

# Search for rare and exotic decays of the Higgs boson and additional scalar particles in ATLAS

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On behalf of the ATLAS Collaboration.

**DIS2022 conference**



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# The Higgs boson exists and then...

- The Higgs boson exists and it's discovered in 2012 → scrutinize its properties and the Higgs sector nature.
- Recent search set a 95% CL upper limit of 21% on the branching ratio for  $H$  boson decays via undetected modes.

▶ arXiv:1909.02845

⇒ Exotic decays of the Higgs boson remain a high priority.

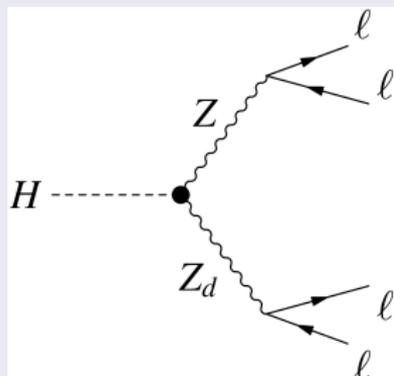
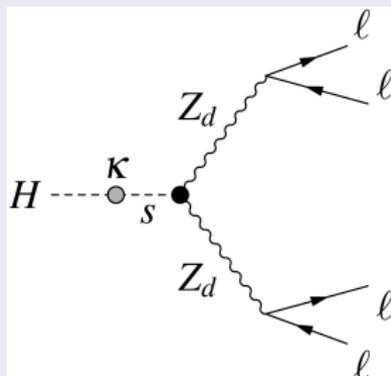


- Even with its excellent successes in providing experimental predictions, the SM leaves some phenomena unexplained.
  - hierarchy problem, baryon asymmetry, dark matter/energy etc...
- Many Beyond Standard Model (BSM) theories predict modified and extended Higgs sectors with additional Scalars

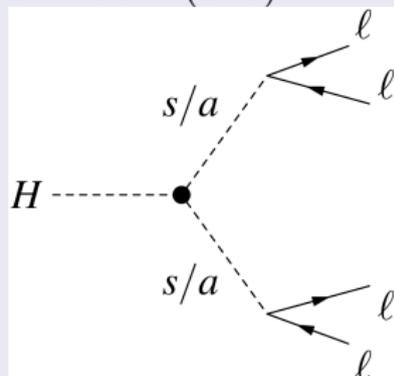
▶ arXiv:1412.0018

## Seven analyses covered

- ①  $H \rightarrow XX/ZX \rightarrow 4\ell$  [▶ arXiv:2110.13673v1](#)
  - **Where X is a dark boson  $Z_d$  or pseudo scalar  $a$ .**
- ②  $H \rightarrow \chi_1\chi_2 \rightarrow bb+\text{MET}$  [▶ arXiv:2109.02447v2](#)
  - **Where  $\chi_1\chi_2$  are the two lightest neutralinos.**
- ③  $WZ \rightarrow \ell\nu\ell'\ell'$  [▶ ATLAS-CONF-2022-005](#)
  - **Which includes H+ interpretation in Georgi-Machacek model.**
- ④  $H^{++}/H^{--} \rightarrow \ell^+\ell^+/\ell^-\ell^-$  [▶ ATLAS-CONF-2022-010](#)
  - **$H^{++}/H^{--}$  in multilepton final states.**
- ⑤  $t\bar{t}H/A \rightarrow t\bar{t}\bar{t}$ . [▶ ATLAS-CONF-2022-008](#)
  - **Where A is a heavy scalar.**
- ⑥ Search for  $t \rightarrow qX(b\bar{b})$  [▶ ATLAS-CONF-2022-027](#): **Brand new analysis**
  - **Where X is a scalar  $\in [20-160]$  GeV.**
- ⑦  $H \rightarrow aa \rightarrow bb\mu\mu$  [▶ arXiv:2110.00313](#)
  - **Search for a narrow dimuon resonance.**

 $Z_d \in [15 - 55] \text{ GeV}$  $Z_d \in [15 - 60] \text{ GeV}$ 

Low Mass(LM)

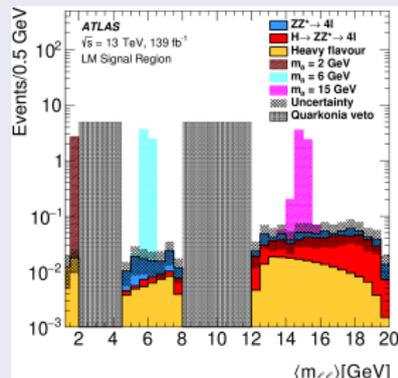
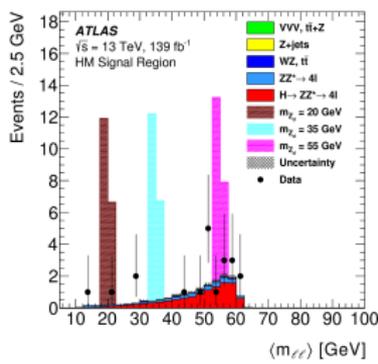
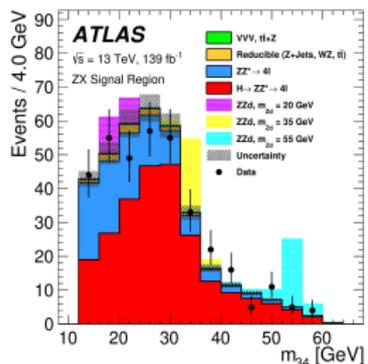
 $a \in [1 - 15] \text{ GeV}$ 

- $\ell \Rightarrow e^-$  or  $\mu$ : for LM only  $\Rightarrow 4\mu$  case is considered.
- Quadruplet with SFOS is selected.
- $m_{12}$  ( $m_{34}$ )  $\Rightarrow$  leading (sub-leading) di-lepton mass.
- $\langle m_{\ell\ell} \rangle$  ( $m_{34}$ ) used as observable for  $Z_d Z_d / aa$  ( $ZZ_d$ ).

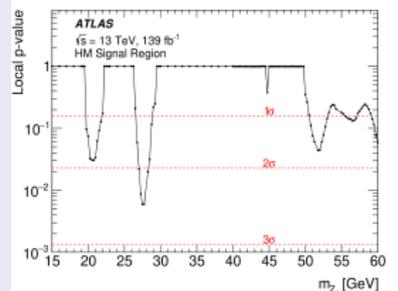
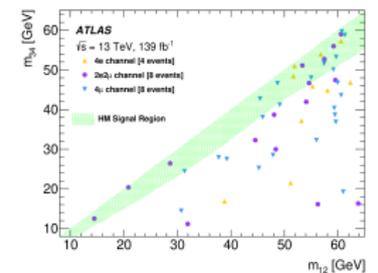
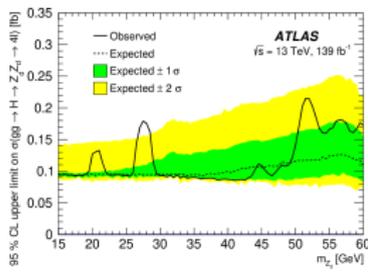
## main bkg

- $H \rightarrow ZZ^* \rightarrow 4\ell$
- $ZZ^* \rightarrow 4\ell$
- Heavy flavor jets faking leptons.

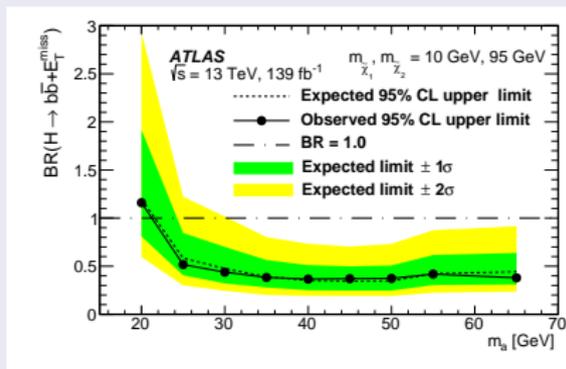
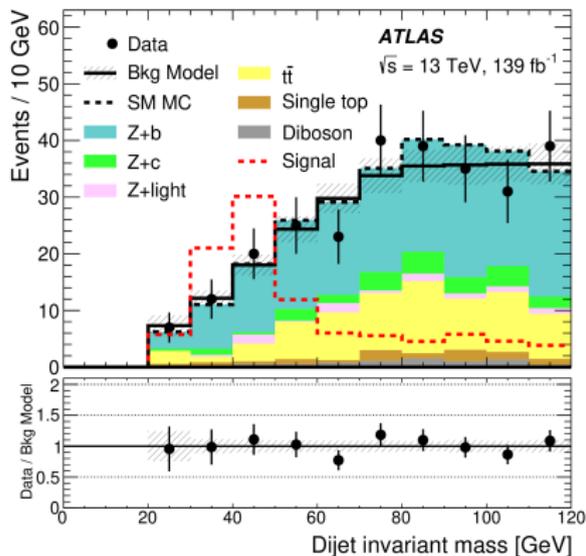
Some excesses in  $Z_d Z_d$  case but not statistically significant



Highest local  $p_0 = 2.5 \sigma$  ( $ZZ_d$  and  $a$  limit in backup).

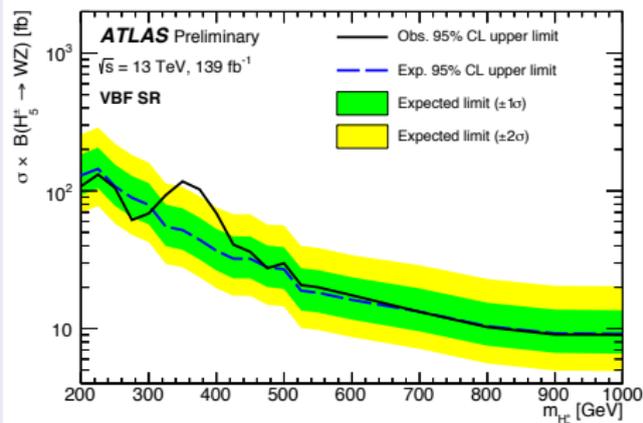
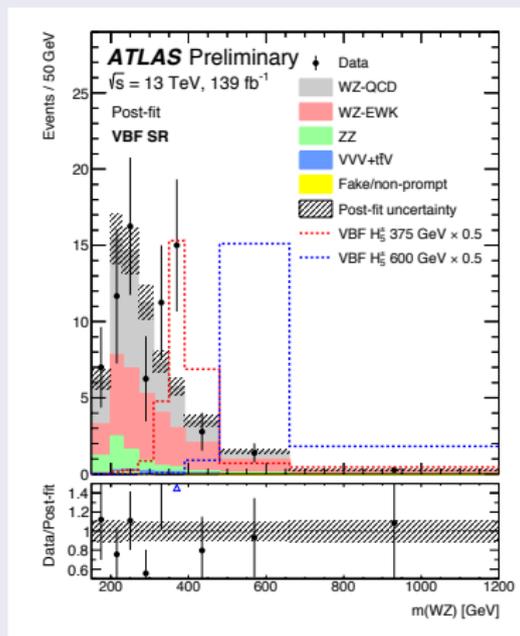


- Production scenario:  $H \rightarrow \chi_1^0 \chi_2^0$  with  $\chi_2^0 \rightarrow a \chi_1^0$  and  $a$  decays to a pair of  $b$ -quarks  $\Rightarrow$  peak in the dijet invariant mass.
- Search for deviation in  $jj$  invariant mass from  $a$  decays. Require at least one  $b$ -jets and suppress top background using the  $p_T$  fraction:  $0.8 \leq \frac{p_T^{jj} + E_T^{\text{miss}}}{p_T^{\ell\ell}} \leq 1.2$ .



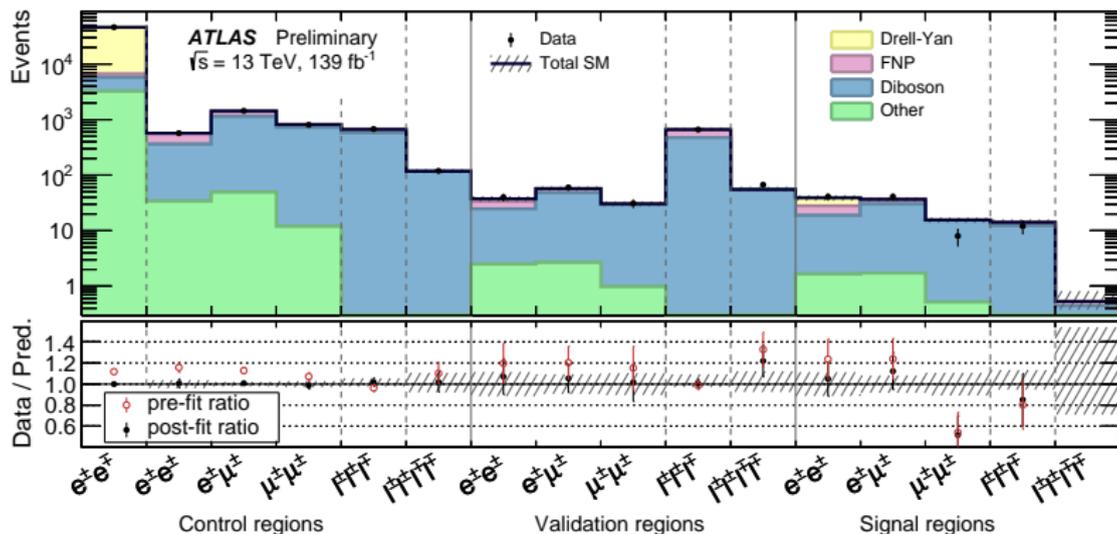
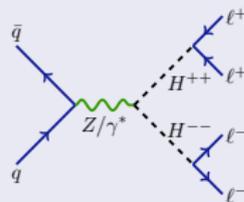
- No excesses seen.
- XS sensitivity down to  $\sim 30\%$ .

- Search for WZ resonance: from WZ-fusion or the DY process
- Artificial Neural Network (ANN) used for the VBF selection.
- A cut-based selection is used to build the Drell-Yan signal region.
- WZ invariant mass used as discriminating variable.



- Observed and expected 95% CL upper limits on XS.
- Highest local significance is  $2.8\sigma \Rightarrow m(WZ)=375$  GeV.

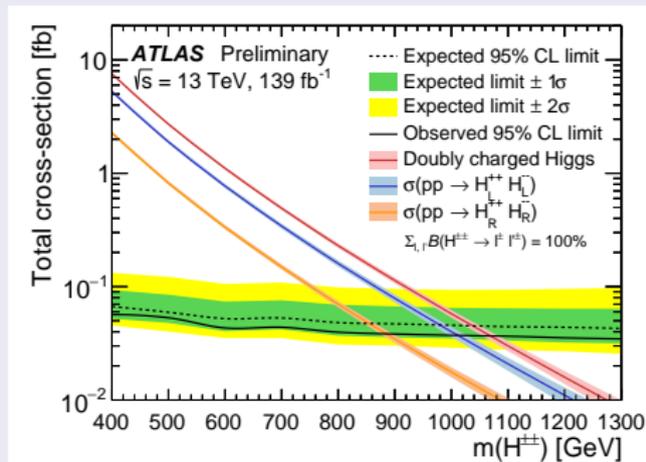
- Main variable  $m(\ell^\pm, \ell^\pm)$ .
- SR:  $300 < m(\ell^\pm, \ell^\pm) < 1300$  GeV.
- With the veto on b-jets, the analysis suppresses contribution from top quark background.



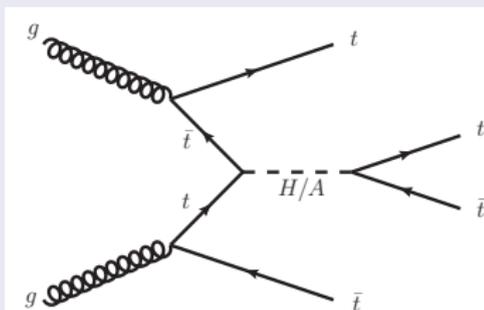
$$H^{++}/H^{--} \rightarrow \ell^+\ell^+/\ell^-\ell^-$$

## No significant excess: Limit is set

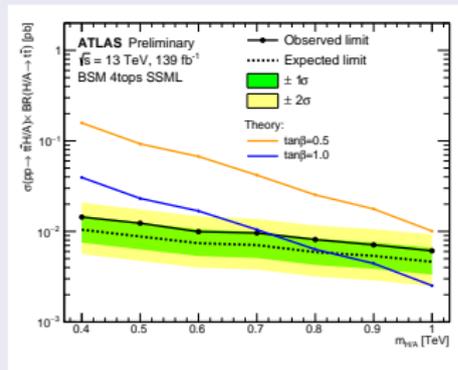
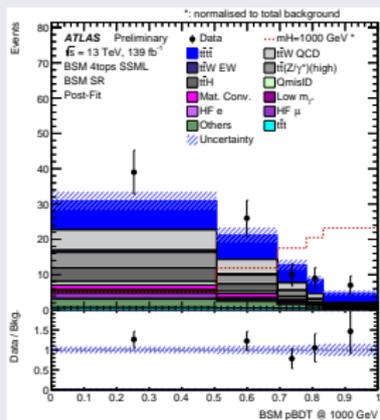
- Observed and expected 95% CL upper limits on the  $H^{\pm\pm}$  pair production cross-section as a function of  $m(H^{\pm\pm})$ .
- $\sum_{\ell\ell'} B(H^{\pm\pm} \rightarrow \ell^\pm\ell'^\pm)$  a 100% is assumed.
- **Blue**, **Orange** and **Red**  $\Rightarrow$  theoretical signal cross-section predictions given by the NLO calculation.
- $\rightarrow$  They corresponds respectively to left-handed  $H_L^{\pm\pm}$ , right-handed  $H_R^{\pm\pm}$  and a sum of both.



- Search for heavy Higgs in range of 400 GeV to 1 TeV.
- Four-top-quarks enriched SR:
  - $N_{jets} \geq 6, N_{b-jets} \geq 2$
  - $\sum p_T^\ell + \sum p_T^j > 500$  GeV.
  - SM BDT and BSM parametrized BDT (pBDT)

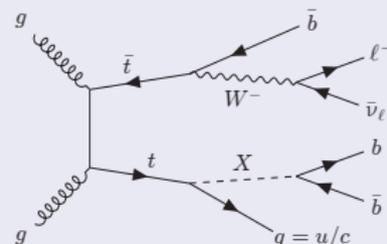


## Results



- Left: BSM SR for the BSM pBDT distribution used for  $m_H=1000$  GeV.
- Right: Observed and expected 95% CL upper limits.

- **Channel:** Lepton+jets  $t\bar{t} \rightarrow q(X)(bl\nu)$  with  $X \rightarrow b\bar{b}$  and  $q = u/c$ .
- $m_X$  range: [20-160] for both  $t \rightarrow cX$  and  $\rightarrow uX$ .
- **For signal-bkg discriminant:** implemented a mass-parameterised neural network.

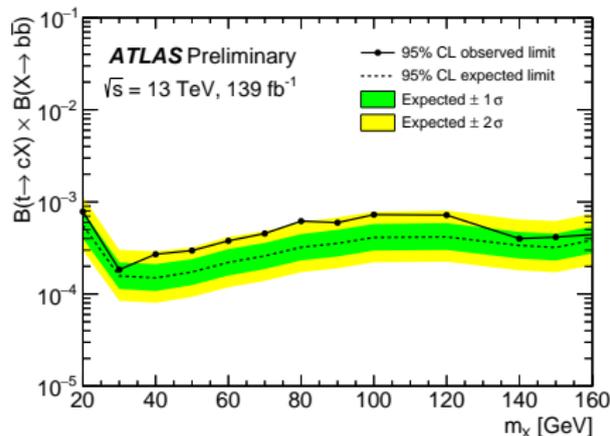
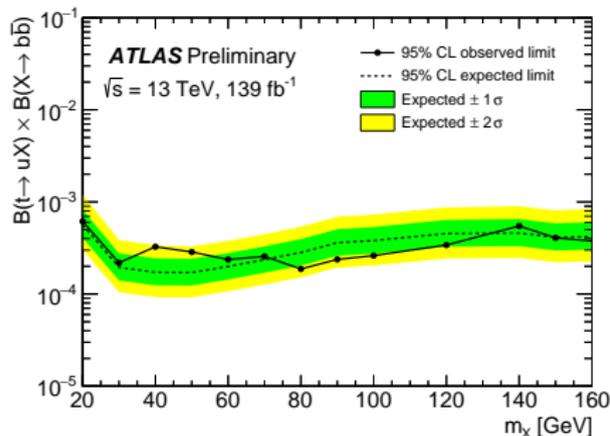


## Event selection:

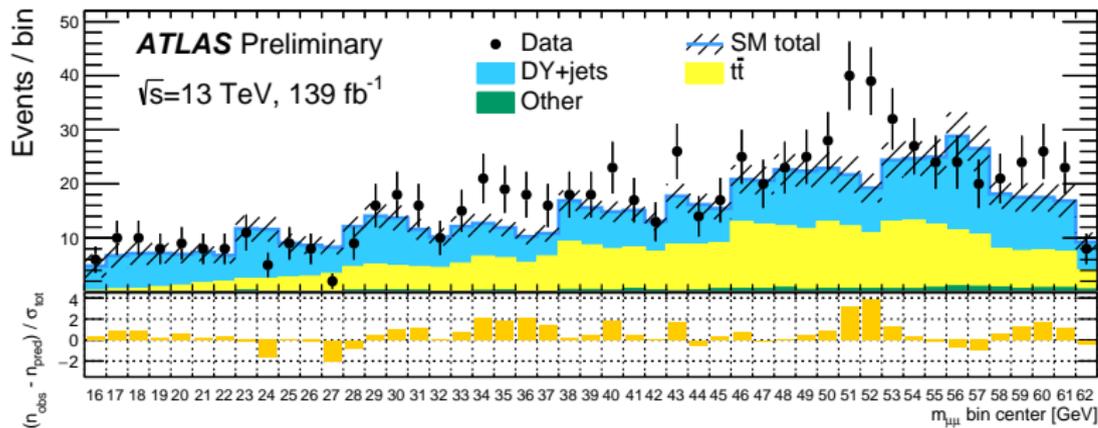
- For the Fit:
  - 3 b-tags at 60% DL1r regions: 4j3b, 5j3b, 6j3b.
  - $\geq 4b$ -tags at 60% DL1r regions: 4j4b, 5j $\geq 4b$ , 6j $\geq 4b$
- To derive  $t\bar{t}$  corrections:
  - 2b-tag + 1b-tag loose(bl):  
4j2b+1bl, 5j2b+1bl, 6j2b+1bl

	2b+1bl	3b	$\geq 4b$
4j	tt RW	SR	tt+ $\geq 1b$ CR
5j	tt RW	SR	tt+ $\geq 1b$ CR
6j	tt RW	SR	tt+ $\geq 1b$ CR

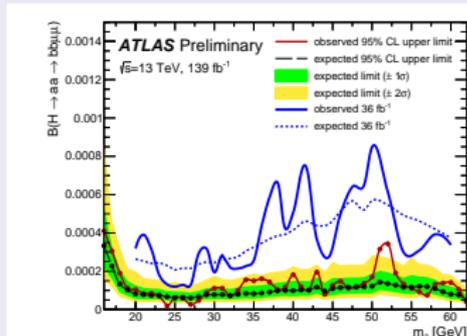
## Results



- **Left: 95% CL limits on  $BR(t \rightarrow uX)$ .**
- **Right: 95% CL limits on  $BR(t \rightarrow cX) \Rightarrow$  slightly higher.**



- Narrow dimuon resonance search.
- Requiring  $m_{bb} = m_{\mu\mu}$ .
- Mass range  $\in [16 - 62]$  GeV.
- The largest excess for  $m_{\mu\mu} = 52$  GeV  $\Rightarrow 3.3\sigma$  and  $(1.7\sigma)$  for local and global p0.



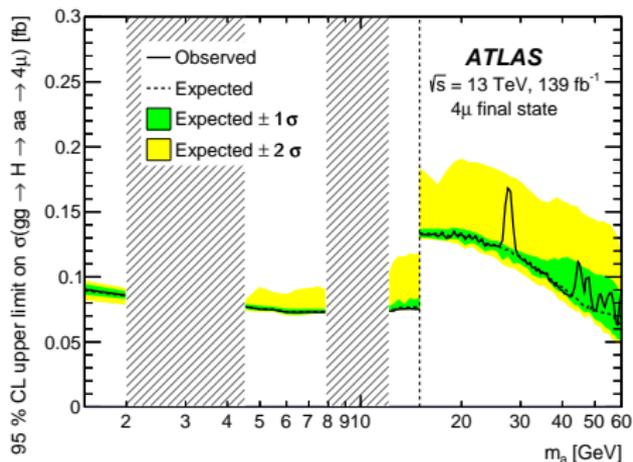
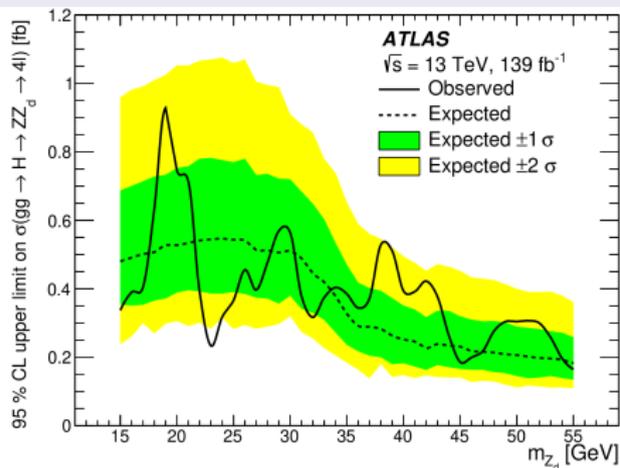
# Conclusion

- Rare and exotic decays search of the Higgs and additional scalar particles in ATLAS is presented by focusing on the more recent analyses.
- Seven analyses are shown where one is the first to be shown in a conference:  $t \rightarrow qX(b\bar{b})$  analysis.
- There are still many uncovered interesting searches - stay tuned for updates...

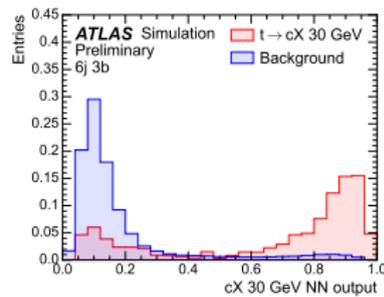
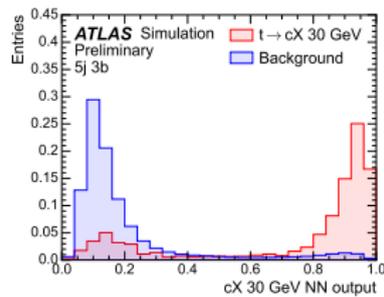
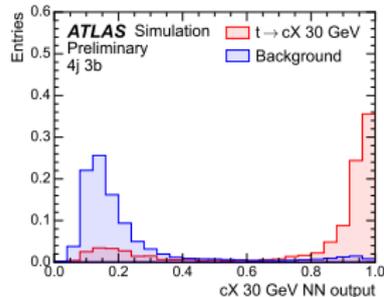
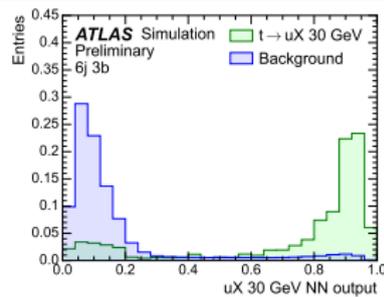
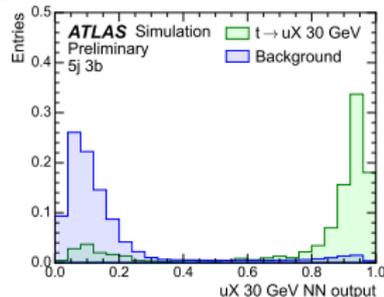
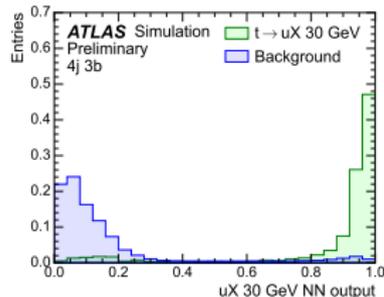
BACKUP

- More results for  $ZZ_d$  and  $aa$  channels.

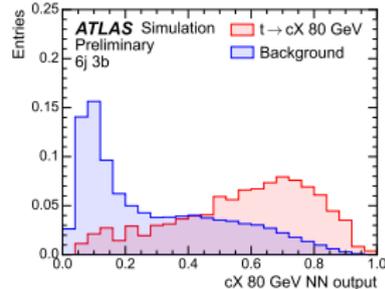
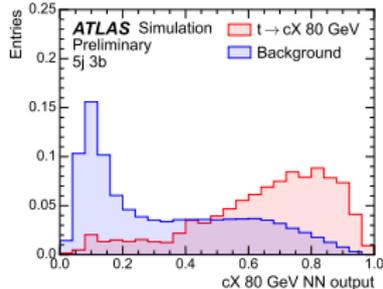
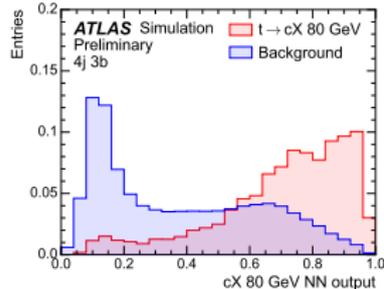
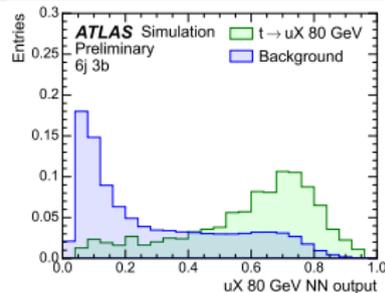
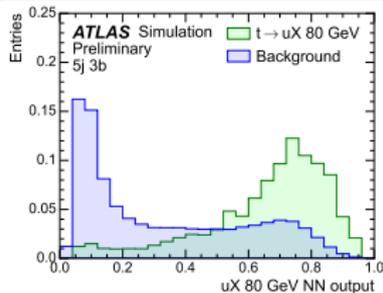
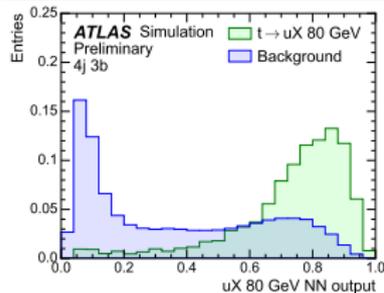
## Results



- NN output distributions in the different 3b SR for the 30 GeV mass and for the  $t \rightarrow cX$  (row) and  $t \rightarrow uX$  (bottom) hypotheses.



- NN output distributions in the different 3b SR for the 80 GeV mass and for the  $t \rightarrow cX$  (row) and  $t \rightarrow uX$  (bottom) hypotheses.



- Post-fit distributions of the NN output for the  $t \rightarrow cX$  (top) and  $t \rightarrow uX$  (bottom) hypotheses fits for the 30 GeV mass hypothesis.

