# **Searches for resonances decaying to pairs of** heavy bosons in ATLAS



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For the ATLAS collaboration







- Diboson resonances with leptonic decays
  - <u>ATLAS-CONF-2022-066</u> <u>Eur. Phys. J. C 81 (2021) 332</u> <u>arXiv:2207.03925</u>
- Higgs and Vector boson tagging
- Higgs boson pairs
  - <u>Phys. Rev. D 106 (2022) 052001</u> <u>arXiv:2209.10910</u>
  - Phys. Rev. D 105 (2022) 092002 ATLAS-CONF-2021-052
- Vector boson + Higgs searches
  - <u>arXiv:2207.00230</u> <u>arXiv:2210.05415</u> <u>arXiv:2211.02617</u>
- Generic X searches with Z or Higgs
  - <u>arXiv:2209.15345</u> <u>ATLAS-CONF-2022-045</u>



### Introduction



- Many BSM models predict final states with SM bosons
- Analyses presented have heavy bosons in the final state
- When bosons decay hadronically jet reconstruction and boson tagging are key analysis ingredients
- Presented analyses use the full Run-2 dataset
- (Some) of the benchmark models used in the presented analyses are
  - Heavy Vector Triplet (HVT) and Randall-Sundrum Graviton
    - JHEP 09 (2014) 060 JHEP 01 (2013) 166 Phys. Rev. Lett. 83 (1999) 3370 Phys. Lett. B 473 (2000) 43
  - Georgi–Machacek Higgs <u>Nuclear Physics B 262 (1985) 463</u> Phys. Lett. B 165 (1985) 105
  - Radion <u>arXiv:1404.0102</u>
  - Narrow Width heavy Higgs <u>arXiv:1610.07922</u>
  - Large Width heavy Higgs <u>arXiv:1106.0034</u>
  - Twin Higgs models <u>JHEP 01 (2006) 126</u>
  - Two Higgs doublets and composite Higgs
    - JHEP 06 (2019) 066 Nucl. Phys. B853, 1 (2011) JHEP 06 (2011) 020 Phys. Rep. 516, 1 (2012)
  - MSSM Nucl. Phys. B193, 150 (1981) JHEP 10 (2013) 028 Eur. Phys. J. C 73, 2650 (2013)



### Diboson resonances with leptonic decays



# Search for Resonance (R), in the channel R $\rightarrow$ WW $\rightarrow$ $|\nu$ $|\nu$



#### ATLAS-CONF-2022-066

- Two Different Flavour, Opposite Sign Leptons, p<sub>T</sub> > 25 GeV
- Third lepton veto,  $p_T > 15 \text{ GeV}$
- B-jet veto
- Main Backgrounds: tt, Wt, WW

Model	Obs. limit [GeV]	Exp. limit $[GeV]$
Radion, ggF	1090	1190
Kaluza-Klein graviton, ggF	1340	1340
Kaluza-Klein graviton, VBF	500	500
HVT scenario A, qqA	2100	1890
HVT scenario B, qqA	2350	2130





# Search for $R \rightarrow ZZ \rightarrow 4I$ and $R \rightarrow ZZ \rightarrow II \nu \nu$



- Improvements in full Run2 analysis
  - Mass range, Particle Flow, ...
- Combination of the 2 final states
- Cross-section limits in several interpretations:
  - NWA heavy Higgs with ggF+VBF, also translated to 2HDM contours
  - LWA heavy Higgs including interference modelling
  - Randall-Sundrum Graviton





Eur. Phys. J. C 81 (2021) 332







# Search for WZ $\rightarrow$ $l\nu$ ll

[dd] (ZW

 $\sigma \times B(W)$ 

10-

 $10^{-2}$ 

ATLAS

 $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$ 

**Drell-Yan SR** 



Obs. 95% CL upper limi

Exp. 95% CL upper limit

Expected limit  $(\pm 1\sigma)$ 

Expected limit  $(\pm 2\sigma)$ HVT Model A, g = 1

HVT Model B, g, = 3

- Main selection:
  - 3 high  $p_T$  leptons
  - Missing transverse energy
  - 2 jets (in case of VBF production mode)
- Signal regions: cut based and ANN
- Resonance benchmark model:
  - Heavy Vector Triplets model
  - Georgi Machacek (GM) Higgs Triplet Model





## Jets techniques



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- Hadronic decays of a boson reconstructed as
  - Two resolved R=0.4 anti- $k_{T}$  jets
  - Single large R=1 jet (for bosons with a large boost the jets merge)
- Use of Particle Flow and Track Calo Cluster (TCC) •
  - Eur. Phys. J. C 77 (2017) 466, ATL-PHYS-PUB-2017-015
- Combined in Unified Flow Objects (UFO) for best performance
  - Eur. Phys. J. C 81 (2021) 334

- **B-tagging** used to identify b-quarks
- Applied to jets and variable radius track jets matched to large R jets
- High level algorithms based on MV2 and DL1

ATLAS Simulation



# **INFN** Tag W/Z boson dijet boson decays

- Boson tagging with R=1 jets and jet substructure variables
- Standard tagger uses calorimeter cluster jets
- TCC jets tagger cuts on 2 variables optimized in each  $p_T$  bin
  - Jet mass, D<sub>2</sub> two prong substructure
  - Efficiency and background rejection calibrated on 80 fb<sup>-1</sup> data

- On going development of UFO jets tagger
- UFO tagger uses NN or 3 variables cuts on
  - Jet mass
  - D<sub>2</sub> two prong substructure
  - number of ID tracks







Tagging Higgs  $\rightarrow$  bb decays



ATL-PHYS-PUB-2021-035

- Xbb tagger distinguish boosted Higgs boson bb decays from QCD jets and top quarks
- Combines flavor discriminants from up to three subjets using a feed-forward neural network
- Tag large R=1 jets





### Higgs boson pairs

Run: 329964 Event: 796155578 2017-07-17 23:58:15 CEST

HEP 2023



## Searches for resonances decaying to Higgs boson pairs



 $HH \rightarrow b\bar{b} \tau^+\tau^-$ 

### $HH \rightarrow b\bar{b} \gamma\gamma$

• Selection

05200

(2022)

106

- 2 tight, isolated photons
- ≥2 jets : p<sub>T</sub>>25 GeV, b-tagging
- Fit of the  $m_{\gamma\gamma}$ 
  - for every  $m(b\overline{b}\gamma\gamma)$  mass point





- Require 2 b-jets and 2 OS au leptons
- Final state  $\tau_{\rm lep} \tau_{\rm had}$  and  $\tau_{\rm had} \tau_{\rm had}$
- Backgrounds: tt, single top, V+jets, diboson, SM Higgs



m<sub>X</sub> [GeV] HEP 2023

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## Higgs pair production in **bbbb** channel and combination



- -MS-Rev. D. 105-100220002  $b\overline{b}$   $b\overline{b}$  is the channel with largest BR for HH (34%)
  - Resolved channel (4 b-jets):
    - Machine learning-based jet pairing algorithm
    - Neural network-based background reweighting
  - Boosted channel (2 large-R jets):
    - Variable radius track jets
    - Extended resonance mass range (to 5 TeV) •



## Higgs pair production in **bbbb** channel and combination



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#### ATLAS-CONF-2021-052

#### Combination of $b\overline{b} \ b\overline{b} + b\overline{b} \ \tau\tau + b\overline{b} \ \gamma\gamma$

The largest excess is at  $m_x = 1.1$  TeV local (global) significance of  $3.2\sigma$  ( $2.1\sigma$ ).



# <sup>*p*</sup> Vector boson + Higgs searches and Generic X searches with Z or Higgs



Run: 349309 Event: 769175011 2018-05-01 07:57:22 CEST



# Search for new resonances decaying into W/Z + Higgs

arXiv:2207.00230



95% CL limit

**Observed limit** 

Expected limit

Expected ±1 s.d.

Expected ±2 s.d.

Expected limit (0L)

Expected limit (2L)

1600

 $\rightarrow$  Zh,  $h \rightarrow b\overline{b} \cos(\beta \cdot \alpha) = 0.1$ 

±2 s.d. Excluded

1800 2000 m, [GeV]

1400

2HDM Type II

±1 s.d.

ATLAS

400

600

ATLAS

139 fb<sup>-</sup>

400

600

800

1000

16

1200

m<sub>A</sub> [GeV]

1400

√s = 13 TeV

 $10^{2}$ 

< 10

ര(gg

 $10^{-2}$ 

 $10^{-}$ 

 $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$ 

aaA combined (0L+2L) lim

- pp $\rightarrow$ W'/Z' $\rightarrow$ W/Z+h (W/Z $\rightarrow$  I $\nu$ /II/ $\nu\nu$  h $\rightarrow$ bb)
- pp $\rightarrow$ A(+bb) $\rightarrow$ Z+h (Z $\rightarrow$  II/ $\nu\nu$  h $\rightarrow$ bb)
- H identified with 1 or 2 b-tags
  - in resolved or merged jets channels
- W/Z channels with 0,1,2 (charged) lepton
- Limits extracted from fits of  $m_{T,Vh}$  and  $m_{Vh}$  discriminants
- Interpreted as HVT, 2HDM models.







# Search for heavy Higgs boson

INFN





## Search for Z+X and $Y \rightarrow Z+X$



• Select high- $p_T Z \rightarrow II (p_T > 100 \text{ GeV})$ ATLAS Background fit √s = 13 TeV, 139 fb • Use 6 "lead" categories for X: small-R, large-R jets, b-jet, e,  $\mu$ ,  $\gamma$ BumpHunter interval  $Z \rightarrow \ell \ell$ , Le · dJ **= 1 TeV,** σ/**m = 3%** 10<sup>5</sup> m<sub>Gaus</sub> = 2 TeV, σ/m = 5% • X candidate formed with all reconstructed objects (except the Z) m<sub>Gaus</sub> = 3 TeV, σ/m = 10% 10<sup>3</sup> p-value: 0.69 Signals: model-independent gaussian-shaped and HVT  $10^{2}$ • Search for local excesses in m<sub>x</sub> and m<sub>zx</sub> spectra iet2 lepton: fat jet lepton2 • HVT upper limits with topology:  $W' \rightarrow ZW \rightarrow IIqq$ Beamline Beamline Beamline PV Z boson Z boson Z boson model-independent gaussian signals 2500 3000 3500 4000 [dd] m<sub>v</sub> [GeV] [dd] - Observed 95% CL - Observed 95% CL [dd] ATLAS ATLAS ATLAS A Observed ----- Expected 95% CL \_√s = 13 TeV, 139 fb<sup>-1</sup>  $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$ ----- Expected 95% CL × 10<sup>-1</sup> Х  $10 = \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$ ----- Expected 15345 Expected  $\pm 1 \sigma$  $Z \rightarrow \ell \ell$ , inclusive  $\Omega_{10^{-1}} \models Z \rightarrow \ell \ell$ , inclusive Expected  $\pm 1 \sigma$ m Expected  $\pm 1 \sigma$  $Z \rightarrow \ell \ell$ , Le-dF-tJ Expected  $\pm 2 \sigma$ Gaussian,  $\sigma/m = 3 \%$ Expected  $\pm 2 \sigma$ Gaussian,  $\sigma/m = 3 \%$ Х Х Expected  $\pm 2 \sigma$ HVT ь ь HVT Model A,  $g_{i} = 1$ 10-2 ≥ HVT Model B, g<sub>v</sub> = 3 d d b 10<sup>-1</sup>  $10^{-3}$  $10^{-3}$  $10^{-2}$  $10^{-4}$ 10<sup>-4</sup> 10 2000 4000 6000 2000 3000 4000 5000 2000 1000 4000 5000 3000 m<sub>zv</sub> [GeV] m<sub>v</sub> [GeV] m<sub>zx</sub> [GeV] 19 HEP 2023



# Search for resonances in the channel Y $\rightarrow$ X+Higgs $\rightarrow$ qq bb

HEP 2023



ATLAS-CONF-2022-045

- At High Y mass (~1-6TeV ), Y Reconstructed with two large-R jets
- Additional resolved region defined for less boosted X
  - X reconstructed with two small-R jets
- H Candidate identified using the Xbb tagger



- Model-independent discovery region
  - Use fully unsupervised variational recurrent neural network to tag X resonance
- HVT signal used as benchmark
- The most significant excess has a global significance of 1.47 σ.





Summary



		ATLAS Dibosor Status: June 2021	n Searches	- 95% CL E	xclusion	Limit	6		£ = (36.1 – 1	39) fb <sup>-1</sup>	<b>ATLAS</b> Prelimin $\sqrt{s} = 13$ T	iary eV
	Model	Channel <sup>†</sup>	Strategy*		Limit				- (	,	Reference	(
Extra dimensions	Bulk RS ( $k\pi r_c = 35$ , $\Lambda_R = 3$ TeV)	$R \rightarrow WW, ZZ \rightarrow \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted		I	I	I		0.3-3.2 TeV		Eur. Phys. J. C 80 (2020)	) 1165
	Bulk RS ( $k\pi r_c = 35$ , $\Lambda_R = 3$ TeV)	$R \rightarrow WW, ZZ \rightarrow qqqq$	boosted						1.3-3.0 TeV		JHEP 06 (2020) 04	2
	RS1 $(k/\overline{M}_{Pl} = 0.01)$	$G_{KK}  ightarrow \gamma\gamma$	resolved					0.5-2.2	TeV		arXiv:2102.13405	
	RS1 $(k/\overline{M}_{Pl} = 0.05)$	$G_{KK}  ightarrow \gamma\gamma$	resolved						0.5-3.9	TeV	arXiv:2102.13405	
	RS1 ( $k/\overline{M}_{Pl} = 0.1$ )	$G_{KK}  ightarrow \gamma\gamma$	resolved						(	).5-4.5 TeV	arXiv:2102.13405	
	Bulk RS ( $k/\overline{M}_{Pl} = 0.5$ )	$G_{KK} \rightarrow WW \rightarrow ev\mu v$	resolved			0.2-0.75 T	εV				Eur. Phys. J. C 78 (201	8) 24
	Bulk RS ( $k/\overline{M}_{Pl} = 1.0$ )	$G_{KK} \rightarrow ZZ \rightarrow \ell \ell \ell \ell' \ell', \nu \nu \ell \ell$	resolved					0.6-1.75 TeV			Eur. Phys. J. C 81 (2021	) 332
	Bulk RS ( $k/\overline{M}_{Pl} = 1.0$ )	$G_{KK} \rightarrow WW \rightarrow ev\mu v$	resolved				0.2-1.1	TeV			Eur. Phys. J. C 78 (201	8) 24
	Bulk RS ( $k/\overline{M}_{Pl} = 1.0$ )	$G_{KK} \rightarrow WW, ZZ \rightarrow \nu \nu q q, \ell \nu q q, \ell \ell q q$	resolved, boosted					0.3-2.0 Te\	2		Eur. Phys. J. C 80 (2020)	) 1165
	Bulk RS ( $k/\overline{M}_{Pl} = 1.0$ )	$G_{KK}  ightarrow WW, ZZ  ightarrow qqqq$	boosted					1.3-1.8 TeV			JHEP 06 (2020) 042	2
	HVT ( $g_F = -0.55, g_H = -0.56$ )	$W' \to WZ \to \ell \nu \ell' \ell'$	resolved					0.25-2.2	6 TeV		Phys. Lett. B 787 (2018	3) 68
	HVT ( $g_F = -0.55, g_H = -0.56$ )	$W' \to WZ \to \nu \nu q q, \ell \nu q q, \ell \ell q q$	resolved, boosted					_	0.3-3.9	TeV	Eur. Phys. J. C 80 (2020)	) 1165
	HVT ( $g_F = -0.55, g_H = -0.56$ )	$W' \to WH \to \ell \nu bb$	resolved, boosted						0.4-2.95 TeV		ATLAS-CONF-2021-0	026
	HVT ( $g_F = -0.55, g_H = -0.56$ )	W'  ightarrow WZ  ightarrow qqqq	boosted						1.3-3.4 TeV	I	JHEP 06 (2020) 042	2
	HVT ( $g_F = -0.55, g_H = -0.56$ )	W'  ightarrow WH  ightarrow qqbb	boosted						1.5-2.9 TeV		Phys. Rev. D 102 (2020)	112008
	HVT ( $g_F = -0.55, g_H = -0.56$ )	$Z' \to WW \to e \nu \mu \nu$	resolved					0.2-1.3 TeV			Eur. Phys. J. C 78 (201	8) 24
	HVT ( $g_F = -0.55, g_H = -0.56$ )	$Z' \to WW \to \ell \nu q q$	resolved, boosted					_	0.3-3.5 TeV	1	Eur. Phys. J. C 80 (2020)	) 1165
	HVT ( $g_F = -0.55, g_H = -0.56$ )	$Z' \to ZH \to \nu\nu bb, \ell\ell bb$	resolved, boosted					_	0.3-2.9 TeV		ATLAS-CONF-2020-0	043
suos	HVT ( $g_F = -0.55, g_H = -0.56$ )	$Z' \rightarrow WW \rightarrow qqqq$	boosted						1.3-2.9 TeV		JHEP 06 (2020) 043	2
po;	HVT ( $g_F = -0.55, g_H = -0.56$ )	Z'  ightarrow ZH  ightarrow qqbb	boosted					1.5-2.2	TeV		Phys. Rev. D 102 (2020)	112008
agu	HVT ( $g_F = 0.14, g_H = -2.9$ )	$W' \to WZ \to \ell \nu \ell' \ell'$	resolved					0.8-	2.46 TeV		Phys. Lett. B 787 (2018	3) 68
Ga	HVT ( $g_F = 0.14, g_H = -2.9$ )	$W' \to WZ \to \nu \nu q q, \ell \nu q q, \ell \ell q q$	resolved, boosted					-	0.8	8-4.3 TeV	Eur. Phys. J. C 80 (2020)	) 1165
	HVT ( $g_F = 0.14, g_H = -2.9$ )	$W' \to WH \to \ell \nu bb$	resolved, boosted						0.8-3.15 TeV		ATLAS-CONF-2021-0	026
	HVT ( $g_F = 0.14, g_H = -2.9$ )	W'  ightarrow WZ  ightarrow qqqq	boosted						1.3-3.6 Te	V	JHEP 06 (2020) 043	2
	HVT ( $g_F = 0.14, g_H = -2.9$ )	W'  ightarrow WH  ightarrow qqbb	boosted						1.5-3.2 TeV		Phys. Rev. D 102 (2020)	112008
	HVT ( $g_F = 0.14, g_H = -2.9$ )	$Z' \to WW \to \ell \nu q q$	resolved, boosted						0.8-3.9	TeV	Eur. Phys. J. C 80 (2020)	) 1165
	HVT ( $g_F = 0.14, g_H = -2.9$ )	$Z' \to ZH \to \nu\nu bb, \ell\ell bb$	resolved, boosted						0.8-3.2 TeV		ATLAS-CONF-2020-0	943
	HVT ( $g_F = 0.14, g_H = -2.9$ )	$Z' \rightarrow WW \rightarrow qqqq$	boosted						1.3-3.1 TeV		JHEP 06 (2020) 04	2
	HVT ( $g_F = 0.14, g_H = -2.9$ )	Z'  ightarrow ZH  ightarrow qqbb	boosted		1				.5-2.65 TeV	1	Phys. Rev. D 102 (2020)	112008
				0.2	0.4	0.6	0.8	1	2 3	4 !	5	
$\sqrt{s} = 13 \text{ TeV}$ Excluded mass range [TeV]												

 Reviewed many ATLAS Run-2 searches with boson final states

- Jet reconstruction and boson tagging are essential
  - Several improvements developed and included in analyses
- Further developments on going for Run-3



<sup>†</sup>with  $\ell = \mu$ , e

\*small-radius (large-radius) jets are used in resolved (boosted) events

**ATL-PHYS-PUB-2021-018** 

# Thanks for your attention



# Combination of searches for resonant Higgs pair production



ATLAS-CONF-2021-052

- Combination of  $b\overline{b} \ b\overline{b} + b\overline{b} \ \tau\tau + b\overline{b} \ \gamma\gamma$
- The largest excess is at  $m_X = 1.1 \text{ TeV}$ 
  - local (global) significance of  $3.2\sigma$  ( $2.1\sigma$ ).



	$b\overline{b}\gamma\gamma$	$b\overline{b} au^+ au^-$	$b\overline{b}b\overline{b}$ resolved (boosted)
$\mathcal{B}(HH \to x\bar{x}y\bar{y})$	$2.6 \cdot 10^{-3}$	0.073	0.339
$\mathcal{L}_{int} \ [fb^{-1}]$	139	139	126 (139)
Discriminant	$m_{\gamma\gamma}$	MVA outputs	m <sub>HH</sub>
Resonance mass $(m_X)$ range [GeV]	251-1000	251-1600	251-1500 (900-3000)



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## Search for resonant Higgs pair production in bb bb channel



#### • Resolved channel (4 b-jets):

- Machine learning-based jet pairing algorithm
- Neural network-based background reweighting
- Boosted channel (2 large-R jets):
  - Variable radius track jets
  - Extended resonance mass range (to 5 TeV)

#### Phys. Rev. D 105 (2022) 092002

- Channel with largest BR for HH (34%)
- Backgrounds QCD multi-jet and ttbar
- Both channels use 3 regions in the Higgs candidate mass plane to extrapolate background in signal region with uncertainty

