Combination and summary of ATLAS dark matter searches interpreted in 2HDM+a

The Fifth Workshop on Frontiers of Particle Physics

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on behalf of the ATLAS Collaboration

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Outline

1. Introduction on 2HDM+a

2. Experimental signatures

3. Statistical combination of results

4. Summary of constraints on 2HDM+a

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

CERN

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Combination and summary of ATLAS dark matter searches interpreted in a 2HDM with a pseudo-scalar mediator using 139 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data

The ATLAS Collaboration

Results from a wide range of searches targeting different experimental signatures with and without missing transverse momentum (E_T^{miss}) are used to constrain a Two-Higgs-Doublet Model (2HDM) with an additional pseudo-scalar mediating the interaction between ordinary and dark matter (2HDM+a). The analyses use up to 139 fb^{-1} of proton–proton collision data at a centre-of-mass energy $\sqrt{s} = 13$ TeV recorded with the ATLAS detector at the Large Hadron Collider during 2015–2018. The results from three of the most sensitive searches are combined statistically. These searches target signatures with large E_T^{miss} and a leptonically decaying Z boson; large E_T^{miss} and a Higgs boson decaying to bottom quarks; and production of charged Higgs bosons in final states with top and bottom quarks, respectively. Constraints are derived for several common and new benchmark scenarios in the 2HDM+a.

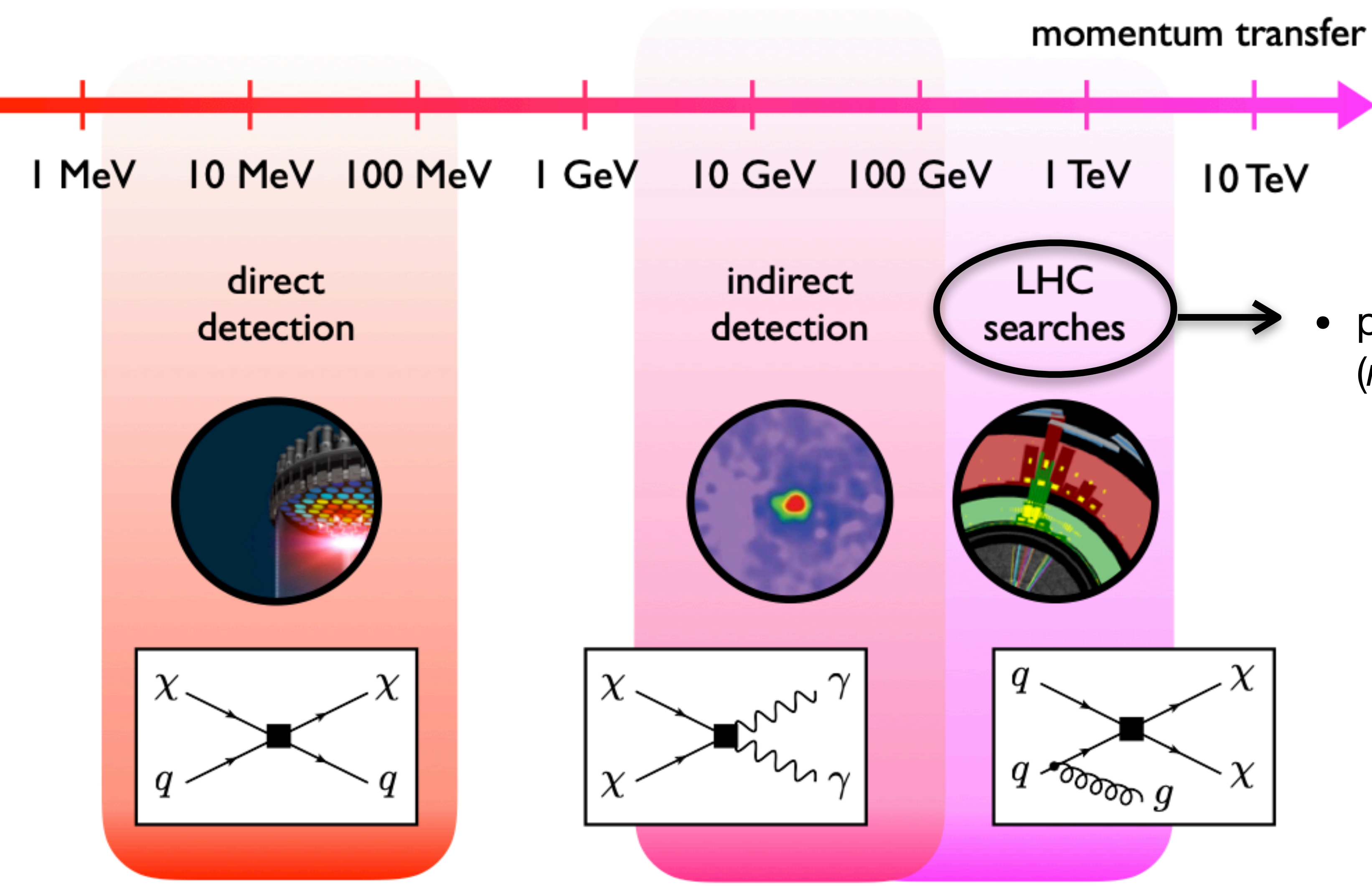
arXiv:2306.00641

accepted by Science Bulletin (1st time by ATLAS on this Chinese SCI journal)

Introduction

- **Dark Matter**: supported by many of astrophysical measurements BUT its nature and properties cannot be explained within the SM framework ⟶ strong consideration in many BSM extensions.

- Complementary probes of DM in several areas

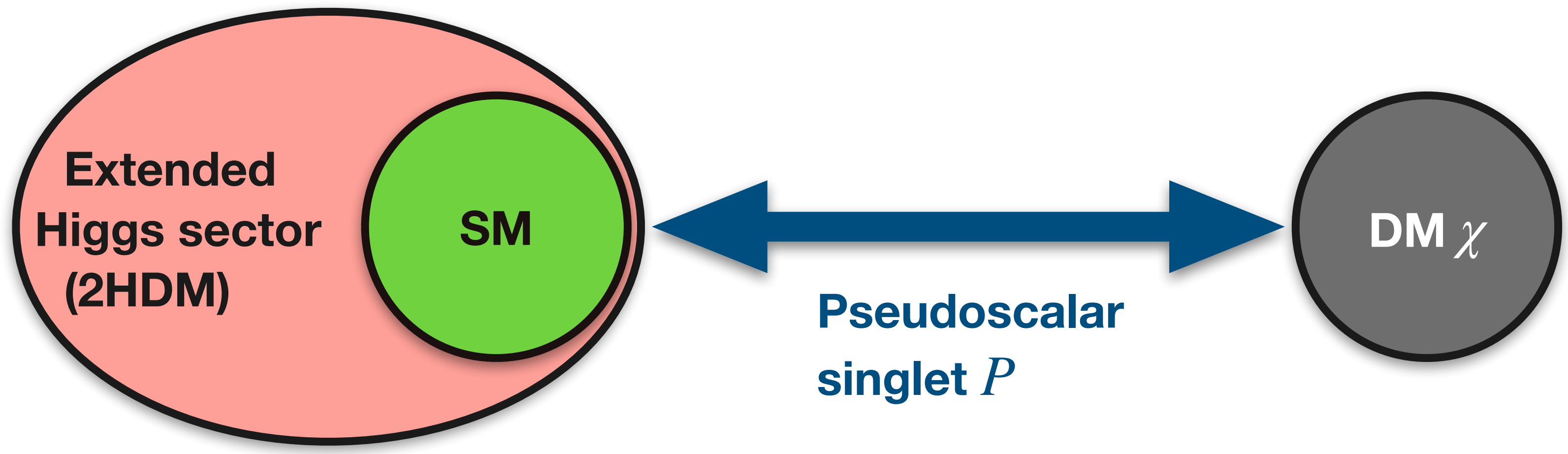


- provide access to nature of DM↔SM interaction (*mediator*), via
  - $E_{\mathrm{T}}^{\mathrm{miss}} + X$ (mono-X, mediator → invisible DM)
  - Resonance / decay product reconstruction (mediator → visible).

$E_{\mathrm{T}}^{\mathrm{miss}}$: missing transverse momentum

2HDM+a

- In this talk, DM searches interpreted in **Two-Higgs-Doublet Model plus a pseudo-scalar mediator (2HDM+a)**



2HDM+a fully defined by 14 parameters

$$v,\ M_h,\ M_A,\ M_H,\ M_{H^\pm},\ M_a,\ m_\chi$$
$$\cos(\beta-\alpha),\ \tan\beta,\ \sin\theta,$$
$$y_\chi,\ \lambda_3,\ \lambda_{P1},\ \lambda_{P_2}$$

EWK, flavour constraints and choices to simplify parameter space

5 unconstrained parameters

$m_A = m_H = m_{H^\pm}$	masses of additional heavy Higgs
m_a	mass of pseudo-scalar mediator
m_χ	DM mass
$\sin\theta$	mixing angle between CP-odd states a and A
$\tan\beta$	ratio of 2 Higgs doublet VEVs

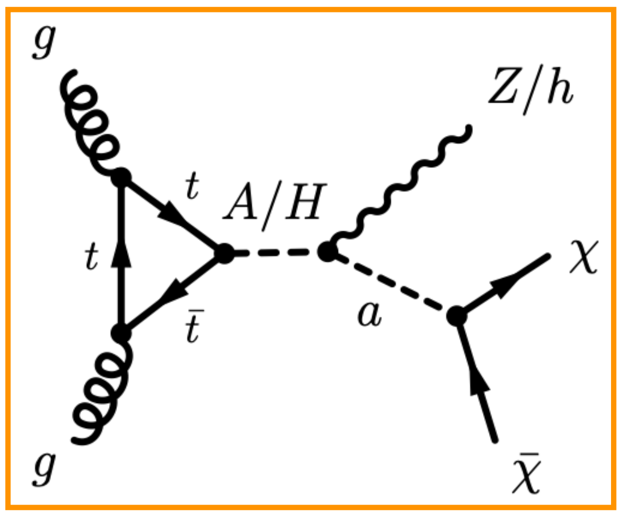
- 2HDM+a is complicated **BUT more theoretically complete**
  - 2-Higgs-Doublet extension well motivated and capable to address many shortcomings of SM.
  - pseudo-scalar mediator able to reproduce the observed relic abundance.
  - predicts broader range of collider signatures.

LHC Dark Matter Working Group
[Phys. Dark Univ. 27 (2020) 100351]
Bauer, Haisch, Kahlhoefer
[JHEP05(2017) 138]

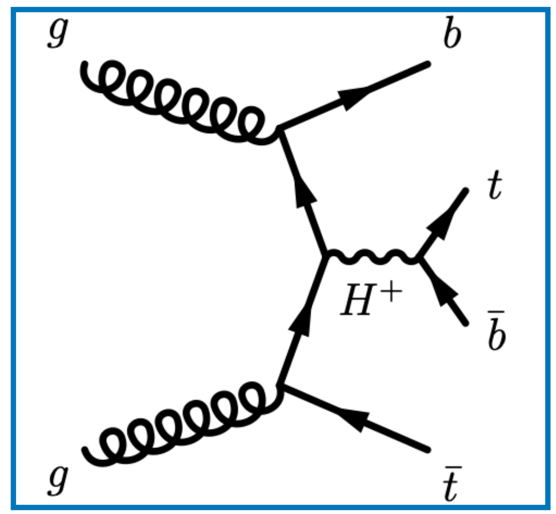
Experimental signatures

- 2HDM+a has rich phenomenology predicting wide range of signatures with both visible and invisible decays
  - resonantly production of $E_{\mathrm{T}}^{\mathrm{miss}} + Z/h$
  - additional (pseudo-)scalar bosons, e.g $tbH^{\pm}(tb)$
  - new signatures, e.g $E_{\mathrm{T}}^{\mathrm{miss}} + tW$

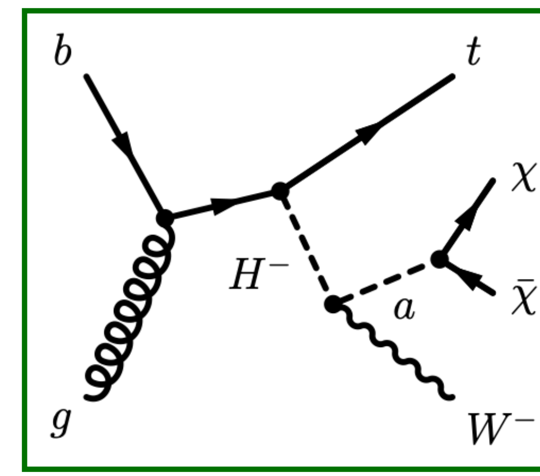
most constraining signatures among ATLAS Run 2 results



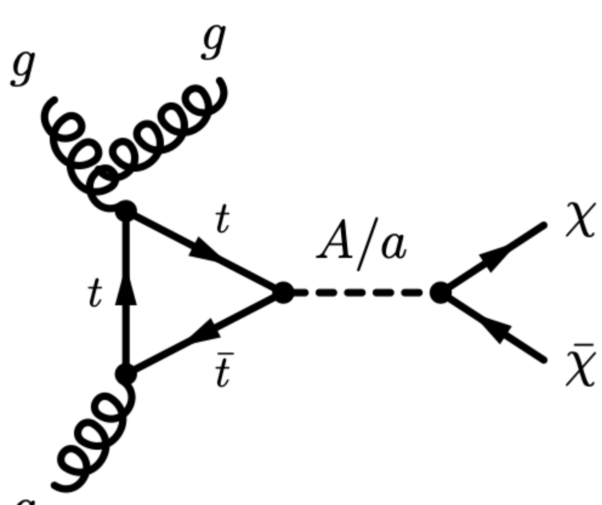
$E_{\mathrm{T}}^{\mathrm{miss}} + Z/h$



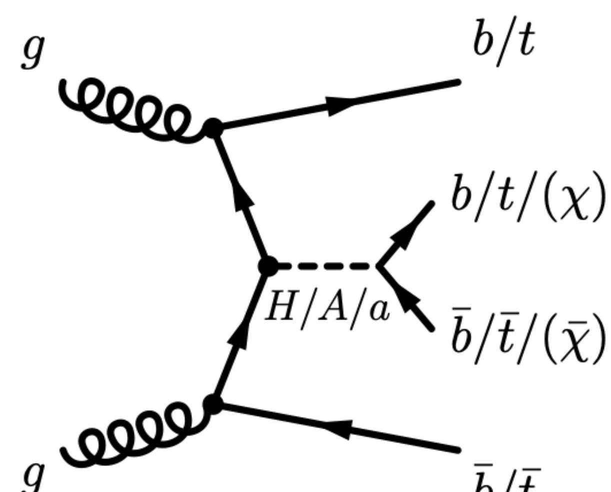
$tbH^{\pm}(tb)$



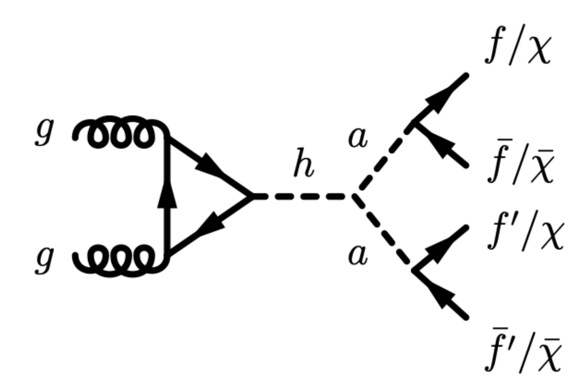
$E_{\mathrm{T}}^{\mathrm{miss}} + tW$



$E_{\mathrm{T}}^{\mathrm{miss}} + \mathrm{jet}$



$t\bar{t}t\bar{t}$

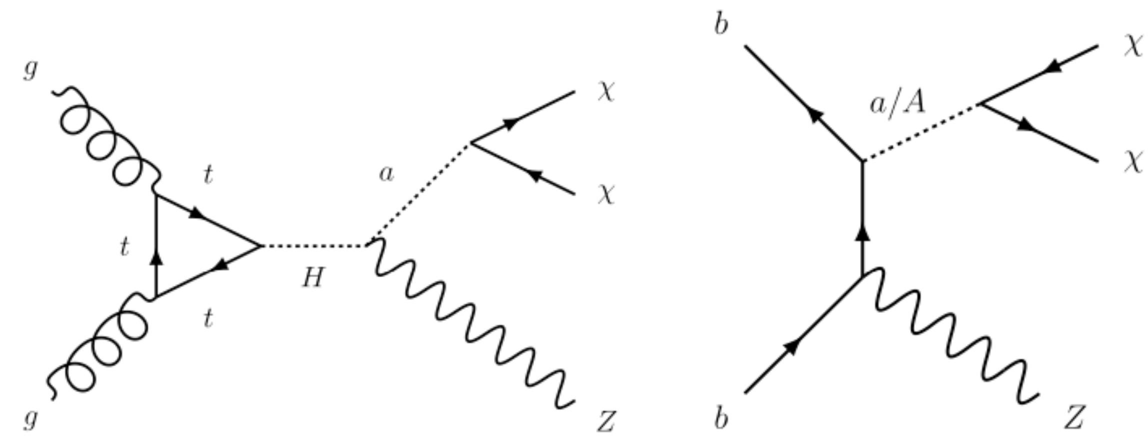


$h \to aa \to 4f$ or $h \to$ invisible

$E_{\mathrm{T}}^{\mathrm{miss}} + Z(ll)$

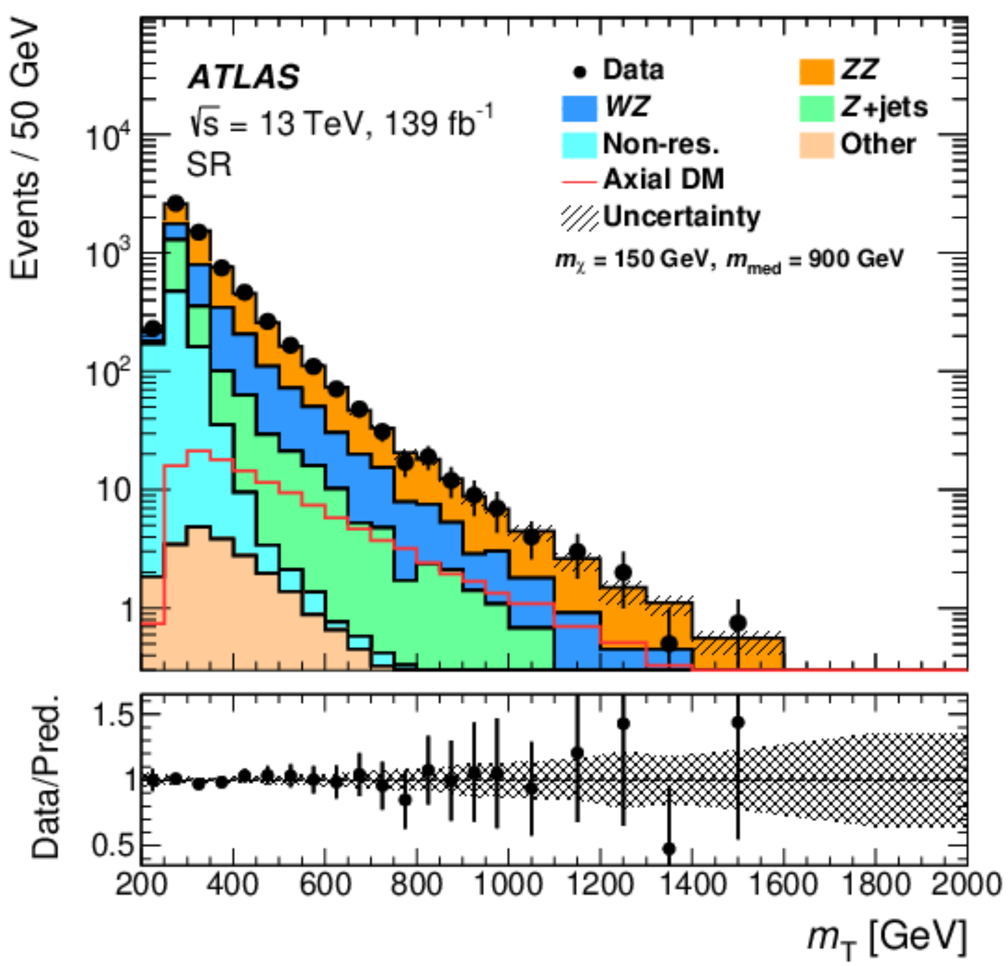
[Phys. Lett. B 829 (2022) 137066](https://doi.org/10.1016/j.physletb.2022.137066)

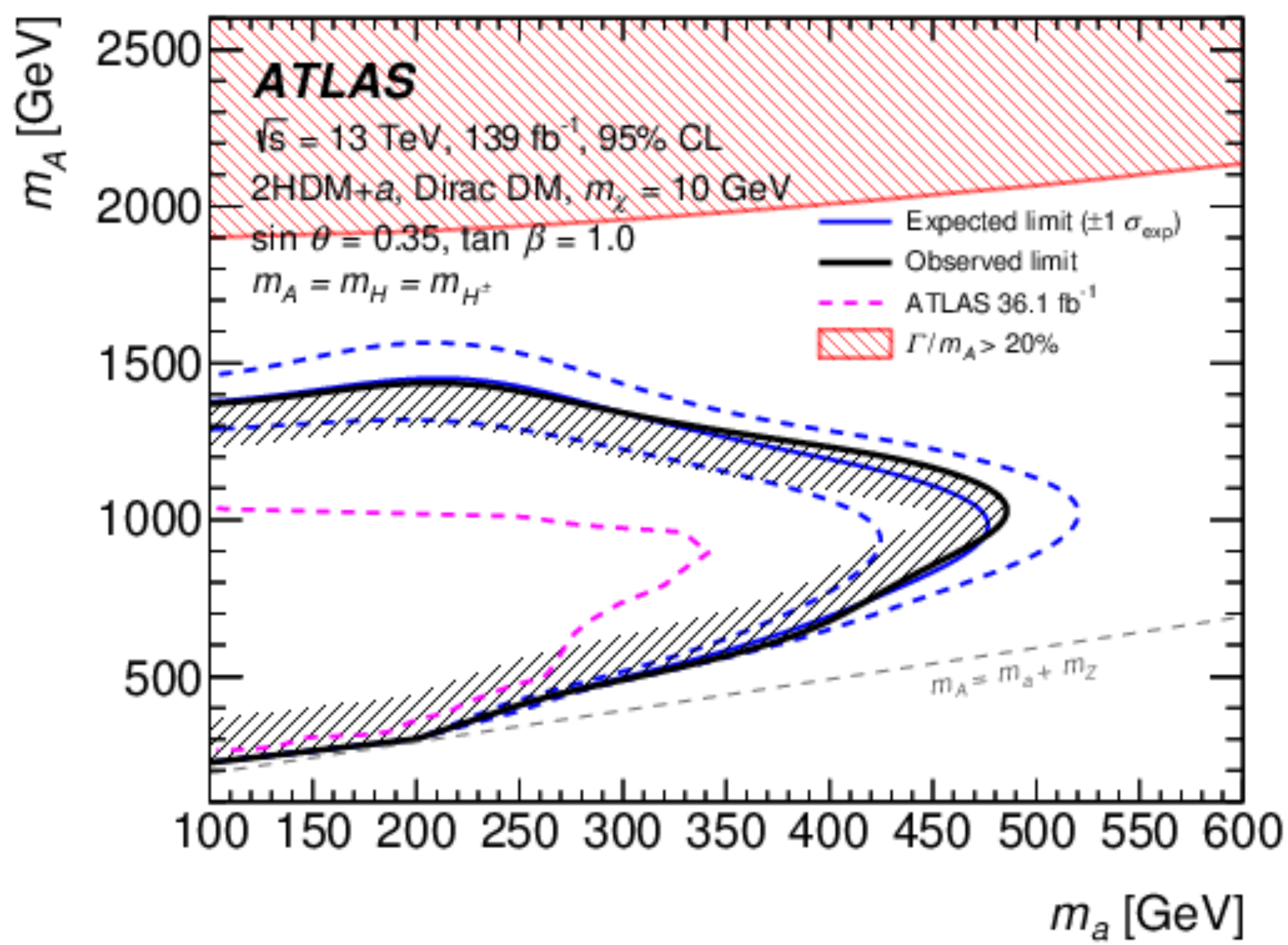
- **Event topology**:
  - Z boson recoiling against large $E_{\mathrm{T}}^{\mathrm{miss}}$
  - Presence of a pair of high-p_{T}, same flavour, oppositely charged leptons.
- SM backgrounds estimated using **dedicated Control Regions.**



gg-initiated bb-initiated

- Fit to data is performed on $m_{\mathrm{T}}^{\mathrm{lep}}$ and $E_{\mathrm{T}}^{\mathrm{miss}}$



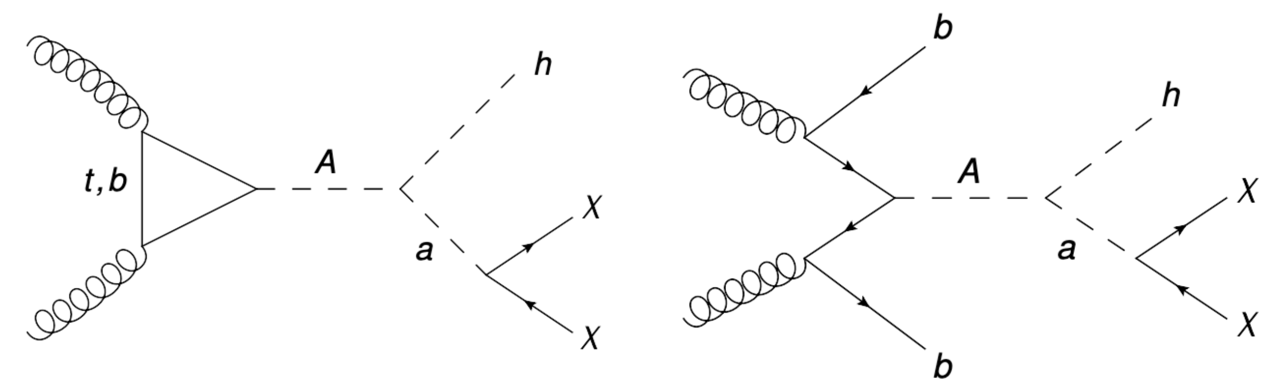


$$m_{\mathrm{T}}^{\mathrm{lep}} = \sqrt{\left[\sqrt{m_Z^2 + (p_{\mathrm{T}}^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_{\mathrm{T}}^{\mathrm{miss}})^2}\right]^2 - \left[\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}\right]^2}$$

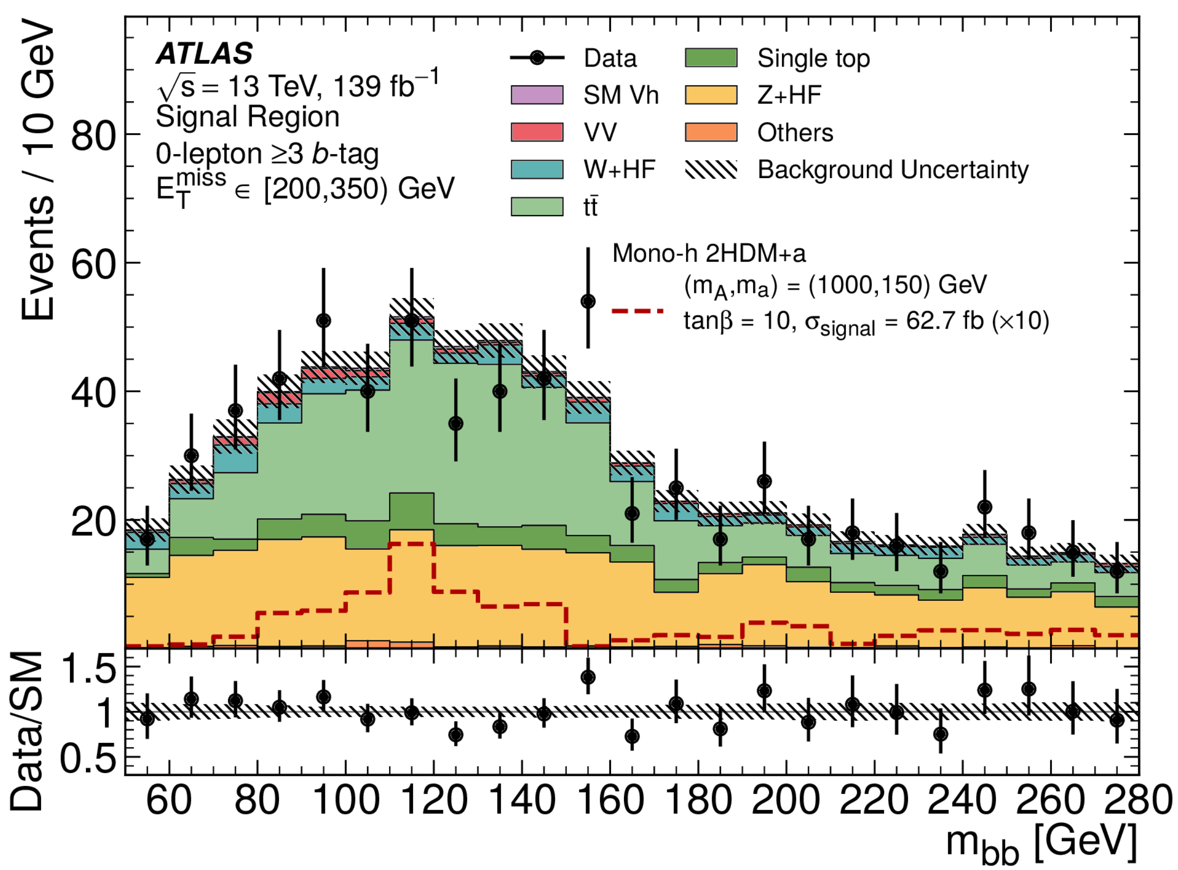
$E_T^{\mathrm{miss}} + h(bb)$

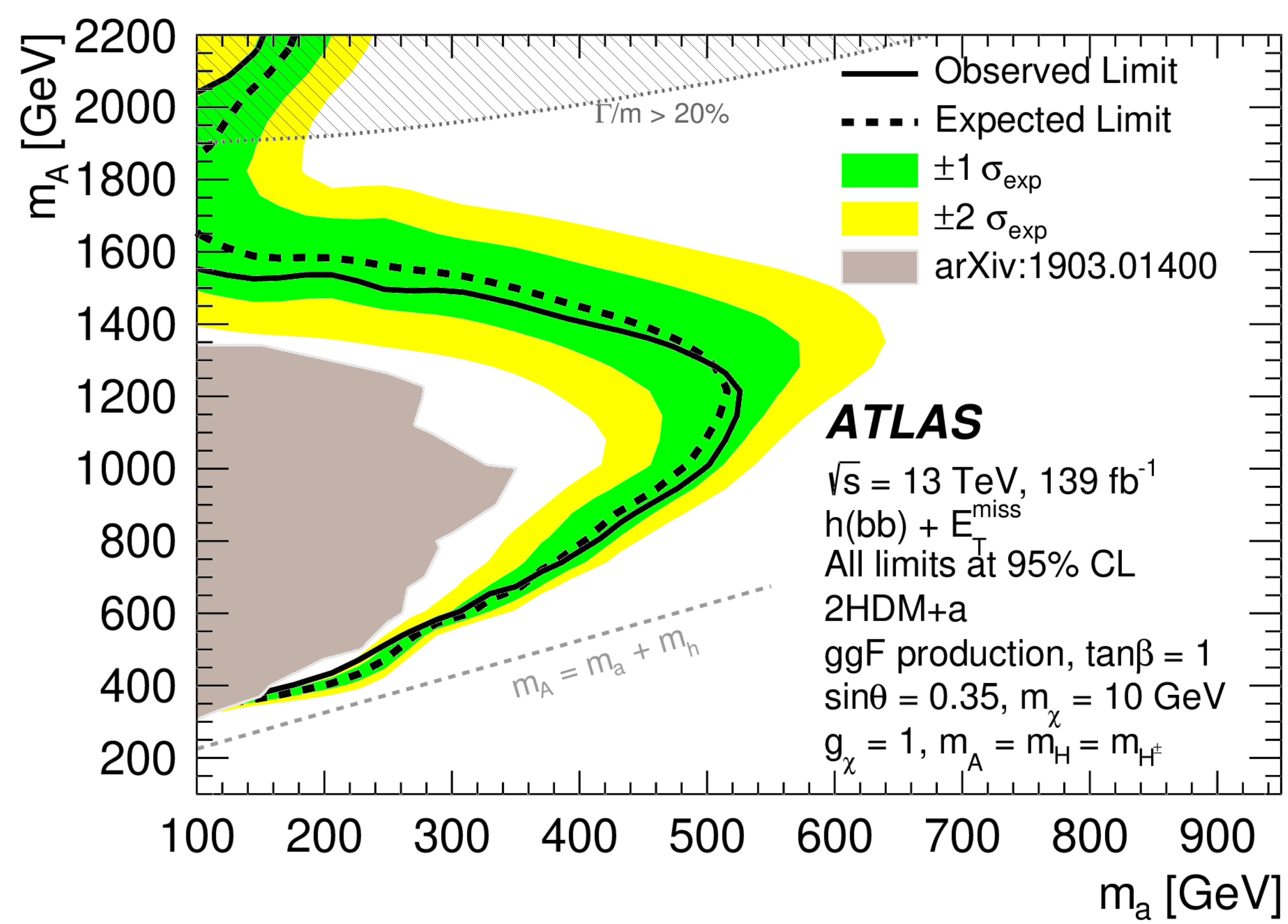
JHEP 11 (2021) 209

- **Event topology:**
  - Higgs boson recoiling against large E_T^{miss}
  - at least 2 b-jets.
  - **Higgs decay reconstructed as single large Radius jet for events with high E_T^{miss}.**
- SM backgrounds estimated from **Control Regions.**
- Fit to data on m_{bb} and event counting in CRs.



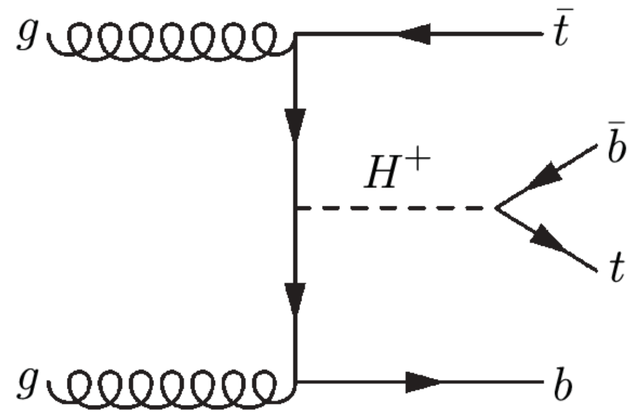
gg-induced   bb-induced



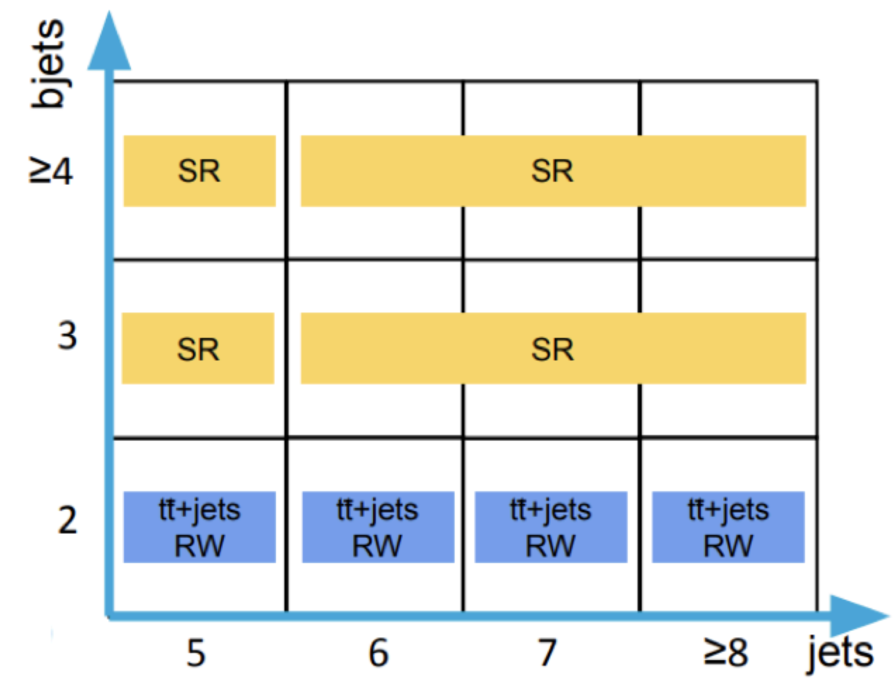


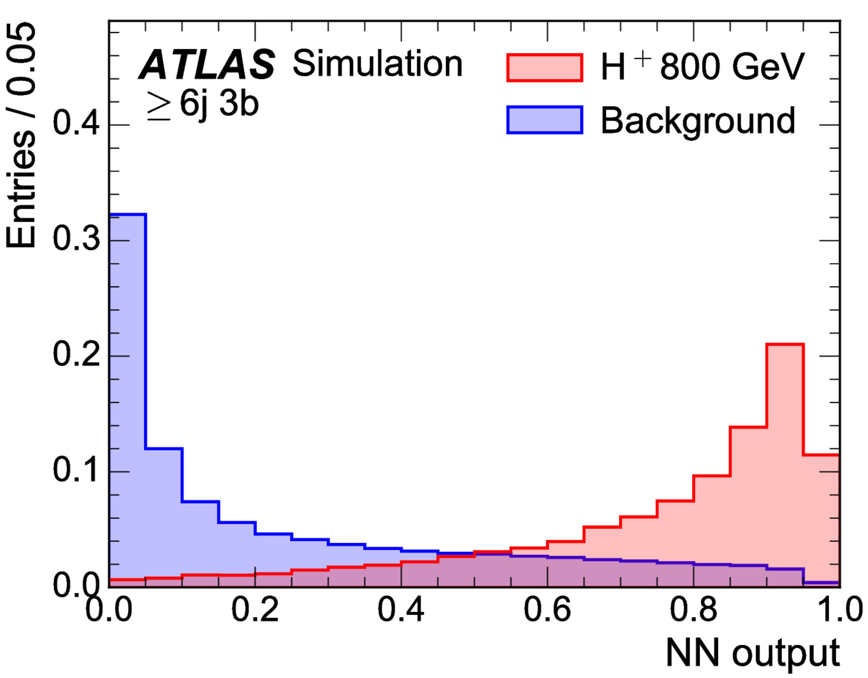
$tbH^{\pm}(tb)$

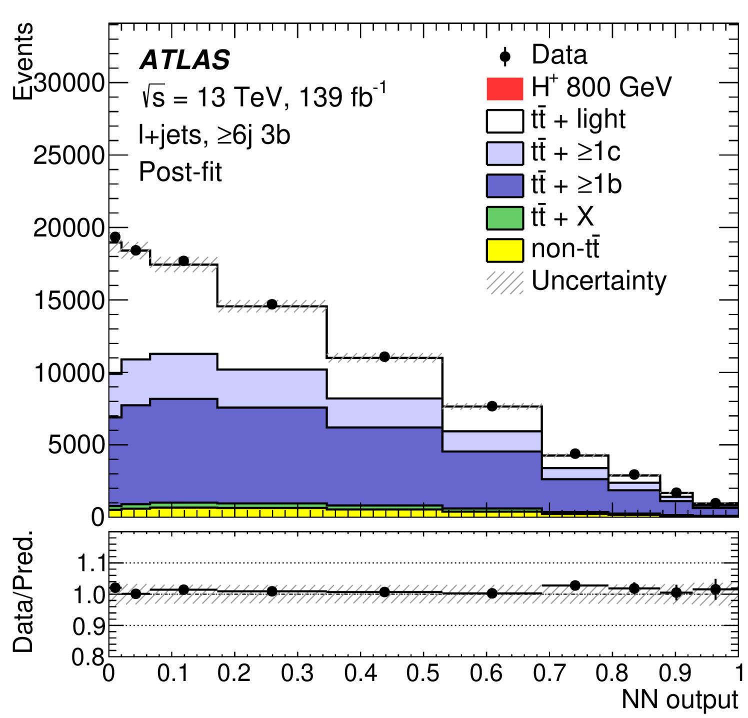
[JHEP 06 (2021) 145]

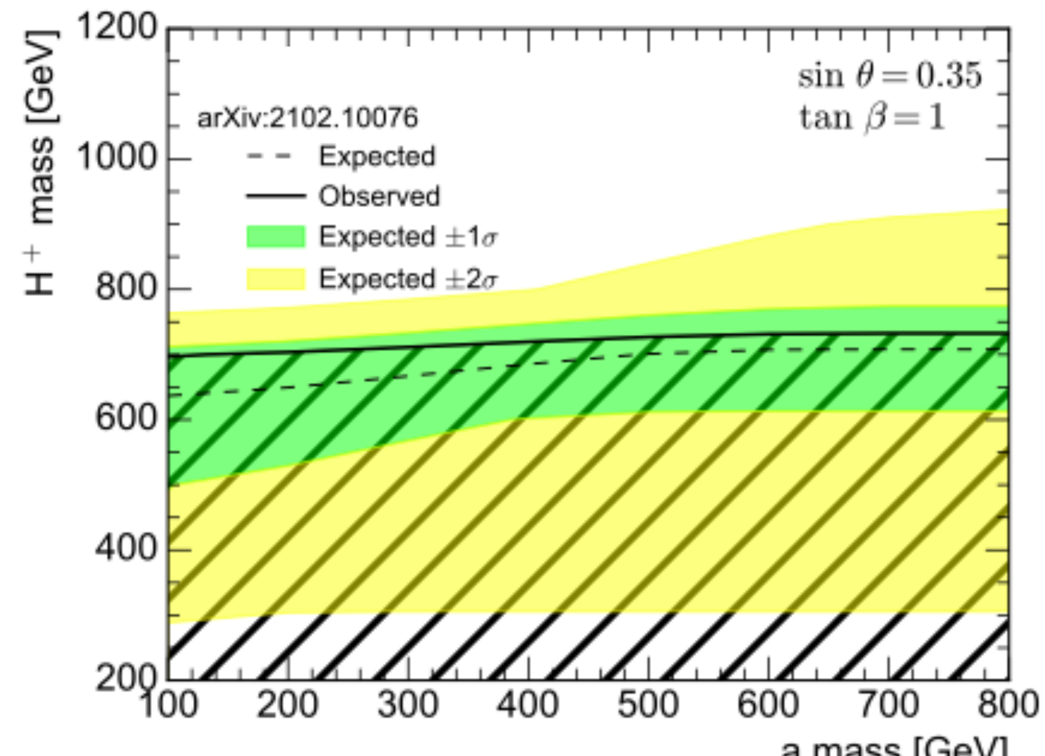


- re-interpretation of general 2HDM search by rescaling exclusion upper limits.
- **Event topology**:
  - **1lepton + $\geq$ 5j + $\geq$ 3b** to target semi-leptonic decay of one of top quarks
- **A Neural Network** used to enhance discrimination between signals and bkgs.
- **Dominant background estimated using data-driven technique.**
- Fit to data performed on NN distributions.



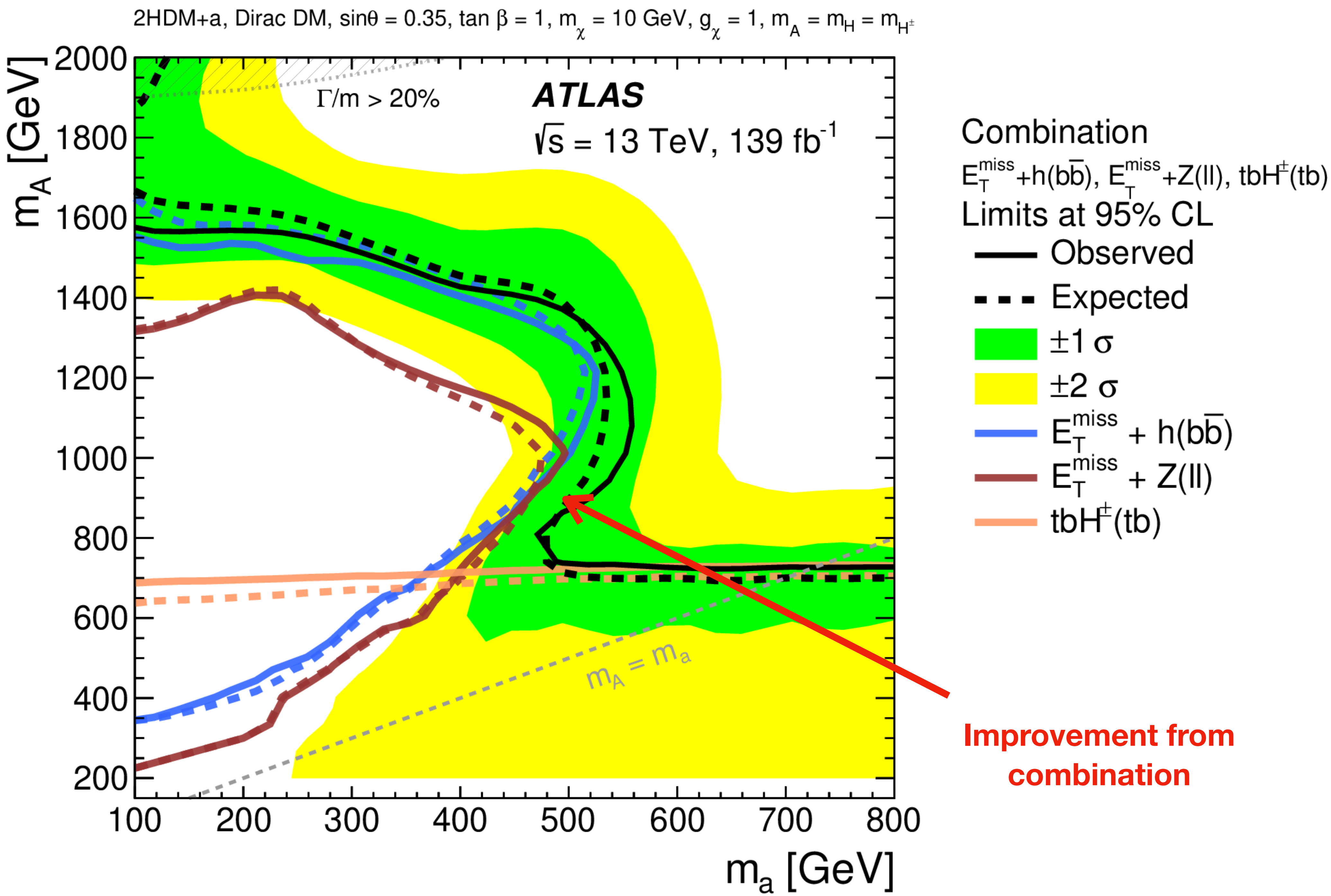






Statistical combination

- $E_{\mathrm{T}}^{\mathrm{miss}} + h(bb)$, $E_{\mathrm{T}}^{\mathrm{miss}} + Z(ll)$ and $tbH^{\pm}(tb)$: Most constraining signatures of 2HDM+a.
    - $tbH^{\pm}(tb)$ gives significant complementarity to sensitivities of $E_{\mathrm{T}}^{\mathrm{miss}} + X$
    - stat. combination of 3 channels to maximize 2HDM+a constraints in parameter space.



Summary of constraints on 2HDM+a

- constraints on 2HDM+a interpreted in **6 benchmark scenarios**.
  - highlight diverse phenomenology of 2HDM+a.
  - study the interplay and complementarities between different signatures.

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)

shows interplay due to mass hierarchies

motivated by similar scans done for general 2HDMs

illustration a-A mixing parameter effect

connection with cosmological constraints and direct/indirect searches

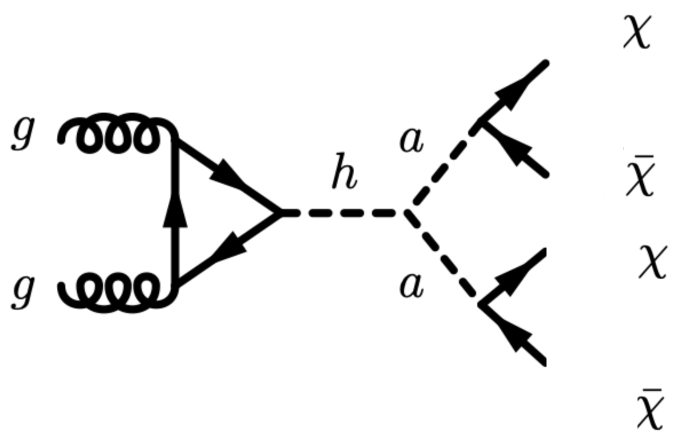
showed for the 1st time

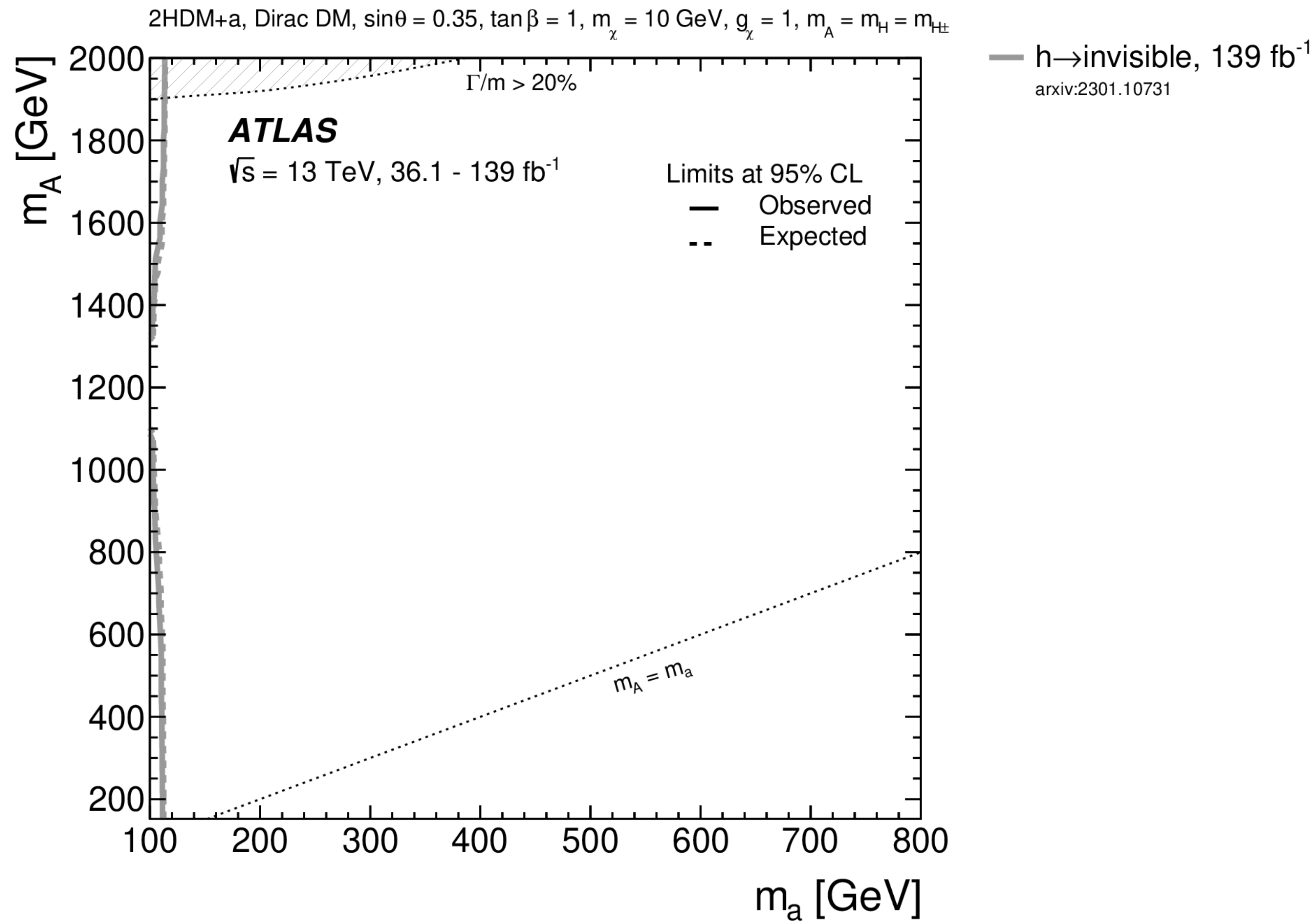
m_χ set to 10 GeV in all scenarios, except 5 and 6

Summary of constraints on 2HDM+a

benchmark: $\sin\theta = 0.35$, $\tan\beta = 1$, m_a-m_A scan

- $h \to$ invisible constrains very low m_a.

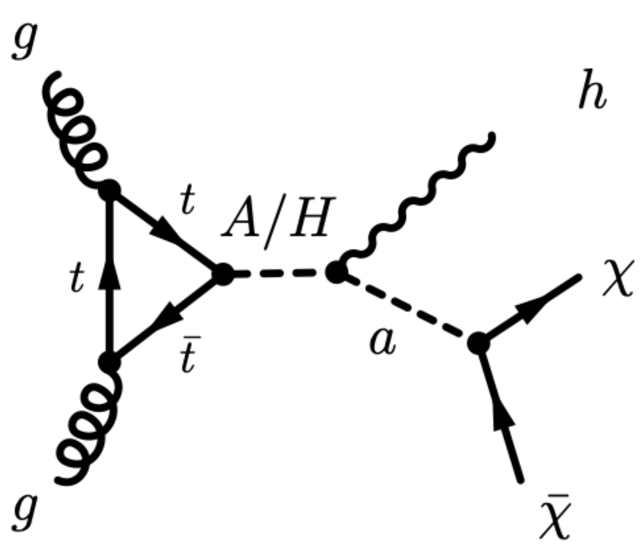


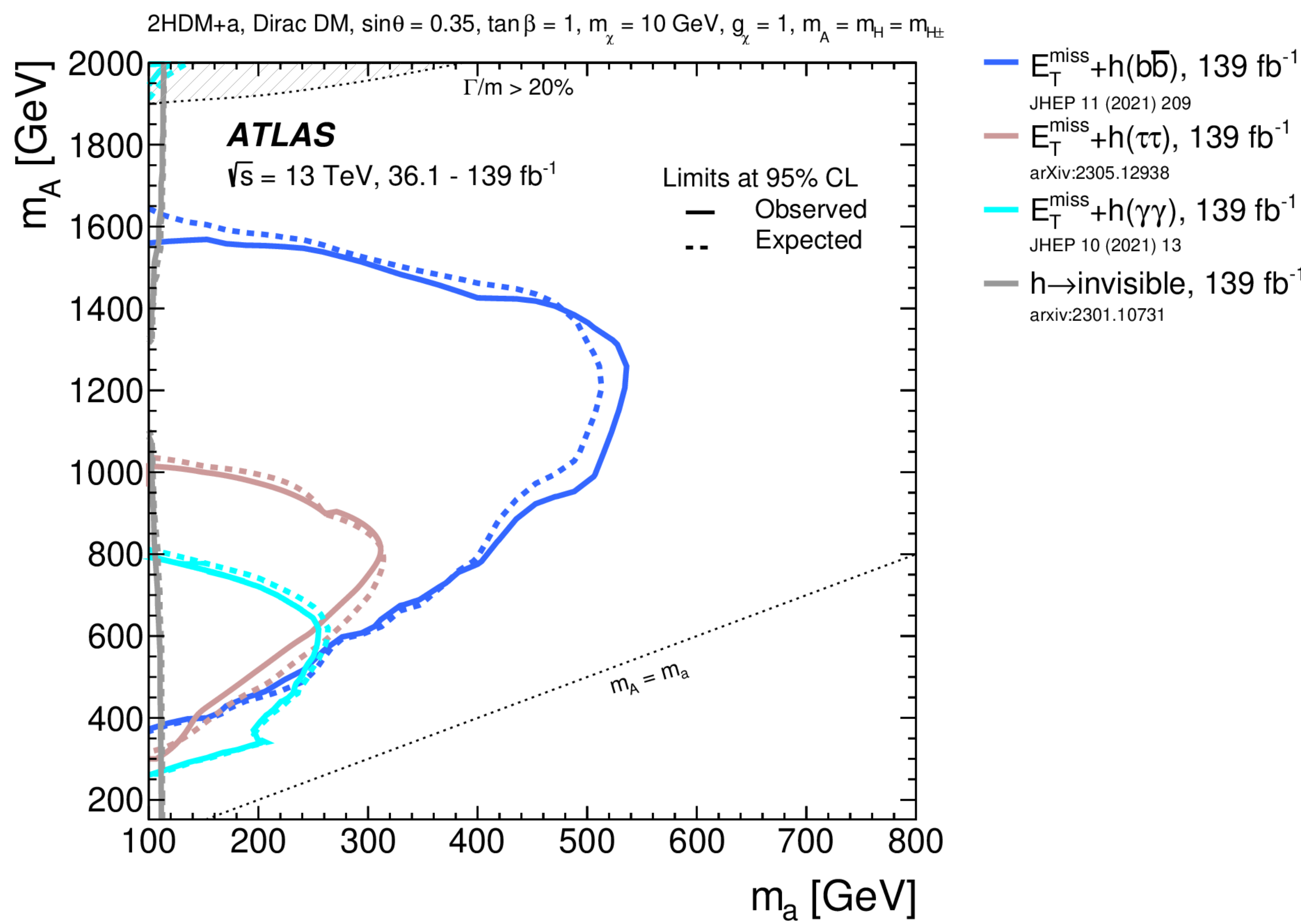


Summary of constraints on 2HDM+a

benchmark: $\sin\theta = 0.35$, $\tan\beta = 1$, m_a-m_A scan

- constraints from $E_{\mathrm{T}}^{\mathrm{miss}} + h$ signatures: similar m_A-m_a dependence, with $h \to bb$ most sensitive.

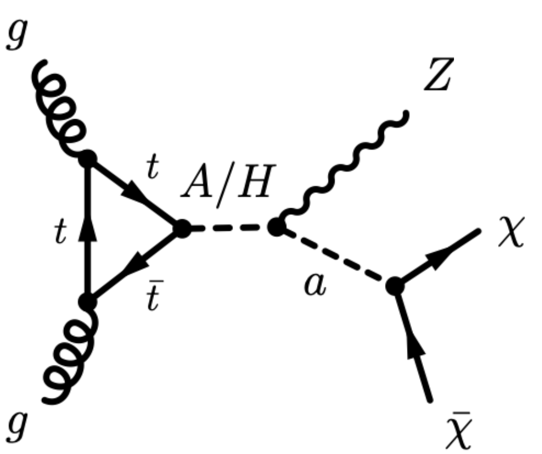


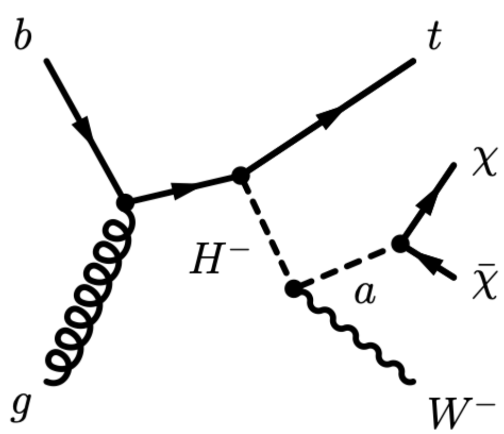


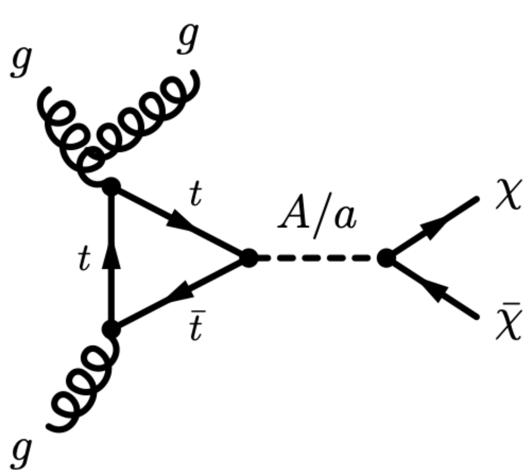
Summary of constraints on 2HDM+a

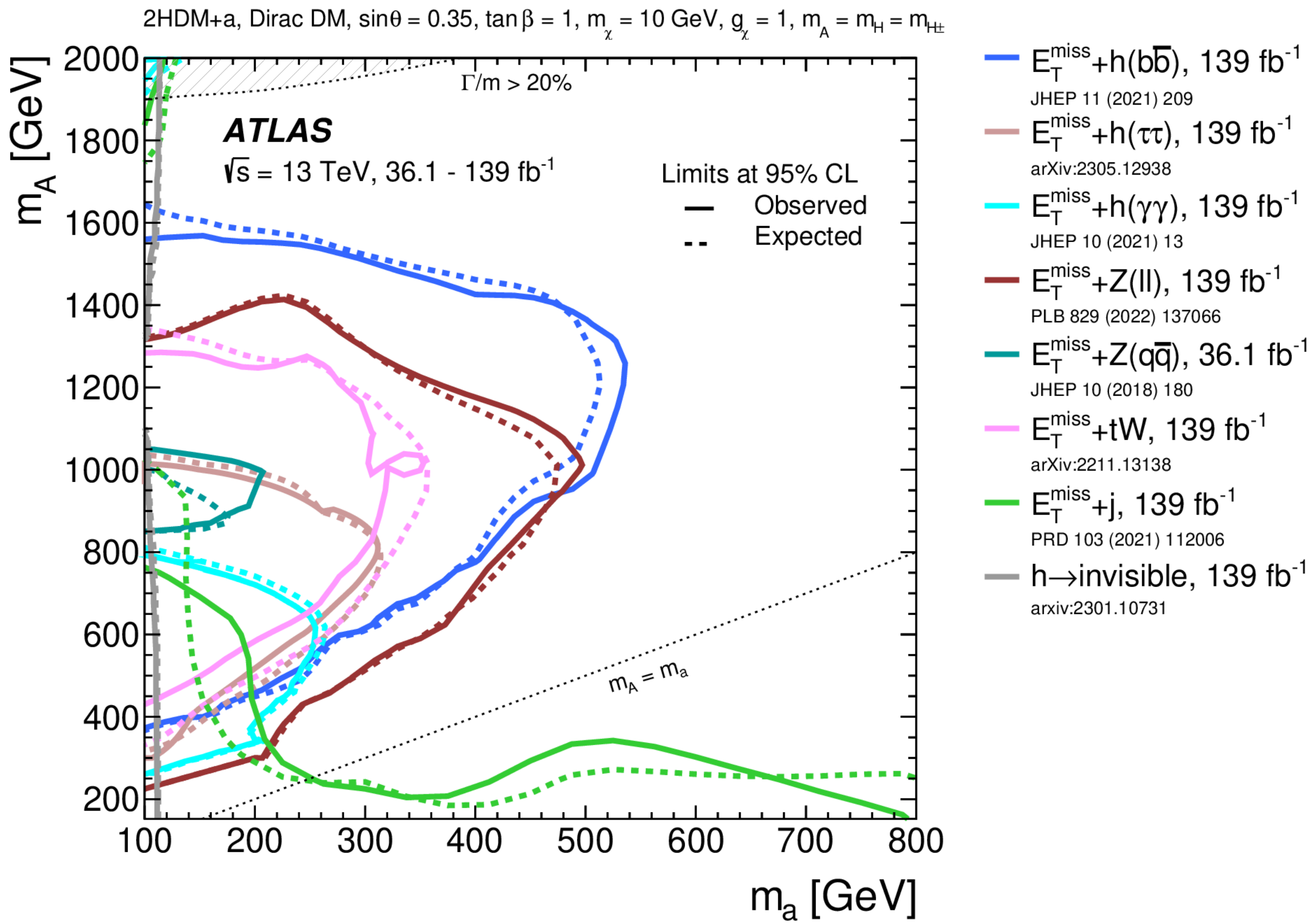
benchmark: $\sin\theta = 0.35$, $\tan\beta = 1$, m_a-m_A scan

- $E_{\mathrm{T}}^{\mathrm{miss}} + Z$ and $E_{\mathrm{T}}^{\mathrm{miss}} + tW$ are similar while $E_{\mathrm{T}}^{\mathrm{miss}}$ + jet notably different.





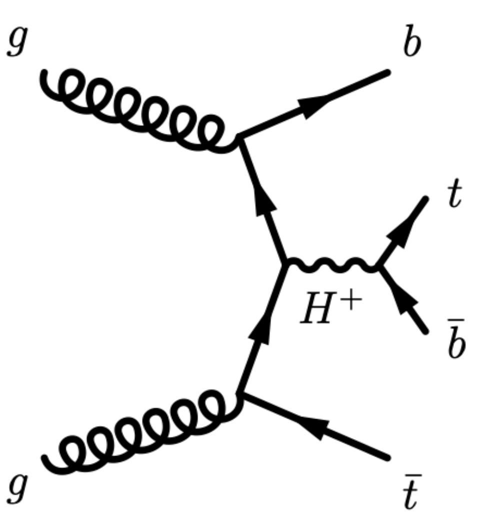


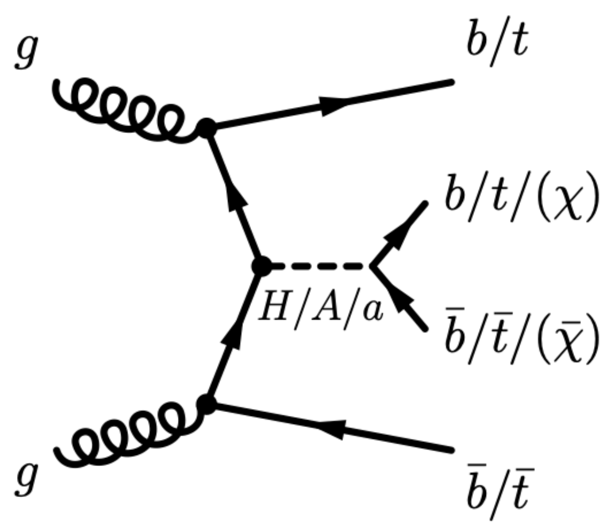


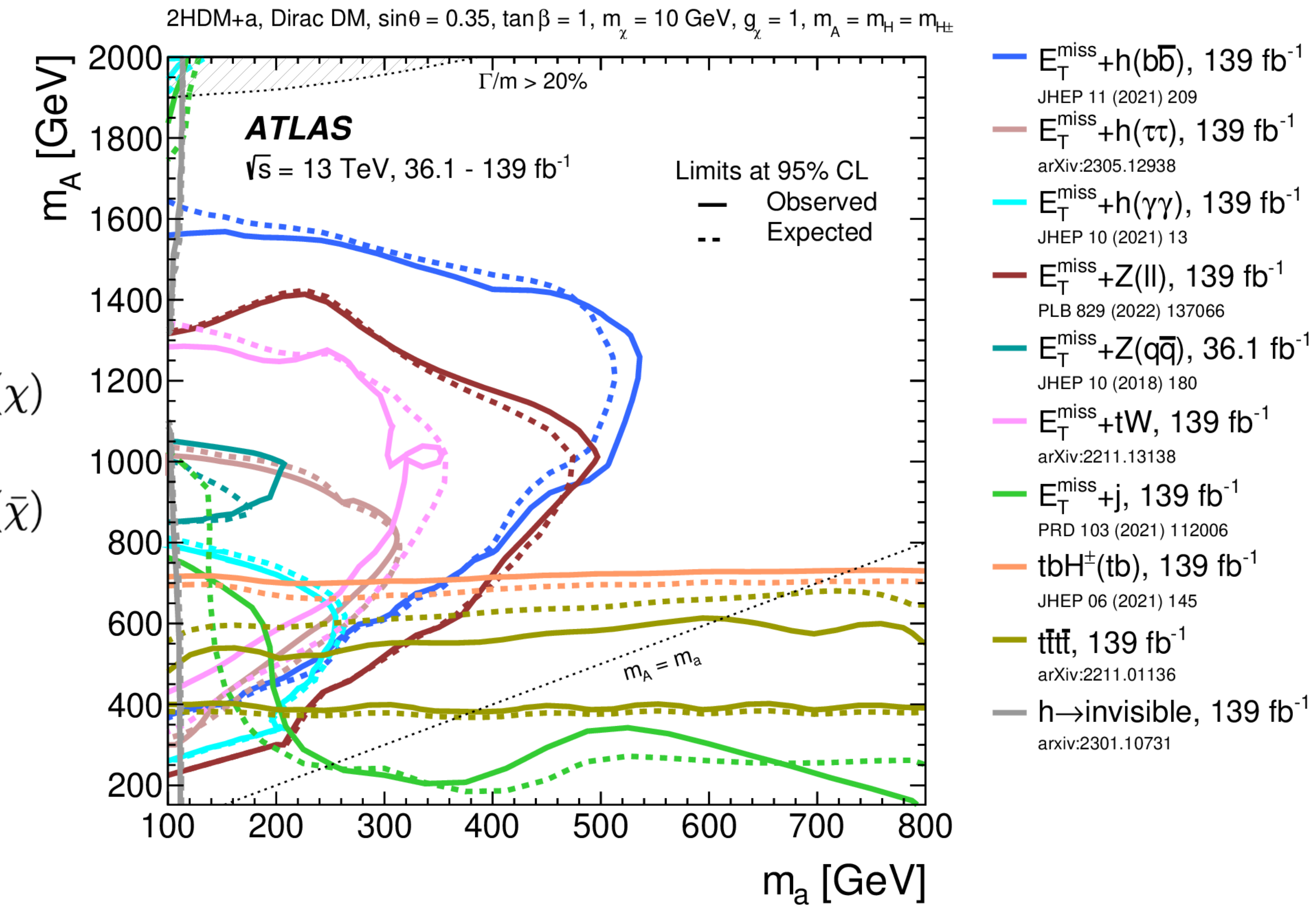
Summary of constraints on 2HDM+a

benchmark: $\sin\theta = 0.35$, $\tan\beta = 1$, m_a-m_A scan

- Complementary constraints from searches not targeting DM.



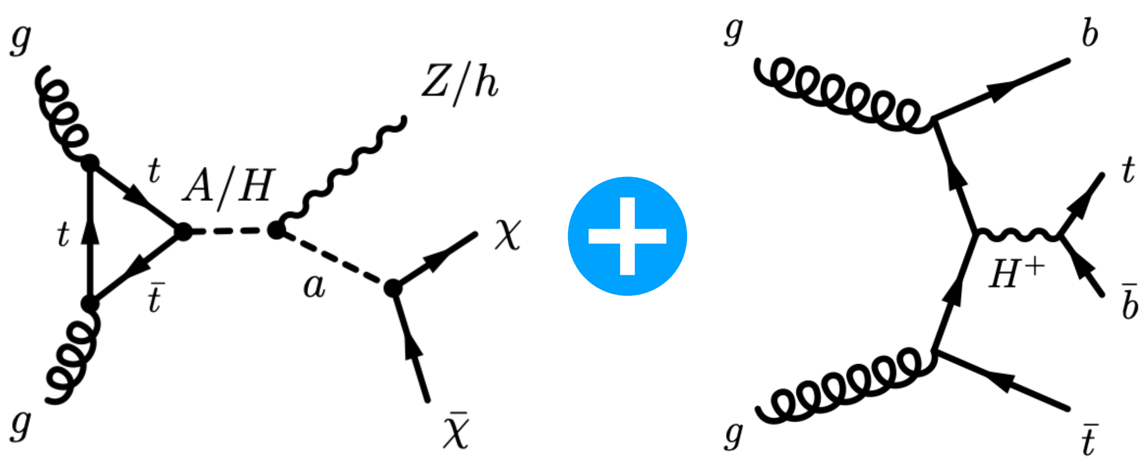


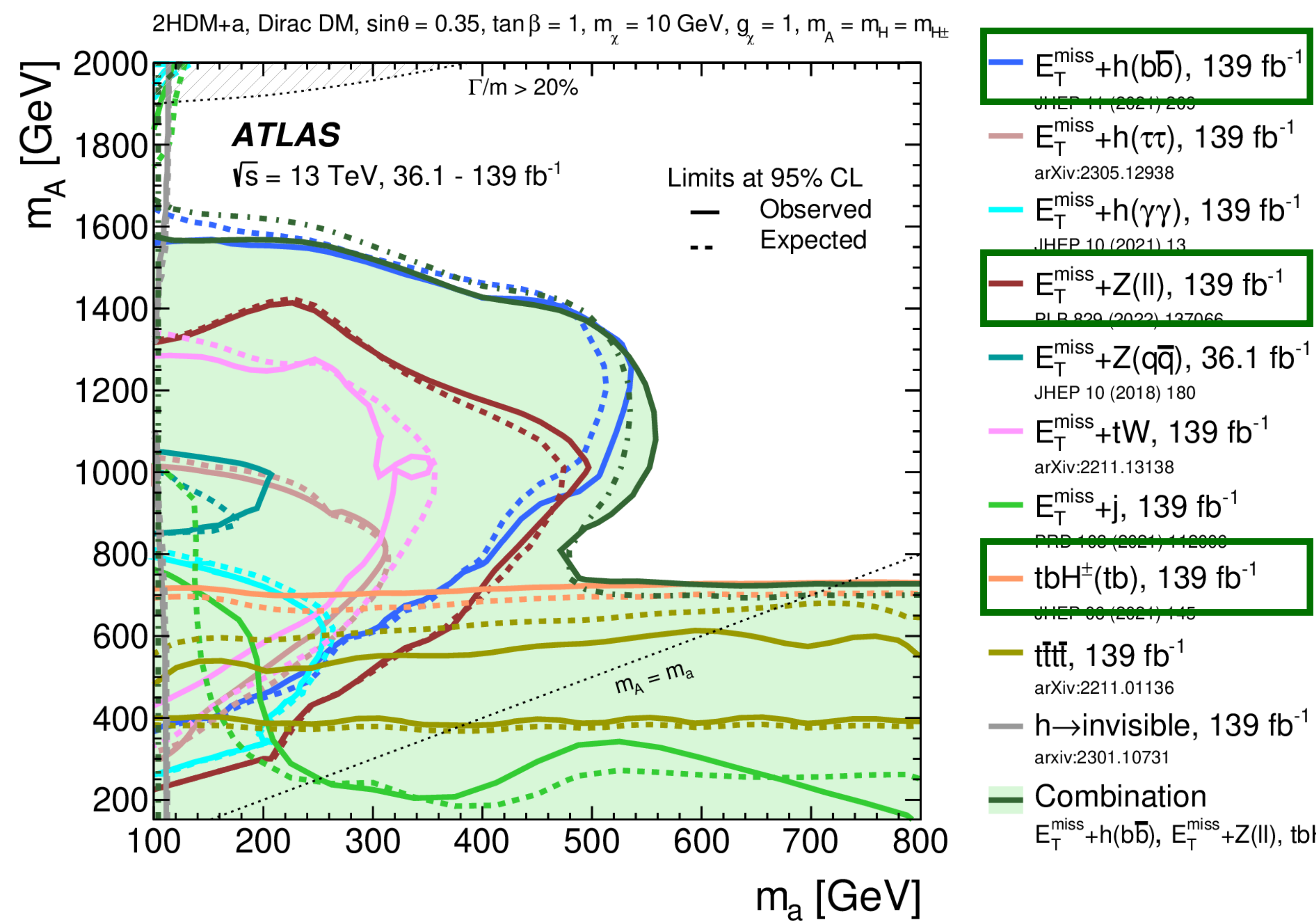


Summary of constraints on 2HDM+a

benchmark: $\sin\theta = 0.35$, $\tan\beta = 1$, m_a-m_A scan

- Sensitivity of 2HDM+a driven by the combination.



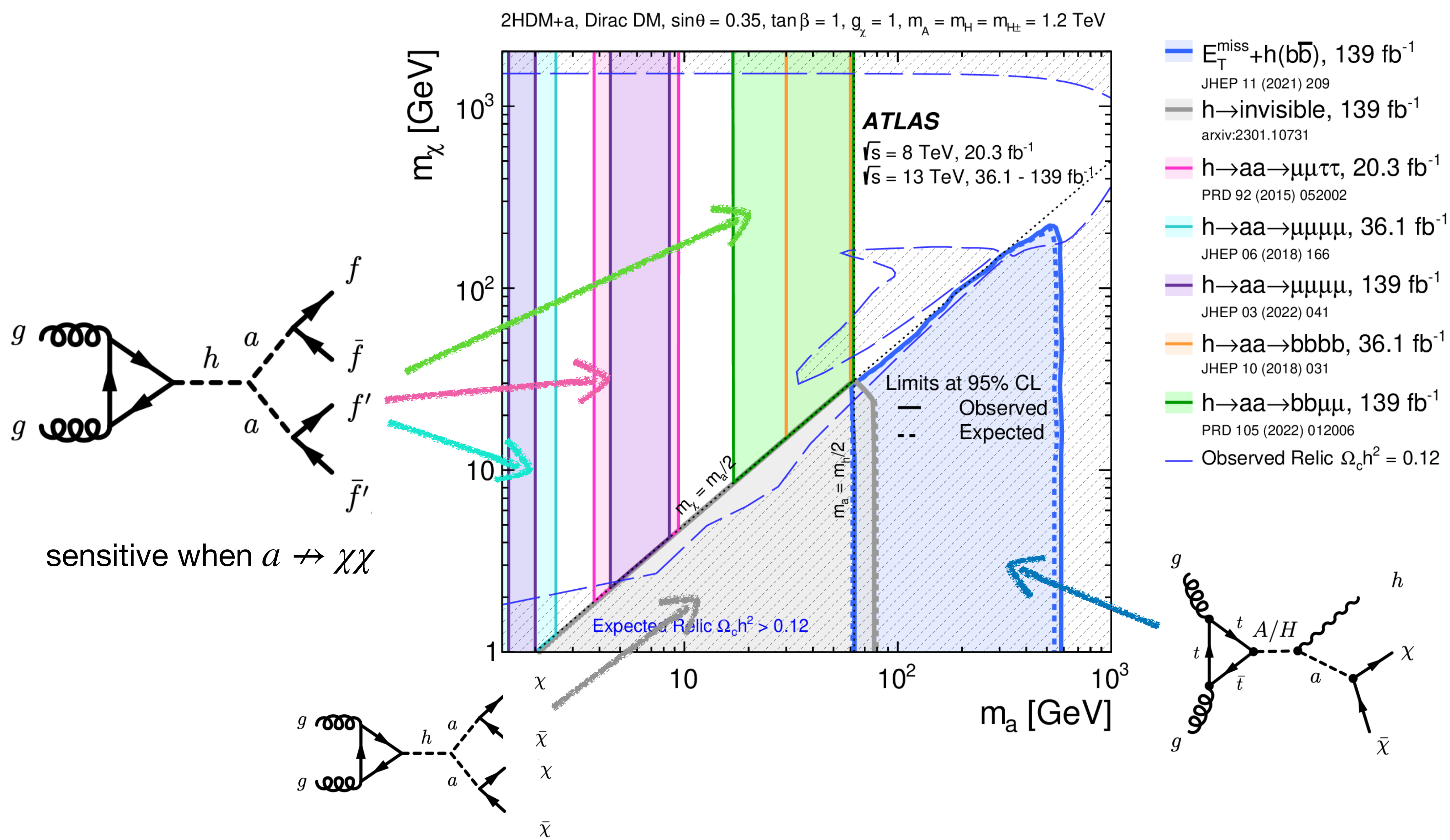


Most comprehensive set of constraints on 2HDM+a to date

Summary of constraints on 2HDM+a

benchmark: $\sin\theta = 0.35$, $\tan\beta = 1$, $m_A = 1.2$ TeV, m_a-m_χ scan

- New interpretation in m_a-m_χ plane:
  - Searches for SM Higgs decaying to 4 fermions via aa constrain previously unprobed region of 2HDM+a.
  - Complementarity to $h \to$ invisible and $E_T^{\rm miss} + h(bb)$ searches.



Conclusion

- The results in this paper represent the most comprehensive set of constraints on the 2HDM+a obtained by the ATLAS Collaboration to date. We have determined the sensitivity of many relevant signatures, determining the exclusions of these channels for the first time.

- Statistical combination of $E_T^{miss} + Z(ll)$, $E_T^{miss} + h(bb)$ and $tbH^{\pm}(tb)$ extends the sensitivity to the 2HDM+a compared to the sensitivities derived from the individual searches across different regions of the 2HDM+a parameter space

- For the first time the results of searches targeting $h \rightarrow aa \rightarrow 4f$ are used to constrain a part of previously unprobed 2HDM+a parameter space.

Thank you for your attention!!!

Backup

2HDM+a

- Coupling of pseudo scalar P to the dark Dirac fermion χ

$$\mathcal{L}_\chi = -iy_\chi P \bar{\chi}\gamma_5\chi\,,$$

- Yukawa couplings of Higgs doublets to SM fermions

$$\mathcal{L}_Y = -\sum_{i=1,2}\left(\bar{Q}Y_u^i\tilde{H}_i u_R + \bar{Q}Y_d^i H_i d_R + \bar{L}Y_\ell^i H_i \ell_R + \text{h.c.}\right)\,.$$

- Most general scalar potential of two Higgs doublets

$$V = V_H + V_{HP} + V_P\,,$$

$$\begin{aligned} V_H = {} & \mu_1 H_1^\dagger H_1 + \mu_2 H_2^\dagger H_2 + \left(\mu_3 H_1^\dagger H_2 + \text{h.c.}\right) + \lambda_1\left(H_1^\dagger H_1\right)^2 + \lambda_2\left(H_2^\dagger H_2\right)^2 \\ & + \lambda_3\left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4\left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) + \left[\lambda_5\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]\,, \end{aligned}$$

$$V_{HP} = P\left(ib_P H_1^\dagger H_2 + \text{h.c.}\right) + P^2\left(\lambda_{P1}H_1^\dagger H_1 + \lambda_{P2}H_2^\dagger H_2\right)\,,$$

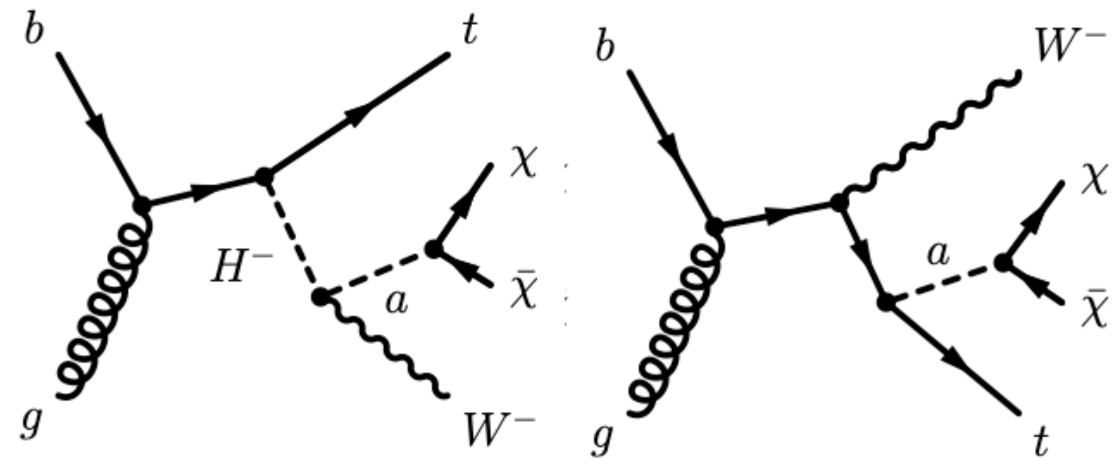
$$V_P = \frac{1}{2}m_P^2 P^2\,.$$

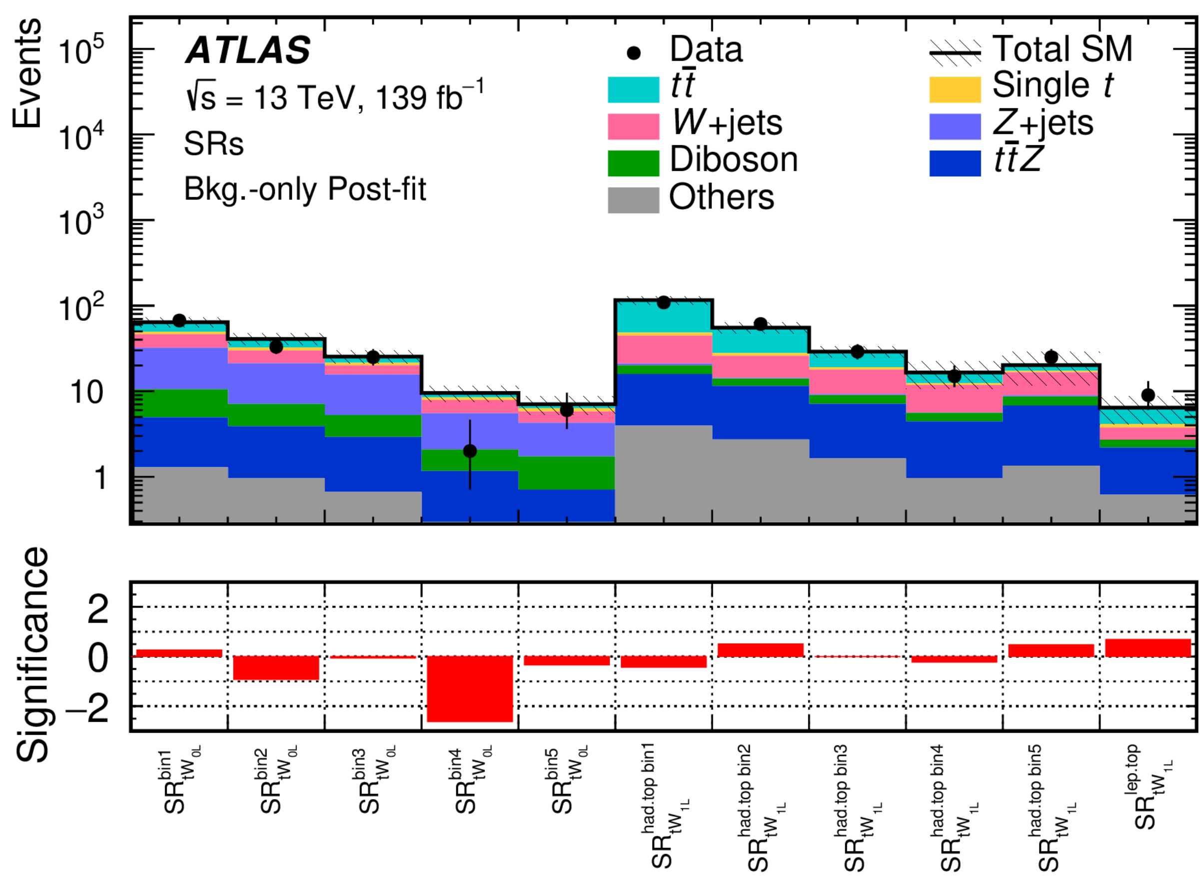
$E_{\mathrm{T}}^{\mathrm{miss}} + tW$ signature

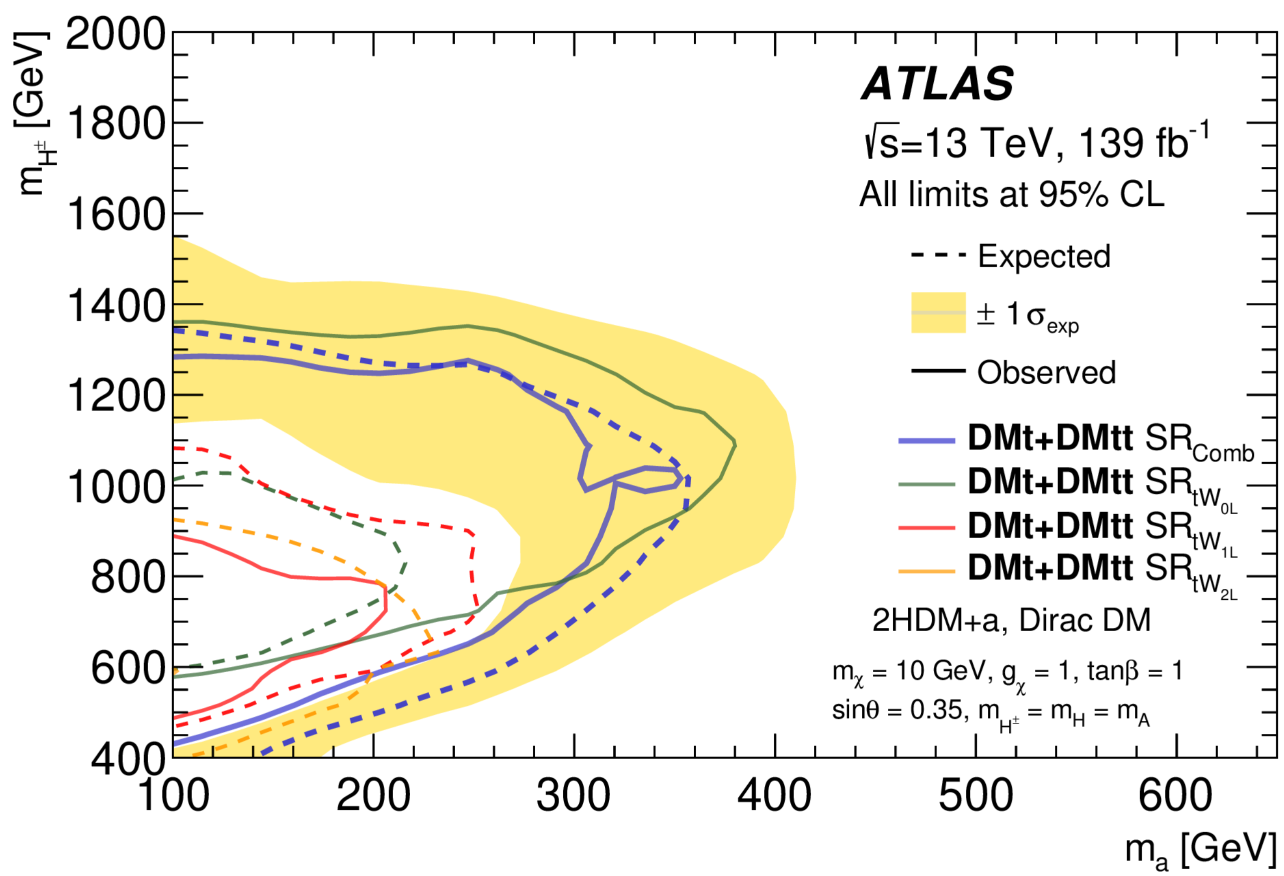
(0- and 1-lepton) Eur. Phys. J. C 83 (2023) 603

(2-lepton) Eur. Phys. J. C 81 (2021) 860

- optimised specifically for 2HDM+a and particularly sensitive to on-shell $H^{\pm} \to W^{\pm}a(\chi\bar{\chi})$
- Final interpretations
  - include both 2HDM+a $E_{\mathrm{T}}^{\mathrm{miss}} + t\bar{t}$ and $E_{\mathrm{T}}^{\mathrm{miss}} + tW$ signal contributions.
  - with combination of all three 0-, 1-, and 2-lepton channels.







HLRS searches

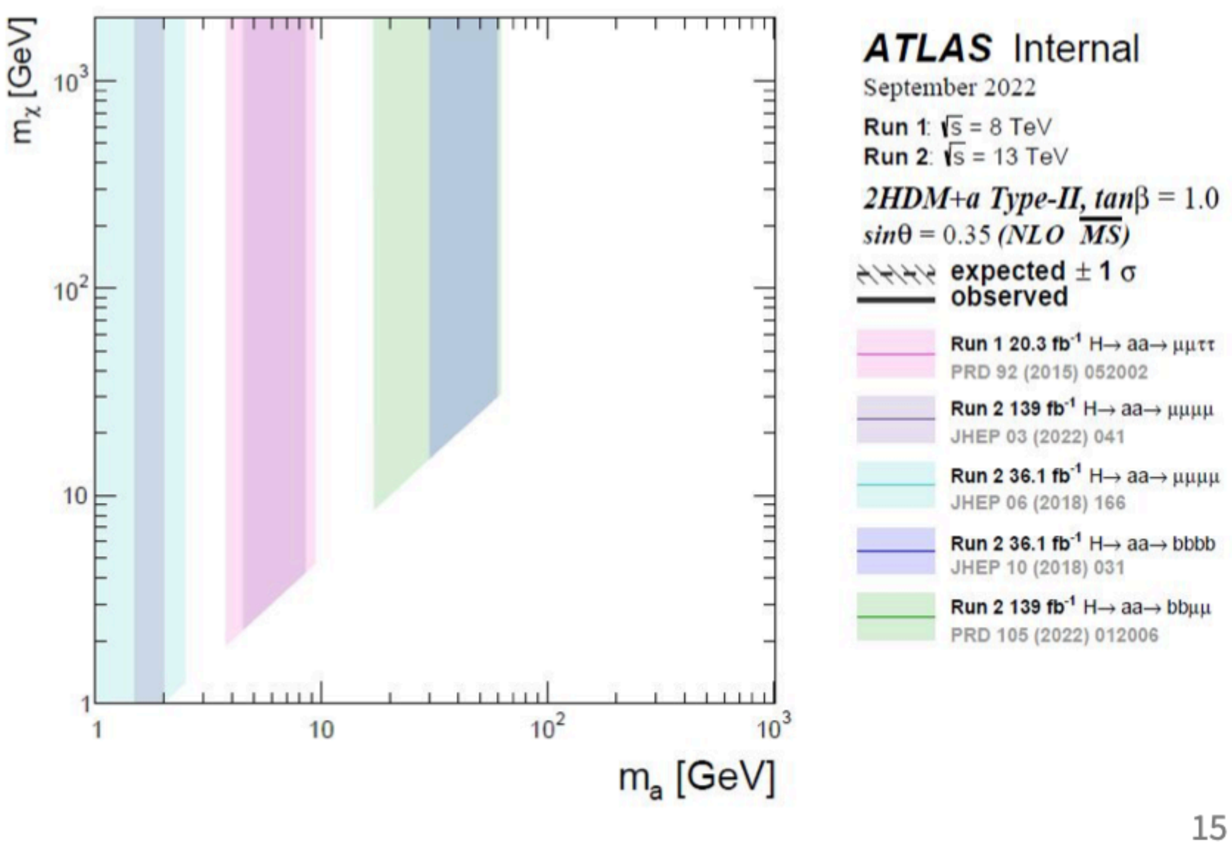
For lower values of m_a, there is strong complementarity with light resonance searches for H->aa->4f. A m_a —m_χ scan has been designed to illustrate that.

Benchmark model parameters tuned to evade constraints from total Higgs width:

$$\{m_A, \tan\beta, \sin\theta, \lambda_3, y_\chi\} = \{1.2\,\mathrm{TeV}, 1, 0.35, 3, 1\}$$

Results from the following searches are used as inputs for m_a—m_χ scan:

- search for $H \to aa \to bb\mu\mu$ [arXiv:2110.00313]
- search for $H \to aa \to bbbb$ [arXiv:1806.07355]
- two searches of the $H \to XX/ZX \to llll$ [arXiv:1802.03388, arXiv:2110.13673]
- search for $H \to aa \to \mu\mu\tau\tau$[arXiv:1505.01609]

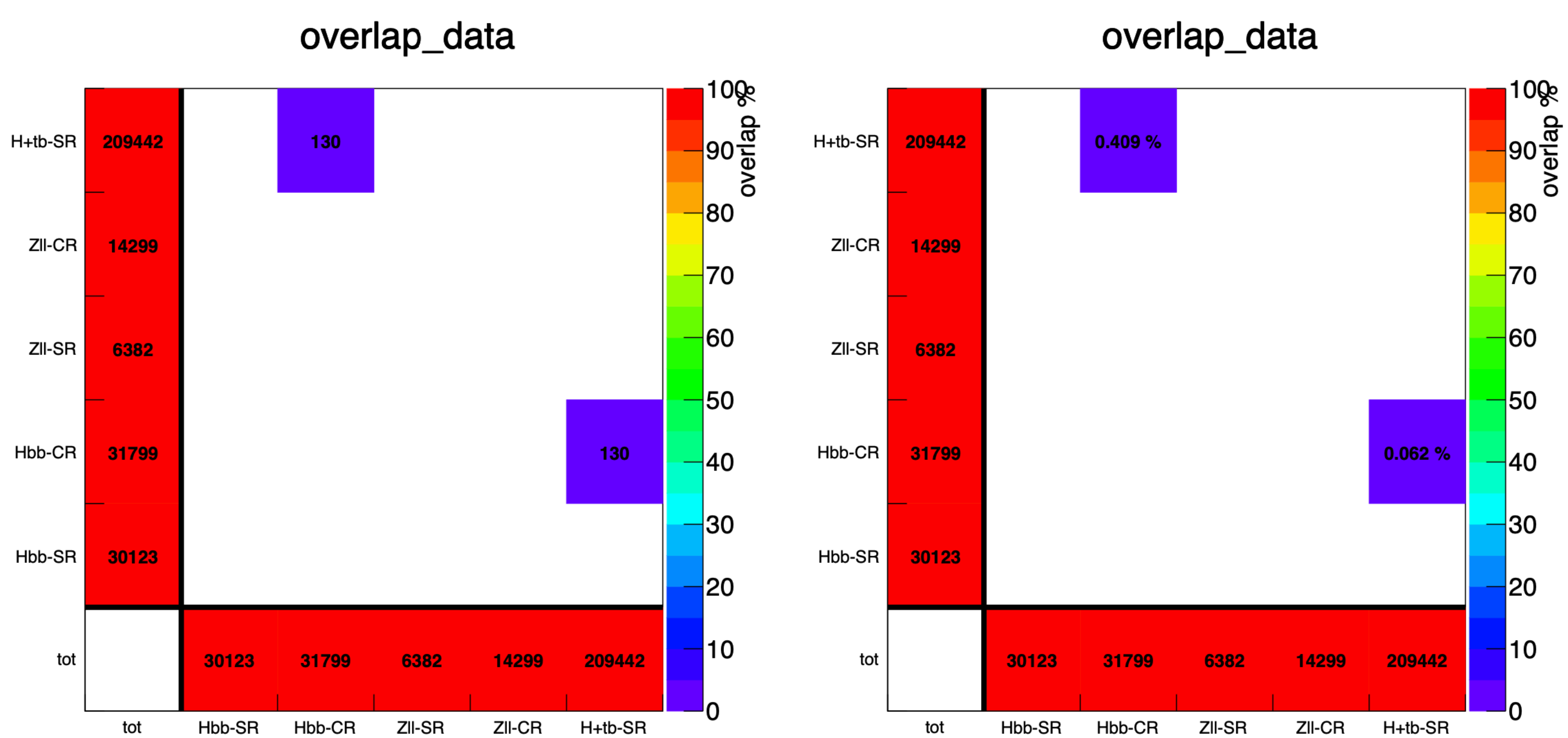


Statistical combination of results

Orthogonality checks

- The statistical combination is facilitated as the input analyses statistically independent.
- Due to b- and lepton-multiplicity requirements, no overlap between the 3 analyses SRs is expected.
- Negligible ($\ll 1\,\%$) event overlap observed between $H^{\pm} \to tb$ SR and $E_T^{miss} + h(bb)$ CR, no impact on the combination.

Input Analysis	Signal selection
EtMiss + Z(ll)	b-jet veto
EtMiss + h(bb)	>= 2 b-jets, 0 lepton
Charged H -> tb	>= 3 b-jets, 1 lepton



(a) Full run 2 data, number of overlapped events

(b) Full run 2 data, fraction of overlapped events

Statistical combination of results

Statistical analysis

- The combination is performed by constructing the analyses' likelihood and maximizing the corresponding profile likelihood ratio.

- The likelihood used in the combination defined as:

Poisson/Gaussian/Log-normal distribution

$$\boxed{\mathcal{L}(\text{data}|\mu, \boldsymbol{\lambda}_{\mu}, \boldsymbol{\theta}_{\mu}) = \prod_{c=1}^{N_{\text{cats}}} \mathcal{L}_c(\text{data}|\mu, \boldsymbol{\lambda}_{\mu}, \boldsymbol{\theta}_{\mu}) \prod_{k=1}^{N_{\text{cons}}} \mathcal{F}(\tilde{\theta}_{\mu,k}|\theta_{\mu,k})}$$

Parameter of interest: signal strength

Norm factors

Nuisance parameters

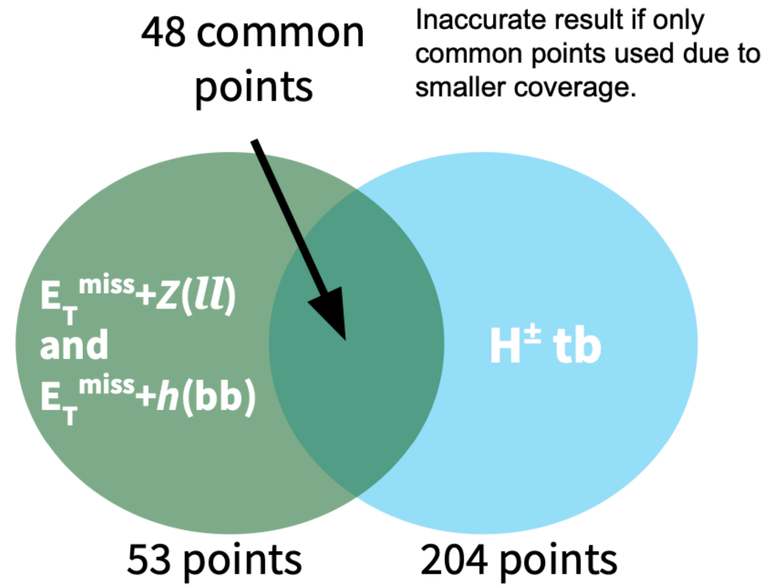
Global observable

- 95% CL limits are obtained using the profile likelihood ratio test statistic as:

$$\boxed{q_{\mu} = \frac{\mathcal{L}(\mu, \hat{\hat{\boldsymbol{\lambda}}}_{\mu}, \hat{\hat{\boldsymbol{\theta}}}_{\mu}))}{\mathcal{L}(\hat{\mu}, \hat{\boldsymbol{\lambda}}_{\hat{\mu}}, \hat{\boldsymbol{\theta}}_{\hat{\mu}})},}$$

Statistical combination of results

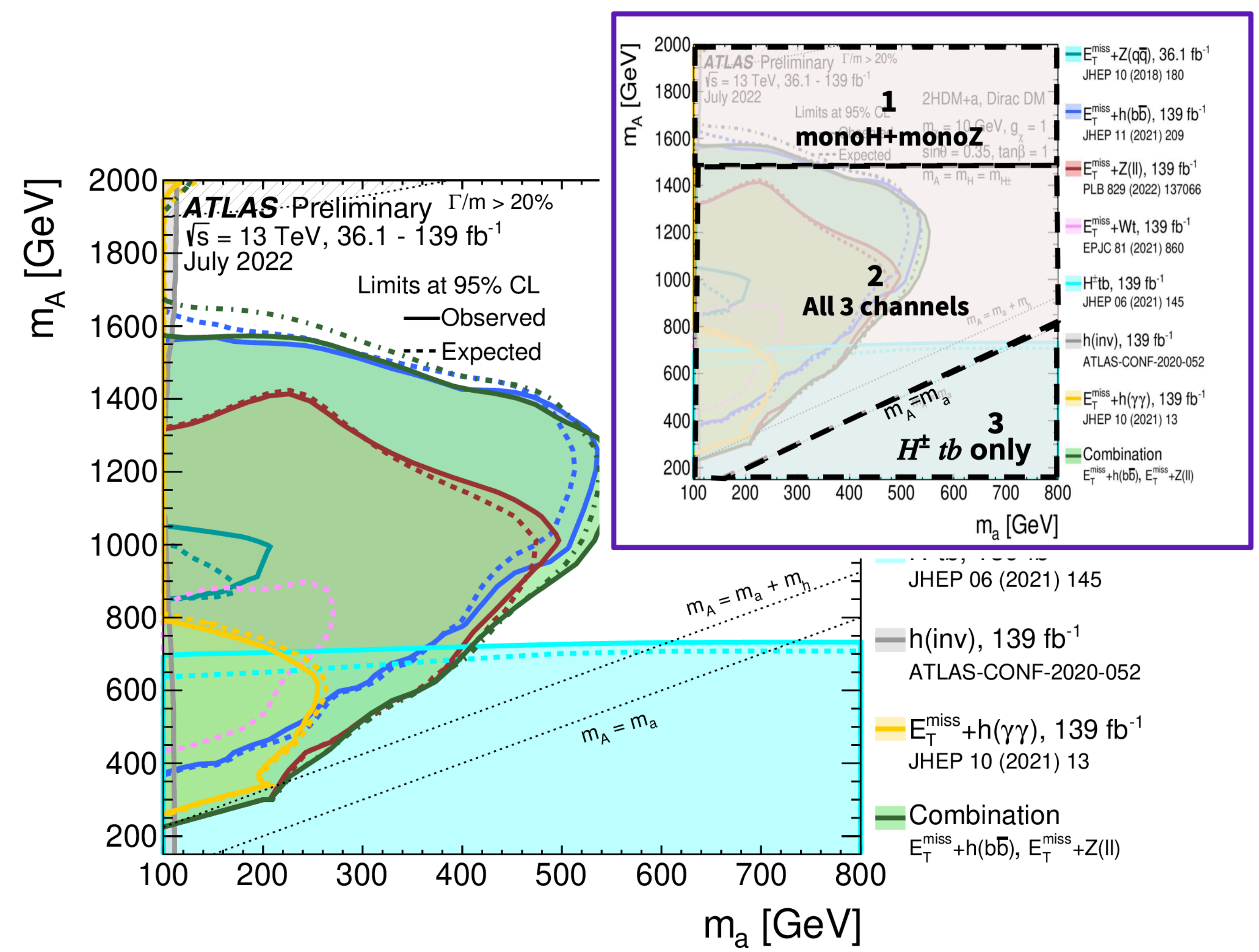
Combination strategy



- $tbH^{\pm}(tb)$ added to stat. combination with $E_T^{miss} + Z(ll)$ and $E_T^{miss} + h(bb)$ for the first time → can significantly improve sensitivity.

- Usually, the combination is done for every common signal point over 3 channels.

- Hybrid combination approach: exclude channels that have negligible sensitivities in a certain region.
  - $m_A > 1500$ GeV: $E_T^{miss} + Z(ll)$ and $E_T^{miss} + h(bb)$.
  - $m_A < 1500$ GeV and $m_A > m_a$: all 3 channels combined.
  - $m_A < m_a$ (off-shell region for mono-X searches): $H^{\pm} \to tb$ only.



Statistical combination of results

Uncertainties and their correlations

- Most experimental uncertainties related to reconstruction of physics objects are correlated across search channels.
- Uncertainties stemming from b-jet identification are not correlated due to different choices of algorithm and operating point.
- Uncertainties constrained in a particular analysis are not correlated to avoid bringing tensions from any phase-space-specific biases across channels.
- Due to different processes and phase spaces being probed, modelling uncertainties are uncorrelated across analyses.
- Different correlation choices for FTAG/JER/MET and strongly-constrained NPs were tested without observed impact on the exclusions.

Uncertainty source	$\Delta\mu$ [%]
Statistical uncertainty	25.0
Systematic uncertainties	27.6
Theory uncertainties	16.2
Signal modelling	2.8
Background modelling	15.9
Experimental uncertainties (excl. MC stat.)	18.8
Luminosity, pile-up	3.9
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	12.3
Flavour tagging	9.1
Electrons, muons	6.1
MC statistical uncertainty	9.3
Total uncertainty	37.2

stat. and syst. uncertainties to tot. uncertainty on the best-fit μ for ($m_a = 450$ GeV, $m_H = 800$ GeV, $\tan\beta = 1$ and $\sin\theta = 0.35$) excluded by the combination but is not by any single input analysis

Statistical combination of results

Uncertainties and their correlations

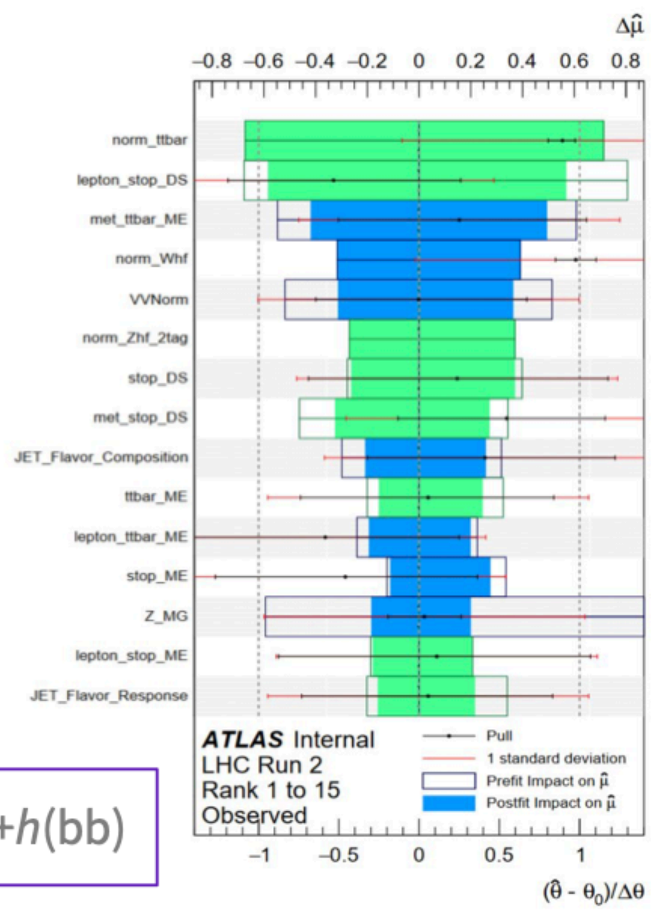
Correlation Scheme

Correlation scheme is studied and developed based on signal at m_A=800, m_a=500, tanβ= 1 and sinθ=0.35, in the "intersection" region where it has not been excluded in all three channels but within the reach of sensitivity from combination.

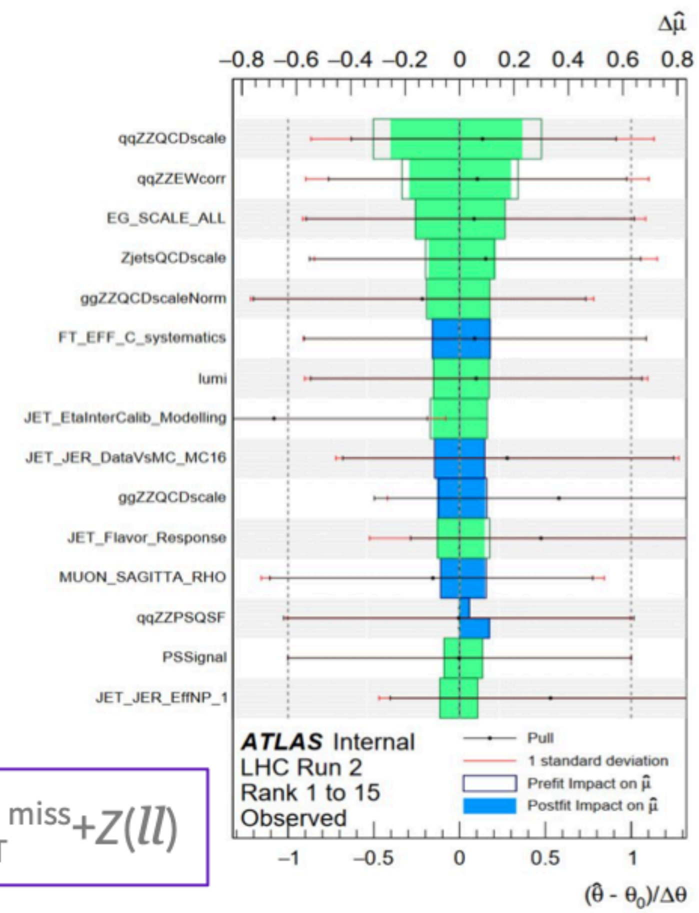
NP rankings for single channels could be reproduced.

The majority of leading NPs are channel-specific systematics (e.g., theory systematics on the background modeling). The impact from correlation should be small.

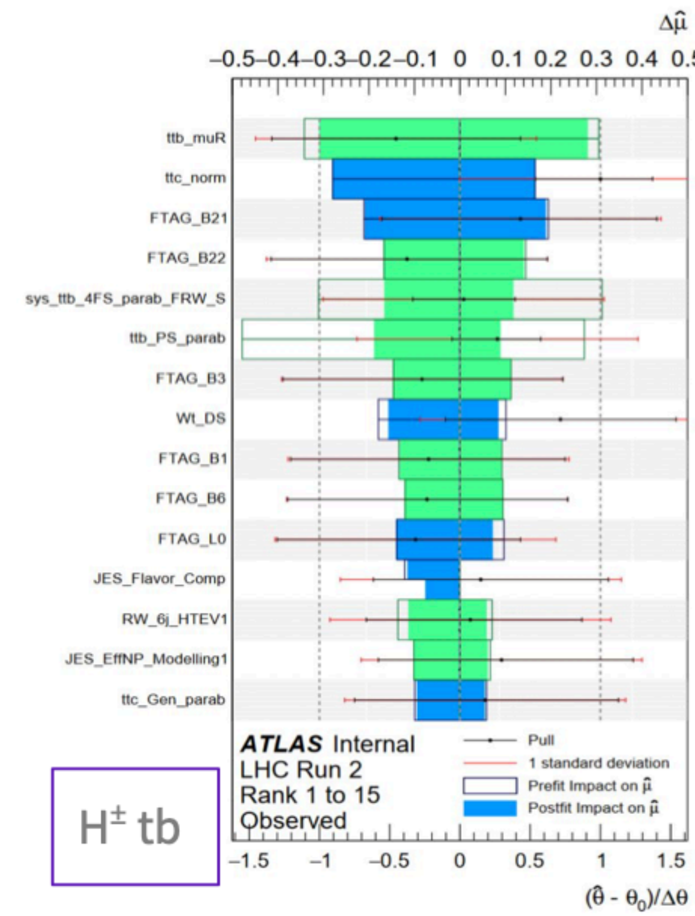
E_T^{miss}+$h(bb)$



E_T^{miss}+$Z(ll)$



$H^{\pm}$ tb



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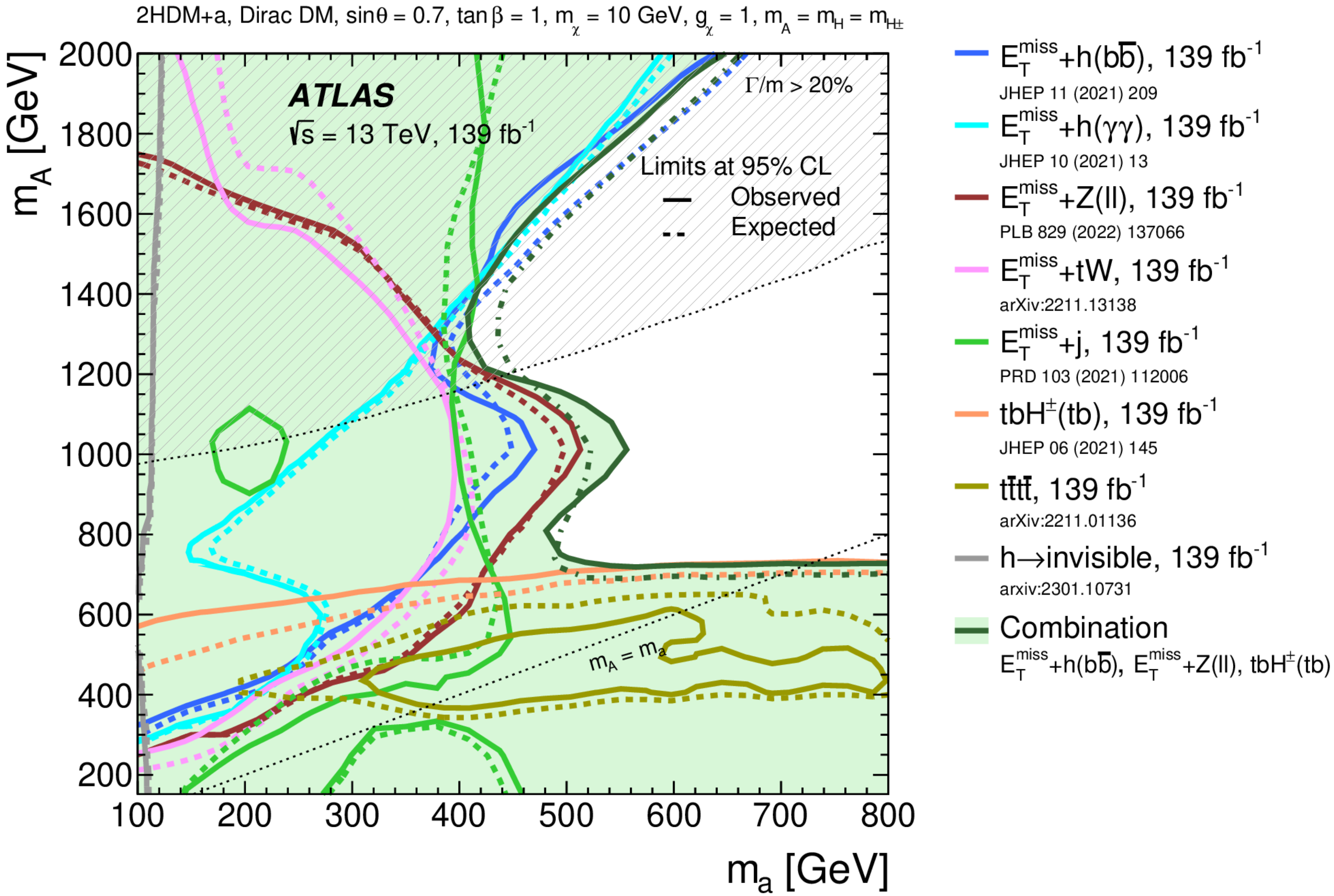
Summary of constraints on 2HDM+a

Variety of searches interpreted in the context of different 2HDM+a benchmark scenarios

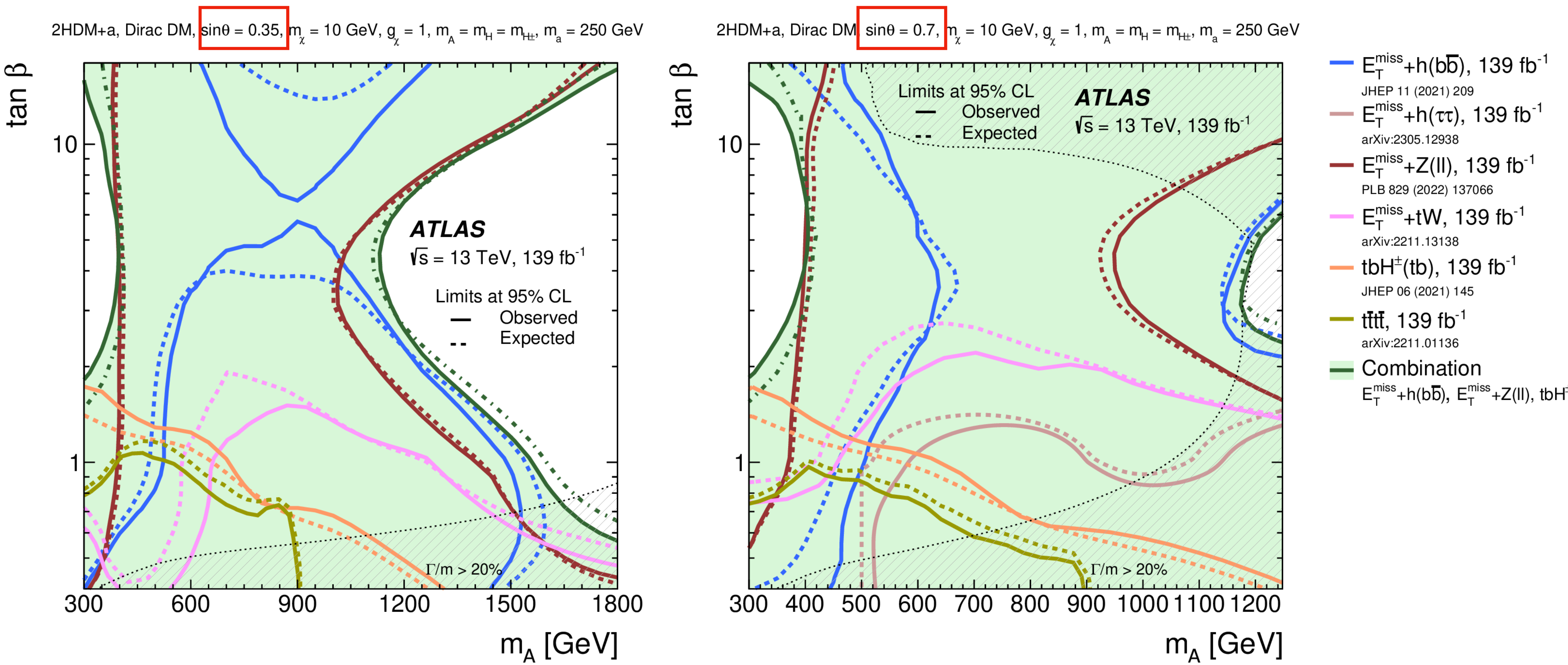
Analysis/Scenario	1a	1b	2a	2b	3a	3b	4a	4b	5	6
$E_{\mathrm{T}}^{\mathrm{miss}} + Z(\ell\ell)$ [74]	x	x	x	x	x	x	x	x	x	
$E_{\mathrm{T}}^{\mathrm{miss}} + h(b\bar{b})$ [75]	x	x	x	x	x	x	x	x	x	x
$E_{\mathrm{T}}^{\mathrm{miss}} + h(\gamma\gamma)$ [84]	x	x			x	x	x	x		
$E_{\mathrm{T}}^{\mathrm{miss}} + h(\tau\tau)$ [78]	x			x						
$E_{\mathrm{T}}^{\mathrm{miss}} + tW$ [77]	x	x	x	x	x	x	x	x		
$E_{\mathrm{T}}^{\mathrm{miss}} + j$ [45]	x	x			x	x	x	x		
$h \to$ invisible [86]	x	x			x					x
$E_{\mathrm{T}}^{\mathrm{miss}} + Z(q\bar{q})$ [127]	x						x	x		
$E_{\mathrm{T}}^{\mathrm{miss}} + b\bar{b}$ [128]							x	x		
$E_{\mathrm{T}}^{\mathrm{miss}} + t\bar{t}$ [128,129]							x	x		
$t\bar{t}t\bar{t}$ [85]	x	x	x	x	x	x	x	x	x	
$tbH^{\pm}(tb)$ [76]	x	x	x	x	x	x	x	x	x	
$h \to aa \to f\bar{f}f'\bar{f}'$ [79,80,81,82,83]										x

Scenario 1b: $\sin\theta = 0.7$ m_A-m_a plane



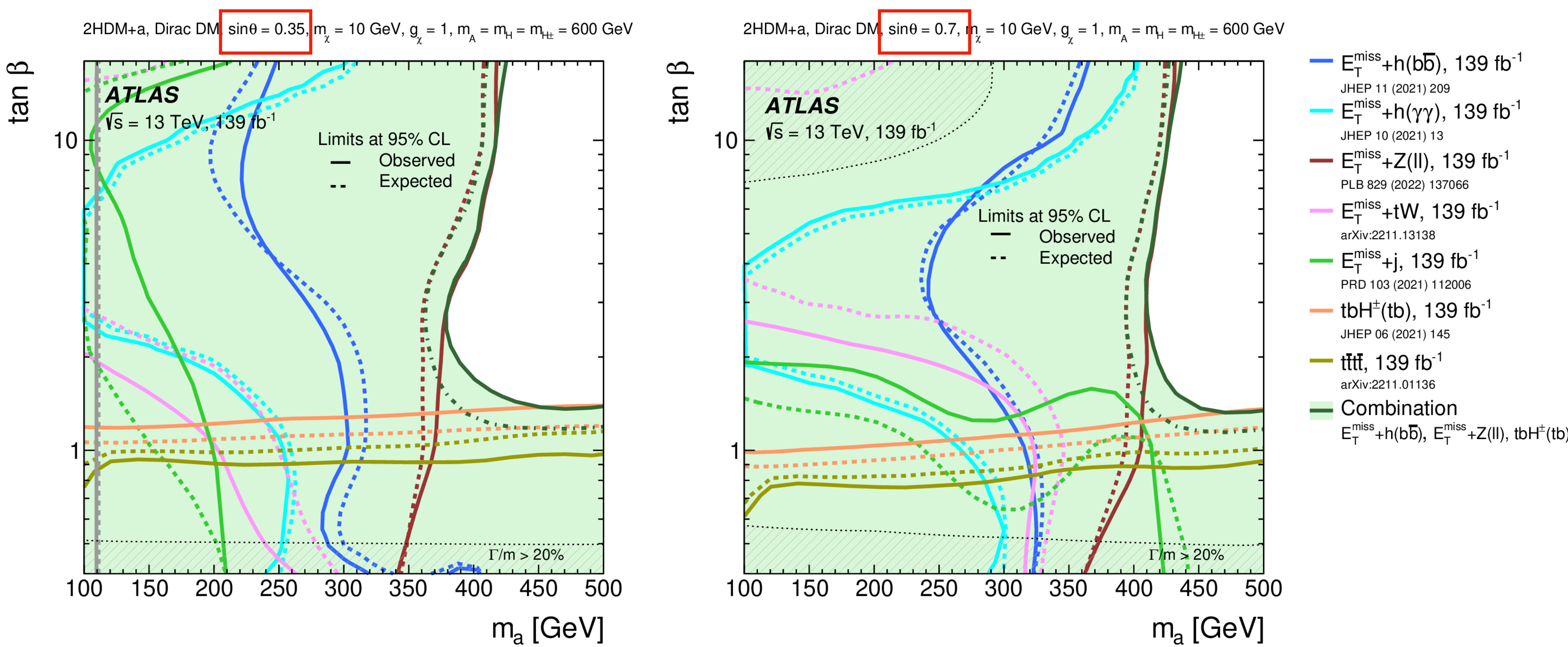
Scenario 2: $m_A - \tan\beta$ planes

- Large fraction of parameter plane excluded by $E_T^{miss} + Z(ll)$, $E_T^{miss} + h(bb)$ dominates in high-m_A but still gives sensitivity in low-m_A with $tbH^{\pm}(tb)$.
- $E_T^{miss} + Z(ll)$ and $E_T^{miss} + h(bb)$ sensitivities driven by the transition from gg- to bb-initiated production with a decrease at $\tan\beta \approx 5$.
- Combination significantly improves the excl. parameter space.



Scenario 3: $m_a - \tan\beta$ planes

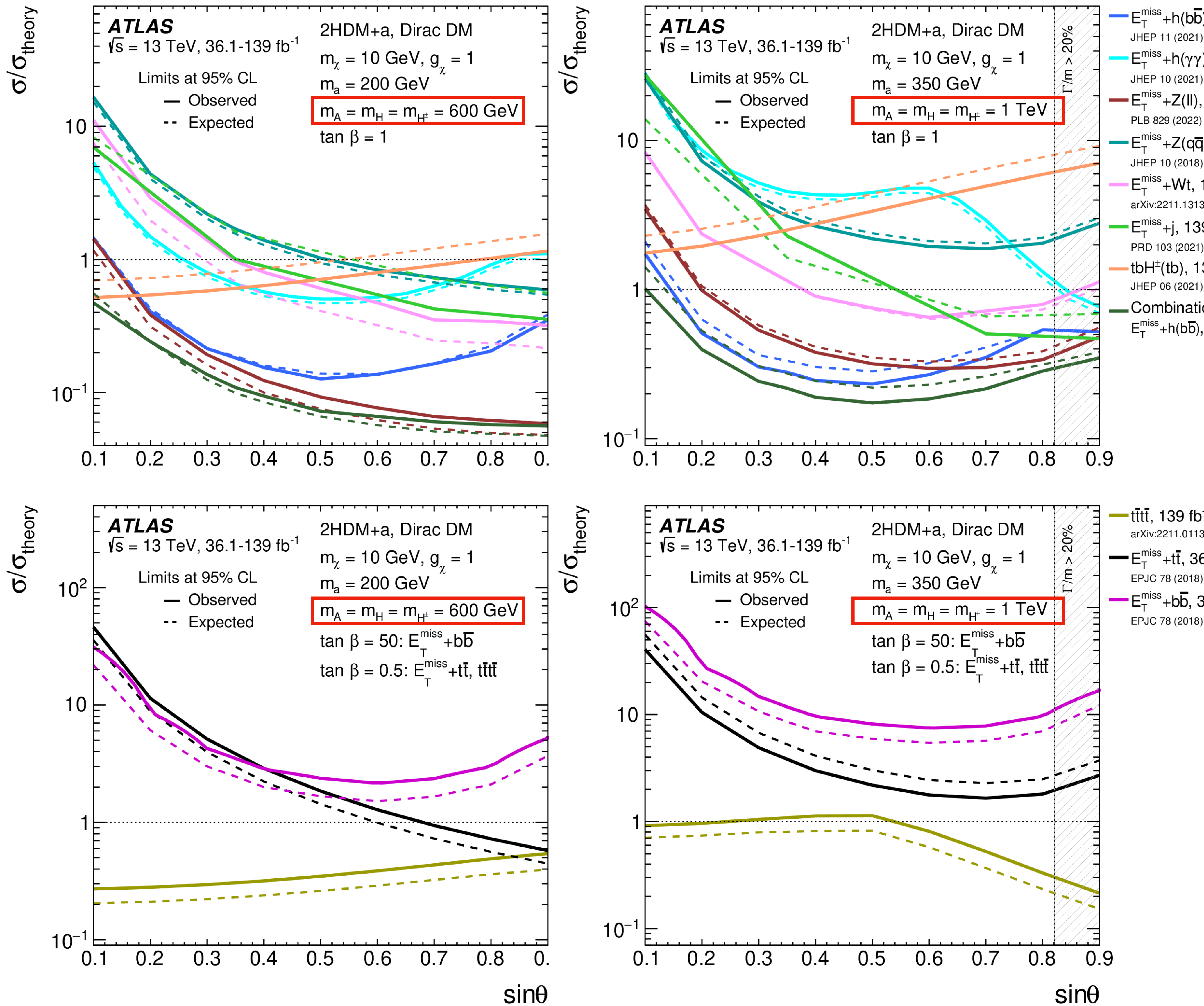
- Strongest exclusion from $E_T^{miss} + Z(ll)$, $tbH^{\pm}(tb)$ is complementary to low-$\tan\beta$ region and moderate dependence on m_a.
- Significant improvement in sensitivity achieved by combination.



Scenario 4: $\sin\theta$ scans

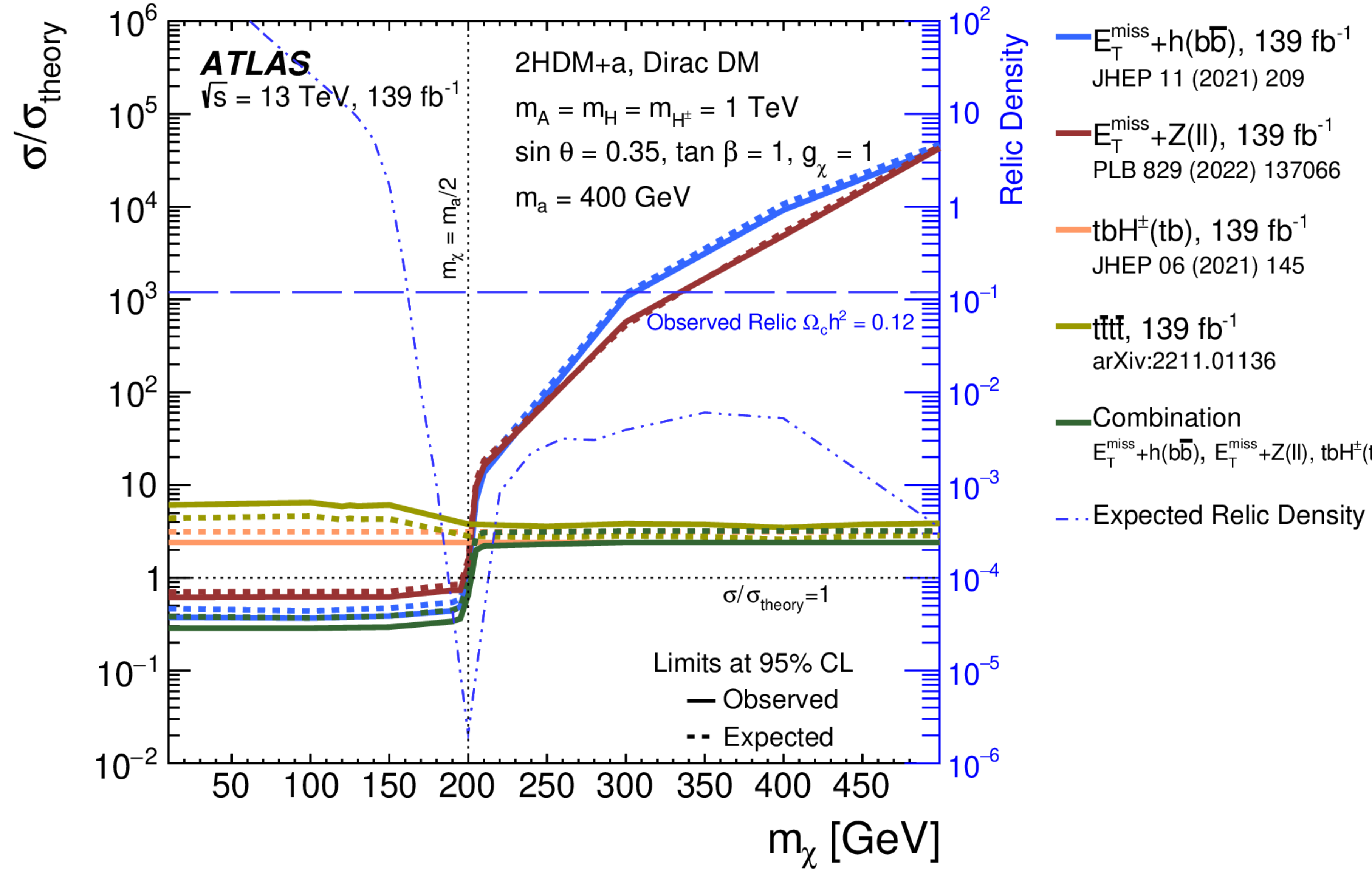
- $E_T^{miss} + Z(ll)$ and $E_T^{miss} + h(bb)$ provide strongest limits.

- Significant improvement from combination, almost the whole range excluded for these two benchmarks.



Scenario 5: m_χ scan

- At low-m_χ ($m_\chi < m_a/2$) sensitivity is driven by $E_T^{miss} + Z(ll)$ and $E_T^{miss} + h(bb)$ as the pseudoscalar is allowed to decay in to $\chi\chi$.
- For higher DM masses ($m_\chi > m_a/2$), the sensitivity of $E_T^{miss} + X$ decreases rapidly, while that of $tbH^\pm(tb)$ and 4top remains nearly constant. Although none of them excludes 2HDM+a.
- Combination provides strongest exclusion.
- Possible to match the observed relic density for $m_\chi \approx 170$ GeV without changing the collider phenomenology.



VBF $H \to \gamma\gamma_d$

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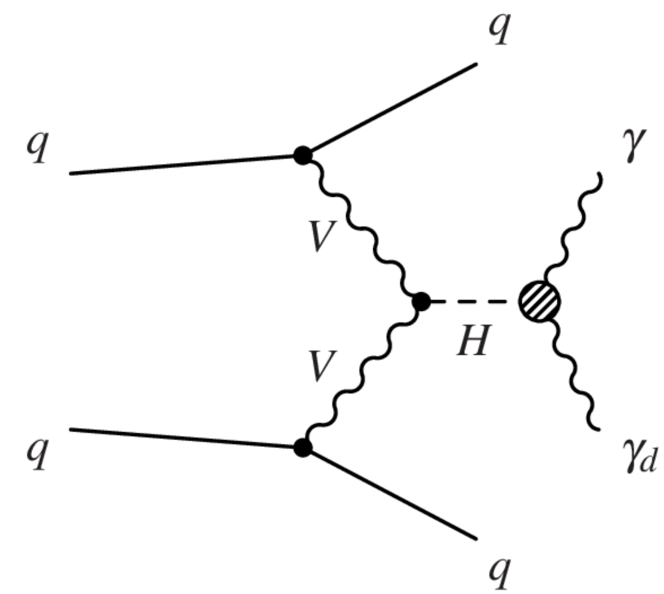
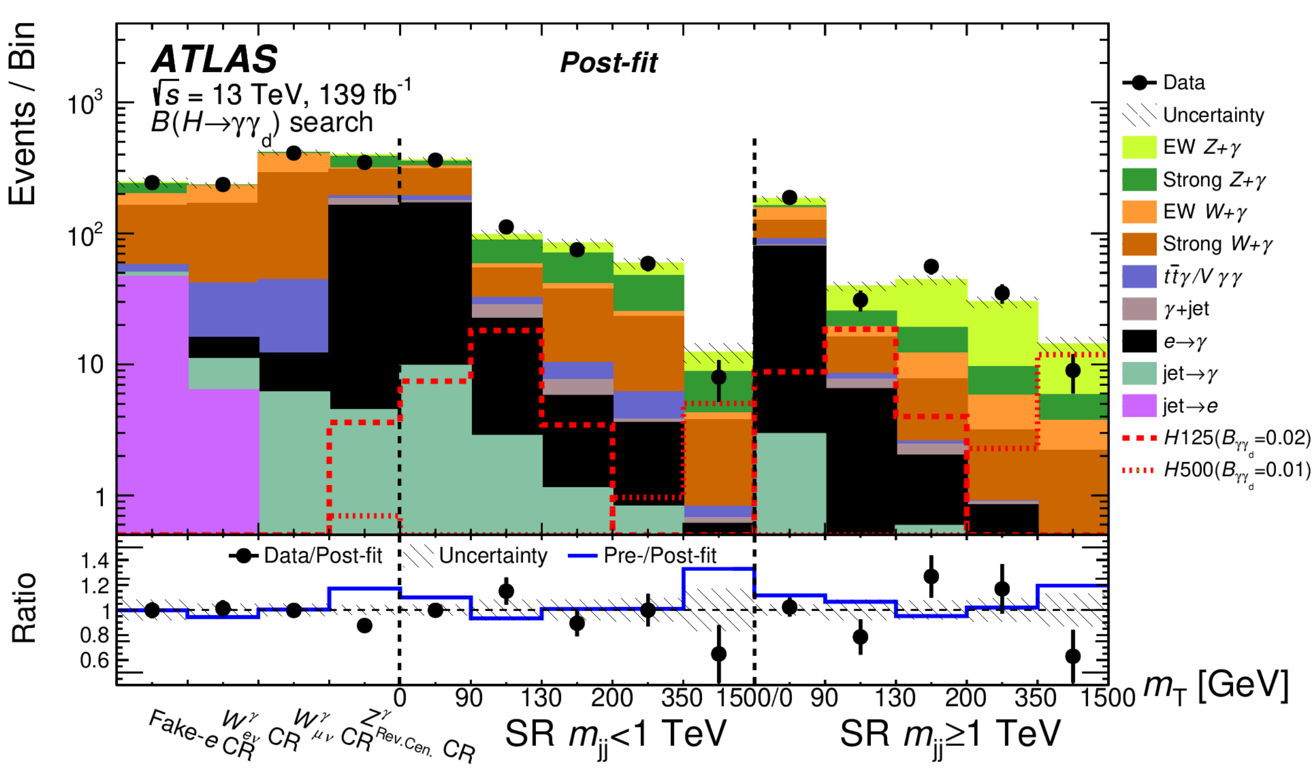
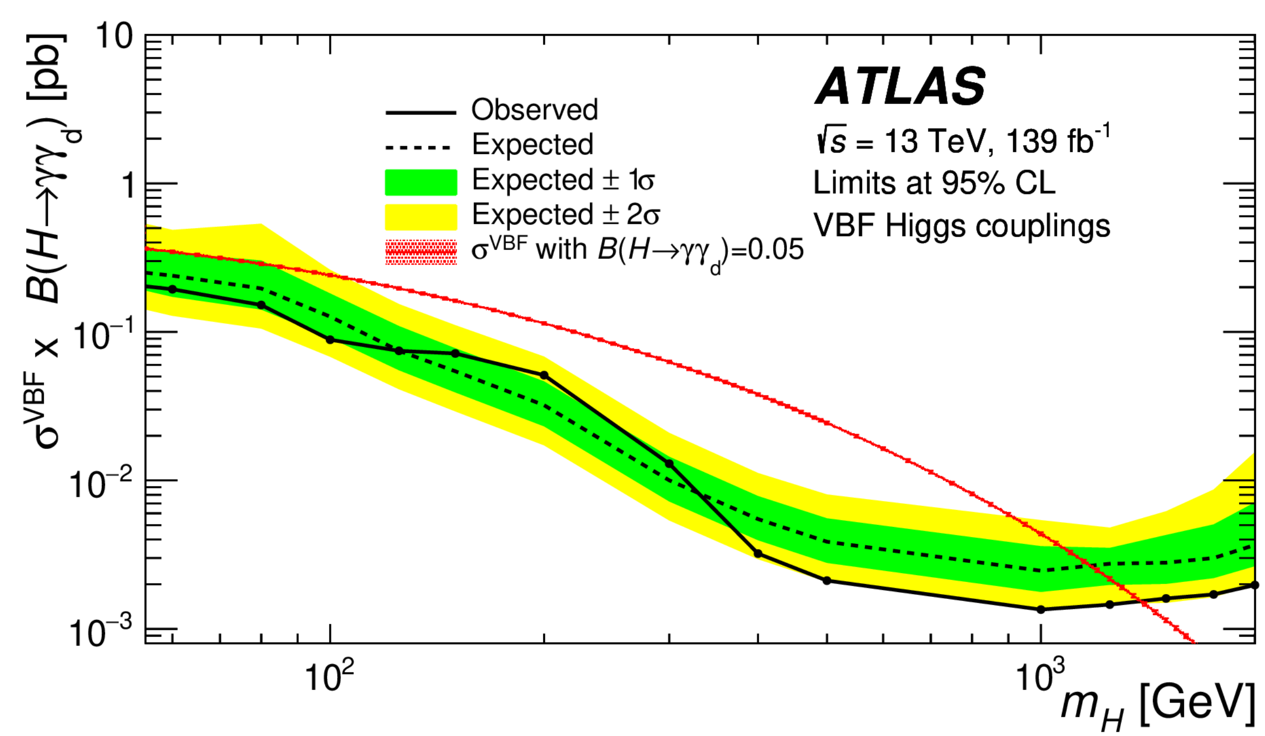


- search for $H \to \gamma\gamma_d$ with VBF production mode
  - $m_H \in [60,2000]$ GeV; massless dark photon;
  - dark photon collider stable → E_T^{miss};
  - final state with 1 photon, jets and E_T^{miss}.
- Signal region: single-photon trigger, isolated photon, 2 forward jets with $|\Delta\eta_{jj}| > 2.5$, high E_T^{miss}.
- SR and CRs divided into 2 bins of m_{jj} with 5 bins of $m_T(\gamma, E_T^{miss})$ each.
- ggF $H \to \gamma\gamma_d$ signal contribution included for 125 GeV Higgs.

An observed (expected) 95% CL upper limit on the branching ratio for this decay is set at 0.018 ($0.017^{+0.007}_{-0.005}$), assuming the SM 125 GeV Higgs boson.





$ZH, H \to \gamma\gamma_d$

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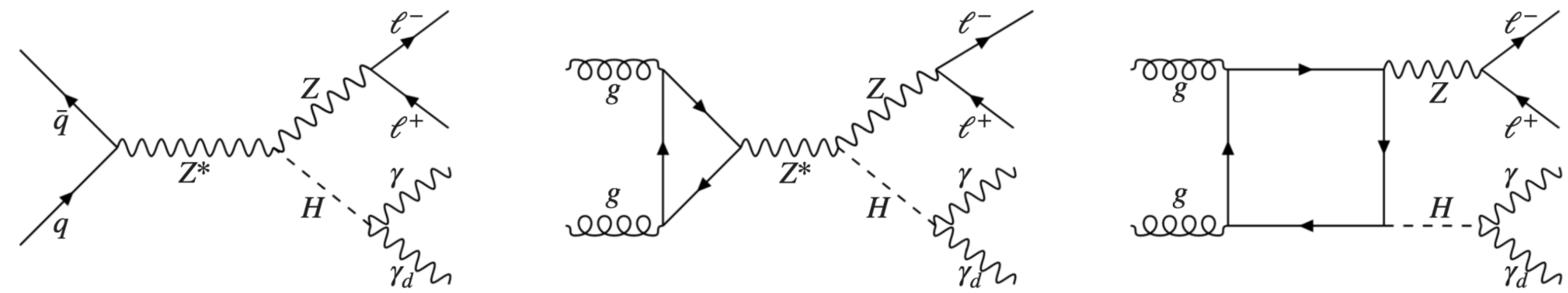
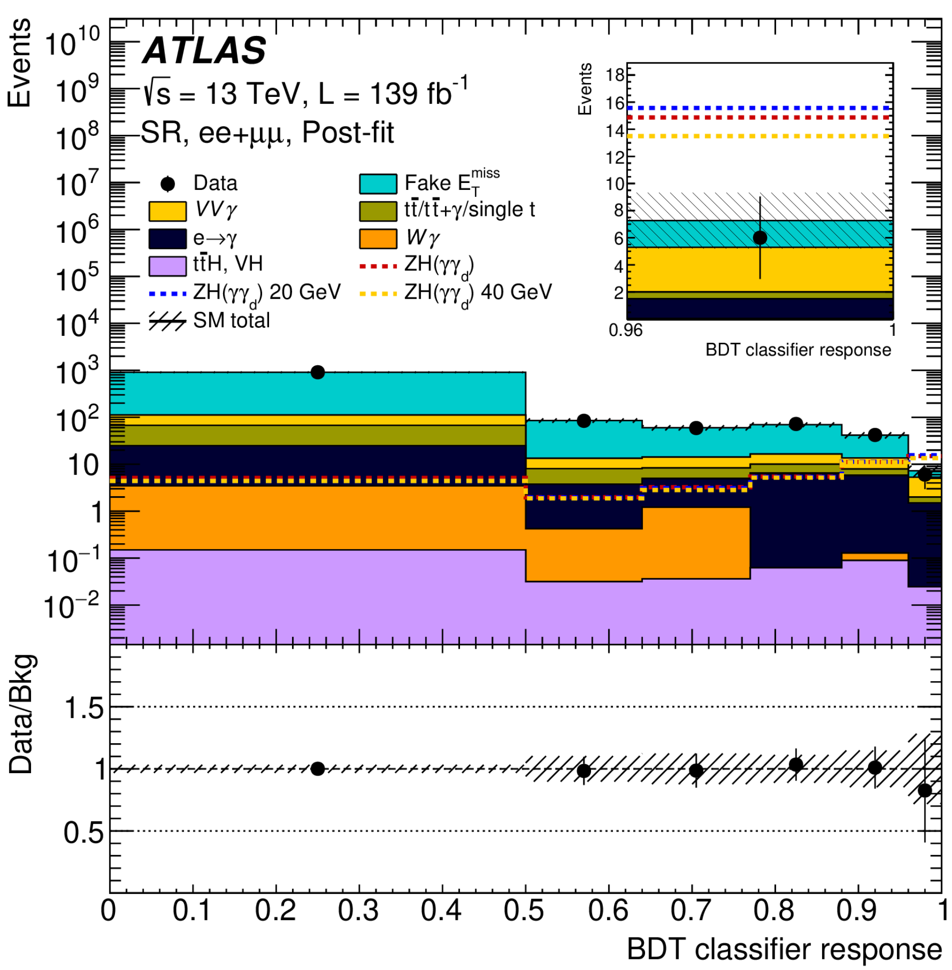
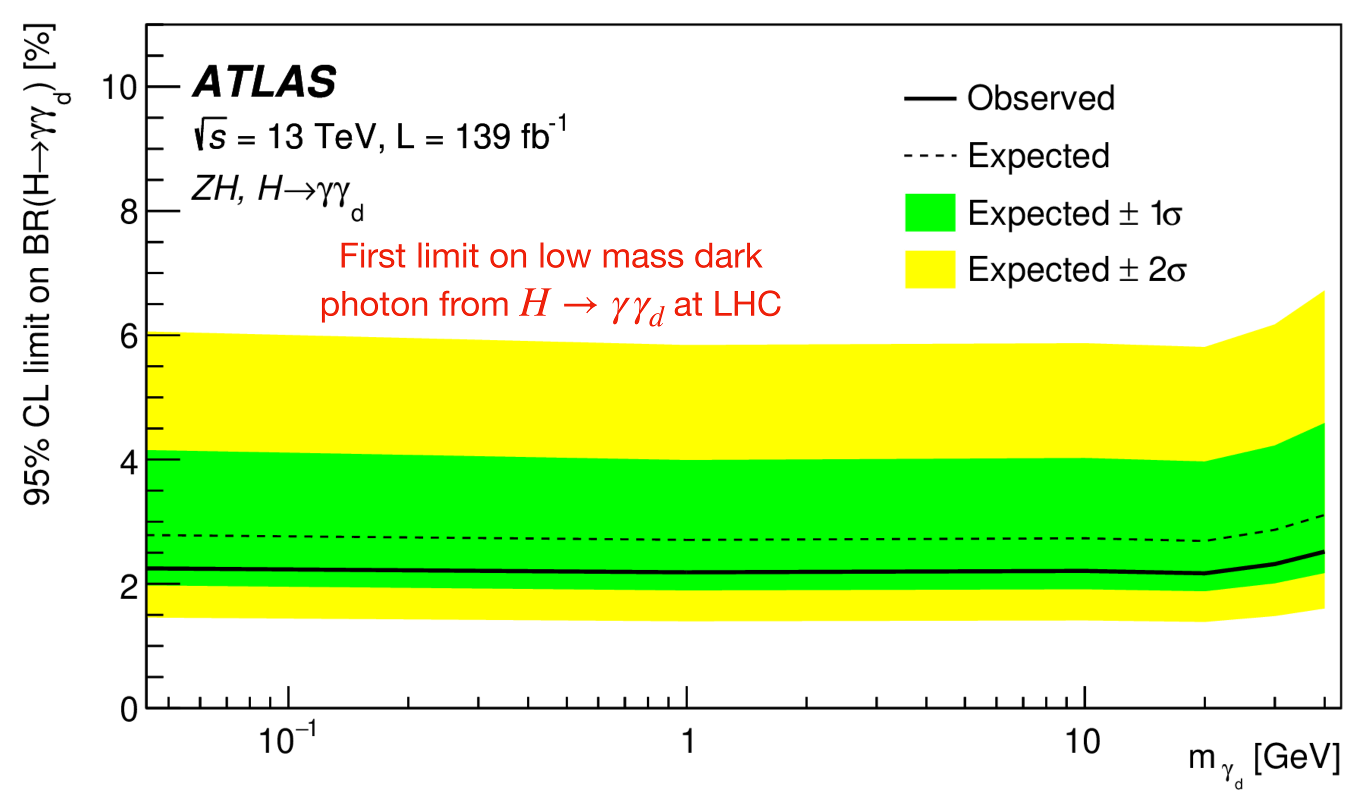
- Search for $H \to \gamma\gamma_d$ with ZH production mode
  - m_H = 125 GeV; $m_{\gamma_d} \in [0,40]$ GeV;
  - dark photon $\to E_{\mathrm{T}}^{\mathrm{miss}}$; $Z \to l^+l^-$;



- BDT (XGBOOST) optimised specifically for 125 GeV Higgs, used to enhance sensitivity.

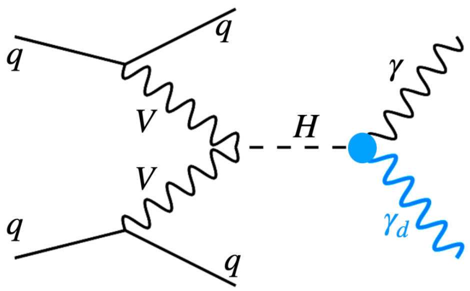




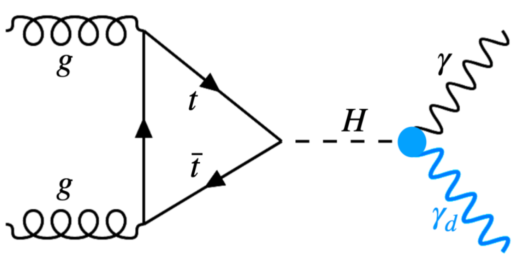
Production	ZH	VBF
ATLAS	2.3 (2.8)%	1.8 (1.7)%
CMS	4.6 (3.6)%	3.5 (2.8)%

Mono-photon re-interpretation for $H \rightarrow \gamma\gamma_d$

- reinterpretation of $E_{\mathrm{T}}^{\mathrm{miss}} + \gamma$ to search for dark photon in high-mass resonances.
  - $m_H \in [400{,}3000]$ GeV; massless dark photon;
  - dark photon $\rightarrow E_{\mathrm{T}}^{\mathrm{miss}}$.



VBF



ggF

- Include contribution from both VBF and ggF production modes.
- Discriminant variable: $E_{\mathrm{T}}^{\mathrm{miss}}$.