

# ATLAS searches for high-mass resonances decaying to pair of bosons

**Kirill Grevtsov**

on behalf of the ATLAS Collaboration



ICHEP2018, Seoul

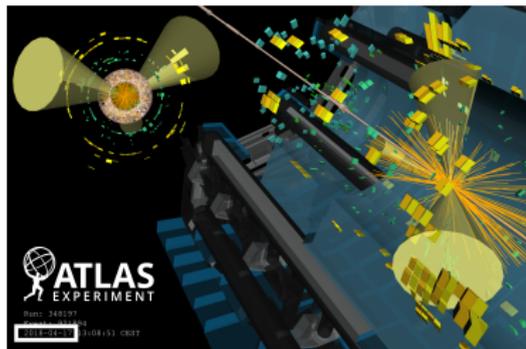
July 5, 2018



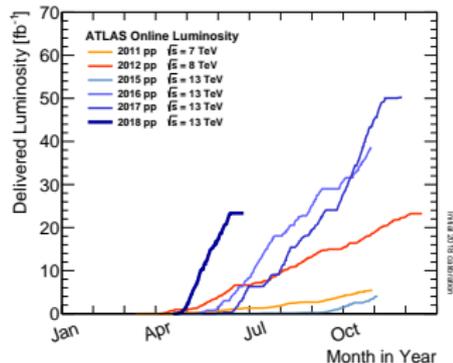
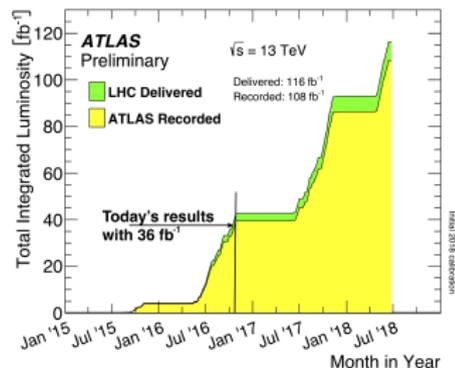
# Searches for heavy resonances in Run-2

## Highlights

- Increased center of mass energy to 13 TeV
- Excellent performance of LHC and ATLAS:
  - ▶ High data-taking efficiency >90%
  - ▶ Collected over  $100 \text{ fb}^{-1}$
- Today present analyses with  $36 \text{ fb}^{-1}$



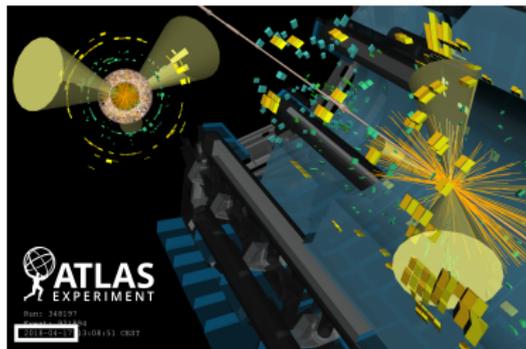
First event display in 2018!



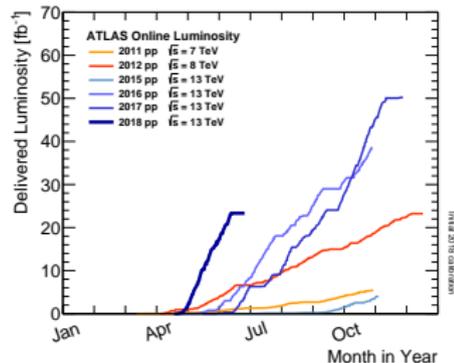
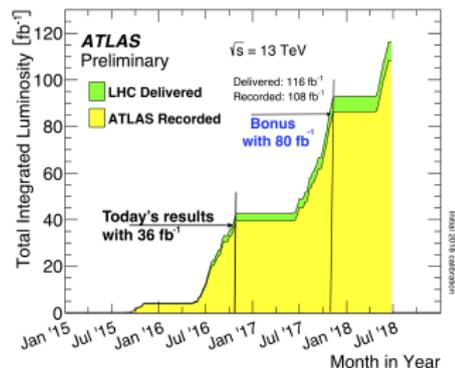
# Searches for heavy resonances in Run-2

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- Excellent performance of LHC and ATLAS:
  - ▶ High data-taking efficiency >90%
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- Today present analyses with  $36 \text{ fb}^{-1}$
- And new results with  $80 \text{ fb}^{-1}$



First event display in 2018!

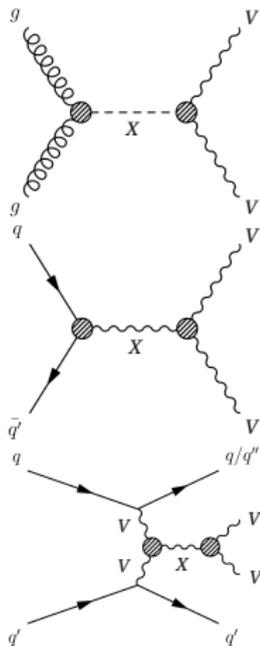


# Searches for heavy resonances

## Motivations

Several BSM models predict the existence of new heavy particles decaying into pairs of gauge bosons, with different:

- spin hypotheses
  - ▶ Spin-0: Two Higgs Doublet model (2HDM)  
Georgi-Machacek model (GM)
  - ▶ Spin-1: Heavy vector triplet (HVT)
  - ▶ Spin-2: Kaluza-Klein gravitons (bulk RS)  
Effective Lagrangian model (ELM)
- resonance width assumptions:
  - ▶ Narrow Width Approximation (NWA)
  - ▶ Large width (LWA)
- production mechanisms
  - ▶ Gluon-gluon fusion ( $ggF$ )
  - ▶ Quark-antiquark annihilation ( $q\bar{q}A$ )
  - ▶ Vector-boson fusion (VBF)



# Searches for heavy resonances with ATLAS detector

In Run-2 with  $36 \text{ fb}^{-1}$  and  $80 \text{ fb}^{-1}$

## ■ Large variety of diboson final states

### ▶ Massive bosons:

- $WW \rightarrow e\nu\mu\nu$
- $ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$  and  $\ell^+\ell^-\nu\bar{\nu}$
- $ZZ/ZW \rightarrow \ell^+\ell^-\text{q}\bar{\text{q}}$  and  $\nu\bar{\nu}\text{q}\bar{\text{q}}$  :
- $WW/WZ \rightarrow \ell\nu\text{qq}$
- $WW/WZ/ZZ \rightarrow \text{qqqq}$
- $WZ \ell\nu\ell\ell$
- $VH \rightarrow \nu\bar{\nu}b\bar{b}, \ell^\pm\nu b\bar{b}, \ell^+\ell^-b\bar{b}$
- $VH \rightarrow \text{q}\bar{\text{q}}'b\bar{b}$

[Eur.Phys.J. C78 \(2018\) 24](#)

[Eur.Phys.J. C78 \(2018\) 293](#)

[JHEP 03 \(2018\) 009](#)

[JHEP 03 \(2018\) 042](#)

[ATLAS-CONF-2018-016](#) **NEW!  $80 \text{ fb}^{-1}$**

[arXiv:1806.01532](#)

[JHEP 03 \(2018\) 174](#)

[Phys. Lett. B 774 \(2017\) 494](#)

### ▶ With photon:

- $\gamma$  and hadronically decaying  $Z/W/H$
- $Z\gamma$  with  $Z \rightarrow \ell\ell$
- $\gamma\gamma$

[arXiv:1805.01908](#) **NEW!**

[JHEP 10 \(2017\) 112](#)

[Phys.Lett.B 775 \(2017\) 105](#)

# Searches for heavy resonances with ATLAS detector

In Run-2 with  $36 \text{ fb}^{-1}$  and  $80 \text{ fb}^{-1}$

## ■ Large variety of diboson final states

### ▶ Massive bosons:

- $WW \rightarrow e\nu\mu\nu$
- $ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$  and  $\ell^+\ell^-\nu\bar{\nu}$
- $ZZ/ZW \rightarrow \ell^+\ell^-q\bar{q}$  and  $\nu\bar{\nu}q\bar{q}$  :
- $WW/WZ \rightarrow \ell\nu qq$

•  $WW/WZ/ZZ \rightarrow qqqq$

- $WZ \ell\nu\ell\ell$
- $VH \rightarrow \nu\bar{\nu}b\bar{b}, \ell^\pm\nu b\bar{b}, \ell^+\ell^-b\bar{b}$
- $VH \rightarrow q\bar{q}'b\bar{b}$

### ▶ With photon:

•  $\gamma$  and hadronically decaying  $Z/W/H$

- $Z\gamma$  with  $Z \rightarrow \ell\ell$
- $\gamma\gamma$

• low-mass  $\gamma\gamma$

Eur.Phys.J. C78 (2018) 24

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**VV+VH comb by S.Willocq**

arXiv:1805.01908 **NEW!**

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ATLAS-CONF-2018-025 **NEW!  $80 \text{ fb}^{-1}$**

## ■ Focus of today's presentation:

- ▶ analysis strategies
- ▶ search results and interpretations in terms of benchmark models

### Event selections:

#### ▶ Signal regions:

- Two VBF:  $N_{\text{jet}}=1 / \geq 2$  jets
- One  $ggF/q\bar{q}A$  region excluding VBF phase space

#### ▶ Control regions for each SR:

- $t\bar{t}$  and single-top
- WW

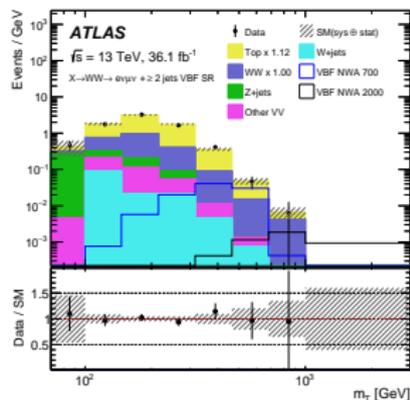
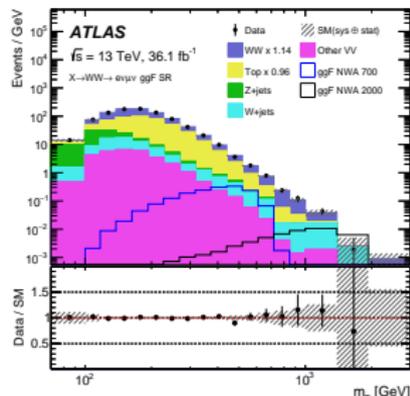
### Discriminant variable $m_T$ : $m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\vec{p}_T^{\ell\ell} + E_T^{\text{miss}}|^2}$

### Signal:

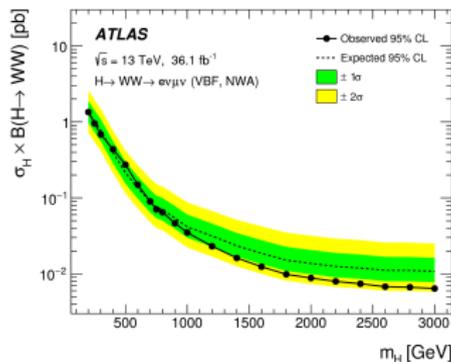
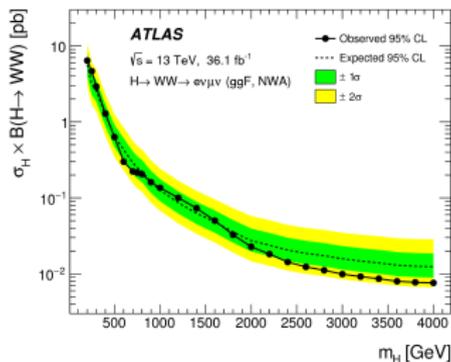
Model	Resonance spin	Production mode			Search range, TeV		
		ggF	qqA	VBF	ggF	qqA	VBF
NWA	Spin-0	x		x	0.2-4		0.2-3
2HDM		x		x			
LWA		x		x			
GM			x				0.2-1
HVT	Spin-1		x	x	0.25-5		0.3-1
Bulk RS ELM	Spin-2	x			0.2-5		0.2-5
				x			0.2-1

### Backgrounds:

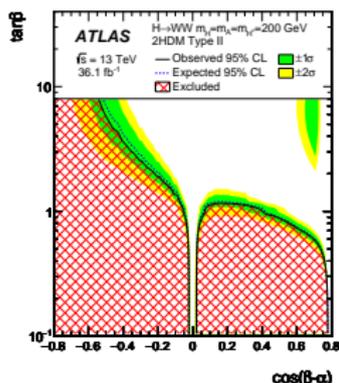
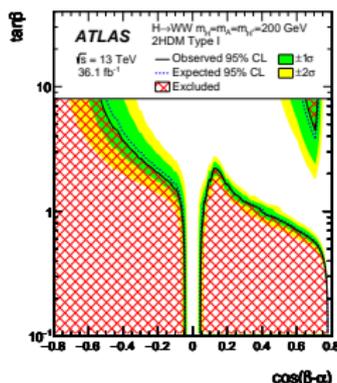
- ▶  $t\bar{t}$  and WW: shape from MC, normalisation: fit  $m_T$  data in CR (after  $p_T^{\ell, \text{lead}}$  reweighting)
- ▶ W+jets data-driven estimates



- Data compatible with SM background predictions
- Upper limits on  $\sigma_H \times B(H \rightarrow WW)$  are set for  $ggF(VBF)$  in range 0.2 - 4(3) TeV



- Limits translated into an exclusion contour in the 2HDM for the phase space where the narrow width assumption is valid



### ■ Spin-0:

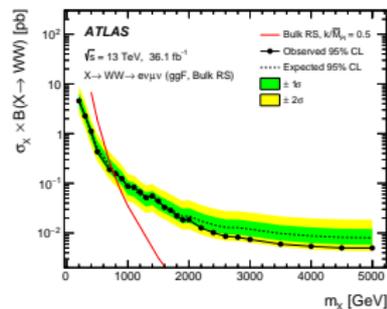
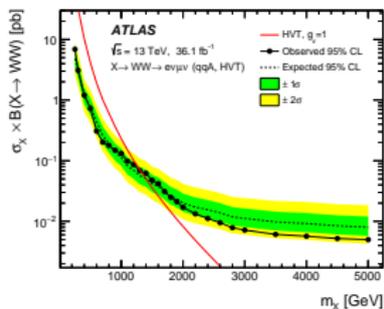
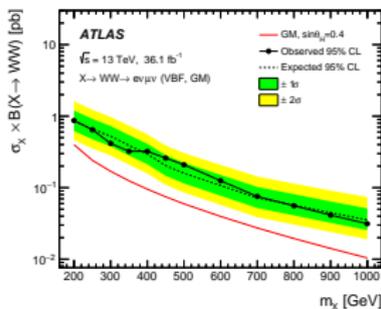
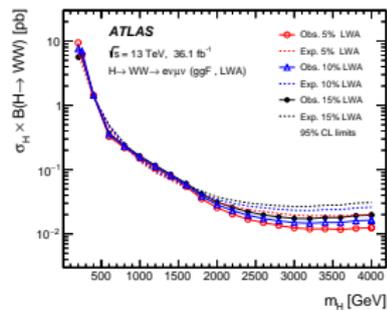
- ▶ The 95% CL limits set to LWA scenario of 5, 10 and 15% of resonance mass
- ▶ Search is not sensitive to GM signal

### ■ Spin-1:

- ▶ HVT signals are excluded below 1.3 TeV in  $q\bar{q}A$

### ■ Spin-2:

- ▶ Observed limits exclude a KK graviton signal below 1100 (750) GeV for  $k/M_{pl} = 1$  (0.5)
- ▶ Current sensitivity is not sufficient to exclude ELM VBF signal



# ZZ → l+l-l+l- and l+l-νν final states

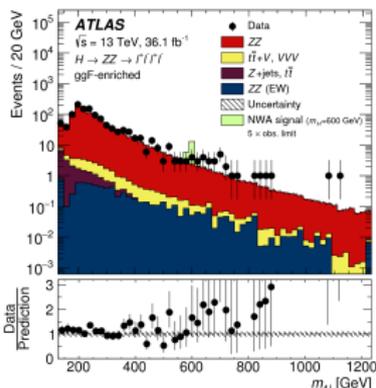
## Analysis strategy

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- Event categories:
  - VBF-enriched:
  - ggF lepton flavour:
- Discriminant variable:
- Search range:
- Signal modelling:
- Background estimation:

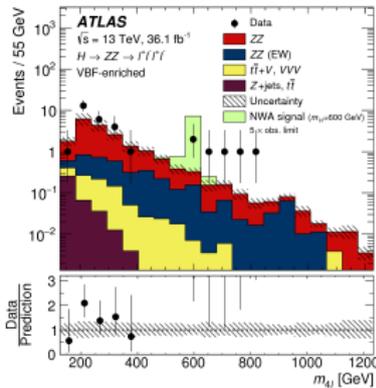
4ℓ	2ℓ2ν
$N_{\text{jets}} \geq 2, p_T^j > 30\text{GeV}$	
$ \Delta\eta_{jj}  > 3.3, m_{jj} > 400\text{GeV}$	$ \Delta\eta_{jj}  > 4.4, m_{jj} > 550\text{GeV}$
4μ, 2e2μ, 4e	$\mu^+\mu^-, e^+e^-$
fully reco $m_{4\ell}$	$E_T^{\text{miss}} > 120\text{GeV}, m_T$
200-1200 GeV	300-1400 GeV
400-1000 GeV, [1,5 and 10%]	
KK graviton 600-2000 GeV, $k/M_{pl} = 1$	
CrystalBall + Gaussian	Moment-morphing
non-res ZZ MC, Z+jets - data-driven	
$\ell\ell + ee : \text{LF}/\gamma \text{ CR}^{e^\pm e^\pm}$	WZ - shape MC norm $\text{CR}^{3\ell}$
$\ell\ell + \mu\mu : t\bar{t}, \text{WZ CR}$	WW, $t\bar{t}, \text{Wt} - \text{MC norm CR}^{e^\pm \mu^\mp}$

4ℓ ggF



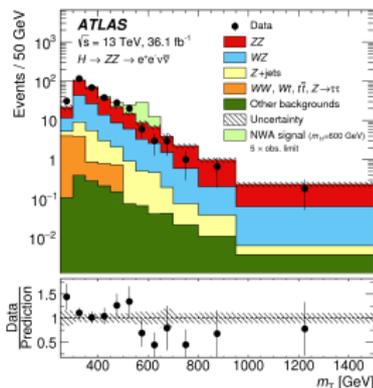
Kirill Grevtsov (ATLAS – DESY)

4ℓ VBF



Searches for high-mass resonances

e+e-νν



July 5, 2018

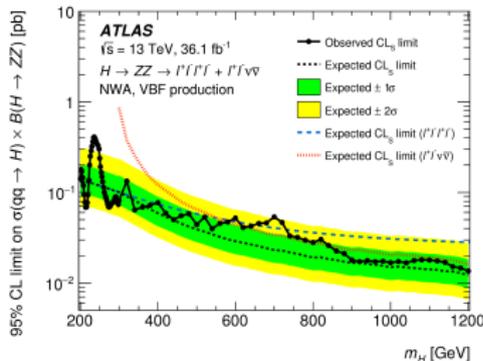
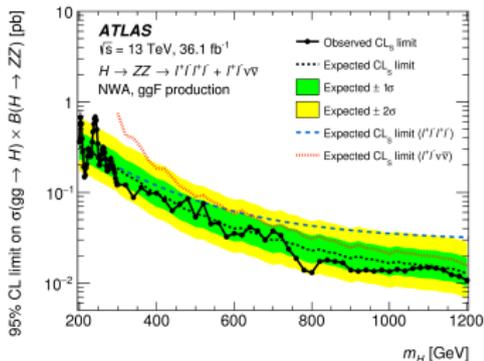
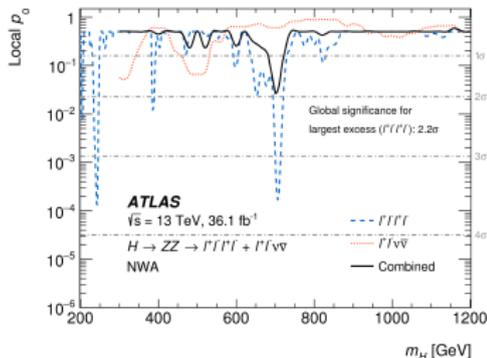
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# ZZ $\rightarrow \ell^+ \ell^- \ell^+ \ell^-$ and $\ell^+ \ell^- \nu \bar{\nu}$ search

## Results for NWA

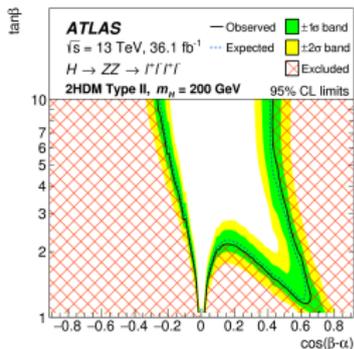
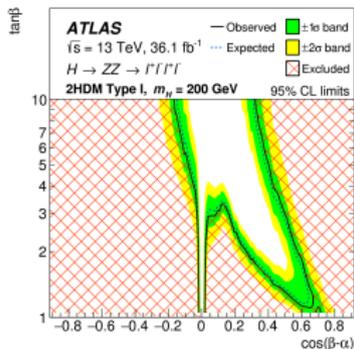
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- Result separately per final state
  - ▶ Two excesses are observed in  $\ell^+ \ell^- \ell^+ \ell^-$   $ggF$ :
    - 240 in 4e only;
    - 700 GeV  $3.6(2.2)\sigma$  loc(glob) in all cat
  - ▶ No significant deviation from the expected background is observed in the  $\ell^+ \ell^- \nu \bar{\nu}$
- Combining two final states:
  - ▶ Data compatible with SM background predictions
- Upper limits on  $\sigma_H \times B(H \rightarrow ZZ)$  are set for  $ggF(VBF)$  production mode in  $m_H$  range 200-1200 GeV



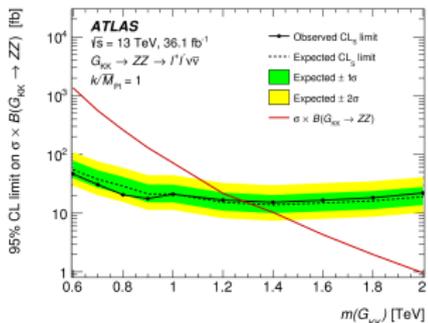
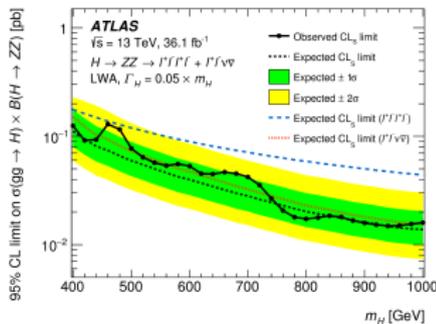
### ■ Spin-0:

- ▶ 95% CL on  $\sigma \times B(H \rightarrow ZZ)$  for narrow scalar resonance for  $ggF$  and  $VBF$  production modes
- ▶ Limits for LWA with 1, 5 and 10% of  $m_H$  are set for  $ggF$  production mode
- ▶ NWA limits translated to 2HDM



### ■ Spin-2:

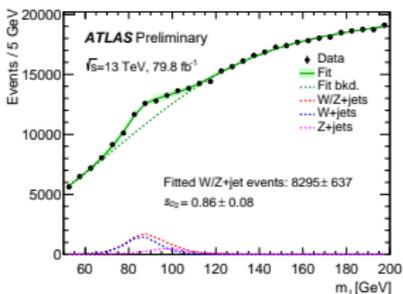
- ▶ Observed limits exclude a KK graviton signal below 1300 GeV for  $k/M_{pl} = 1$



### Searches for narrow signals:

- ▶ Spin-1: HVT  $W'/Z'$
- ▶ Spin-2: RS graviton  $G_{KK}$

### Analysis strategy



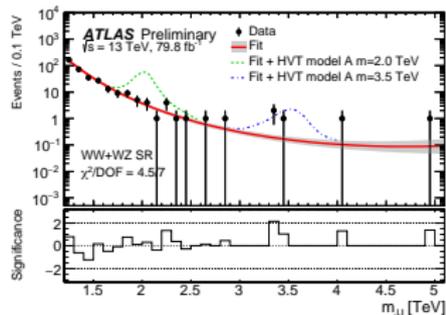
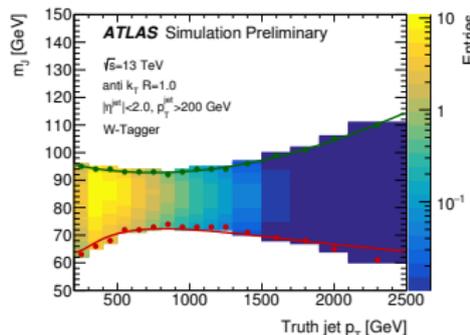
▶ highly-boosted jets reco with Track-CaloClusters

- robust against pile-up
- ▶ Novel tagger:  $W/Z$  vs multijet
- jet mass  $m_J$  and substructure  $D^2$
- $\epsilon^{V\text{-tag}}$  fit  $m_J$  in CR  $V$ +jets

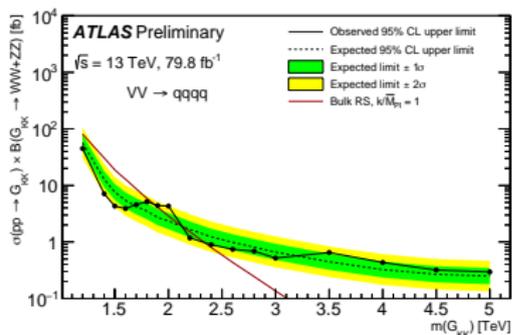
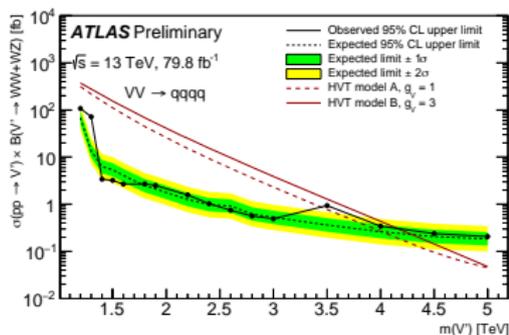
▶ Five signal regions :  $WW, ZZ, WZ, WZ/WW, WW/ZZ$

### Signal and background modelling:

- ▶ Signal:  $m_X$  distribution from MC
- ▶ Background:
  - functional form + spurious signal
  - $f(m_{JJ})$  modelind validated in CR  $ABCD$



- Data compatible with SM background predictions
  - ▶ Largest deviation ( $1.8\sigma$ ) observed for HVT  $W' \rightarrow WZ$  at 3.5 TeV
- Upper limits on  $\sigma_X \times B(X \rightarrow VV)$  are set for benchmark signals in range 1.2-5 TeV
  - ▶ Spin-1 HVT model A(B) with  $g_V=1(3)$  is excluded in range  $m(V')$  1.2-3.4(1.2-4.15) TeV
  - ▶ Production of a  $G_{KK}$  with  $k/M_{Pl} = 1$  is excluded in  $m(G_{KK})$  ranges 1.2-1.9 TeV and 2.1-2.3 TeV

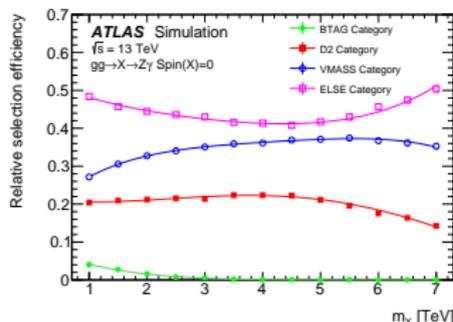


### ■ Search for narrow signal:

- ▶  $ggF$ :  $Z\gamma$  for Spin-0/2
- ▶  $q\bar{q}A$ :  $Z\gamma$  Spin2,  $W\gamma$  and  $H\gamma$  (first time!) Spin-1

### ■ Event selection

- ▶ Exploit high  $B(V \rightarrow \text{had})$  with boosted di-jet merged to large- $R$  jet and photon with  $p_T^\gamma > 140\text{GeV}$
- ▶ Classification (decrease  $\text{bkg.rej}$  at high  $m_{J\gamma}$ ):



- $b$ -tagging "BTAG" ( $Z/H \rightarrow b\bar{b}$  vs.  $g \rightarrow b\bar{b}$ )
- jet substructure "D2" ( $Z/W(\text{had})$  vs.  $q/g$  jets)
- jet mass requirement "VMASS"

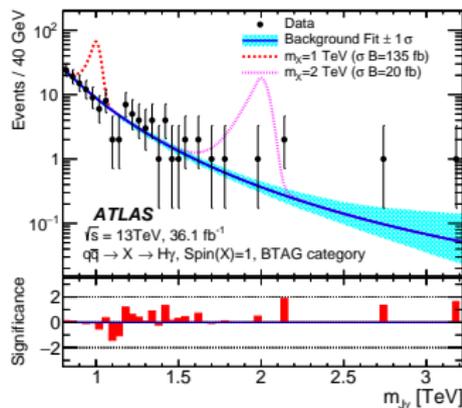
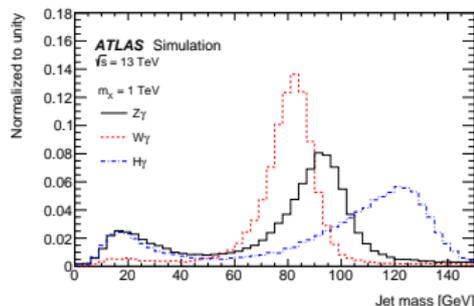
### ■ Signal and background modelling:

#### ▶ Signal modelling:

- CrystalBall + Gaussian

#### ▶ Background: functional form + spurious signal

- $\gamma$ +jets,  $V\gamma$  - from MC; multijet data-driven

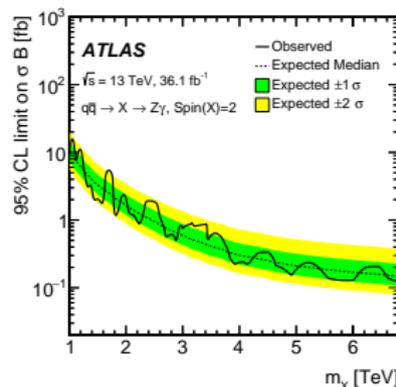
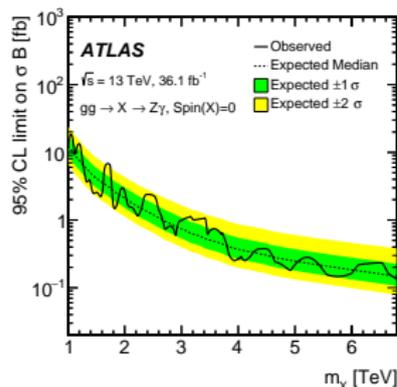
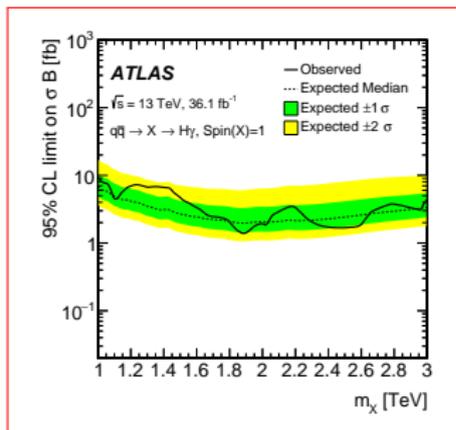
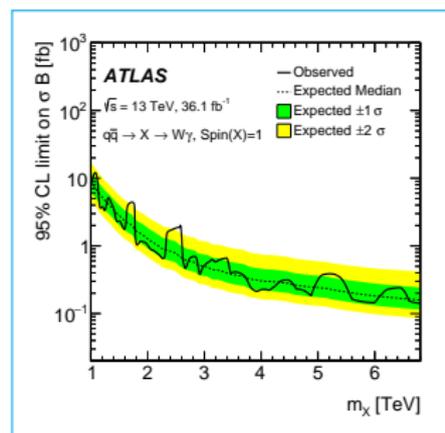


# Searches for heavy resonances decaying to $\gamma$ and $Z/W/H$ boson

## Results

arXiv:1805.01908

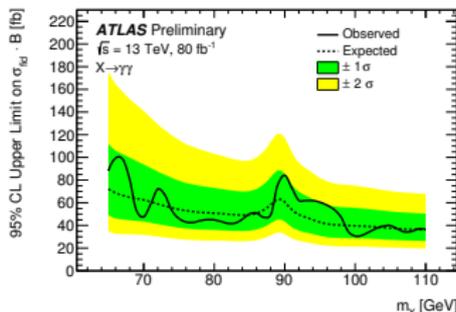
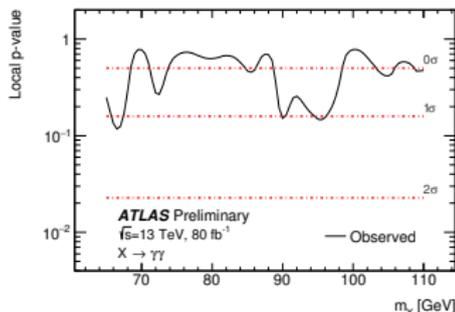
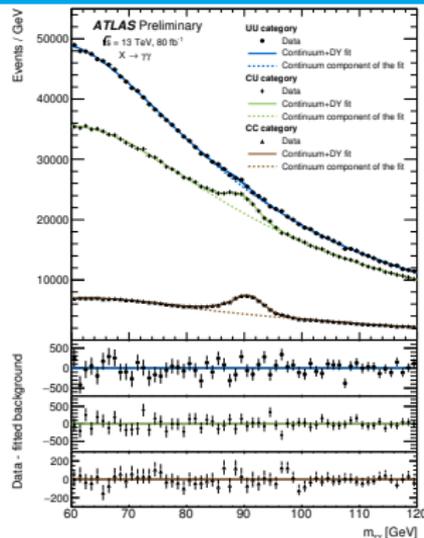
- Data compatible with SM background predictions
  - ▶ Largest deviation observed for  $W\gamma$  corresponding to  $2.7(>1)\sigma$  local (global) for  $m_{J\gamma} = 2.5$  TeV
- Limits set for  $\sigma \times B(W\gamma \rightarrow \text{had})$  in  $m_\chi$  range 1-6.8 TeV → first evaluation in hadronic  $W$  decays
- **First limits** on  $H\gamma$  production ( $q\bar{q}A$  Spin-1) set in mass range 1-3 TeV
- Limits on  $Z\gamma$  production set for  $m_\chi$  between 1 and 6.8 TeV for different hypothesis:  $ggF$  Spin-0/2 and  $q\bar{q}A$  Spin-2



# Searches for low-mass diphoton resonances with $80 \text{ fb}^{-1}$

ATLAS-CONF-2018-025

- Event categories based on  $\gamma$  reconstruction:
  - ▶ both unconverted (UU)
  - ▶ converted-unconverted (CU)
  - ▶ both converted (CC)
- Signal and background modelling:
  - ▶ Signal (narrow resonance): double sided Crystal Ball
  - ▶ Background: functional form + spurious signal
    - $\gamma\gamma$  continuum- from simulation
    - reducible ( $\gamma j, jj$ ) data-driven
    - DY from  $Z \rightarrow ee$  data-driven
- First results at 13 TeV with  $80 \text{ fb}^{-1}$ :
  - ▶ Upper limits on  $\sigma_{\text{fid}}(pp \rightarrow X) \times BR(X \rightarrow \gamma\gamma)$  set for range  $65 < m_{\gamma\gamma} < 110 \text{ GeV}$ .

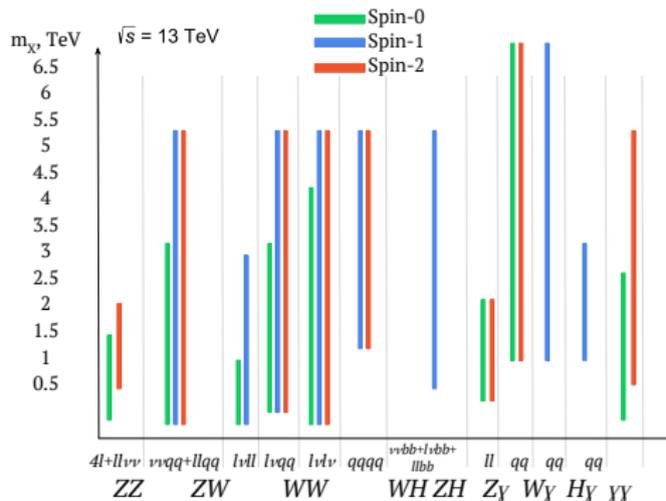


# Summary

## Searches for high-mass resonances

- Broad programme of searches for high mass resonances at ATLAS
  - ▶ Exploring the data in various final states
  - ▶ Cover many benchmarks

- Presented analyses searching for resonance in diboson final states:
    - ▶ high-mass with 36 and with 80  $\text{fb}^{-1}$
    - ▶ low-mass with 80  $\text{fb}^{-1}$
- no deviation from SM predictions found



- Run-2 - still six months to go:
  - ▶ Collecting more luminosity - already  $>100\text{fb}^{-1}$
  - ▶ Ongoing work on improvements of combined performance and analysis techniques

Backup



# Searches for $Z\gamma$ high-mass resonances

$Z \rightarrow \ell\ell$

## Event categories:

- $Z \rightarrow ee$  ( $\mu\mu$ ) better  $m_X$  resolution at large  $m_{Z\gamma}$ :  
 $\sigma_{CB} = 2.8$  (3.1) GeV at  $m_X=250$  to 16(36) GeV at 2.4 TeV

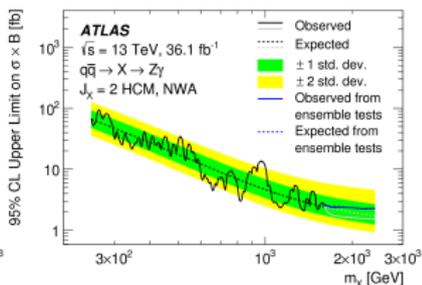
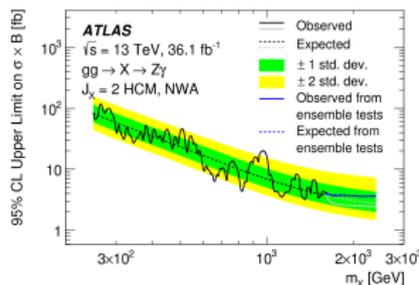
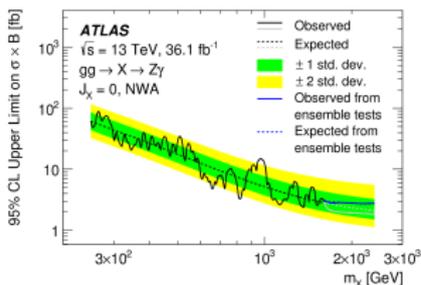
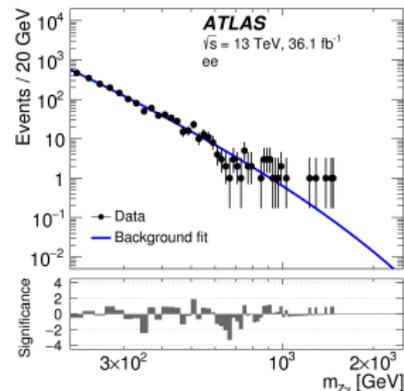
## Search range for Spin-0 (2): 300-2500 (250-2500) GeV

## Signal and background modelling:

- Signal modelling: double sided Crystal Ball
- Background: functional form + spurious signal
  - non-res  $Z + \gamma$ ,  $Z$ +jets - data-driven
  - $t\bar{t}$ ,  $W/Z$  - from MC

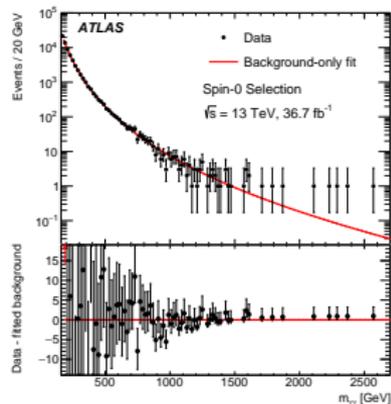
## Results:

- Upper limits on  $\sigma(pp \rightarrow X) \times BR(X \rightarrow Z\gamma)$  set for spin-0 hypothesis
- Results are interpreted in terms of spin-2 for  $gg(q\bar{q})$  process using the Higgs Characterisation Model



# Searches for high-mass diphoton resonances

- Search range for Spin-0 (2): 200-2700 (500-5000) GeV  
NWA -  $10\% m_X$  ( $k/M_{pl} 0.01 - 0.3$ )
- Event selections: different kinematic for Spin-0 and Spin-2
- Signal and background modelling:
  - ▶ Signal modelling: NWA double sided Crystal Ball  
LWA:  $NWA \otimes \text{LineShape}$
  - ▶ Background:
    - Spin-0: functional form + spurious signal  
 $\gamma\gamma$  - MC, reducible ( $\gamma j, jj$ ) data-driven
    - Spin-2: template fit  
irreducible component weighted to NLO, free  $N$



## ■ Results:

- ▶ Spin-0: upper limits on  $\sigma_{\text{fid}}(pp \rightarrow X) \times BR(X \rightarrow \gamma\gamma)$  set for various width  $[0-10\% m_X]$
- ▶ Search exclude KK graviton below 4.1 TeV for  $k/M_{pl}$  0.1

