Search beyond SM Higgs boson with the ATLAS experiment

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on behalf of the ATLAS collaboration

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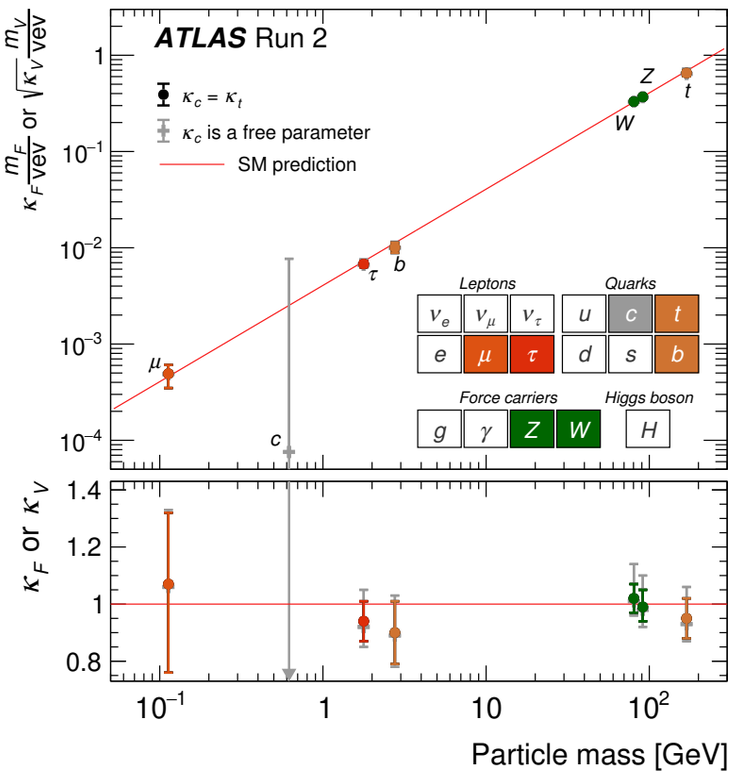
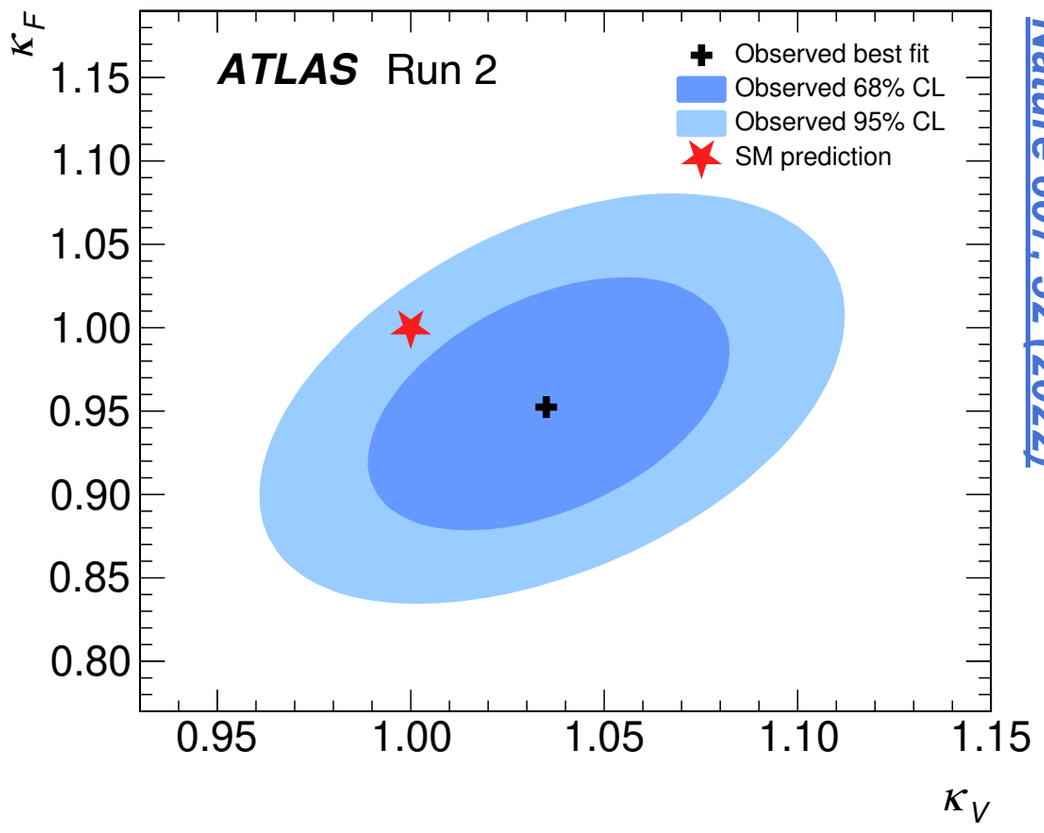
The Higgs Boson

The Standard Model (SM)

- Only one neutral Higgs boson, with spin 0, CP even
- Until now, all the Higgs properties measured from experiments are consistent with the SM prediction
- No BSM particle has been found up to now





Questions related to the SM Higgs sector

- Mass of neutrino
- Dark matter
- Baryogenesis

The SM cannot be the final, complete theory
The SM Higgs boson is not the only Higgs boson

Extensions of the Higgs sector

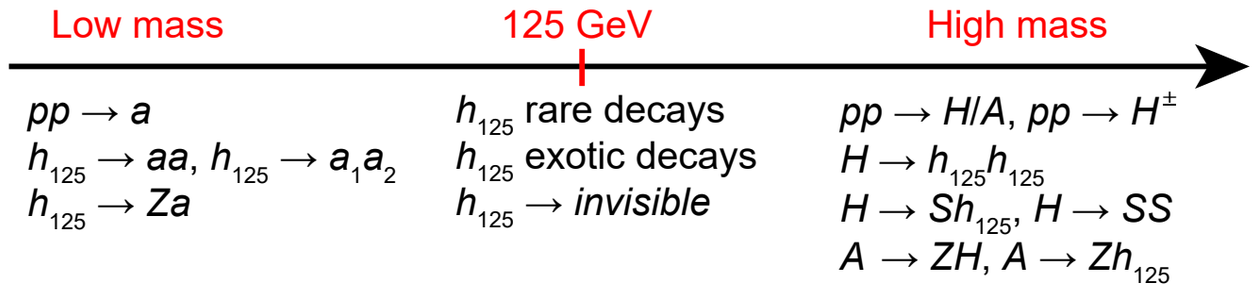
- SM + one singlet
  - 2 neutral CP-even Higgs bosons h, H
- SM + two-real-singlet model
  - 3 neutral CP-even Higgs h_1, h_2, h_3
- Two Higgs Doublet Model (2HDM, e.g. MSSM)
  - 5 Higgs bosons: 2 neutral CP-even, 1 neutral CP-odd and two charged h, H, A, H^+, H^-
  - Different Type dependent on the coupling with up/down quarks and leptons

2HDM Type	Up-type quarks couple to	Down-type quarks couple to	Charged leptons couple to
Type-I	Φ_2	Φ_2	Φ_2
Type-II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

- 2HDM + singlet (e.g. NMSSM)
  - 7 Higgs bosons: 5 of the 2HDM + 2 additional neutral (1 CP-even and 1-CP odd) S, a
- Higgs triplet model
  - 7 Higgs bosons: 5 of the 2HDM + 2 double charged H^{++}, H^{--}
- Georgi–Machacek (GM) model: SM Higgs + adding two triplets
  - 10 Higgs $h, H, H_3, H_3^{\pm}, H_5, H_5^{\pm}, H_5^{\pm\pm}$

Experimental signatures

- group the experimental signatures by the mass of the new scalar resonance



Overview of ATLAS Run2 results

Heavy neutral CP-even Higgs
Decays to SM particles

Heavy neutral CP-odd Higgs
Decays to SM or heavy Higgs

Charged Higgs

Heavy neutral CP-even Higgs
Decays to SM Higgs (or scalar)

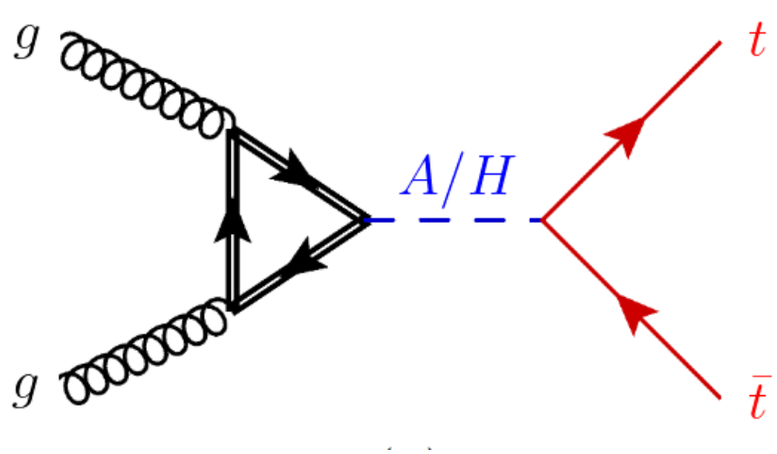
SM Higgs exotic decays

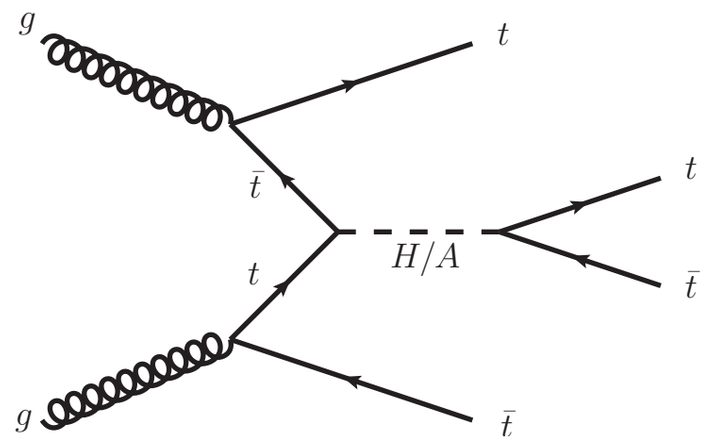
Decay channel	Production mode	Mass [GeV]	Significance local	Significance global	L [fb^{-1}]
$H \to \tau\tau$	b-associated	400	2.7σ	n.a.	139
$H \to \tau\tau$	ggF	400	2.2σ	n.a.	139
$H \to \mu\mu$	b-associated	480	2.3σ	0.6σ	36
$H \to t\bar{t}$	ggF	800	2.3σ	n.a.	140
$H \to t\bar{t}/t\bar{q}$	qq and qg	900	2.8σ	n.a.	139
$H \to ZZ \to 4\ell/2\ell 2\nu$	ggF	240	2.0σ	0.5σ	139
$H \to ZZ \to 4\ell/2\ell 2\nu$	VBF	620	2.4σ	0.9σ	139
$H \to \gamma\gamma$	ggF	684	3.3σ	1.3σ	139
$H \to \gamma\gamma$	ggF	95.4	1.7σ	n.a.	140
$H \to Z(\ell\ell)\gamma$	ggF	420	2.3σ	n.a.	140
$H \to Z(q\bar{q})\gamma$	ggF	3640	2.5σ	n.a.	139
$A \to Zh_{125}(b\bar{b})$	ggF	500	2.1σ	1.1σ	139
$A \to Zh_{125}(b\bar{b})$	b-associated	500	1.6σ	n.a.	139
$A \to ZH \to \ell\ell b\bar{b}$	ggF	610 (A), 290 (H)	3.1σ	1.3σ	139
$A \to ZH \to \ell\ell b\bar{b}$	b-associated	440 (A), 220 (H)	3.1σ	1.3σ	139
$A \to ZH \to \ell\ell WW$	ggF	440 (A), 310 (H)	2.9σ	0.8σ	139
$A \to ZH \to \ell\ell t\bar{t}$	ggF	650 (A), 450 (H)	2.9σ	2.4σ	140
$A \to ZH \to Zh_{125}(b\bar{b})h_{125}(b\bar{b})$	VH	420 (A), 320 (H)	3.8σ	2.8σ	139
$H^+ \to cb$	$t\bar{t}$ decay	130	3.0σ	2.5σ	139
$H^+ \to Wa(\mu\mu)$	$t\bar{t}$ decay	120–160 (H^+), 27 (a)	2.4σ	n.a.	139
$H^+ \to WZ$	VBF	375	2.8σ	1.6σ	139
$H^{++} \to WW$	VBF	450	3.2σ	2.5σ	139
$H \to h_{125}h_{125} \to 4b$	ggF	1100	2.3σ	0.4σ	126–139
$H \to h_{125}h_{125} \to 4b$	VBF	550	1.5σ	n.a.	126
$H \to h_{125}h_{125} \to b\bar{b}\tau\tau$	ggF	1000	3.1σ	2.0σ	139
$H \to h_{125}h_{125}$ combination	ggF	1100	3.3σ	2.1σ	126–139
$X \to Sh_{125} \to b\bar{b}\gamma\gamma$	ggF	575 (X), 200 (S)	3.5σ	2.0σ	140
$h_{125} \to Z_d Z_d \to 4\ell$	ggF	28	2.5σ	n.a.	139
$h_{125} \to ZZ_d \to 4\ell$	ggF	39	2.0σ	n.a.	139
$h_{125} \to aa \to b\bar{b}\mu\mu$	ggF, VBF, VH	52	3.3σ	1.7σ	139
$h_{125} \to aa \to 4\gamma$	ggF	10–25	1.5σ	n.a.	140
$h_{125} \to e\tau$ and $h_{125} \to \mu\tau$	ggF, VBF, VH	125	2.1σ	n.a.	138

Very fruitful results have been provided by ATLAS using Run-2 data

Only a couple of recent results will be presented today

Heavy Higgs $H \to t\bar{t}$

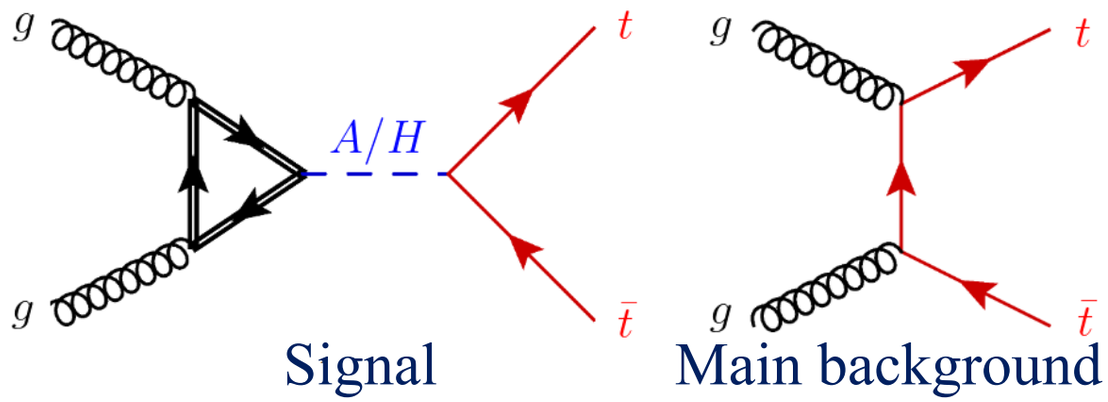




Heavy Higgs $H/A \to t\bar{t}$ (1)

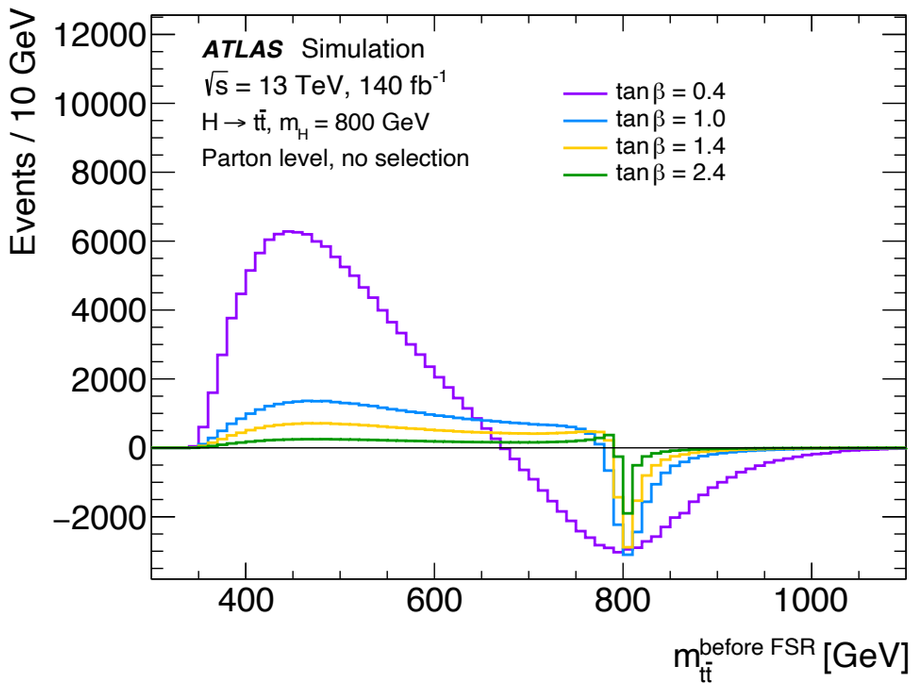
arXiv:2404.18986

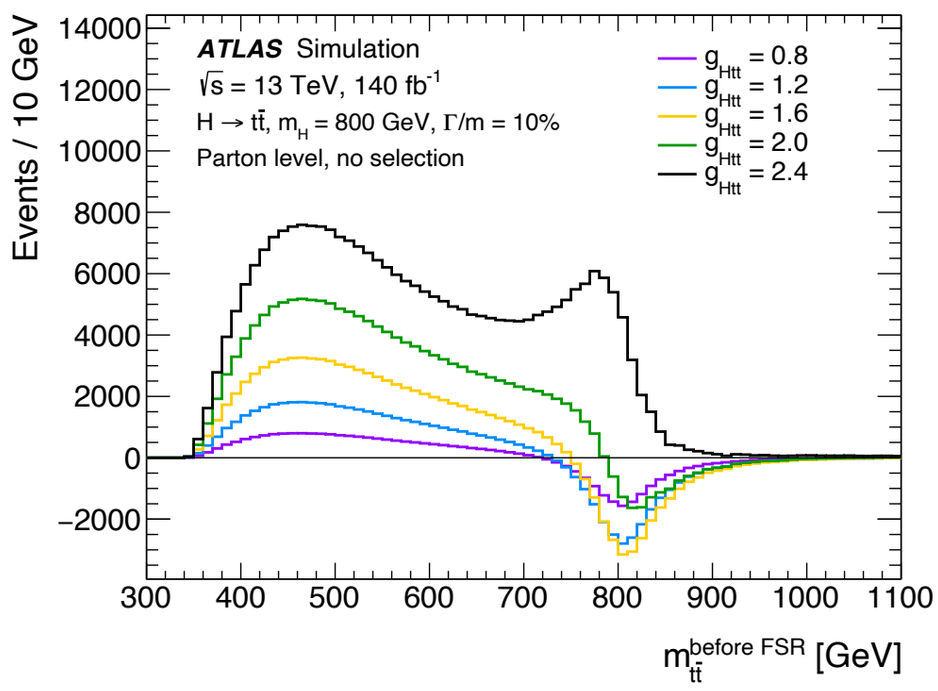
- Massive scalar (H) and pseudo-scalar (A) decaying to $t\bar{t}$
- Gluon-gluon fusion production mode



Signal framework

- Type-II 2HDM and hMSSM
- The interference pattern depends on the coupling modifier $g_{A/Ht\bar{t}}$
  - In type-II 2HDM $g_{At\bar{t}} = 1/\tan\beta$, $g_{Ht\bar{t}} = -1/\tan\beta$
  - $\tan\beta$ the ratio of the vacuum expectation values of the two Higgs doublets





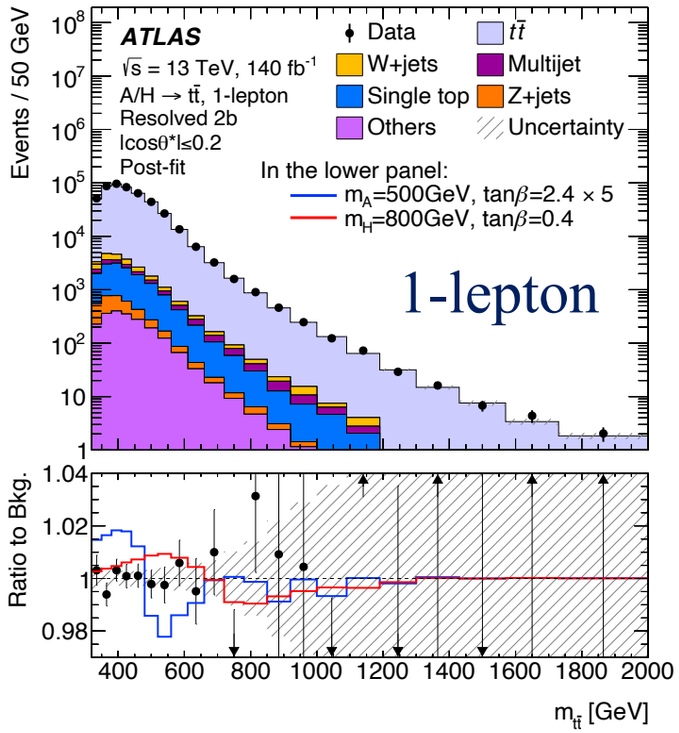
Signal-plus-interference distributions

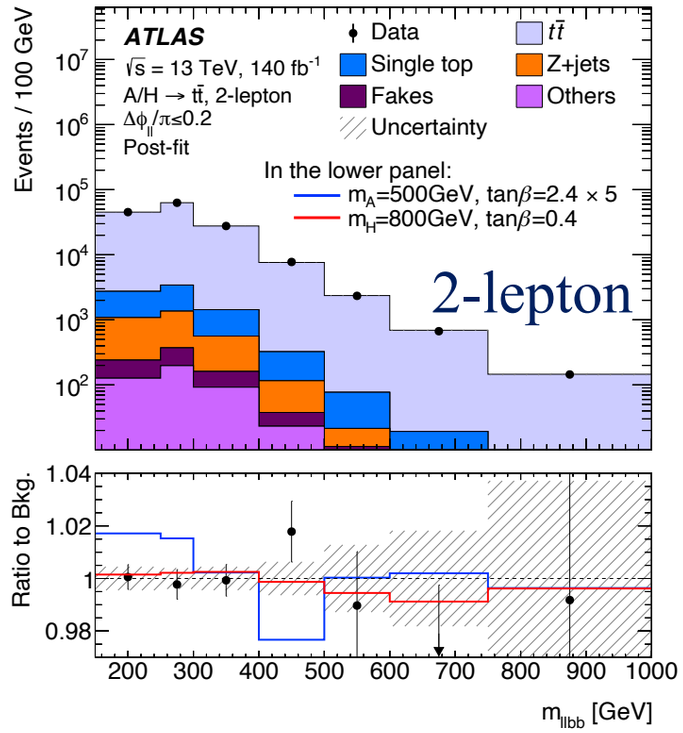
Heavy Higgs $H/A \to t\bar{t}$ (2)

arXiv:2404.18986

Analysis strategy

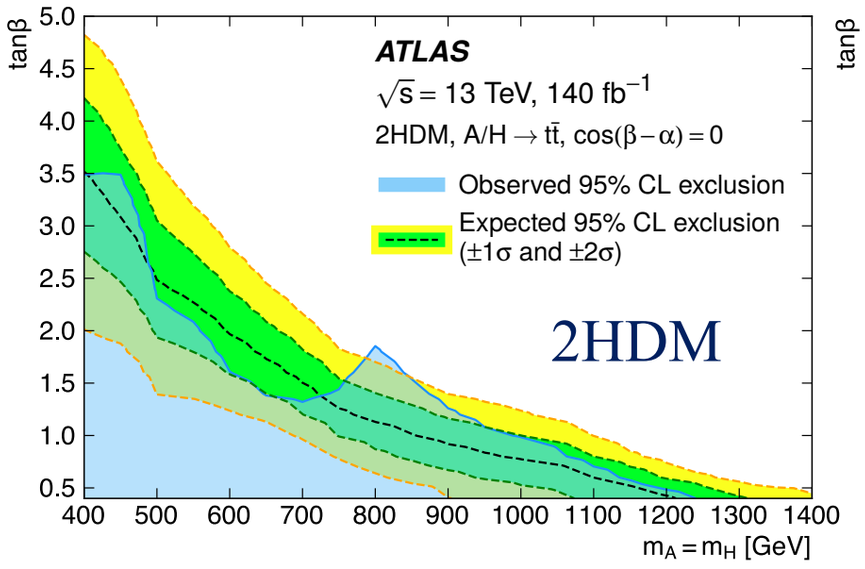
- Depending on the number of leptons (electron or muon), separate into 1-lepton and 2-lepton channels
- In the 1-lepton channel, separate to merged-topology (≥ 1 large variable radius jet) and resolved-topology (≥ 4jets)
- Use angle information to further categorise the events

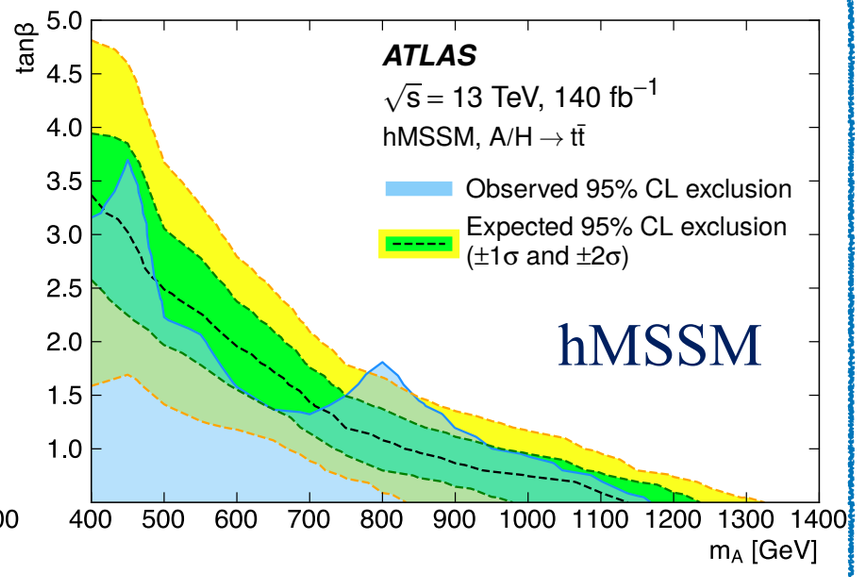




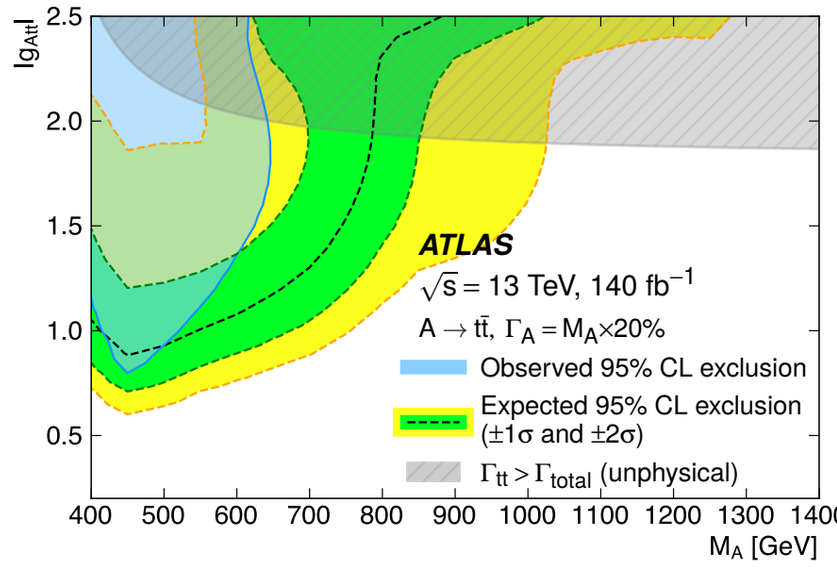
Results

- The highest local significance is 2.3σ, at $m_A = 800$ GeV, $\Gamma_A/m_A = 10\%$





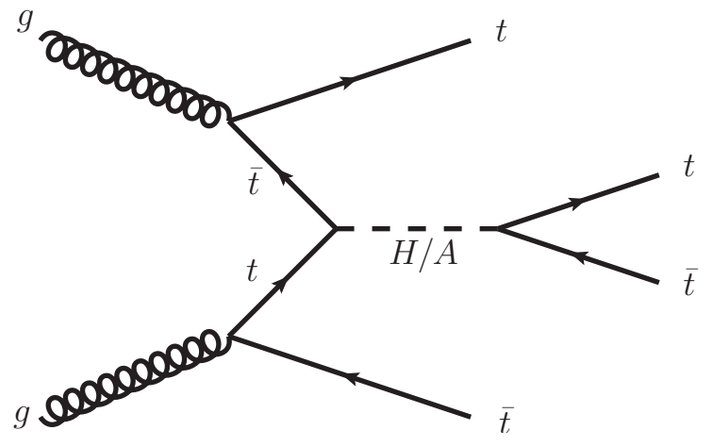
Exclusion of $\tan\beta$ in different mass region



Constraints on $g_{At\bar{t}}$

Heavy Higgs $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$

ATLAS-CONF-2024-002



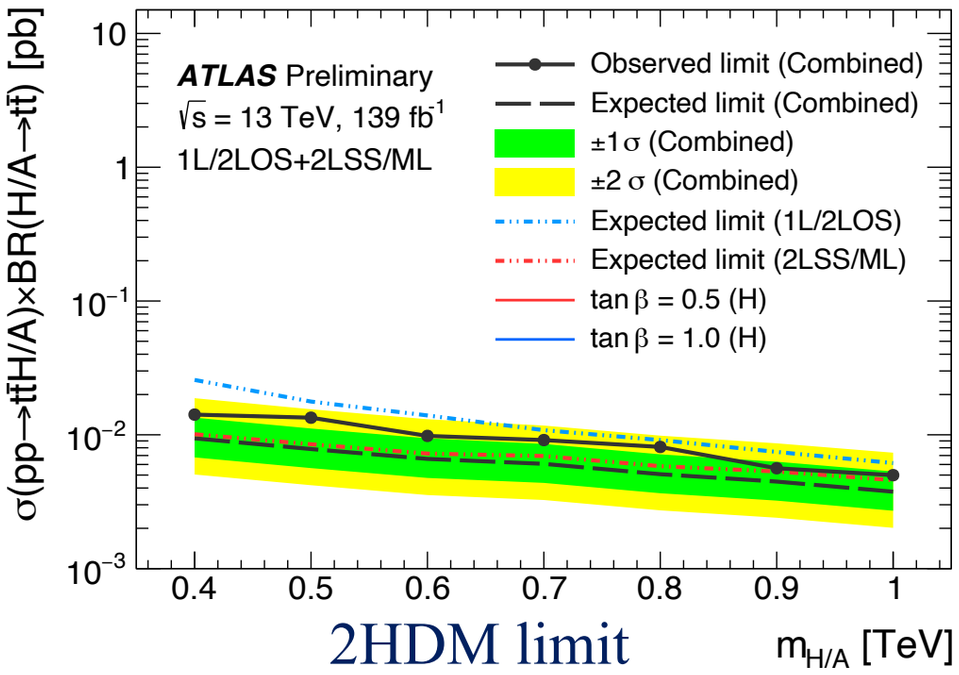
- Massive scalar (H) and pseudo-scalar (A) decaying to $t\bar{t}$
- production in association with top pairs
  - less susceptible to interference effects with the SM 4 top production

Two analyses presented:

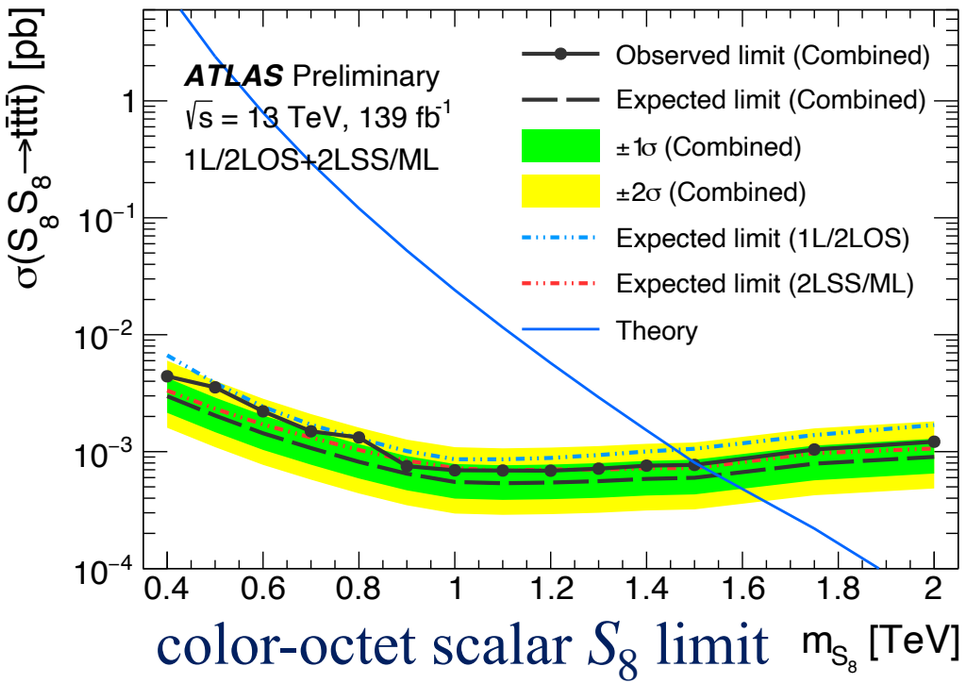
- Two same-sign leptons or at least three leptons [JHEP 07 (2023) 203]
- One lepton or two opposite-sign leptons [ATLAS-CONF-2024-002]

Results

- 2LSS/ML: No significant excess of events over the Standard Model expectation is observed
- 1L/2LOS: Largest local significance: 2.1σ at $m_{A/H} = 500$ GeV
- Combined limit:

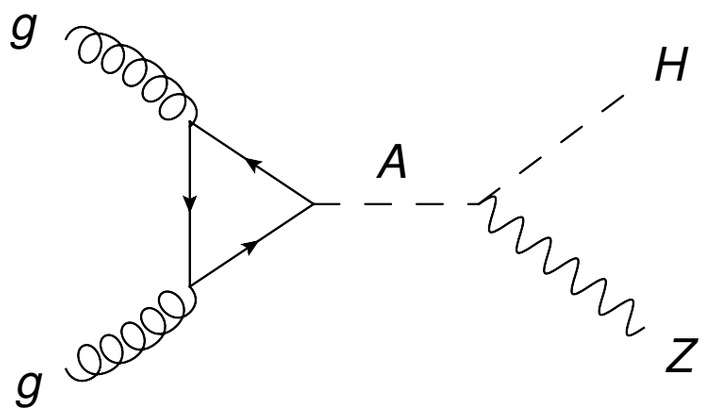


2HDM limit

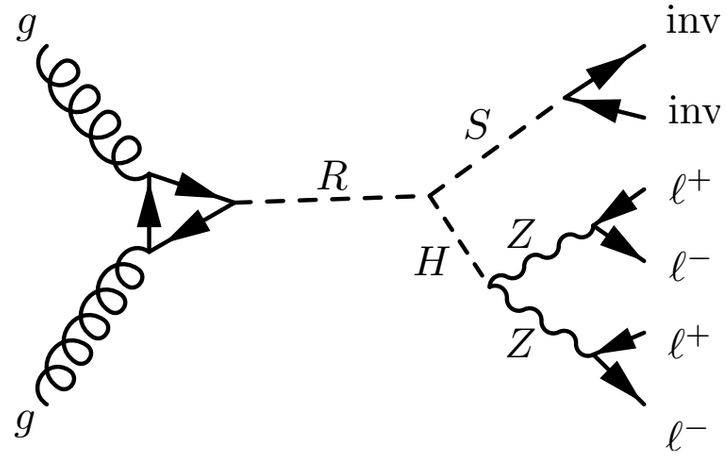


color-octet scalar S_8 limit

$A \to ZH, R \to SH$



- A: Heavy pseudo-scalar
- H: Heavy scalar



- R: Heavy pseudo-scalar
- S: scalar

$A \to ZH \to \ell\ell t\bar{t}/\nu\nu b\bar{b}$

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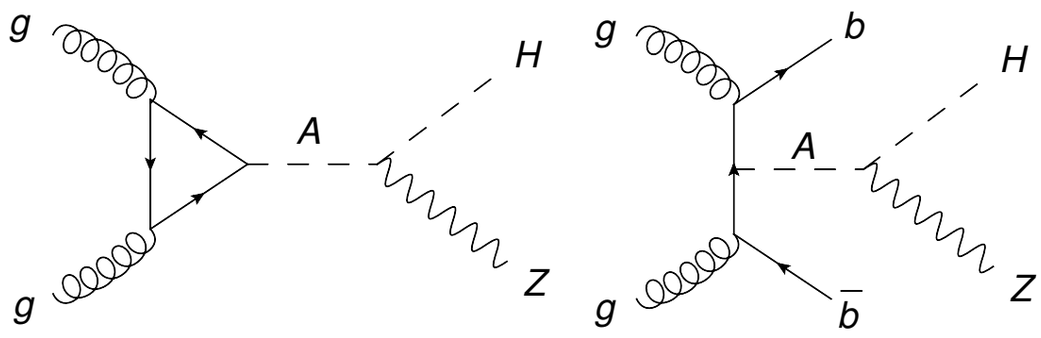
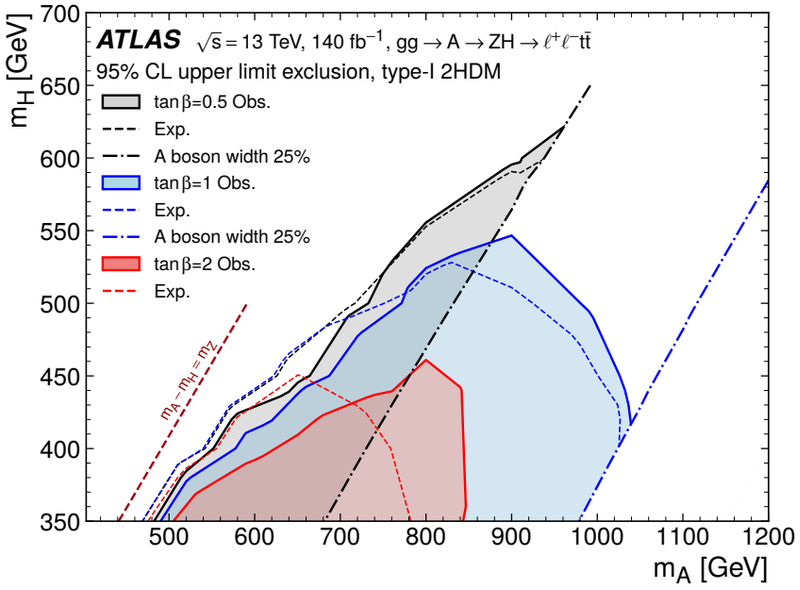
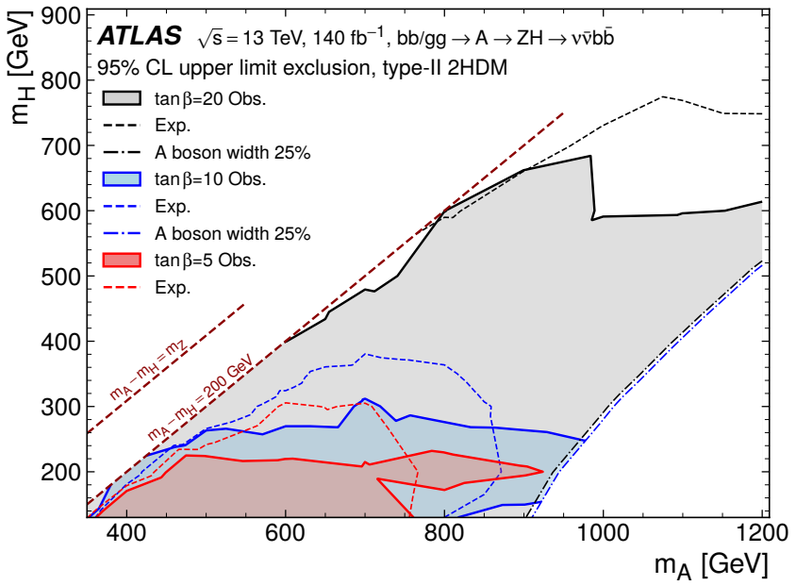
- High mass pseudo-scalar (A) decay to massive scalar (H) and Z boson
- $\ell\ell t\bar{t}$: only gluon-gluon fusion production is considered
- $\nu\nu b\bar{b}$: consider both gluon-gluon fusion and b-pair association production for Type-II 2HDM interpretation

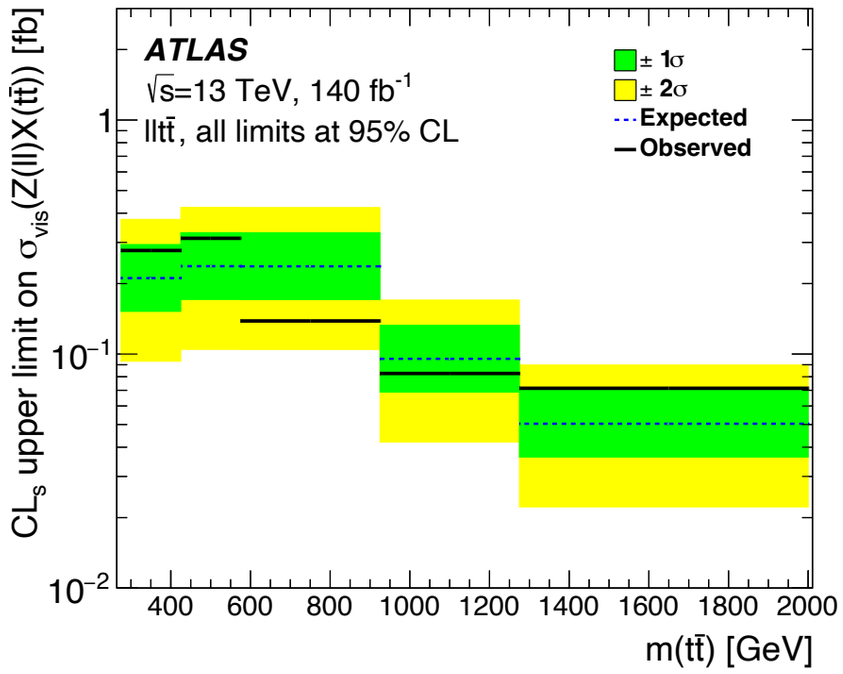


Results

- Provide (m_A, m_H) limit in different $\tan\beta$
- Largest local significance: 2.85σ in $\ell\ell t\bar{t}$ channel, at $(m_A, m_H) = (650,450)$ GeV
- Model-independent limits are also provided in the $\ell\ell t\bar{t}$ and $\nu\nu b\bar{b}$ channel separately







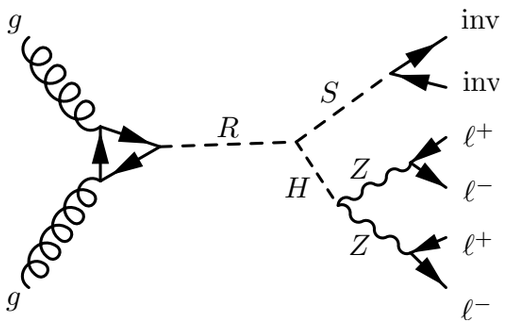
$A \to ZH$ and $R \to SH$

arXiv:2401.04742

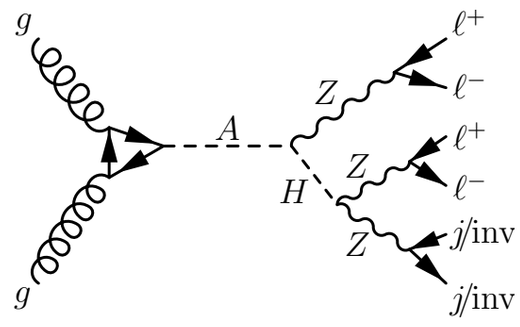
- Two signal models are considered: 2HDM and 2HDM + S
- 2HDM + S:

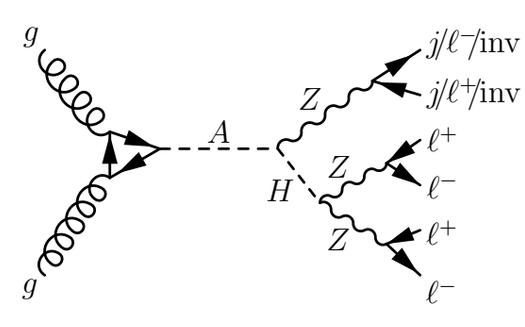
  S: a scalar boson, assumed to be a dark matter portal with $S \to \chi\bar{\chi}$ decay

  R: additional heavy scalar
- Final status: 4 leptons + jet/E_T^{miss}



2HDM+S, $R \to SH \to 4\ell + E_T^{miss}$

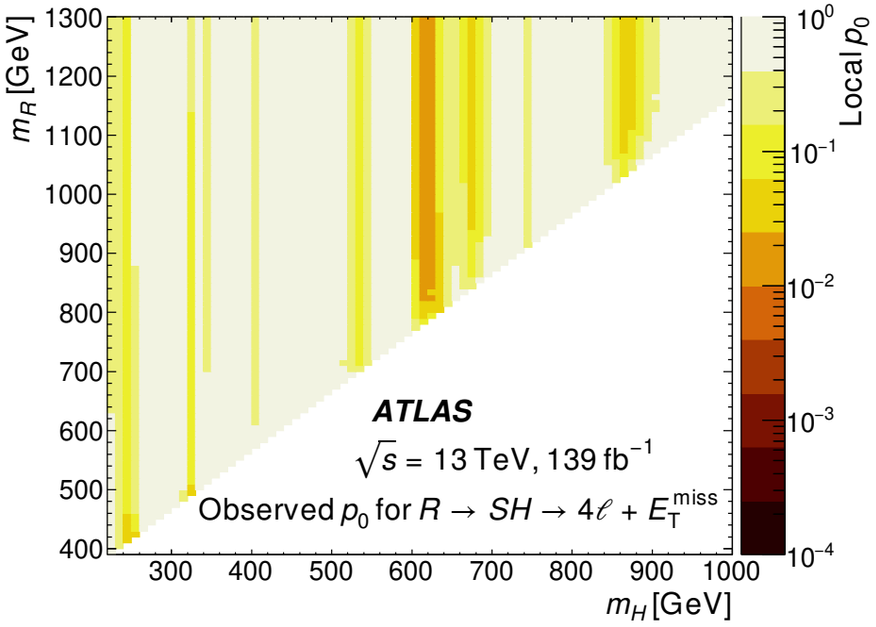


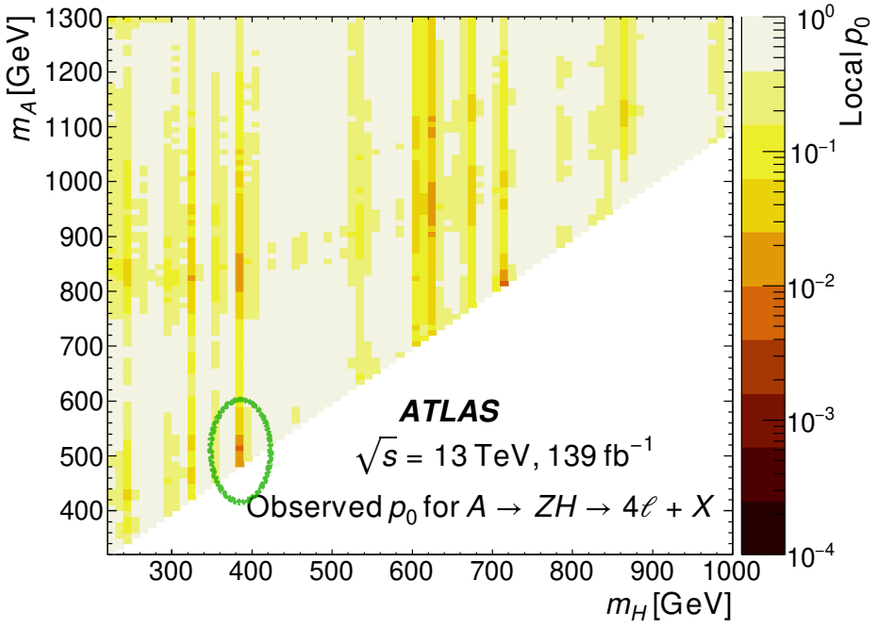


2HDM, $A \to ZH \to 4\ell + X$

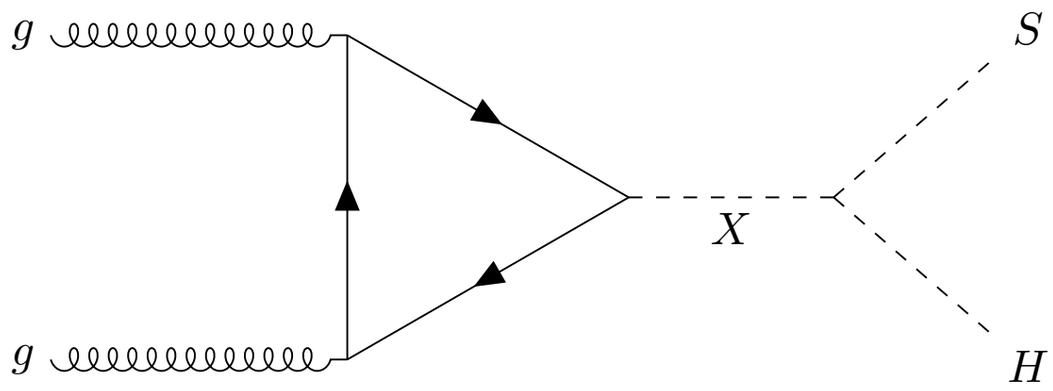
Results

- No significant deviation from the SM backgrounds is observed
- Largest excess: $(m_A, m_H) = (510, 380)$ GeV, local significance 2.5σ





$X \to SH$

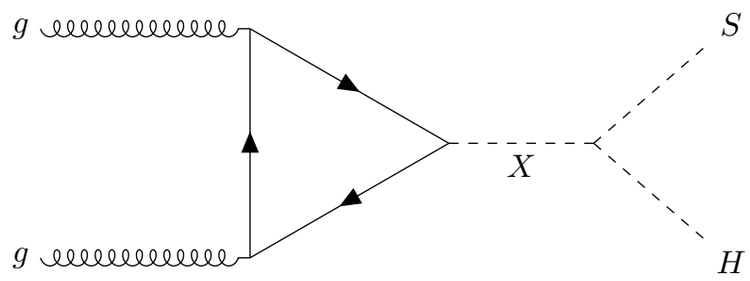


- X: heavy scalar
- S: scalar, can be light or heavy
- H: SM Higgs boson

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

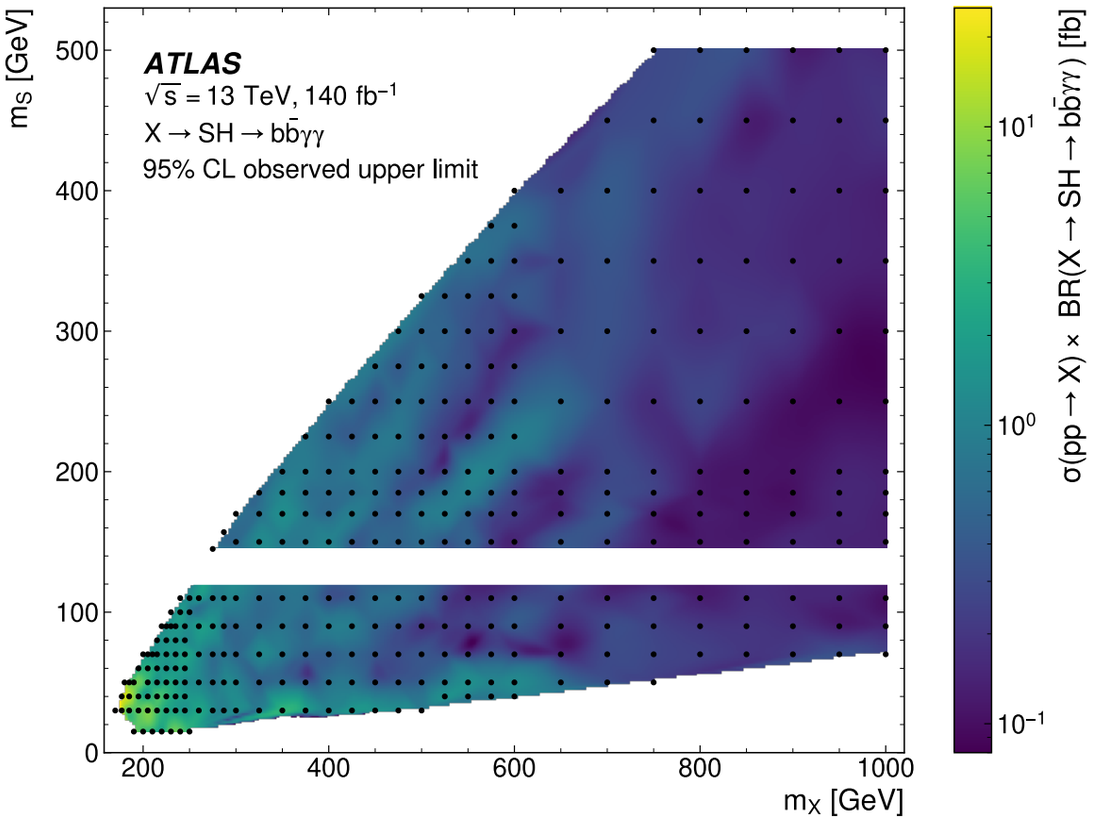
arXiv:2404.12915

- Heavy scalar X decays to SM Higgs (H) and another BSM scalar (S)
- SM $H \to \gamma\gamma$, $S \to b\bar{b}$
- m_X between 170 and 1000 GeV, m_s between 15 and 500 GeV
- $120 < m_{\gamma\gamma} < 130$ GeV
- Parameterised neural network is used as the final discriminant



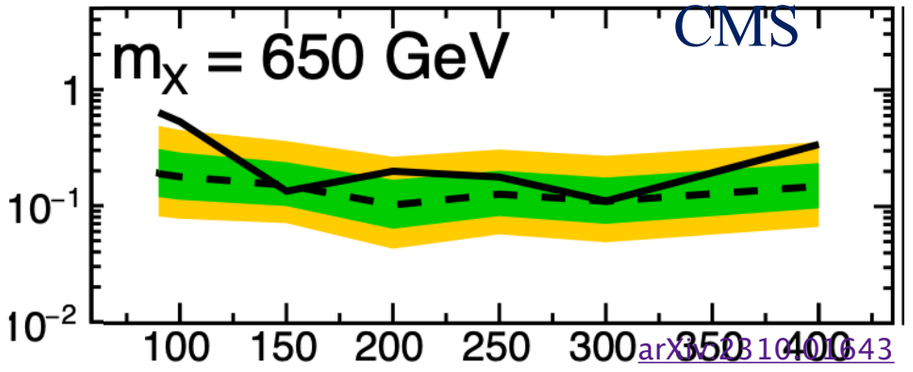
Results

- Largest excess: $(m_X, m_S) = (575, 200)$ GeV, local significance 3.5σ
- Global significance 2.0σ



Compare the largest excess to CMS results

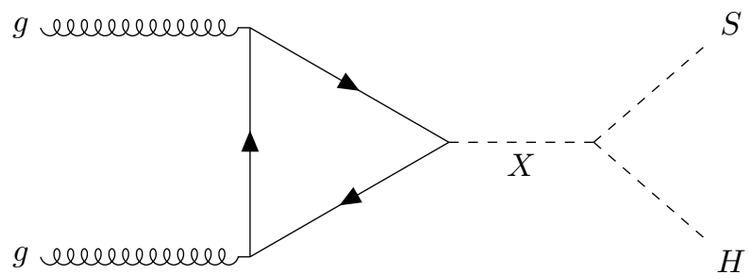
- CMS largest excess: $(m_X, m_S) = (650, 90)$ GeV, local significance 3.8σ
- Using the cross section 0.35fb (best fit reported by the CMS experiment) yields a local excess 2.7σ from ATLAS measurement



$X \to SH \to WW\gamma\gamma/ZZ\gamma\gamma$

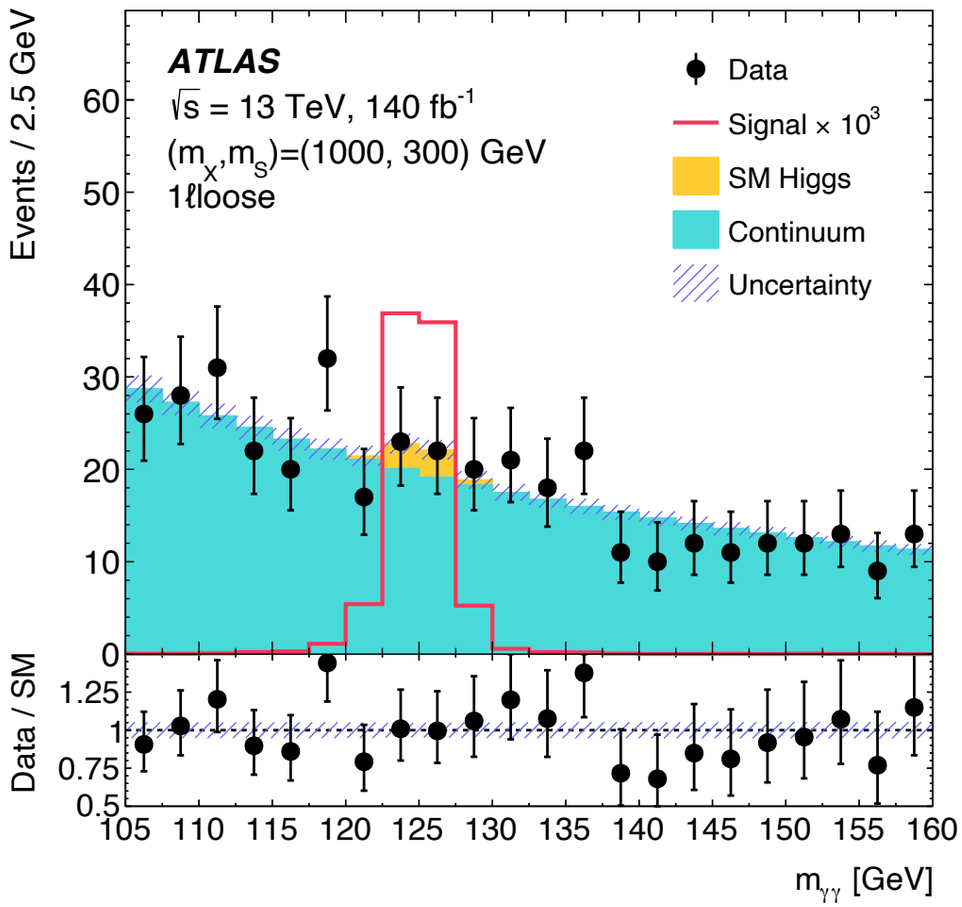
arXiv:2405.20926

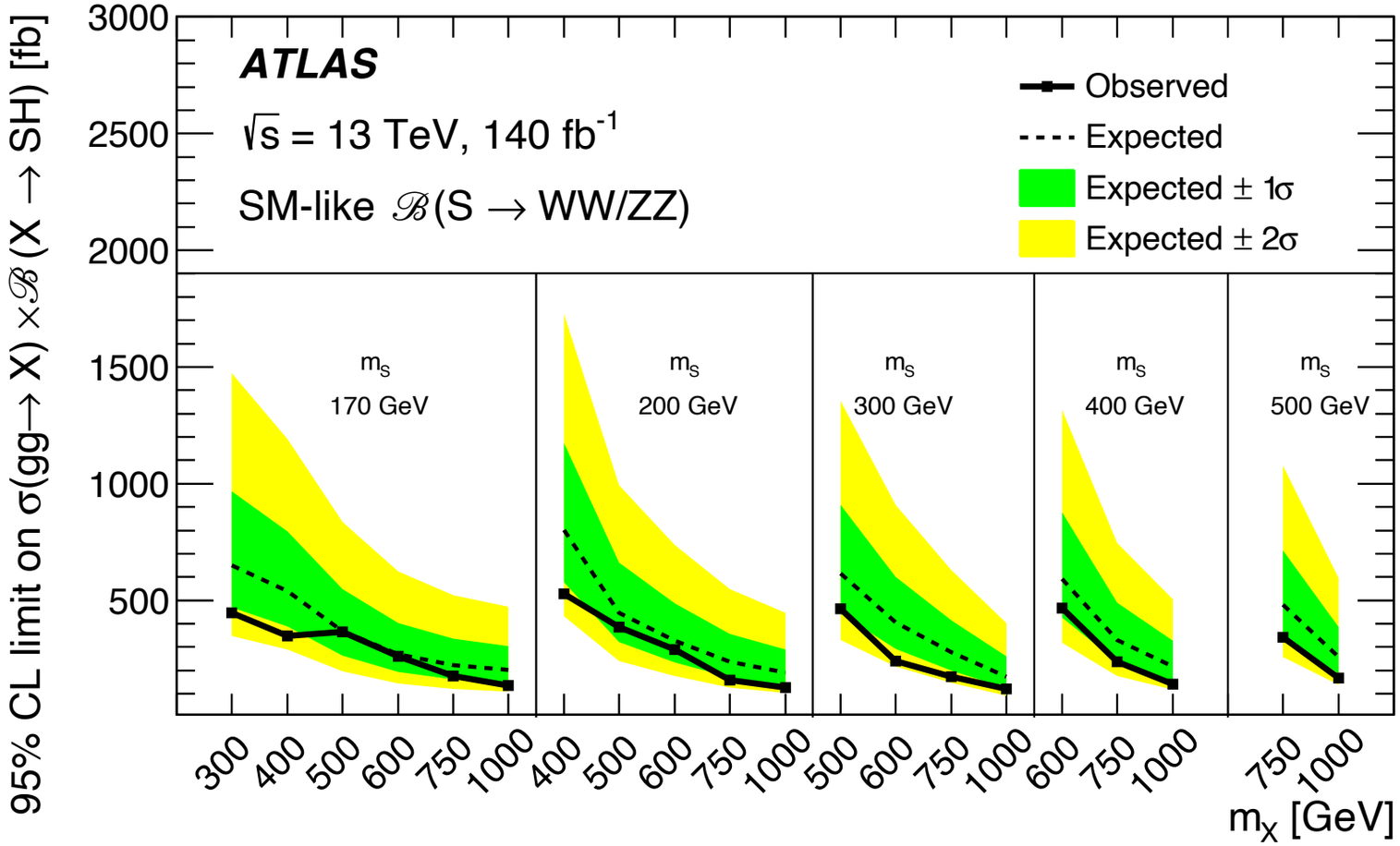
- Heavy scalar X decays to SM Higgs (H) and another BSM scalar (S)
- SM $H \to \gamma\gamma$, $S \to WW/ZZ \to$ leptons + jets
- m_X between 300 and 1000 GeV, m_s between 170 and 500 GeV
- Events are classified into 4 different regions depending on the number and flavour of leptons
- Using BDT for further categorisation to improve the sensitivity



Results

- No excess above SM prediction is observed





$X \to SH \to WW\tau\tau/ZZ\tau\tau$

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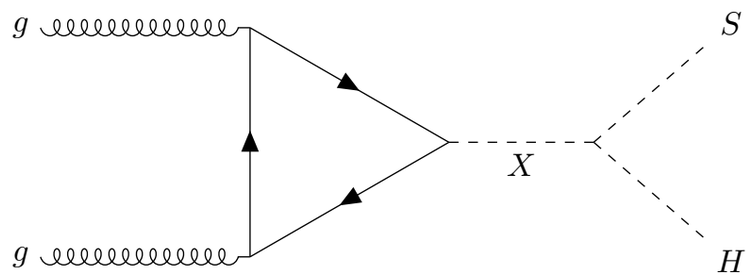
- Heavy scalar X decays to SM Higgs (H) and another BSM scalar (S)
- SM $H \to \tau\tau$, both τ hadronically decay
- $S \to WW/ZZ$, one or two leptons (e, μ) + jets/E_T^{miss}
- m_X between 500 and 1500 GeV, m_s between 200 and 500 GeV
- The final discriminant: the BDT outputs, separately training in different m_s region



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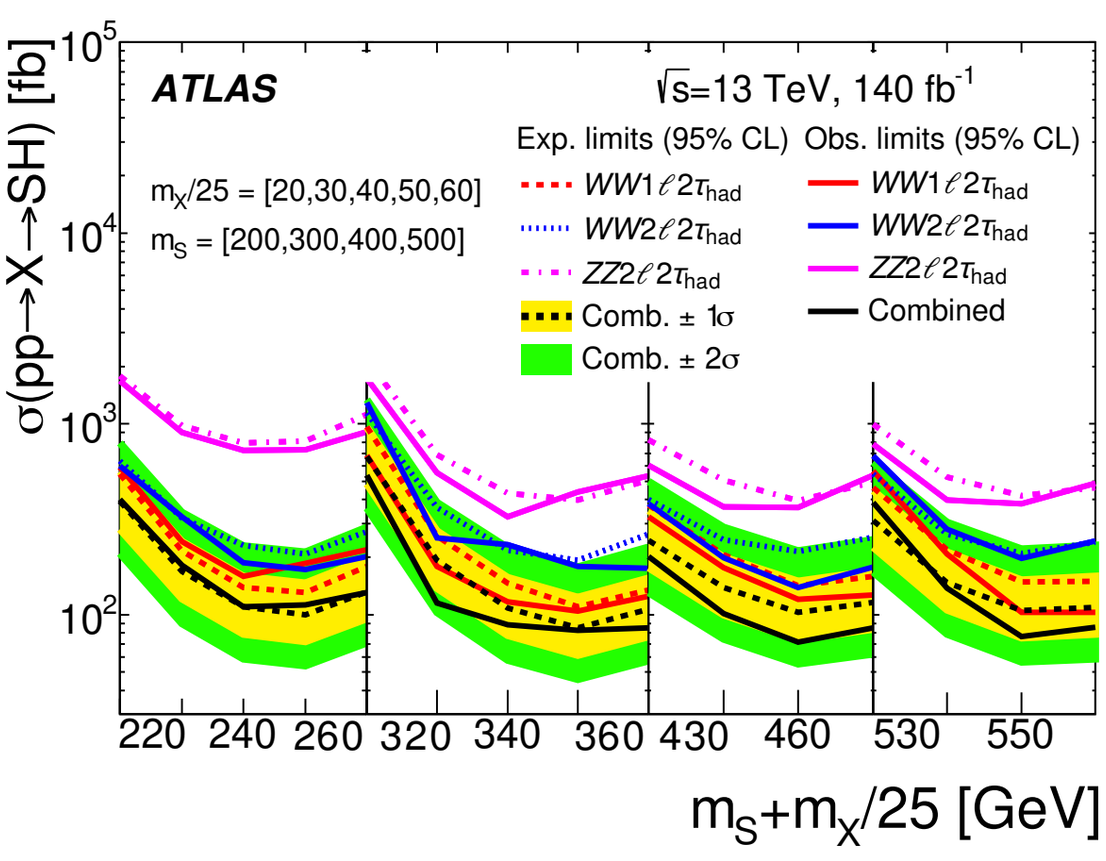
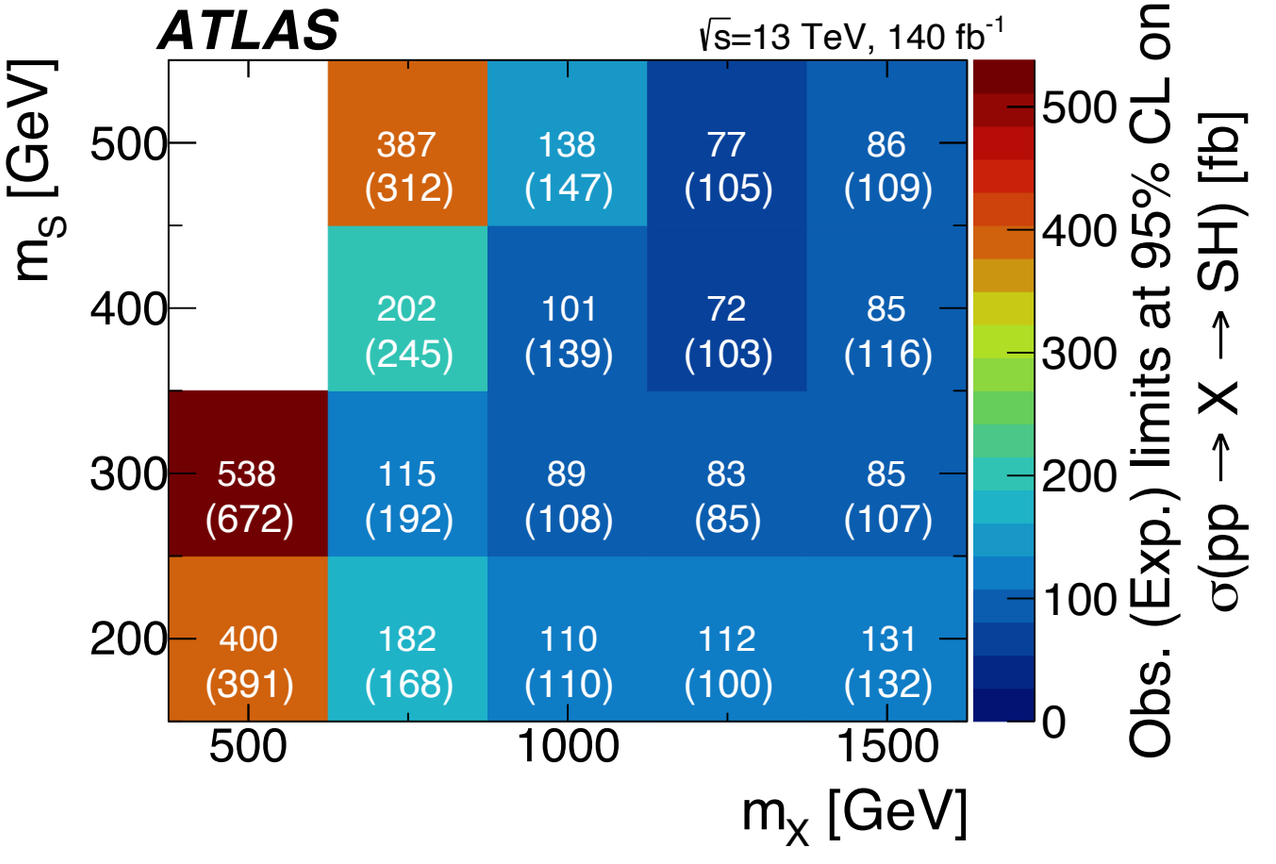
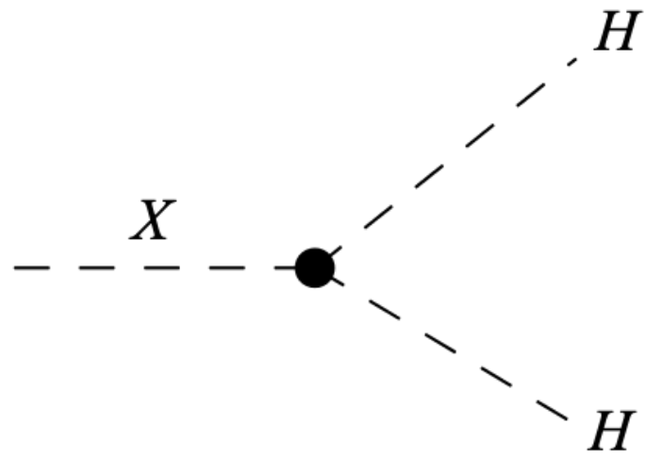
- No excess above SM prediction is observed





$X \rightarrow HH$

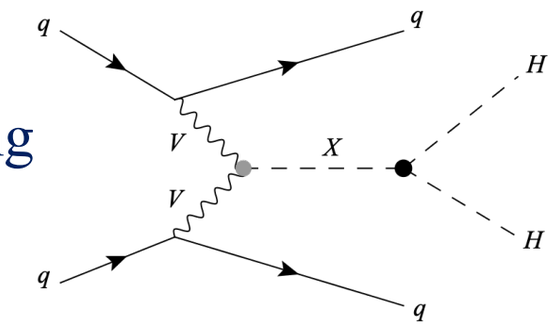


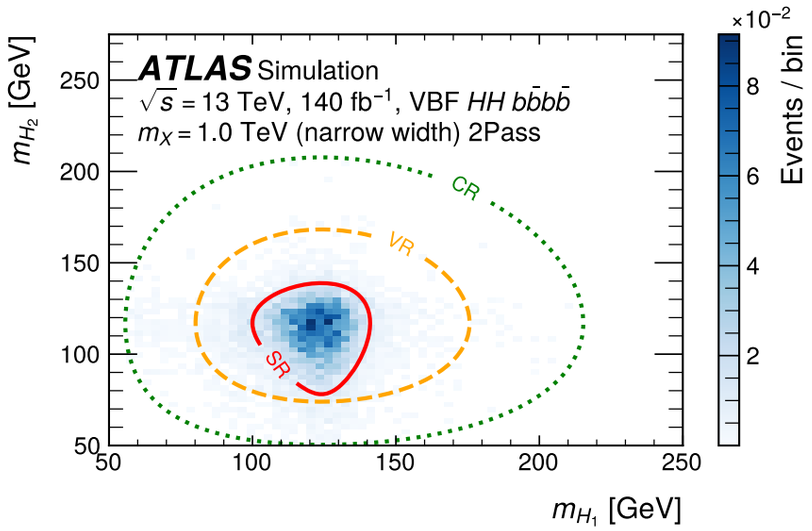
Heavy BSM resonance (X) decays to SM Higgs pair

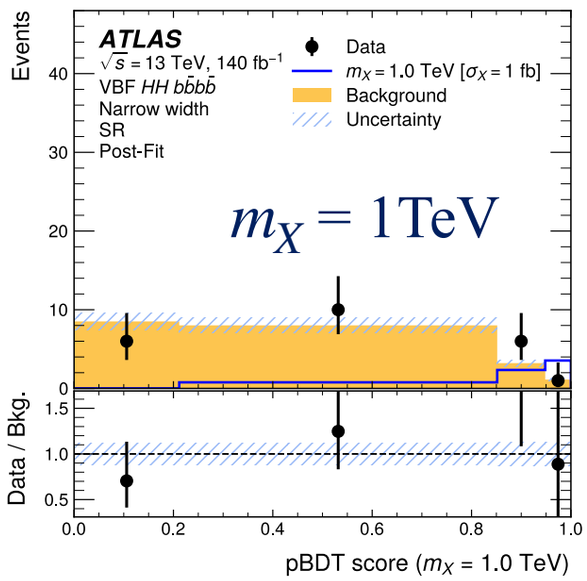
Boosted VBF $X \to HH \to b\bar{b}b\bar{b}$

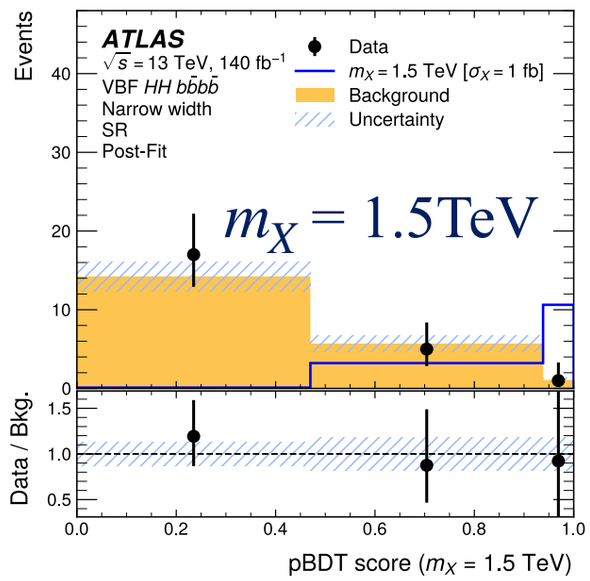
arXiv:2404.17193

- Heavy BSM resonances (X) may contribute to SM Higgs pair production
- Higgs candidate: large-R jet (Anti-k_t $R = 1.0$), deep neural network bb tagging
  $p_T^{H_1} > 450$ GeV, $p_T^{H_2} > 250$ GeV, use Higgs mass to categorise the events
- Using the BDT as the final discriminate



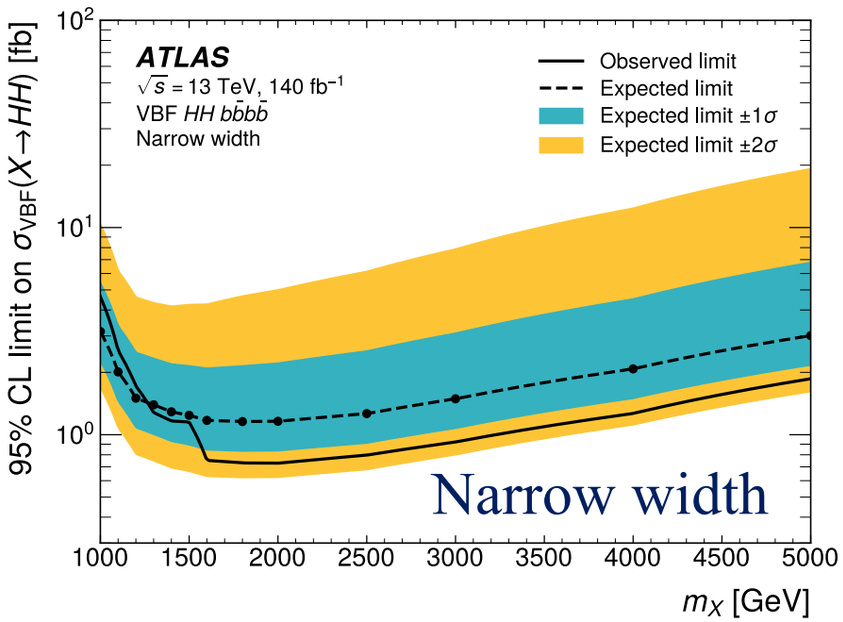


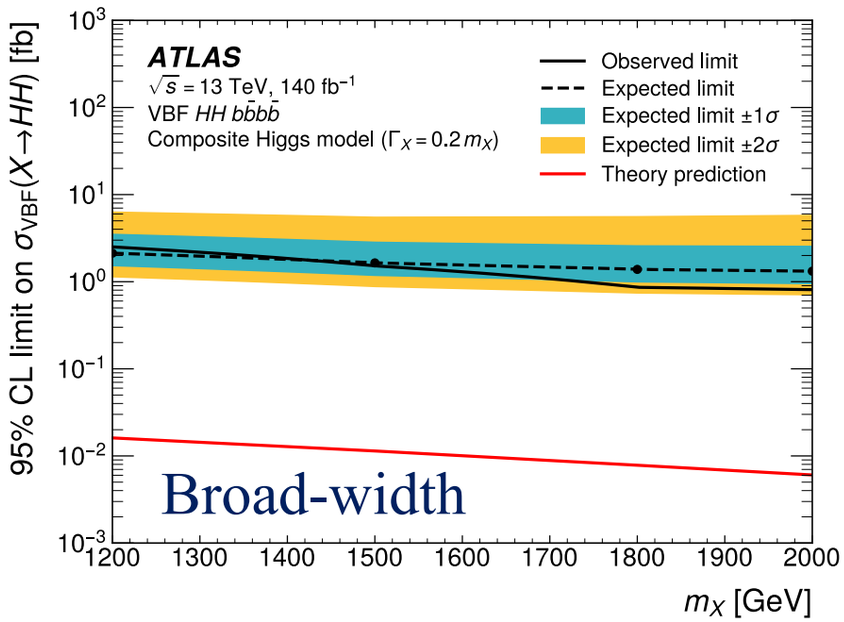




Results

- No significant excess is observed

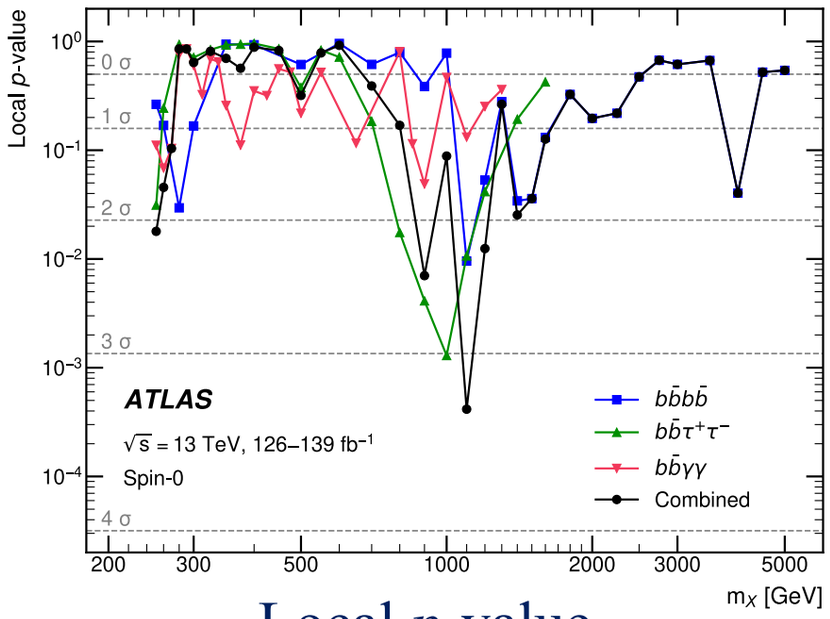




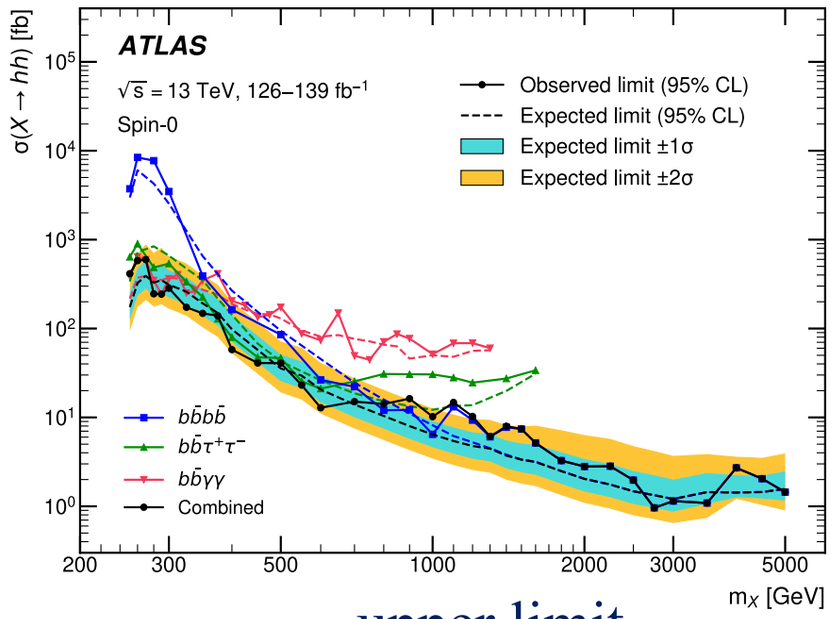
Combination of $X \to hh$

arXiv:2311.15956

- Heavy resonance H decays to two SM Higgs bosons h
- Include three decay channels: $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$
- No significant excess above the expected background is observed

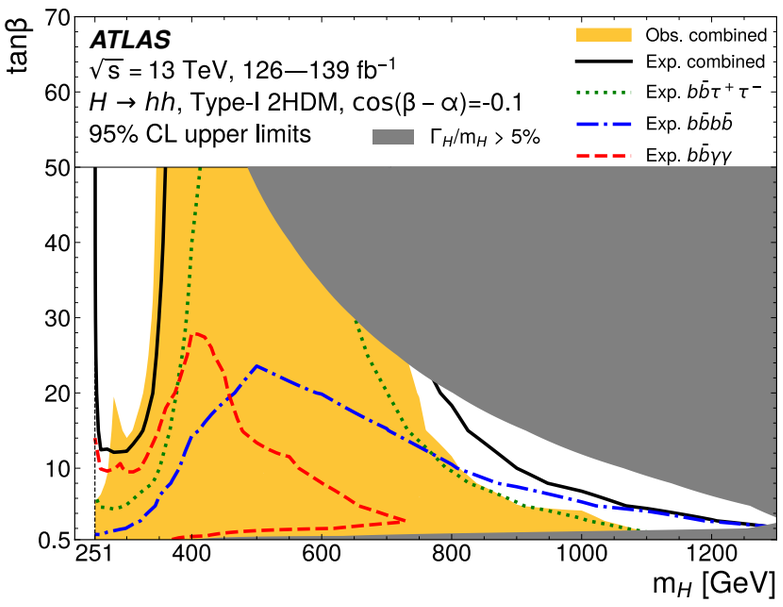


Local p-value

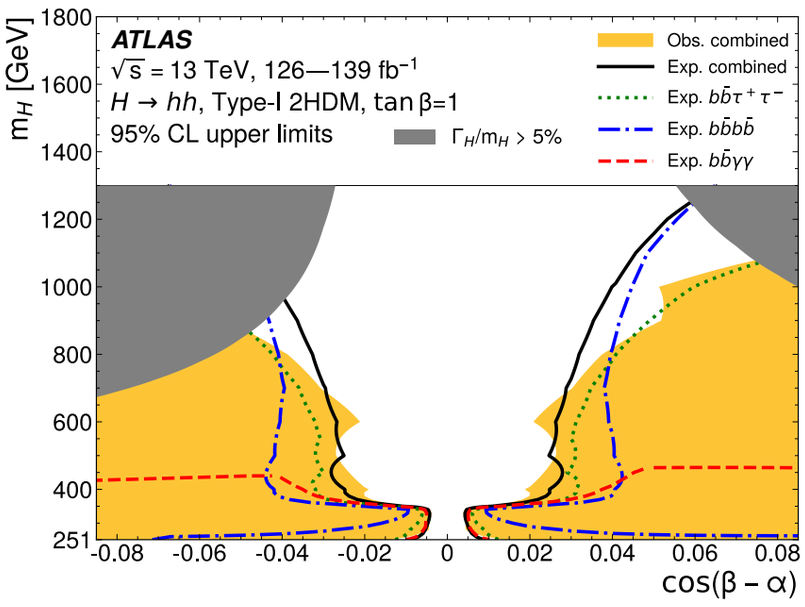


upper limit

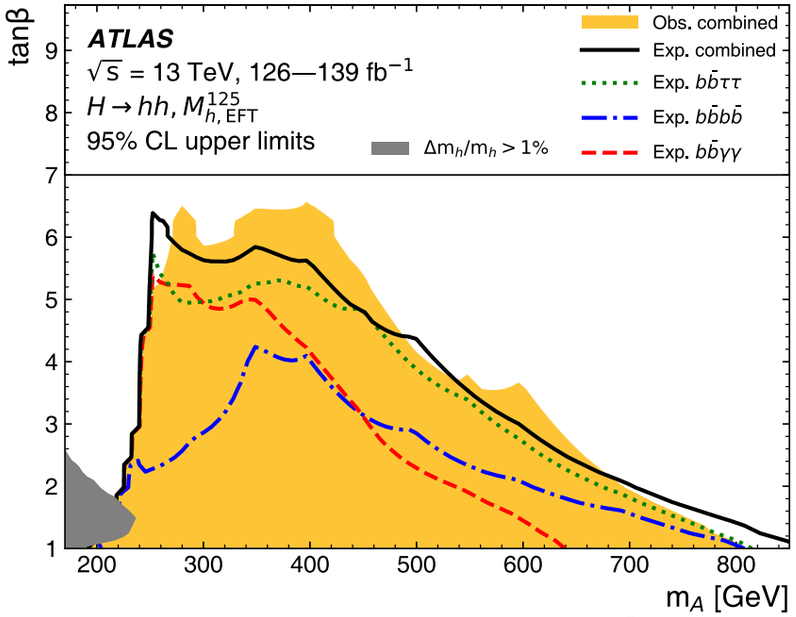
Interpretation for 2HDM and MSSM



2HDM $m_H - \tan\beta$



2HDM $m_H - \cos(\beta - \alpha)$

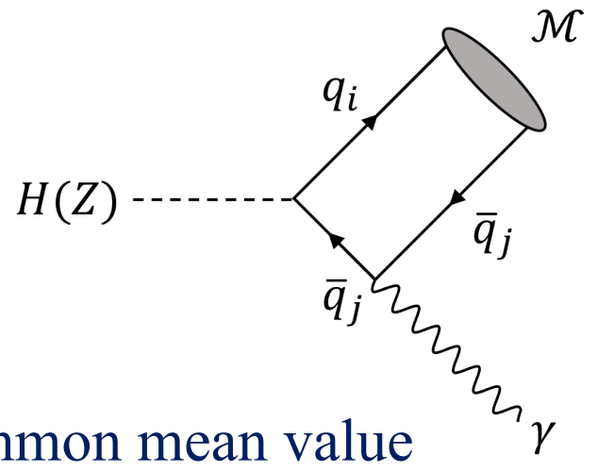


2HDM $m_A - \tan\beta$

SM Higgs exotic decay

$H \to D^*\gamma$ and $Z \to D^0\gamma/K_s^0\gamma$

arXiv:2402.18731



- Rare Higgs decay: Higgs boson decays into a meson and a photon: flavour-violating Higgs decay
- Analogous Z Decay: potential flavour-changing neutral current

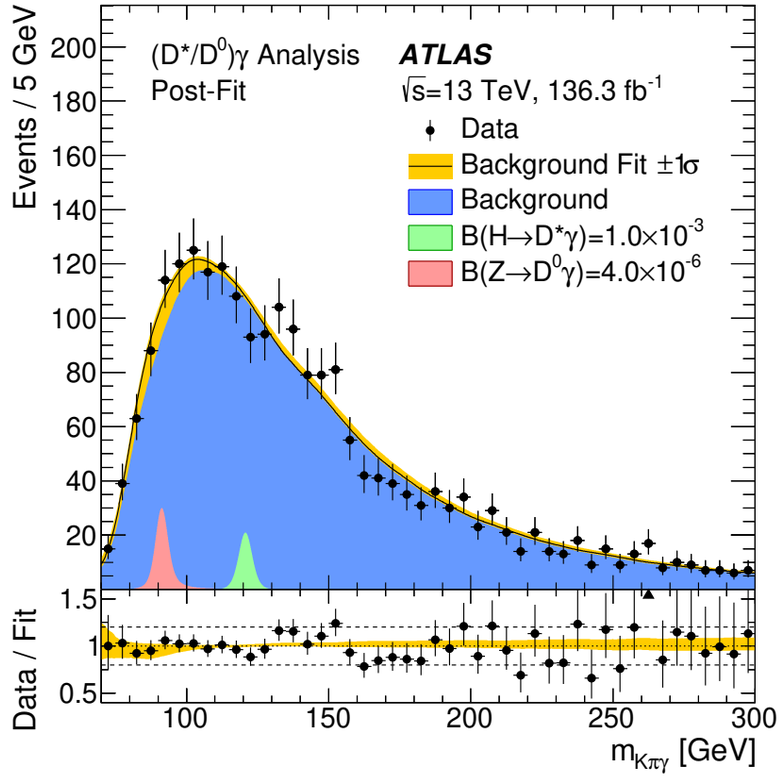
Analysis strategy

- Higgs mass is modelled with a sum of two Gaussian functions with a common mean value
- Z boson mass is modelled with a Voigtian function
- $m_{\mathcal{M}\gamma}$ distributions are used as the discriminating variable

Results

- Compatible with the SM predication

	95% CL upper limits			
	Branching Fraction		$\sigma \times \mathcal{B}$ [fb]	
Channel	Observed	Expected	Observed	Expected
$H \to D^*\gamma$	1.0×10^{-3}	$1.2^{+0.5}_{-0.3} \times 10^{-3}$	58	68^{+28}_{-19}
$Z \to D^0\gamma$	4.0×10^{-6}	$3.4^{+1.4}_{-1.0} \times 10^{-6}$	235	200^{+82}_{-56}
$Z \to K_s^0\gamma$	3.1×10^{-6}	$3.0^{+1.3}_{-0.8} \times 10^{-6}$	185	176^{+77}_{-49}



Light Higgs

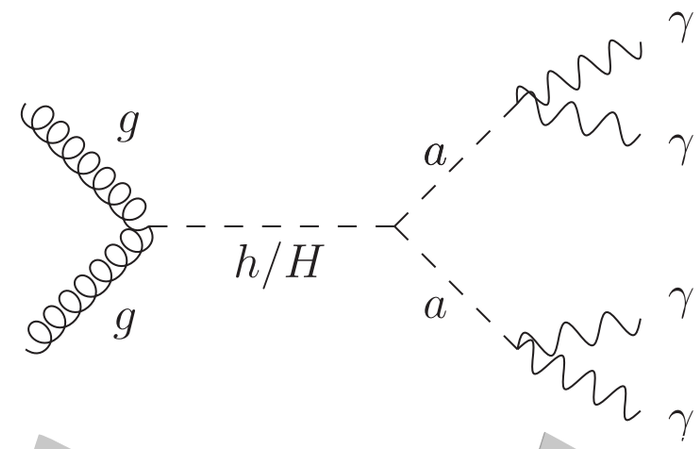
Axion-like particles $H \to aa \to 4\gamma$ (1)

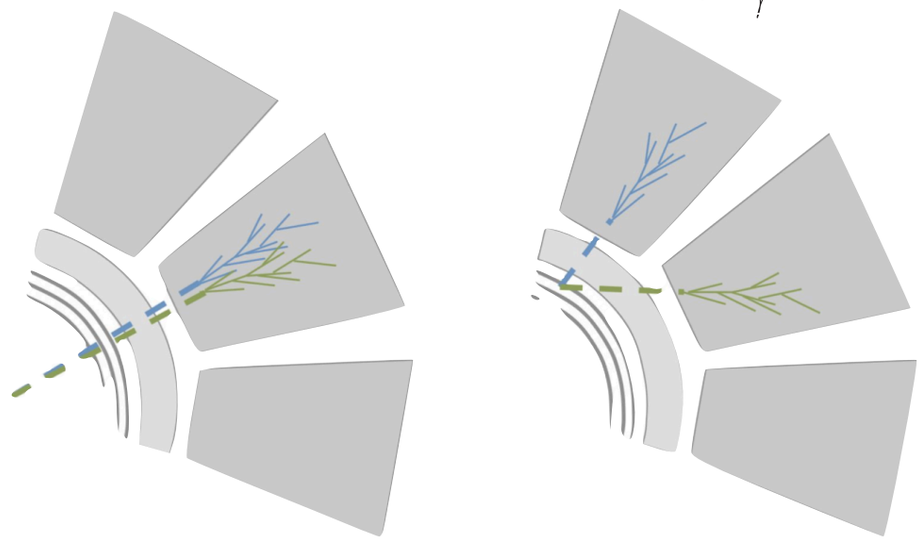
arXiv:2312.03306

- SM Higgs boson decays to two a to 4 photons
- a: Axion-like particles, light (pseudo) scalars

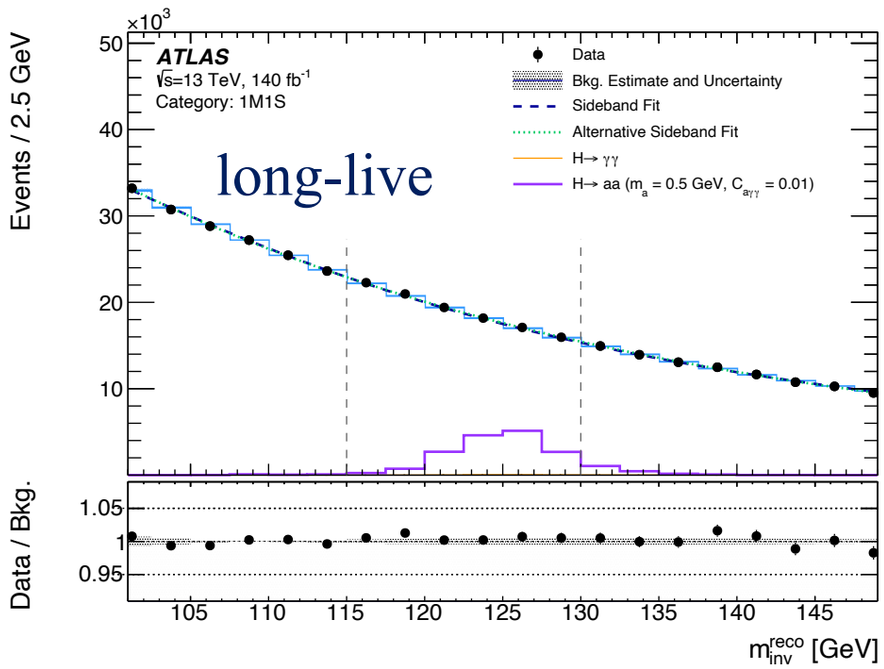
Analysis strategy

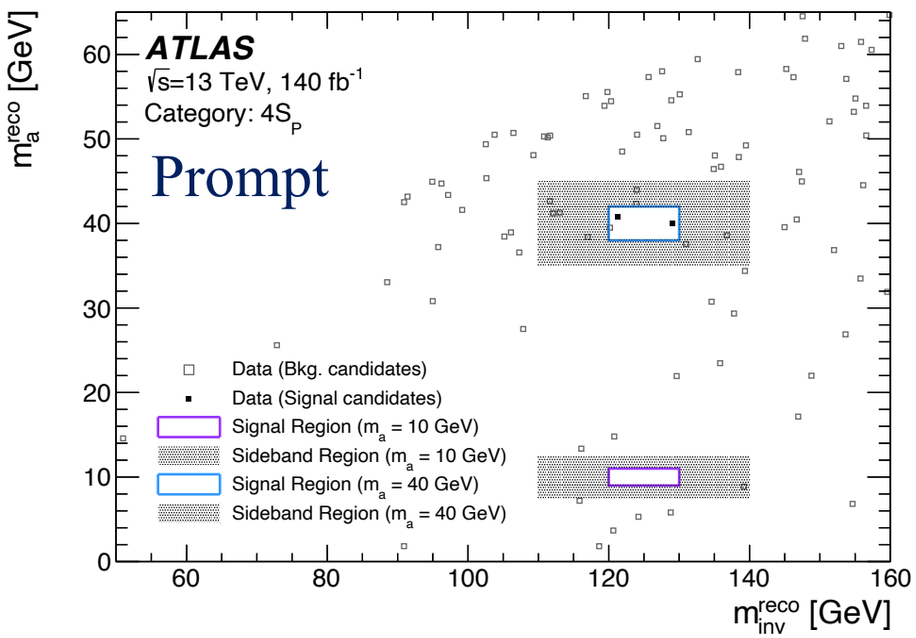
- The coupling between a and γ ($C_{a\gamma\gamma}$) determines the lifetime and the distance of the vertex
  - Promptly decaying $C_{a\gamma\gamma} \geq 0.1$
  - Small $C_{a\gamma\gamma}$: long-lived $a \to \gamma\gamma$
- Events are classified depending on merged photon or single photon
- SR definition: Use invariant mass of all photon candidates m_{inv} for long-live and (m_{inv}, m_a) for prompt search





One merged photon Two single photons



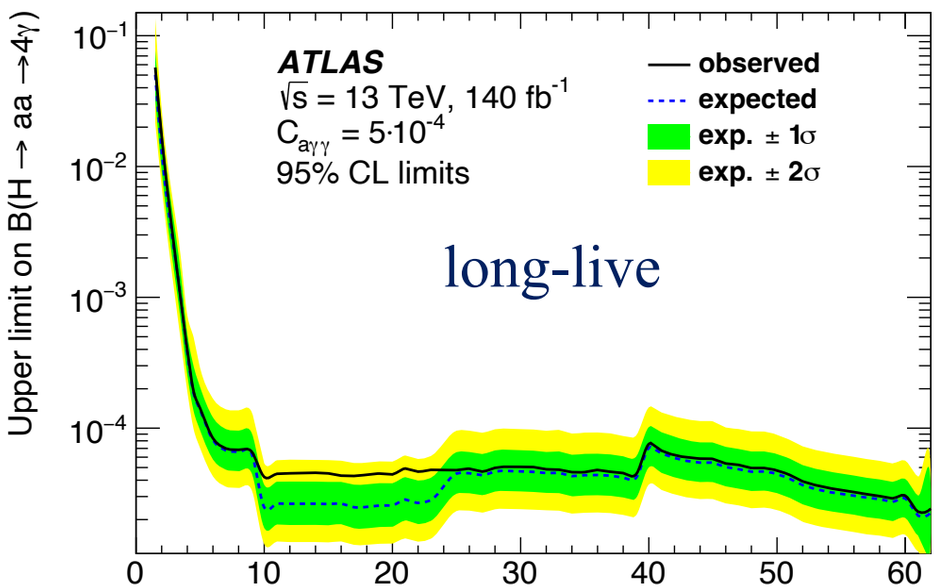


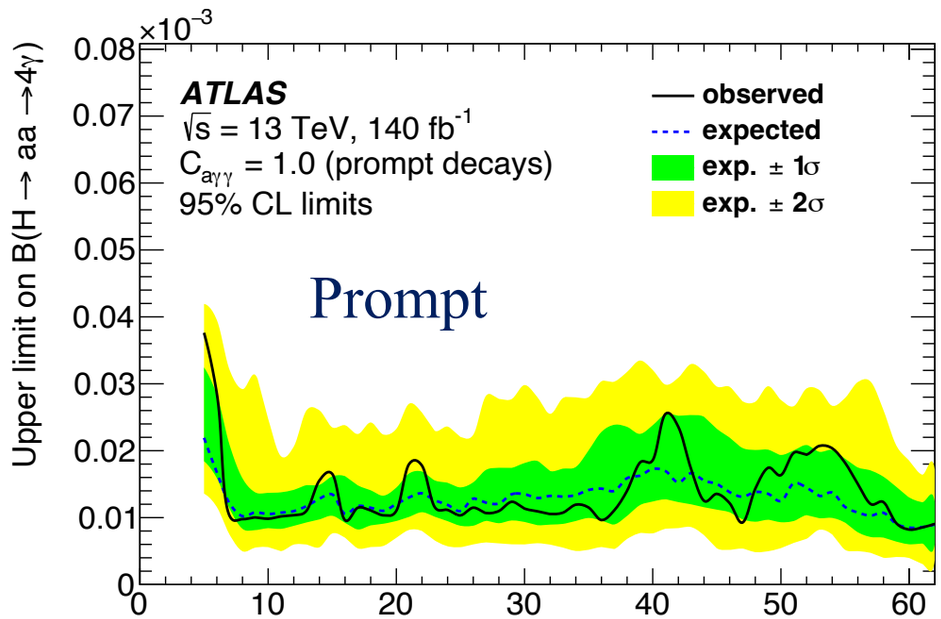
Axion-like particles $H \to aa \to 4\gamma$ (2)

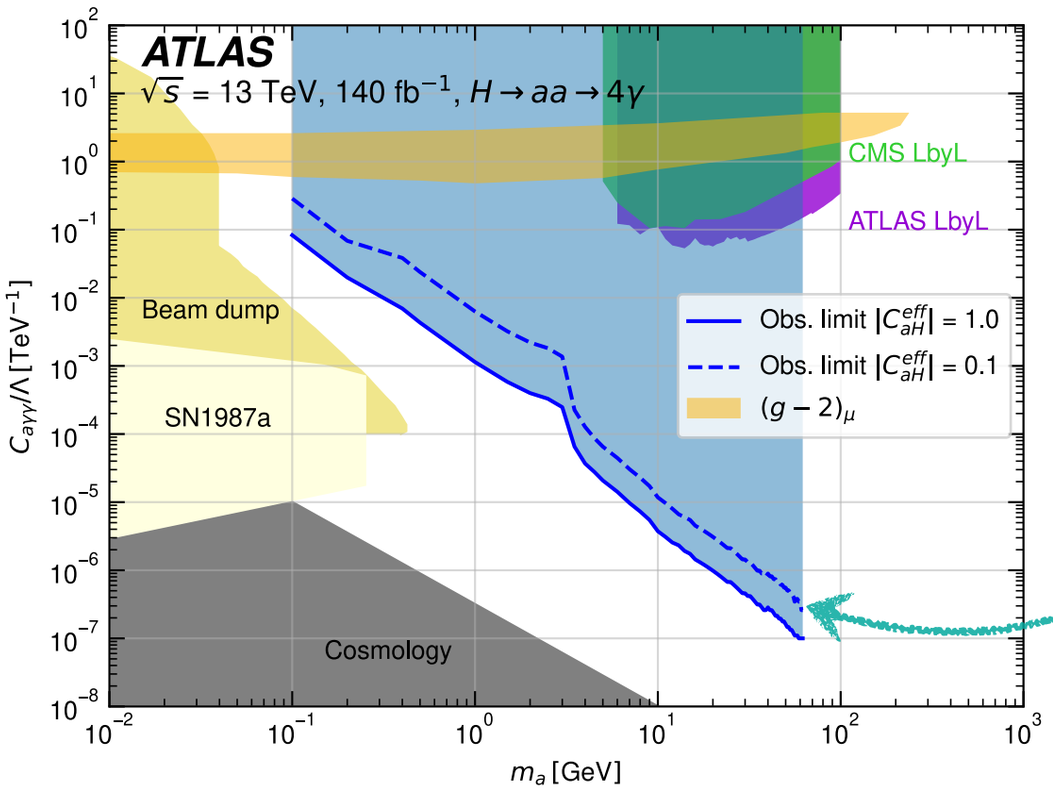
arXiv:2312.03306

Results

- Largest deviation 1.5σ in $10 < m_a < 25$ GeV







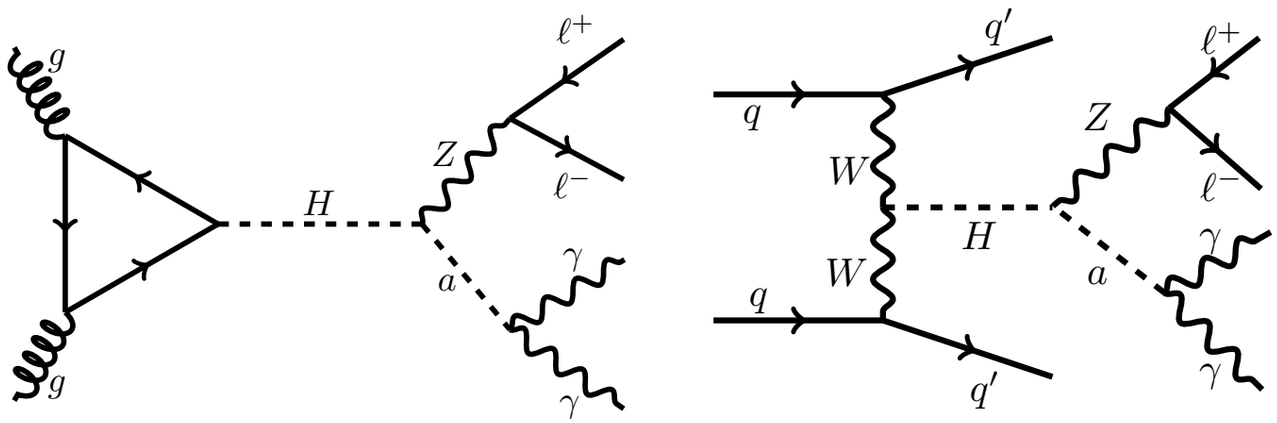
Limit on m_a and $C_{a\gamma\gamma}$

- assuming $\mathcal{B}(a \to \gamma\gamma) = 1$, $\Lambda = 1$ TeV
- significantly reduces the allowed parameter space for ALP-based models

$H \to Za \to \ell\ell\gamma\gamma$ (1)

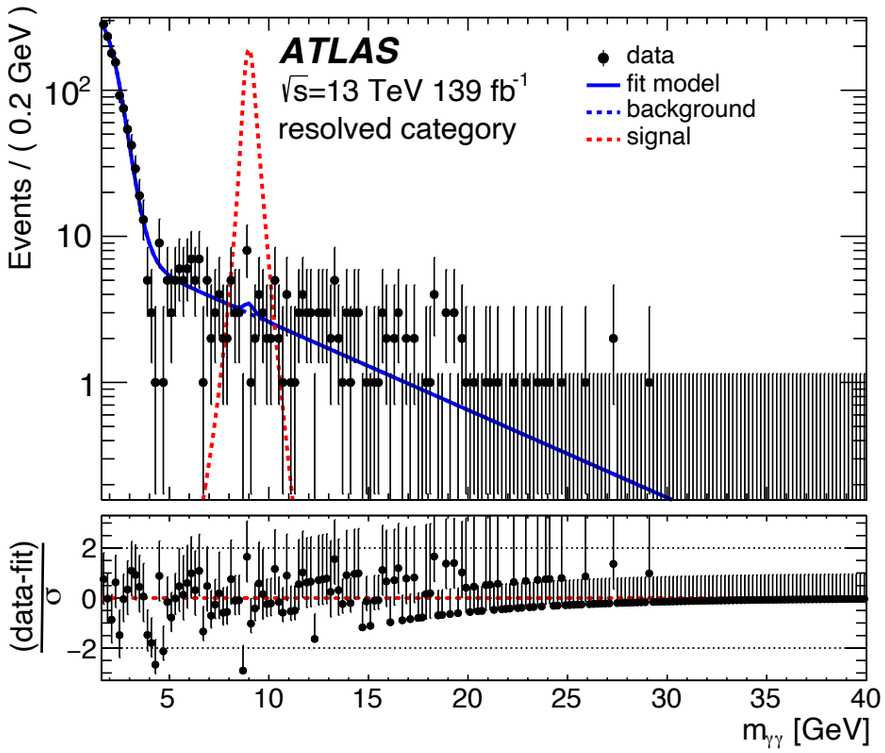
Phys. Lett. B 848 (2024) 138536

- SM Higgs boson decays to Z a
  $Z \to \ell\ell$ and $a \to \gamma\gamma$
- a: light pseudoscalars particle
  m_a between 0.1 GeV and 33 GeV



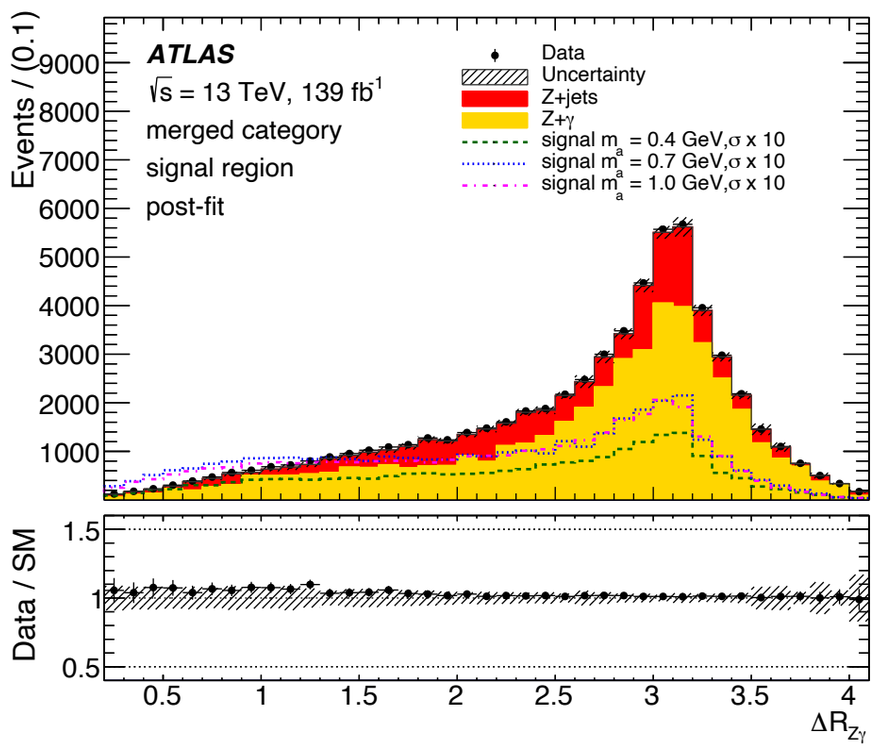
Analysis strategy

- Considers both the merged (one merged photon) and the resolved (two single photon) $a \to \gamma\gamma$ decay
- Exactly two electrons or two muons for $Z \to \ell\ell$ decay



Resolved category: $m_{Z\gamma\gamma}$ range 110-140 GeV

Result extracted by fitting $m_{\gamma\gamma}$ distribution



Merged category: $m_{Z\gamma}$ range 110-140 GeV

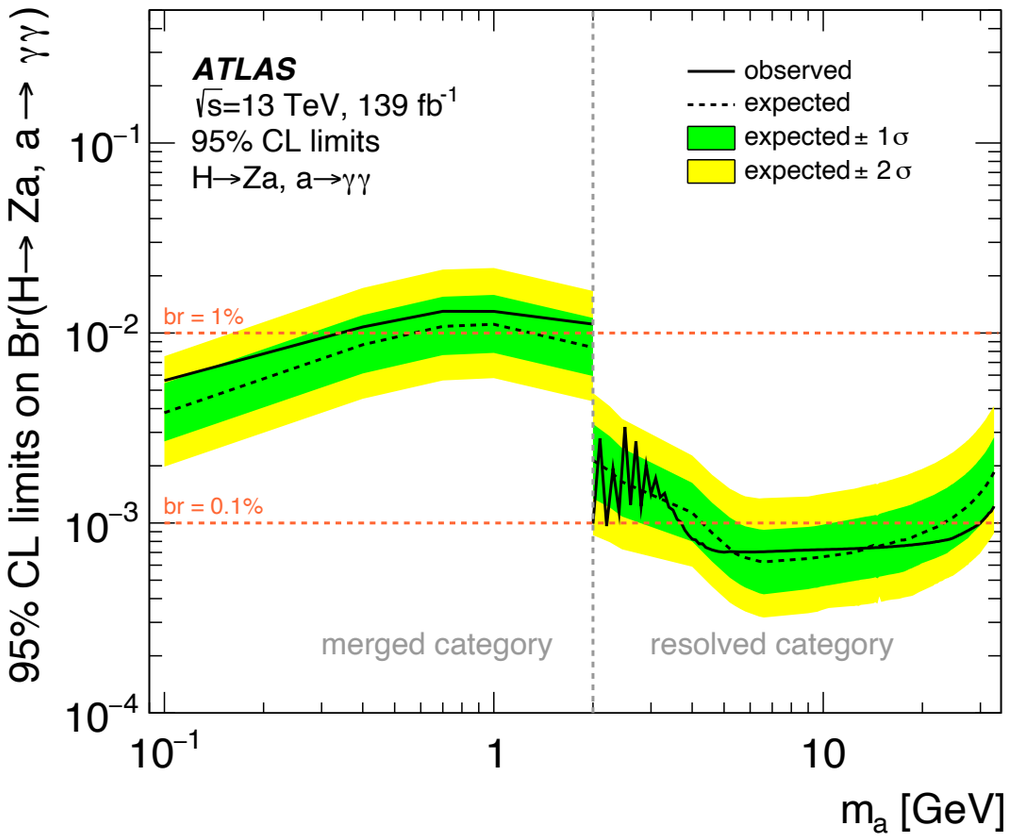
Result extracted by fitting $\Delta R_{Z\gamma}$ distribution

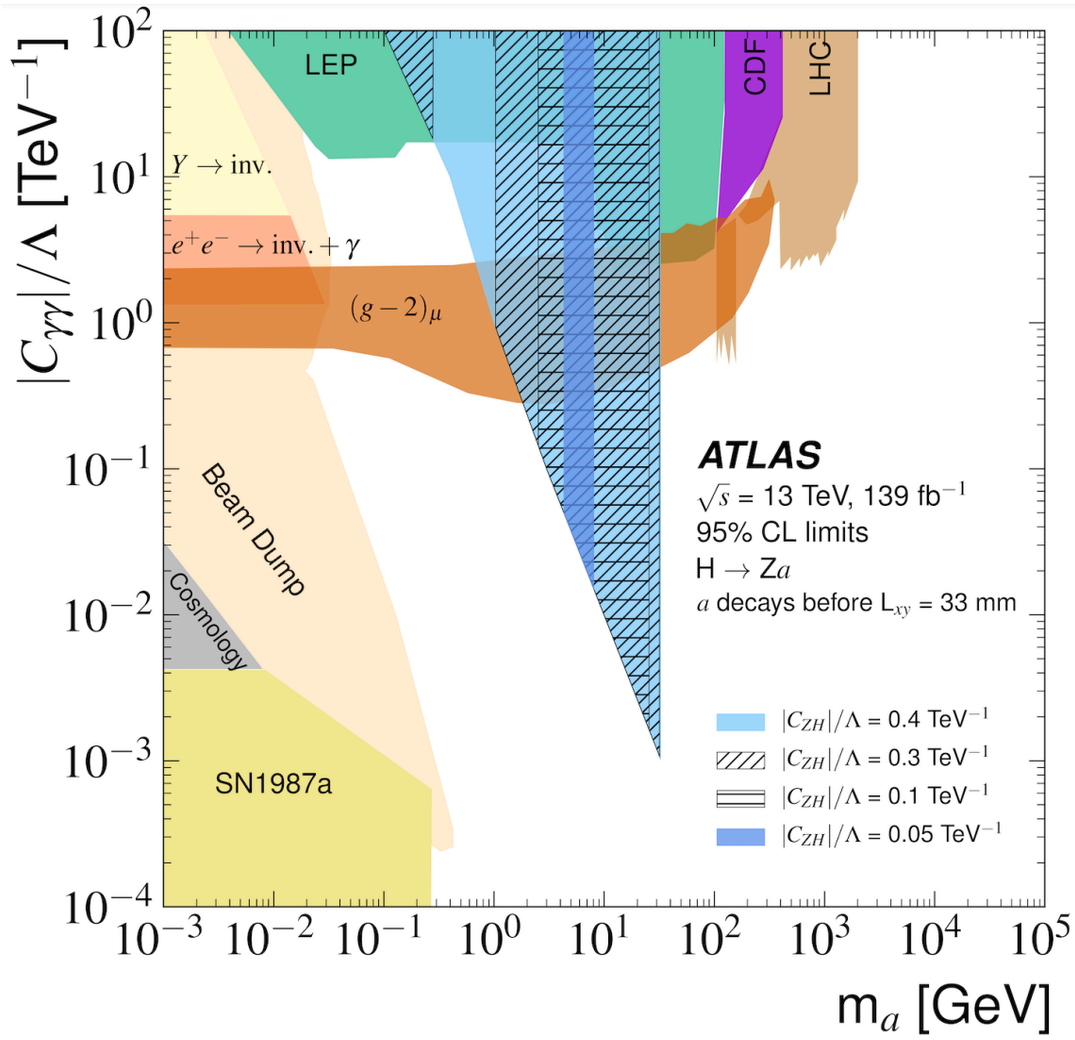
$H \to Za \to \ell\ell\gamma\gamma$ (2)

Phys. Lett. B 848 (2024) 138536

Results

- No significant excesses are observed





- Boundary of the merged and resolved category: $m_a = 2$ GeV
- Branch ratio $H \to Za, a \to \gamma\gamma$ $0.08\% \sim 2\%$

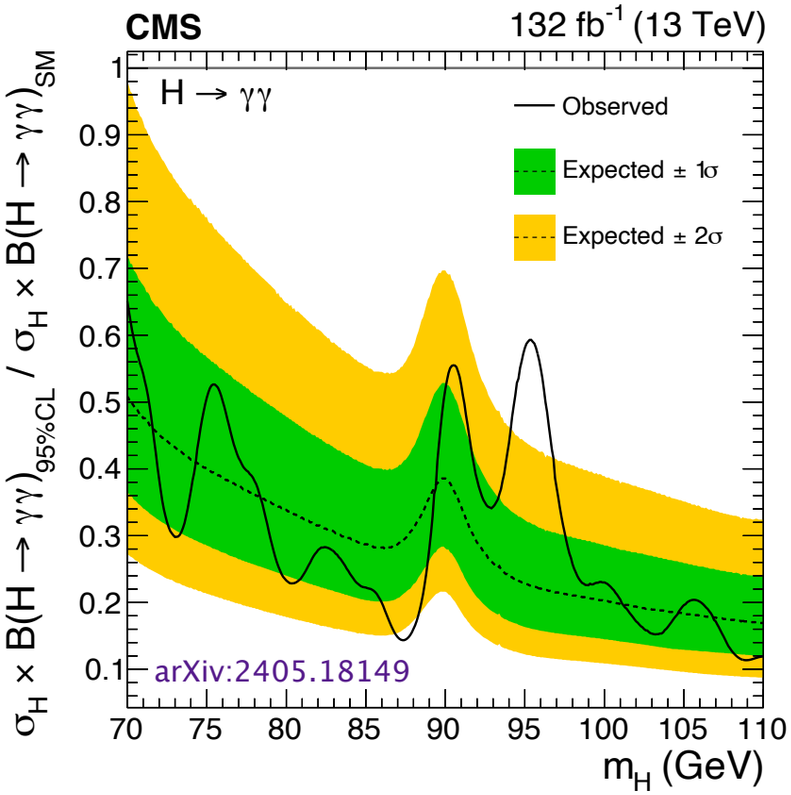
Interpretation in axion-like particles model

- Show limit on the effective coupling $|C_{\gamma\gamma}|/\Lambda$
- With different Higgs - Za coupling $|C_{ZH}|/\Lambda$

Low mass $H \rightarrow \gamma\gamma$

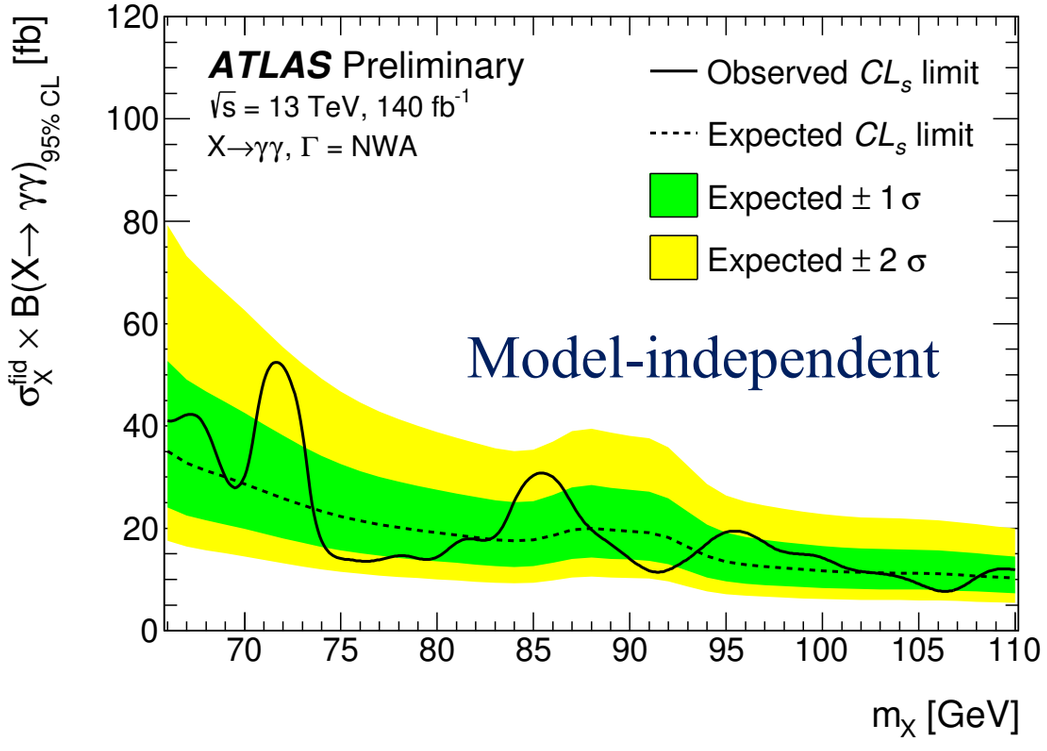
[ATLAS-CONF-2023-035]

- A local significance of 2.9 σ at 95.4 GeV was reported by CMS

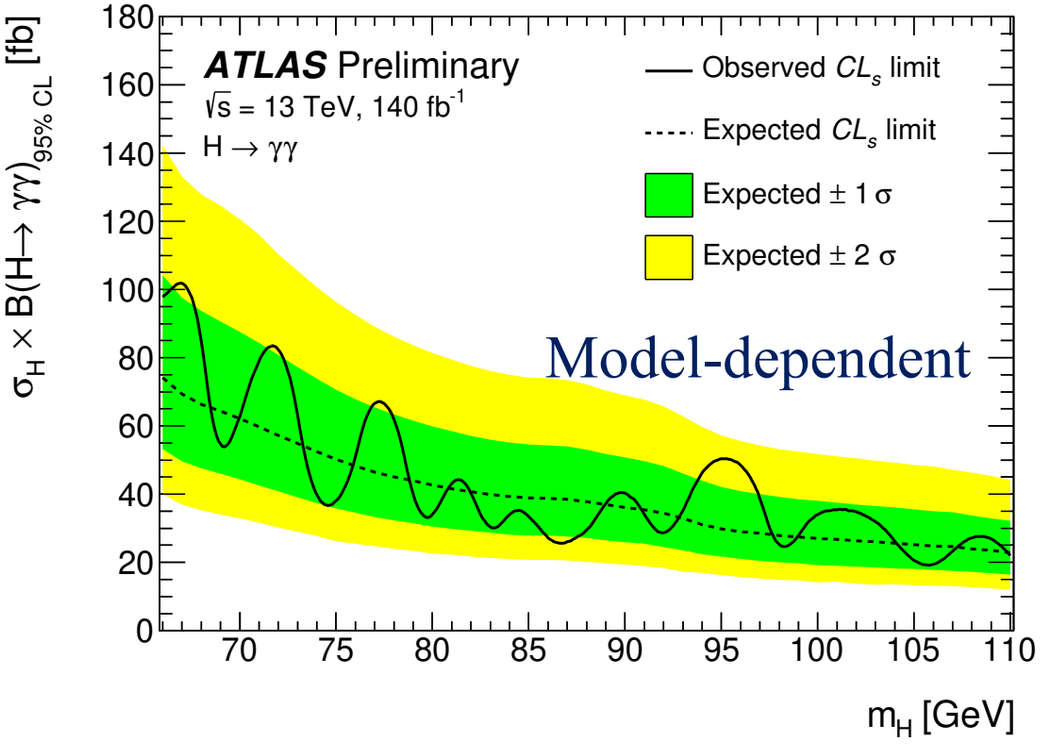


Two signal models are considered at ATLAS

- Model-independent: Light, spin-0 bosons X decaying to two photons
- Model-dependent: low-mass SM-like Higgs boson (assuming SM Higgs production-mode cross-sections), employs a BDT for event categorisation



Largest local deviation 2.2σ at 71.8 GeV



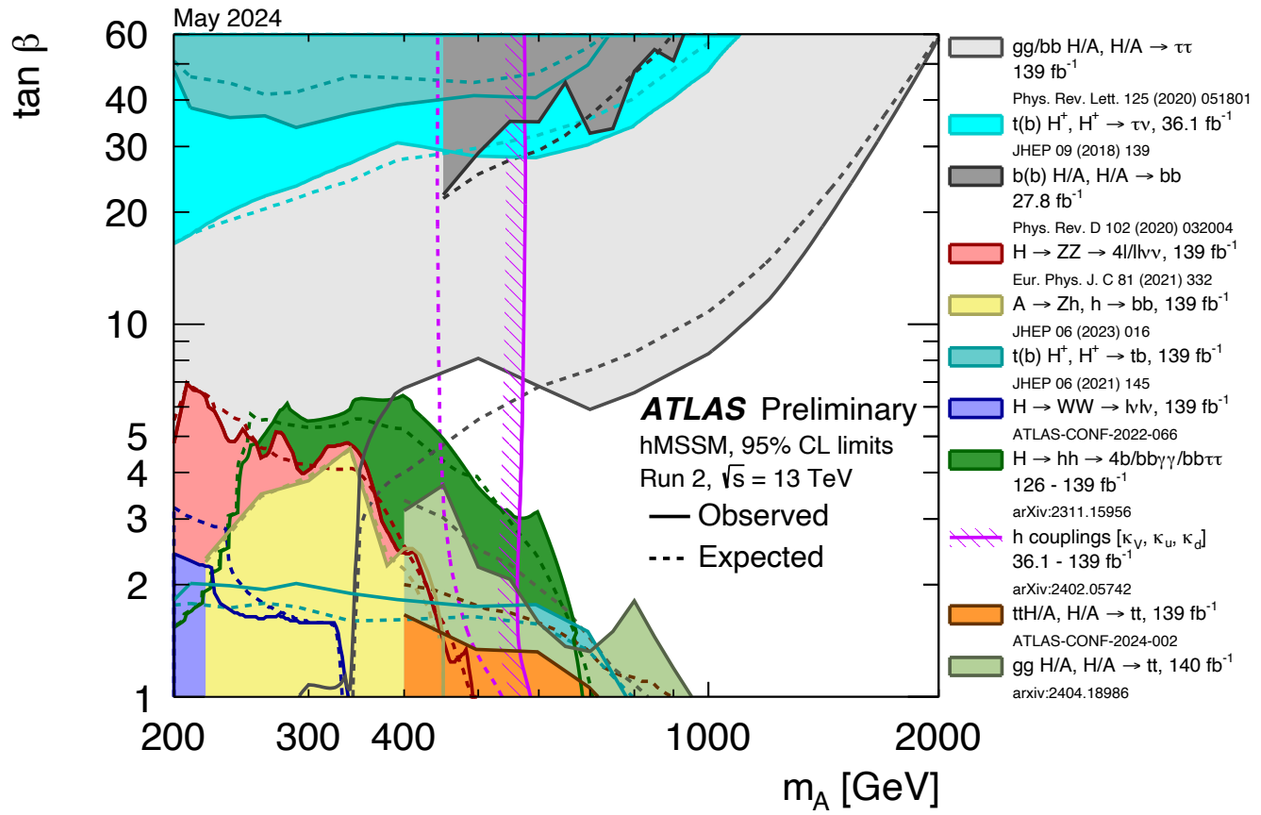
Largest local deviation 1.7σ at 95.4 GeV

Summary and outlook

ATL-PHYS-PUB-2024-008

- ATLAS provide a huge number of BSM Higgs searchers using the Run 2 data, with a lot of different final states and benchmark models

- Some small excesses were found in Run 2 data relative to the SM predictions, but no significant excess was observed (global significances below 3σ)



Uncovered signatures

- High mass: $H^{\pm} \to WH, H/A \to WH^{\pm}, H^{\pm} \to W\gamma, H \to SS\ , H \to \chi\chi, \ldots$
- Low mass: axion-like particles involving higher-dimension operators, Long-lived particles …

There is still space for BSM physics

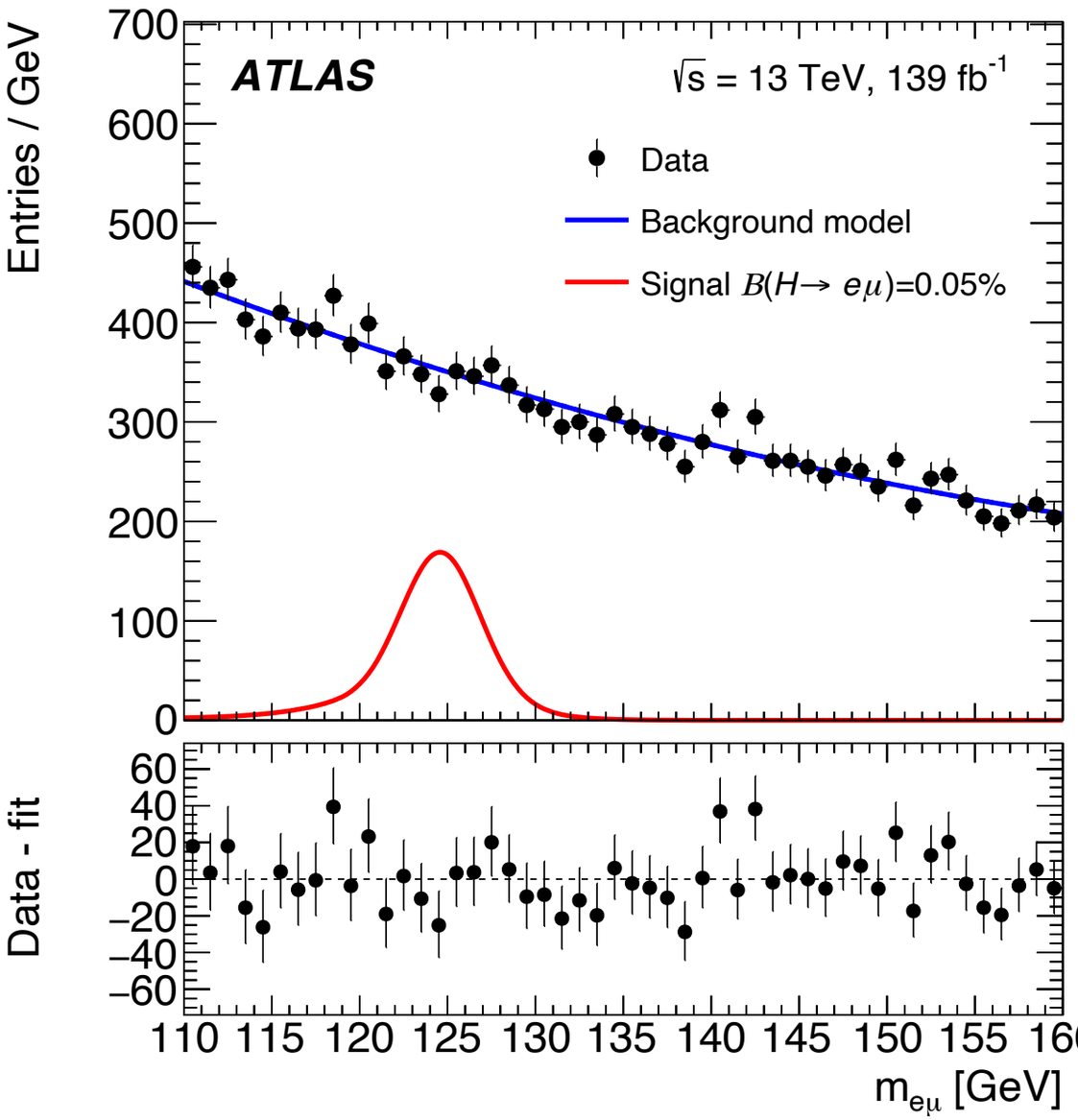
- Continued meticulous effort is needed
- Searches in currently unexplored channels or phase-space, long-lived particles, cascade decays …

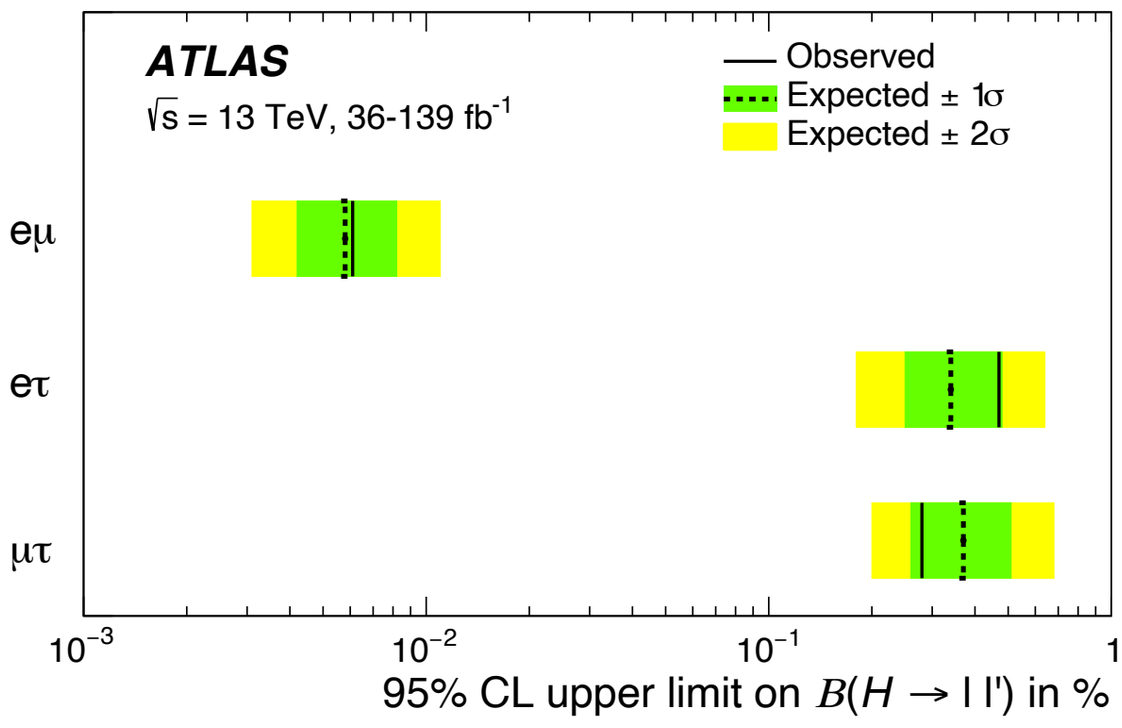
Looking forward to Run 3 and HL-LHC

Back up

SM $H \to e\mu$

[Phys. Lett. B 801 (2020) 135148]





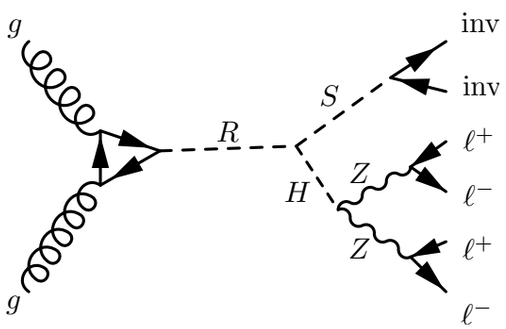
$A \to ZH$ and $R \to SH$ (1)

arXiv:2401.04742

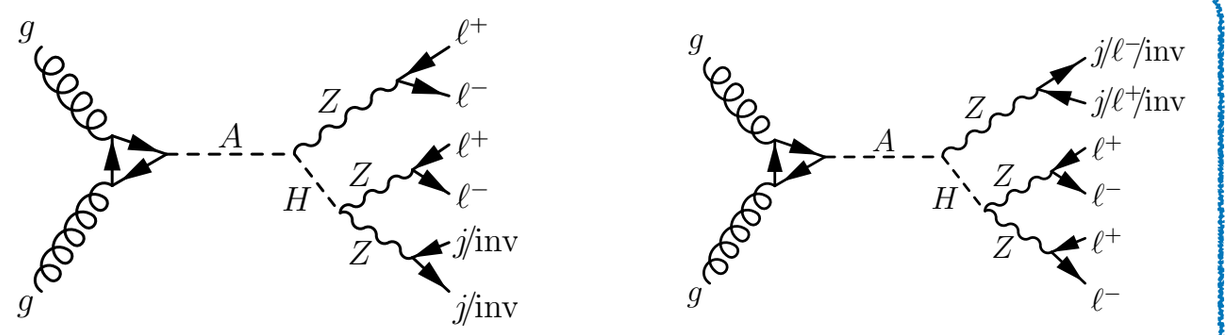
- Two signal models are considered: 2HDM and 2HDM + S
- 2HDM + S:

  S: a scalar boson, assumed to be a dark matter portal with $S \to \chi\bar{\chi}$ decay

  R: additional heavy scalar



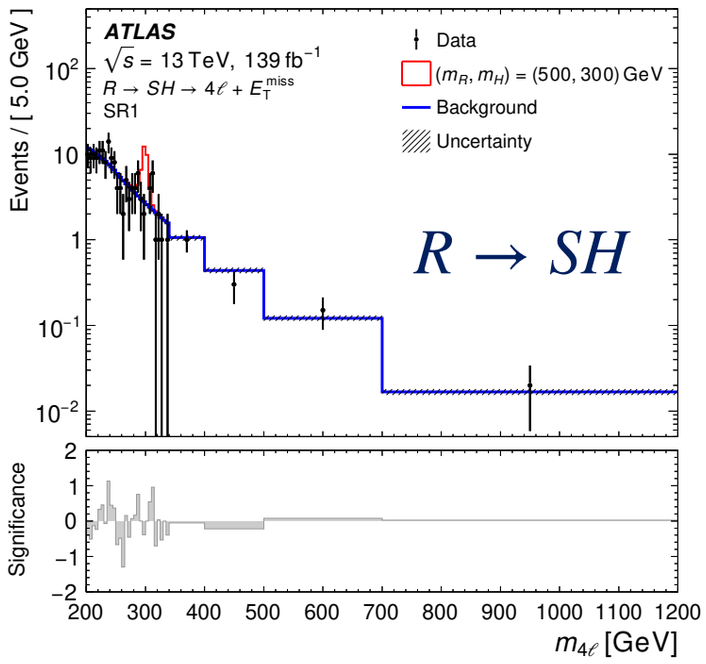
2HDM+S, $R \to SH \to 4\ell + E_T^{miss}$

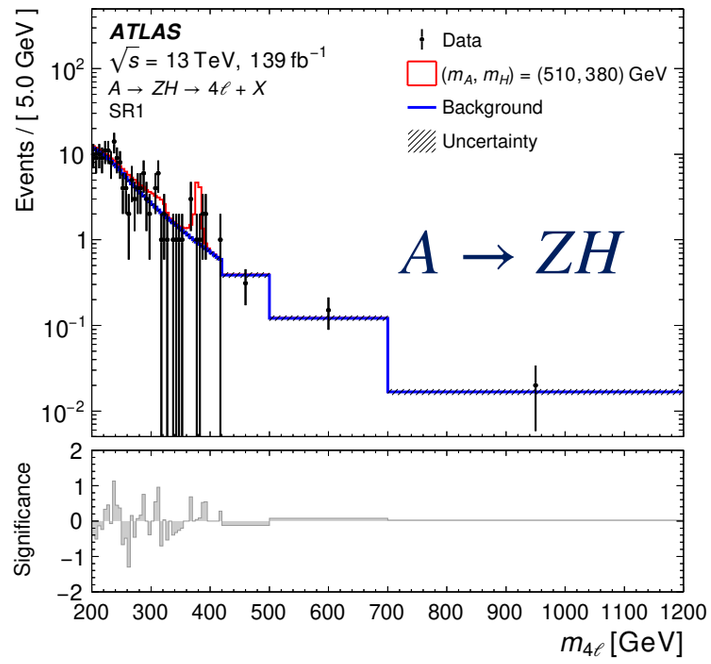


2HDM, $A \to ZH \to 4\ell + X$

Analysis strategy

- Based on the kinematics variables, the events are categorised into 7 different signal regions
- A parameterised empirical function is used to describe background $m_{4\ell}$ shape



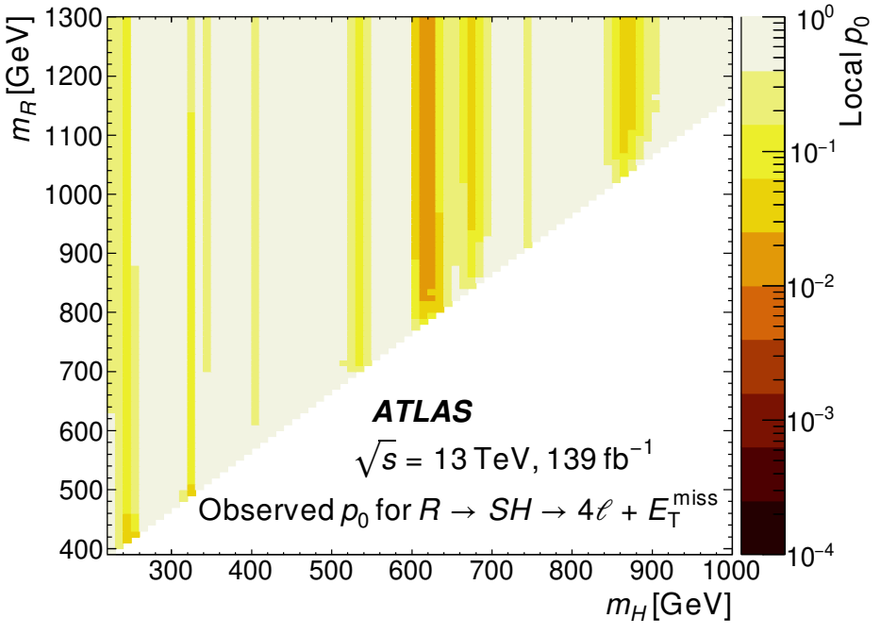


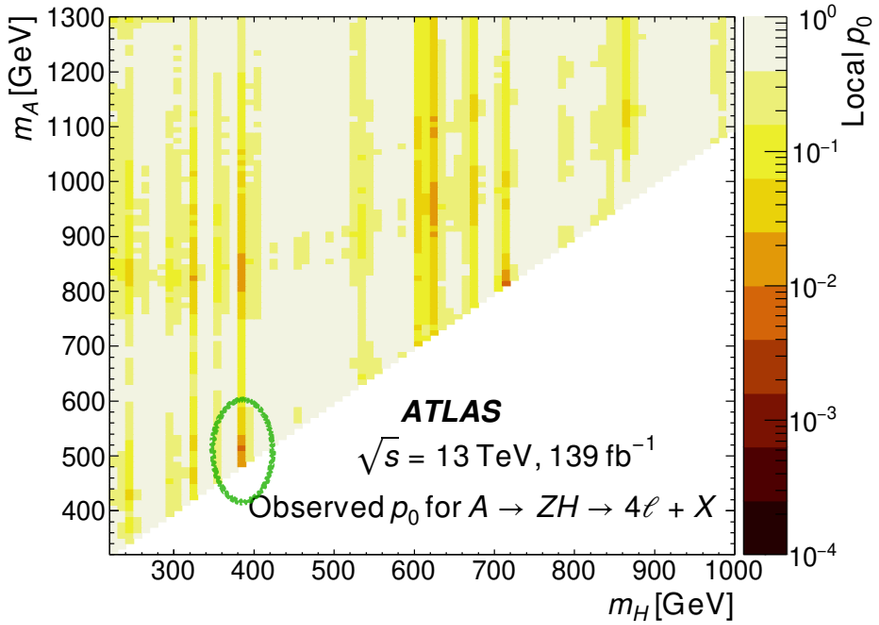
$A \rightarrow ZH$ and $R \rightarrow SH$ (2)

arXiv:2401.04742

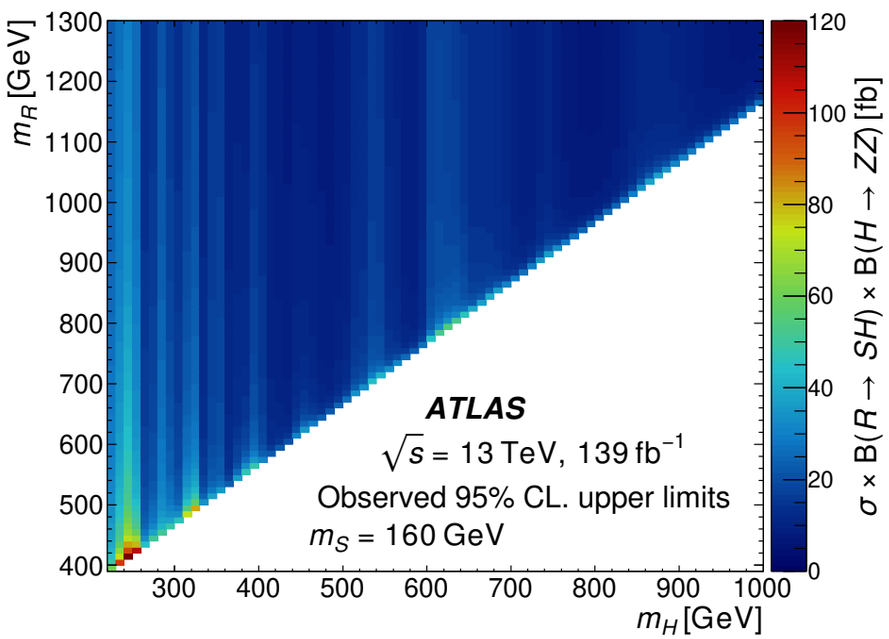
Results

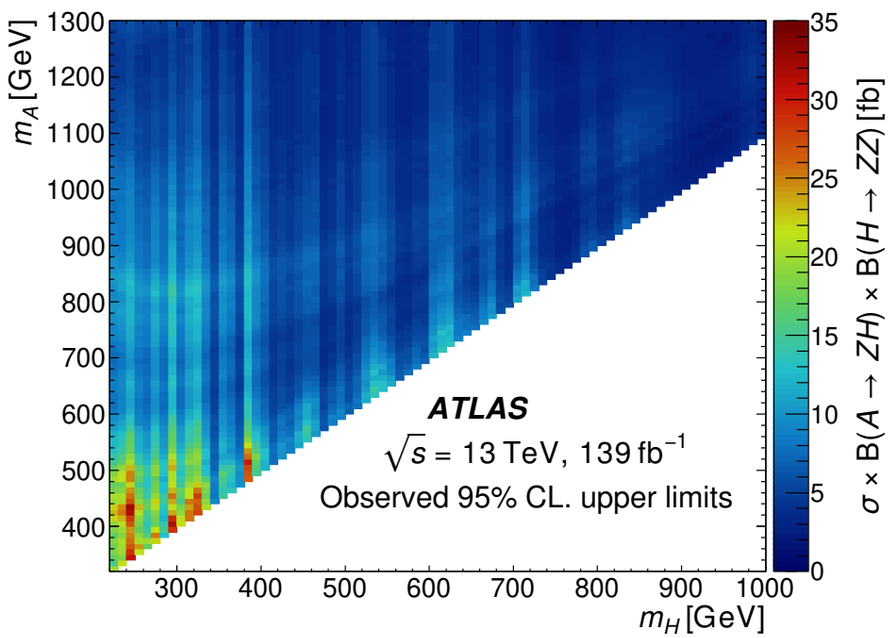
- No significant deviation from the SM backgrounds is observed
- Largest excess: $(m_A, m_H) = (510, 380)$ GeV, local significance 2.5σ





Upper limit

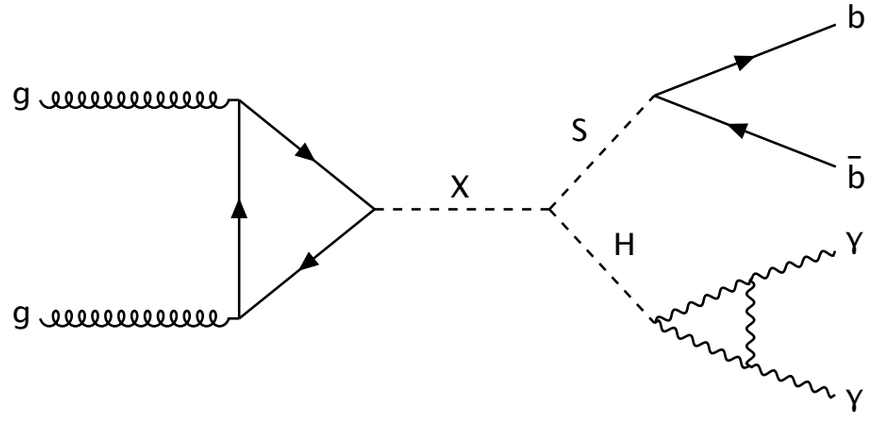




$X \to SH \to b\bar{b}\gamma\gamma$ (1)

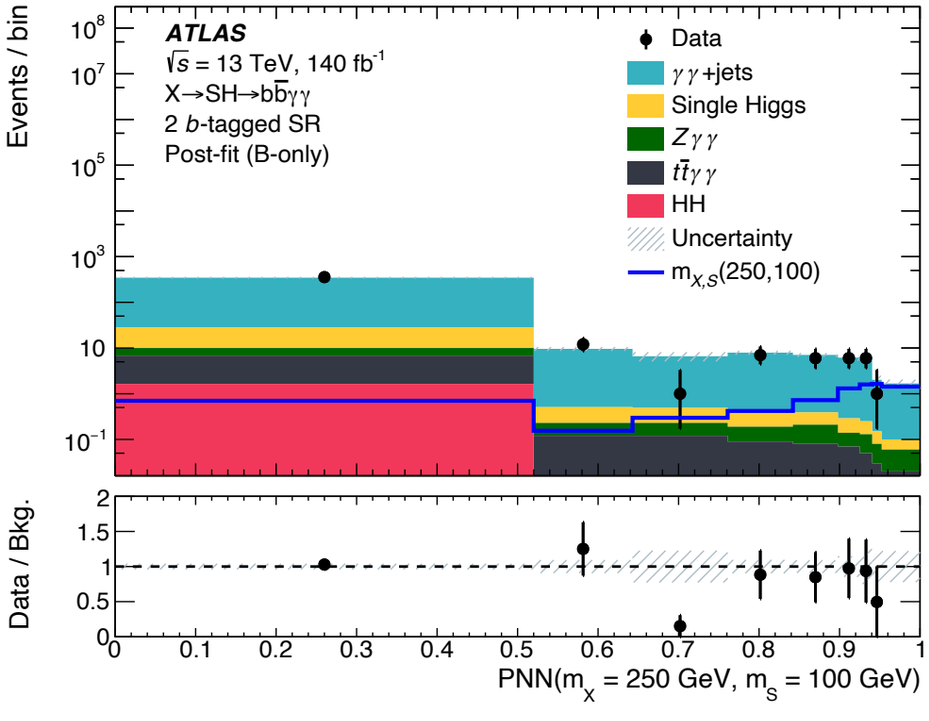
arXiv:2404.12915
2024-04-19

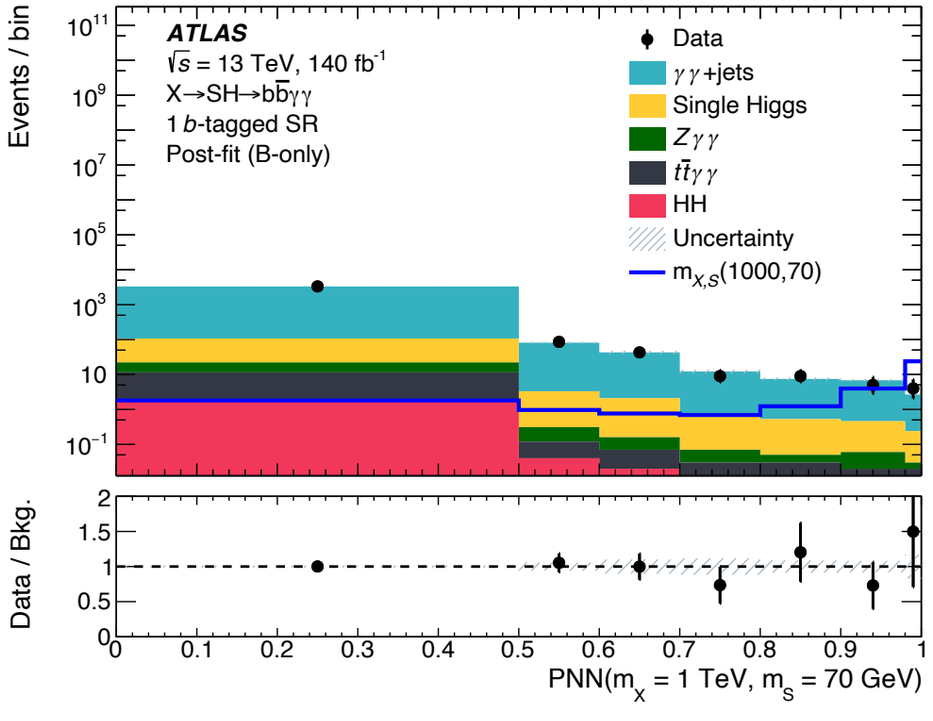
- Heavy scalar X decays to SM Higgs (H) and another BSM scalar (S)
- m_X between 170 and 1000 GeV
- m_s between 15 and 500 GeV
- SM Higgs decays to photon pair and S decays b quark pair



Analysis strategy

- 2 signal regions: 1 $b-$tagged jet and 2 $b-$tagged jets
- $120 < m_{\gamma\gamma} < 130$ GeV
- Parameterised neural network is used as the final discriminant





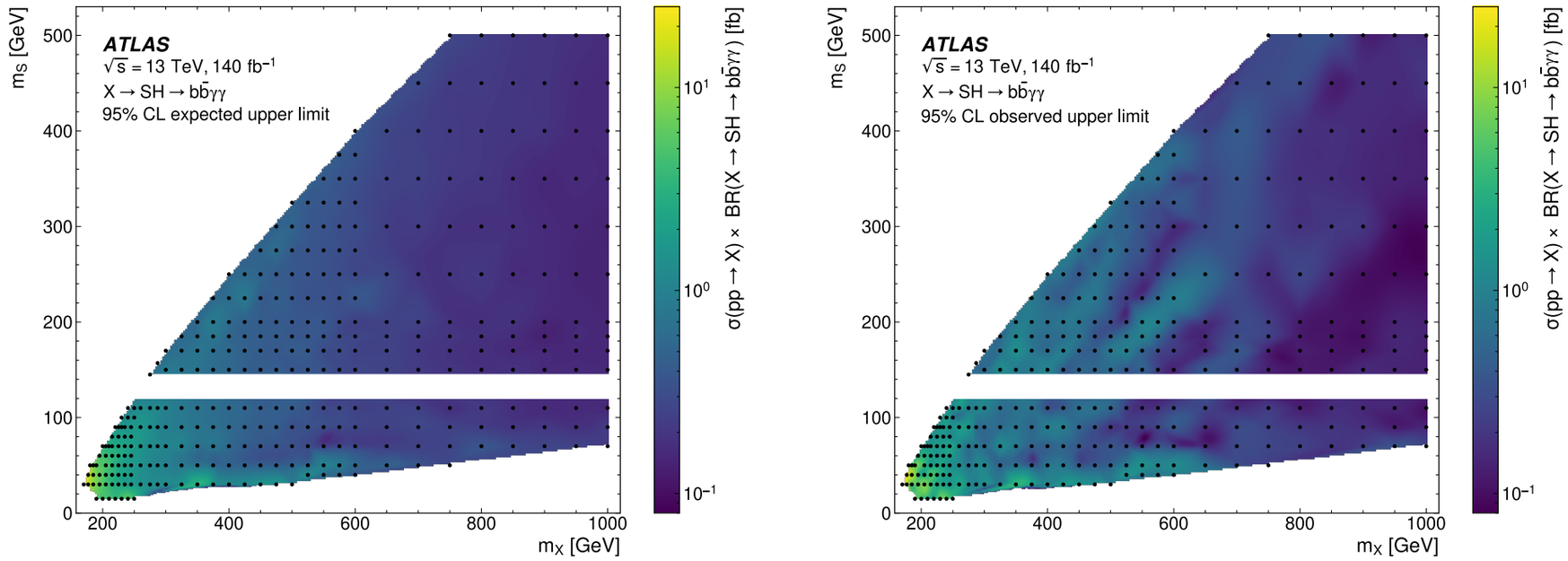
$X \to SH \to b\bar{b}\gamma\gamma$ (2)

arXiv:2404.12915

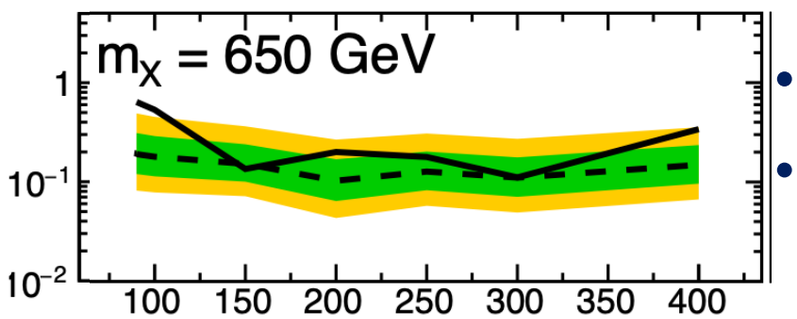
Results

- Largest excess: $(m_X, m_S) = (575, 200)$ GeV, local significance 3.5σ
- Global significance 2.0σ

Expect and observed limit



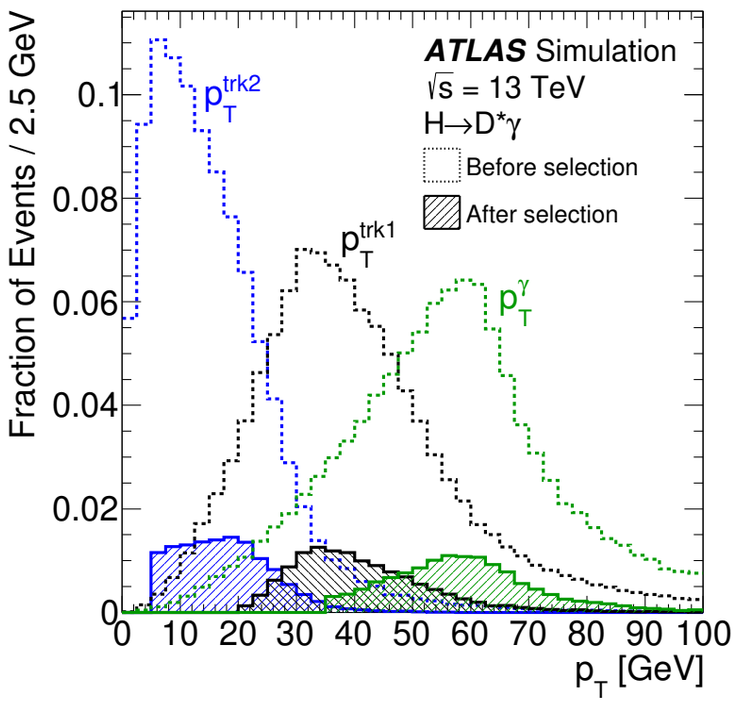
Compare the largest excess to CMS results

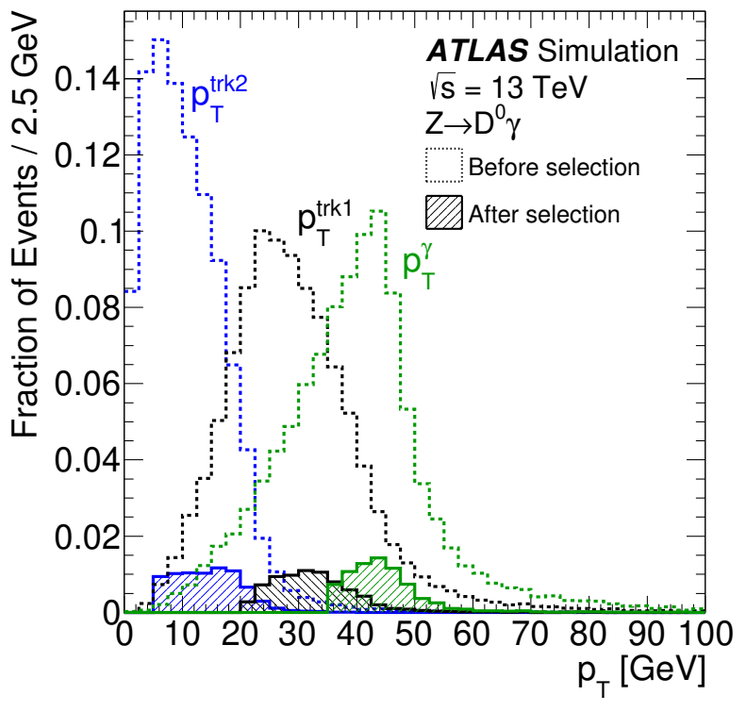


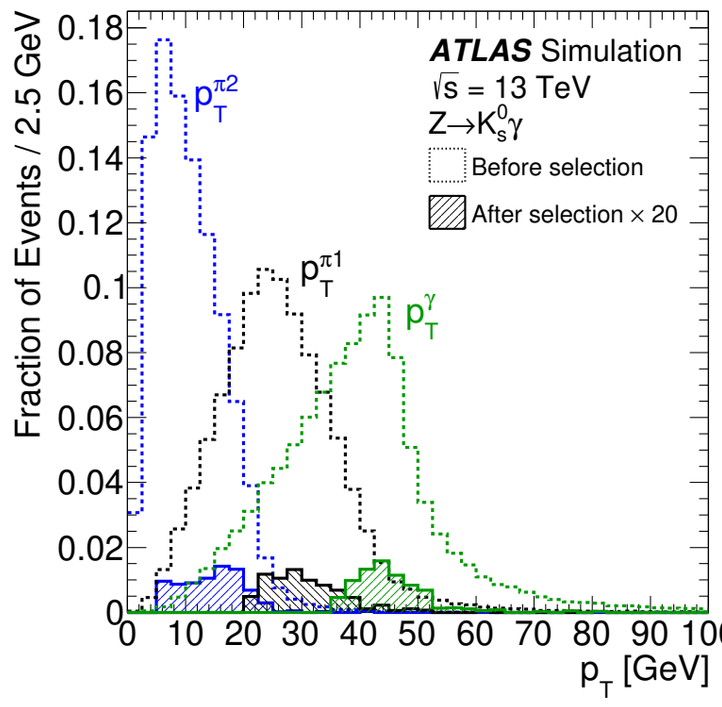
- CMS largest excess: $(m_X, m_S) = (650, 90)$ GeV, local significance 3.8σ
- Using the cross section 0.35fb (best fit reported by the CMS experiment) yields a local excess 2.7σ from ATLAS measurement

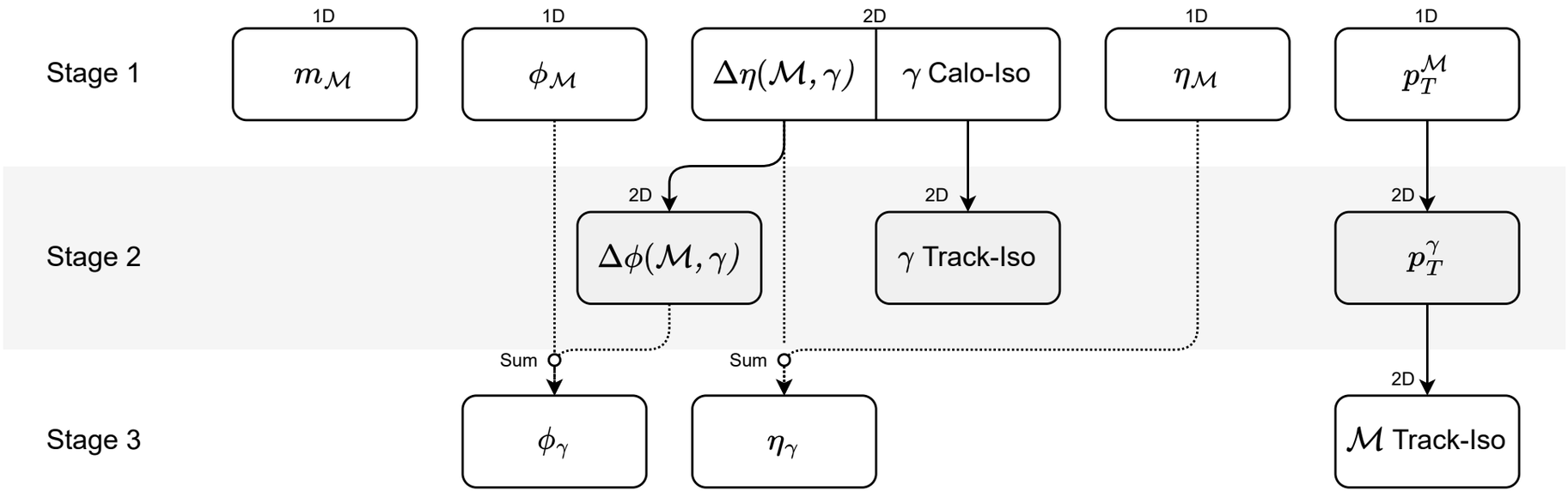
Rare decay of the h_{125} to D* and photon

arXiv:2402.18731



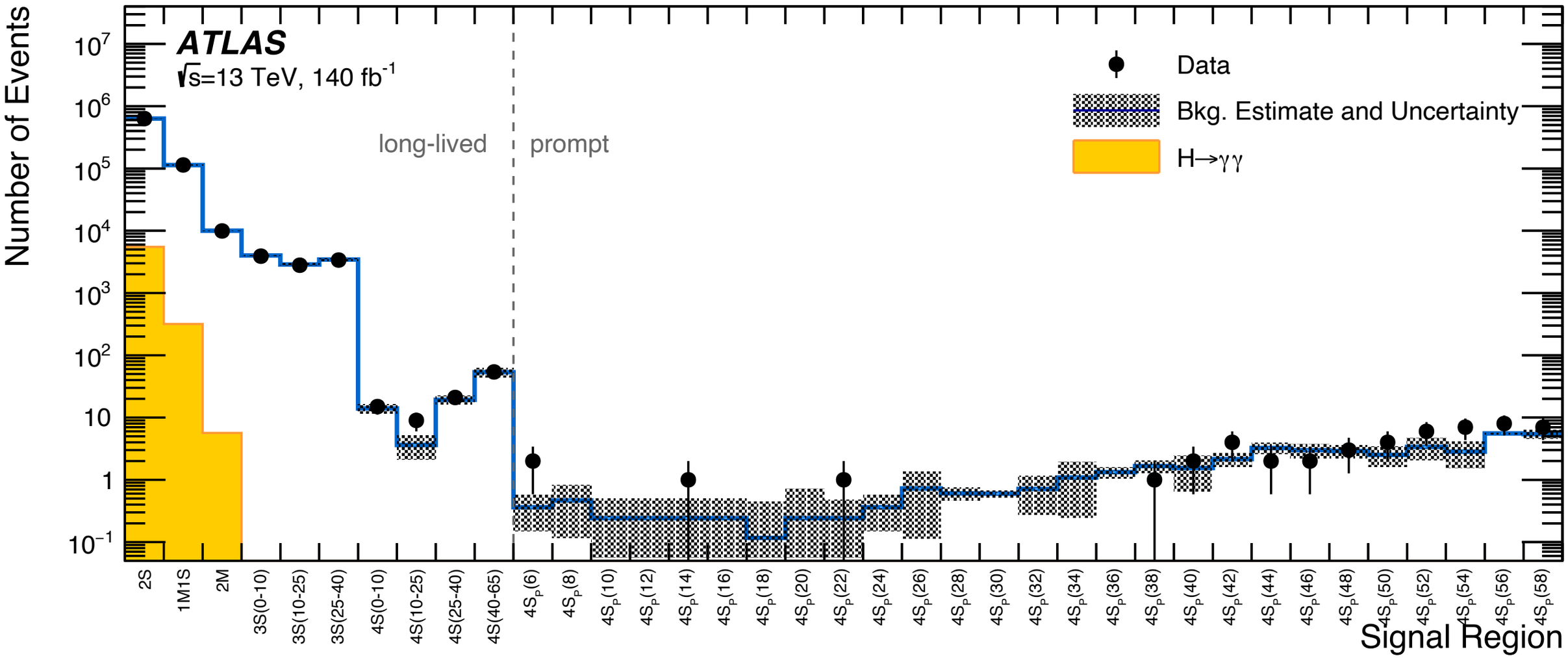






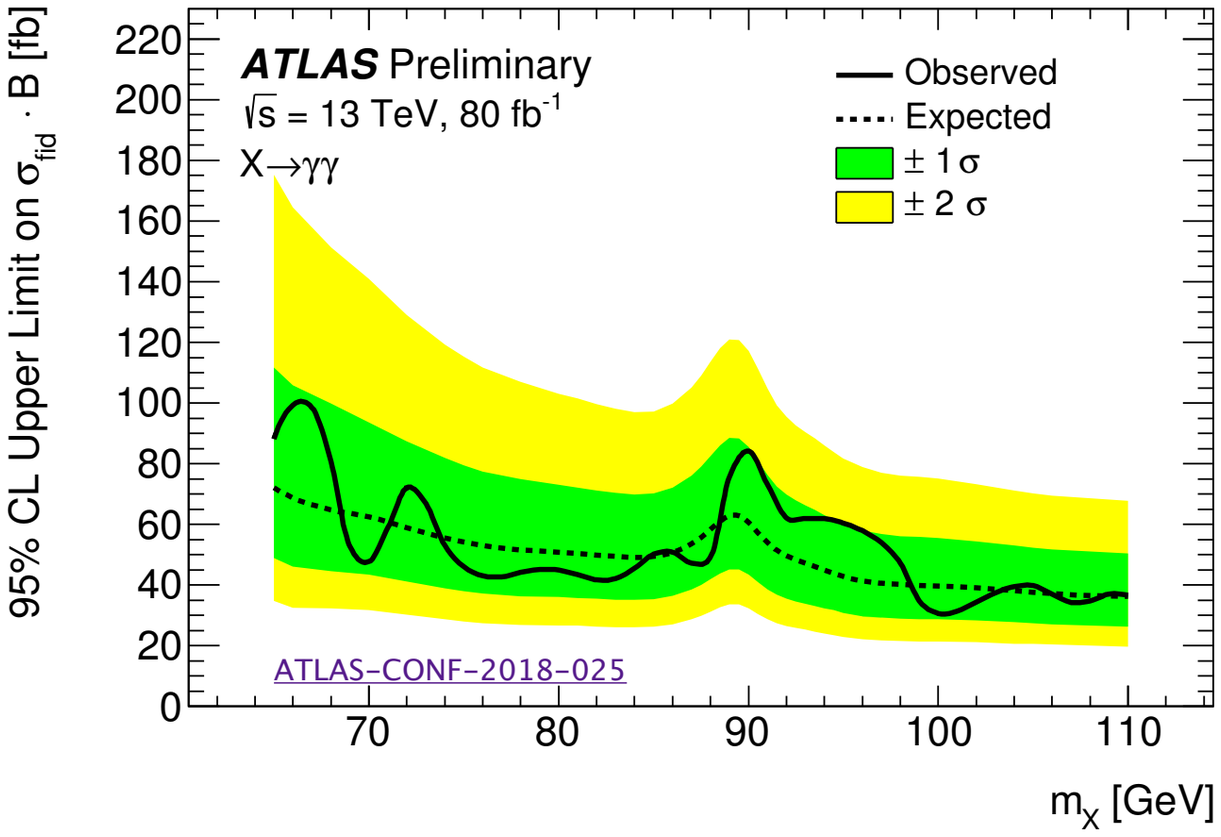
Axion-like particles $H \rightarrow aa \rightarrow 4\gamma$

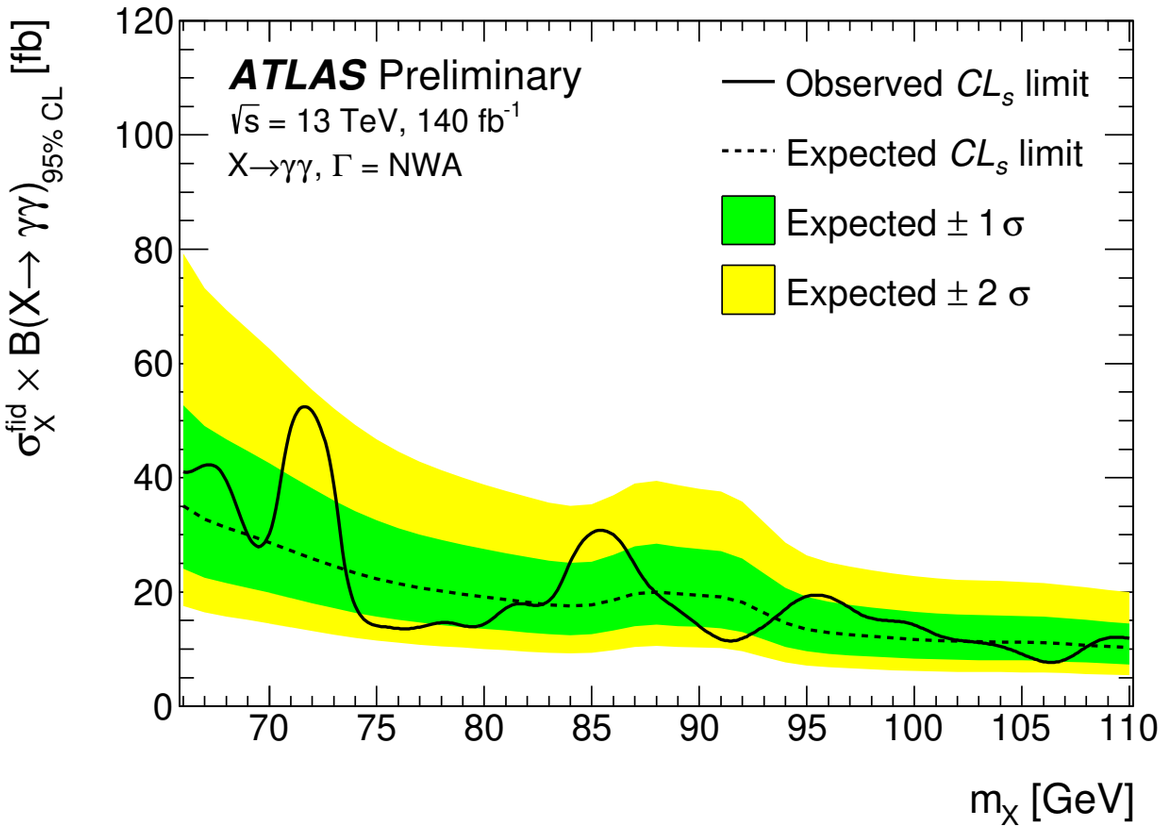
arXiv:2312.03306



Low mass $H \rightarrow \gamma\gamma$

Compare to previous ATLAS results





~ 50% improvement on the upper limit