

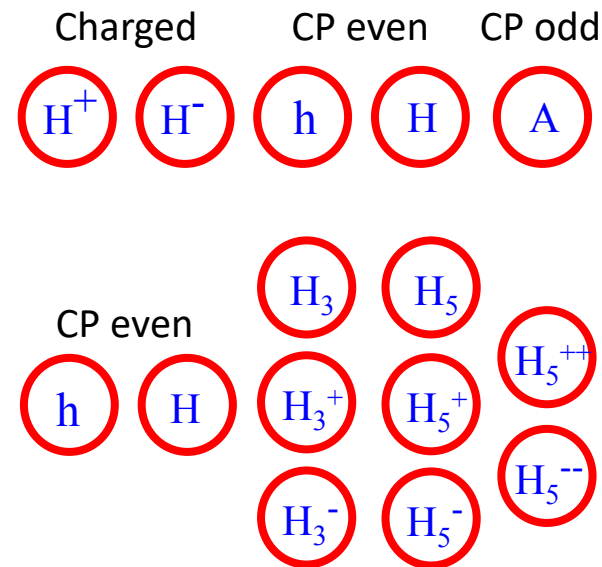
# Searches for new physics in the Higgs sector at ATLAS

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on behalf of the ATLAS Collaboration  
Rencontres de Blois  
17 May 2023



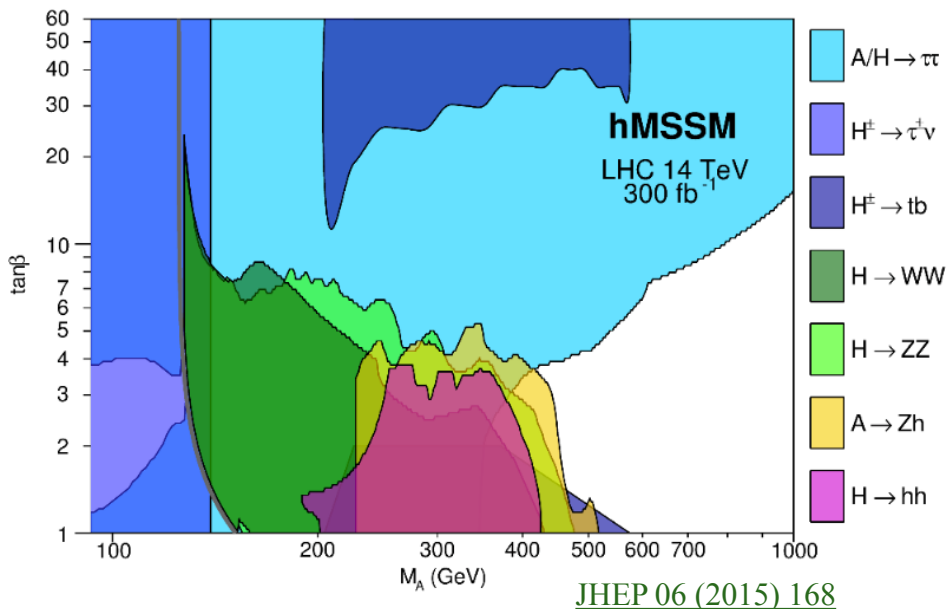
# Introduction

- The Standard Model is a **very successful theory but fails to:**
  - Provide new sources of CP violation
  - Provide a dark matter candidate, etc.
- An **extended Higgs sector** can solve some of these problems and require additional scalar Higgs states:
  - **Two Higgs doublet models (2HDM)** are required in the minimal supersymmetric extension of the SM
    - Parameters: mixing angle  $\alpha$  between neutral states,  $\tan \beta$  (ratio of VEVs), masses
  - **Higgs triplets** are required in models with a type-I or type-II see saw mechanism
    - One Higgs doublet and two Higgs triplets in the **Georgi-Machacek model**
    - Parameters: mixing angle  $\alpha$  between neutral states, ratio of doublet and triplet VEVs, masses
  - **Rich phenomenology and final states**



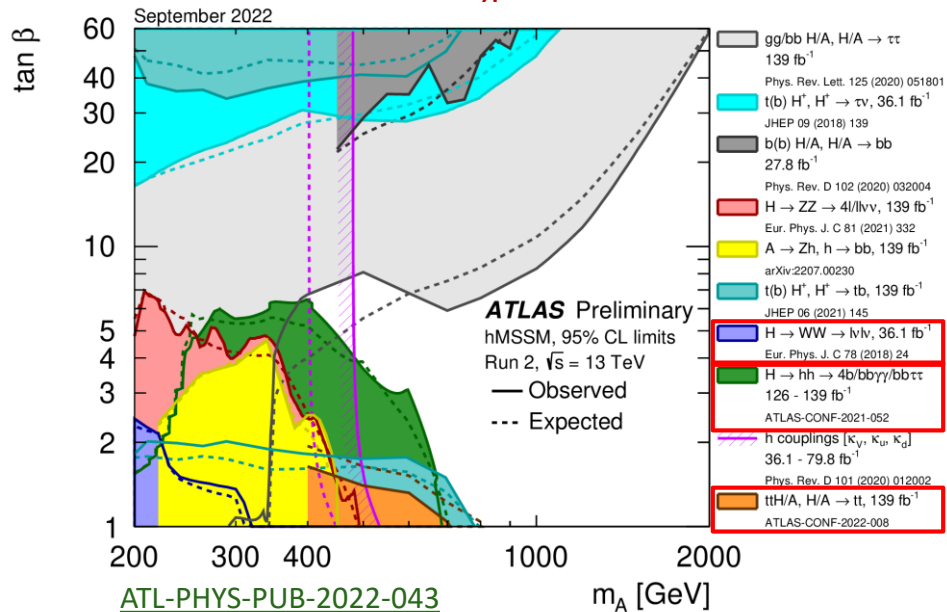
# Status of Higgs searches exclusion in ATLAS

LHC sensitivity in  $(m_A, \tan \beta)$  plane with  $300 \text{ fb}^{-1}$



- Already achieved better than expected sensitivity with the full Run 2 data

ATLAS excluded regions in  $(m_A, \tan \beta)$  with Run 2



- Latest results shown today:
  - $H \rightarrow WW, H \rightarrow hh, ttH/A(tt),$   
low mass  $a \rightarrow \mu\mu$

# Search for a heavy Higgs boson $H \rightarrow WW \rightarrow e\nu\mu\nu$

ATLAS-CONF-2022-066 (Nov 2022)

## Introduction:

- Studied ggF and VBF production modes separately
- Search for new resonances with leptonic Ws ( $e\nu\mu\nu$  final state)
- Used  $m_T$  between  $\ell\ell$  system and MET as discriminating variable

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{\text{miss}}|^2}$$

## Event categorization in signal and control regions (SR/CR):

- 3 SRs: ggF, VBF 1J, VBF  $\geq 2$ J with  $m_{jj} > 500$  GeV
- 2 Top background CRs: ggF, VBF
- 2 WW background CRs: ggF, VBF1J

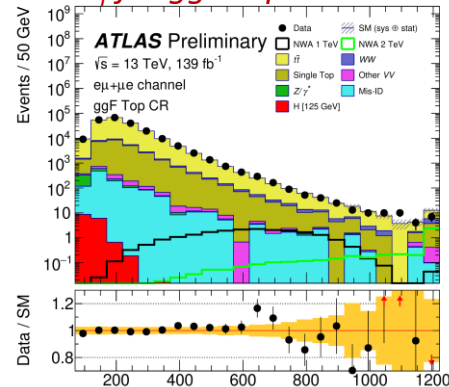
## Main backgrounds:

- tt and single-top, WW
- Smaller backgrounds from W/Z+jets

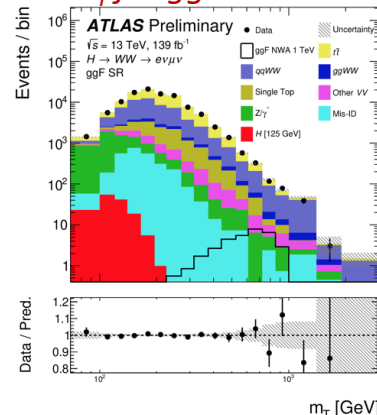
## Interpretation in three models:

- Spin-0 NWA, GM scalar and Radion

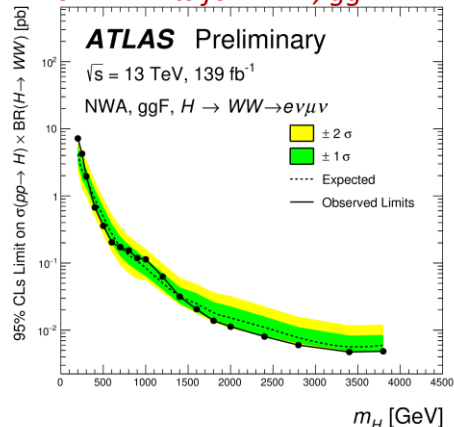
$m_T$  for ggF Top CR events



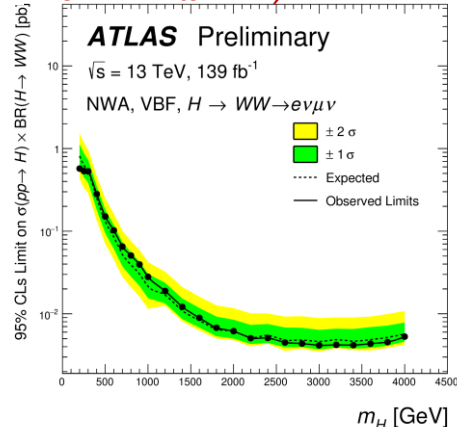
$m_T$  for ggF SR events



$\sigma \times B$  limits for NWA, ggF



$\sigma \times B$  limits NWA, VBF



# Search for new scalars in association with V

arXiv:2210.05415 (Oct 2022)

## • Introduction:

- Search for a resonant hh production
- Two BSM scenarios considered:  $V \rightarrow VH$  and  $A \rightarrow ZH$

## • Final state and event categorization:

- Leptonic V and  $h \rightarrow bb$
- 3 SRs:
  - 4 b-jets and  $0\ell / 1\ell / 2\ell$  for  $Z \rightarrow \nu\nu / W \rightarrow \ell\nu / Z \rightarrow \ell\ell$

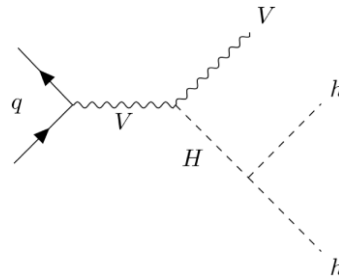
## • Analysis:

- Use of a BDT trained in each SR
- Backgrounds estimated with MC and CRs for tt and V+jets

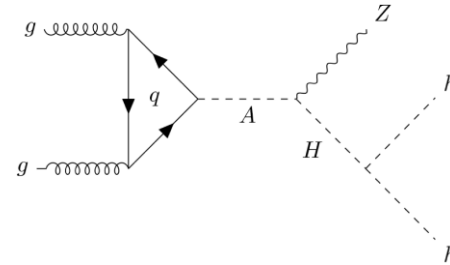
## • Result:

- Small excess with a local(global) significance of  $3.8\sigma$  ( $2.8\sigma$ ) at  $(m_A, m_H) = (420, 320)$  GeV for LW A

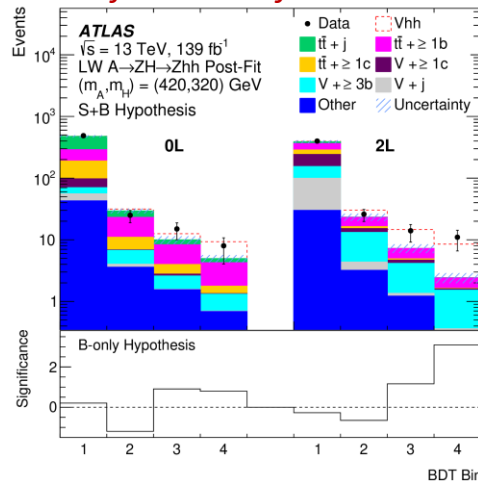
Higgs-strahlung from off-shell V



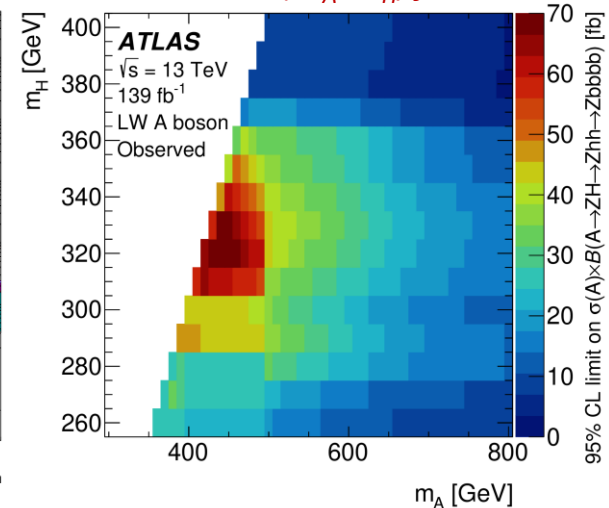
ZH decay from a heavy A



Post-fit BDT bin for LW A  $\rightarrow$  ZH



$\sigma \times B$  limits in  $(m_A, m_H)$  for LW A



# Search for new bosons $A/H \rightarrow t\bar{t}$ decays

arXiv:2211.01136 (Nov 2022)

## Introduction:

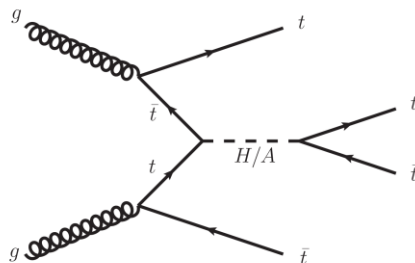
- Search for heavy scalar or pseudo-scalar produced in association with  $t\bar{t}$  with  $A/H \rightarrow t\bar{t}$

## Final state:

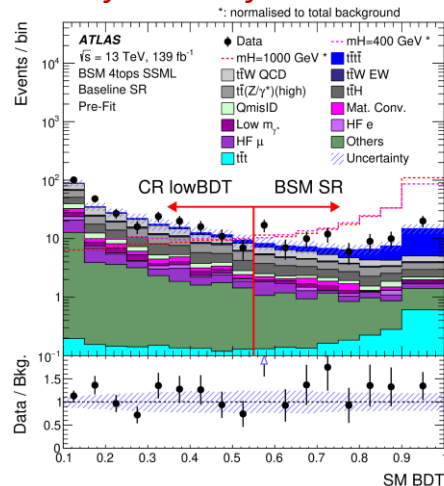
- Two (same-sign) or three charged leptons
- 4 b-jets
- 2 or 4 light-flavour jets

## Analysis strategy:

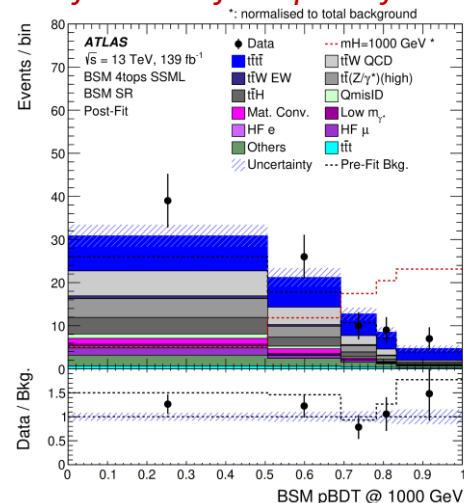
- Two sequential BDTs are used:
  1. SM BDT: to distinguish 4 tops from the rest of backgrounds
  2. Mass parameterised BDT (pBDT): uses SM BDT and  $H_T$  as inputs to distinguish signal from all backgrounds
- Dedicated CRs used to constrain backgrounds



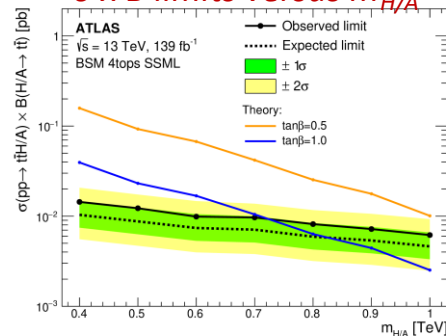
Pre-fit distr. of the SM BDT



Post-fit distr. of the pBDT for 1 TeV



$\sigma \times B$  limits versus  $m_{H/A}$



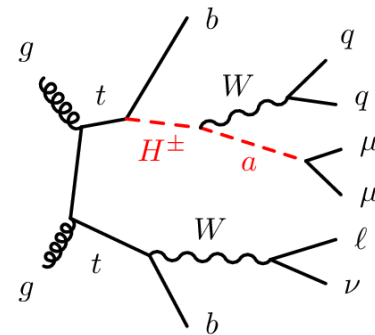
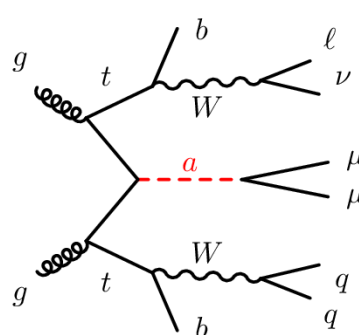


# Search for $a \rightarrow \mu\mu$ in top quark pair events

arXiv:2304.14247 (Apr 2023)

## • Introduction:

- Search for a light pseudo-scalar produced in association with  $tt$
- Used two signal models:
  - $pp \rightarrow tta(\mu\mu)$  with  $15 \text{ GeV} < m(a) < 72 \text{ GeV}$
  - $pp \rightarrow tt$  with  $t \rightarrow bH^\pm(Wa)$  and  $a \rightarrow \mu\mu$  with  $120 \text{ GeV} \leq m(H^\pm) \leq 160 \text{ GeV}$



## • Signature:

- $\geq 3$  jets,  $\geq 1$  b-jet, three leptons:  $e\mu\mu$  or  $\mu\mu\mu$

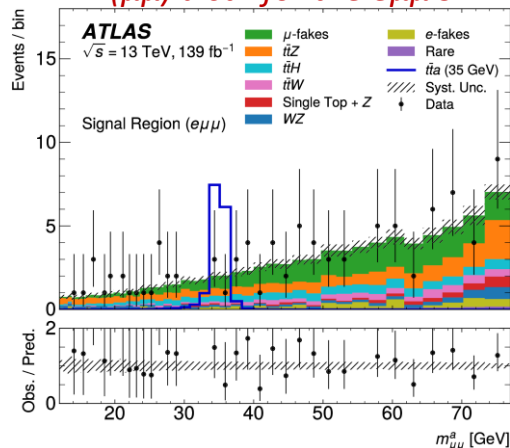
## • Analysis strategy:

- Used 2 SRs
- Used  $ttZ$  CRs with various jet and b-jet multiplicities and  $tt$  CR with 1 non-prompt  $\mu$
- Fit  $m(\mu\mu)$

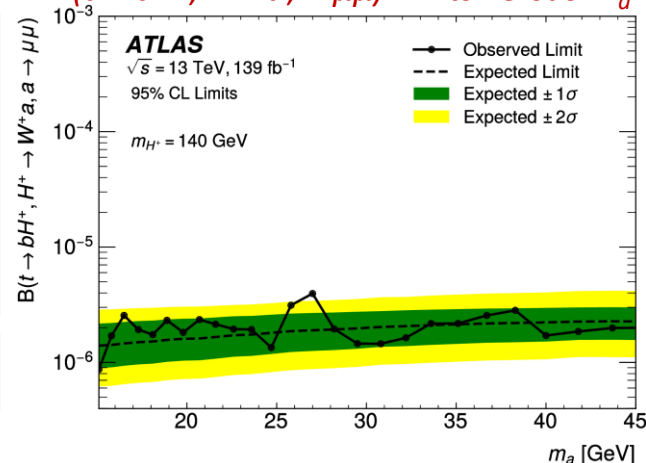
## • Results:

- Local significance of  $2.4\sigma$  at  $m(a)=27 \text{ GeV}$

$m(\mu\mu)$  distr. for the  $e\mu\mu$  SR

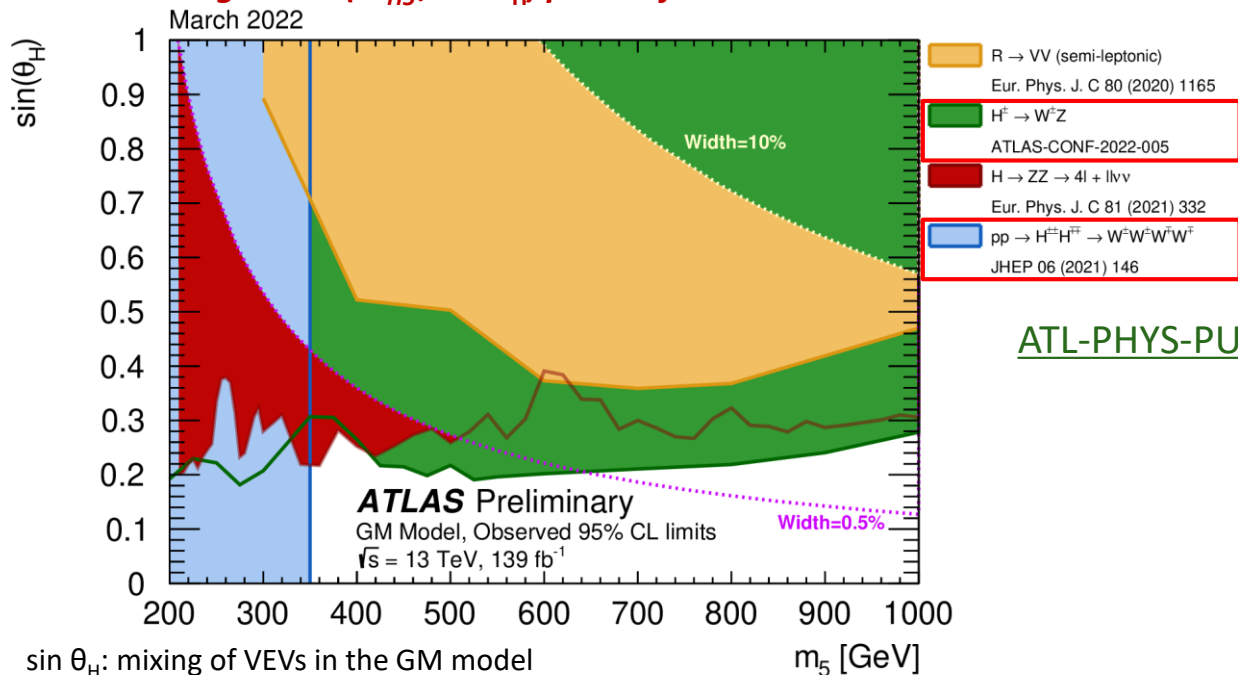


$B(t \rightarrow bH^\pm, H^\pm \rightarrow Wa, a \rightarrow \mu\mu)$  limits versus  $m_a$



# Status of GM Higgs searches exclusion in ATLAS

ATLAS excluded regions in  $(m_{H_5}, \sin \theta_H)$  plane of the GM model with Run 2



[ATL-PHYS-PUB-2022-008](#)

- **Latest results shown today:**

- Fermiophobic  $H^+ \rightarrow WZ$ ,  $H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm$ ,  $H^+ \rightarrow cb$ , FCNC  $t \rightarrow qX$



# Search for fermiophobic $H^+ \rightarrow WZ$

arXiv:2207.03925 (July 2022)

- Introduction:**

- Assumed triplets states heavier than fiveplet scalars
- Fiveplet can only decay to WZ, with cross-section proportional to  $\sin^2 \theta_H$

- Experimental signature:**

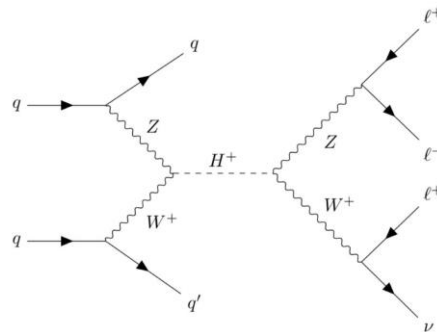
- Three charged leptons
- Missing transverse energy
- Two jets (in the forward direction)

- Analysis:**

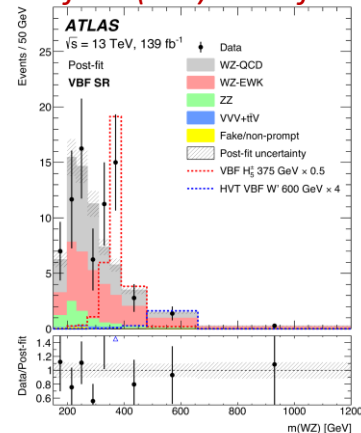
- Used a classification NN to define CRs and SR
- Used ZW and ZZ control regions and one SR
- Used  $m(WZ)$  for fitting

- Result:**

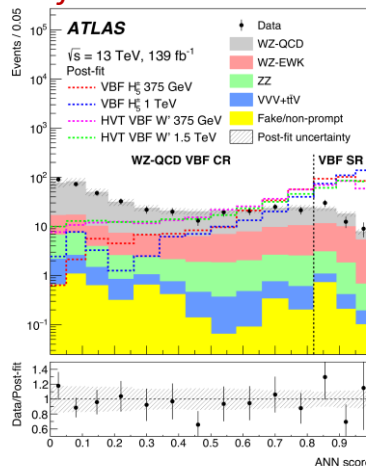
- Small excess with a local (global) significance of  $2.8\sigma$  ( $1.6\sigma$ ) at  $m(WZ)=375$  GeV



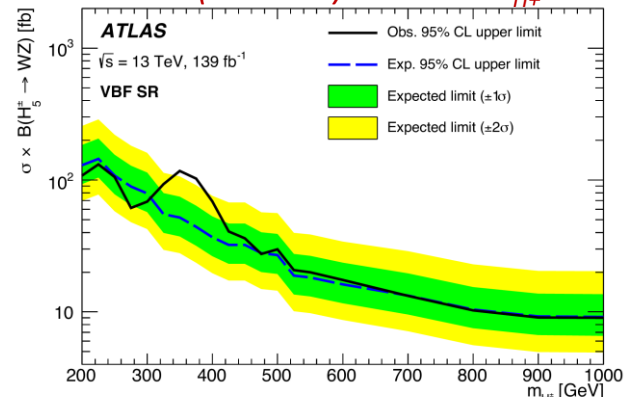
Post-fit  $m(WZ)$  distr. for SR



Post-fit NN score distribution



$\sigma \times B(H^+ \rightarrow WZ)$  limits vs  $m_{H^\pm}$



# Doubly charged Higgs $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ search

arXiv:2211.07505 (Nov 2022)

## • Introduction:

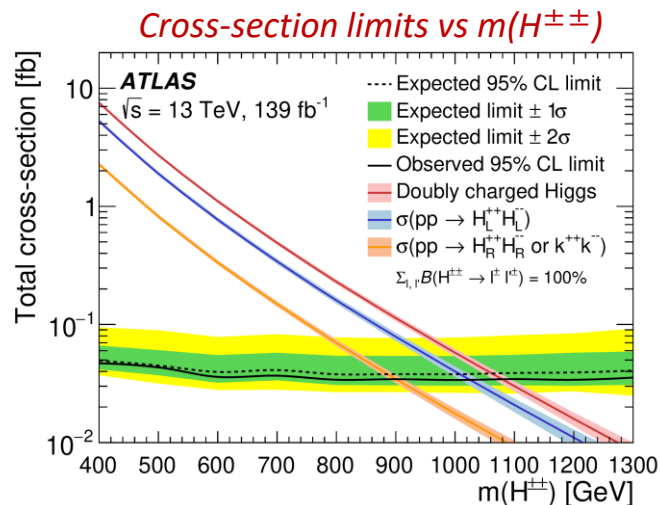
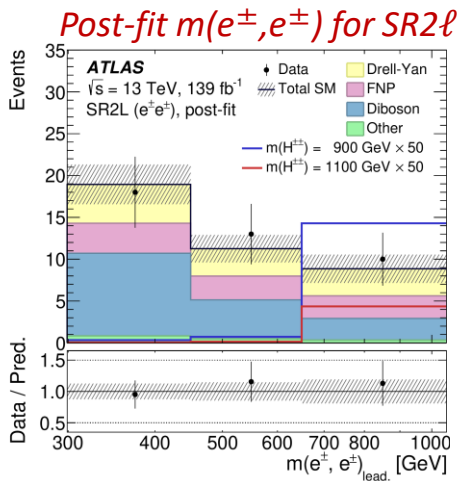
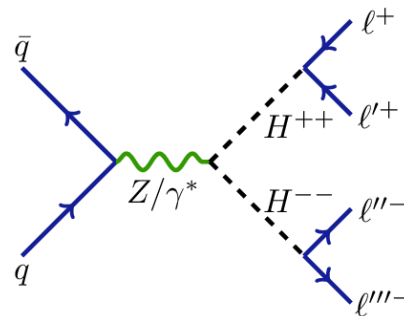
- Drell-Yan production of two doubly charged Higgs in multi-lepton final states
- Predicted by left-right symmetric models, type-II see saw models, GM model, etc.

## • Selection:

- Same-charge lepton pairs with 2, 3 or 4 leptons
- Electrons or muons considered

## • Analysis:

- CRs, validation and signal regions defined with various lepton charge multiplicities
- Used  $m(\ell^{\pm}\ell'^{\pm})$  for the fit with  $\ell=(e,\mu)$



# Search for $H^+ \rightarrow cb$ in top-quark decays

arXiv:2302.11739 (Feb 2023)

- Introduction:**

- Predicted by 3HDMs:

- 3 CP even, 2 CP odd neutral Higgs and  $2H^\pm$

- Experimental signature:**

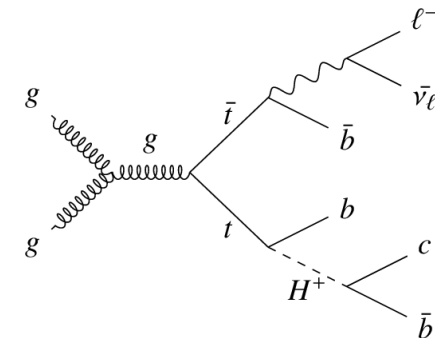
- $1\ell$  (e or  $\mu$ ),  $E_T^{\text{miss}}$ ,  $\geq 4$  jets,  $\geq 3$  b-tags

- Analysis:**

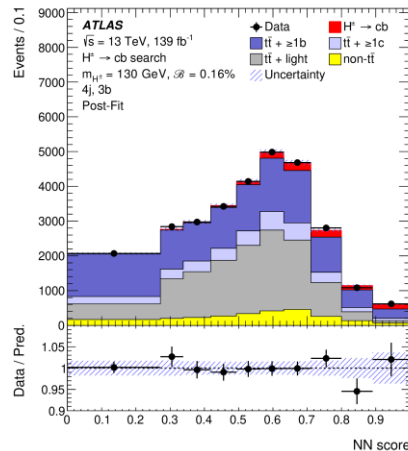
- NN used to distinguish signal from background
- Used CRs to correct the tt background
- Used SRs with 4,5,6 jets and 3 b-jets or  $\geq 4$  b-jets

- Result:**

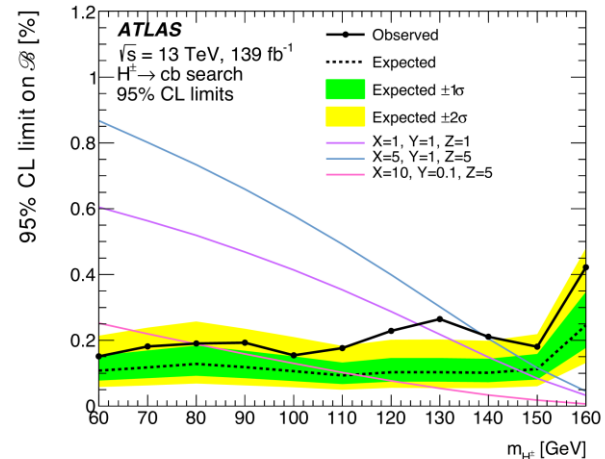
- Small excess with a local (global) significance of  $3\sigma$  ( $1.6\sigma$ ) at 130 GeV



Post-fit NN distr. for 4j3b



$B(H^+ \rightarrow cb)$  limits vs  $m_{H^+}$



# Search for a scalar $X \rightarrow bb$ in FCNC top-quark decays

arXiv:2301.03902 (Jan 2023)

## • Introduction:

- Search for new scalar in flavour-changing neutral current top quark decays
- Predicted by the Froggatt-Nielsen mechanism
  - Introduces a flavon, a field with charge

## • Experimental signature:

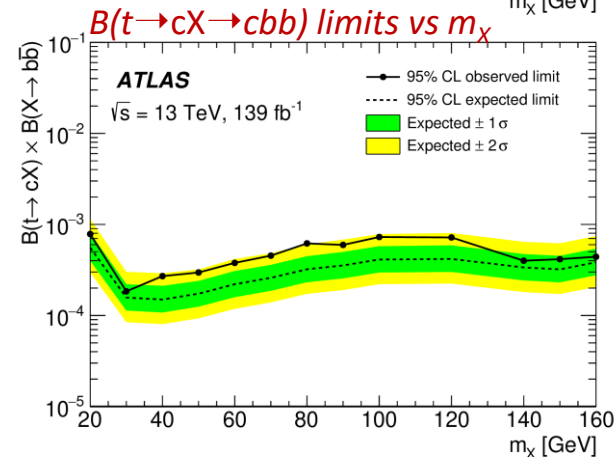
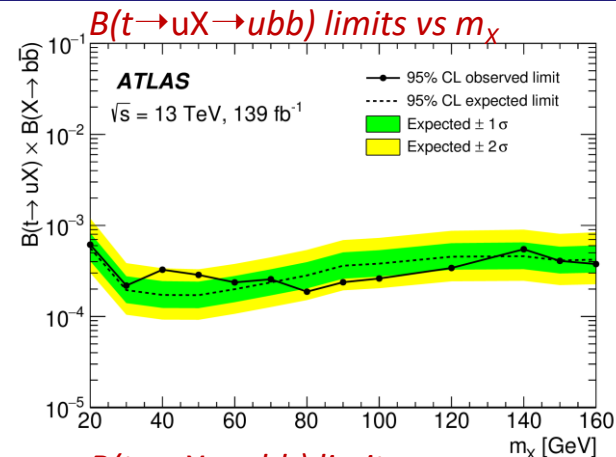
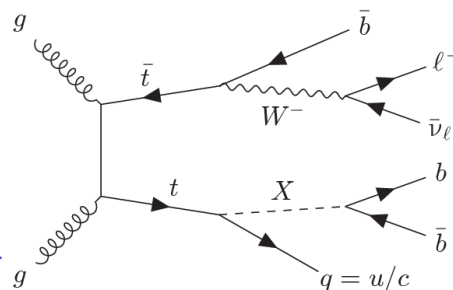
- $1\ell$  (e or  $\mu$ ),  $E_T^{\text{miss}} \geq 4$  jets,  $\geq 3$  b-tags

## • Analysis:

- Very similar strategy to the  $H^+ \rightarrow cb$  search with similar CRs and SRs with various jet and b-jet multiplicities
- Mass-parameterised NN used to distinguish signal from background

## • Result:

- About  $2\sigma$  excess in the  $t \rightarrow cX$  channel through a broad  $m_X$  range, incompatible with a X resonance

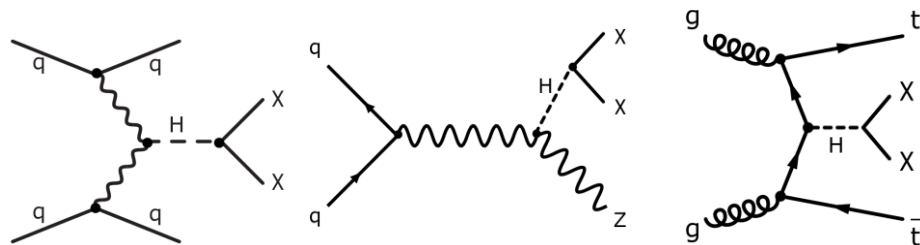


# Higgs to a dark matter portal

arXiv:2301.10731 (Jan 2023)

- Introduction:**

- Many models predict a massive, stable and electrically neutral particle,  $\chi$ , as a dark matter candidate
- The Higgs boson acts as a portal between the SM and the dark sector,  $H \rightarrow \chi\chi$

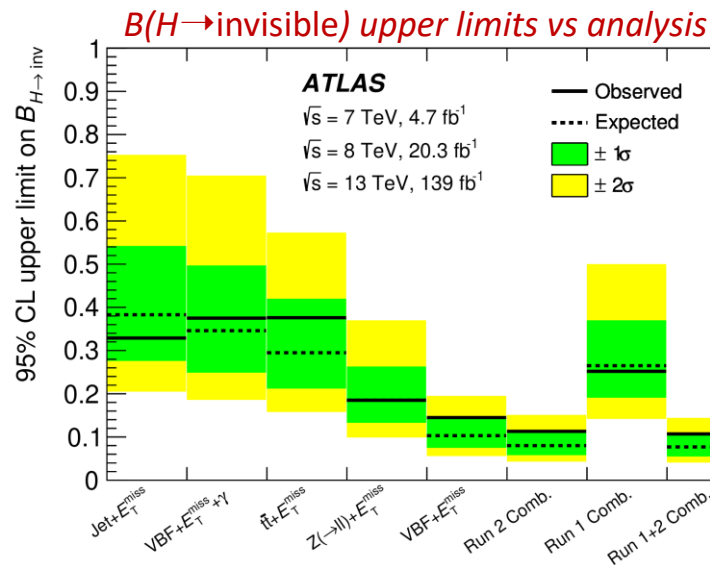


- Analysis:**

- Combined searches of invisible decays of the Higgs across multiple production modes and including the Run 1 results

- Result:**

- $B(H \rightarrow \text{invisible}) < 10.7\%$  (7.7% expected)



# Search for $ZH, H \rightarrow \gamma\gamma_{\text{dark}}$

arXiv:2212.09649 (Dec 2022)

## • Introduction:

– Search for dark photons  $\gamma_d$  from Higgs boson decays via the  $ZH$  production mode

### – Dark Higgs Vector Portal:

- $U(1)$  gauge boson: visible photon,  $\gamma$
- $U(1)_D$  gauge boson: massive (or massless) dark photon,  $\gamma_d$

## • Experimental signature:

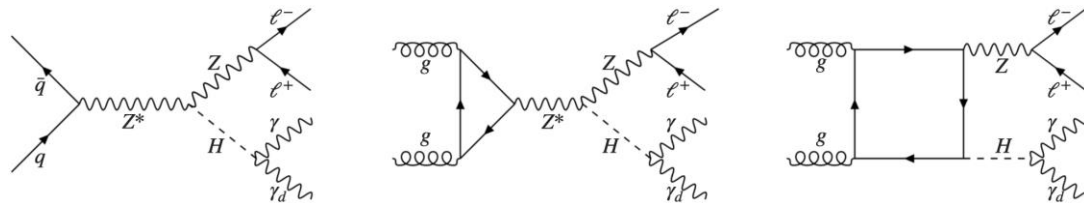
- 2 leptons ( $ee$  or  $\mu\mu$ ), one isolated  $\gamma$  and  $E_T^{\text{miss}}$
- $ZH$  production mode provides di-lepton pair for triggering and background rejection

## • Main backgrounds:

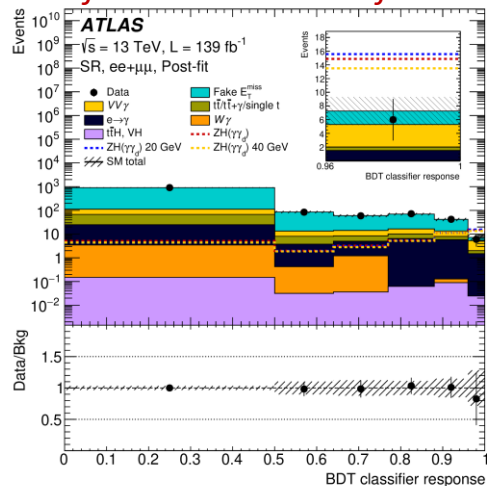
- Fake  $E_T^{\text{miss}}$  (from data)
- top processes,  $e \rightarrow \gamma, VV\gamma$  (from CRs in the fit)

## • Analysis:

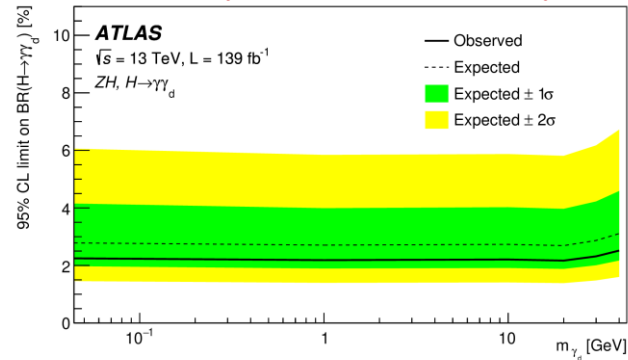
- BDT response as discriminant



## Post-fit BDT distribution for the SR



## $B(H \rightarrow \gamma\gamma_d)$ upper limits vs $m(\gamma_d)$





# Search for Dark Higgs boson

ATLAS-CONF-2023-016 (Mar 202)

- Introduction:**

- Search for a  $A'$  produced in association with a  $h_D$  via rare decays of the Z boson
- Motivated by a dark Abelian Higgs model:
  - Adds a  $U(1)_D$  gauge symmetry  $\rightarrow$  **dark photon,  $A'$** : mediator of the dark sector interactions with the SM
  - Symmetry spontaneously broken by a Higgs mechanism  $\rightarrow A'$  acquires mass, adding a **dark Higgs boson,  $h_D$**

– Search for  $Z \rightarrow A' h_D \rightarrow A' A' A'^{(*)}, A' \rightarrow \ell^+ \ell^-$  ( $\ell = e, \mu$ )

- Experimental signature:**

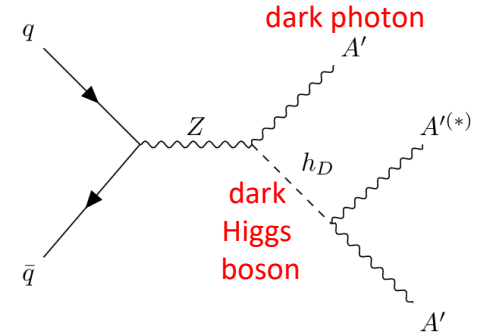
- 4 soft and isolated leptons
- Select  $\geq 2$  same-flavour opposite sign leptons

- Main backgrounds:**

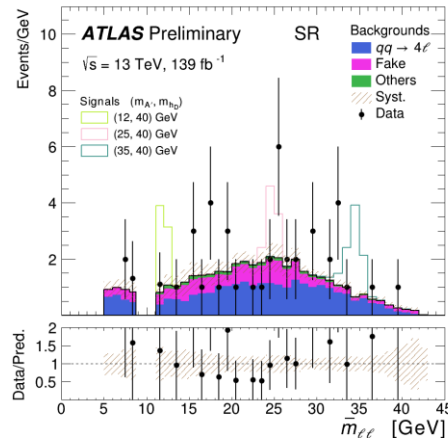
- $qq \rightarrow 4\ell$  (used a CR)
- Fake factor method for non-prompt leptons

- Fit average  $\langle m_{\ell\ell} \rangle$**

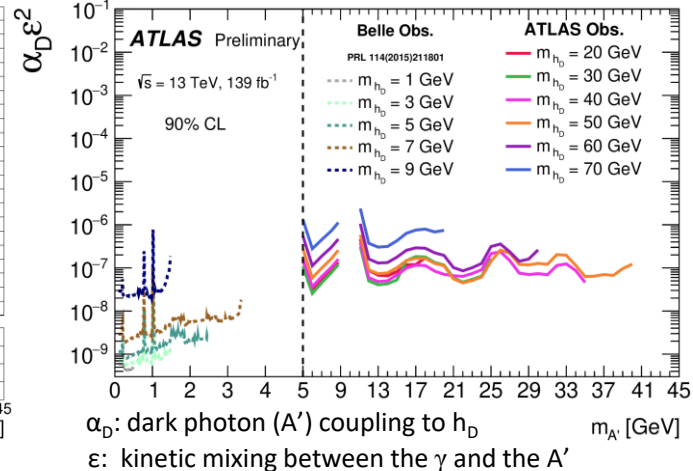
- Result complementary to a search by Belle**



$\overline{m}(\ell\ell)$  distribution for the SR



$\alpha_D \epsilon^2$  limits ( $\propto$  linearly signal yield) vs  $m(A')$



$\alpha_D$ : dark photon ( $A'$ ) coupling to  $h_D$   
 $\epsilon$ : kinetic mixing between the  $\gamma$  and the  $A'$

# Summary and conclusions

- The **extended Higgs sector has a rich phenomenology** where to look for new physics
- Many **interesting searches for additional Higgs bosons** including dark Higgs and exotic Higgs boson decays are performed by ATLAS
- **No significant deviation** from the SM has been observed so far
  - There are however **small deviations of 2 or 3 $\sigma$**  that have to be followed up
- Further results using the full Run-2 data are to be expected in the future
- Analyses will continue in Run 3 and eventually at the HL-LHC
  - **New production and decay channels will become available**
- **Stay tuned!**

**THANK YOU!**