



# WZ $\rightarrow$ $lvll$ resonance search

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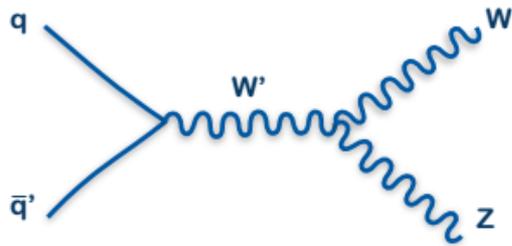
**On behalf of the ATLAS collaboration  
University of Science and Technology of China**

**2020/01/09**

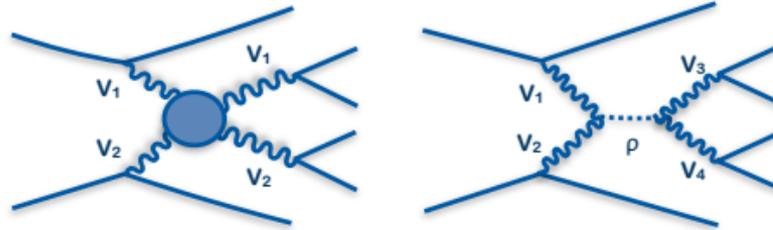
**Paper: arXiv:1806.01532 (<https://arxiv.org/abs/1806.01532>)**

# Introduction

Using  $36.1 \text{ fb}^{-1}$  of  $\sqrt{s} = 13 \text{ TeV}$  pp data collected by the ATLAS experiment at the LHC during the 2015 and 2016 run periods.



qq production mode



VBS/VBF production modes

- Aim of this analysis: fully leptonic  $WZ$  decay ( $e, \mu$ ) in exclusive qq and VBS/VBF production modes
  - ▶ Clean signature:
    - 3 high  $p_T$ , isolated leptons,
    - Missing transverse energy
  - ▶ Backgrounds
    - $WZ$  SM (dominant),  $ZZ$ ,  $Z$ +jets,  $Z+\gamma$ ,  $VVV$  and Top
  
- Two benchmark models:
  - ▶ Heavy Vector Triplets (HVT)
  - ▶ Georgi-Machacek (GM) Higgs Triplet Model :  $H_5^+$

# Event selection

## ➤ Event Selection

- *Pass single-electron triggers or single-muon triggers*
- *Exactly three leptons with  $p_T > 25$  GeV and  $|\eta| < 2.5$*
- *MET > 25 GeV*
- *ZZ veto: remove events with 4 or more muons or electrons with  $p_T > 7$  GeV*
- *Select Opposite sign, Same Flavour pairs to build Z*
- *$|M_{ll} - 91.1875 \text{ GeV}| < 20$  GeV*
- *If there are multiple choices, choose the pair that has the invariant mass closest to the Z mass*
- *W lepton: Likelihood Tight ID and Gradient isolation*
- *leading lepton  $p_T > 27$  GeV (in 2016 the trigger threshold was increased to 26 GeV)*
- *Longitudinal momentum of neutrinos reconstructed using W mass constrain*

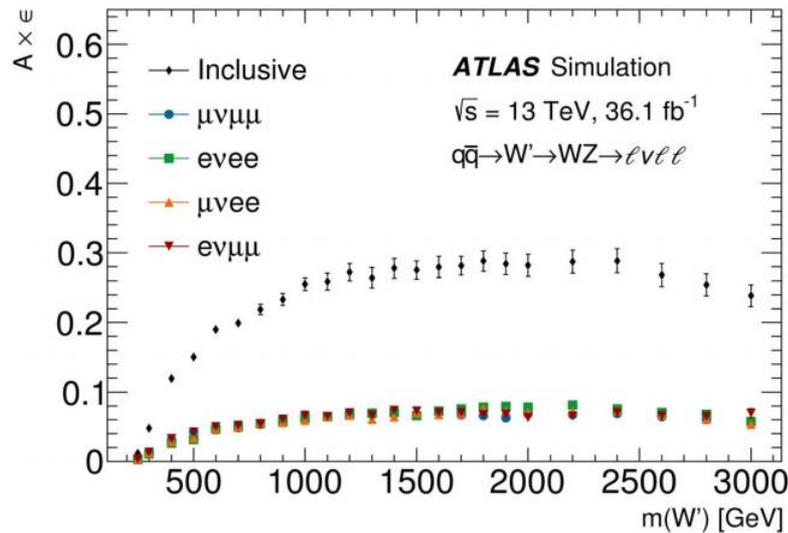
## ➤ VBS/VBF Category

- *At least 2 jets with  $p_T > 30$  GeV and  $|\eta| < 4.5$*
- *$m_{jj} > 500$  GeV and  $\Delta\eta_{jj} > 3.5$  (using the two  $p_T$ -leading ones)*

## ➤ qq Category

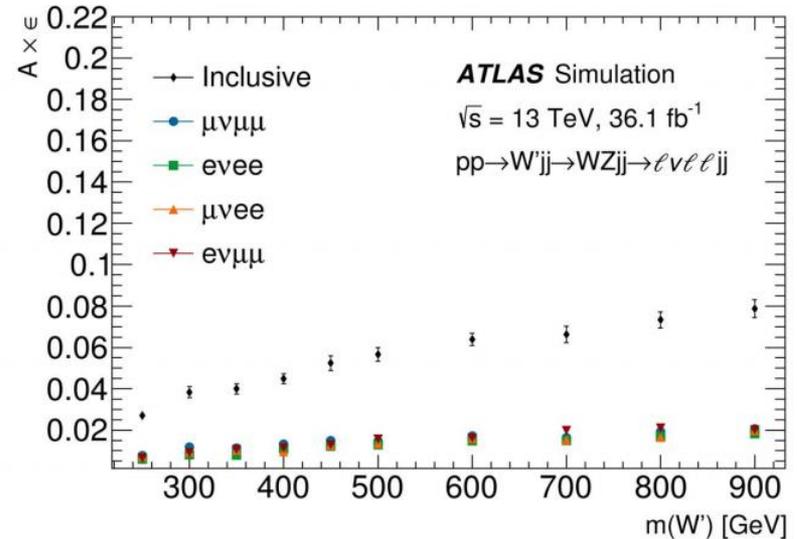
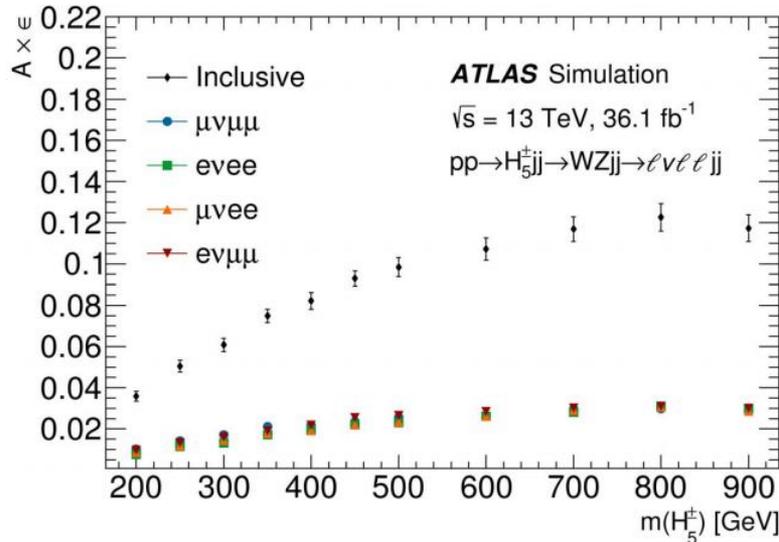
- *Fail VBS/VBF cuts*
- *$p_T(Z)/\text{Mass}(WZ) > 0.35$*
- *$p_T(W)/\text{Mass}(WZ) > 0.35$*

# Event selection: signal $A \times \epsilon$



➤ **The signal selection acceptance times efficiency ( $A \times \epsilon$ )**

- For  $qq$  category, the  $A \times \epsilon$  increases from about 15% to 25%. The values decrease for resonance masses above approximately 2 TeV due to the collinearity of electrons from the  $Z \rightarrow ee$  decays which spoils the isolation
- For VBS/VBF category, the  $A \times \epsilon$  falls in the range 2–8% and 3–12% for HVT and  $H_5^+$  respectively. The difference being due, with approximately equal importance, to the generator level selection and to the different angular distributions of the final products



# Background estimation

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~ 90% Real leptons : Estimated using MC

- WZ (Sherpa)
  - ▶ QCD WZ dominant background ( $\sim 80\%$  of the total)
  - ▶ Uncertainties: 10% normalization, shapes used for PDF and Scale shape uncertainties, EWK corrections not available yet for our phase space
- ZZ (Powheg (qq) and Sherpa (gg)) : 10% theory uncertainty
- $t\bar{t}V$  ( $V=Z,W$ ) (MadGraphPythia) 13% theory uncertainty for  $t\bar{t}W$  and 12%  $t\bar{t}Z$
- $tZ$  (MadGraphPythia) 15% theory uncertainty
- $VV$  ( $V=Z,W$ ) (Sherpa) 20% theory uncertainty

~10 % Fake leptons : Estimated using Matrix Method

# Background estimation Matrix Method

- ▶ **Tight** leptons match the WZ lepton selection.
- ▶ **Loose** leptons are defined by inverting some selection cuts i.e isolation, electron identification.
- ▶ We want to determine the background due to “fake” leptons.
  - ▶ 3 leptons  $\Rightarrow$  (# of Fake Real Real  $\rightarrow$  Tight Tight Tight) + (# of Fake Fake Real  $\rightarrow$  Tight Tight Tight) + ...
- ▶  $N_{TTT}$ ,  $N_{TTL}$  ... are related to  $N_{RRR}, N_{RRF}$  by the fake matrix:

$$\begin{array}{c} \text{Observation} \end{array} \xrightarrow{\hspace{10em}} \begin{array}{c} \text{Calculated} \end{array}$$

$$\begin{pmatrix} N_{TTT} \\ N_{TTL} \\ N_{TLT} \\ N_{LTT} \\ N_{TLL} \\ N_{LTL} \\ N_{LLT} \end{pmatrix} = \begin{pmatrix} e_1 e_2 e_3 & e_1 e_2 f_3 & e_1 f_2 e_3 & f_1 e_2 e_3 & e_1 f_2 f_3 & f_1 e_2 f_3 & f_1 f_2 e_3 \\ e_1 e_2 \bar{e}_3 & e_1 e_2 \bar{f}_3 & e_1 f_2 \bar{e}_3 & f_1 e_2 \bar{e}_3 & e_1 f_2 \bar{f}_3 & f_1 e_2 \bar{f}_3 & f_1 f_2 \bar{e}_3 \\ e_1 \bar{e}_2 e_3 & e_1 \bar{e}_2 f_3 & e_1 \bar{f}_2 e_3 & f_1 \bar{e}_2 e_3 & e_1 \bar{f}_2 f_3 & f_1 \bar{e}_2 f_3 & f_1 \bar{f}_2 e_3 \\ \bar{e}_1 e_2 e_3 & \bar{e}_1 e_2 f_3 & \bar{e}_1 f_2 e_3 & f_1 e_2 e_3 & \bar{e}_1 f_2 f_3 & f_1 e_2 f_3 & f_1 \bar{f}_2 e_3 \\ e_1 \bar{e}_2 \bar{e}_3 & e_1 \bar{e}_2 \bar{f}_3 & e_1 \bar{f}_2 \bar{e}_3 & f_1 \bar{e}_2 \bar{e}_3 & e_1 \bar{f}_2 \bar{f}_3 & f_1 \bar{e}_2 \bar{f}_3 & f_1 \bar{f}_2 \bar{e}_3 \\ \bar{e}_1 e_2 \bar{e}_3 & \bar{e}_1 e_2 \bar{f}_3 & \bar{e}_1 f_2 \bar{e}_3 & f_1 e_2 \bar{e}_3 & \bar{e}_1 f_2 \bar{f}_3 & f_1 e_2 \bar{f}_3 & f_1 \bar{f}_2 \bar{e}_3 \\ \bar{e}_1 \bar{e}_2 e_3 & \bar{e}_1 \bar{e}_2 f_3 & \bar{e}_1 \bar{f}_2 e_3 & f_1 \bar{e}_2 e_3 & \bar{e}_1 \bar{f}_2 f_3 & f_1 \bar{e}_2 f_3 & f_1 \bar{f}_2 e_3 \end{pmatrix} \begin{pmatrix} N_{RRR} \\ N_{RRF} \\ N_{RFR} \\ N_{FRR} \\ N_{RFF} \\ N_{FRF} \\ N_{FFR} \end{pmatrix}$$

$i = 1, \text{ } W \text{ lepton}$   
 $i = 2, 3 \text{ } Z \text{ leptons}$ 


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 $T = \text{passes tight selection}$   
 $L = \text{fail tight selection}$

$$\bar{e} = (1-e)$$

$$\bar{f} = (1-f)$$

- ▶ **e** real efficiency : is the probability that a Real lepton is reconstructed as Tight.
- ▶ **f** fake probability : is the probability that a Fake lepton is reconstructed as Tight.
- ▶ By inverting the matrix, we calculate the fake contribution to our TTT signal

# Background estimation Matrix Method

Fakes in our selection

$$N_{TTT} - e_1 e_2 e_3 N_{RRR} = [N_{TTL} - e_1 e_2 \bar{e}_3 N_{RRR}] f_3 / \bar{f}_3 + [N_{TLT} - e_1 \bar{e}_2 e_3 N_{RRR}] f_2 / \bar{f}_2 + [N_{LTT} - \bar{e}_1 e_2 e_3 N_{RRR}] f_1 / \bar{f}_1 + [N_{TLL} - e_1 \bar{e}_2 \bar{e}_3 N_{RRR}] f_2 f_3 / \bar{f}_2 \bar{f}_3 + [N_{LTL} - \bar{e}_1 e_2 \bar{e}_3 N_{RRR}] f_1 f_3 / \bar{f}_1 \bar{f}_3 + [N_{LLT} - \bar{e}_1 \bar{e}_2 e_3 N_{RRR}] f_1 f_2 / \bar{f}_1 \bar{f}_2$$

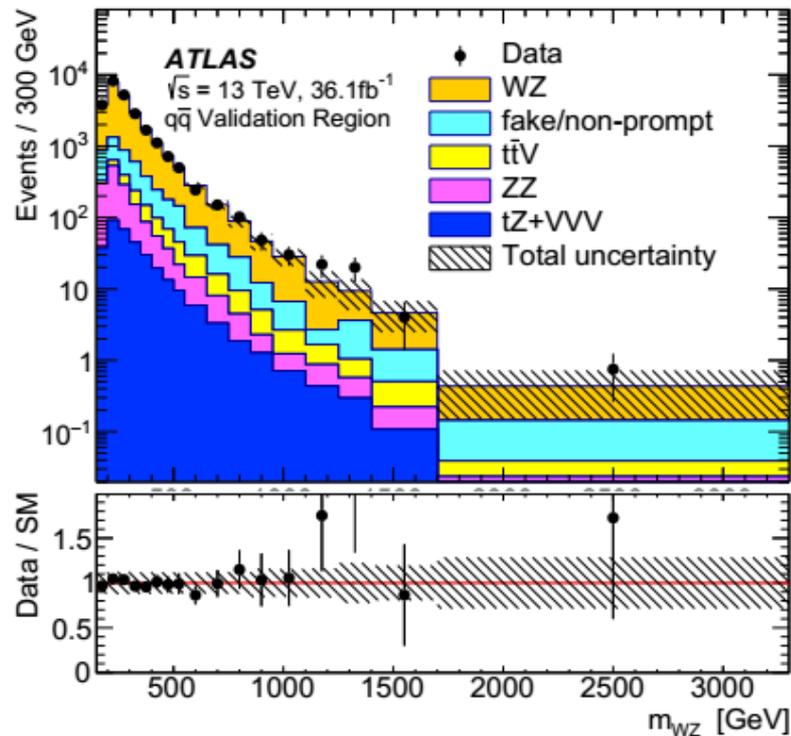
- Background in the signal region
- real leptons ZZ, WZ ... from MC
- Loose Control regions
- Fake rates  $F_i = f_i / \bar{f}_i$

- ▶  $N_{TTT}, N_{TTL}, N_{TLT}$  ... measured by applying or inverting selection cuts
- ▶  $e_1 e_2 \bar{e}_3 N_{RRR}, e_1 \bar{e}_2 e_3 N_{RRR}$  ... real lepton contamination from MC
- ▶ Fake Rates :
  - ▶ 2 different lepton selection for W and Z leptons → 2 fake rates  $f_1$  and  $f_2$  ( $f_2 = f_3$ )
  - ▶ Measured in dedicated control regions

# Background estimation validation

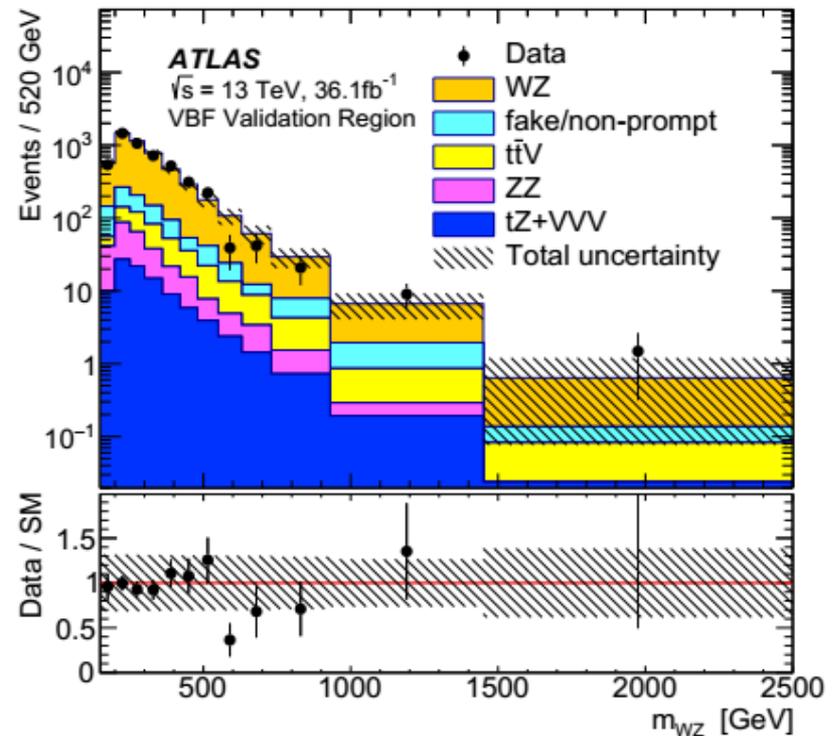
## ➤ qq Validation Region

- Fail VBF/VBS selection
- $p_T(Z)/\text{Mass}(WZ) < 0.35$  or  $p_T(W)/\text{Mass}(WZ) < 0.35$



## ➤ VBS/VBF Validation Region

- At least 2 jets with  $p_T > 30 \text{ GeV}$  and  $|\eta| < 4.5$
- $m_{jj} < 500 \text{ GeV}$  &  $m_{jj} > 100 \text{ GeV}$  &  $\Delta\eta_{jj} < 3.5$
- $p_T(Z)/\text{Mass}(WZ) < 0.35$  or  $p_T(W)/\text{Mass}(WZ) < 0.35$



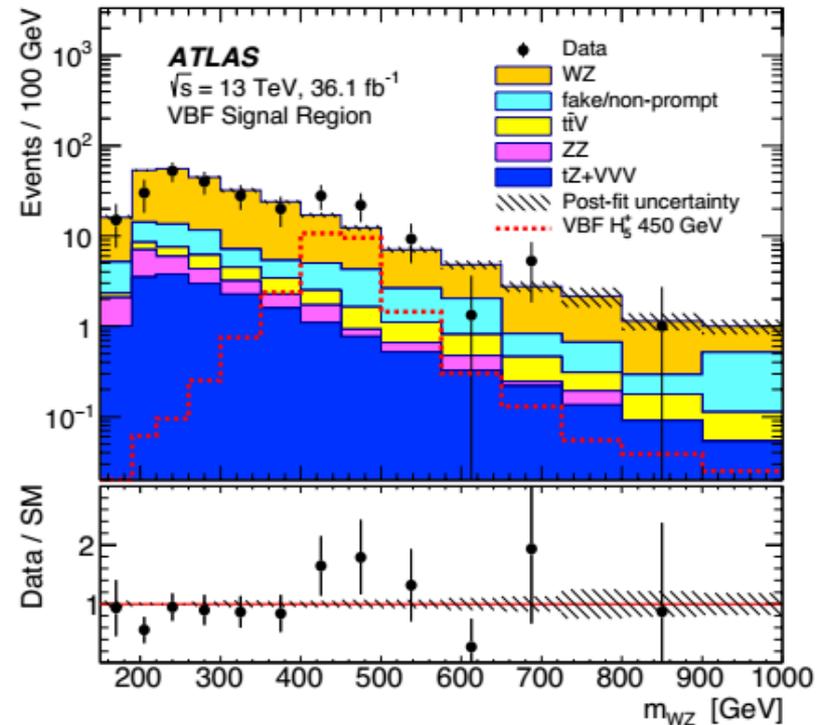
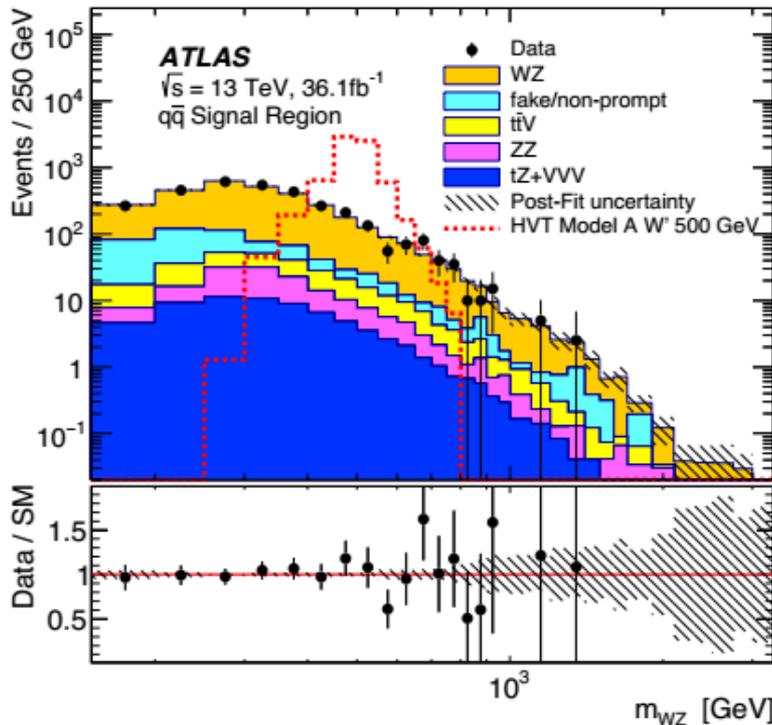
# Systematics uncertainties

Source	$\Delta\mu/\mu$ [%]	
	$q\bar{q}$ Category $m(W') = 800$ GeV	VBF Category $m(H_5^\pm) = 450$ GeV
WZ background modelling : Scale, PDF	5	11
WZ background modelling : Parton Shower	10	6
MC statistical uncertainty	7	8
Electron identification	4	2
Muon identification	3	3
Jet uncertainty	1	8
Missing transverse momentum	2	1
Fake/non-prompt	1	5
Total systematic uncertainty	17	21
Statistical uncertainty	53	52

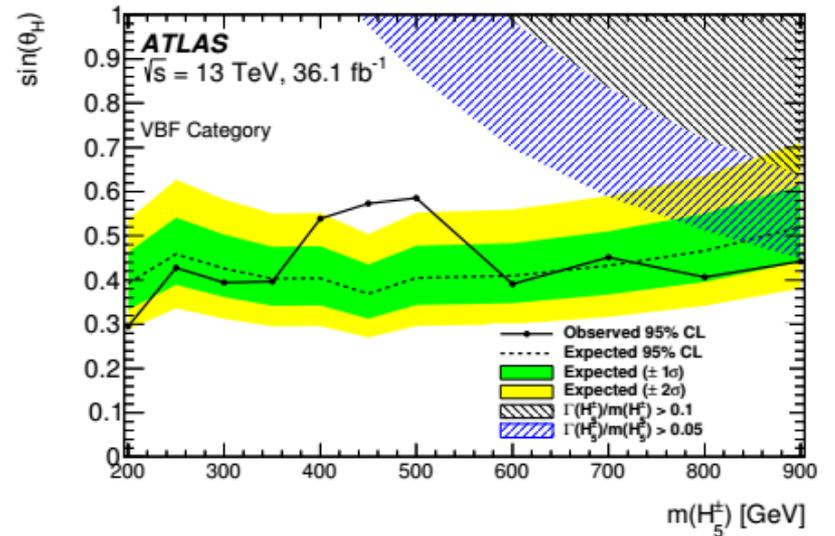
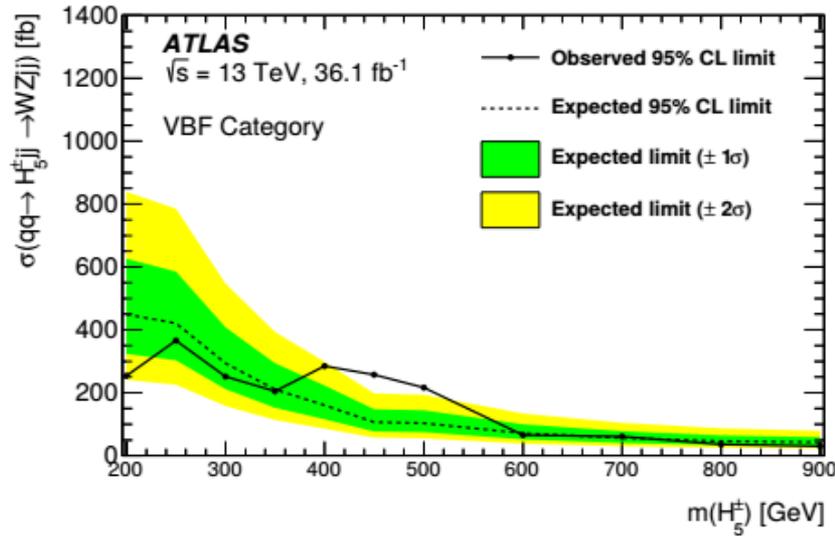
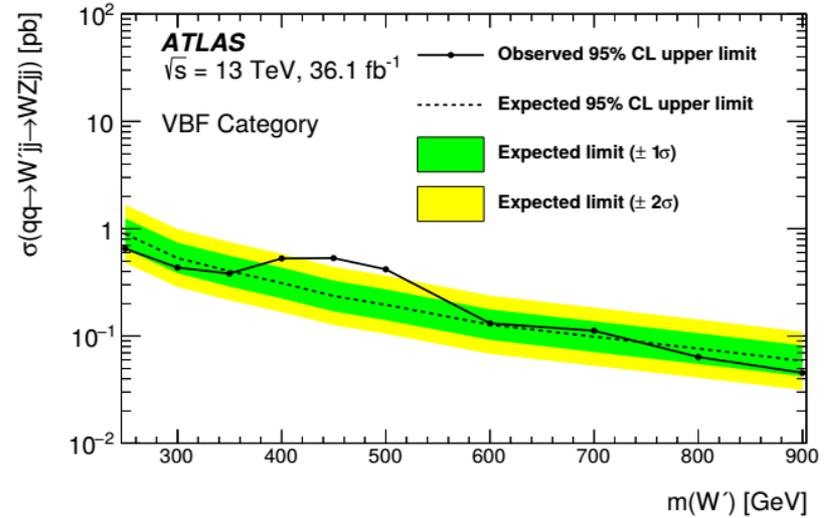
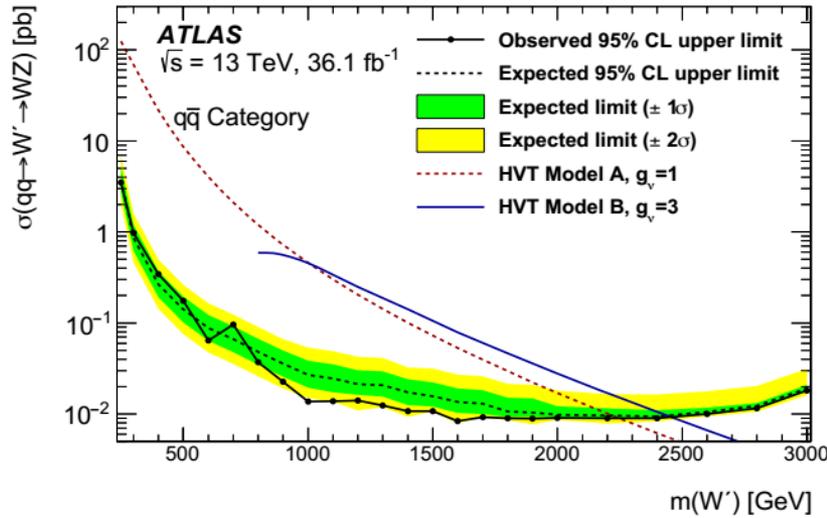
# Results

- A binned likelihood function, constructed from the Poisson probability of the sum of the background and of hypothetical signal of strength  $\mu$ , is used to set limits on the signal

	$q\bar{q}$ Signal Region	VBF Signal Region
$WZ$	$521 \pm 29$	$87 \pm 12$
Fake/non-prompt	$64 \pm 13$	$15 \pm 4$
$t\bar{t}V$	$29 \pm 4$	$4.9 \pm 0.8$
$ZZ$	$18.9 \pm 2.0$	$4.4 \pm 1.0$
$tZ + VVV$	$14.1 \pm 2.9$	$8.1 \pm 1.8$
Total Background	$647 \pm 25$	$120 \pm 11$
Observed	650	114



# Results



# Summary

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- **A search is performed for resonant WZ production in fully leptonic final states (electrons and muons) using  $36.1 \text{ fb}^{-1}$  of  $\sqrt{s} = 13 \text{ TeV}$  pp data collected by the ATLAS experiment at the LHC during the 2015 and 2016 run periods**
  - *qq category: Masses below 2260 GeV for HVT WZ Model A and 2460 GeV for model B, are excluded at 95% CL*
  - *VBS category: Limits on the production cross-section times branching ratio are obtained as a function of the mass of a charged member of a Heavy Vector Triplet or of the fiveplet scalar in the Georgi-Machacek model. The results show a local excess of events over the Standard Model expectations at a resonance mass of around 450 GeV. The local significances for signals of  $H_5^+$  and of a heavy vector  $W'$  boson are 2.9 and 3.1 standard deviations respectively. The respective global significances calculated considering the Look Elsewhere effect are 1.6 and 1.9 standard deviations respectively*
- **CMS has also produced an analysis for new physics in WZ + two jets events (<http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-18-001>) with similar limits obtained for  $\sin(\theta_H)$**
- **A full run-II ATLAS analysis searching for resonant WZ production in fully leptonic final states is ongoing**