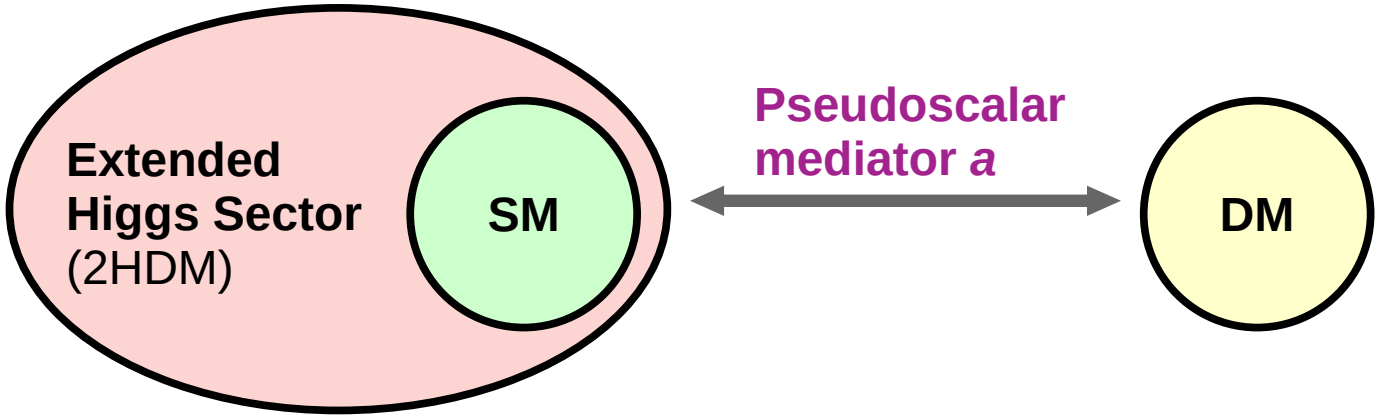
Dark Matter with extended Higgs sectors: An ATLAS perspective

Roadmap of DM models for Run 3
15 May 2024

Katharina Behr



HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
ATLAS EXPERIMENT
DESY.

Why consider DM with an extended Higgs sector?

> Early Run 2: interest from community to go beyond simplified models

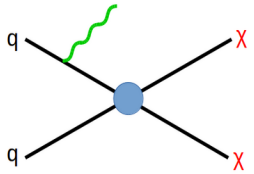
> Want a more (UV-)complete model of DM with an extended Higgs sector

- Richer collider phenomenology (“leave no stone unturned”)
- Combines two theoretically well motivated concepts: DM and extended Higgs sectors

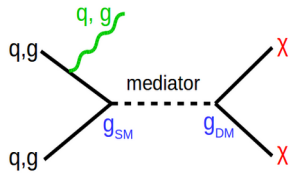
Effective field theories — Simplified models — UV-complete theories

model-independent, limited validity

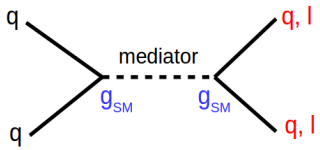
model-dependent, rich phenomenology



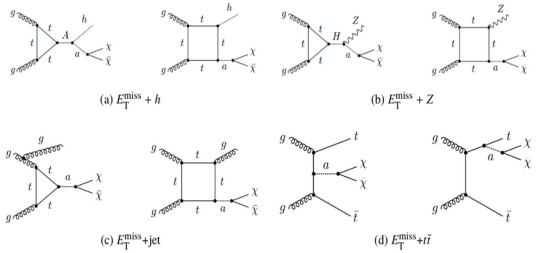
Mono-jet

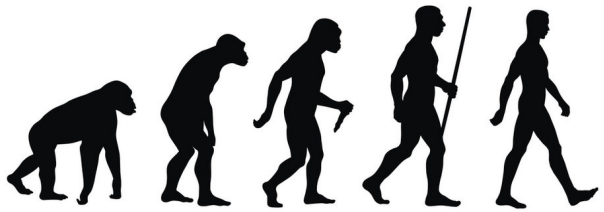


Mono-jet



Di-jet



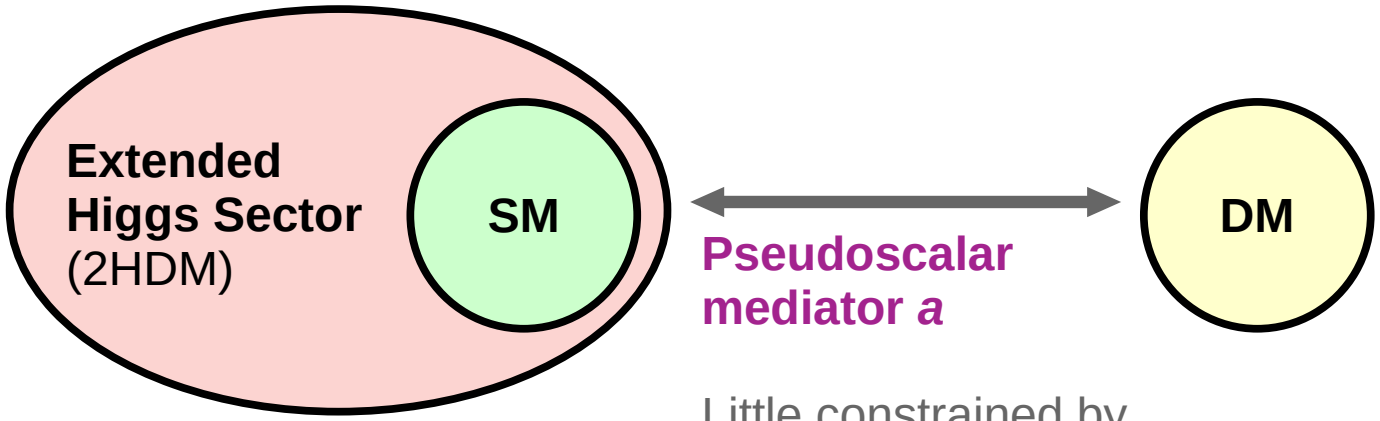


A brief history of the 2HDM+a

- Sep 2016: LHC DM WG meeting dedicated to extensions of simplified models [agenda]
- Dec 2016: LHC DM WG discussion on extended Higgs models [agenda]
  - Settle on 2HDM+a as new benchmark
  - Based on M. Bauer, F. Kahlhoefer, U. Haisch [JHEP 05 (2017) 138]
- Jan-Dec 2017: various working meetings [rolling agenda][agenda]
  - Study phenomenology, identify most relevant signatures
  - Define representative benchmark scenarios
- Dec 2017: concluding discussions in LHC DM WG meeting [agenda]
- Oct 2018: Release of LHC DM WG whitepaper [Phys.Dark Univ. 27 (2020) 100351]
- Mar 2019: Publication of first ATLAS DM summary paper [JHEP 05 (2019) 142]
  - Comprehensive set of 36 fb^{-1} results interpreted (amongst others) in 2HDM+a
- June 2023: Publication of ATLAS 2HDM+a summary paper [arXiv:2306.00641, acc. by Science Bulletin]

2HDM+a

- Minimal, UV-complete extension of pseudo-scalar simplified models
- Type-II 2HDM in the alignment limit
- 14 parameters, 5 of which are varied in the different benchmark scans



- Scalars: h, H,
- Pseudoscalar: A,
- Charged Higgs: $H^{\pm}$

Little constrained by direct detection experiments

LHC Dark Matter Working Group: Phys. Dark Univ. 27 (2020) 100351

Bauer, Haisch, Kahlhoefer: JHEP05(2017) 138

2HDM+a

- Minimal, UV-complete extension of pseudo-scalar simplified models
- Type-II 2HDM in the alignment limit
- 14 parameters, 5 of which are varied in the different benchmark scans

6 new particles

- Neutral Higgs bosons: ***A, H***
- Charged Higgs bosons: H^+, H^-
- Pseudoscalar mediator: ***a***
- Dark matter: χ

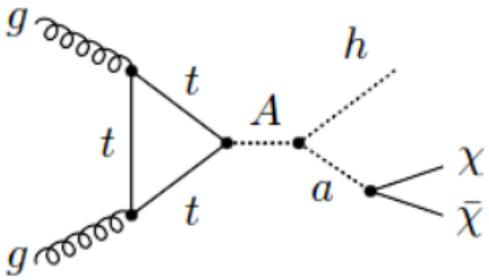
5 scanned parameters

- $m_A = m_H = m_{H+,H-}$: heavy Higgs mass
- m_a : mediator mass
- m_χ : dark matter mass
- $\tan\beta$: ratio of VEVs of the two Higgs fields
- $\sin\theta$: mixing angle of the pseudoscalars

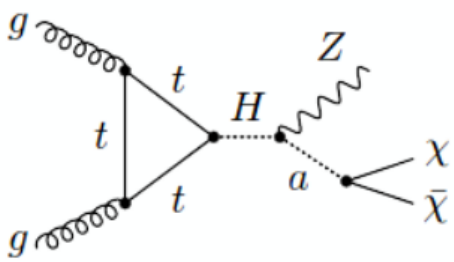
Rich collider phenomenology

> Variety of signatures with both visible and invisible decays

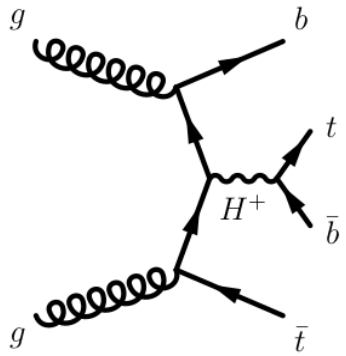
- Resonantly enhanced production of MET+h and MET+Z signatures
- Additional Higgs bosons
- Processes enhanced compared to by simplified models
  - Inspires new searches, e.g. MET+tW search (**ATLAS:** EPJC83(2023)603, EPJC81(2021)860)



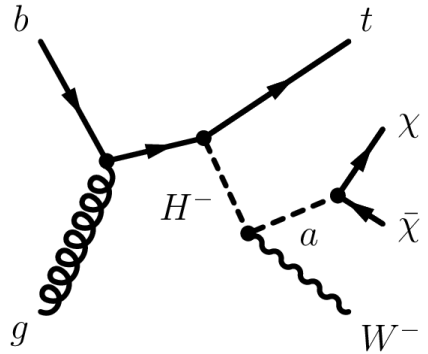
MET+h



MET+Z



tb $H^{\pm}$(tb)



MET+tW

Benchmark scenarios explored in ATLAS

> Building on whitepaper recommendations

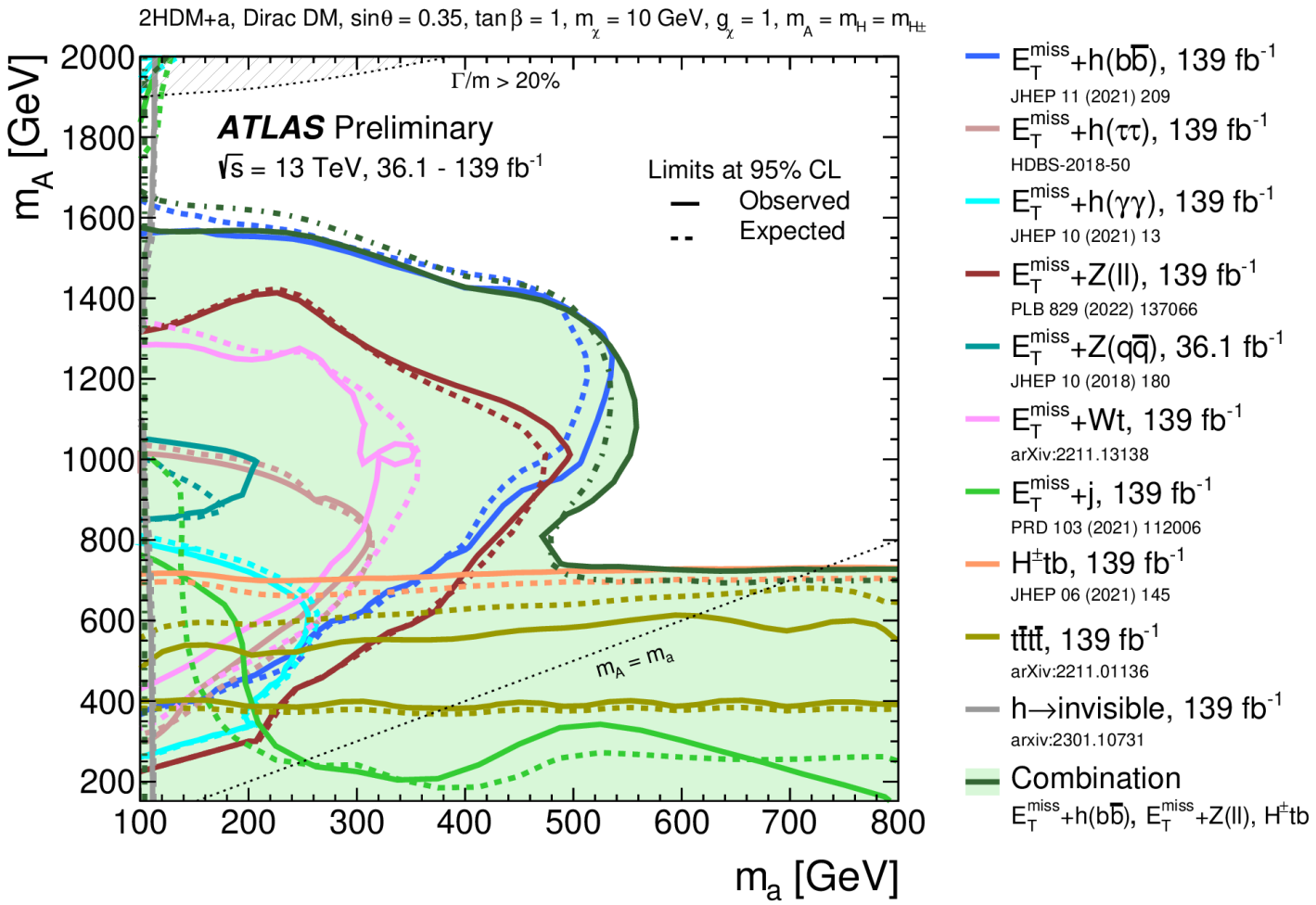
> Added new benchmark scans (green), modified one that was fully excluded (orange)

Scenario		Fixed parameter values				Varied parameters
		$\sin\theta$	m_A [GeV]	m_a [GeV]	$\tan\beta$	
1	a	0.35	–	–	1.0	(m_a, m_A)
	b	0.70	–	–	1.0	
2	a	0.35	–	250	–	$(m_A, \tan\beta)$
	b	0.70	–	250	–	
3	a	0.35	600	–	–	$(m_a, \tan\beta)$
	b	0.70	600	–	–	
4	a	–	600	200	1.0	$\sin\theta$
	b	–	1000	350	1.0	
5		0.35	1000	400	1.0	m_χ
6		0.35	1200	–	1.0	(m_a, m_χ)

Example: scan in m_a vs m_A

arXiv:2306.00641

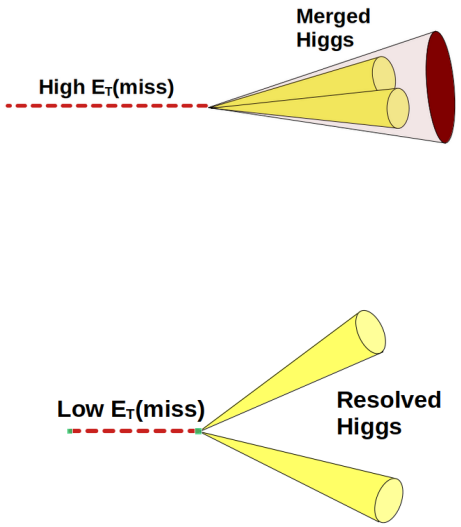
> Benchmark scenario with $m_A = m_H = m_{ChargedH}$ and moderate a-A mixing [LHC DM WG recommendation]

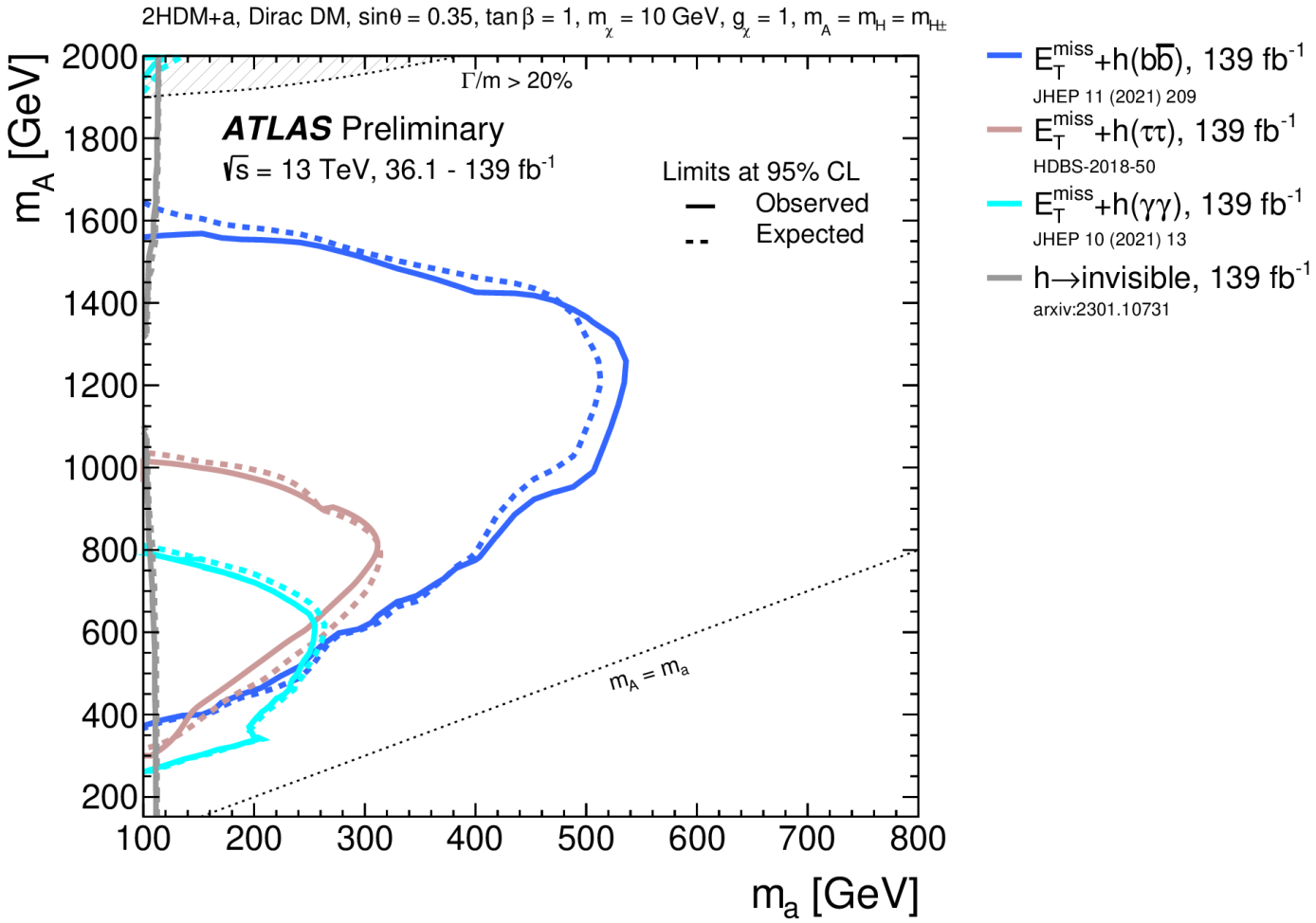


Example: scan in m_a vs m_A

arXiv:2306.00641

> Benchmark scenario with $m_A = m_H = m_{ChargedH}$ and moderate a-A mixing [LHC DM WG recommendation]





E_T^{miss}+h($b\bar{b}$), 139 fb^{-1}
JHEP 11 (2021) 209

E_T^{miss}+h($\tau\tau$), 139 fb^{-1}
HDBS-2018-50

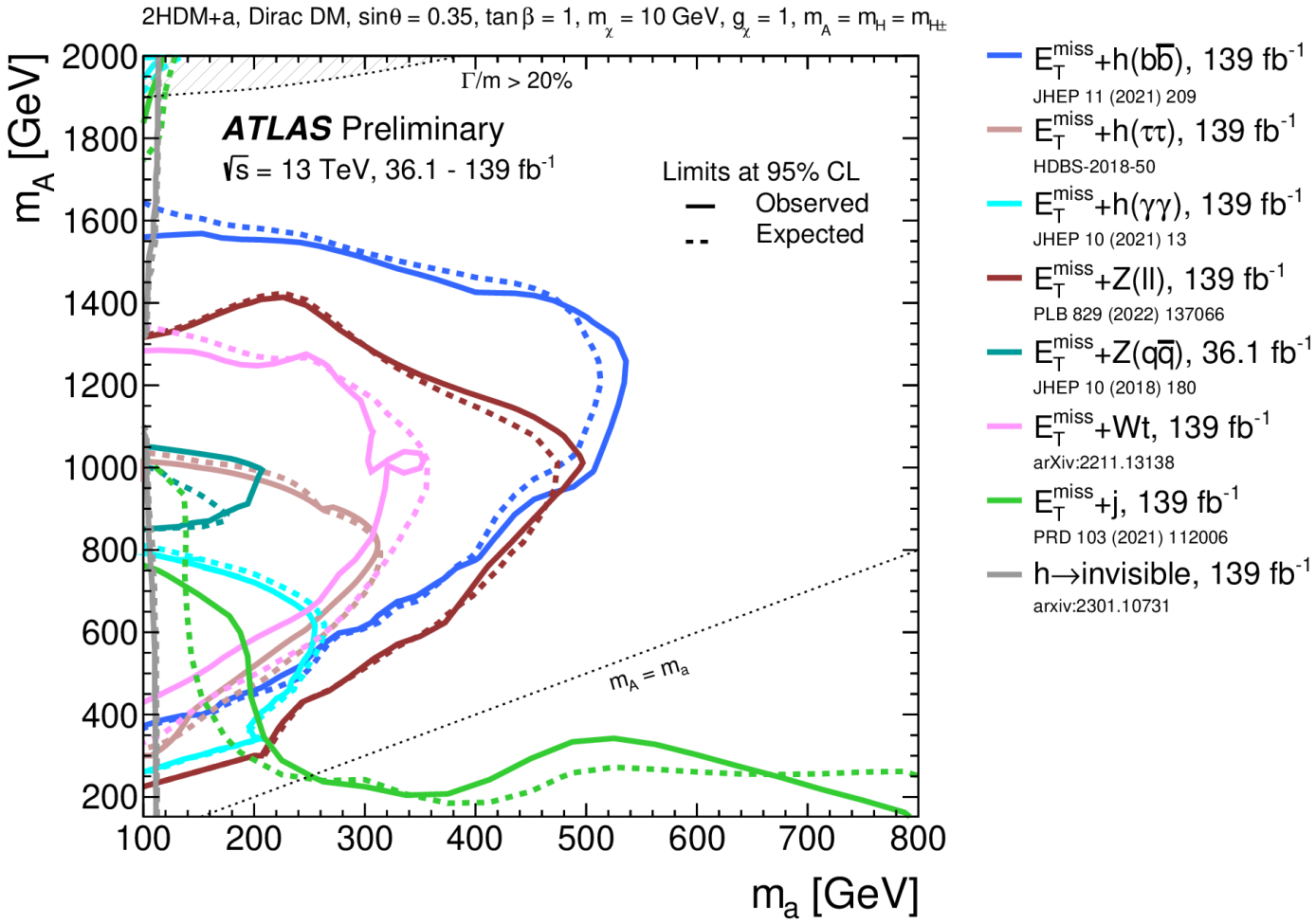
E_T^{miss}+h($\gamma\gamma$), 139 fb^{-1}
JHEP 10 (2021) 13

h→invisible, 139 fb^{-1}
arxiv:2301.10731

Example: scan in m_a vs m_A

arXiv:2306.00641

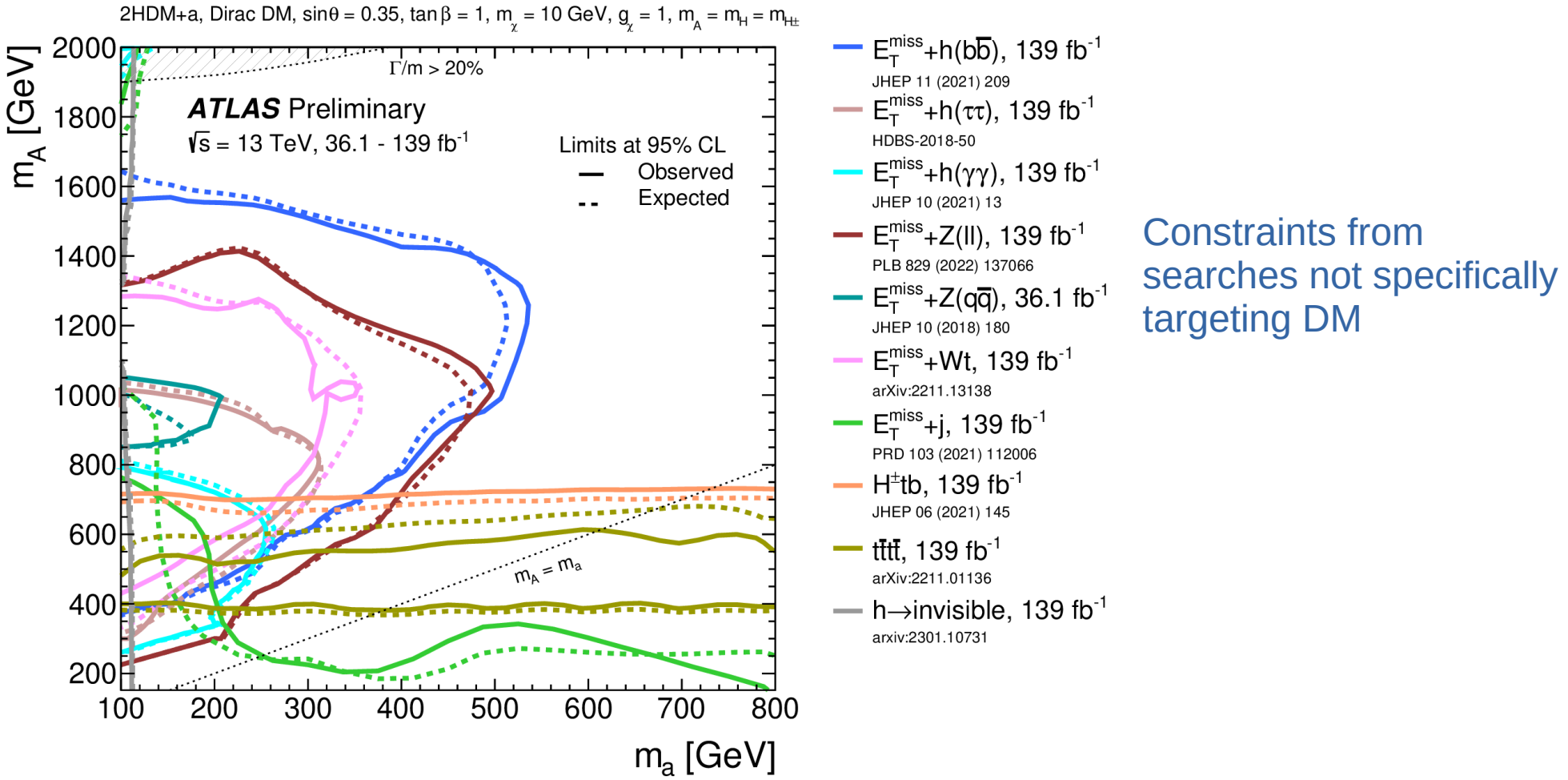
> Benchmark scenario with $m_A = m_H = m_{ChargedH}$ and moderate a-A mixing [LHC DM WG recommendation]



Example: scan in m_a vs m_A

arXiv:2306.00641

> Benchmark scenario with $m_A = m_H = m_{ChargedH}$ and moderate a-A mixing [LHC DM WG recommendation]

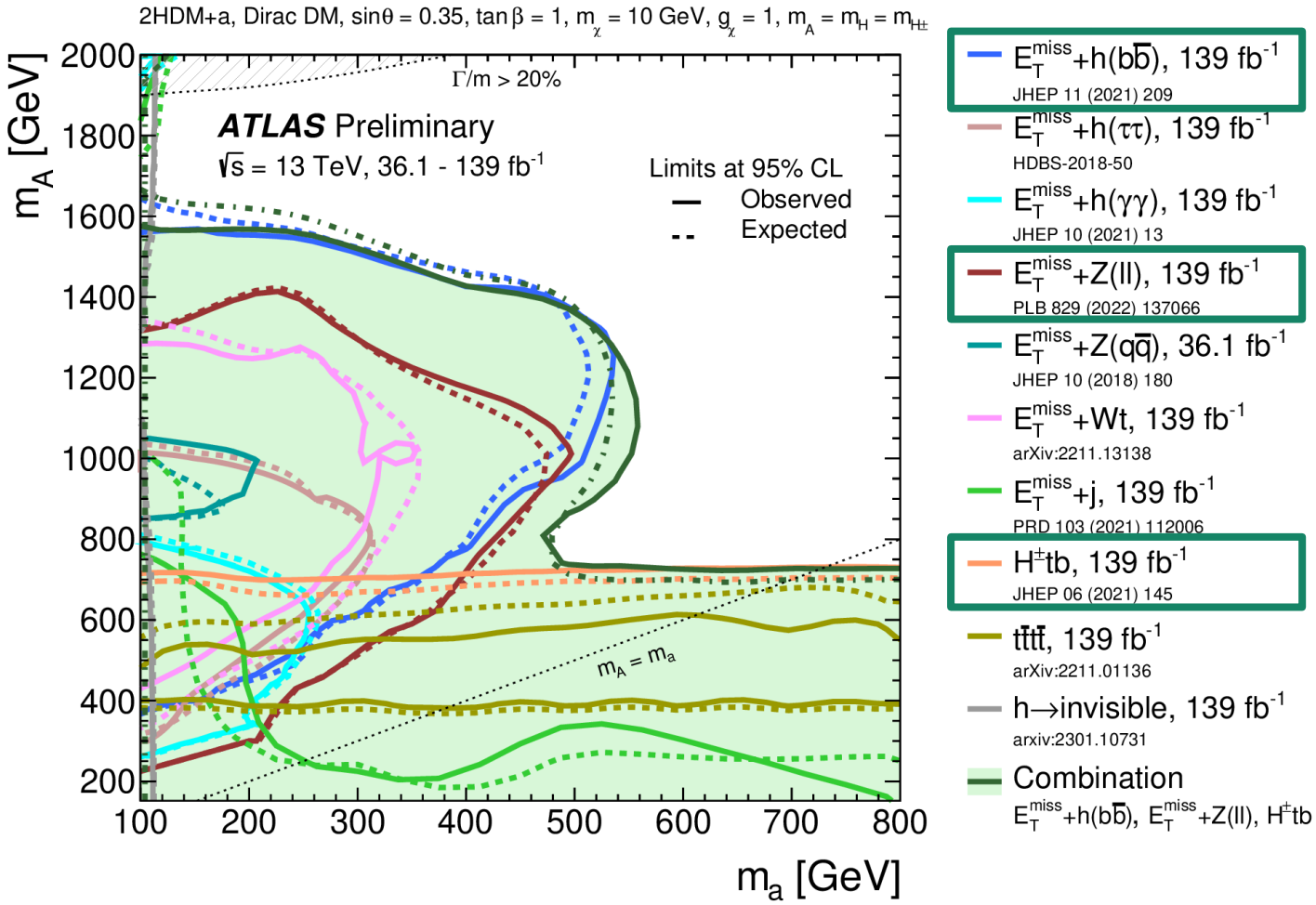


Constraints from searches not specifically targeting DM

Example: scan in m_a vs m_A

arXiv:2306.00641

> Benchmark scenario with $m_A = m_H = m_{ChargedH}$ and moderate a-A mixing [LHC DM WG recommendation]



Statistical combination

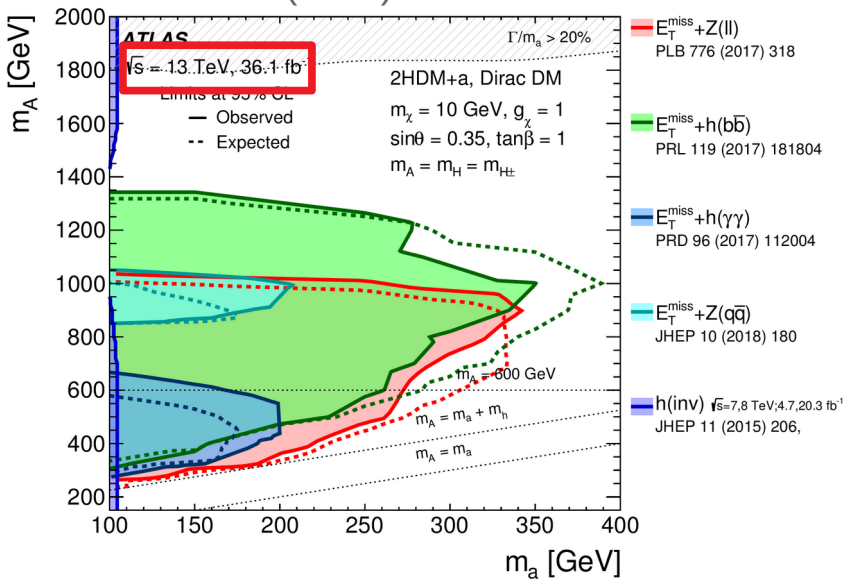
Most comprehensive set of constraints on the 2HDM+a to date!

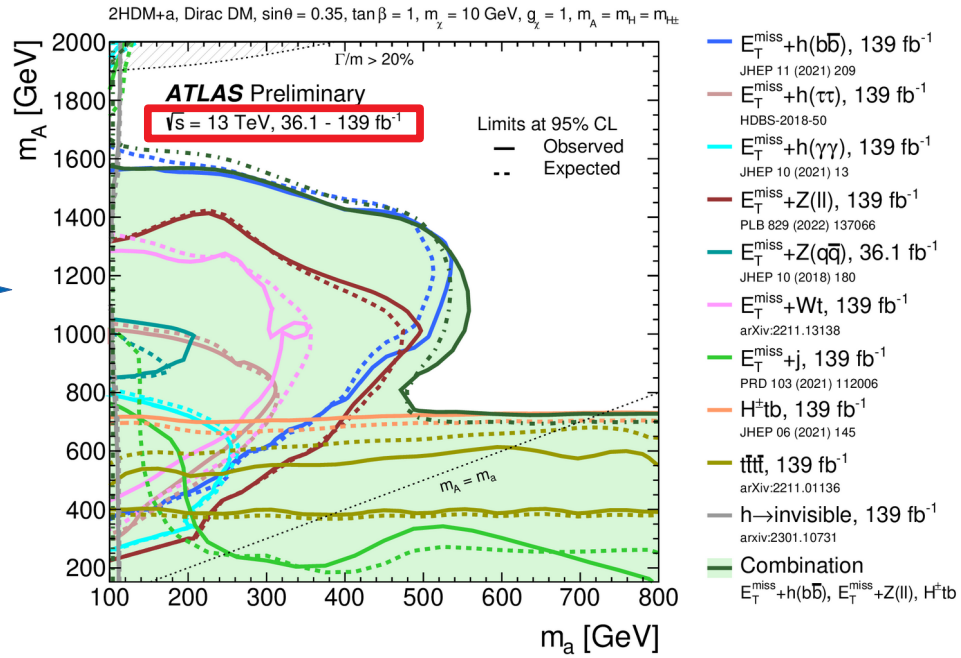
Improvements compared to 36 ifb result

arXiv:2306.00641

- Significant improvement of parameter space coverage thanks to:
  - Improved analysis techniques
  - Additional searches

JHEP 05 (2019) 142

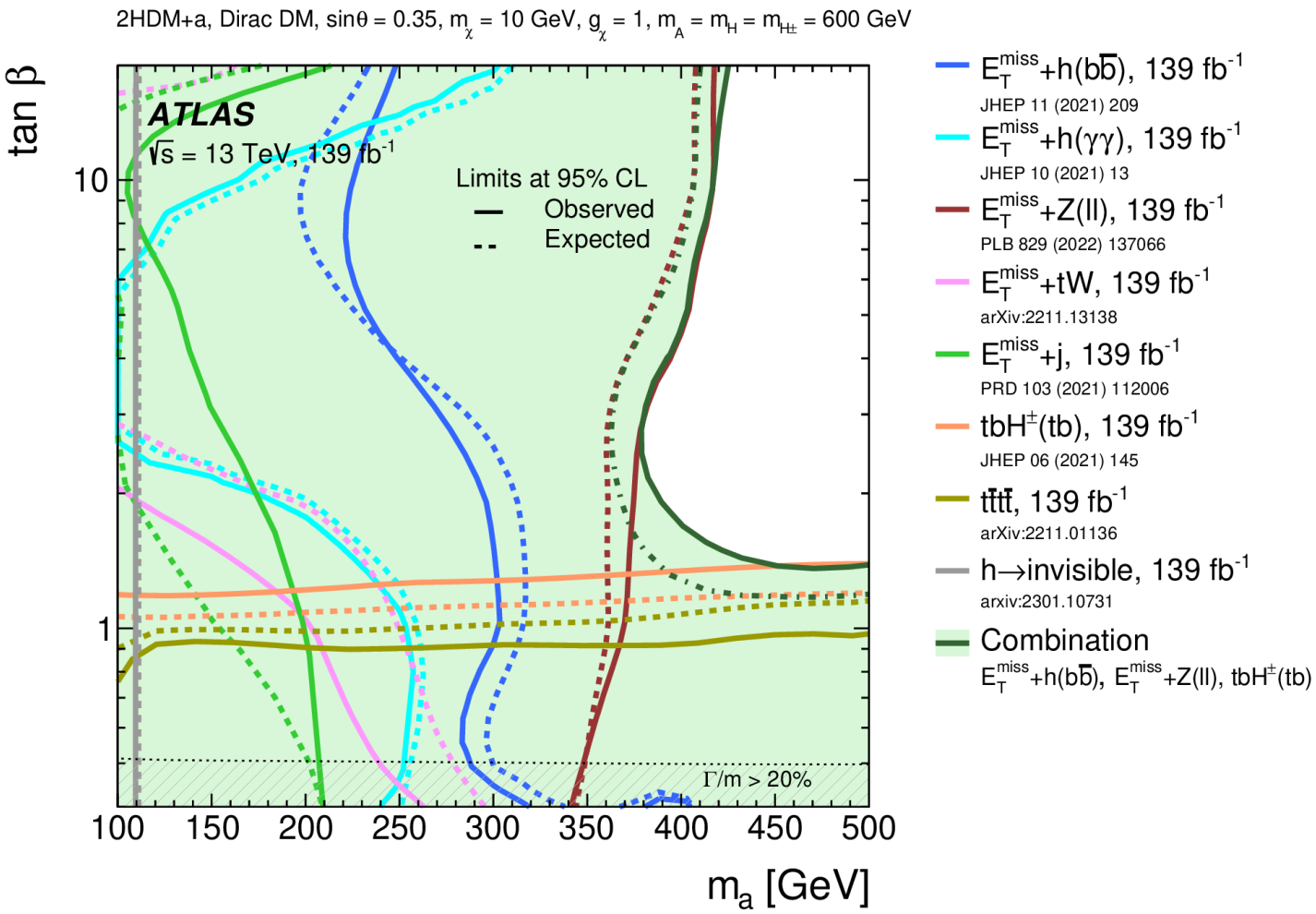




Example: scan in m_a vs tanβ

arXiv:2306.00641

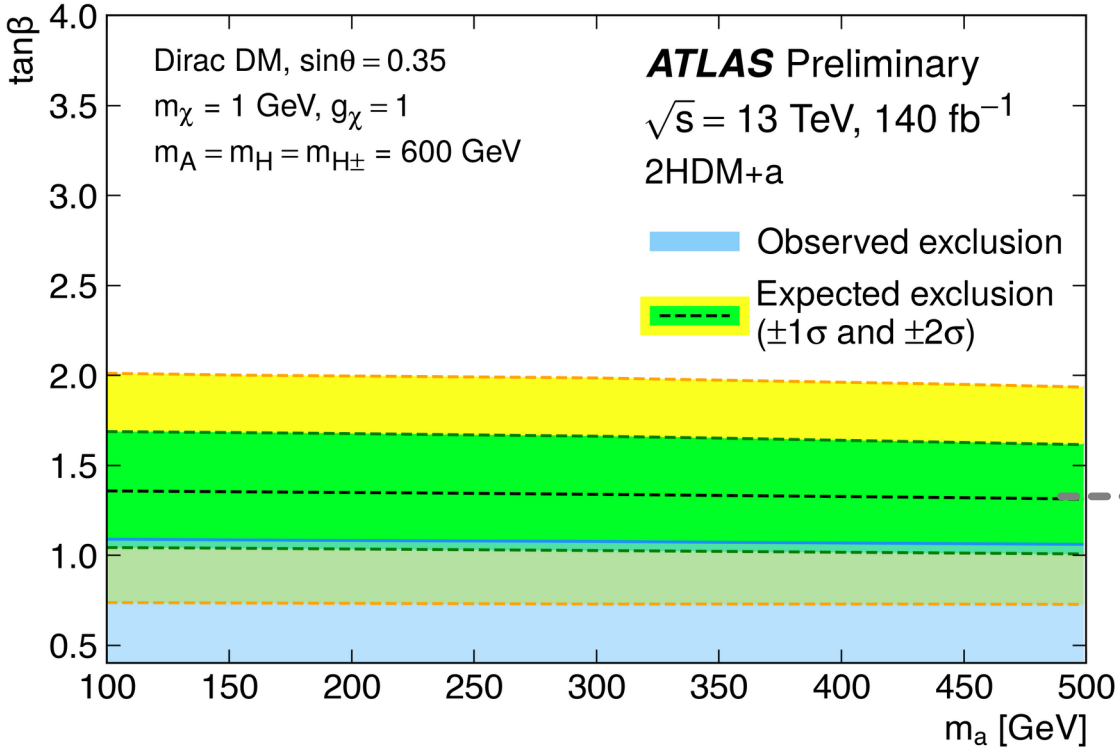
> The “2HDM”-type scan

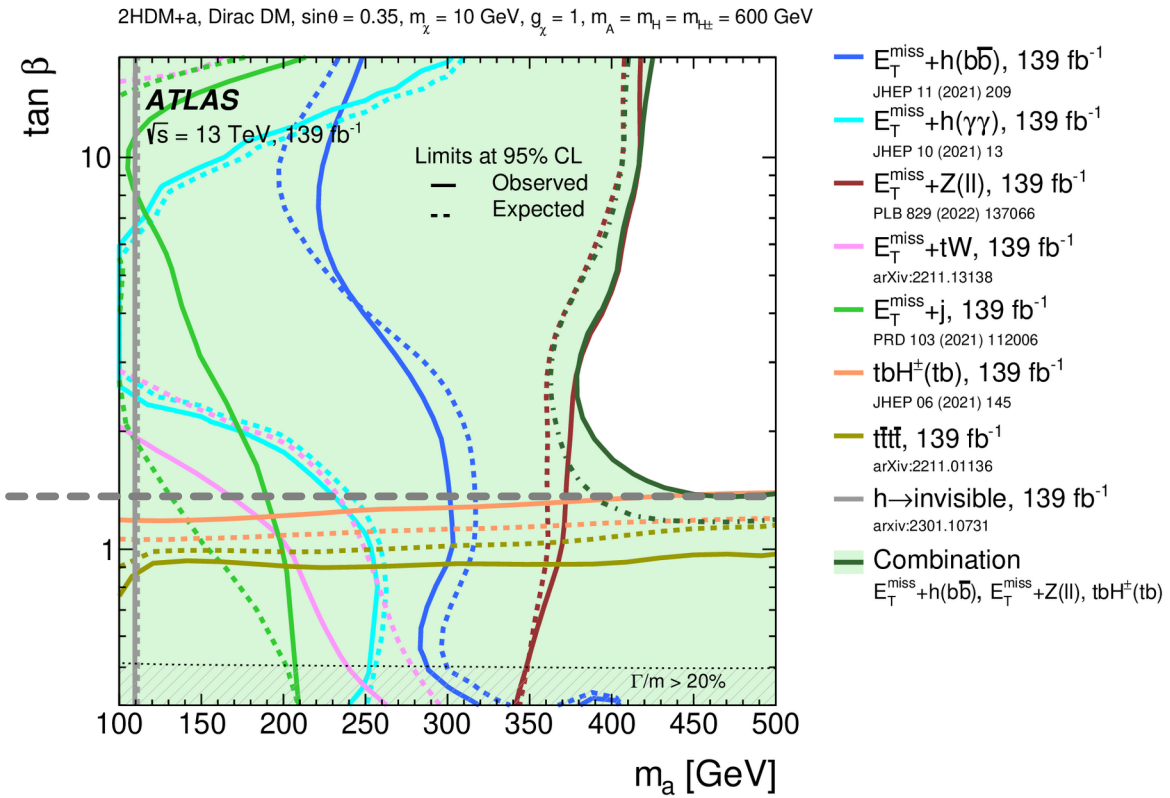


Additional constraints from A/H → ttbar interference search

arxiv:2404.18986

- Leading expected exclusion at high mediator mass, observed exclusion weaker due to downward fluctuation
- Special 2HDM+a UFO created to allow for interference modelling in 2HDM+a (at LO in QCD)
- Result based on LO cross-sections because no NLO calculation available for case with a-A mixing
  - NLO cross-section roughly factor 2 larger!



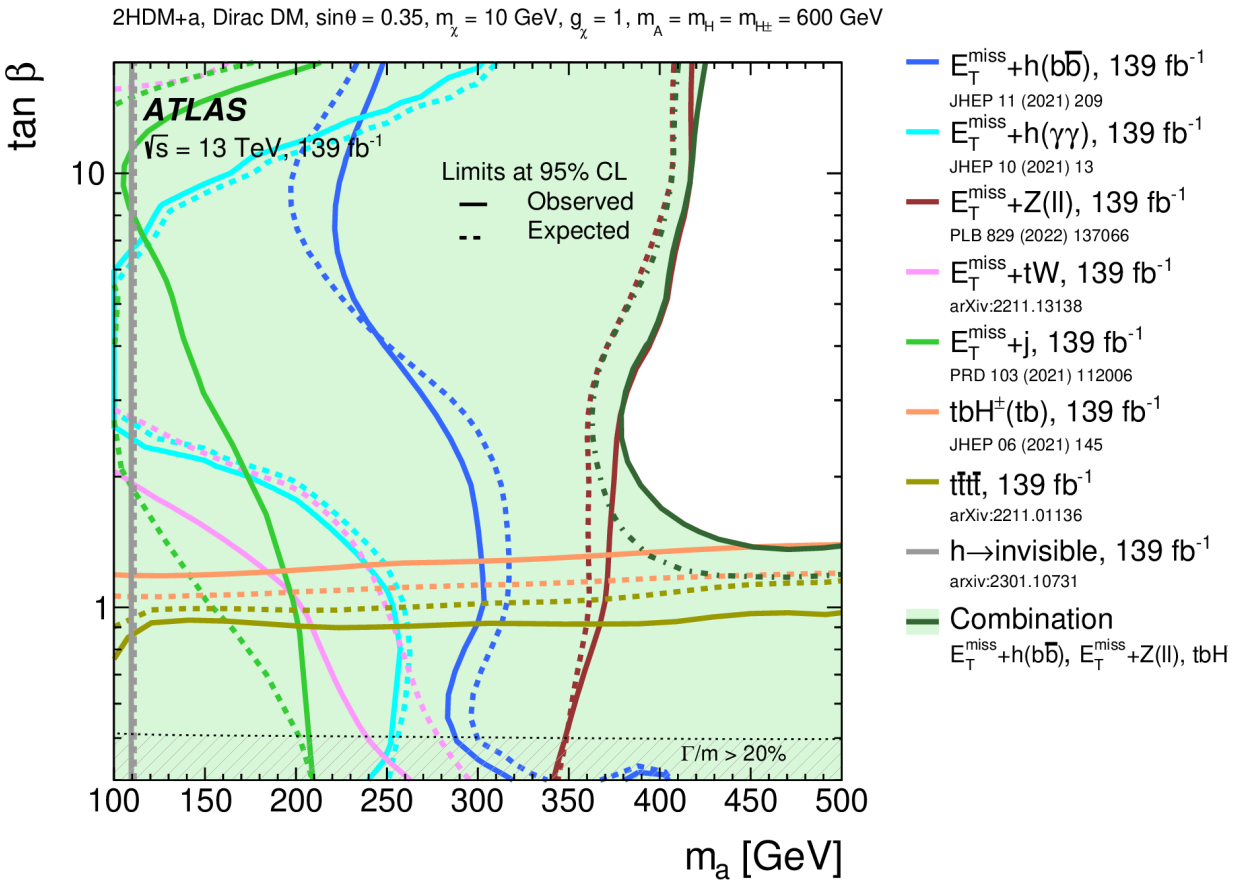


Example: scan in m_a vs tanβ

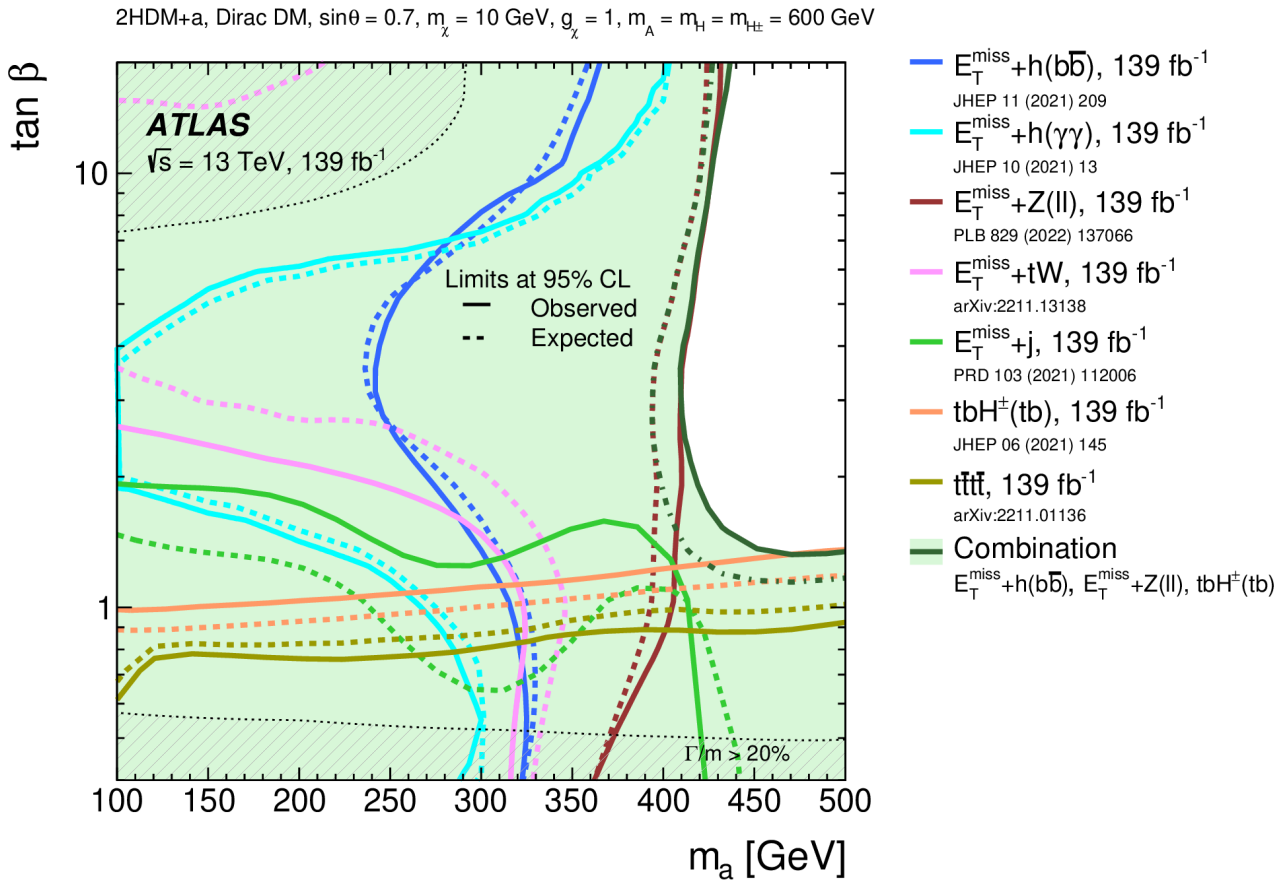
arXiv:2306.00641

> Choice of sinθ → changes relative importance of searches, in particular MET+j and MET+tW

sinθ = 0.35

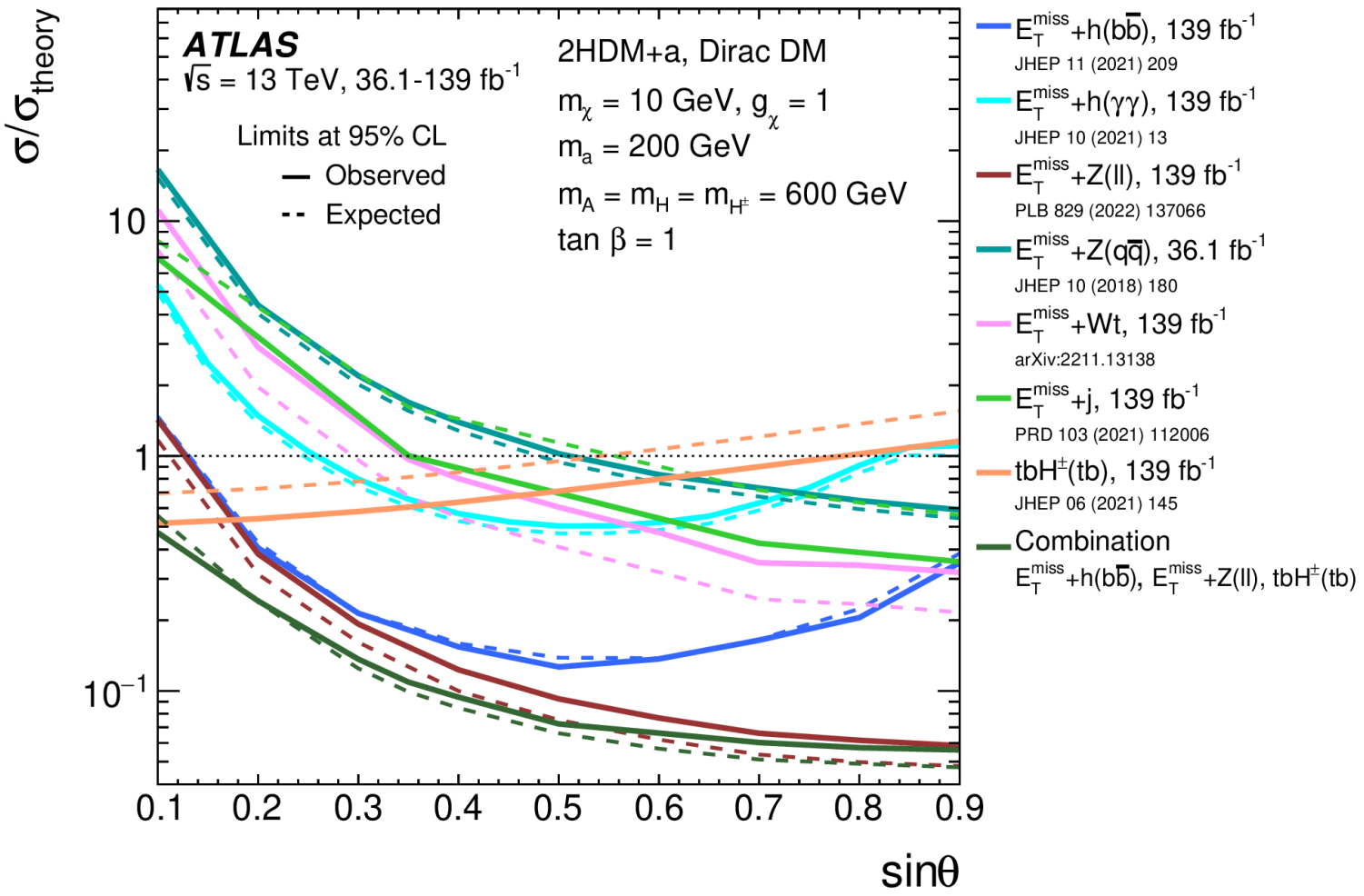


sinθ = 0.7



Relevance of a-A mixing angle

> Variations of sinθ change relative importance of MET- and non-MET-signatures

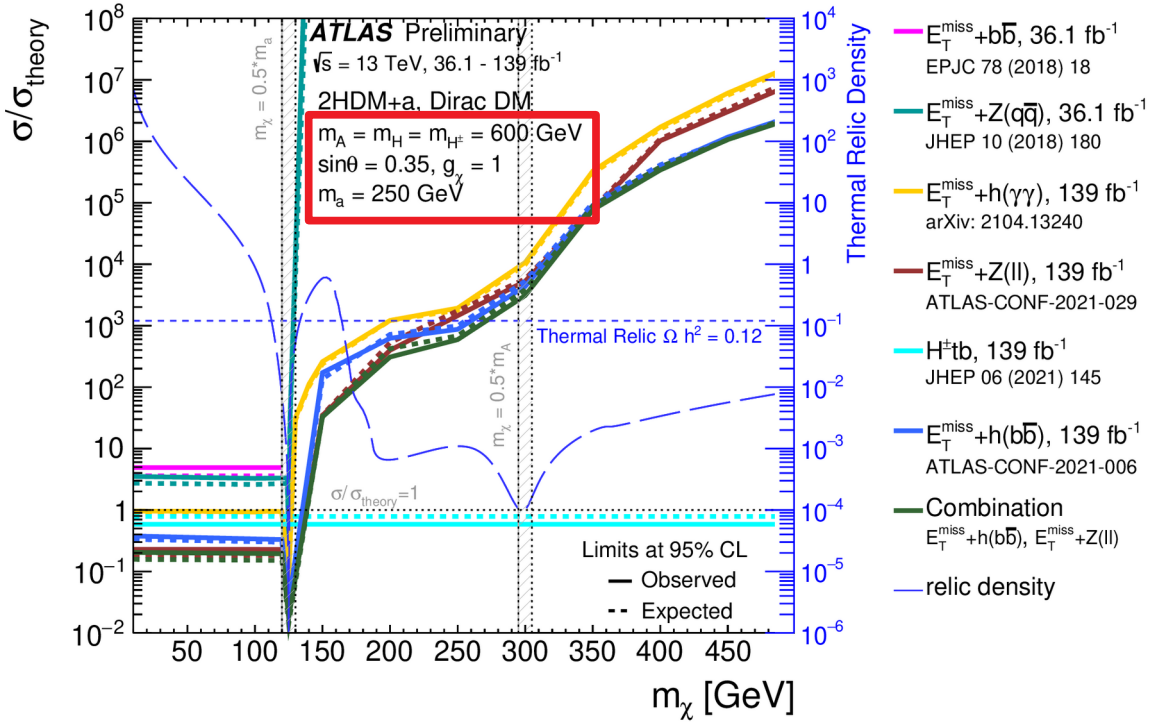


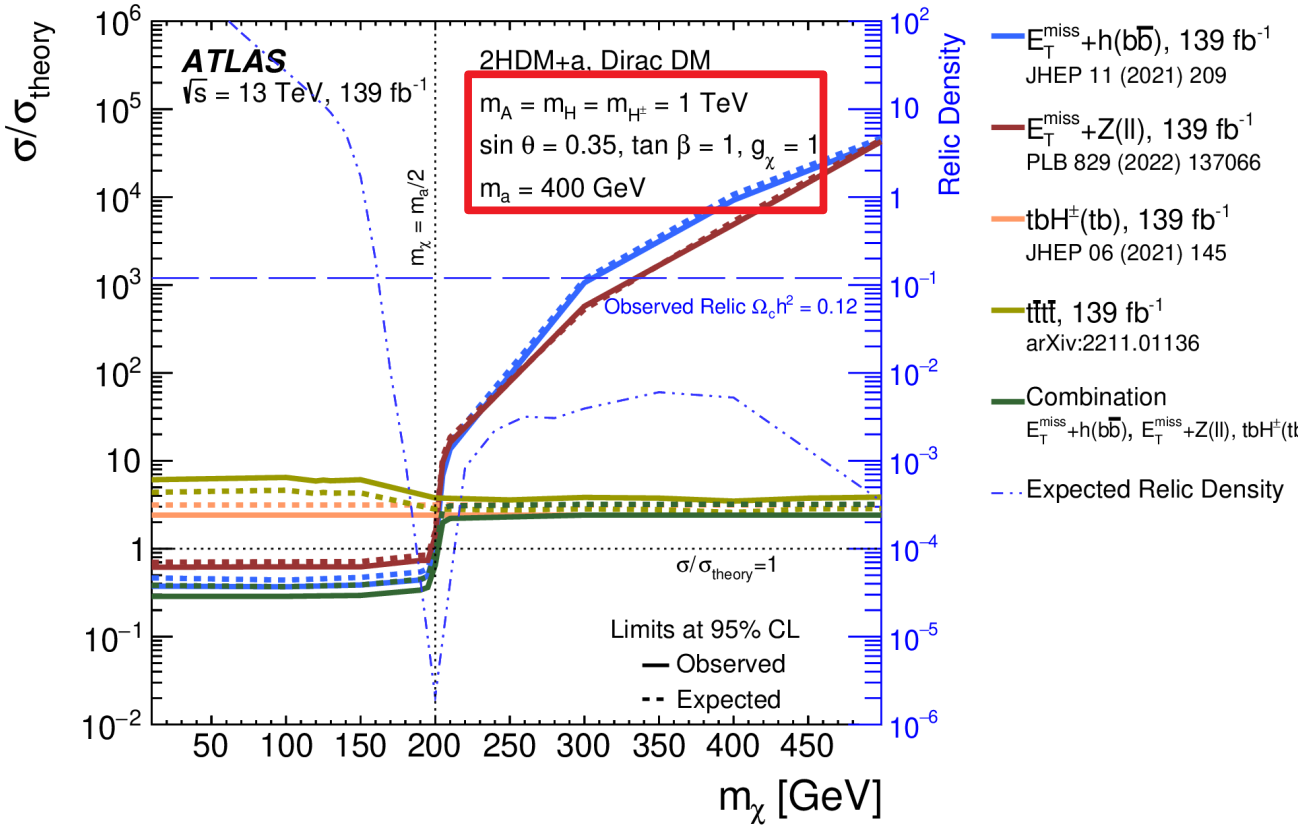
Scan in the DM mass

arXiv:2306.00641

- Small change in benchmark definition between preliminary and final full-Run-2 results
- Scenario from whitepaper fully excluded based on full-Run-2 tbH(tb) search alone!
- Underlines relevance of non-DM searches in these less simplified models!

ATLAS-CONF-2021-036

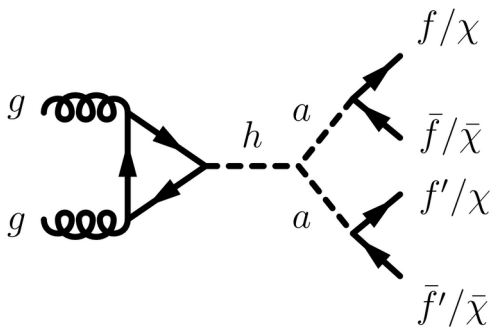


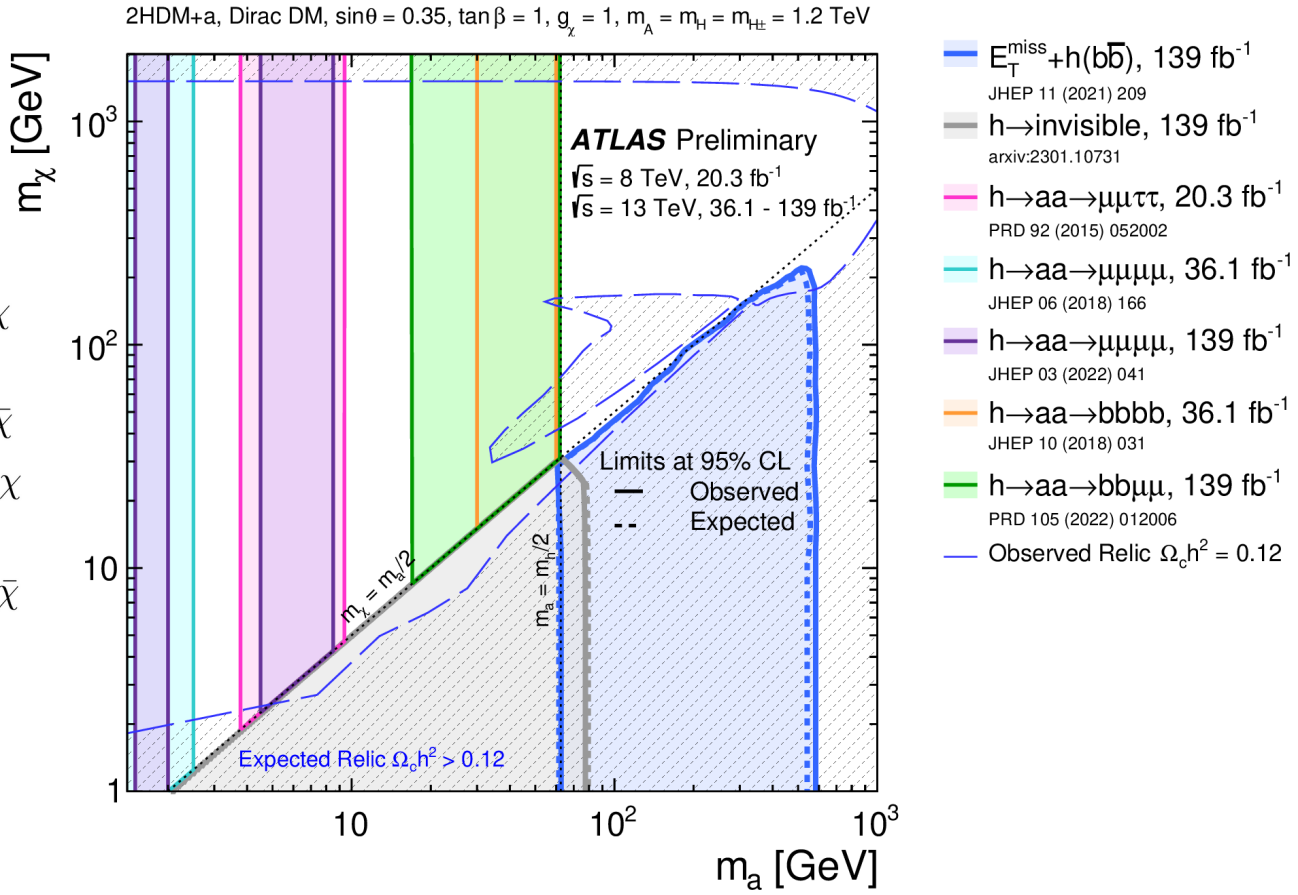


New benchmark scan in m_a and m_χ

arXiv:2306.00641

- First explored in ATLAS Run-2 summary paper, based on [arxiv:2202.12631] and discussions in LHC DM WG
- Searches for SM Higgs decaying to 4 fermions via aa constrain previously unprobed region of 2HDM+a
- Complementarity to h(inv) and MET+h(bb) searches



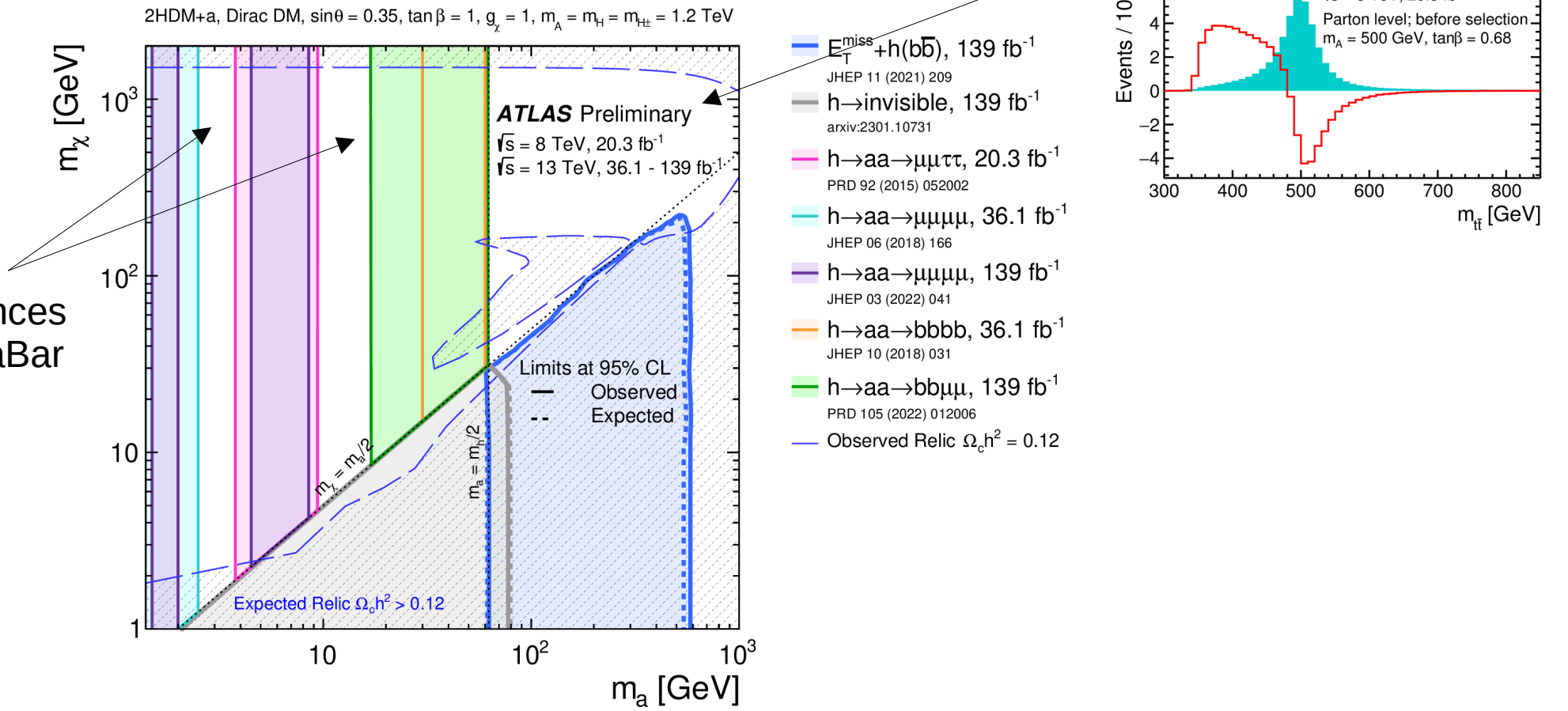


New benchmark scan in m_a and m_χ

arXiv:2306.00641

> Some currently unexplored regions...

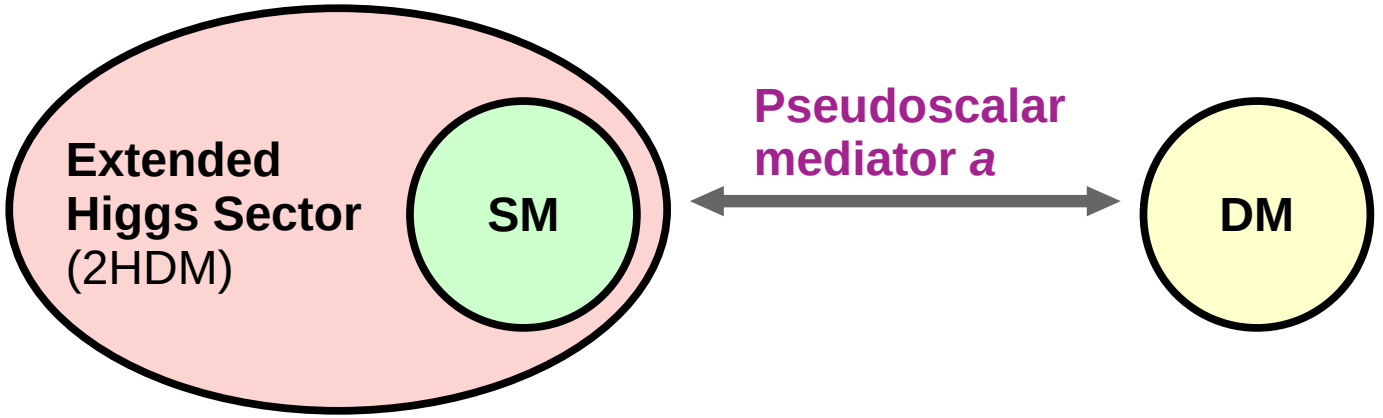
- J/Psi and Y resonances
- Constraints from BaBar and LHCb?



gg → a/A → ttbar

Summary

- Comprehensive set of ATLAS searches on full Run 2 dataset interpreted in 2HDM+a
  - Including searches that are not specifically targeting DM
  - Statistical combination of three most sensitive searches
  - Most comprehensive constraints on 2HDM+a to date
- Updates compared to whitepaper:
  - New benchmark scenarios exploring previously uncovered regions of parameter space
  - Updated one fully excluded benchmark



New directions

> Within the 2HDM+a

- Loosening current assumptions?
  - Drop mass degeneracy: m_A =/= m_H → new decays, e.g. A → ZH [arxiv:2404.05704]
  - Different Yukawa coupling type, e.g. type-I to lift flavour constraints (lower bounds on $m_{A/H}$) [arxiv:2404.05704]
  - Move away from alignment limit → di-boson signatures
- Comparison to direct and indirect detection results?

> Beyond the 2HDM+a

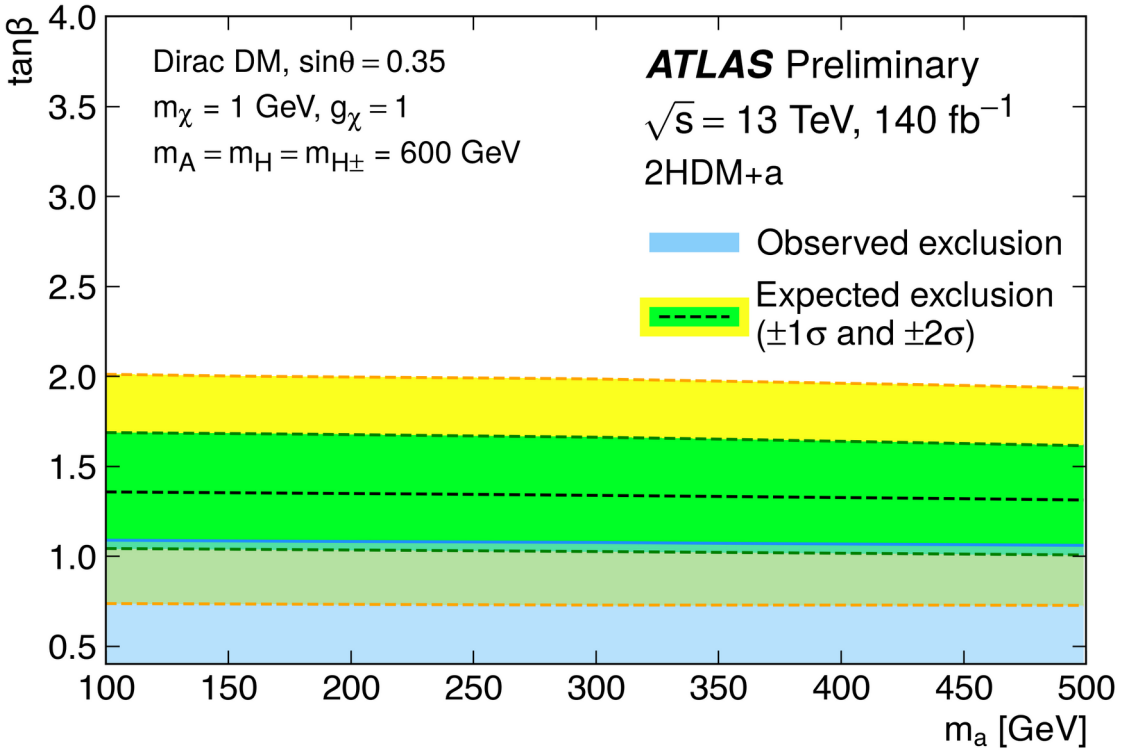
- Uncovered signatures in other extended Higgs models?
  - E.g. 2HDM+scalar or other?
- LLP signatures in extended Higgs models?
  - E.g. [arxiv:2302.02735]

Extra Material

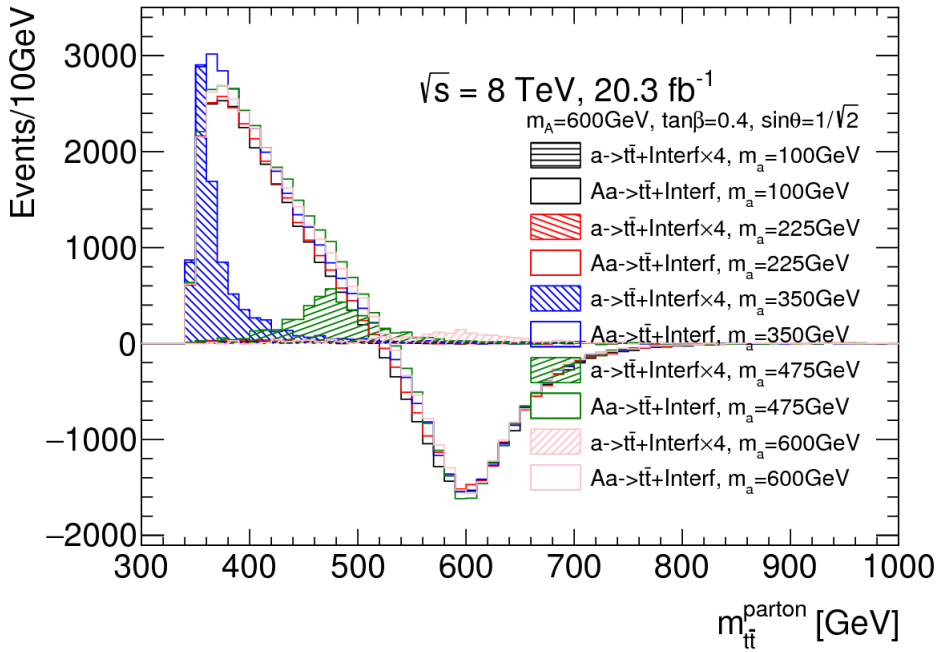
Additional constraints from gg → A/H → ttbar search

arxiv:2404.18986

- Signal process interferes strongly with SM ttbar background
- Interference pattern highly model-dependent
- Search interpreted in terms of single A or single H as well as 2HDM, hMSSM, 2HDM+a
- Special 2HDM+a UFO created to allow for interference modelling in 2HDM+a (at LO in QCD)



PhD thesis Y. Chen + LHCDMWG

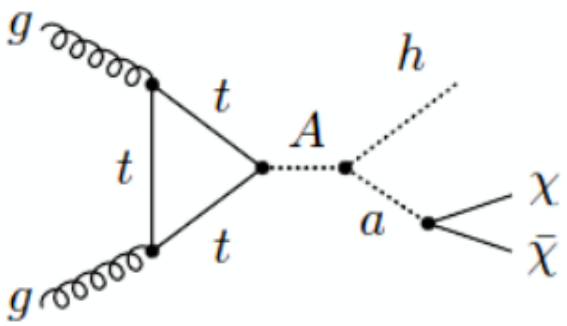


Signature: MET+h(bb)

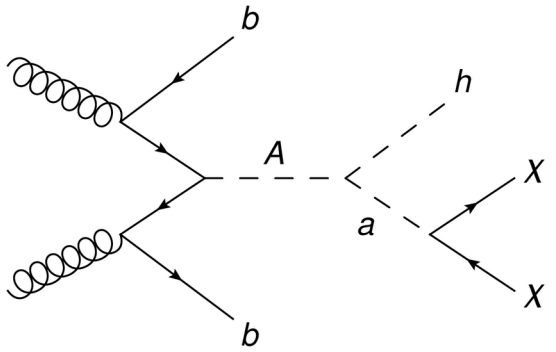
[JHEP 11 (2021) 209]

- Higgs boson recoiling against large MET
- MET trigger to select events: requires MET > 150 GeV
  - MET threshold limits sensitivity to small A-a mass splittings
- Search targets both gg- and bb-induced production
  - Two event categories: == 2 b-jets or ≥ 3 b-jets

Signature predicted also in other models, e.g. 2HDM+Z'



gg induced

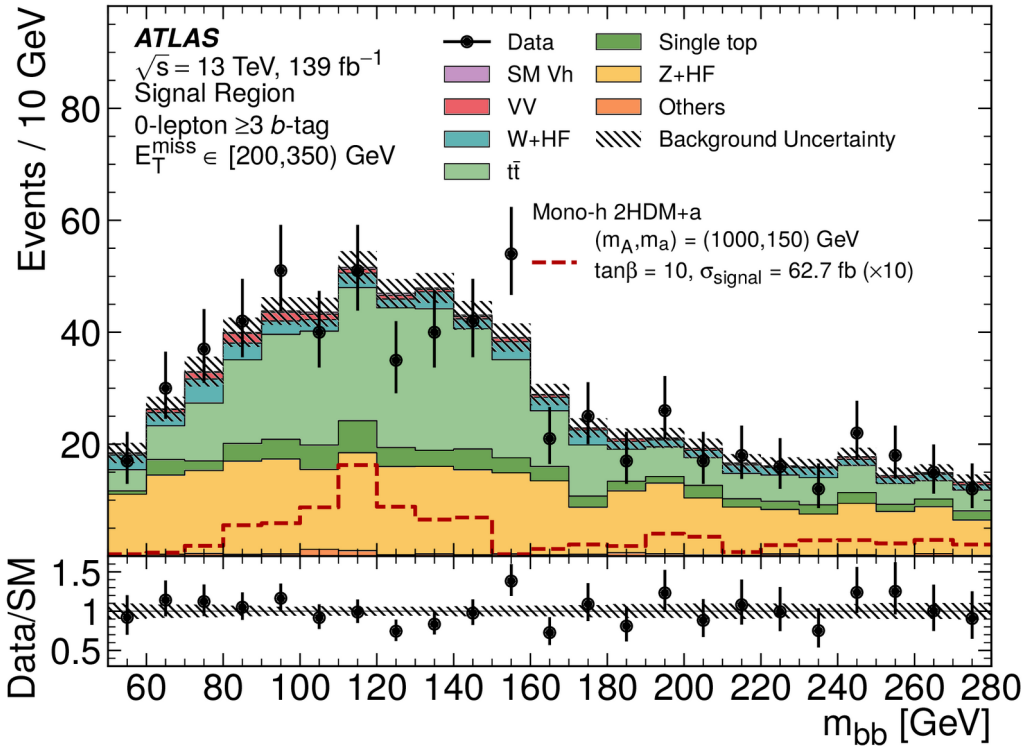


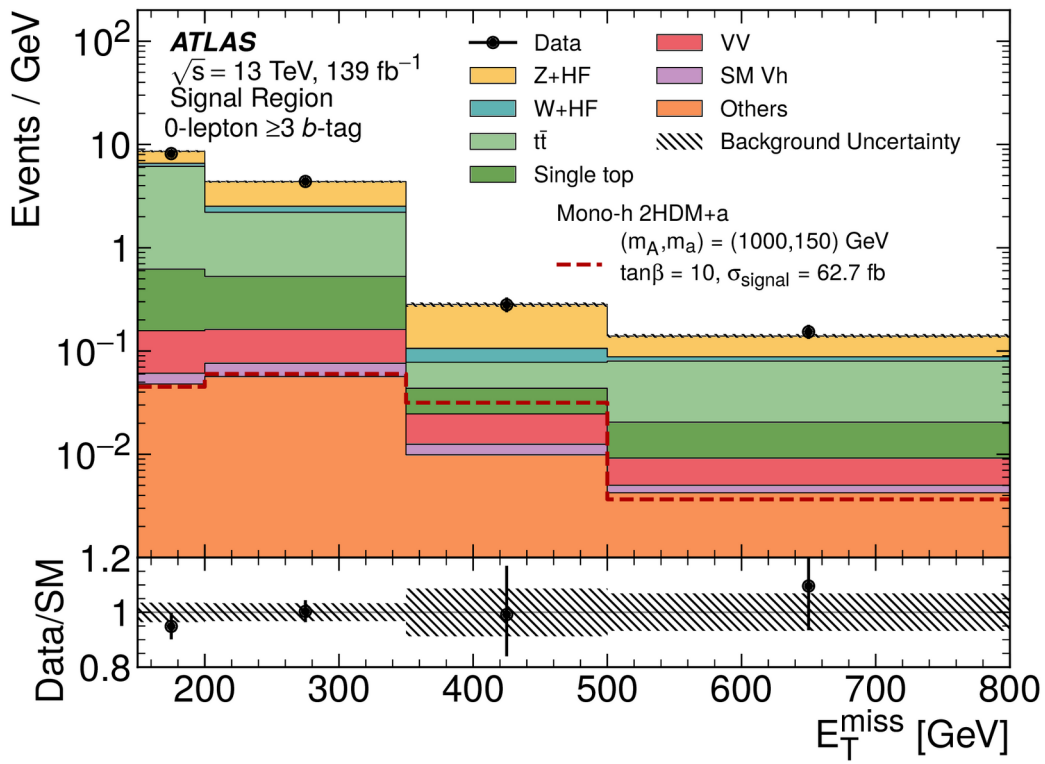
bb induced

Signature: MET+h(bb)

[JHEP 11 (2021) 209]

- Both categories divided into MET bins to obtain orthogonal signal regions
- Higgs decay reconstructed as single large-radius jet for MET > 500 GeV
- Fit m_{bb} distribution in each signal region

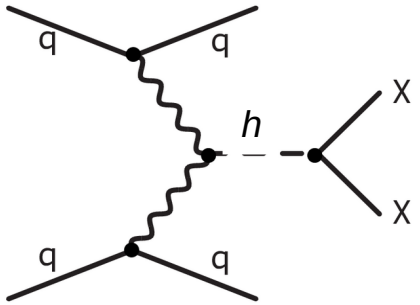




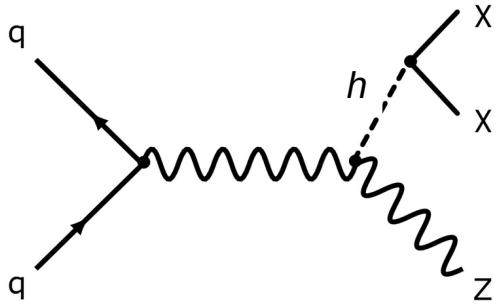
Signature: invisible Higgs boson decays

> Processes h → aa → χχ and h → aχχ → χχχ

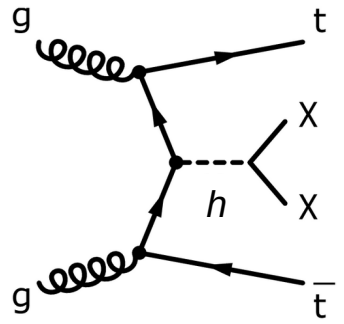
> Different Higgs production modes:



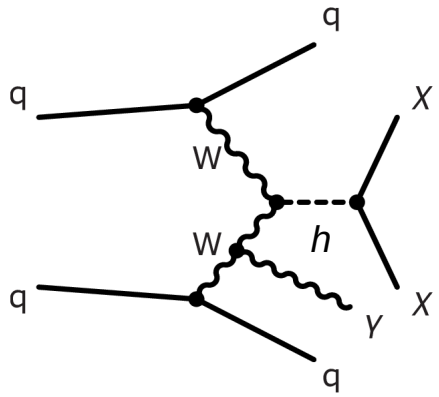
Vector-boson fusion (VBF)



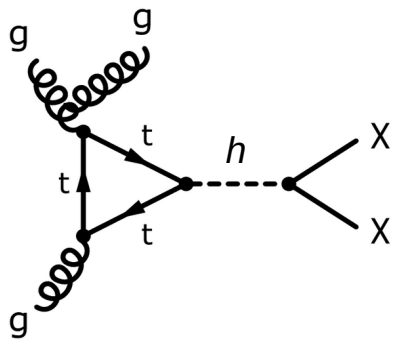
Higgs strahlung (Zh)



Top-quark associated (tth)



VBF + photon

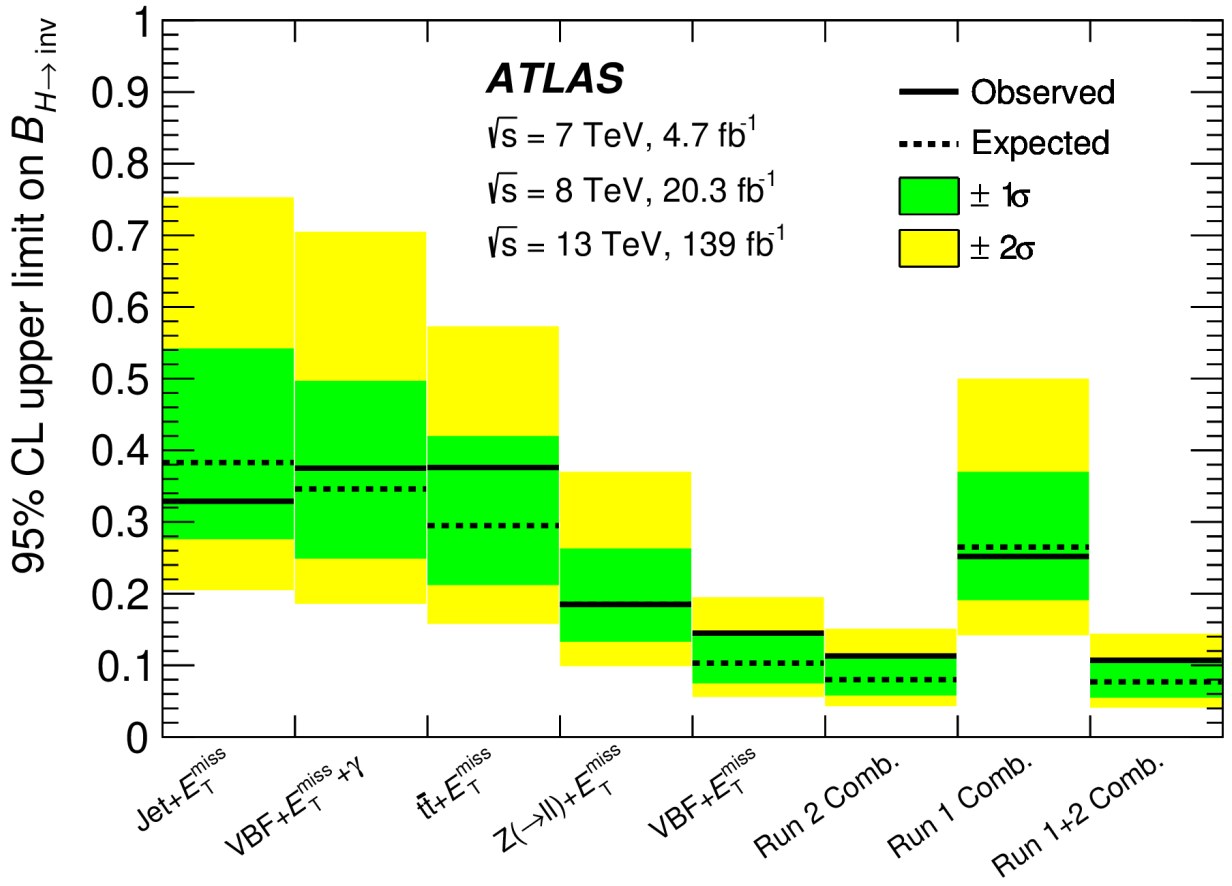


Gluon fusion

Signature: invisible Higgs boson decays

arXiv:2301.10731

- Includes LHC Run 2 results targeting invisible Higgs decays in all relevant production modes
  - VBF+MET, Z(ℓℓ)+MET, tt+MET, VBF+γ+MET, jet+MET
- Additonally: results on at √s = 7 and 8 TeV data included in previous Run-1 combination



BR(h → inv) < 0.107 ($0.077^{+0.030}_{-0.022}$)

at 95% CL

Latest CMS constraint:

BR(h → inv) < 0.16 at 95% CL

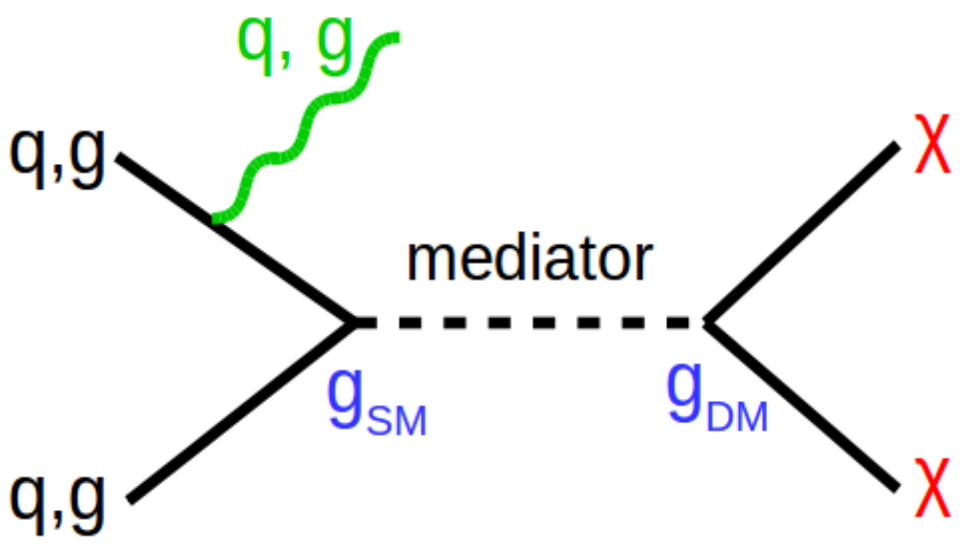
[Nature 607, 60–68 (2022)]

s-channel mediators

> Aim to detect invisible decays of the mediator to DM → missing transverse momentum (MET)

> Problem: Need a hard object to trigger on the event

> Solution: **initial-state radiation (ISR)**



Signatures

MET+jet

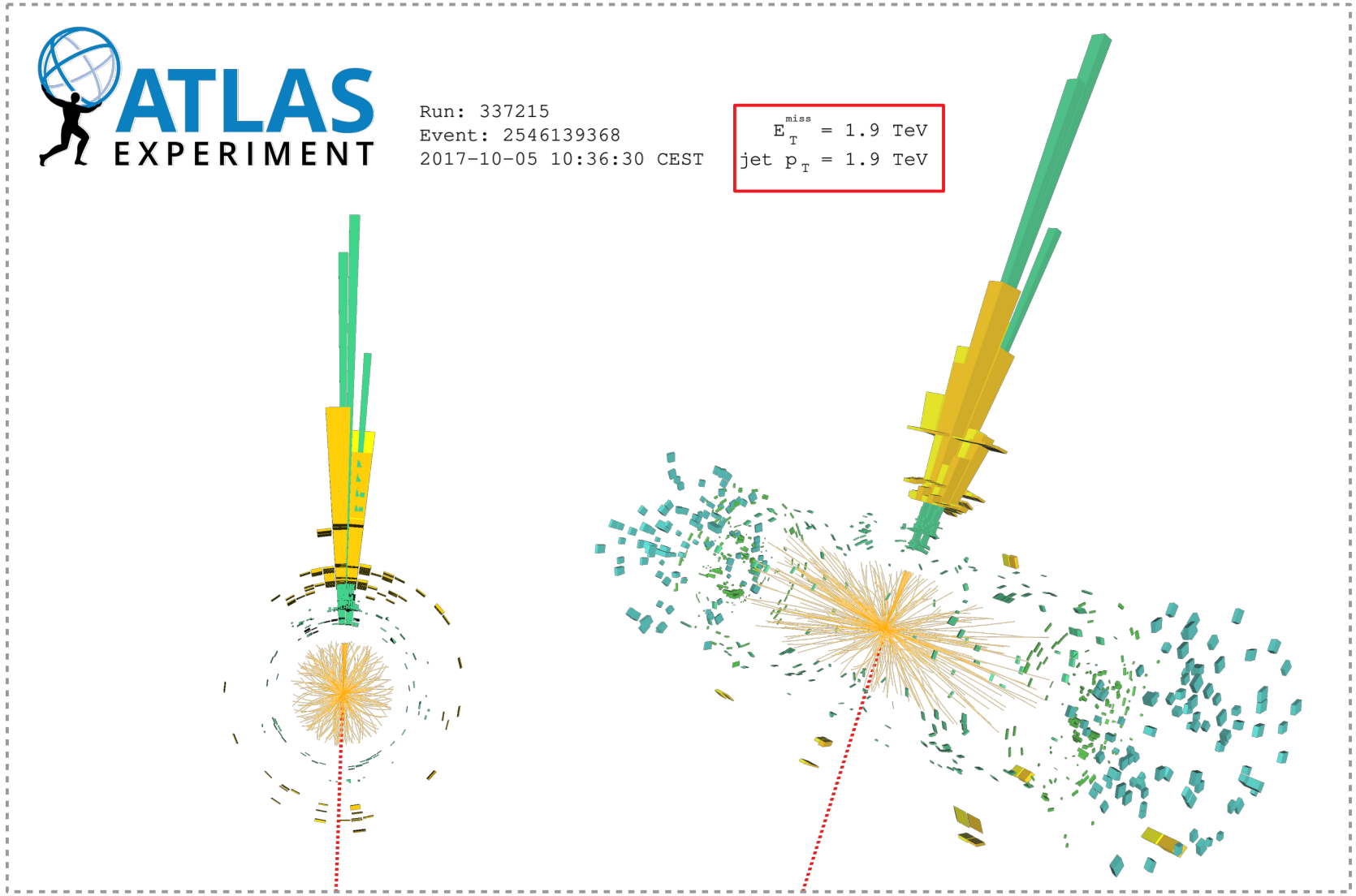
MET+photon

MET+W/Z

A classic DM candidate event

> MET+jet signature

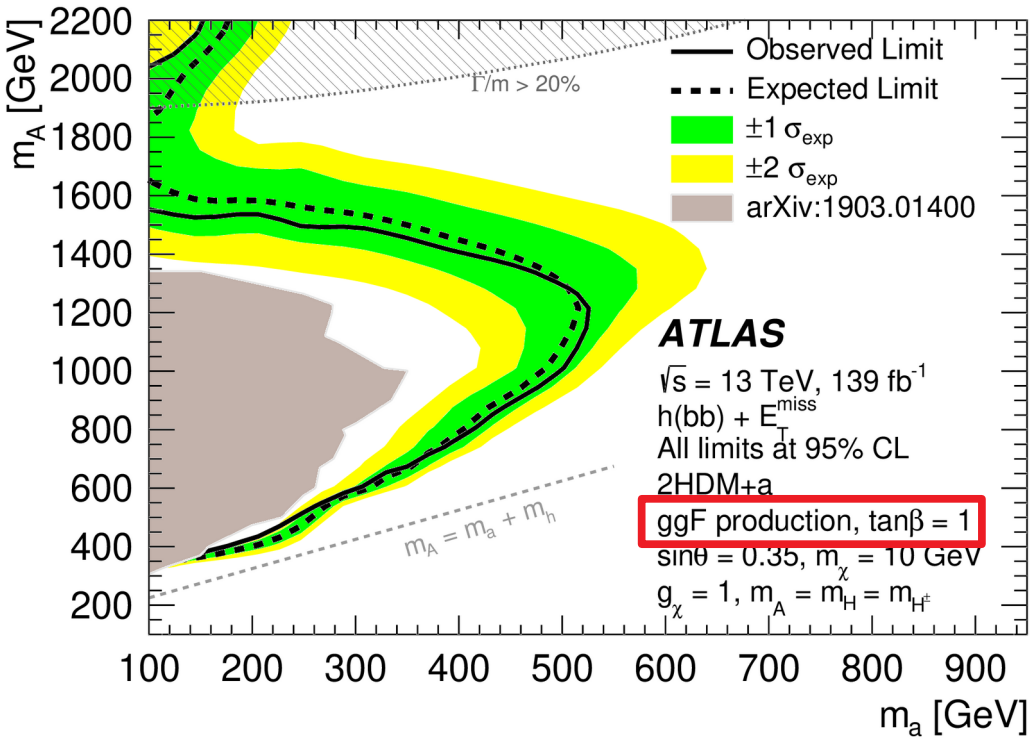
> ATLAS, 2017

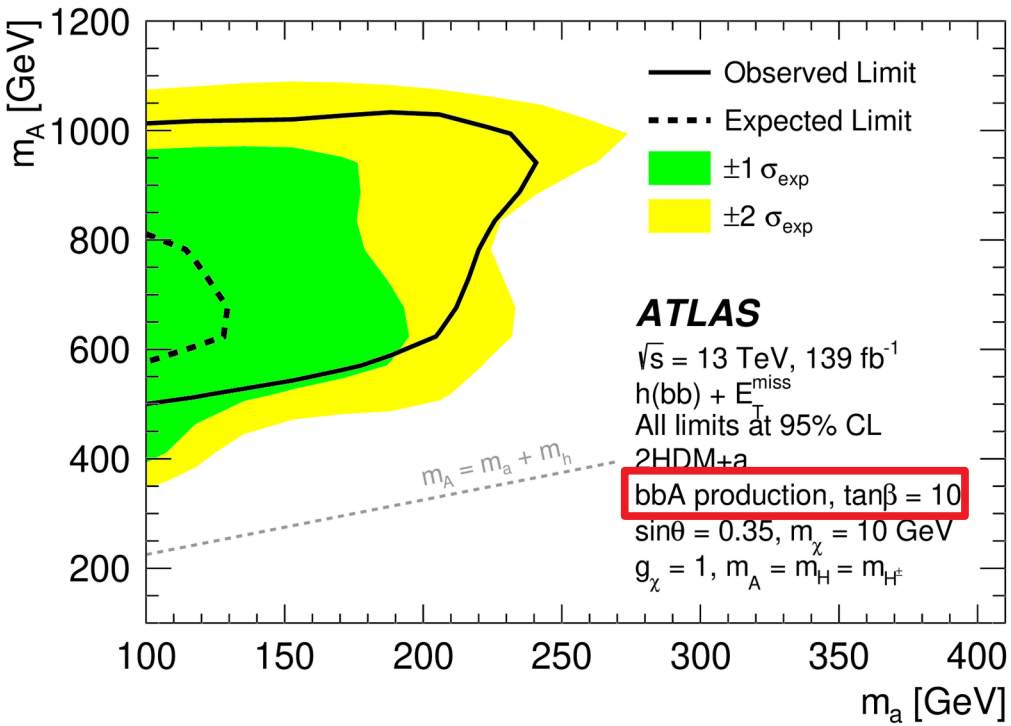


2HDM+a signature: MET+h(bb)

[JHEP 11 (2021) 209]

- Limits derived separately for gg- and bb-induced production
- Production from bb relevant at larger values of tanβ
- Significant sensitivity improvement compared to earlier result on partial Run 2 dataset (36 fb^{-1})



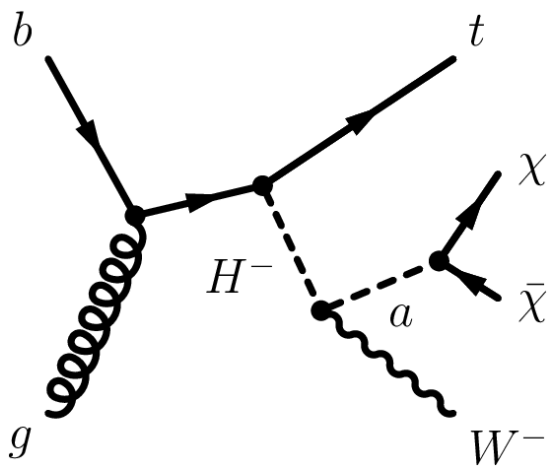


Signatures: MET+tW

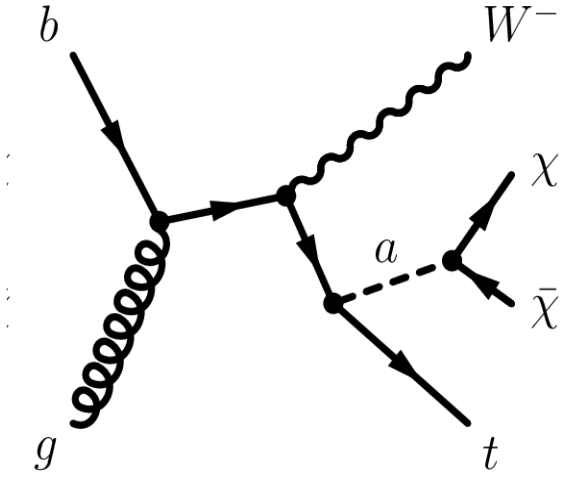
arXiv:2211.13138

> Additional: tW+MET and tj+MET production modes in 2HDM+a

Representative diagrams for tW+MET signature



Not in simplified model



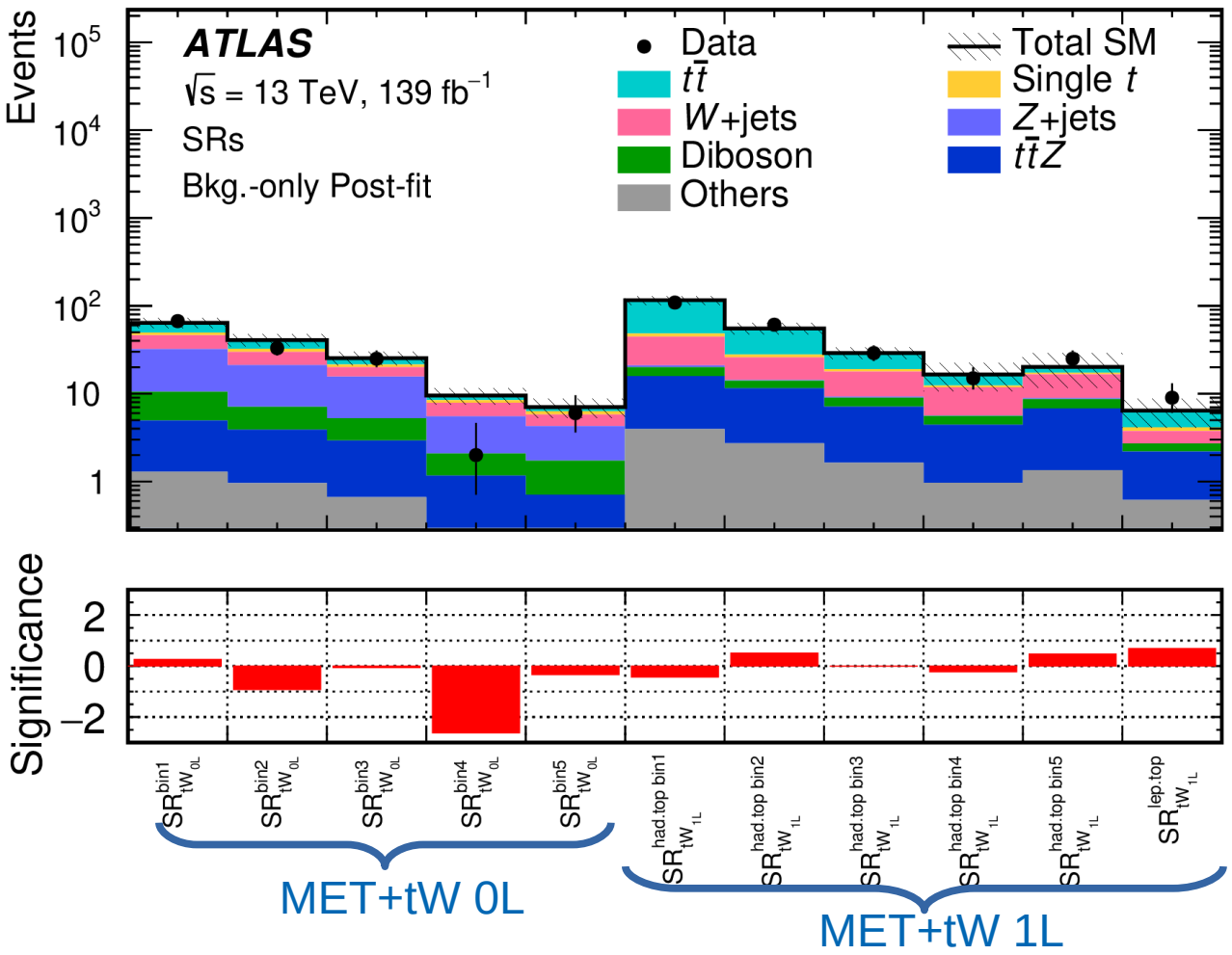
Predicted also by simplified model

Pani, Polesello:
Phys. Dark Univ.21(2018) 8-15

Signatures: MET+tW

arXiv:2211.13138

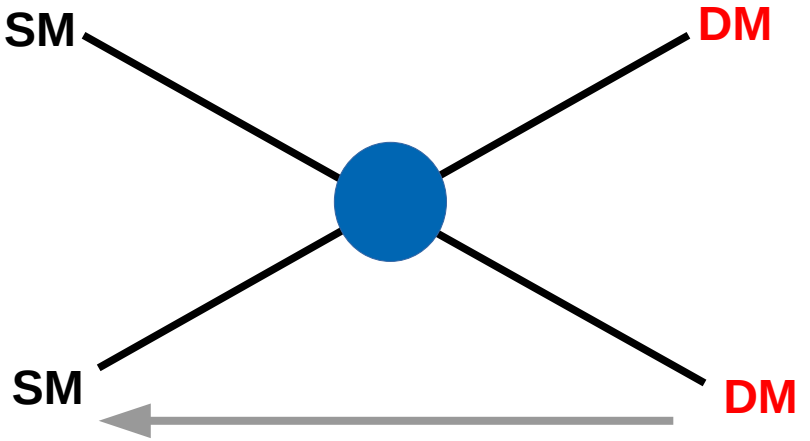
- Final states with 0 or 1 charged lepton (electron or muon), at least one b-jet and large MET
- 11 signal regions defined based on MET and angular requirements

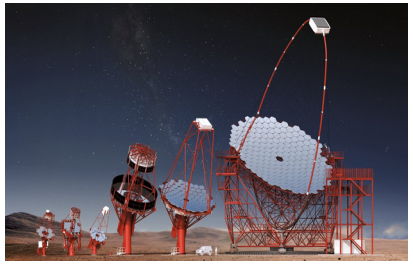


Good agreement with SM prediction

Collider production of dark matter

collider production





- Potentially sensitive to nature of DM-SM interaction
- Caveat: can only detect DM indirectly via missing transverse momentum (MET)

Transverse momentum conservation:
$p_T^{miss} = - \sum p_T^{visible}$