

# ATLAS additional scalar bosons

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Ke Li

on behalf of ATLAS Collaboration

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Higgs hunting 2021

UNIVERSITY of WASHINGTON



# Introduction

> Many BSM models predict an extended scalar sector.

- > 2HDM, 2HDM+singlet, 3HDM, hMSSM ...
- > Additional scalars:  $H, A, H^\pm, H^{\pm\pm}$

**Parameters in 2HDM:**

Higgs bosons masses

$\alpha$ : mixing angle between  $h$  and  $H$

$\tan\beta$ : Ratio of vacuum expectation values

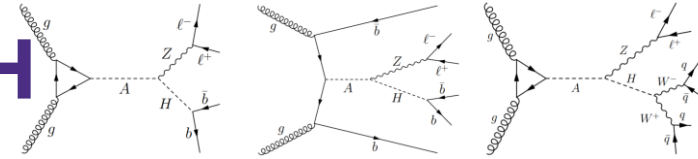
Recent searches for new scalars in ATLAS

Target	Channels	Luminosity ( $fb^{-1}$ )	Reference
Heavy neutral $H/A$	$A \rightarrow Zh$ ( $h = 125$ GeV Higgs)	139	<a href="#">ATLAS-CONF-2020-043/</a>
	$A \rightarrow ZH$ ( $H \neq 125$ GeV Higgs)	139	<a href="#">EPJC 81 (2021) 396</a>
	$H \rightarrow ZZ$	139	<a href="#">EPJC 81 (2021) 332</a>
	$A/H \rightarrow \gamma\gamma$	139	<a href="#">arXiv:2102.13405</a>
	$A/H \rightarrow \tau\tau$	139	<a href="#">PRL 125 (2020) 051801</a>
Charged $H^\pm/H^{\pm\pm}$	$H^\pm \rightarrow cb$	139	<a href="#">ATLAS-CONF-2021-037</a>
	$t \rightarrow H^\pm b, H^\pm \rightarrow AW^\pm, A \rightarrow \mu\mu$	139	<a href="#">ATLAS-CONF-2021-047</a>
	$H^{\pm\pm} \rightarrow W^\pm W^\pm$ and $H^\pm \rightarrow W^\pm Z$	139	<a href="#">JHEP 06 (2021) 146</a>

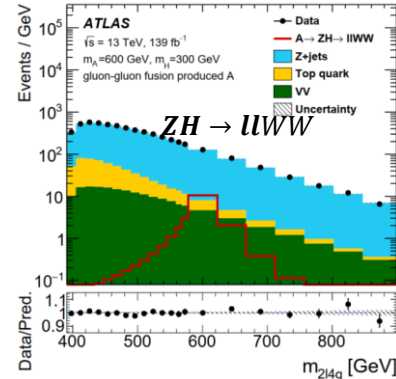
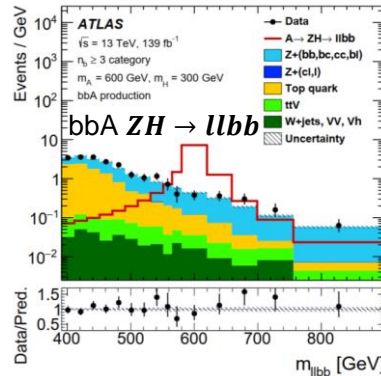
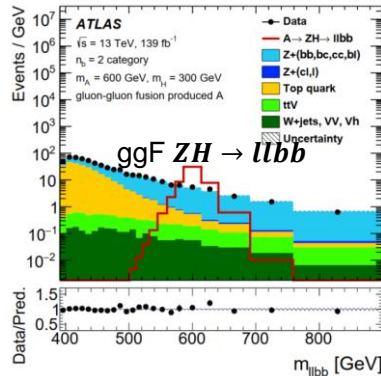
**Di-higgs:** see Petar's talk  
 $H^\pm \rightarrow tb$ : see Adrian's talk  
**H(125) BSM decays:** see Adriana's talk



# Heavy neutral Higgs: $A \rightarrow ZH$



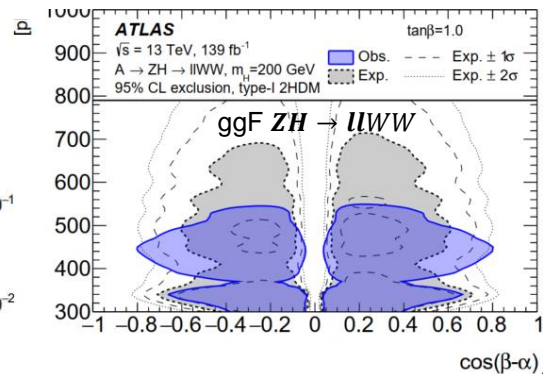
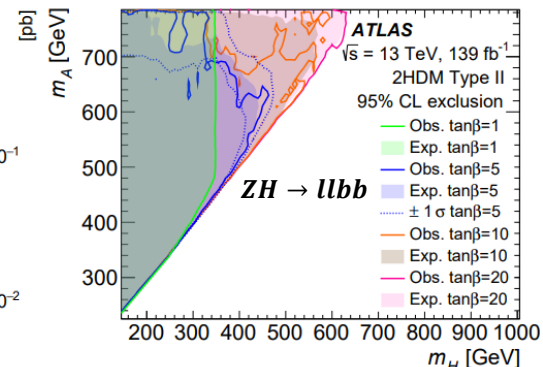
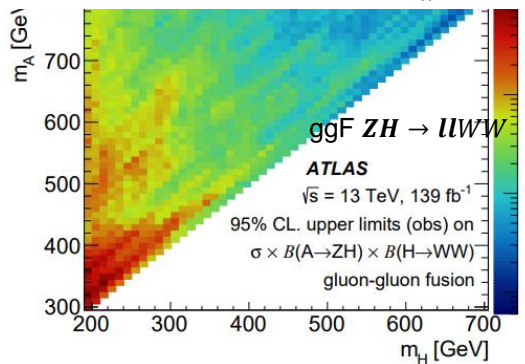
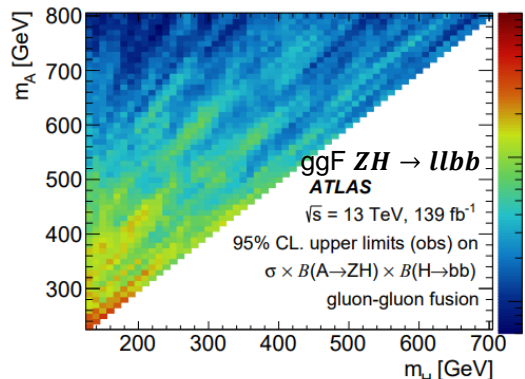
- > **A: CP-odd; H: CP even heavy Higgs.**
- >  **$ZH \rightarrow llbb$  from ggF and bbA.**
  - $H \rightarrow bb$  dominant in large part of 2HDM parameters space, especially in the weak decoupling limit ( $\cos(\beta - \alpha) = 0$ )
- >  **$ZH \rightarrow llWW \rightarrow ll4q$  from ggF.**
  - $H \rightarrow WW$  dominant in the space close to the weak decoupling limit
- > **Analysis: select a Z candidate ( $ee$  or  $\mu\mu$ ), and 2 b-jets(ggF  $llbb$ ) or  $\geq 3$  b-jets (bbA  $llbb$ ) or  $\geq 4$  jets (ggF  $llWW$ ).**
- > **Dominant background, Z+jets,  $t\bar{t}$ , are constrained from data CRs**



# Heavy neutral Higgs: $A \rightarrow ZH$

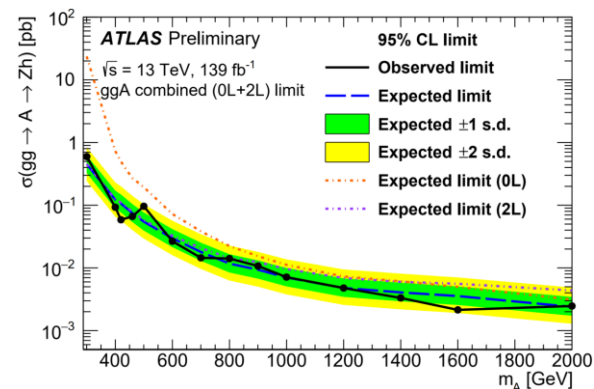
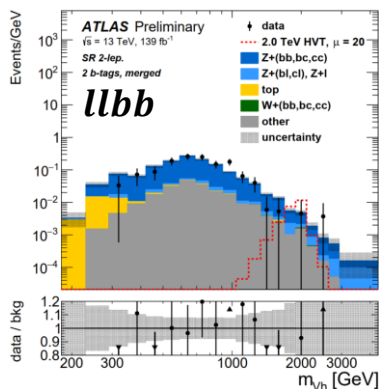
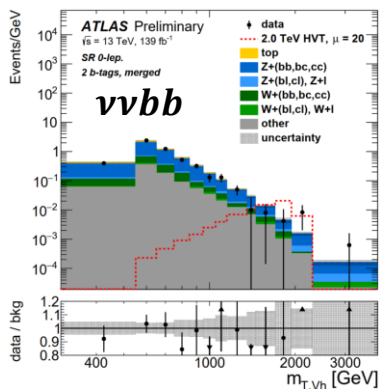
- The search is performed in the  $(m_H, m_A)$  plane for different models (type-I, type-II, lepton-specific and flipped).
- No significant deviation from the SM is observed.
- Most significant excess:

$(m_A, m_H)$ (GeV)	Global(local) significance ( $\sigma$ )	channel
(610, 290)	1.3(3.1)	ggF $llbb$
(440, 220)	1.3(3.1)	bbA $llbb$
(440, 310)	0.8(2.9)	ggF $llWW$



# Heavy neutral Higgs: $A \rightarrow Zh$ ( $h=125$ GeV Higgs)

- >  $Zh \rightarrow llbb$  and  $\nu\nu bb$  from  $ggF$ .
- > Good sensitivity for small  $\tan\beta$ .
- >  $h \rightarrow bb$  could be resolved (2 small-R jets) or merged (1 large-R jet).
- > Dominant background:  $t\bar{t}$  and  $Z$ +jets, constrained from data.

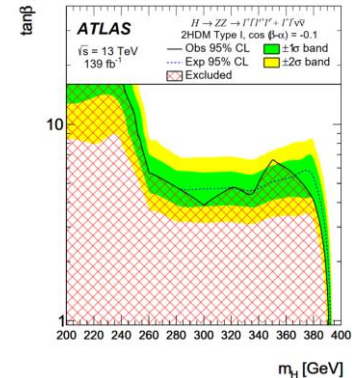
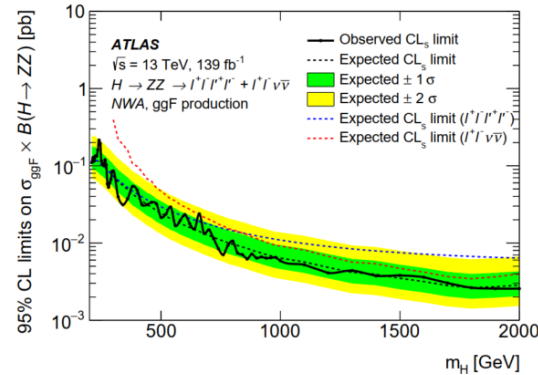
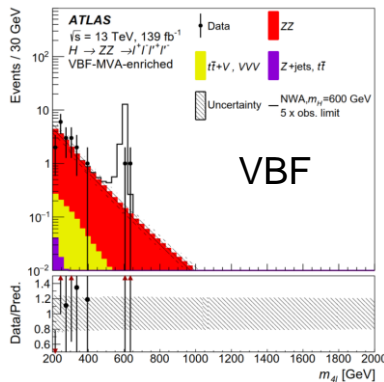
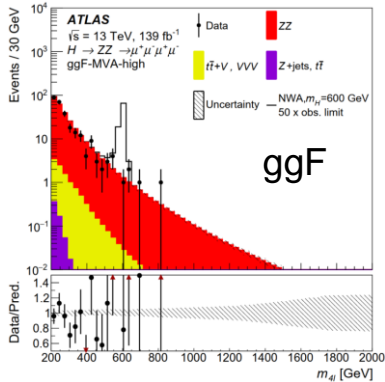


- Largest excess is at 500 GeV ( $llbb$  channel) with a local significance of  $1.6\sigma$ .



# Heavy neutral Higgs: $H \rightarrow ZZ$

- >  $ZZ \rightarrow llll$  or  $ll\nu\nu$  from ggF and vector boson fusion (VBF).
- > Main background: SM  $ZZ$ , normalization is derived from data.
- > Two classifier (ggF and VBF) of Deep neural networks (DNN) to improve the sensitivity.



- Interpreted the search for type-I and type-II 2HDM models.
- Both large width and narrow width resonances are searched.
- No significant deviation from the SM is observed.

# Heavy neutral Higgs: $H \rightarrow \gamma\gamma$

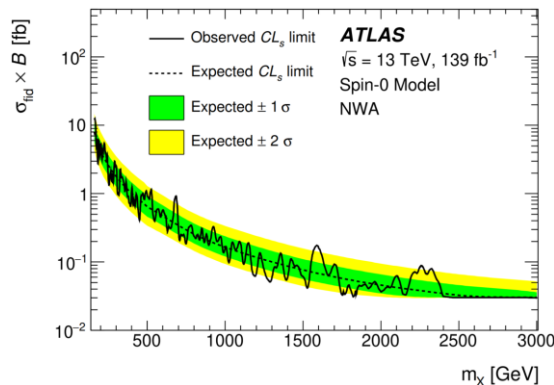
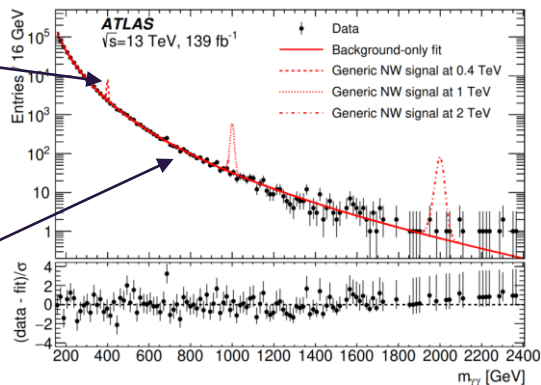
- > Search strategy: search for resonant structures in the high-mass  $\gamma\gamma$  spectrum, fitting signal and background components using analytical functions.
- > Optimized selections and updated calibrations and systematics treatment for full-Run-2 dataset.
- > Require two photons with tight identification and isolation.
- > Background shape derived from  $\gamma\gamma$  events and data-driven  $\gamma$ +jets events.

**Signal template:**  
Double-sided crystal ball convolved with BW

**Background template:**

$$f(x; b, a_0, a_1) = N(1 - x^{1/3})^b x^{a_0 + a_1 \log(x)}$$

where  $x = m_{\gamma\gamma} / \sqrt{s}$ .



- Most significant excess is at  $\sim 684$  GeV with  $1.3\sigma$  ( $3.3\sigma$ ) global (local) significance.
- Scanned both signal mass and a range of width hypotheses.

[arXiv:2102.13405](https://arxiv.org/abs/2102.13405)

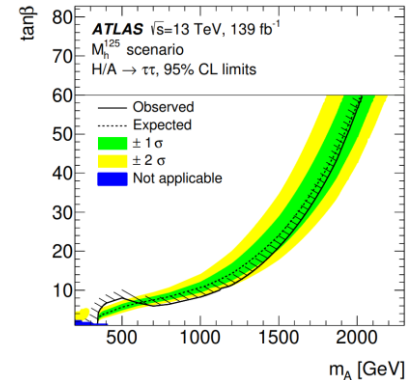
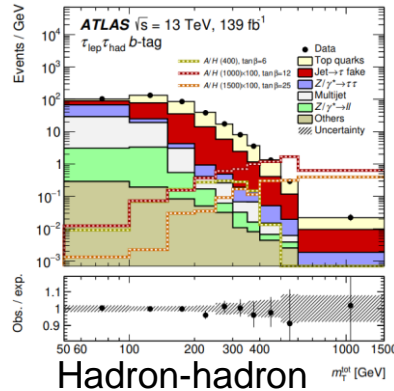
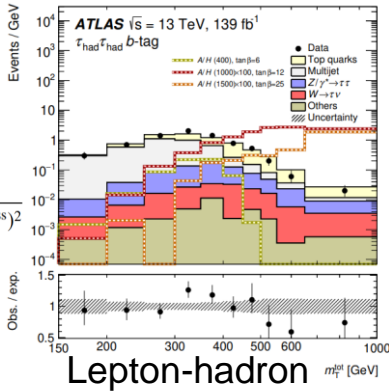


# Heavy neutral Higgs: $A/H \rightarrow \tau\tau$

- >  $A/H \rightarrow \tau\tau$  is enhanced in Type-II 2HDM, or MSSM.
- > ggF and bbA production with  $\tau\tau$  decay to lepton-hadron and hadron-hadron final states.
- > Dominant backgrounds, W+jets and multijets, are constrained from data.

Total transverse mass

$$\sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{\text{miss}})^2 - (\mathbf{p}_T^{\tau_1} + \mathbf{p}_T^{\tau_2} + \mathbf{E}_T^{\text{miss}})^2}$$



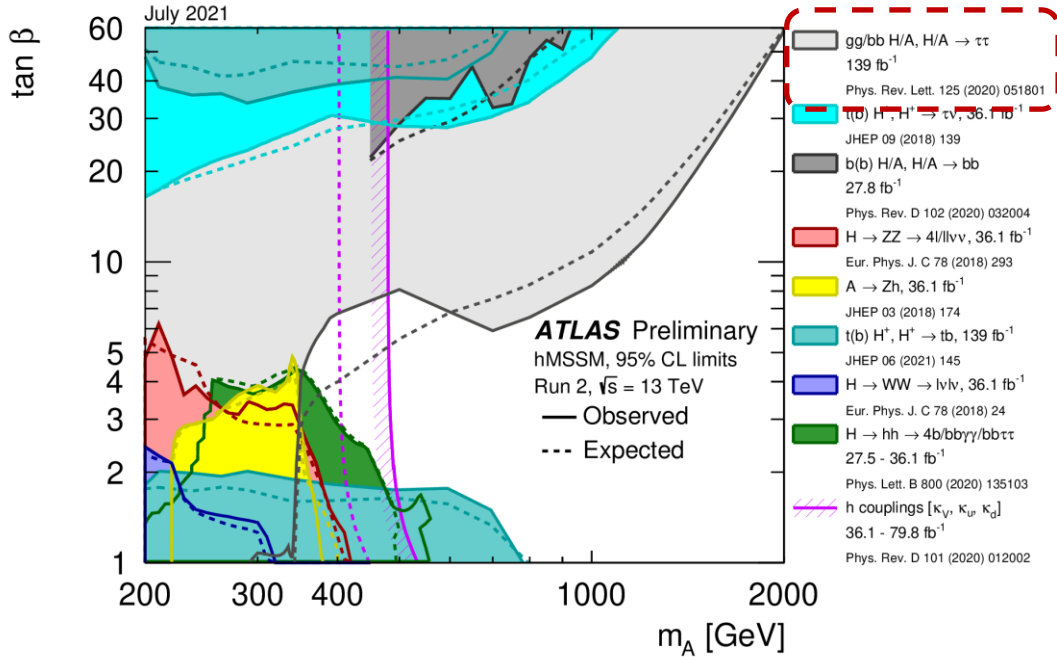
- Most significant excess is at  $\sim 400$  GeV with local significance of  $2.2\sigma$  from ggF and  $2.7\sigma$  from bbA.
- Strongest MSSM limits, especially at high  $\tan\beta$ .
- In the  $M_h^{125}$  scenario, exclude  $\tan\beta > 8(21)$  at  $m_A = 1.0(1.5)$  TeV.





# Run 2 summaries: hMSSM

## Exclusion plot from direct and indirect searches



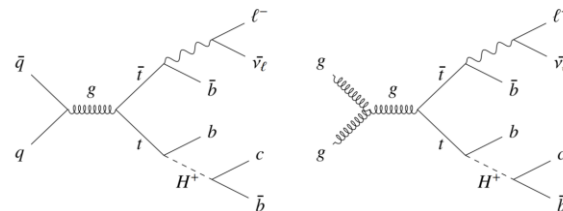
- > At tree level, depends on two BSM parameters:
  - $m_A$  and  $\tan\beta$
- > At high  $m_A$ , strongest limits come from  $A \rightarrow \tau\tau$ .
- > At low  $m_A$ , exclude by several channels.
- > More studies with full run-2 data.

# Singly and doubly charged Higgs bosons

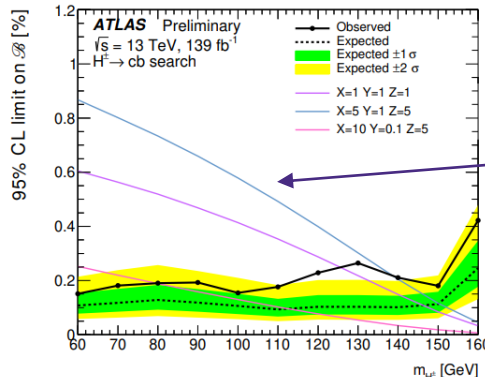
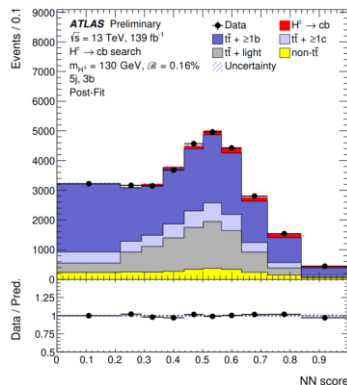
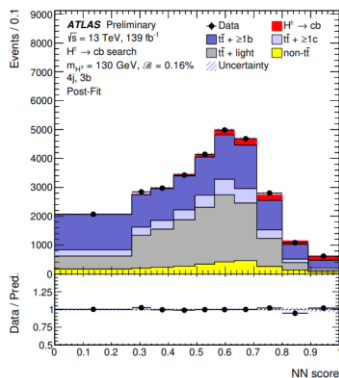
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	$H^{\pm\pm} \rightarrow WW$	139	<a href="#">JHEP 06 (2021) 146</a>



# Charged Higgs: $H^\pm \rightarrow cb$



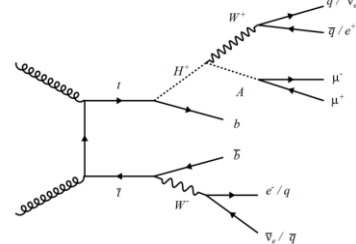
- > The charged higgs can be lighter than the top quark  $\rightarrow t \rightarrow H^\pm b$ .
- >  $H^\pm \rightarrow cb$  channel has lower irreducible SM background from  $t\bar{t}$  and W decays compared to  $H^\pm \rightarrow \tau\nu/cs$ .
- > One electron/muon +  $\geq 4$  jets ( $\geq 2$  b-jets).
- >  $t\bar{t}$ +jets is the dominant background, corrected by a data-based approach.
- > NN classifier exploiting kinematic and b-tagging information is used to enhance signal sensitivity.



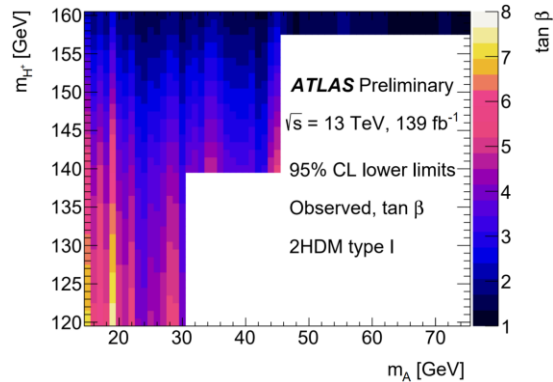
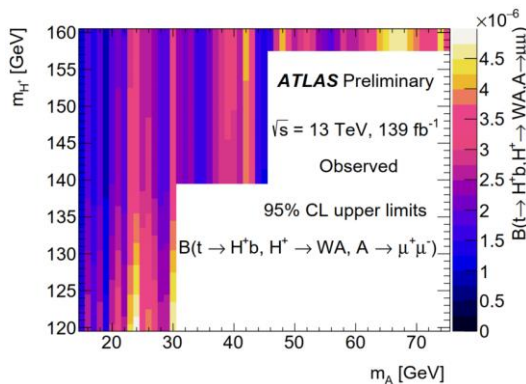
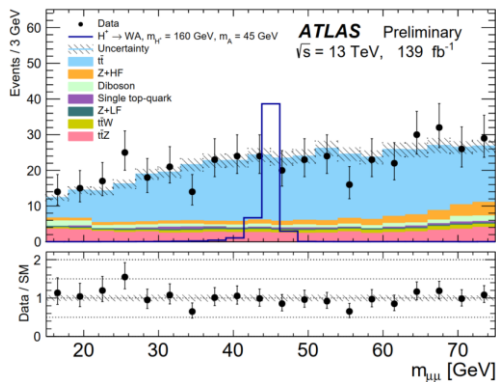
3HDM predictions

- Most significant excess is at  $\sim 130$  GeV with global (local) significance of  $\sim 2(3)\sigma$ .

# Charged Higgs: $H^\pm \rightarrow AW^\pm$



- Previous searches focused on the  $\tau\nu/cs/cb$  channels.
- If the A is light and  $H^\pm \rightarrow AW^\pm$  is kinematically allowed, the  $\tau\nu/cs/cb$  will be suppressed.
- Signal signature:  $\mu^+\mu^-e^{\pm+} \geq 3\text{jets} (\geq 1 \text{ b jet})$ .
- Main backgrounds,  $(t\bar{t}, ttZ, Z + FH)$  are normalized from 3 data CRs.



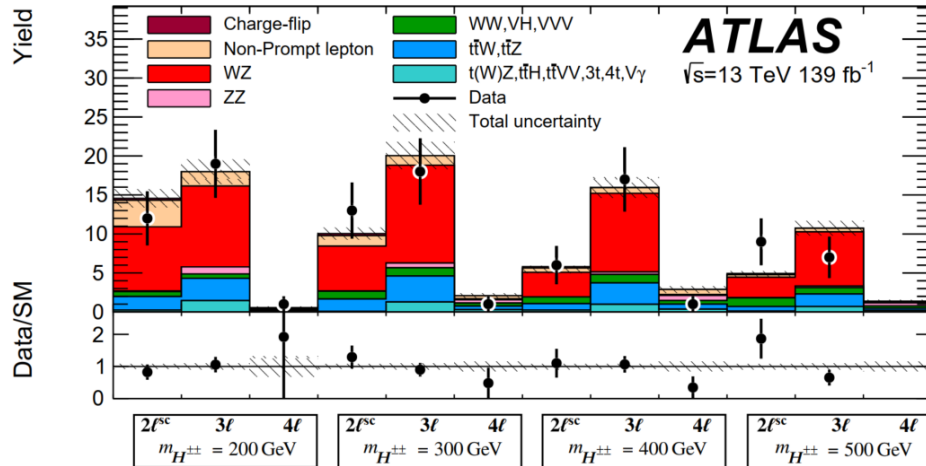
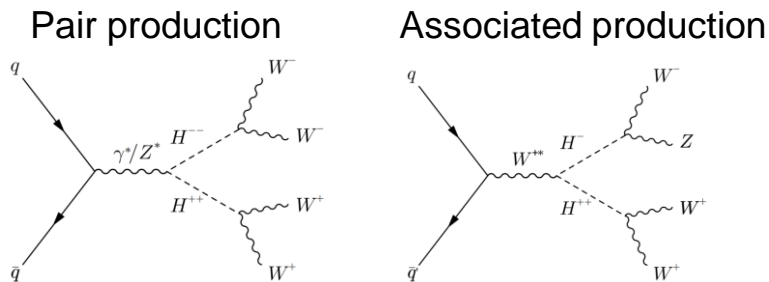
- No significant deviation from the SM predictions is observed.
- Largest excess is at 24 GeV with a local significance of  $1.24\sigma$ .
- The results are interpreted in type-I 2HDM.



# Charged Higgs: $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ and $H^{\pm} \rightarrow W^{\pm}Z$

> Two scenarios from type-II seesaw model:

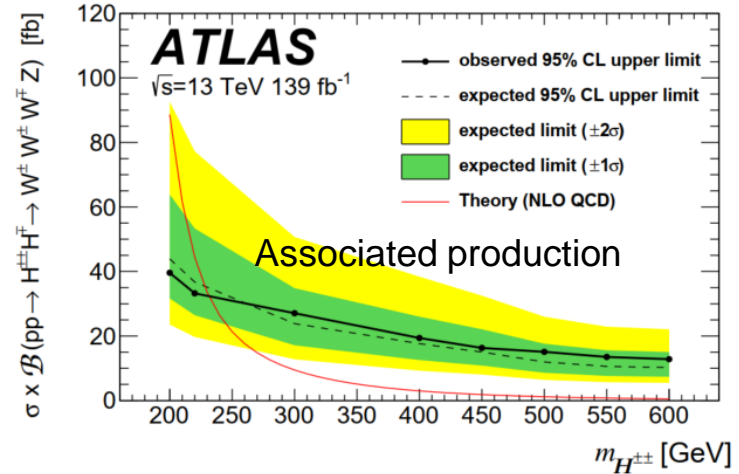
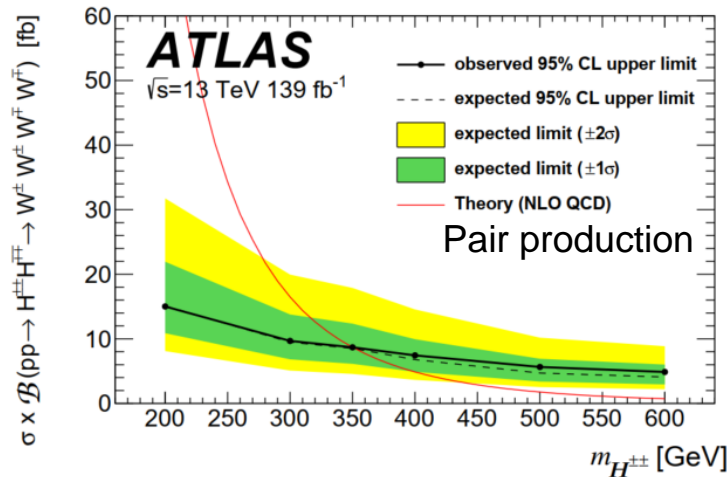
- $m_{H^+} - m_{H^{++}} \geq 100$  GeV, searched in pair production of  $H^{\pm\pm} H^{\mp\mp}$
- $|m_{H^+} - m_{H^{++}}| \leq 5$  GeV, searched in associated production of  $H^{\pm\pm} H^{\mp}$



- > Search in 3 channels ( $2\ell, 3\ell, 4\ell$ ).
- > Optimized for pair production mode.
- > Prompt lepton background: MC simulation + WZ (normalized from a data CR).
- > Non-prompt lepton and electron charge-flip background: data-driven estimation.



# Charged Higgs: $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ and $H^{\pm} \rightarrow W^{\pm}Z$



- Separate profile likelihood test for each signal hypothesis, combine the  $2l, 3l$  and  $4l$  channels to estimate the upperlimit.
- The model is excluded for  $H^{\pm\pm}$  below 350 GeV (pair production) and 230 GeV (associated production).

# Summary

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- > Lots of interesting new results on additional scalar searches with full Run2 data ( $139 \text{ fb}^{-1}$ ).
  - Many more are in the pipeline
- > No strong evidence for any BSM scalars yet !
  - But many excesses w.r.t. SM prediction are observed with  $\sim 1(3)\sigma$  global (local) significance
- > Run3 data taking will start at 2022.
  - Hopefully  $> 150 \text{ fb}^{-1}$  data

Thanks for the attention.

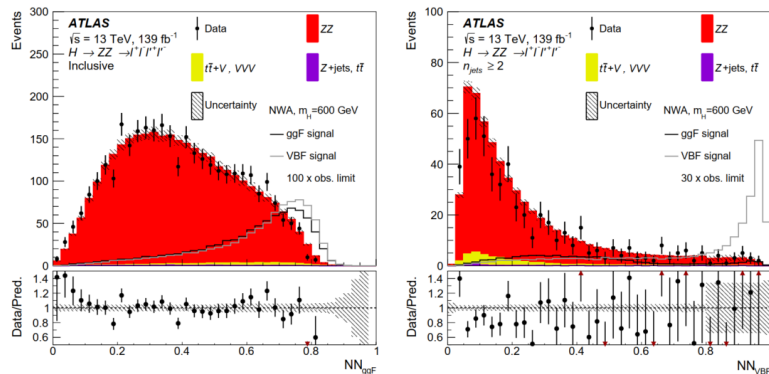
# Back-up

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# Heavy neutral Higgs: $H \rightarrow ZZ$

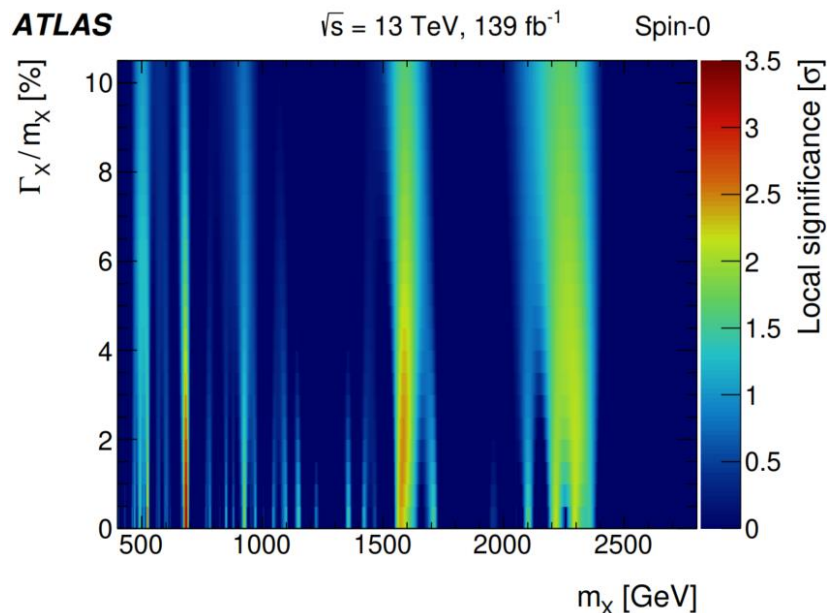
- > Two DNN classifier for ggF and VBF
- > ggF classifier input:
  - Four lepton invariant mass, momentum and pseudorapidity, helicity angles of lepton in Z rest frame,  $P_T$  and pseudorapidity of leading jet
- > VBF classifier input:
  - Invariant mass of four lepton,  $P_T$  and invariant mass of two leading jets, difference in pseudorapidity between four lepton and leading jet, minimum angular separation between lepton pair and jet



# Heavy neutral Higgs: $H \rightarrow \gamma\gamma$

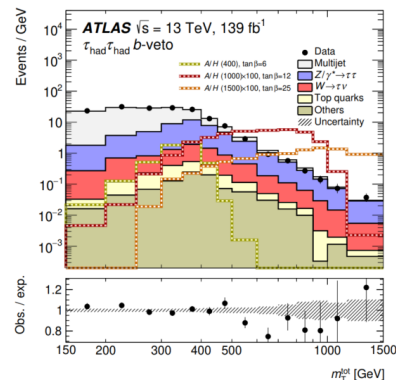
> 2D scan of resonance mass and width in  $\gamma\gamma$  spectrum

	<i>Spin-0</i>	
$m_X$	400 GeV	2800 GeV
NWA	1.1 fb	0.03 fb
$\Gamma_X/m_X = 2\%$	2.5 fb	0.03 fb
$\Gamma_X/m_X = 6\%$	4.4 fb	0.03 fb
$\Gamma_X/m_X = 10\%$	8.3 fb	0.04 fb

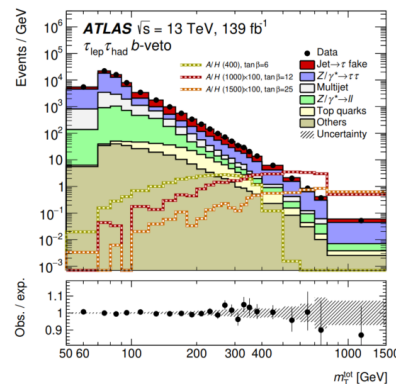


# Heavy neutral higgs: $A/H \rightarrow \tau\tau$

- **Hadronic  $\tau$  reconstruction:**
  - Seeded by jets
  - BDT classifier to distinguish from quark/gluon jets
    - Based on calorimeter shower shapes and tracking information
- **Dominant background**
  - Hadhad: multijets, constrained from a CR in data
  - LepHad:
    - W+jets (b-veto category): data-driven estimation
    - $\bar{t}t$  (b-tag category): constrained from a CR in data



ggF HadHad



ggF LepHad

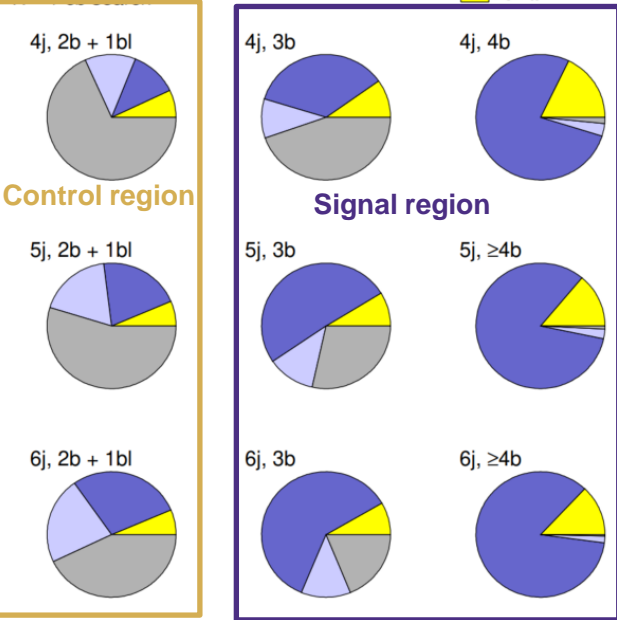
# Charged Higgs: $H^\pm \rightarrow cb$

- > Categories based on numbers of jets and b-jets
- > Binned likelihood fit is performed on the NN score in 6 SRs

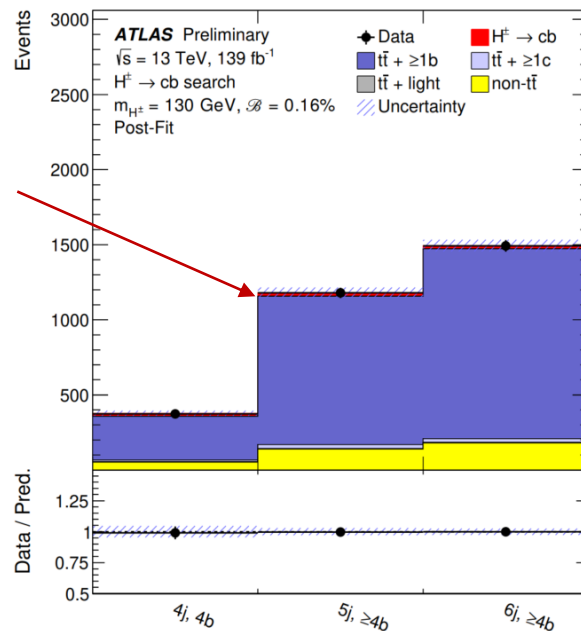
ATLAS Simulation Preliminary

$\sqrt{s} = 13$  TeV

$H^\pm \rightarrow cb$  search

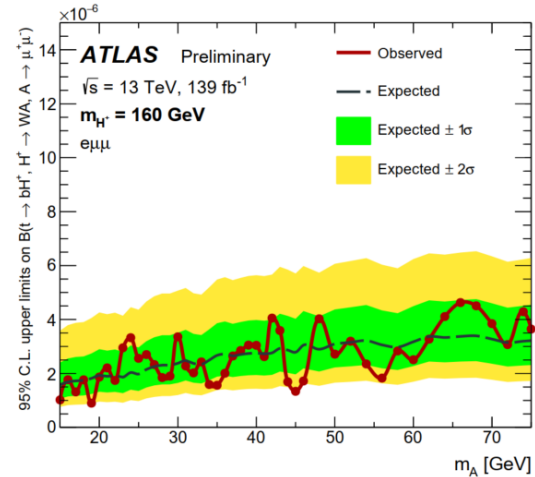
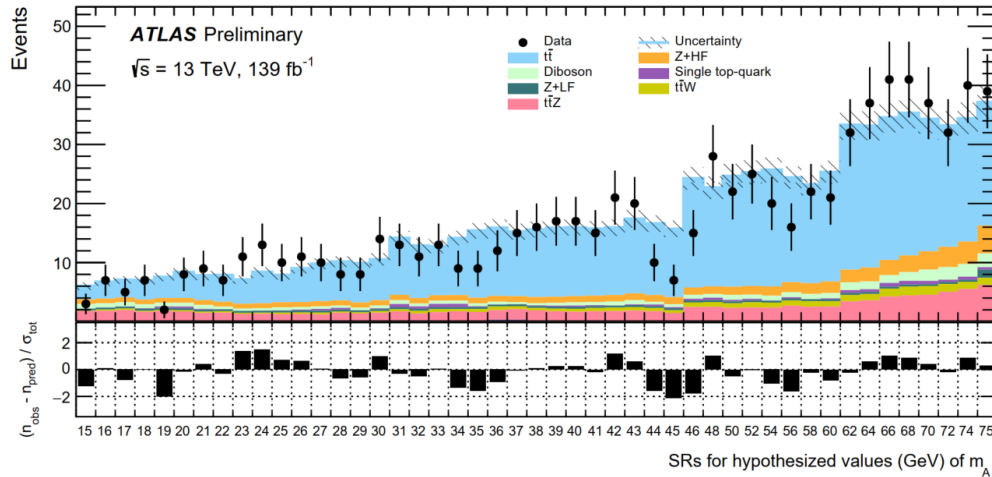


$m_{H^\pm} = 130$  GeV  
Most significant excess



# Charged Higgs: $H^\pm \rightarrow AW^\pm$

- >  $\mu\mu$  mass spectrum is used to perform the search
- > Divided into small windows and search for the deviation from SM prediction



- The limits for different masses of  $H^\pm$  and A are estimated

