

# Searches for high-mass resonances in fully leptonic final states

SUSY2018

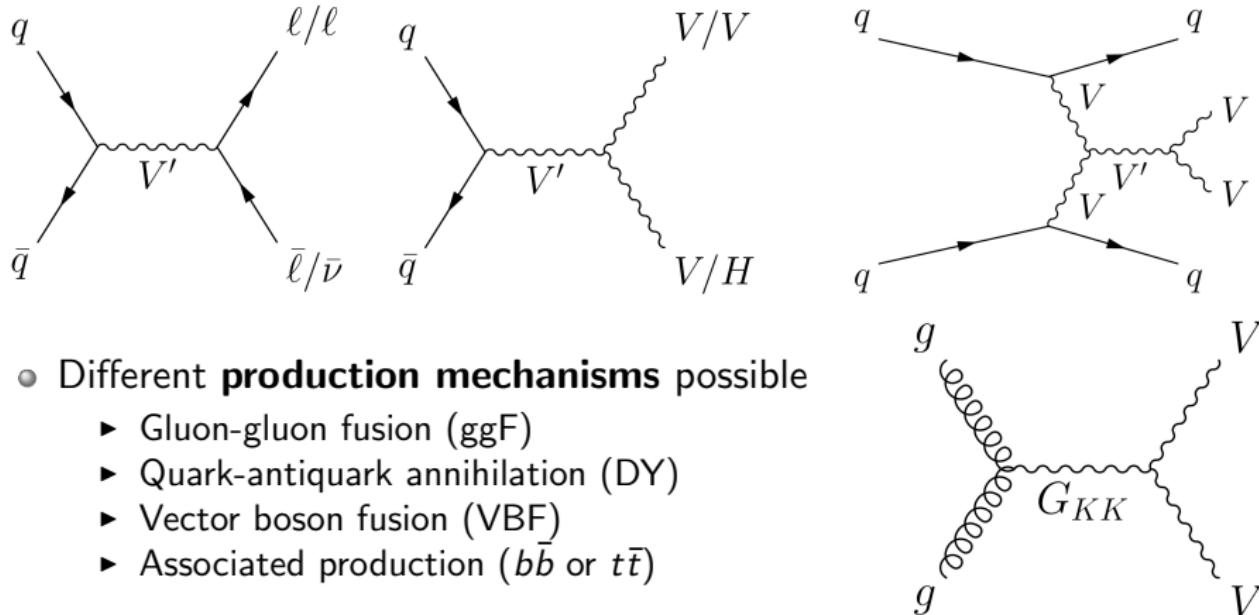
Peter Falke (LAPP / CNRS)  
on behalf of the ATLAS collaboration

25th July 2018



# Motivation behind searches for heavy resonances

- Various SM extensions predict **new resonances**, for example
  - ▶ **Spin-0**: Extended Higgs sector (e.g. 2HDM, SUSY, ...)
  - ▶ **Spin-1**: Extra gauge symmetries (e.g. Heavy Vector Triplet, SSM, dark matter mediators, ...)
  - ▶ **Spin-2**: Warped extra dimensions (e.g. Randall-Sundrum model)



- Different **production mechanisms** possible
  - ▶ Gluon-gluon fusion (ggF)
  - ▶ Quark-antiquark annihilation (DY)
  - ▶ Vector boson fusion (VBF)
  - ▶ Associated production ( $b\bar{b}$  or  $t\bar{t}$ )

## Overview of final states

- Variety of final states with different experimental signatures

## ► Hadronic decays

- Light quarks and gluons
  - $b$ - or  $t$ -quarks

### ► Leptonic decays

- $\ell \in \{e, \mu\}$
  - $\tau$
  - Neutrinos

#### ► Diboson production

- $VV, VH, HH$
  - $\gamma\gamma, V\gamma, H\gamma$
  - $V/H$ : Many decay modes

ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

Stamps: July 2018

\*Only a selection of the available mass limits on new states or phenomena is shown.

**Small-angle (cone-angle) jets are denoted by the letter (A).**

- **Combination** of final states can enhance sensitivity
  - **Further channels** presented in this session by [Vincent](#) and [Gabriele](#)
  - All **public ATLAS results** can be found at [this website](#)

# Overview of final states

- **Variety of final states** with different experimental signatures
  - ▶ Hadronic decays
    - Light quarks and gluons
    - $b$ - or  $t$ -quarks
  - ▶ Leptonic decays
    - $\ell \in \{e, \mu\}$
    - $\tau$
    - Neutrinos
  - ▶ Diboson production
    - $VV$ ,  $VH$ ,  $HH$
    - $\gamma\gamma$ ,  $V\gamma$ ,  $H\gamma$
    - $V/H$ : Many decay modes
- **Combination** of final states can enhance sensitivity
- **Further channels** presented in this session by [Vincent](#) and [Gabriele](#)
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## Contents of this talk

$WZ \rightarrow \ell\nu ll$  search ( $36 \text{ fb}^{-1}$ )

$VV/VH/\ell\nu/\ell\ell$  combination ( $36 \text{ fb}^{-1}$ )

$W' \rightarrow \ell\nu$  search ( $80 \text{ fb}^{-1}$ )

Low-mass  $\gamma\gamma$  search ( $80 \text{ fb}^{-1}$ )

# Benchmark model for combining various channels

- **Heavy Vector Triplet (HVT) model ([arXiv:1402.4431](https://arxiv.org/abs/1402.4431))**

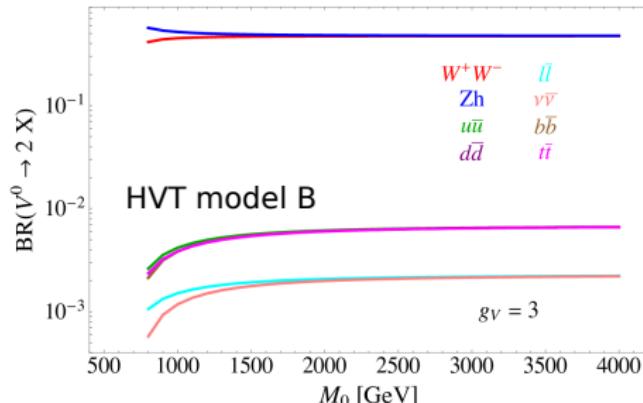
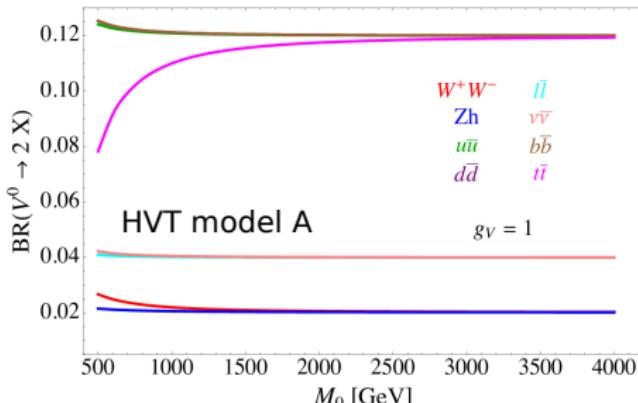
- ▶ Triplet of colorless vector bosons  $V' \in \{W'^\pm, Z'\}$

$$\mathcal{L}_W^{\text{int}} = -g_q W_\mu^a \bar{q}_k \gamma^\mu \frac{\sigma_a}{2} q_k - g_\ell W_\mu^a \bar{\ell}_k \gamma^\mu \frac{\sigma_a}{2} \ell_k - g_H \left( W_\mu^a H^\dagger \frac{\sigma_a}{2} i D^\mu H + \text{h.c.} \right)$$

- ▶  $g_q$  and  $g_\ell$ : Universal coupling strength to quarks and leptons
- ▶  $g_H$ : Coupling strength to Higgs field → enables diboson decays

- **Special coupling points inside model**

- ▶ **HVT A** →  $g_H = -0.56$ ,  $g_F = -0.55$  → weakly coupled, e.g. ext. gauge symmetry
- ▶ **HVT B** →  $g_H = -2.9$ ,  $g_F = 0.14$  → strongly coupled, e.g. composite Higgs

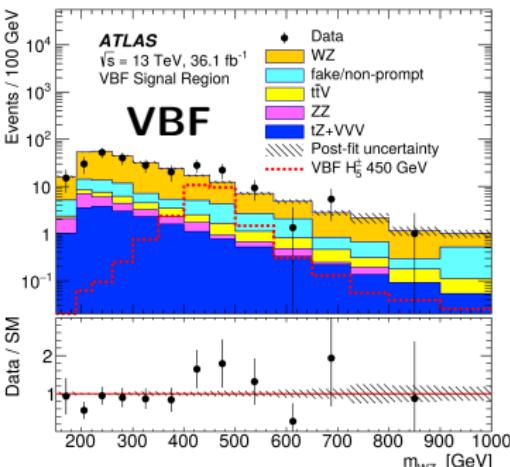
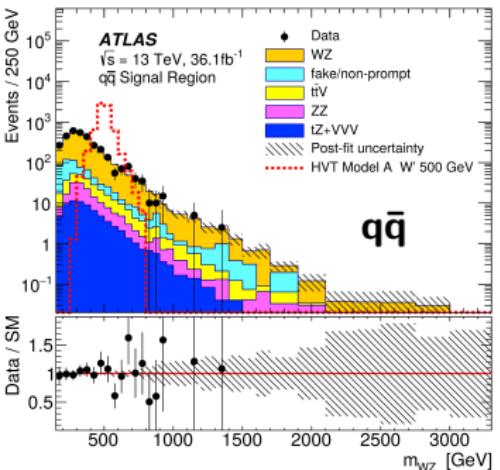


# $WZ \rightarrow \ell\nu\ell\ell$ search

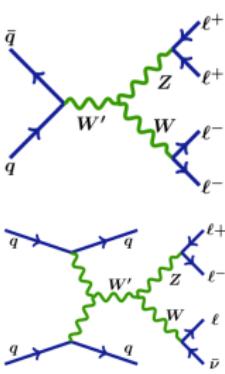
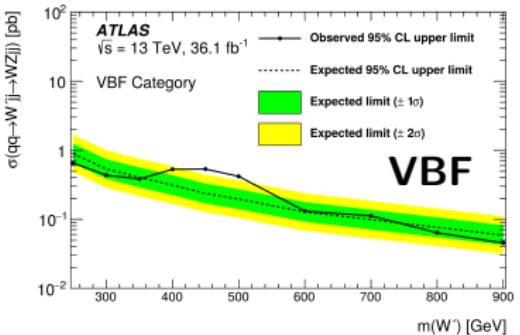
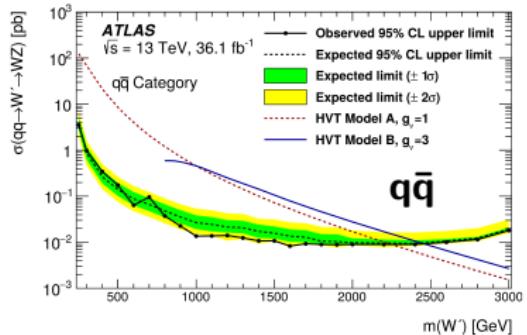
[arXiv:1806.01532](https://arxiv.org/abs/1806.01532)

# Analysis strategy

- $WZ \rightarrow (\ell\nu)(\ell\ell)$  search ( $\ell \in \{e, \mu\}$ )
  - ▶ Use single lepton trigger
  - ▶ Two opposite-sign same-flavour leptons with  $|M_{\ell\ell} - M_Z| < 20$  GeV
- Special  $q\bar{q}$  and VBF selections
  - ▶ VBF category: 2 light-quark jets with  $\Delta\eta_{jj} > 3.5$  and  $M_{jj} > 500$  GeV
  - ▶  $q\bar{q}$  category: Remaining events
- Main backgrounds
  - ▶ SM  $WZ$  production (irreducible)
  - ▶ Data-driven fake/non-prompt estimate
- Signal extraction
  - ▶ Template fit to  $M_{WZ}$  distribution



# Results of the $WZ \rightarrow \ell\nu\ell\ell$ search

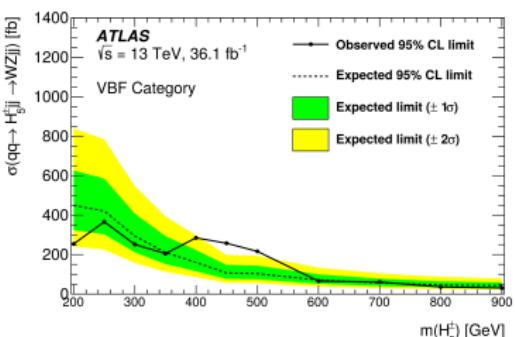


- Heavy Vector Triplet  $W'$  boson interpretation

- $q\bar{q}$  category: Mass limit for HVT A (B) at 2260 (2460) GeV
- VBF category: Slight excess at 450 GeV with  $2.9\sigma$  (local),  $1.6\sigma$  (global, LEE)

- $H_5^\pm$  in Georgi-Machacek model

- $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$  fiveplet
- Fermiophobic  $\rightarrow$  VBF category
- Slight excess at 450 GeV:  $3.1\sigma$  (local),  $1.9\sigma$  (global, LEE)

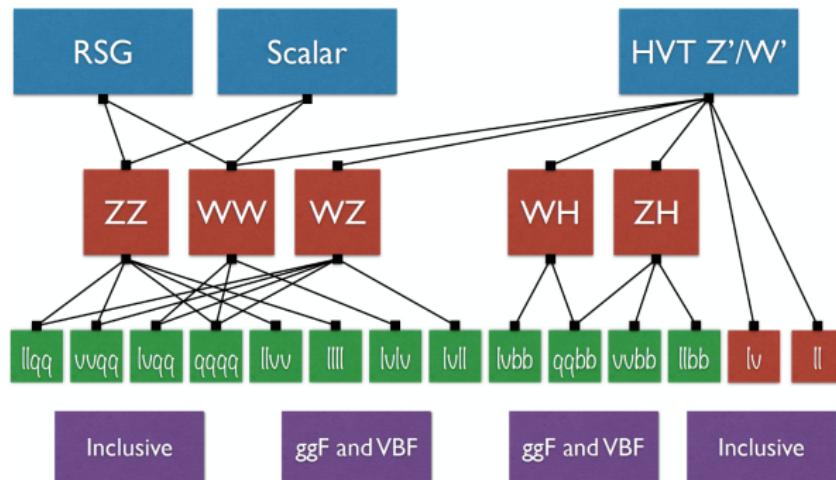


# $VV/VH/\ell\nu/\ell\ell$ combination

ATLAS-EXOT-2017-31

# Final states used for combination

- Combination scope
  - Use inputs from published baseline analyses
  - 14 final states** →  $VV/VH/\ell\ell/\ell\nu$  decay modes → interpretation
  - Systematic uncertainties correlated** where necessary
  - Narrow width assumption ( $\Gamma/M < 5\%$ ); neglect interference effects



- Chose **step-wise combination** procedure
  - $VV + VH + (\ell\nu/\ell\ell) \rightarrow (VV/VH) + (\ell\nu/\ell\ell) \rightarrow (VV/VH/\ell\nu/\ell\ell)$
  - Intermediate combination results included in paper, too

# Selection and statistical analysis

- Overview of **selections**

- ▶ Final states involve  $e$ ,  $\mu$ , jets (different types) and  $E_T^{\text{miss}}$
- ▶ **Orthogonality** between channels ensured due to chosen cuts

Channel	Diboson state	Selection			VBF cat.
		Leptons	$E_T^{\text{miss}}$	Jets	
$qqqq$	$WW/WZ/ZZ$	0	veto	2J	–
$vvqq$	$WZ/ZZ$	0	yes	1J	–
$\ell vqq$	$WW/WZ$	$1e, 1\mu$	yes	2j, 1J	–
$\ell \ell qq$	$WZ/ZZ$	$2e, 2\mu$	–	2j, 1J	–
$\ell \ell vv$	$ZZ$	$2e, 2\mu$	yes	–	0
$\ell v \ell v$	$WW$	$1e+1\mu$	yes	–	0
$\ell v \ell \ell$	$WZ$	$3e, 2e+1\mu, 1e+2\mu, 3\mu$	yes	–	0
$\ell \ell \ell \ell$	$ZZ$	$4e, 2e+2\mu, 4\mu$	–	–	yes
$qbbb$	$WH/ZH$	0	veto	2J	1, 2
$vvbb$	$ZH$	0	yes	2j, 1J	1, 2
$\ell vbb$	$WH$	$1e, 1\mu$	yes	2j, 1J	1, 2
$\ell \ell bb$	$ZH$	$2e, 2\mu$	veto	2j, 1J	1, 2
$\ell v$	–	$1e, 1\mu$	yes	–	–
$\ell \ell$	–	$2e, 2\mu$	–	–	–

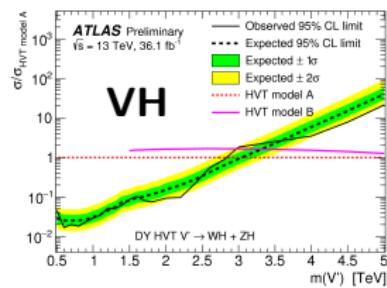
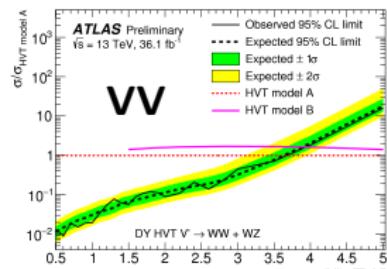
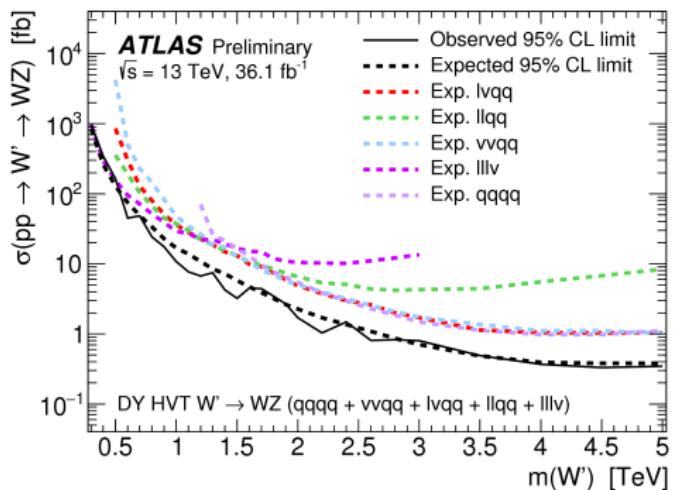
j = small- $R$  jet, J = large- $R$  jet

- Channels combined with **profile likelihood approach to yield**
  - ▶ Exclude regions with  $CL_S < 0.05$
  - ▶ Rely on **asymptotic assumption** for full pole mass range

# Cross-section limits from bosonic decay modes

## • Sensitivity comparison

- ▶ Fully leptonic: Sensitive mainly to low  $M_{V'}$
- ▶ Semi-leptonic: Broad sensitivity distribution
- ▶ All-hadronic: Main contribution at high  $M_{V'}$

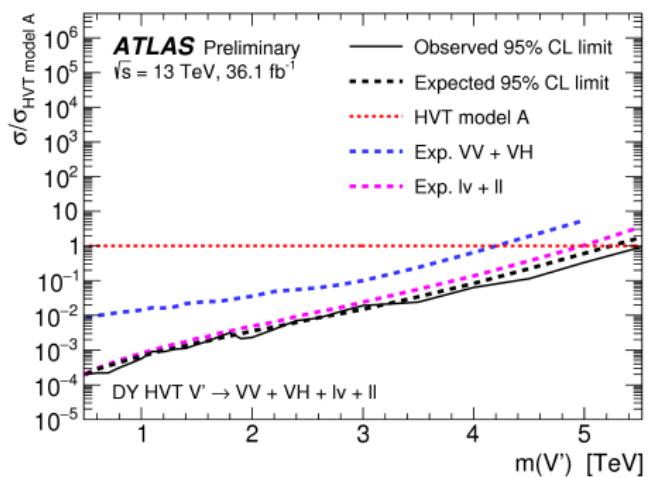


## • Significant sensitivity improvements

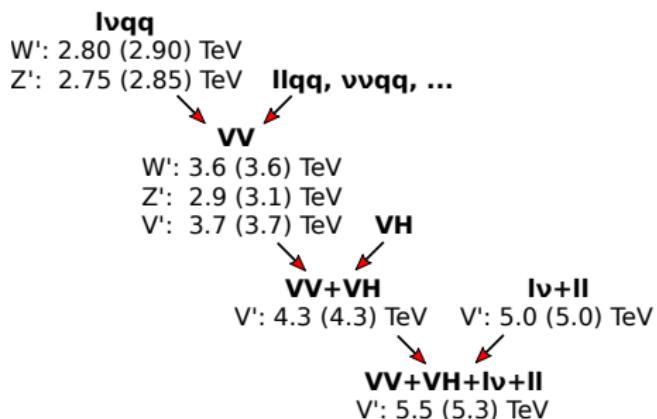
- ▶  $VV$  compared to single best channel ( $\ell\nu qq$ )
- ▶  $VV/VH$  compared to  $VV$

# Leptonic and combined cross-section limits

- Examples here give limits for HVT A
  - ▶ Relative importance of  $VV/VH$  and  $\ell\nu/\ell\ell$  depends on couplings
  - ▶ HVT B dominated by  $VV/VH$
- Combination of leptonic channels
  - ▶  $\ell\nu/\ell\ell$  similar sensitive in full mass range



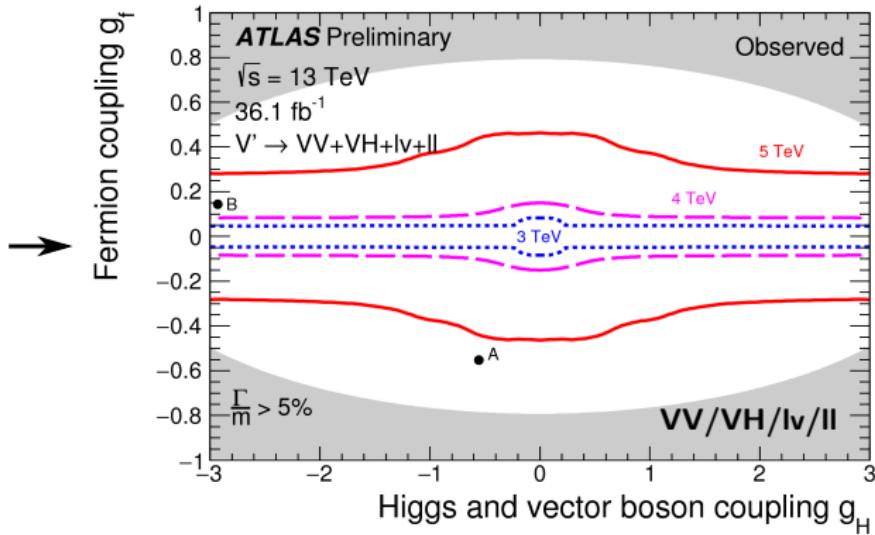
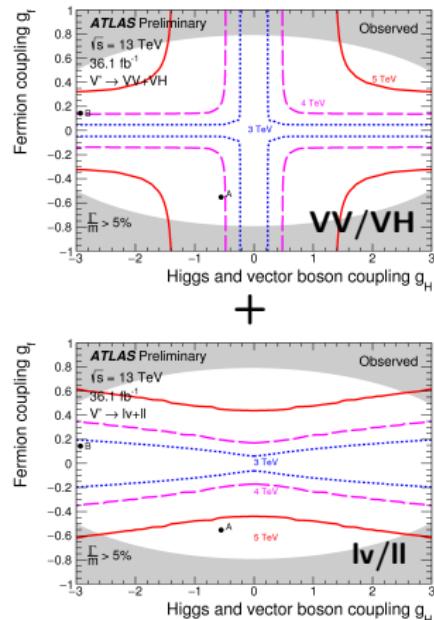
Observed (expected) mass limits for HVT A



# $VV/VH$ and $\ell\nu/\ell\ell$ mass limits in coupling plane

## • Higgs and (universal) fermion couplings

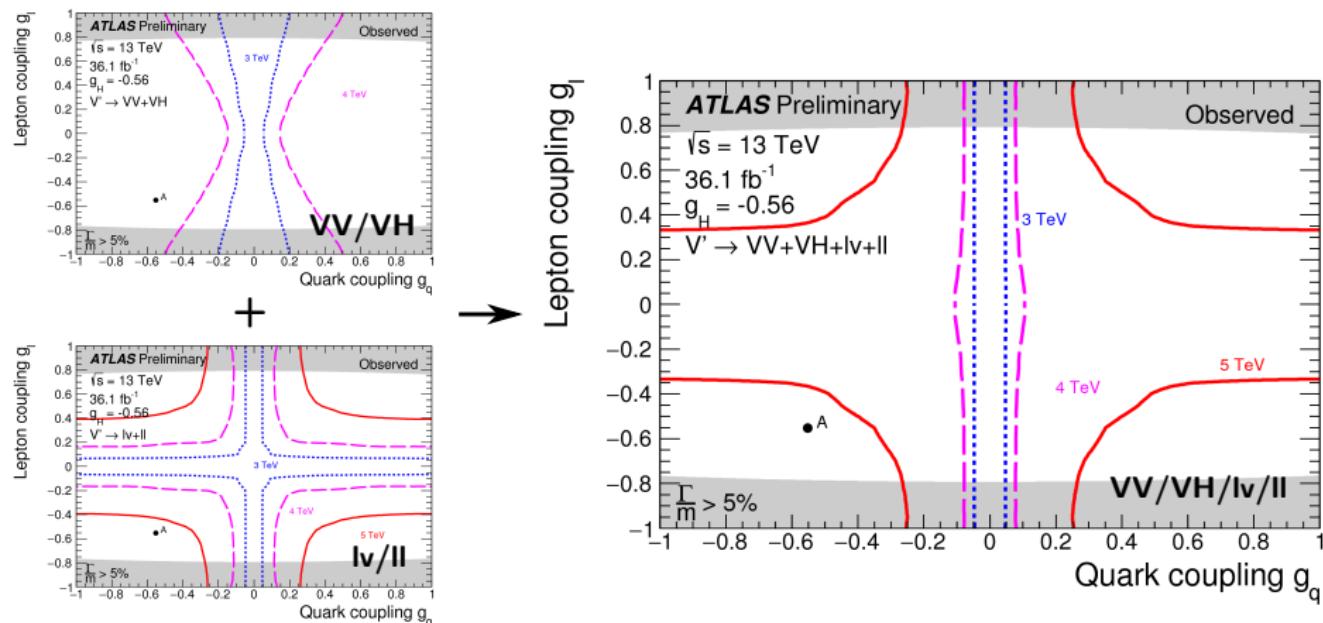
- ▶ Couplings regions outside contours are excluded
- ▶  $VV/VH$ : Excludes large  $g_H$  regions;  $BR \rightarrow 0$  for  $g_H \rightarrow 0$
- ▶  $\ell\nu/\ell\ell$ : Provides sensitivity for small  $g_H$



# $VV/VH$ and $\ell\nu/\ell\ell$ mass limits in coupling plane

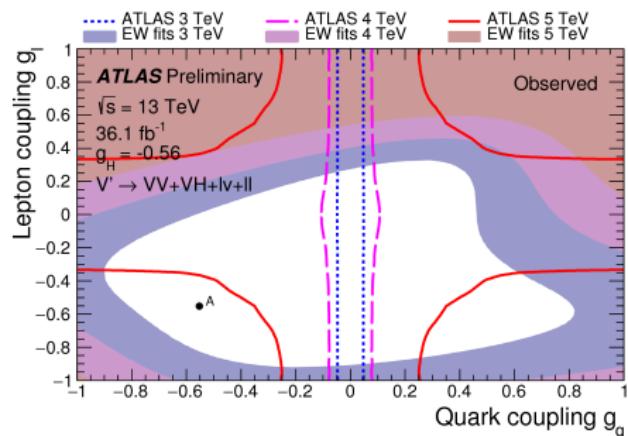
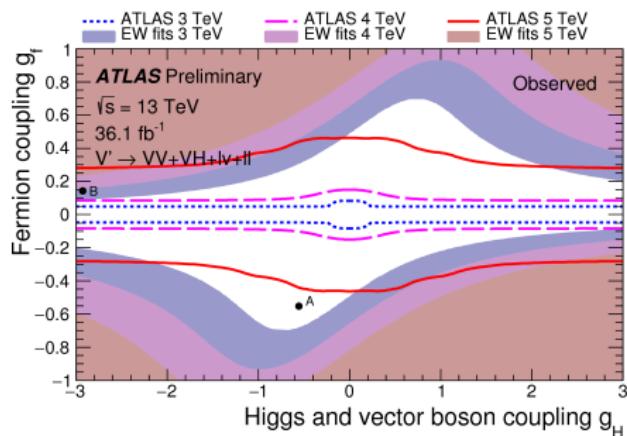
- **Quark and lepton couplings** for  $g_H = -0.56$

- ▶ No sensitivity for low  $g_q$  as cross-section  $\rightarrow 0$
- ▶ Strongest constraints from  $\ell\nu/\ell\ell$ , except at low  $g_l$  ( $BR \rightarrow 0$ )
- ▶  $VV/VH$  complements sensitivity at low  $g_l$



# Constraints from precision EWK measurements

- Comparison with constraints from  $VV/VH/\ell\nu/\ell\ell$  combination
  - ▶ Stronger in entire  $(g_H, g_F)$  plane
  - ▶ Stronger in most of  $(g_q, g_l)$  plane
    - Exception is low  $g_q$  region  $\rightarrow$  cross-section  $\rightarrow 0$  at LHC
  - ▶ Asymmetric behaviour due to interference effects



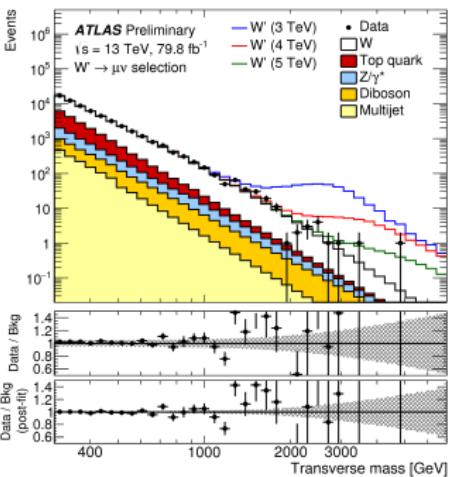
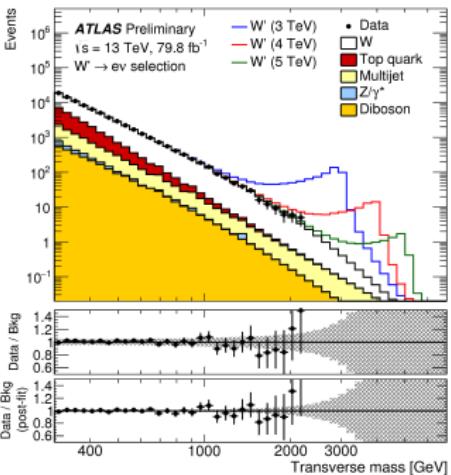
EWK curves from J. de Blas (update of [arXiv:1005.3998](https://arxiv.org/abs/1005.3998))

# $W' \rightarrow \ell\nu$ search

ATLAS-CONF-2018-017

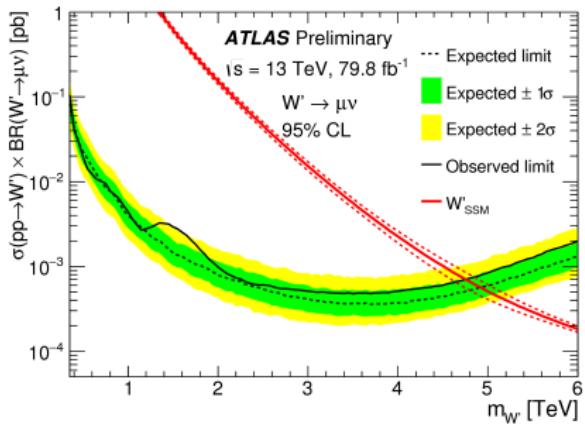
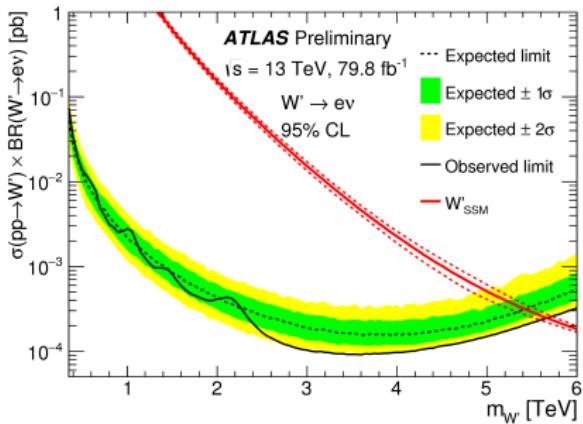
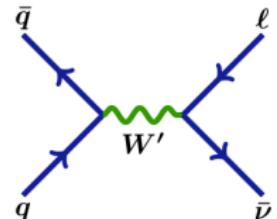
# Analysis strategy

- Signature: **Hard lepton +  $E_T^{\text{miss}}$** 
  - Use single lepton trigger
  - $e\nu$ :  $p_{T,e} > 65 \text{ GeV}$ ,  $E_T^{\text{miss}} > 65 \text{ GeV}$
  - $\mu\nu$ :  $p_{T,\mu} > 55 \text{ GeV}$ ,  $E_T^{\text{miss}} > 55 \text{ GeV}$
  - Dedicated muon selection**  
→ good reconstruction at high  $p_T$
- Variable of interest: **Transverse mass**
  - $M_T = \sqrt{2p_T^\ell E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi_\ell, E_T^{\text{miss}})}$
- Main backgrounds
  - SM off-shell  $W \rightarrow \ell\nu$  production
  - Top-quark production
  - Data-driven fake/non-prompt estimate  
→ originating from multijet events
- Signal extraction
  - Template fit to  $M_T$  distribution  
for  $M_T > 300 \text{ GeV}$



# Results of the $W' \rightarrow \ell\nu$ search

- **Sequential Standard Model** used as benchmark
  - ▶ Identical couplings of  $W'$  to fermions as SM  $W$
  - ▶ Equal to HVT model at  $g_q = g_l = \frac{e}{\sin \theta_W}$



- Limits set on **production rate**
  - ▶ No excess observed
  - ▶  $e\nu$ :  $\sigma \times \text{BR} < 10^{-1} - 9 \cdot 10^{-5} \text{ pb}$
  - ▶  $\mu\nu$ :  $\sigma \times \text{BR} < 10^{-1} - 4 \cdot 10^{-4} \text{ pb}$
- **$W'_{\text{SSM}}$  excluded up to 5.6 TeV**

Decay	$m_{W'}$ lower limit [TeV] Expected	$m_{W'}$ lower limit [TeV] Observed
$W' \rightarrow e\nu$	5.4	5.7
$W' \rightarrow \mu\nu$	4.9	4.8
$W' \rightarrow \ell\nu$	5.5	5.6

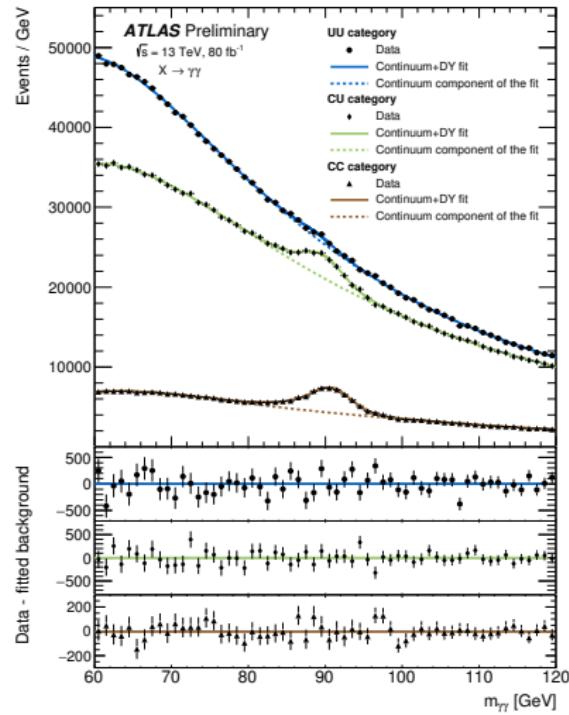
# Low-mass $\gamma\gamma$ search

ATLAS-CONF-2018-025

(High-mass  $\gamma\gamma$  search available at [arXiv:1707.04147](https://arxiv.org/abs/1707.04147))

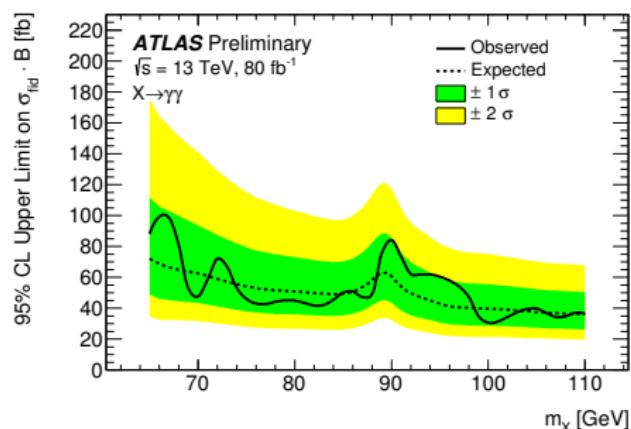
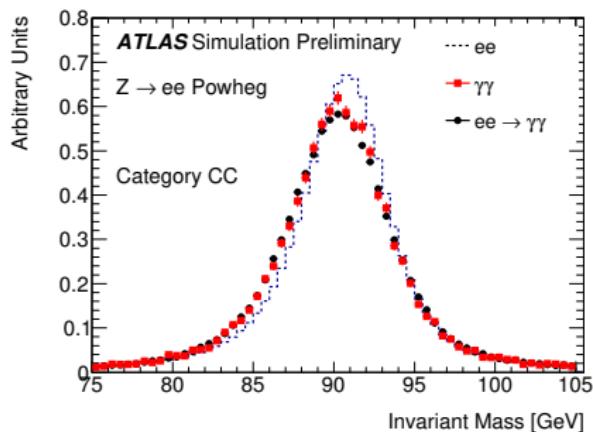
# Analysis strategy

- Search for  $X \rightarrow \gamma\gamma$  decays ( $M_X < M_H$ )
  - Use diphoton triggers with  $E_{T,\text{thr}} = 20(22)$  GeV
  - $E_{T,\gamma} > 22$  GeV required offline  
→ close to **trigger turn-on**
- Categories for **(un)converted photons**
  - Separation between UU, CU and CC
- Main **backgrounds**
  - SM  $\gamma\gamma$ ,  $\gamma j$  and  $jj$  QCD production
  - Mis-ID of ee pairs from DY production
- Signal extraction
  - Fit of analytic functions to  $60 \text{ GeV} < M_{\gamma\gamma} < 120 \text{ GeV}$  range
  - Signal model with  $\Gamma/M \simeq 0$   
→ dominated by detector resolution



# Results of the low-mass $\gamma\gamma$ search

- **Modelling of misidentified ee pairs from DY production**
  - ▶ Shape determination from ee data after kinematic transformation (correction for Bremsstrahlung)
  - ▶ Normalisation computed from  $e \rightarrow \gamma$  fake rates in data



- **Exclusion limits set on  $X \rightarrow \gamma\gamma$  production**
  - ▶  $\sigma_{fid} \times BR < 40 - 75$  fb, slightly higher limit around  $Z$  peak
  - ▶ Cannot confirm  $2.8\sigma$  (local) effect at  $M_X = 95$  GeV **reported by CMS**

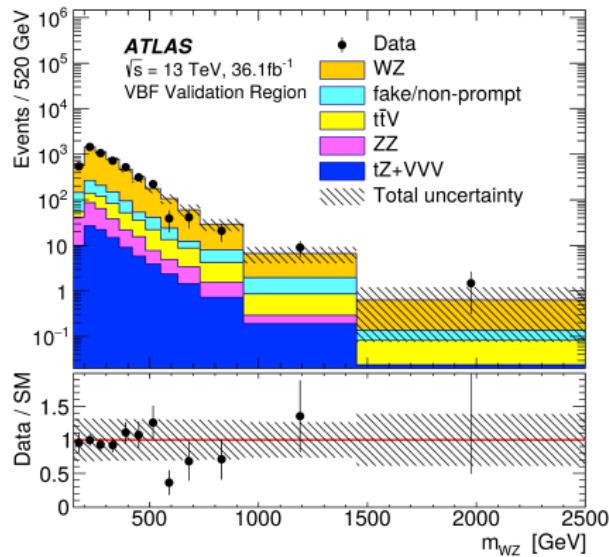
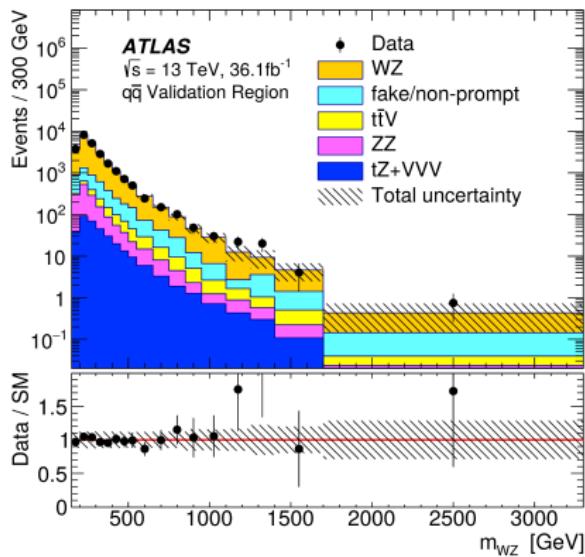
# Summary

# Summary

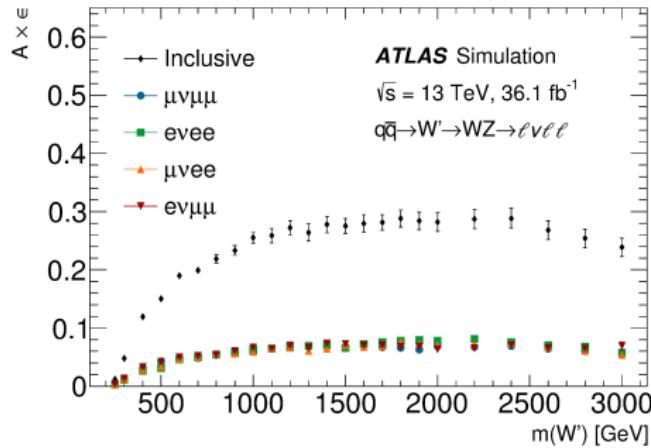
- High-mass resonances with various final states investigated at ATLAS
- **Extensive analysis of 2015/16 dataset**
  - ▶  $WZ \rightarrow l\nu ll$  search
  - ▶ **First VV/VH/lν/lI combination** performed at the LHC
- **First results including 2017 data** are available
  - ▶  $W' \rightarrow l\nu$  search
  - ▶ Low-mass  $\gamma\gamma$  search
- Demonstrated **readiness for full Run-2 analyses**
- **No new physics found yet**
  - ▶ More data and new topologies will allow the extend search range

# Backup

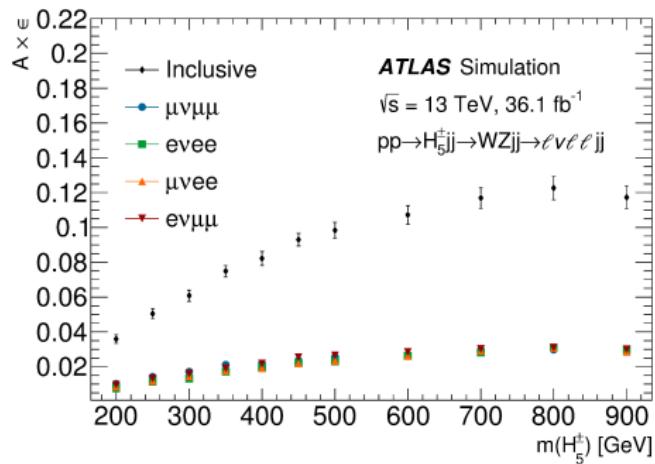
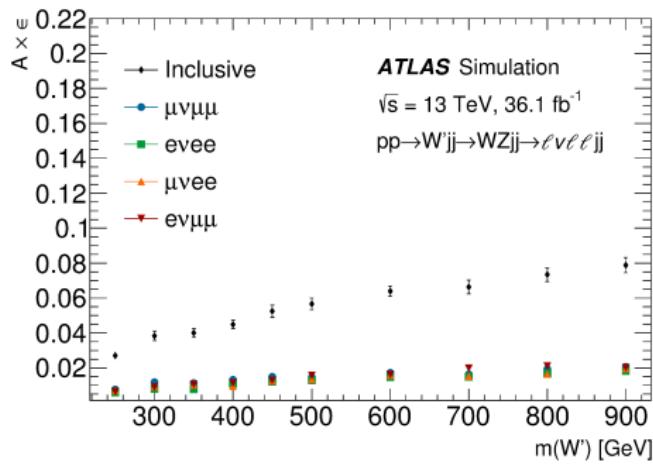
# $WZ \rightarrow \ell\nu\ell\ell$ validation region



# $WZ \rightarrow \ell\nu\ell\ell$ acceptance $\times$ efficiency



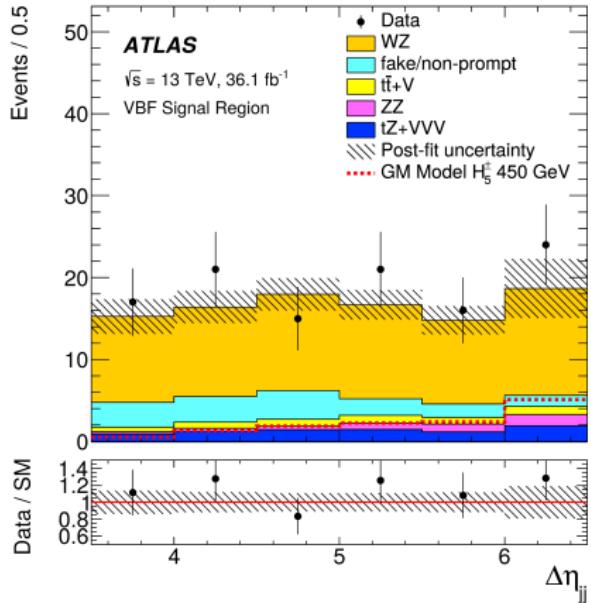
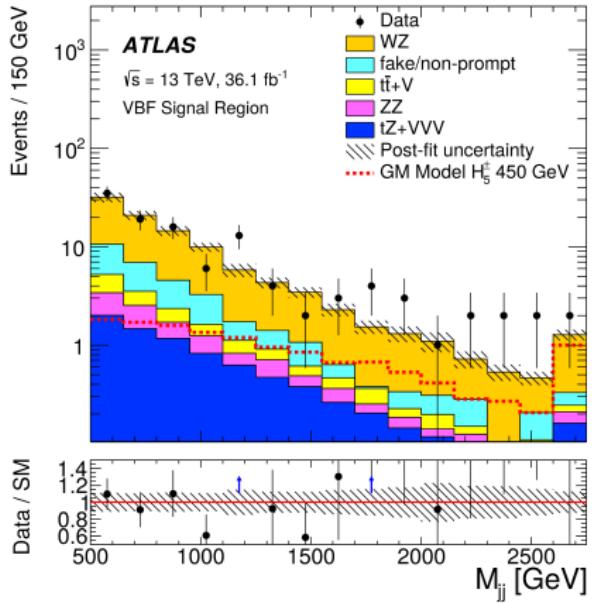
# $WZ \rightarrow \ell\nu\ell\ell$ acceptance $\times$ efficiency



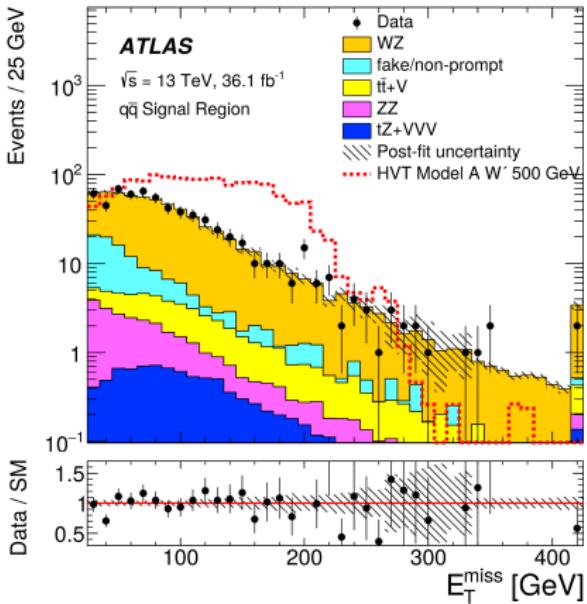
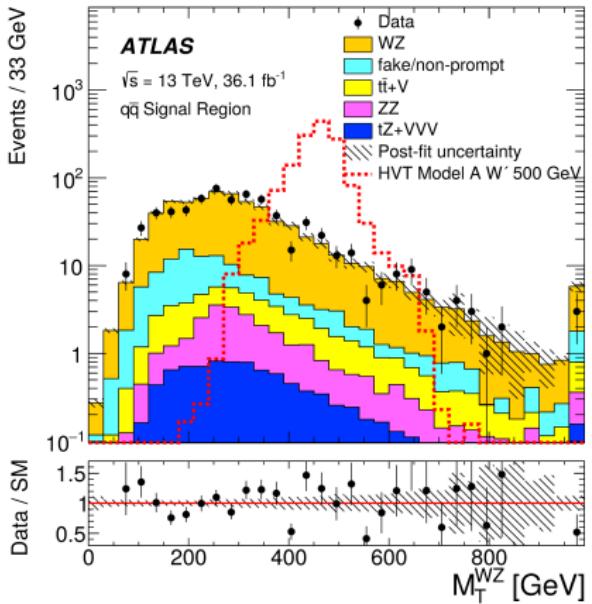
# $WZ \rightarrow \ell\nu\ell\ell$ systematics

Source	$\Delta\mu/\mu [\%]$	
	$q\bar{q}$ Category $m(W') = 800$ GeV	VBF Category $m(H_5^\pm) = 450$ GeV
$WZ$ modelling : Scale, PDF	5	11
$WZ$ 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

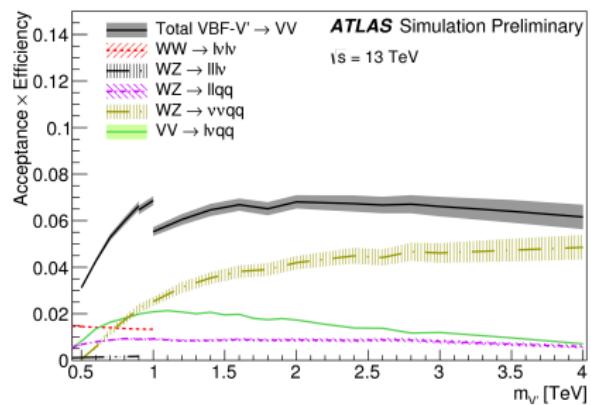
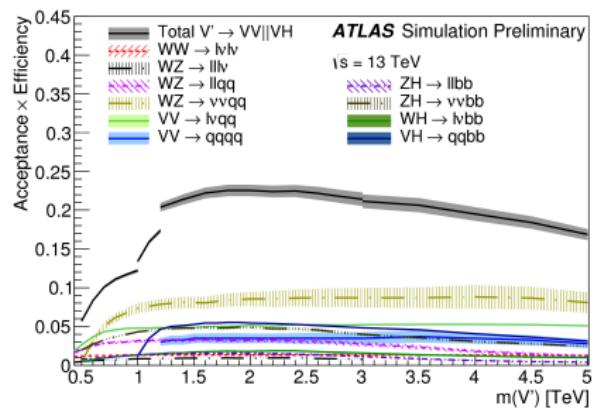
# $WZ \rightarrow \ell\nu\ell\nu$ kinematic distributions



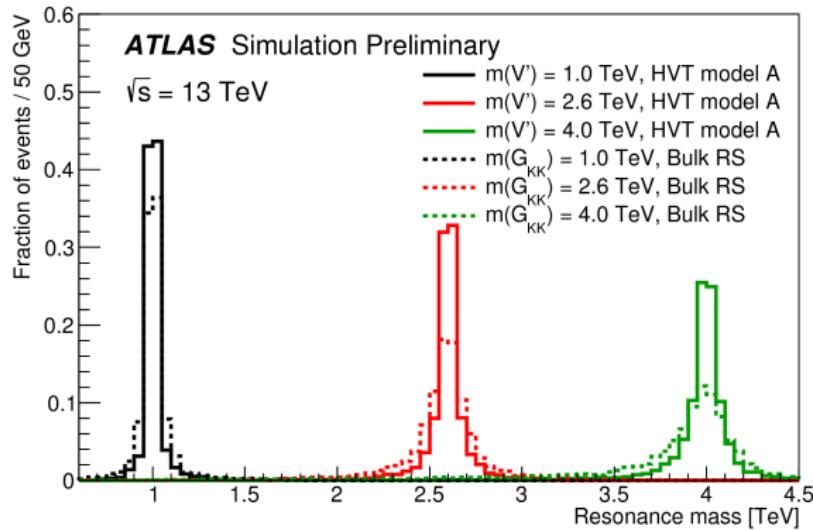
# $WZ \rightarrow \ell\nu\ell\nu$ kinematic distributions



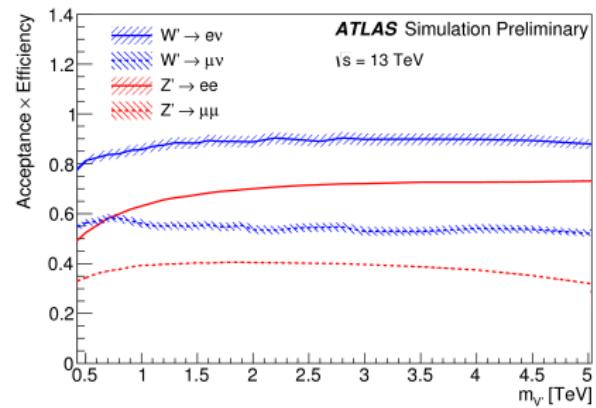
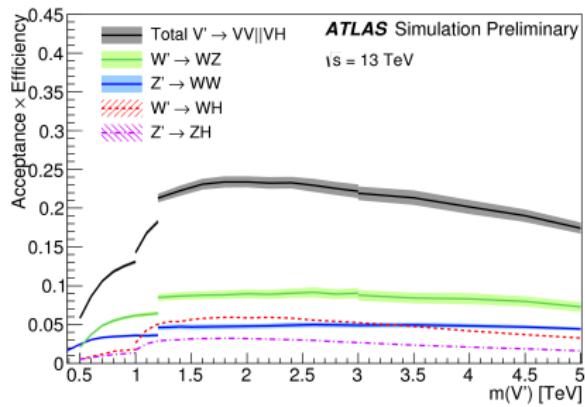
# Combination acceptance $\times$ efficiency



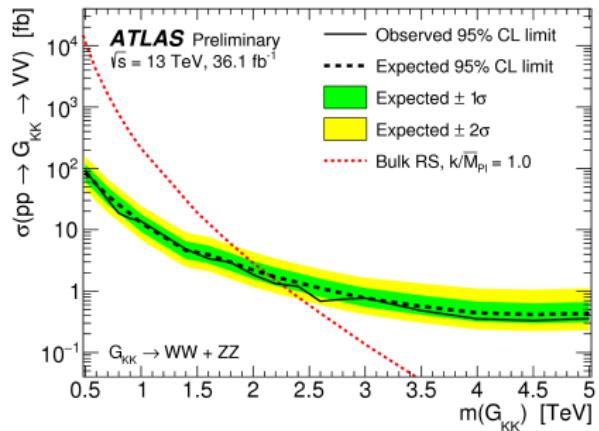
# Combination signal templates



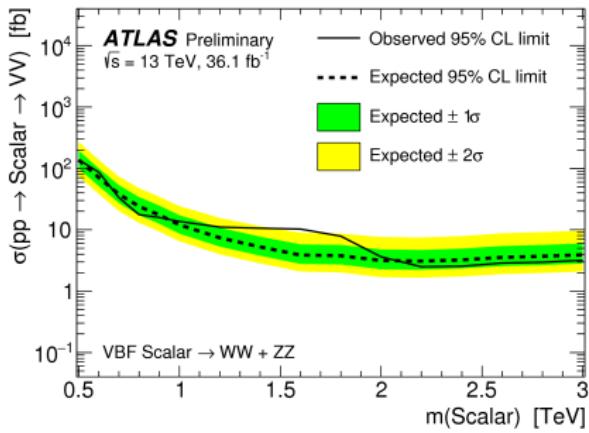
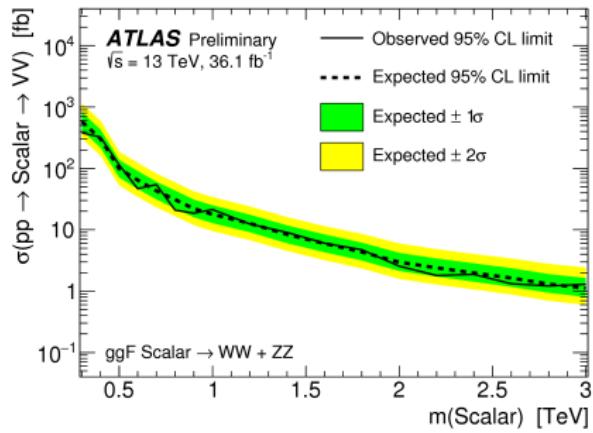
# Combination acceptance $\times$ efficiency



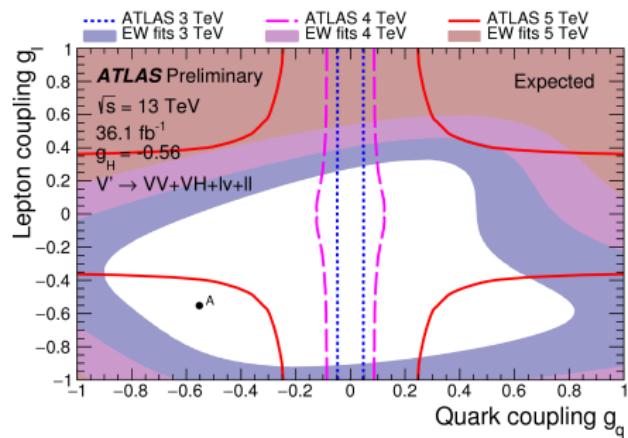
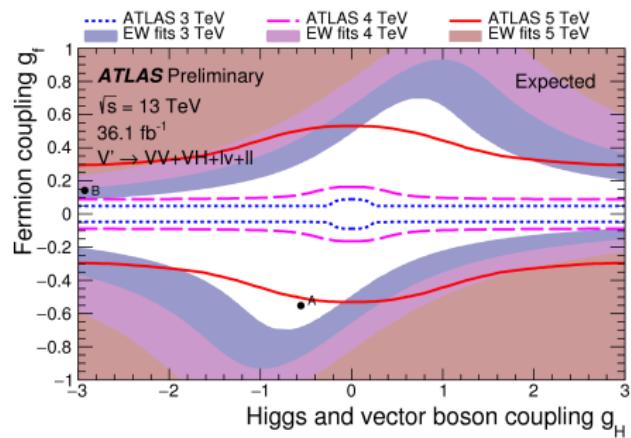
# Combination Graviton limits



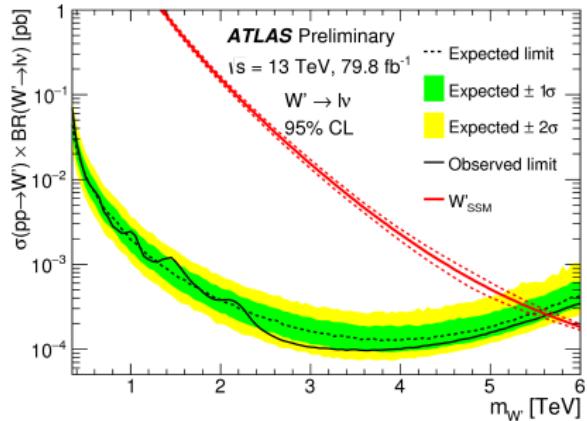
# Combination scalar limits



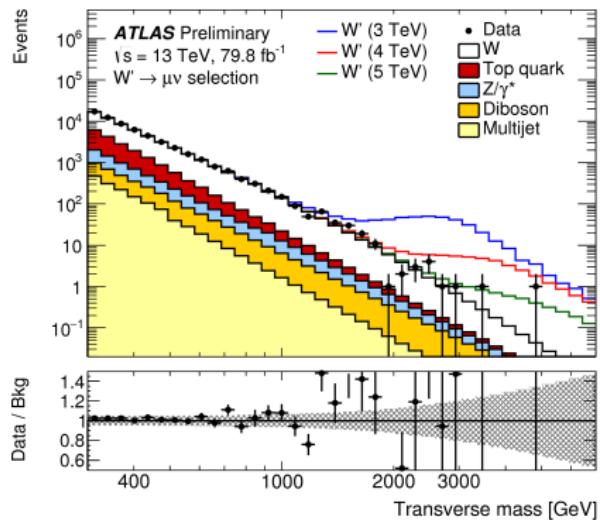
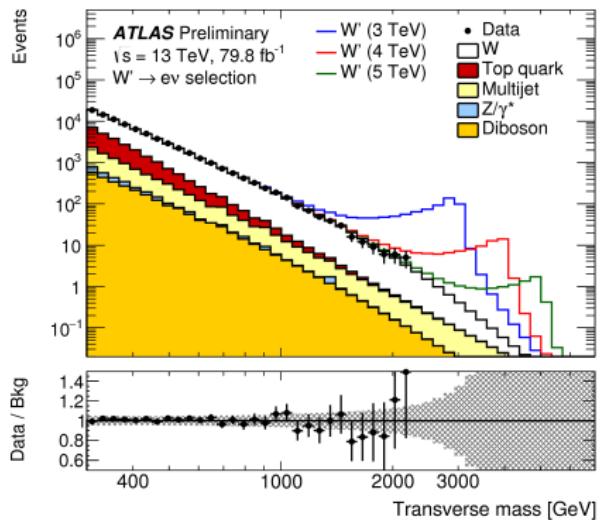
# Combination expected HVT limits



# $W' \rightarrow \ell\nu$ combined limit



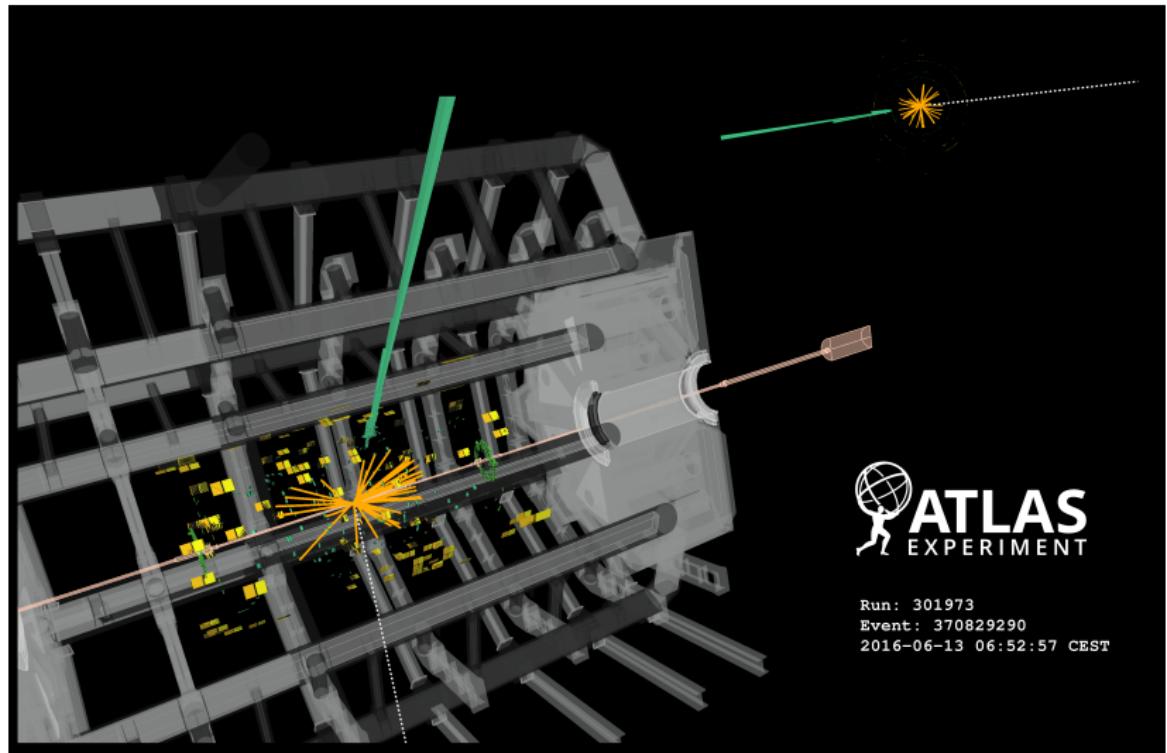
# $W' \rightarrow \ell\nu$ $E_T^{\text{miss}}$ distribution



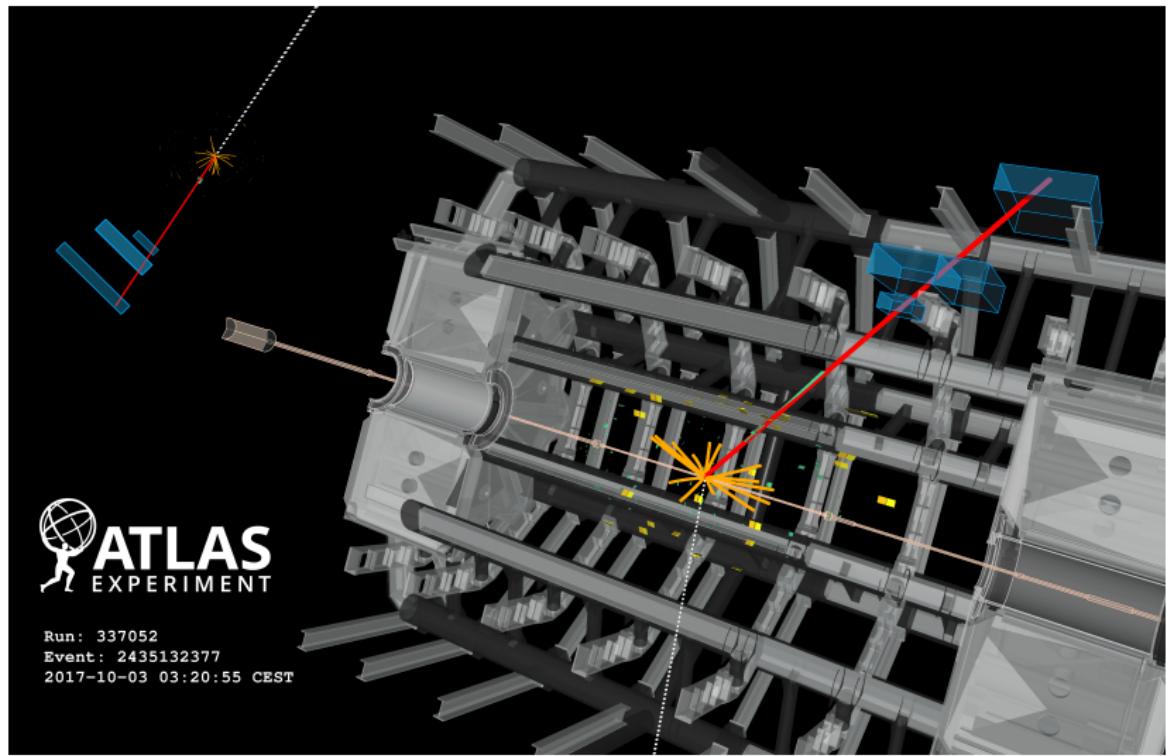
# $W' \rightarrow \ell\nu$ systematics

Source	Electron channel		Muon channel	
	Background	Signal	Background	Signal
Trigger	negl. (negl.)	negl. (negl.)	1% (1%)	2% (2%)
Lepton reconstruction and identification	negl. (negl.)	negl. (negl.)	7% (21%)	5% (29%)
Lepton momentum scale and resolution	4% (3%)	4% (3%)	3% (12%)	7% (10%)
Multijet background	7% (113%)	N/A (N/A)	1% (1%)	N/A (N/A)
Top extrapolation	2% (5%)	N/A (N/A)	3% (3%)	N/A (N/A)
Top normalization	< 0.5% (< 0.5%)	N/A (N/A)	< 0.5% (< 0.5%)	N/A (N/A)
Diboson extrapolation	2% (9%)	N/A (N/A)	3% (10%)	N/A (N/A)
PDF choice for DY	1% (14%)	N/A (N/A)	< 0.5% (< 0.5%)	N/A (N/A)
PDF variation for DY	8% (12%)	N/A (N/A)	7% (11%)	N/A (N/A)
EW corrections for DY	4% (5%)	N/A (N/A)	4% (6%)	N/A (N/A)
Luminosity	2% (1%)	2% (2%)	2% (2%)	2% (2%)
Total	13% (115%)	4% (4%)	12% (29%)	9% (31%)

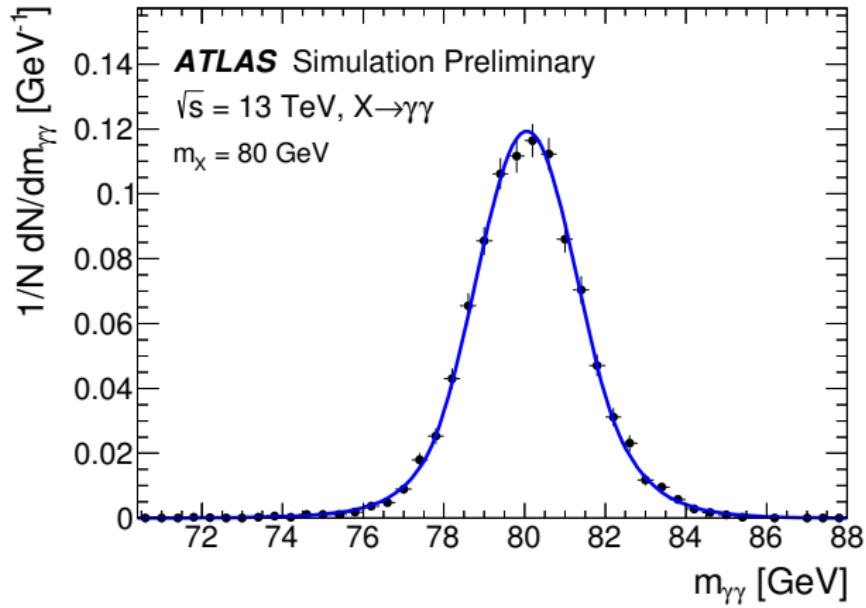
# $W' \rightarrow \ell\nu$ event display for $e\nu$ ( $M_T = 2.2$ TeV)



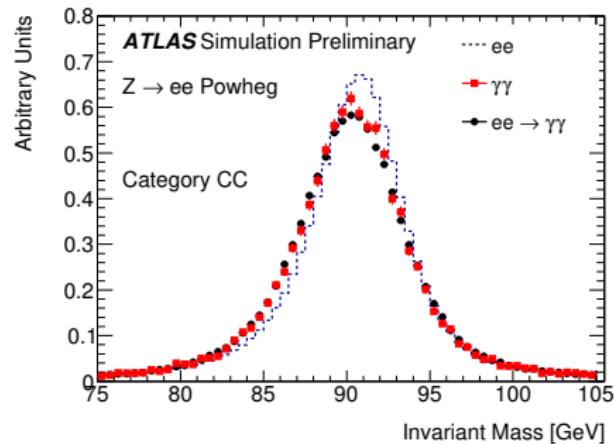
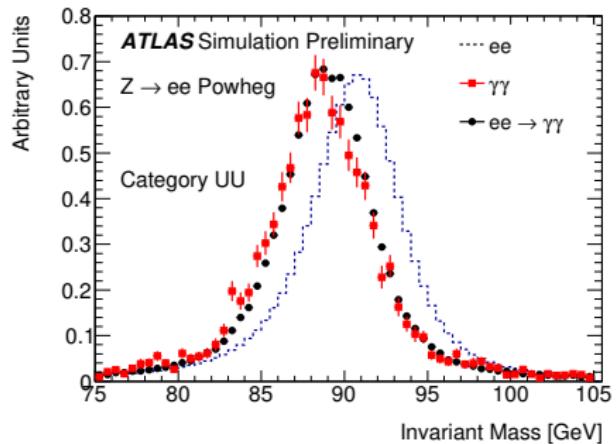
# $W' \rightarrow \ell\nu$ event display for $\mu\nu$ ( $M_T = 5.0$ TeV)



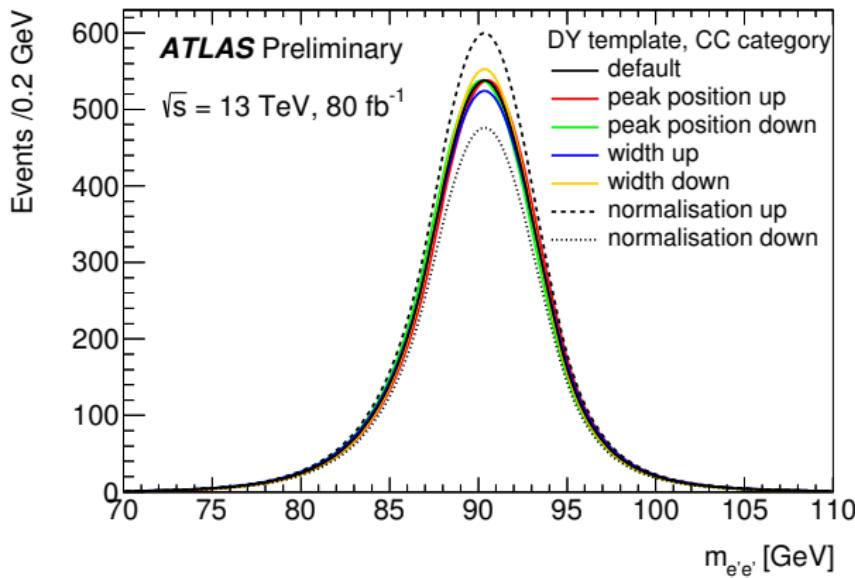
# Low-mass $\gamma\gamma$ signal template



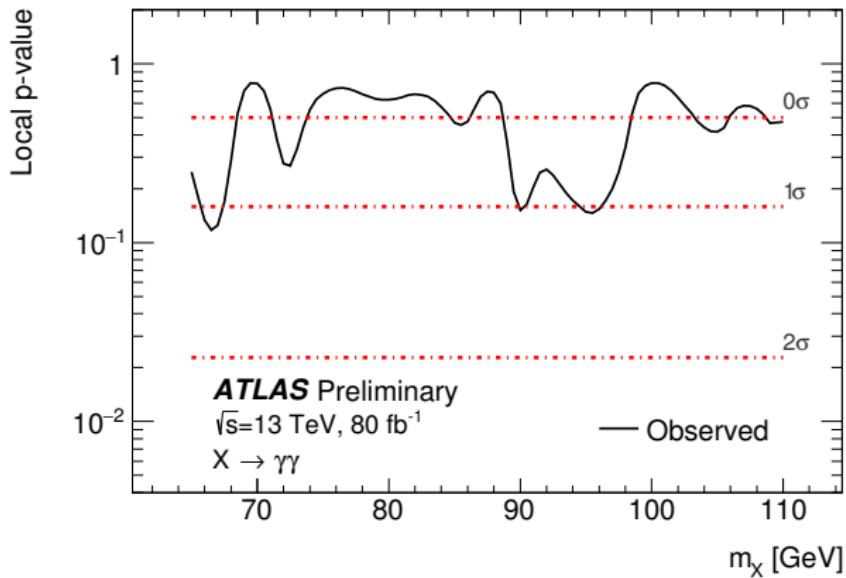
# Low-mass $\gamma\gamma$ DY background



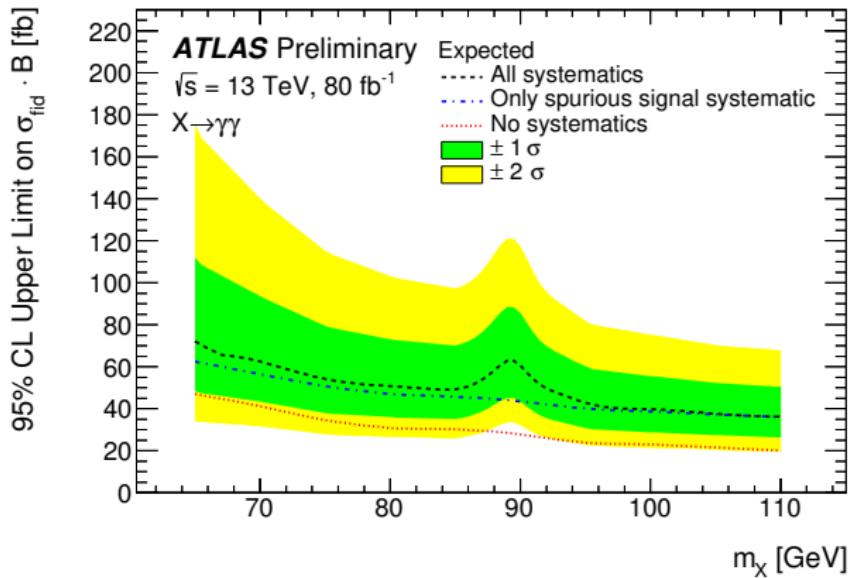
# Low-mass $\gamma\gamma$ DY background



# Low-mass $\gamma\gamma$ local $p$ -values



# Low-mass $\gamma\gamma$ impact of systematics



# Low-mass $\gamma\gamma$ systematics

Source	Uncertainty [%]	Remarks
<i>Signal yield</i>		
Luminosity	$\pm 2$	
Trigger eff.	$\pm 1.4 - 1.7$	$m_X$ -dependent
Photon identification eff.	$\pm 1.5 - 2.3$	$m_X$ -dependent
Isolation eff.	$\pm 4$	
Photon energy scale	$\pm 0.13 - 0.49$	$m_X$ -dependent
Photon energy resolution	$\pm 0.053 - 0.28$	$m_X$ -dependent
Pile-up	$\pm 1.8 - 4.1$	$m_X$ -dependent
Production mode	$\pm 2.4 - 25$	$m_X$ -dependent
<i>Signal modeling</i>		
Photon energy scale	$\pm 0.3 - 0.5$	$m_X$ - and category-dependent
Photon energy resolution	$\pm 2 - 8$	$m_X$ - and category-dependent
<i>Migration between categories</i>		
Material	$-2.0 / +1.0 / +4.1$	category-dependent (UU/CU/CC)
<i>Non-resonant Background</i>		
Spurious Signal	128 / 104 / 79 (604 / 496 / 181 events)	ratio to the expected spurious signal uncertainty (category-dependent)
<i>DY Background modeling</i>		
Peak position	$\pm 0.1 - 0.2$	category-dependent
Peak width	$\pm 2 - 3$	category-dependent
Normalization	$\pm 9 - 21$	category-dependent