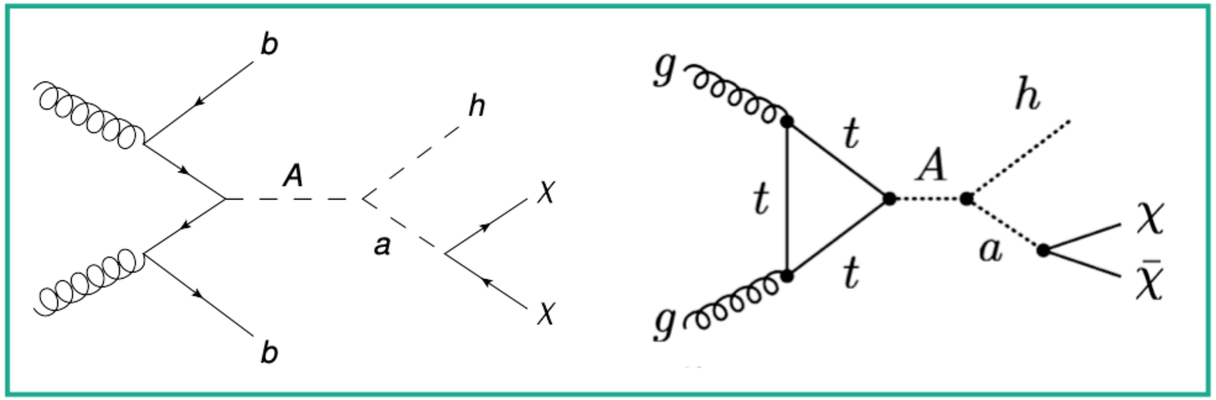
- Huge ATLAS search program yielding complementary sensitivity to direct detection experiment results
  - Results provided for both Vector & Axial vector mediators according to LHC DM WG recommendations on g_q / g_χ

Higgs boson portal

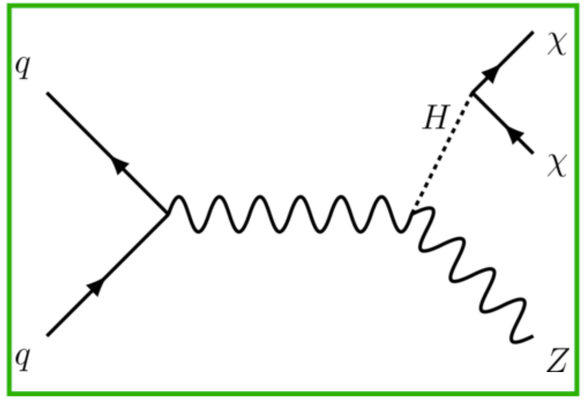
Higgs boson as a Portal to the Dark Sector

- There are two possible classes of models:
  - SM Higgs portal models → invisible decay modes of the Higgs boson
  - Dark matter interacting with an extended Higgs sector
- Benchmark models: *Phys. Dark Univ. 27 (2020) 100351*
  - Type II two-Higgs doublet model, including 5 new fields **h**, **H0**, **H±**, **A** + additional pseudo-scalar **a**
  - 14 free parameters, mostly constrained by EW measurements - assumptions can reduce those to 7 or 8

Mono-H



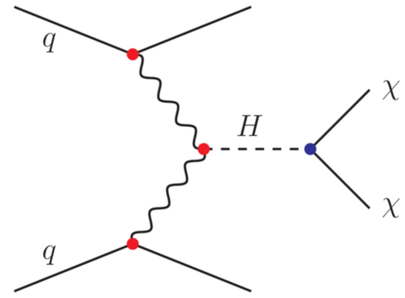
Mono-Z

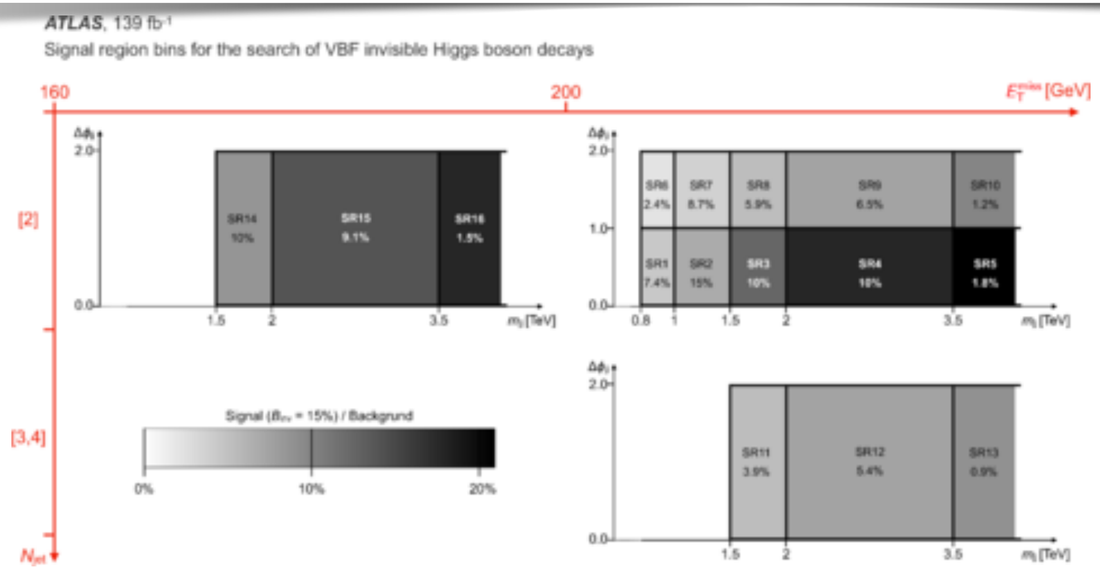


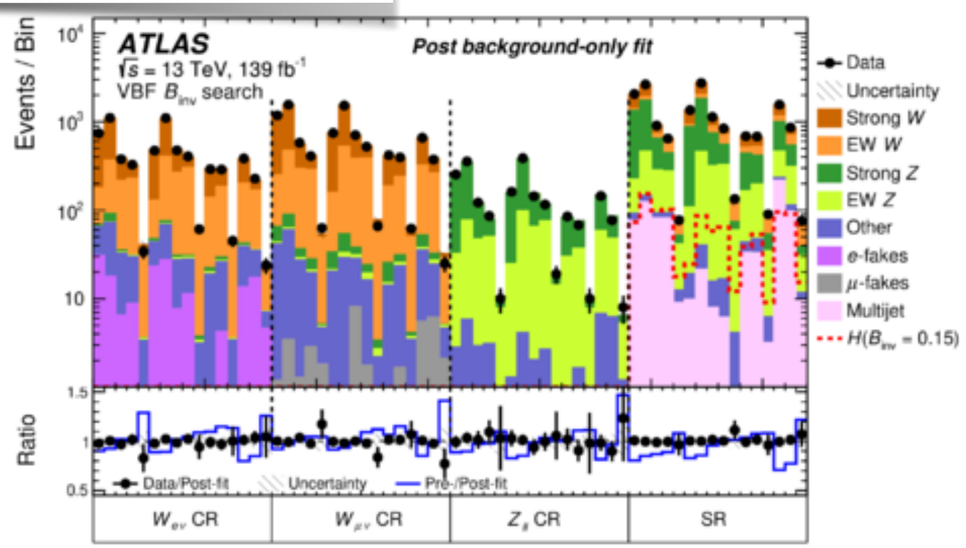
(Vector Boson Fusion) Higgs + E_T^{Miss}

JHEP 08 (2022) 104

- The Standard Model branching ratio is $BR(H \to inv) = 0.12\%$, from $H \to ZZ \to \nu\bar{\nu}\nu\bar{\nu}$
- 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 , veto on leptons/photons
- *Z+jets* background is estimated also from the *W+jets* CR (with high statistics) —> a collaboration with theorists has been made to provide the full NLO prediction of the Z/W ratio in the phase space of this analysis
- Two independent data-driven methods have been developed to estimate the multijet backgroud, that is small but has larger uncertainties
- 16 signal region bins defined by *n*jets , $\Delta\varphi_{jj}$, m_{jj} , E_T^{Miss}





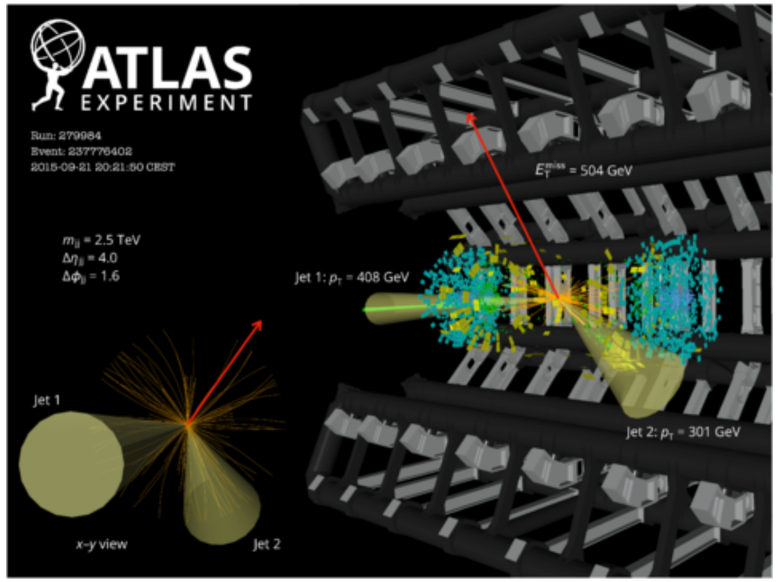


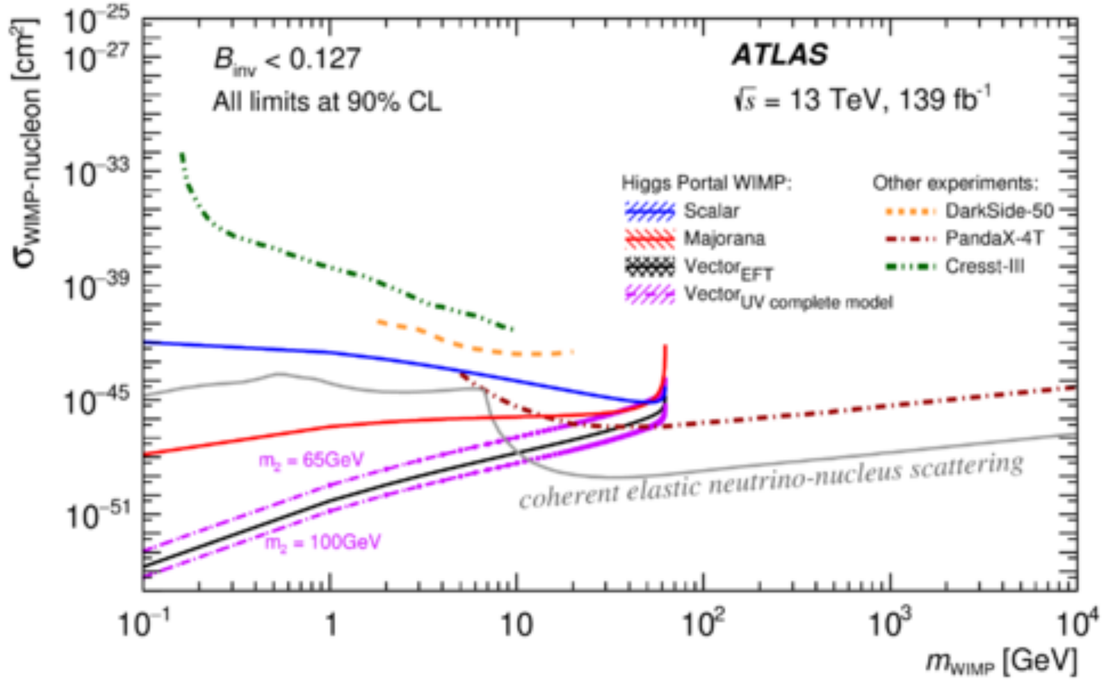
Dark Sector at ATLAS - LHCDays 2022

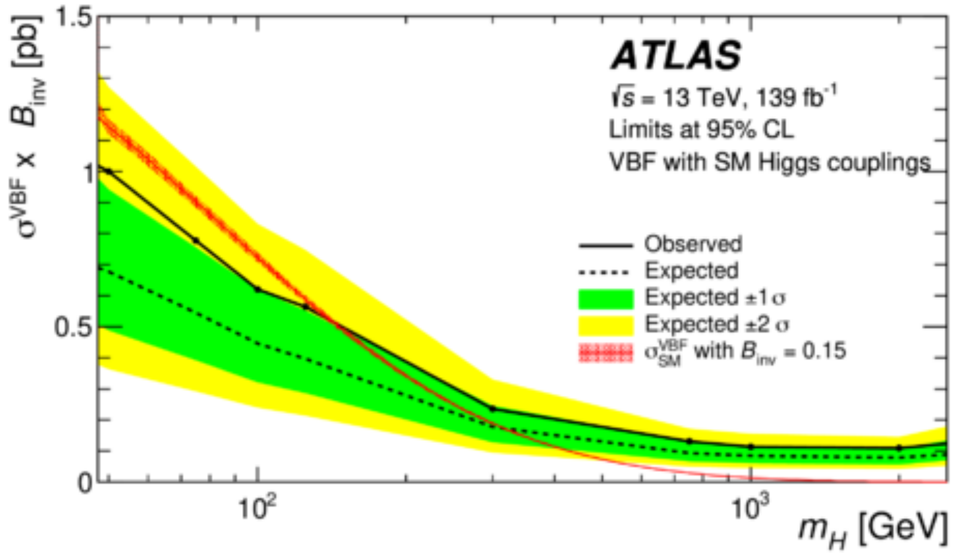
(Vector Boson Fusion) Higgs + E_T^{Miss}

JHEP 08 (2022) 104

- 95% C.L. 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



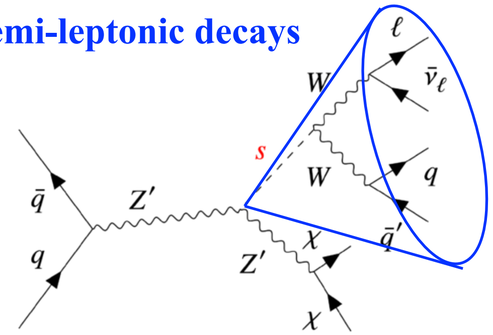




Dark Higgs boson searches

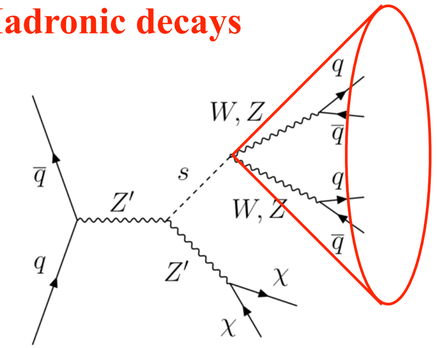
- Introduce an additional scalar particle **s**, the dark Higgs boson
  - Additional mass parameter to simplified models {m_X, $m_{Z'}$, m_s, g_q, g_X}
  - SM-Higgs-like decays: $s \rightarrow WW\ (ZZ)$ for m_S > 160 (180) GeV

Semi-leptonic decays



Resolved category
Merged category
Large R-jet
m_s: discriminating variable

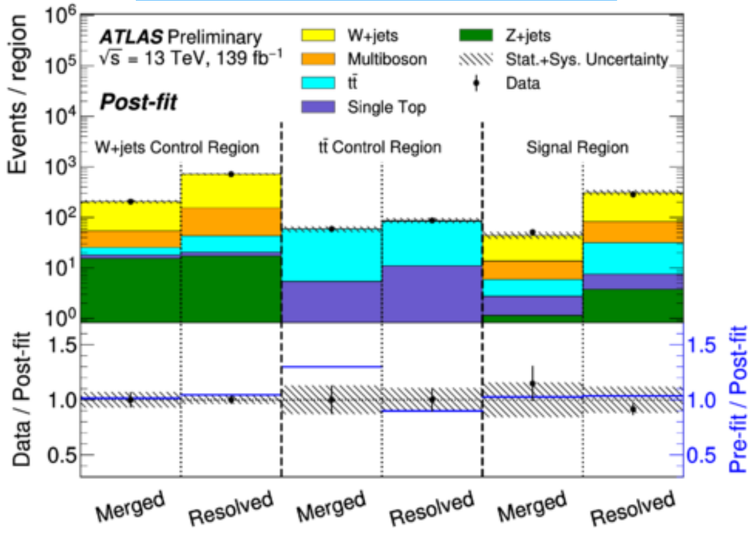
Hadronic decays



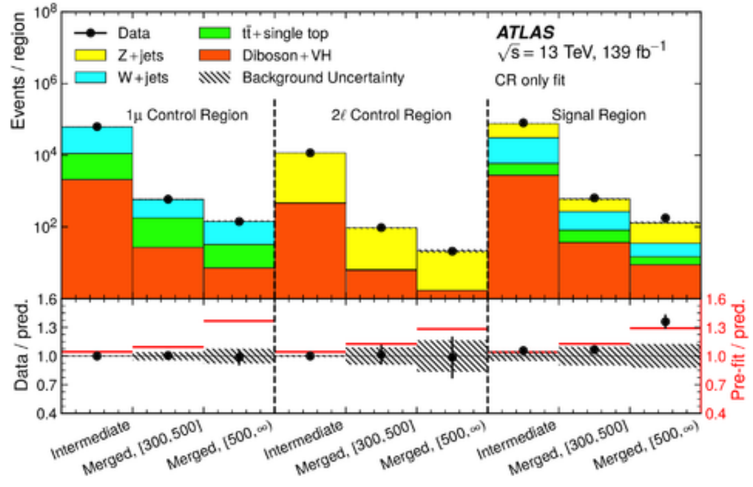
Large R-jet
m_j: discriminating variable

- Better sensitivity for the semi-leptonic channel
- Complementarity with other preliminary Run-2 (i.e. H(bb) +E_T^{Miss} final state)
- Boost sensitivity in the [80,150] GeV m_{bb} range

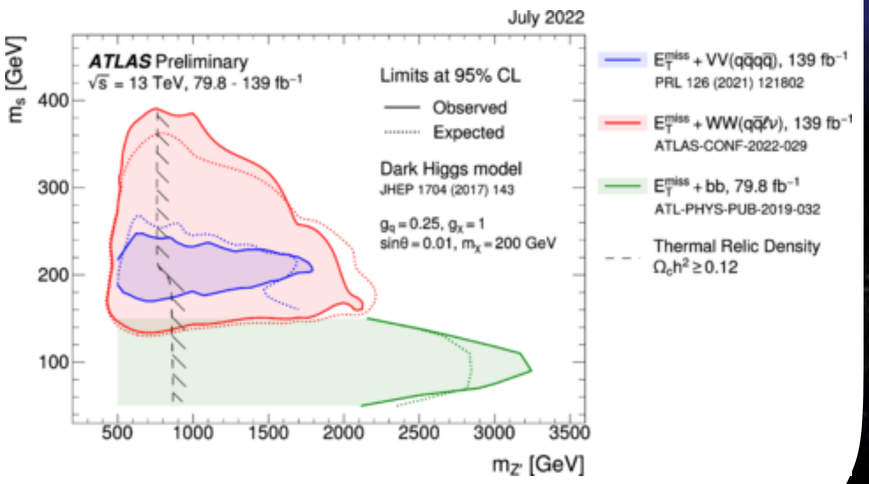
[ATLAS-CONF-2022-029]



[Phys. Rev. Lett. 126 (2021) 121802]



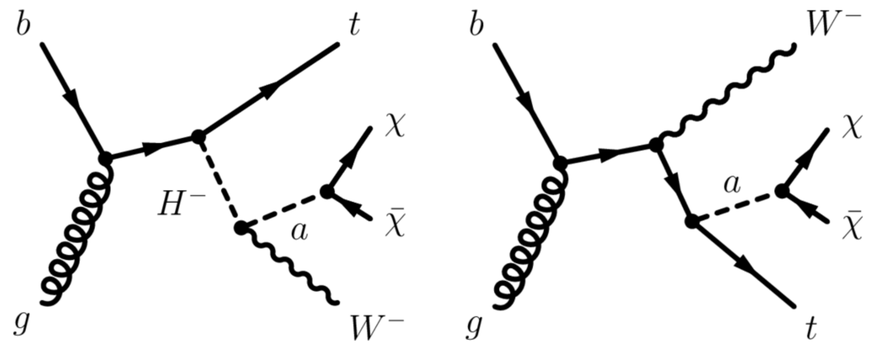
[ATLAS-CONF-2022-036]

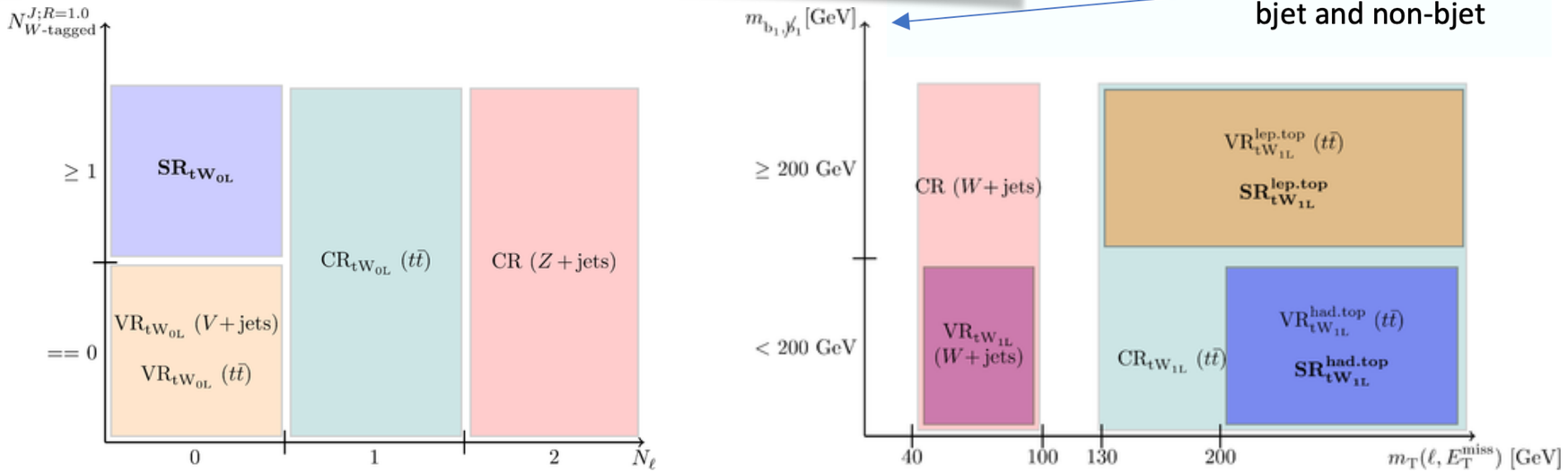


Searches in the $tW + E_T^{Miss}$ final state

ATLAS-CONF-2022-012

- Extension of the 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 the low 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 light leptons (e, μ), ≥ 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, tW1l* and *tW2l*

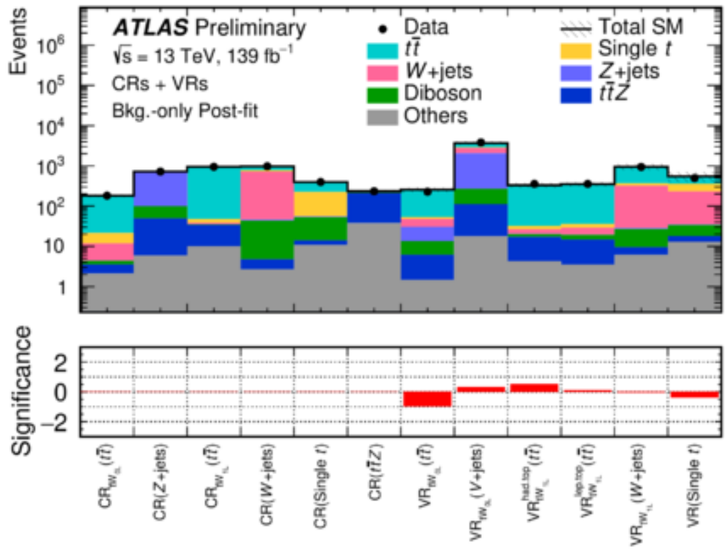


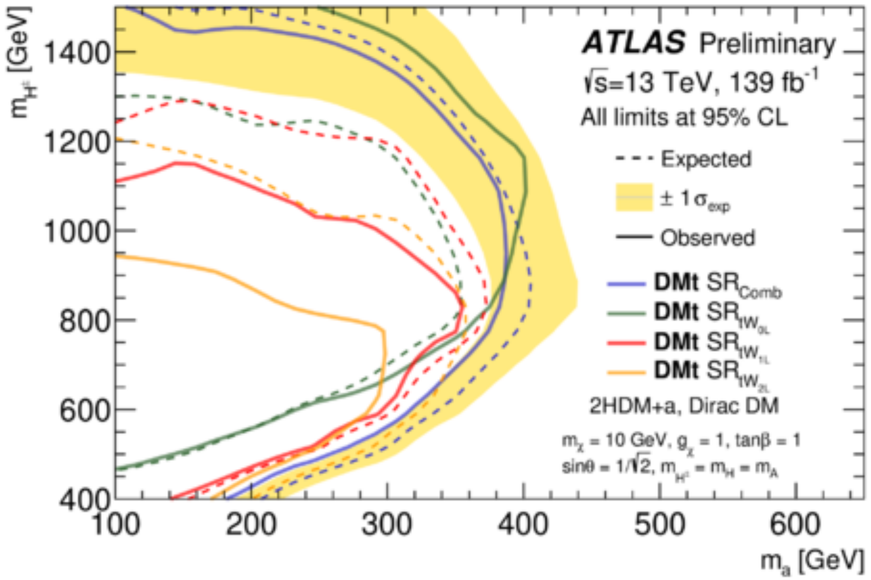


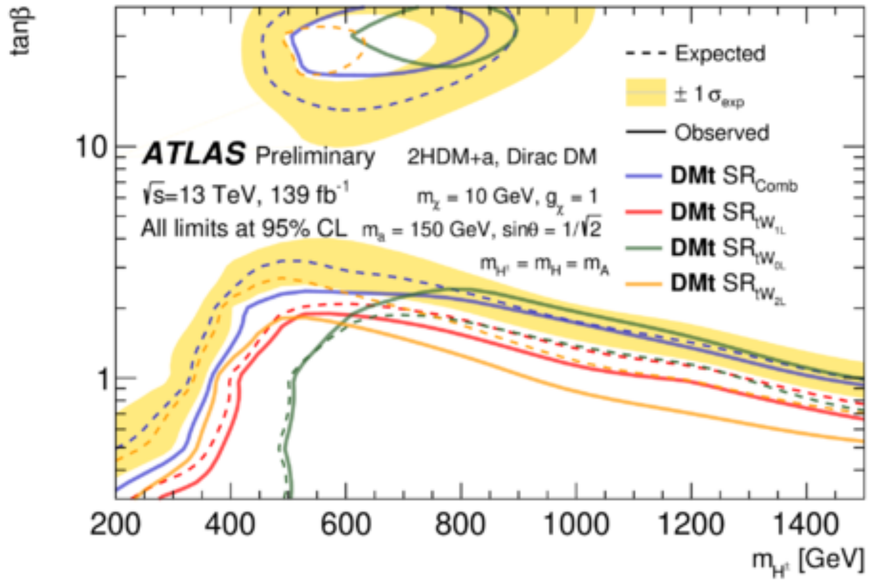
Results of the $tW + E_T^{Miss}$ final state

ATLAS-CONF-2022-012

- Combination with the *tW2l* final state (*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



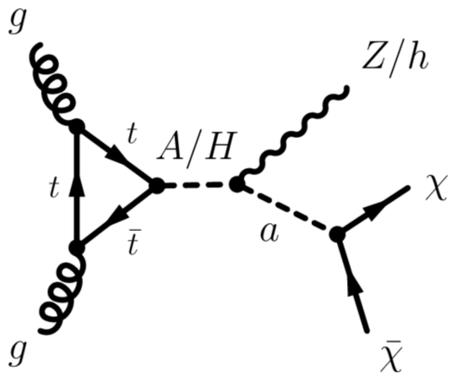


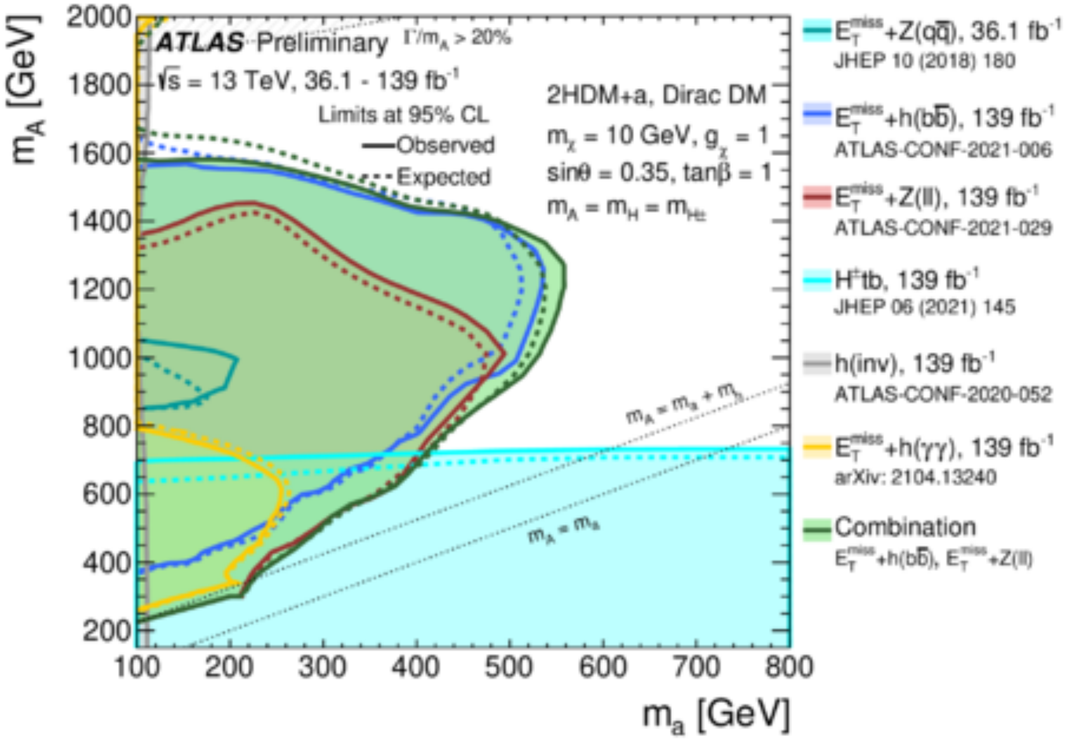


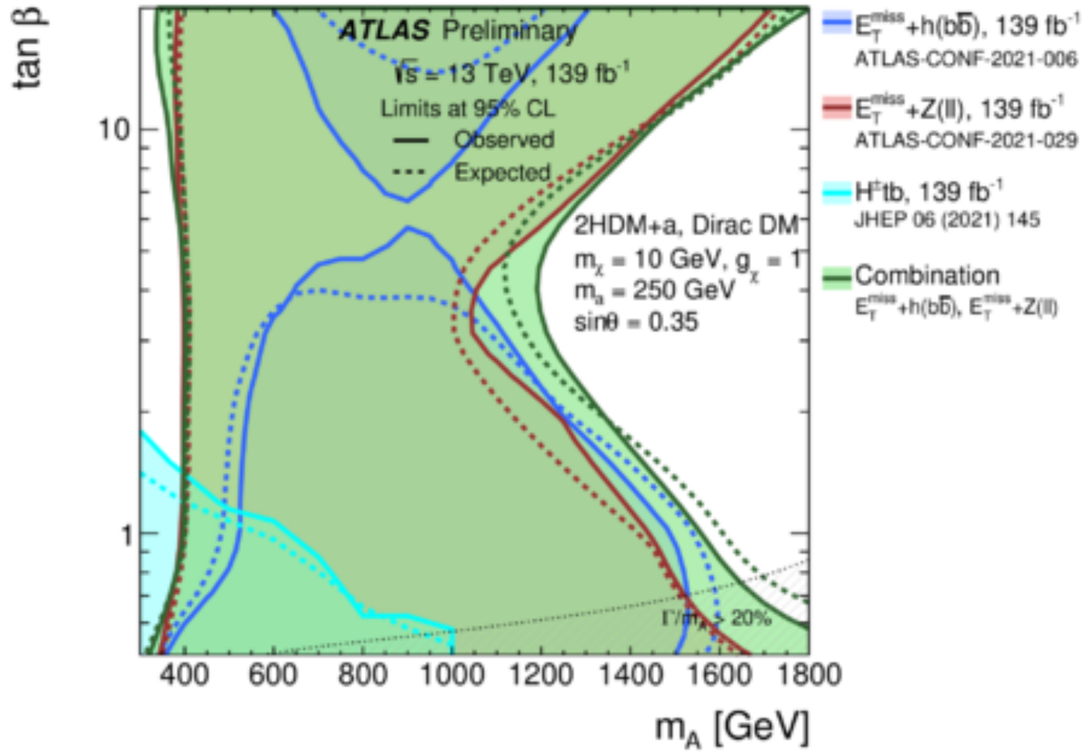
Summary of the Results

ATLAS-CONF-2022-036

- Many scans of parameters performed
  - Excellent complementarity covering a large part of the probed parameter space, especially between E_T^{Miss} + h(bb) and E_T^{Miss} + $Z(ll)$
  - Excellent complementarity between monoX and non-MET signatures (H+tb)
  - Multiple parameters scans reported in ATL-PHYS-PUB-2022-036







Conclusions

- A broad 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!
  - Many Run 2 analyses are finalised
  - Run 3 already started
  - Eventual 3000 fb^{-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 *WW* 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*

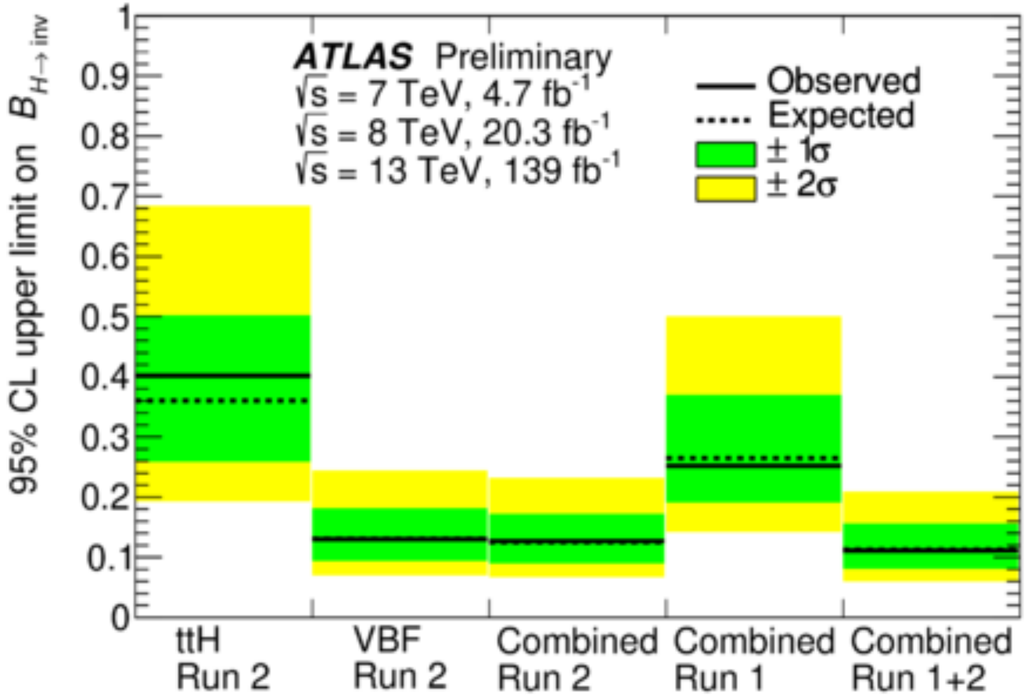
Thanks a lot for listening!

Back-Up Slides

Higgs to Invisible Decays Combination

ATLAS-CONF-2020-052

- ATLAS preliminary combination of some full Run 2 results, including
- $t\bar{t} + E_T^{Miss}$ analysis, only 0 and 2 lepton channels
- VBFH, H→invisible preliminary analysis result - not including W to Z corrections & low regime [160, 250] GeV



- $t\bar{t} + E_T^{Miss}$ 0+1+2 lepton channels combined
- monojet: BR(H→inv.) < **34% (39%)** - obs (exp)
- VBFH+γ: BR(H→inv.) < 37% (34%) - obs (exp)
- mono-Z(ll): BR(H→inv.) < **19% (19%)** - obs (exp)

Combined upper limit: *BR*(H→inv.) < 11% (11% exp) @95% CL