

# SEARCHES FOR VH AND HH RESONANCES

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EPS-HEP, Venice

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# Overview

## Massive Higgs + Boson Resonances

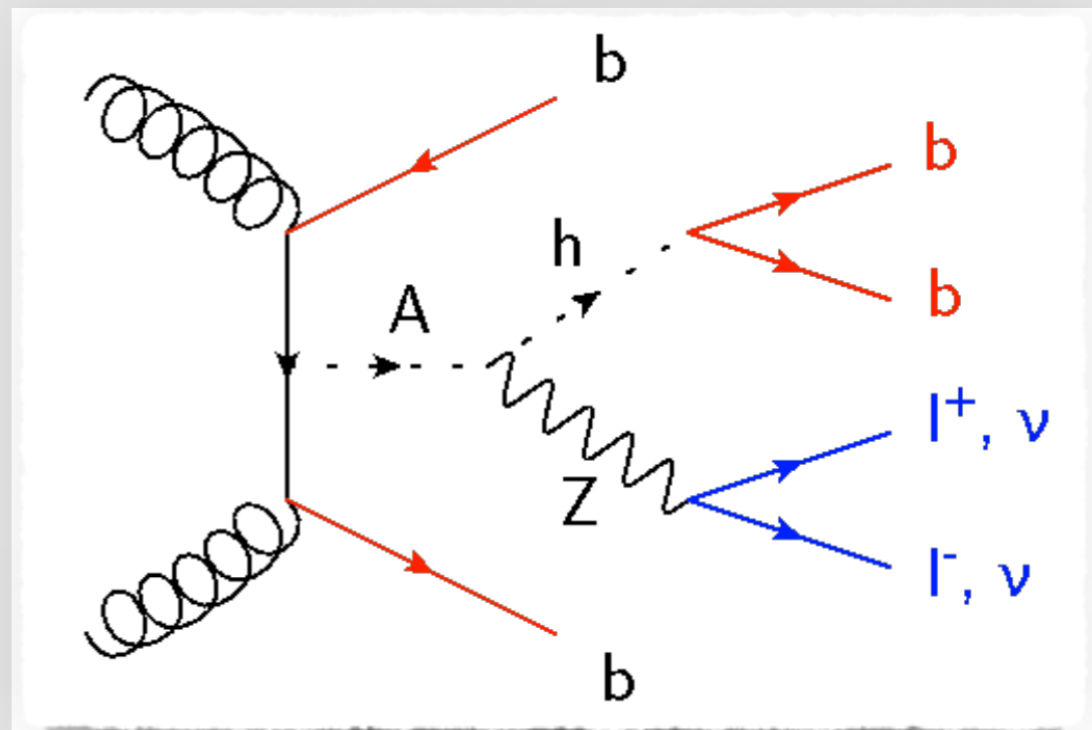
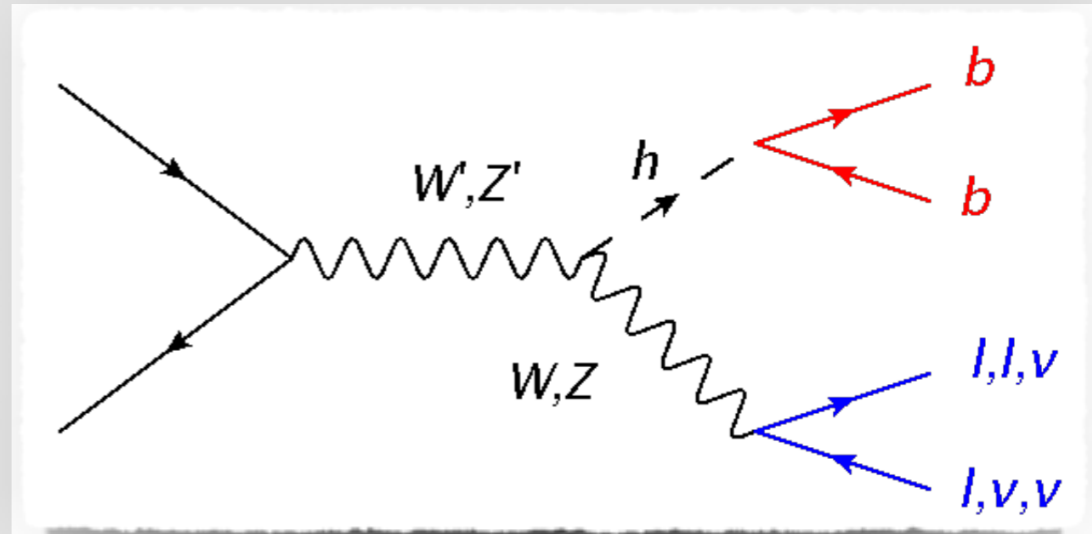
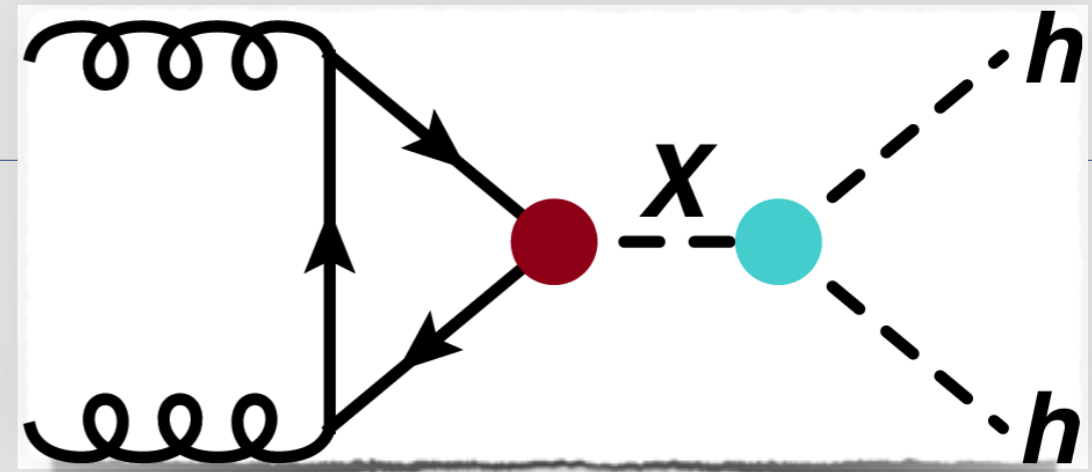
- Neither exhaustive nor complete summary of ATLAS results

## Vector Boson + Higgs Resonances

- Semi-leptonic searches
- Fully hadronic search
- Vector Triplet and 2HDM interpretations

## Di-Higgs Searches

- Resonant and non-resonant searches
- $bbbb$ ,  $bb\gamma\gamma$  and  $bbWW$  final states



# Vector Boson + Higgs Resonances

## Search for resonances decaying into Zh or Wh

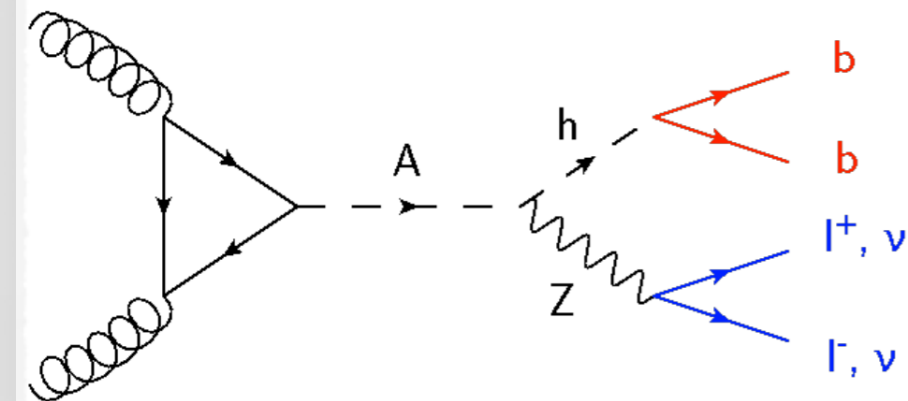
### 2 Higgs Doublet Models

- Extension of SM with additional Higgs doublet  $\Rightarrow$  5 Higgses: H, h, H<sup>+</sup>, H<sup>-</sup>, **A**
- Appear in extensions of the SM such as SUSY, axion models, baryogenesis

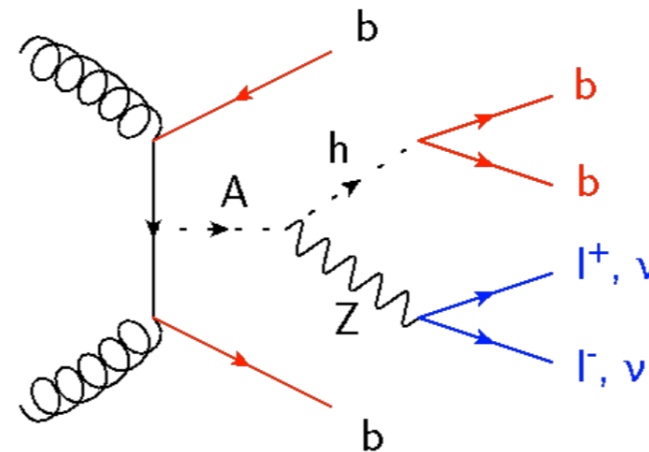
### Heavy Vector Triplets

- Several SM extensions predict the existence of heavy vector bosons
- HVT: simplified model with **additional SU(2) vector triplet**  $\Rightarrow$  **W'<sup>+</sup>, W'<sup>-</sup>, Z'**

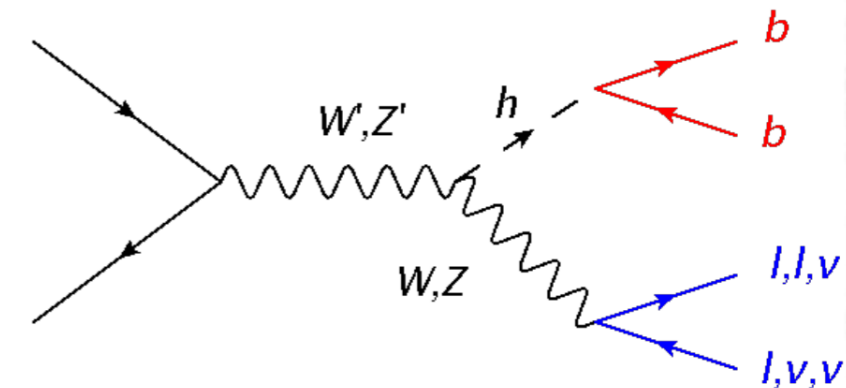
#### gluon fusion - A



#### bbA



#### W',Z' production



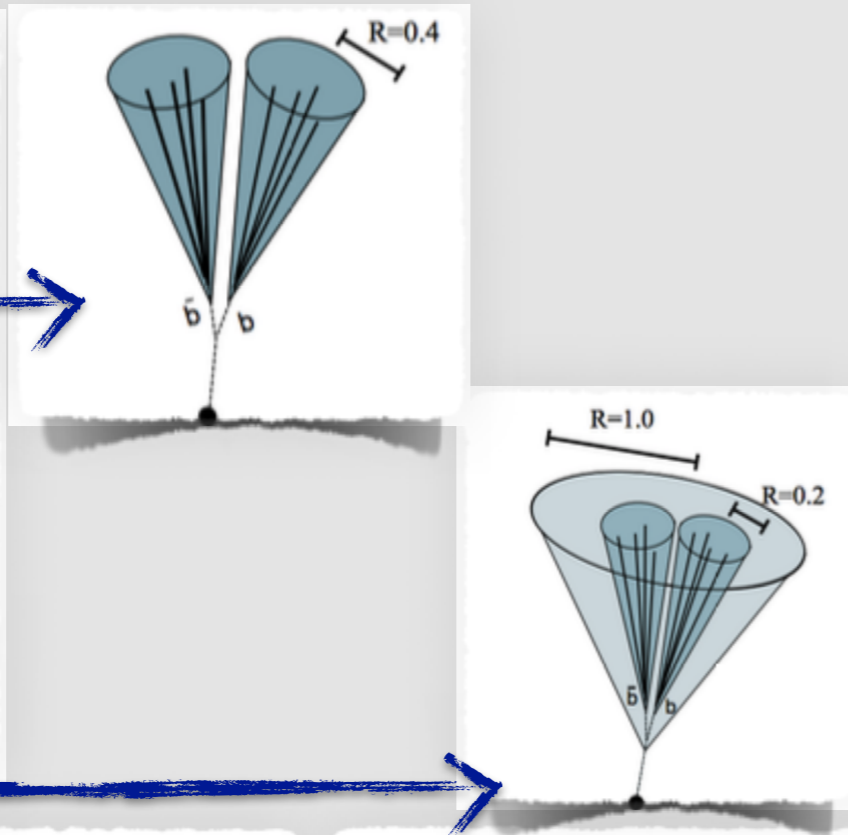
# Semi-Leptonic VH

**Resolved**

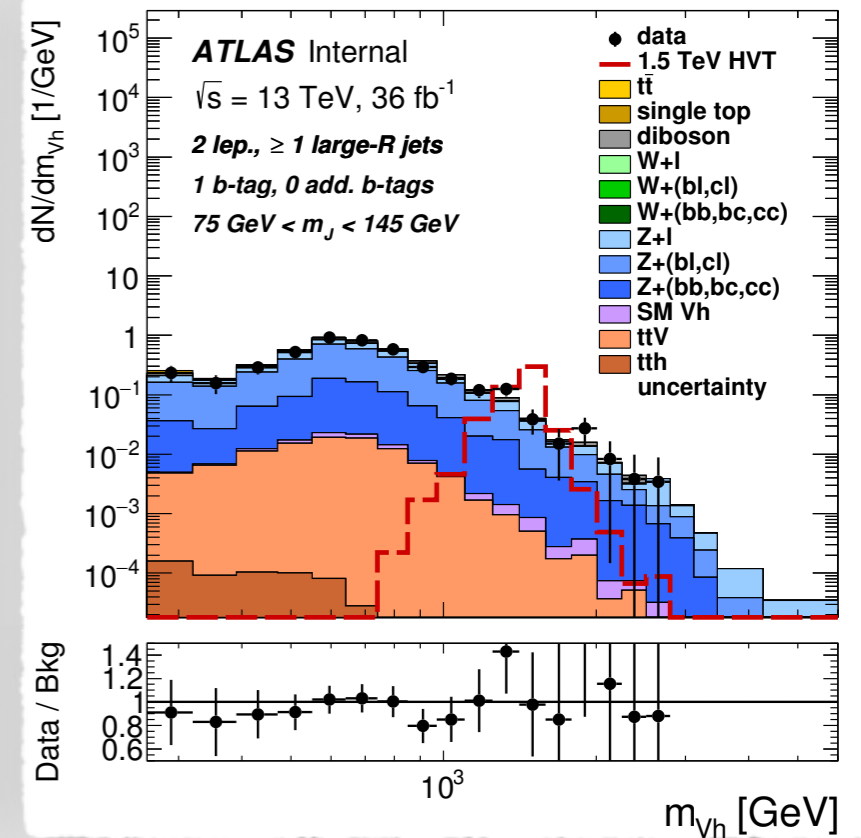
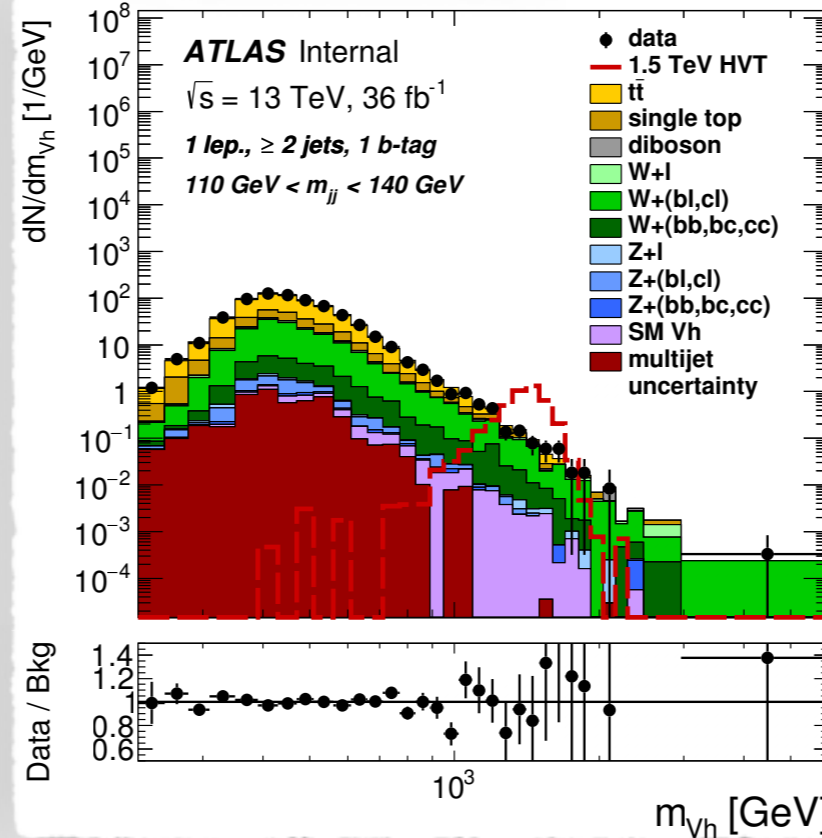
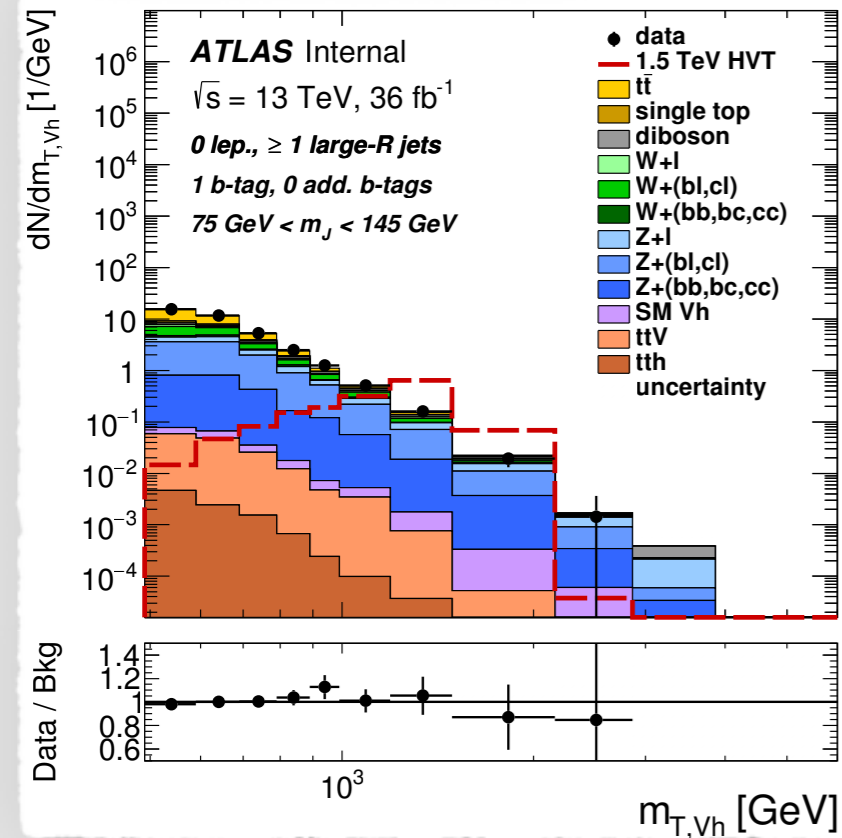
R=0.4  
calo-jets

**Merged**

R=1 calo-jet  
+ ghost associated  
R=0.2 track-jets



- **Resolved & merged** categories
- **3 channels** based on V decays
  - 0/2-lepton (A, Z')
  - 1-lepton (W')
- **b-tag categories:**
  - 1/2-tag used for A and V'
  - 3+ tag used for A (sensitive to bbA)
- **Fit  $m(Vh)$  or  $m_T(Vh)$  spectrum**

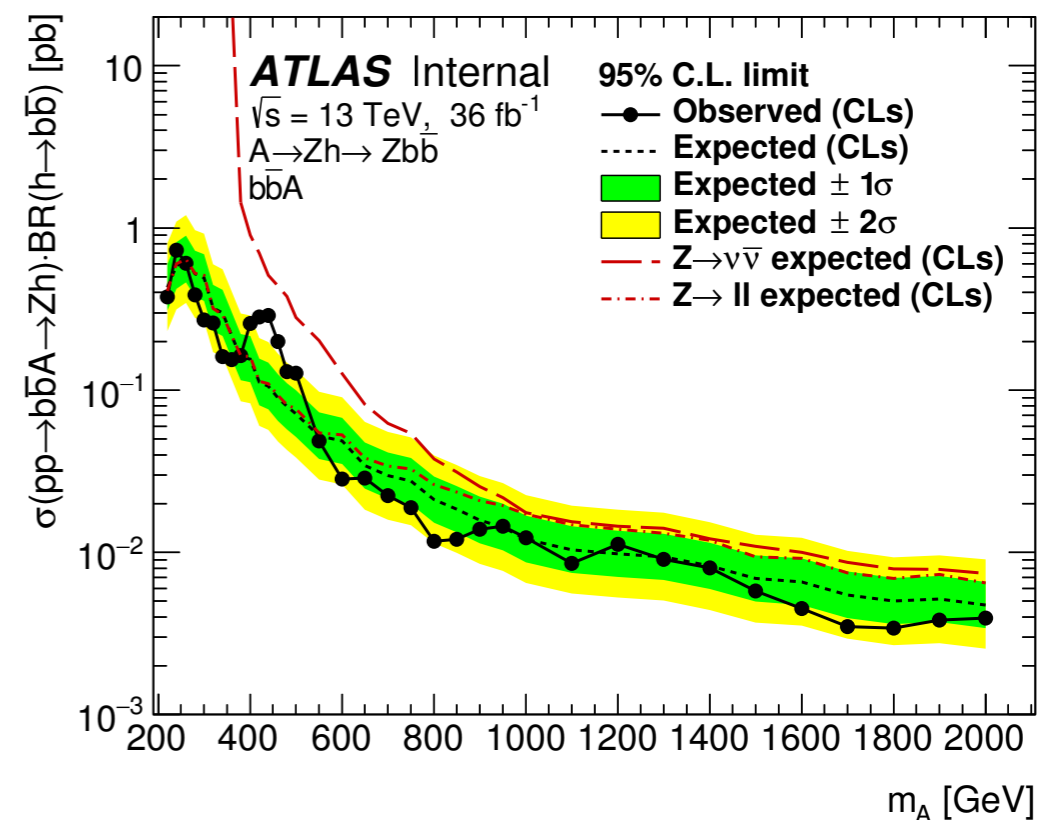
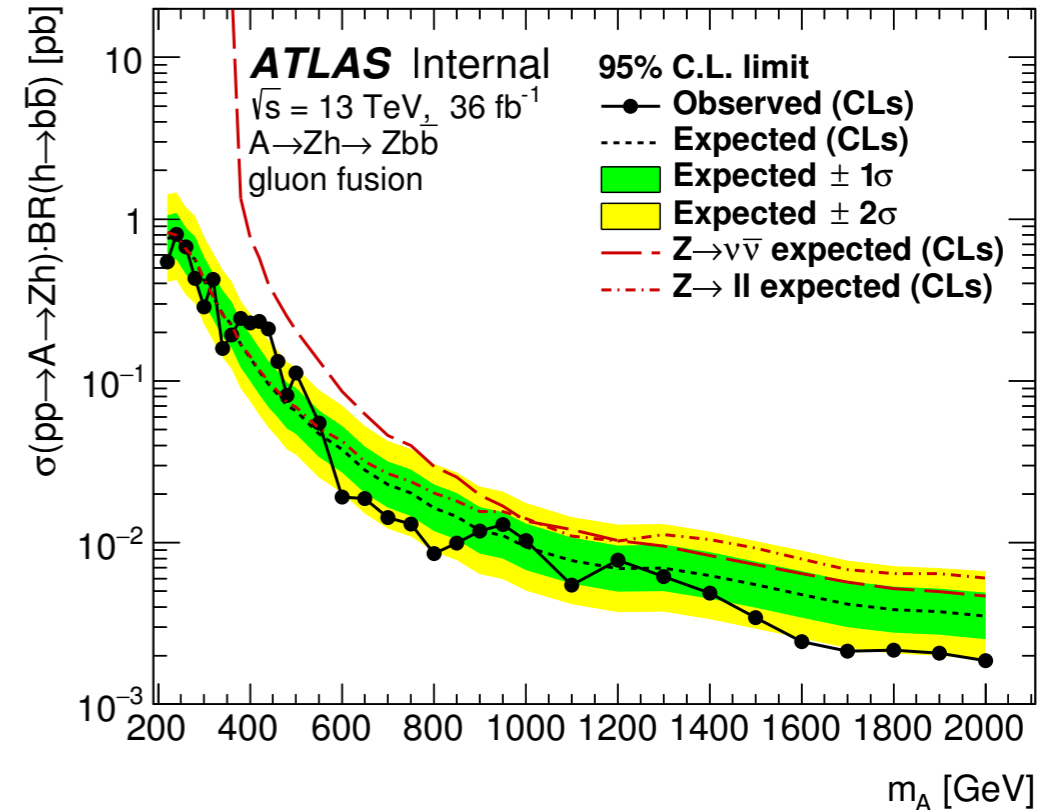


# VH Leptonic: $A \rightarrow Zh$ Interpretation

A-boson:

- Mild excess at  $m=440$  GeV - mostly coming from 3+ tag region in 2-lepton
- Local (global) significance: 3.6 (2.4)  $\sigma$
- 2D limits as a function of  $m_A$ ,  $\tan\beta$  or  $\tan\beta$ ,  $\cos(\beta-\alpha)$

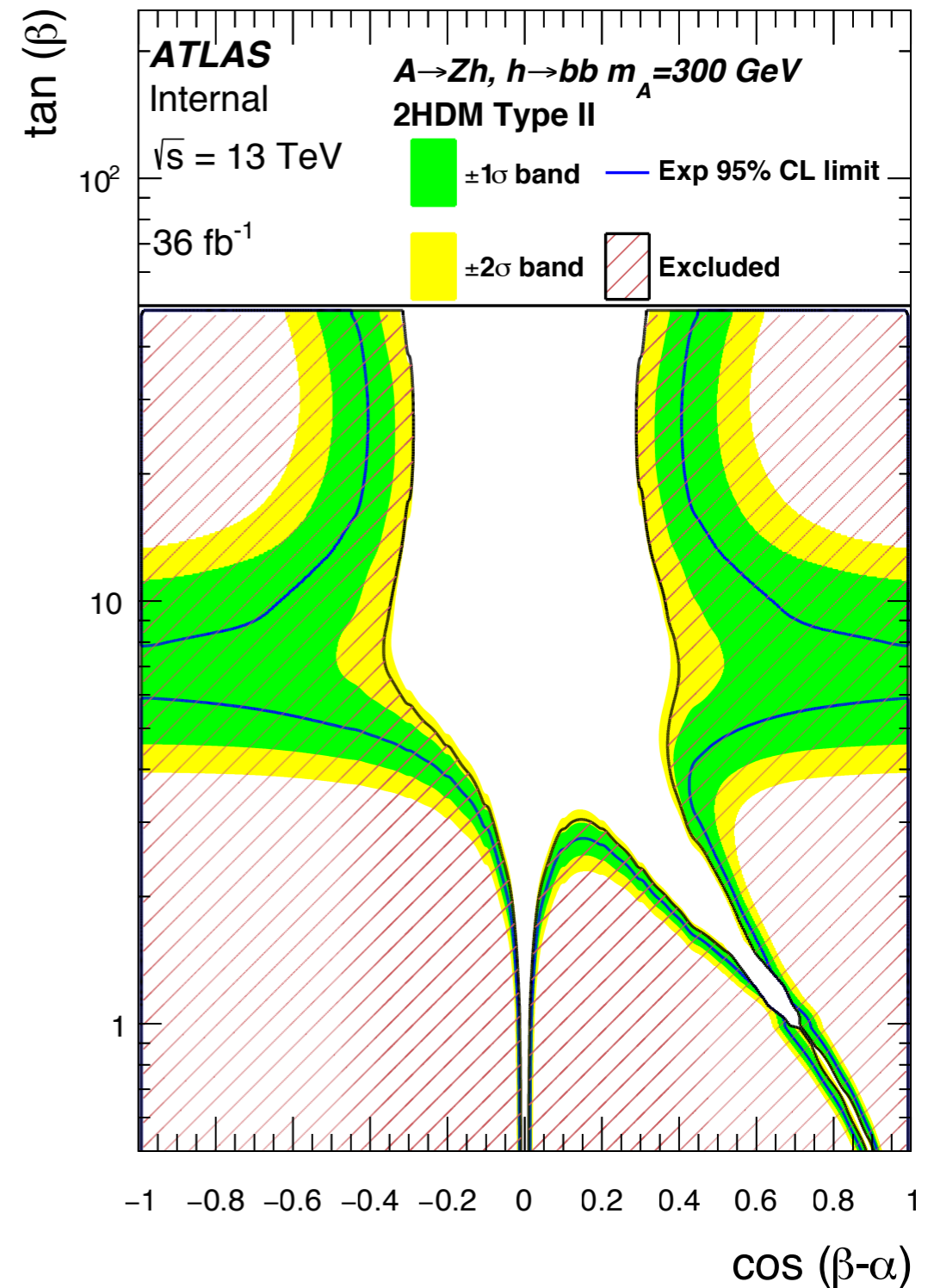
ATLAS-CONF-????-???



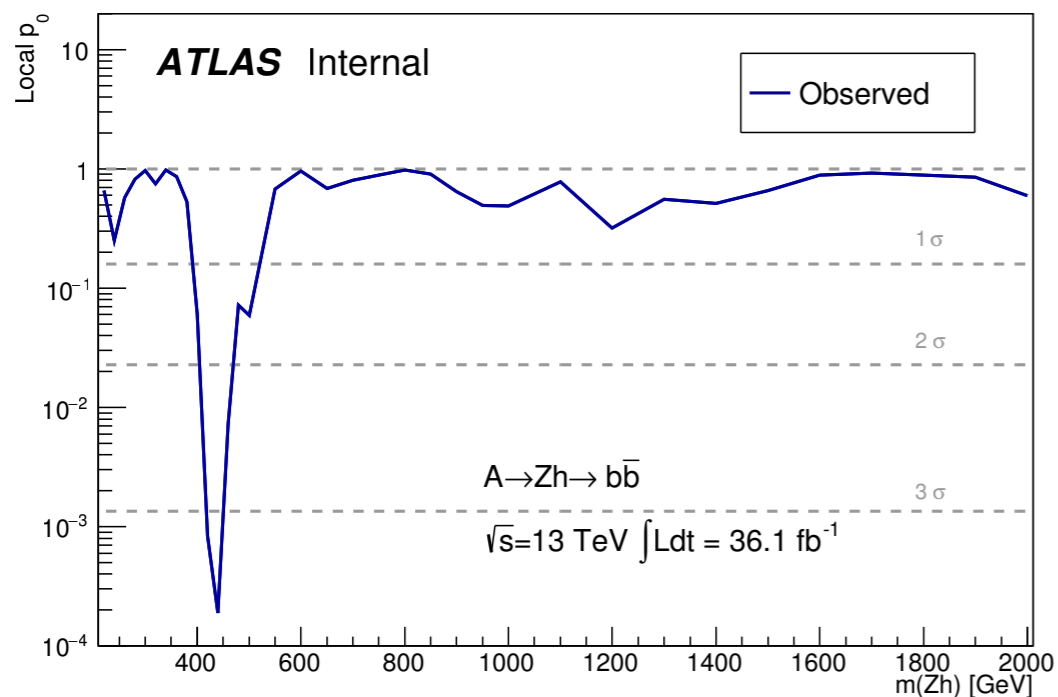
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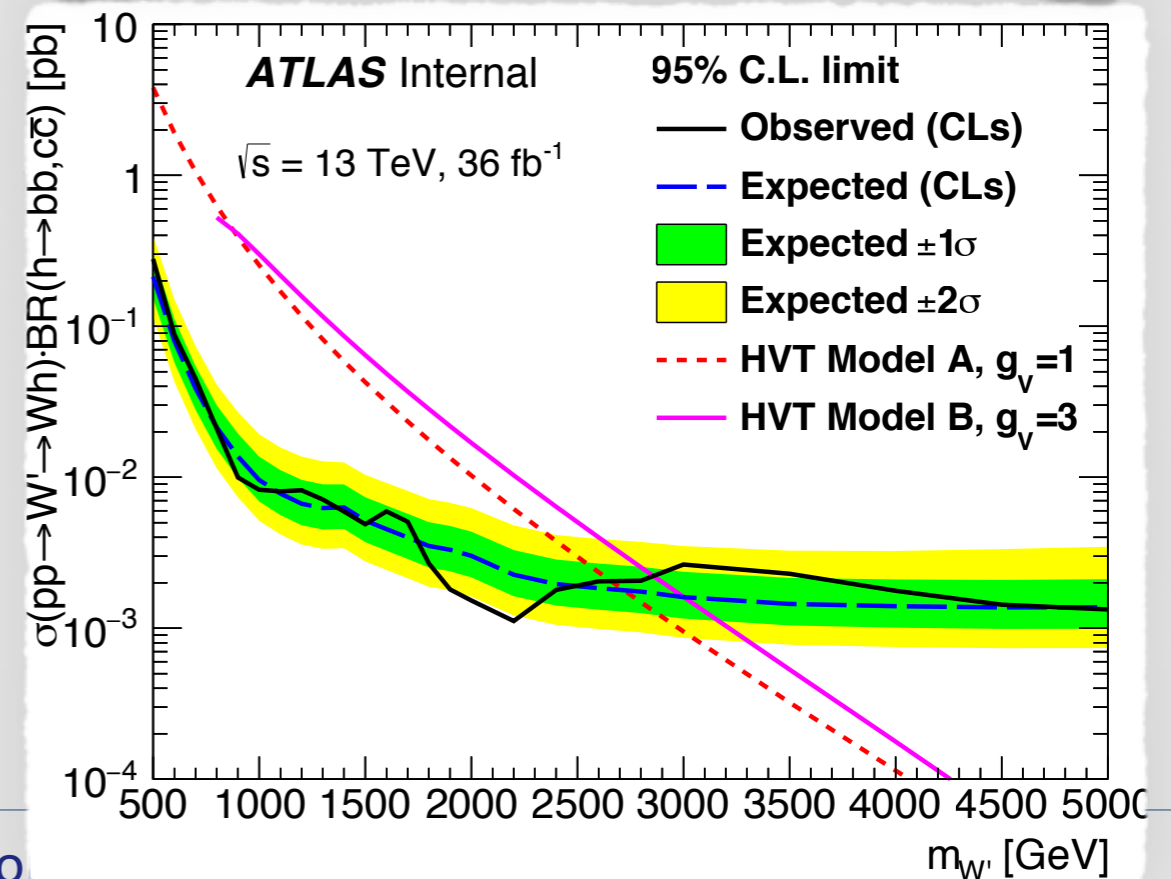
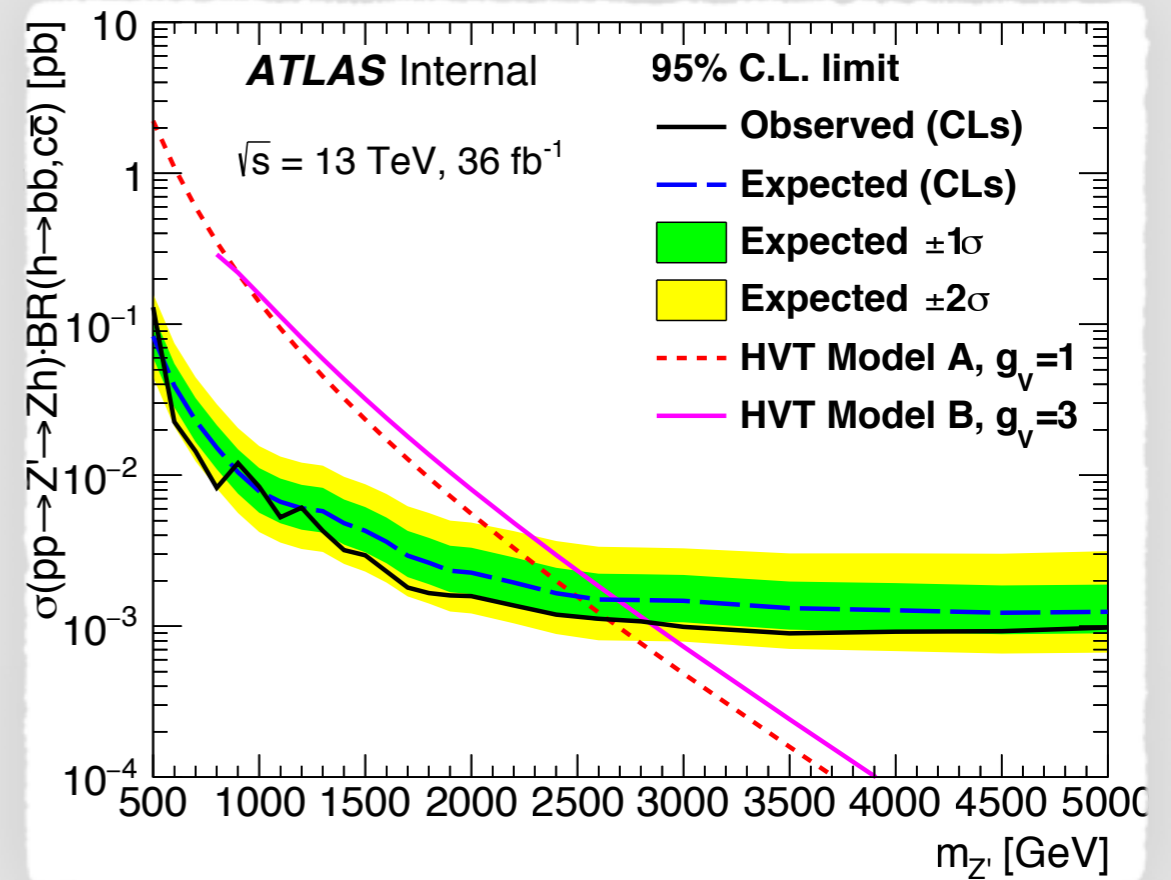


# VH Leptonic: HVT Interpretation

## HVT:

- No significant excess observed
- Exclusions for Model A (B):
  - $m_{W'} < 2670$  (2860) GeV
  - $m_{Z'} < 2650$  (2830) GeV
- Interpretation in terms of fermionic and bosonic couplings

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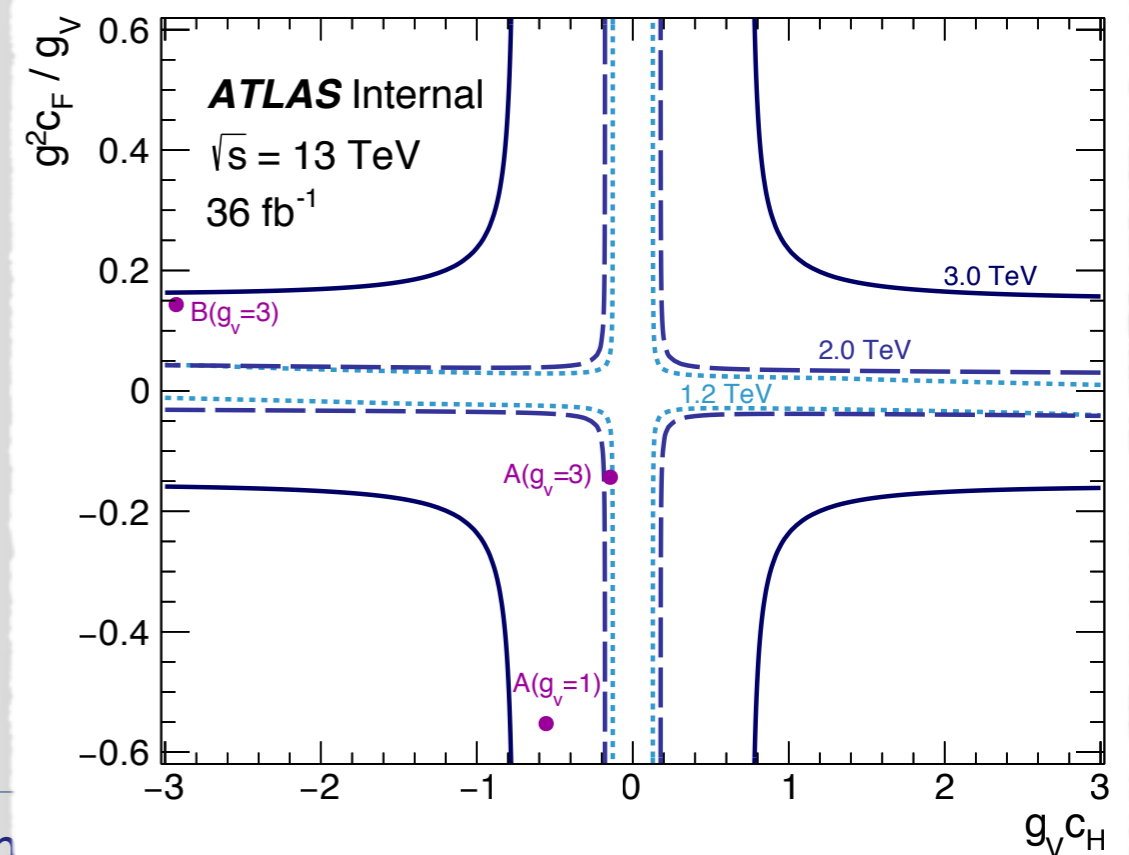
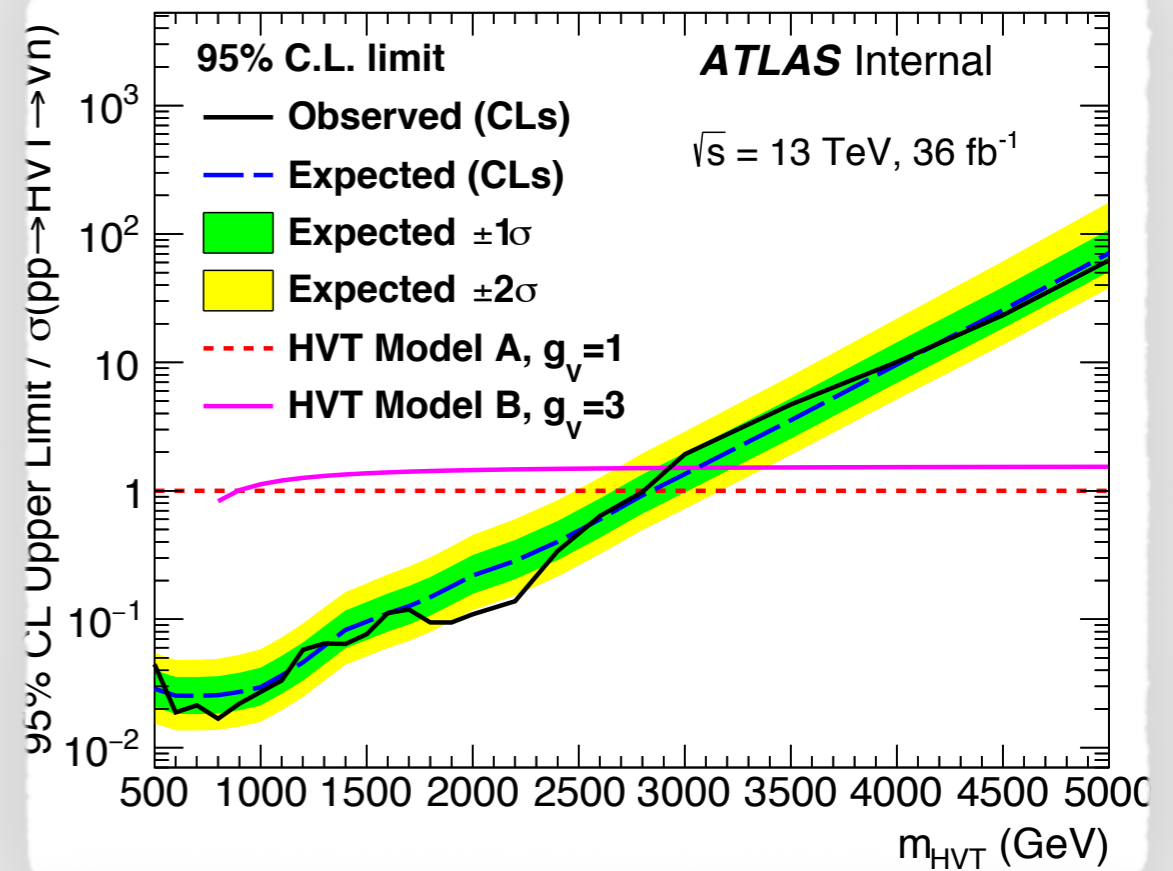


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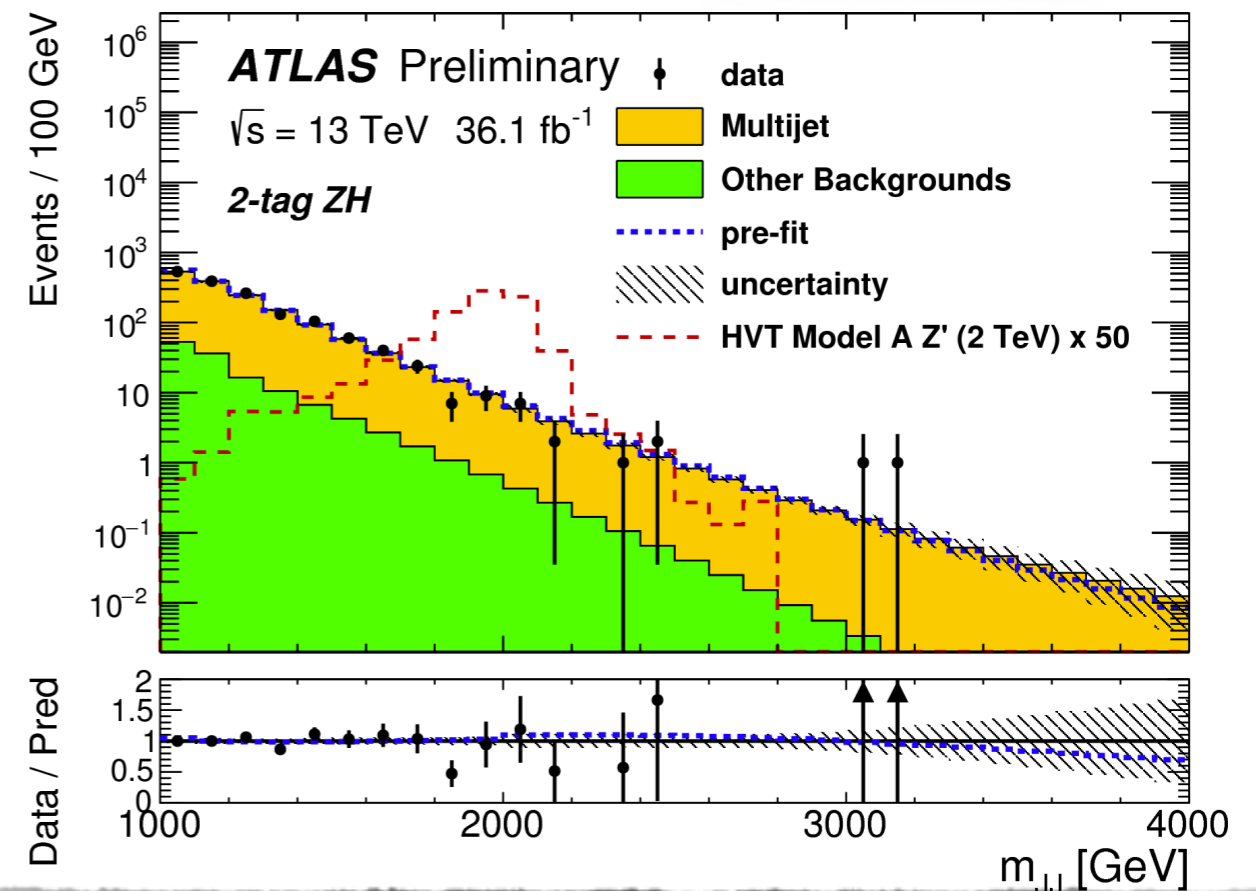
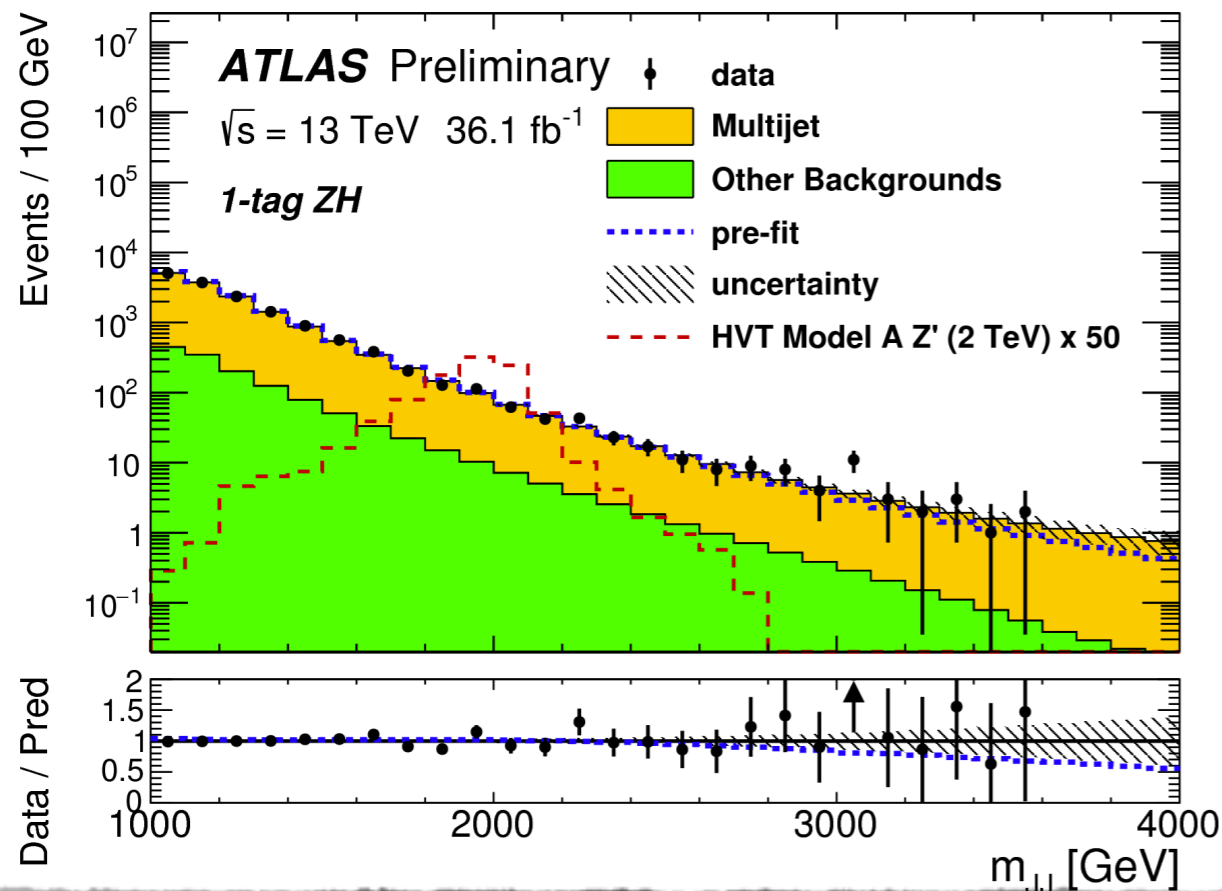
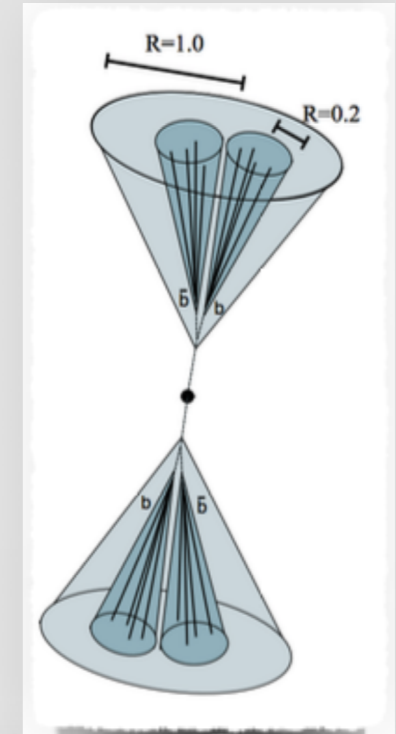


# VH Hadronic

ATLAS-CONF-2017-018

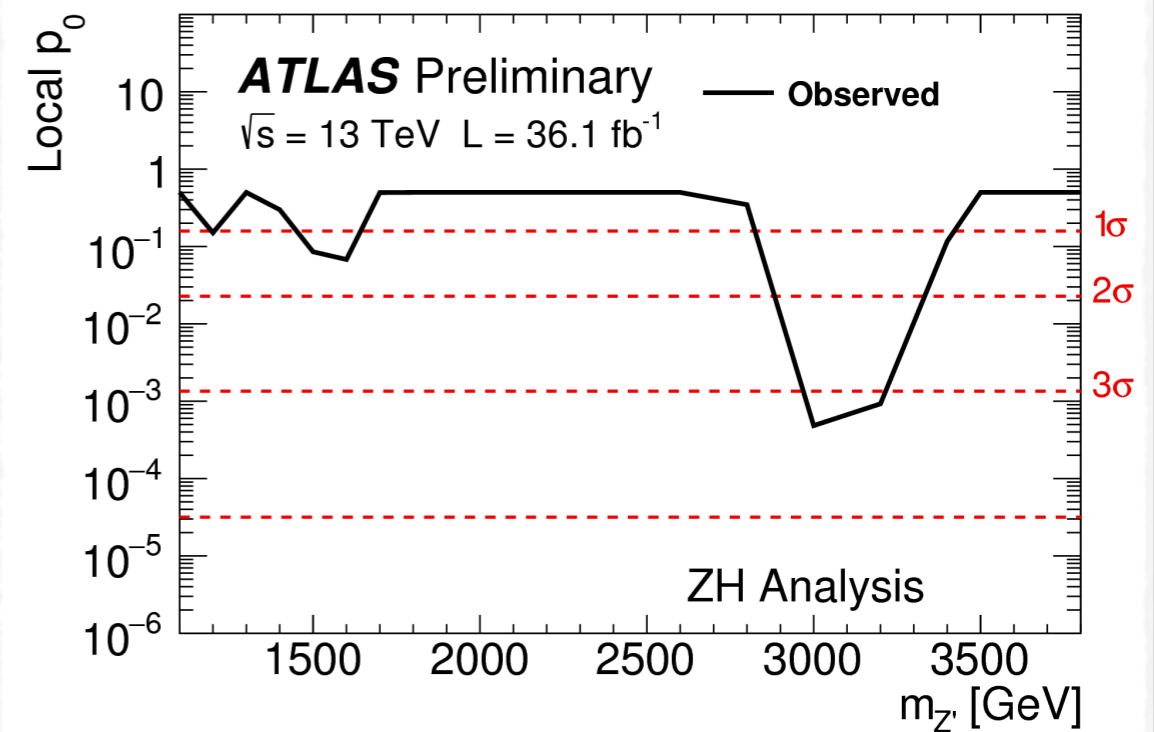
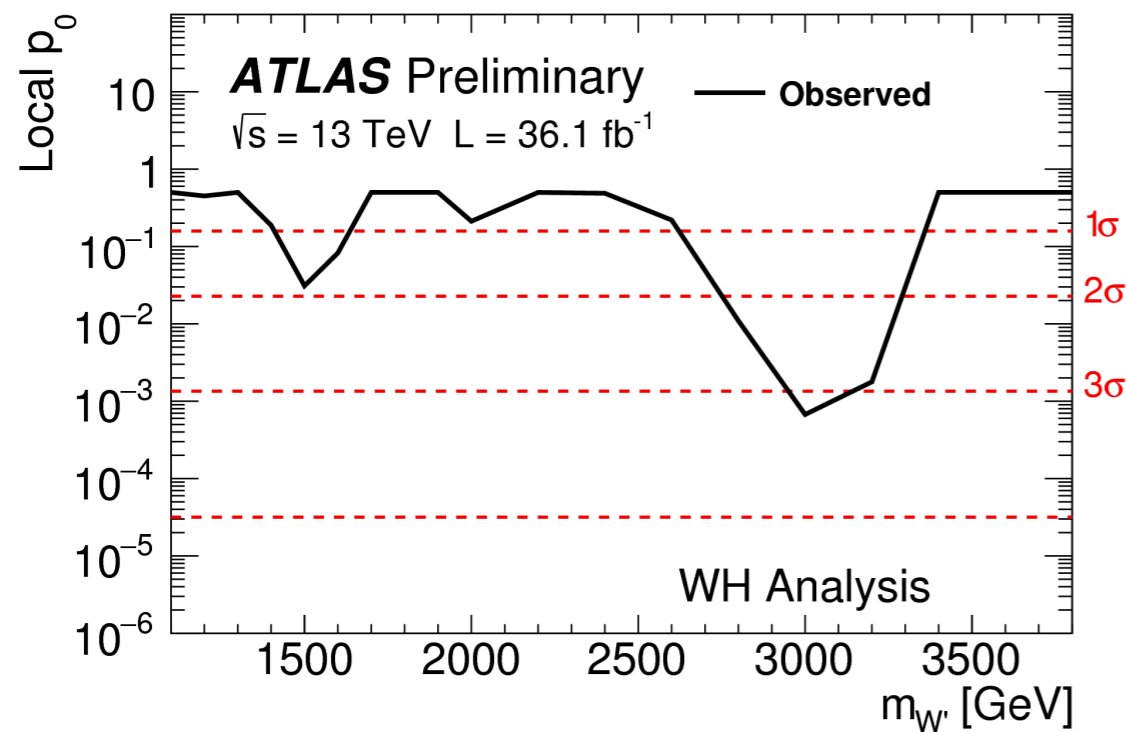
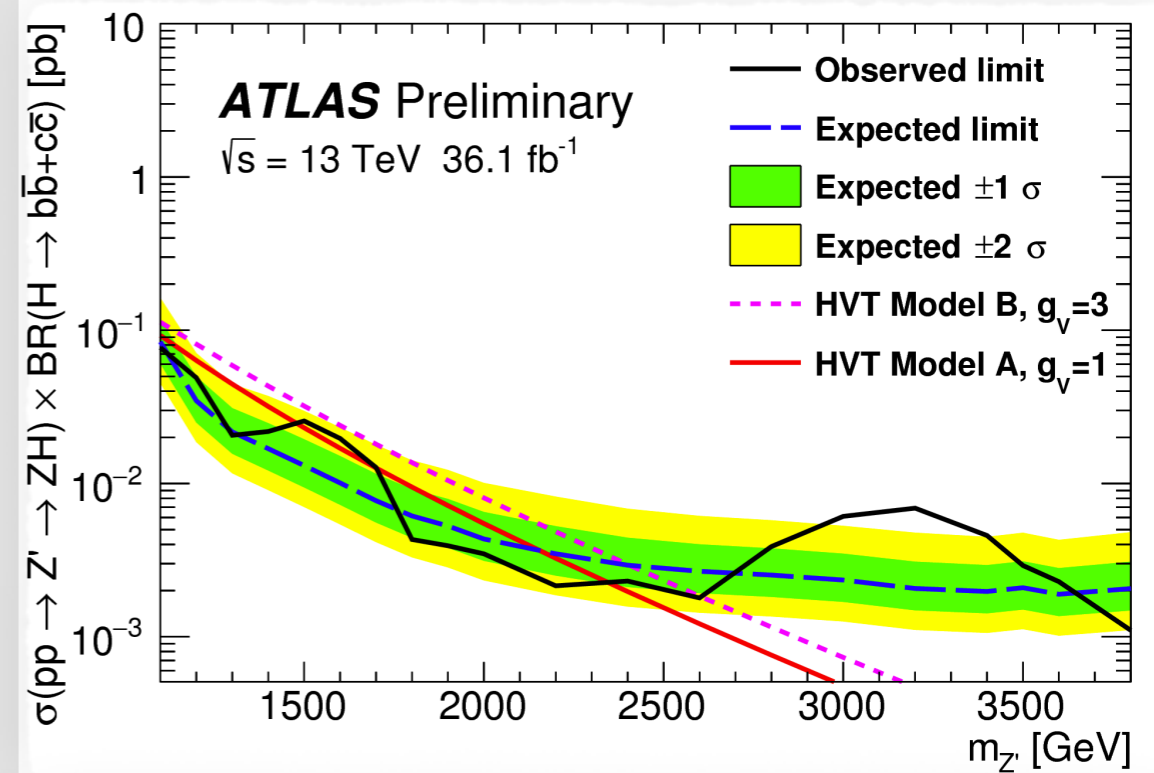
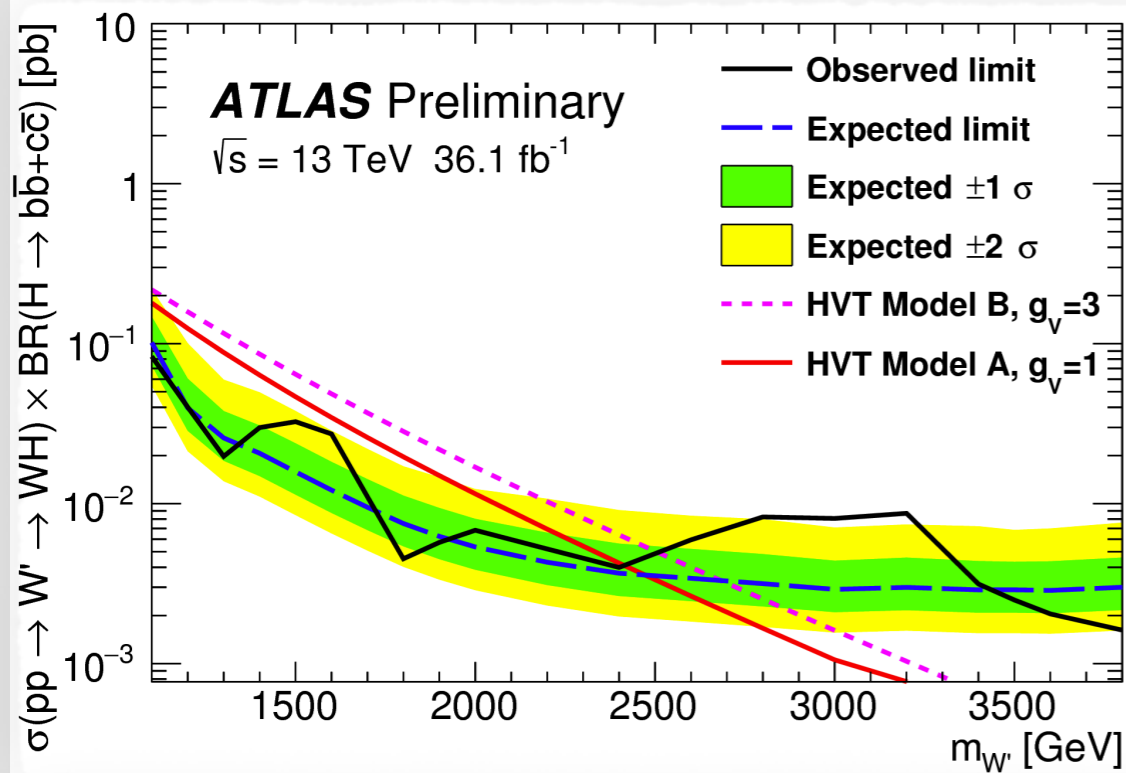
$X \rightarrow VH \rightarrow qqbb$  Signature:

- Vector boson and Higgs decays reconstructed as large-R jets.
- Jet substructure and b-tagging applied to reduce backgrounds.
- Higher mass jet assigned as Higgs candidate.



# VH Hadronic

ATLAS-CONF-2017-018



**Largest excess @ 3 TeV with global significance  $2.2\sigma$**

# Di-Higgs Resonances

## SM $hh$ Production:

- Extremely small SM expectation due to destructive interference among diagrams
- Important for measuring the Higgs self-coupling

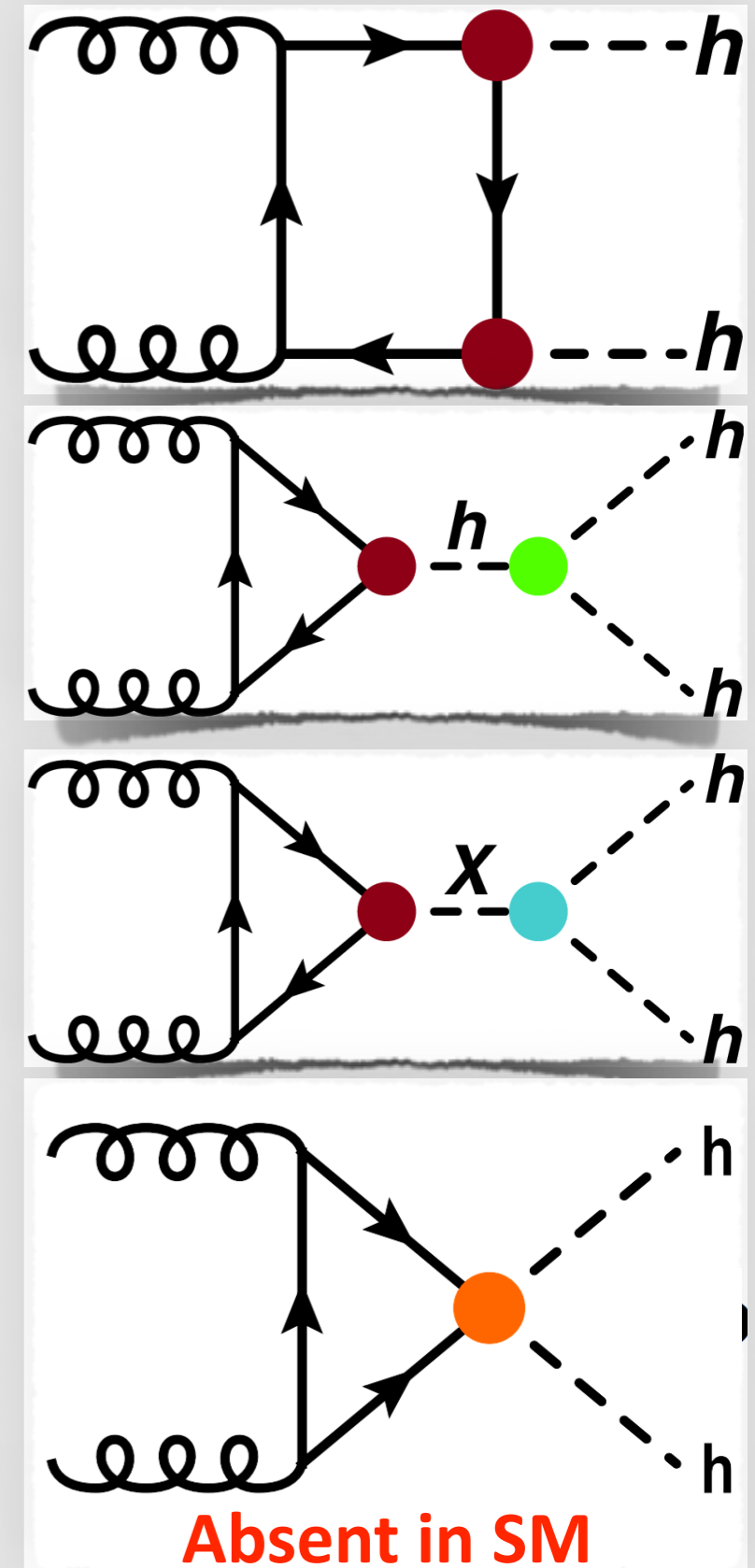
## BSM $hh$ Production:

### Non-resonant signals:

- Activating  $t\bar{t}hh$  vertex, modifying  $t\bar{t}h$  vertex
- Modified  $\lambda_{hhh}$

### Resonant signals:

- KK Graviton: spin-2
  - predicted in the bulk Randall-Sundrum model
- Heavy Higgs: 2HDM, spin-0
  - i.e: The heavy neutral scalar  $H$  of 2HDMs



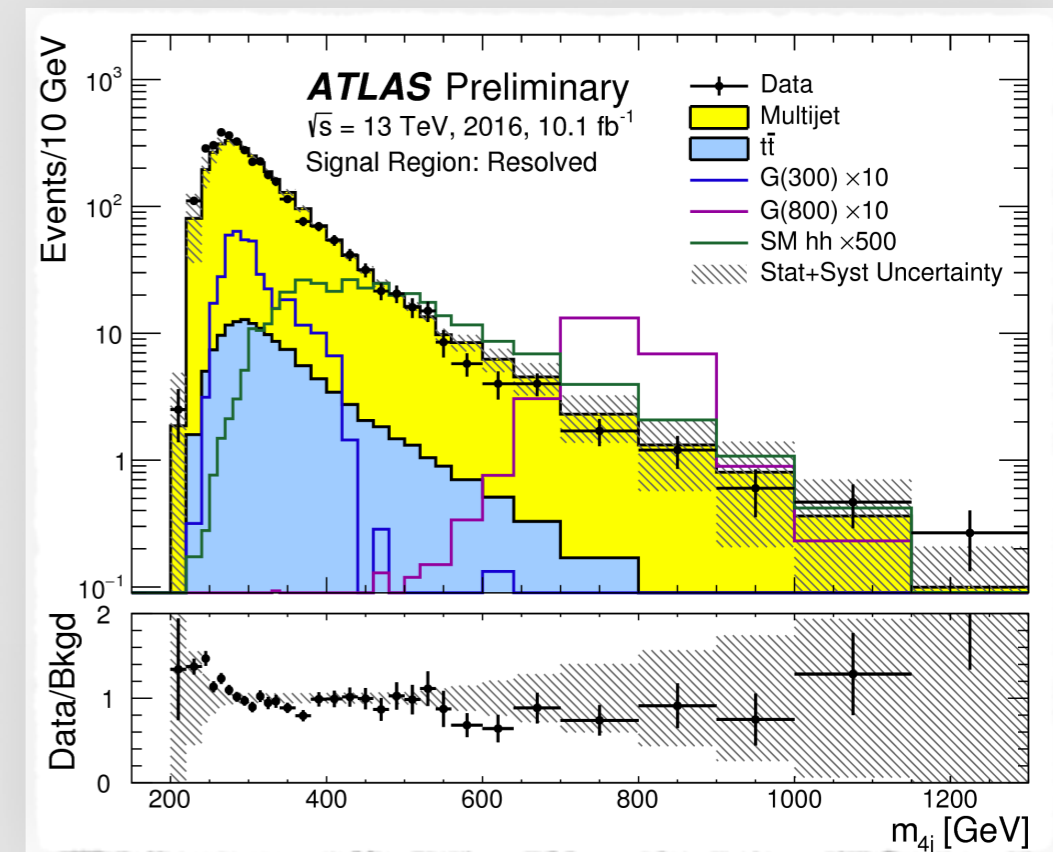
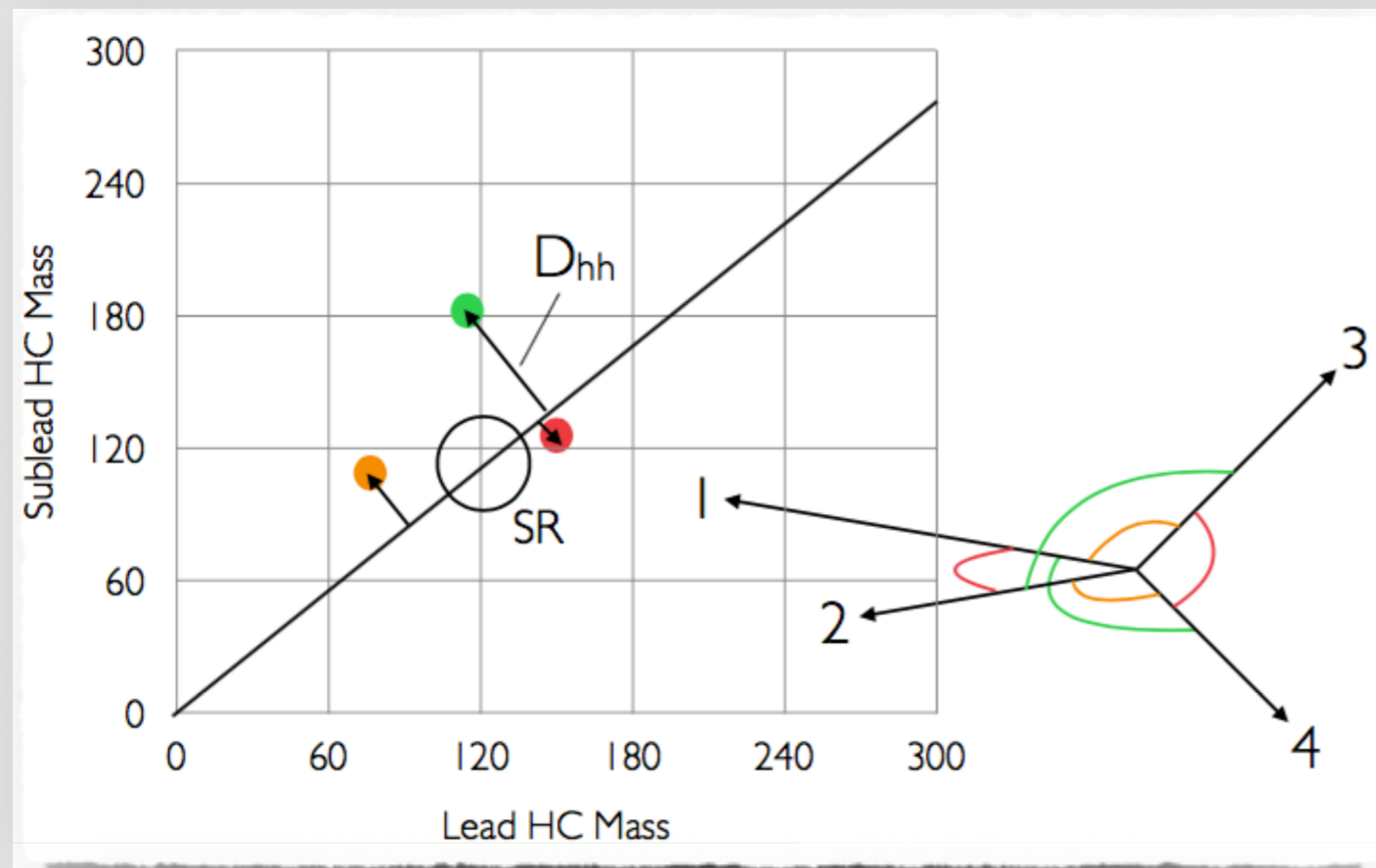
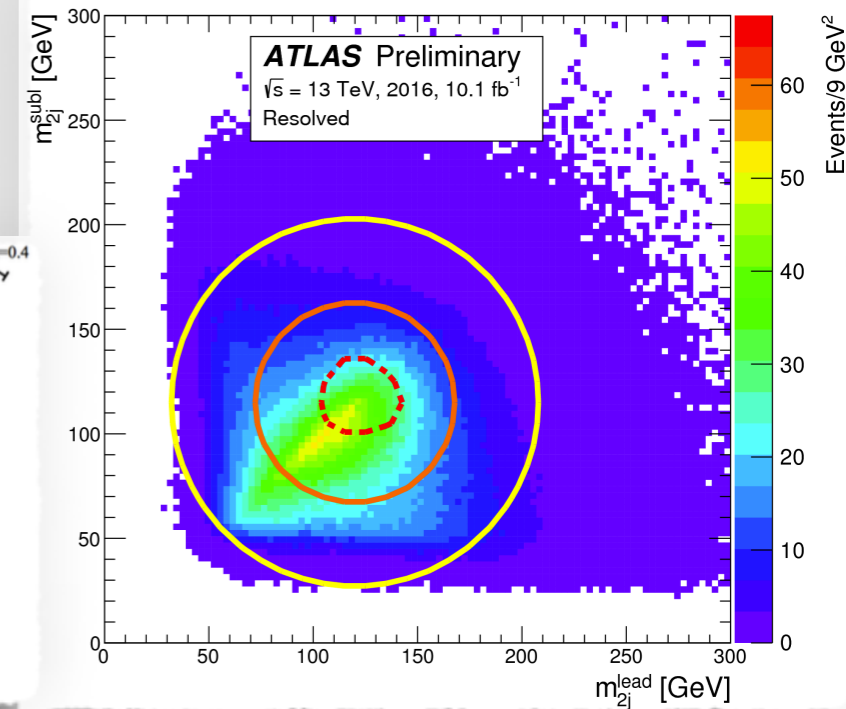
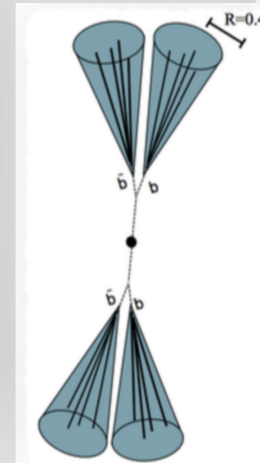
# HH → 4b

ATLAS-CONF-2016-049

- Large  $h \rightarrow bb$  branching fraction
- High statistics control regions, but suffers from large multi-jet background

## Resolved:

- Four b-tagged  $R=0.4$  anti-kt jets
- Di-jet pairs assigned by minimizing mass difference ( $D_{hh}$ )



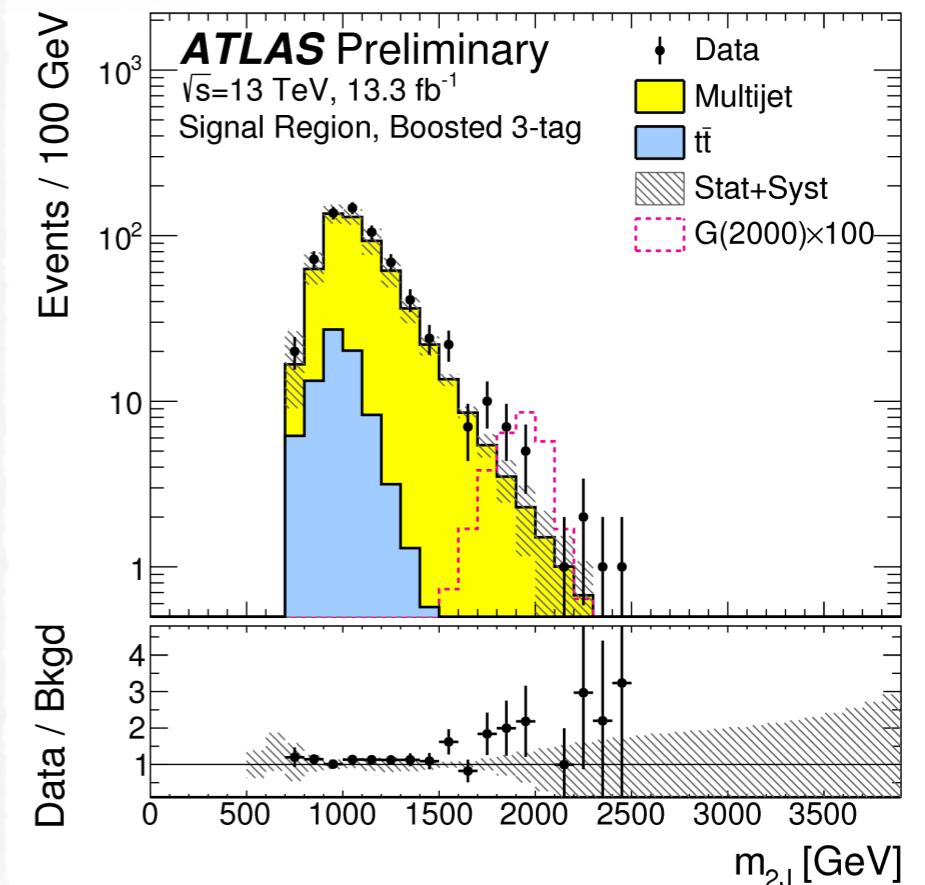
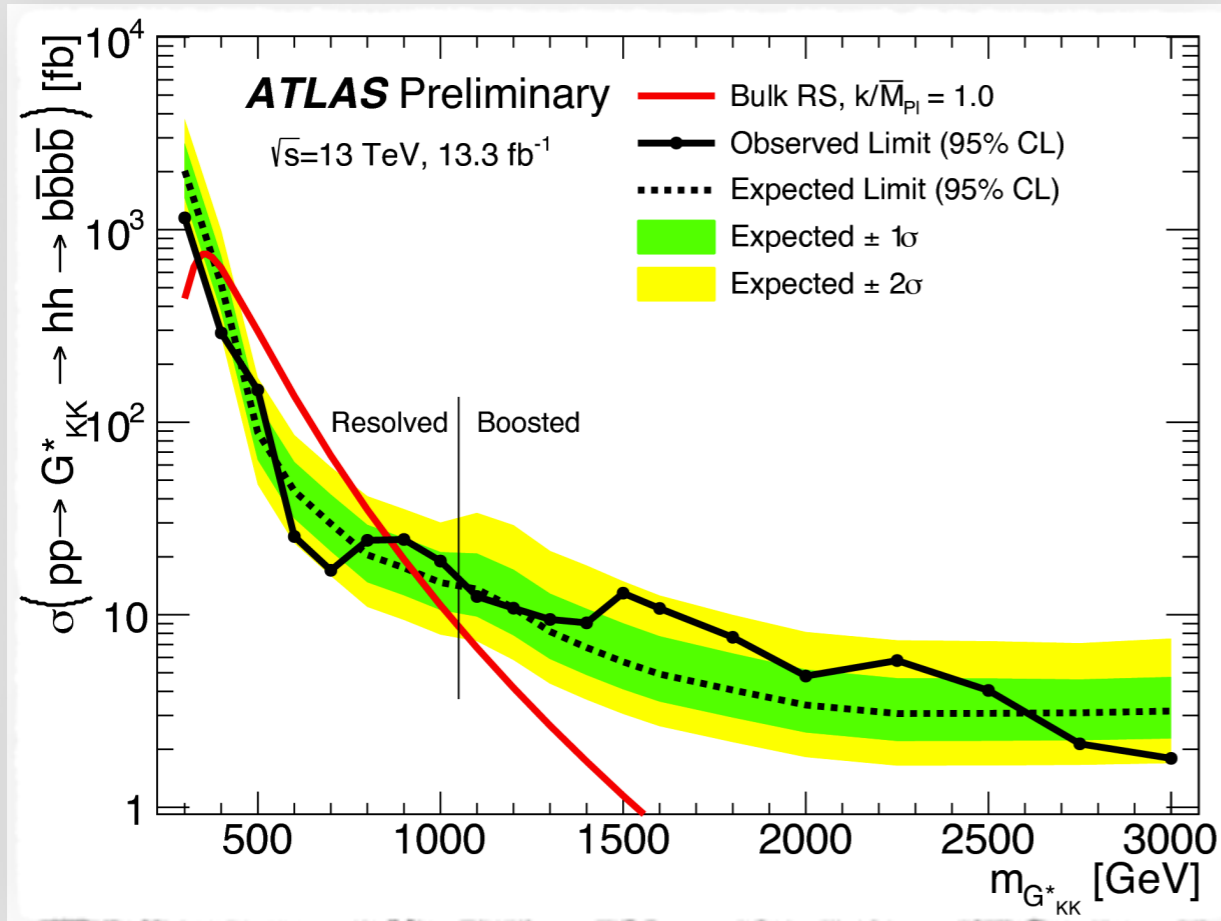
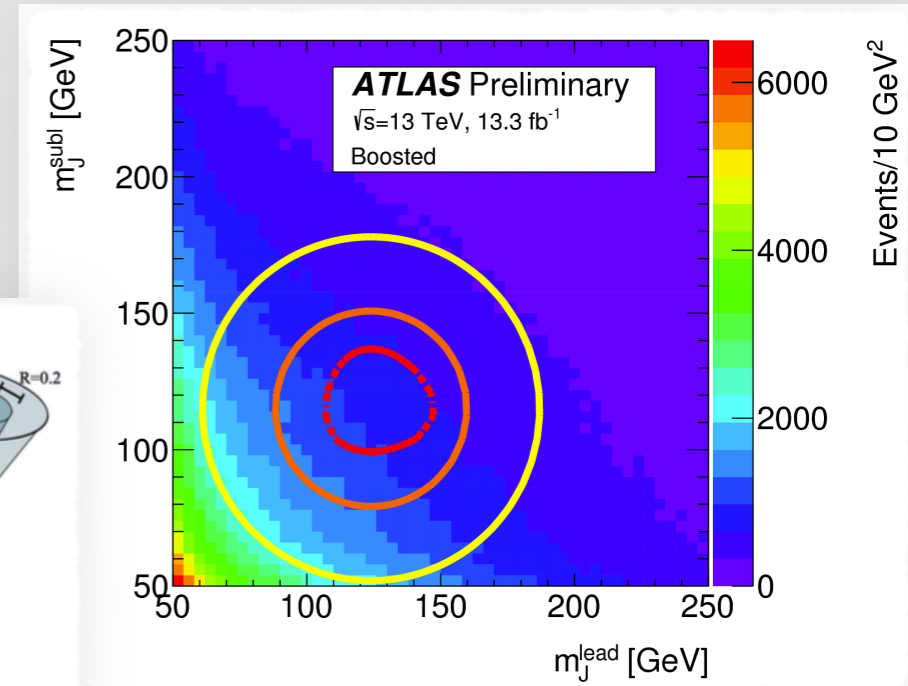
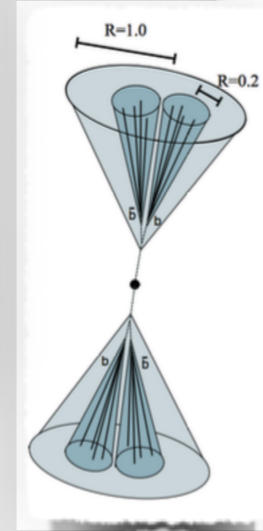
$$D_{hh} = \sqrt{(m_{2j}^{\text{lead}})^2 + (m_{2j}^{\text{subl}})^2} \left| \sin \left( \tan^{-1} \left( \frac{m_{2j}^{\text{subl}}}{m_{2j}^{\text{lead}}} \right) - \tan^{-1} \left( \frac{115}{120} \right) \right) \right|$$

# HH → 4b

- Large  $h \rightarrow bb$  branching fraction
- High statistics control regions, but suffers from large multi-jet background

## Merged/Boosted:

- Two  $R=1.0$  anti-kt jets,  $p_T > 250$  GeV
- At least 1 tagged  $R=0.2$  track-jets associated to each jet
  - Creates 2-,3-,4-tag categories of varying purity



# HH $\rightarrow$ $\gamma\gamma WW$

ATLAS-CONF-2016-071

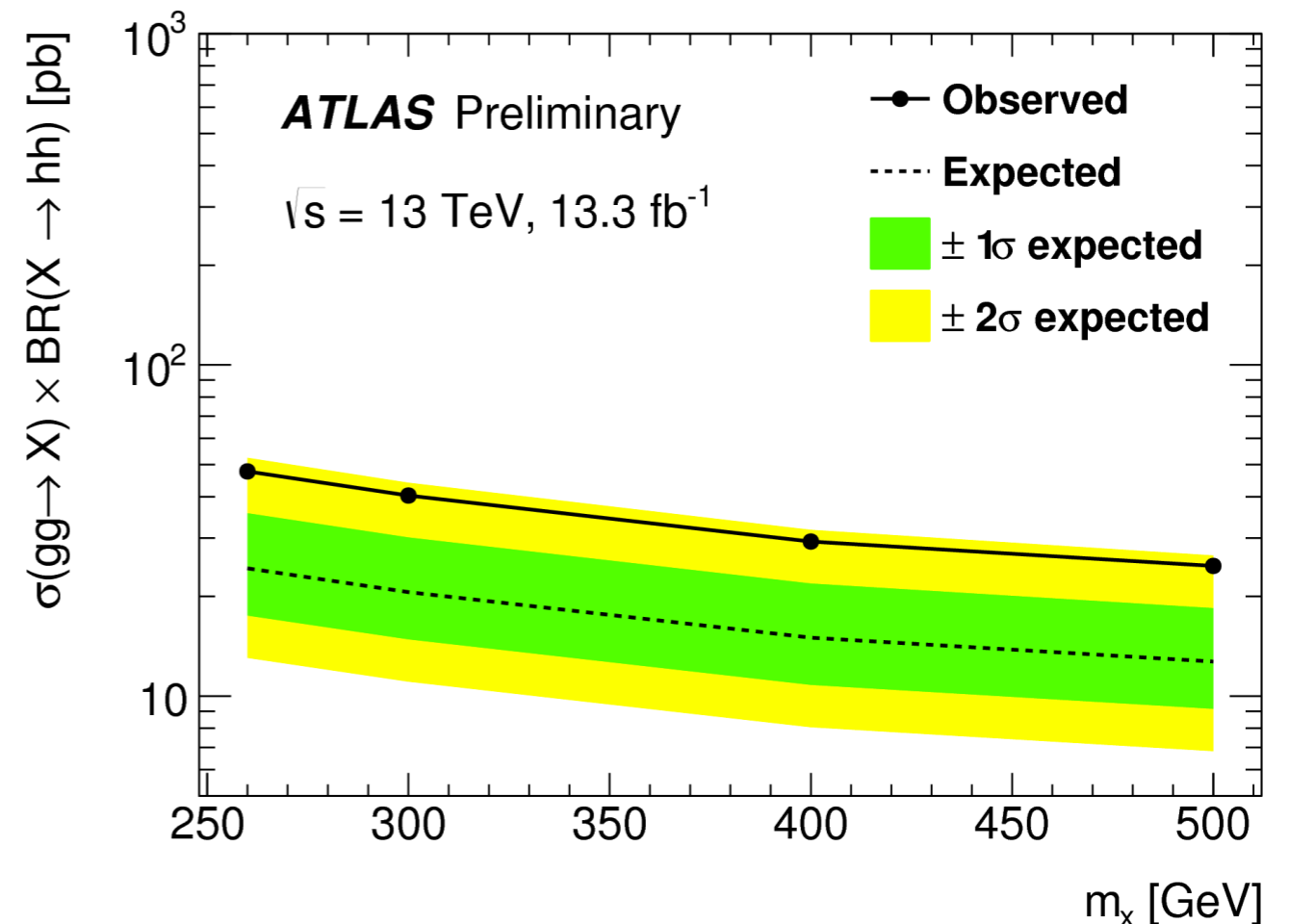
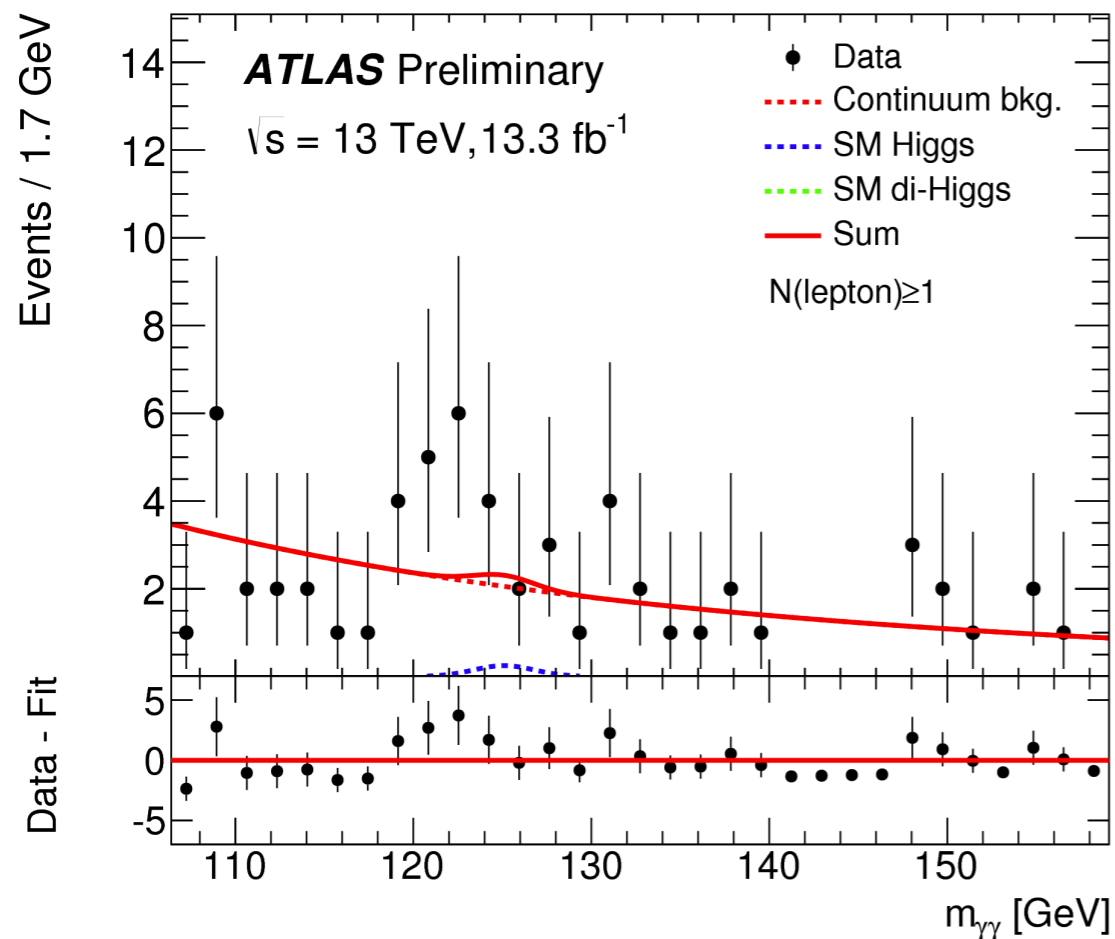
- Final state  $\gamma\gamma lvqq$ : two photons, 2+ jets and no b-jets ( $105 < m_{\gamma\gamma} < 160$  GeV)

## Signal Region:

- One lepton region - requiring at least one lepton
- The di-photon mass  $m_{\gamma\gamma}$  to be within a  $2\sigma$  window of the Higgs boson mass

## Control/Sideband Regions:

- CR: Zero lepton region - requiring no lepton
- SB: Reversing the tight mass window in either the one-lepton region or the zero-lepton region



# HH → $\gamma\gamma$ bb

## Event Selection:

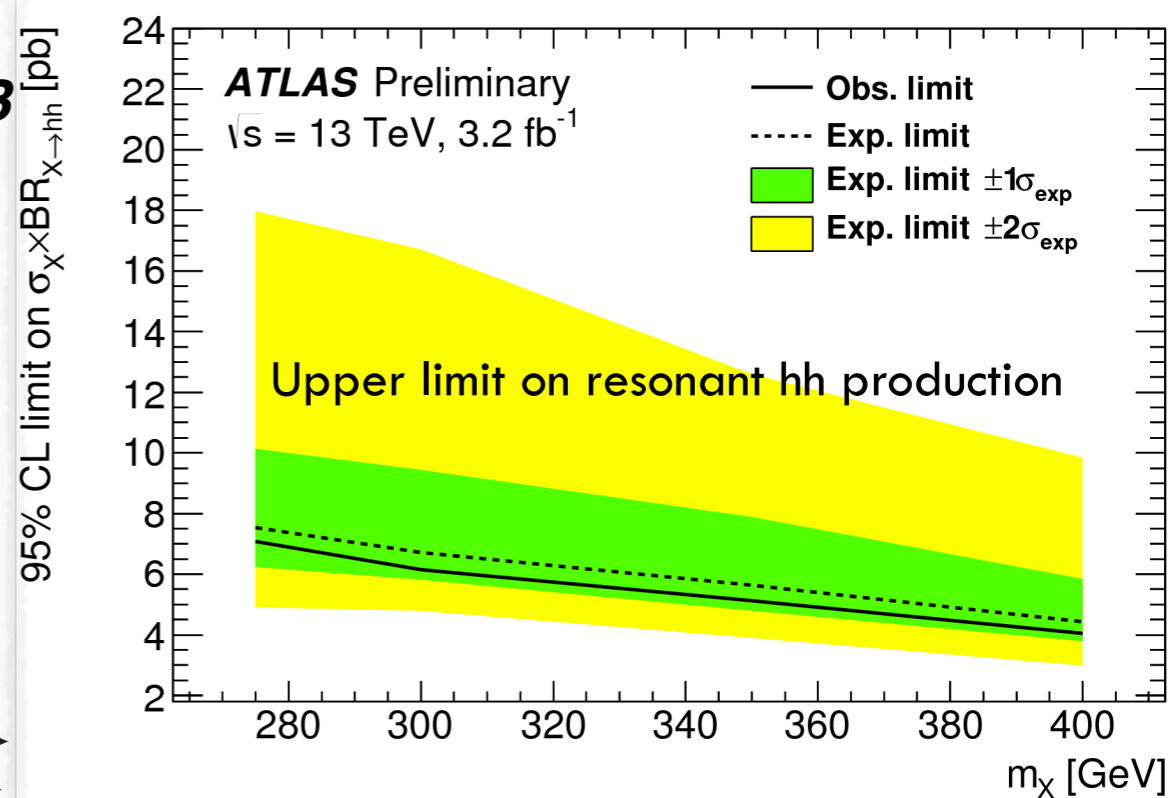
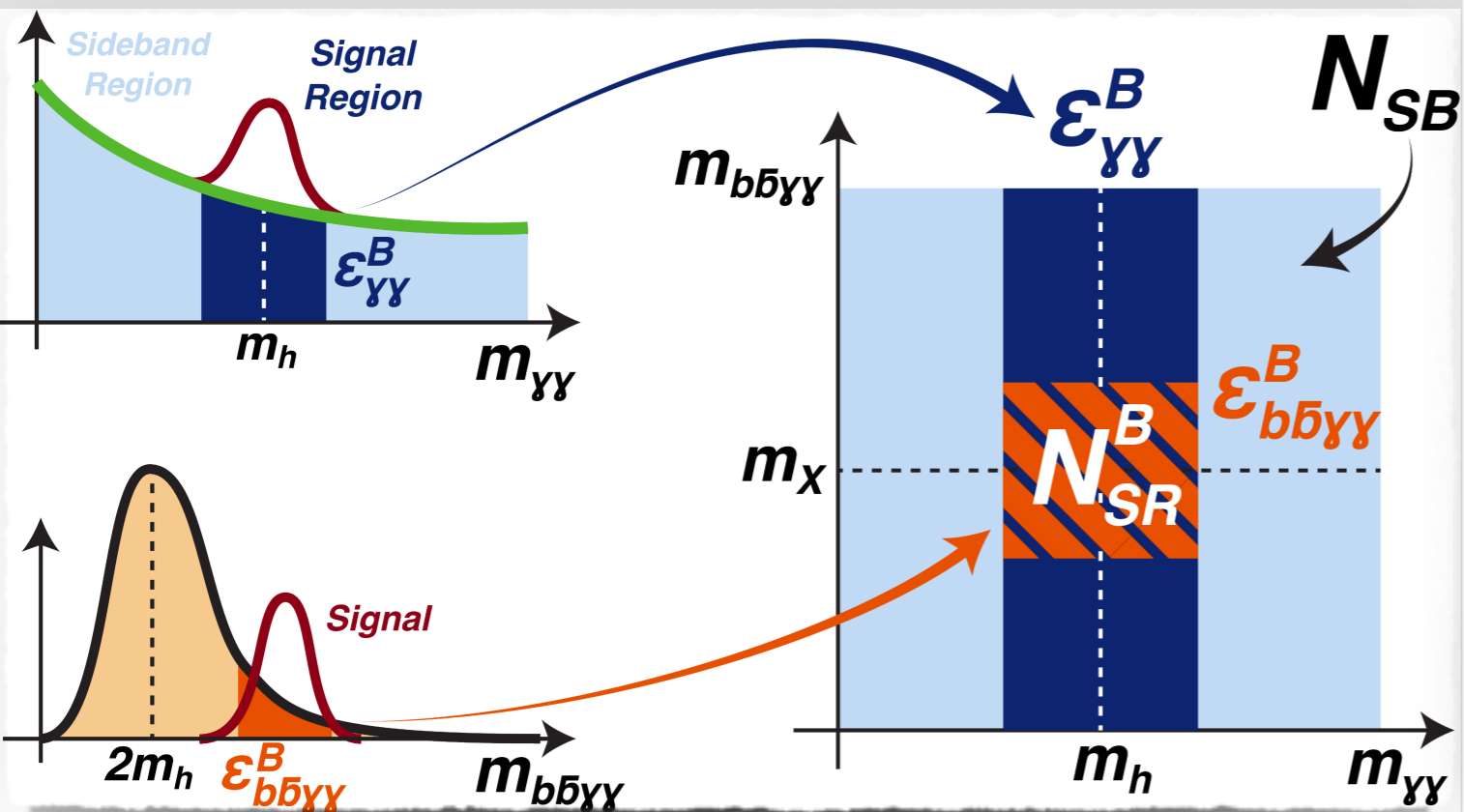
- Require  $105 < m_{\gamma\gamma} < 160$  GeV
- Require  $95 < m_{bb} < 135$  GeV
- 2 b-tag category - signal region
- 0 b-tag category - control region

## Non-Resonant Analysis:

- Simultaneous S+B fit to  $m_{\gamma\gamma}$  in both SR and CR
- $m_{\gamma\gamma}$  background fitted with exponential in CR
- Single Higgs background and di-Higgs signal from MC

## Resonant Analysis:

- Counting approach with  $2\sigma$  window cut on  $m_{\gamma\gamma}$
- Count in 95% efficiency  $m_{\gamma\gamma}bb$  window
- CR used to determine background efficiency



# Conclusions

## Massive Higgs + Boson Resonances @ ATLAS

- This presentation was neither exhaustive nor complete

## Vector Boson + Higgs Resonances

- Vector Triplet and 2HDM interpretations

Run2:

VH semi-leptonic (ATLAS-CONF-2017-???)

VH all-hadronic (ATLAS-CONF-2017-018)

## Di-Higgs Searches

- Resonant and non-resonant searches

Run2:

$hh \rightarrow bbbb$  (ATLAS-CONF-2016-049),  $hh \rightarrow \gamma\gamma WW^*$  (ATLAS-CONF-2016-071),

$hh \rightarrow bb\gamma\gamma$  (ATLAS-CONF-2016-004)

Run1:

$hh \rightarrow bbbb$ ,  $hh \rightarrow bb\gamma\gamma$ ,  $hh \rightarrow bb\tau\tau$ ,  $hh \rightarrow \gamma\gamma WW^*$  combined (arXiv:1509.04670v2)



FIN

# VH Hadronic Yields

	$ZH$ 2-tag	$ZH$ 1-tag
Multijet	1440 $\pm$ 60	13770 $\pm$ 310
Other Backgrounds	135 $\pm$ 45	1350 $\pm$ 270
Total Backgrounds	1575 $\pm$ 40	15120 $\pm$ 130
Data	1574	15112
<i>Model B, M=2 TeV</i>	25 $\pm$ 7	29 $\pm$ 10
	$WH$ 2-tag	$WH$ 1-tag
Multijet	1525 $\pm$ 65	13900 $\pm$ 290
Other Backgrounds	110 $\pm$ 45	1310 $\pm$ 260
Total Backgrounds	1635 $\pm$ 40	15220 $\pm$ 120
Data	1646	15212
<i>Model B, M=2 TeV</i>	51 $\pm$ 10	62 $\pm$ 16