Searches for resonances decaying into Higgs boson pairs with the ATLAS Experiment

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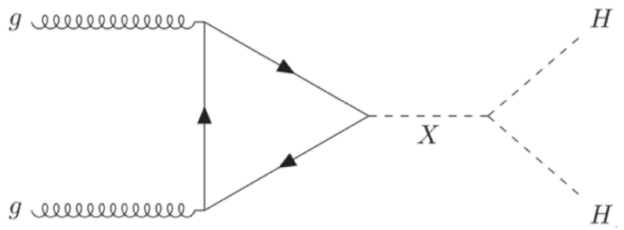
Introduction

- Various BSM theories predict a heavy resonance (X) decaying into two Higgs bosons (HH) or one scalar plus one Higgs (SH)

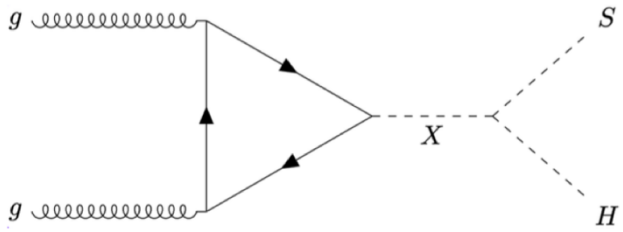
X→HH

- Additional scalars from existence of multiple Higgs doublets (2HDM, MSSM)
- Spin-2 Kaluza-Klein graviton (Randall-Sundrum model)



X→SH

- SM extension with additional two real scalar model (TRSM)
- 2 Higgs-doublet + singlet (2HDM + s, NMSSM)



Outline

- X→HH
  - X→HH combination (bb$\tau\tau$, bb$\gamma\gamma$ and 4b) [PRL 132 (2024) 231801]
  - VBF X→HH→4b [PLB 858 (2024) 139007]
- X→SH
  - X→S(→bb) H(→$\gamma\gamma$) [ATLAS-CONF-2025-009] New!
  - X→S(→WW/ZZ) H(→$\gamma\gamma$) [JHEP 10 (2024) 104]
  - X→SH→HHH→6b [PRD 111 (2025) 032006]

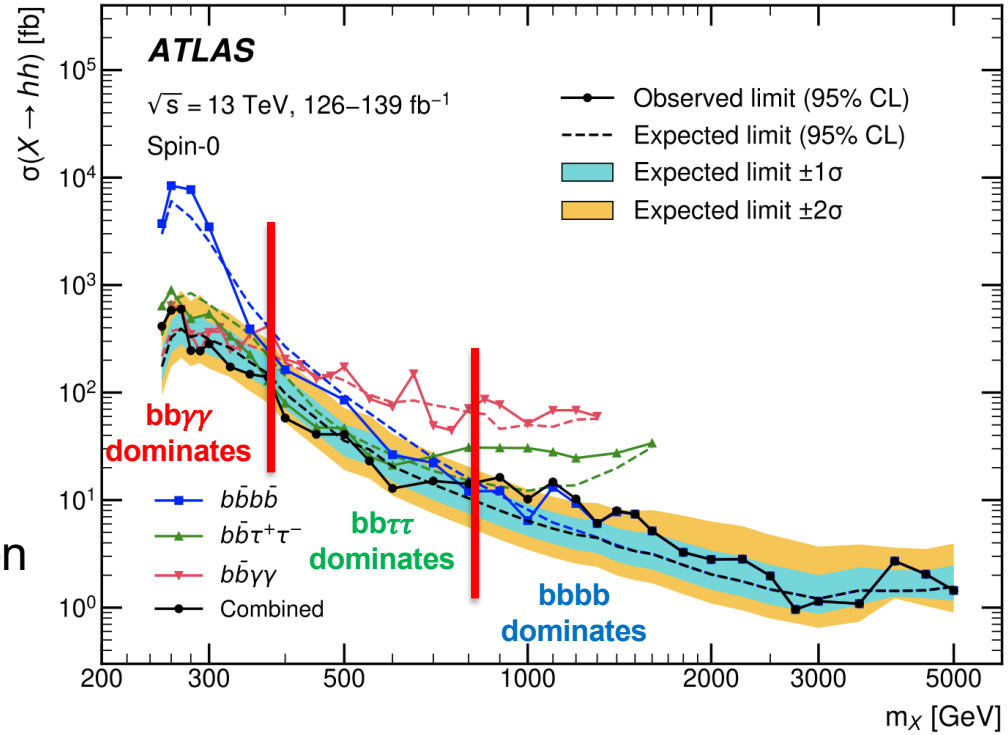
Disclaimer: due to time constraint, will only cover the results published since 2024.

X→HH

X→HH Combination (1/3)

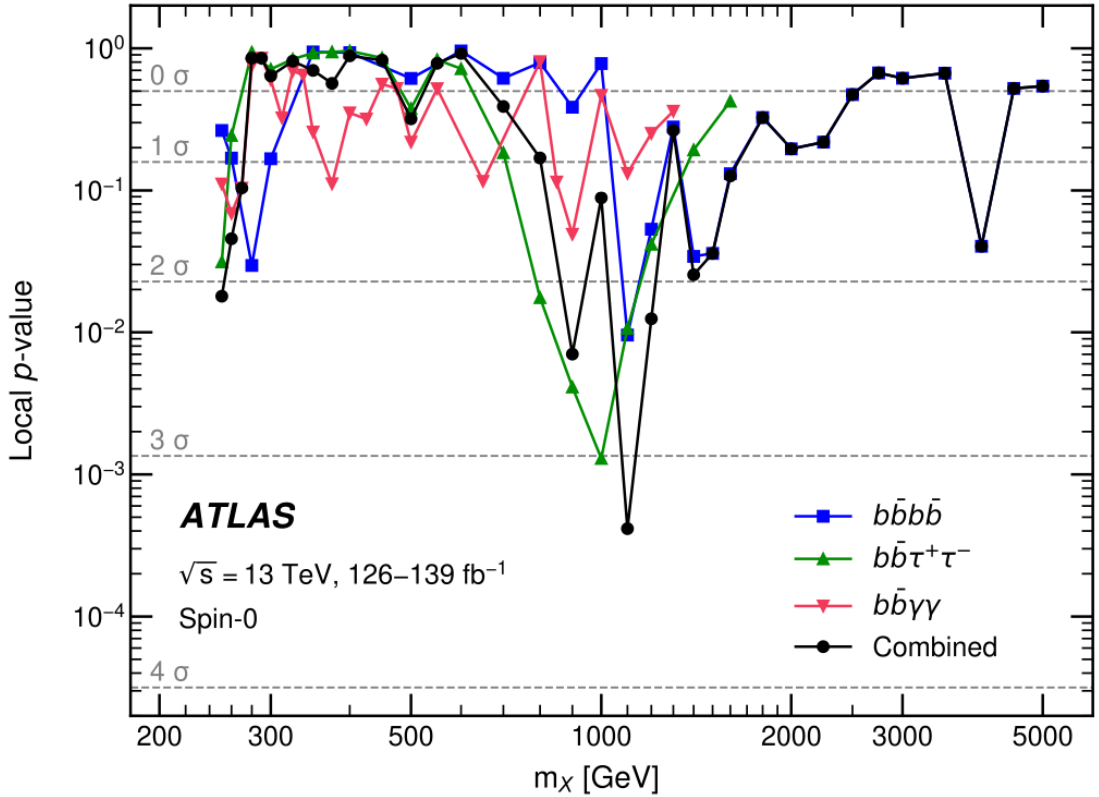
PRL 132 (2024) 231801

- Combination of bb$\tau\tau$, bb$\gamma\gamma$ and 4b channels
- Improved by a factor 2-5 w.r.t previous Run-2 results (36 fb^{-1})
- Major updates:
  - Full Run-2 dataset
  - Advanced b-tag with DL1r
  - Optimized Higgs reconstruction
  - Enhanced bkg. modeling
  - Extended phase space and refined categorization



X→HH Combination (2/3)

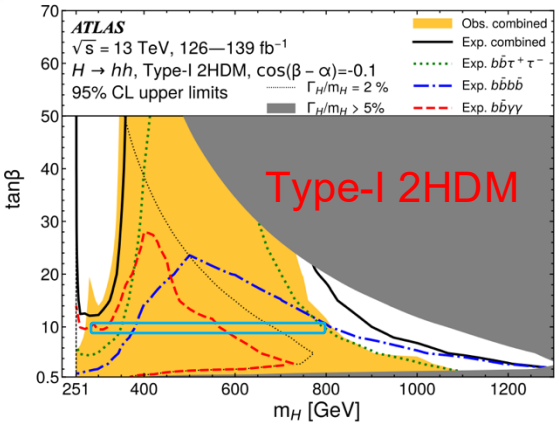
PRL 132 (2024) 231801

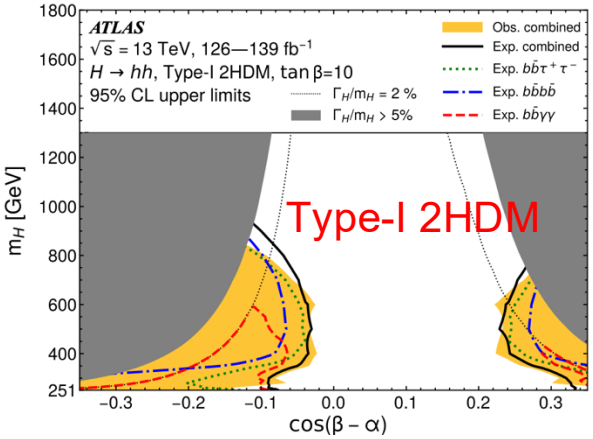


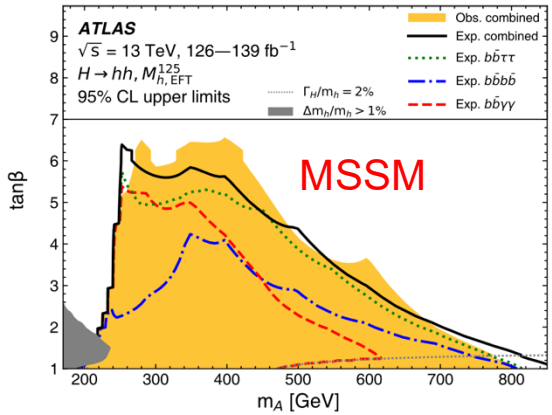
No statistically significant excess found
Largest excess at 1.1 TeV: local (global) significance is 3.3σ (2.1σ)
CMS not seeing excess in the same region

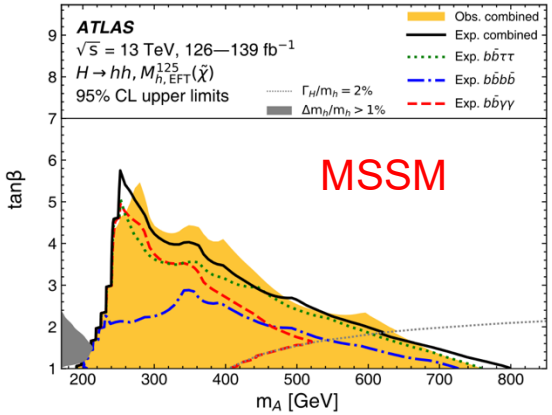
X→HH Combination (3/3)

PRL 132 (2024) 231801





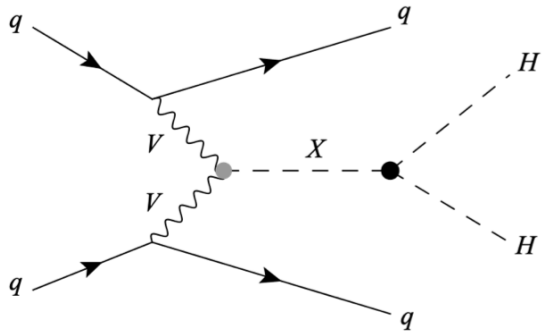




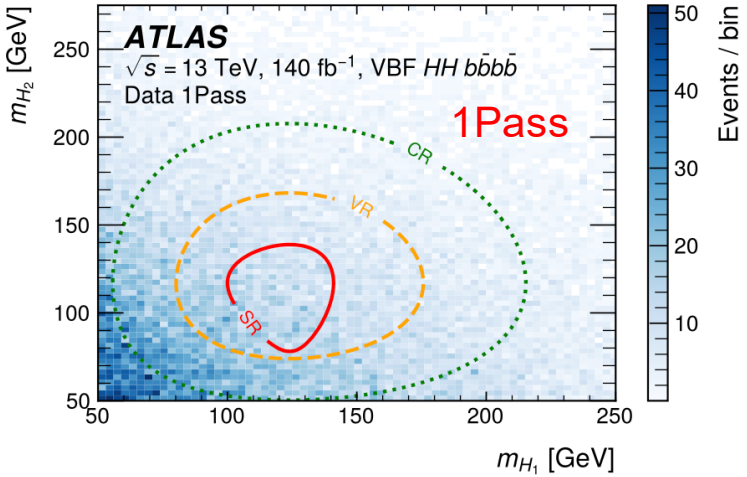
Type-I 2HDM: 270-810 GeV excluded for tanβ=10, cos(β-α)=-0.1

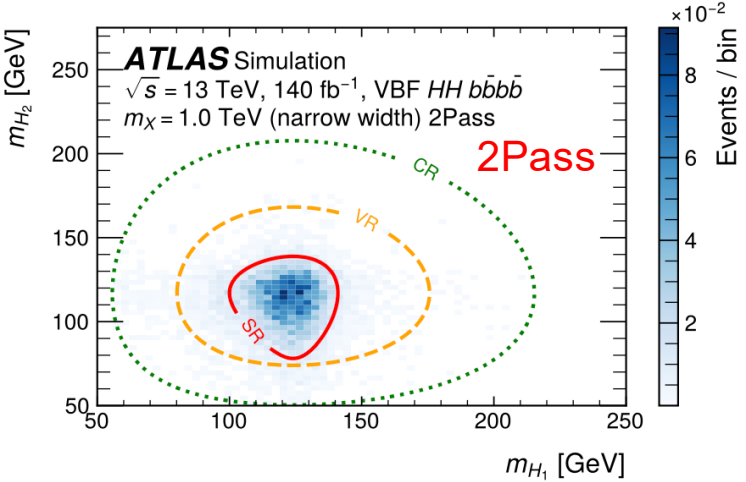
VBF X→HH→4b (1/3)

PLB 858 (2024) 139007



- First search for X→HH using VBF production mode in 1-5 TeV regime
- Signature: two large-R jets tagged by X_{bb} algorithm [Ref.: ATL-PHYS-PUB-2020-019]
- Dominant bkg.: multi-jet, estimated with data-driven method

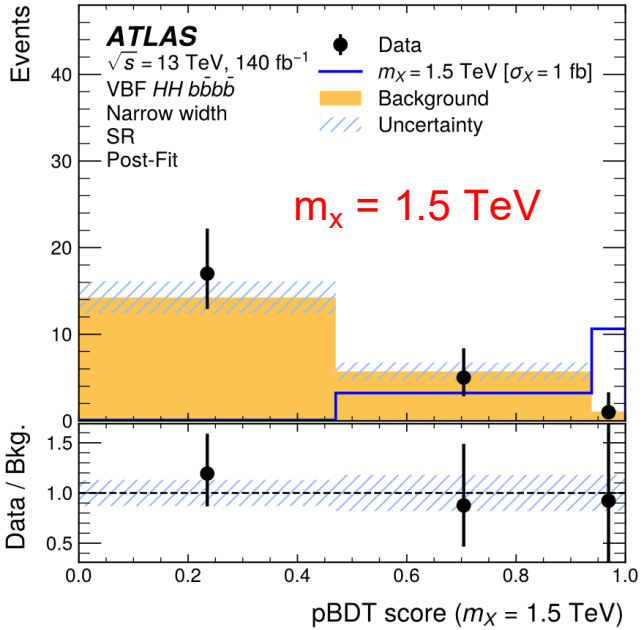


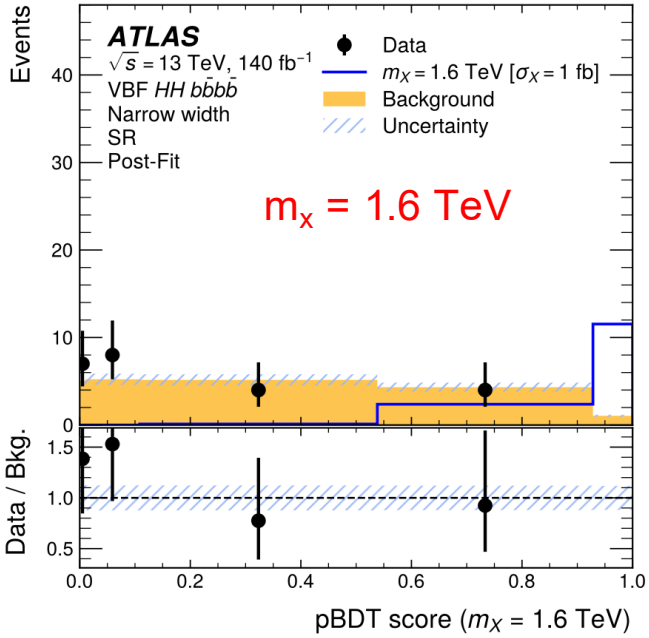


VBF X→HH→4b (2/3)

PLB 858 (2024) 139007

- A mass-parameterized BDT (pBDT) trained to separate sig./bkg. and used as final discriminant for fitting

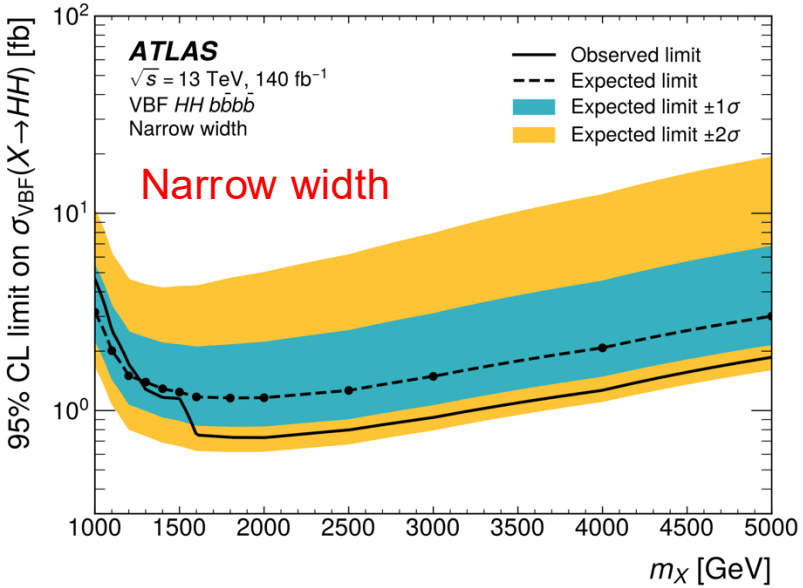


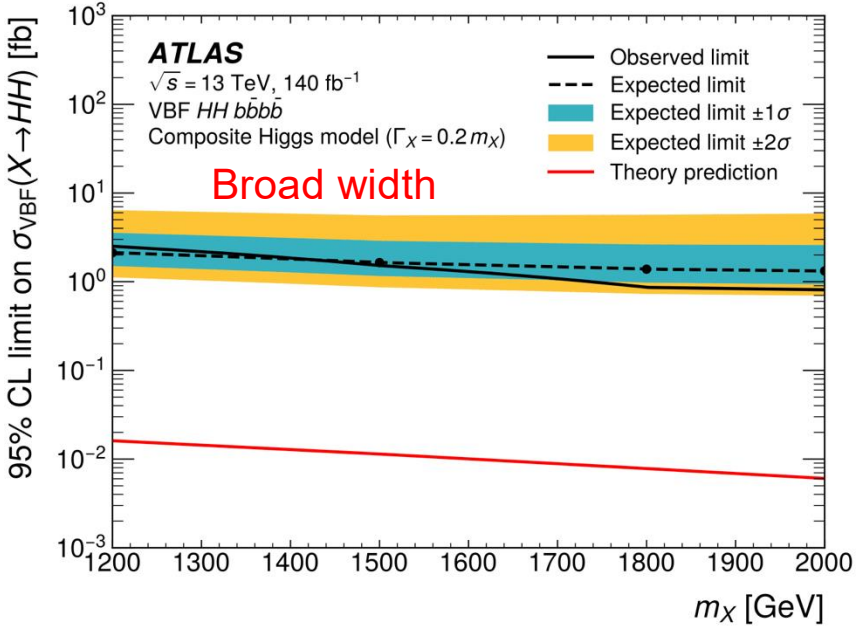


VBF X→HH→4b (3/3)

PLB 858 (2024) 139007

- Upper limits set for narrow- and broad-width assumptions respectively





Obs. (exp.) limits: 0.7-4.6 fb (1.2-3.1 fb)

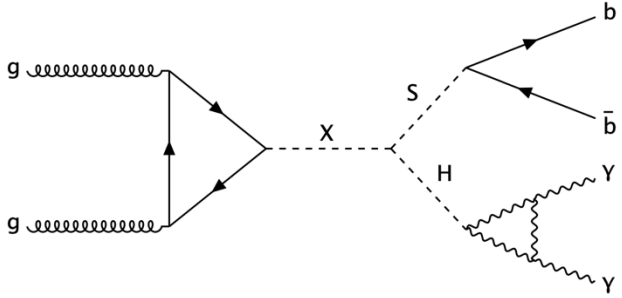
Obs. (exp.) limits: 0.8-2.5 fb (1.3-2.1 fb)

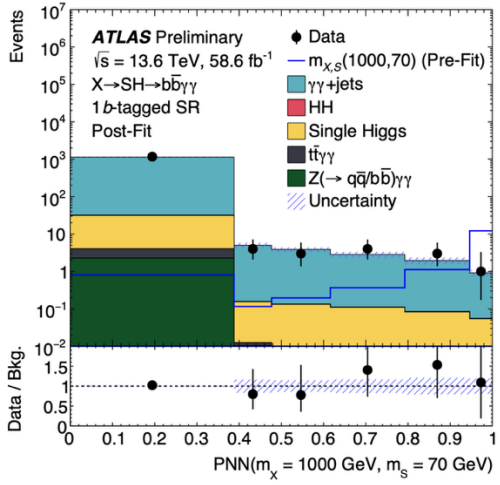
X→SH

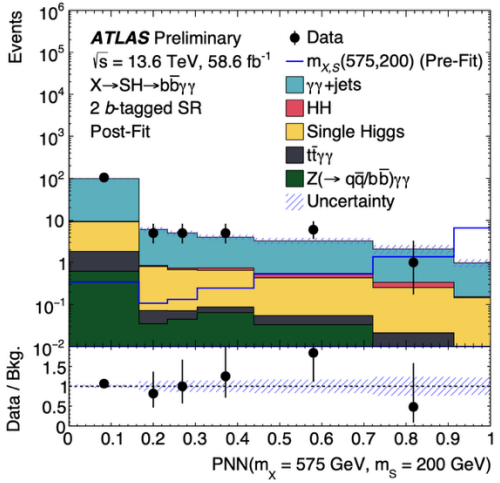
X→S(→bb) H(→γγ) (1/3)

ATLAS-CONF-2025-009

- Search performed for 170<m_X<1000 GeV, 15<m_S<500 GeV using full Run-2 and partial Run-3 datasets (199 fb^{-1})
- 2 SRs: 2 b-tagged for larger m_S/m_X, 1 b-tagged for smaller m_S/m_X
- $m_{\gamma\gamma}$ within 122.5-127.5 GeV for SR
- PNN trained to separate sig. from bkg. (dominated by $\gamma\gamma$+jets)

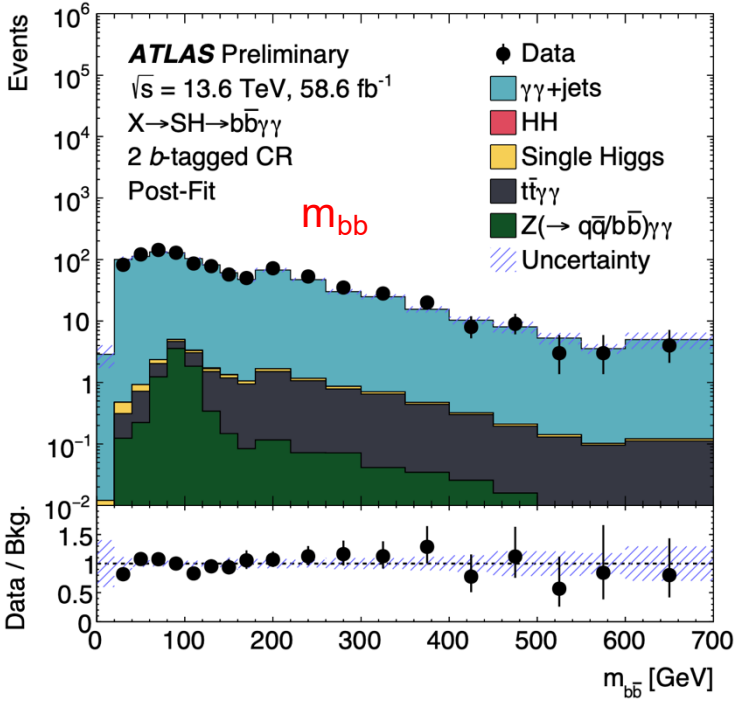


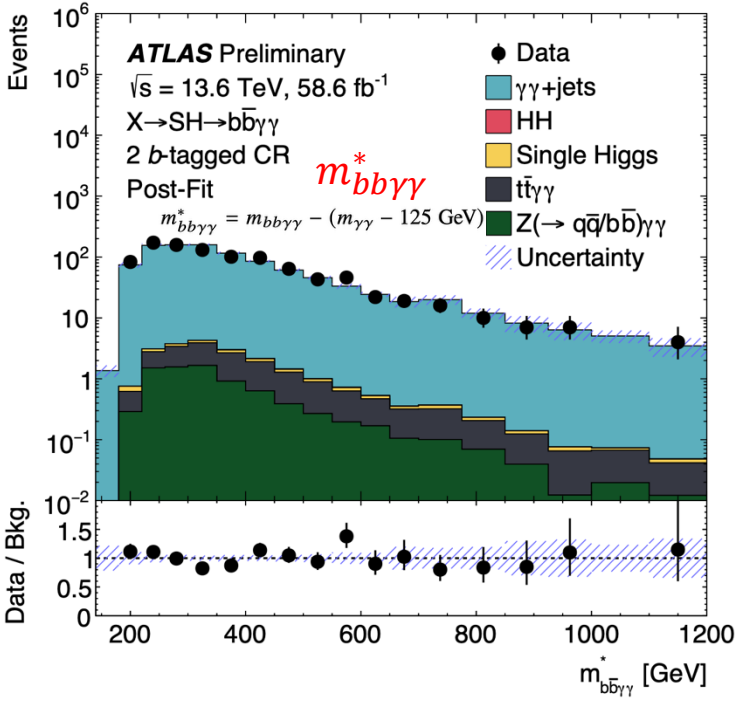




X→S(→bb) H(→γγ) (2/3)

ATLAS-CONF-2025-009



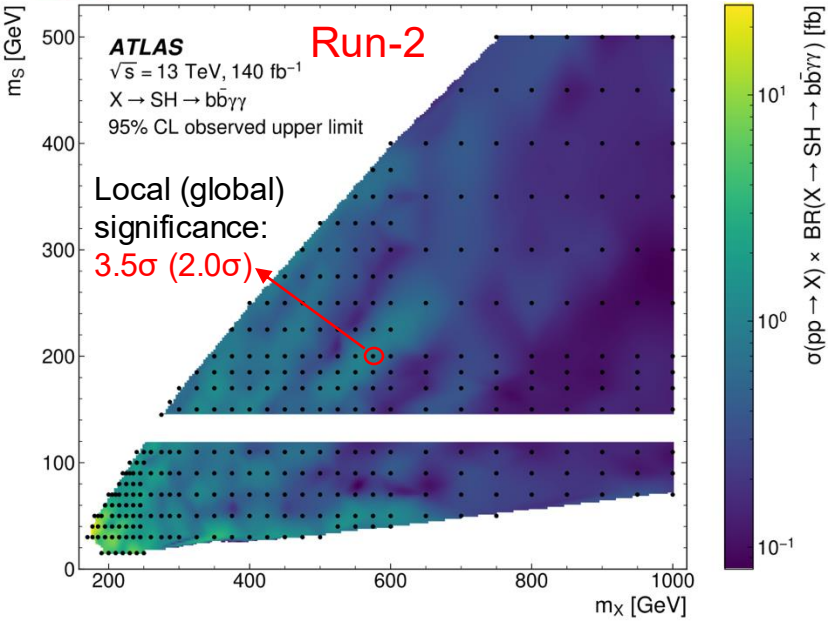


Non-resonant $\gamma\gamma$+jets: shapes taken from simulation, normalization factors derived independently for Run-2/Run-3 in CRs

X→S(→bb) H(→γγ) (3/3)

New!

JHEP 11 (2024) 047



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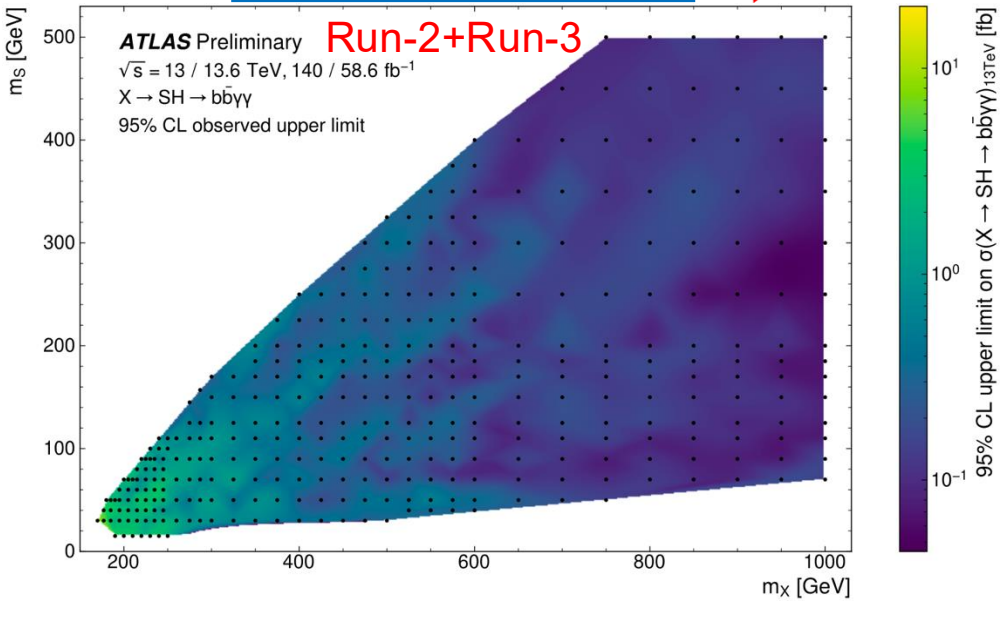
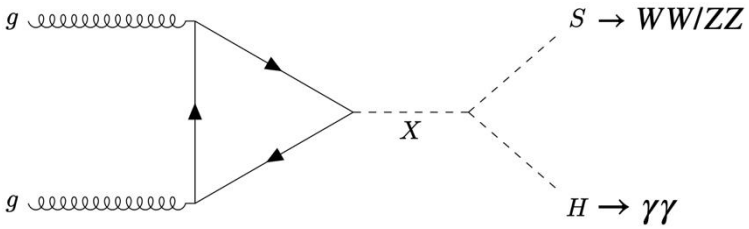


No significant deviation from the SM expectation is observed
15-73% improvement on the sensitivity w.r.t. previous Run-2 result
Driven by Run-3 data, tighter $m_{\gamma\gamma}$, GN2 b-tagging, updated PNN

X→S(→WW/ZZ) H(→γγ) (1/2)

JHEP 10 (2024) 104



- Target: 300<m_X<1000 GeV, 170<m_S<500 GeV
- Four regions are defined depending the WW/ZZ decays

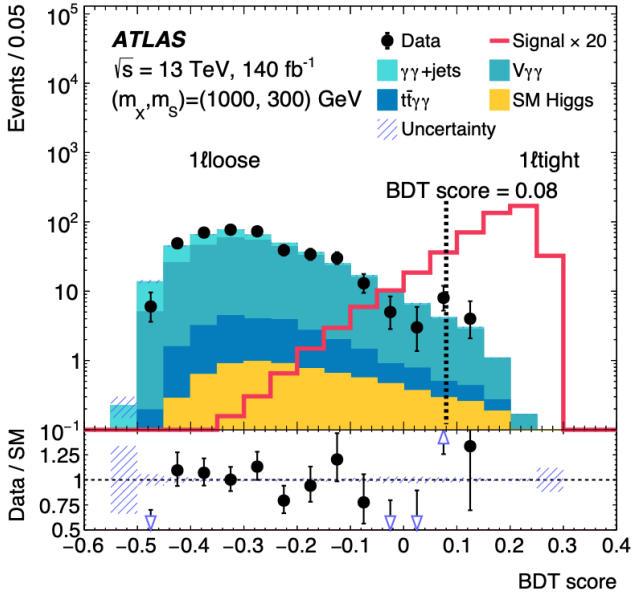
From WW decays

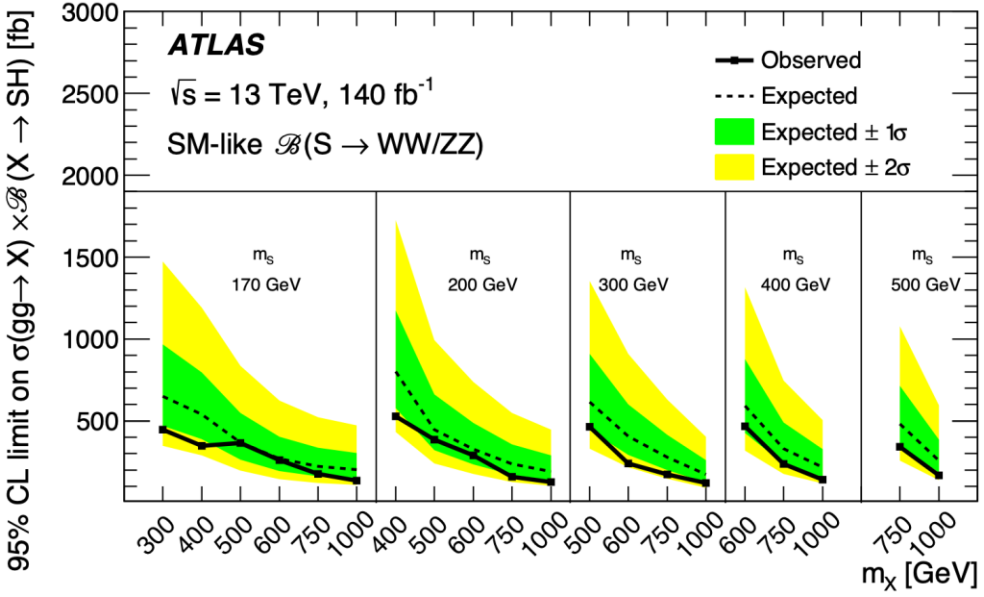
Preselection	Two photon candidates and no b-tagged jets			
Region	1ℓ	$e\mu$	$2\ell(WW)$	$2\ell(ZZ)$
Strategy	BDT	Cut-based	BDT	Cut-based
Number of signal regions	2	1	2	1
$m_{\gamma\gamma}$ region	[105, 160] GeV			

X→S(→WW/ZZ) H(→γγ) (2/2)

JHEP 10 (2024) 104

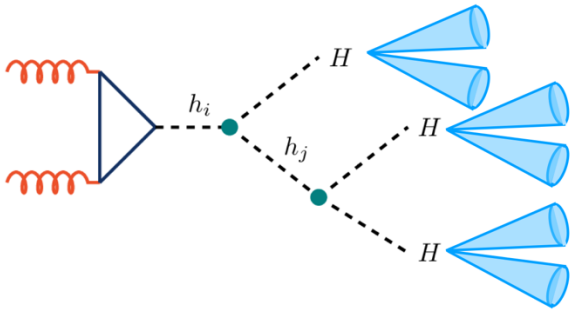
- BDT/cut-based categorization adopted
- A simultaneous fit to the $m_{\gamma\gamma}$ distributions in all six SRs
- Obs. (exp.) upper limits: 530–120 fb (800–170 fb)





X→SH→HHH→6b (1/2)

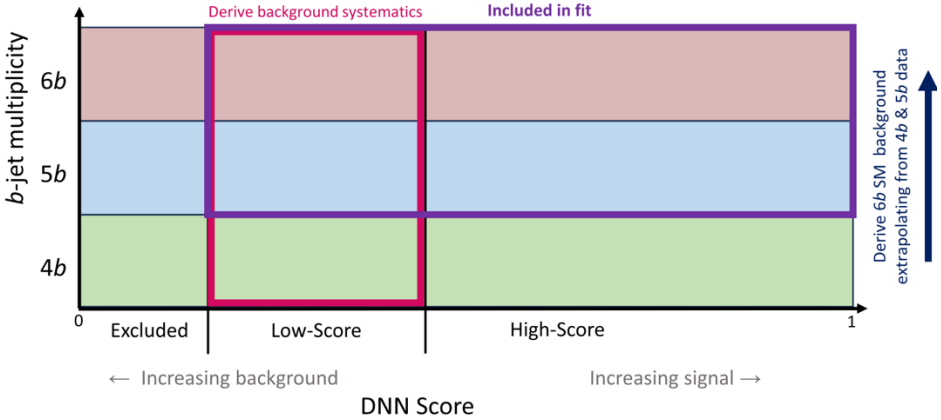
PRD 111 (2025) 032006

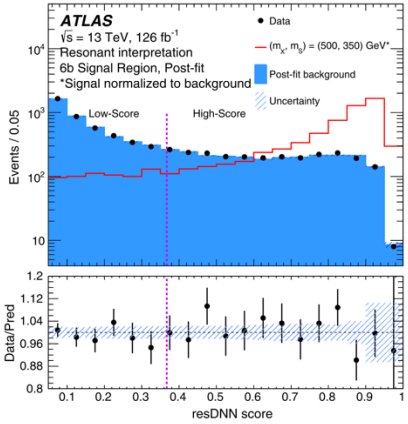


- TRSM: 325<m_X<575 GeV, 200<m_S<350 GeV
- Generic: 500<m_X<1500 GeV, 275<m_S<1000 GeV
- Signature: 6 resolved b-jets, pairing algorithm minimizing

$$|m_{H1} - 120\ \text{GeV}| + |m_{H2} - 115\ \text{GeV}| + |m_{H3} - 110\ \text{GeV}|$$

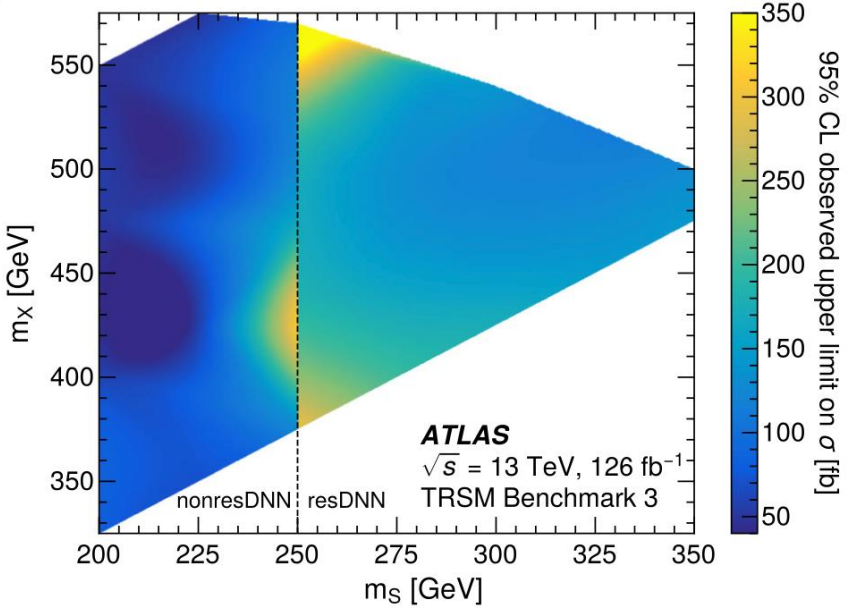
- DNN used for sig. vs bkg. separation and as fitting discriminant

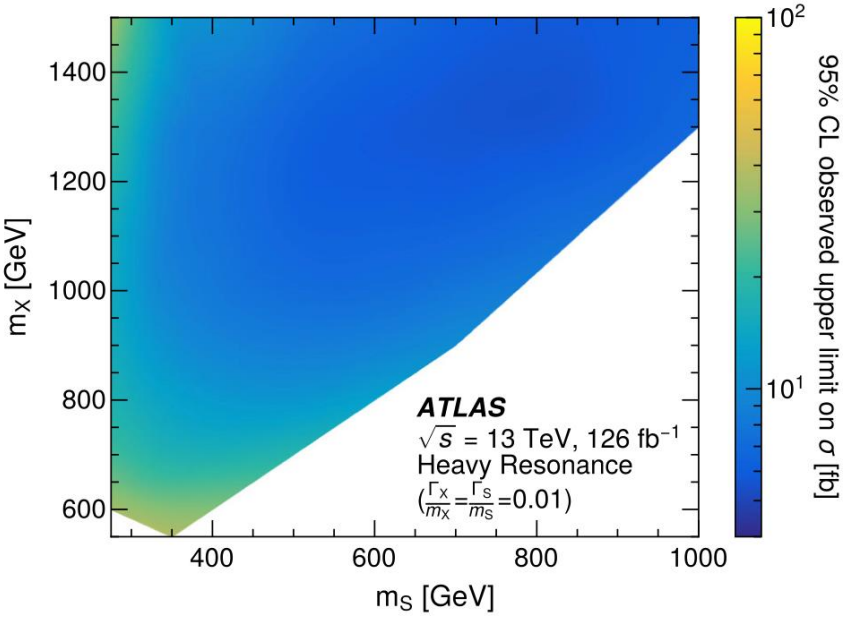




X→SH→HHH→6b (2/2)

PRD 111 (2025) 032006



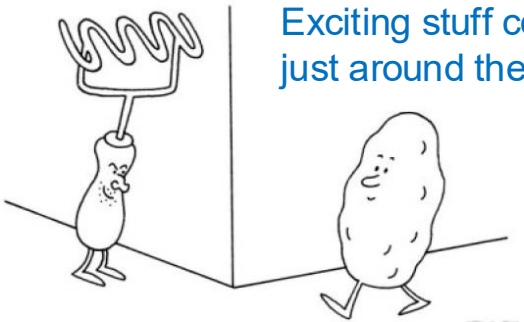


Obs. (exp.) limits for TSRM: 48-310 fb (46-350 fb)

Obs. (exp.) limits for narrow width: 5.7-38 fb (4.7-69 fb)

Summary

- Presented the latest searches for resonances decaying to HH/SH with full Run-2 (and partial Run-3) data
- No sign of new physics observed, stringent limits have been set according to relevant models
  - Previous excess in X→S(→bb) H(→$\gamma\gamma$) not seen in latest results
- Large amount of Run-3 data will provide us room for more sensitive probe, stay tuned!

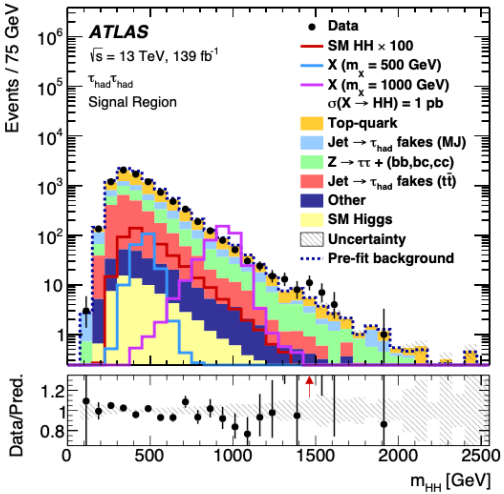


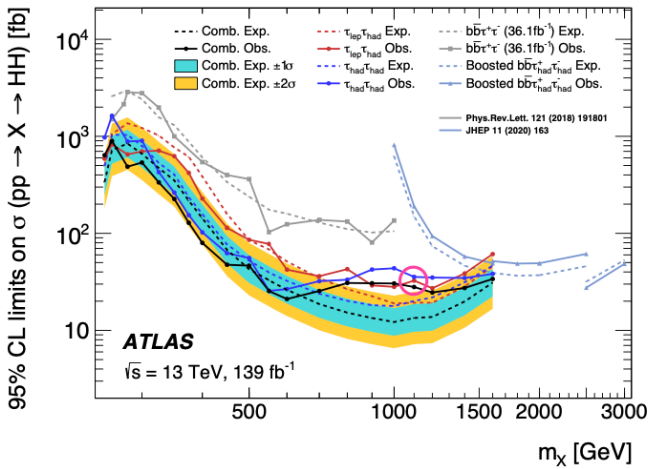
Backup

- Contribute intermediate-mass region (350 GeV < m_X < 800 GeV)
  Moderate branching ratio (~7.3%)
  Relatively well-controlled bkgs, optimal balance between sig. significance & bkg. Rejection

  Two sub-channels:
  - $\tau_{\text{had}}\tau_{\text{had}}$: Requires two hadronic taus with opposite charge and no electrons or muons
  - $\tau_{\text{lep}}\tau_{\text{had}}$: Requires one lepton (e or μ) and one hadronic tau with opposite charge

  Requires exactly two R = 0.4 b-jets
  Final discriminant : Output score from a mass-parametrized neural network.

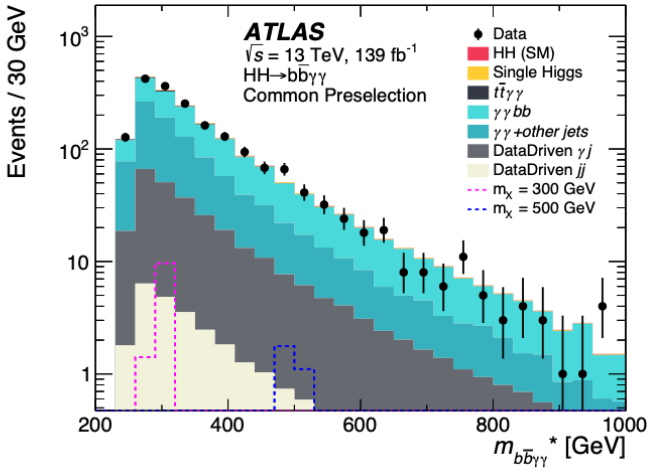


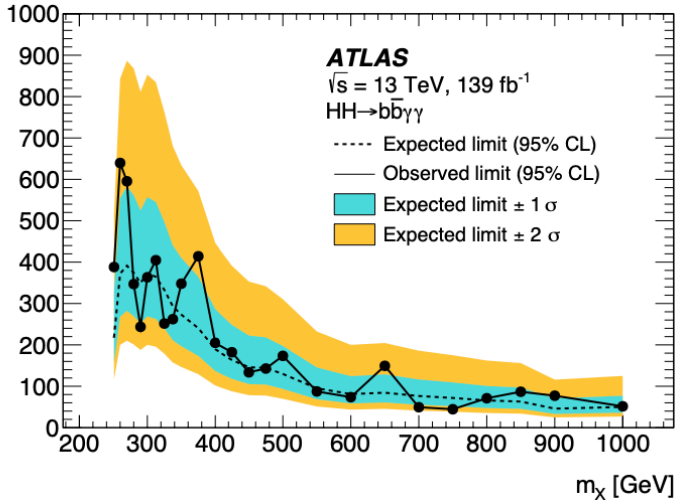


[Taken from Minori Fujimoto's talk (same for following slides)]

- Contribute low-mass region (m_X <= 350 GeV)
  Lowest branching ratio (~0.3%)
  Excellent photon reco. Efficiency and trigger performance, superb $m_{\gamma\gamma}$ resolution

Requires exactly two photons, two R=0.4 b-jets, and no electrons or muons.
Two BDTs are used to reject $t\bar{t}\gamma\gamma$ and single-Higgs backgrounds.
Signal region: $m_{\gamma\gamma}$ ~m_{H}, $m_{bb\gamma\gamma}$ ~ m_{X}
$m_{\gamma\gamma}$ as the final discriminant





- Contribute high-mass region (m_X >= 800 GeV)

  Highest branching ratio (~33.9%)

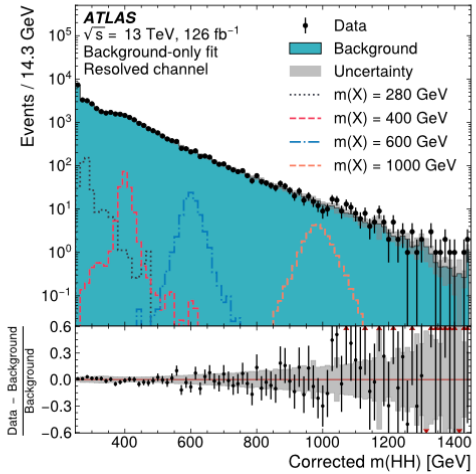
  At lower mass, sensitivity reduced by high trigger thresholds and significant multijet bkg.

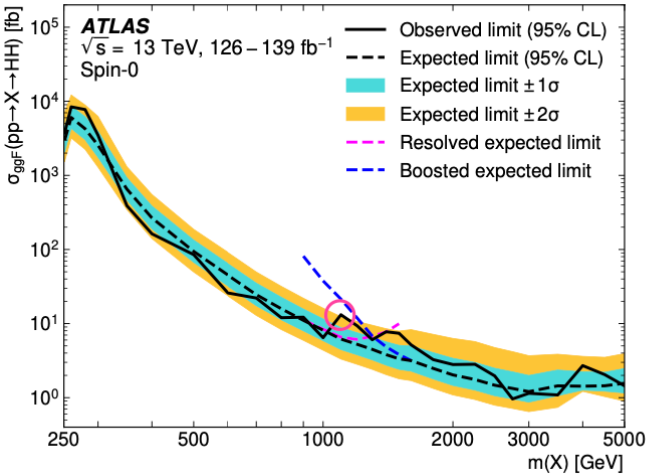
  Two sub-channels

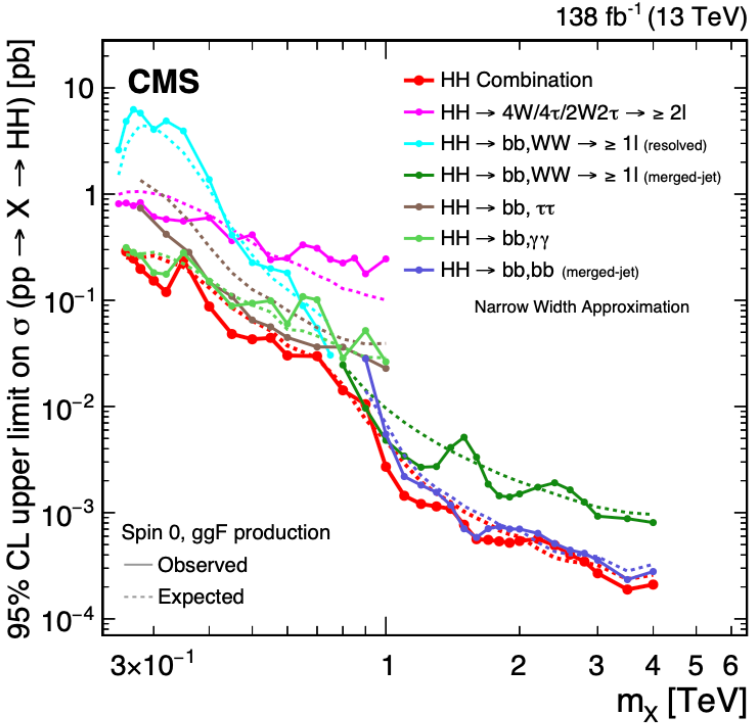
  Resolved : Uses 4 small-R (R=0.4) jets, forming Higgs candidates with a BDT pairing.
  Requires ≥4 b-tagged jets.

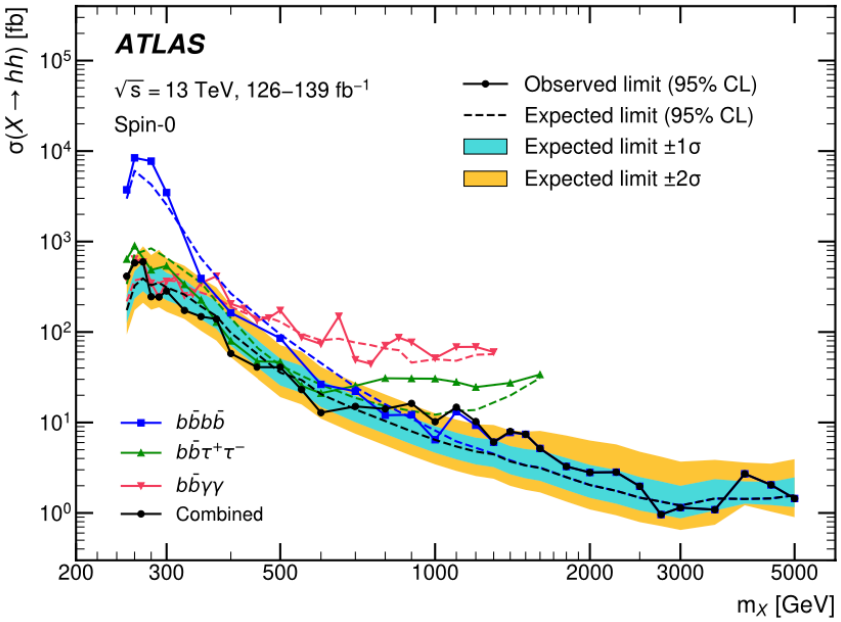
  Boosted : Uses two large-R (R=1.0) jets.
  Events are categorized as 2b, 3b, or 4b depending on the number of b-tagged jets.

  m_{HH} is used to define SR, CR, VR and as a final discriminant









- Comparable CMS combination results of Spin 0 resonance as X
  [Physics Reports 1115 (2025) 368]
- The small excess with combined local (global) signifiacance of 3.3σ (2.1σ) was not found in the CMS

- 2 Higgs Doublet Model (2HDM)
  Extend the SM with two scalar doublets with
  - 2 CP-even neutral scalar : h, H
  - 1 CP-odd neutral scalar : A
  - 2 charged scalar : $H^{\pm}$

  Free parameters :
  m_H
  $tan\beta$ (Ratio of the vacuum expectation values (vev) of the two Higgs doublets
  α (Mixing angle of CP-even neural scalars h and H)

- Minimal Supersymmetric Standard Model (MSSM)
  MSSM is a restricted version of a Type-II 2HDM
  The MSSM Higgs potential is tightly constrained by supersymmetry
  Free parameters :
  $tan\beta$ (Ratio of the vacuum expectation values (vev) of the two Higgs doublets
  m_A