## Searches for Heavy Resonances Decaying to Bosons

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## Motivation

- Continued and mounting evidence pointing to the SM not being the complete theory  $% \left( {{{\rm{D}}_{{\rm{S}}}}_{{\rm{S}}}} \right)$ 
  - 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

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

- "General purpose" detectors: most decay models accessible

X

- High energy: many models predict TeV scale particles
- High luminosity: predicted cross-sections can be low

 $V/h/\gamma$ 

# CMS+ATLAS diboson resonance searches

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

- qqqq/qqbb
- $\ell \ell q q / \ell \ell b b$
- *ννqq*
- $\ell \nu q q / \ell \nu b b$
- $\ell \nu \ell \nu$

#### ATLAS has similar:

- *llbb/lvbb/vvbb*
- $\ell^{\pm}\nu\ell^{\pm}\nu + jj$
- $\ell \nu \ell \ell$
- $\ell \nu \ell \nu$
- $\ell\ell\ell\ell/\ell\ell\nu\nu$

- $-\ell^{\pm}\nu\ell^{\pm}\nu/\ell\nu\ell\ell+jj$
- -bbWW
- bbbb
- bb au au
- $bb\gamma\gamma$
- qqbb, qqqq
- $\ell \ell q q / \ell \nu q q / \nu \nu q q$
- 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



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### Boosted Boson Reconstruction

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

- When searching for new heavy resonance the boson  $p_{\rm T}$  often very high
- Opening angle of decay products  $\sim \frac{2m(V/h)}{n_T(V/h)}$ 
  - 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  $VV/Vh \rightarrow qqqq/qqbb$ 
  - Largest SM BR
  - Challenging background of multijet events
    - At very high- $p_{\mathrm{T}}$  this becomes small as well
- At high  $p_{\rm T}$  the boson decay products become increasingly collimated
  - Cluster each  $V\!/h$  as one large R=0.8 jet
  - CMS DeepAK8 tagger to separate  $W/Z/t/h/{
    m QCD}$  jets from each other
- Background extracted from simultaneous 3D fit of individual jet masses and dijet mass system
  - Some minor  $2.3\sigma$  excesses at  $2.1/2.9~{\rm TeV}$
  - Limits in benchmark models



# VV fully leptonic resonances

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 GeV < m(X) < 1 TeV

This analysis focused on VBF-produced signals

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







# Vh semileptonic resonances



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

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

Different reconstruction techniques for  $h \rightarrow bb$ 

- Two resolved  ${\cal R}=0.4~{\rm jets}$
- One large R = 1.0 jet

Results consistent with SM

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

# Heavy Resonance Combination

#### ATLAS-CONF-2022-028

- ATLAS published combination of all  $VV/Vh/\ell\bar{\ell}$  resonance searches
  - Check if local excesses coincide
  - Strongest limits
  - Limits directly on couplings of benchmark HVT model

#### CMS provides similar summary plots





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### Resonant *hh* Combination

#### ATLAS-CONF-2021-052

ATLAS performed similar combination of hh 
ightarrow bbbb, bb au au,  $bb\gamma\gamma$  searches

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





## $Y \to XH \to bbbb$

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  $h/X \rightarrow bb$ 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

#### HDBS-2019-23

√s = 13 TeV, 139 fb

0.6 0.8

# $Y \to XH \to qqbb$



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



Vormalized to Unity

0.22

0.2

0.18

0.16

0.14

0.12

0.0

0.06 0.04

0.02

Dark Jets

m. = 3.0 TeV

А→ВС→ЬБЪБ

-0.8 - 0.6 - 0.4 - 0.2

A→BC→aaaaaa

(m = 3.0 TeV, m\_ = 200 GeV, m\_ = 400 GeV)

(m = 3.0 TeV, m\_ = 200 GeV, m\_ = 400 GeV)

0.2

0.4

0

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

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

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

- 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  $H(\rightarrow bb)\gamma$ 

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



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HIG-20-002

### Low-mass diphoton Resonances HIG-20-002, ATLAS-CONF-2023-035

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 GeV by CMS  $\rightarrow 1.7\sigma$  local excess seen at m = 95.4 GeV by ATLAS

### Multiboson Resonances

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

CMS searched for cascading *WWW* resonances

- Fully hadronic qqqqqq final state
- Semi-leptonic  $\ell \nu q q q q$  final state
- Multiple jet-tagging based regions on R = 0.8 jets in the events
  - One for identifying individual  $W \to q q$
  - One for identifying completely merged  $WW \to qqqq$ 
    - Also include the possible contained  $W \rightarrow \ell \nu$
  - All done with central CMS DeepAK8 tagger



## Vhh Resonances

#### Eur. Phys. J. C 83 (2023) 519



ATLAS BSM search for

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





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## DM VV production

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

- Also interest in two-mediator models with spin-1  $Z^\prime$  and scalar s
- $s \rightarrow VV$  dominates above  $m > 160 {
  m ~GeV}$

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







- Dominant channels is  $\ell\nu qq$
- Similar merged
- $WW \rightarrow qqqq$  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

