Search for rare Higgs boson decays and BSM Higgs bosons

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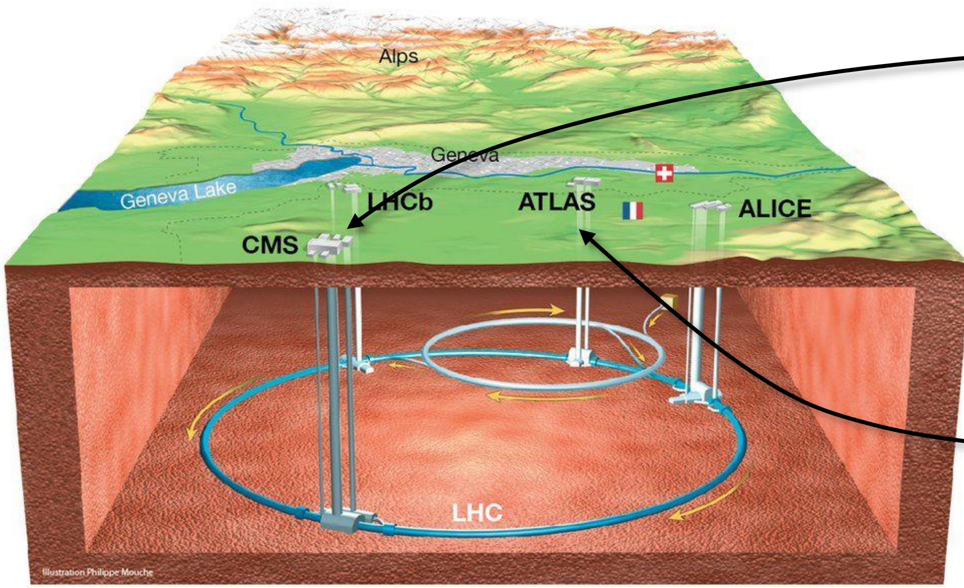
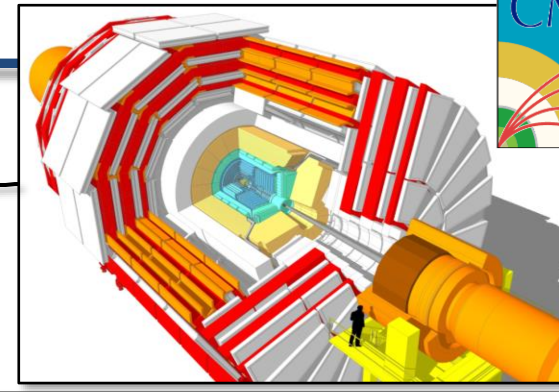
On behalf of the ATLAS and CMS Collaborations

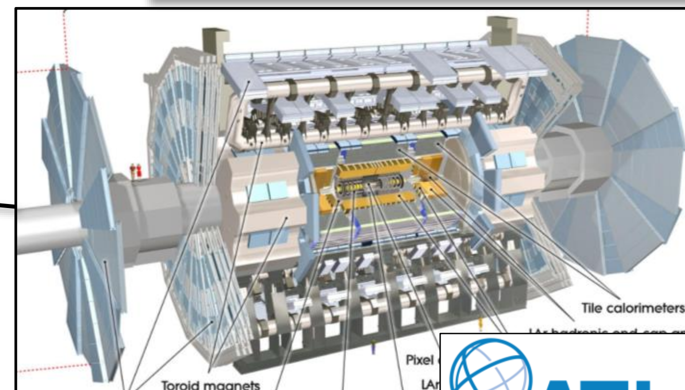
3rd June, 2024

Large Hadron Collider Physics Conference 2024

■ ATLAS and CMS at LHC





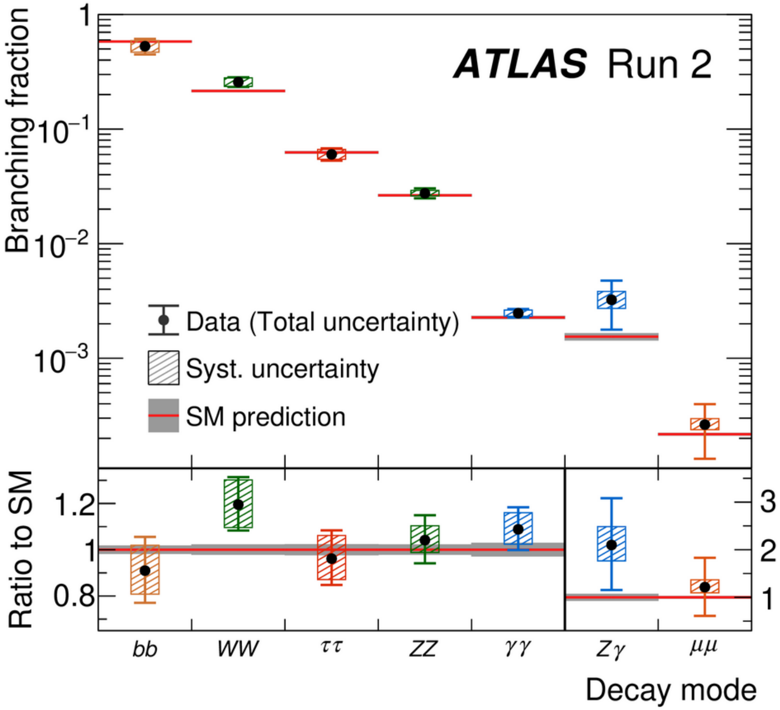


- Two large general purpose detectors
  - ATLAS: large size (D = 25 m) provides long lever arm
  - CMS: compact (D = 15 m) with a stronger solenoid field of 3.8 T

  Both detectors are suitable to efficiently collect Higgs boson data with complementary performance
- Each experiment has accumulated data with ~12M Higgs bosons

■ Rare Higgs decays

- The abundant data allowed us to achieve observation of all the main Higgs decay channels
  - Branching ratios with 3rd-generation fermions and bosons are at ~10% precision



[ATLAS arXiv:2404.05498](https://arxiv.org/abs/2404.05498)

Also from CMS:

[Nature 607 (2022) 60]

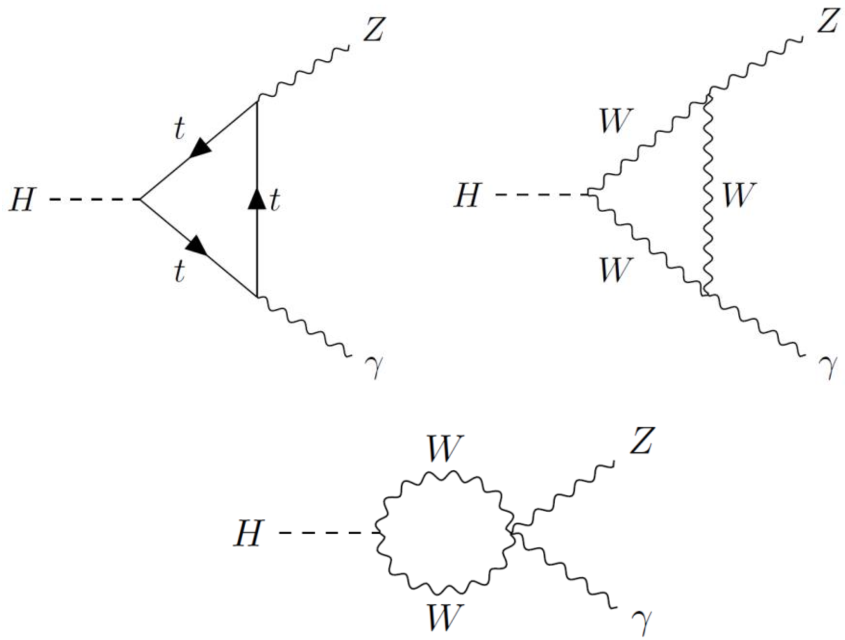
- Rarer channels such as 2nd generation or radiative decays are being possible

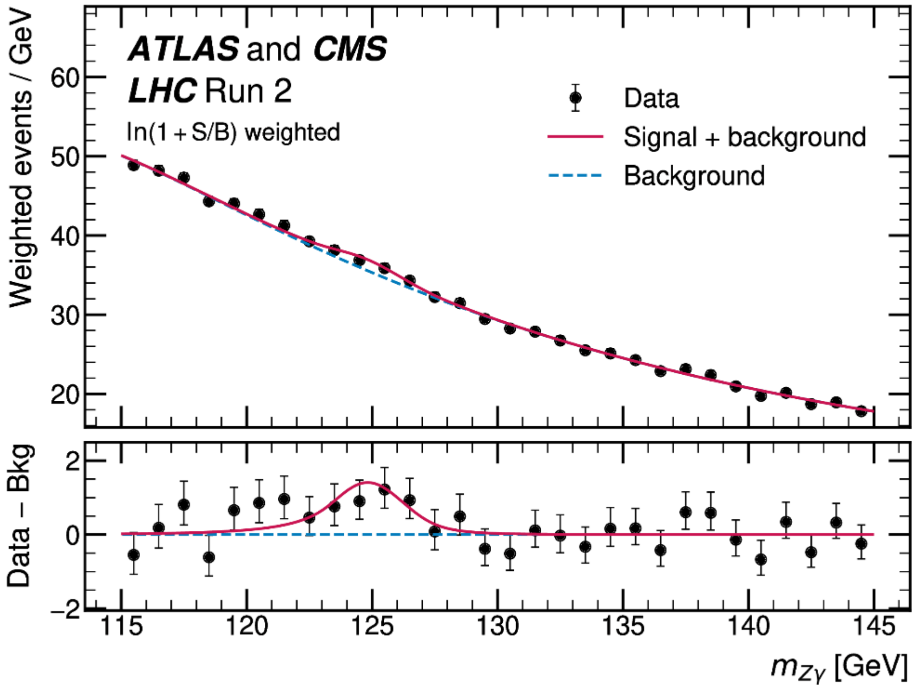
  E.g. $H \to \mu\mu$ E.g. $H \to Z\gamma$

  - Rare decays may be sensitive to BSMs as its SM amplitude is suppressed
- Experimentally challenging
  - Small number of signals ⟷ Need to reduce relatively large background with attaining high signal efficiency

■ $H \to Z\gamma$

ATLAS and CMS, PRL 132 (2024) 021803





- Rare decay via a loop diagram
  - $\mathrm{BR}(H \to Z\gamma)_{\mathrm{SM}} = (1.5 \pm 0.1) \times 10^{-3}$
- ATLAS+CMS combination reached 3.4σ → First evidence!

$$\mathrm{BR}(H \to Z\gamma) = (3.4 \pm 1.1) \times 10^{-3}$$

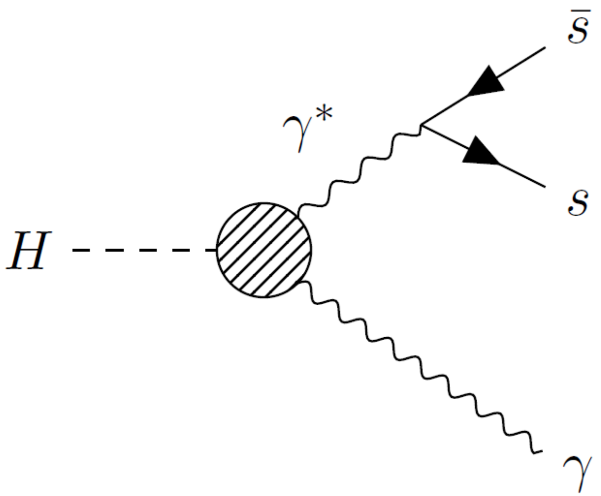
Measured value is 2.2 times higher than the SM expectation

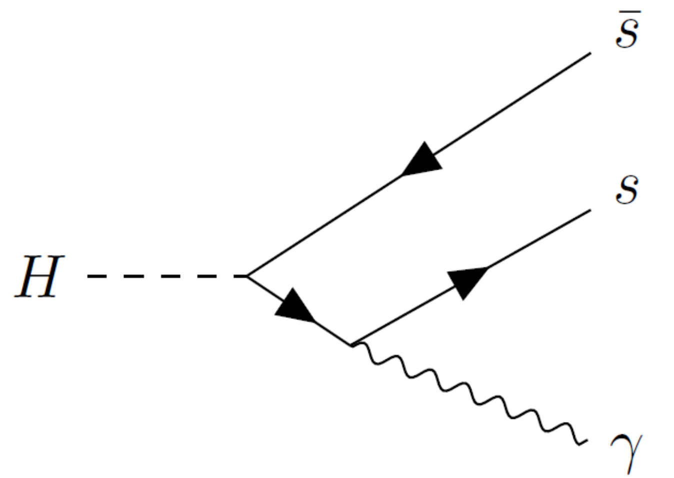
■ $H \to M\gamma$: M = a meson

- Radiative Higgs boson decays containing a meson
  - Induced via a loop diagram or a direct coupling to lighter quarks

BSM in the loop?

Yukawa coupling to light-flavour quarks



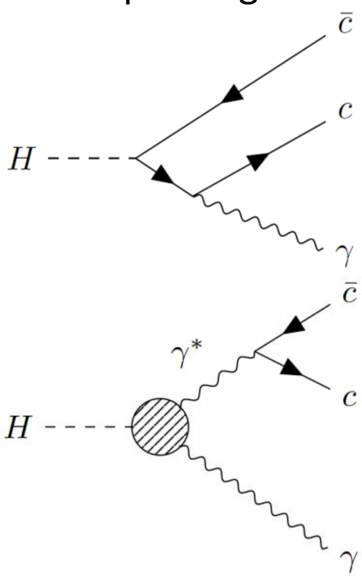


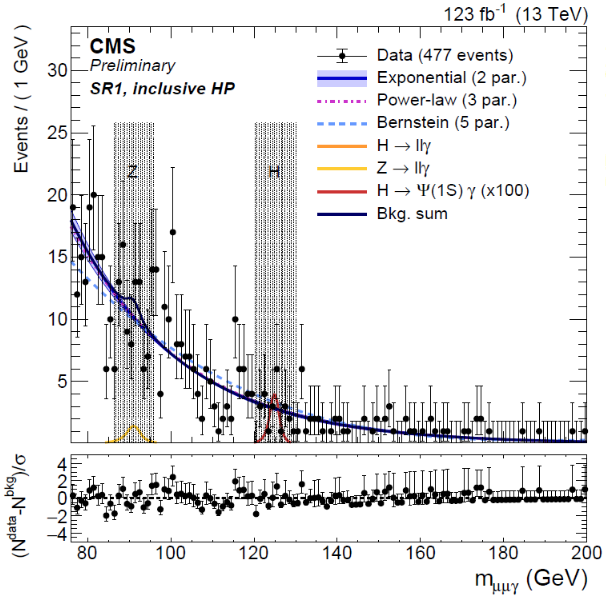
- Challenge to identify light quark flavours at ATLAS/CMS
  - No particle identification system → Need to find a parent meson based on K/π 'hypothesis' (exceptions are decays to di-lepton)
  - Need to catch a relatively low-p_{T} single photon
    → Dedicated triggers using γ with reduced p_{T} threshold + a few tracks

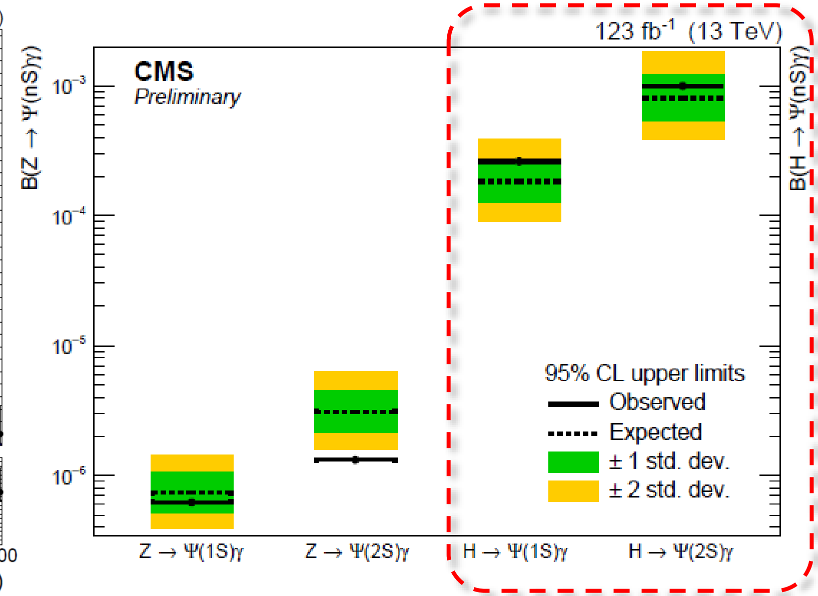
■ $H \to J/\psi\gamma$

[CMS, PAS-SMP-22-012 (2023)]

Example diagrams







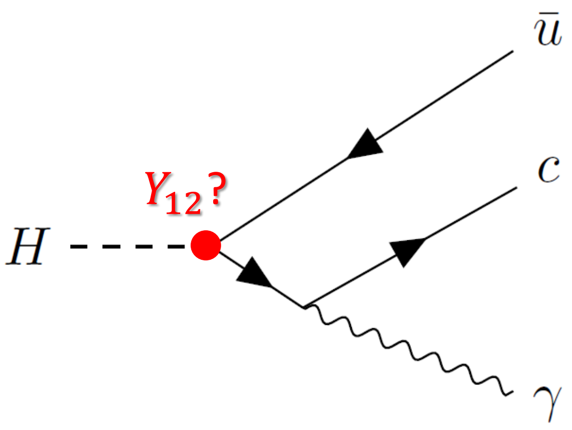
- Search for H to charmonium + γ by CMS
  - Sensitive to H-c coupling (the decay is also induced via a bosonic loop)
  - In SM, the branching ratios are small
    - BR($H \to J/\psi\gamma$) = $(3.01 \pm 0.15) \times 10^{-6}$
    - BR($H \to \psi(2S)\gamma$) = $(1.03 \pm 0.06) \times 10^{-6}$
  - Simultaneous search for Z to charmonium + γ

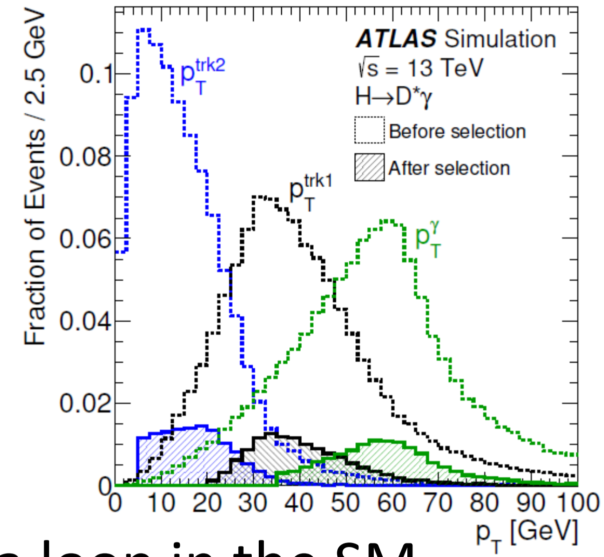
BR($H \to J/\psi\gamma$) < 2.6×10^{-4}, BR($H \to \psi(2S)\gamma$) < 9.9×10^{-4}

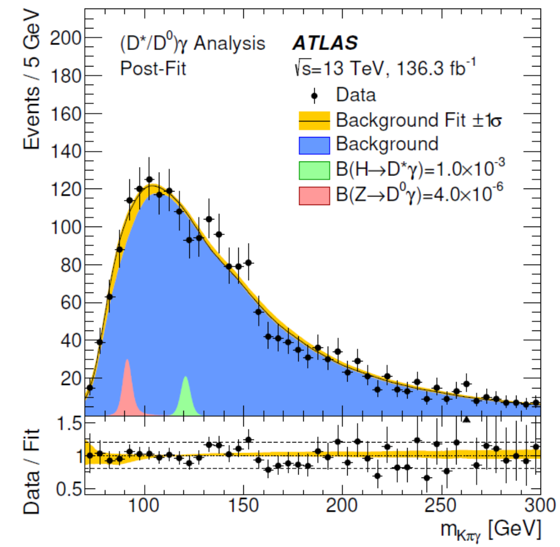
Similar results also from ATLAS: [Eur. Phys. J. C 83 (2023) 781]

■ $H \to D^{*0}\gamma$

[ATLAS, arXiv:2402.18731](https://arxiv.org/abs/2402.18731)







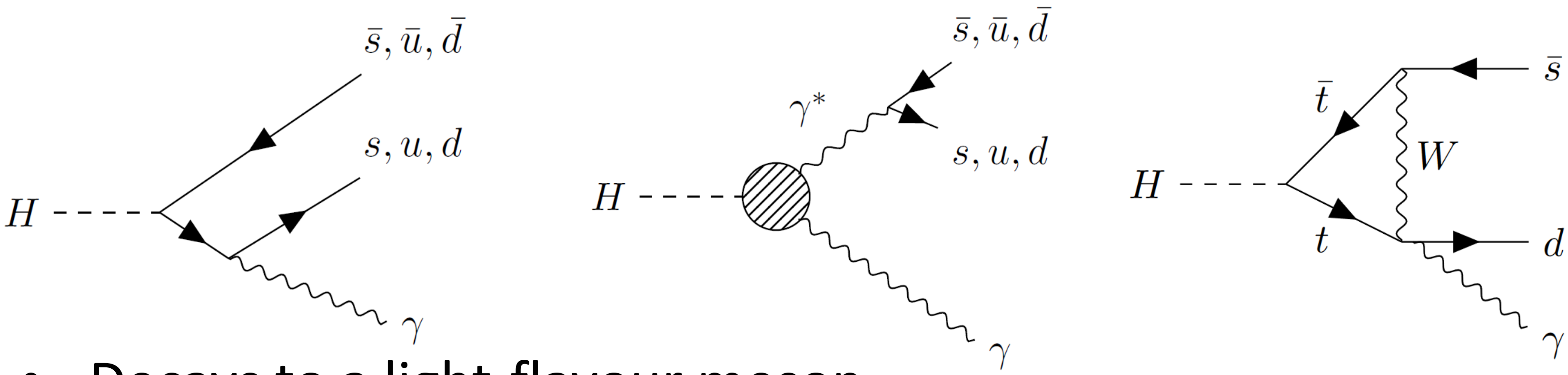
- Possible only via a loop in the SM
  - Very suppressed branching ratio in the SM: ~5×10^{-20}
  - BSMs that allow FCNC may significantly enhance the branching ratio
- Search for $H \to D^{*0}\gamma$ (and $Z \to D^0\gamma$ and $K_S^0\gamma$) by ATLAS
  - D^{*0} reconstructed from $D^{*0} \to D^0(\pi^0, \gamma)$ followed by $D^0 \to K^-\pi^+$
  - Efficiently trigger the 'γ + two tracks' events (used from May 2016)

Modified τ trigger algorithm

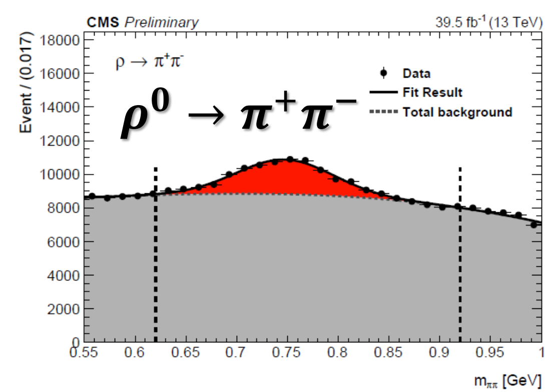
BR($H \to D^{*0}\gamma$) < 1.0×10^{-3}

$H \to \rho^0\gamma, \phi^0\gamma, K^{*0}\gamma$

CMS, PAS-HIG-23-005 (2024)

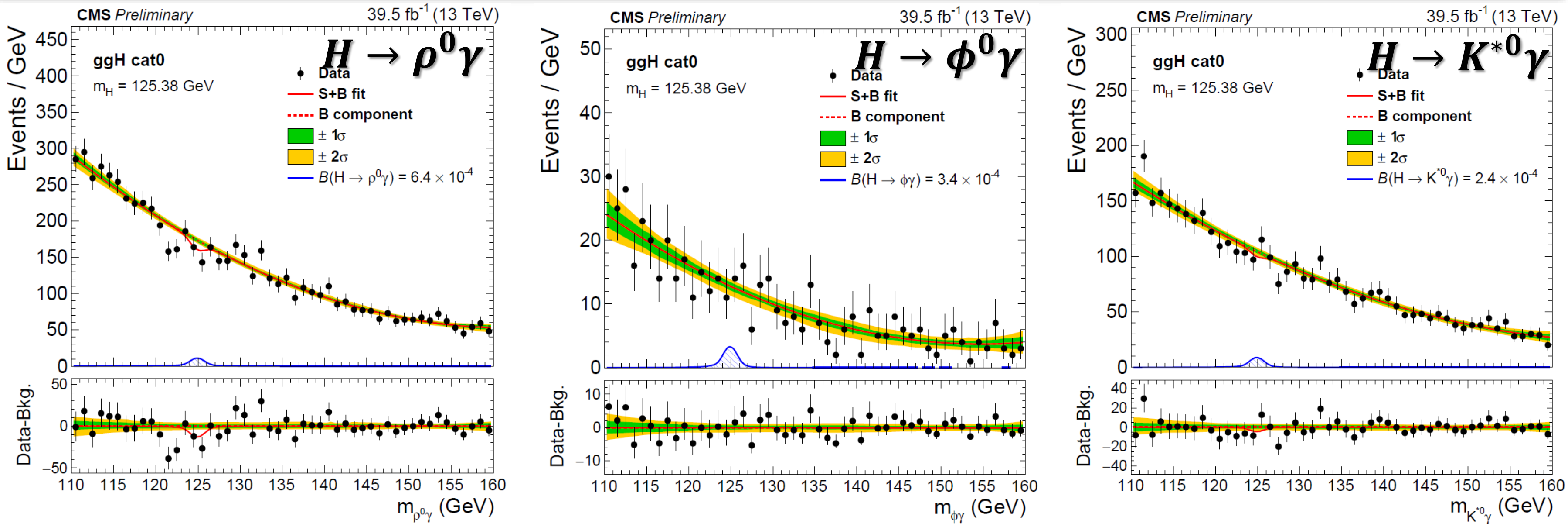


- Decays to a light-flavour meson
  - $H \to \rho^0\gamma, \phi^0\gamma$: BR_{SM} at $O(10^{-6}$ to $10^{-5})$ due to a large contribution from loop diagrams
  - $H \to K^{*0}\gamma$: $BR_{SM} = 1.0 \times 10^{-19}$
- Triggers are important to efficiently catch signal events
  - VH: leptons from the weak boson decay [138 fb^{-1}]
  - ggH and VBF: a photon + a few jets
    - $\gamma(E > 75$ GeV$)$ + a VBF jet pair [86.9 fb^{-1}]
    - $\gamma(E > 35$ GeV$)$ + a 'τ-like' jet ($p_T > 35$ GeV) having two tracks [39.5 fb^{-1}]
- Mesons reconstructed using K/π hypothesis



■ $H \to \rho^0\gamma, \phi^0\gamma, K^{*0}\gamma$

CMS, PAS-HIG-23-005 (2024)



- Combining a photon to the meson, fit is performed to the invariant mass distributions

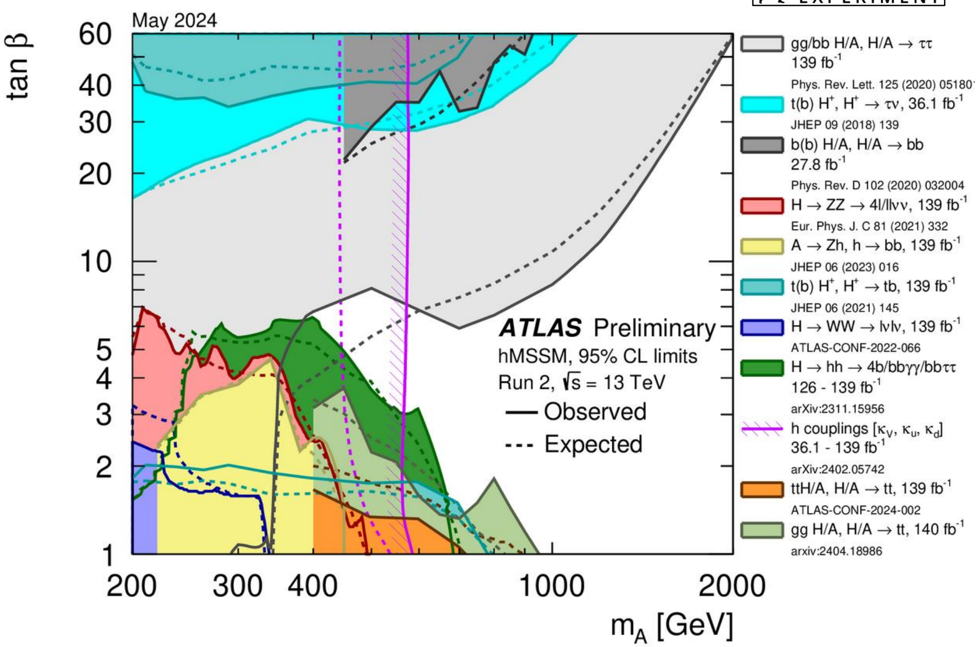
$$\mathrm{BR}(H \to \rho^0\gamma) < 3.7 \times 10^{-4} \quad \mathrm{BR}(H \to \phi^0\gamma) < 3.0 \times 10^{-4}$$
$$\mathrm{BR}(H \to K^{*0}\gamma) < 1.7 \times 10^{-4}$$

  - The ggF category is most sensitive despite its lower integrated luminosity

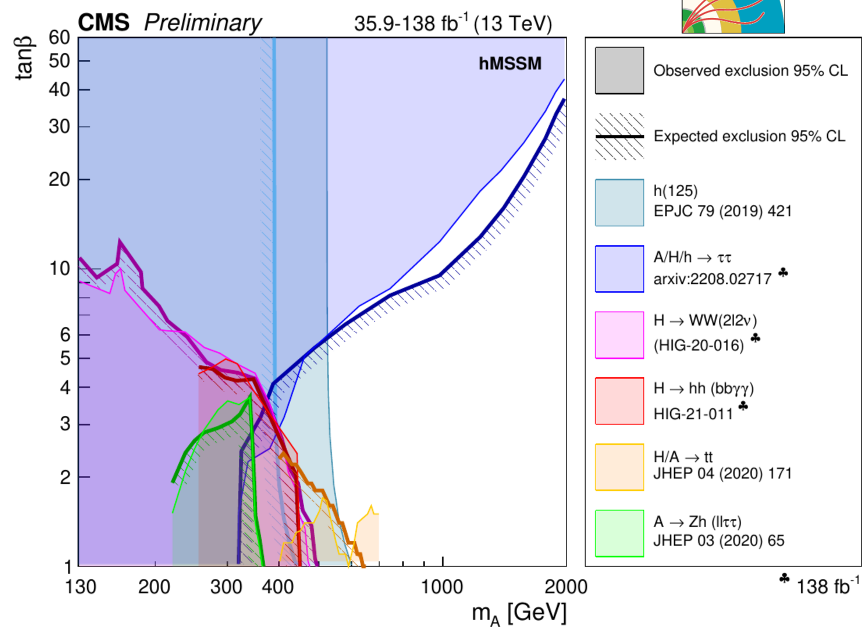
Similar results from ATLAS: Phys. Lett. B 847 (2023) 138292 ($H \to \omega^0\gamma, K^{*0}\gamma$)
JHEP 07 (2018) 127 ($H \to \phi^0\gamma, \rho^0\gamma$)

■ BSM Higgs bosons

NEW! [ATLAS, ATL-PHYS-PUB-2024-008](#)



[CMS, Higgs PAG Summary Plots](#)

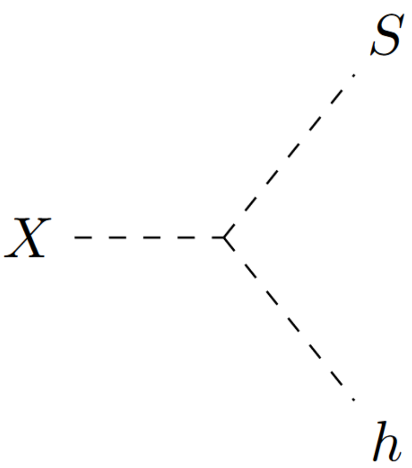


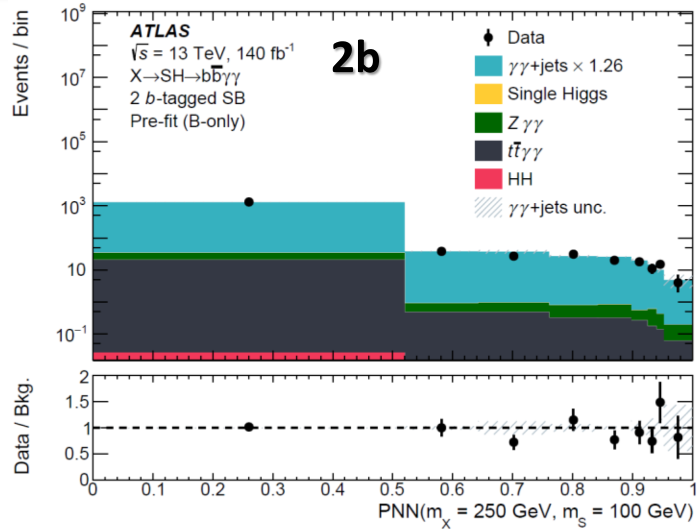
- Several Higgs bosons can appear in extended Higgs models
  - Naive extension is 2HDM with one extra Higgs doublet
    → Five Higgs bosons appear: h, H, A, H^+, H^-
  - Variety of the extended models can be considered
- Focus on recent heavy Higgs searches in this talk

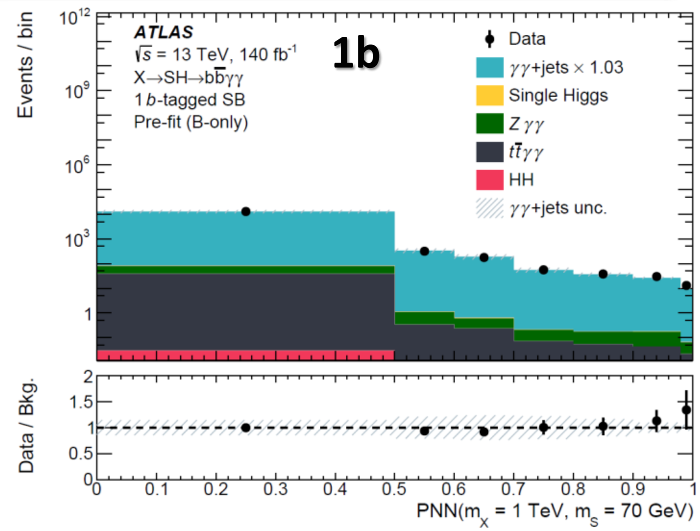
Let me use consistent notation
- h for 125 GeV Higgs boson
- S for extra scalar
- X for unknown parent

■ $X \to Sh \to bb\gamma\gamma$

ATLAS, arXiv:2404.12915





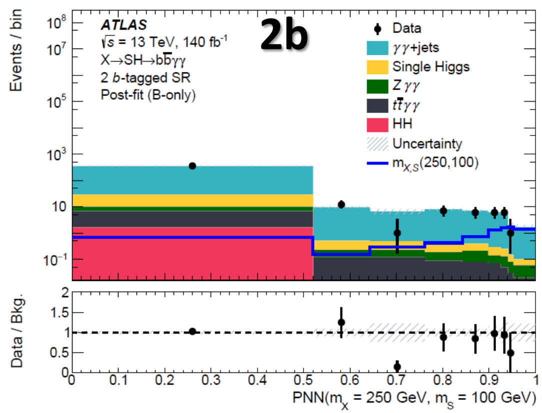


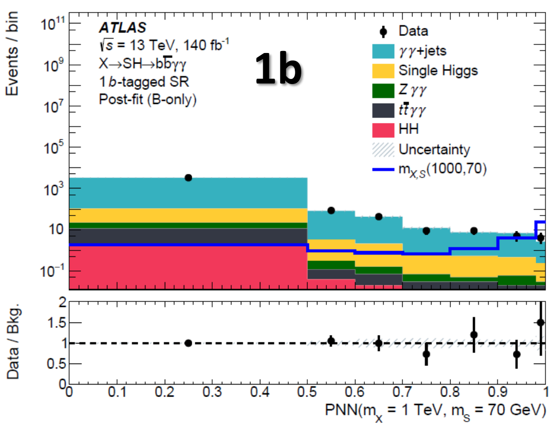
- Search for new scalars X and S using $S \to bb$, $h \to \gamma\gamma$
  - They may appear in 2HDM + real scalar, NMSSM etc.
- Two regions defined
  - 2b: aim to fully detect two b-jets from $S \to bb$
  - 1b: only one of the b-jets is detected when $\Delta(m_X - m_S)$ is large
- PNN is trained for fit variable
  - Good agreement with data in the $m_{\gamma\gamma}$ sidebands

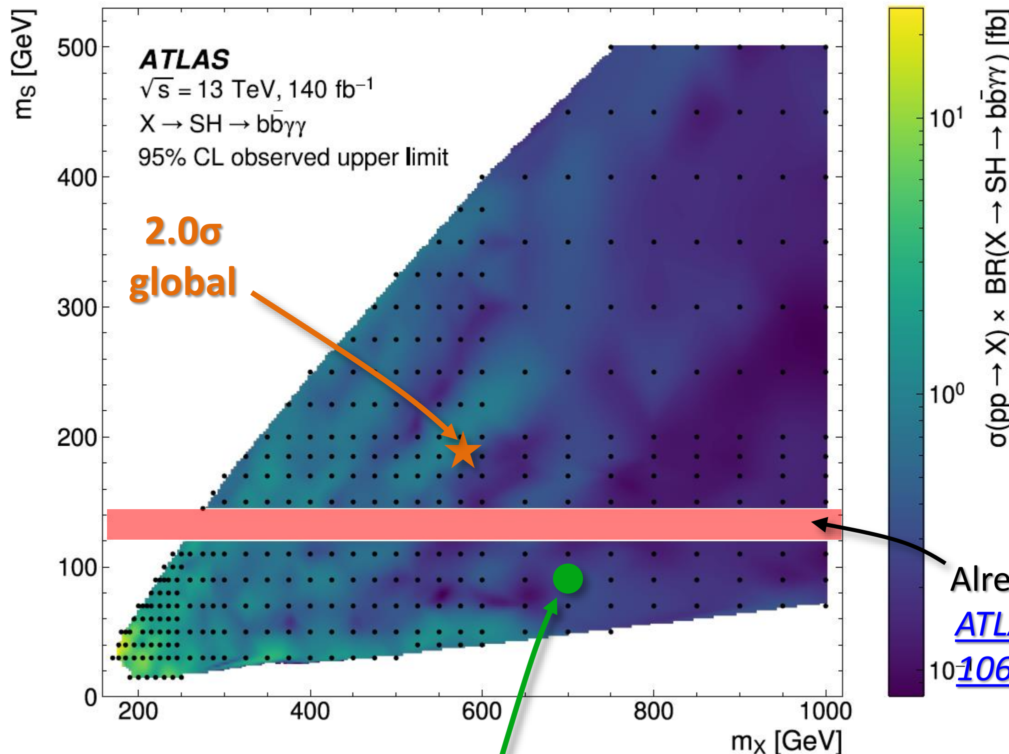
■ $X \to Sh \to bb\gamma\gamma$

ATLAS EXPERIMENT

[ATLAS, arXiv:2404.12915](https://arxiv.org/abs/2404.12915)







Already searched in [ATLAS, Phys. Rev. D 106 (2022) 052001](https://doi.org/10.1103/PhysRevD.106.052001) $(S = h)$

No excess here where 2.8σ global was reported in [CMS, arXiv:2310.01643](https://arxiv.org/abs/2310.01643)

- No significant excess was found
  - Upper limit set in the range up to ~1 TeV (500 GeV) for m_X (m_S)
  - Highest significance at (m_X, m_S) = (575, 200) GeV [global 2.0σ]
  - CMS previously reported an excess at (m_X, m_S) = (650, 90) GeV [global 2.8σ] but no excess was found in this analysis

■ $X \to Sh \to$ multileptons + $\gamma\gamma$ **NEW!**

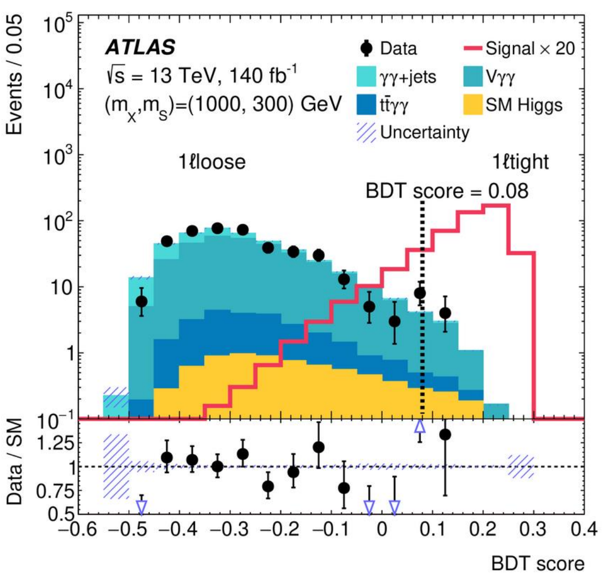
ATLAS, arXiv:2405.20926

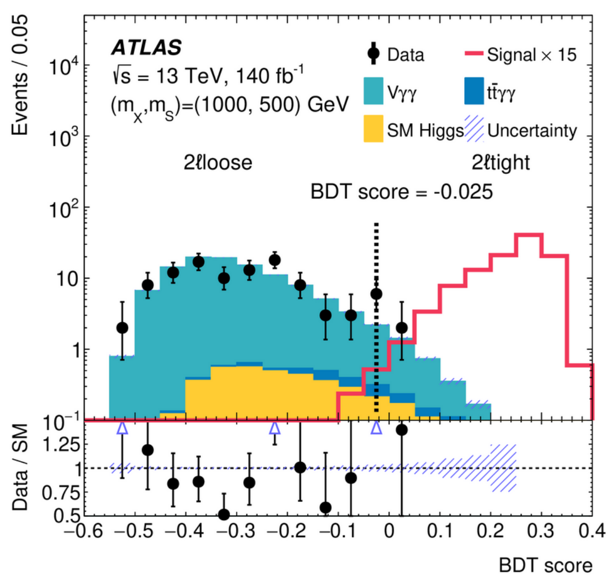
- Search for $X \to Sh$ using different final state
  - Target is $S \to VV \to \geq 1\ell$ + jets and $h \to \gamma\gamma$

	1ℓ	$2\ell\ (e\mu)$	$2\ell\ (WW)$	$2\ell\ (ZZ)$
N_ℓ	≥1	≥2	≥2 $\lvert m_{\ell\ell} - m_Z \rvert$ > 10 GeV	≥2 $\lvert m_{\ell\ell} - m_Z \rvert$ < 10 GeV
Njets	≥2	Not required	Not required	≥2
Strategy	BDT	Cut-based	BDT	Cut-based

BDT used to define high/low purity regions

Cut-based due to low stat. and high purity



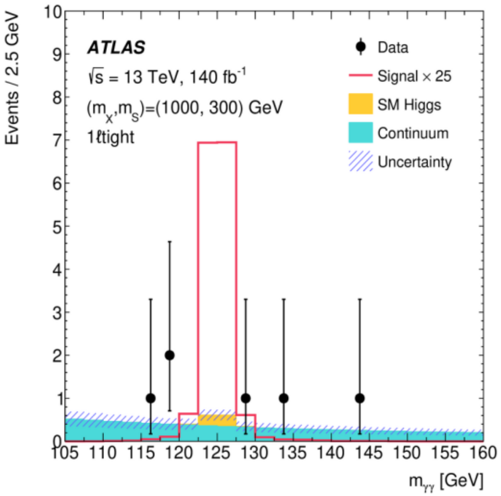


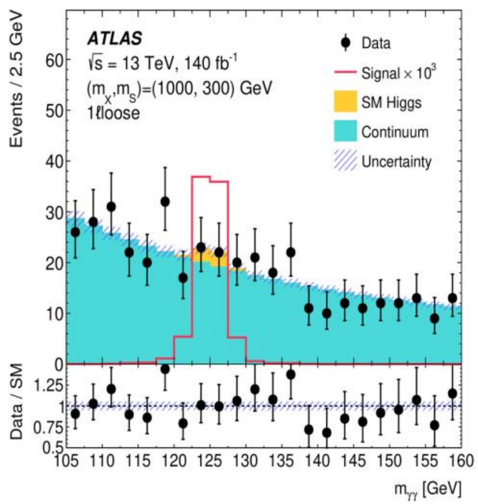
In total, six signal regions are defined

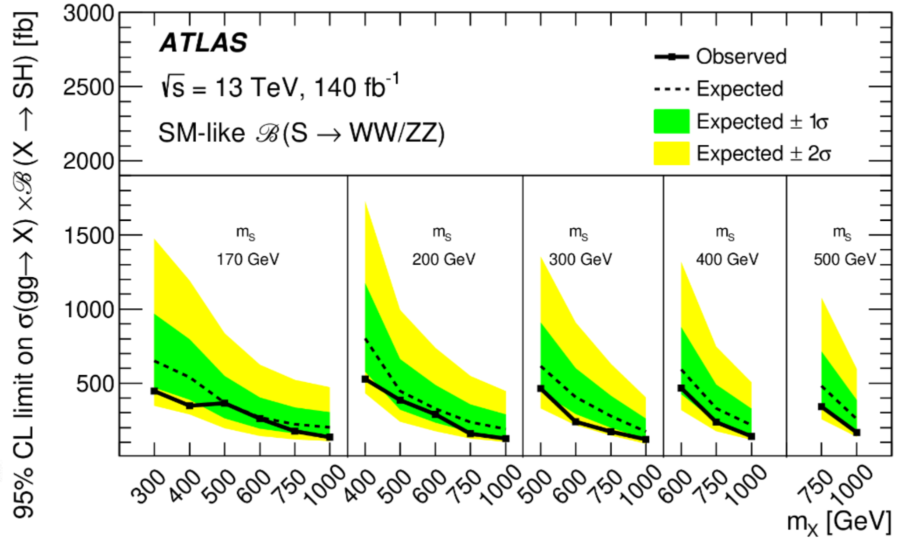
■ $X \to Sh \to$ multileptons + $\gamma\gamma$ NEW!

ATLAS, arXiv:2405.20926

1 lepton category



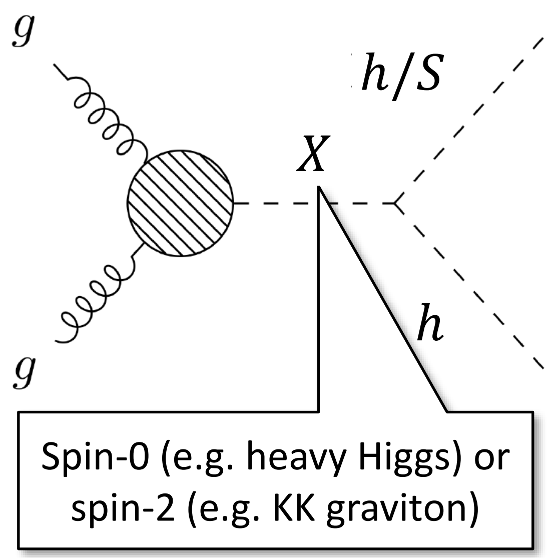


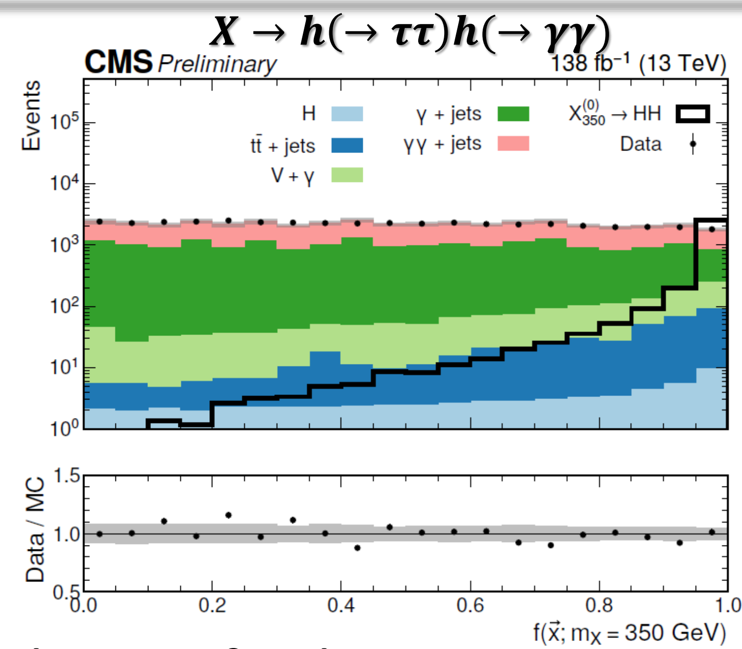


- Fit performed with $m_{\gamma\gamma}$ distributions
  - No significant excess was observed
- Upper limits are set up to ~1 TeV (500 GeV) for m_X (m_S)
  - Other hypothesis are also tested in the paper: BR($S \to WW$) = 100% or BR($S \to ZZ$) = 100%

■ $X \to (S,h)h \to \gamma\gamma\tau\tau$

[CMS, PAS-HIG-22-012 (2024)](#)

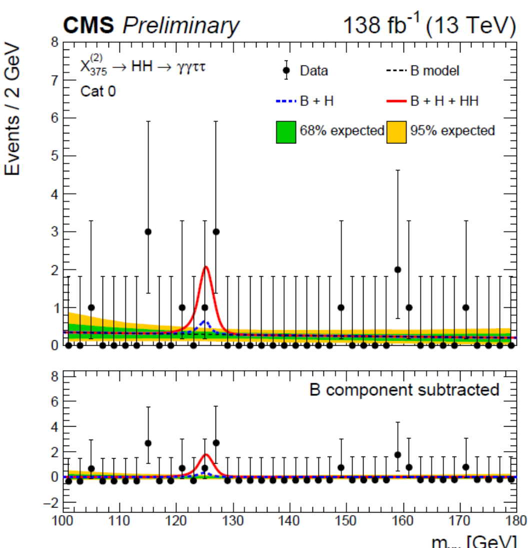




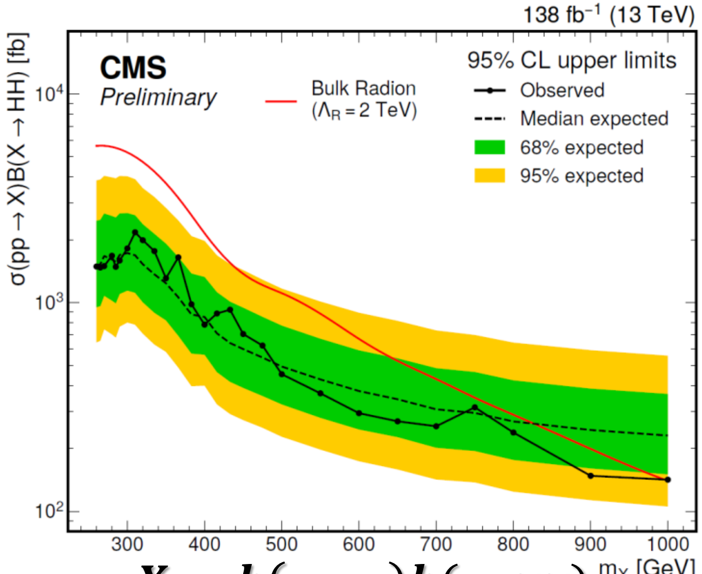
- Di-Higgs resonance search with $\gamma\gamma\tau\tau$ final state
  - One of h or S decays into $\gamma\gamma$ and the partner to $\tau\tau$
  - All di-τ final states are used: $\ell\ell'(\ell,\ell' = e,\mu)$, $\tau_{\rm had}\ell$, $\tau_{\rm had}\tau_{\rm had}$
- PNN is used to separate signals from backgrounds
  - Training separately for $X \to h(\to \tau\tau)h(\to \gamma\gamma)$, $X \to S(\to \tau\tau)h(\to \gamma\gamma)$, $X \to S(\to \gamma\gamma)h(\to \tau\tau)$ [high mass S / low mass S]
  - Defined 10 SRs for each final state using PNN score

$X \to (S,h)h \to \gamma\gamma\tau\tau$

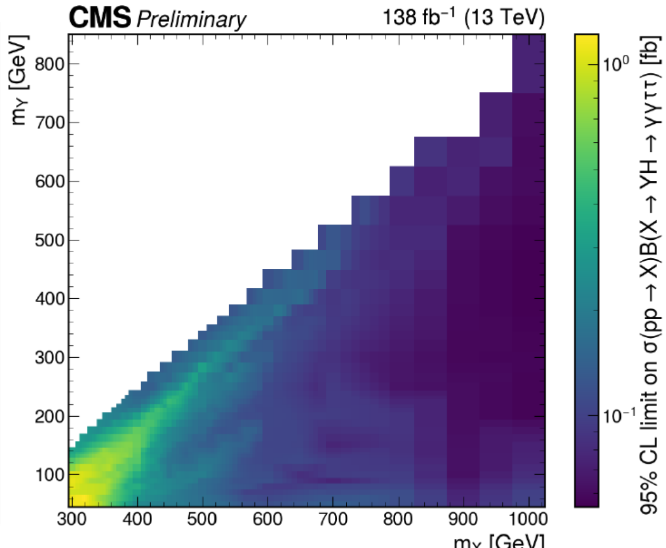
CMS, PAS-HIG-22-012 (2024)



$X \to hh$, Cat. 0



$X \to h(\to \tau\tau)h(\to \gamma\gamma)$

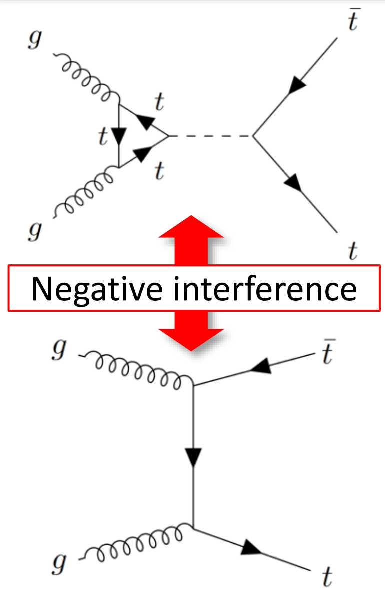


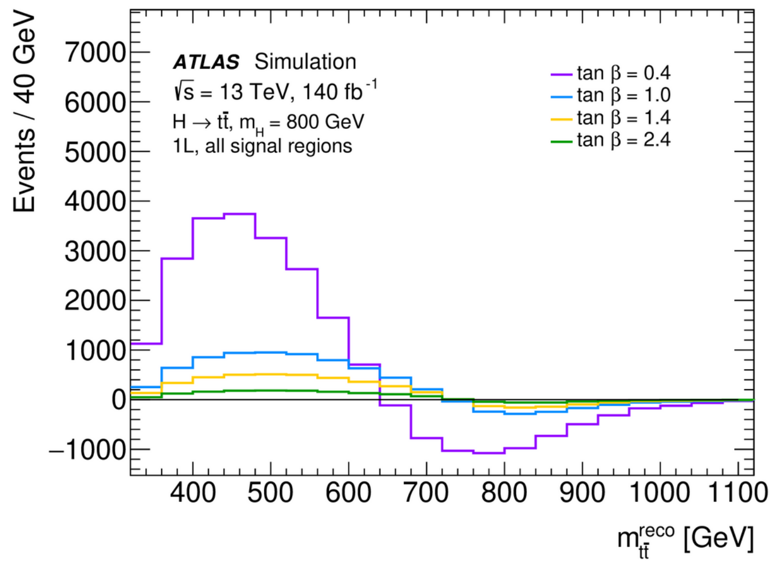
$X \to S(\to \tau\tau)h(\to \gamma\gamma)$

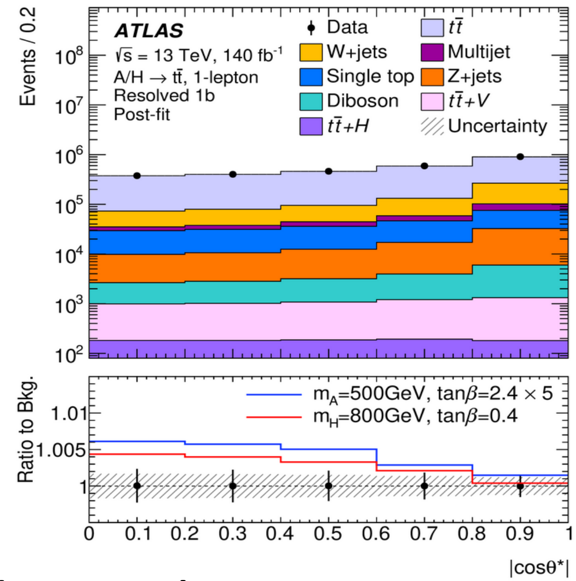
- Fit performed using $m_{\gamma\gamma}$
  - No significant excess found
- Various scenarios are tested in this analysis
  - Spin-2 X particle search
  - Non-resonant Higgs pair production
- Review of $X \to (S,h)h$ searches by CMS arXiv:2403.16926

■ $A \rightarrow t\bar{t}$

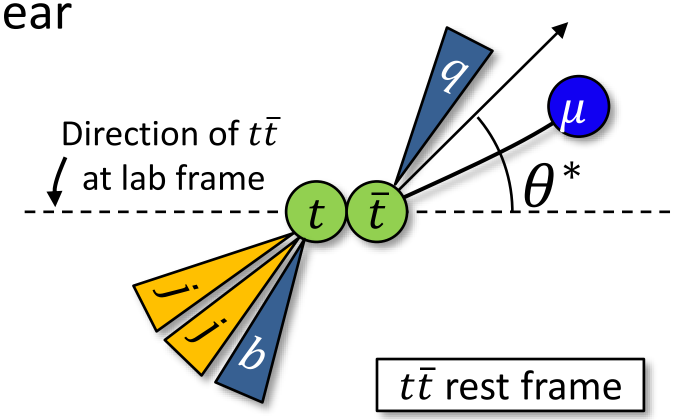
[ATLAS, arXiv:2404.18986](https://arxiv.org/abs/2404.18986)





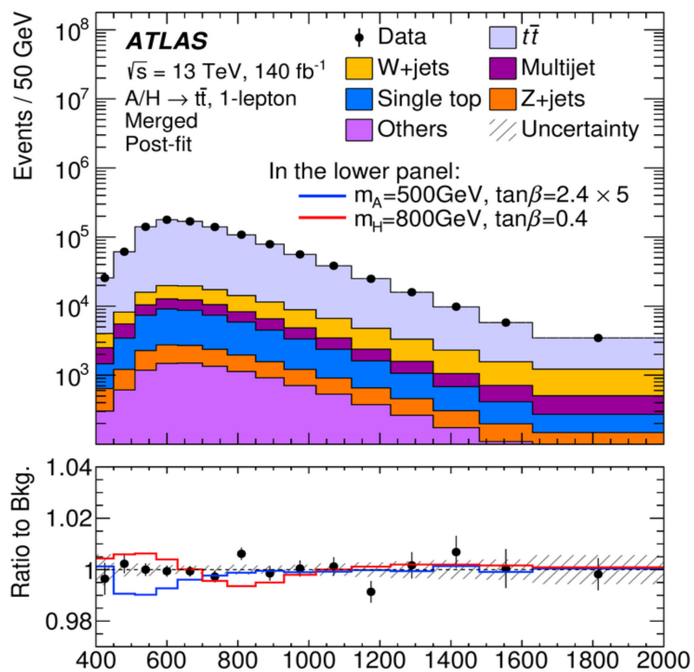


- Large cross section when $\tan\beta$ is small and m_A is large
- Important to handle the interference properly
  - Characteristic peak-dip structure may appear
- Angular distribution is effective to separate signals (spin = 0) from $t\bar{t}$
  - Signal distributes flatter while $t\bar{t}$ populates around $|\cos\theta^*| \sim 1$
  - $\Delta\phi_{\ell\ell}$ is used for the di-lepton channel

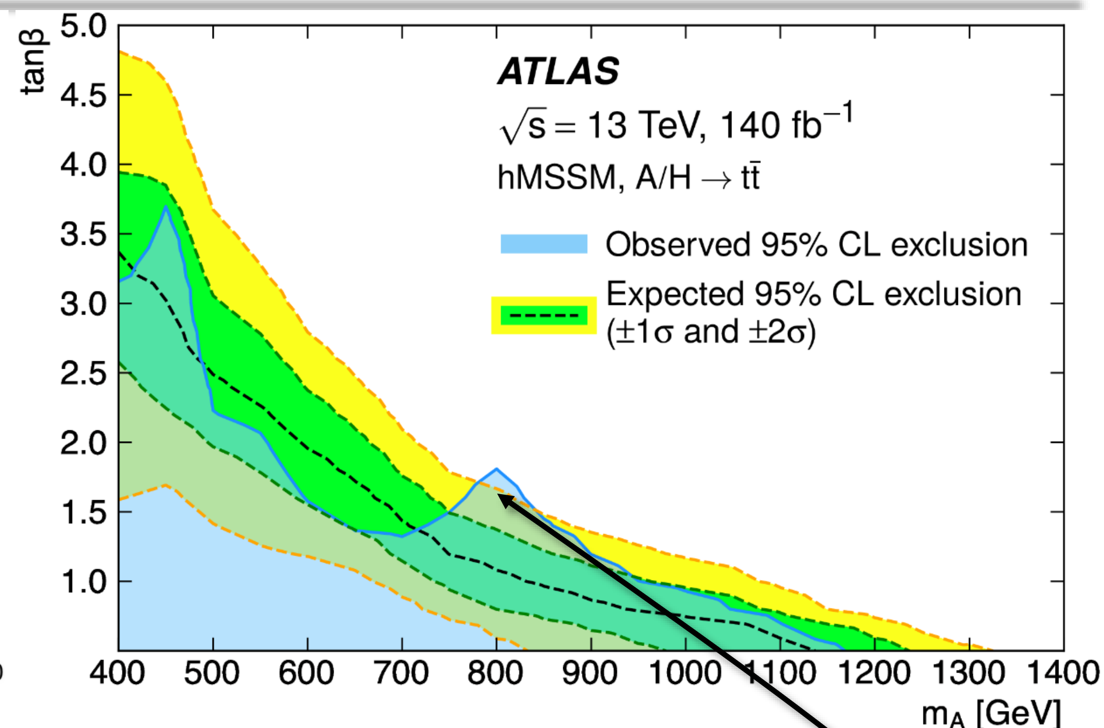


$A \to t\bar{t}$

ATLAS, arXiv:2404.18986



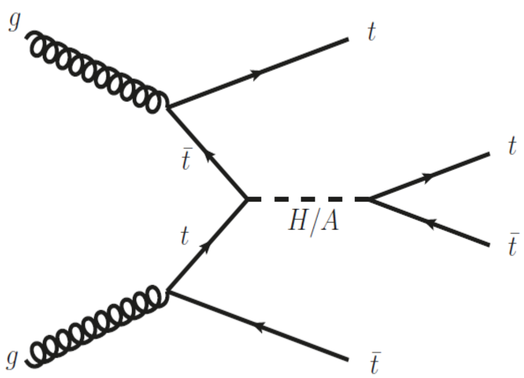
Merged top region

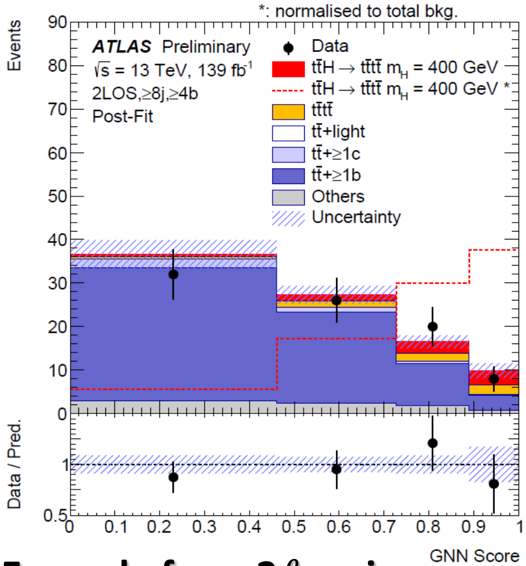


- Simultaneous fit performed with $m_{t\bar{t}}$
  - Four categories: merged top, resolved (1b, 2b), 2 leptons
- No significant excess observed
  - Most significant excess around $m_A \sim 800$ GeV (2.8σ local)
- Various other interpretations are given in the paper: 2HDM-II, 2HDM+a, effective coupling $g_{At\bar{t}}$

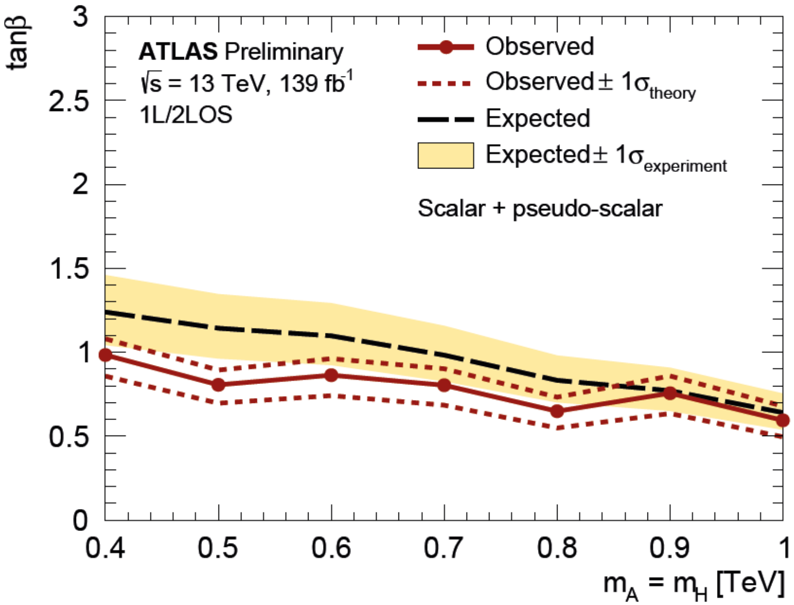
$t\bar{t}A \to t\bar{t}t\bar{t}$

ATLAS, CONF-2024-002 (2024)





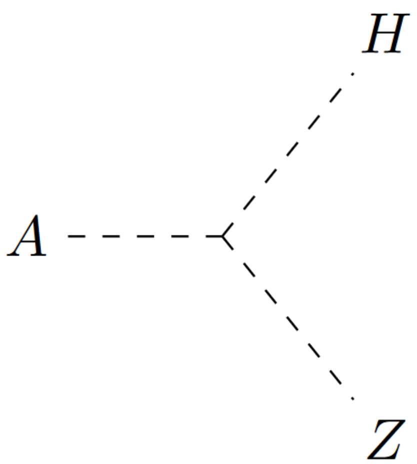
Example from 2ℓ region

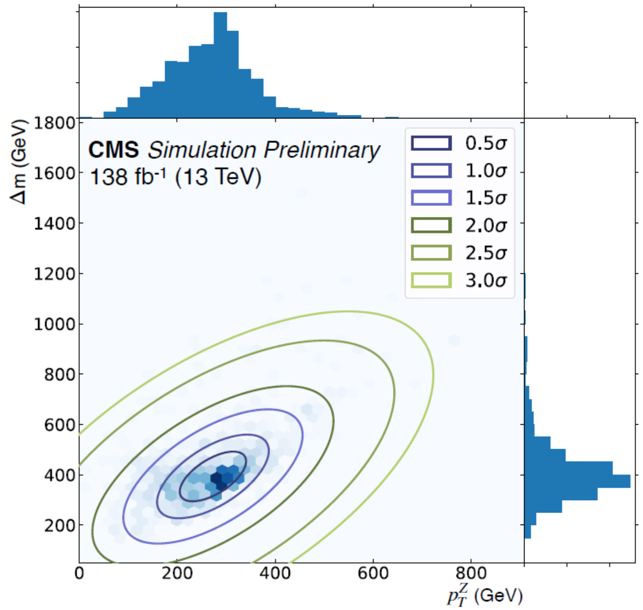


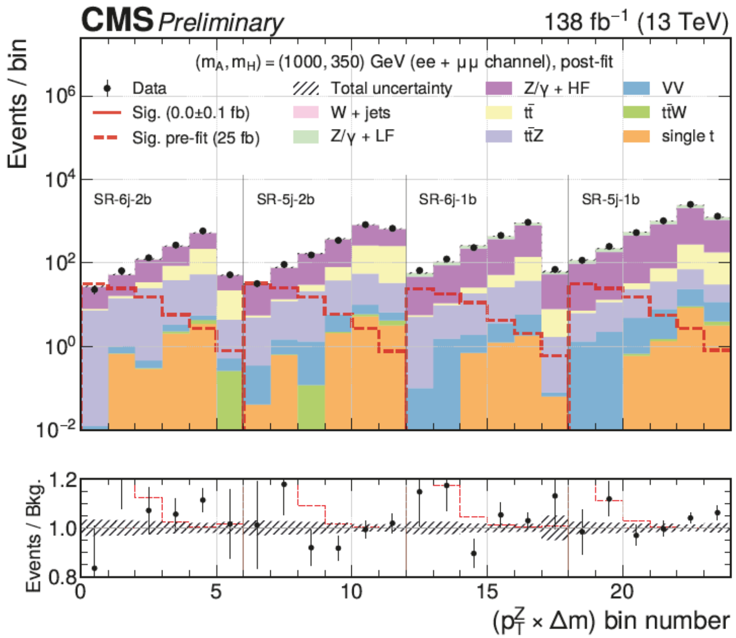
- Basic analysis strategy same as the 4-top search ATLAS, JHEP 11 (2021) 118
  - Improved analysis methods exploiting GNN
- Dominant background is $t\bar{t}$ + heavy flavour jets, which is difficult to model in MC
  - Careful modelling using flavour rescaling and NN-based reweighting
- No significant excess observed
  - Limit set up to $m_A \sim 1$ TeV at tanβ = 0.5

■ $A \to ZH, H \to t\bar{t}$

CMS, PAS-B2G-23-006 (2024)



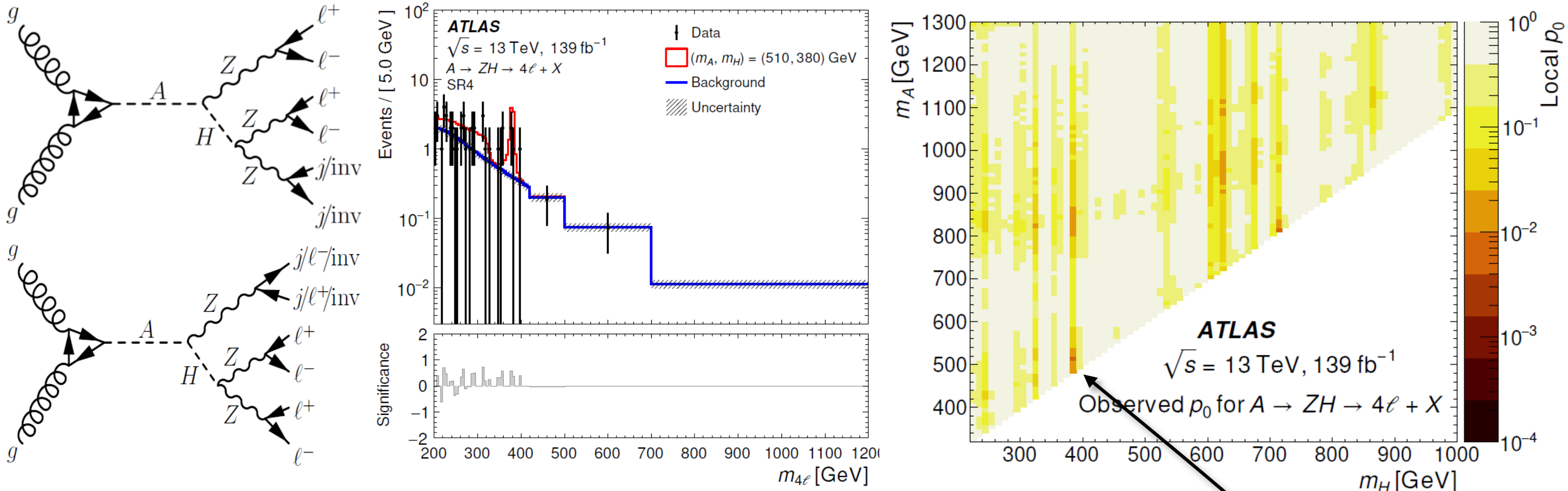




- Search for $A \to ZH$ production
  - Large mass splitting between A and H allows first-order phase transition
  - For $m_H > 400$ GeV, $H \to t\bar{t}$ becomes dominant
- Construct fit discriminant using $\Delta m = m_{t\bar{t}Z} - m_{t\bar{t}}$ and p_{T}^{Z}
  - Six bins are defined for each SR using the 'x-σ' ellipses
- No significant excess was found
  - Limit up to $m_A \sim 1$ TeV is set (for the case of 2HDM-II)

$A \to ZH, H \to ZZ$

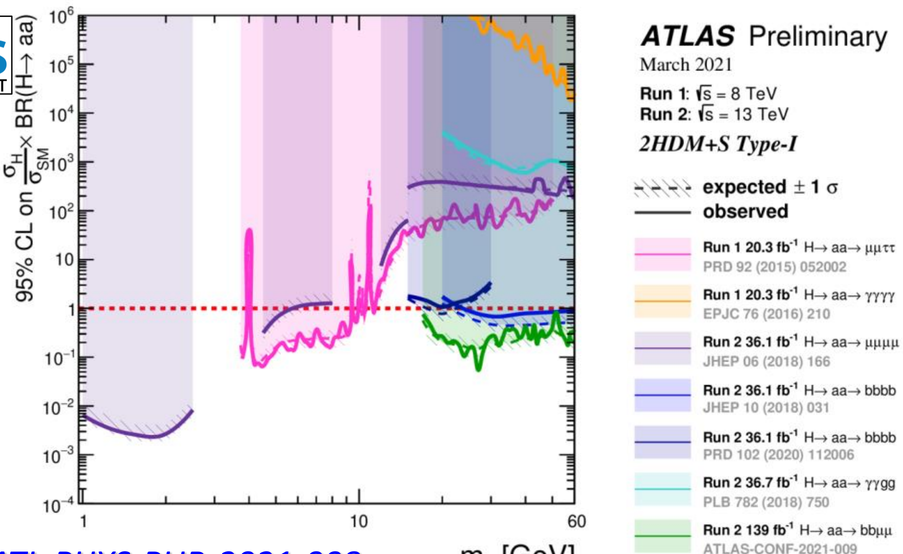
ATLAS, arXiv:2401.04742



- Similar search using the tri-Z final state
- Simple analysis strategy
  - Cut-based analysis with seven SRs with different number of (b-)jets
  - Final fit using the 4-lepton mass $m_{4\ell}$
- No significant excess found
  - Largest significance at (m_A, m_H) = (510, 380) GeV (local 2.5σ)
    [N.B. ~5,000 mass points are scanned in this analysis]

■ Light BSM Higgs(−like) bosons

- Light pseudo-scalar boson (a) appears in e.g. 2HDM + S
  - ATLAS/CMS search for the a boson using various final states



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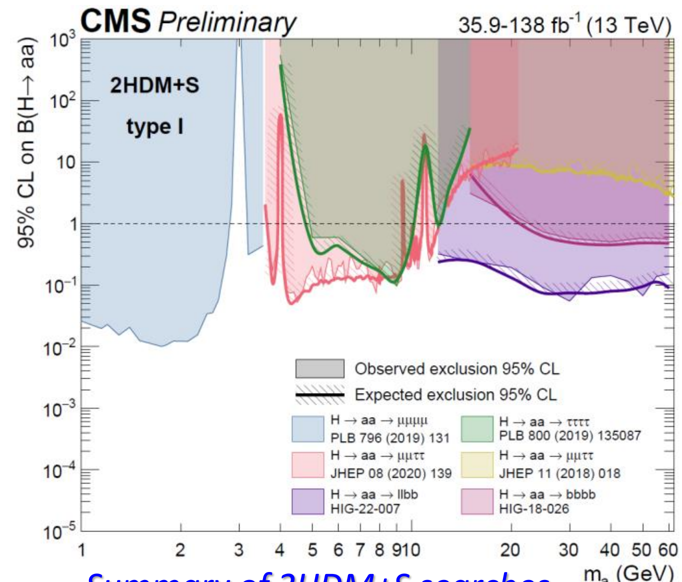

Summary of 2HDM+S searches

- Recent results from ATLAS and CMS:

- $h \to aa \to \gamma\gamma\gamma\gamma$:
  ATLAS, arXiv:2312.03306
- $h \to Za, a \to \gamma\gamma$:
  ATLAS, Phys. Lett. B 848 (2024) 138536

- Model independent $aa \to \mu\mu\mu\mu$:
  CMS-PAS-HIG-21-004
- $H \to aa \to bbbb$ using VH:
  CMS, arXiv:2403.10341

See talks by I. Riu (ATLAS) and A. Malara (CMS) on Thursday!

■ Summary

- ATLAS and CMS have been collecting data for >10 years
  - Statistics accumulated by each experiment corresponds to ~12M Higgs bosons as of today
- I introduced various interesting results using Run 2 data
  - Higgs rare decays with 1st / 2nd generation flavours
  - BSM searches targeting 2HDM and various extended Higgs models
- More data are important!
  - Statistics will be 3x larger by the end of Run 3 (w.r.t. Run 2)
  - Observation of $H \to \mu\mu$, confirmation of $H \to Z\gamma$ excess, ...
  - Wider searches for extra Higgs bosons (not only heavy ones but also lighter scalars)

Various analyses using Run 2+3 data are ongoing!