# Beyond the Standard Model in the Higgs Sector

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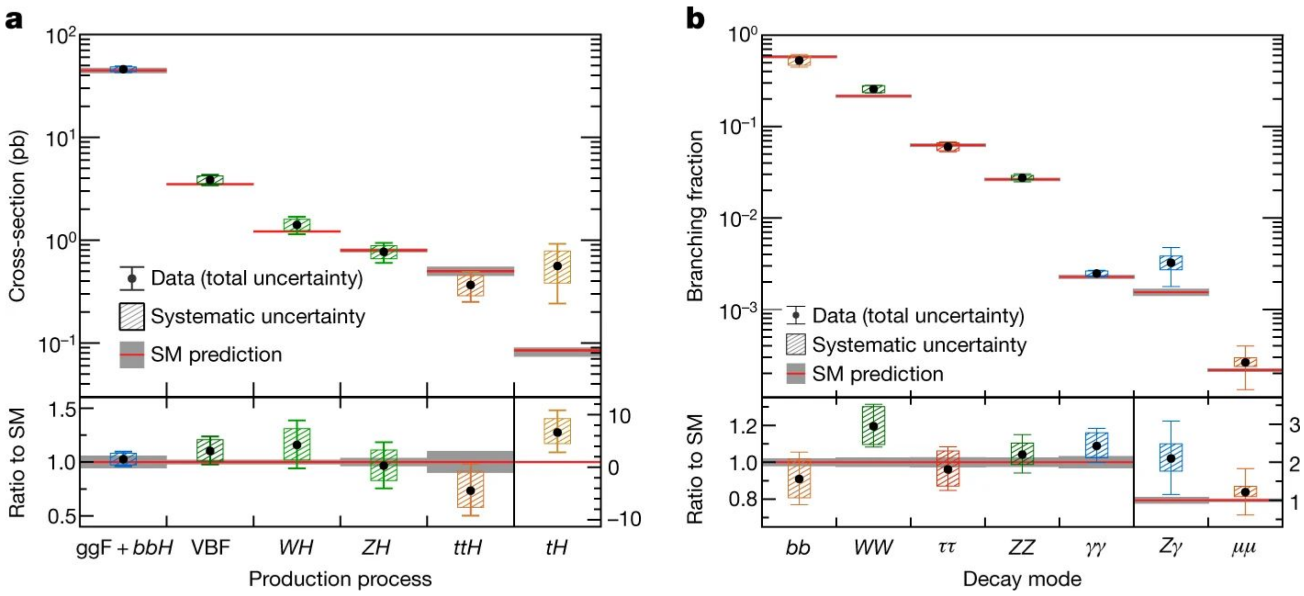
On behalf of the ATLAS collaboration

# Current landscape

A multitude of measurements have confirmed that the properties of the Higgs are compatible with the SM predictions.




Main production and decay processes were observed and measured with ~10% precision.

Nature 607 52 (2022)

# Current landscape

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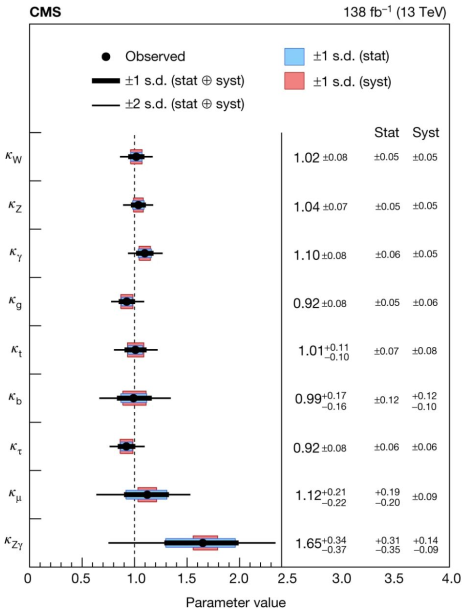
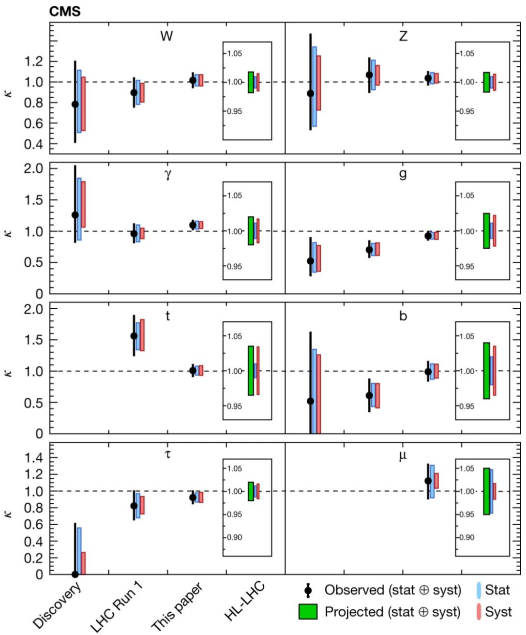



Coupling modifiers were measured with ~10 - 40 % precision.

[Nature 607 60-68 (2022)]

# Shortcomings of the SM

**Why is the electroweak interaction so much stronger than gravity?**

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs boson with the *W* and *Z* bosons?

**Why is there more matter than antimatter in the Universe?**

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-Universe electroweak phase transition?
- Are there multiple Higgs sectors?

**What is the origin of the vast range of quark and lepton masses in the Standard Model?**

- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs boson decay into pairs of quarks or leptons with distinct flavours (for example, $H \to \mu^+\tau^-$)?

**What is dark matter?**

- Can the Higgs boson provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs boson?

**What is the origin of the early Universe inflation?**

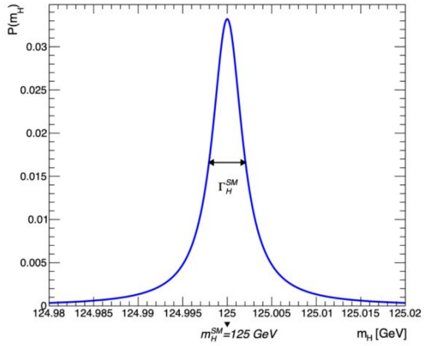
- Any imprint in cosmological observations?

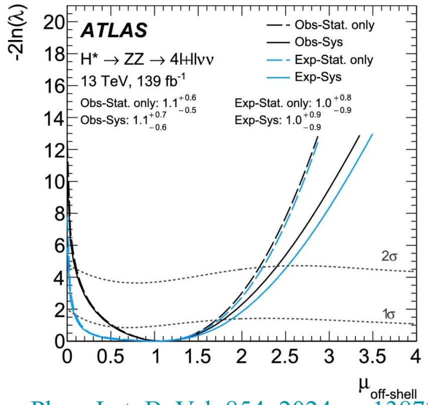
Precision measurements of the Higgs Boson properties and direct searches for BSM Higgs and rare decay modes of can help us to get to the bottom of these questions.

# Motivation

The Higgs width predicted by the SM is extremely small (w.r.t. the experimental resolution).

- Most recent measurement of total width: $\boldsymbol{\Gamma}_{\mathrm{H}}=4.5_{-2.5}^{+3.3}$ MeV
  - Even very small couplings to new particles can give sizable branching ratios BR
  - Most recent combination from ATLAS:
    - BR($H \rightarrow$ undetected) < 12%
    - BR($H \rightarrow$ invisible) < 10.7%




Phys. Let. B. Vol. 854, 2024, p. 138734

# Theoretical models

Various BSM scenarios being considered

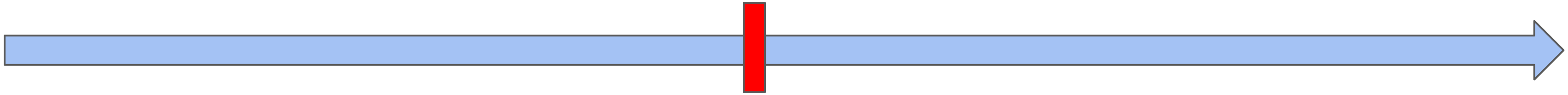
- Two Higgs Doublet Model (2HDM) and its variations (e.g. MSSM)
    - 5 Higgs Bosons: h, $H$, $A$, $H^+$ , $H^-$
    - 7 free parameters: 5 Higgs masses, α, $tan\beta$
    - Widely used as a benchmark for BSM Higgs searches

- 2HDM + Singlet and its variations
    - e.g: Complex singlet + SUSY conditions → NMSSM
    - 7 Higgs Bosons: five of 2HDM, with 2 additional neutral bosons (1 CP-even and 1 CP-odd)

- Axions and axion-like particles (ALPs)
    - Interact with the known particles through higher-dimensional operators suppressed by the mass scale Λ

# BSM Higgs search landscape in ATLAS

Low mass | 125 GeV | High mass



**Low mass**

$pp \to a$
$h_{125} \to aa$
$h_{125} \to a_1 a_2$
$h_{125} \to Za$

**125 GeV**

$h_{125}$ rare decays
$h_{125}$ exotic decays
$h_{125} \to$ invisible

**High mass**

$pp \to ttH/A,\ H/A$
$H \to h_{125} h_{125}$
$H \to Sh_{125},\ SS$
$H^+ \to tb\ /\boldsymbol{\tau}^+ \boldsymbol{\nu}$
$A \to ZH,\ Zh_{125}$

[arxiv:2405.04914](https://arxiv.org/abs/2405.04914)

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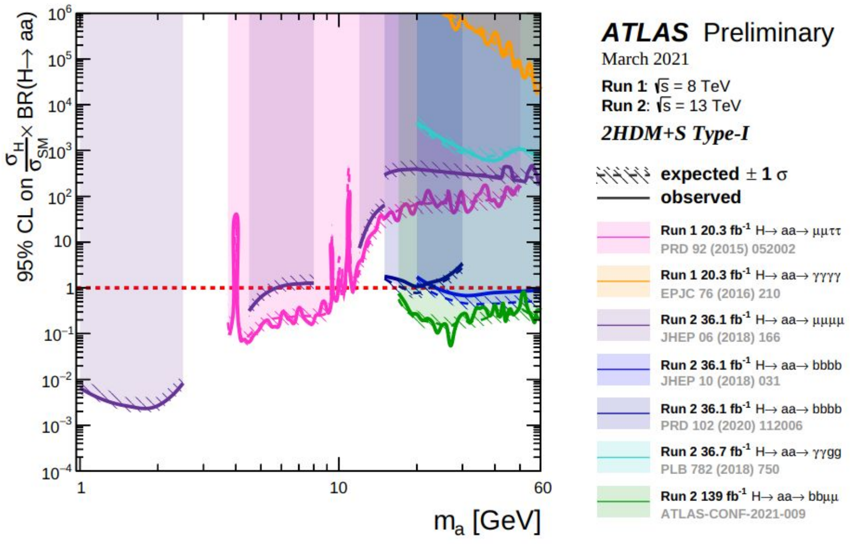
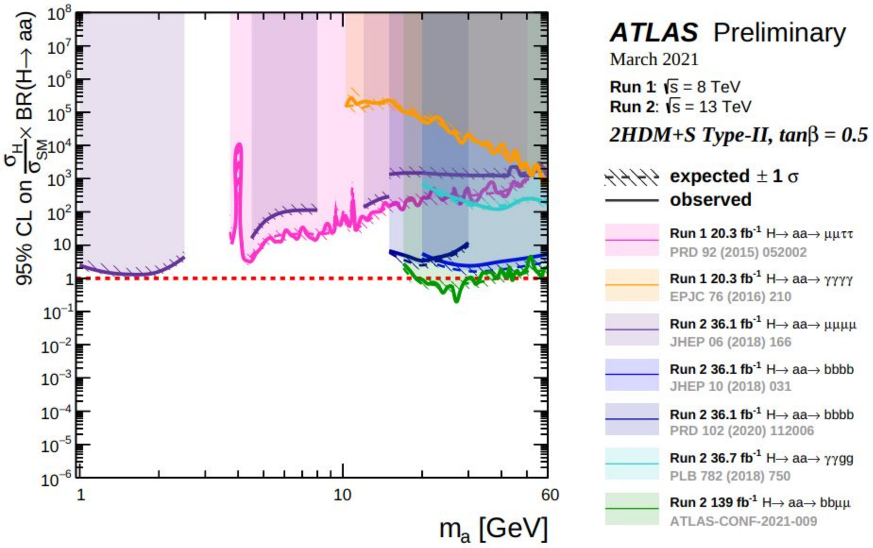
[arxiv:2405.04914](arxiv:2405.04914)

# Summary 2HDM+S with $H \to aa$

- Limits on the branching ratio of $H \to aa$ assuming a 2HDM + S type-N scenario
- Limits improved since then!



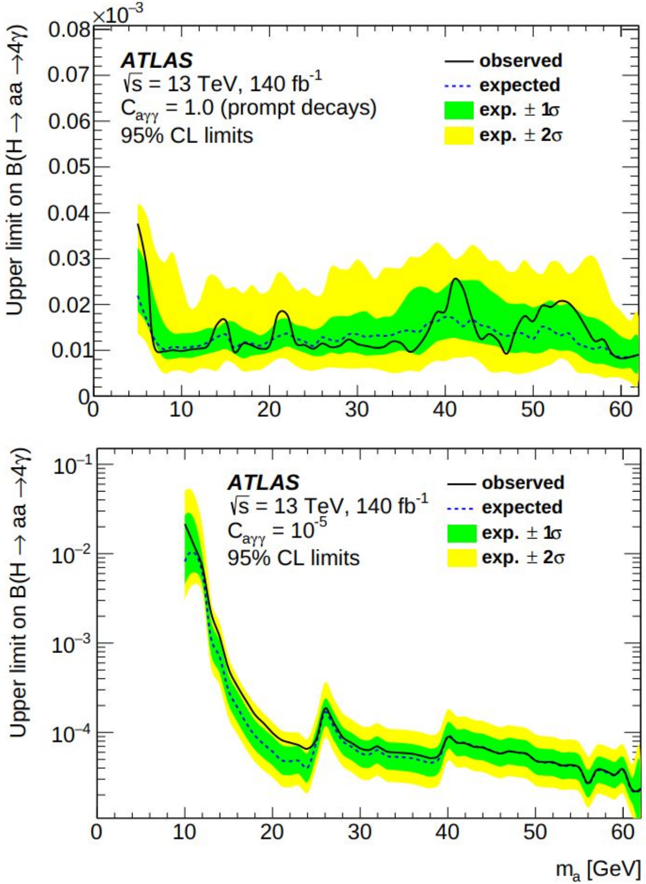




ATL-PHYS-PUB-2021-008

# $H \to aa \to \gamma\gamma\gamma\gamma$

Full Run 2 analysis

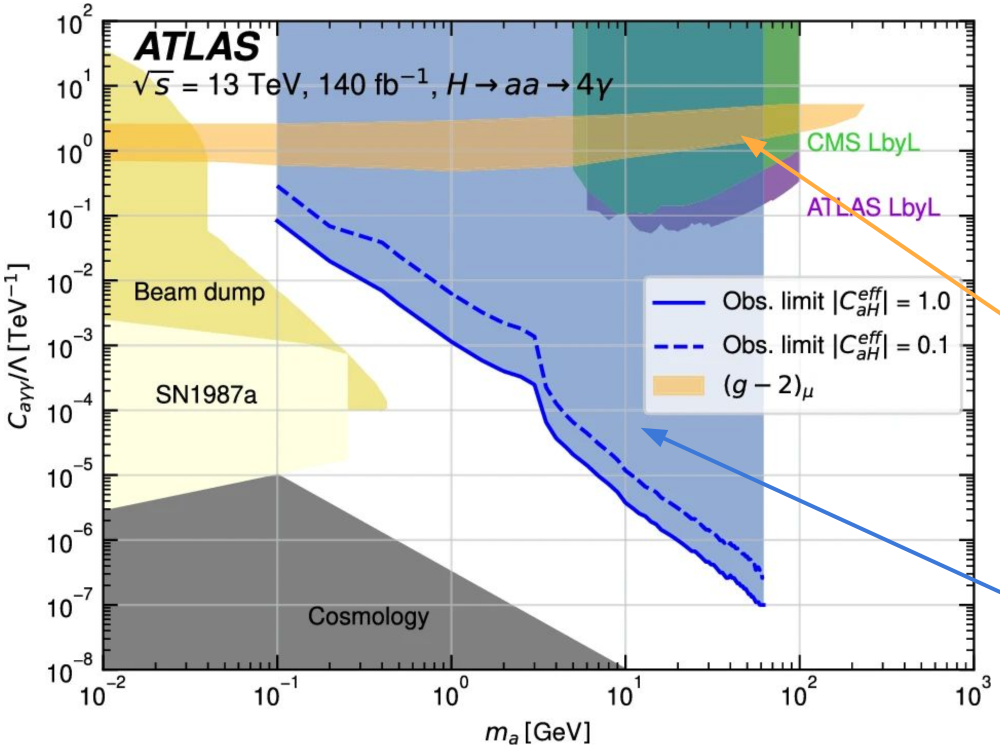
- Anomalous Higgs boson decays into two ALPs
- Both prompt and long-lived $a \to \gamma\gamma$ signatures explored
- Final discriminant is the ALP mass $m_a^{reco}$
- $C_{a\gamma\gamma}$ coupling determines the lifetime, limits set for different ALP-photon couplings $C_{a\gamma\gamma}$
  - $C_{a\gamma\gamma} \geq 0.1$ promptly decaying, smaller couplings long-lived
  - $C_{a\gamma\gamma} < 10^{-5}$ cannot be probed because would decay outside of detector
- No significant excess over the SM backgrounds is observed.




ATL-COM-PHYS-2022-1171

# $H\rightarrow aa\rightarrow\gamma\gamma\gamma\gamma$

Full Run 2 analysis




- Limit on branching ratio converted to limit on photon coupling. Assuming new physics scale $\Lambda$= 1.
- Allowed parameter space for ALP-based models that could explain the $(g-2)\mu$ discrepancy in the $H\rightarrow aa\rightarrow 4\gamma$ decay mode significantly reduced

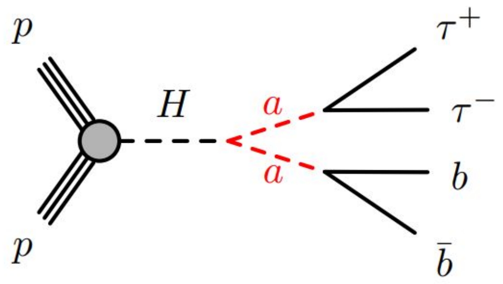
Orange shaded area indicates the region favoured by an ALP explanation for the $(g-2)\mu$ discrepancy

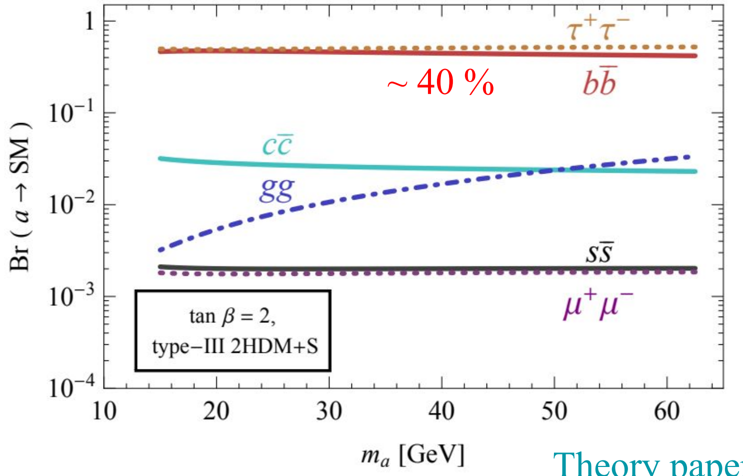
Region excluded by this analysis

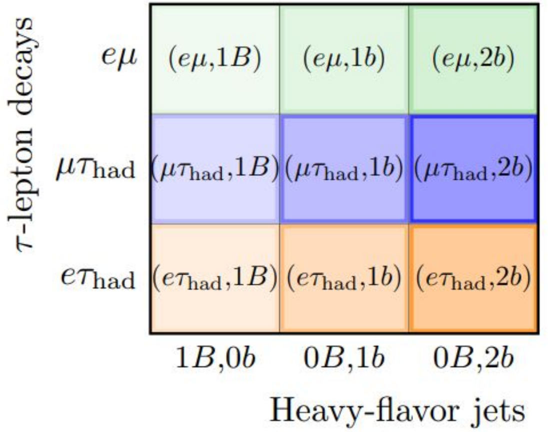
# Search for $H \to aa \to b\bar{b}\tau^+\tau^-$

Full Run 2 analysis

- Search for Higgs boson decays into a pair of new pseudoscalars particles $a$
- When the $a$-boson mixes with the SM Higgs boson, it inherits its Yukawa couplings to fermions. Decays of the $a$-boson into heavy fermions such as $b$-quarks and $\tau$-leptons are favored.
- The analysis defines different event categories depending on $\tau$-lepton decay modes ($e\mu$, $e\tau_{\text{had}}$, and $\mu\tau_{\text{had}}$) and strategies for identifying heavy-flavor jets (merged $b$-jet pairs ($B$), single $b$-jets ($b$))



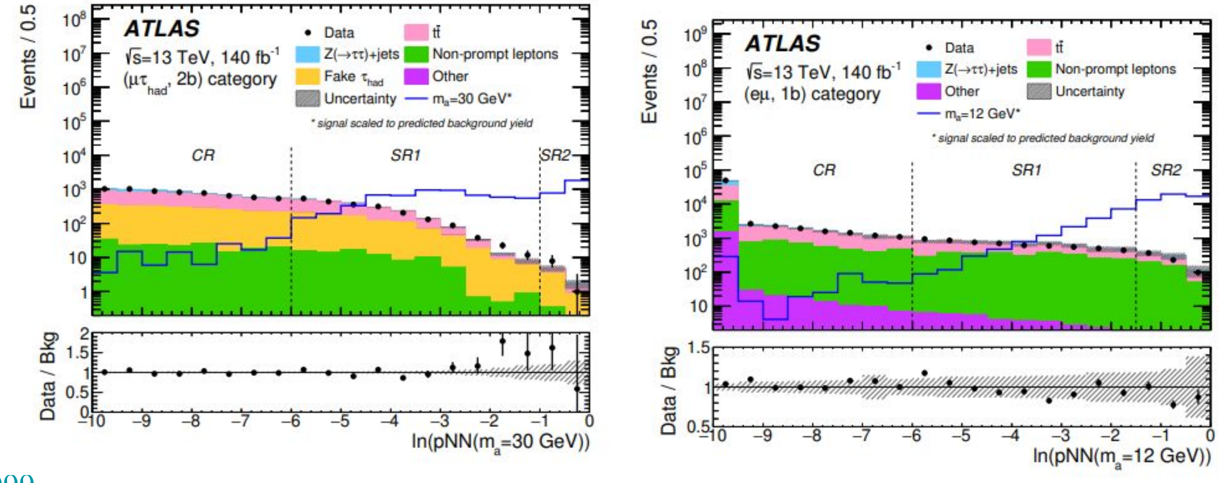

Theory paper

ATL-COM-PHYS-2024-099

# Search for $H \rightarrow aa \rightarrow b\bar{b}\tau^+\tau^-$

Full Run 2 analysis

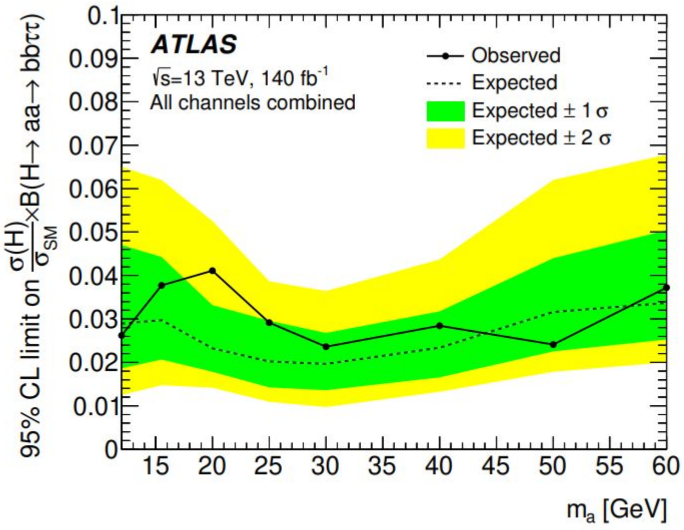
- For $m_a \leq 20$ GeV: *a*-boson has a large Lorentz boost and its decay products can be collimated
  - Dedicated algorithm to identify low-mass, merged, "double *b*-quark" jets (*B*-jets)
    - Uses the tracks from the $R = 0.8$ track-jets to reconstruct secondary vertices, which provide a distinctive signature of merged *b*-jets
  - Displaced tracks, secondary vertices, etc. fed into neural network to classify the flavor of the jet.

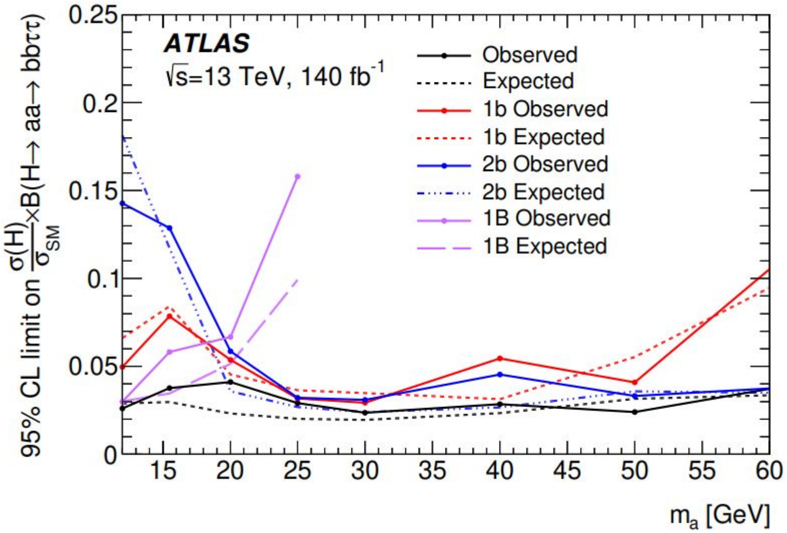



ATL-COM-PHYS-2024-099

# Search for $H \to aa \to b\bar{b}\tau^+\tau^-$

- No significant excess observed over Standard Model predictions.
- Upper limits on BR($H \to aa \to b\bar{b}\tau^+\tau^-$)
  - Ranges from 2.2% to 3.9% for all categories combined

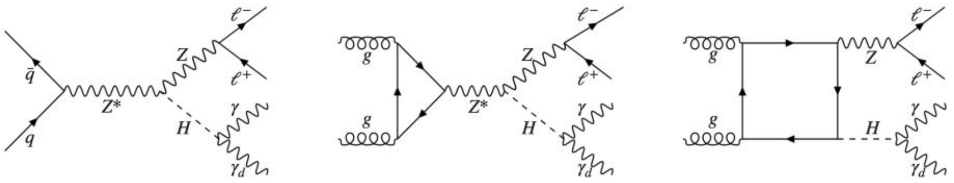


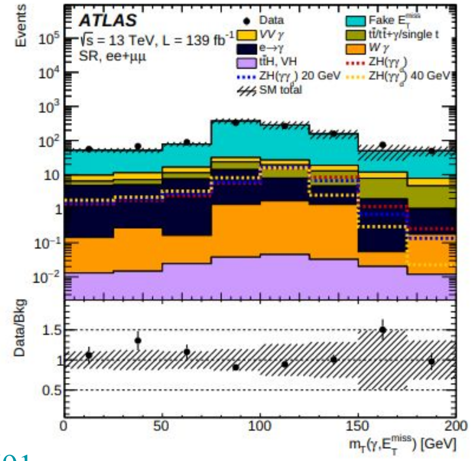



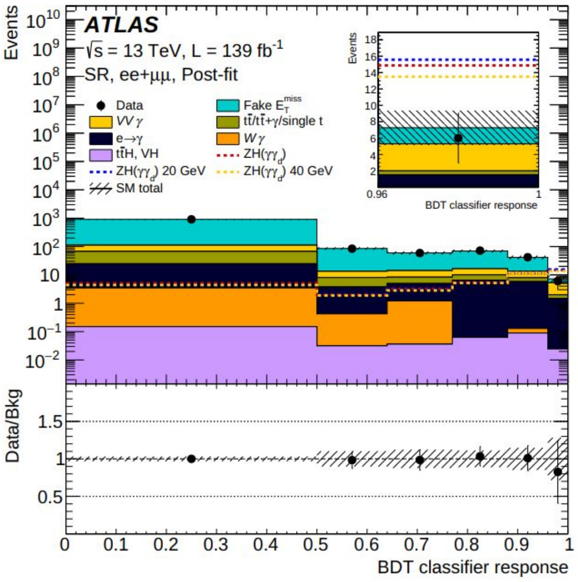
# Search for dark photons

Full Run 2 analysis

- Search for Higgs bosons decays ($H \rightarrow \gamma\gamma_d$) produced through the *ZH* production mode
  - Signature: Two leptons + single photon + $E_T^{miss}$
- Massive dark photon has received so far most of the attention because it couples directly to the SM currents and more accessible in the experimental searches.
- BDT enhances signal sensitivity
  - $m_T$ of the $\gamma$-$E_T^{miss}$ system included in BDT score



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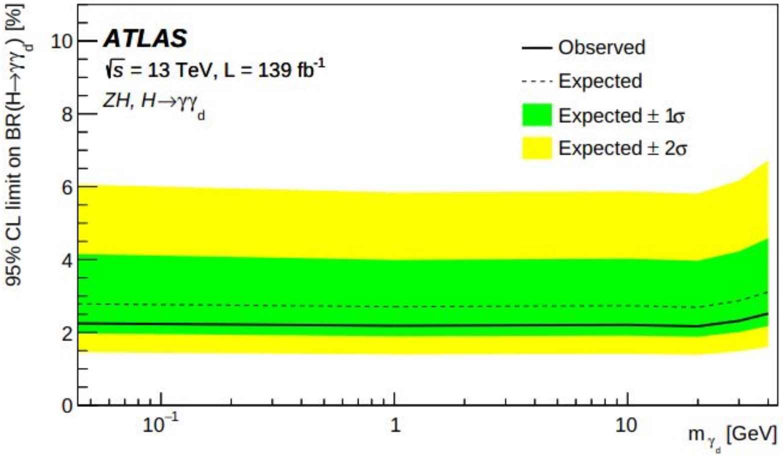
# Search for dark photons

- Binned maximum likelihood fit is performed to the distribution of the BDT classifier
- No excess over the Standard Model observed.
- Observed limits:
  - Massless $\gamma_d$: $BR(H\to\gamma\gamma_d) < 2.28\%$
  - Massive $\gamma_d$: $BR(H\to\gamma\gamma_d)$ within [2.19,2.52]%



# BSM Higgs search landscape

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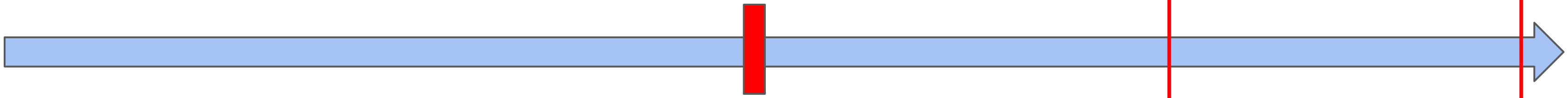

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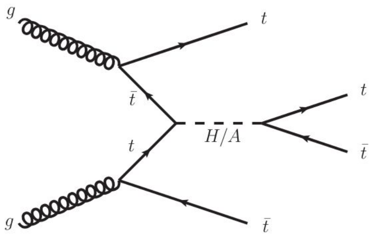
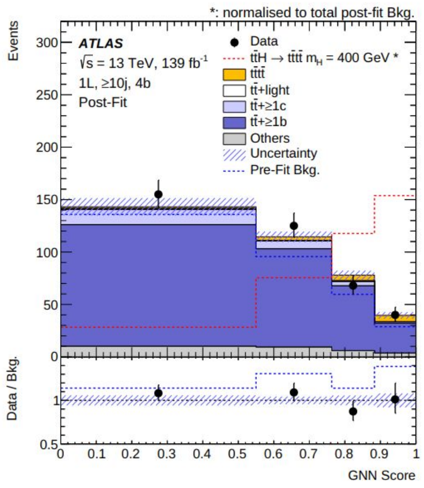
[arxiv:2405.04914](arxiv:2405.04914)

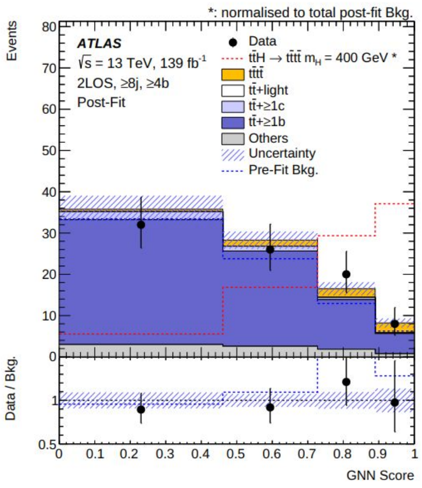
# Heavy Higgs

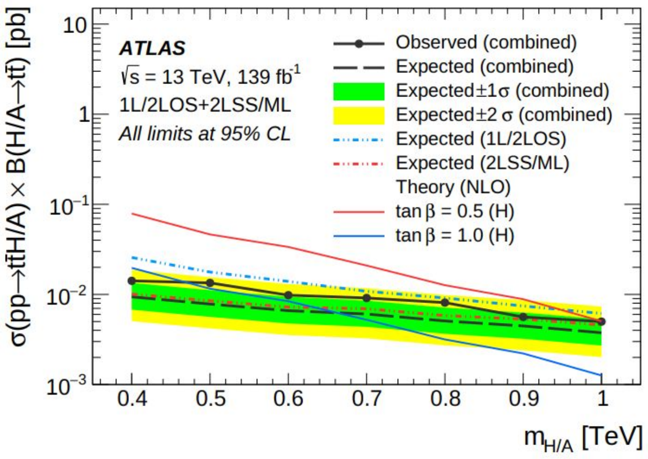
Search for a heavy scalar $H$ or pseudo-scalar $A$ predicted by 2HDM in association with a top pair, with the $H/A$ decaying to a top pair and opposite sign leptons in the final state




GNN is used to optimise the signal-background discrimination



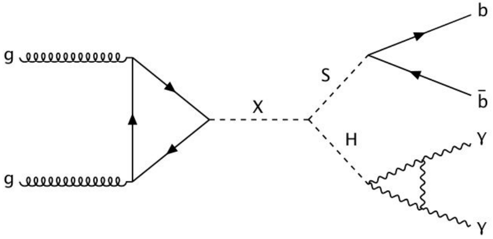




- Results combined with previous search from ATLAS with multilepton final states
- Combined observed limit ranges from 14.2 fb at $m_{A/H}$ of 400 GeV and 5.0 fb at 1000 GeV

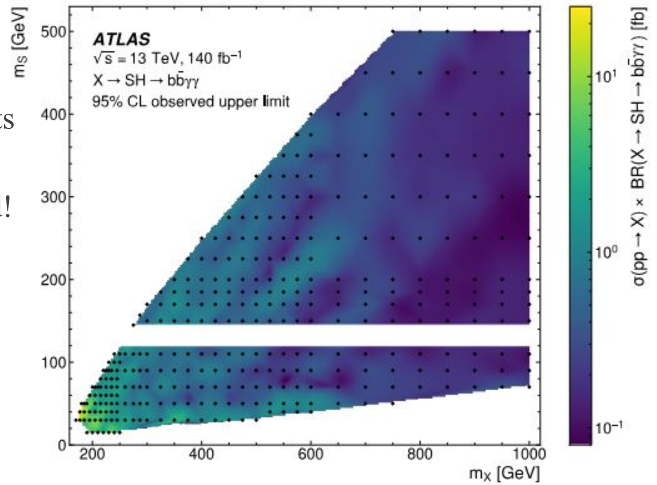
arXiv.2408.17164

# Heavy Higgs

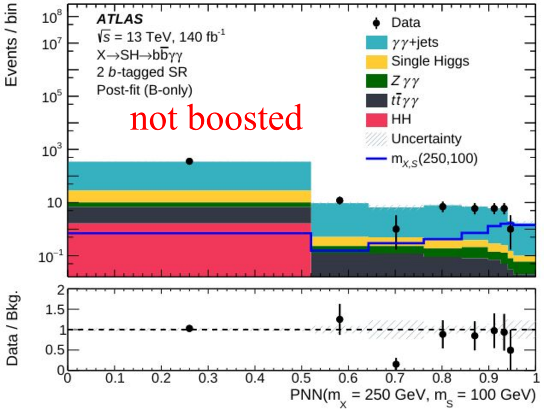
Search for a heavy scalar $X$ decaying into another scalar $S$ and a Higgs boson $H$
$X \rightarrow S(\rightarrow bb)H(\rightarrow \gamma\gamma)$

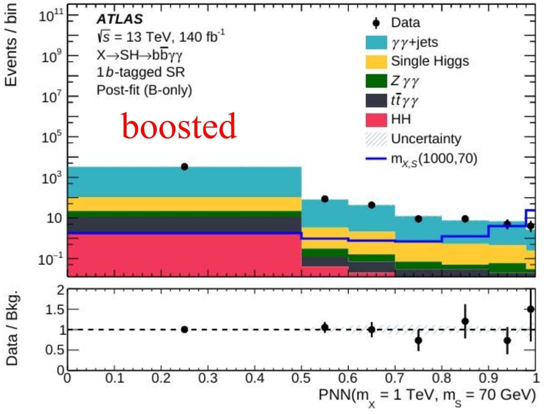



For setting limits 359 ($m_X$, $m_S$) pairs are probed!




Parameterised neural networks for signal discrimination in resolved and boosted decays



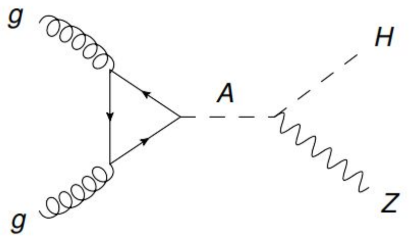

- No significant excess above the expected background is found
- Earlier LHC searches expanded to lower masses $m_S$ and $m_X$
- Upper limits range from 39 fb to 0.09 fb
  - Excluding small CMS excess at ($m_X$, $m_S$) = (650,90) GeV

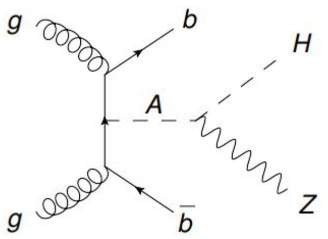
arXiv:2404.12915

# Search for $A \rightarrow H + Z$

Full Run 2 analysis

- Search for a heavy CP-odd Higgs boson A decaying into a heavy CP-even Higgs boson H and a Z boson
- Final states analyzed: $\ell^+\ell^- t\bar{t}$ and $\nu\bar{\nu}b\bar{b}$
    - Top-quark pairs (from $H$) in which one top-quark decays semileptonically and the other decays hadronically are considered
    - In addition, search with $Z$ boson decaying into neutrinos and the $H$ boson decaying into a pair of $b$-quarks is performed
- Extends the sensitivity for high mass regions:
    - $\ell^+\ell^- t\bar{t}$ for $m_H > 350$ GeV
    - $\nu\bar{\nu}b\bar{b}$ for $m_A > 800$ GeV and $m_H < 350$ GeV
- Employs model-dependent and independent interpretations

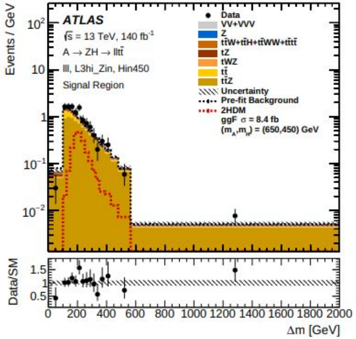


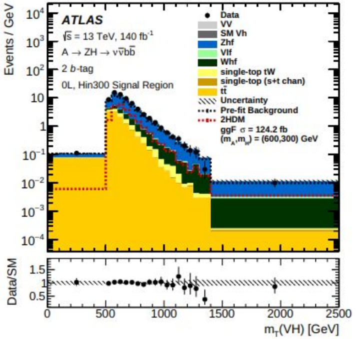



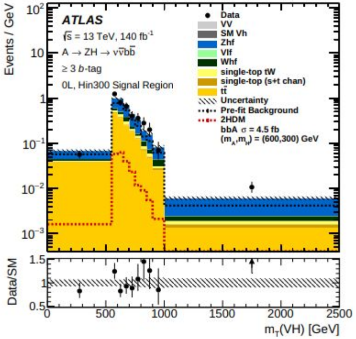

ATL-COM-PHYS-2023-113

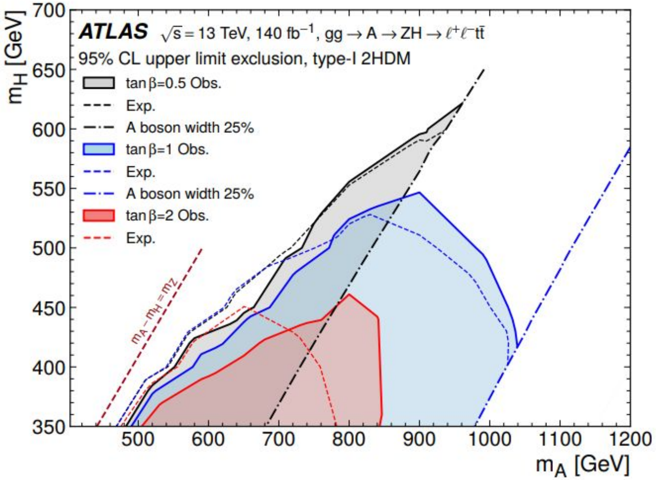
# Search for $A \to H+Z$

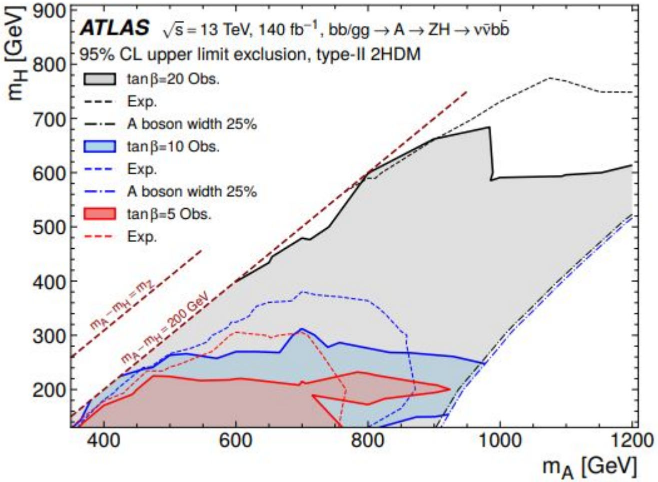
- Model-dependant limits set on $m_H$ and $m_A$ mass plane for various $\tan\beta$ values
- Based on the assumption that the *Z* and *H* candidates in the final state are produced resonantly and have a significant model dependence.



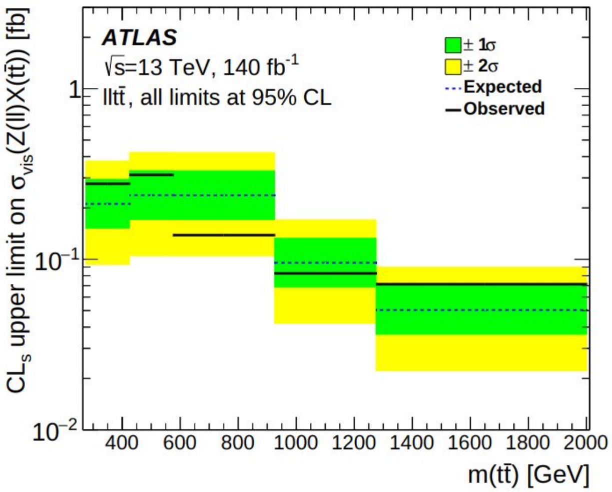



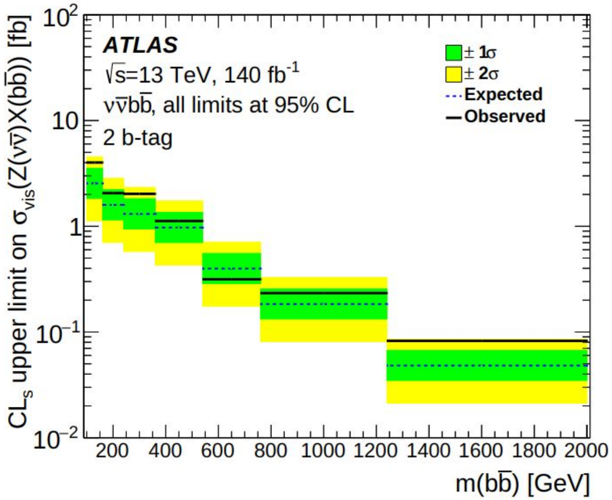



# Search for $A \to H + Z$

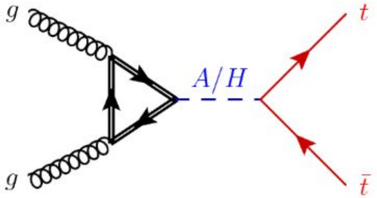
- Independent limits set on "visible" production cross-section.
- Number of signal events recorded by the detector in a given bin of $m(tt)$ or $m(bb)$ will be equal to the integrated luminosity times the 'visible cross-section' $\sigma_{vis}(Z(\ell\ell)X(tt))$ or $\sigma_{vis}(Z(\nu\nu)X(bb))$.



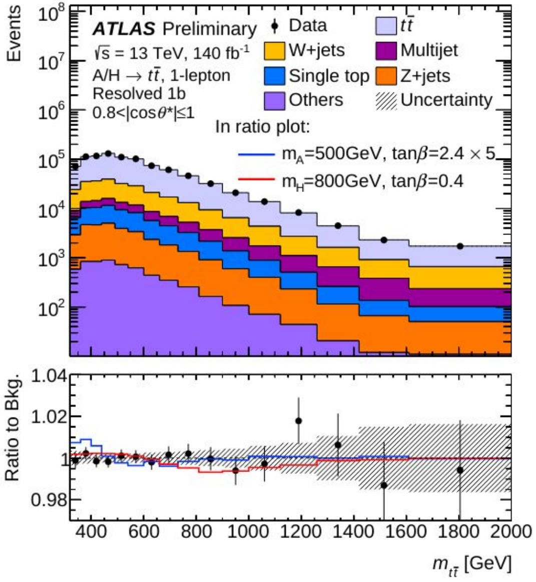



# Heavy Higgs

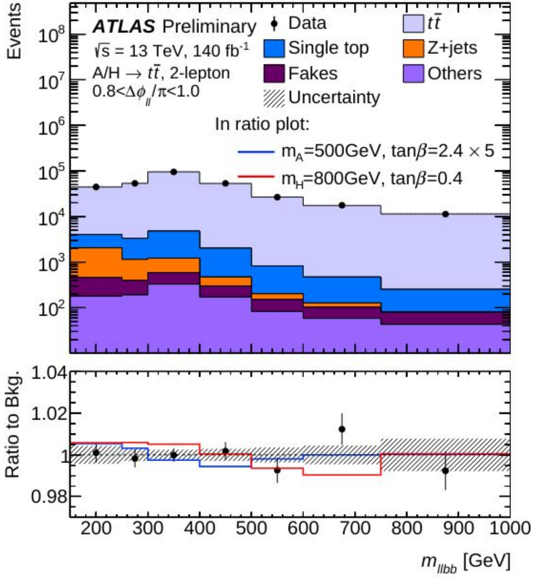
Search for heavy scalar $H$ or pseudo-scalar $A$ decaying into a top pair in a semi- or fully leptonic final state




1-lepton channel




2-lepton channel

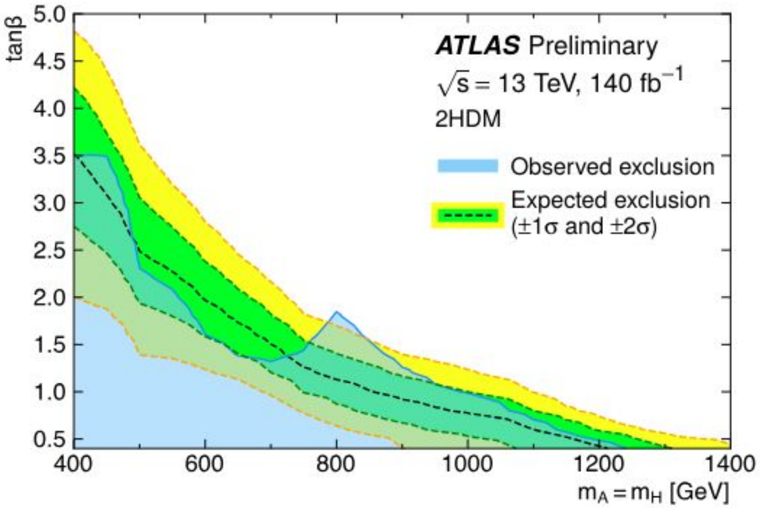


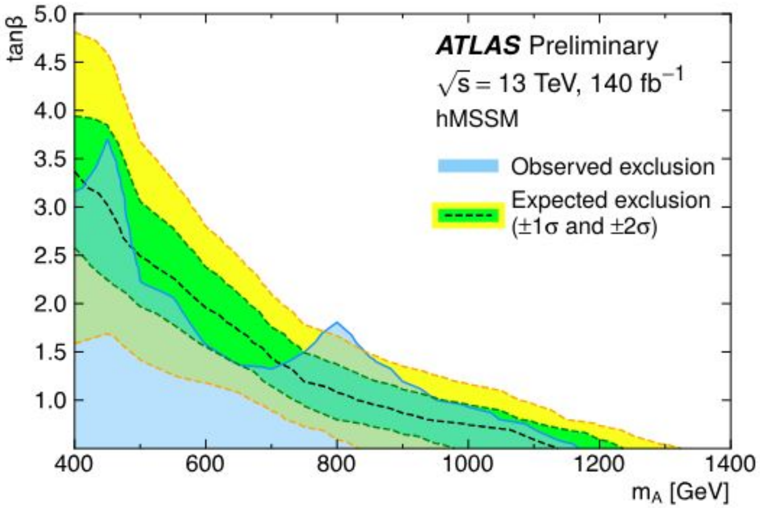



arXiv:2404.18986

# Heavy Higgs

- No significant deviation from SM is observed
- **Most stringent constraints on the 2HDM** and **hMSSM** parameter space **for high $m_A$ and low tan$\beta$** to date

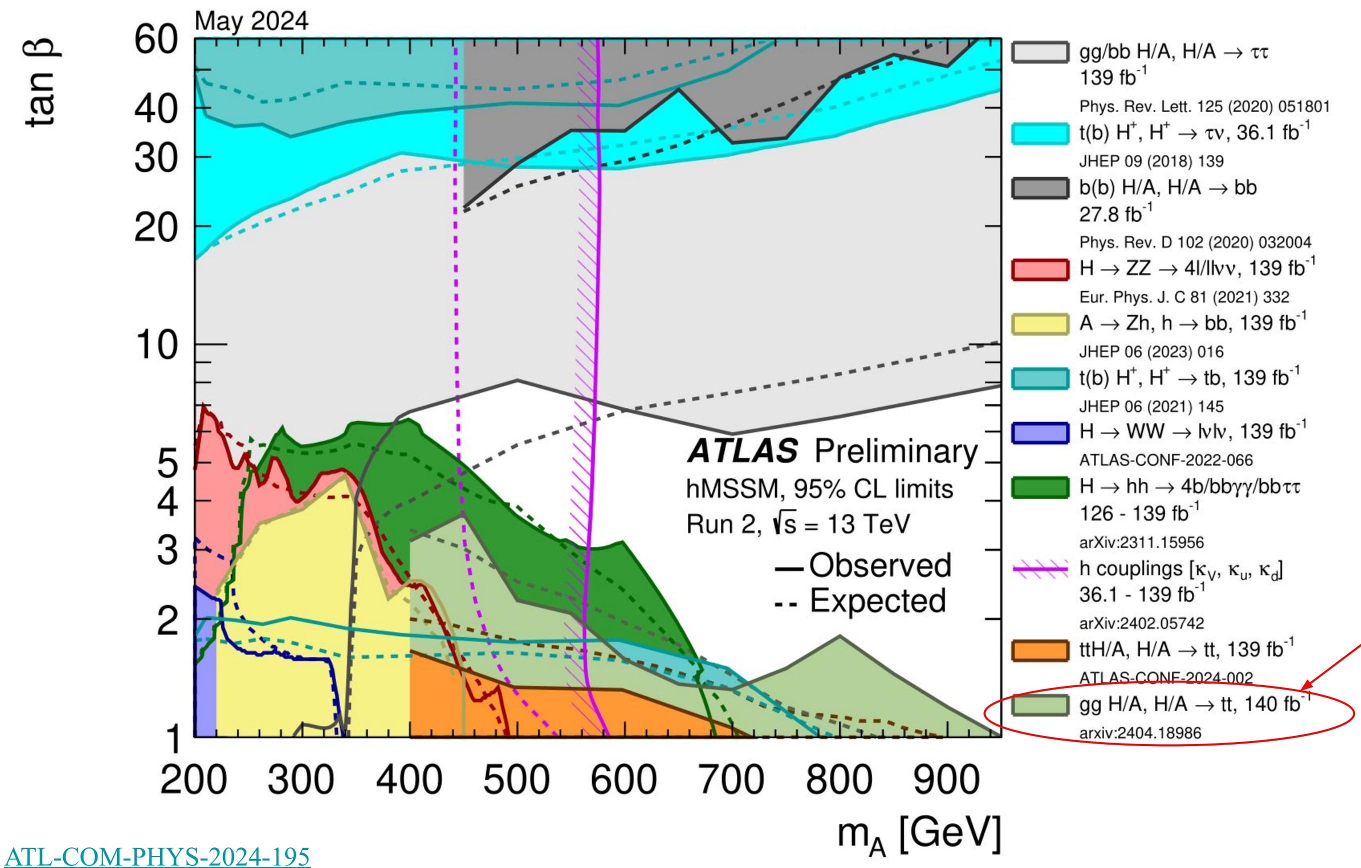





arXiv:2404.18986

# Heavy Higgs summary plot



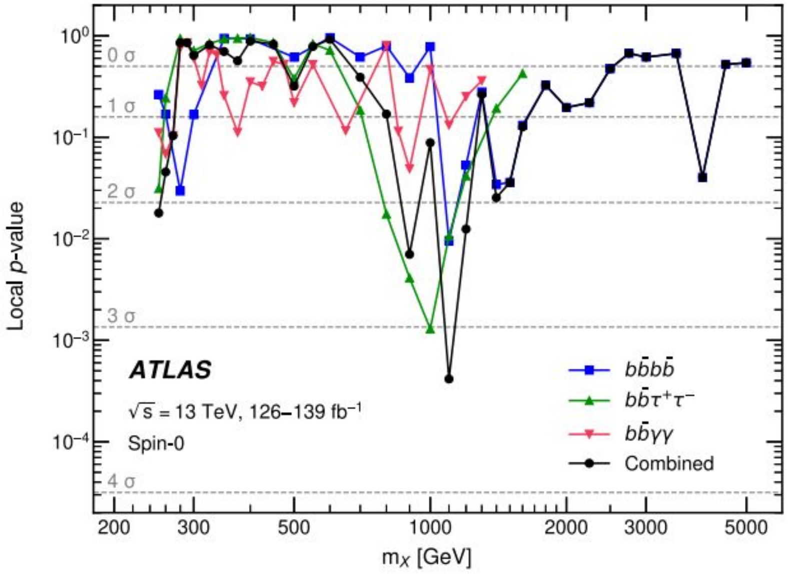

Excluded regions of [$m_A$, tan$\beta$] plane excluded in the hMSSM via direct searches for heavy Higgs bosons

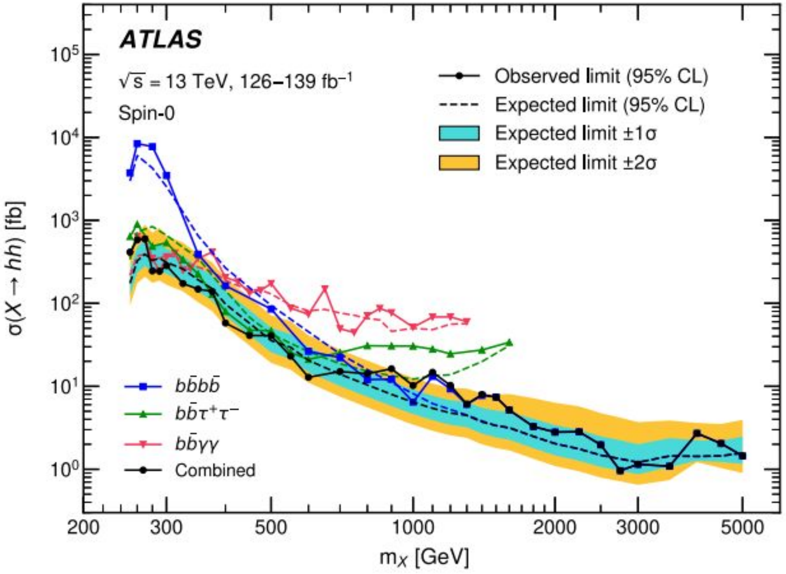
- *gg H/A , H/A→ tt* adds to exclusion at low tan$\beta$!

ATL-COM-PHYS-2024-195

# Resonant $X \to HH$

- Combination of new resonance $X \to HH \to b\bar{b}b\bar{b}$ / $\gamma\gamma bb$/ $\bar{b}b\tau^{\mp}\tau^{-}$ channels
- Largest excess at $m_X$ = 1.1 TeV, with a local (global) significance of 3.3σ (2.1σ).




PhysRevLet.132.230801

# Summary

- At ATLAS we have a very broad BSM Higgs boson physics program
  - Many more results can be found here.
  - No significant excess found, hence constraining the phase space of possible models.
  - Sensitivity mostly limited by the available data

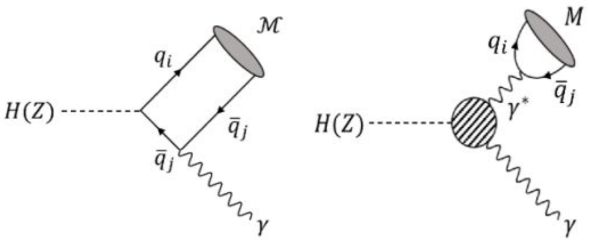
- More data and continued efforts are needed
  - to extend the coverage
  - to further study the presence of small excesses in a few searches

- Run 2 analyses mostly concluded. Focus now on Run 3!

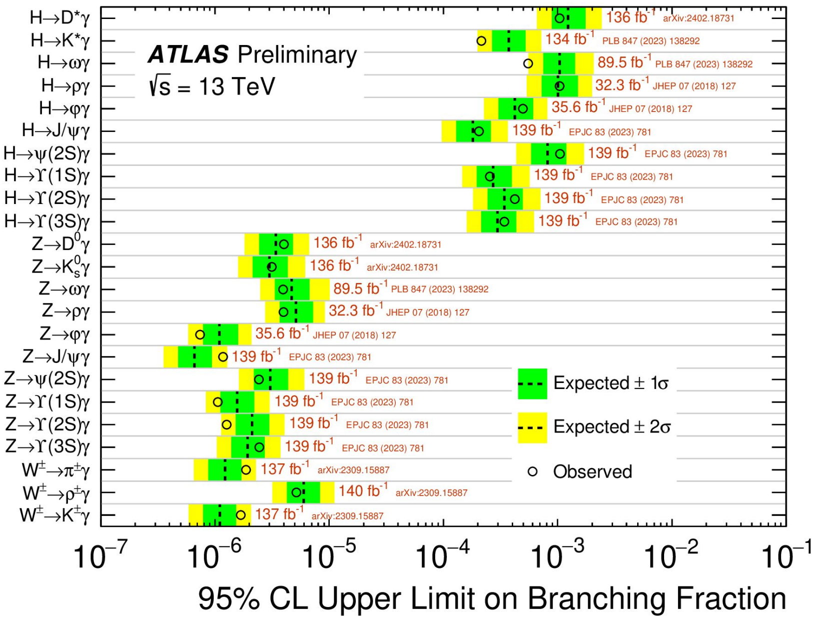
# Backup

# Summary H →meson + $\gamma$

- Searches for exclusive, radiative decays of the $H$ into a vector meson state $M$ and a photon offer an alternative way to probe the quark Yukawa couplings
- $H \to M\gamma$ decays can also provide a probe to potential flavour-violating Yukawa couplings, where $M$ is instead an electrically neutral, flavoured meson such as $K^*$ or $D^*$




** $i$ and $j$ refer to the flavour of the quark, and $i \neq j$




No significant deviations from SM were found.

ATL-PHYS-PUB-2023-004

# Anomalous magnetic moment of muon

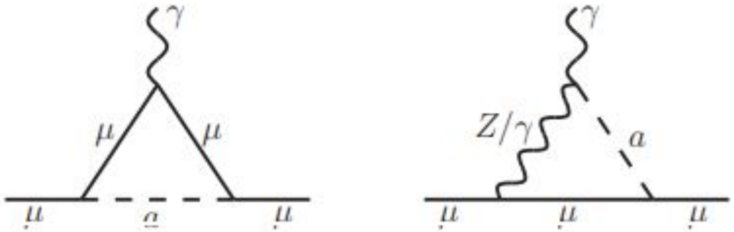



**Figure 5**. One-loop diagrams contributing to the anomalous magnetic moment of the muon.

The first graph, in which the ALP couples to the muon line, gives a contribution of the wrong sign. However, its effect may be overcome by the second diagram, which involves the ALP coupling to photons (or to γZ), if the Wilson coefficient C is sufficiently large.

# Identifying hadronic taus

The reconstruction of $\tau_{\text{had}}$ candidates is seeded using jets reconstructed using the anti-*kt* algorithm with distance parameter $R = 0.4$ whose inputs are topoclusters, three-dimensional clusters of calorimeter cells. Reconstructed $\tau_{\text{had}}$ candidates have $p$T > 20 GeV and $|\eta| < 2.5$, excluding the region $1.37 < |\eta| < 1.52$. The identification of $\tau_{\text{had}}$ uses a recurrent neural network (RNN) algorithm, which uses as inputs tracks and calorimeter clusters associated to $\tau_{\text{had}}$ candidates, as well as high-level discriminating variables

A dedicated $\tau$-jet-vertex algorithm (TJVA) is used to associate $\tau_{\text{had}}$ candidates to a PV.

# Search for $A \rightarrow H + Z$

Assuming that a resonance $X$ that decays into a $t$op-pair or $bb$ pair is produced in association with a $Z$ boson, the number of signal events that will be recorded by the detector in a given bin of the reconstructed $m(tt)$ or $m(bb)$ distribution will be equal to the integrated luminosity times the 'visible cross-section' $\sigma_{vis}(Z(\ell\ell)X(tt))$ or $\sigma_{vis}(Z(\nu\nu)X(bb))$.

Limits set on $\sigma_{vis}$