Searches for Heavy Resonances Decaying to Bosons

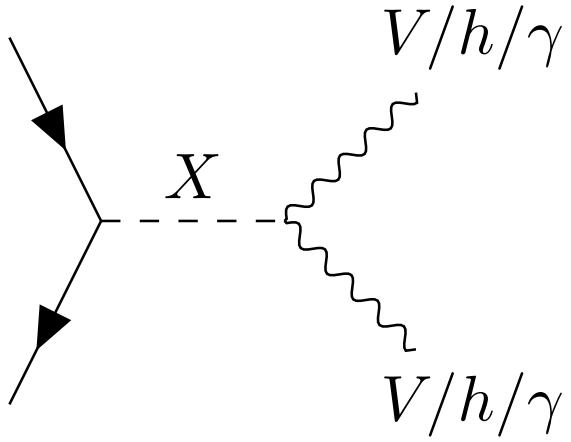
Robert Les,
On behalf of the ATLAS and CMS collaborations

CKM2023,
September 21, 2023

Motivation

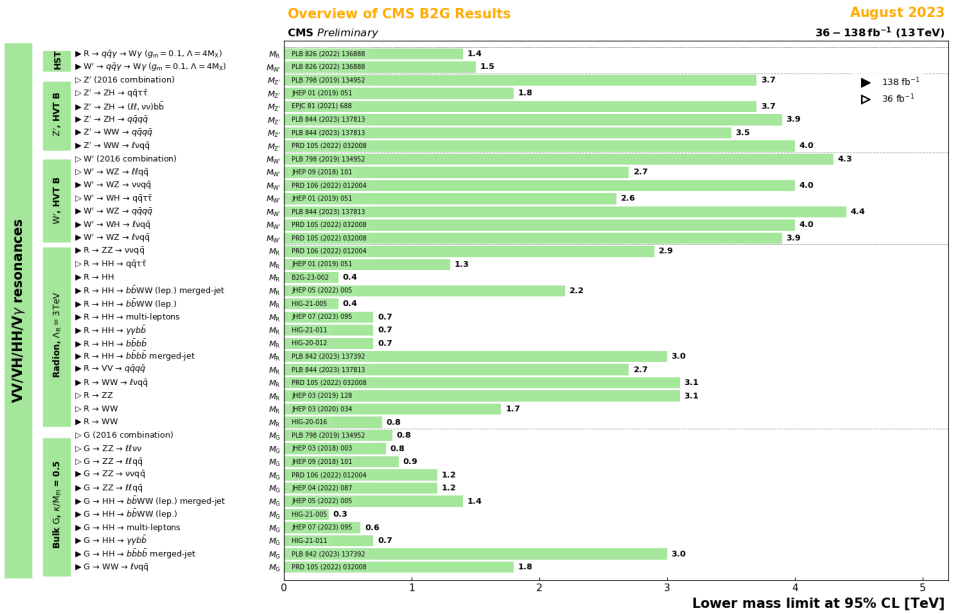
Continued and mounting evidence pointing to the SM not being the complete theory

- Electroweak theory might be low-energy effective theory
- Possibly CKM/PMNS is part of this story



Many extensions to the SM have been proposed

- Extended gauge and Higgs sectors, composite particle models, gravity models
- A frequent feature are new heavy resonances decaying to SM $W/Z/h/\gamma$ bosons



ATLAS and CMS are some of the main constraints for these types of searches

- "General purpose" detectors: most decay models accessible
- High energy: many models predict TeV scale particles
- High luminosity: predicted cross-sections can be low

CMS+ATLAS diboson resonance searches

CMS has an extensive search program for "diboson" resonances in $VV/Vh/hh$

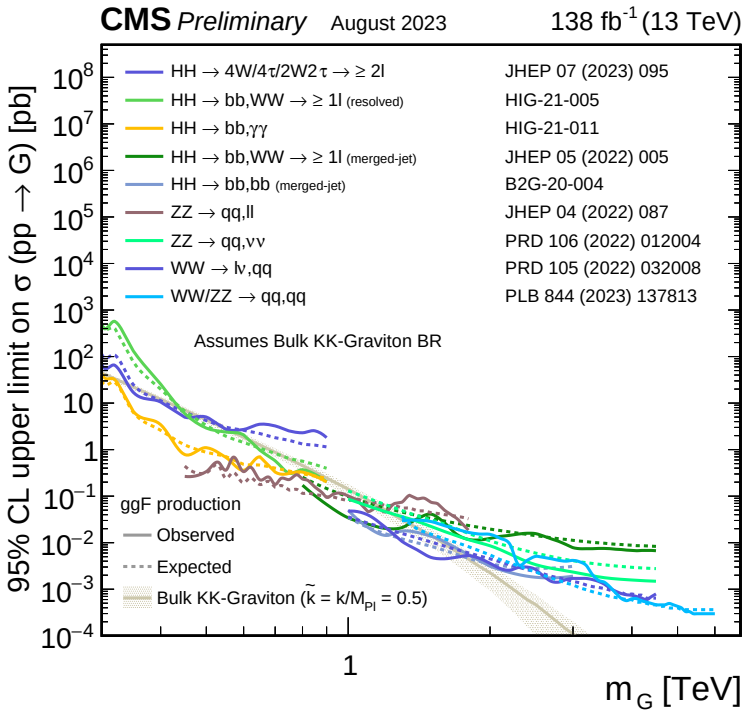
- $qqqq/qqbb$
- $\ell\ell qq/\ell\ell bb$
- $\nu\nu qq$
- $\ell\nu qq/\ell\nu bb$
- $\ell\nu\ell\nu$
- $\ell^{\pm}\nu\ell^{\pm}\nu/\ell\nu\ell\ell + jj$
- $bbWW$
- $bbbb$
- $bb\tau\tau$
- $bb\gamma\gamma$

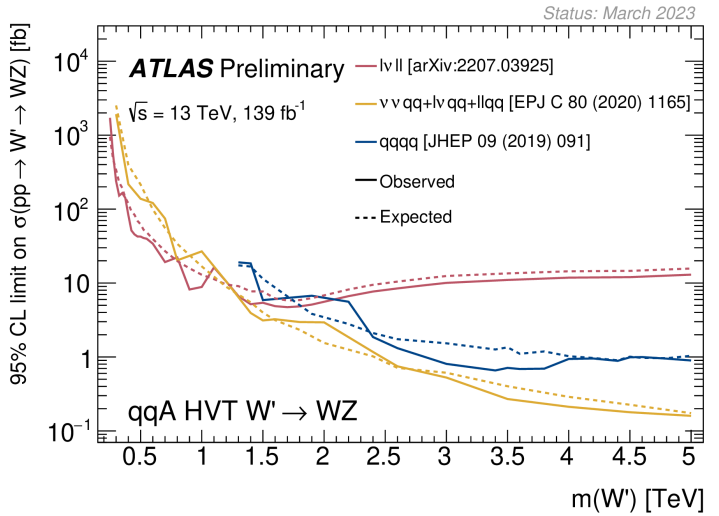
ATLAS has similar:

- $\ell\ell bb/\ell\nu bb/\nu\nu bb$
- $\ell^{\pm}\nu\ell^{\pm}\nu + jj$
- $\ell\nu\ell\ell$
- $\ell\nu\ell\nu$
- $\ell\ell\ell\ell/\ell\ell\nu\nu$
- $qqbb$, $qqqq$
- $\ell\ell qq/\ell\nu qq/\nu\nu qq$
- $bbbb$
- $bb\tau\tau$
- $bb\gamma\gamma$

Both ATLAS and CMS present limit on 3 benchmark models for these models:

- Neutral Spin-0: Randal-Sundrum Radion
- Charged Spin-0: Georgi-Machacek
- Spin-1: Heavy vector triplet (HVT)
- Spin-2: Randall-Sundrum Graviton





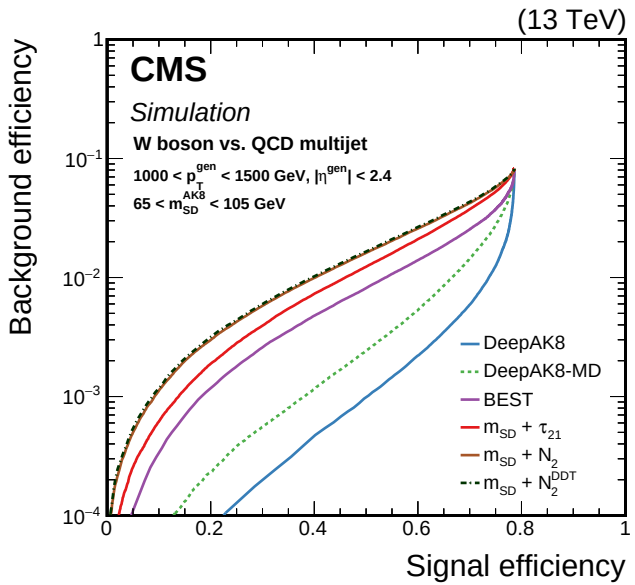
Boosted Boson Reconstruction

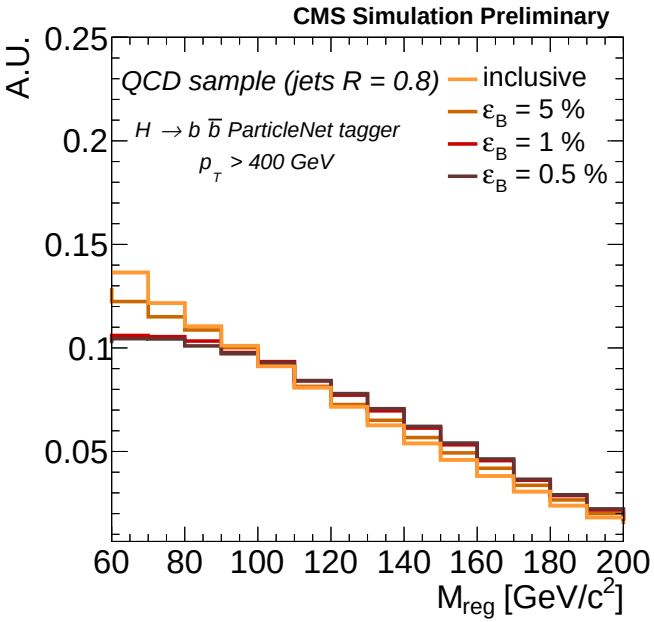
Largest BR of $W/Z/h/t$ is to quarks

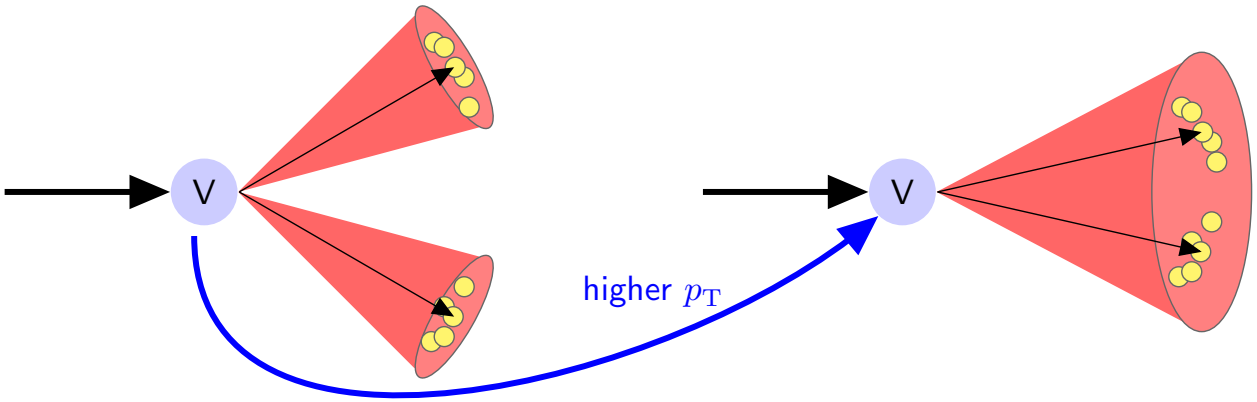
- When searching for new heavy resonance the boson p_{T} often very high
- Opening angle of decay products $\sim \frac{2m(V/h)}{p_{\mathrm{T}}(V/h)}$
  - Can't reconstruct as individual jets

Many analysis rely on very modern machine-learning techniques to "tag" large-R jets as $W/Z/h/etc$

- CMS ParticleNet and previous DeepAK8 taggers are current top-of-the-line
  - Multi-class network for different decay types
  - Decorrelated with respect to jet-mass
- Several recent ATLAS studies on architecture comparisons for tagging [1], [2], [3]







Very generic search of $VV/Vh \to qqqq/qqbb$

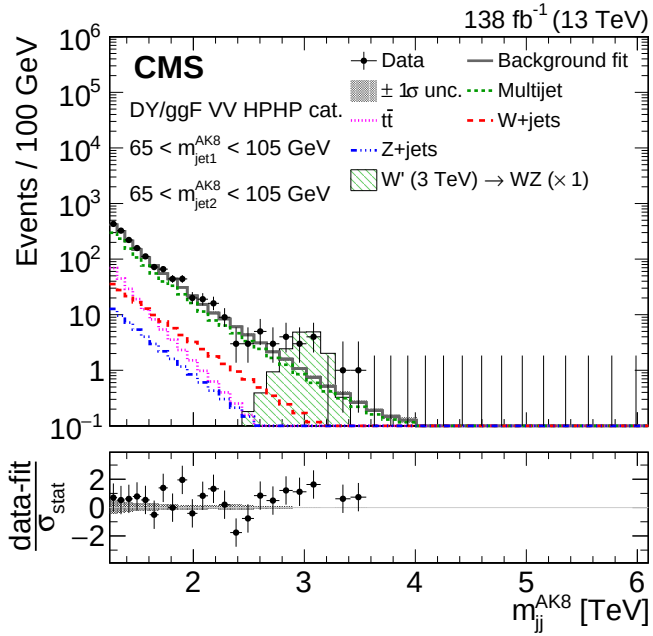
- Largest SM BR
- Challenging background of multijet events
  - At very high-p_{T} this becomes small as well

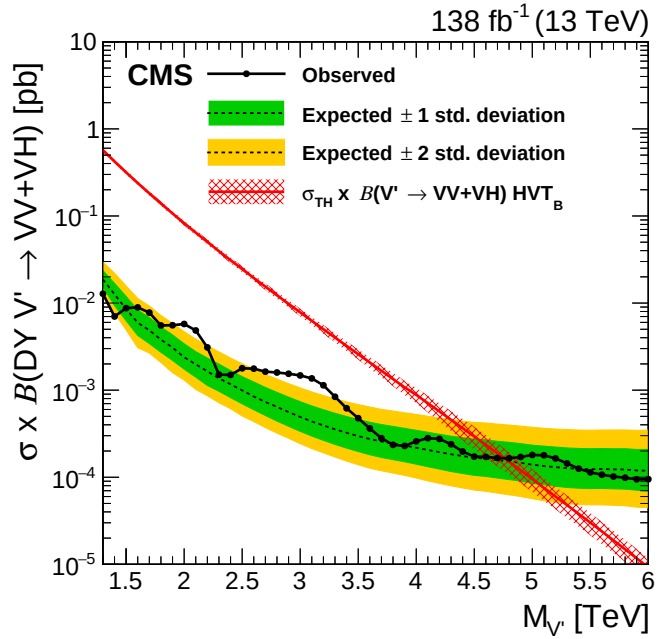
At high p_{T} the boson decay products become increasingly collimated

- Cluster each V/h as one large $R = 0.8$ jet
- CMS DeepAK8 tagger to separate $W/Z/t/h/\mathrm{QCD}$ jets from each other

Background extracted from simultaneous 3D fit of individual jet masses and dijet mass system

- Some minor 2.3σ excesses at $2.1/2.9$ TeV
- Limits in benchmark models



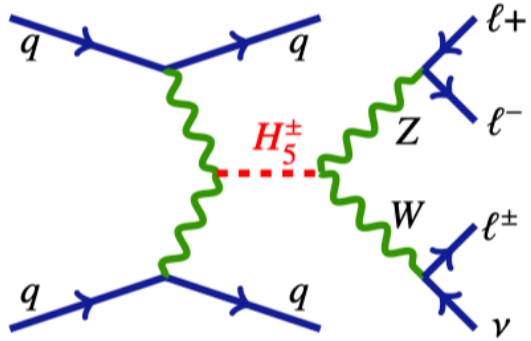


VV fully leptonic resonances

Eur. Phys. J. C 83 (2023) 633

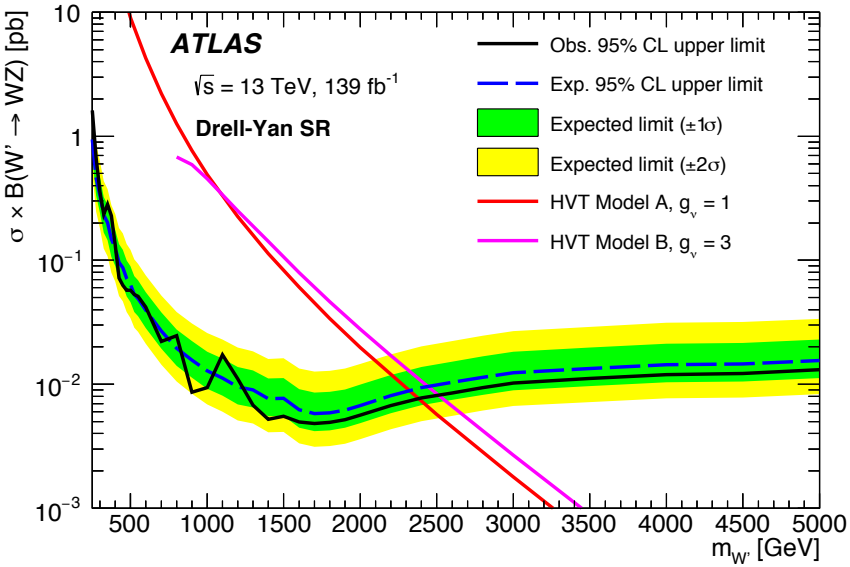
Complementary to fully-hadronic searches, are searches with leptonic decays, here $WZ \to \ell\nu\ell\ell$

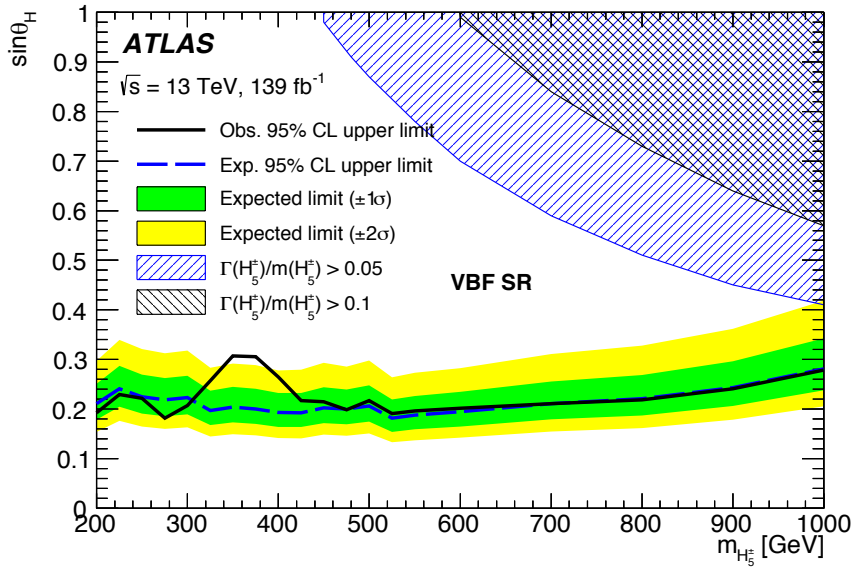
- Very low-background, but lower signal
- Can rely on good MC predictions
- Better constraints at mid-mass $300\ \text{GeV} < m(X) < 1\ \text{TeV}$

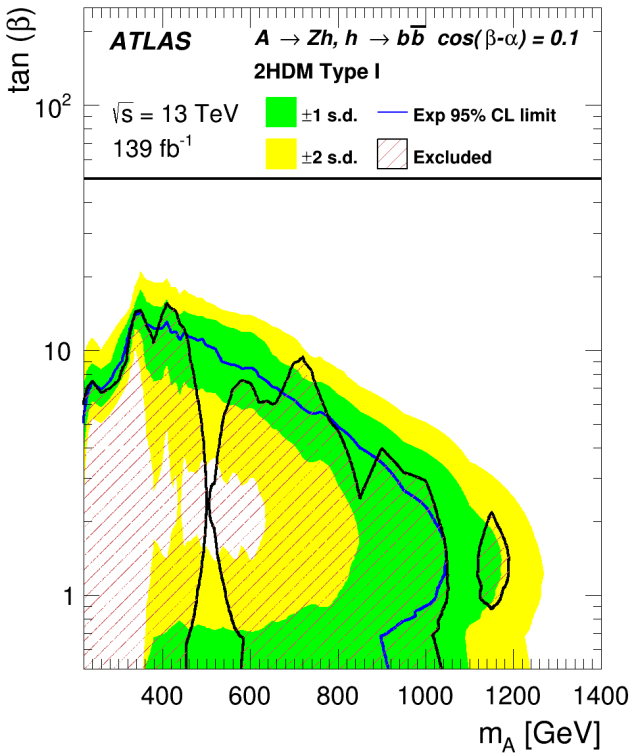


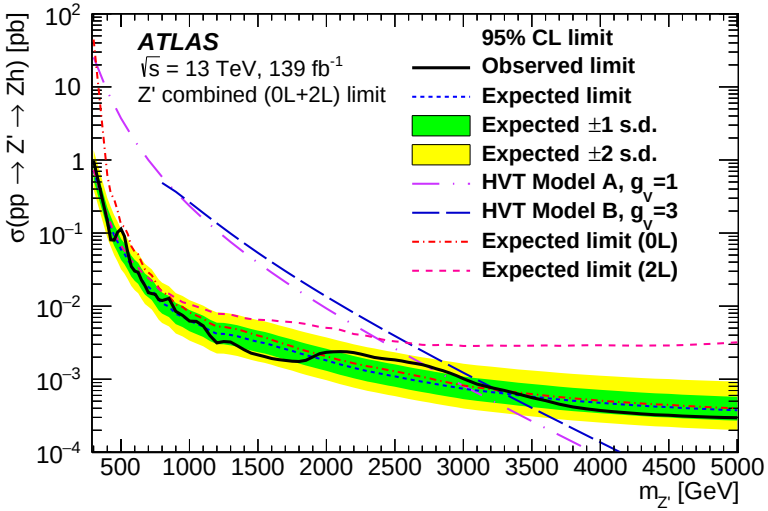
This analysis focused on VBF-produced signals

- Special neural-net to separate inclusive vs VBF production
- Strong limits in fermiophobic GM model









Also recent search for $Vh \to \ell\ell bb/\ell\nu bb/\nu\nu bb$

- Middle between background rejection and signal BR
- Dedicated control regions on major backgrounds through mass sidebands and $e\mu$ events

Different reconstruction techniques for $h \to bb$

- Two resolved $R = 0.4$ jets
- One large $R = 1.0$ jet

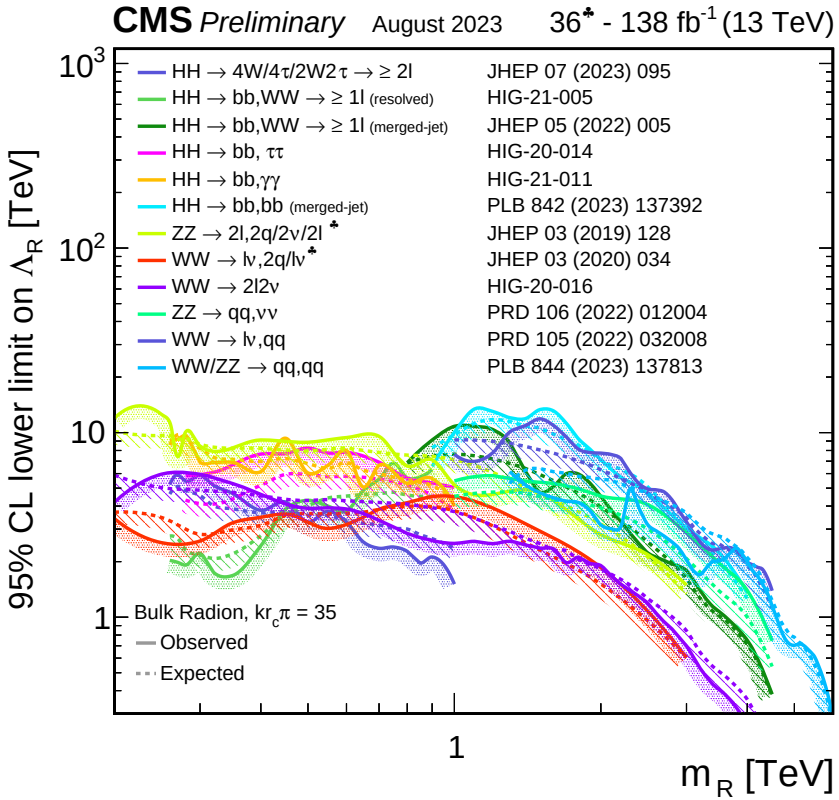
Results consistent with SM

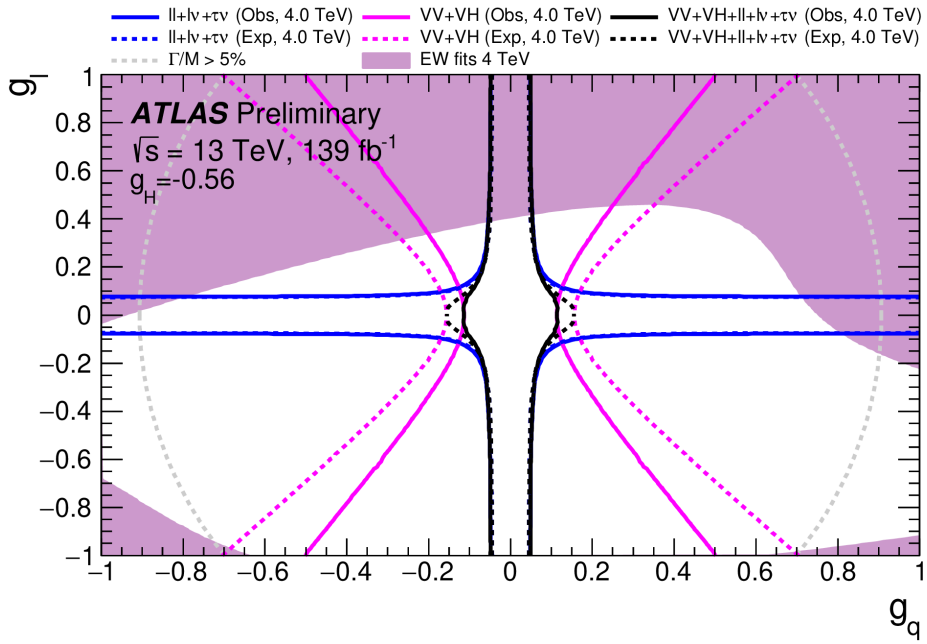
- Limits on HVT model
- Also limits on 2HDM model in inclusive and $b\bar{b}$-associated

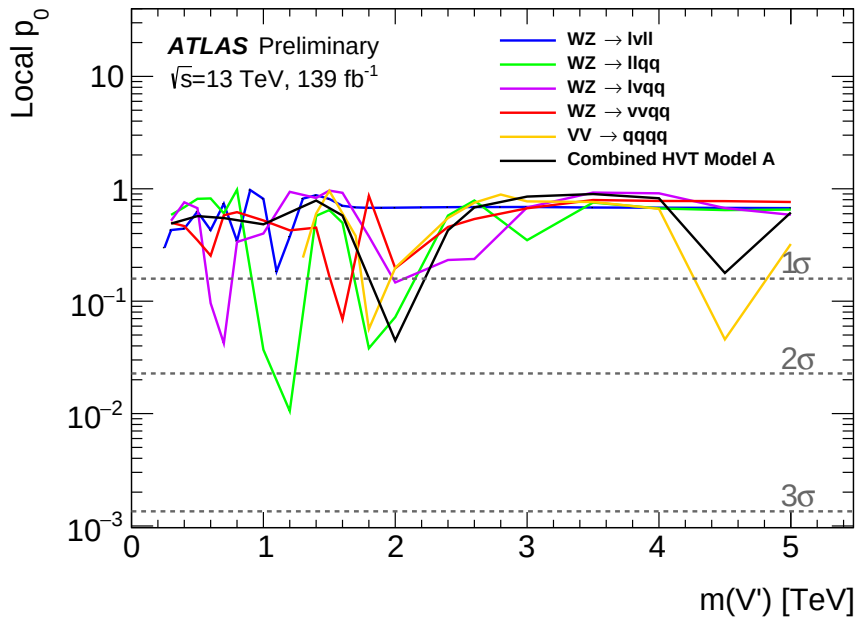
ATLAS published combination of all $VV/Vh/\ell\ell$ resonance searches

- Check if local excesses coincide
- Strongest limits
- Limits directly on couplings of benchmark HVT model

CMS provides similar summary plots

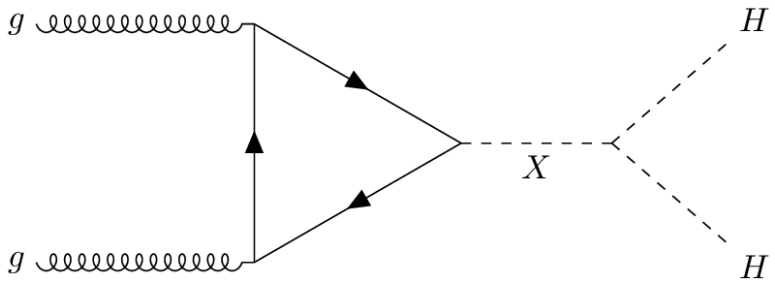


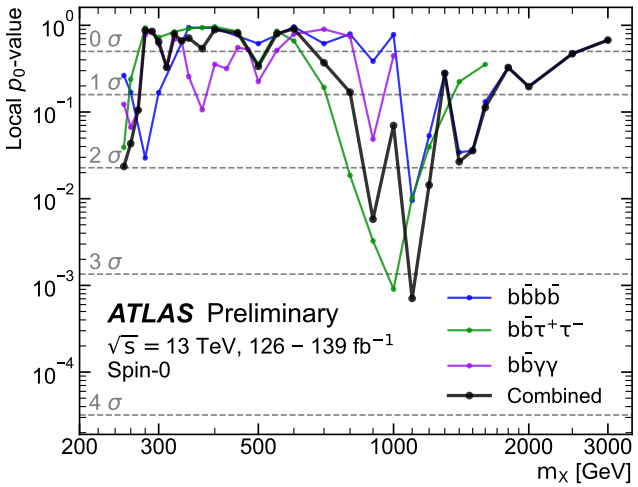


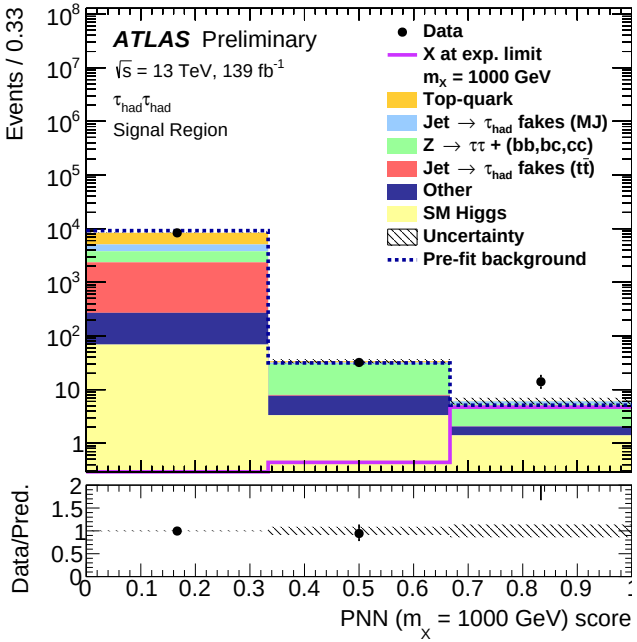


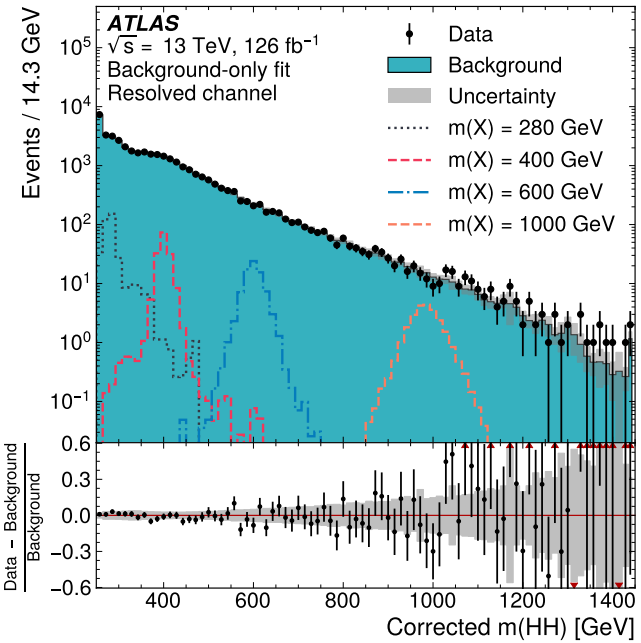
ATLAS performed similar combination of $hh \to bbbb$, $bb\tau\tau$, $bb\gamma\gamma$ searches

- $bb\tau\tau$: Local 3σ (2σ) @ 0.9 TeV
  - Not visible in traditional bump-hunt but seen via neural-network in $\tau_{had}\tau_{had}$
- $bbbb$: Local 2.3σ (0.4σ) @ 1.1 TeV
  - Small excess above data-driven bkg in resolved region
- Combined: Local 3.2σ (2.1σ) @ 1.1 TeV
  - Peaks co-linear

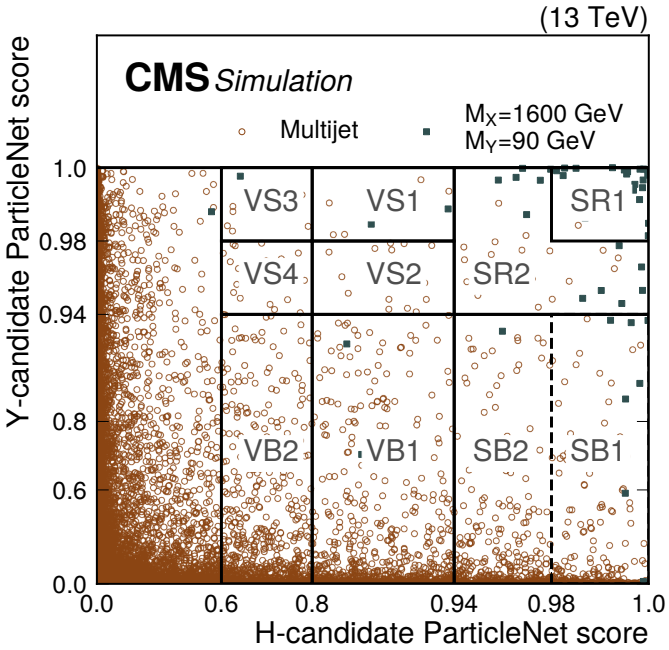


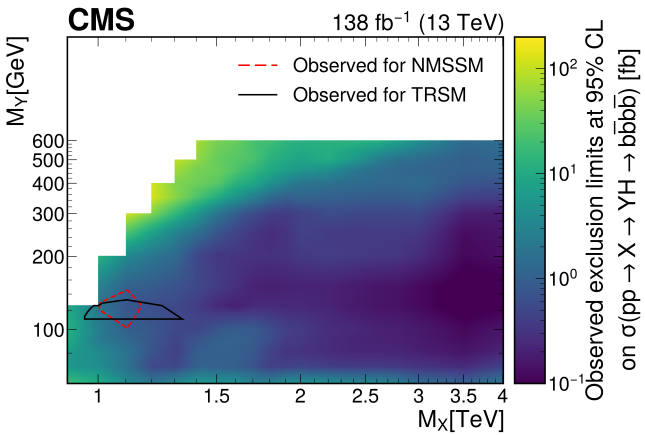




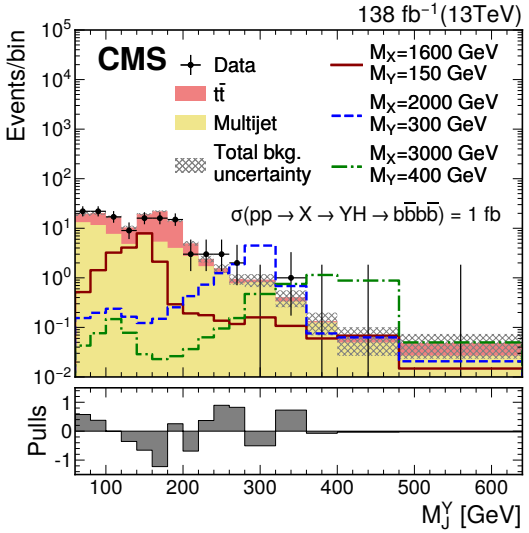


CMS provides more broad $Y \to Xh$ $(X \neq 125\text{GeV})$ searches in same $bbbb$, $bb\tau\tau$, $bb\gamma\gamma$ channels





Most recent $bbbb$ search uses the current bleeding edge ParticleNet tagging technology to identify boosted $h/X \to bb$ candidates

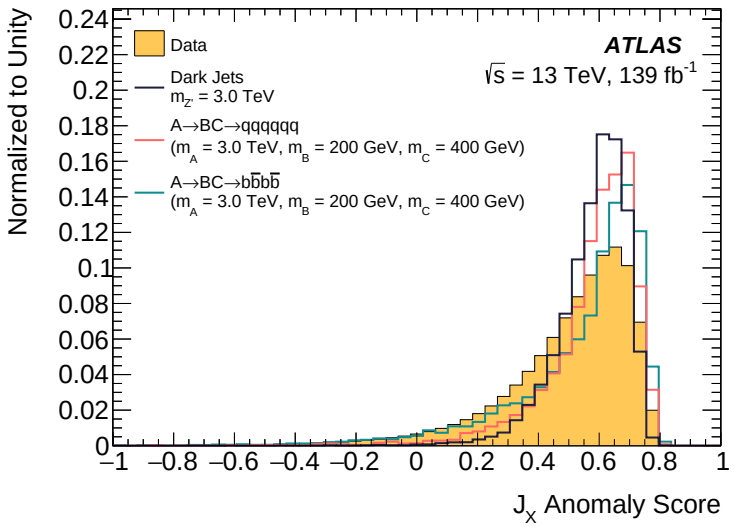


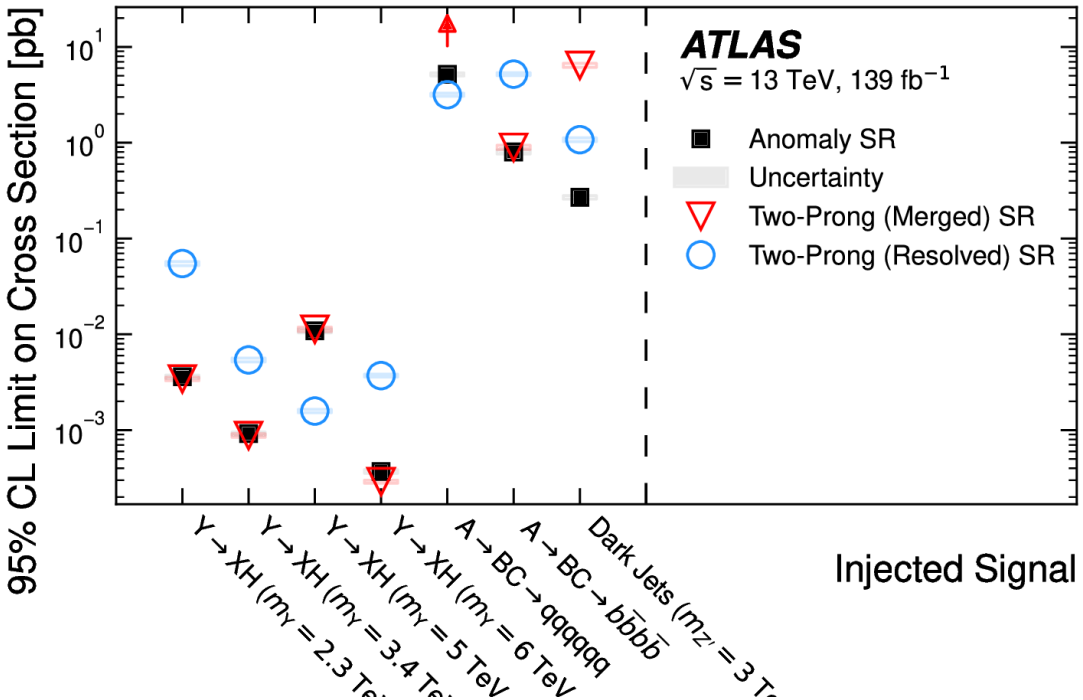
- Defined signal regions and control/validation region for QCD backgrounds
- ttbar background from simulation, corrected in lepton+jet region
- Limits on next-to-MSSM

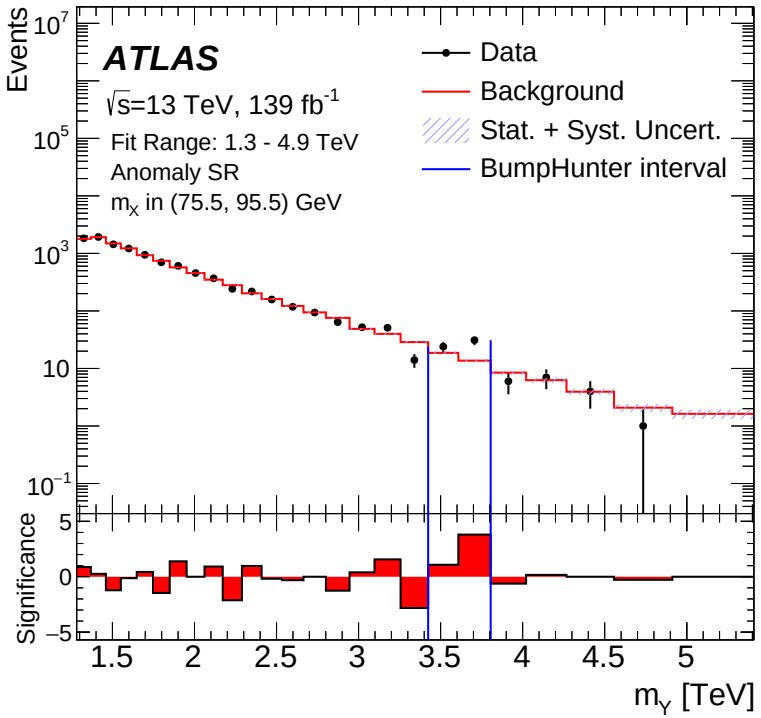
ATLAS published $Y \to XH \to qqbb$ search

Two approaches investigated:

- Cut-based regions defined on jet-substructure variables
- Anomaly detection machine-learning discriminant
  - More model independent strategy/limits





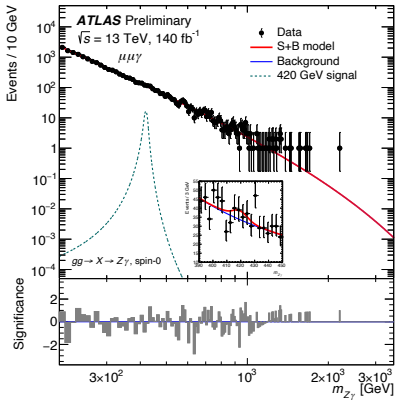


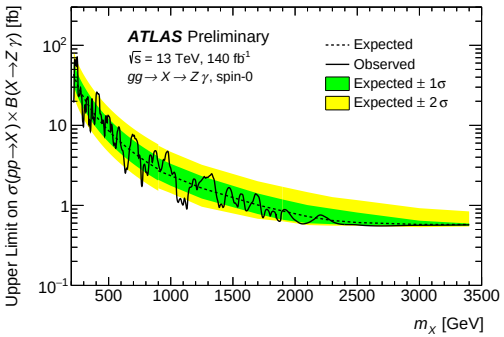
ATLAS search in $Z(\to \ell\ell)\gamma$:

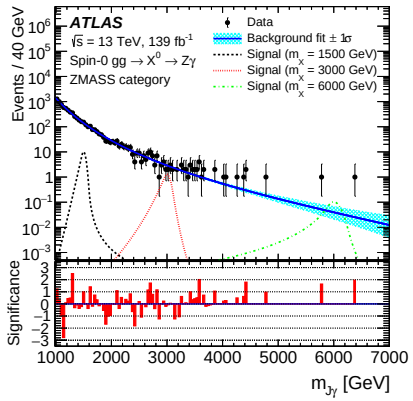
- Exploits very good lepton reconstruction of the Z
- Best mid-range limits in $X \in [300\ \mathrm{GeV}, 1\mathrm{TeV}]$

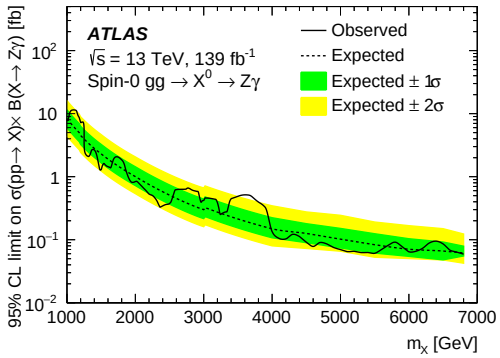
ATLAS search in $V(\to qq)\gamma$

- Relies on recent advances in hadronic boson tagging
- Strong high-mass limits





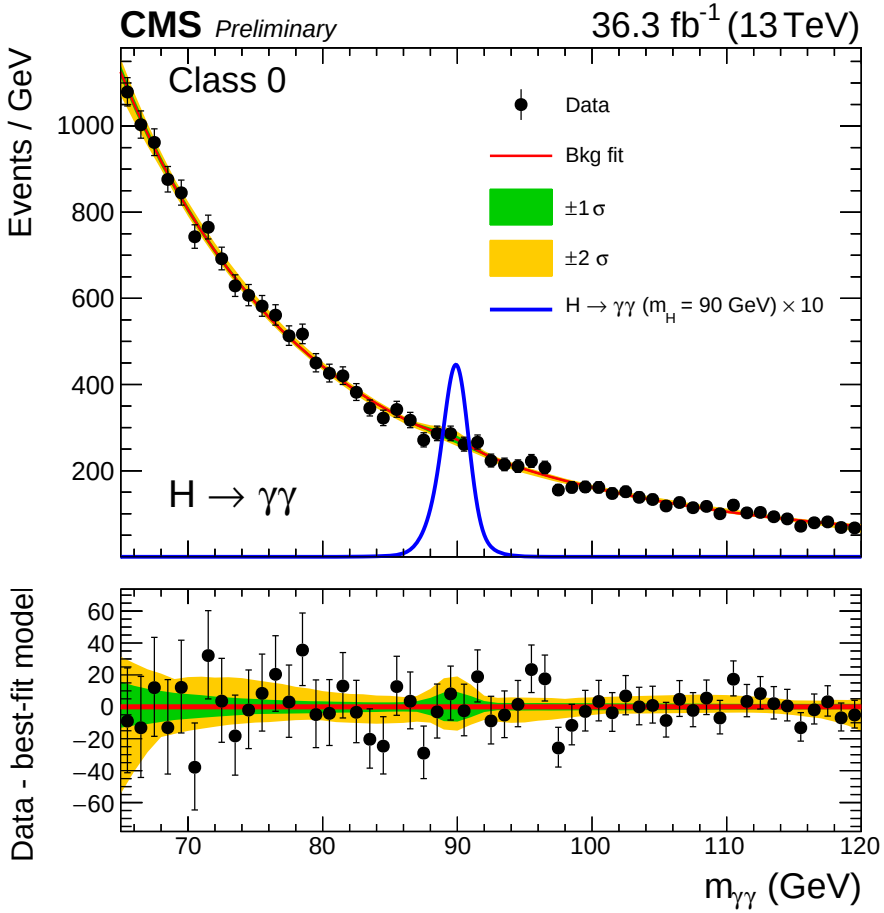


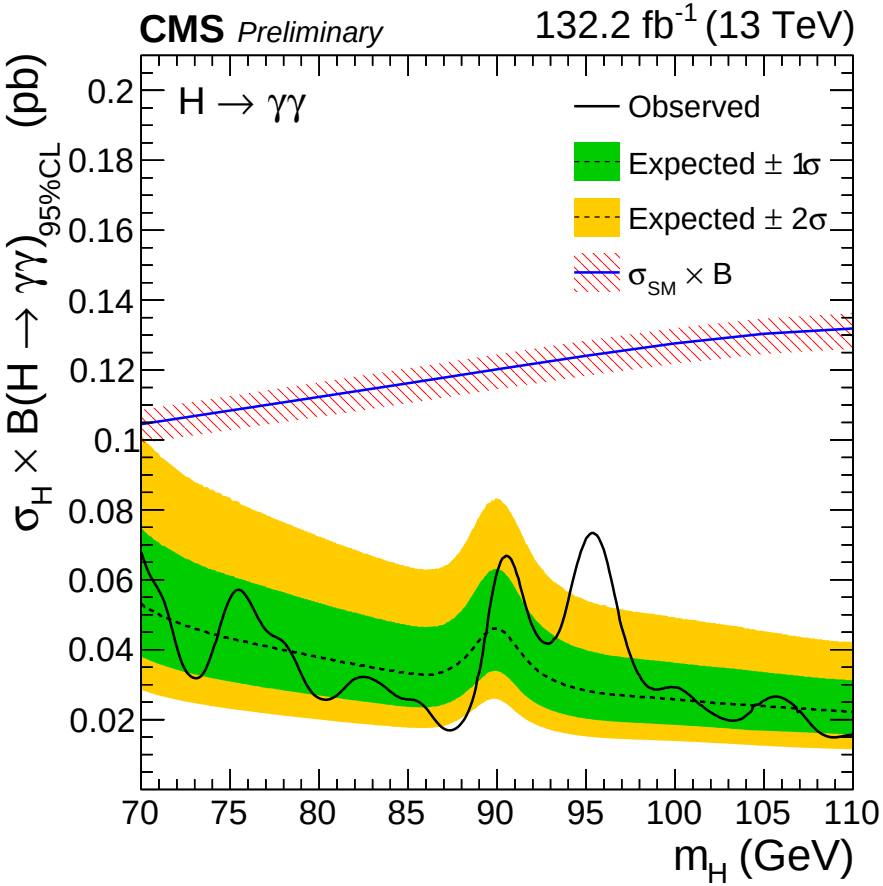


Also previous searches in CMS in $W\gamma$, $Z\gamma$ channels, and ATLAS $H(\to bb)\gamma$

All rely on data-driven function form estimates of the background and clear high-p_{T} photon identification+reconstruction+isolation

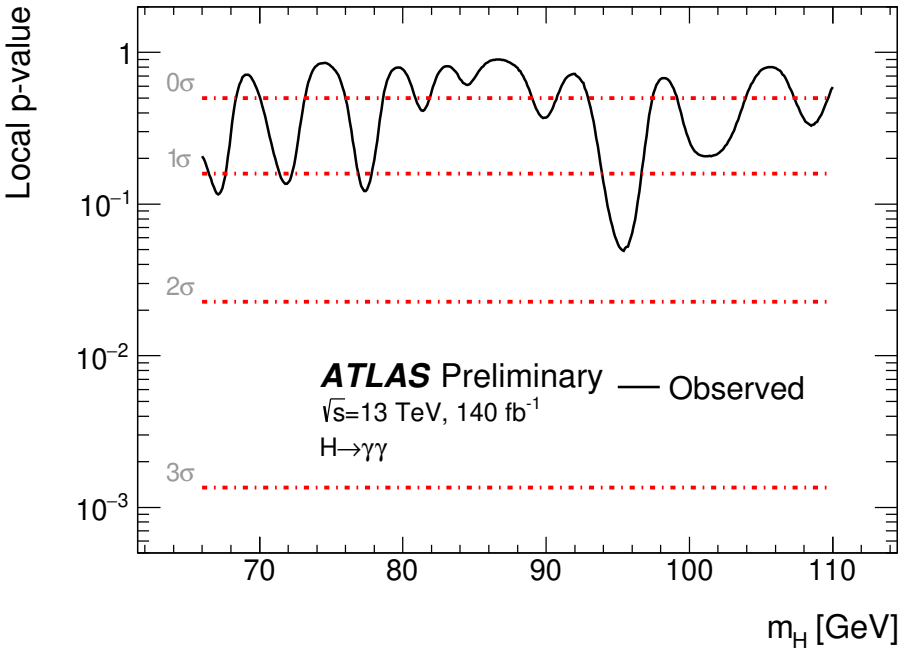
Recent CMS search for "low-mass" $[70, 100]\ \mathrm{GeV}$ extra Higgs-like particle decaying to photon pairs

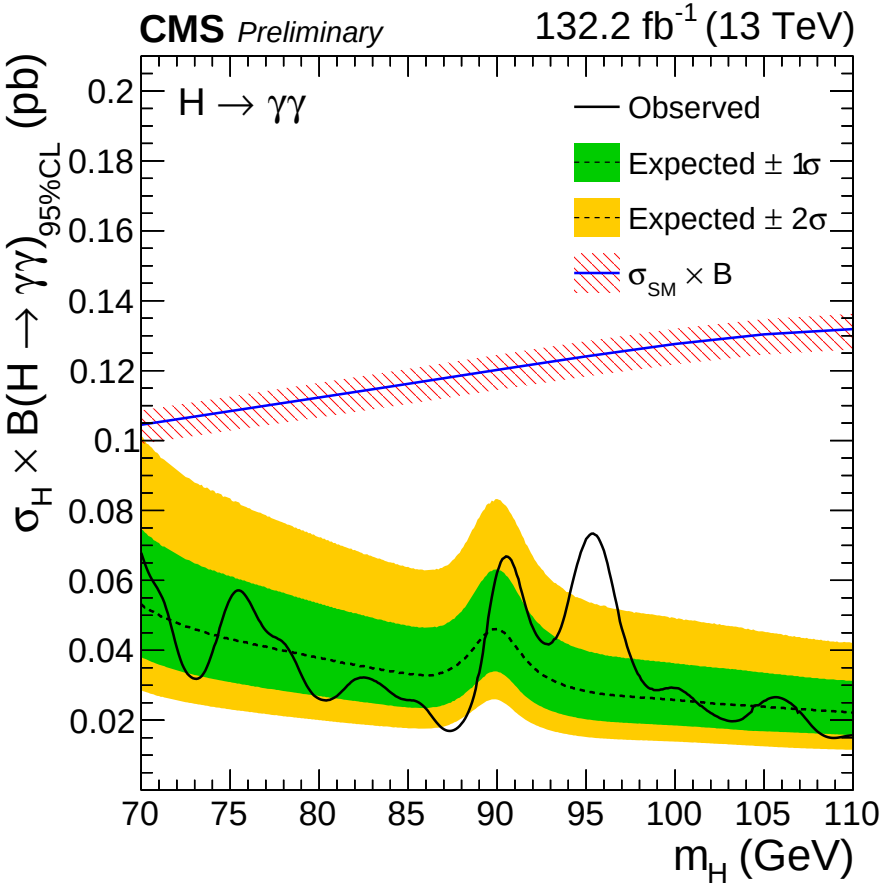




$\rightarrow 2.9\sigma(1.35\sigma)$ local(global) excess seen at $m = 95.4\mathrm{GeV}$ by CMS

Same analysis for "low-mass" diphoton resonances performed by ATLAS





$\rightarrow 2.9\sigma(1.35\sigma)$ local(global) excess seen at $m = 95.4\text{GeV}$ by CMS

$\rightarrow 1.7\sigma$ local excess seen at $m = 95.4\text{GeV}$ by ATLAS

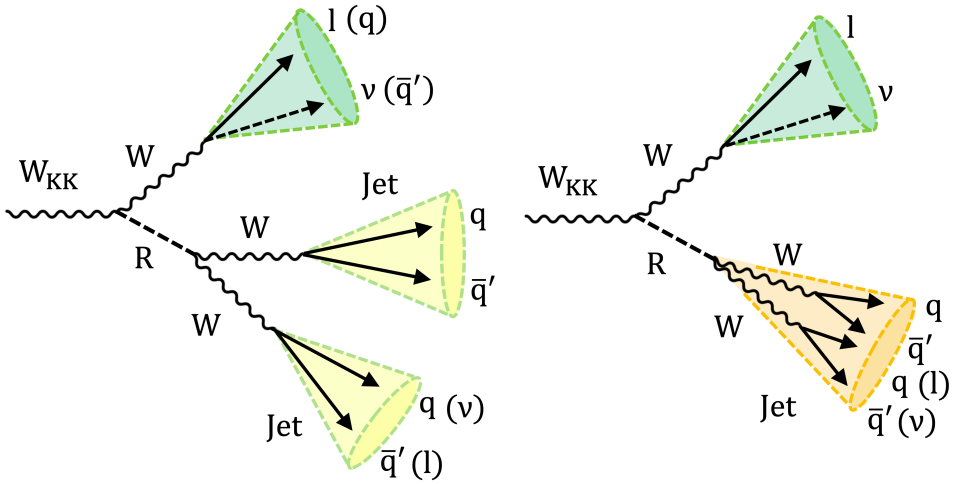
Limits on simple 2-body decays are being very tightly constrained

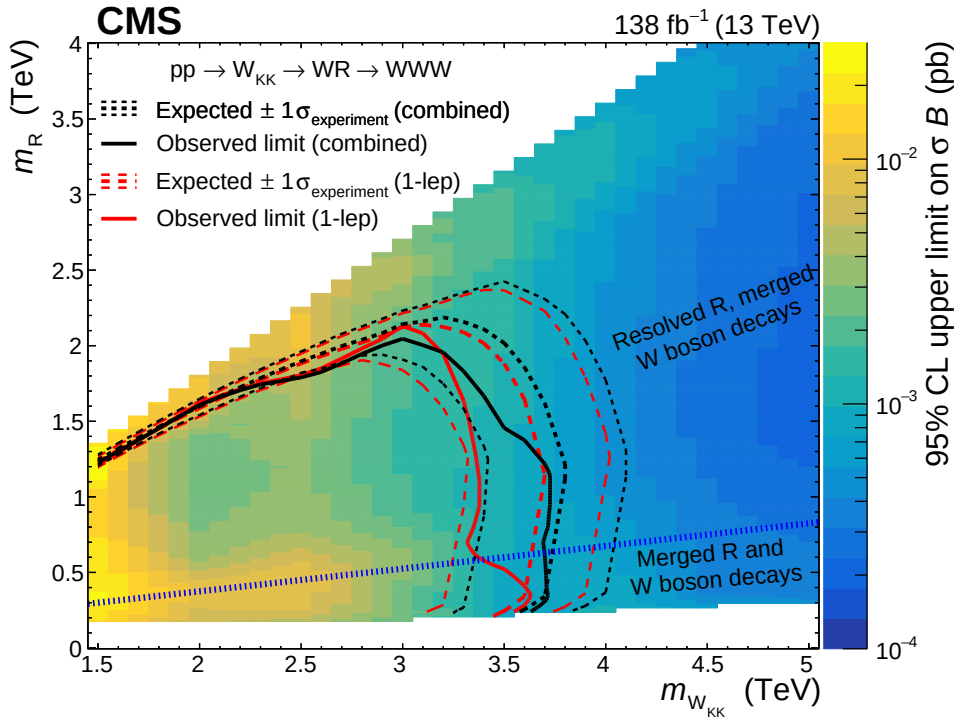
CMS searched for cascading WWW resonances

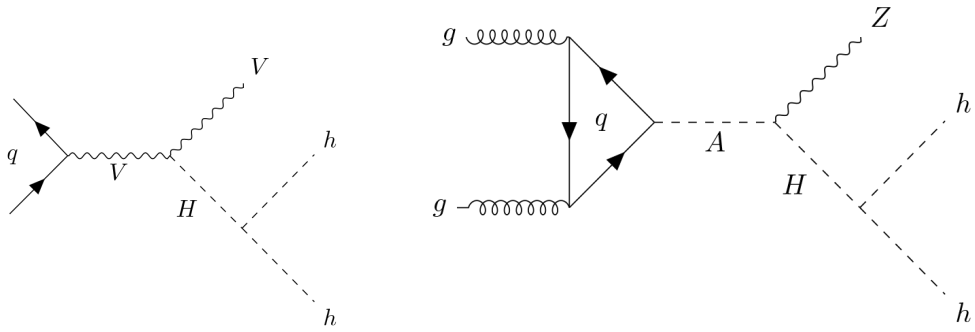
- Fully hadronic $qqqqqq$ final state
- Semi-leptonic $\ell\nu qqqq$ final state

Multiple jet-tagging based regions on $R = 0.8$ jets in the events

- One for identifying individual $W \to qq$
- One for identifying completely merged $WW \to qqqq$
  - Also include the possible contained $W \to \ell\nu$
- All done with central CMS DeepAK8 tagger

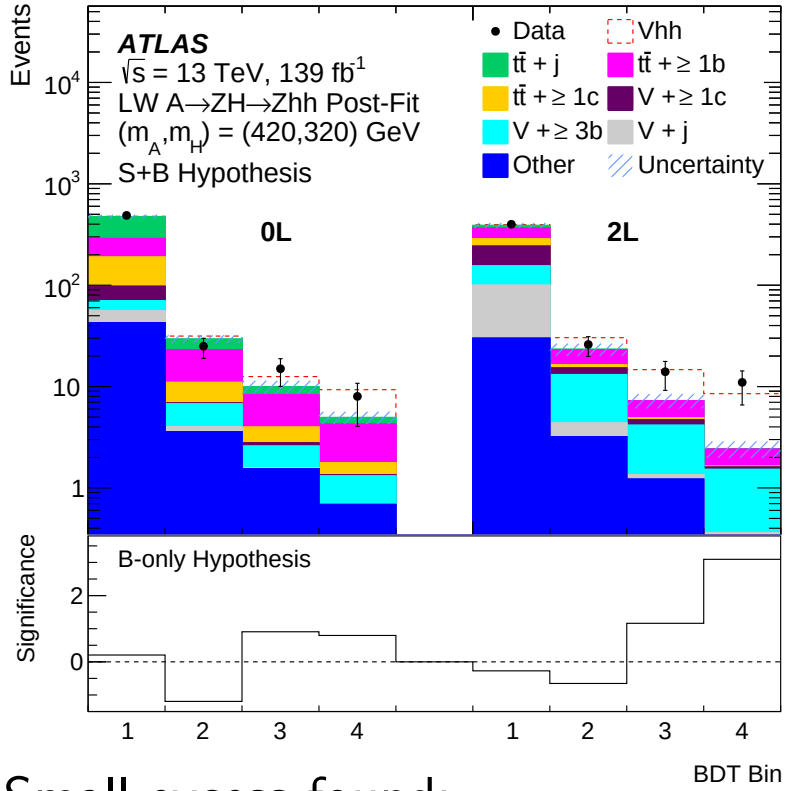


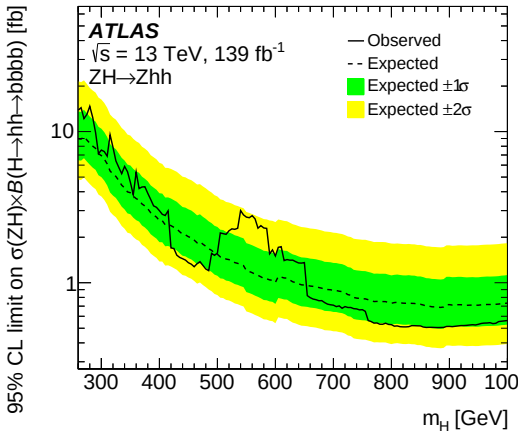


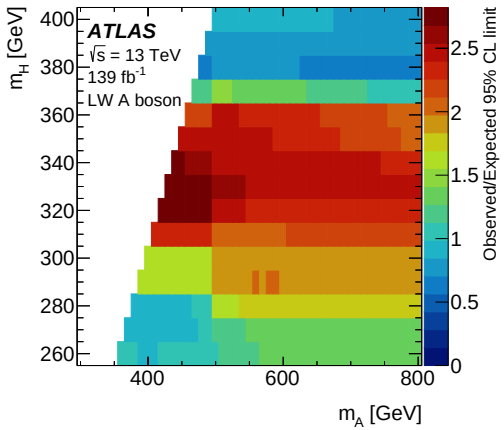


ATLAS BSM search for

- non-resonant Vhh with higgs-vertex modifications
- resonant H-strahlung: $VH \to Vhh$
- resonant 2HDM: $A \to VH \to Vhh$





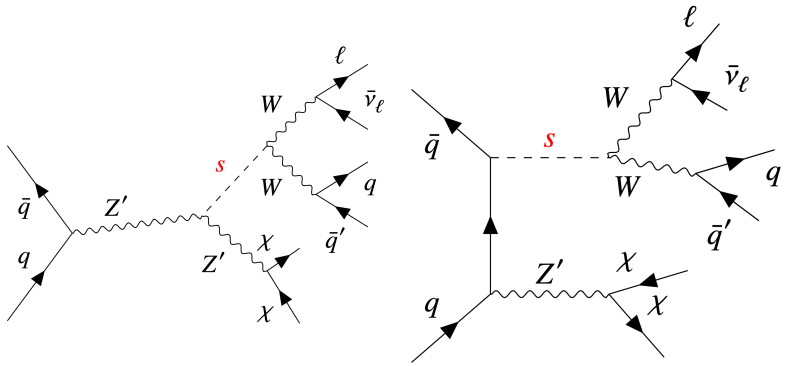


Small excess found:

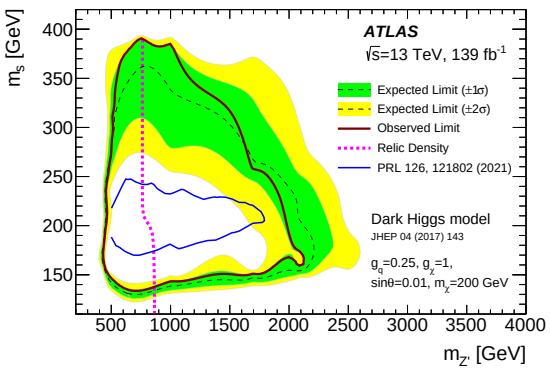
- ZH: Local (global) 2.7σ (1.4σ) @ $m(H) = 550$ GeV
- AZH:
  - Large-width: 3.8σ (3.0) @ $m(H)/m(A) = 320/420$ GeV
  - Narrow-width: 3.6σ (1.4) @ $m(H)/m(A) = 300/800$ GeV

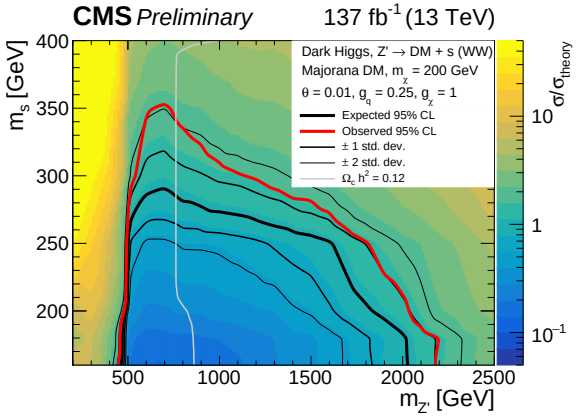
Many DM searches at LHC rely on the $E_{\mathrm{T,miss}} + X$ framework with WIMP-like particles recoiling again SM particles

- Also interest in two-mediator models with spin-1 Z' and scalar s
- $s \to VV$ dominates above $m > 160$ GeV



Both ATLAS and CMS have done searches in $VV + E_{\mathrm{T,miss}}$ signatures





- Dominant channels is $\ell\nu qq$
- Similar merged $WW \to qqqq$ categories as WWW searches
- Limits comparable and no excesses
- Rely on assumptions of DM mass and couplings

Summary

The LHC experiments have a very broad search programs for resonances with final state bosons

- Long history of di-$W/Z/h/\gamma$ searches
- Exploring more complex phase spaces with cascades of resonances

Many of these analysis utilize state-of-the-art reconstruction techniques

- Boosted $W/Z/h/t$-tagging is now commonplace
- Many advanced machine-learning techniques at play

LHC continues to tightly exclude heavy resonance

- EFTs provide framework to extend searches to tail effects of even heavier resonances
- ATLAS provided simultaneous fit of Higgs+EWK measurements with LEP precision data in SMEFT model
  - Some operators constrained more tightly with LHC then LEP