

# Searching for additional Higgs bosons at ATLAS (and BSM decays of Higgs)

Lake Louise Winter Institute 2023

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on behalf of the ATLAS Collaboration

# Decays in BSM particles (Motivated by DM)

## Searches of Exotic decays of SM Higgs:

- $H_{SM} \rightarrow \gamma\gamma_{Dark}$
- $H_{SM} \rightarrow \chi_1\chi_2$
- $H_{SM} \rightarrow XX/XZ$
- $H_{SM} \rightarrow aa \rightarrow bb\mu\mu$

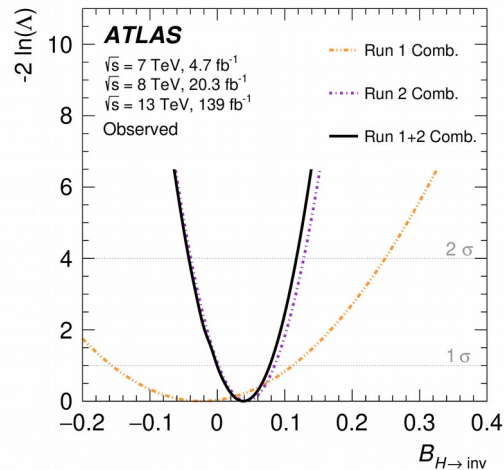
SM Higgs ( $H_{SM}$ )

BSM Higgs ( $H_{BSM}$ )

Motivated by DM and inflation

Combination of all invisible decays searches  
 $BR(H \rightarrow inv) < 0.107$   
 (0.077)@95% CL

[arXiv 2301.10731](https://arxiv.org/abs/2301.10731)



Only Prompt Signatures. Displaced decays in Simone's talk on Thursday

## Searches for BSM Higgs:

- $H_{BSM} \rightarrow \gamma\gamma$  (High and Low mass)
- $H_{BSM}^{++} \rightarrow l^+l^+/W^+W^+$
- $ttH_{BSM} \rightarrow tttt$  ( $H_{BSM} \rightarrow tt, tu, tc$ )

Decays in SM particles

# Decays in BSM particles

- $H_{SM} \rightarrow \gamma\gamma_{Dark}$
- $H_{SM} \rightarrow \chi\chi$
- $H_{SM} \rightarrow \chi\chi/\chi Z$
- $H_{SM} \rightarrow aa \rightarrow bb\mu\mu$

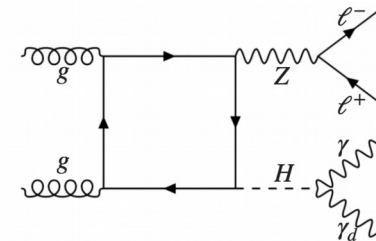
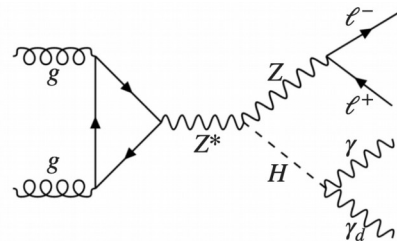
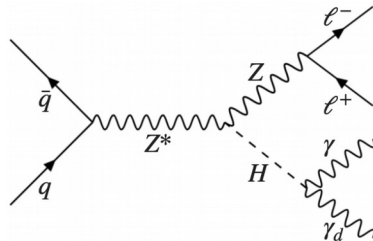
SM Higgs ( $H_{SM}$ )

BSM Higgs ( $H_{BSM}$ )

- $H_{BSM} \rightarrow \gamma\gamma$  (High and Low mass)
- $H^{++}_{BSM} \rightarrow l^+l^+/W^+W^+$
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# Decays in SM particles

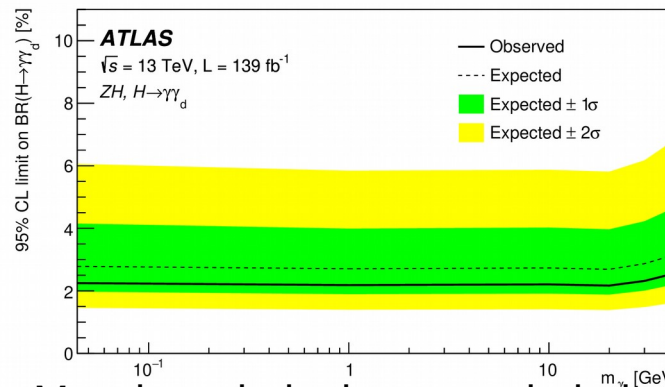
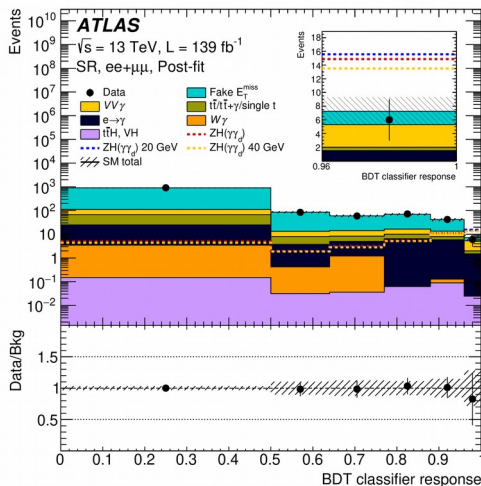
$H_{SM} \rightarrow \Upsilon\Upsilon_d$



Higgs boson as portal with Dark Sector

ZH Production  $\rightarrow$  Final state:  $ee/\mu\mu + \text{photon} + \cancel{E}_T$

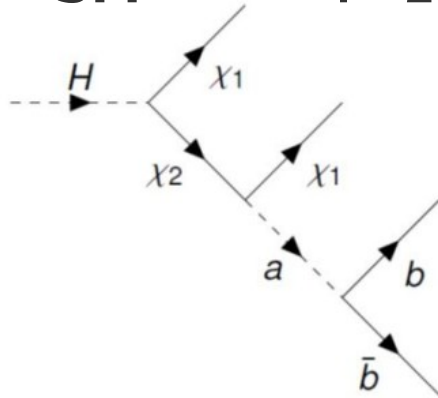
Main background: Z+y and Z+jets. Irreducible background  $V\Upsilon$



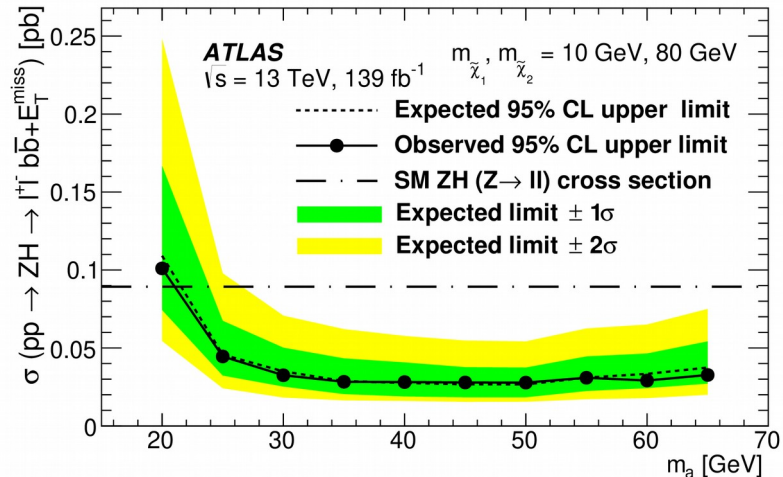
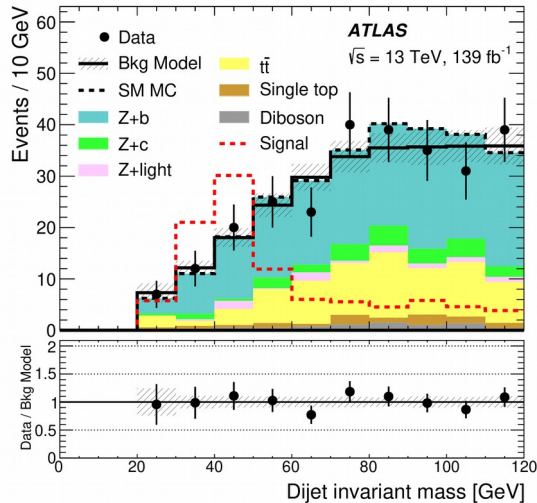
Massless dark photon excluded  
up to:  $BR(H \rightarrow \Upsilon\Upsilon_d) < 2.3\%$

BDT to increase signal vs Background discrimination

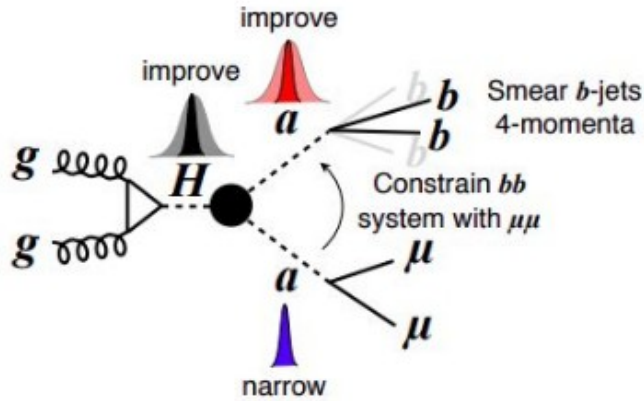
$$H_{SM} \rightarrow \chi_1 \chi_2$$



SM Higgs boson produced *via*  $ZH \rightarrow$   
 BSM decay of  $H_{SM}$  in NMSSM (neutralinos). In the Peccei Quinn  
 limit (small coupling  $H \leftrightarrow a/h_{BSM}$ ),  
 $H \rightarrow \chi_1 \chi_2$  favored over  $H \rightarrow aa$  ( $a \rightarrow b\bar{b}$ )  
 $b\bar{b} + ee/\mu\mu + \cancel{E}_T$  final state  
 Main background:  $Z+b$  and  $t\bar{t}$   
 $\rightarrow$  Normalization from Control Regions

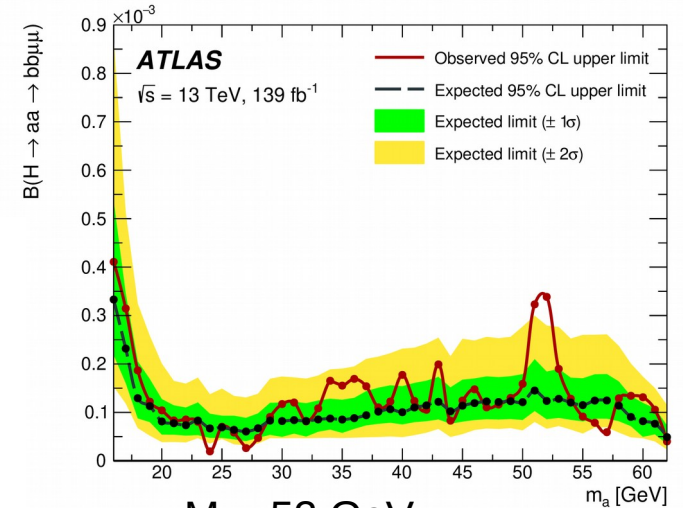
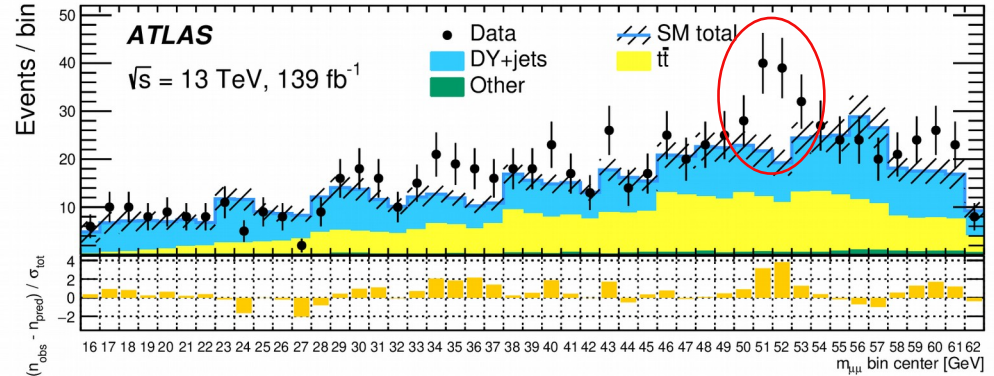
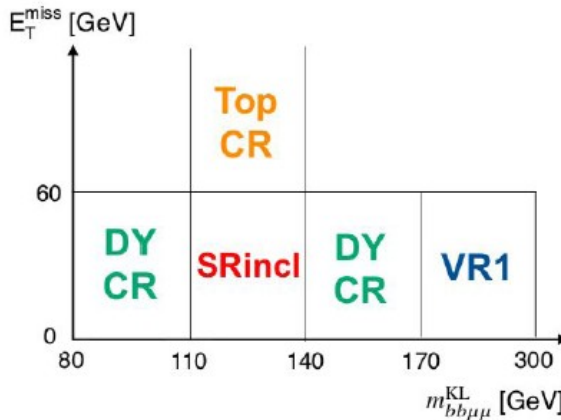


# $H_{SM} \rightarrow aa \rightarrow bb\mu\mu$



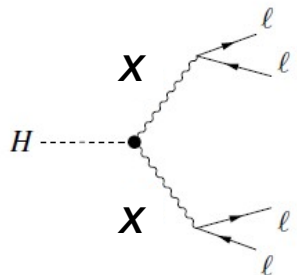
Searches in 2 muon final + 2 bjet final states  
 Kinematic Likelihood fit to constrain the  $m_{bb}$  to the  $m_{\mu\mu}$  mass and improve the resolution of the  $m_{\mu\mu bb}$  peak.

Train one BDT for each mass point



$M_a \sim 52$  GeV:  
 local sig 3.27  $\sigma$   
 global sig 1.67  $\sigma$

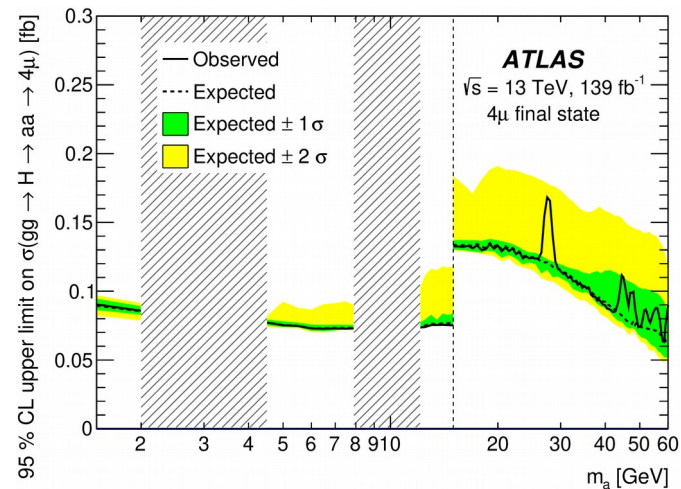
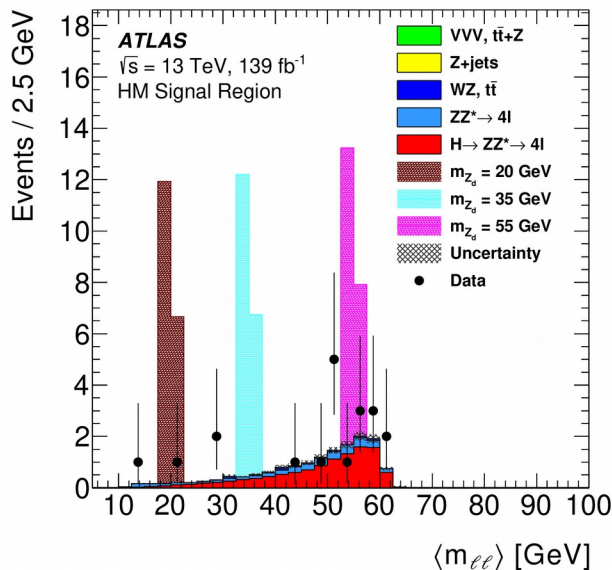
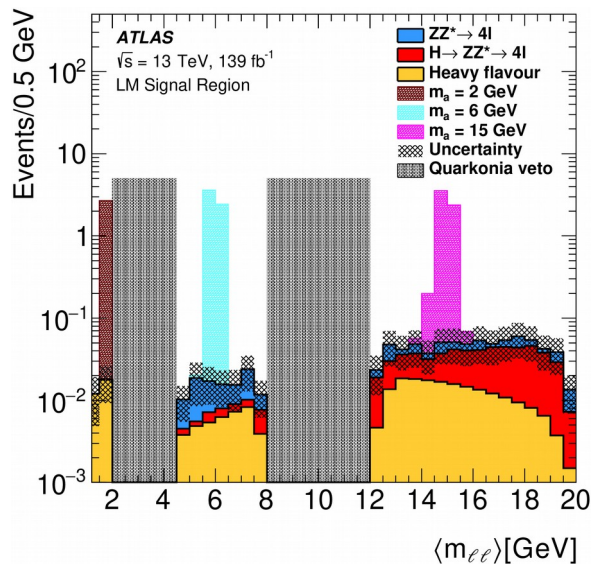
# $H_{SM} \rightarrow X(X/Z) \rightarrow 4 \text{ leptons}$



Three analysis channels:

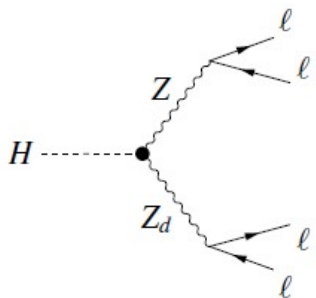
- $H_{SM} \rightarrow XX$  low mass [1,15] GeV
- $H_{SM} \rightarrow XX$  high mass [15,55] GeV
- $H_{SM} \rightarrow ZX$  [15,60] GeV

4 leptons (4e, 2e2 $\mu$ , 2 $\mu$ 2e, 4 $\mu$ ) final state



Low Mass and High Mass  $m_x$  limits

# $H_{SM} \rightarrow X(X/Z) \rightarrow 4 \text{ leptons}$



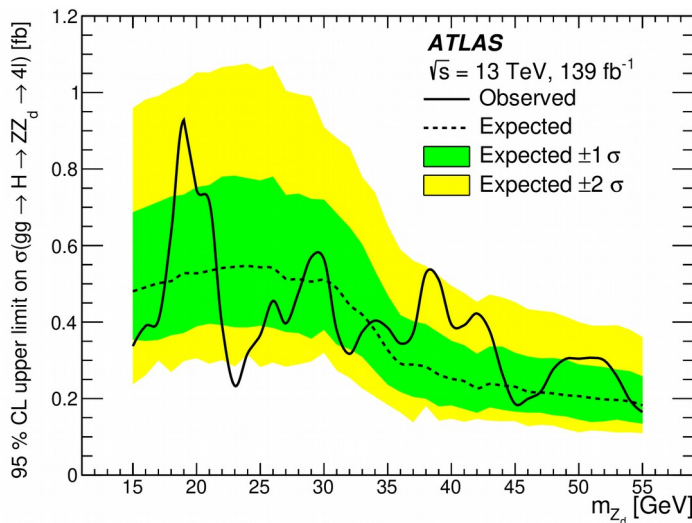
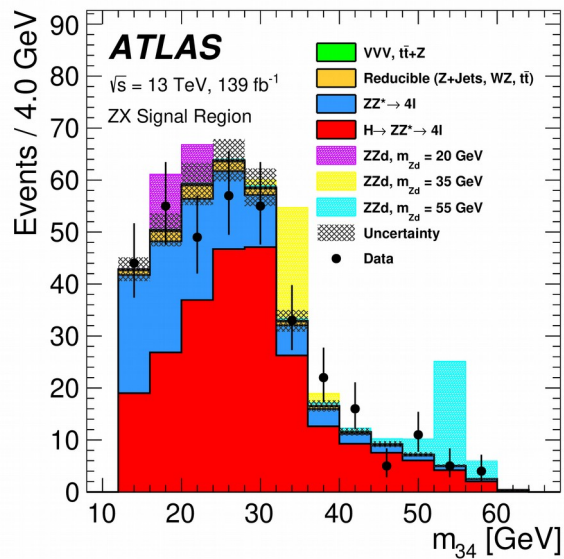
Three analysis channels:

$H_{SM} \rightarrow XX$  low mass [1,15] GeV

$H_{SM} \rightarrow XX$  high mass [15,55] GeV

$H_{SM} \rightarrow ZX$  [15,60] GeV

} 4 leptons (4e, 2e2μ, 2μ2e, 4μ) final state



$Z_d$  mass limits in  $H_{SM} \rightarrow ZZ_d$



Decays in BSM particles

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 $H_{SM} \rightarrow XX$   
 $H_{SM} \rightarrow XX/XZ$   
 $H_{SM} \rightarrow aa \rightarrow bb\mu\mu$

SM Higgs ( $H_{SM}$ )

BSM Higgs ( $H_{BSM}$ )

$H_{BSM} \rightarrow \gamma\gamma$  (High and Low mass)  
 $H^{++}_{BSM} \rightarrow l^+l^+/W^+W^+$   
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Decays in SM particles

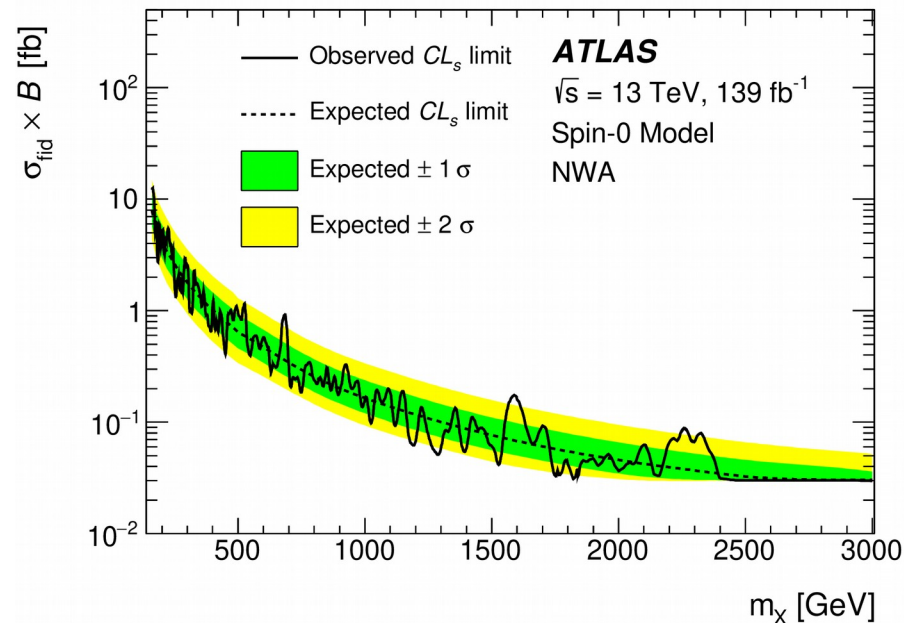
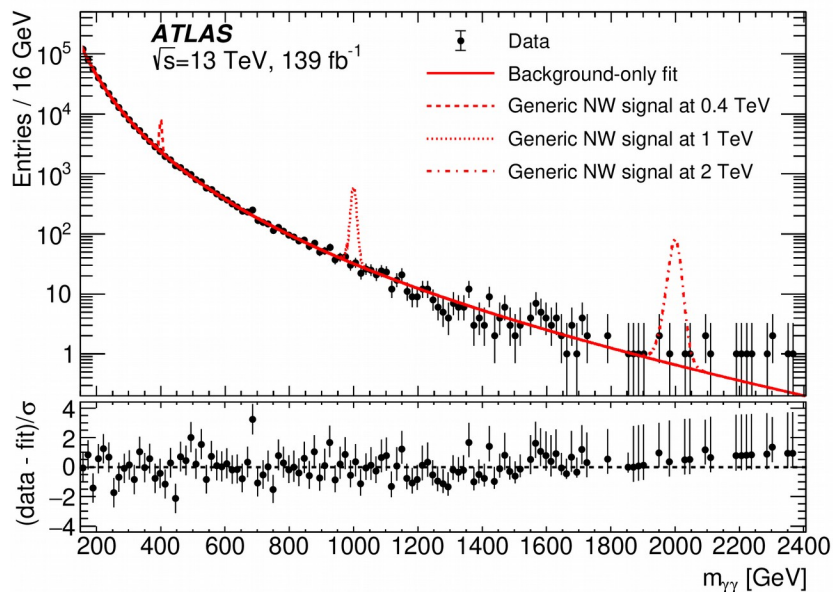
[arXiv 2301.10731](https://arxiv.org/abs/2301.10731)

# $H_{\text{BSM}} \rightarrow \gamma\gamma$ (High Mass)

PLB 822 (2021) 136651

Search for  $\gamma\gamma$  resonance with  $M_{H_{\text{BSM}}} > 160$  GeV. Spin-0 independent search (NWA and LW up to  $\Gamma_{H_{\text{BSM}}}/M_{H_{\text{BSM}}} = 10\%$ )

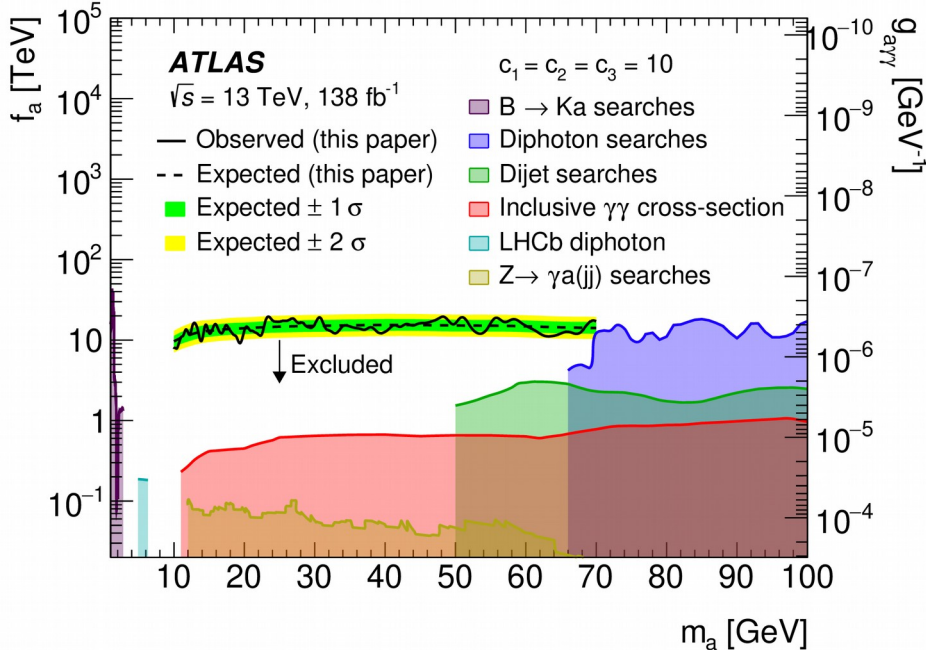
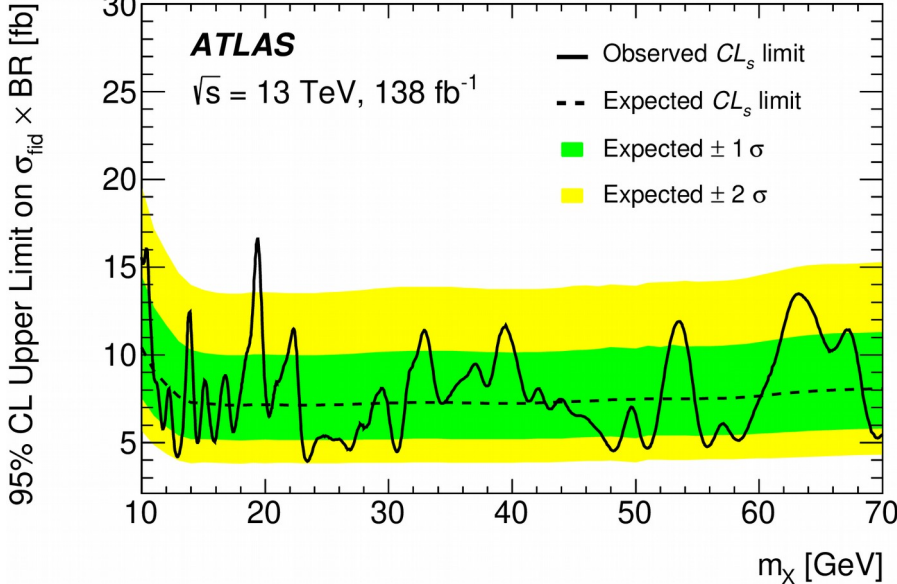
Background template:  $\gamma\gamma$  (from MC) +  $\gamma j$  (+ $jj$ ) (data driven)



# $H_{\text{BSM}} \rightarrow \gamma\gamma$ (Low Mass)

Gap in at low masses in  $\gamma\gamma$  resonant searches [arXiv: 1702.02152](https://arxiv.org/abs/1702.02152)  
 → Poorly explored region

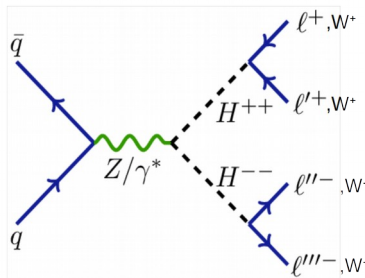
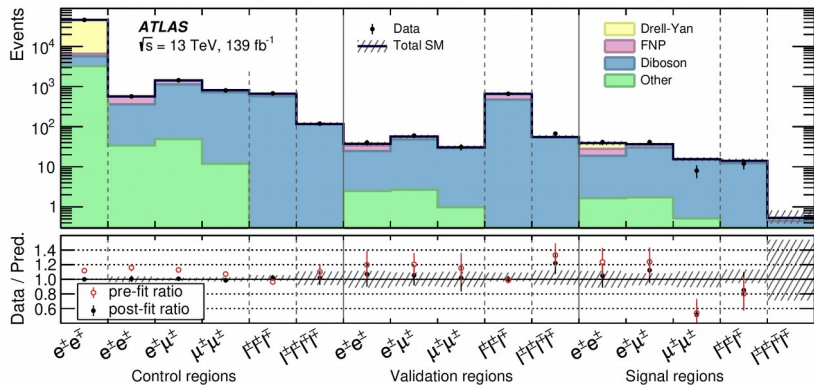
Low mass  $10\text{GeV} < M_{\text{HBSM}} < 70\text{GeV}$   
 Background template:  $\gamma\gamma$  (from MC) +  $y\gamma$  (+jj)(data driven)  
 → analytical function



# $H^{++} \xrightarrow{\text{BSM}} l^+l^+ / W^+W^+$

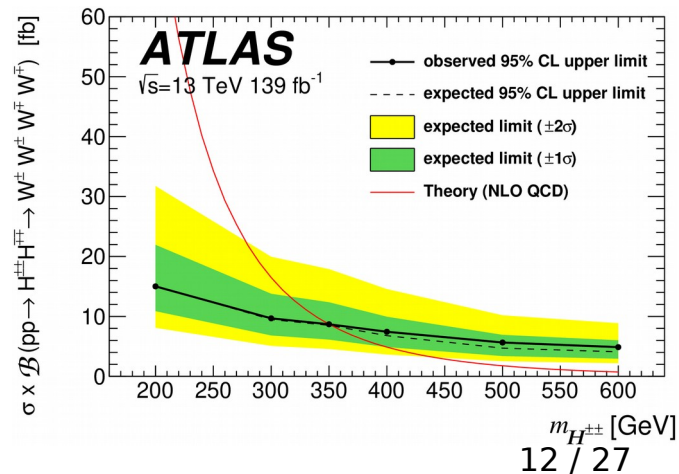
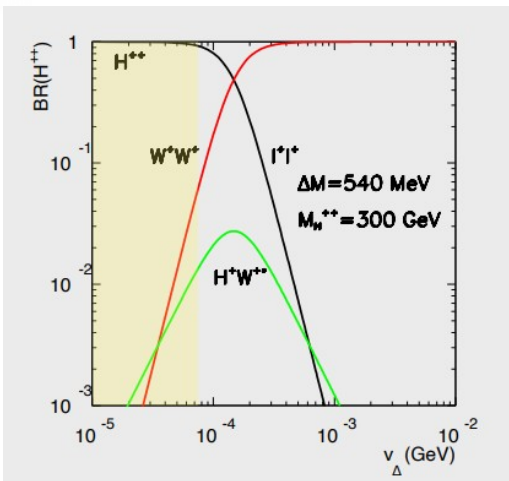
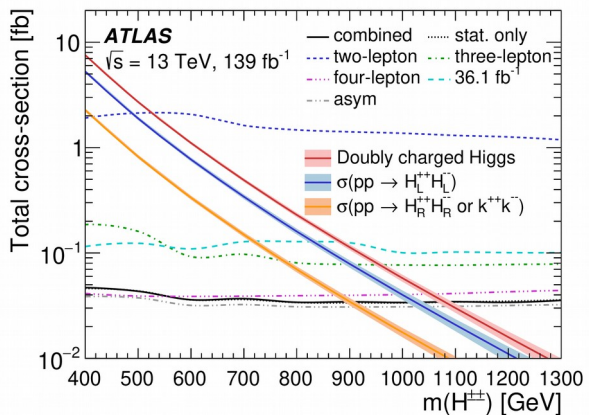
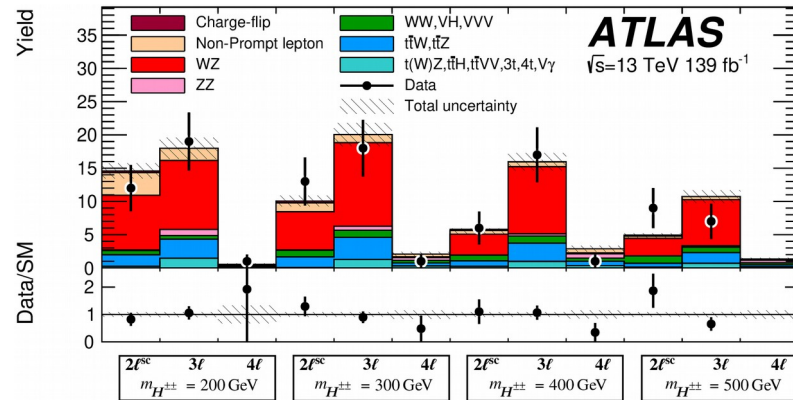
arXiv 2211.07505

$H^{++} \rightarrow l^+l^+$



Drell-Yan production  
Decays in dileptons  
or  $W^+W^+$  depending  
on  $v_{\Delta}$

$H^{++} \rightarrow W^+W^+$

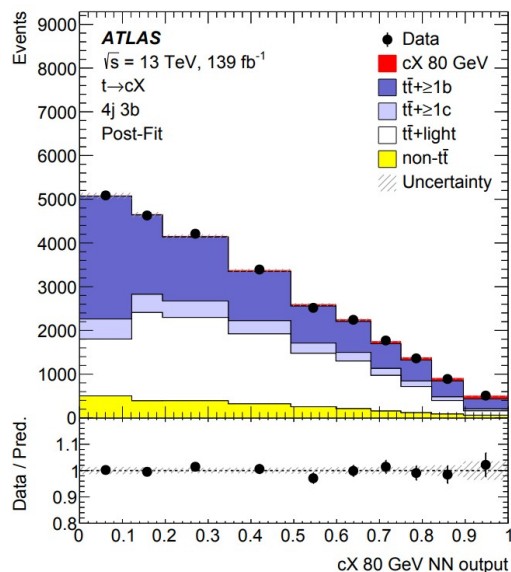


# $t \rightarrow H_{\text{BSM}} q$ with $H_{\text{BSM}} \rightarrow b\bar{b}$

arXiv 2301.03902

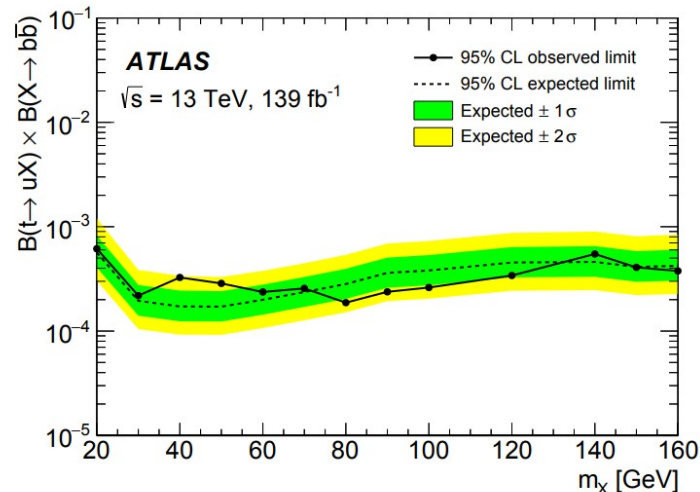
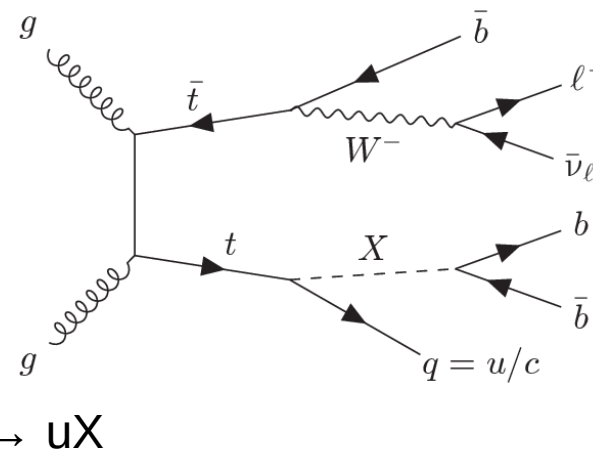
Look for  $H_{\text{BSM}}$  scalar decaying in  $H_{\text{BSM}} \rightarrow b\bar{b}$  in  $t\bar{t}$  production process.

Two options  $t \rightarrow uH_{\text{BSM}}$  and  $t \rightarrow cH_{\text{BSM}}$  (FCNC process)

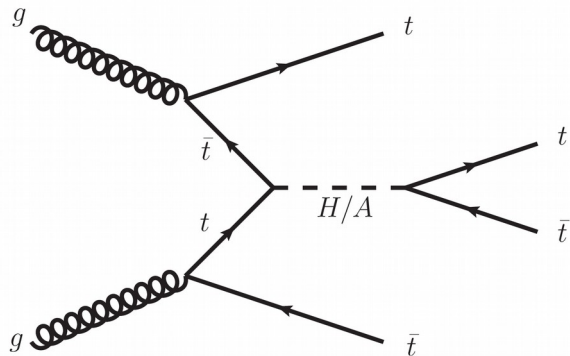


Use pDNN to distinguish sig vs bkg  
 Mass Range [20,160] GeV  
 Events with 4, 5 and 6j with 3,  $\geq 4$  b-jets

Multijet events with multi b-jets



# $ttH_{\text{BSM}} \rightarrow tttt$

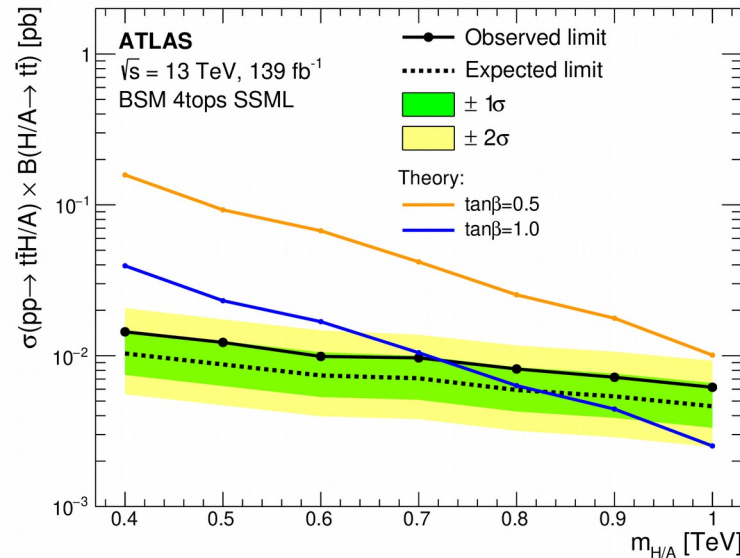
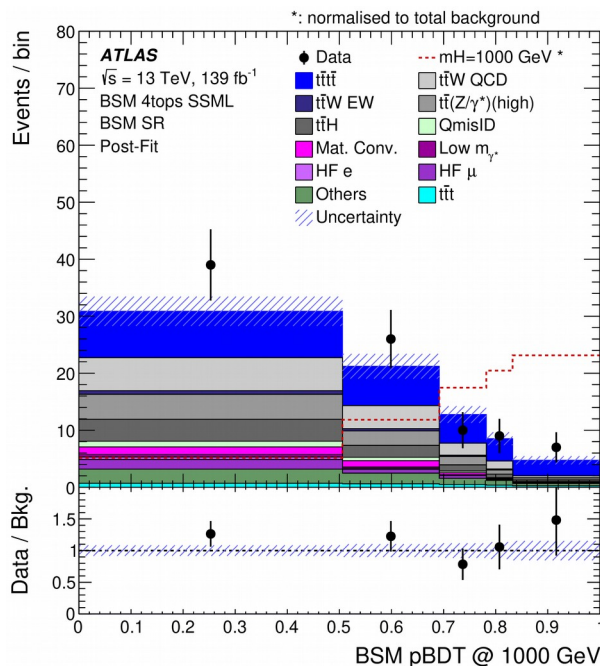


Search in multileptonic final states (2 lep Same Sign + 3 leptons)  
 BDT applied in two steps:  
 1) to separate 4 tops (SM) from SM background (ttW, ttZ,...)  
 2) separate 4 tops (SM) from ttA  $\rightarrow$  4 tops (parameterized BDT)

Search for HBSM in the range 400 GeV to 1 TeV  
 Low  $\tan\beta$  region where similar couplings with SM  
 Motivated by 4 tops SM tension

$$\mu_{\text{SM4top}} = 2.0^{+0.8}_{-0.6}$$

[Eur. Phys. J. C 80, 1085 \(2020\)](#)



# $H_{BSM} \rightarrow tq$ (tt,tu,tc)

2HDM model  $\rightarrow$  Only coupling with top quarks  $\rightarrow$  Focusing on benchmarks with

$\rho_{tt}, \rho_{tu}, \rho_{tc} \neq 0$  (tensions in the 4 tops and ttW measurement)

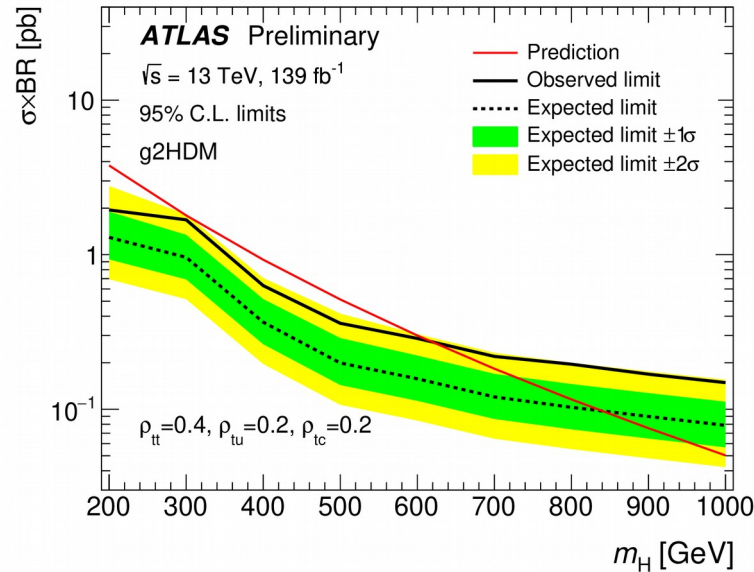
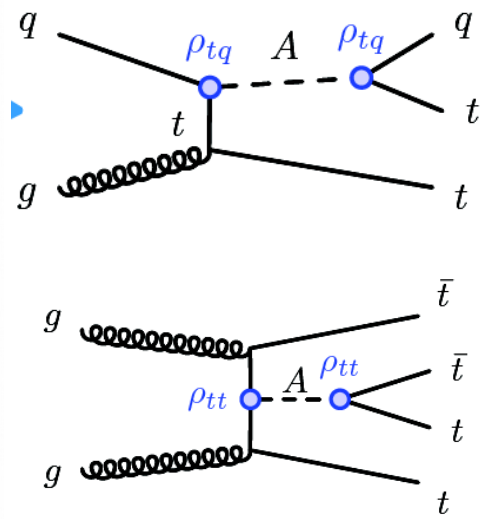
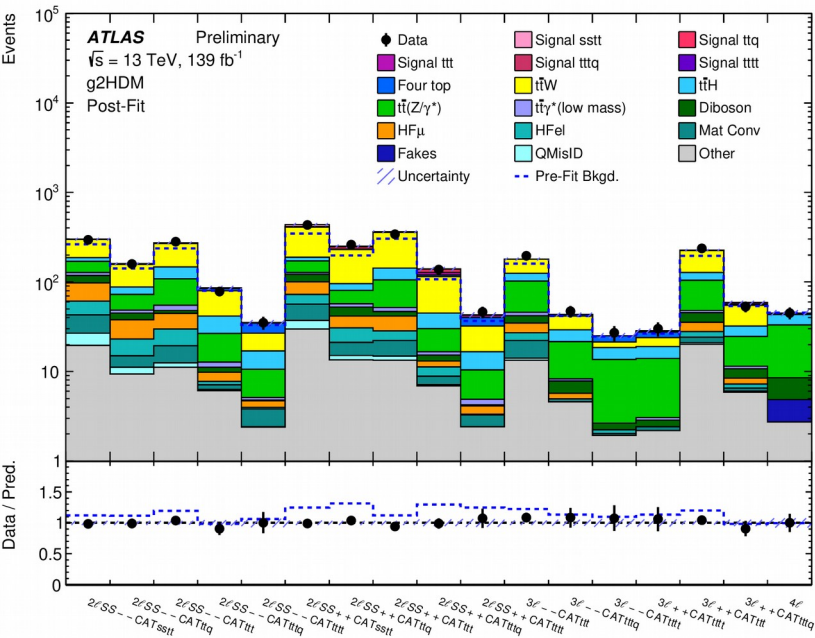
Final states  $\rightarrow$  2 same sign top, 3 tops, 4 tops

Analysis channels: 2 lepton SS, 3 leptons and 4 leptons

After lepton multiplicity categorization

DNN applied in two steps:

- 1) to categorize in BSM 2SSStt, ttt and tttt
- 2) increase in each category S/B





# Summary

- ▶ Many results in exotic Higgs decays and BSM Higgs searches
- ▶ There is still room for exotic decays of SM Boson Higgs → SM Higgs boson a portal for BSM sectors (Dark sector, ...). Different ways to look for new Higgs bosons decays
- ▶ Additional Higgs bosons well motivated by theoretical arguments.
- ▶ Still room for uncovered final states to be studied with Run2 and new Run3 data
- ▶ Some intriguing discrepancies to be followed up in Run3



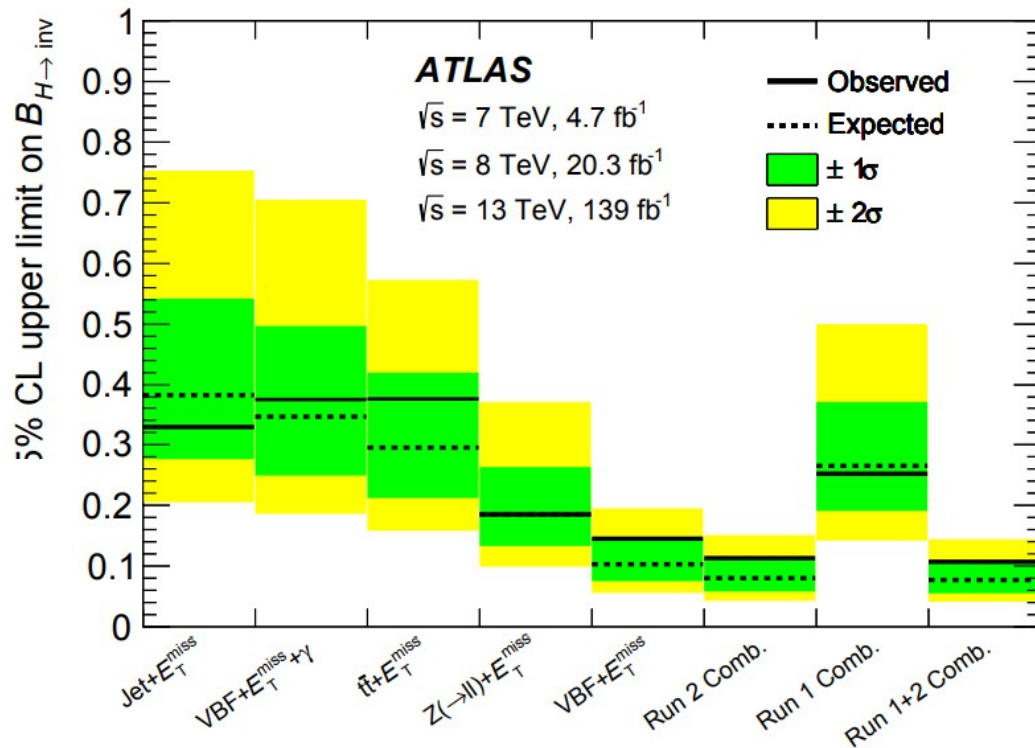
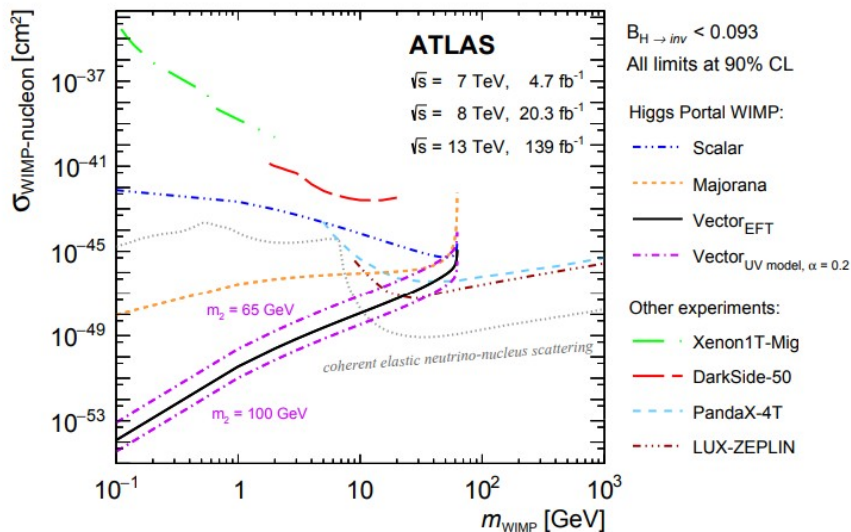


# BackUp

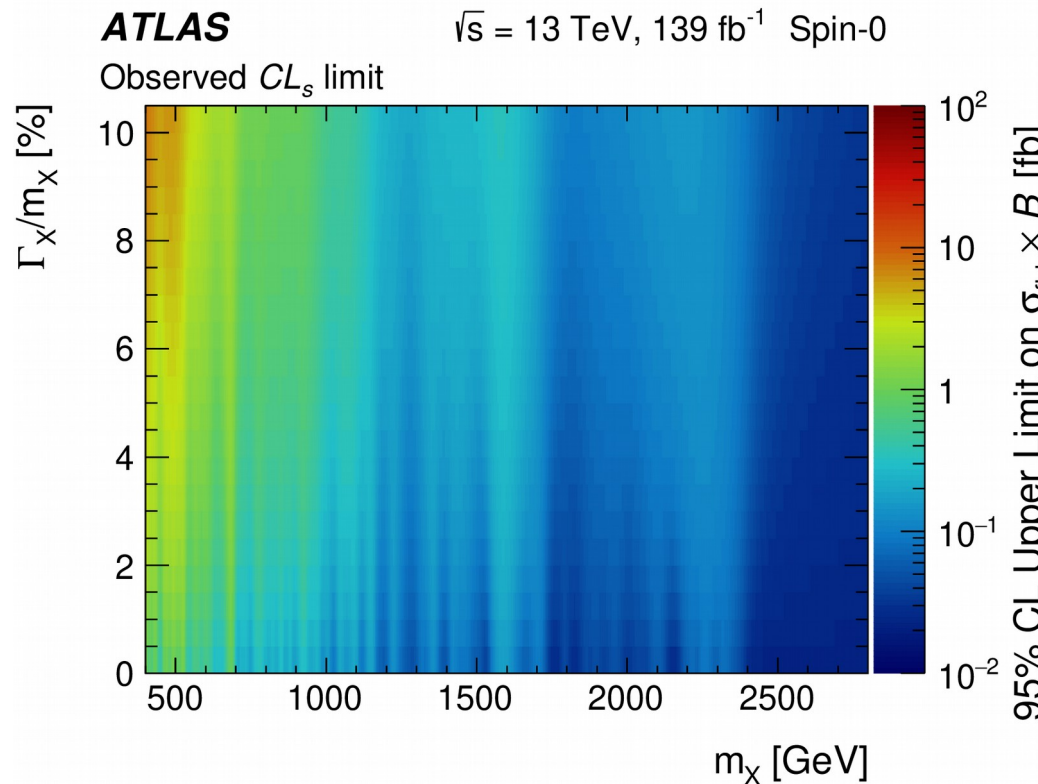
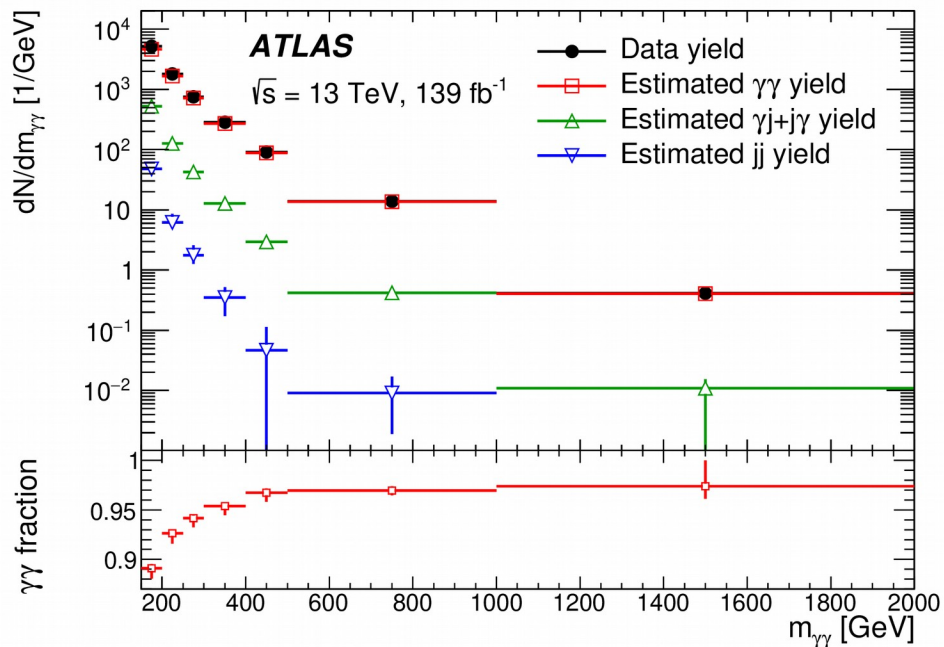
# H → Invisible

Combined measurements:

- VBF topology +  $E_T$
- Associated production Z +  $E_T$
- Associated production ttH +  $E_T$
- VBF topology + photon +  $E_T$
- Gluon gluon fusion +  $E_T$

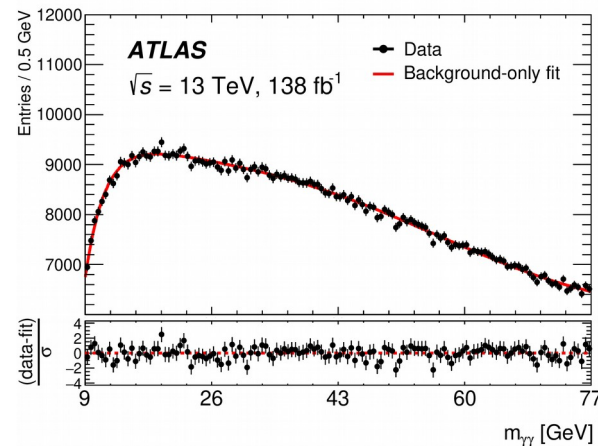
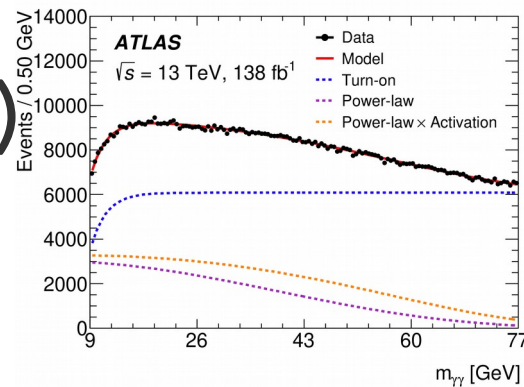
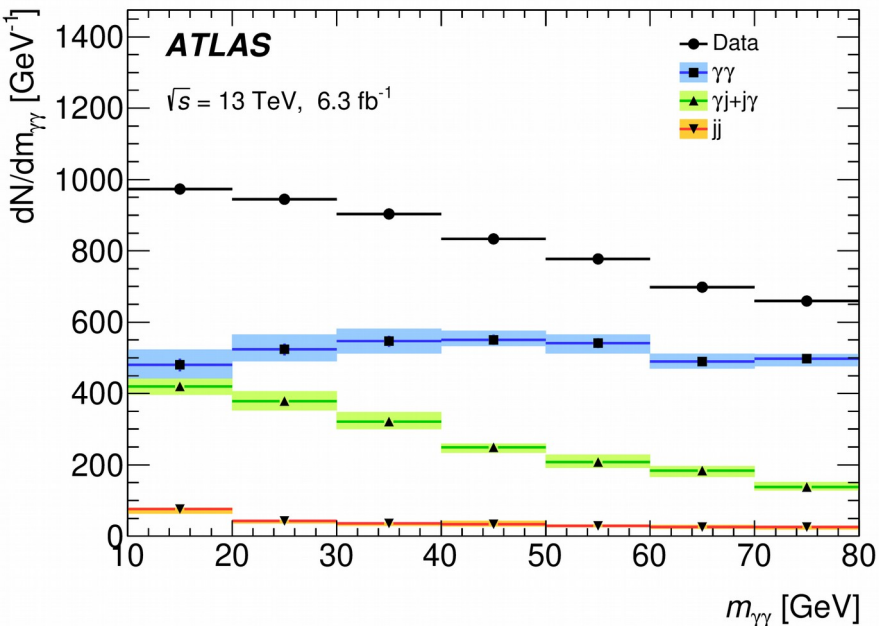


$$H_{SM} \rightarrow \Upsilon\Upsilon_d$$



# $H_{\text{BSM}} \rightarrow \gamma\gamma$ (Low Mass)

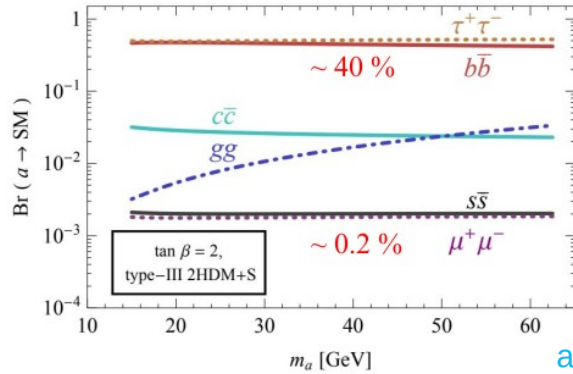
arXiv: 2211.0417  
2



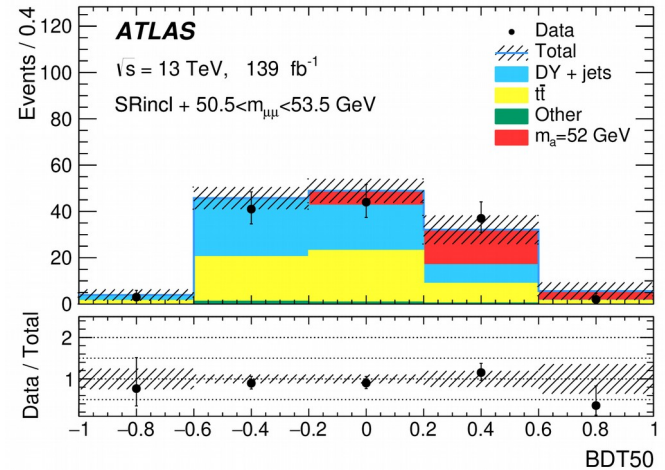
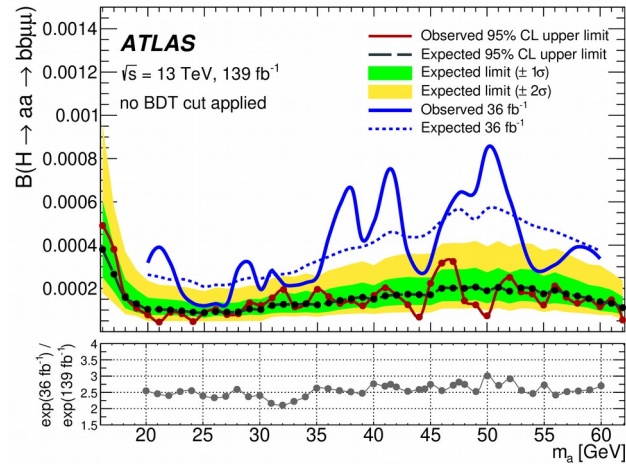
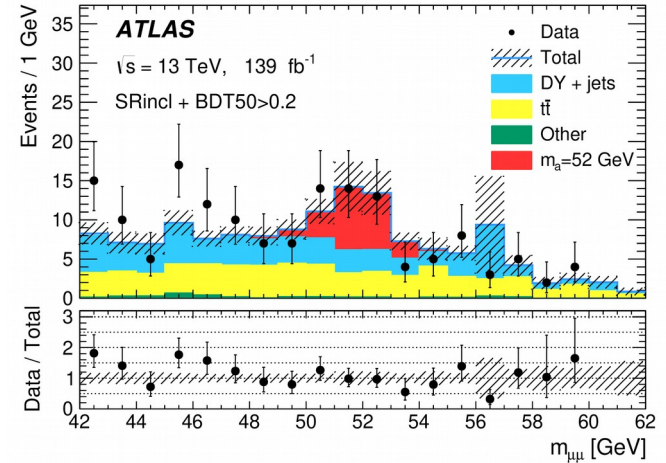
$$f(m_{\gamma\gamma}, \vec{\theta}) = \text{Flat} + [\text{PowLaw} \times \text{Activation}] =$$

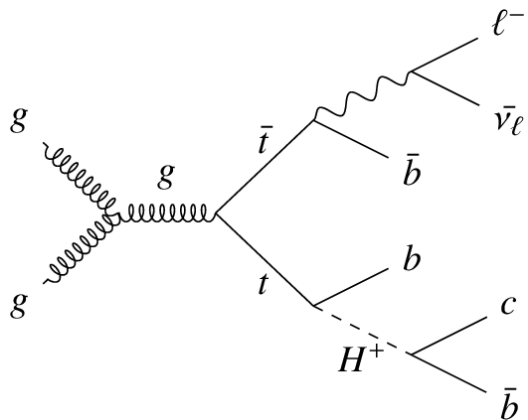
$$= \left[ 1 - (1 - f_0) e^{-\frac{m_{\gamma\gamma} - 10}{\tau_{\text{flat}}}} \right] \text{frac} + (1 - \text{frac}) \left[ \underbrace{\left( 1 - \left( \frac{m_{\gamma\gamma}}{c_1} \right)^{a_0} \right)^{c_0}}_{\text{PowLaw}} \underbrace{\left( 1 + \frac{e^{-\frac{m_{\gamma\gamma} - \delta_{\text{tail}}}{\tau_{\text{tail}}}}}{1 + e^{-\frac{m_{\gamma\gamma} - \delta_{\text{thresh}}}{\tau_{\text{thresh}}}}} \right)}_{\text{Activation function}} \right]$$

# $H_{SM} \rightarrow aa \rightarrow bb\mu\mu$

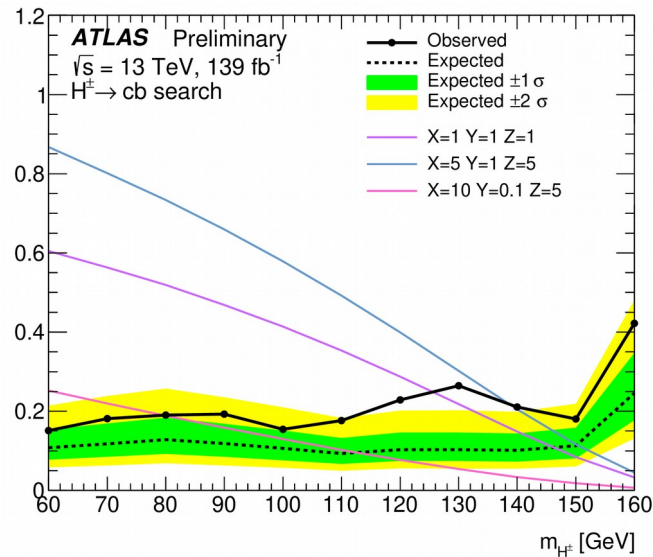
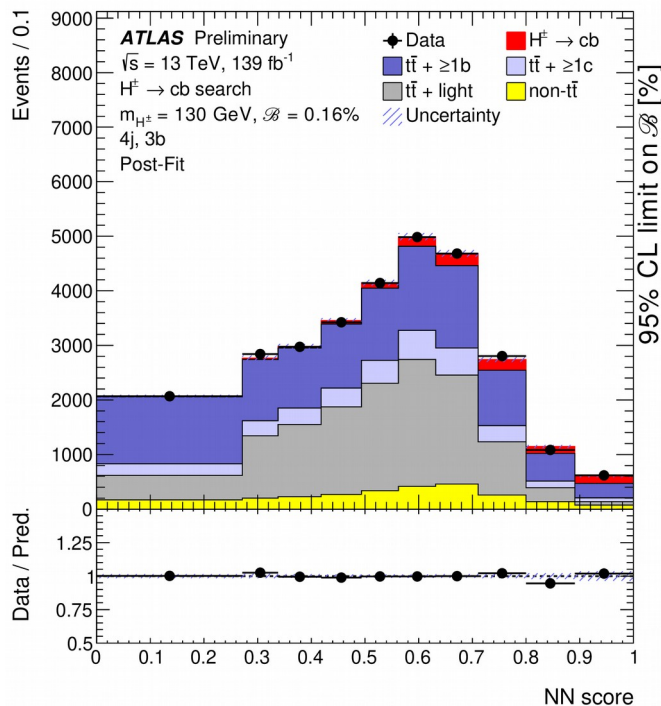


arXiv: 1412.4779

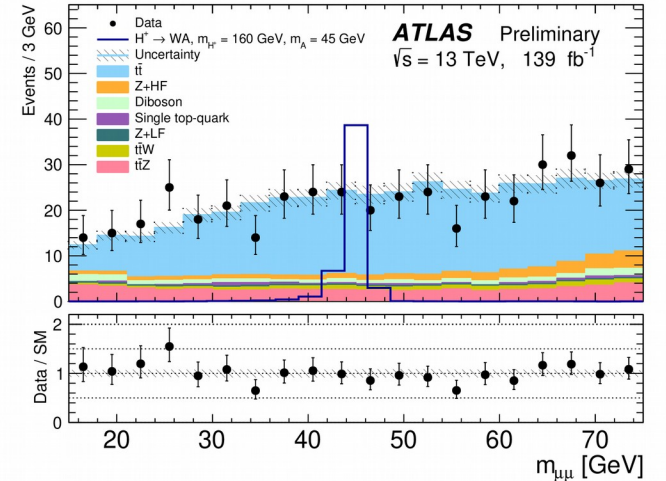
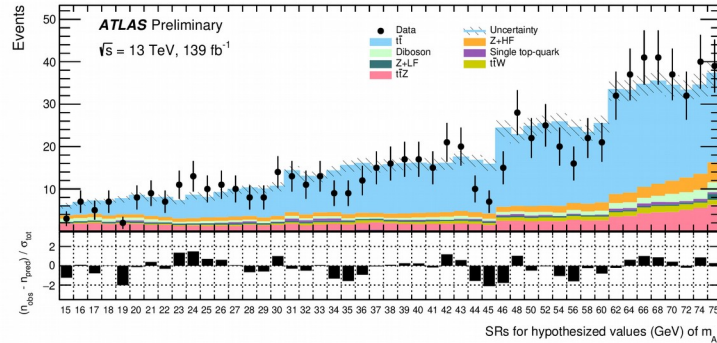
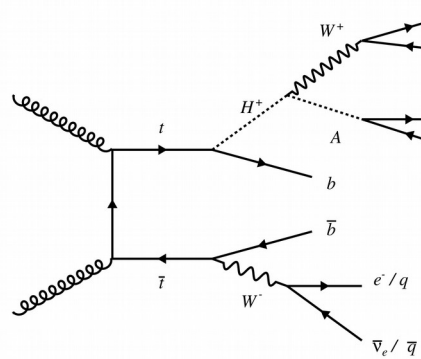




2HDM model  
 $H_{\text{BSM}}^+$  in [60,160]GeV range  
 Multijet final state  
 4, 5 and 6 jets with 3, 4 or  $\geq 4$  b-jets  
 Parametrized  $M(H_{\text{BSM}}^+)$  NN



# $H^+_{BSM} \rightarrow WA \quad A \rightarrow \mu\mu$



Bosonic decays of  $H^+_{BSM}$

Target masses interval:

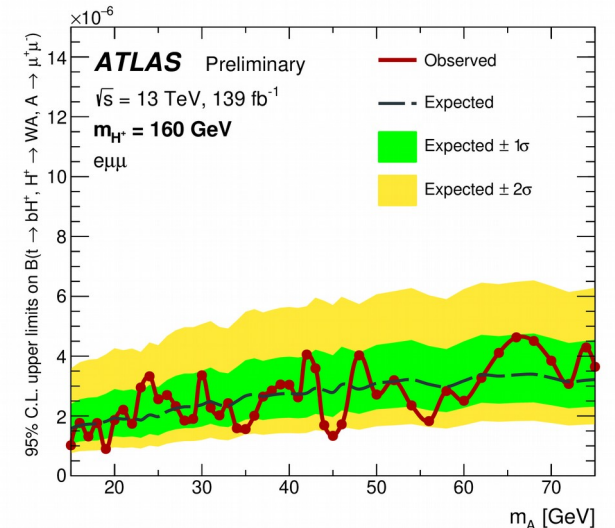
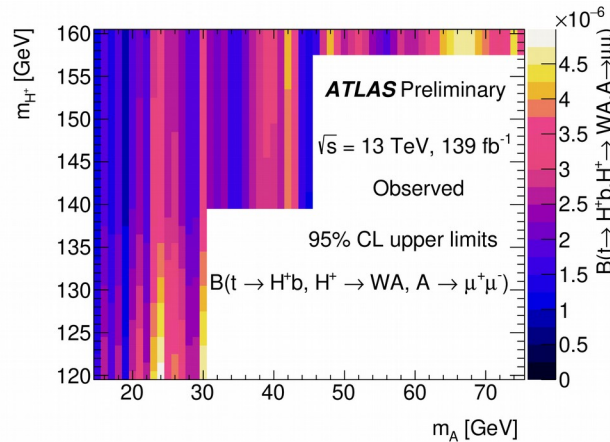
$H^+_{BSM} [100,160] \text{ GeV}$

$A [15,75] \text{ GeV}$

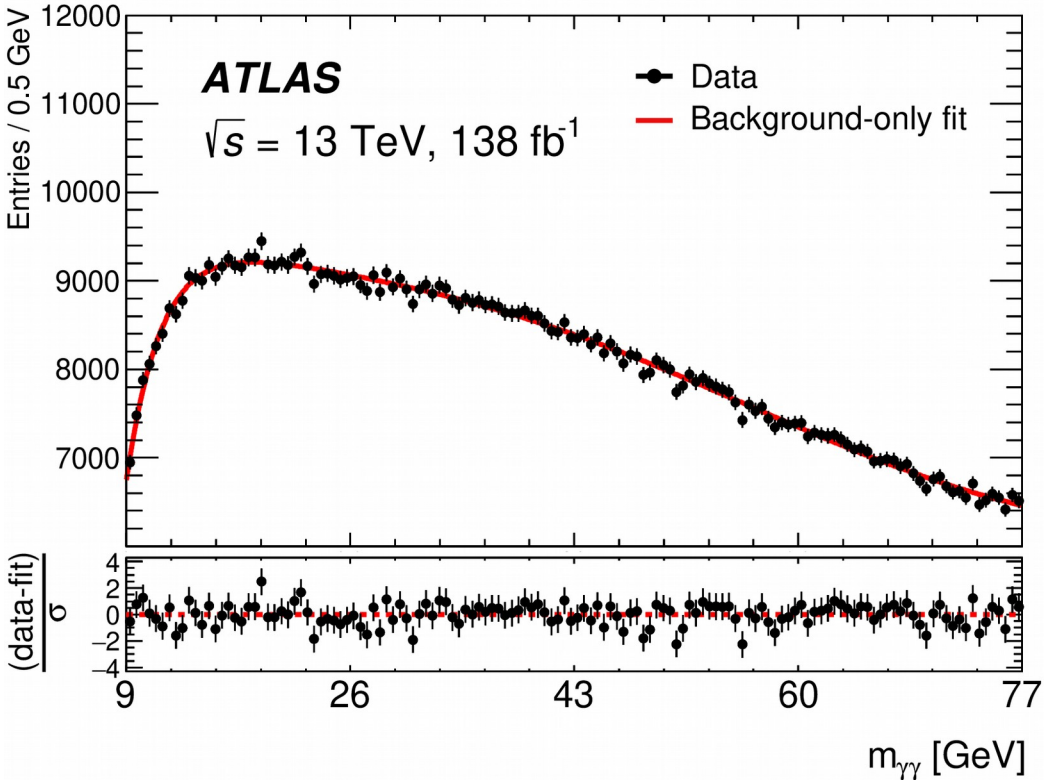
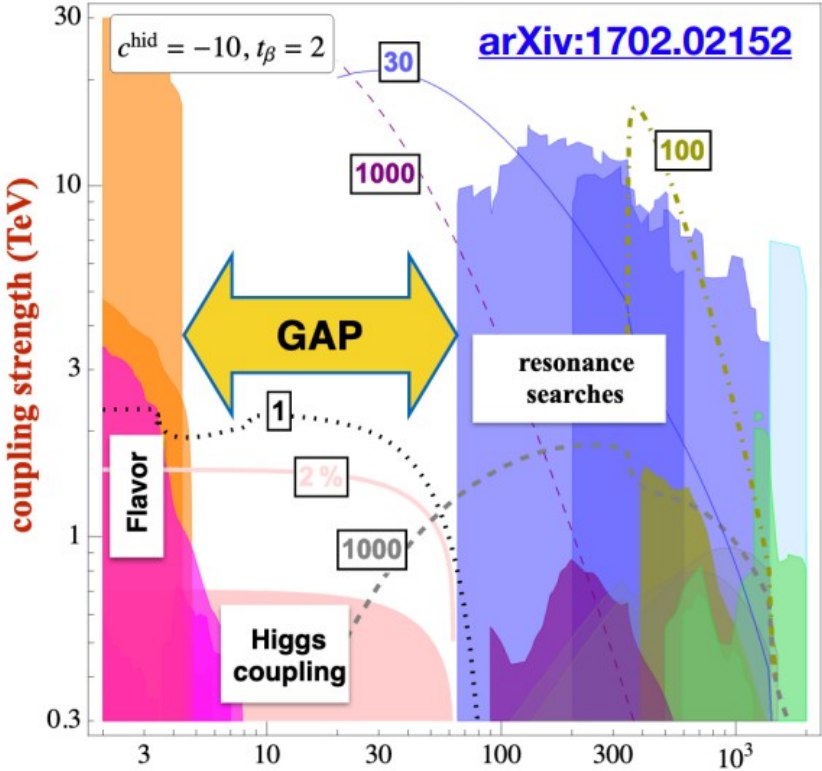
$H^+_{BSM} \rightarrow W^+A$

$A \rightarrow \mu\mu$

Final state studied:  $e\mu\mu$ +jets



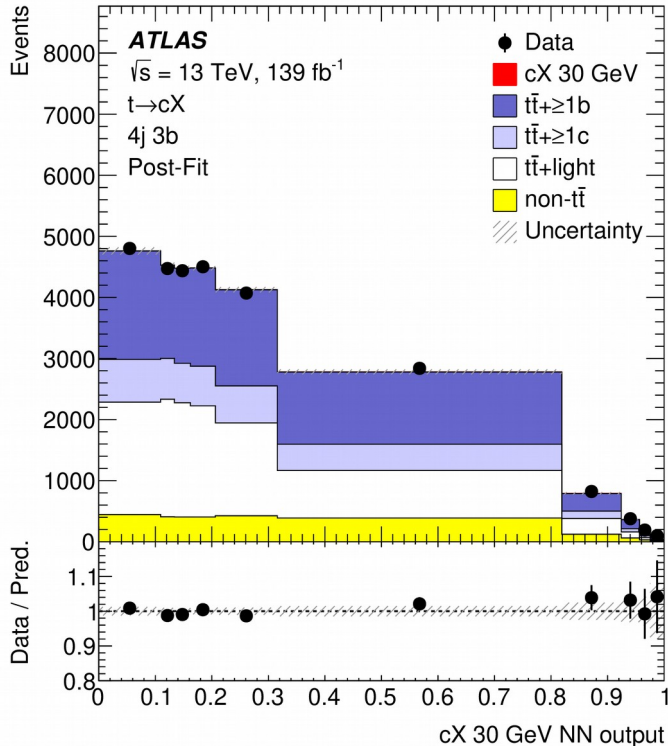
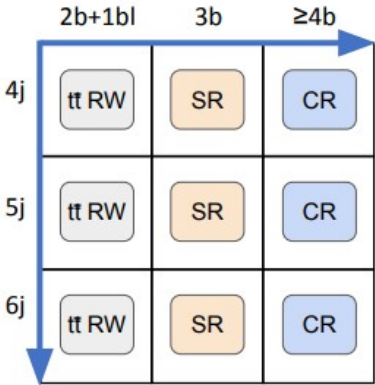
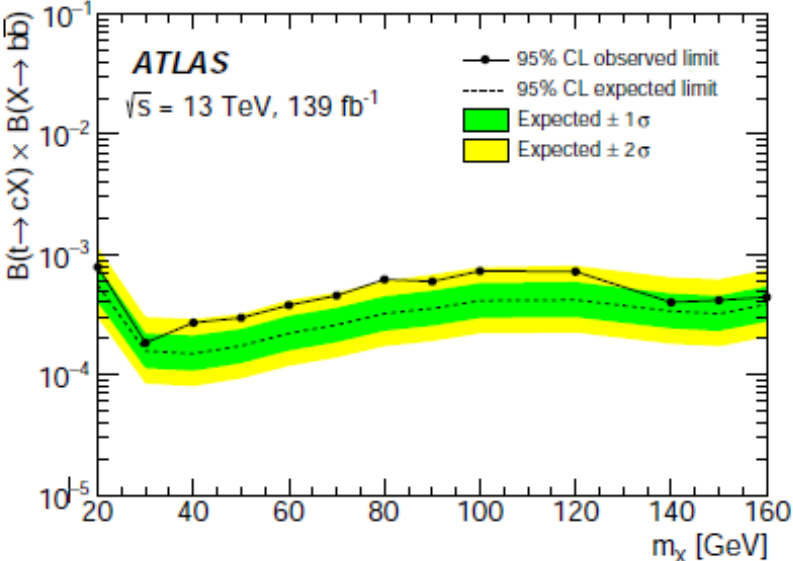
# $H_{\text{BSM}} \rightarrow \gamma\gamma$ (Low Mass)





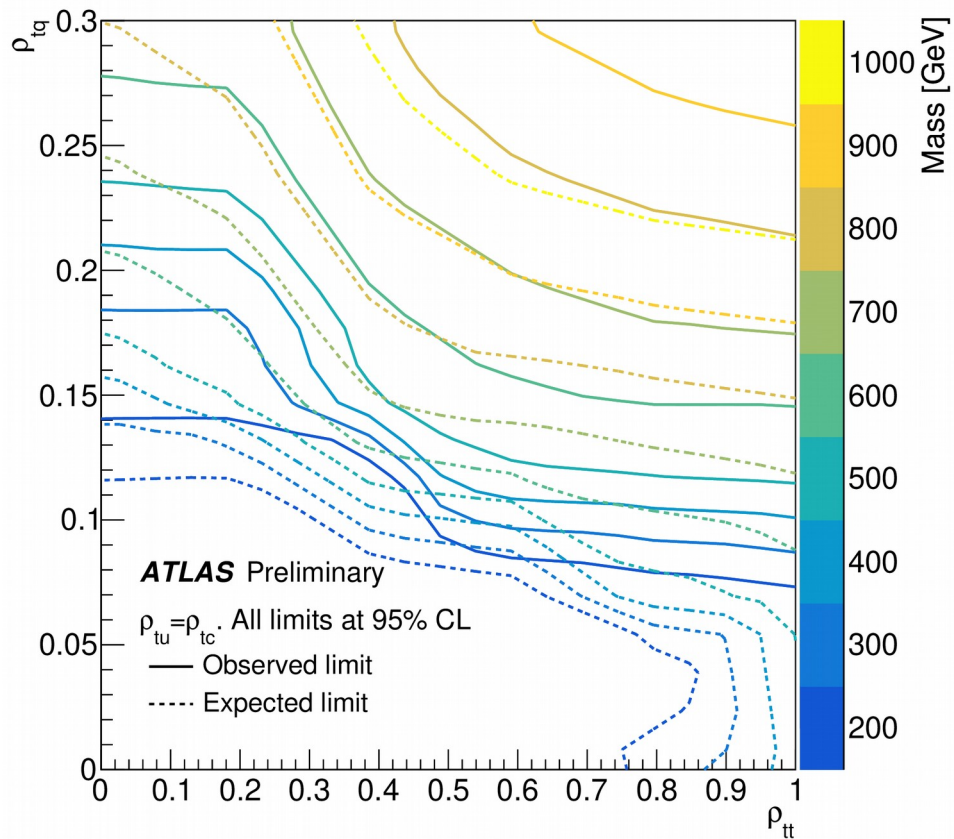
# $t \rightarrow H_{BSM} q$ with $H_{BSM} \rightarrow bb$

$t \rightarrow cX$



# $H_{\text{BSM}} \rightarrow tq$ ( $tt, tu, tc$ )

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# $H_{\text{BSM}} \rightarrow tq$ (tt,tu,tc) ATLAS-CONF-2022-039

