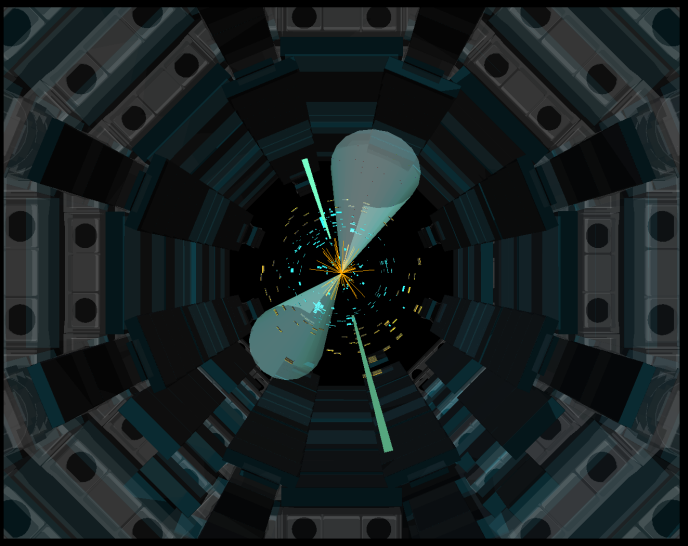


Searches for New Massive Scalars in ATLAS

LHCP 2024

12th edition of the Large Hadron Collider Physics

Northeastern University, **Boston, USA, 03-07.06.2024**

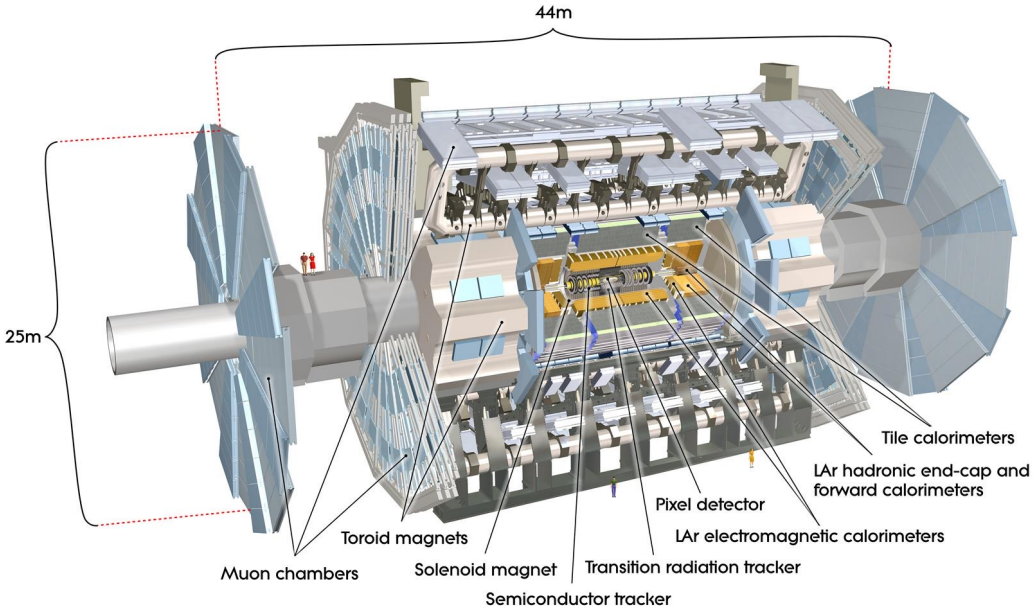
Pawel Brückman de Renstrom
(Institute of Nuclear Physics P.A.N., Cracow PL)

Foreword

We are getting to know the H_{125} resonance ever better.
It has confirmed it's SM Higgs predicted properties

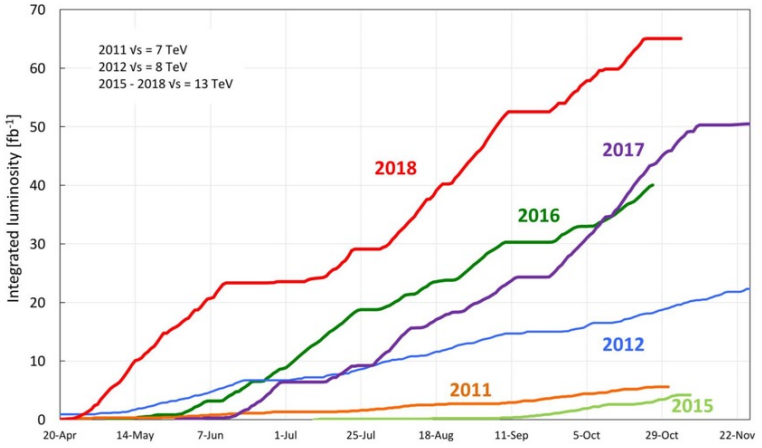
⇒ BSM ~alignment limit

⇒ suppressed bosonic couplings



- Couplings to down-type fermions probed by tauonic & $b\bar{b}$ final states ✗
- Couplings to up-type fermions @ high masses require $t\bar{t}$ final states (particularly difficult!) ✓
- Generic scenarios can be probed in scalar cascades ✓
- Numerous searches rely on Narrow Width Approximation (**NWA**) !

140 fb^{-1} of Run 2 data still in the game!



Menu of the talk – Search for heavy scalar resonances

In the decay to a $t\bar{t}$ pair:

- $A/H \to t\bar{t}$, (l, ll_{OS} final state) **NEW**
- $t\bar{t}A/H \to t\bar{t}t\bar{t}$, ($l, ll_{\text{OS}}$ final state) **NEW**
- $A \to ZH \to l^+l^- + t\bar{t}$ (in the backup)

In cascade decays involving H_{125} and/or other scalar states:

- $R/A \to SH/ZH \to 4l + E_T^{miss}$ **NEW**
- $X \to SH_{125} \to b\bar{b}\gamma\gamma$ **NEW**
- $X \to SH_{125} \to VV\gamma\gamma$ (in the backup) **NEW!!!**

Talk from Shigeki on Monday

In the decay into a H_{125} pair:

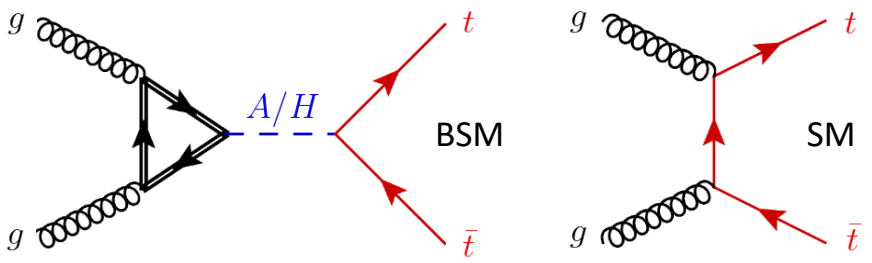
- $X \to HH \to b\bar{b}b\bar{b}, b\bar{b}\tau^+\tau^-, b\bar{b}\gamma\gamma$ combination

Full Run 2 ATLAS data (~140 fb^{-1})

Search for heavy CP even/odd scalar decaying to a pair of top quarks in the leptonic final state

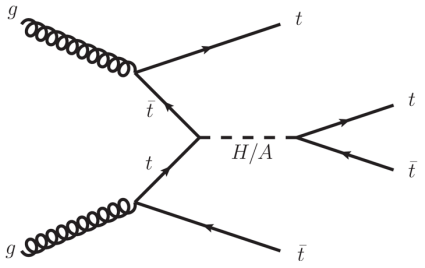
- Inclusive channel suffers from the strong interference with $t\bar{t}$ continuum

$\mathrm{A/H} \rightarrow t\bar{t}$
(l, ll_{OS} final state)



- Top associated production potentially less prolific

$t\bar{t}\mathrm{A/H} \rightarrow t\bar{t}t\bar{t}$
(l, ll_{OS} final state)

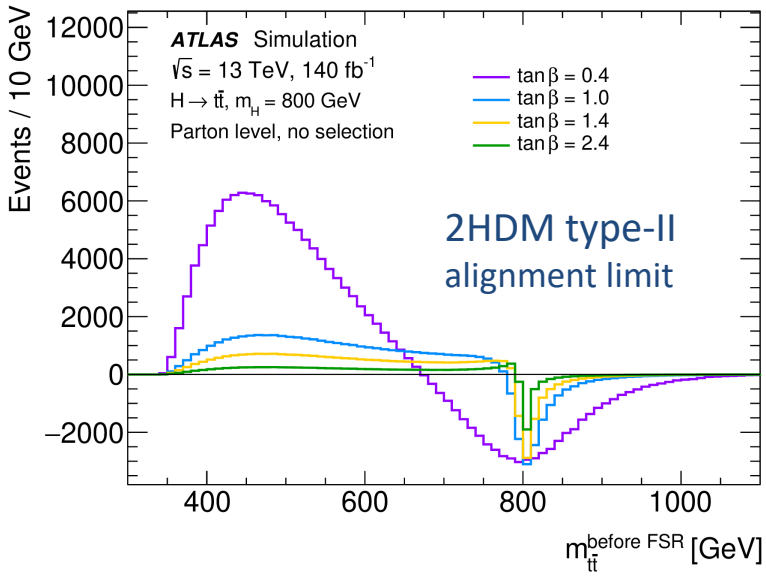


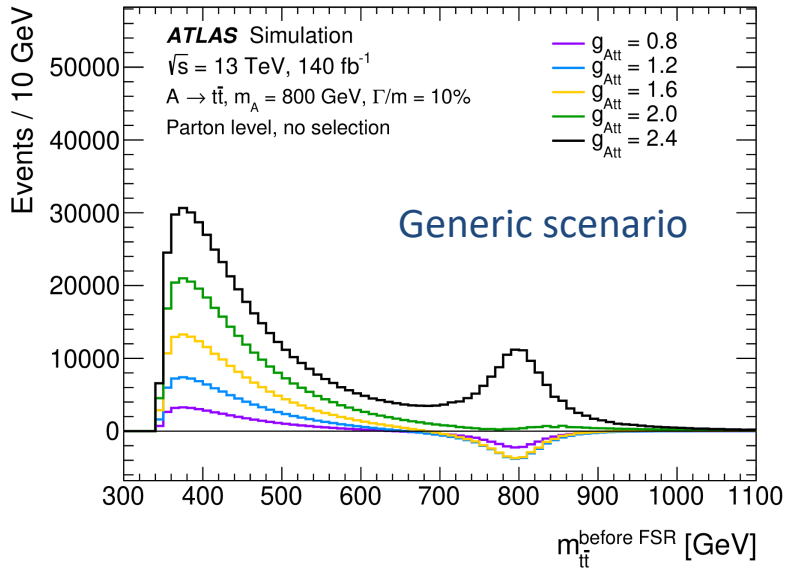
$A/H \to t\bar{t}$ (l, ll_{OS} final states)

arXiv:2404.18986

Meticulous treatment of the signal model!

- Simple limit on μ not feasible ☹
  $\mu S + \sqrt{\mu} I + B = (\mu - \sqrt{\mu})\boldsymbol{S} + \sqrt{\mu}(\boldsymbol{S} + \boldsymbol{I}) + \boldsymbol{B}$
- Signal generated with MadGraph (LO) with a dedicated provision to subtract the $B_{t\bar{t}}$ component:
  $S + I = (S + I + B_{t\bar{t}}) - B_{t\bar{t}}$
- Signal S and $S + I$ simulations for individual $(m_{A/H}, \tan\beta)$ or $(m_{A/H}, \Gamma_{A/H})$ with event-by-event reweighting after detector simulation separately for *H* & *A* hypothesis
- *k*-factors applied affecting both shape & normalisation of the $S + I$.





$A/H \to t\bar{t}$ (l, ll_{OS} final states)

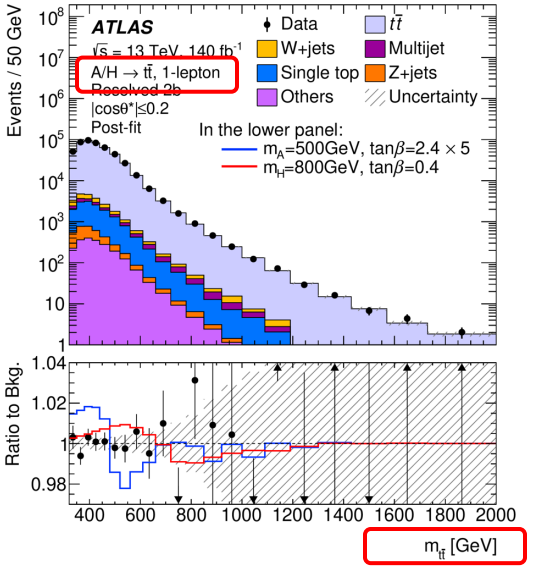
arXiv:2404.18986

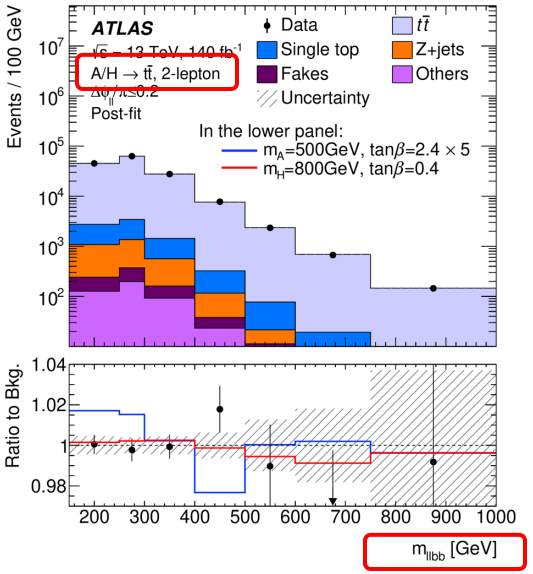
- Multiple **scenarios considered**:
  2HDM type-II, hMSSM, 2HDM+a, Simplified Generic ($m_{A/H}, \Gamma_{A/H}, g_{A/Ht\bar{t}}$)

- **1-lepton** channel (exactly 1 e or μ $p_T > 28$ GeV , $\geq 1b$-jet) : **11 S**ignal **R**egions, discriminant: $\boldsymbol{m_{tt}}$
  - merged topology (1 large-VR (re-clustered) jet $p_T > 200$ GeV, $m > 100$ GeV, $\geq 1b$-jet)
  - resolved topology (≥ 4 jets $p_T > 25$ GeV, $\geq$ 1top), χ^2-based $t\bar{t}$ reconstruction - further split into 10 SR's based on 1/2 b-jet & $|\cos\theta^*|$

- **2-lepton** channel (OS lepton pair, ≥ 2 jets, $\geq 1b$-jet, $m_{ll} > 15$ GeV, **5** SR's, discriminant: $\boldsymbol{m_{llbb}}$ ($E_T^{miss} > 45$ GeV, $m_{ll} \neq m_Z)_{ee,\mu\mu}$
  - further split into 5 $\Delta\phi_{ll}$ SR's

- Main systematic from $t\bar{t}$ background modelling (theory)





$A/H \to t\bar{t}$ (l, ll_{OS} final states)

arXiv:2404.18986

Non-standard statistical analysis!

(for details see talk from Nicola De Biase)

❖ **Search stage**: Fit $\sqrt{\mu}$

$$(\mu - \sqrt{\mu})\boldsymbol{S} + \sqrt{\mu}(\boldsymbol{S} + \boldsymbol{I}) + \boldsymbol{B}$$

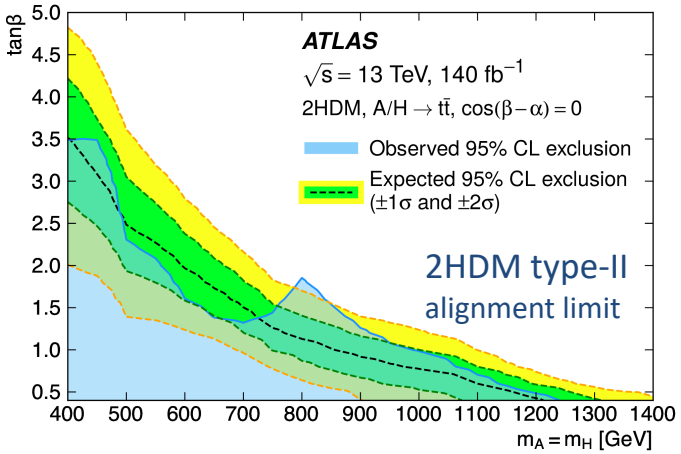
for each mass/width hypothesis.

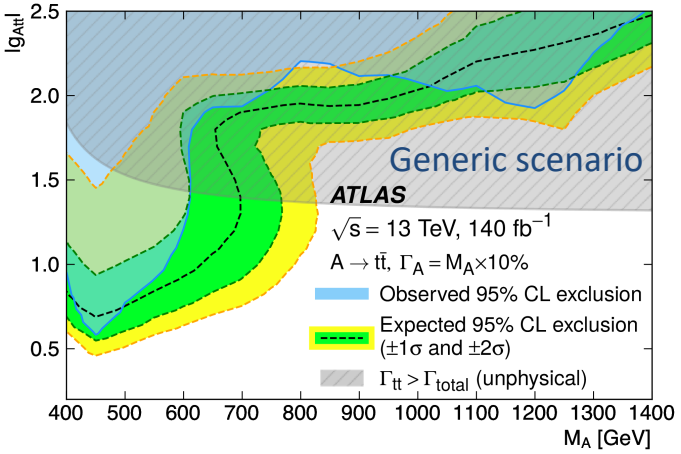
Goal: potential rejection of $\mu = 0$ hyp.

❖ **Exclusion stage**: $q = -2\ln(\mathcal{L}_1/\mathcal{L}_0)$

Goal: reject $\mu = 1$ hyp. against $\mu = 0$ one.

❖ Nonlinear dependence of $\mathcal{L}$ on $\sqrt{\mu}$!
Disjoint exclusions possible. Full scan of H/A $(m_{A/H}, \tan\beta)$ or $(m_{A/H}, g_{Att}, \Gamma_{A/H})$!





Data found compatible with the SM prediction.

Largest deviation for $m_A \approx 800$ GeV, $\frac{\Gamma_A}{m_A} = 10\%$ $\sqrt{\mu} = 4$ @ 2.3σ

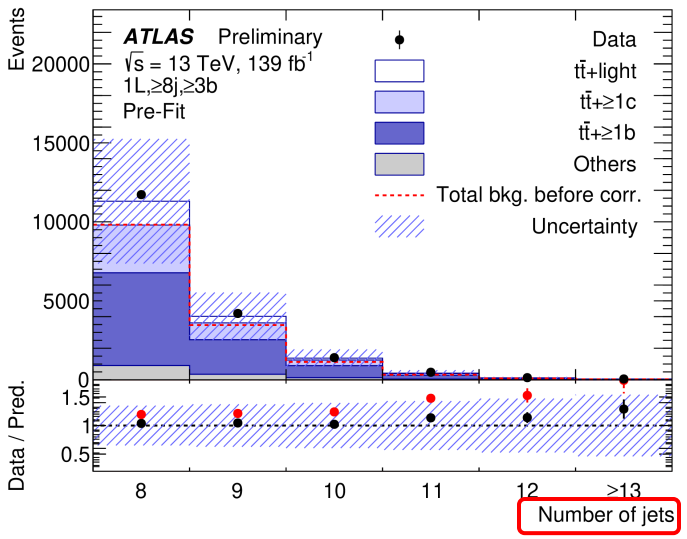
95% CL exclusions for the considered models extracted $(400 < m_{A/H} < 1400)$

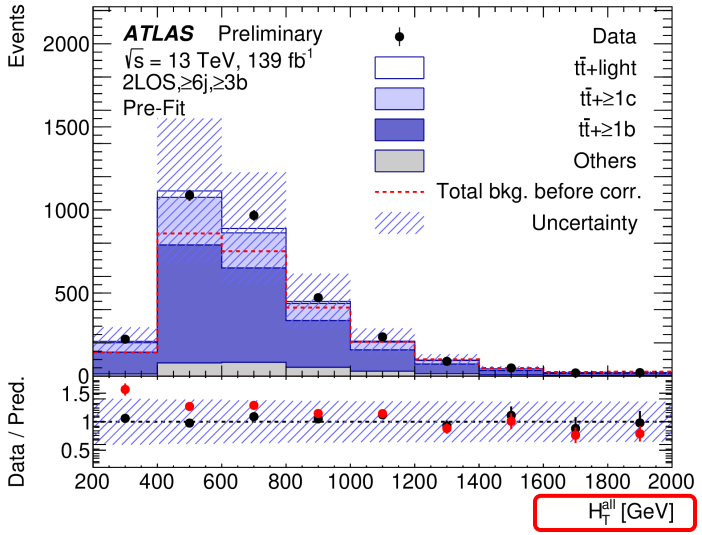
$t\bar{t}\mathrm{A/H} \rightarrow t\bar{t}t\bar{t}$ (l, ll_{OS} final states)

ATLAS-CONF-2024-002

Not suffering from significant interference!

- SM $t\bar{t}t\bar{t}$ has been established by ATLAS & CMS!
  (featuring a mild excess)
- Difficult modelling of the dominant $t\bar{t}$+jets background ⇐ data-driven "flavour rescaling" (in 5j & 7j bins)
- NN binary classifier trained to discriminate data from MC - multidim. kinematics (**x**) ⇒ w(**x**). Applied to MC on event-by-event basis
- Uncertainties dominated by the $t\bar{t}$+jets modelling and modelling of the SM $t\bar{t}t\bar{t}$ process (both theory & data-driven corrections)
- GNN are trained on multiple input variables separately for 1L and 2LOS categories.



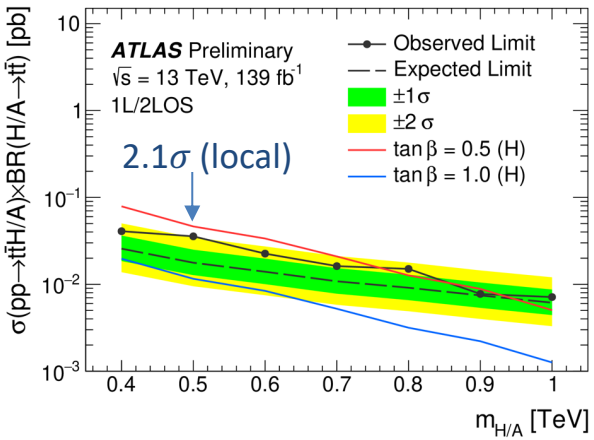


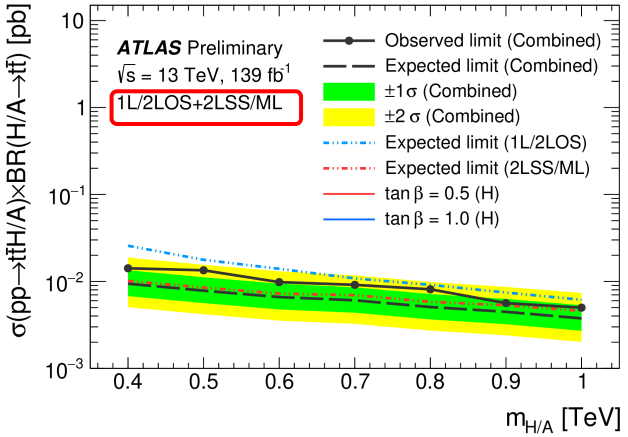
$t\bar{t}A/H \rightarrow t\bar{t}t\bar{t}$ (l, ll_{OS} final states)

ATLAS-CONF-2024-002

Limits obtained from simultaneous fit to GNN score in the SR's and H_T in the CR's

⊕JHEP 07 (2023) 203

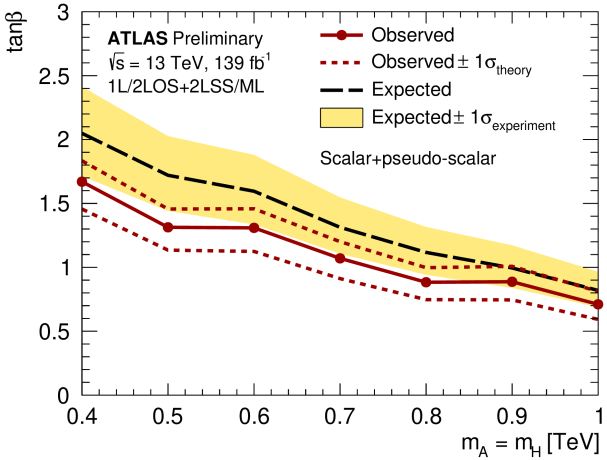


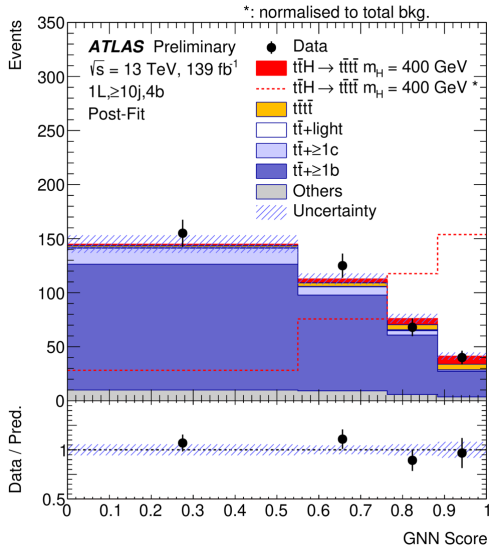


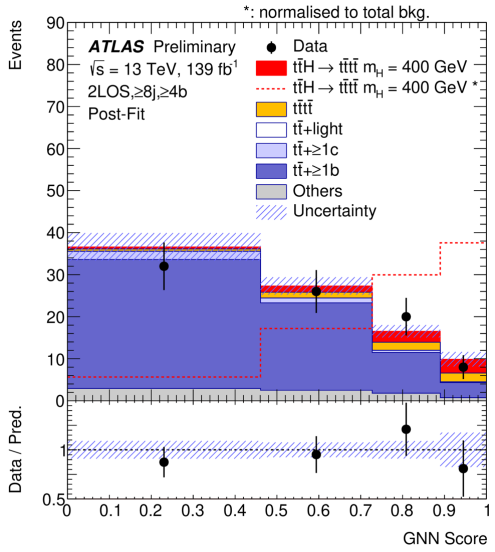
No significant excess over SM

95% CL limits are set on $\sigma \times BR$ ($400 < m_{A/H} < 1000$)

⇒Exclusions in 2HDM type-II in the alignment limit



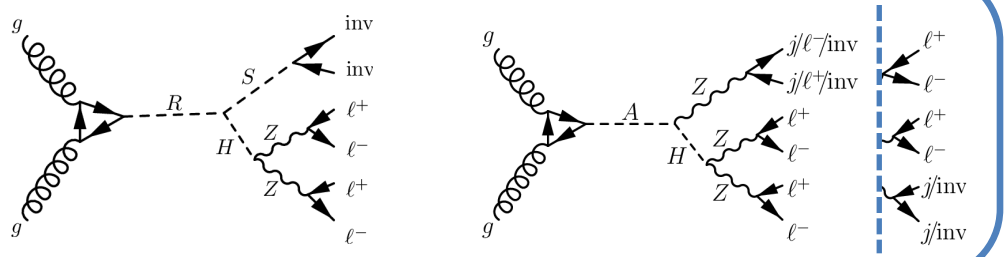




Search for heavy CP even/odd scalar in cascade decays involving another scalar

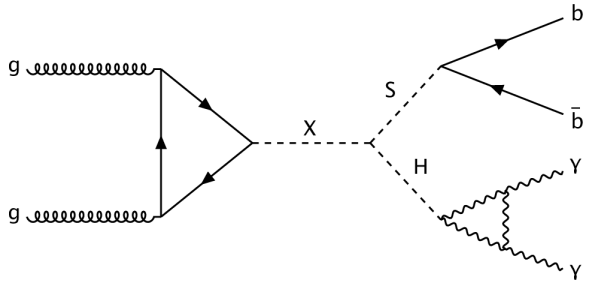
- CP even scalar R (CP odd A) decaying to a lighter scalar *S* (*Z* boson) and a heavy Higgs going to a *ZZ* pair

$R/A \rightarrow SH/ZH$
($4l + E_T^{miss}$ final state)



- A scalar X decaying to a lighter scalar S and SM Higgs

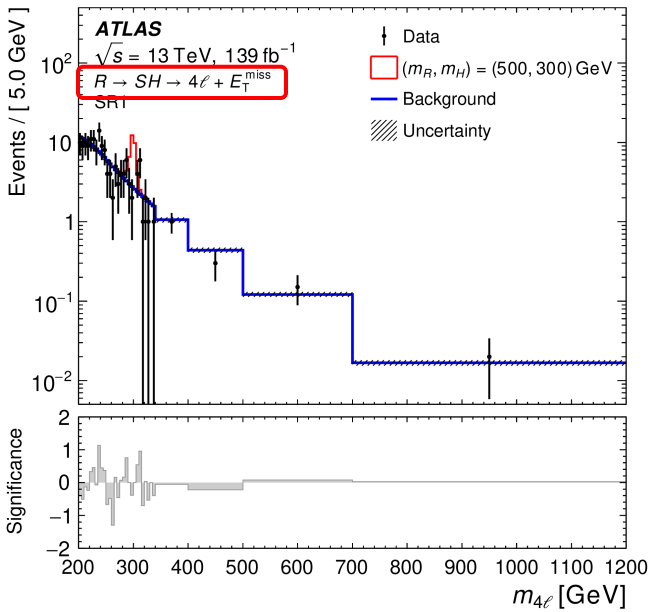
$X \rightarrow SH_{125} \rightarrow b\bar{b}\gamma\gamma$

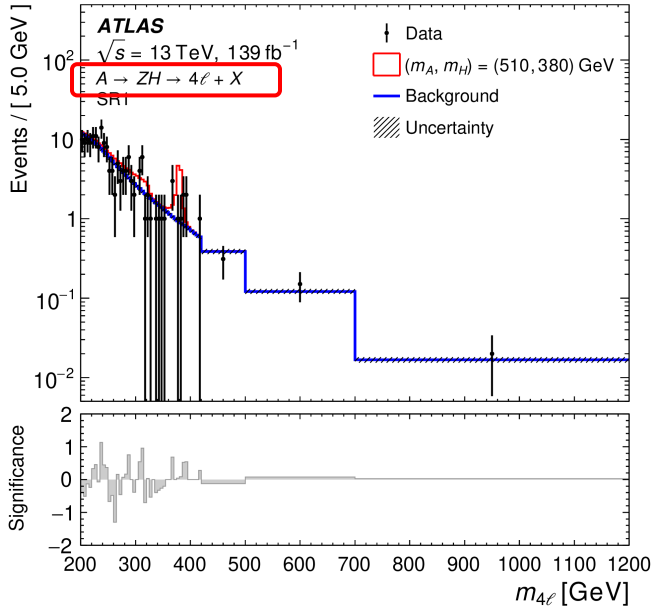


$$R \rightarrow SH \rightarrow 4l + E_T^{miss}$$
$$A \rightarrow ZH \rightarrow 4l + X$$

arXiv:2401.04742

- **Scenarios considered**:
  - (extended) 2HDM+*S*, *S* decays invisibly (DM portal!)
  - 2HDM-based baryogenesis; *X* stands for $ll/\ jj/\ inv.$
- **Selection:** single/multi- lepton triggers, 2 SFOS leptons (μ or e) consistent with m_Z. FSR correction & m_Z constraint improve 4l mass resolution.
- **7** SR's defined by n_{jets}, n_{b-jets} and E_T^{miss} signific.
- Main background from $(q\bar{q})$ ZZ production
- A dense grid of mass points generated, further proliferated by interpolation.
- A simultaneous fit is performed on the $\boldsymbol{m_{4l}}$ distributions in the SR's.





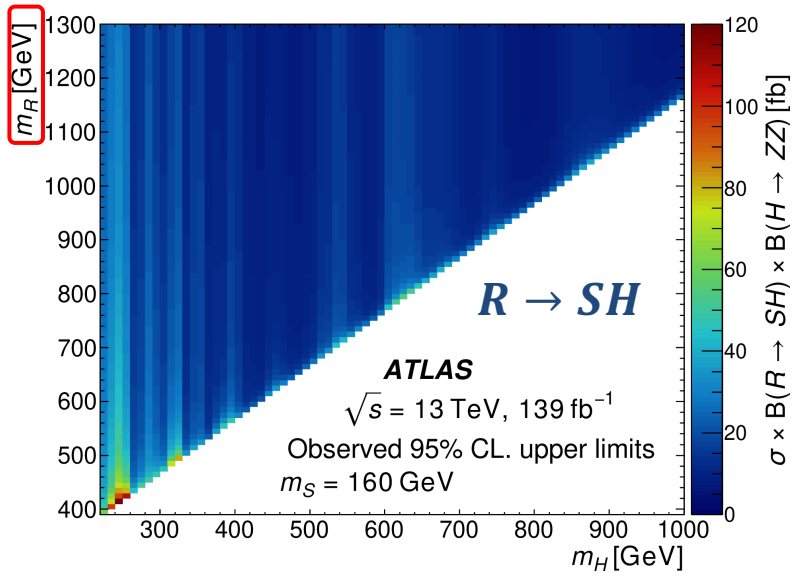
$$R \rightarrow SH \rightarrow 4l + E_T^{miss}$$
$$A \rightarrow ZH \rightarrow 4l + X$$

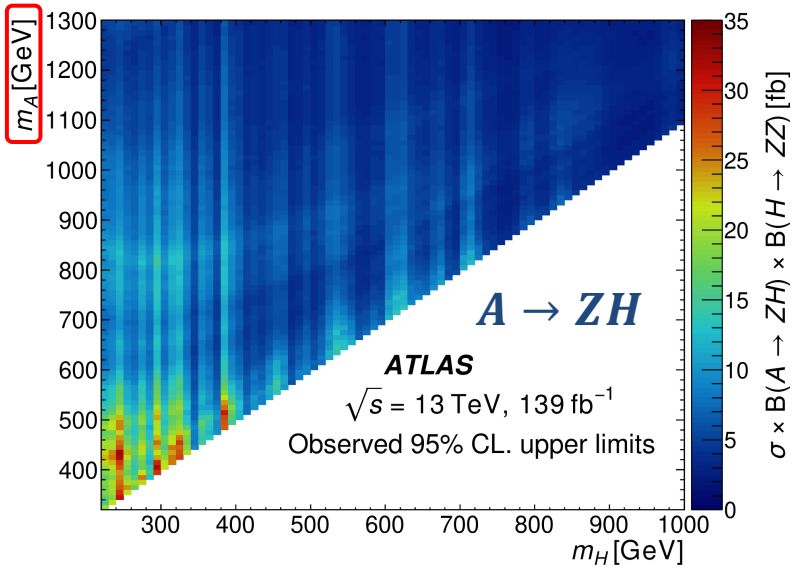
arXiv:2401.04742

Results

- No significant excess of data over SM background observed.
- Limits were set on m_R/m_H & m_A/m_H plane under the NWA, with negligible dependence on m_S (fixed to 160 GeV)
- Impact from Large Width Approx. also evaluated:

Width assumptions	Mass points [GeV]	Upper limits in the $\sigma(gg \rightarrow A)$ [fb]		Ratio w.r.t Narrow width
		Observed	Expected	
Narrow width	$(m_A, m_H) = (320, 220)$	19.6	25.1	1.0
	$(m_A, m_H) = (1190, 600)$	4.8	3.5	1.0
$(\Gamma_A/m_A, \Gamma_H/m_H) = (15\%, 5\%)$	$(m_A, m_H) = (320, 220)$	31.5	36.2	1.4
	$(m_A, m_H) = (1190, 600)$	8.3	6.0	1.7
$(\Gamma_A/m_A, \Gamma_H/m_H) = (30\%, 10\%)$	$(m_A, m_H) = (320, 220)$	38.9	42.5	1.7
	$(m_A, m_H) = (1190, 600)$	8.9	6.6	1.9





$X \to S(\to b\bar{b})H_{125}(\to \gamma\gamma)$

arXiv:2404.12915

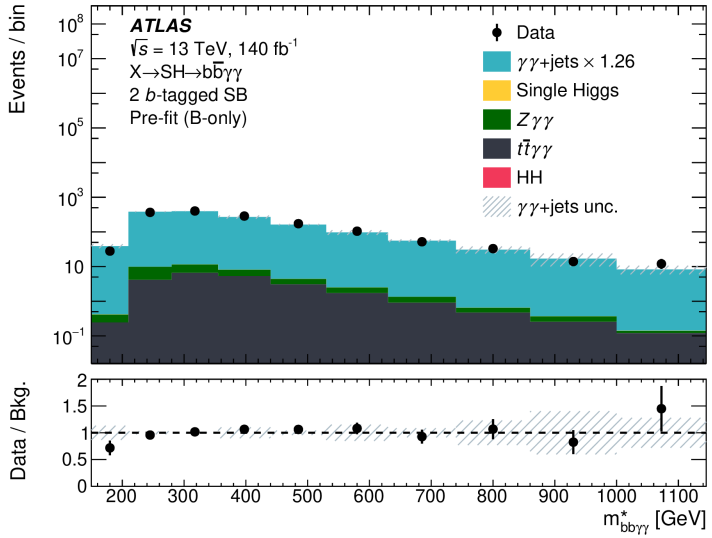
- **Scenarios considered**:
- Generic search targeting 2HDM type models or SM extended by singlets with at least 2 DoF's.

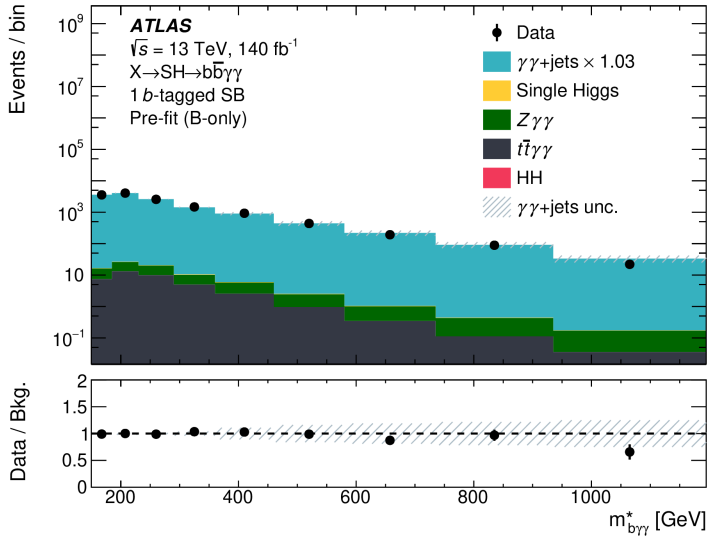
- **NWA** is assumed throughout.

- **Selection:** di-photon triggers, 2 photon mass consistent with H_{125} [120,130], exactly one b-jet (**1b SR**) or exactly 2 b-jets (**2b SR**)

- Main background ($\gamma\gamma$+jets) normalised from $m_{\gamma\gamma}$ side bands

- **Discriminant:**
  - 1b SR: PNN parameterised in (m_X)
  - 2b SR: PNN parameterised in (m_X, m_S)

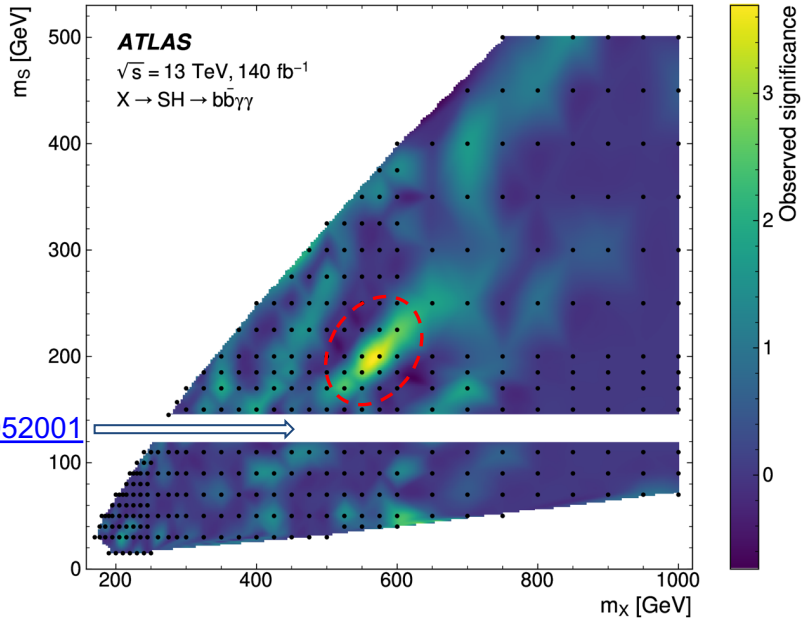




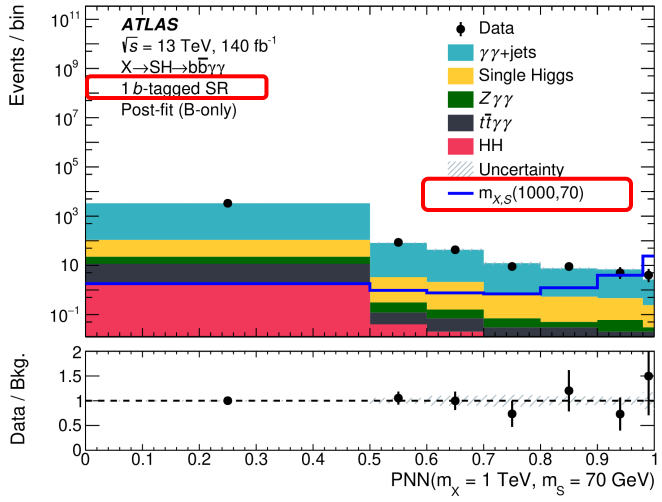
$X \to S(\to b\bar{b})H_{125}(\to \gamma\gamma)$

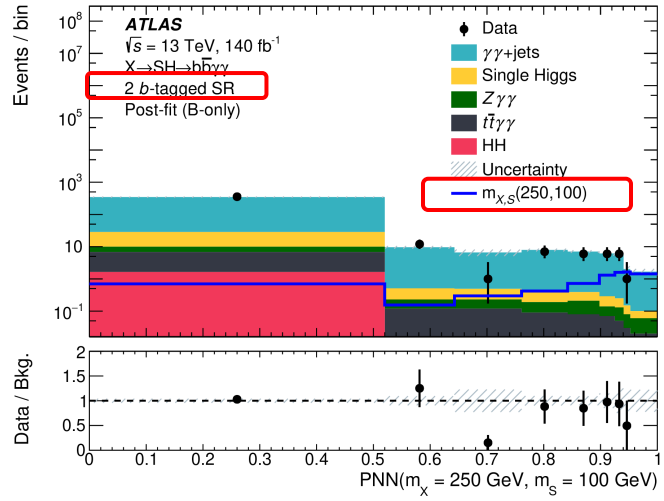
arXiv:2404.12915

Results



Covered by dedicated analysis
Phys. Rev. D **106** (2022) 052001

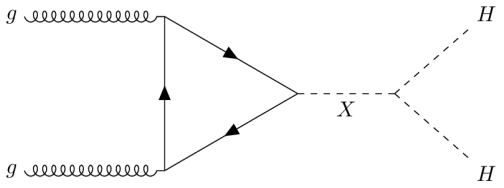




- A simultaneous fit is performed on the PNN score distributions in the SR's & sideband CR's.
- Model independent limits on $\sigma(X \to SH_{125} \to b\bar{b}\gamma\gamma)$

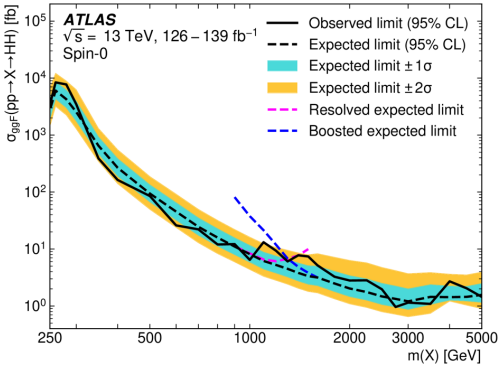
Data found compatible with the SM prediction.
Largest deviation for (m_X, m_S)=(575,200) GeV @ local (gobal) $3.5(2.0)\sigma$
CMS excess @ (m_X, m_S)=(650,90) GeV, $3.8(2.8)\sigma$, arXiv:2310.01643 not confirmed.

Search for a heavy scalar in the decay into a H_{125} pair



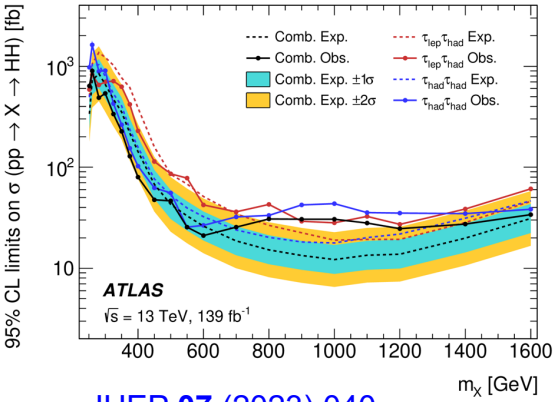
- Combining three recent searches for resonant di-Higgs production (complementary in the *X* mass coverage):

$X \to HH \to b\bar{b}b\bar{b}$



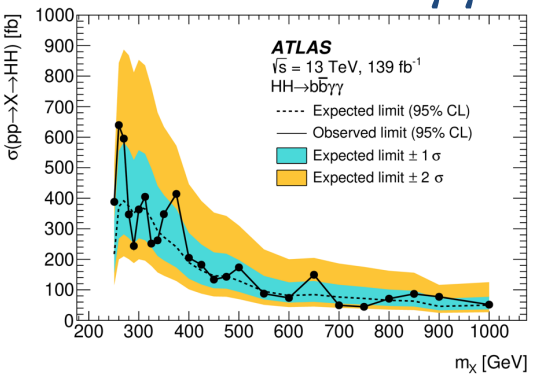
Phys. Rev. D **105** (2022) 092002

$X \to HH \to b\bar{b}\tau^{+}\tau^{-}$



JHEP **07** (2023) 040

$X \to HH \to b\bar{b}\gamma\gamma$



Phys. Rev. D **106** (2022) 052001

$X \to H_{125}H_{125}$

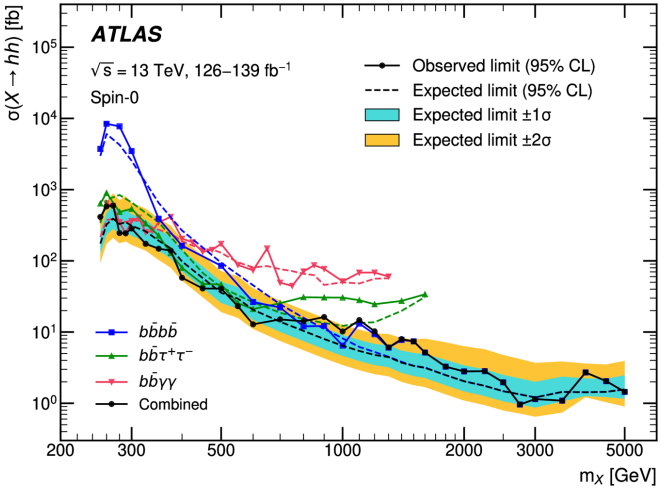
arXiv:2311.15956

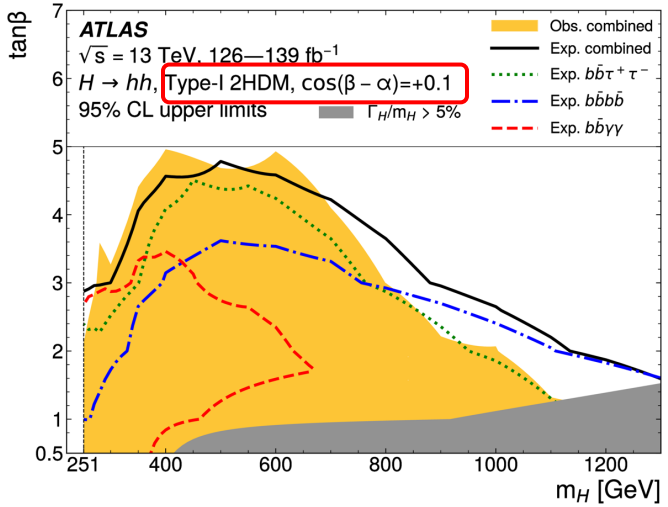
Results

- $b\bar{b}b\bar{b}$ exploits both four b-tagged R=0.4 jets as well as two R=1.0 jets tagged by constituent track jets.
  Final variable: $m_{b\bar{b}b\bar{b}}$
- $b\bar{b}\tau\tau$ exploits $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ channels.
  Final variable: PNN score
- $b\bar{b}\gamma\gamma$ exploits high resolution of the $\gamma\gamma$ system.
  Final variable: $m_{\gamma\gamma}$

- The upper limits on the resonant $\sigma(X \to hh)$ is extracted from a simultaneous fit of all signal categories.

- Limits interpreted in 2HDM type-1 & MSSM models.

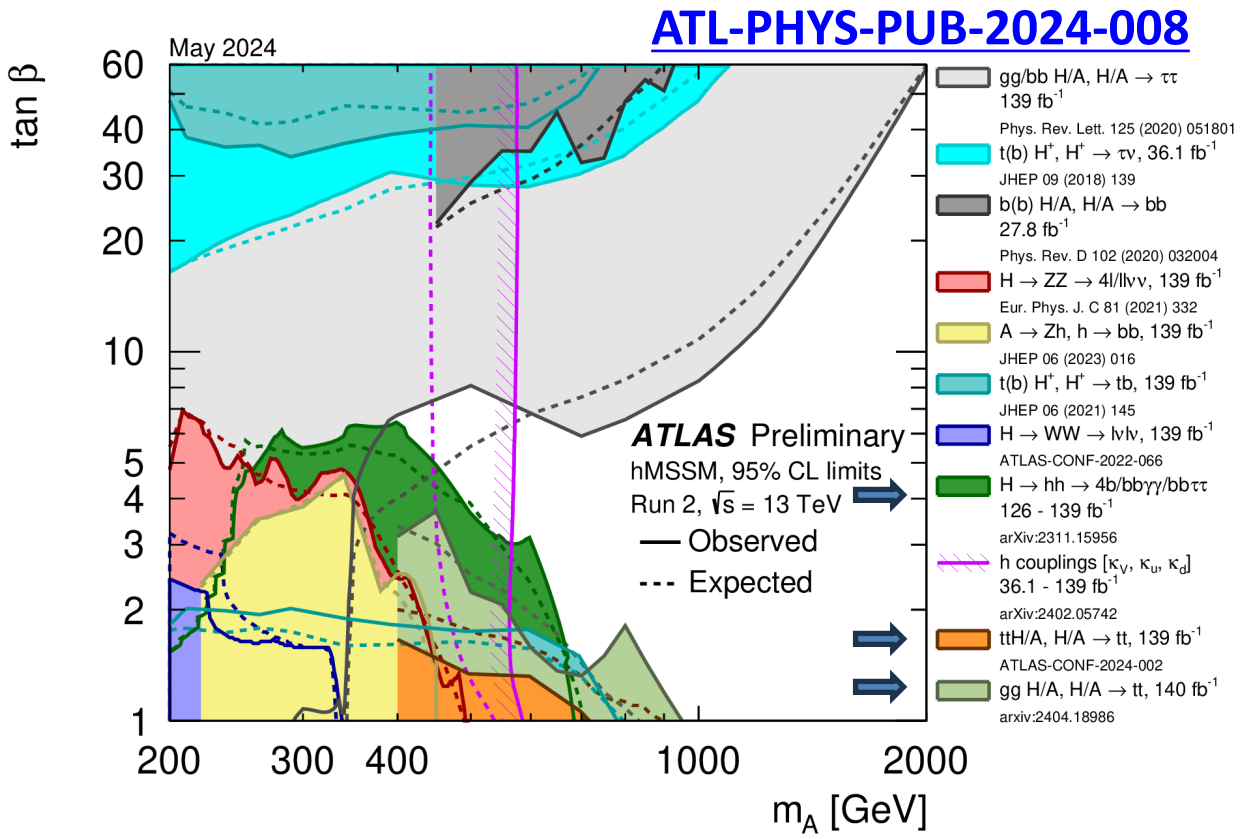




Data found compatible with the SM background prediction over the entire mass range 251 GeV to 5 TeV
Largest excess seen @ 1.1 TeV with local (global) significance 3.3 (2.1)σ

SUMMARY

- No new heavy scalar resonance confirmed so far.
- $t\bar{t}$ and di-Higgs final states extend exclusions on 2HDM-type models in the low and intermediate $\tan\beta$ range



- New exclusions on generic models with at least two additional heavy (pseudo)scalars (2D scans)

THANK YOU

BACKUP

$X \to S(\to VV)H_{125}(\to \gamma\gamma)$
$\gamma\gamma + 1(2)l$

arXiv:2405.20926

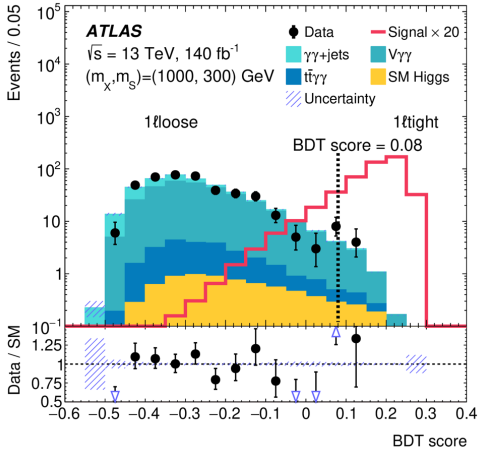
- **Scenarios considered**:
- Generic search targeting 2HDM+S type models.

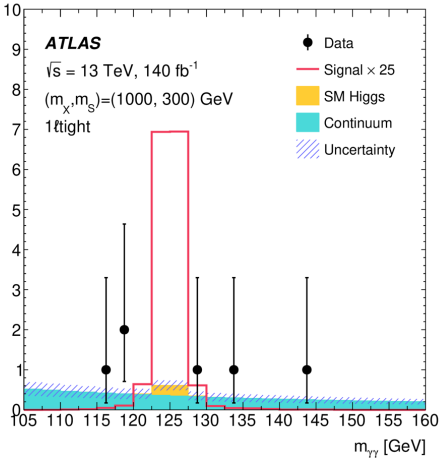
- **Selection:** di-photon triggers, 2 photon mass consistent with H_{125} [120,130], exactly one ($1l$) or two leptons ($2l$) , b-veto

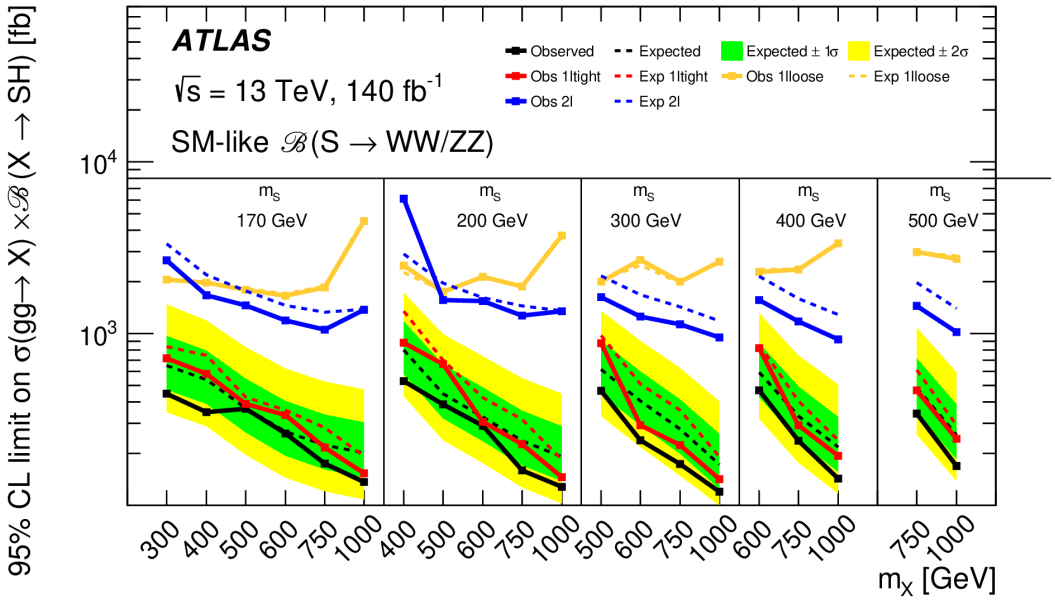
- Further enhanced by BDT in the $\gamma\gamma$WW SR.

- Main bacground ($\gamma\gamma$+jets) normalised from $m_{\gamma\gamma}$ side bands

- **Discriminant:** $m_{\gamma\gamma}$



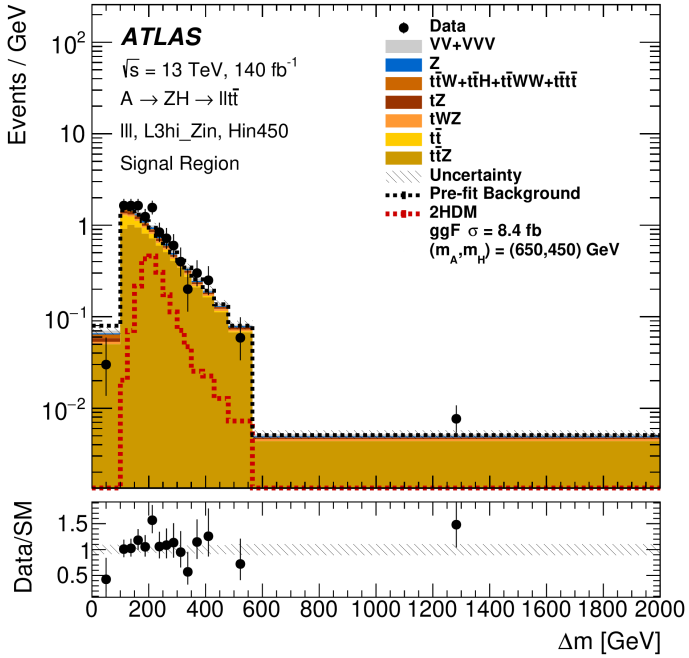




$A \to ZH \to l^+l^- + t\bar{t}$

[JHEP 02 (2024) 197]

- Motivated by: 2HDM-based baryogenesis ($m_A > m_H$)
- **Selection:** three high-p_T leptons (OSSF pair, μ or e, consistent with m_Z), ≥ 4 jets, 2 b-jets
- SR/VR's/CR's based on m_{ll} (Z) and $m_{t\bar{t}}$ (H sliding w.)
- Main background from $t\bar{t}Z$ events and leptonic $t\bar{t}$ events with a non-prompt third lepton.



Requirement	Regions				
	ss (CR)	L3hi_Zout (VR)	L3hi_Zin		L3lo_Zin (VR)
			Hlo / Hhi (CR)	Hin (SR)	
Number of leptons	3				
$p_T(\ell_1)$	> 27 GeV				
Number of jets	≥ 4				
Number of b-jets	2				
$\lvert\eta^{ZH\text{-r.fr.}}_{H\text{-cand}}\rvert$	$< 2.2 + 0.0004 \cdot m(t\bar{t})\,[\text{GeV}] - 0.0011 \cdot m(\ell^+\ell^- t\bar{t})\,[\text{GeV}]$				
$p_T(\ell_3)$	> 13 GeV				> 7 GeV & < 13 GeV
Lepton flavour	$ee\mu/\mu\mu e$	$eee/ee\mu/\mu\mu e/\mu\mu\mu$			
OSSF lepton pairs	0	≥ 1			
$\lvert m_Z^{\text{cand}} - m_Z\rvert$	< 20 GeV	> 10 GeV & < 20 GeV	< 10 GeV		
$\lvert m(t\bar{t}) - m_H\rvert$ $m_H < 500$ GeV	-		$> 0.32 \cdot m_H$	$< 0.32 \cdot m_H$	-
$\lvert m(t\bar{t}) - m_H\rvert$ $m_H \geq 500$ GeV			$> 0.24 \cdot m_H$	$< 0.24 \cdot m_H$	

$A \to ZH \to l^+l^- + t\bar{t}$

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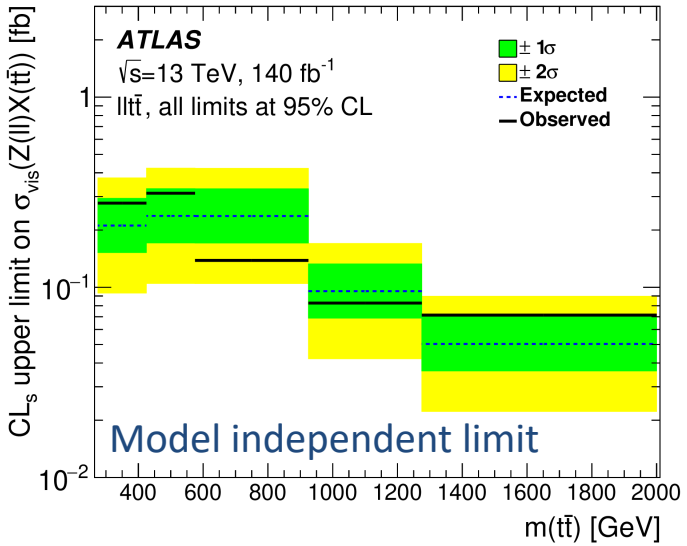
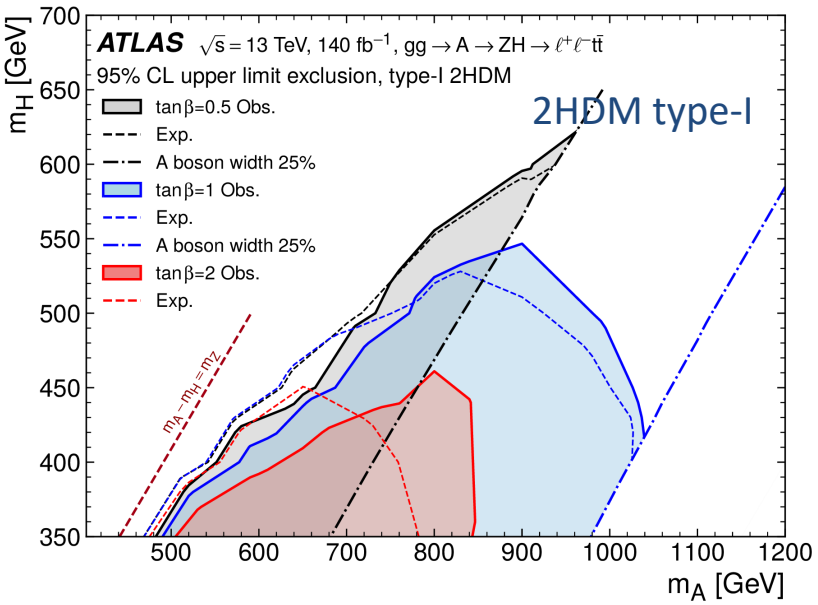
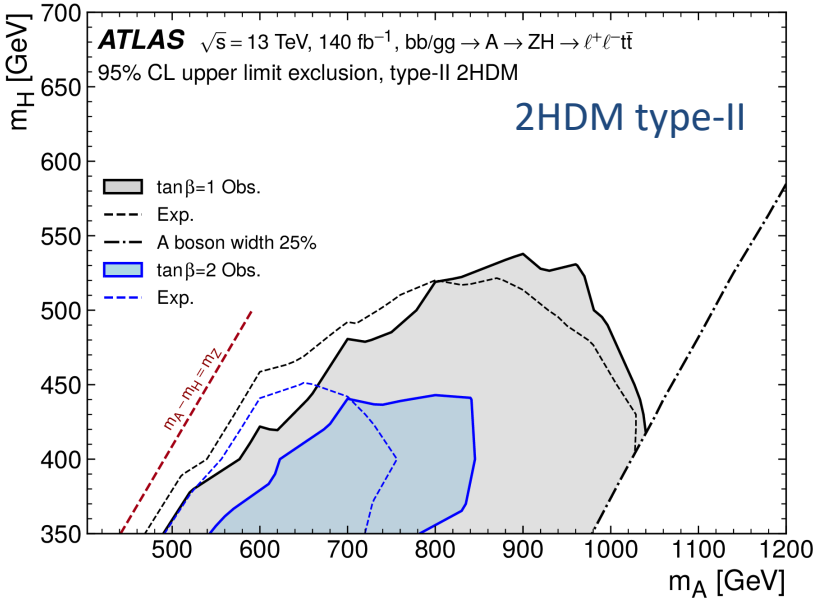
- A simultaneous fit is performed to the $\Delta m = m(lltt\bar{t}) - m(t\bar{t})$ distribution in SR and event yields in the SS ($t\bar{t}$ norm.), Hlo & Hhi ($t\bar{t}Z$ norm.) CR's.
- The result is limited statistically

No significant excess over SM observed
The largest excess of local (global) significance 2.85 (2.35) σ observed for (m_A,m_H) = (650,450) GeV

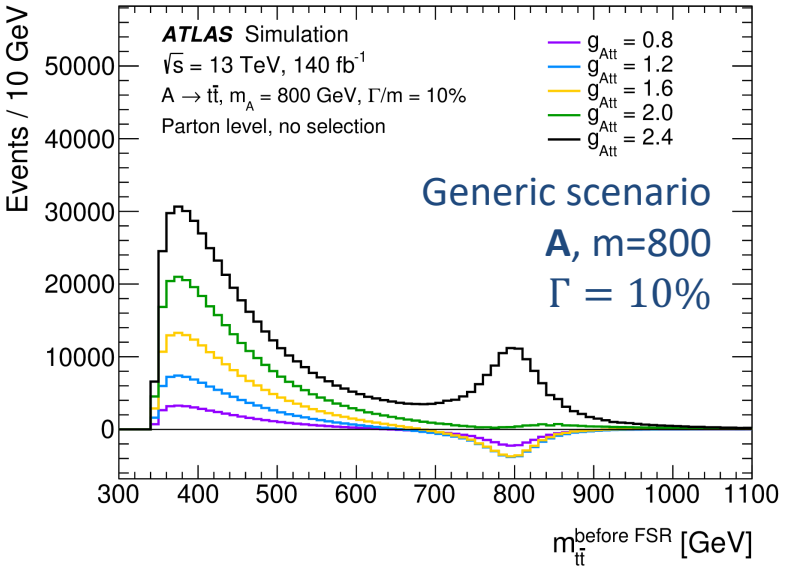


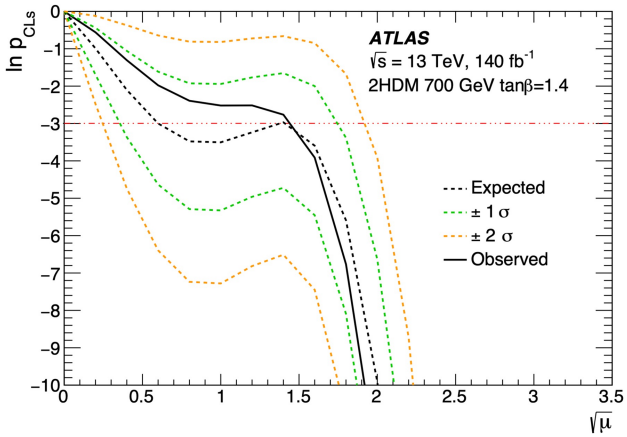


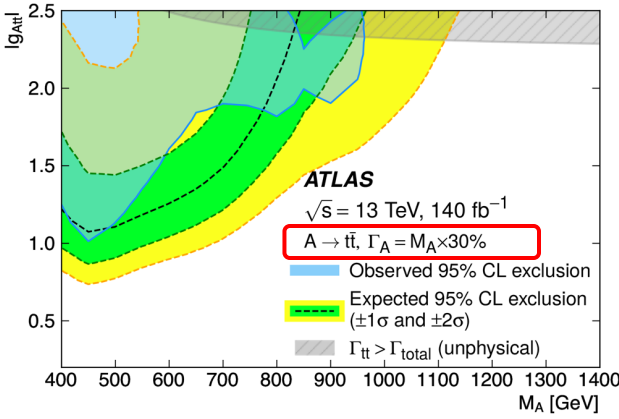


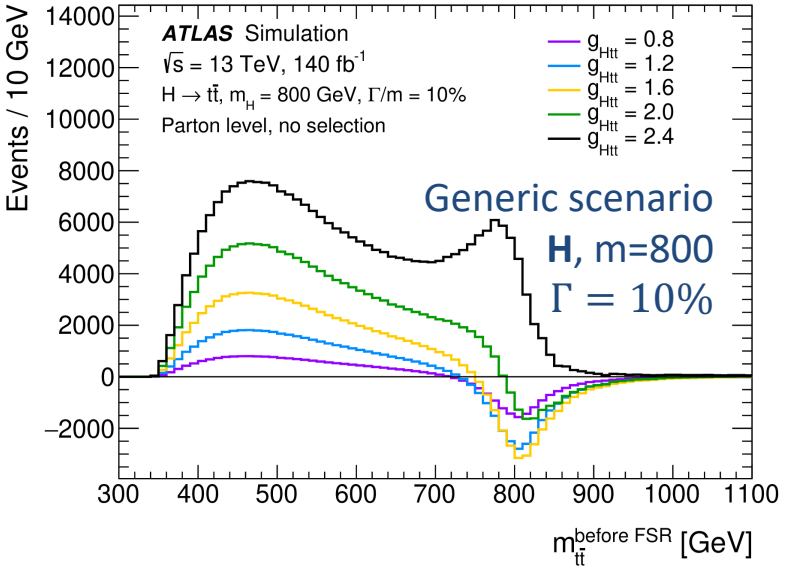
A/H → $t\bar{t}$ (l, ll_{OS} final states)

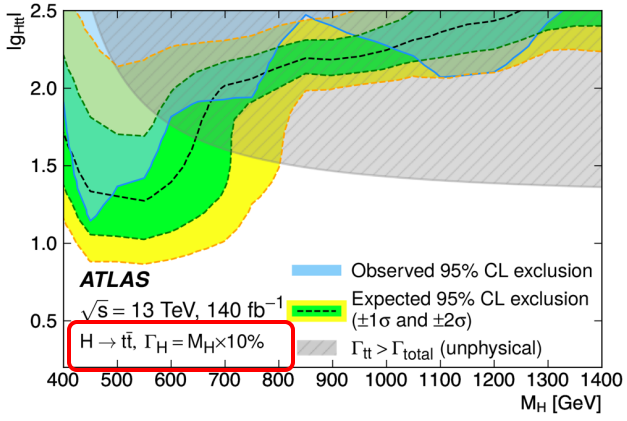
arXiv:2404.18986

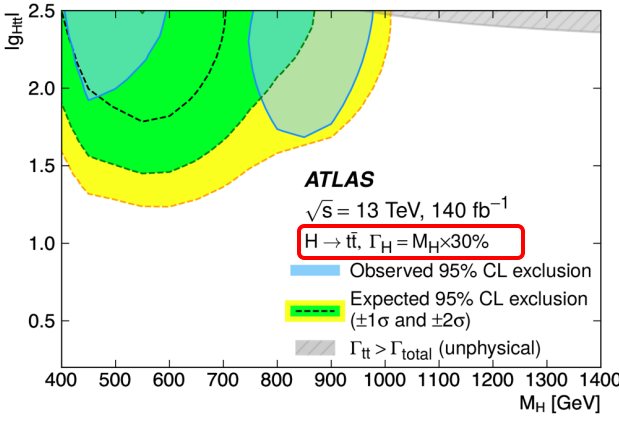






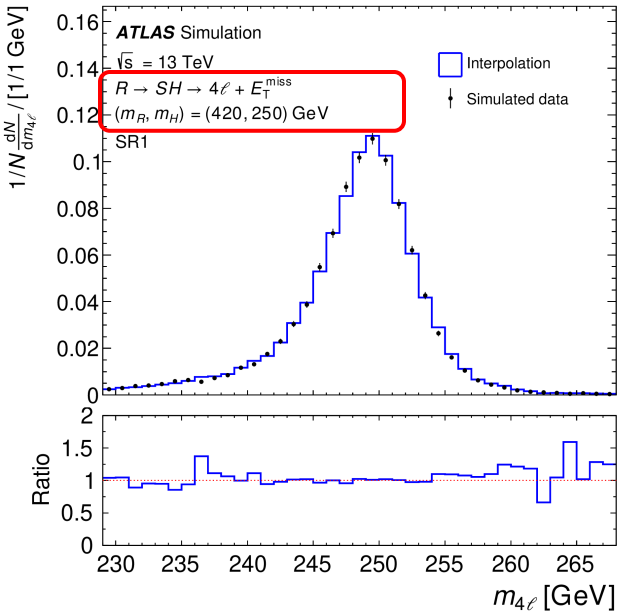


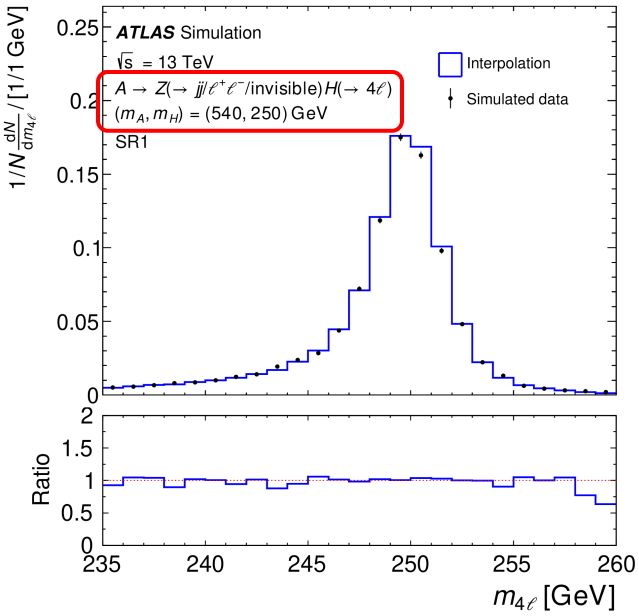


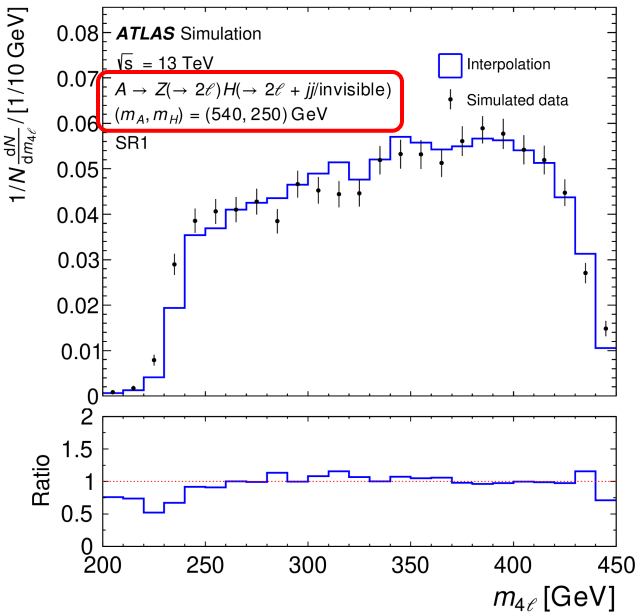


$R \rightarrow SH \rightarrow 4l + E_T^{miss}$
$A \rightarrow ZH \rightarrow 4l + X$

arXiv:2401.04742



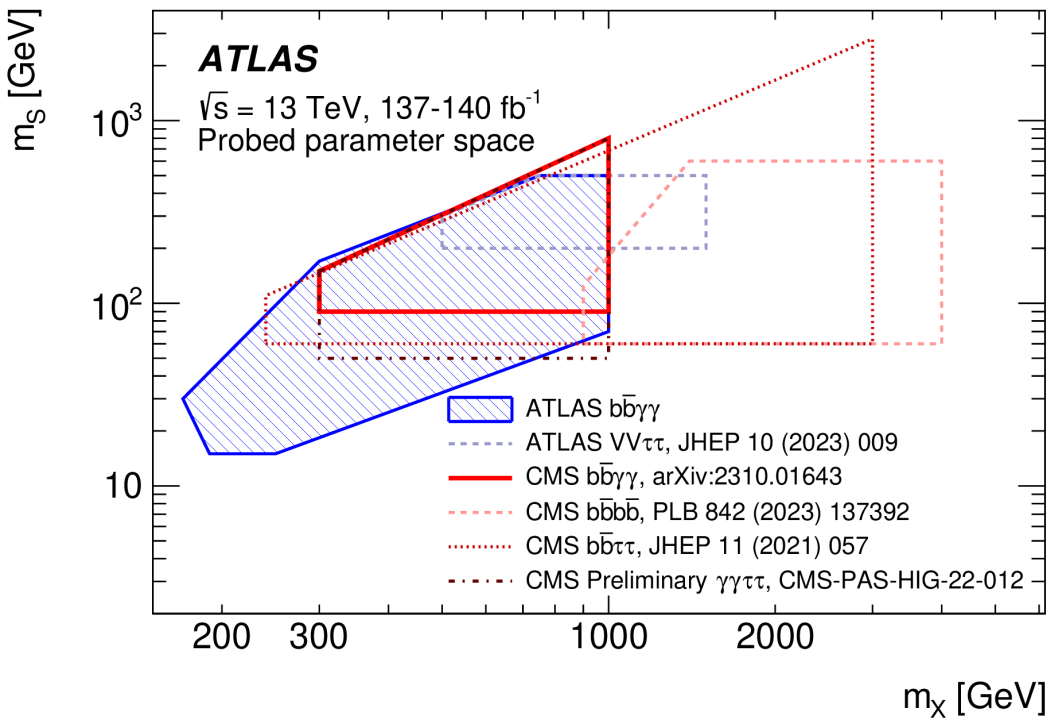


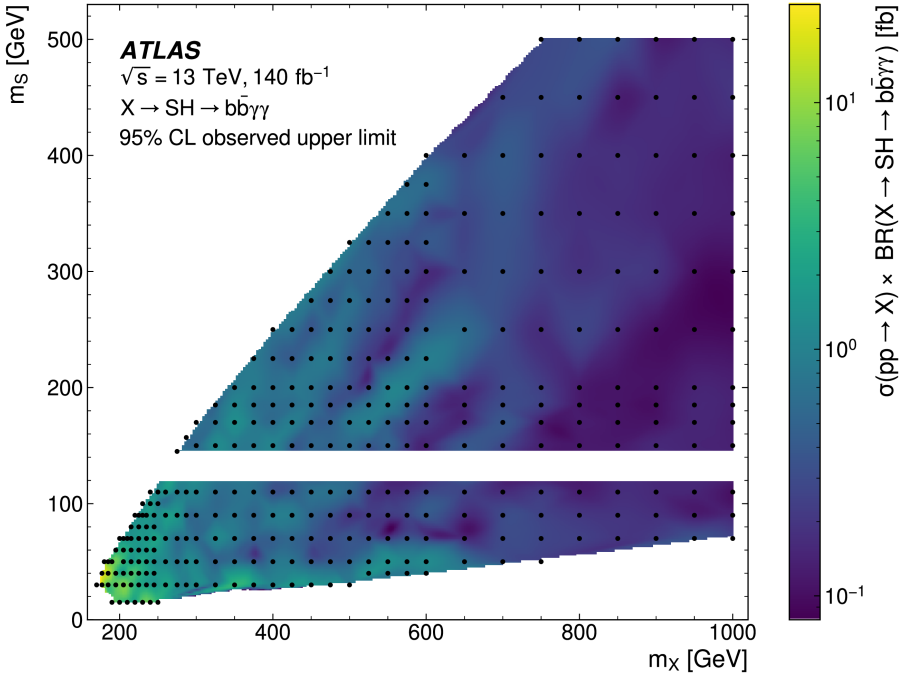


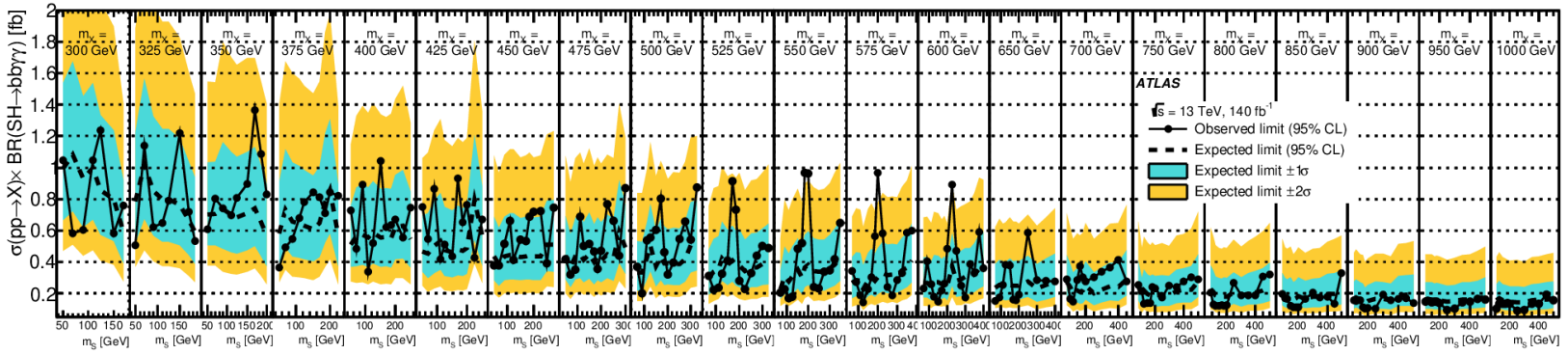
Signal region	$R \rightarrow SH \rightarrow 4\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ and $A \rightarrow ZH \rightarrow 4\ell + X$			
SR1	$n_{b\text{-jets}} = 0$	$n_{\mathrm{jets}} = 0$	$p_{\mathrm{T}}^{4\ell} > 20$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance >2.0
SR2		$n_{\mathrm{jets}} \geq 1$	$p_{\mathrm{T}}^{4\ell} > 10$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 3.5
SR3			$p_{\mathrm{T}}^{4\ell} < 10$ GeV	$2.5 < E_{\mathrm{T}}^{\mathrm{miss}}$ significance < 3.5
	$A \rightarrow ZH \rightarrow 4\ell + X$			
SR4	$n_{b\text{-jets}} = 0$	$n_{\mathrm{jets}} \geq 2$	$\lvert m_{jj} - m_Z \rvert < 20$ GeV	
SR5			$\lvert m_{jj} - m_Z \rvert > 20$ GeV	
SR6		$n_{\mathrm{jets}} = 1$		
SR7	$n_{b\text{-jets}} \geq 1$			

$X \to S(\to b\bar{b})H_{125}(\to \gamma\gamma)$

arXiv:2404.12915







Other related ATLAS results

CDM (2HDM+a) combination: **EXOT-2018-64**

$t\bar{t}\mathrm{A}/\mathrm{H} \rightarrow t\bar{t}t\bar{t}$ (ll_{SS} , ML final states) **EXOT-2019-26**

$X \rightarrow$ multilepton + b-jets **HDBS-2020-03**

$X \rightarrow HS \rightarrow VV\tau\tau$ **HDBS-2022-44**

Corresponding CMS results

$A/H \to t\bar{t}$	HIG-17-027	(36 fb^{-1})
$A \to ZH \to \tau\tau ll$	HIG-18-023	
$X \to SH_{125} \to b\bar{b}\gamma\gamma$	HIG-21-011	NEW
$X \to HY \to b\bar{b}b\bar{b}$	B2G-21-003	
$X \to HS \to b\bar{b}\tau\tau$	HIG-20-014	
$X \to HH \to b\bar{b}WW$	HIG-21-005	NEW
$X \to HH \to WWWW, WW\tau\tau, \tau\tau\tau\tau$	HIG-21-002	