

# Searches for additional neutral Higgs bosons in ATLAS

Alessandra Betti

on behalf of the ATLAS Collaboration

European Physical Society Conference on High Energy Physics (EPS-HEP 2023)

Universität Hamburg Campus, Hamburg, Germany

21/08/2023



SAPIENZA  
UNIVERSITÀ DI ROMA

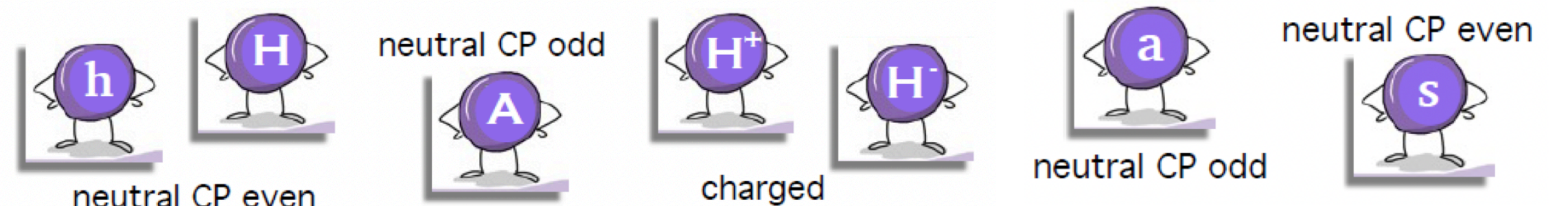


# Searches for additional neutral Higgs bosons in ATLAS

- The discovery of the Higgs boson with  $m_H = 125 \text{ GeV}$  completed the observations of particles predicted by the Standard Model (SM) and all measurements so far are compatible with the SM
  - The SM leaves some open questions and there are many theories Beyond the Standard Model (BSM) that predict additional Higgs bosons
  - Many searches for additional Higgs bosons performed in ATLAS targeting different production and decay modes and different mass ranges
- Selection of the most recent searches for additional high-mass and low-mass neutral Higgs bosons, performed in ATLAS using full LHC Run 2 dataset ( $140 \text{ fb}^{-1}$ )

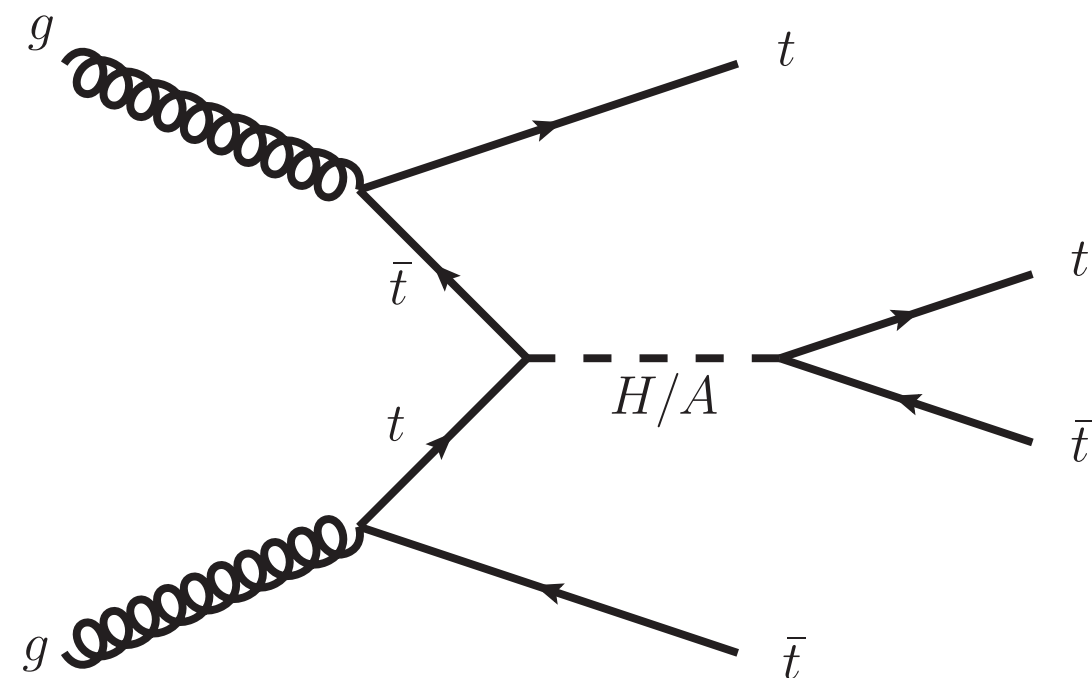
[All ATLAS public results can be found here](#)

Analysis	Reference
$ttH/A \rightarrow 4t(2\ell SS/3\ell)$	<a href="#">JHEP 07 (2023) 203</a>
$A \rightarrow ZH \rightarrow \ell\ell tt/\nu\nu bb$	<a href="#">ATLAS-CONF-2023-034</a>
Heavy Higgs in multi-leptons plus b-jets	<a href="#">arXiv:2307.14759 (Sub. to JHEP)</a>
$t \rightarrow qX, X \rightarrow bb$	<a href="#">JHEP 07 (2023) 199</a>
$tta, a \rightarrow \mu\mu$	<a href="#">arXiv:2304.14247 (Sub. to PRD)</a>

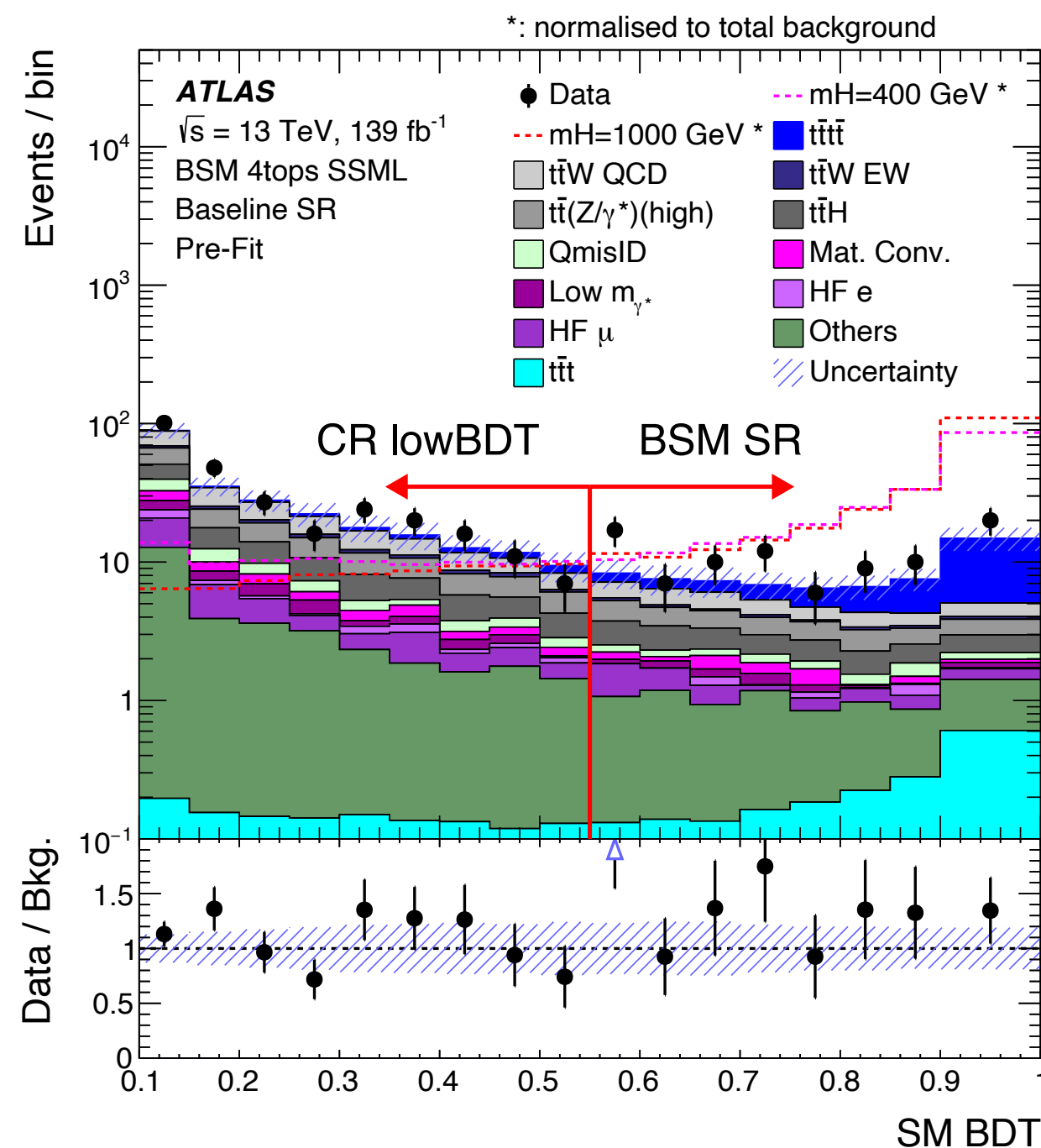


# $ttH/A \rightarrow 4t$

Search for heavy Higgs bosons (H/A) produced in association with a top-quark pair and decaying in a top-quark pair



- Heavy BSM Higgs (H/A) in the mass range 400-1000 GeV
  - Heavy scalar (H) or pseudo-scalar (A) BSM Higgs bosons from the [Two Higgs Doublet Model \(2HDM\) of Type-II \(MSSM-like\)](#)
  - BSM Higgs H/A produced in association with a top-quark pair and decaying in a top-quark pair leading to a 4 tops final state
- Analysis performed in the 2ISS and  $\geq 3l$  plus  $\geq 6$  jets and  $\geq 1$  b-jet final states

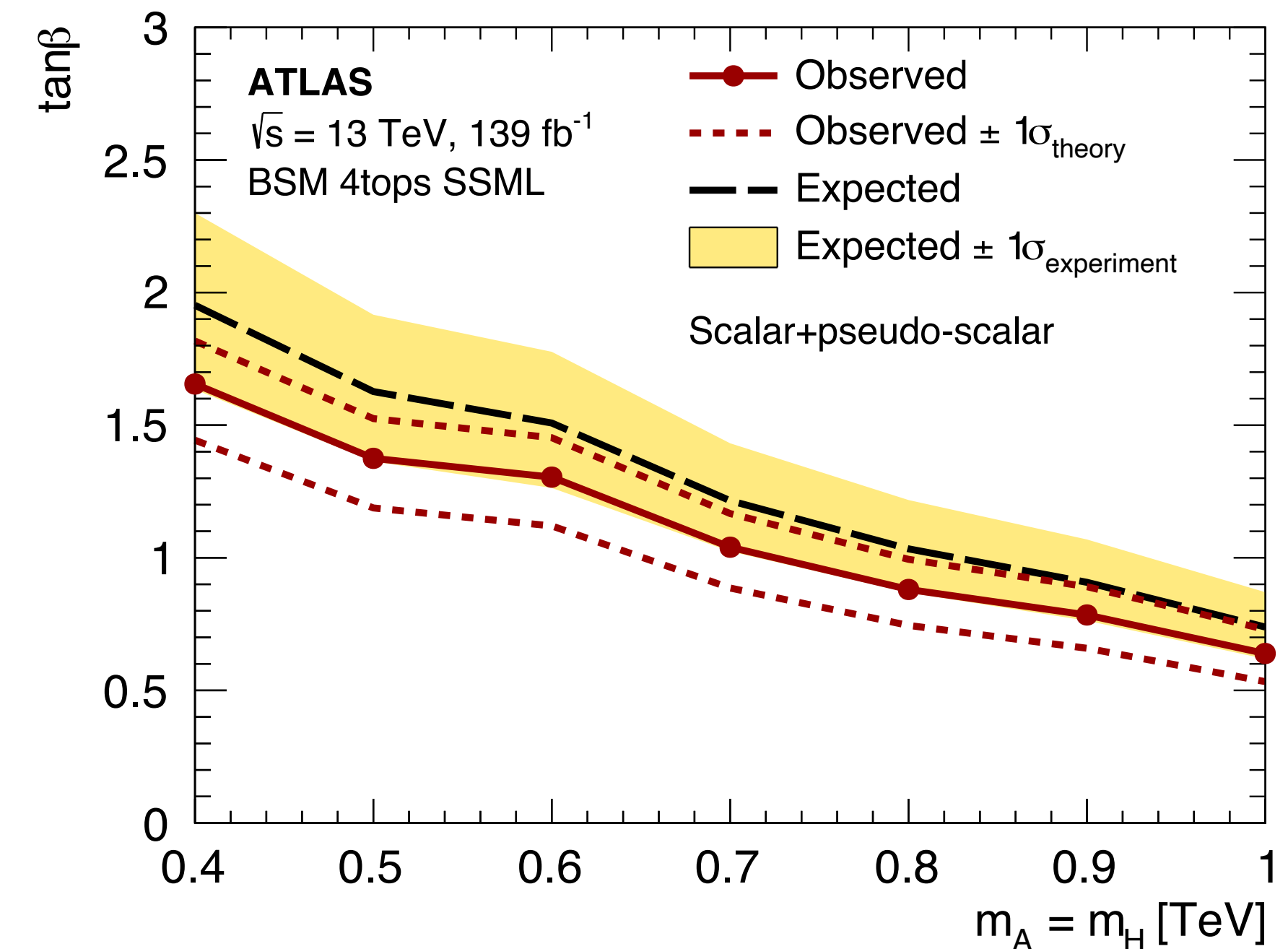
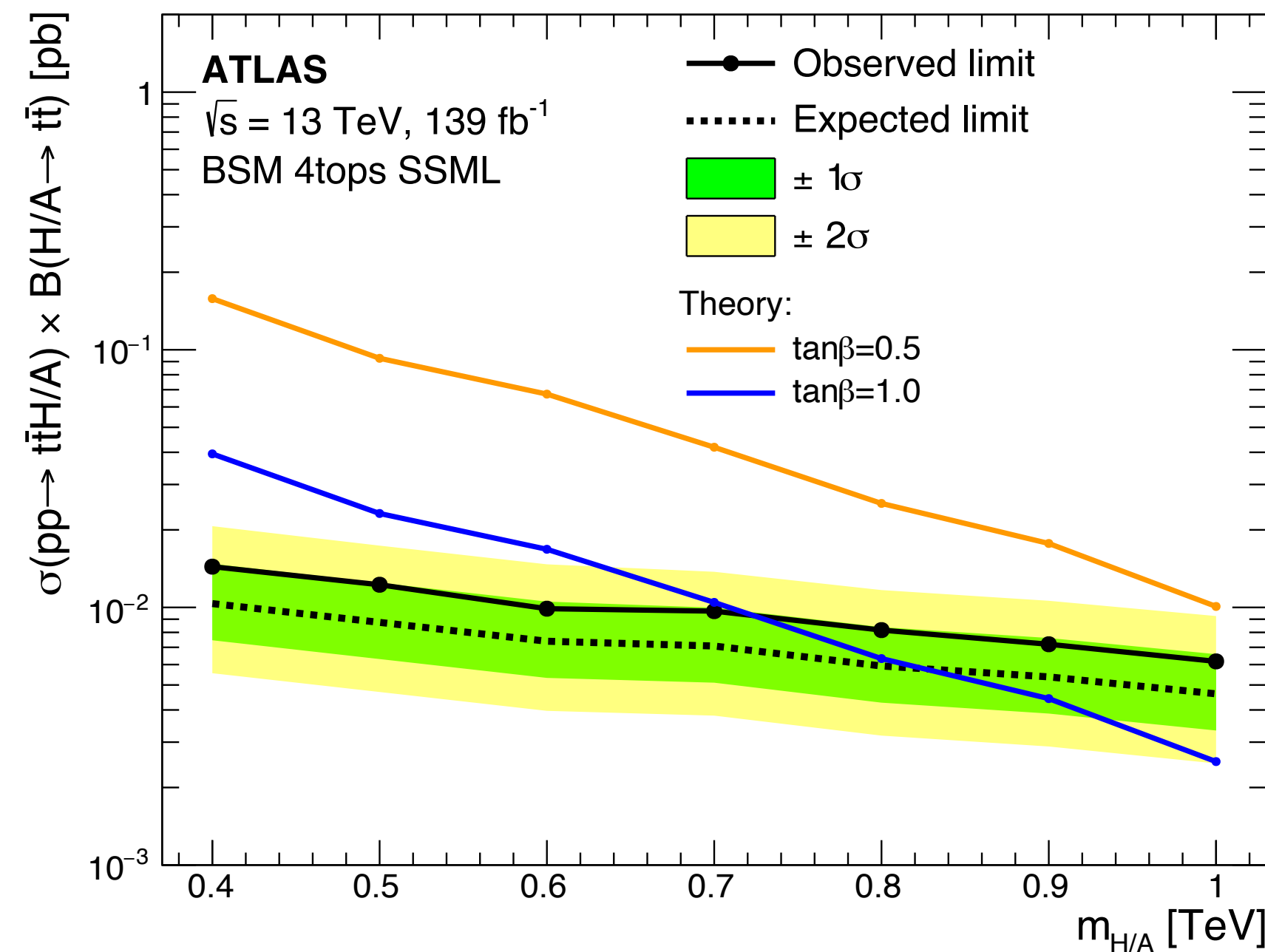
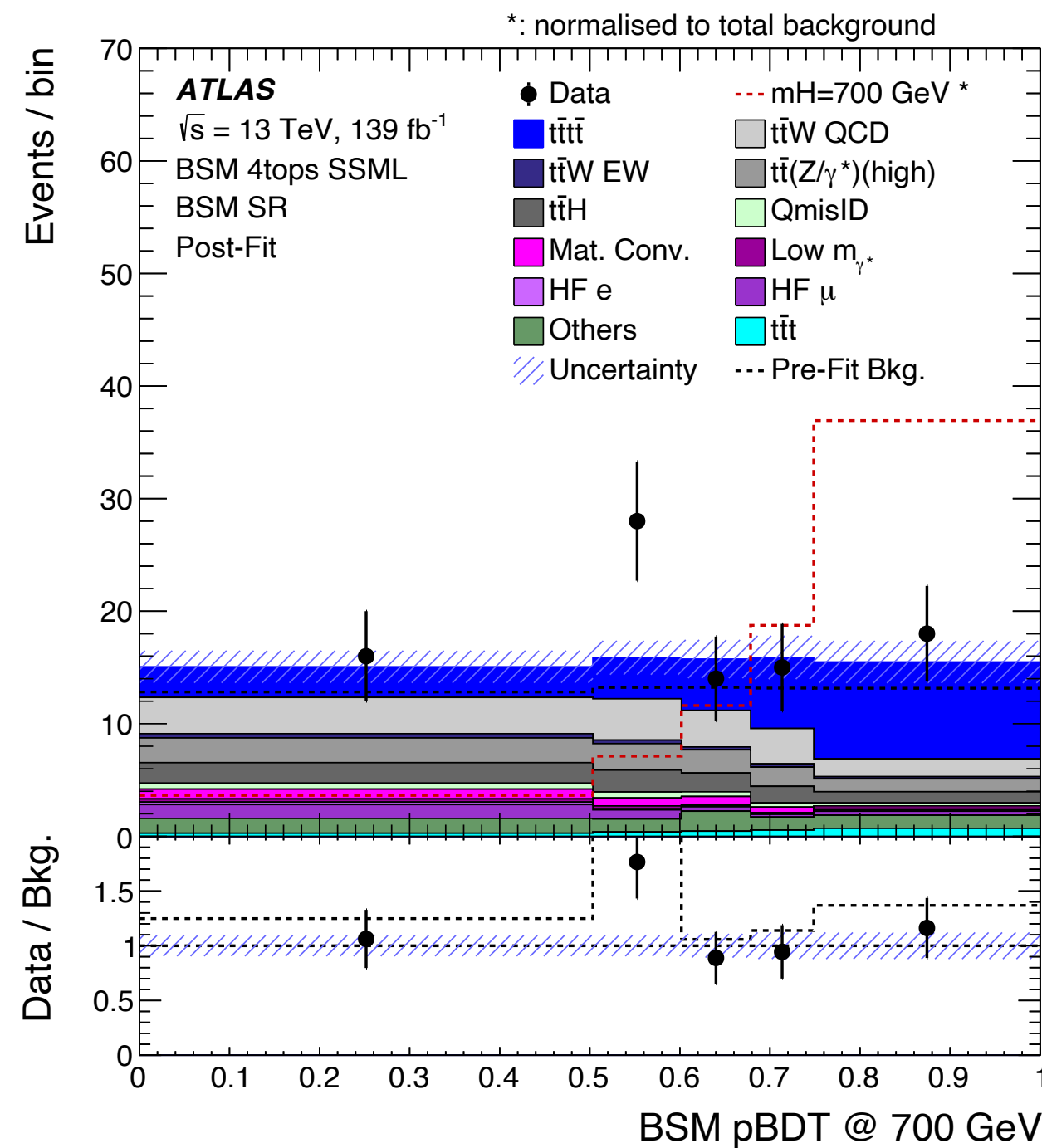


- Boosted Decision Tree (BDT) classifier trained to distinguish the SM 4tops events from the rest of the backgrounds (SMBDT) and used to define the **BSM Signal Region (BSM SR)** and a **low-BDT Control Region (lowBDT CR)**
- Other 4 Control Region (CR) categories for controlling HF non-prompt leptons, photon conversion, and ttW

# $ttH/A \rightarrow 4t$

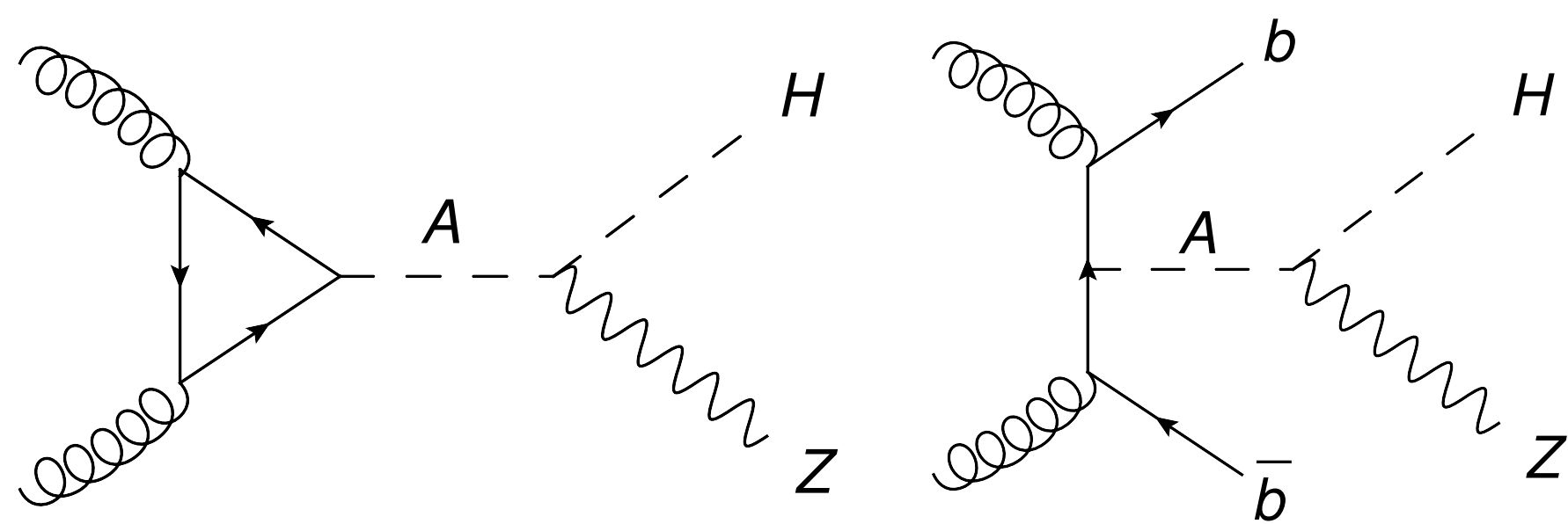
Search for heavy Higgs bosons produced in association with a top-quark pair and decaying in a top-quark pair

- Mass-parameterised BDT (BSM pBDT) trained in the SR to distinguish between the signal and all backgrounds and pBDT output used as final discriminant variable in the SR
- Upper limits set on  $\sigma \times BR$  as a function of  $m_H$  from fit of SR and all CRs
- Upper limits set on  $\tan \beta$  as a function of  $m_H$  in the 2HDM Type-II
- No significant excess above the SM predictions observed



# $A \rightarrow ZH \rightarrow \ell\ell tt/\nu\nu bb$

Search for a heavy CP-odd Higgs boson (A) decaying to a heavy CP-even Higgs Boson (H) and a Z in the  $\ell\ell tt/\nu\nu bb$  channels

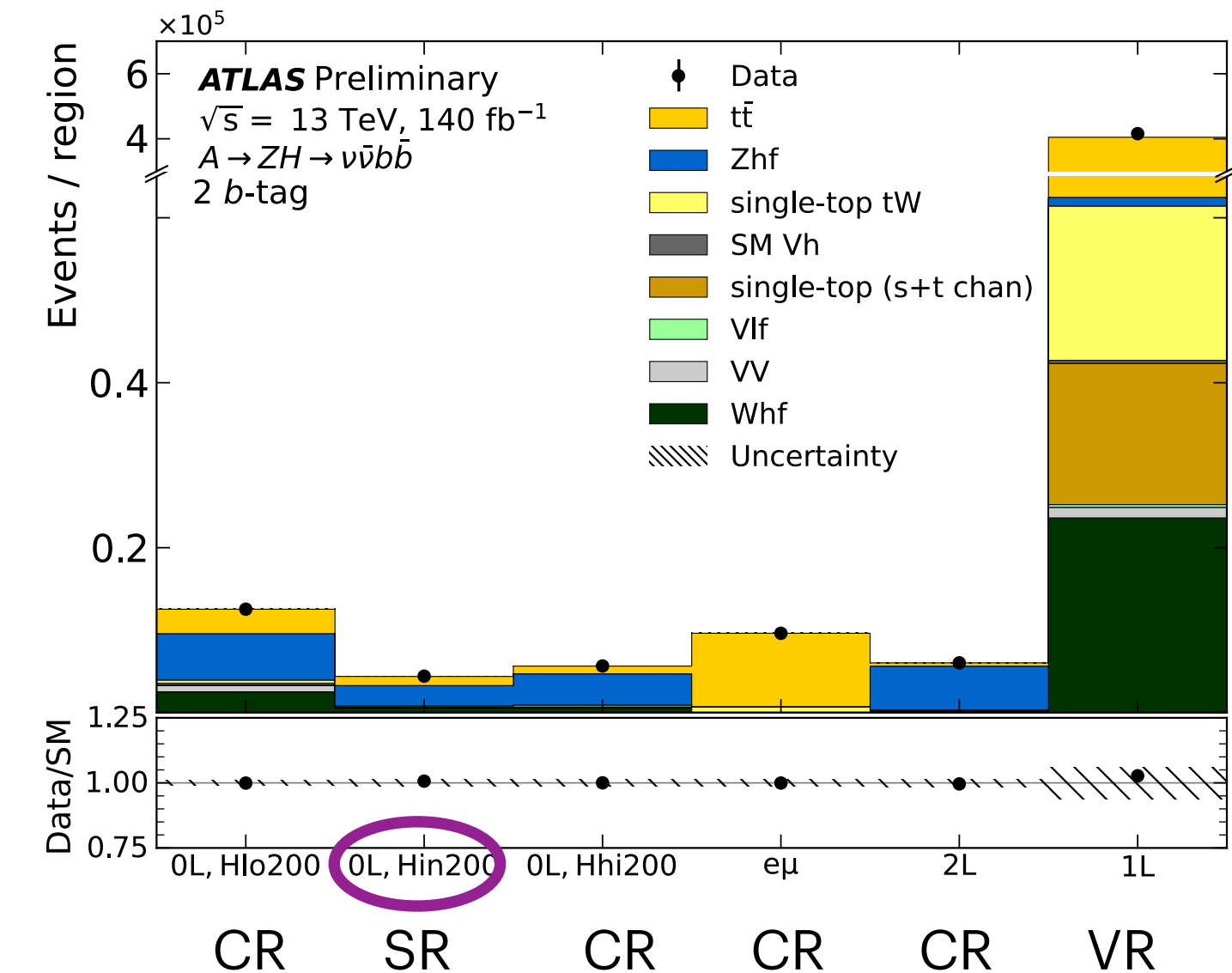
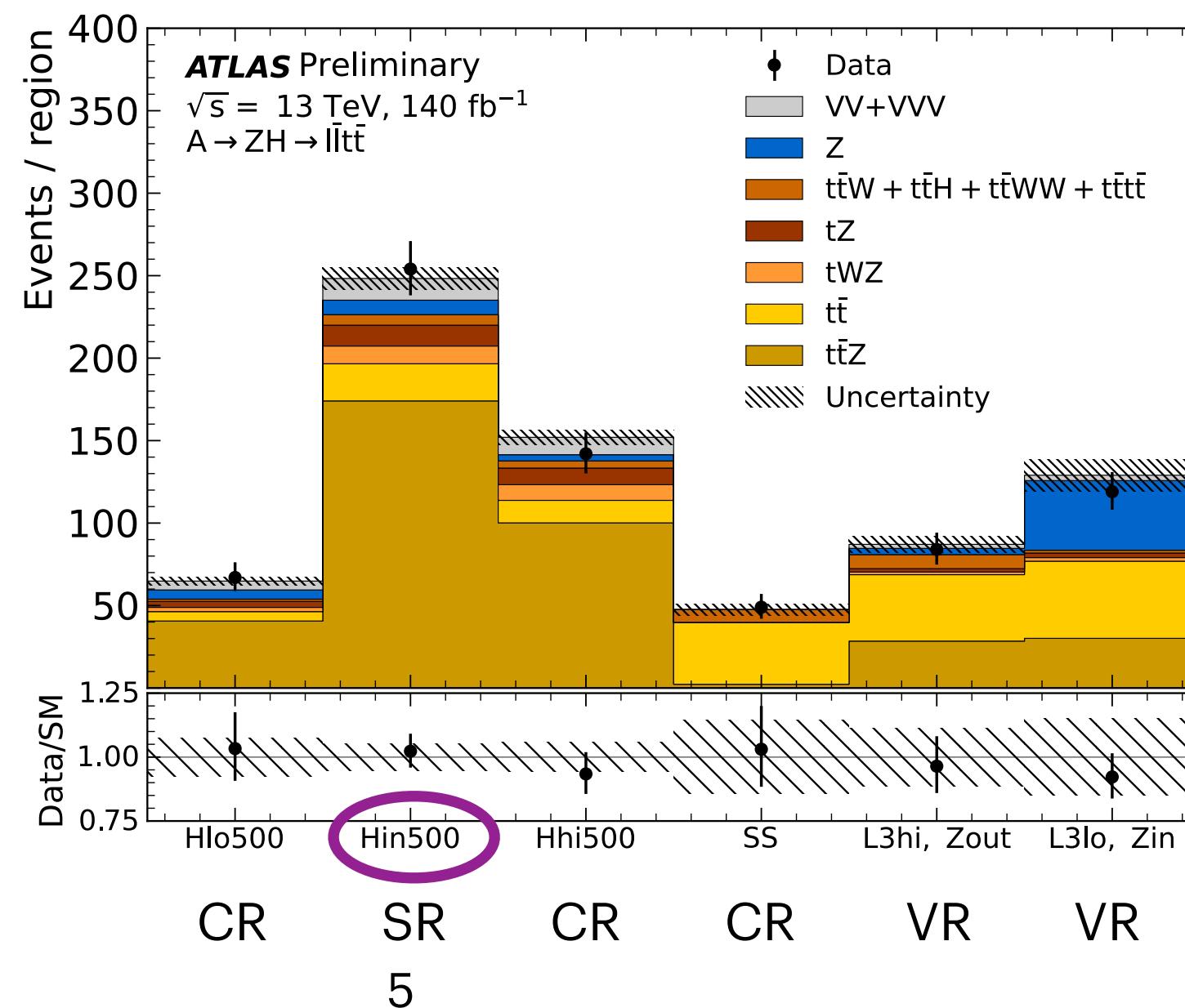


- Heavy CP-odd Higgs (A) in the mass range 450-1200 GeV and heavy CP-even Higgs (H) in the mass range 350-800 GeV
- Heavy BSM Higgs bosons (A/H) from the [Two Higgs Doublet Model \(2HDM\)](#)
- BSM A boson produced via gluon-gluon fusion or in association with a b-quark pair and decaying to a BSM H boson and a Z boson
- Z boson decaying to  $2l$  or  $2\nu$  and H boson decaying to  $tt$  or  $bb$ , leading to  $\ell\ell tt$  and  $\nu\nu bb$  final states

3 Signal Region categories defined based on requirements on the number of leptons, jets, b-jets, MET, reconstructed Z and H boson masses:

- 1  $\ell\ell tt$  SR: 3l,  $\geq 4$  jets and 2 b-jets
- 2  $\nu\nu bb$  SRs: 0l, MET, 2 b-jets and  $\geq 3$  b-jets

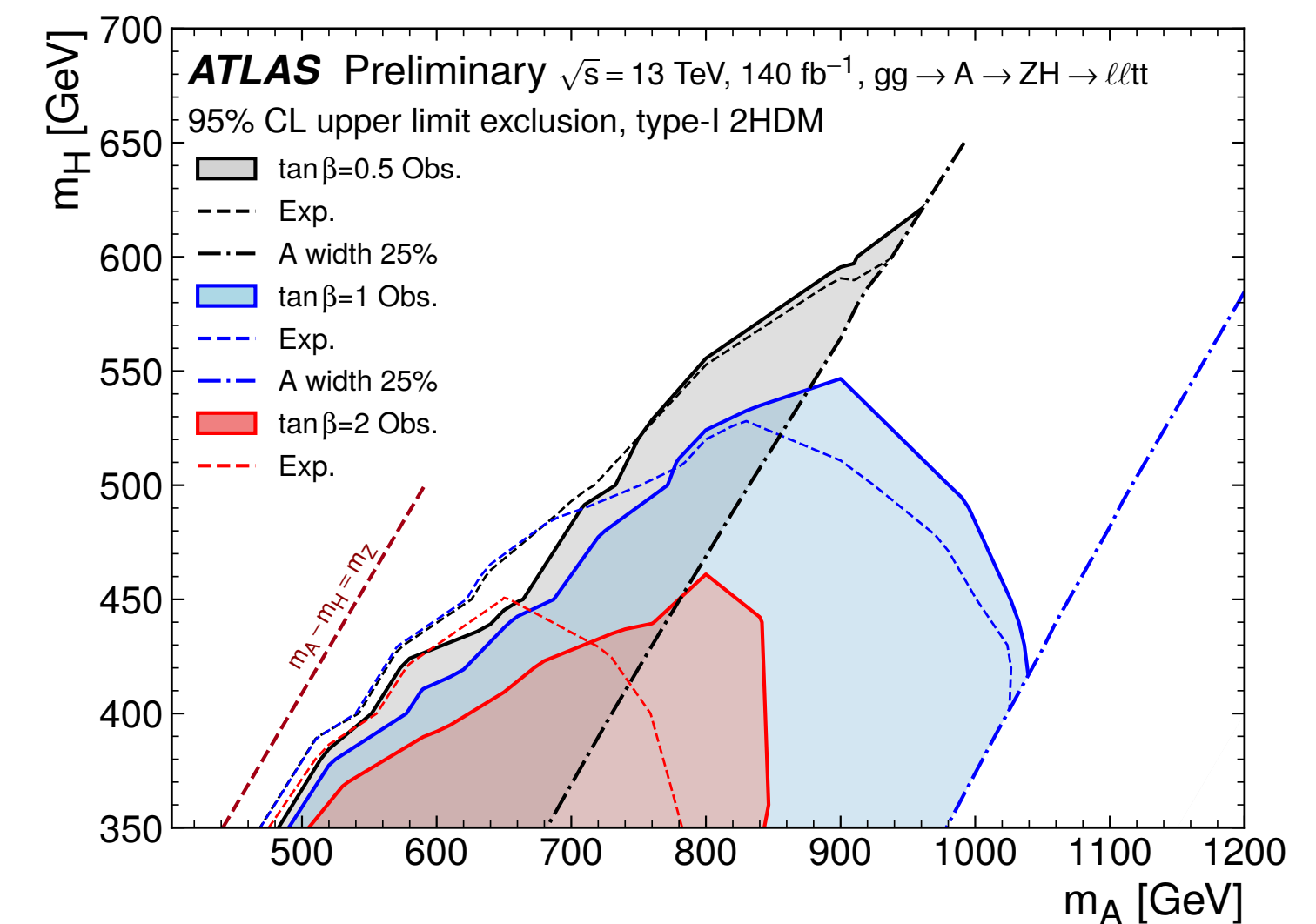
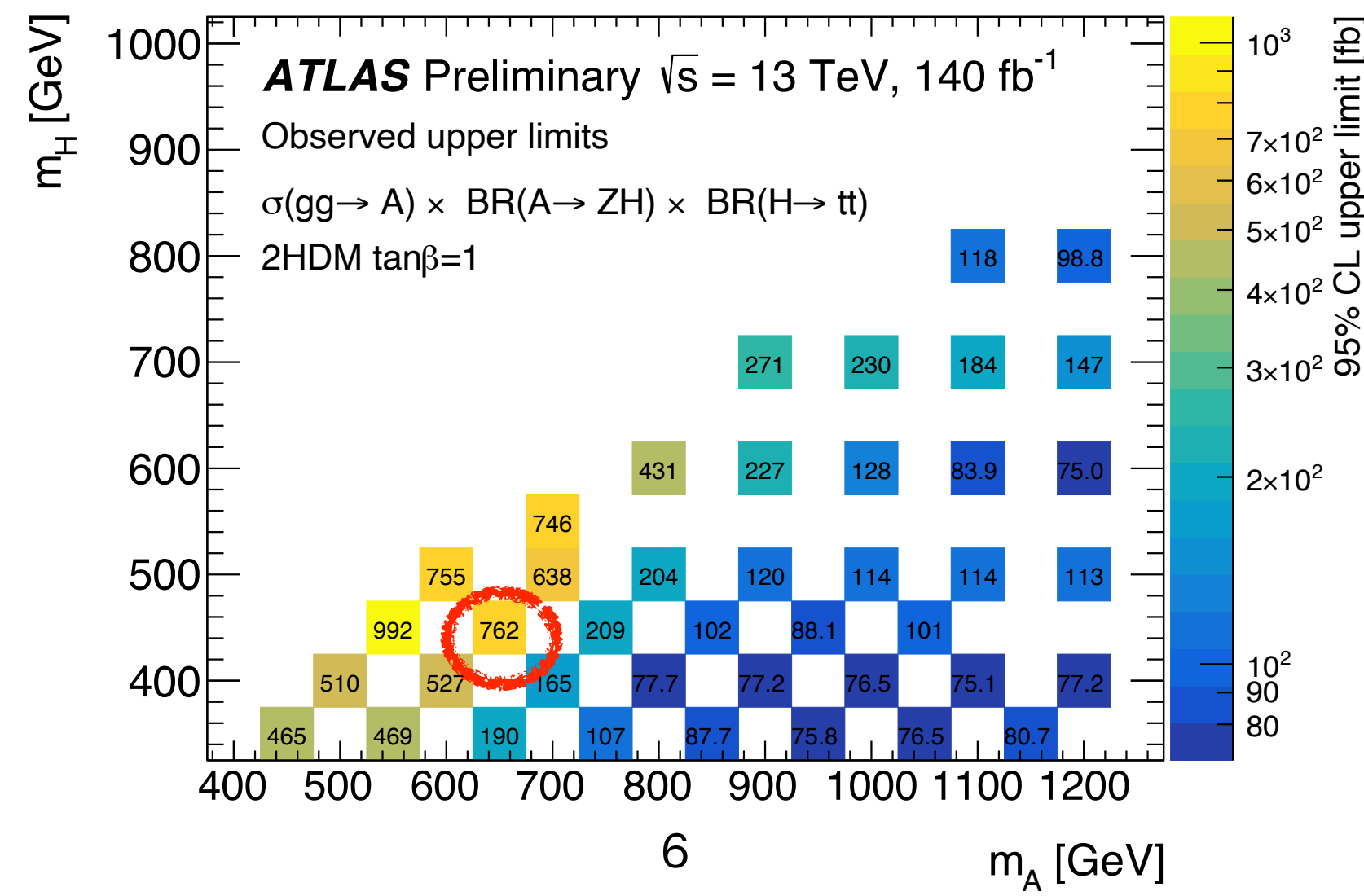
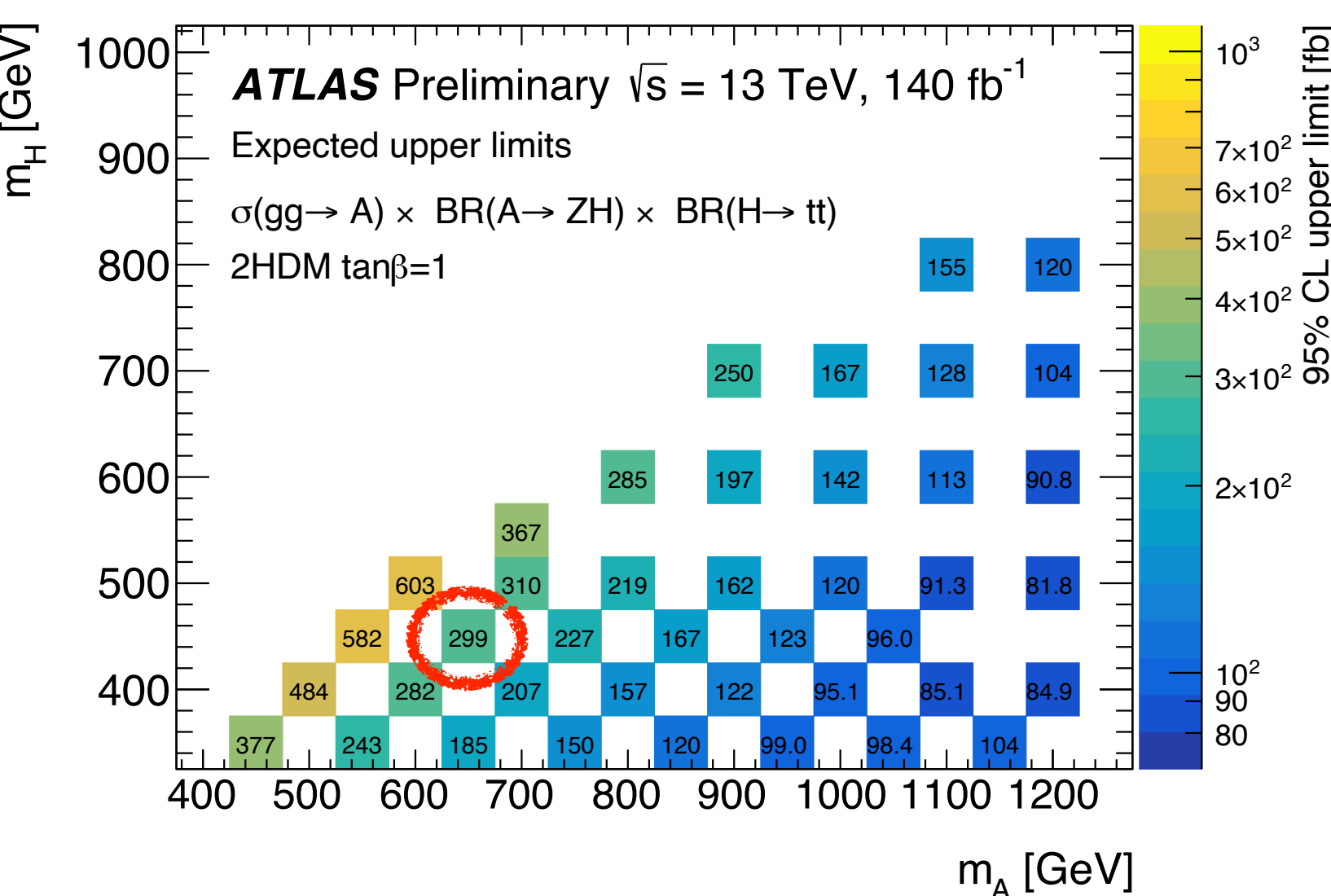
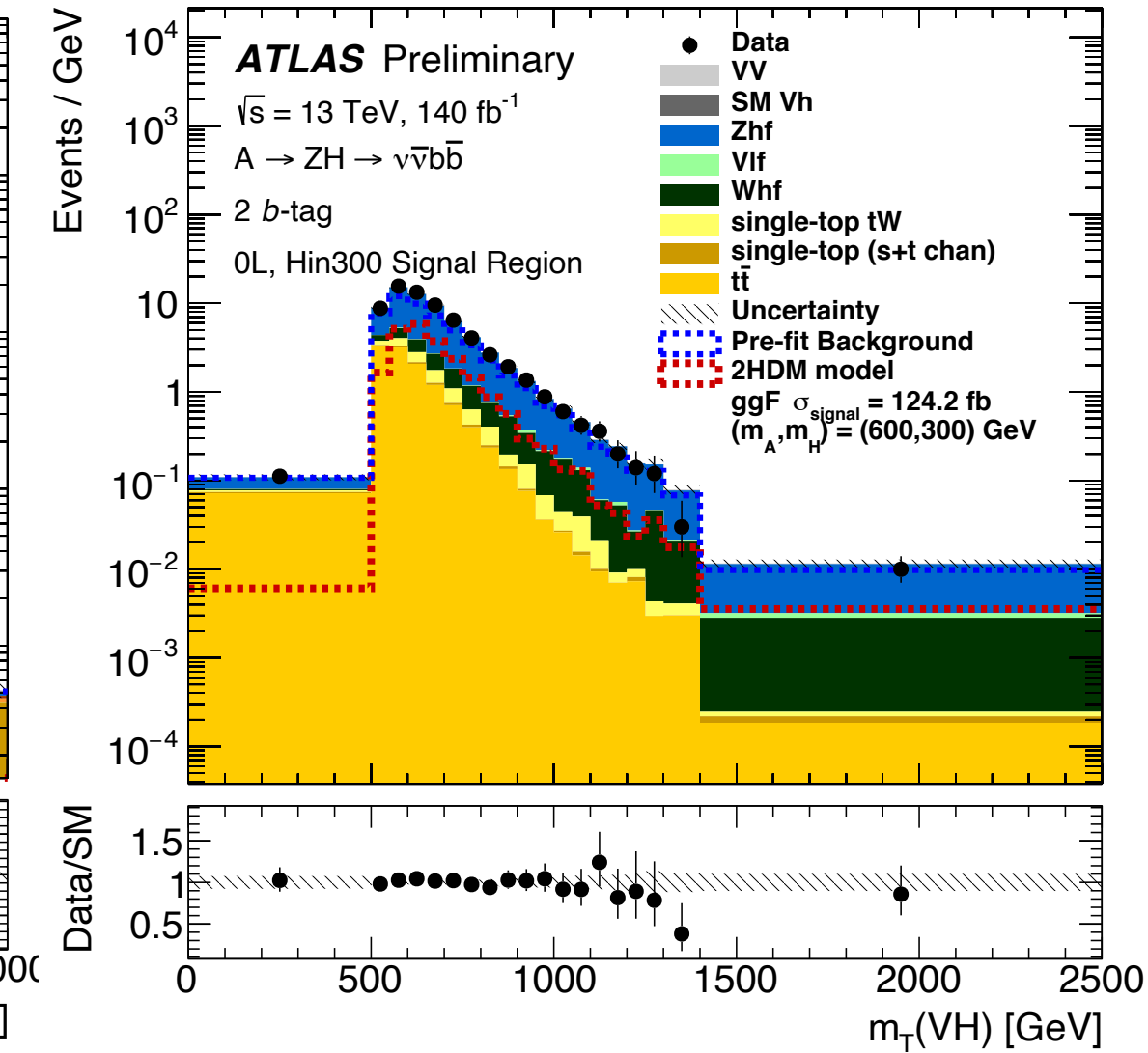
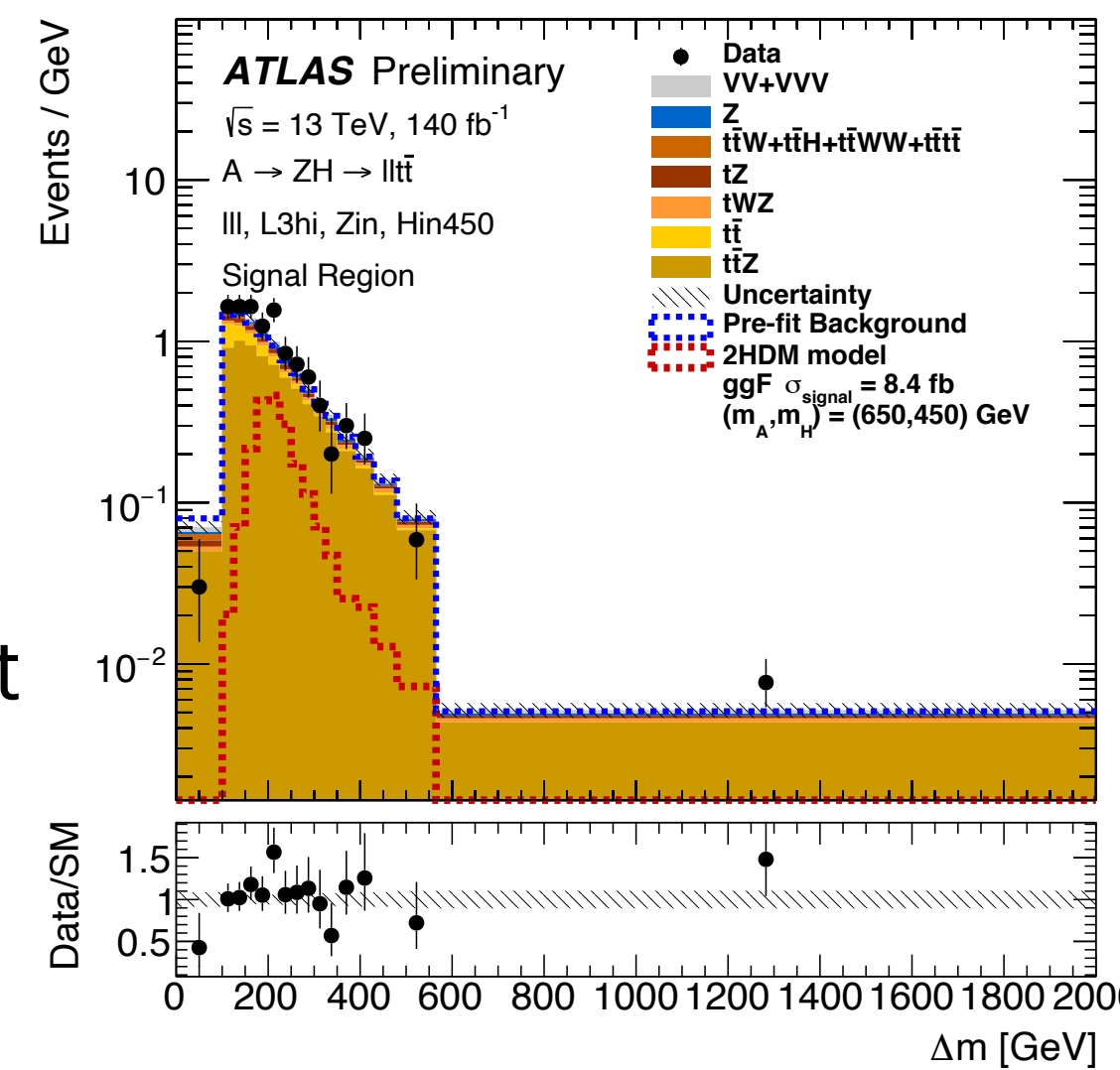
11 Control region categories for controlling  $ttZ$  and  $ttbar$  in the  $\ell\ell tt$  (3 CRs) and Z+HF and  $ttbar$  in the  $\nu\nu bb$  channel (8 CRs)



# $A \rightarrow ZH \rightarrow \ell\ell tt/\nu\nu bb$

Search for a heavy CP-odd Higgs boson (A) decaying to a heavy CP-even Higgs Boson (H) and a Z in the  $\ell\ell tt/\nu\nu bb$  channels

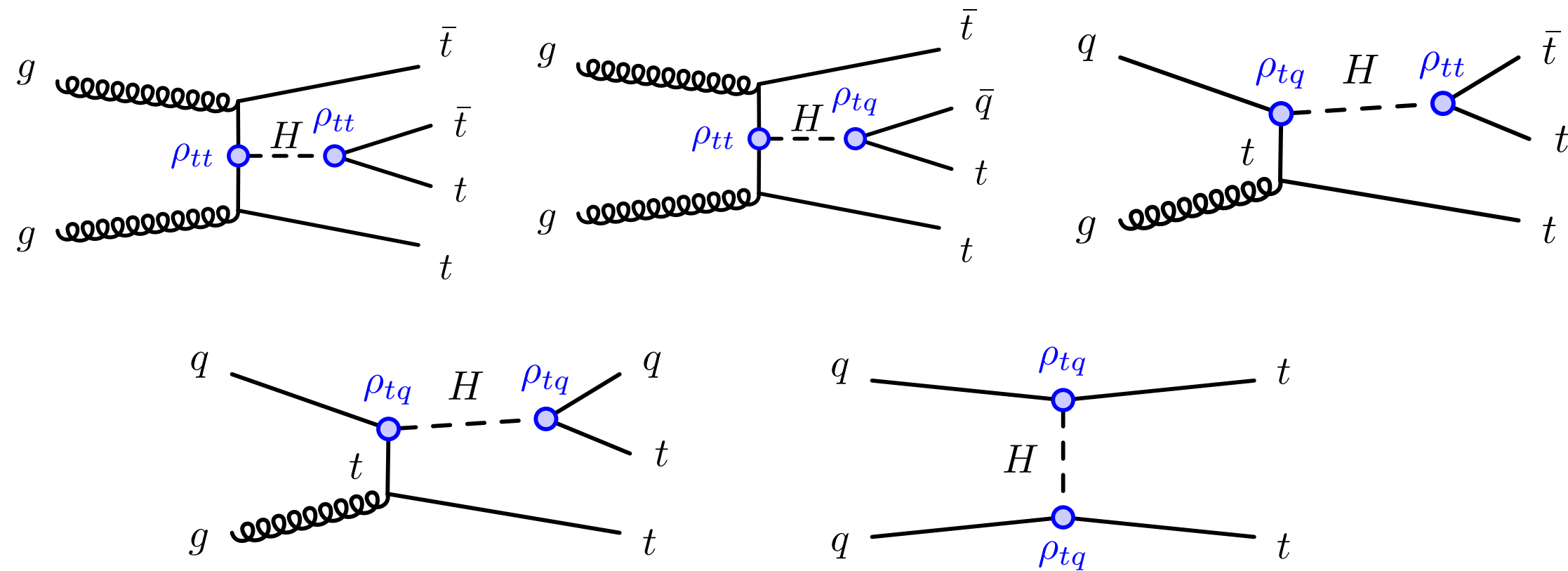
- Mass difference between A and H  $\Delta m = m_A - m_H$  and transverse mass of A  $m_T(VH)$  used as final discriminant variables in the SRs
- Upper limits set on  $\sigma \times BR$  in the  $m_H - m_A$  plane from fit of SRs and CRs, separately for the 2 channels
- No significant excess above the SM predictions observed
- Mild excess observed in the  $\ell\ell tt$  with most significant deviation at  $(m_A, m_H) = (650 \text{ GeV}, 450 \text{ GeV})$  with local significance of  $2.85\sigma$
- Constraints set on the 2HDM Type-I and Type-II in the  $m_H - m_A$  plane for different values of  $\tan\beta$



# Heavy Higgs in multi-lepton plus b-jets

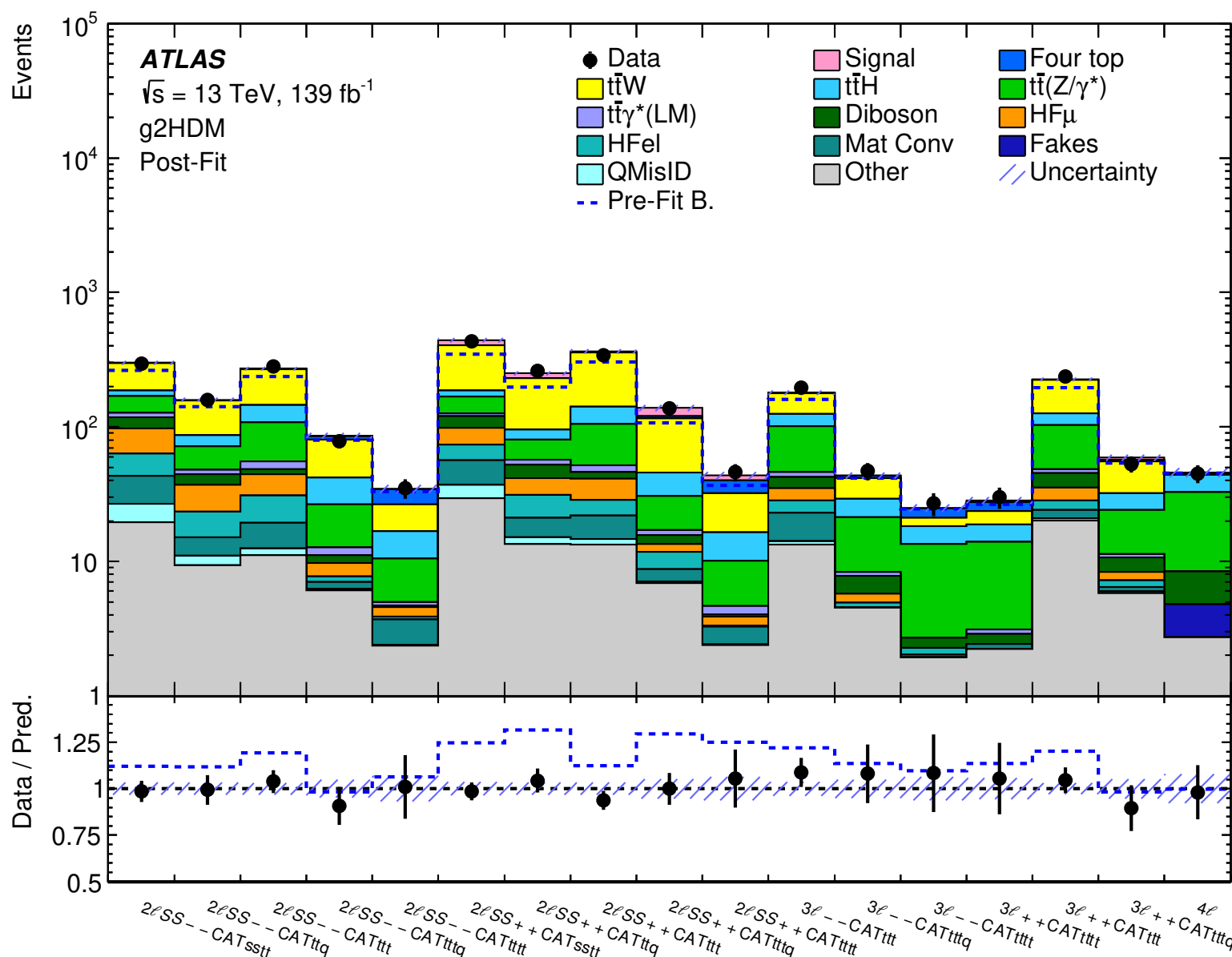
Search for heavy Higgs bosons in multilepton plus b-jets final states

[arXiv:2307.14759](https://arxiv.org/abs/2307.14759) (Sub. to JHEP)



- Heavy BSM Higgs (H) in the mass range 200-1000 GeV
- BSM Higgs (H) from the Two Higgs Doublet Model with extra flavor-changing neutral Higgs interactions (FCNH) (g2HDM)
  - Considering only BSM couplings of the Higgs involving the top-quark and the 3 up-type quarks ( $\rho_{tt}, \rho_{tc}, \rho_{tu}$ )
- Targeted signals lead to final states with a same-sign top-quark pair, three top-quarks, or four top-quarks
  - Analysis performed in final states with 2l, 3l or 4l, + b-jets

17 Signal Region categories



17 Signal Region (SR) categories defined based on:

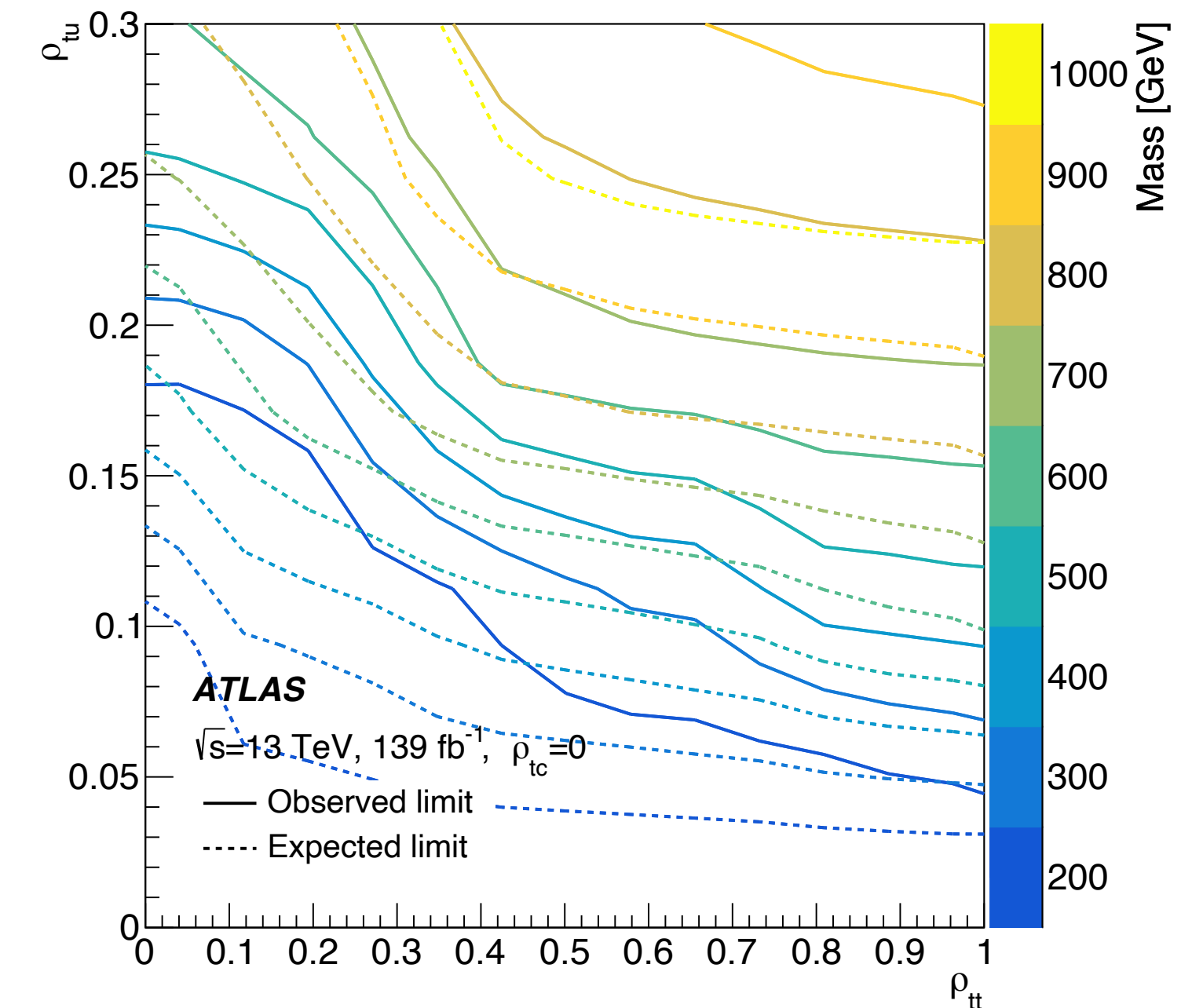
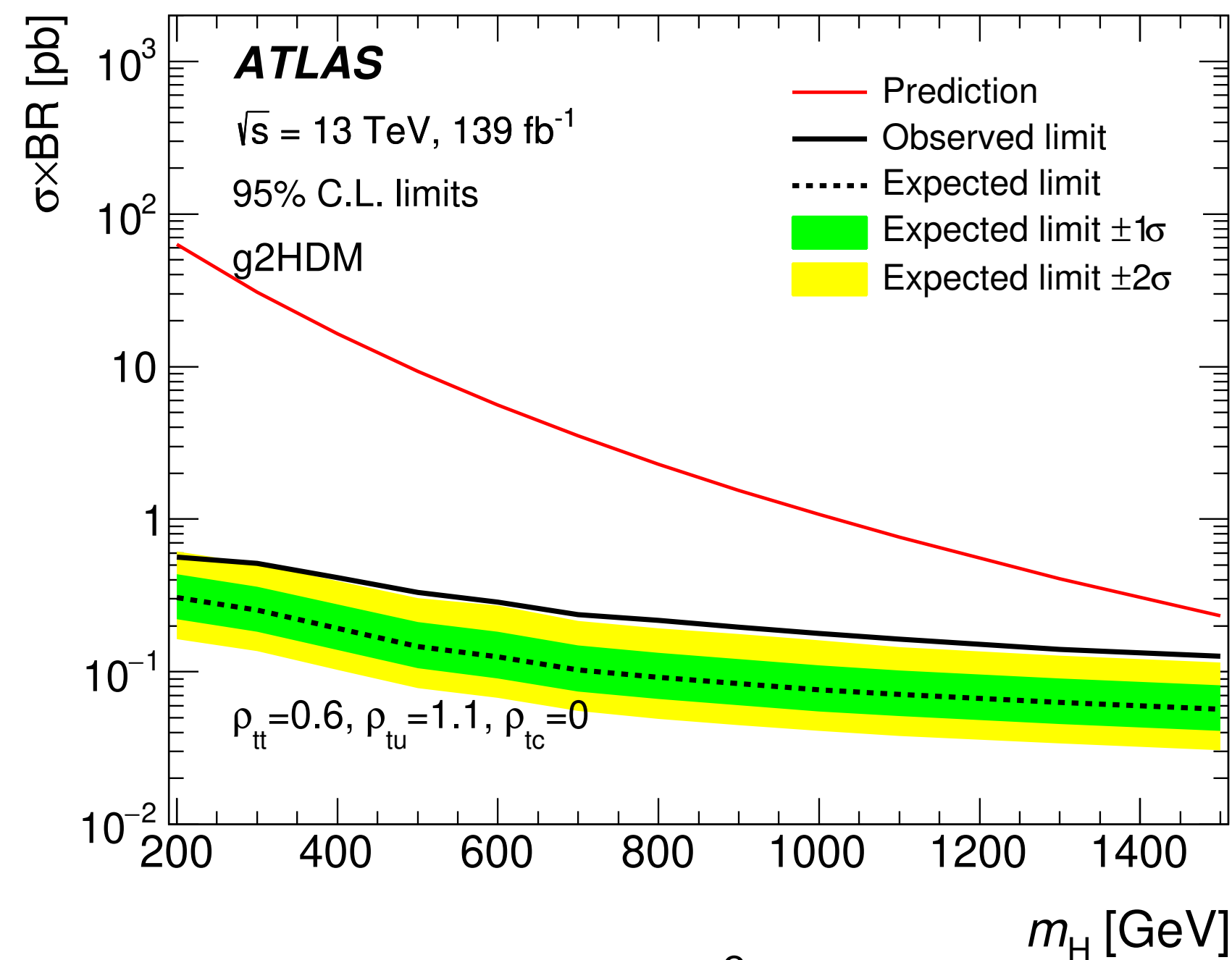
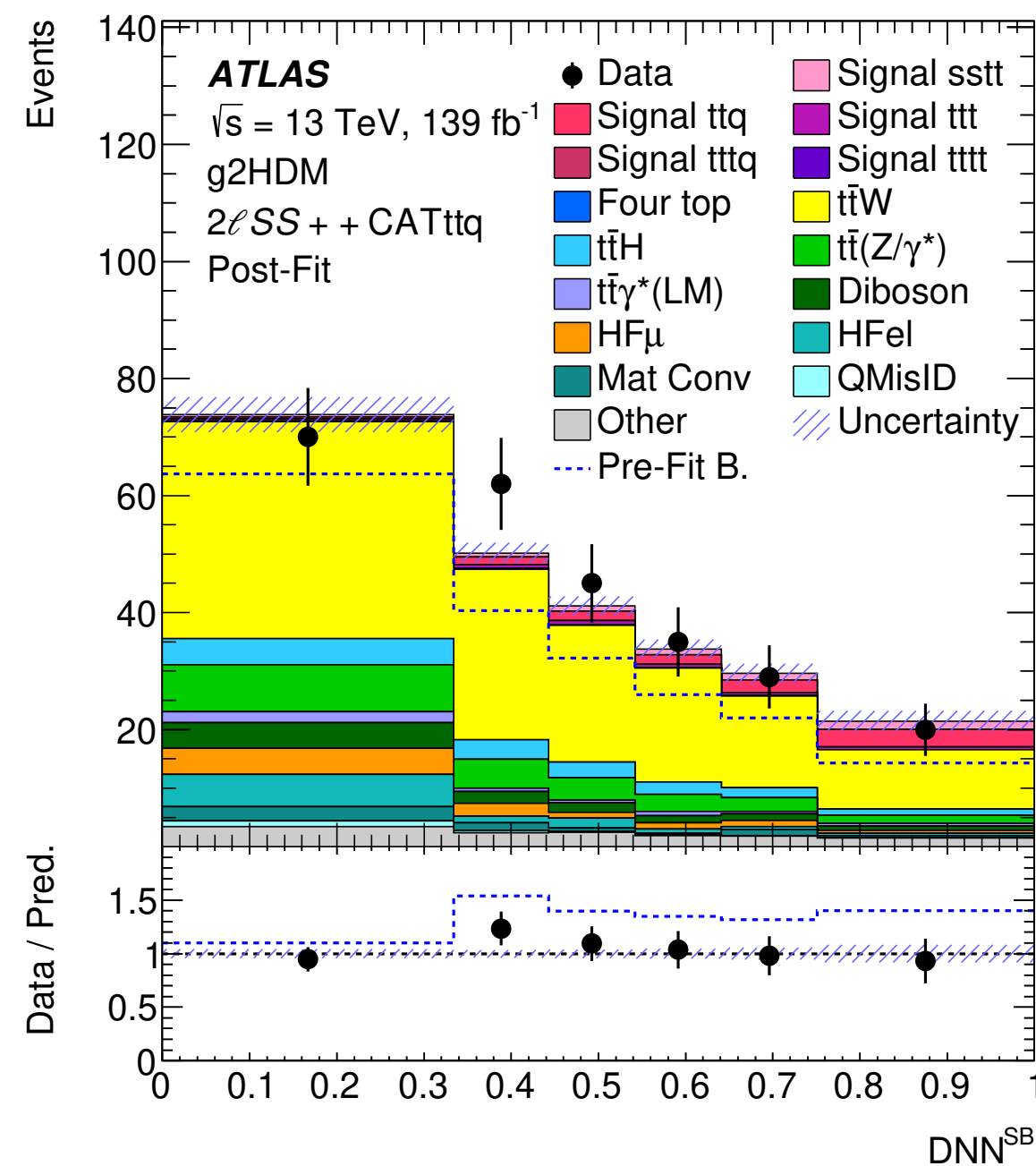
- Number of leptons
- Charge sign of leptons
- Deep Neural Network (DNN) classifier trained to distinguish the different production/decay modes

10 Control Region (CR) categories for controlling HF non-prompt leptons, photon conversion, VV and ttZ

# Heavy Higgs in multi-lepton plus b-jets

Search for heavy Higgs bosons in multilepton plus b-jets final states [arXiv:2307.14759 \(Sub. to JHEP\)](https://arxiv.org/abs/2307.14759)

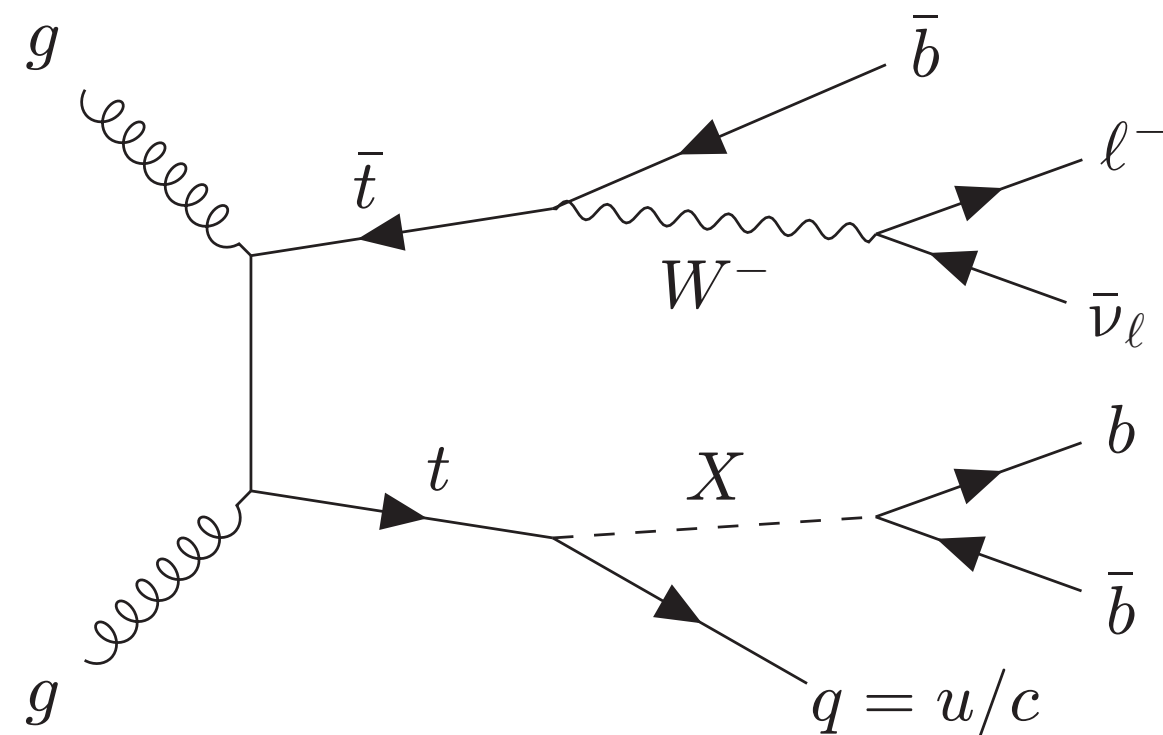
- Deep Neural Network (DNN) classifier trained in each SR to separate signal and background and DNN output used as final discriminant variable in all SRs
- Upper limits set on  $\sigma \times BR$  and on the BSM Higgs couplings  $\rho$  as a function of  $m_H$  from fit of all SRs and CRs
- No significant excess above the SM predictions observed
- Mild excess observed with most significant deviation at  $m_H = 900$  GeV for  $\rho_{tt}, \rho_{tc}, \rho_{tu} = (0.6, 0.0, 1.1)$  with local significance of  $2.8\sigma$





# $t \rightarrow qX, X \rightarrow bb$

Search for new scalars  $X$  produced in the decay of a top-quark and decaying to  $bb$



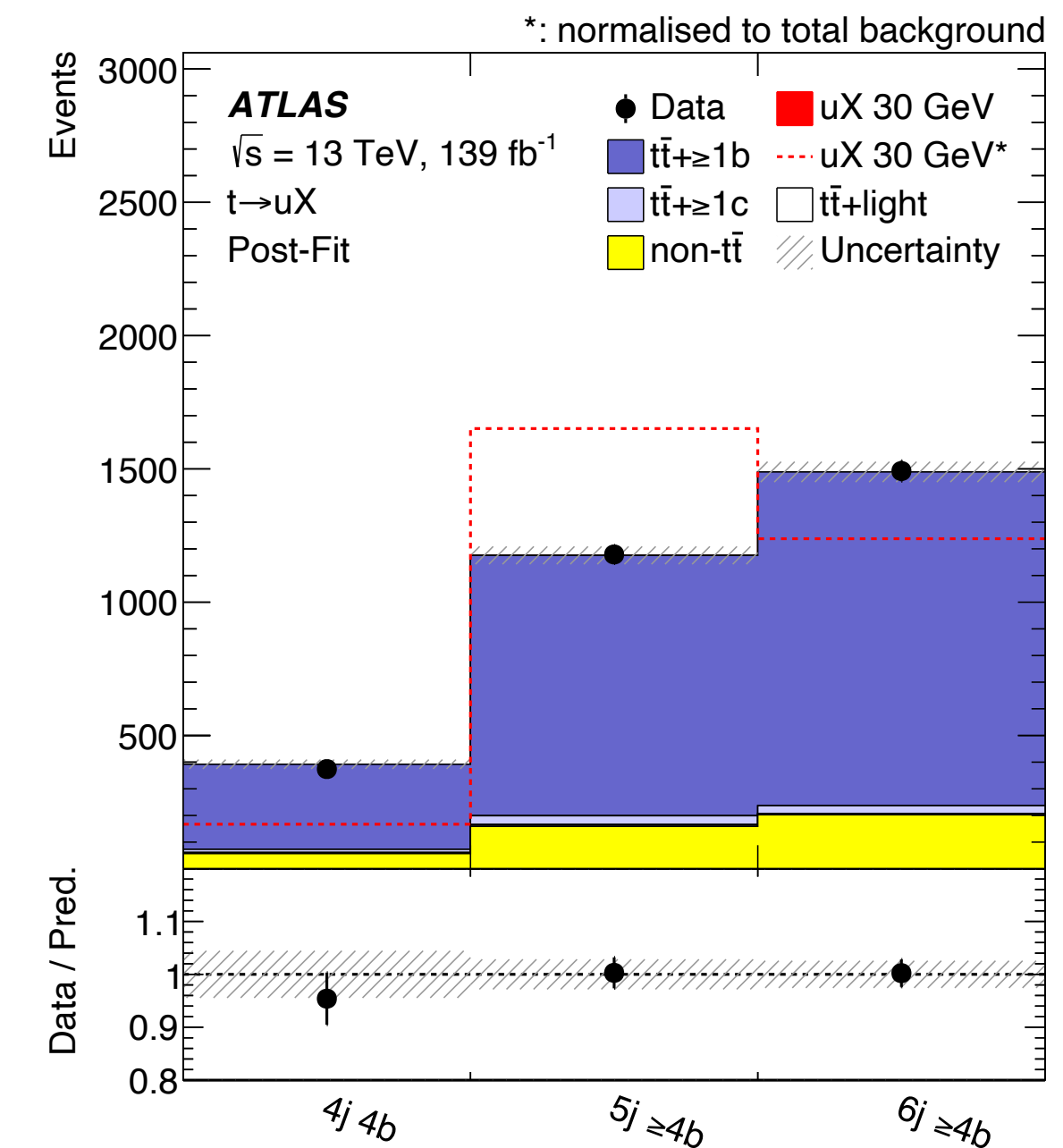
- New scalars ( $X$ ) in the mass range 20-160 GeV
  - New scalar ( $X$ ) inspired by the non-SM Higgs from the [Flavon Model](#) with flavor-changing neutral current (FCNC) top-decays
  - Considering top-quark pair production with 1 top decaying to  $bW$  according to the SM and 1 top decaying to  $Xq(u,c)$  and  $X$  decaying to  $bb$
- Analysis performed in final states with 1l,  $\geq 4$  jets and 3 b-jets

3 Signal Region categories defined based on number of jets and b-jets:

- 4j 3b
- 5j 3b
- 6j 3b

3 Control Region categories defined for controlling the  $t\bar{t}$ +jets

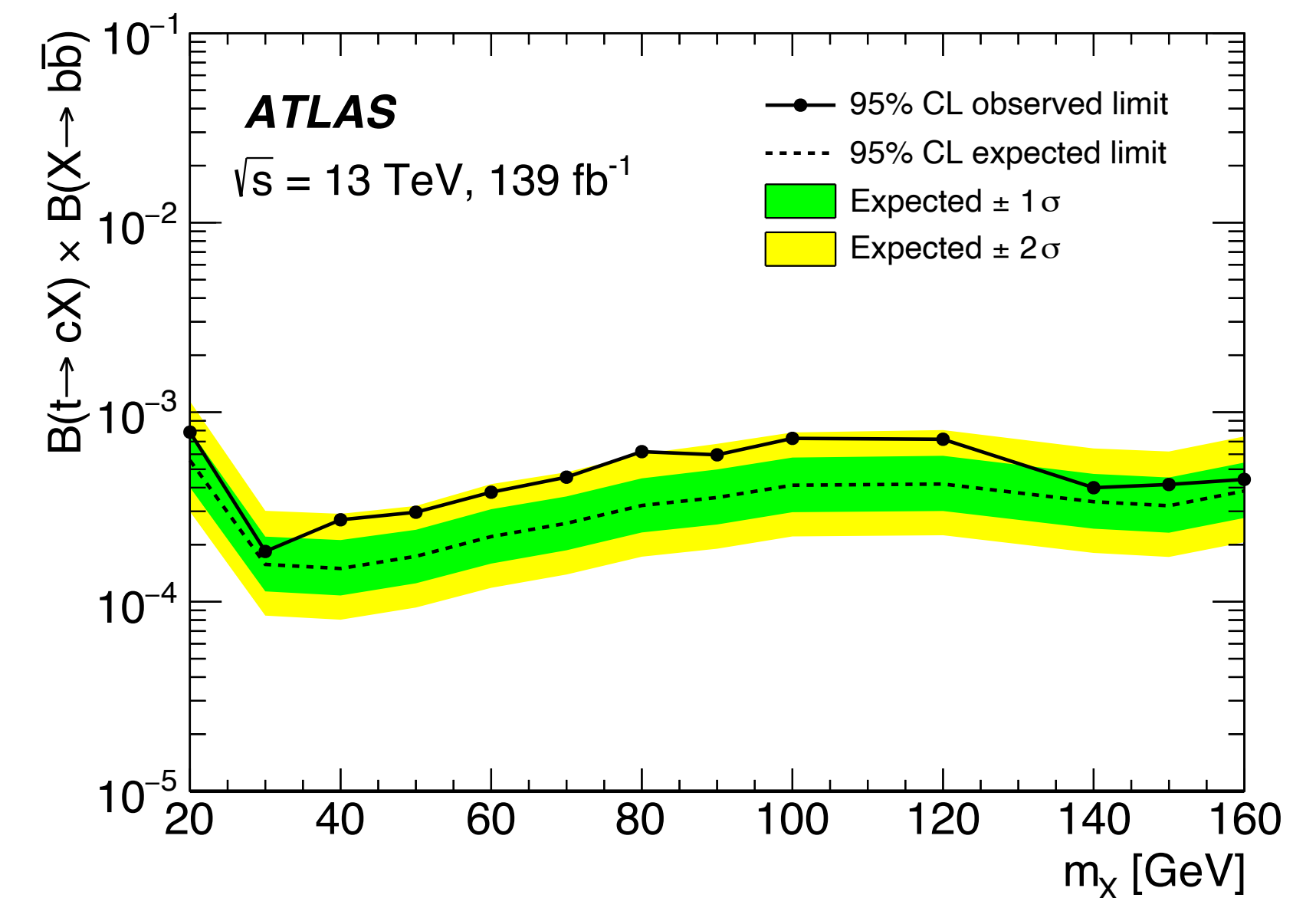
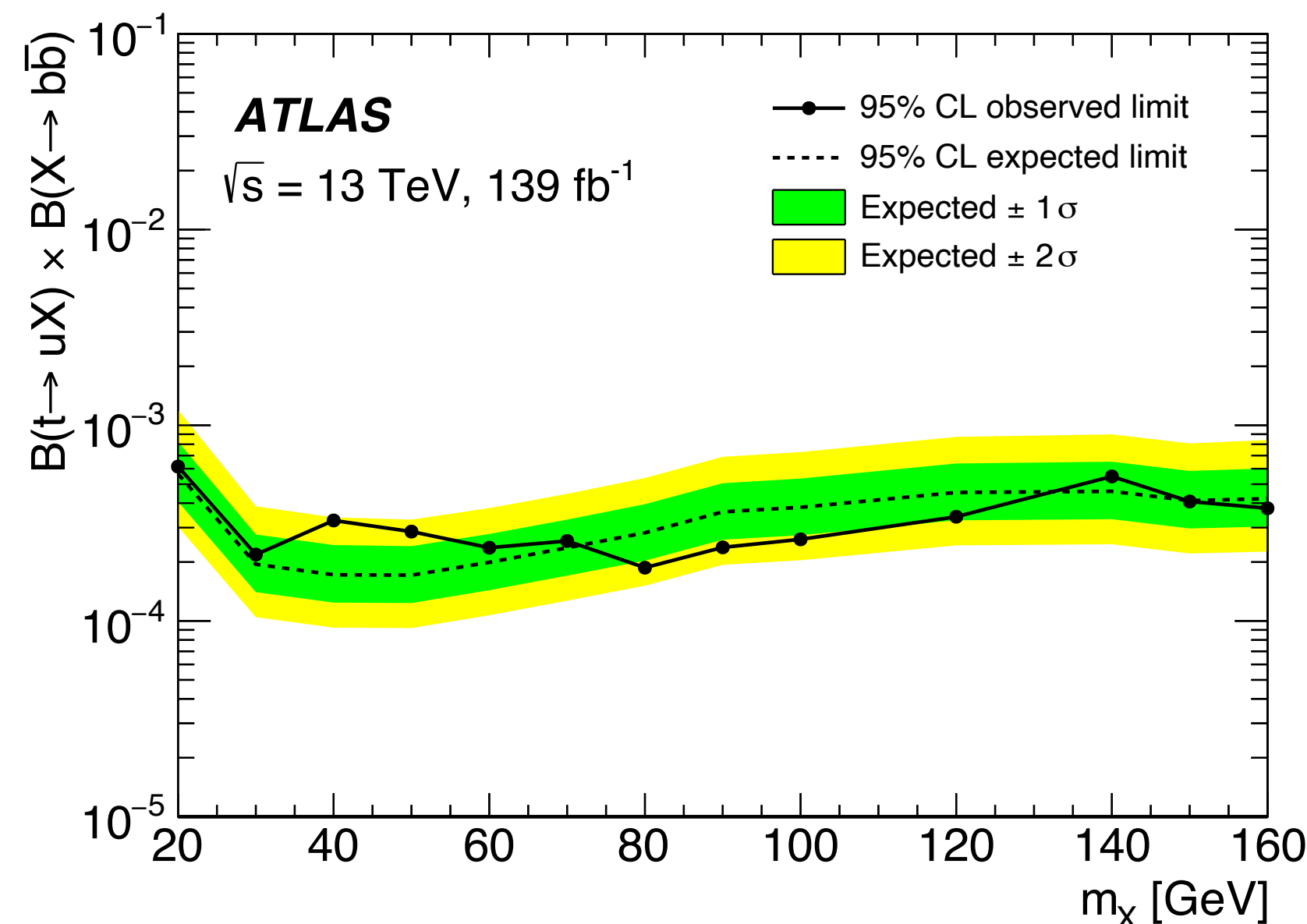
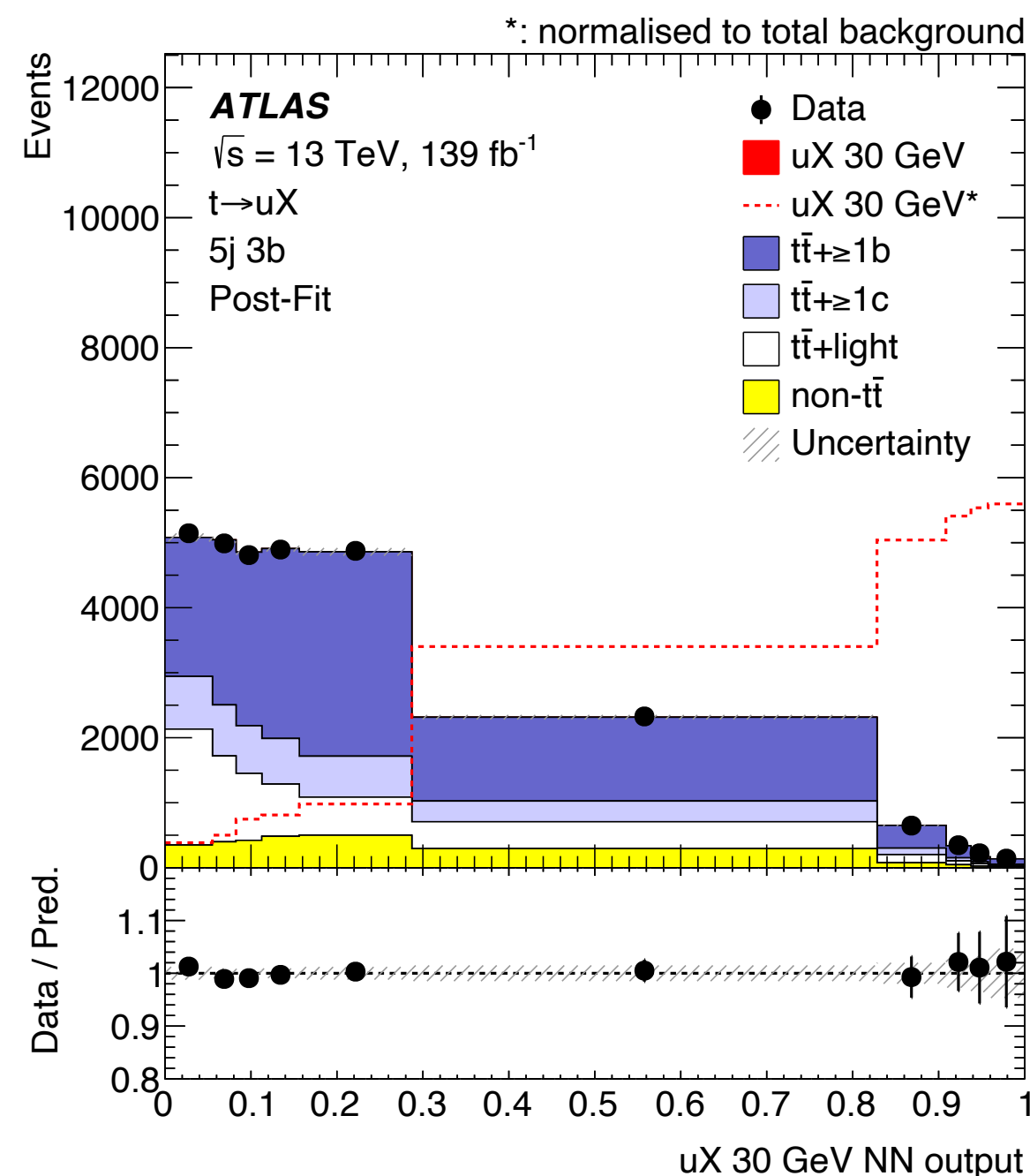
3 Control Region categories



# $t \rightarrow qX, X \rightarrow bb$

Search for new scalars produced in the decay of a top-quark and decaying to  $bb$

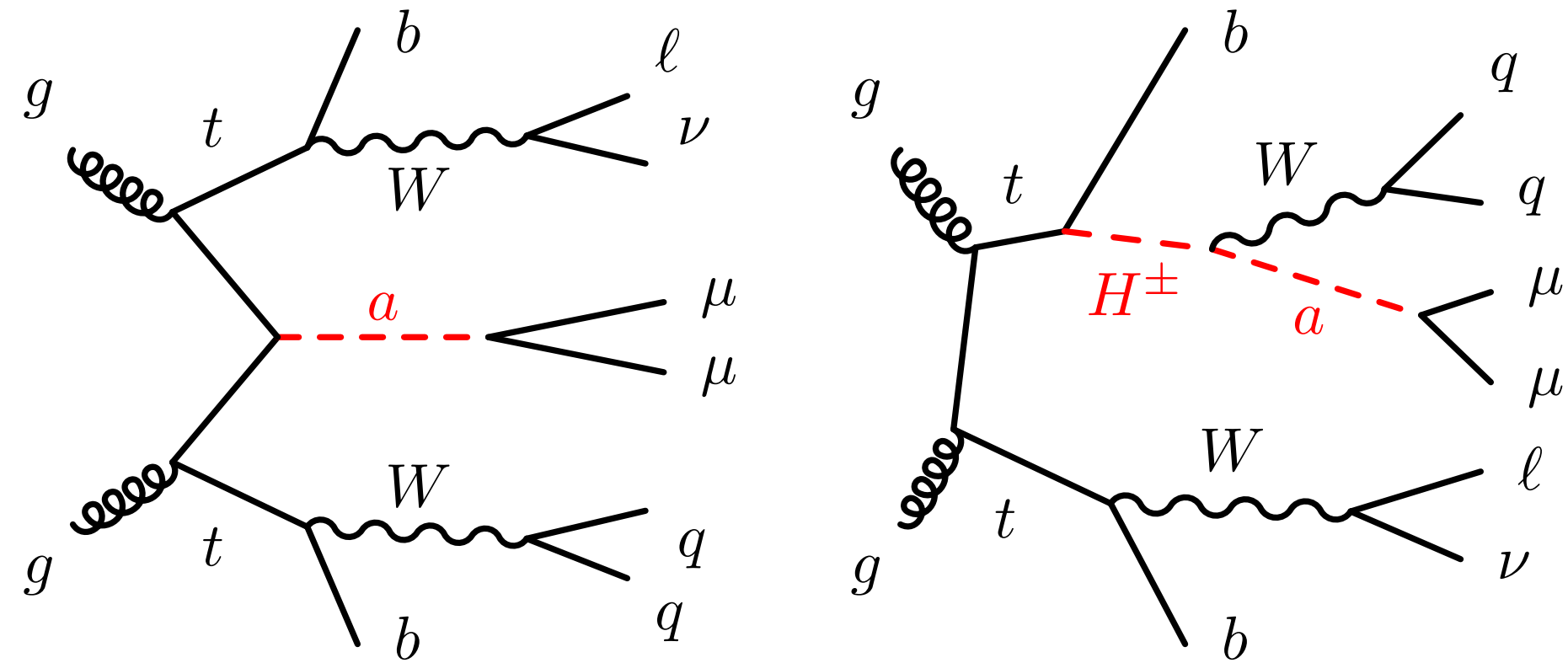
- Mass-parameterised Neural Network (pNN) classifier trained to separate signal and background, separately for the  $uX$  and  $cX$  channels, and pNN output used as final discriminant variable in all SRs
- Upper limits set on  $BR(t \rightarrow uX) \times BR(X \rightarrow bb)$  and on  $BR(t \rightarrow cX) \times BR(X \rightarrow bb)$  as a function of  $m_X$  from fit of all SRs and CRs
- No significant excess above the SM predictions observed
- Mild excess observed in the  $uX$  channel at  $m_X = 40$  GeV with local significance of  $1.8\sigma$
- Mild excess of roughly  $2\sigma$  local observed in the  $cX$  channel in the broad mass range 40 GeV - 120 GeV



# $t\bar{t}a, a \rightarrow \mu\mu$

[arXiv:2304.14247 \(Sub. to PRD\)](https://arxiv.org/abs/2304.14247)

Search for light pseudo-scalar Higgs bosons ( $a$ ) produced in association with a top-quark pair and decaying in  $\mu\mu$

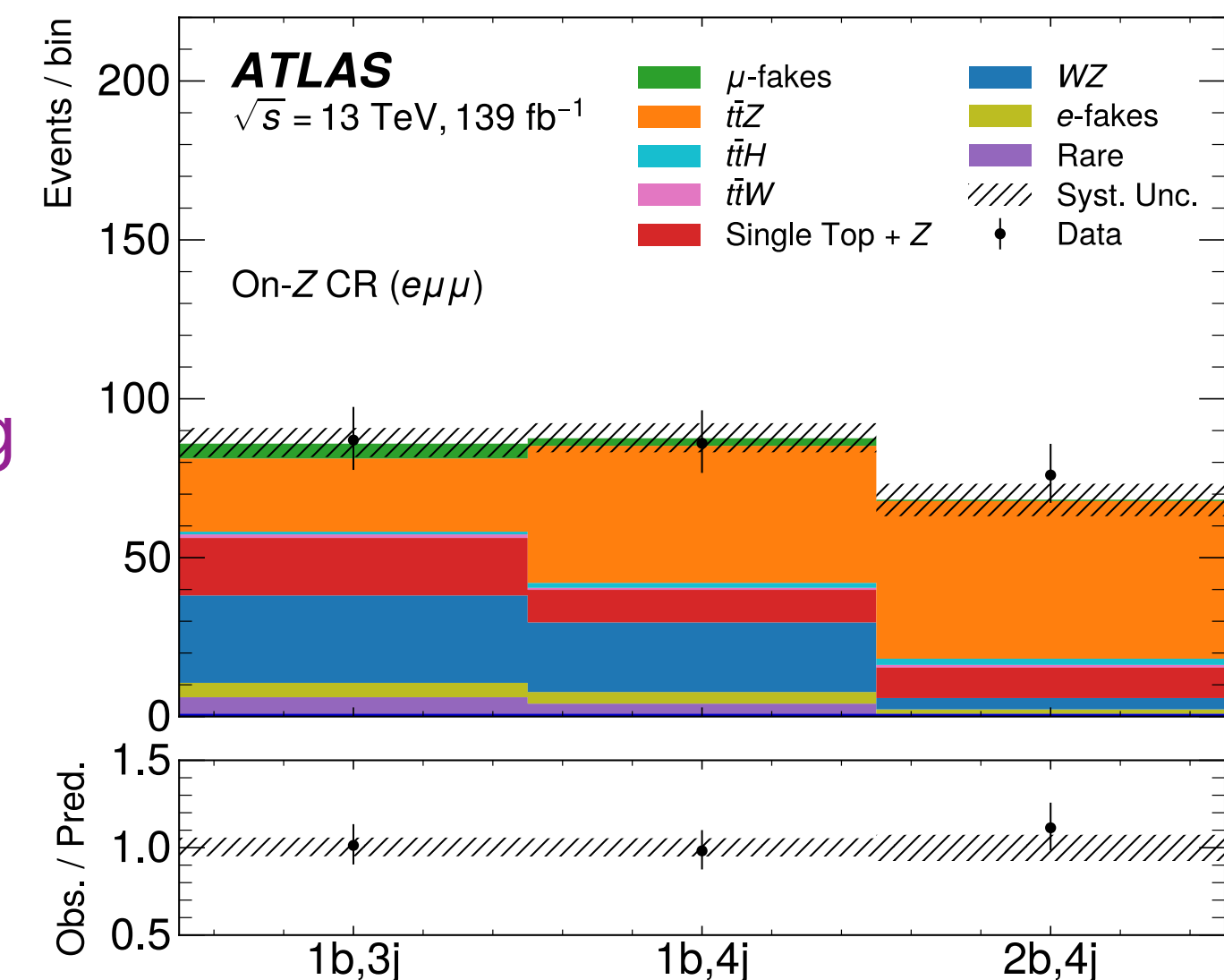


- Light pseudo-scalar Higgs ( $a$ ) in the mass range 15-72 GeV
  - BSM Higgs ( $a$ ) from the 2HDM+a extended Higgs sector model (NMSSM-like)
  - $a$  produced in association with a top-quark pair ( $t\bar{t}a$ ) or produced from the decay of a charged Higgs coming from the top-quark decay ( $t \rightarrow H^\pm \rightarrow Wa$ )
  - $a$  decaying in a muon pair
- Analysis performed in the  $3l (e\mu\mu, \mu\mu\mu)$  plus  $\geq 3$  jets and  $\geq 1$  b-jets final states

2 Signal Region categories defined based on lepton flavours and di-muon invariant mass requirements:

- $e\mu\mu$  with  $12 \text{ GeV} < m_{\mu\mu}^a < 77 \text{ GeV}$
- $\mu\mu\mu$  with  $12 \text{ GeV} < m_{\mu\mu}^a < 77 \text{ GeV}$  and  $m_{\mu\mu}^{\text{other}} < 77 \text{ GeV}$  or  $> 107 \text{ GeV}$

3 Control Region categories for controlling  $t\bar{t}Z/WZ$  and  $t\bar{t}$

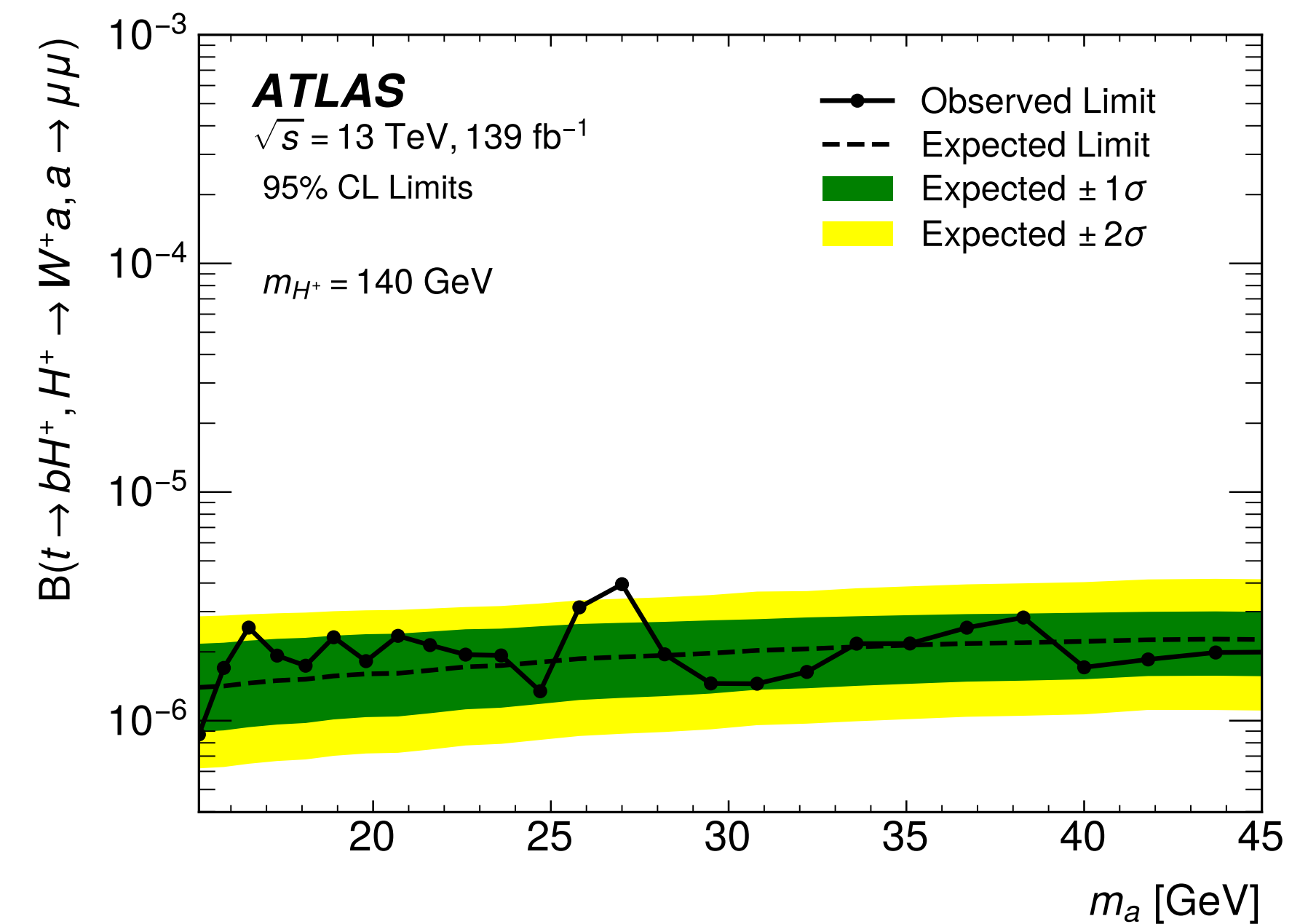
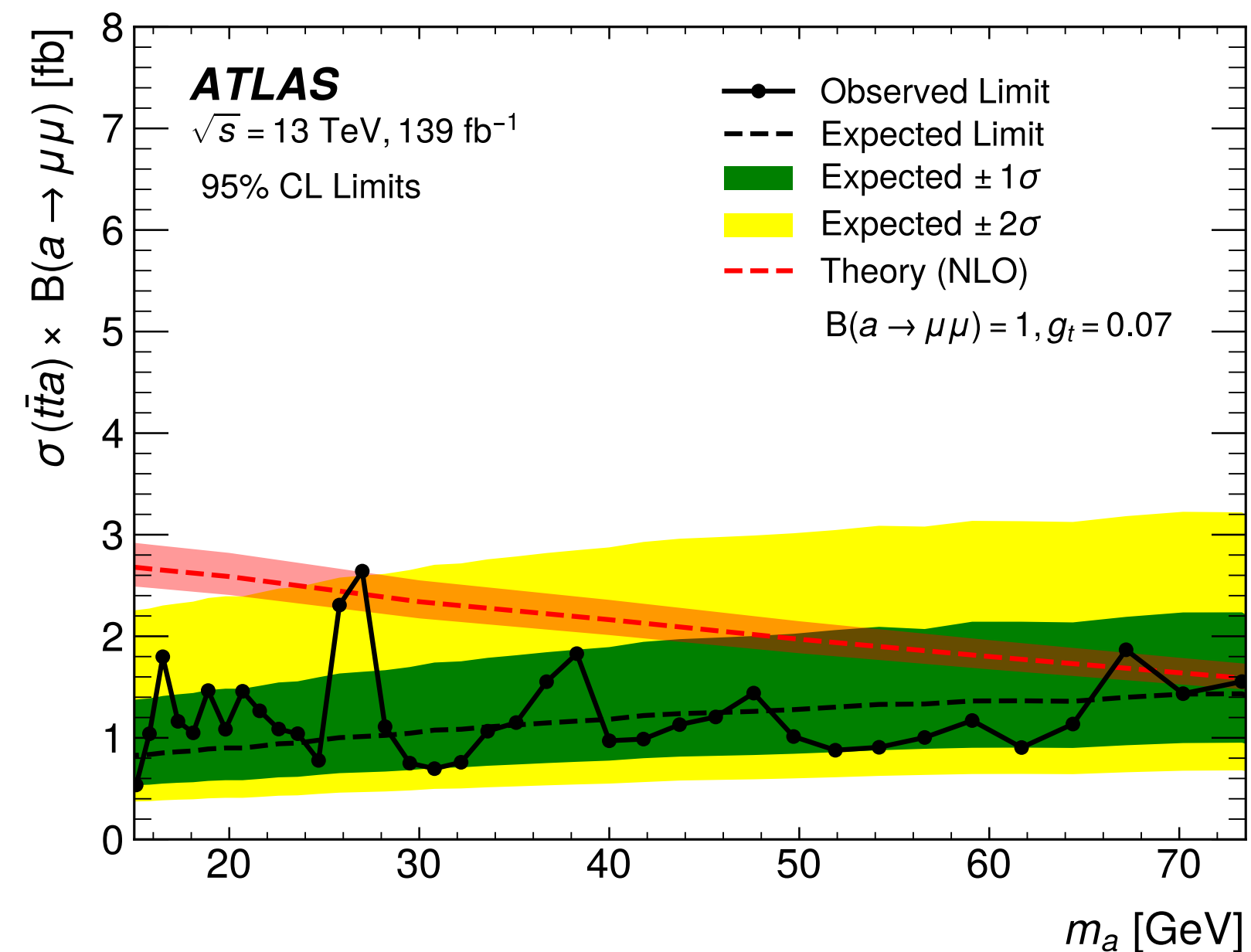
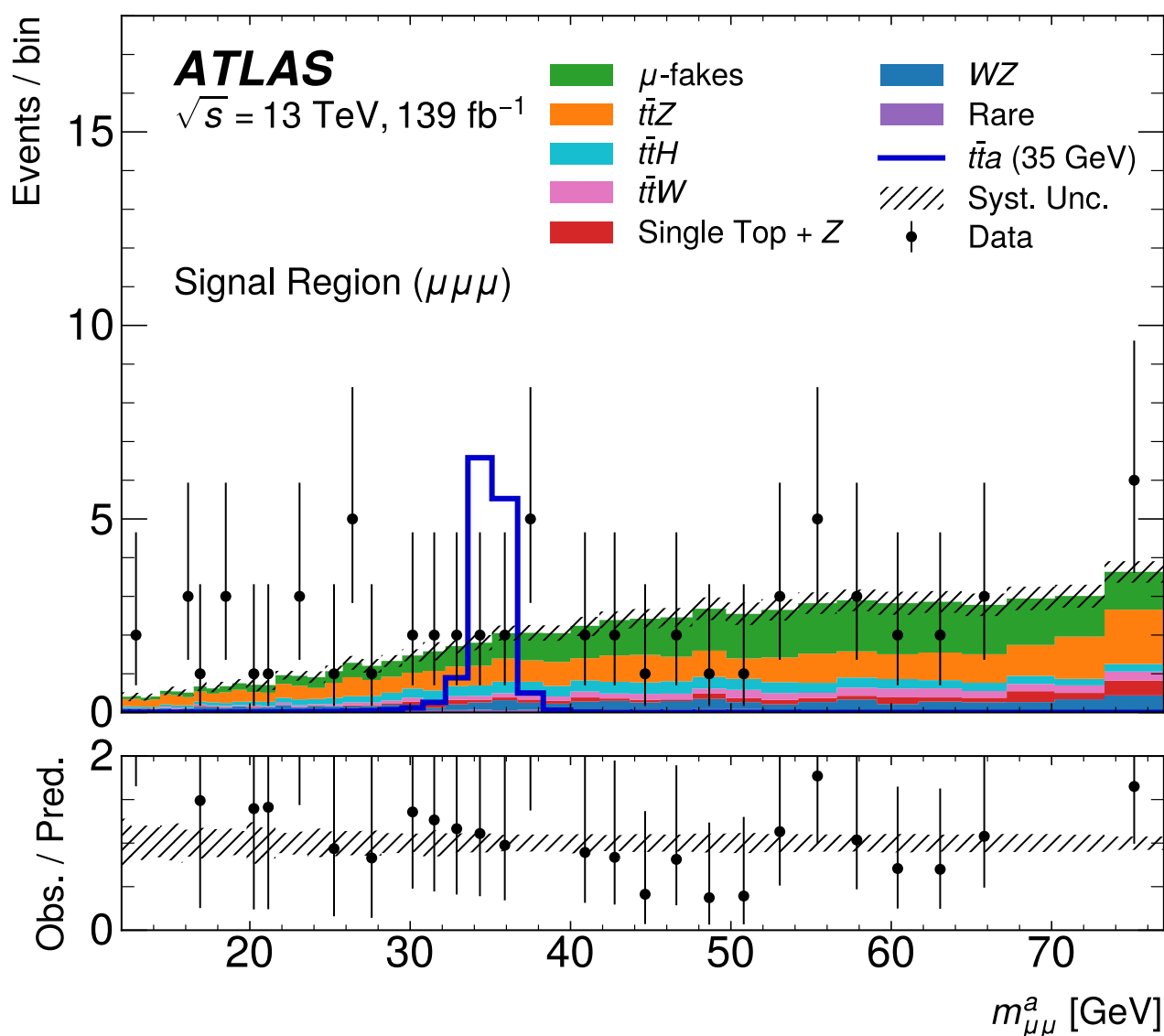
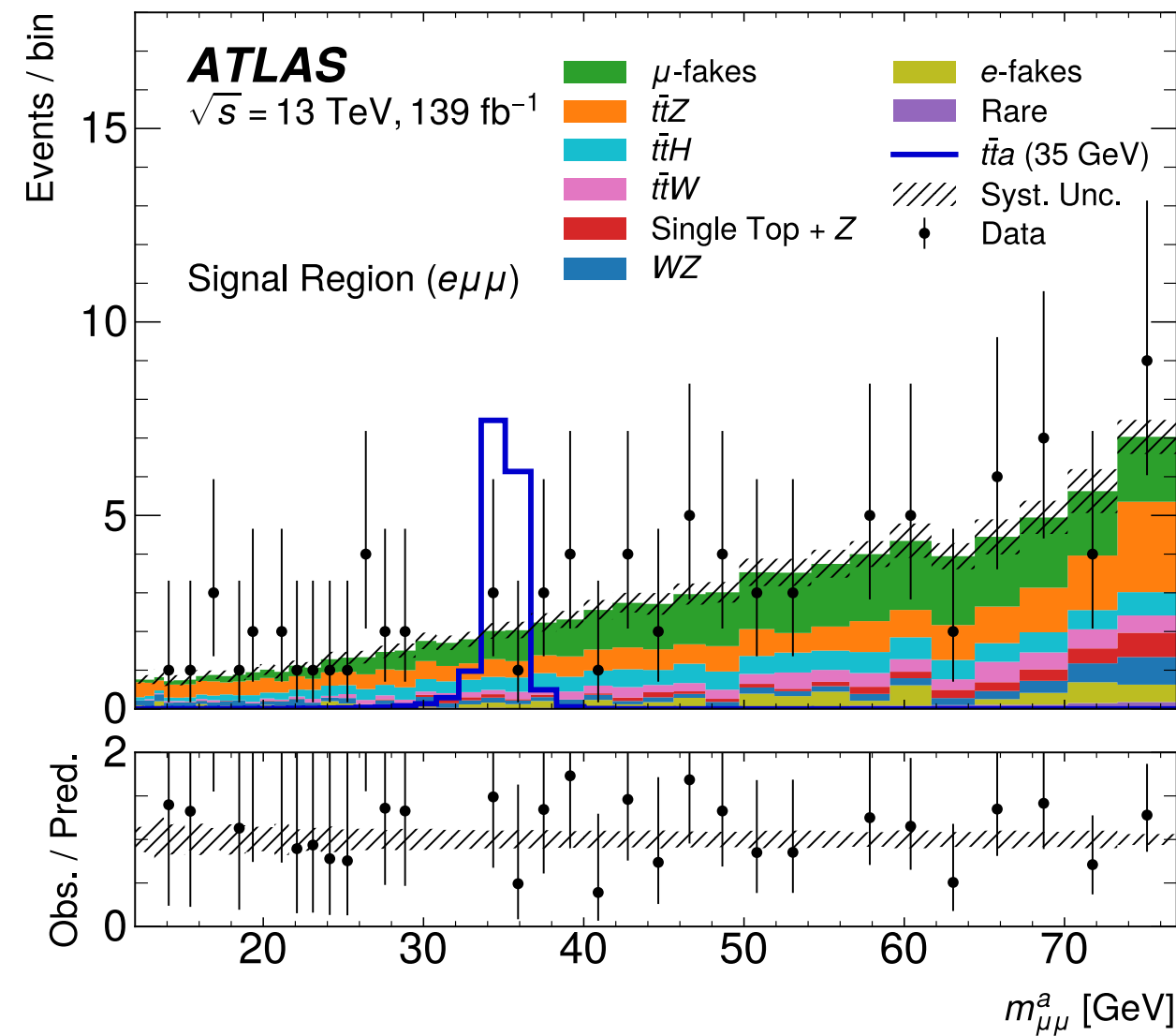


# $t\bar{t}a, a \rightarrow \mu\mu$

arXiv:2304.14247 (Sub. to PRD)

Search for light pseudo-scalar Higgs bosons produced in association with a top-quark pair and decaying in  $\mu\mu$

- Di-muon invariant mass used as final discriminant variable in the SRs
- Upper limits set on  $\sigma(t\bar{t}a) \times BR(a \rightarrow \mu\mu)$  and on  $BR(t \rightarrow bH^+) \times BR(H^+ \rightarrow W^+a) \times BR(a \rightarrow \mu\mu)$  as a function of  $m_a$  (for 3 values of  $m_{H^+} = 120, 140, 160$  GeV) from fit of all SRs and CRs
- No significant excess above the SM predictions observed
- Mild excess observed in both channels at  $m_a = 27$  GeV with local significance of  $2.4\sigma$



# Summary and outlook

Vast program of searches for additional neutral Higgs bosons in ATLAS motivated by many BSM models

Searches with full LHC Run 2 dataset covering several production modes and final states and covering broad mass range

→ Improved sensitivity compared to previous searches thanks to larger dataset and improved analysis techniques

→ Previously uncovered final states and mass ranges probed

No significant deviations from the SM observed so far

LHC Run 3 data-taking is ongoing, stay tuned for new results in the future!



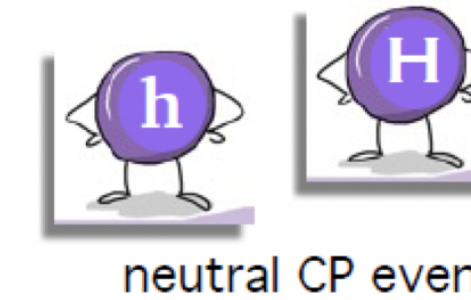
**Thank you for your attention!**

**Back-up slides**

# Why searching for additional neutral Higgs bosons?

- Many extensions of the SM introduce additional fields that produce additional physical Higgs bosons, for example:

- **Electroweak Singlet Model**: SM Higgs doublet + additional singlet  
→ 2 neutral CP even Higgs bosons

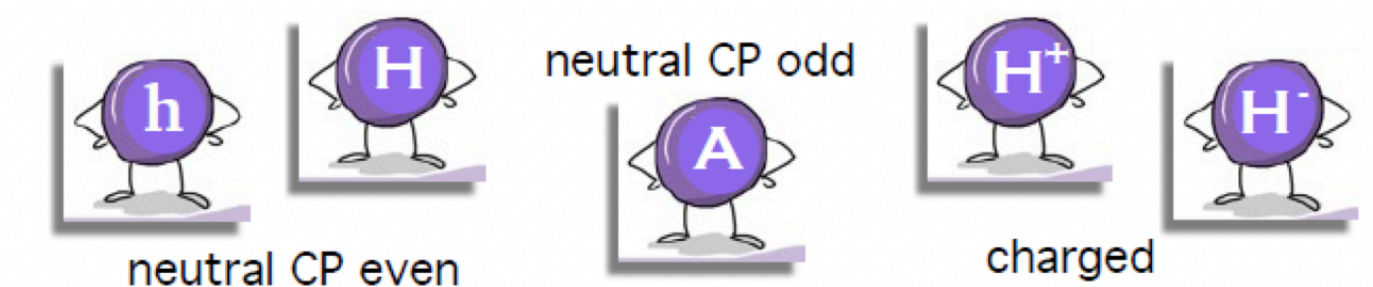


- **Two Higgs Doublet Model (2HDM, e.g. MSSM)**: SM Higgs doublet + additional doublet

→ 5 Higgs bosons: 2 neutral CP even, 1 neutral CP odd and two charged

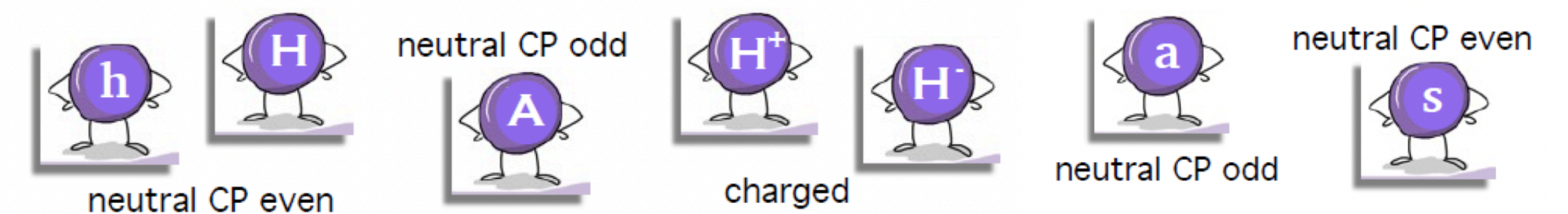
2HDM Type-I: all quarks and leptons couple to only one doublet

2HDM Type-II (MSSM-like): one doublet couples to up-type quarks, the other to down-type quarks and leptons



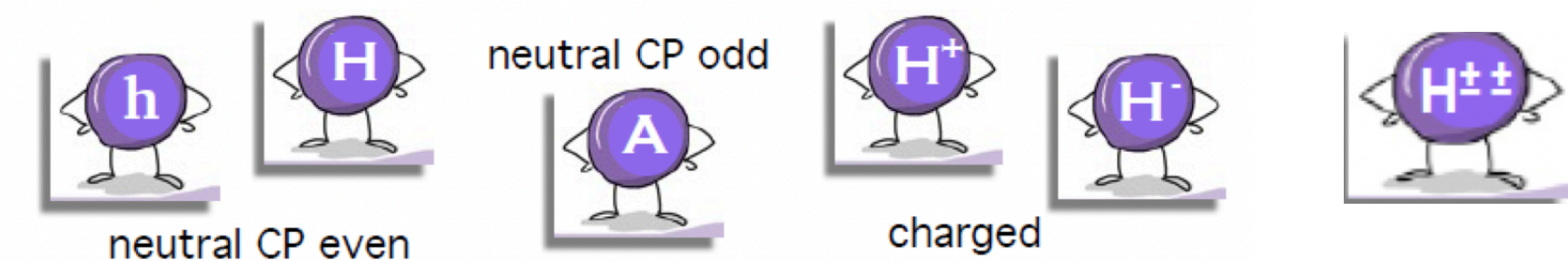
- **2HDM + singlet (e.g. NMSSM)**: SM Higgs doublet + additional doublet + additional singlet

→ 7 Higgs bosons: 5 of the 2HDM + 2 additional neutral (1 CP even and 1 CP odd)



- **Higgs triplet model**: SM Higgs doublet + additional triplet

→ 7 Higgs bosons: 5 of the 2HDM + 2 additional double charged



- **Georgi-Machacek model (GM)**: SM Higgs doublet + 2 additional triplets

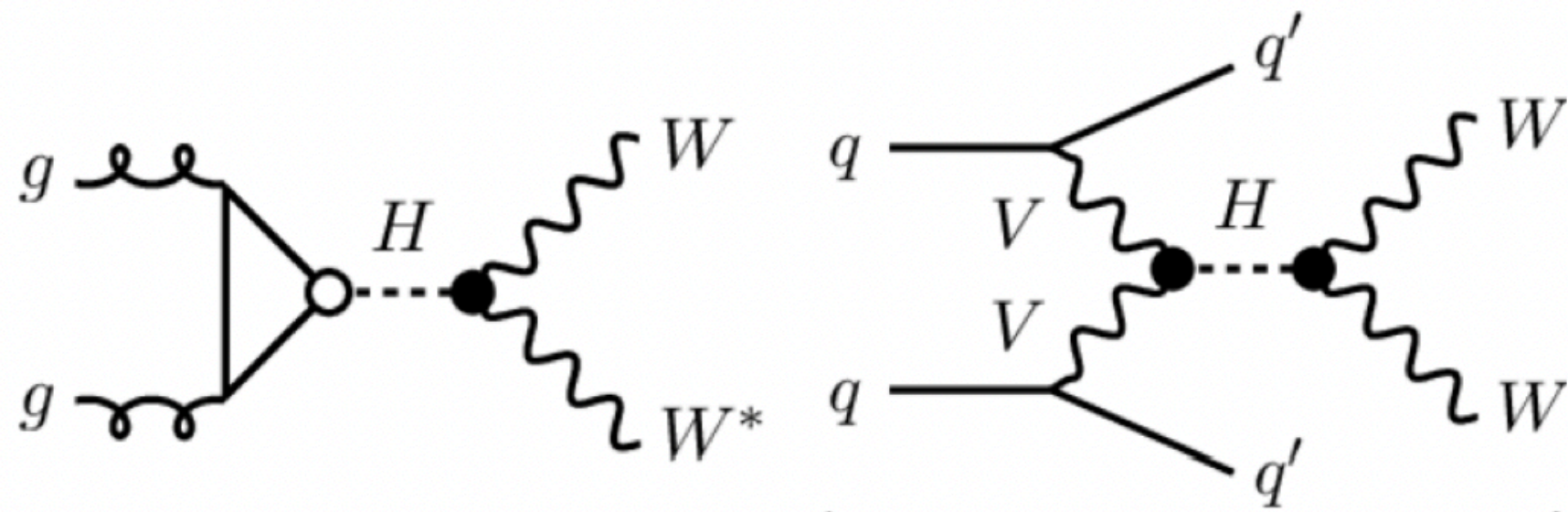
→ 10 Higgs bosons



# Heavy $H \rightarrow WW \rightarrow e\nu\mu\nu$

Search for heavy resonances decaying to  $WW$  in  $e\nu\mu\nu$  final states

[ATLAS-CONF-2022-066](#)



- Heavy resonances in the mass range 300-4000 GeV
- Resonances produced via ggF and VBF and decaying to  $WW$   
 → Analysis performed in the  $e\nu\mu\nu$  final state

Interpretations of the results with heavy resonances from 5 different models, two of them being extended Higgs sectors models:

- [Two Higgs Doublet Model \(2HDM, NWA\)](#)
- [Georgi-Machacek model \(GM\)](#): include a fermiophobic Higgs 5-plet (that can only produced via VBF mode)

Model	Resonance spin	Production mode		
		ggF	qqA	VBF
NWA	Spin-0	x		x
GM				x
Radion		x		x
HVT	Spin-1		x	x
RS $G_{KK}^*$	Spin-2	x		x

3 Signal Region (SR) categories defined based on the number of reconstructed VBF jets:

- VBF 1jet: 1 VBF jet
- VBF 2jets: at least 2 VBF jets
- ggF: all events not going into VBF 1jet or VBF 2jets

4 Control Region (CR) categories for controlling  $WW$  and Top backgrounds, defined based on:

- Number of reconstructed VBF jets
- Number of b-jets
- $|\Delta\eta_{\ell,\ell}|$  requirements

# Heavy $H \rightarrow WW \rightarrow e\nu\mu\nu$

Search for heavy resonances decaying to  $WW$  in  $e\nu\mu\nu$  final states

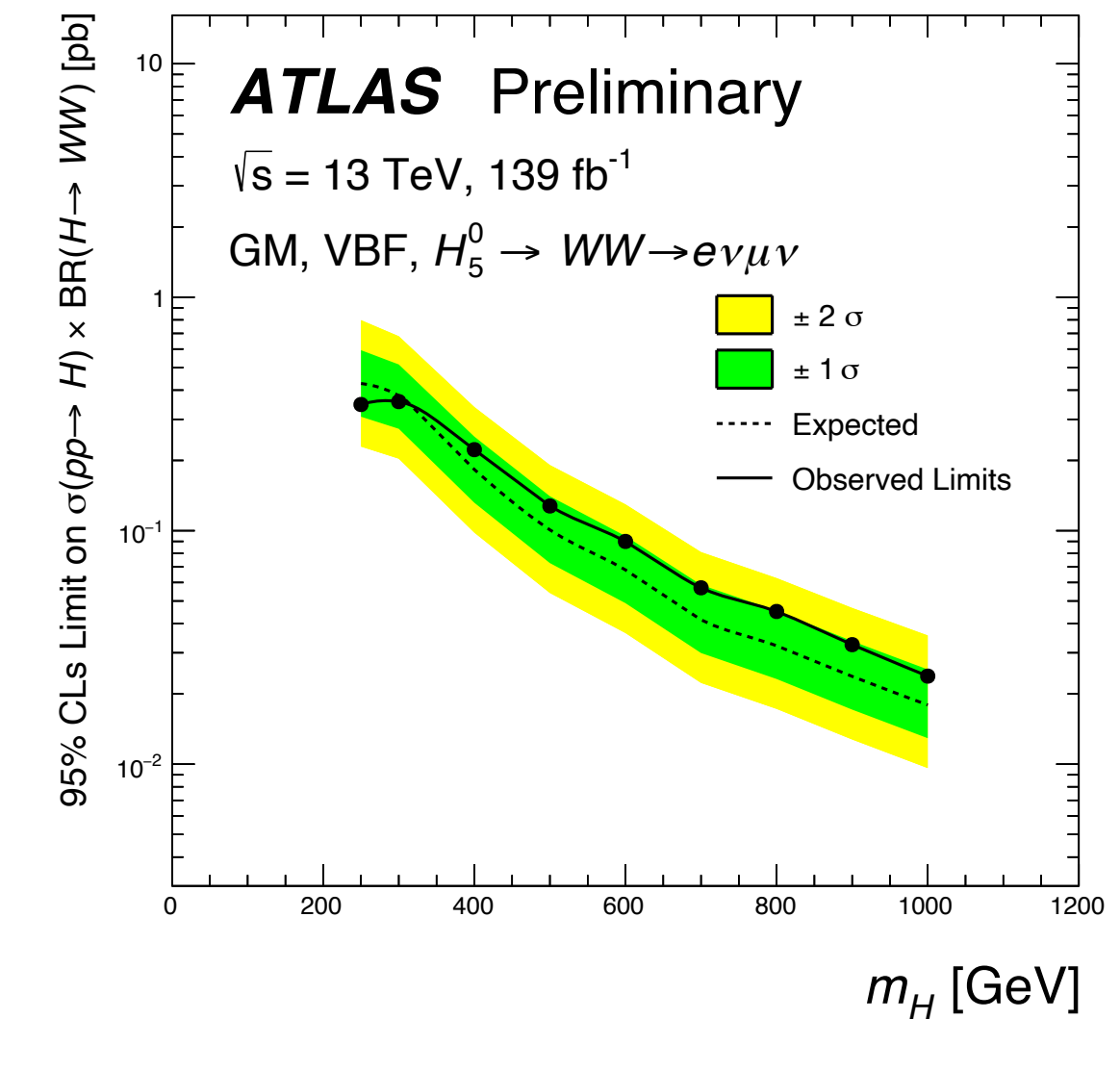
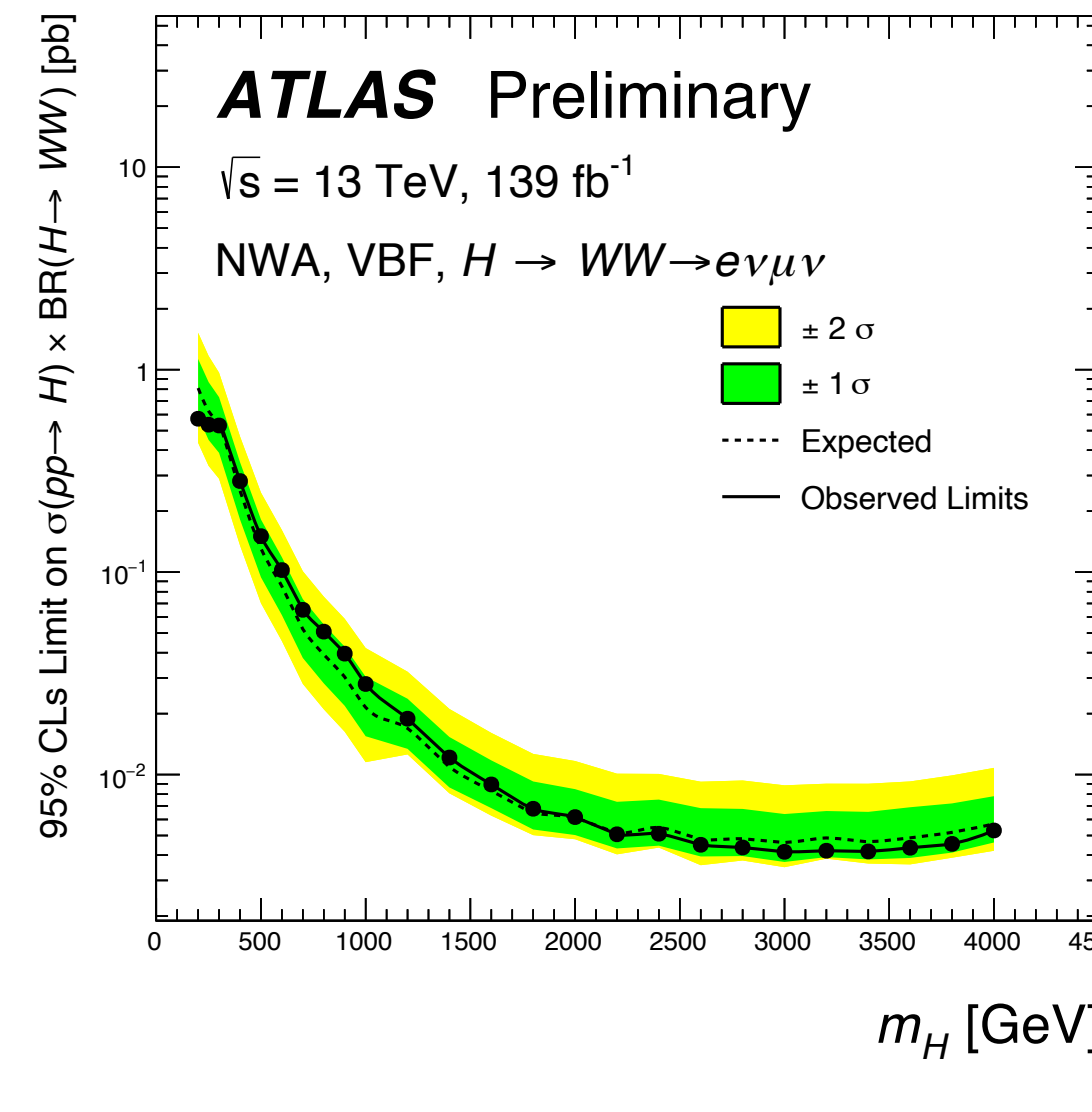
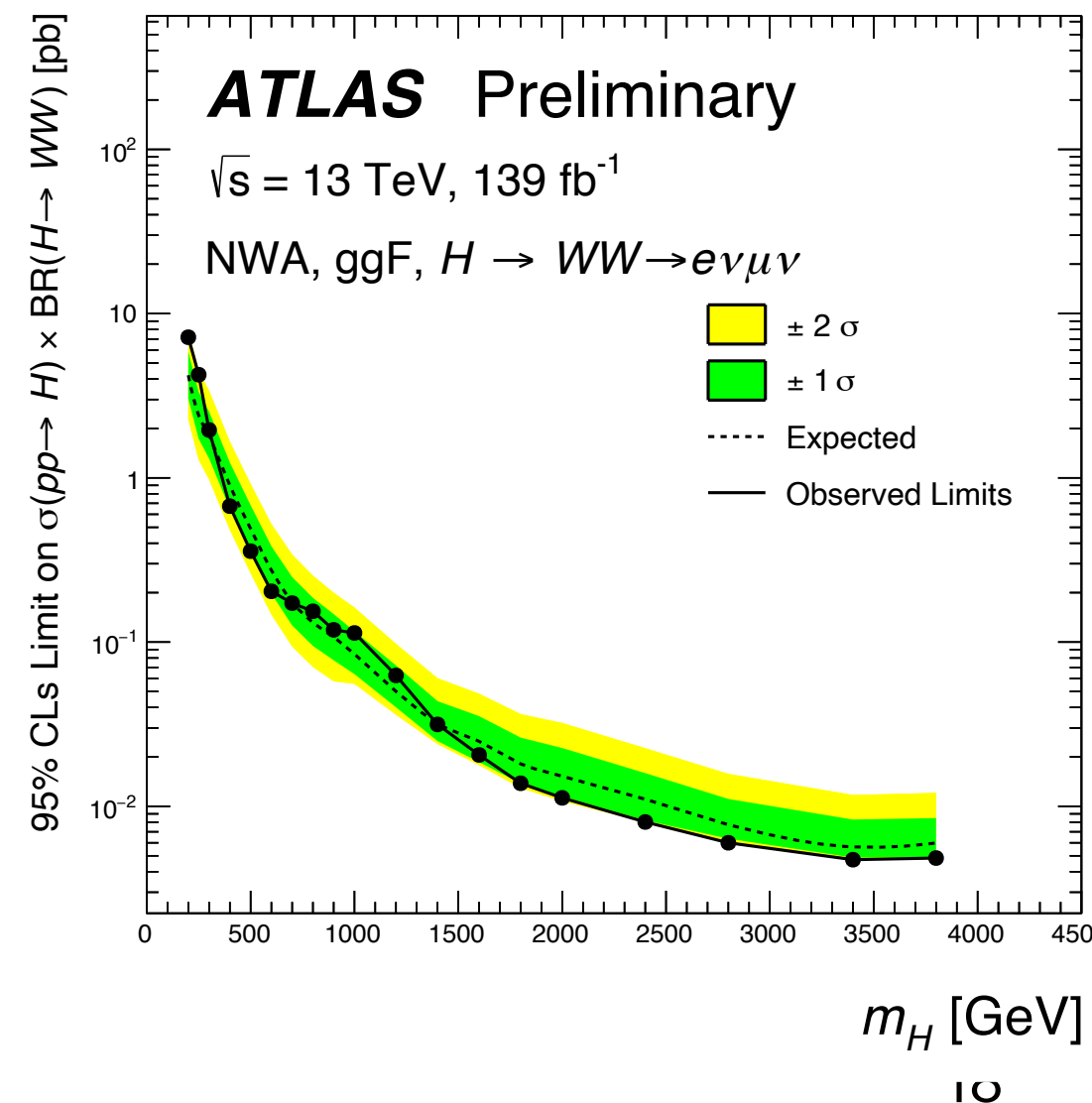
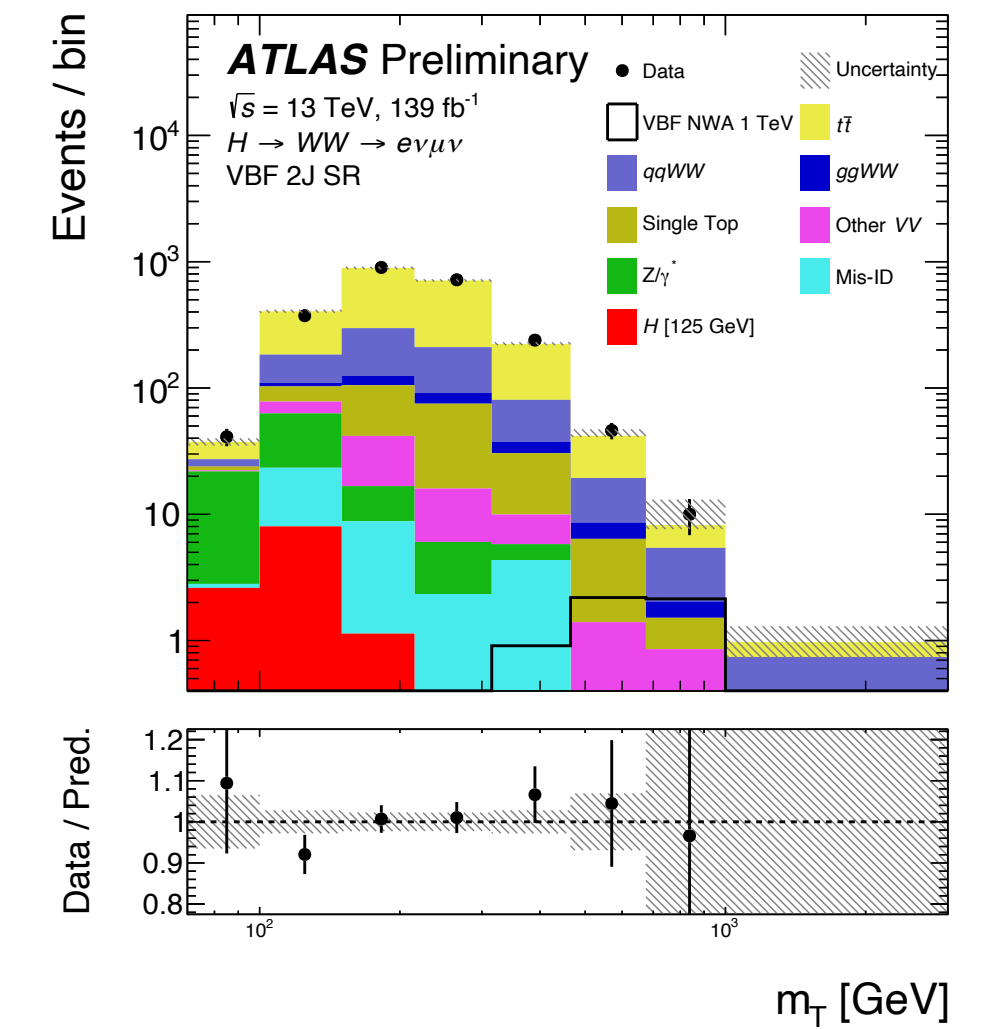
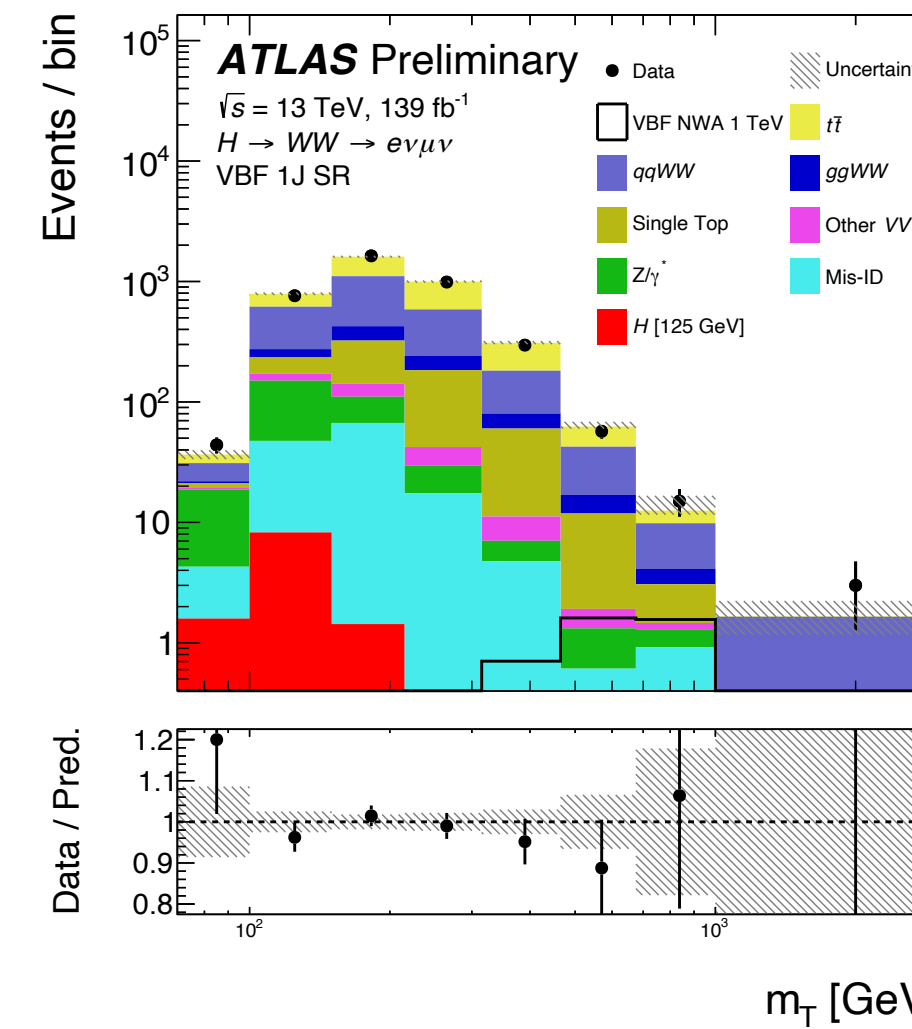
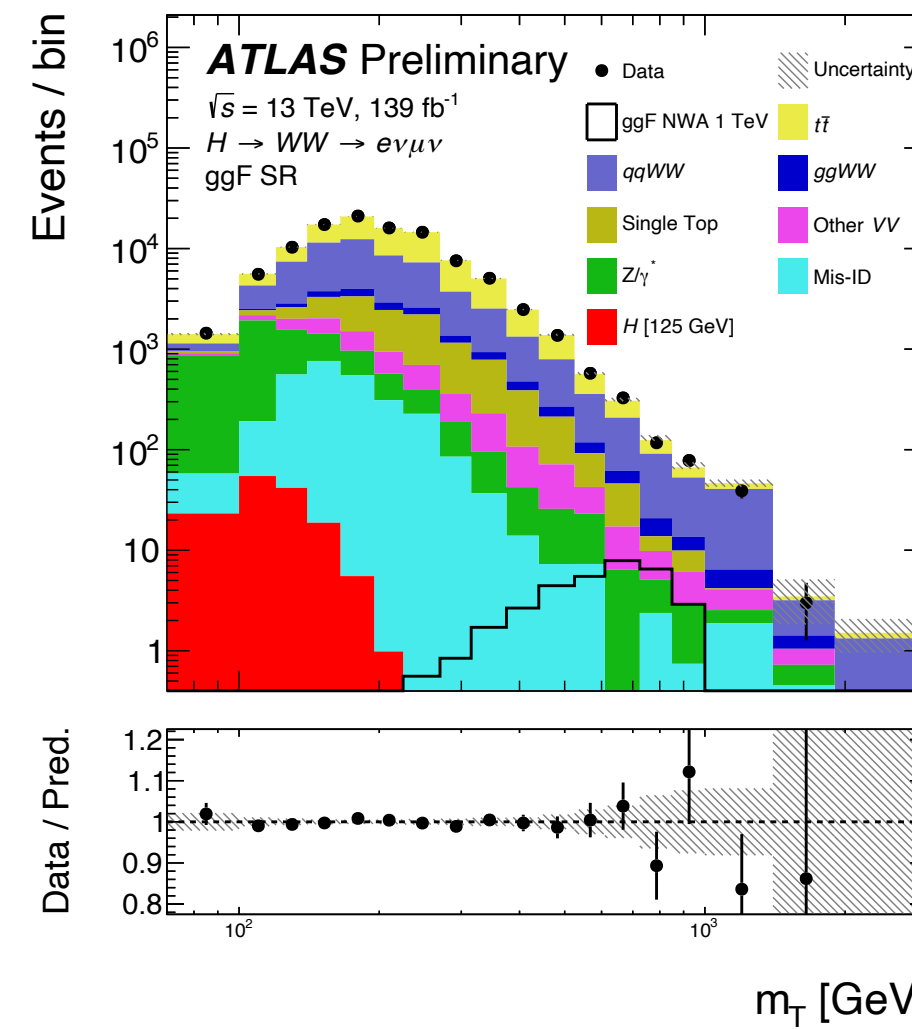
[ATLAS-CONF-2022-066](#)

- Final discriminant variable in all SRs is the transverse mass  $m_T$ :

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

$$\text{with } E_T^{\ell\ell} = \sqrt{|\vec{p}_T^{\ell\ell}|^2 + m_{\ell\ell}^2}$$

- Upper limits set on  $\sigma \times BR$  as a function of  $m_H$  from fit of all SRs and CRs for the different models considered
- No significant excess above the SM predictions observed



# Heavy $H \rightarrow WW \rightarrow e\nu\mu\nu$

Search for heavy resonances decaying to WW in  $e\nu\mu\nu$  final states

[ATLAS-CONF-2022-066](#)

## 3 Signal Region categories:

- VBF 1jet: 1 VBF jet
- VBF 2jets: at least 2 VBF jets
- ggF: all events not going into VBF 1jet or VBF 2jets

## 4 Control Region categories for controlling WW and Top backgrounds defined based on:

- Number of reconstructed VBF jets
- Number of b-jets
- $|\Delta\eta_{\ell,\ell}|$  requirements

### Signal regions

Pre-Selection		
Two Different Flavour, Opposite Sign Leptons, $p_T^\ell > 25$ GeV		
Third lepton veto, $p_T^\ell > 15$ GeV		
Common Selection		
$N_{b\text{-tag}} = 0$		
$ \Delta\eta_{\ell\ell}  < 1.8$		
$m_{\ell\ell} > 55$ GeV		
$p_T^{\ell,\text{lead}} > 45$ GeV		
$p_T^{\ell,\text{sublead}} > 30$ GeV		
$\max(m_T^W) > 50$ GeV		
SC <sub>ggF</sub>	SC <sub>VBF1J</sub>	SC <sub>VBF2J</sub>
Inclusive in $N_{\text{jet}}$ but excluding SC <sub>VBF1J</sub> and SC <sub>VBF2J</sub>	$N_{\text{jet}} = 1$ and $ \eta_j  > 2.4$ , $\min( \Delta\eta_{j\ell} ) > 1.75$	$N_{\text{jet}} \geq 2$ and $m_{jj} > 500$ GeV, $ \Delta y_{jj}  > 4$

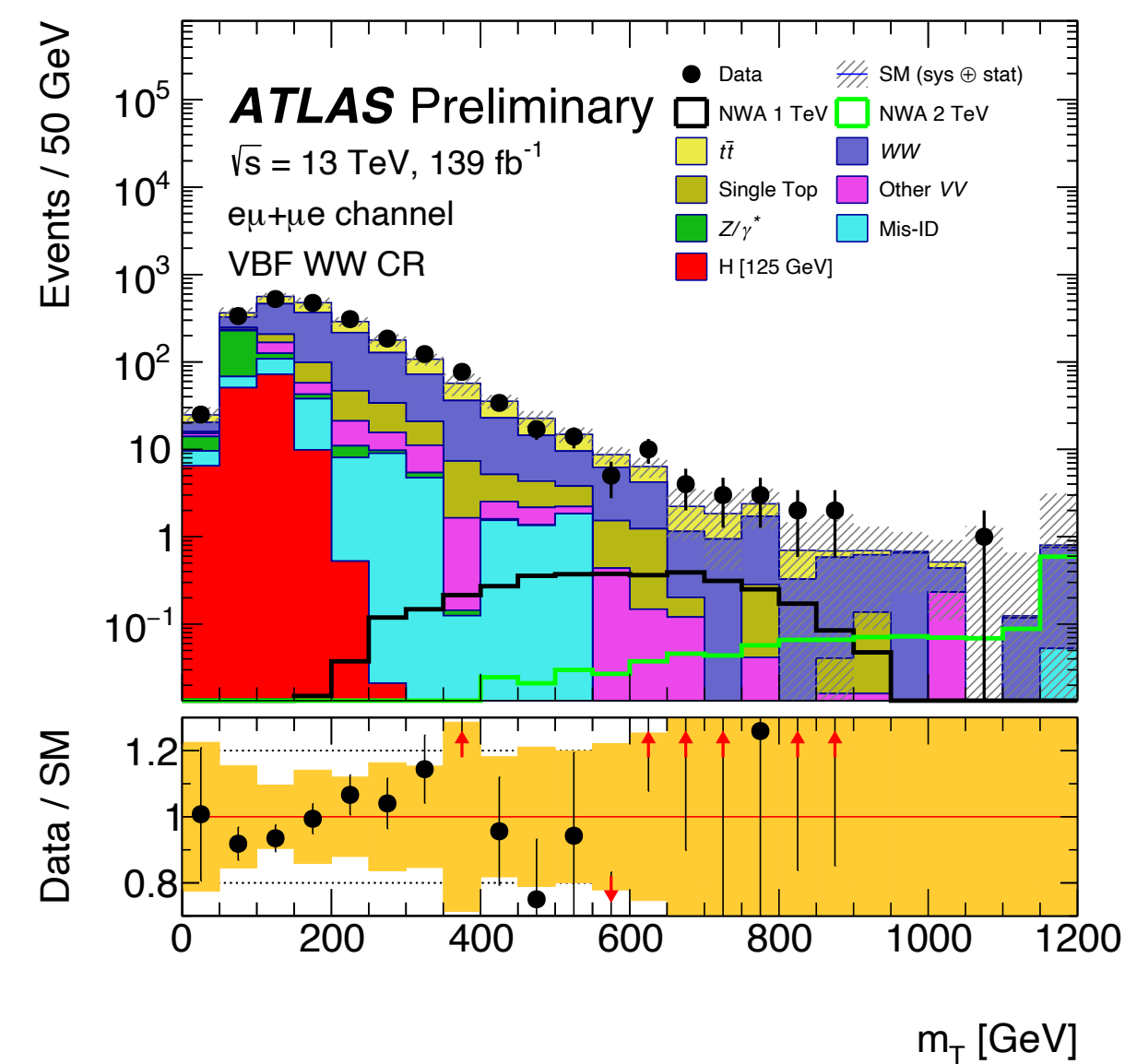
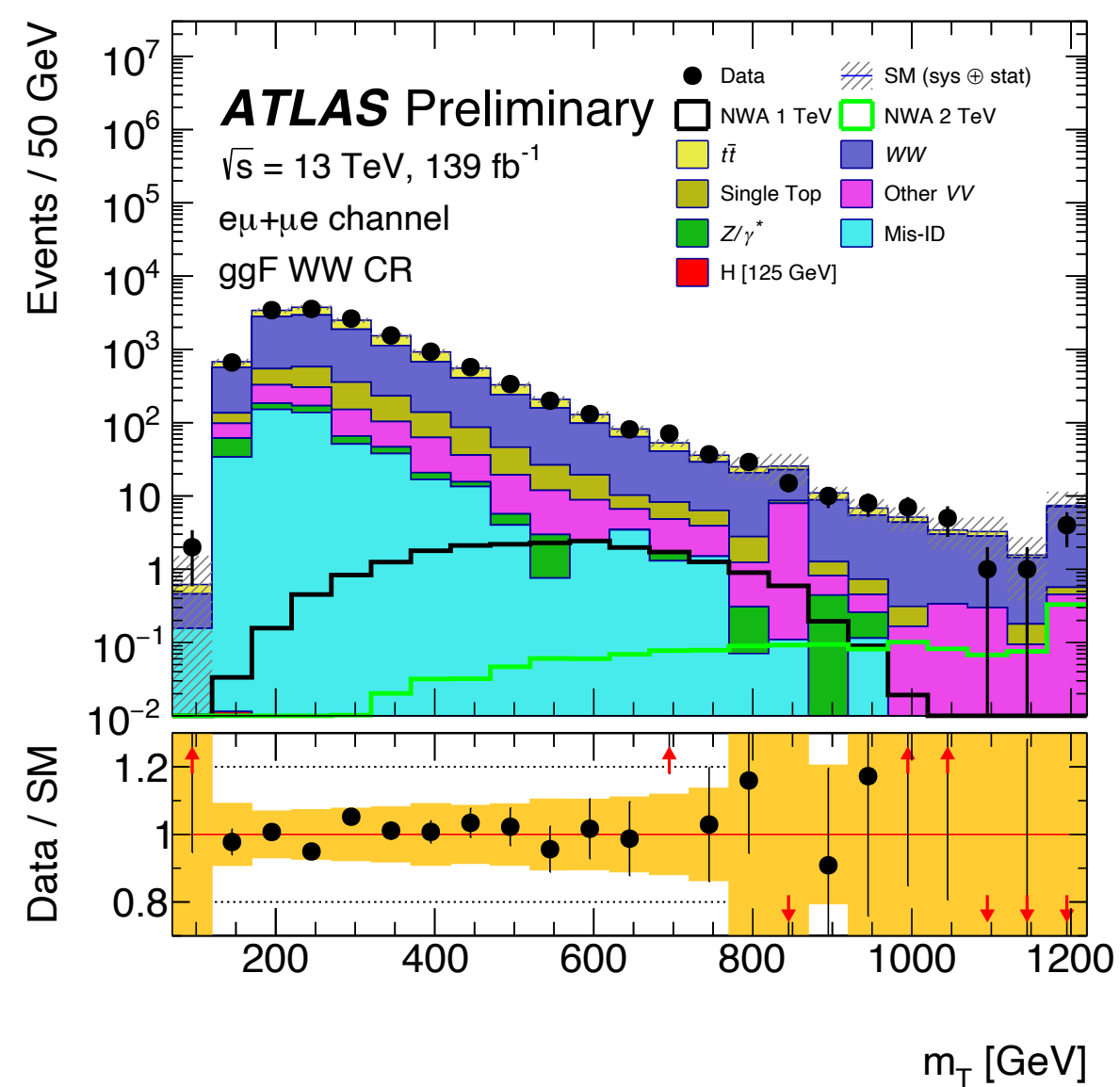
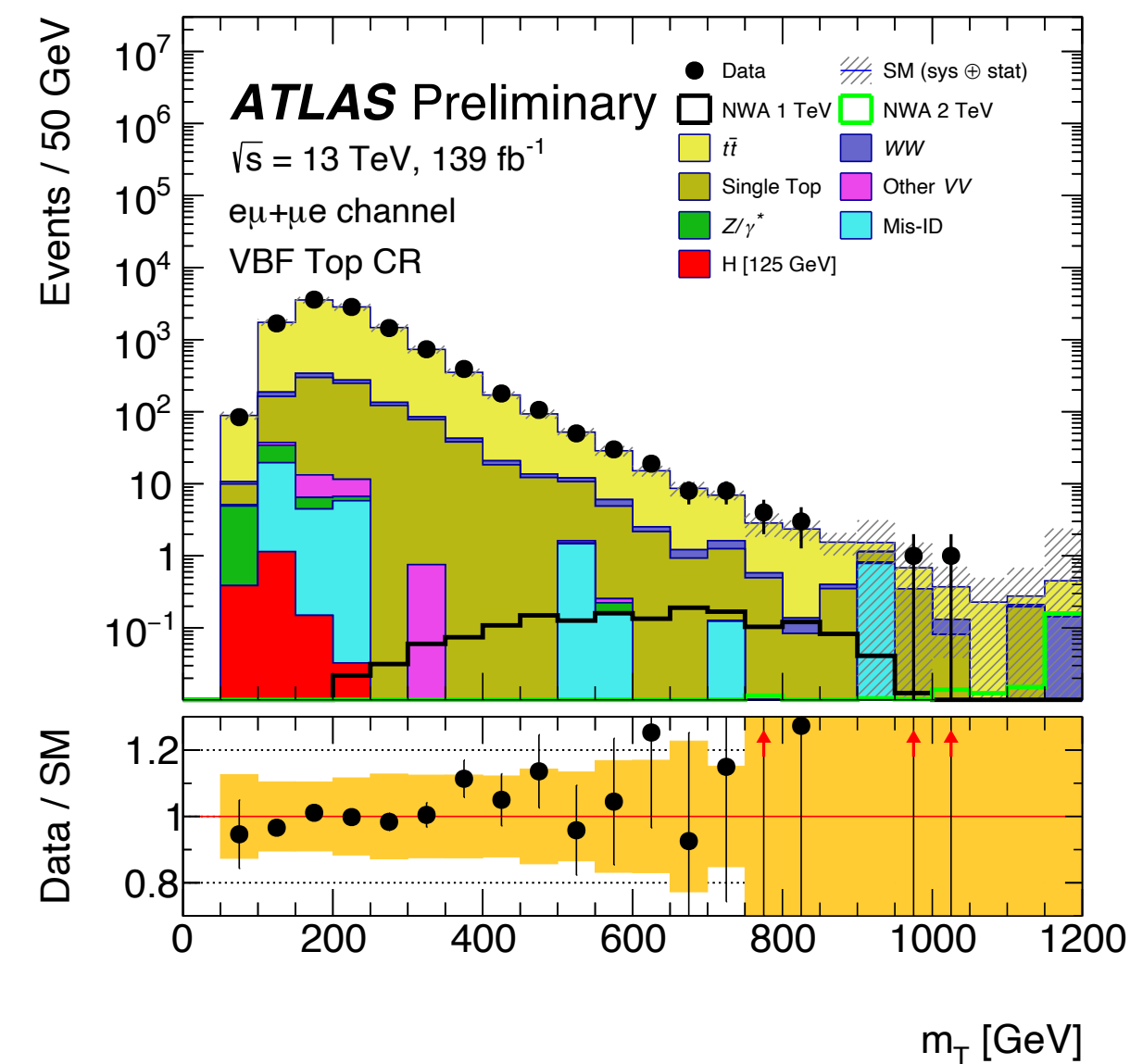
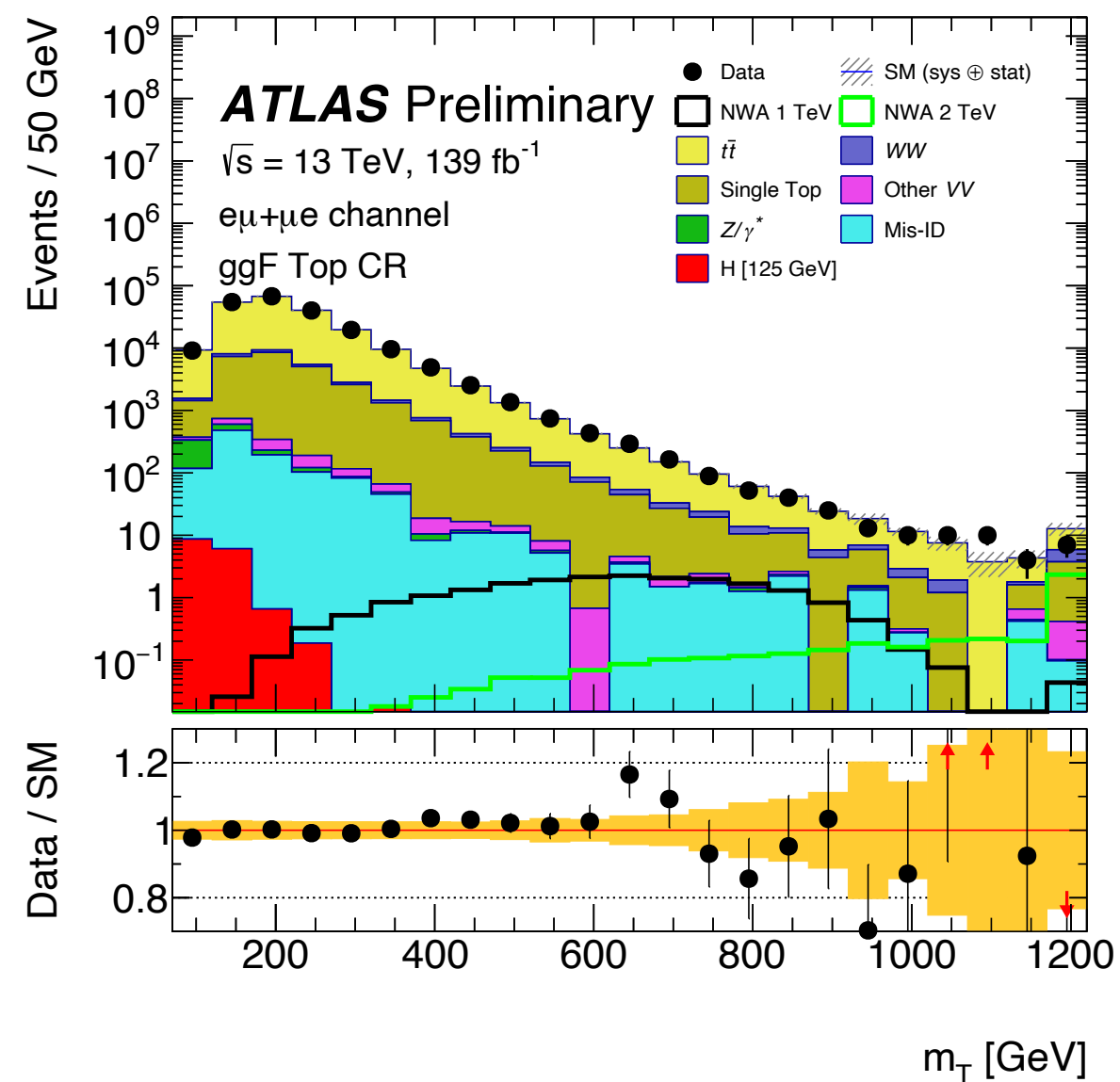
### Control regions

Pre-Selection			
Two Different Flavour, Opposite Sign Leptons, $p_T^\ell > 25$ GeV			
Third lepton veto, $p_T^\ell > 15$ GeV			
WW CR <sub>ggF</sub>	Top CR <sub>ggF</sub>	WW CR <sub>VBF1J</sub>	Top CR <sub>VBF</sub>
$N_{b\text{-tag}} = 0$	$N_{b\text{-tag}} = 1$	$N_{b\text{-tag}} = 0$	$N_{b\text{-tag}} \geq 1$
$ \Delta\eta_{\ell\ell}  > 1.8$	$ \Delta\eta_{\ell\ell}  < 1.8$	$( \Delta\eta_{\ell\ell}  > 1.8$ or $10 \text{ GeV} < m_{\ell\ell} < 55 \text{ GeV})$	$ \Delta\eta_{\ell\ell}  < 1.8$
$m_{\ell\ell} > 55$ GeV			$m_{\ell\ell} > 55$ GeV
$p_T^{\ell,\text{lead}} > 45$ GeV		-	$p_T^{\ell,\text{lead}} > 45$ GeV
$p_T^{\ell,\text{sublead}} > 30$ GeV		-	$p_T^{\ell,\text{sublead}} > 30$ GeV
$\max(m_T^W) > 50$ GeV		-	$\max(m_T^W) > 50$ GeV
METSigRatio $> 0.8 \text{ GeV}^{-1}$	-	-	-
Excluding VBF1/2J phase space		VBF1J phase space	VBF1/2J phase space

# Heavy $H \rightarrow WW \rightarrow e\nu\mu\nu$

Search for heavy resonances decaying to  $WW$  in  $e\nu\mu\nu$  final states

[ATLAS-CONF-2022-066](#)

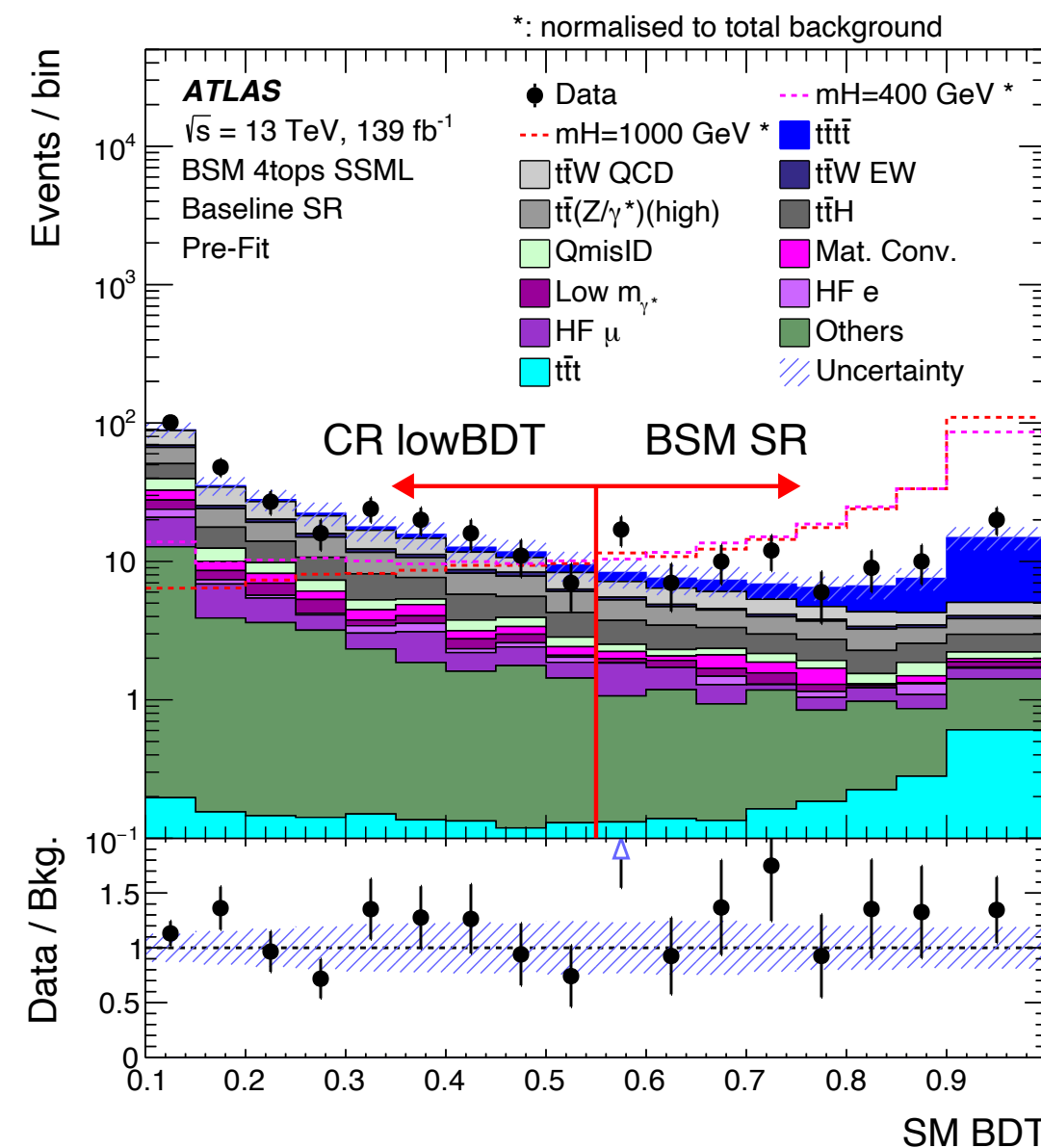


# $ttH/A \rightarrow 4t(2\ell SS/3\ell)$

arXiv:2211.01136

Search for heavy Higgs bosons produced in association with a top-quark pair and decaying in a top-quark pair

- Boosted Decision Tree (BDT) classifier trained to distinguish the SM 4tops events from the rest of the background (SMBDT) and used to define the **Beyond the Standard Model Signal Region (BSM SR)** and a **low-BDT Control Region (lowBDT CR)** by applying a cut on this BDT output
- **Other 4 Control Region (CR) categories** for controlling HF non-prompt leptons, photon conversion, and ttW, defined based on different requirements on:
  - Flavour and charge of the leptons
  - Number of jets and b-jets



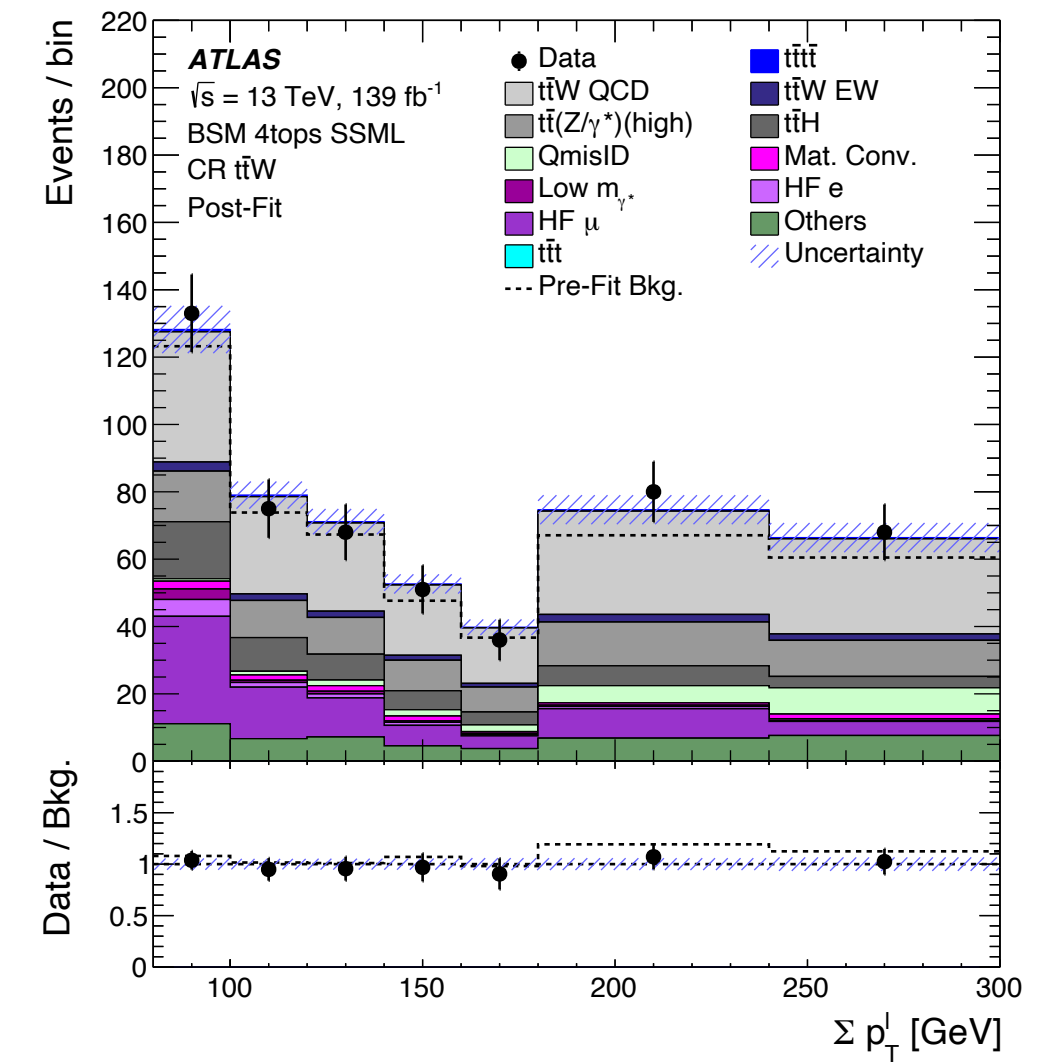
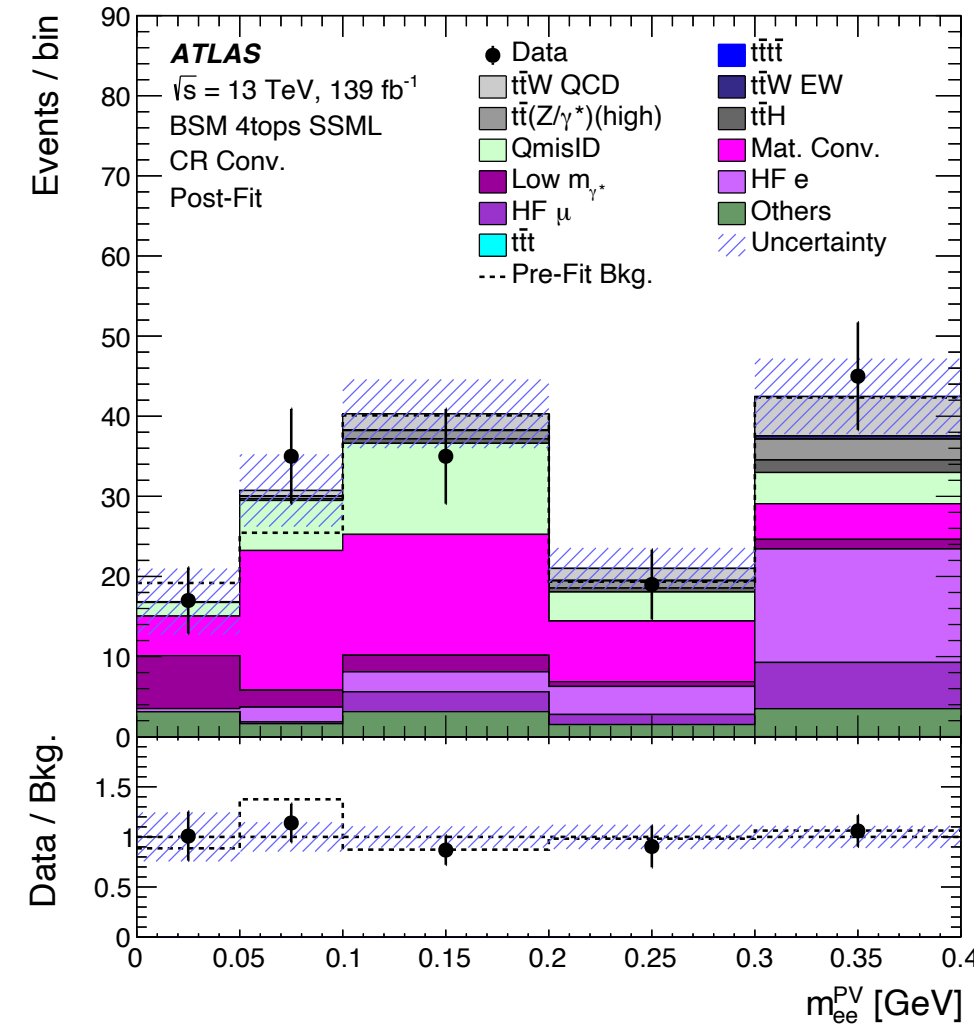
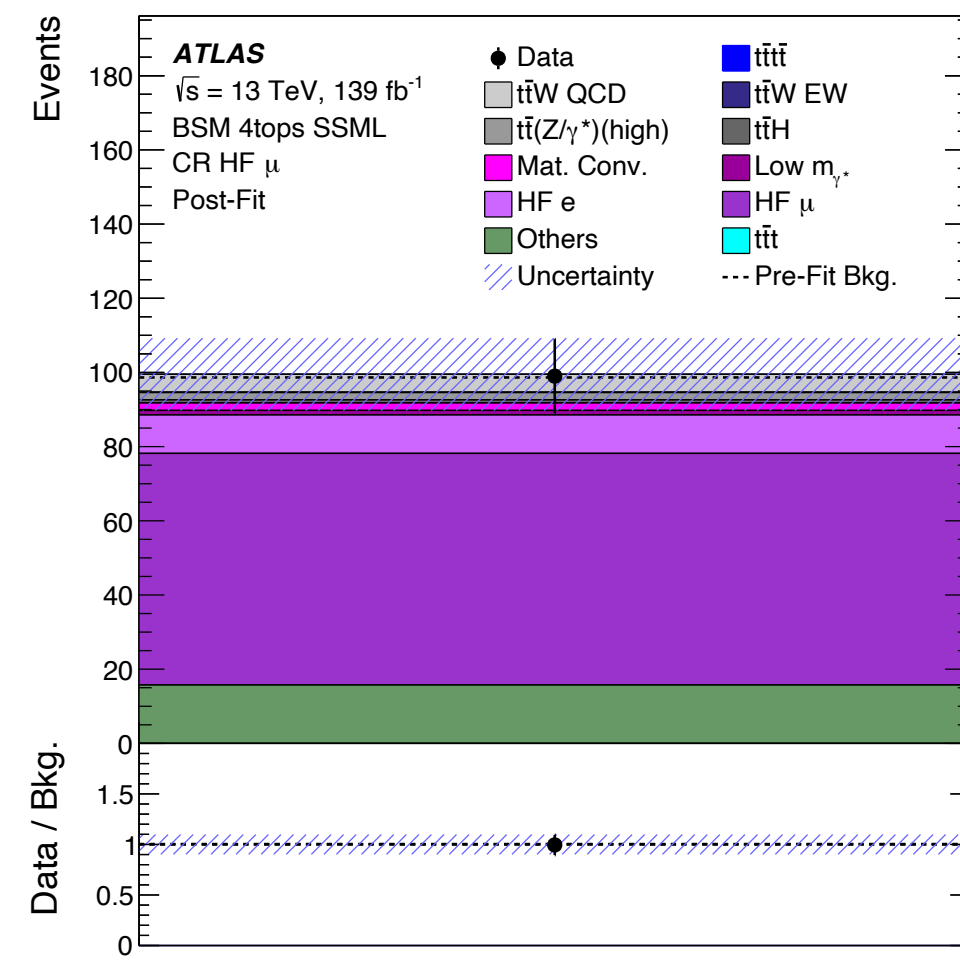
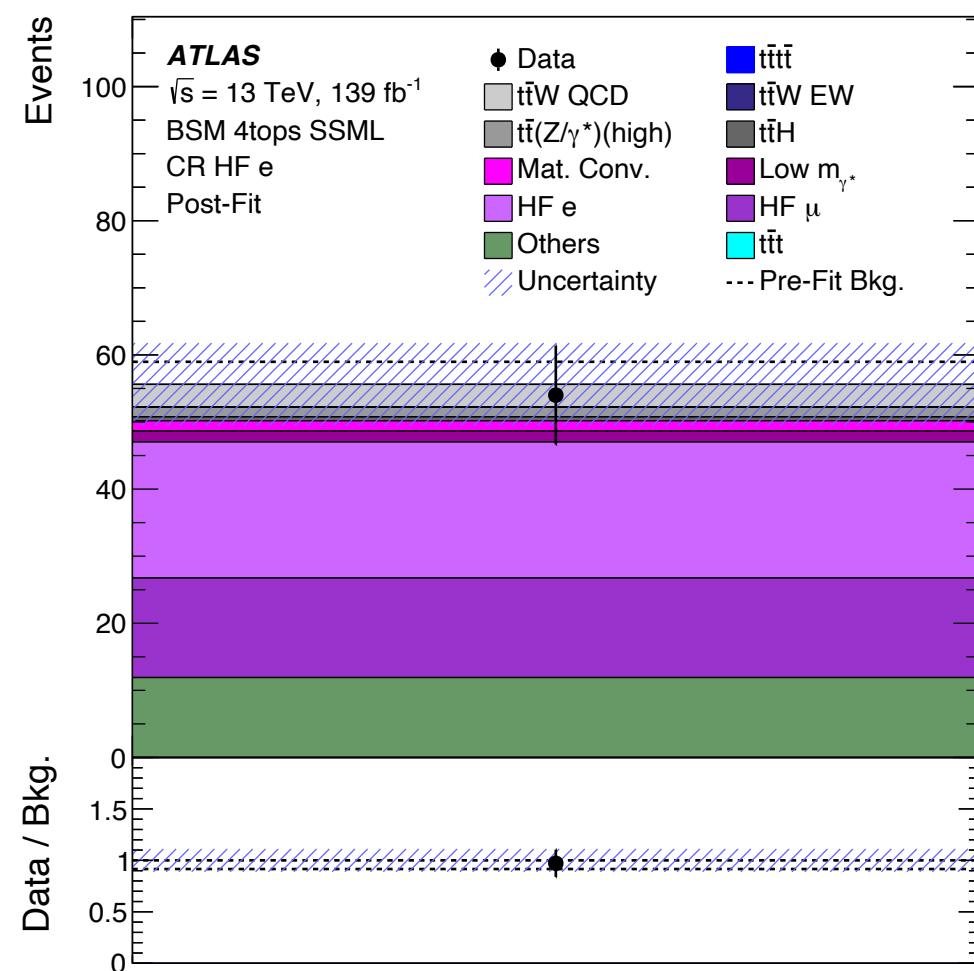
Signal Region and Control Regions

Region	Channel	$N_j$	$N_b$	Other selection requirements	Fitted variable
CR Conv	$e^\pm e^\pm \parallel e^\pm \mu^\pm$	$4 \leq N_j < 6$	$\geq 1$	$m_{ee}^{CV} \in [0, 0.1] \text{ GeV}$ $200 < H_T < 500 \text{ GeV}$	$m_{ee}^{PV}$
CR HF e	$eee \parallel ee\mu$		$= 1$	$100 < H_T < 250 \text{ GeV}$	Yield
CR HF $\mu$	$e\mu\mu \parallel \mu\mu\mu$		$= 1$	$100 < H_T < 250 \text{ GeV}$	Yield
CR $t\bar{t}W$	$e^\pm \mu^\pm \parallel \mu^\pm \mu^\pm$	$\geq 4$	$\geq 2$	$m_{ee}^{CV} \notin [0, 0.1] \text{ GeV},  \eta(e)  < 1.5$ for $N_b = 2, H_T < 500 \text{ GeV}$ or $N_j < 6$ ; for $N_b \geq 3, H_T < 500 \text{ GeV}$	$\sum p_T^\ell$
CR lowBDT	SS+3L	$\geq 6$	$\geq 2$	$H_T > 500 \text{ GeV}, \text{SM BDT} < 0.55$	SM BDT
BSM SR	SS+3L	$\geq 6$	$\geq 2$	$H_T > 500 \text{ GeV}, \text{SM BDT} \geq 0.55$	BSM pBDT

# $ttH/A \rightarrow 4t(2\ell SS/3\ell)$

Search for heavy Higgs bosons produced in association with a top-quark pair and decaying in a top-quark pair

- Boosted Decision Tree (BDT) classifier trained to distinguish the SM 4tops events from the rest of the background (SMBDT) and used to define the **Beyond the Standard Model Signal Region (BSM SR)** and a **low-BDT Control Region (lowBDT CR)** by applying a cut on this BDT output
- **Other 4 Control Region (CR) categories** for controlling HF non-prompt leptons, photon conversion, and ttW, defined based on different requirements on:
  - Flavour and charge of the leptons
  - Number of jets and b-jets



$$ttH/A \rightarrow 4t(2\ell SS/3\ell)$$

[arXiv:2211.01136](https://arxiv.org/abs/2211.01136)

Search for heavy Higgs bosons produced in association with a top-quark pair and decaying in a top-quark pair

- Boosted Decision Tree (BDT) classifier trained to distinguish the SM 4tops events from the rest of the background (SMBDT) and used to define the **Beyond the Standard Model Signal Region (BSM SR)** and a **low-BDT Control Region (lowBDT CR)** by applying a cut on this BDT output
- **Mass-parameterised BDT (BSM pBDT)** trained in the SR to distinguish between the signal and all backgrounds and used as final discriminant variable in the SR

#### Input variables for the SM BDT

- Jet multiplicity
- Pseudo-continuous b-tagging score of the b-jets
- Minimum DeltaR between two leptons among all pairs
- pt of leptons and jets, MET
- Scalar sum of pt of all objects
- DeltaR of two leptons for all possible pairs
- Maximum DeltaR between a b-jet and a lepton among all pairs
- Minimum DeltaR between a jet and a b-jet among all pairs

#### Input variables for the BSM pBDT

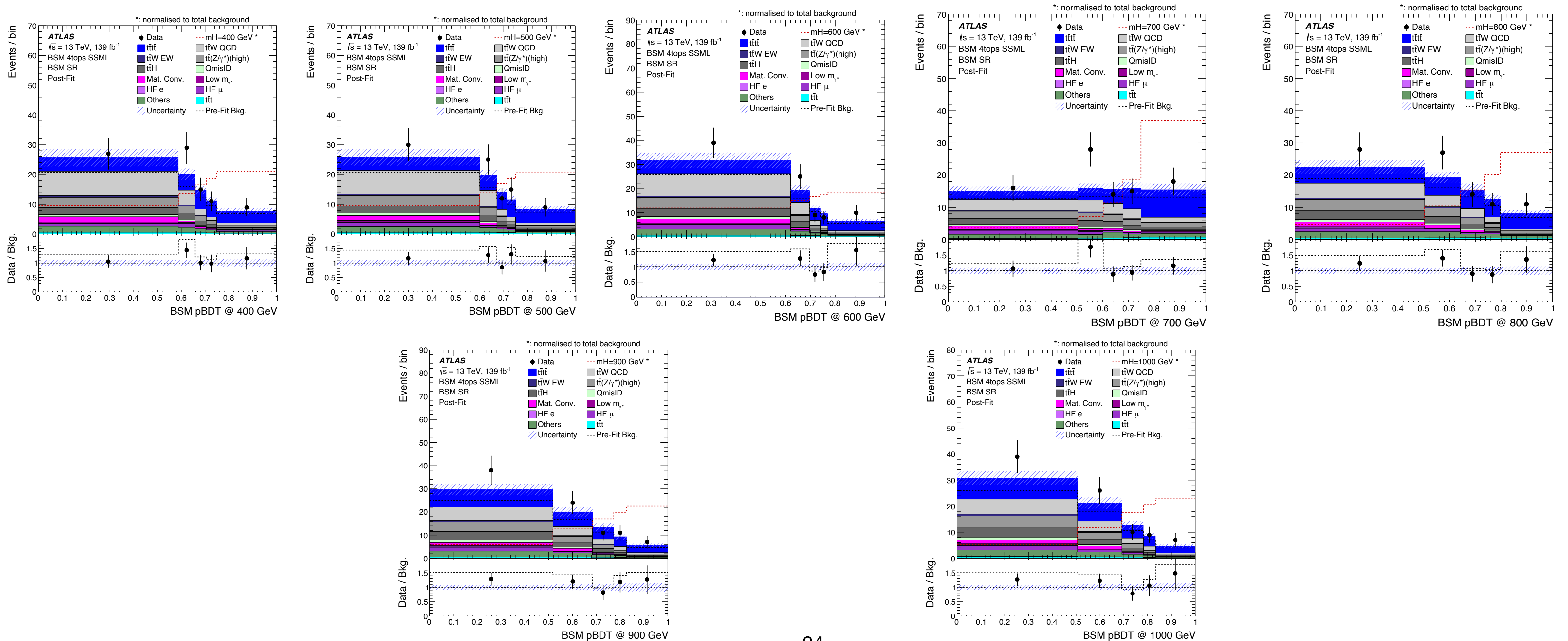
- SM BDT output (most important)
- ...

# $ttH/A \rightarrow 4t(2\ell SS/3\ell)$

arXiv:2211.01136

Search for heavy Higgs bosons produced in association with a top-quark pair and decaying in a top-quark pair

- Mass-parameterised BDT (BSM pBDT) trained in the SR to distinguish between the signal and all backgrounds and used as final discriminant variable in the SR





# $A \rightarrow ZH \rightarrow \ell\ell tt/\nu\nu bb$

Search for a heavy CP-odd Higgs boson (A) decaying to a heavy CP-even Higgs Boson (H) and a Z in the  $\ell\ell tt/\nu\nu bb$  channels

3 Signal Region categories defined based on requirements on the number of leptons, jets, b-jets, MET, reconstructed Z and H boson masses:

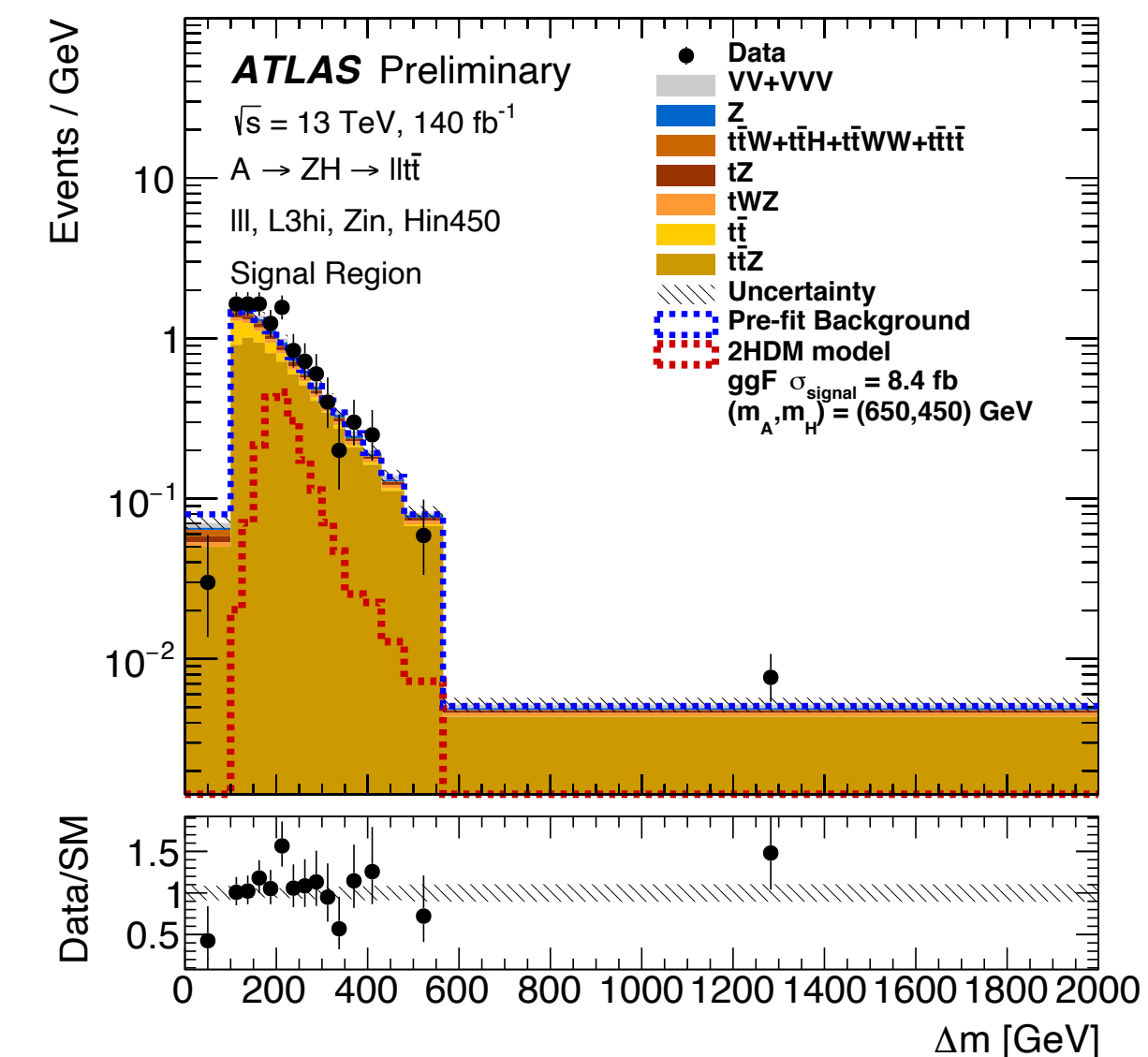
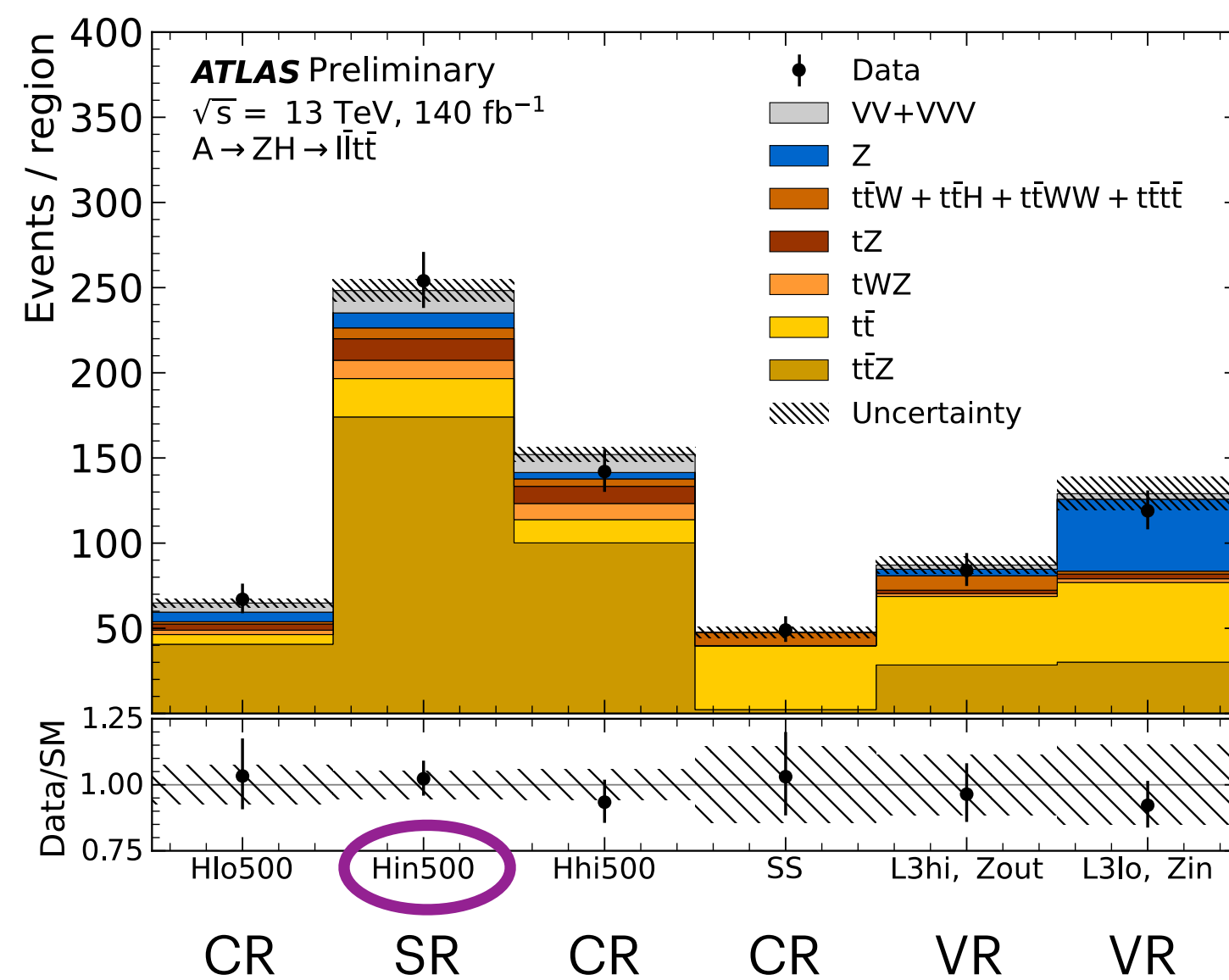
- 1  $\ell\ell tt$  SR: 3l,  $\geq 4$  jets and 2 b-jets
- 2  $\nu\nu bb$  SRs: 0l, MET, 2 b-jets and  $\geq 3$  b-jets

11 Control region categories for controlling ttZ in the  $\ell\ell tt$  (3 CRs) and Z+HF and ttbar in the  $\nu\nu bb$  channel (8 CRs)

Signal Region and Control Regions

Cut	Regions				
	ss (CR)	L3hi_Zout (VR)	Hlo / Hhi (CR)	Hin (SR)	L3lo_Zin (VR)
N leptons	3				
$p_T(\ell_1)$	$> 27$ GeV				
N jets	$\geq 4$				
N b-jets	2				
$ \eta_{H-cand}^{ZH-r.fr.} $	$< 2.2 + 0.0004 \cdot m_H^{cand} - 0.0011 \cdot m_A^{cand}$				
$p_T(\ell_3)$	$\ell\ell tt$			$> 13$ GeV	$> 7$ GeV & $< 13$ GeV
Lepton flavour	$ee\mu/\mu\mu e$		$eee/ee\mu/\mu\mu e/\mu\mu\mu$		
OSSF lepton pairs	0		$\geq 1$		
$ m_Z^{cand} - m_Z $	$< 20$ GeV	$> 10$ GeV & $< 20$ GeV	$< 10$ GeV		
$ m_H^{cand} - m_H^{hypo} $	$m_H^{hypo} < 500$ GeV $m_H^{hypo} > 500$ GeV		$> 0.32 \cdot m_H^{hypo}$	$< 0.32 \cdot m_H^{hypo}$	-
			$> 0.24 \cdot m_H^{hypo}$	$< 0.24 \cdot m_H^{hypo}$	-

$\ell\ell tt$  Signal Region and Control Regions



# $A \rightarrow ZH \rightarrow \ell\ell tt/\nu\nu bb$

Search for a heavy CP-odd Higgs boson (A) decaying to a heavy CP-even Higgs Boson (H) and a Z in the  $\ell\ell tt/\nu\nu bb$  channels

3 Signal Region categories defined based on requirements on the number of leptons, jets, b-jets, MET, reconstructed Z and H boson masses:

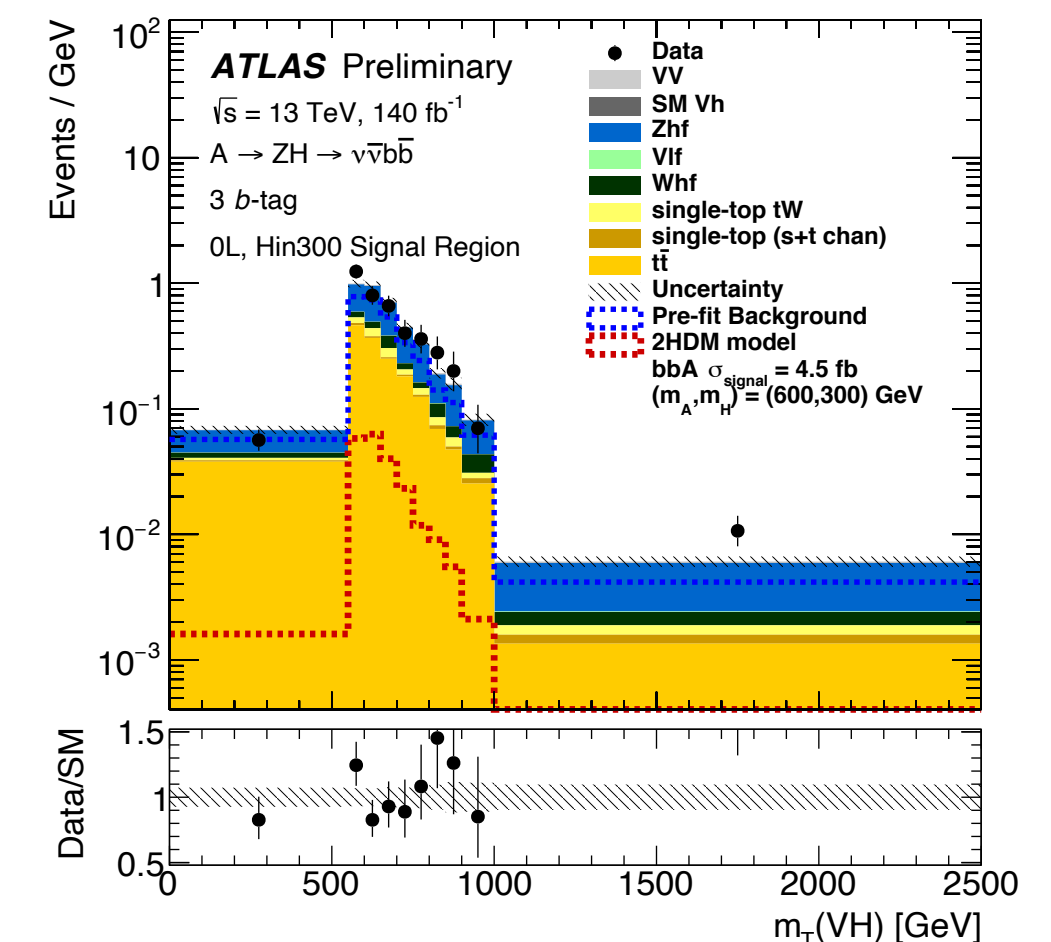
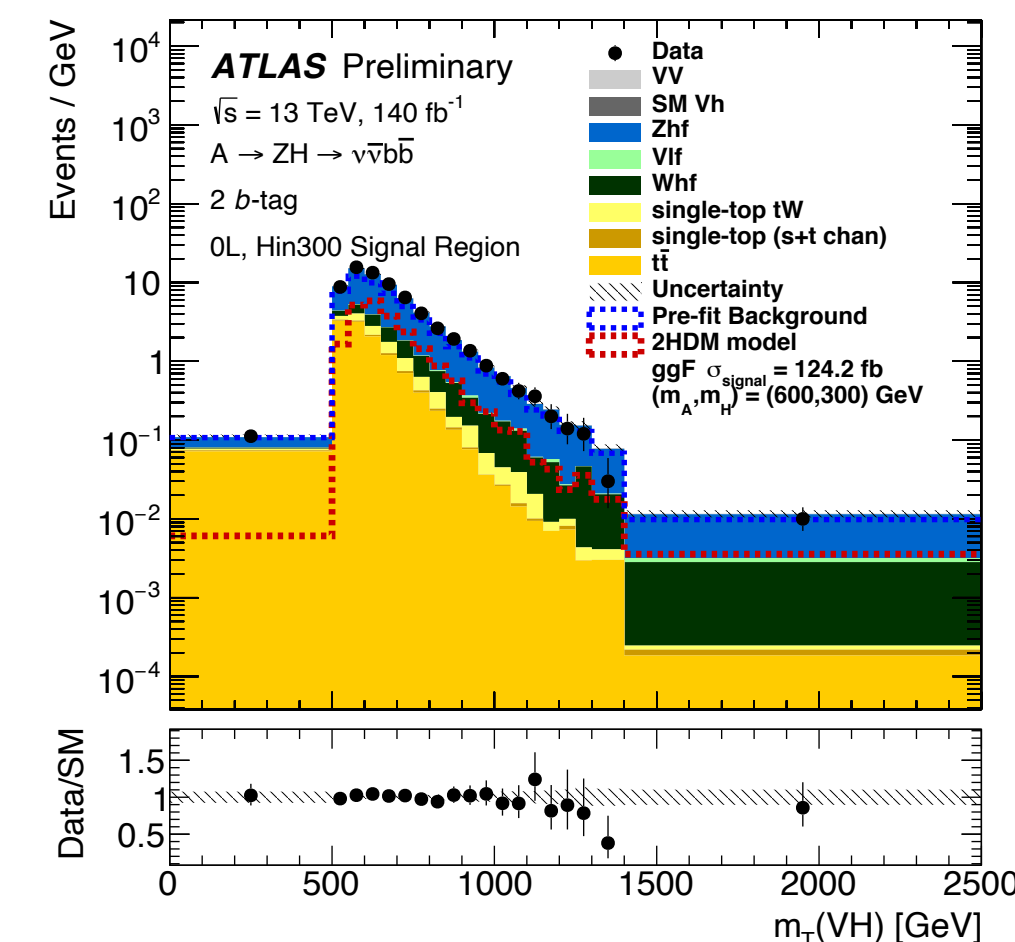
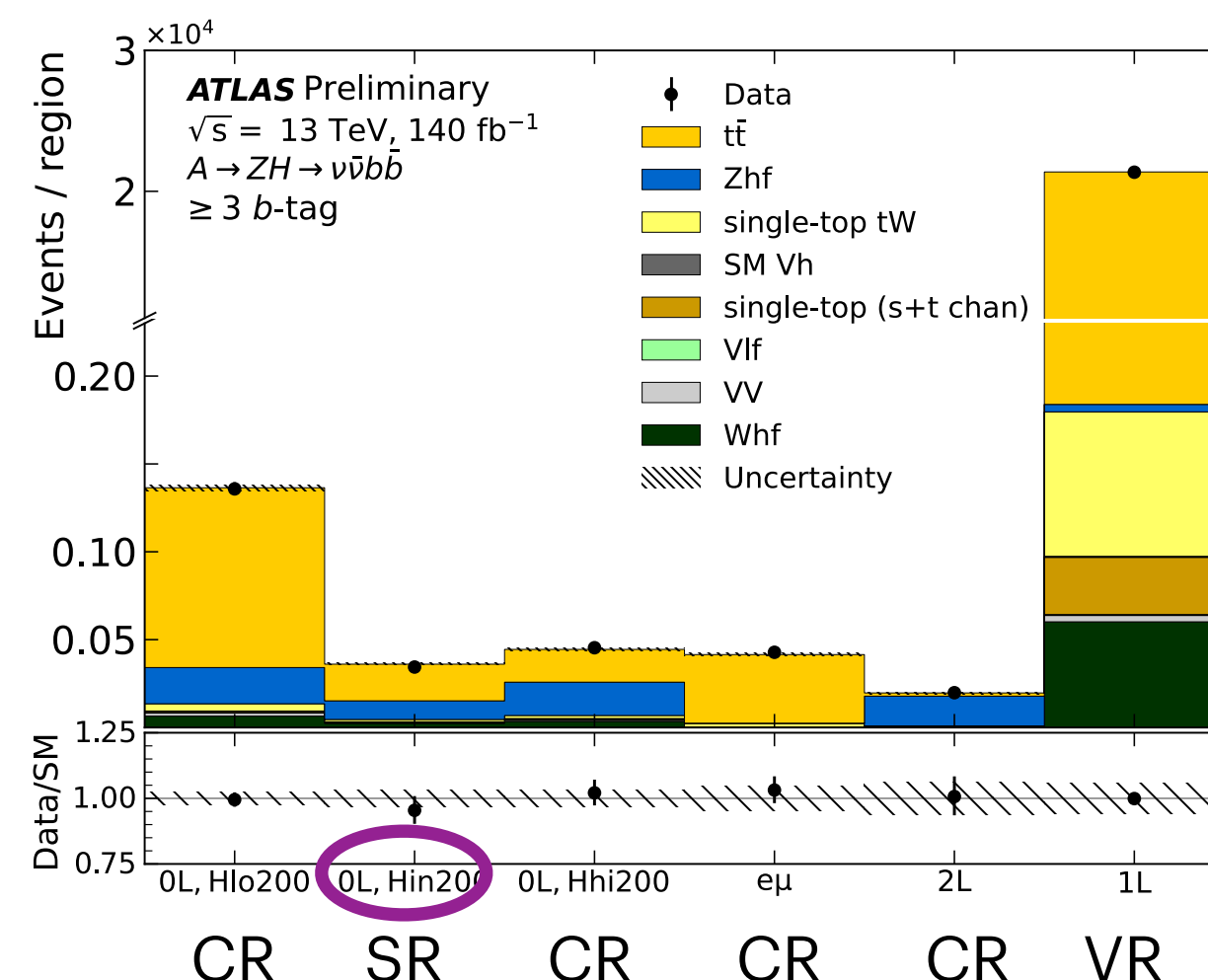
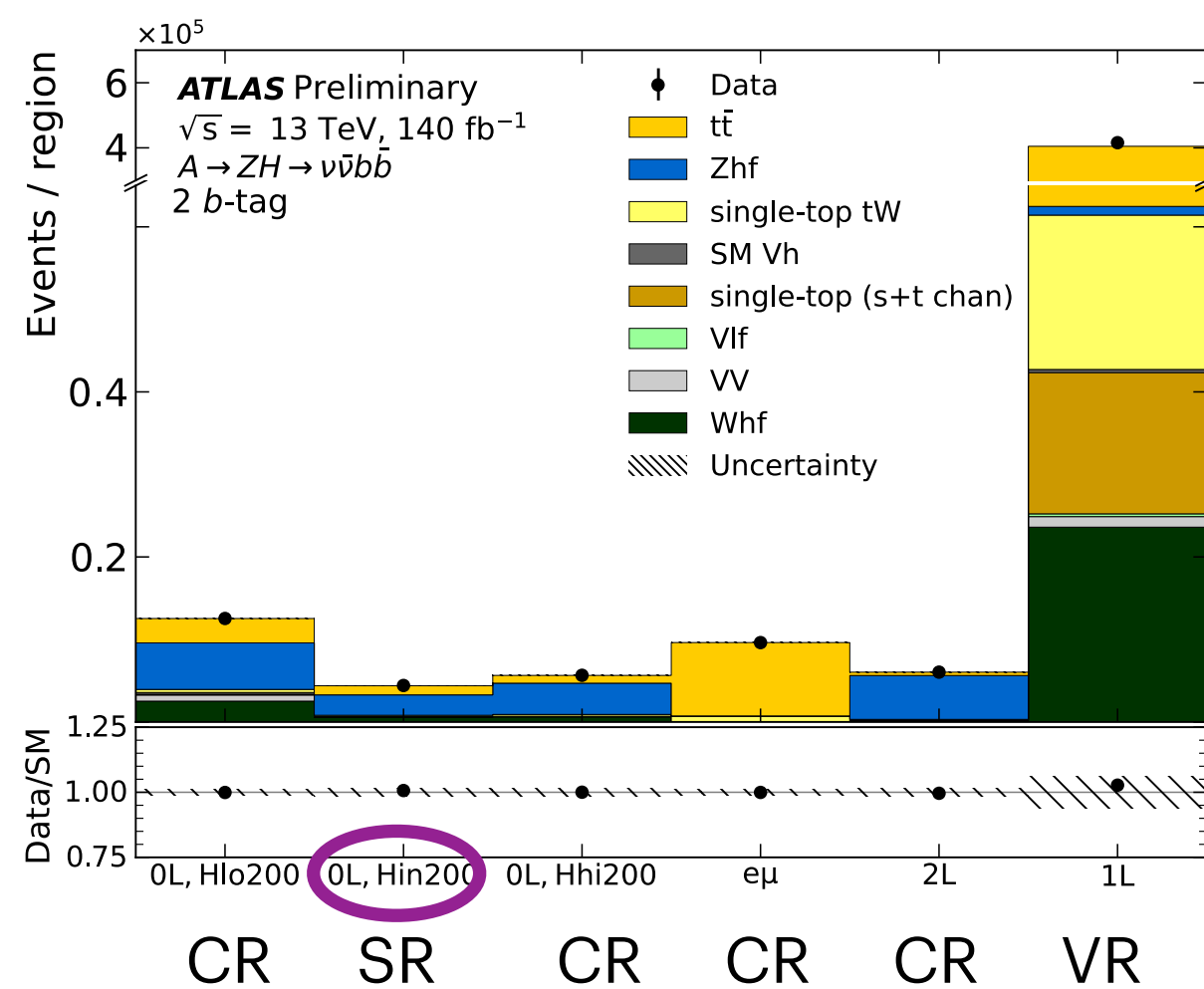
- 1  $\ell\ell tt$  SR: 3l,  $\geq 4$  jets and 2 b-jets
- 2  $\nu\nu bb$  SRs: 0l, MET, 2 b-jets and  $\geq 3$  b-jets

11 Control region categories for controlling ttZ in the  $\ell\ell tt$  (3 CRs) and Z+HF and ttbar in the  $\nu\nu bb$  channel (8 CRs)

$\nu\nu bb$  Signal Region and Control Regions

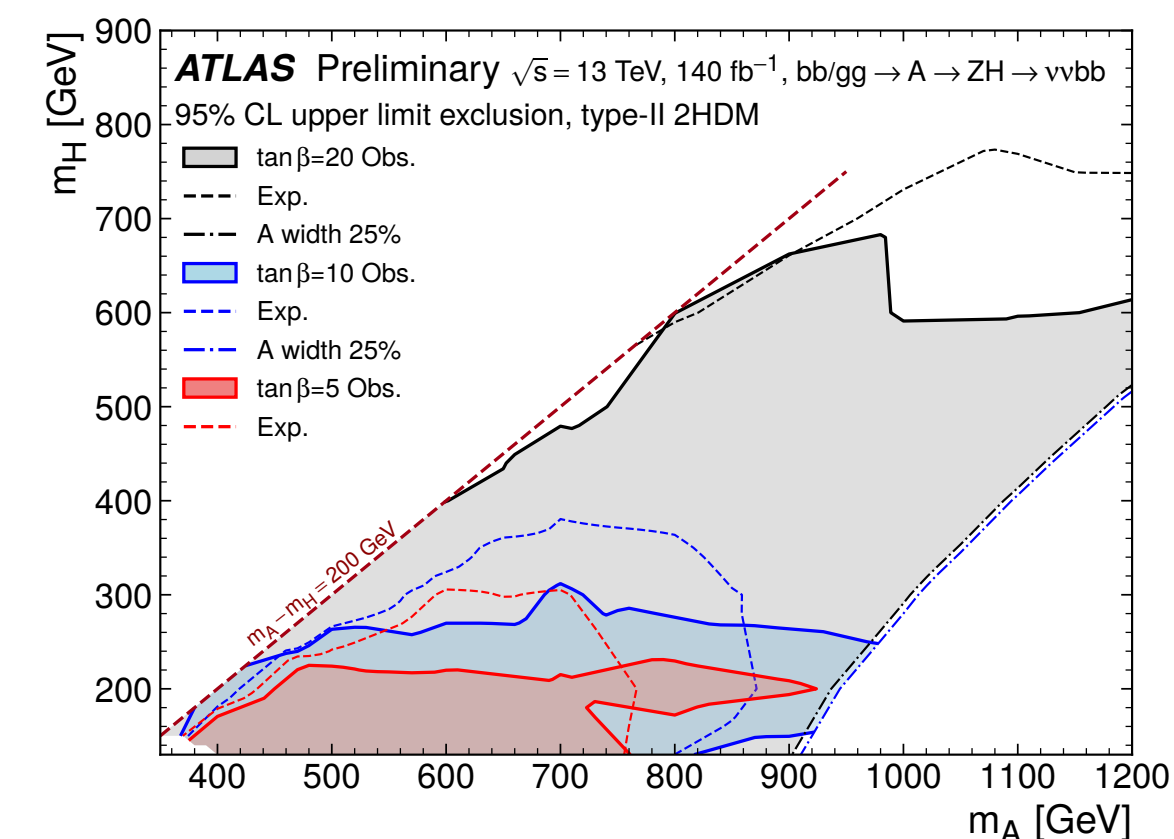
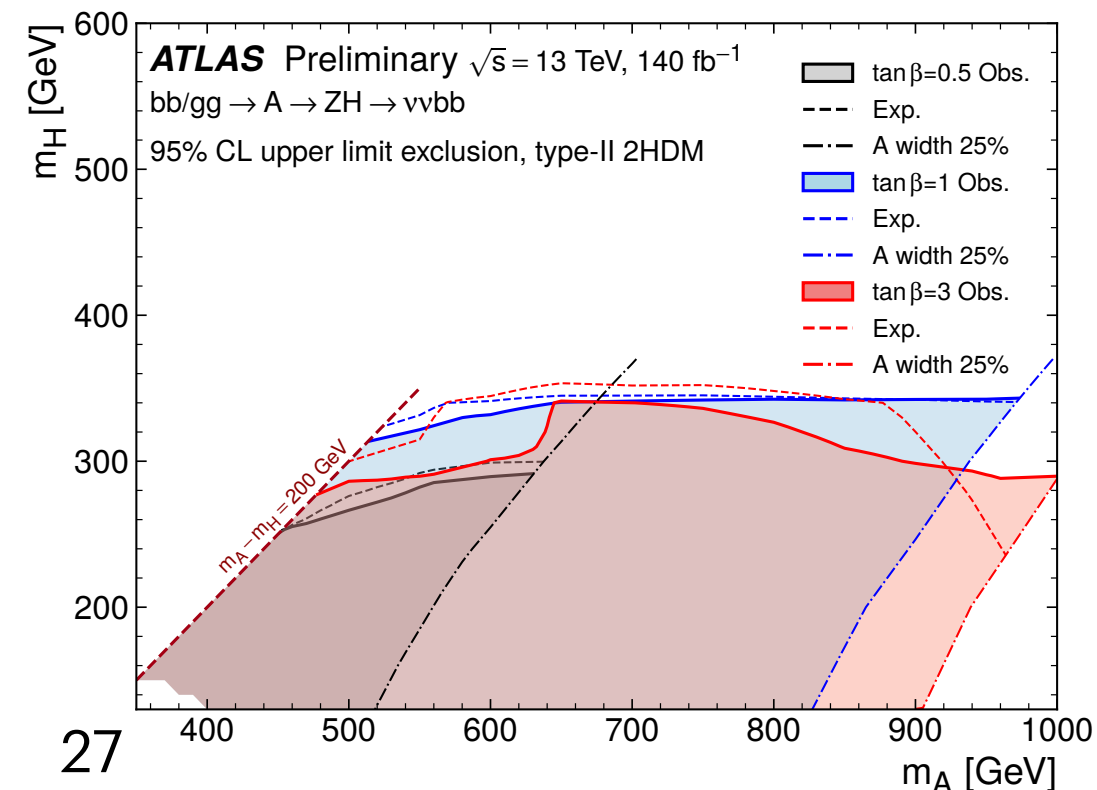
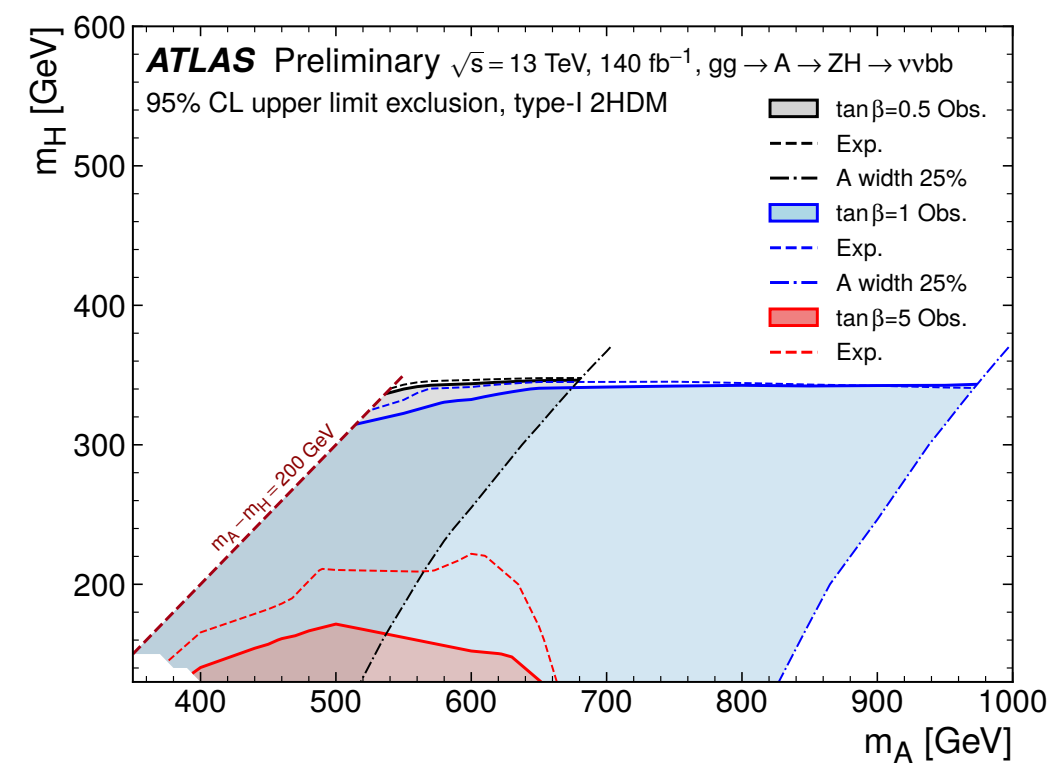
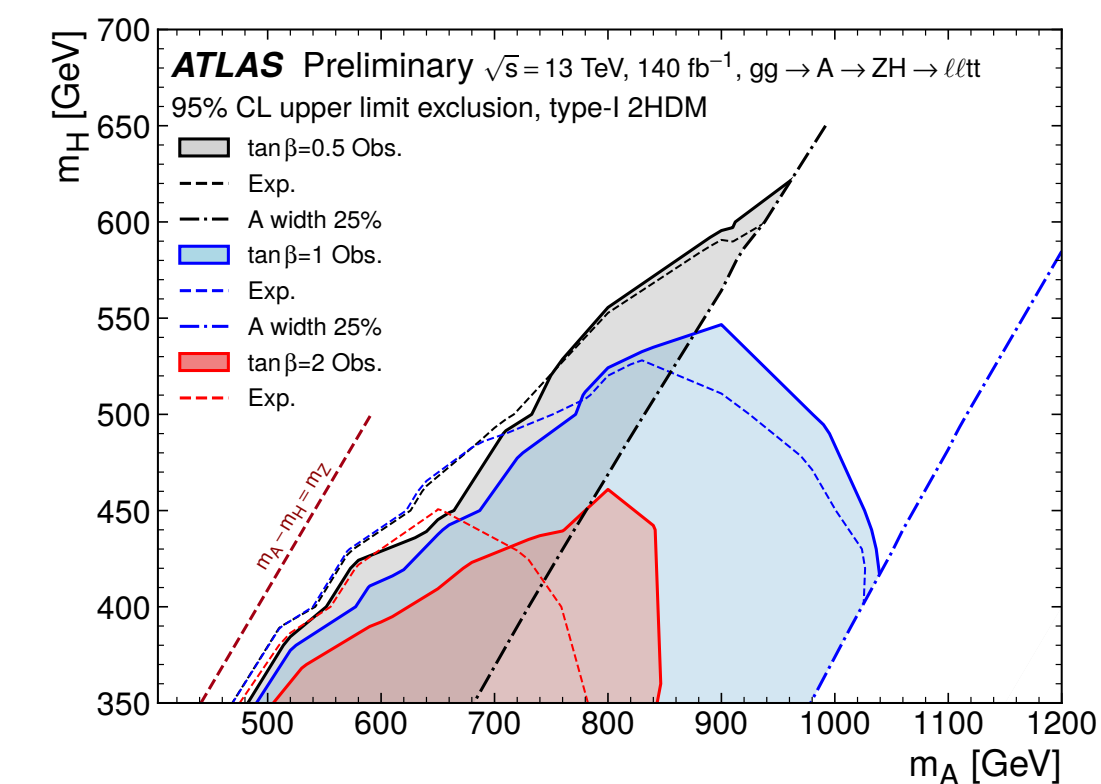
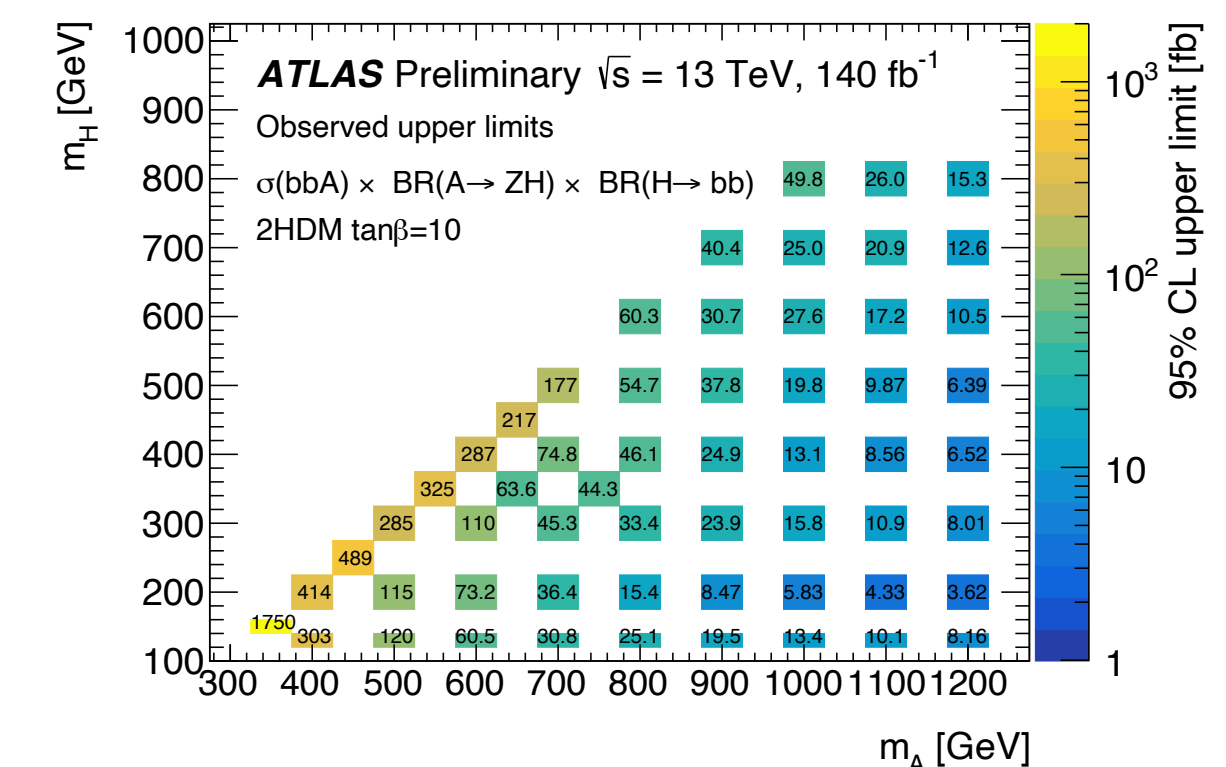
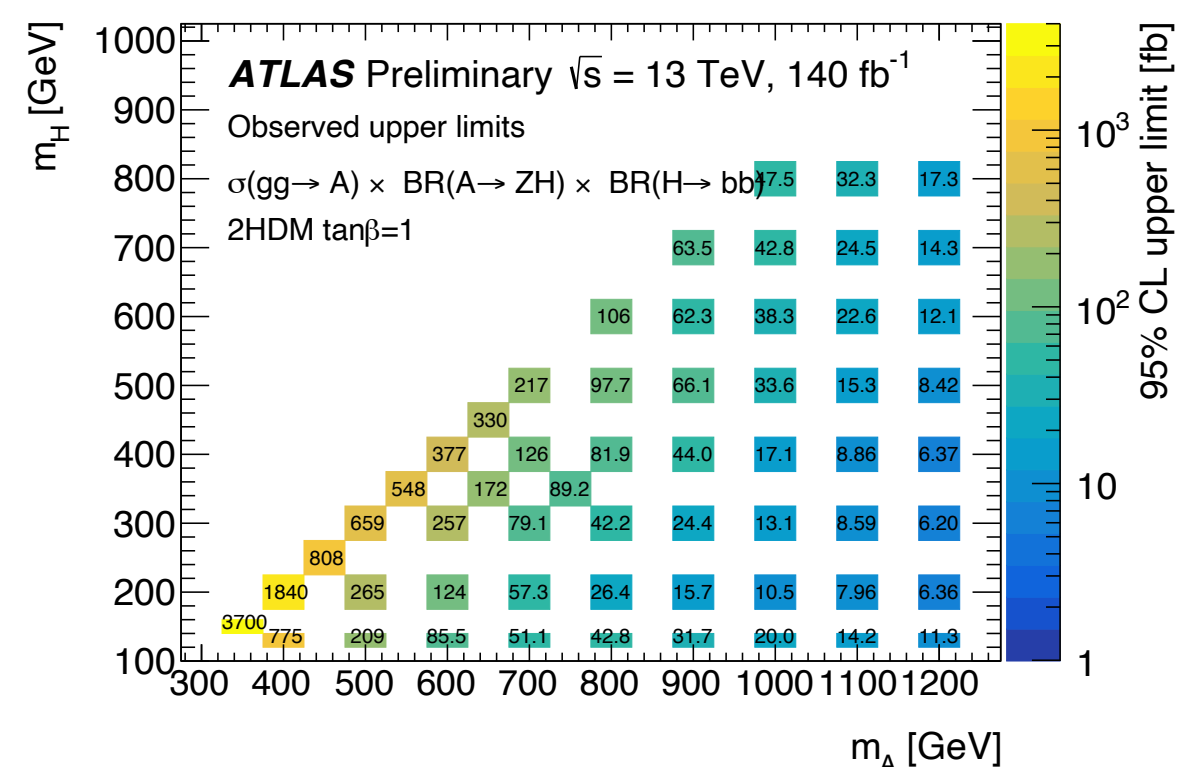
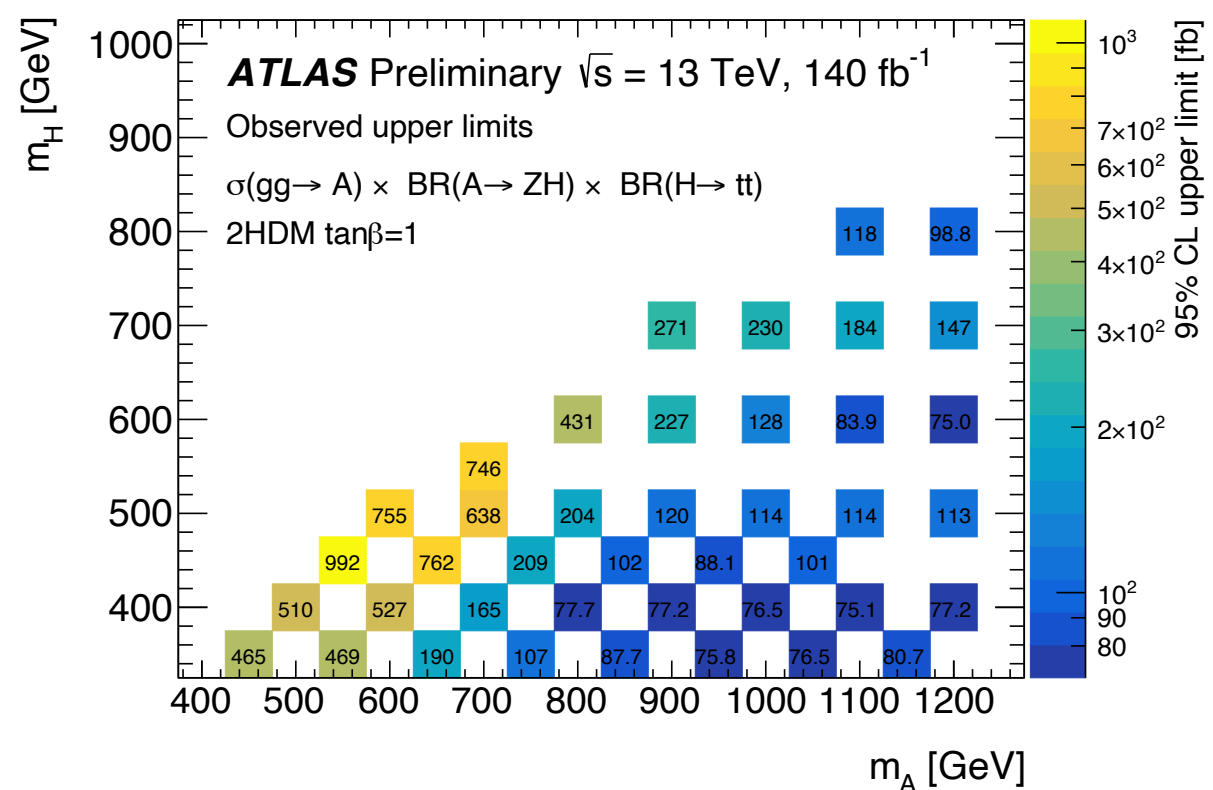
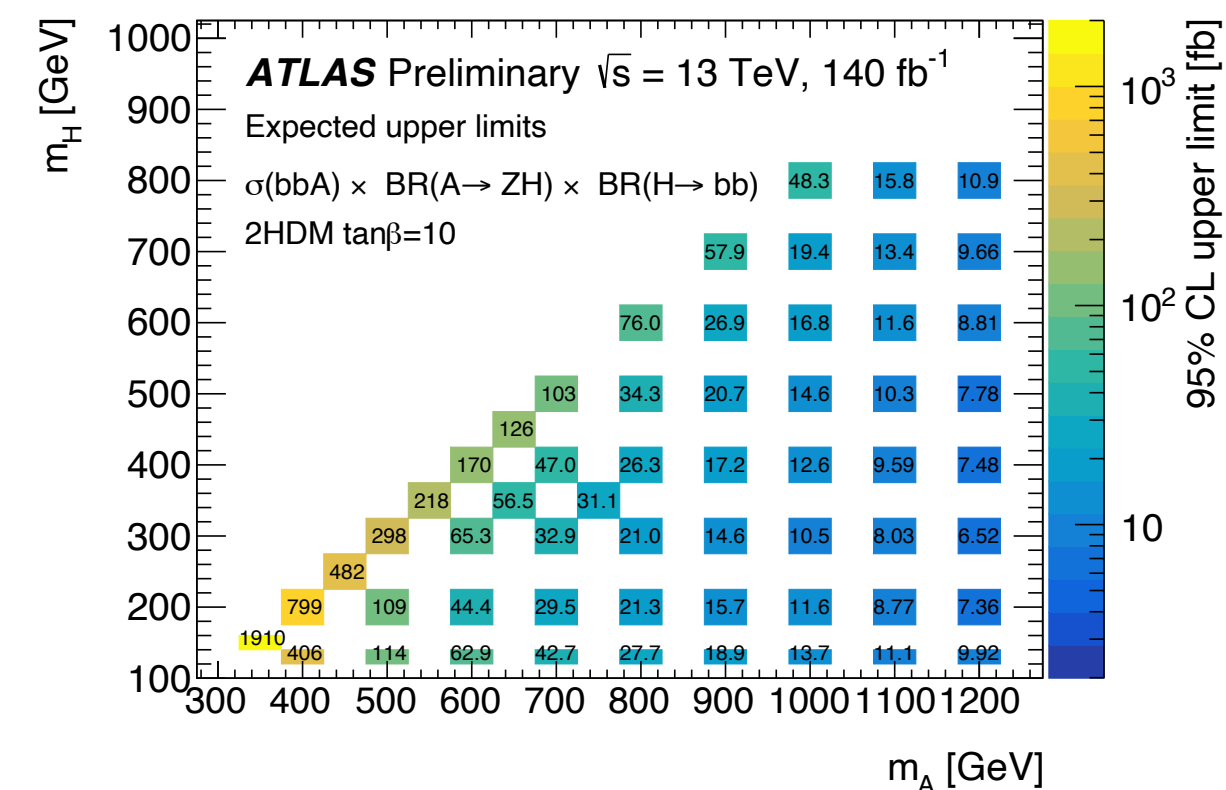
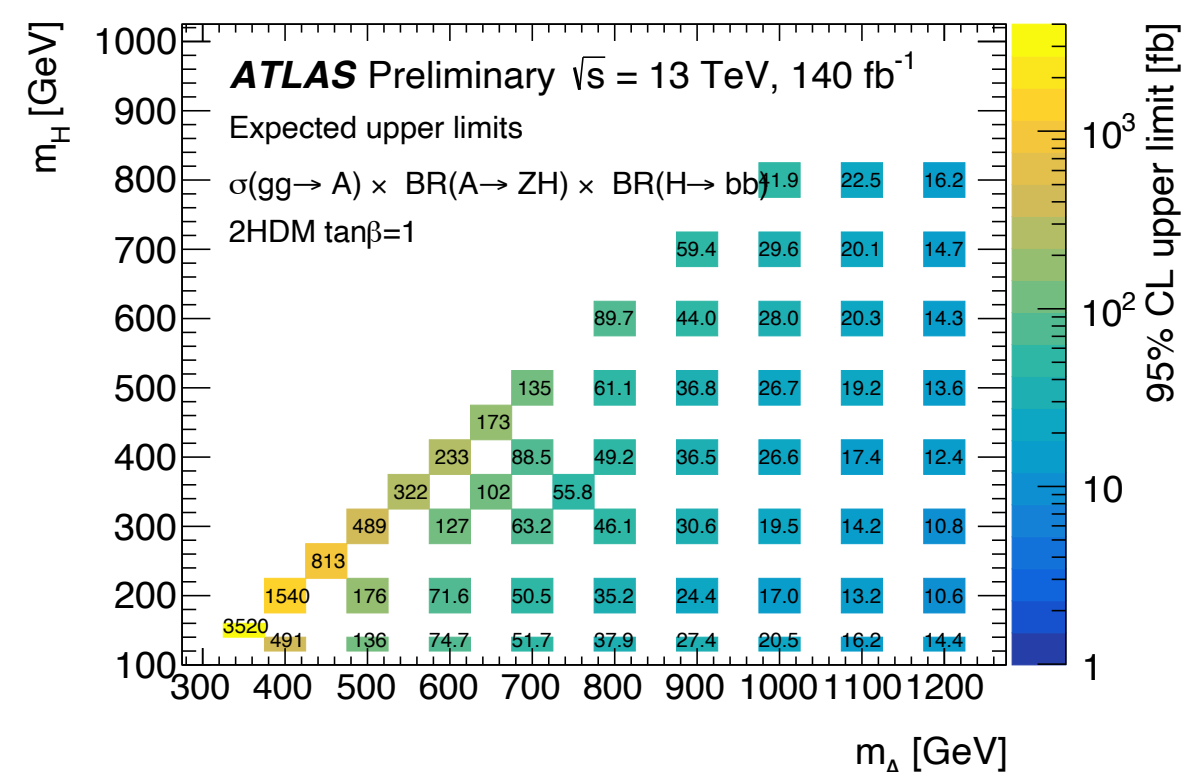
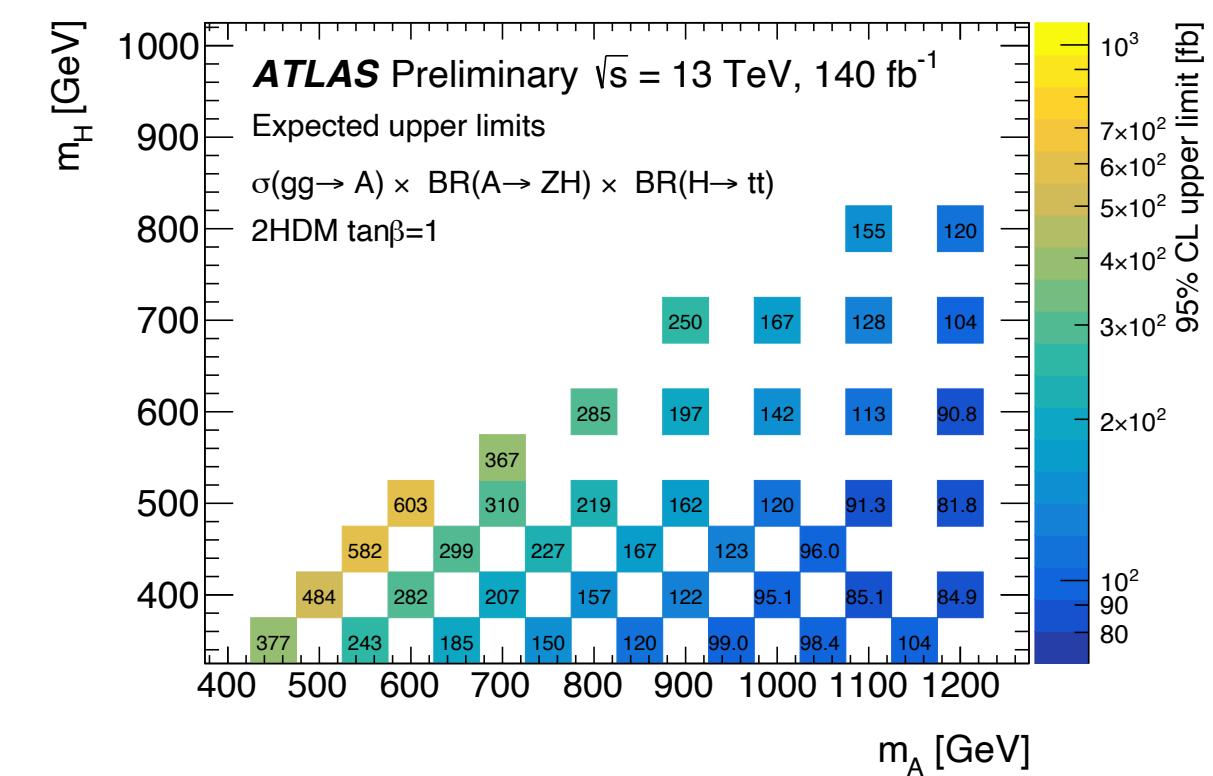
Cut	Regions				
	2L (CR)	e $\mu$ (CR)	1L (VR)	Hlo / Hhi (CR)	Hin (SR)
N jets	2-5				
N b-jets	$> 2$				
$m_H^{\text{cand}}$	$> 50$ GeV				
N hadronically decaying $\tau$ -leptons	0				
$p_T(V)$	$> 150$ GeV				
$\min_i \Delta\phi(\vec{E}_T^{\text{miss}}, \vec{p}_i^{\text{jet}})$	$> \pi/10$				
$\Delta R(b_1, b_2)$	$< 3.3$ (2 b-jets) $< 3.5$ ( $\geq 3$ b-jets)				
N leptons	2		1	0	
Lepton flavour	ee/ $\mu\mu$	e $\mu$	e/ $\mu$	-	
$p_T(\ell_1)$	$> 27$ GeV				-
$ m_Z^{\text{cand}} - m_Z $	$< 10$ GeV	-			
$S_{\text{MET}}$	$< 5$	-	$> 3$	$> 10$	
$m_{\text{top}}^{\text{near}}$	-			$> 180$ GeV	
$m_{\text{top}}^{\text{far}}$	-			$> 200$ GeV	
$ m_H^{\text{cand}} - m_H^{\text{hypo}} $	-			$> 0.2 \cdot m_H^{\text{hypo}}$	$< 0.2 \cdot m_H^{\text{hypo}}$

$\nu\nu bb$  Signal Region and Control Regions



# $A \rightarrow ZH \rightarrow \ell\ell tt/\nu\nu bb$

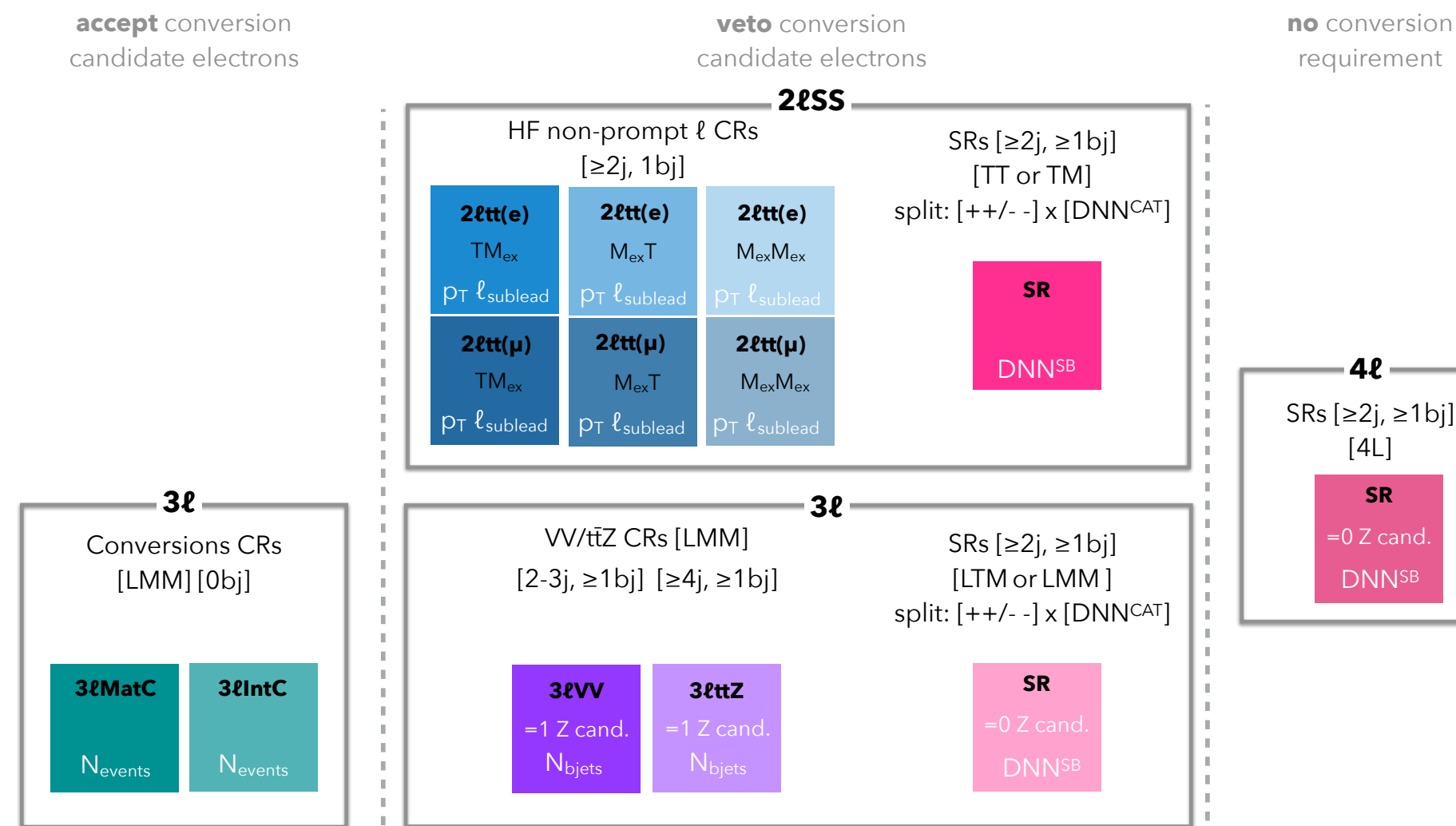
Search for a heavy CP-odd Higgs boson ( $A$ ) decaying to a heavy CP-even Higgs Boson ( $H$ ) and a  $Z$  in the  $\ell\ell tt/\nu\nu bb$  channels



# Heavy Higgs in multi-lepton plus b-jets

Search for heavy Higgs bosons in multilepton plus b-jets final states

[arXiv:2307.14759](https://arxiv.org/abs/2307.14759)



17 signal region categories defined based on:

- Number of leptons
- Charge sign of leptons
- DNN classifier trained to distinguish the different production/decay modes

10 control region categories for controlling HF non-prompt leptons, photon conversion, VV and ttZ defined based on different requirements on:

- Lepton definition
- dilepton invariant mass
- jet and b-jet multiplicities

Signal regions

Lepton category	2ℓSS	3ℓ	4ℓ
Lepton definition	(T, T) with $\geq 1 b^{60\%}$    (T, M) with $\geq 2 b^{77\%}$	(L, T, M) with $\geq 1 b^{60\%}$    (L, M, M) with $\geq 2 b^{77\%}$	(L, L, L, L)
Lepton $p_T$ [GeV]	(20, 20)	(10, 20, 20)	(10, 10, 10, 10)
$m_{\ell^+\ell^-}^{OS-SF}$ [GeV]	-	$> 12$	-
$ m_{\ell^+\ell^-}^{OS-SF} - m_Z $ [GeV]	-	$> 10$	-
$N_{jets}$	-	$\geq 2$	-
$N_{b-jets}$	-	$\geq 1 b^{60\%} \parallel \geq 2 b^{77\%}$	-
Region split	(sstt, ttq, ttt, ttq, ttt) $\times (Q^{++}, Q^{--})$	(ttt, ttq, ttt) $\times (Q^+, Q^-)$	-
Region naming	2ℓSS ++ CAT sstt 2ℓSS ++ CAT ttq 2ℓSS ++ CAT ttt 2ℓSS ++ CAT ttq 2ℓSS ++ CAT ttt 2ℓSS ++ CAT ttt 2ℓSS -- CAT sstt 2ℓSS -- CAT ttq 2ℓSS -- CAT ttt 2ℓSS -- CAT ttq 2ℓSS -- CAT ttt	3ℓ ++ CAT ttt 3ℓ ++ CAT ttq 3ℓ ++ CAT ttt 3ℓ -- CAT ttt 3ℓ -- CAT ttq 3ℓ -- CAT ttt	4ℓ

Control regions

Control regions	WZ	ttZ	Conversions	HF non-prompt
$N_{jets}$	2 or 3	$\geq 4$	$\geq 0$	$\geq 2$
$N_{b-jets}$	$\geq 1 b^{60\%} \parallel \geq 2 b^{77\%}$	$\geq 2 b^{77\%}$	$0 b^{77\%}$	$1 b^{77\%}$
Lepton requirement	3ℓ	3ℓ	$\mu\mu e^*$	2ℓSS
Lepton definition	(L, M, M)	(L, M, M)	(L, M, M)	(T, M <sub>ex</sub> )    (M <sub>ex</sub> , T)    (M <sub>ex</sub> , M <sub>ex</sub> )
Lepton $p_T$ [GeV]	(10, 20, 20)	(10, 20, 20)	(10, 20, 20)	(20, 20)
$m_{\ell^+\ell^-}^{OS-SF}$ [GeV]	$> 12$	$> 12$	$> 12$	-
$ m_{\ell^+\ell^-}^{OS-SF} - m_Z $ [GeV]	$< 10$	$> 10$	$> 10$	-
$ m_{\ell\ell} - m_Z $ [GeV]	-	-	$< 10$	-
$m_T(\ell_0, E_T^{miss})$ [GeV]	-	-	-	$< 250$
Region split	-	-	internal / material	subleading $e/\mu \times [(T, M_{ex}), (M_{ex}, T), (M_{ex}, M_{ex})]$
Region naming	3ℓVV	3ℓttZ	3ℓIntC 3ℓMatC	2ℓtt(e) <sub>(T, M<sub>ex</sub>)</sub> , 2ℓtt(e) <sub>(M<sub>ex</sub>, T)</sub> , 2ℓtt(e) <sub>(M<sub>ex</sub>, M<sub>ex</sub>)</sub> 2ℓtt(μ) <sub>(T, M<sub>ex</sub>)</sub> , 2ℓtt(μ) <sub>(M<sub>ex</sub>, T)</sub> , 2ℓtt(μ) <sub>(M<sub>ex</sub>, M<sub>ex</sub>)</sub>

Lepton definitions

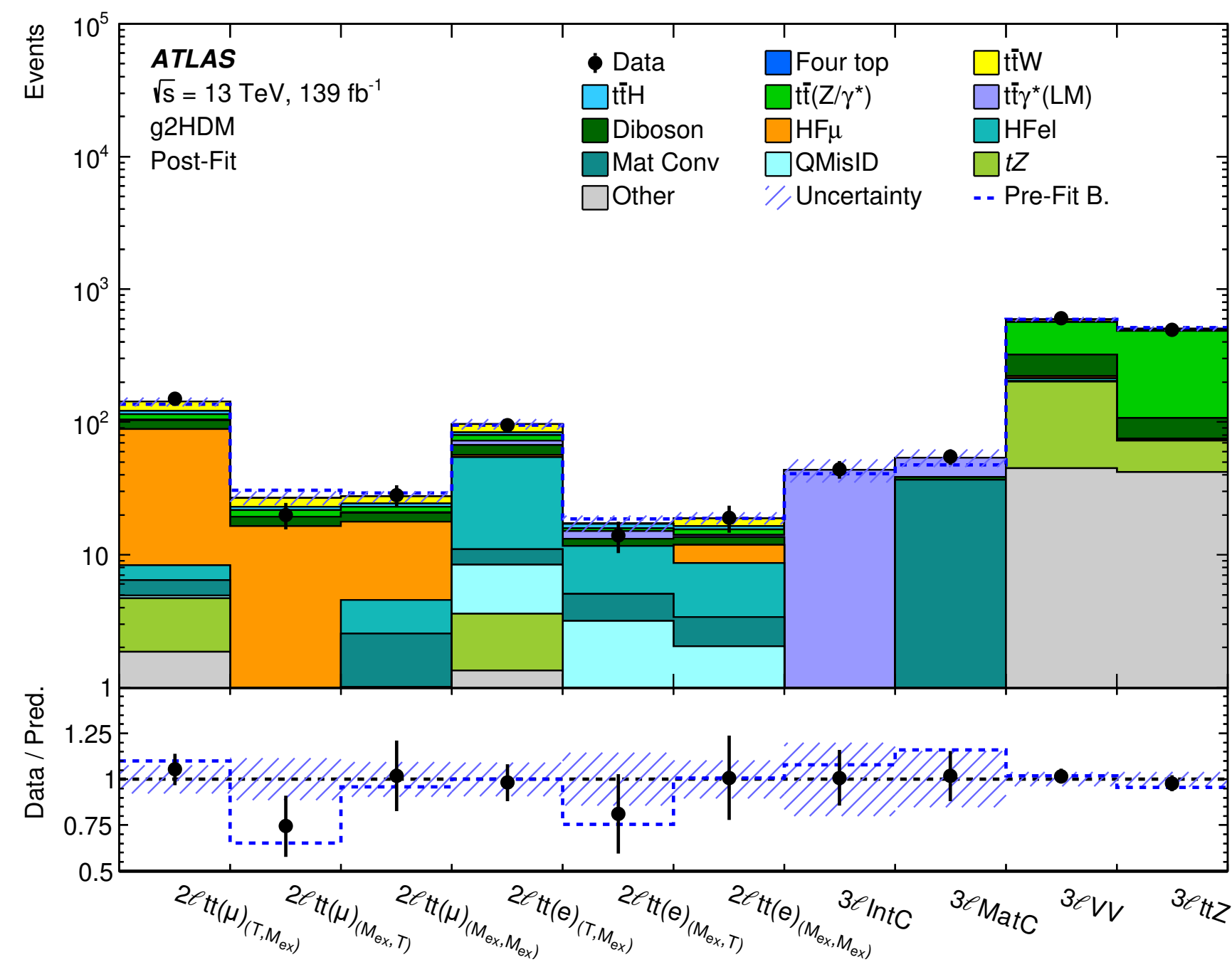
Lepton categorization	e				μ			
	L	M	M <sub>ex</sub>	T	L	M	M <sub>ex</sub>	T
Isolation	Yes							
Non-prompt lepton BDT WP	No	Tight	Tight-not-VeryTight	VeryTight	No	Tight	Tight-not-VeryTight	VeryTight
Identification	Loose	Tight			Loose	Medium		
Electron charge-misassignment veto	No	Yes			Not applicable			
Electron conversion candidate veto	No	Yes (except $e^*$ )			Not applicable			
Transverse impact parameter significance $ d_0 /\sigma_{d_0}$	$< 5$				$< 3$			
Longitudinal impact parameter $ z_0 \sin \theta $	$< 0.5$ mm							

# Heavy Higgs in multi-lepton plus b-jets

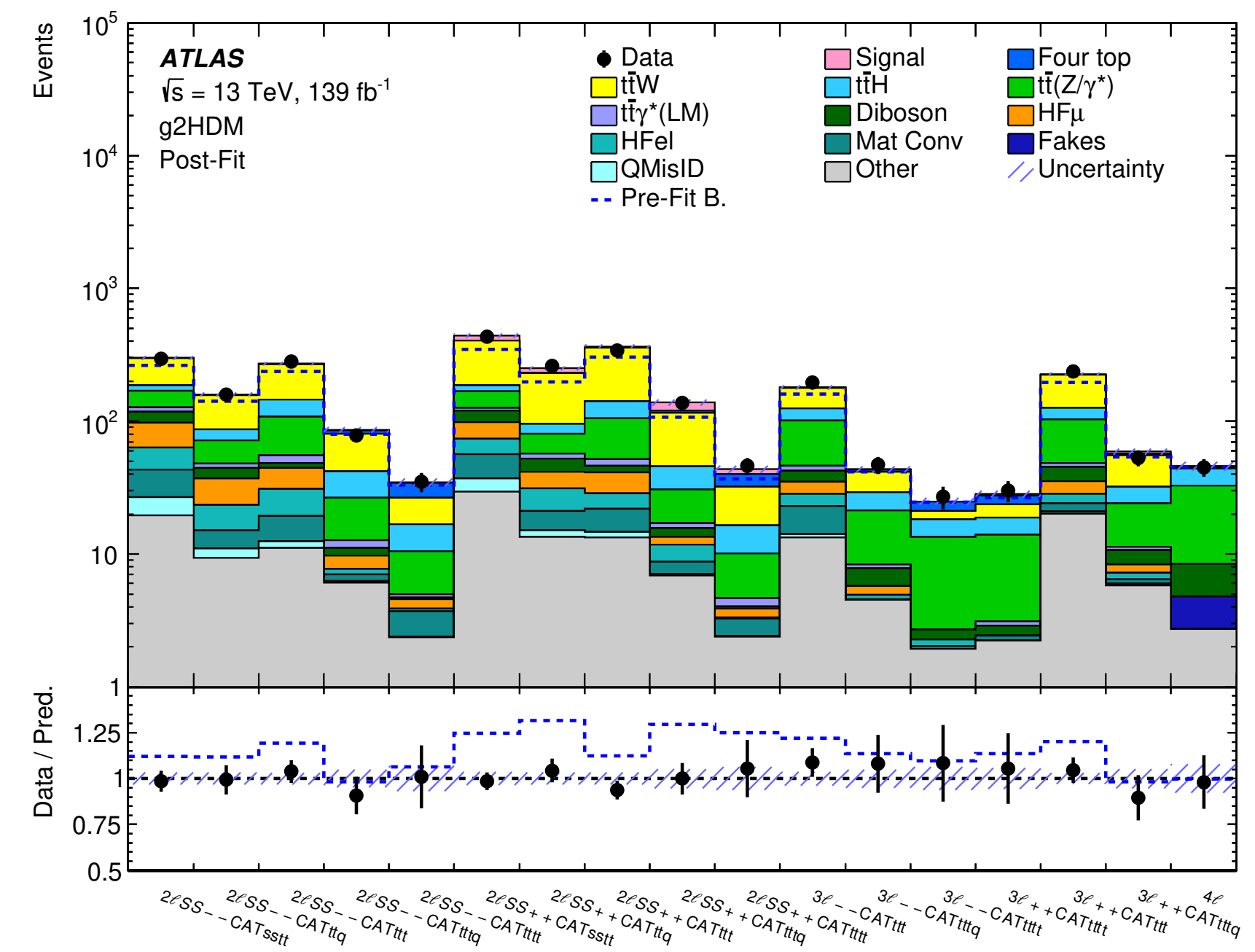
Search for heavy Higgs bosons in multilepton plus b-jets final states

[arXiv:2307.14759](https://arxiv.org/abs/2307.14759)

10 Control Region categories



17 Signal Region categories



# Heavy Higgs in multi-lepton plus b-jets

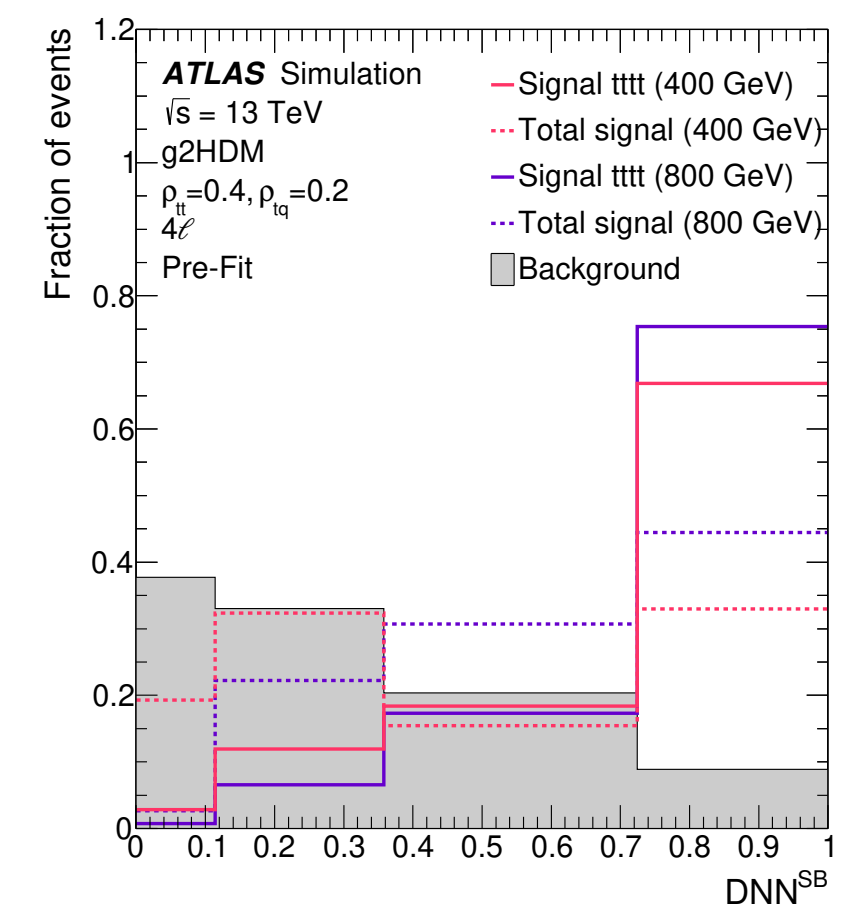
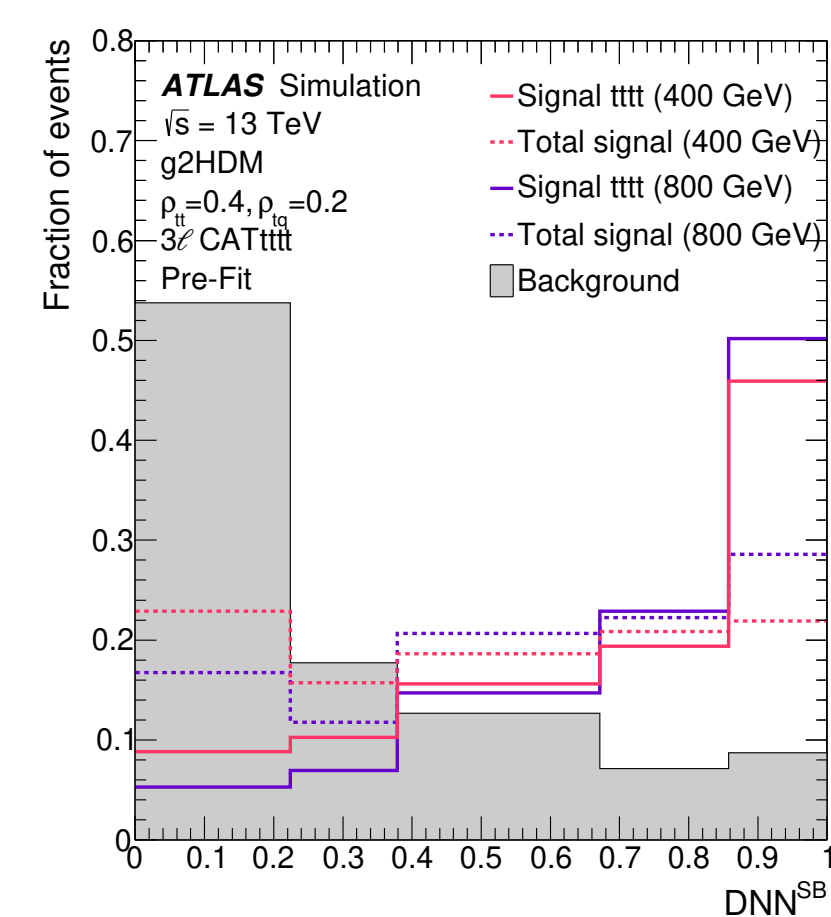
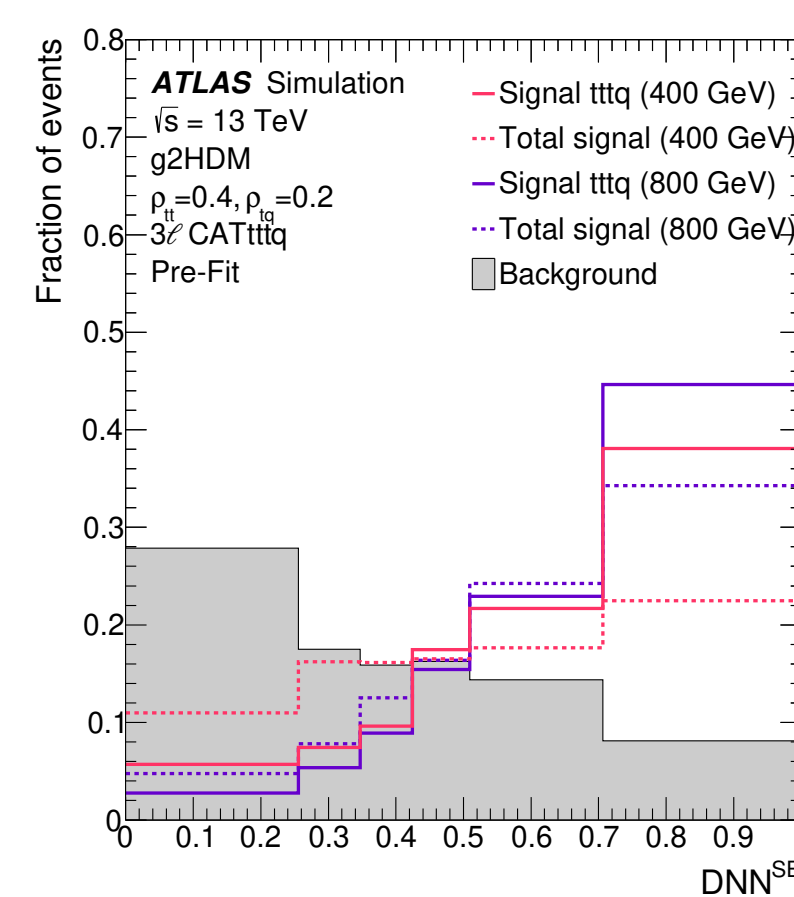
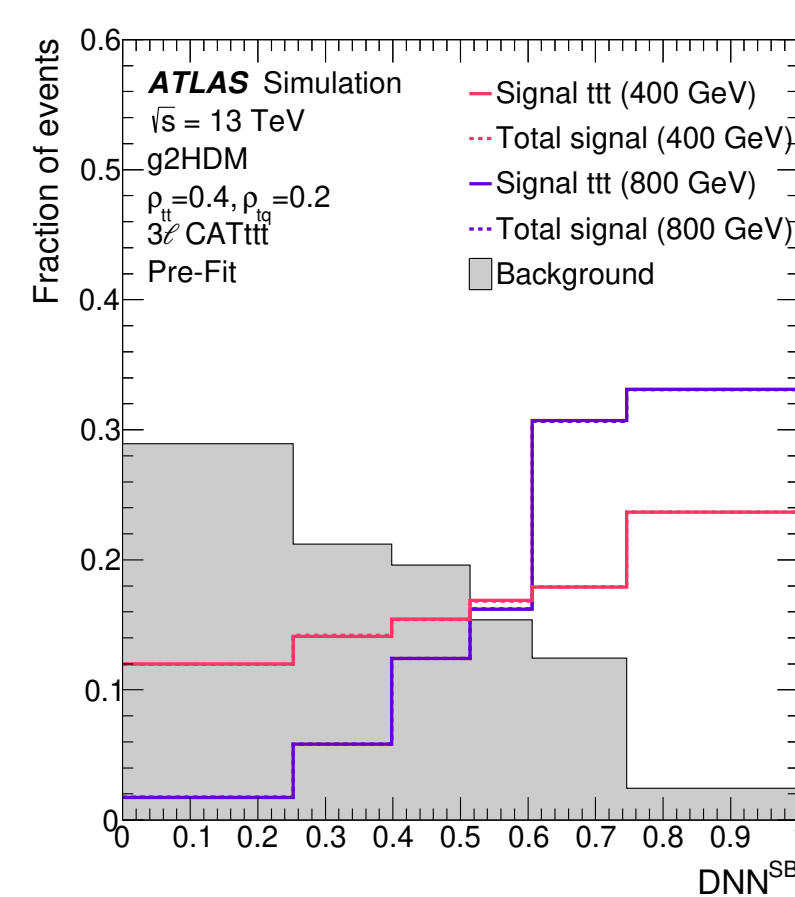
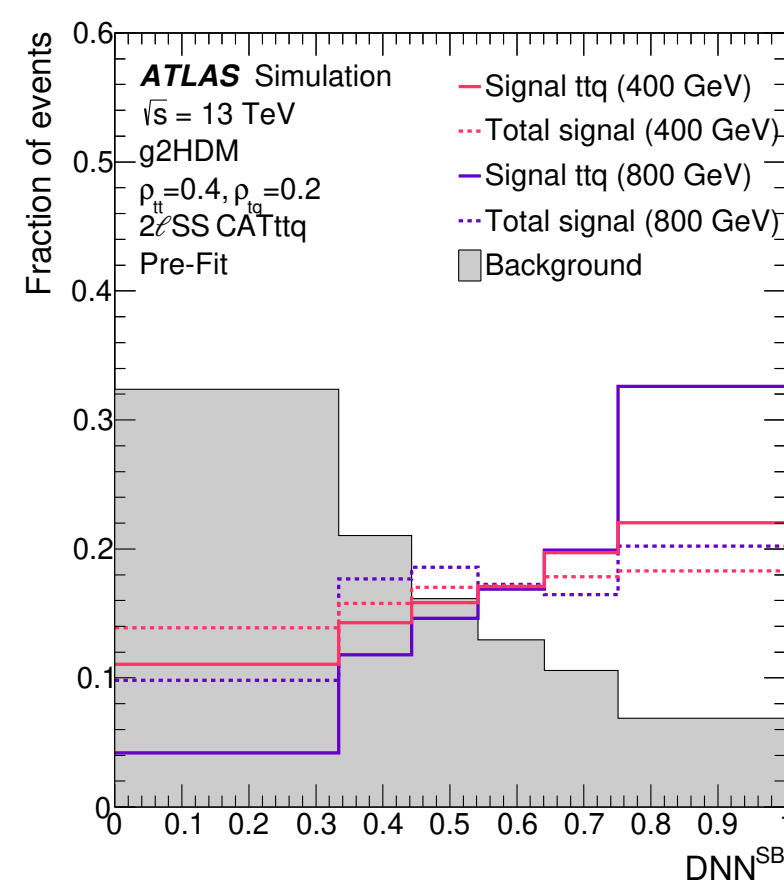
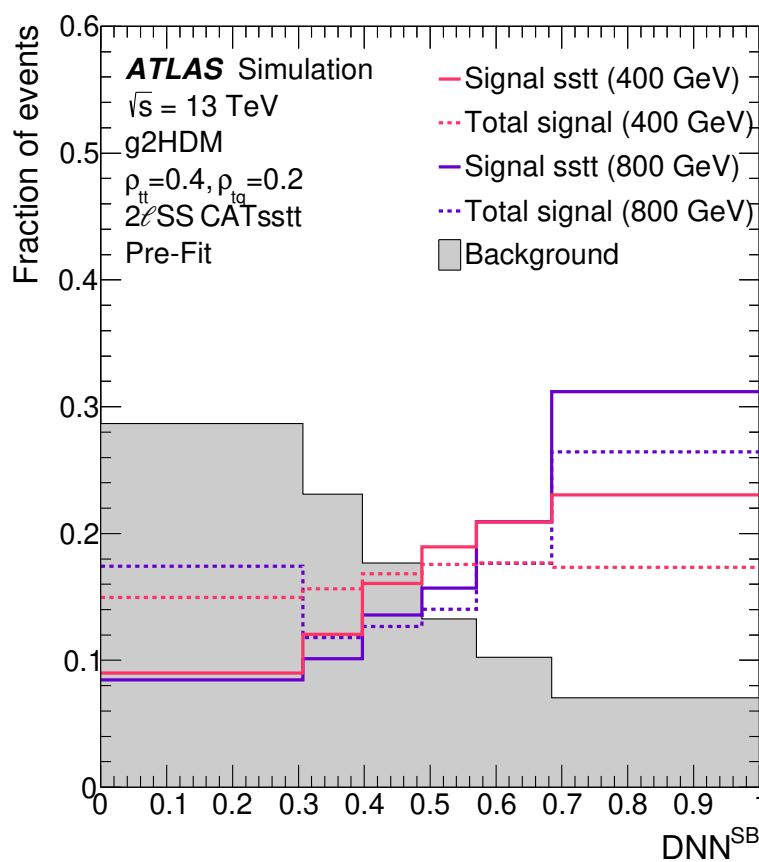
Search for heavy Higgs bosons in multilepton plus b-jets final states

[arXiv:2307.14759](https://arxiv.org/abs/2307.14759)

- Categorisation DNN trained on all signal types and all signal mass points
- S vs B DNN trained in each SR on the targeted signal using all mass points (with a mass decorrelation penalty term added to the loss function via distance correlation to minimize the mass dependence of the performance)

DNNs input variables

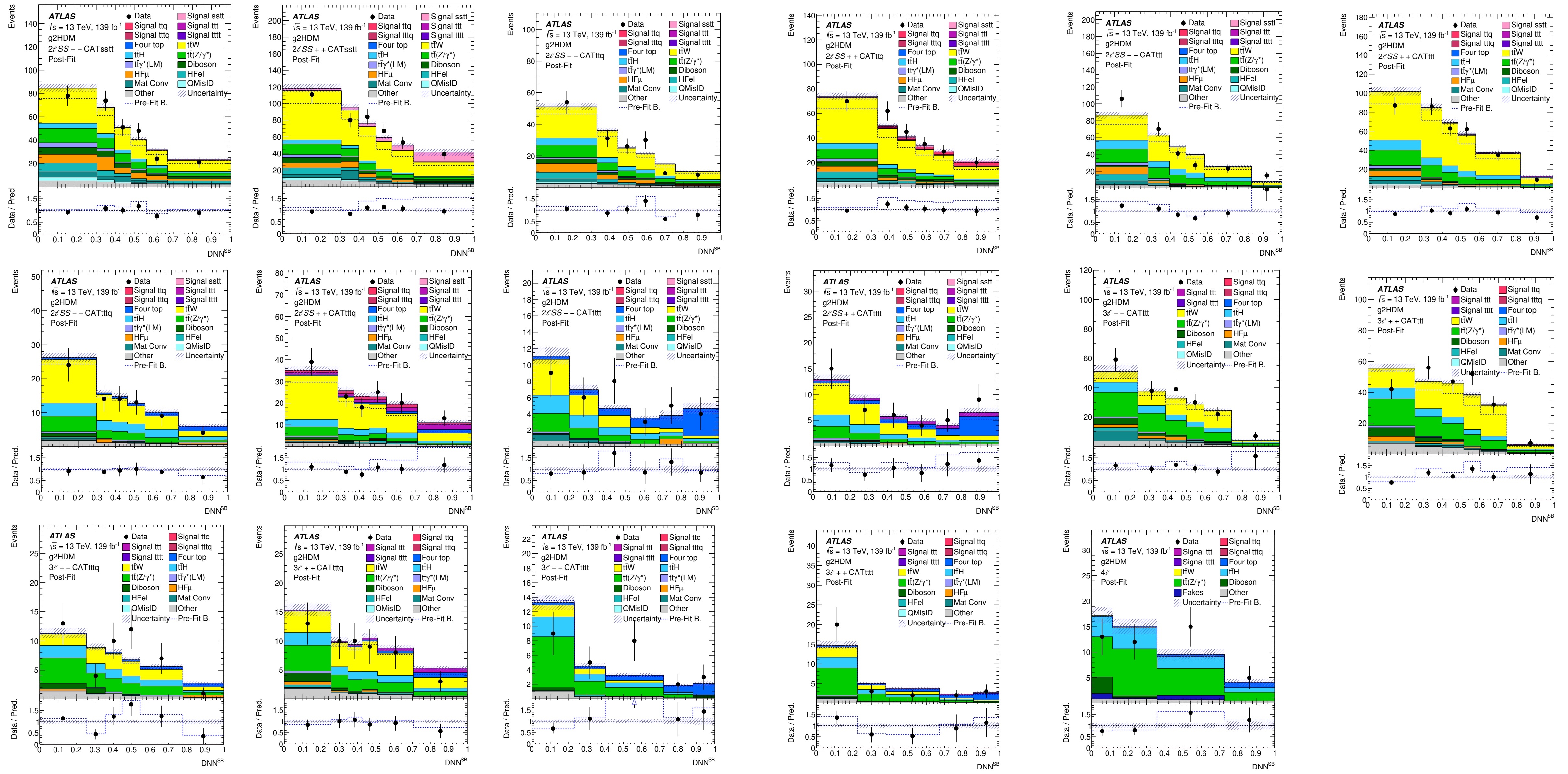
Variable	DNN <sup>cat</sup>	DNN <sup>SB</sup>
Number of jets ( $N_{\text{jets}}$ )	✓	✓
Sum of pseudo-continuous $b$ -tagging scores of jets	✓	✓
Pseudo-continuous $b$ -tagging score of 1st, 2nd, 3rd leading jet in $p_T$	✓	✓
Sum of $p_T$ of the jets and leptons ( $H_{T,\text{jets}}, H_{T,\text{lep}}$ )	✓	✓
Angular distance of leptons (sum in the case of $3\ell$ and $4\ell$ )	✓	✓
Missing transverse energy	✓	✓
Leading transverse momentum of jet	-	✓
Invariant mass of leading lepton and missing transverse energy	-	✓
Di/tri/quad-lepton type variable (associated with the number of electrons/muons in event)	-	✓



# Heavy Higgs in multi-lepton plus b-jets

Search for heavy Higgs bosons in multilepton plus b-jets final states

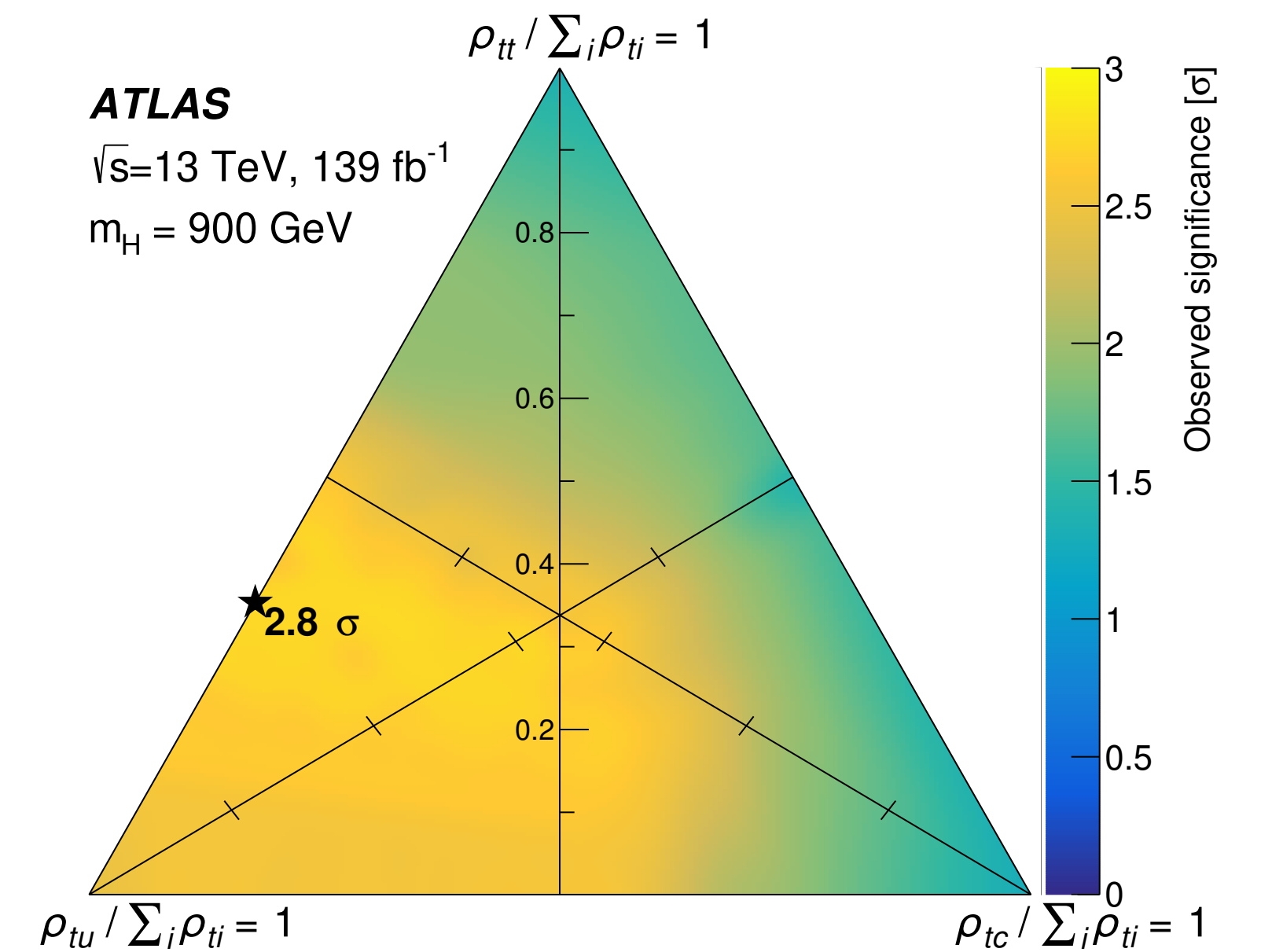
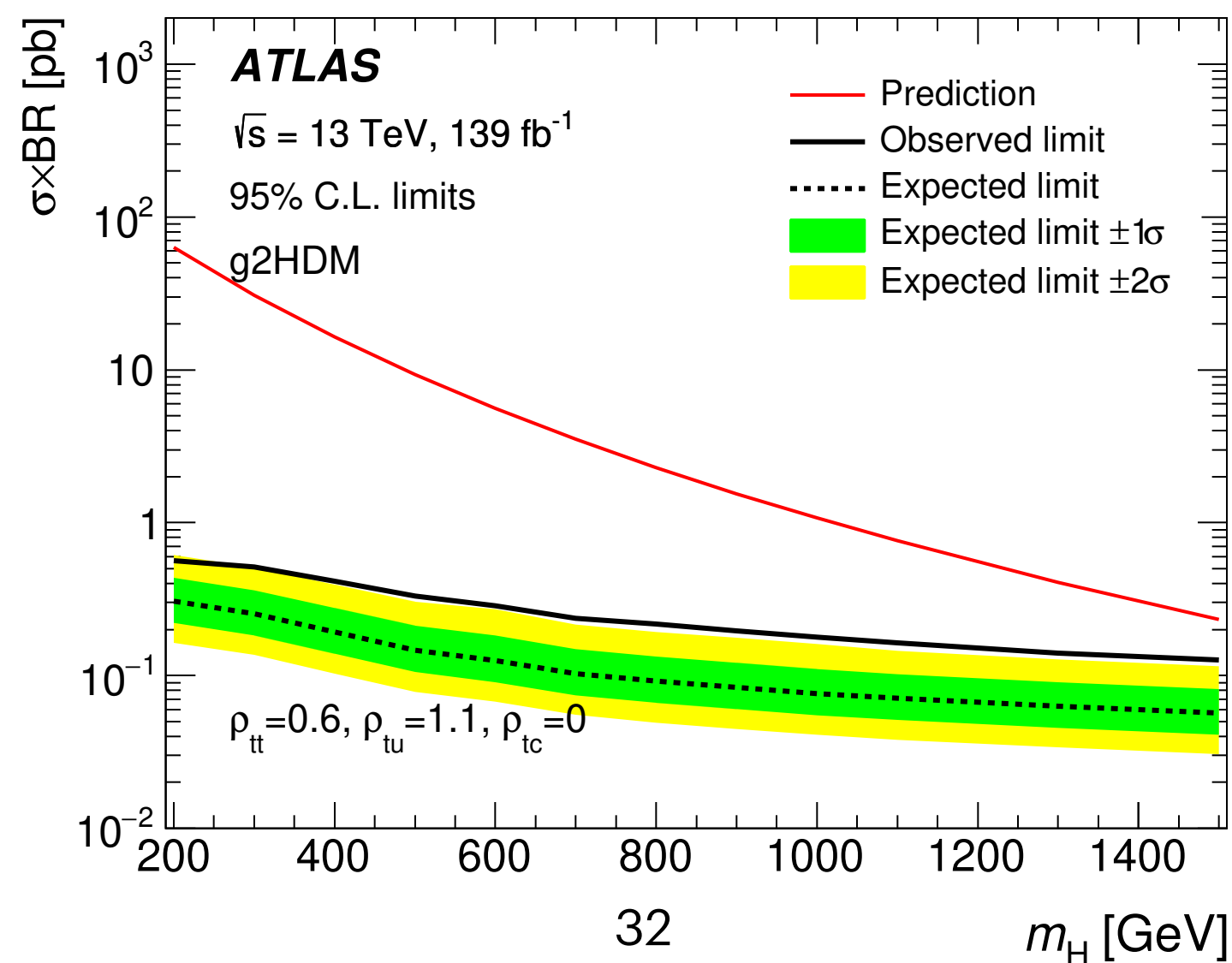
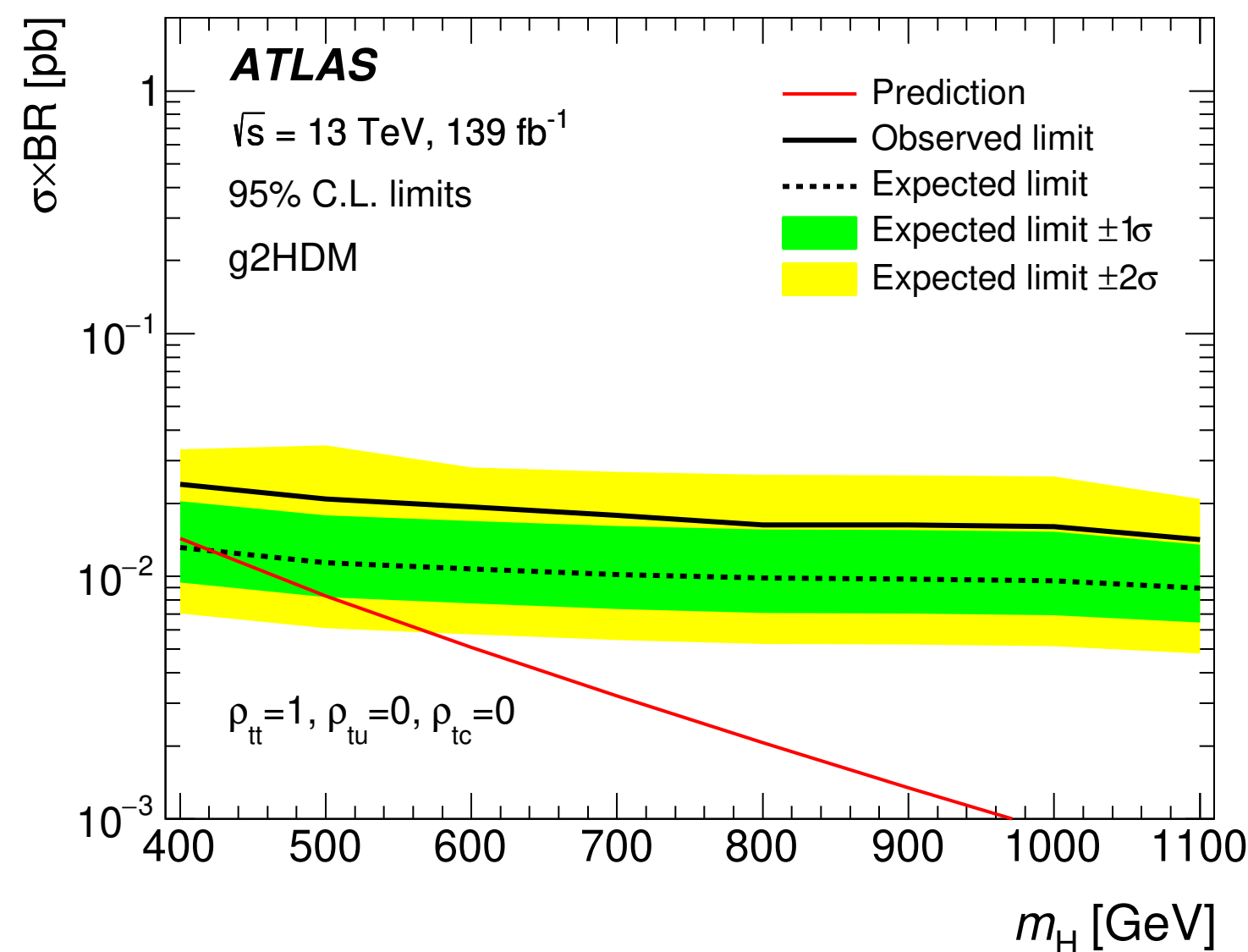
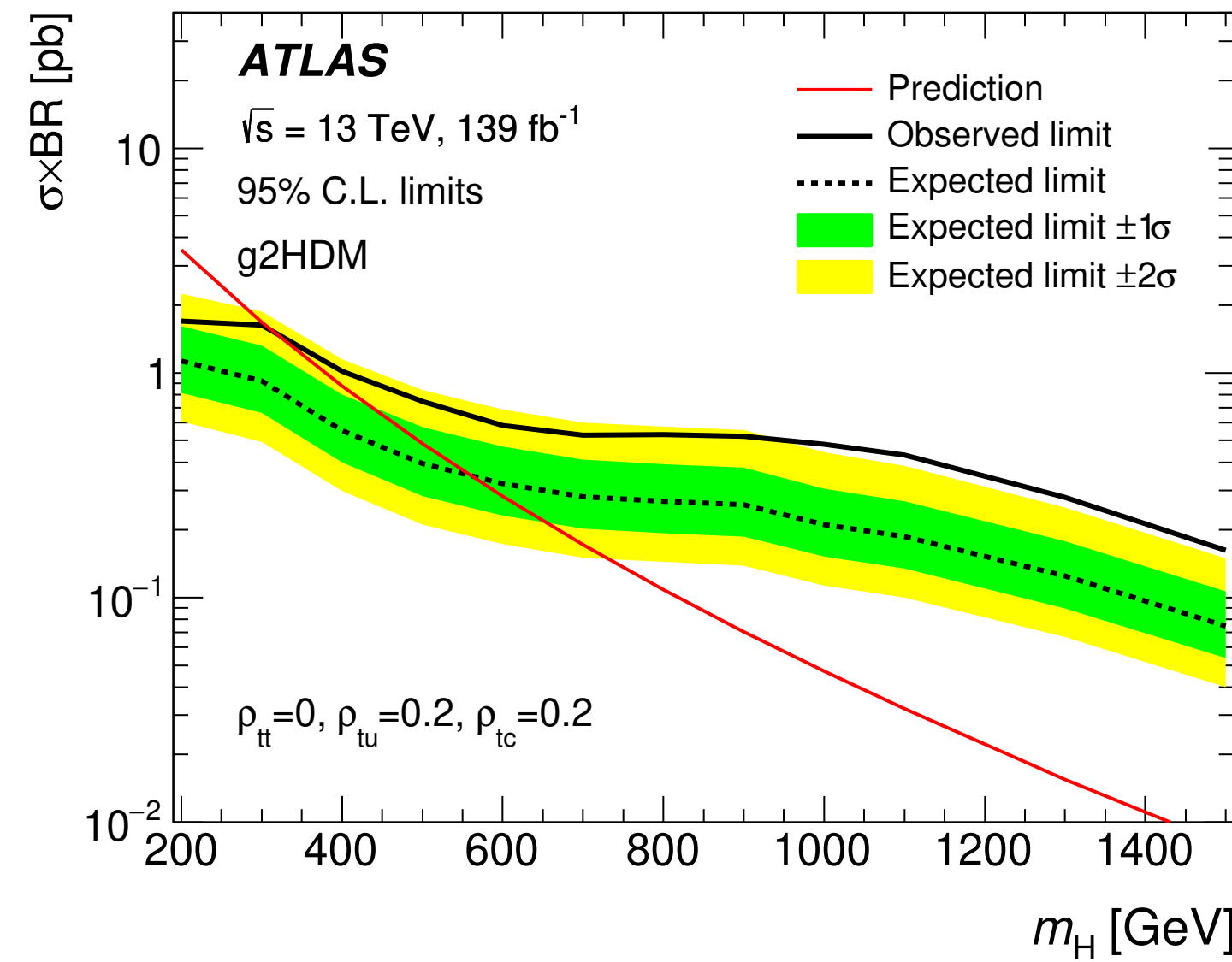
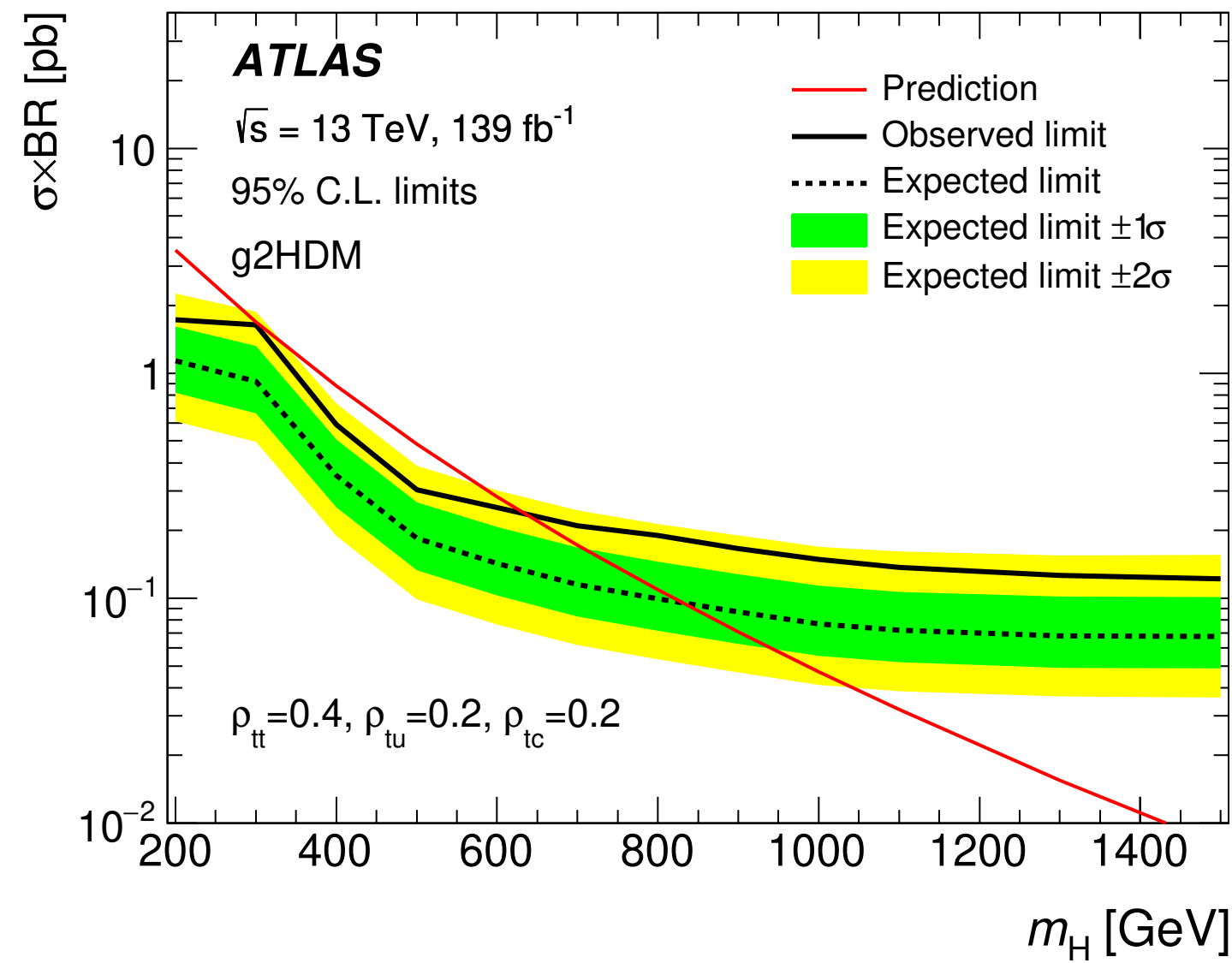
[arXiv:2307.14759](https://arxiv.org/abs/2307.14759)



# Heavy Higgs in multi-lepton plus b-jets

Search for heavy Higgs bosons in multilepton plus b-jets final states

[arXiv:2307.14759](https://arxiv.org/abs/2307.14759)

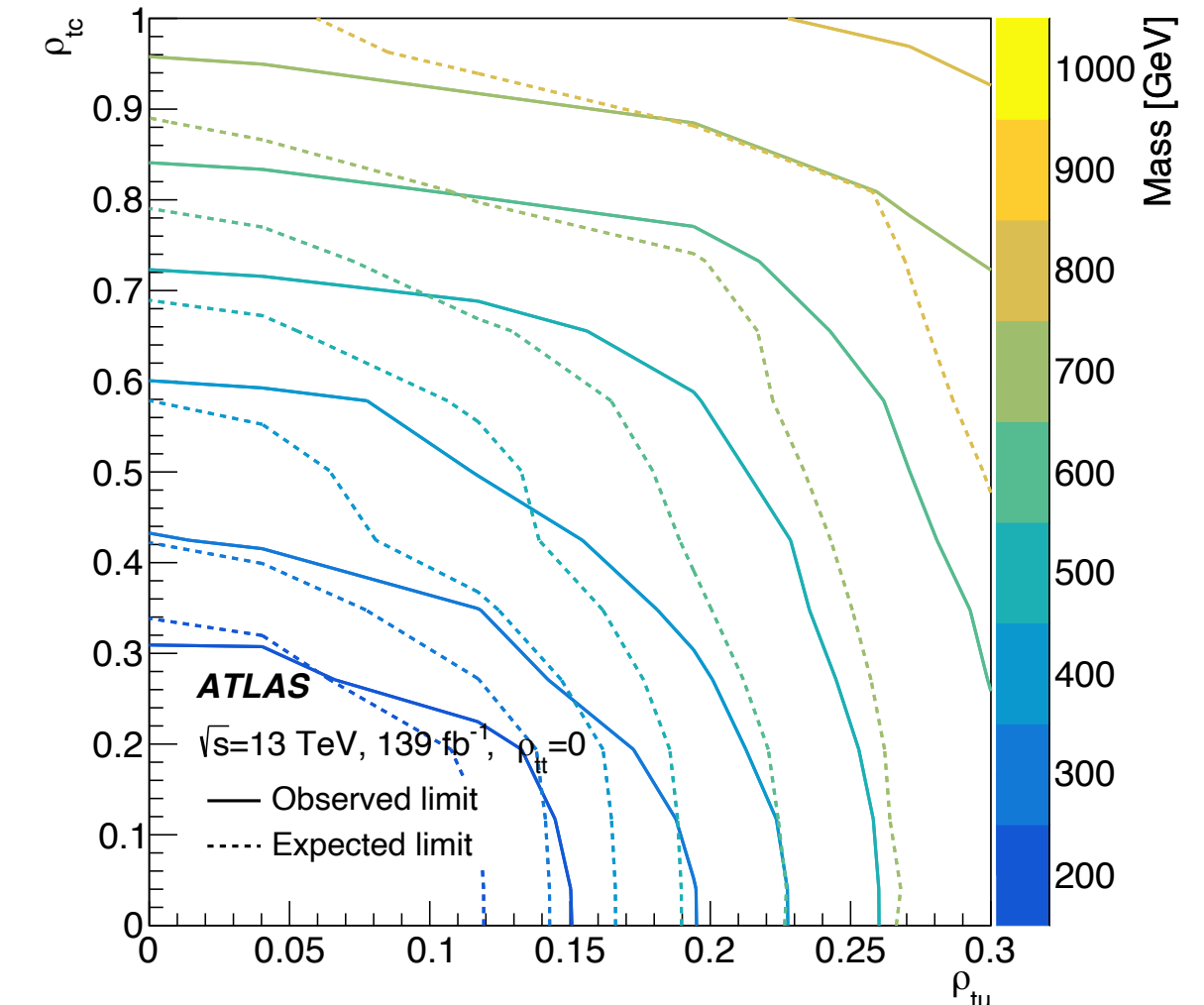
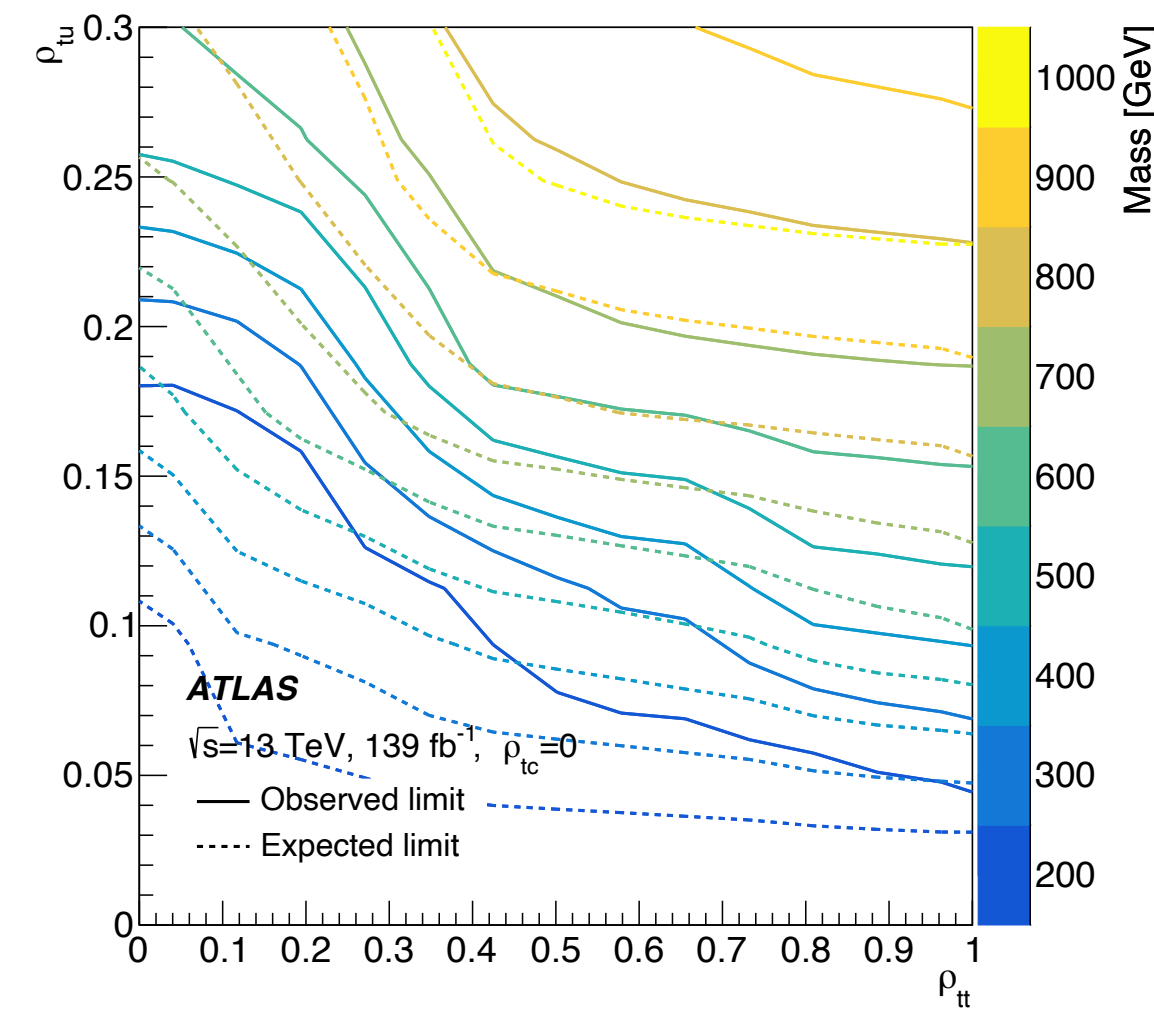
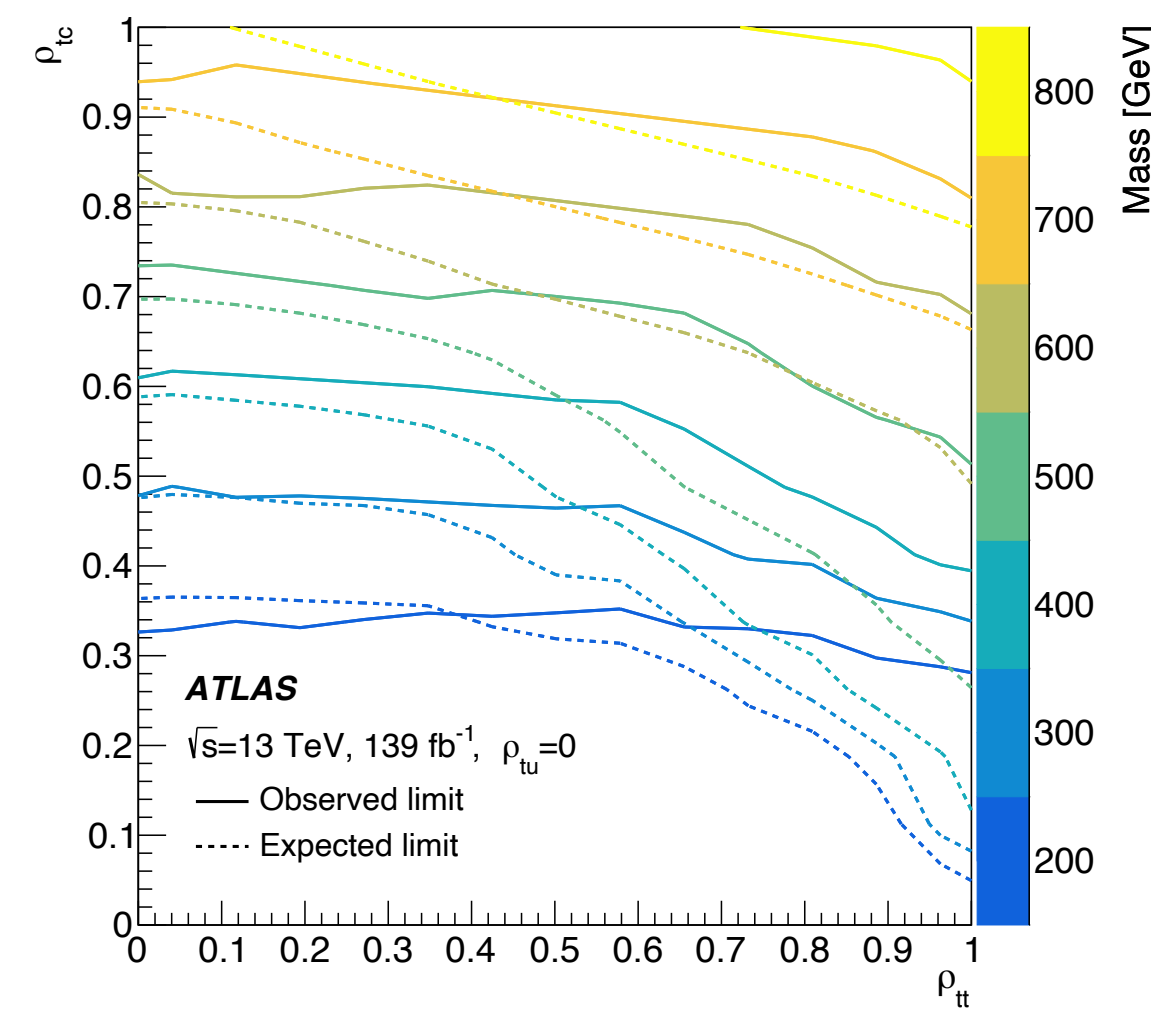
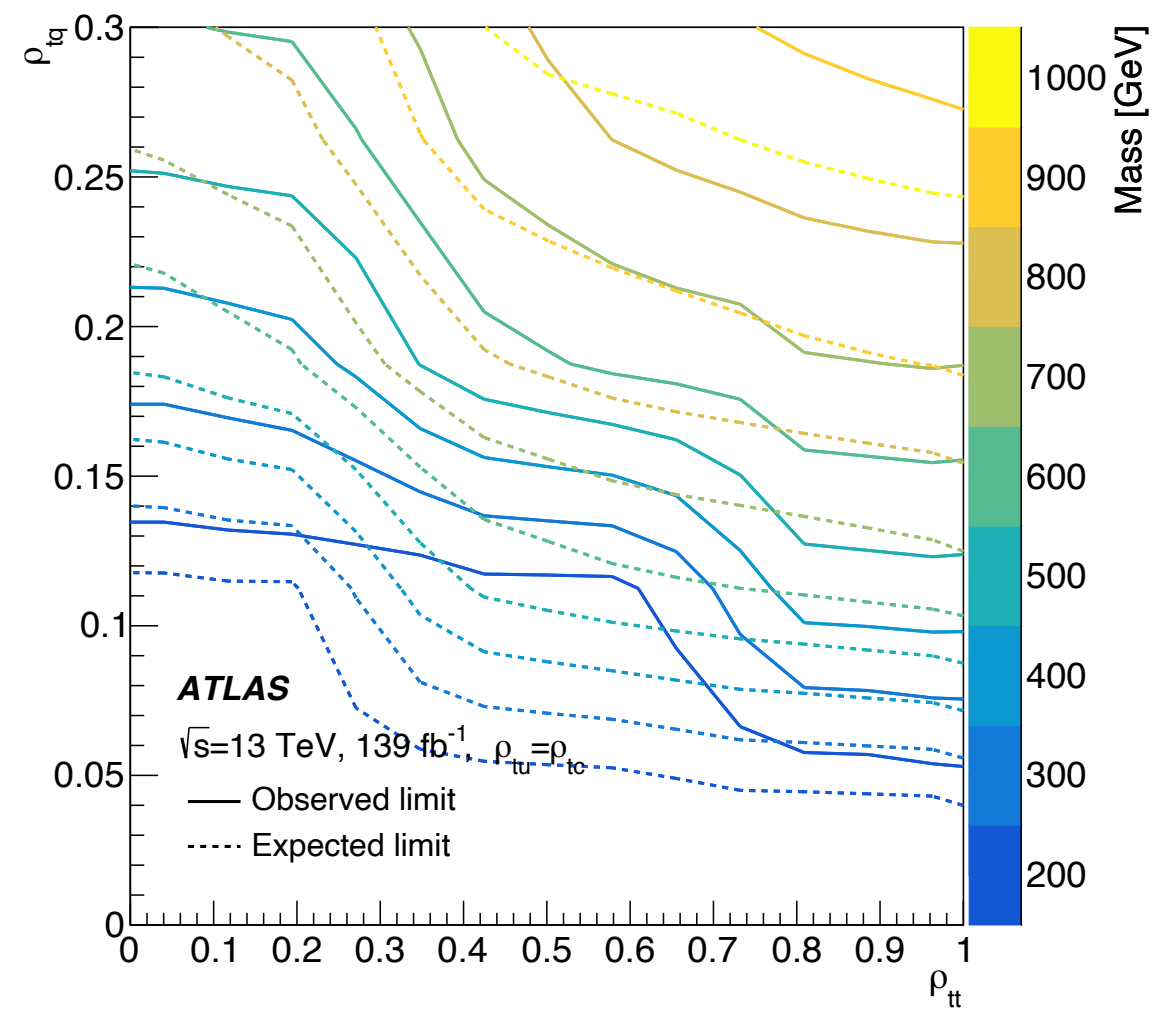




# Heavy Higgs in multi-lepton plus b-jets

Search for heavy Higgs bosons in multilepton plus b-jets final states

[arXiv:2307.14759](https://arxiv.org/abs/2307.14759)



$$t \rightarrow qX, X \rightarrow bb$$

[arXiv:2301.03902](https://arxiv.org/abs/2301.03902)

Search for new scalars produced in the decay of a top-quark and decaying to  $bb$

- Mass-parameterised Neural Network (pNN) classifier trained to separate signal and background, separately for the  $uX$  and  $cX$  channels, and pNN output used as final discriminant variable in all SRs

Input variables for the pNN:

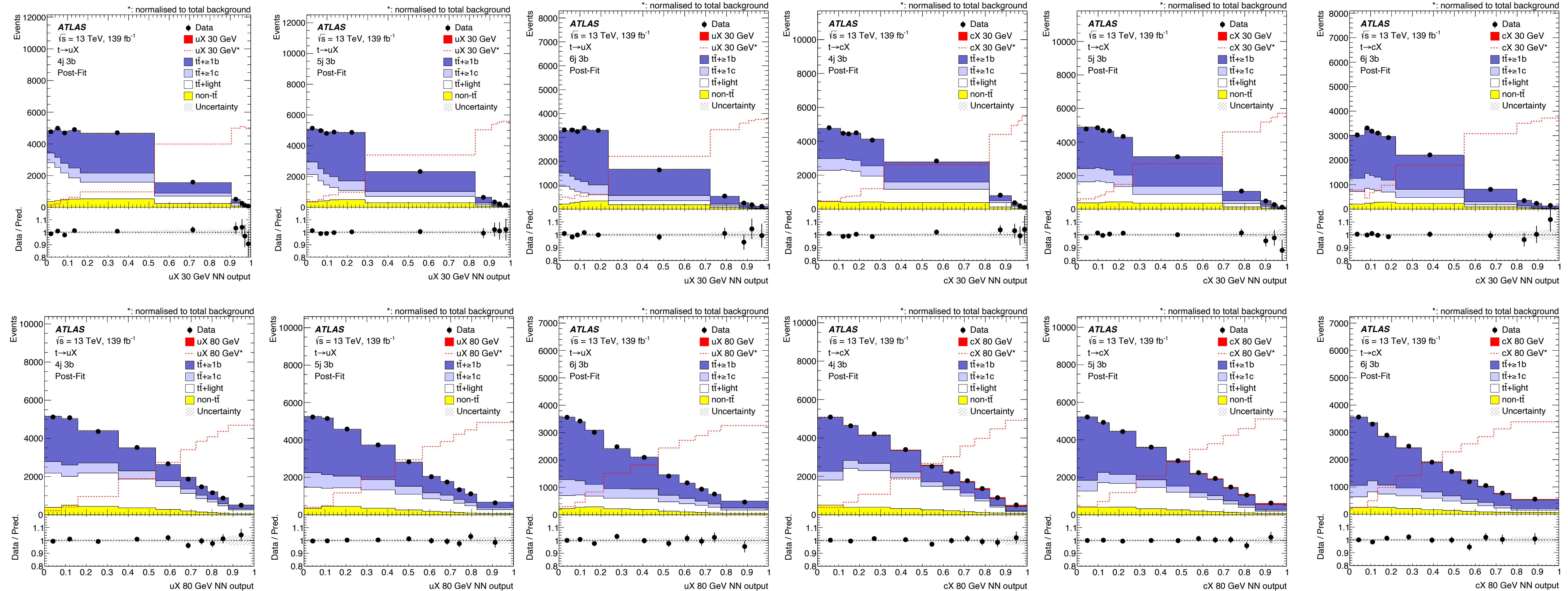
- $P_t$ ,  $\eta$  and  $\phi$  of the jets
- Pseudo-continuous b-tagging score of the b-jets
- $P_t$  and  $\eta$  of the leptons
- MET and MET  $\phi$
- 3 Invariant masses of two b-jets from the three leading jets combined in pairs
- 3  $\Delta R$  between two b-jets from the three leading jets combined in pairs

# $t \rightarrow qX, X \rightarrow bb$

arXiv:2301.03902

Search for new scalars produced in the decay of a top-quark and decaying to  $bb$

- Mass-parameterised Neural Network (pNN) classifier trained to separate signal and background, separately for the  $uX$  and  $cX$  channels, and pNN output used as final discriminant variable in all SRs



# $t\bar{t}a, a \rightarrow \mu\mu$

Search for light pseudo-scalar Higgs bosons produced in association with a top-quark pair and decaying in  $\mu\mu$

2 Signal Region categories defined based on lepton flavours and di-muon invariant mass requirements:

- $e\mu\mu$  with  $12 \text{ GeV} < m_{\mu\mu}^a < 77 \text{ GeV}$
- $\mu\mu\mu$  with  $12 \text{ GeV} < m_{\mu\mu}^a < 77 \text{ GeV}$  and  $m_{\mu\mu}^{\text{other}} < 77 \text{ GeV}$  or  $> 107 \text{ GeV}$

3 Control Region categories for controlling  $t\bar{t}Z/WZ$  and  $t\bar{t}$ , defined based on:

- Lepton flavours
- Di-muon invariant mass
- Number of jets and b-jets

	Signal Regions		on-Z Control Region		$t\bar{t}$ Control Region
Channel	$e\mu\mu$	$\mu\mu\mu$	$e\mu\mu$	$\mu\mu\mu$	$e\mu\mu$
Binning	$m_{\mu\mu}^a$	$m_{\mu\mu}^a$	$n_{\text{jets}}, n_{b\text{-jets}}$	$n_{\text{jets}}, n_{b\text{-jets}}$	$p_{\text{T}}^{\mu, \text{fake}}$
$n_{\text{electrons}}$	1	0	1	0	1
$n_{\text{muons}}$	2	3	2	3	2
$m_{\mu\mu} [\text{GeV}]$	$12 < m_{\mu\mu}^a < 77$	$12 < m_{\mu\mu}^a < 77$ and $m_{\mu\mu}^{\text{other}} < 77$ or $> 107$	$77 < m_{\mu\mu}^a < 107$	$77 < m_{\mu\mu}^a < 107$ or $77 < m_{\mu\mu}^{\text{other}} < 107$	$12 < m_{\mu\mu}^a < 77$
$n_{\text{jets}}$	$\geq 3$				1 or 2
$n_{b\text{-jets}}$	$\geq 1$				1

