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On behalf of the ATLAS Collaboration

Searches for additional neutral Higgs bosons in ATLAS

Higgs 2023

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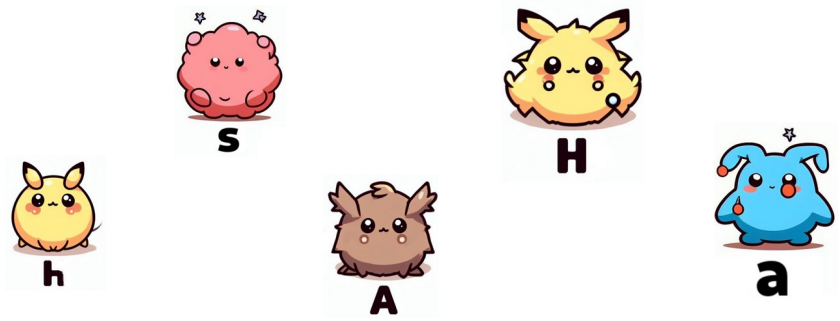
Searches for additional neutral Higgs bosons in ATLAS

- Discovery of the Higgs boson with m_H = 125 GeV completed Standard Model (SM)
  - ⇨ So far all measurements compatible with SM
  - ⇨ But SM leaves several open questions
- Many theories **Beyond the Standard Model** (BSM) predict additional Higgs bosons
  - ⇨ **Many searches in ATLAS** targeting different production and decay modes and mass ranges
- Presenting most recent searches for **additional neutral Higgs bosons** in ATLAS from LHC Run 2



Analysis	Reference
$t\bar{t}H/A \to t\bar{t}t\bar{t}$	JHEP 07 (2023) 203
Flavourful 2HDM multi-b multi-lepton	arXiv:2307.14759 (Sub. to JHEP)
$A \to ZH \to ll t\bar{t}$ / $\nu\bar{\nu}b\bar{b}$ (m_H != 125 GeV)	arXiv:2311.04033 (Sub. to JHEP)
$t \to qX$ (q=u,c), $X \to b\bar{b}$	JHEP 07 (2023) 199
$X \to WW \to e\nu\mu\nu$	ATLAS-CONF-2022-066
Low-mass $H \to \gamma\gamma$	ATLAS-CONF-2023-035

All ATLAS publications can be found here

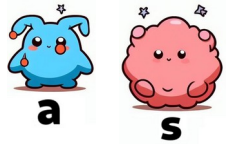
Why searching for additional neutral Higgs bosons?

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

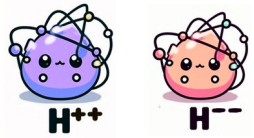
- **Electroweak Singlet Model:** SM Higgs doublet + additional singlet
  - ⇨ 2 neutral CP-even Higgs bosons

- **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
  - ⇨ 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

$t\bar{t}\,H/A \rightarrow t\bar{t}t\bar{t}$

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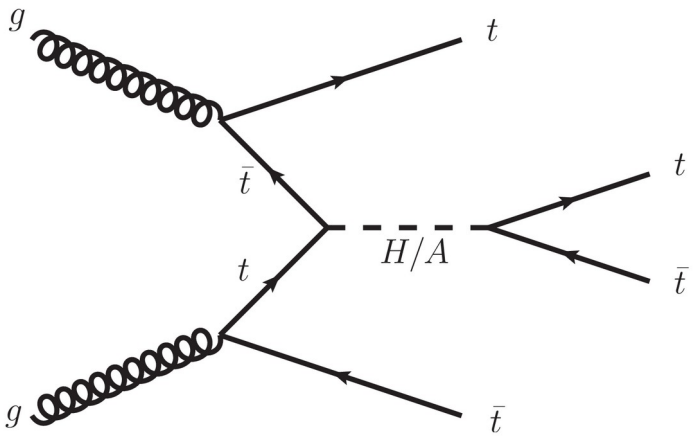
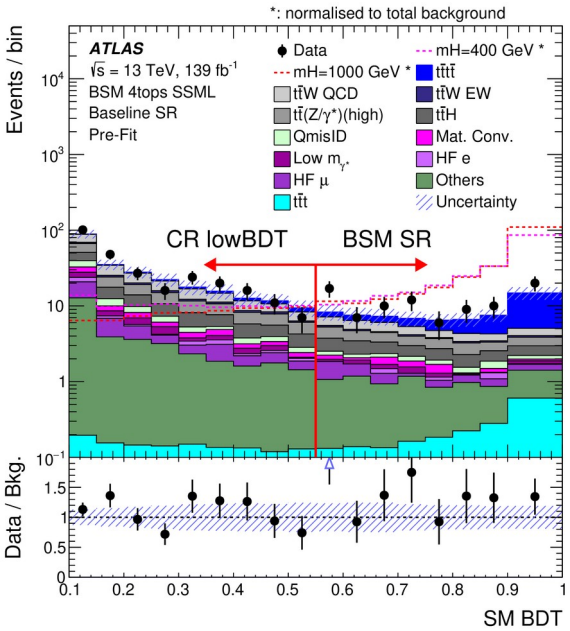
Search for heavy Higgs bosons (*H*/*A*) produced in association with a top-quark pair and decaying into a top-quark pair



- Heavy scalar (*H*) or pseudo-scalar (*A*) Higgs bosons from the 2HDM of Type-II (MSSM-like)
  - ⇨ Search in mass range **400-1000 GeV**
  - ⇨ Analysis performed in the **2*l*SS** and **≥3*l*** + ≥6 jets and ≥2 *b*-jets final states

- Main backgrounds: SM 4*t*, *ttW* QCD
- Boosted Decision Tree (BDT) to distinguish the SM 4*t* events from other backgrounds (SM BDT)
  - ⇨ Define **Signal Region (SR)** and a **low-BDT Control Region (lowBDT CR)**
- **4 additional CR** categories for controlling HF non-prompt leptons, photon conversion and *ttW*



$t\bar{t}\,H/A \rightarrow t\bar{t}t\bar{t}$

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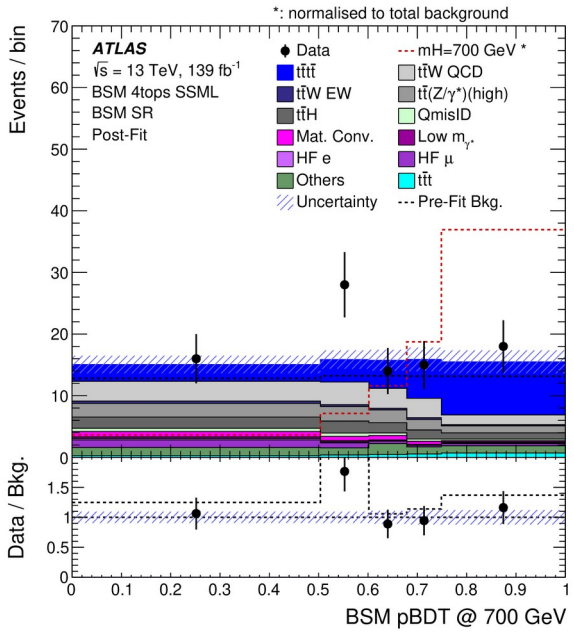
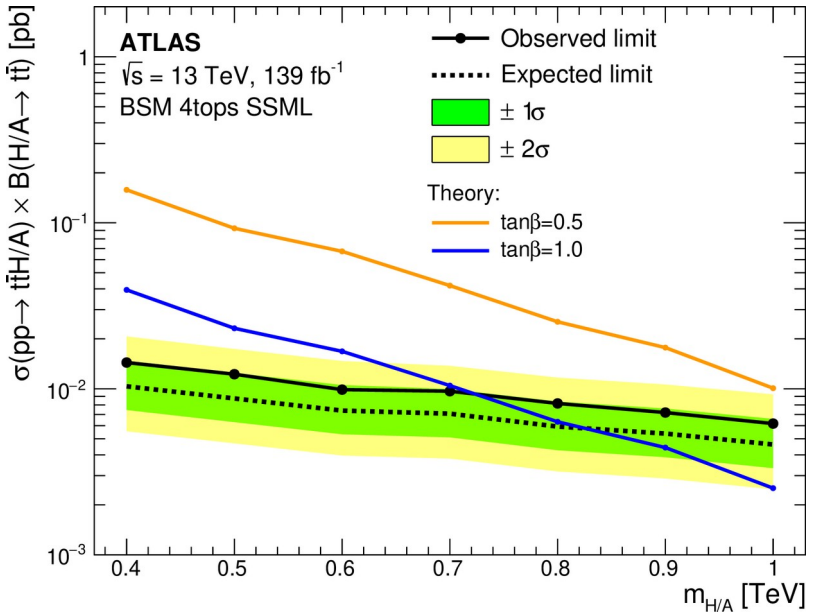
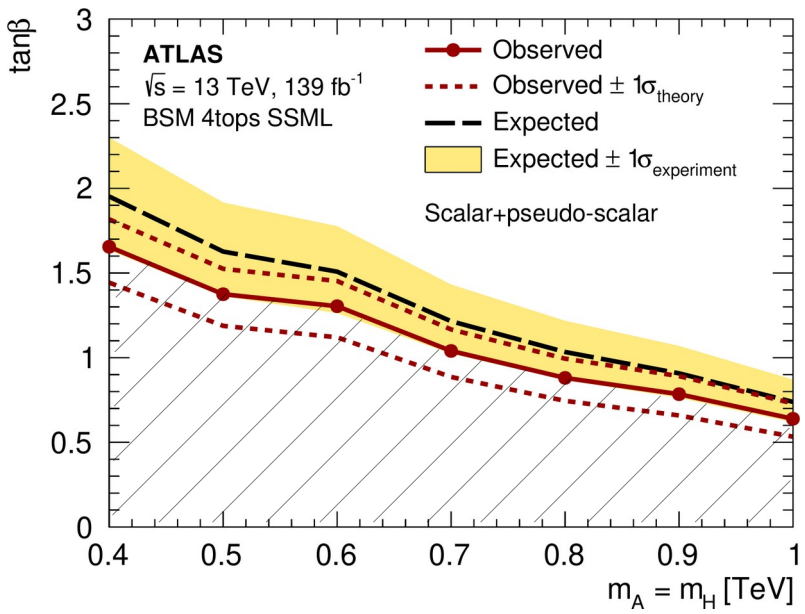
- **Mass-parametrized BDT** (pBDT) trained in the SR to distinguish between the signal and all backgrounds
  - ⇨ pBDT output used as final discriminant variable
- No significant excess above SM predictions observed
  - ⇨ Upper limits set on **σ × BR** as a function of m_H from fit of SR and all CRs



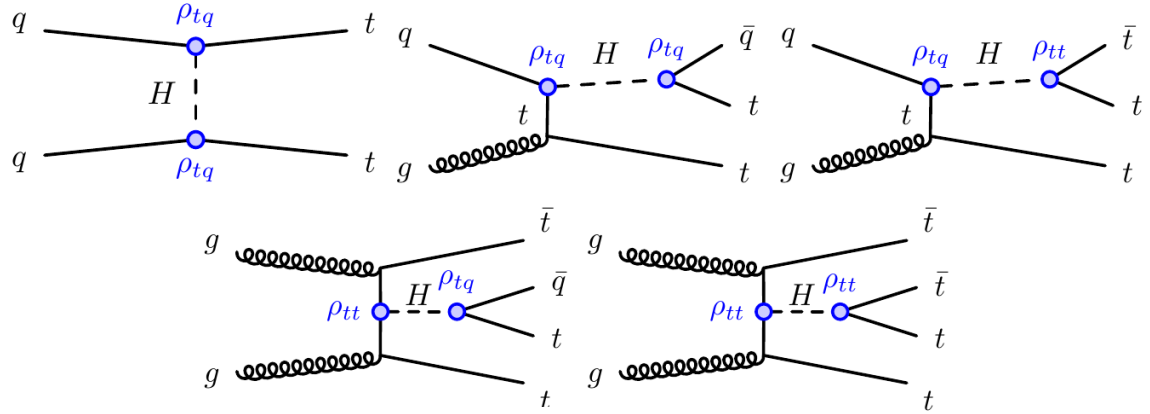


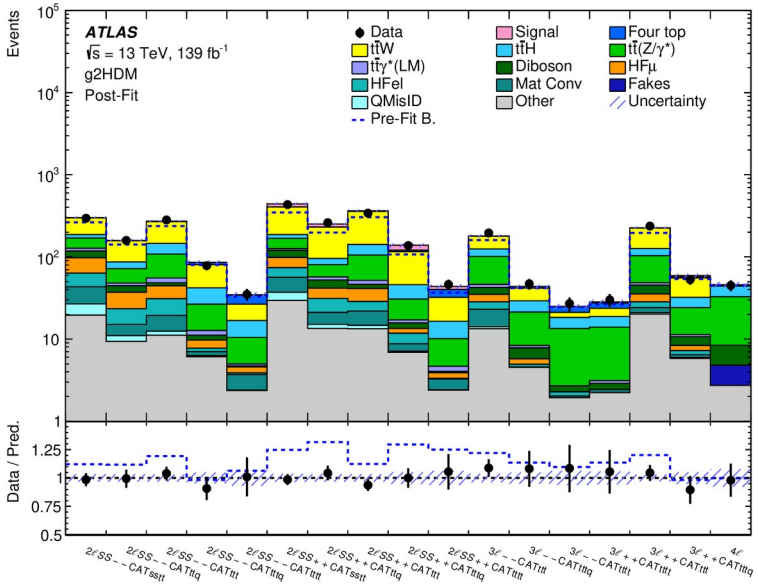


arXiv:2307.14759 (Sub. to JHEP)

Flavourful 2HDM multi-b multi-lepton

Search for heavy Higgs bosons in flavour-violating decays with multiple leptons and *b*-jets final states





- Heavy Higgs *H* in **mass range 200-1500 GeV**
- 2HDM with **extra flavour-changing neutral Higgs interactions** (FCNH) (g2HDM)
  - ⇨ Considering only BSM couplings involving the top-quark (ρ_{tt},ρ_{tc} ,ρ_{tu})
  - ⇨ Can explain generation of baryon asymmetry
- Resulting in a same-sign top-quark pair, 3 or 4 top-quarks
  - ⇨ Search in final states with ***2l*,*3l* or *4l*, + *b*-jets**

- Main background: *ttW*

17 Signal Region (SR) categories, based on:

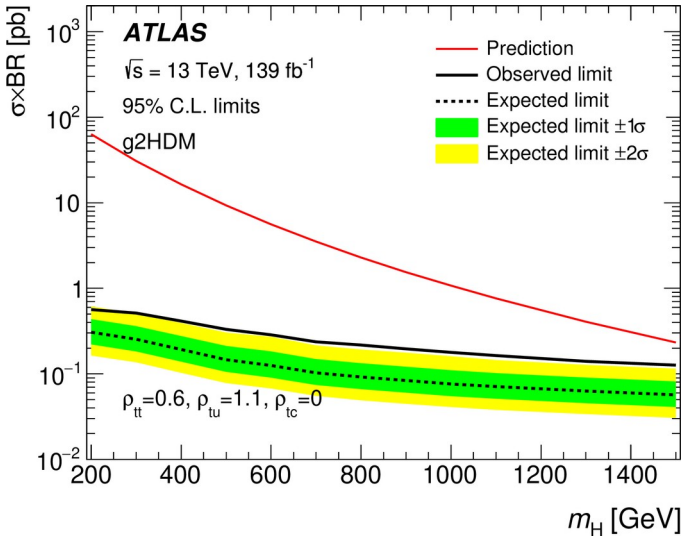
- Number and charge sign of leptons
- Deep neural network (DNN) to distinguish different production/decay modes

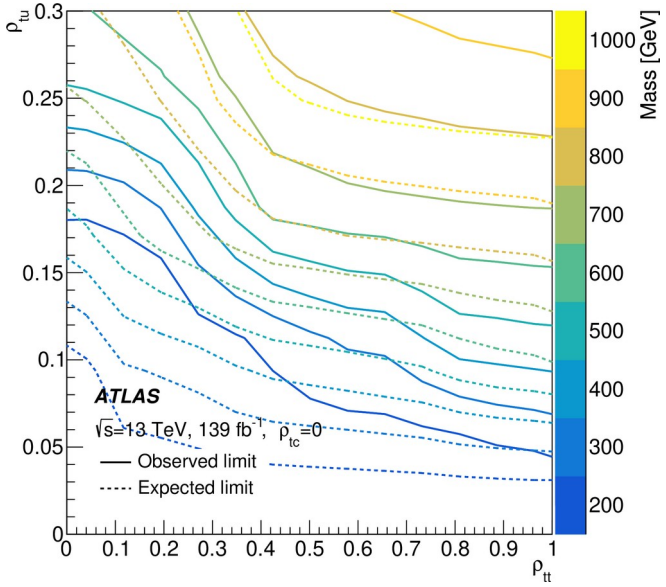
10 Control Region (CR) categories controlling HF non-prompt leptons, photon conversion, *VV* and *ttZ*

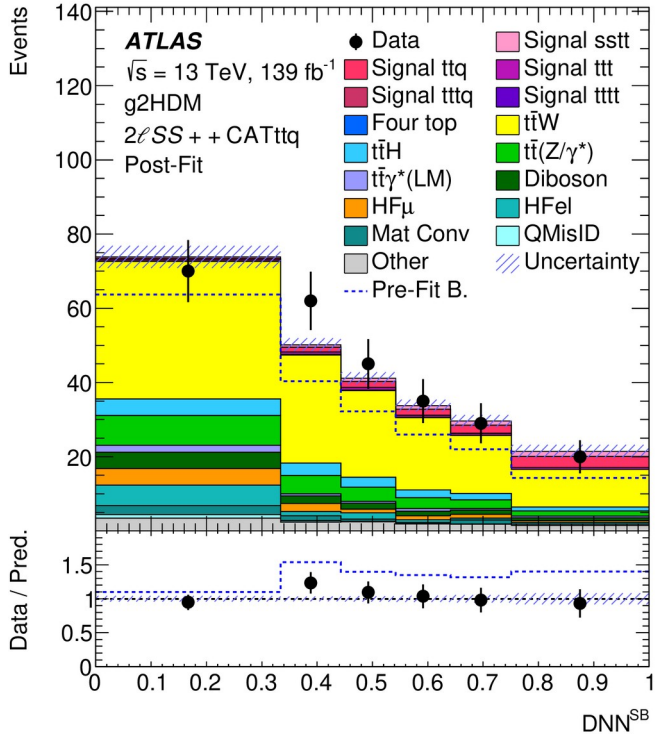
arXiv:2307.14759 (Sub. to JHEP)

Flavourful 2HDM multi-b multi-lepton

- DNN trained in each SR to separate signal and background, output used as final discriminant
- No significant excess above the SM predictions observed
  - ⇨ **Mild excess** observed at m_H = 900 GeV for (ρ_{tt}, ρ_{tc}, ρ_{tu}) = (0.6, 0.0, 1.1) with local significance of **2.8σ**
- Upper limits set on **σ × BR** and on the BSM Higgs **couplings ρ_{tq}** as a function of m_H from fit of all SRs and CRs



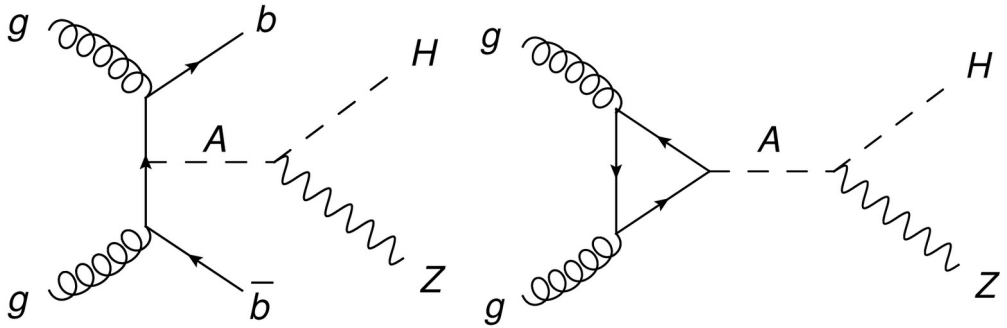




arXiv:2311.04033 (Sub. to JHEP)

A → ZH → *llt$\bar{t}$ / vv$\bar{b}\bar{b}$*

Search for a heavy CP-odd Higgs boson (*A*) decaying to a heavy CP-even Higgs Boson (*H*) and a *Z* in the *llt$\bar{t}$ / vv$\bar{b}\bar{b}$* channels



- Heavy Higgs bosons *(A/H)* from the 2HDM
- Mass range **400-1200 GeV for *A***, and **130-800 GeV for *H***
  - ⇨ Decay of *A* to a BSM Higgs boson *H* and a *Z* boson
  - ⇨ *Z* → 2*l* or 2*ν* and *H* → *t$\bar{t}$* or *bb*, leading to ***lltt* and *vvbb* final states**

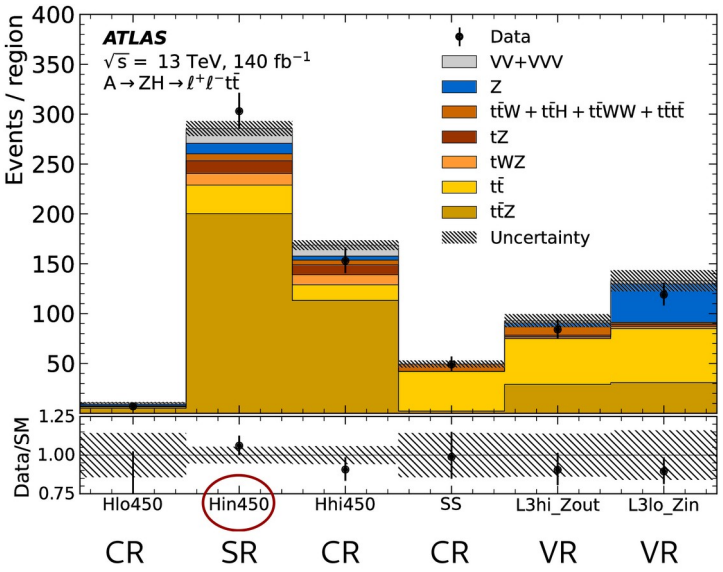
- Main backgrounds: *ttZ* / *Z*+hf, *t$\bar{t}$*

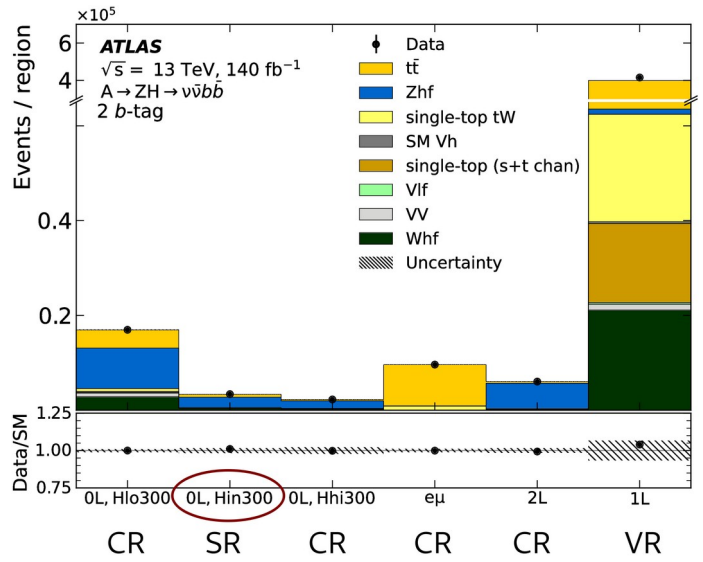
3 SR categories, based on number of leptons, jets, *b*-jets, MET, reconstructed *Z* and *H* boson masses:

- 1 *lltt* SR: 3*l*, ≥4 jets and 2 *b*-jets
- 2 *vvbb* SRs: 0*l*, MET, 2 *b*-jets and ≥3 *b*-jets

11 CR categories for controlling:

- *ttZ* and *t$\bar{t}$* in the *lltt* channel (3 CRs)
- *Z*+HF and *t$\bar{t}$* in the *vvbb* channel (8 CRs)

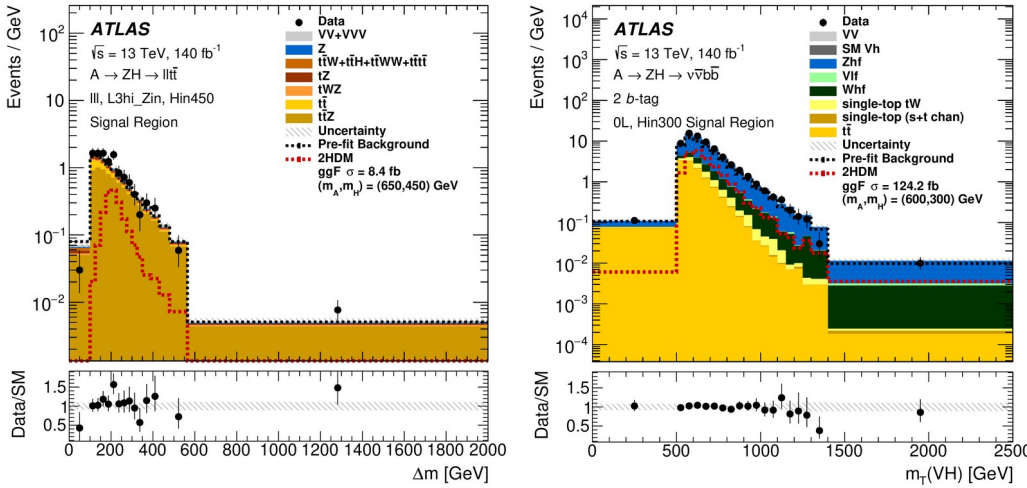


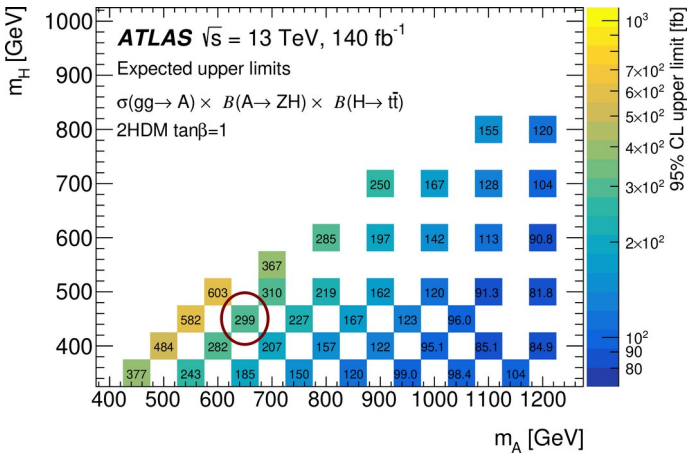


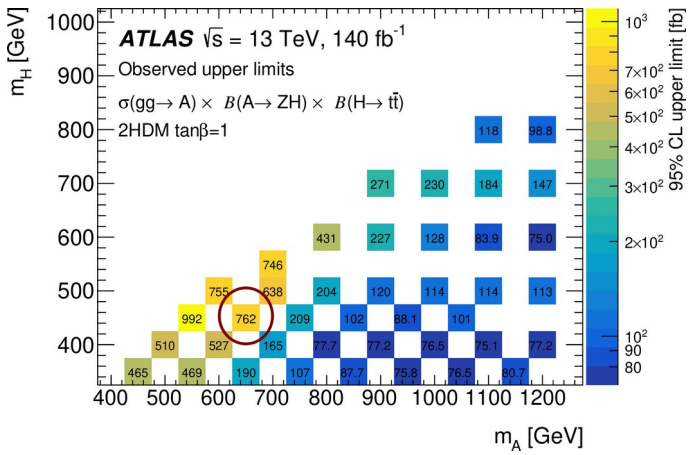
arXiv:2311.04033 (Sub. to JHEP)

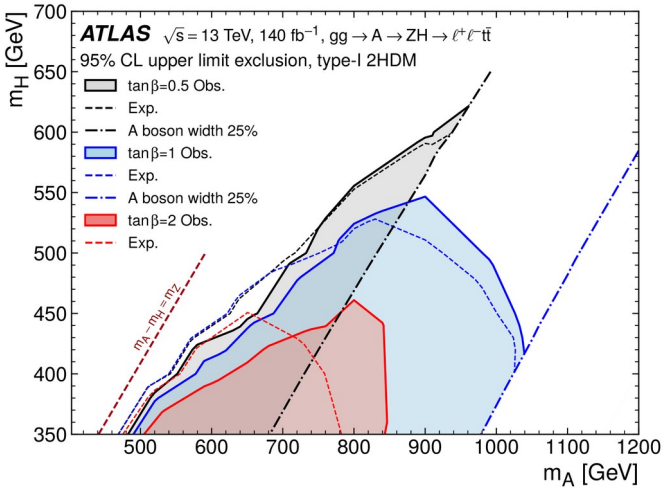
A → ZH → *llt$\bar{t}$ / vvb$\bar{b}$*

- Final discriminant variables:
  - ⇨ *llt$\bar{t}$* SR: mass difference between *A* and *H*: $\Delta m = m(l^+l^-t\bar{t}) - m(t\bar{t})$
  - ⇨ *vvbb* SRs: transverse mass of *A* $m_T(VH)$
- No significant excess above SM observed
  - ⇨ **Mild excess** observed in the *llt$\bar{t}$* channel for (m_A, m_H) = (650 GeV, 450 GeV) with local significance of **2.85σ**
- Upper limits set on **σ × BR** in the **m_H - m_A plane** from fit of SRs and CRs
- Constraints set on the 2HDM Type-I and Type-II in the **m_H - m_A plane** for different tan β









$t \to qX,\ X \to b\bar{b}$

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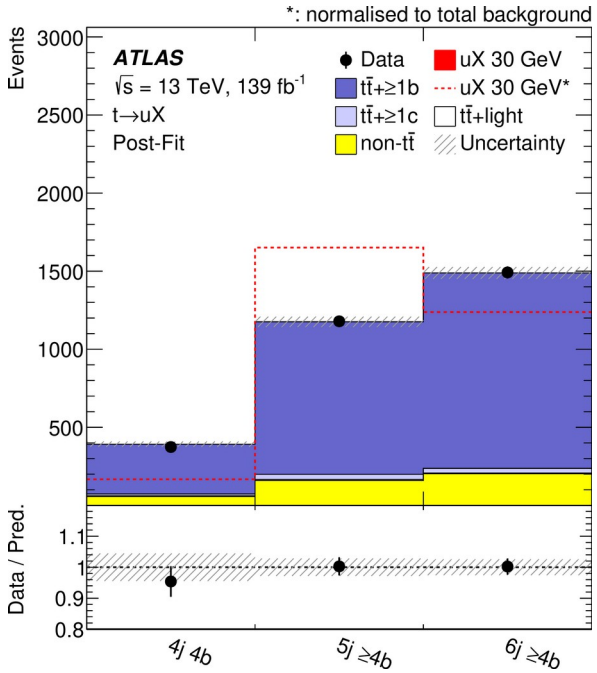
Search for new scalars *X* produced in the decay of a top-quark and decaying to *bb*

3 CRs:



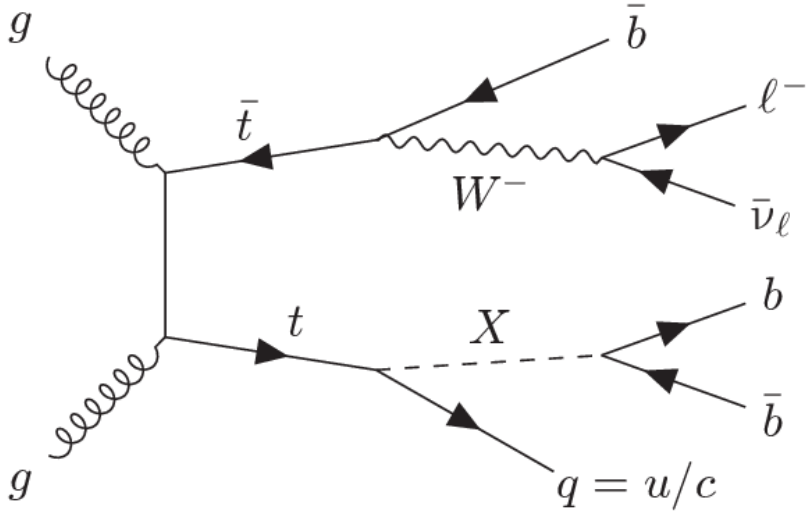
- Main backgrounds: $t\bar{t}$+light, $t\bar{t}$+*b*

3 CR categories defined for controlling $t\bar{t}$+jets

3 SR categories based on number of jets and *b*-jets:

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

- New scalar *X* in the mass range **20-160 GeV**
  - ⇨ Inspired by the non-SM Higgs from the Flavon Model with **flavour-changing neutral current** (FCNC) top-decays
  - ⇨ Analysis performed in final states with **1l, ≥4 jets and 3 *b*-jets**



$t \to qX,\ X \to b\bar{b}$

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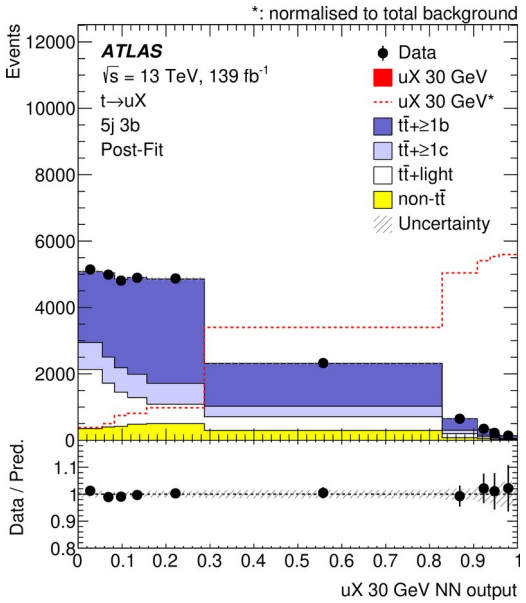
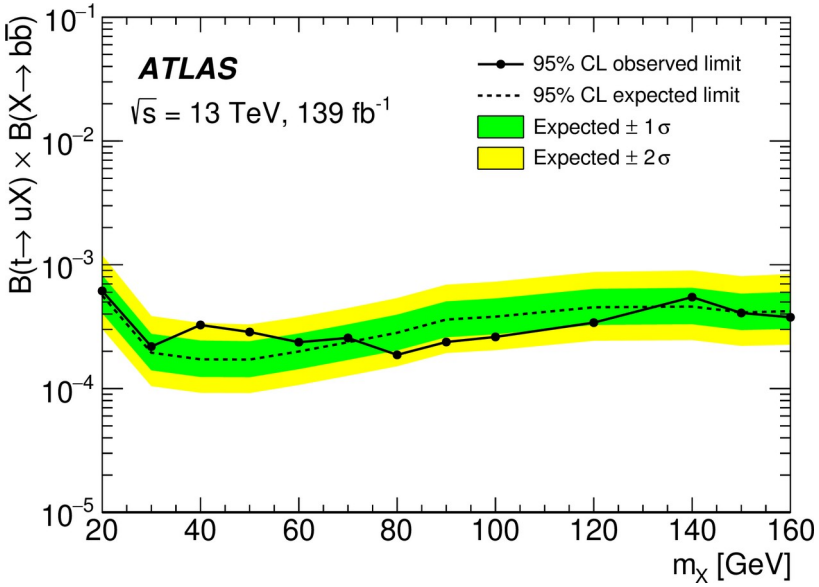
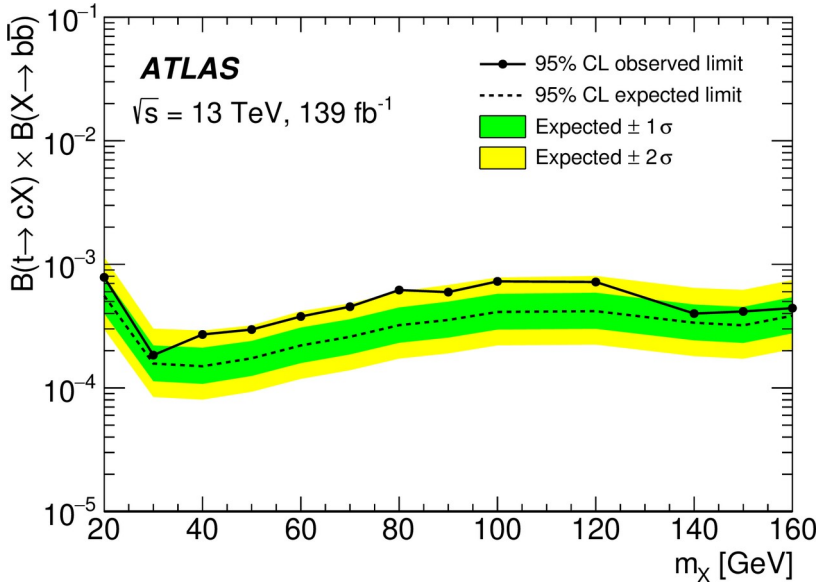
- **Mass-parametrized Neural Network** (pNN) trained to separate signal and background, separately for *cX* and *uX* channels
  - ⇨ pNN output used as final discriminant variable in all SRs





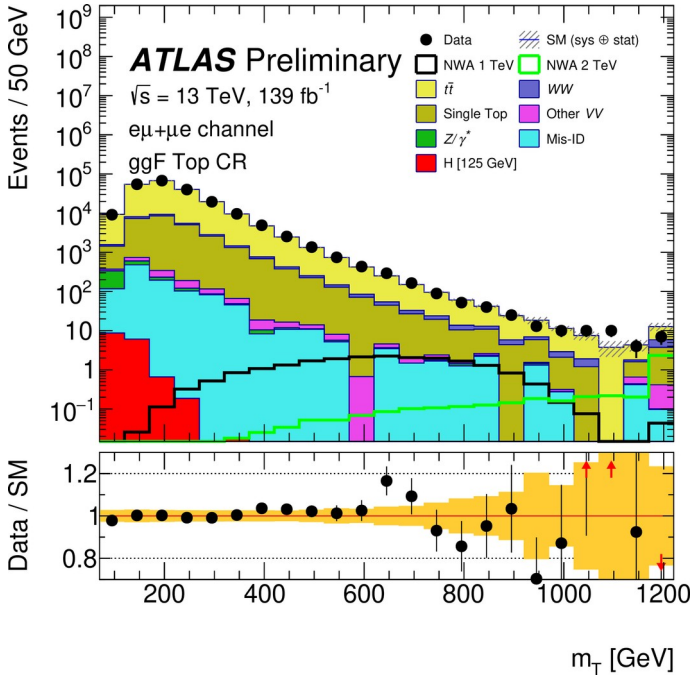


- No significant excess above SM observed
  - ⇨ **Mild excess** observed in the *uX* channel at m_X = 40 GeV with local significance of **1.8σ**
  - ⇨ **Mild excess** of roughly **2σ** local observed in the *cX* channel in the range 40-120 GeV
  - ⇨ Upper limits set on **BR($t \to uX$) × BR($X \to bb$)** and on **BR($t \to cX$) × BR($X \to bb$)** as function of m_X from fit of all SRs and CRs

$X \to WW \to e\nu\mu\nu$

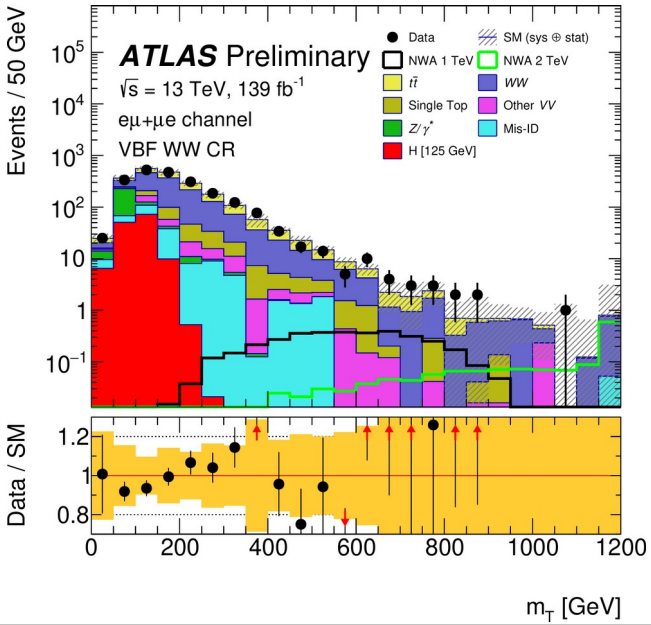
ATLAS-CONF-2022-066

Search for heavy resonances (X) in the decay channel $W^+W^- \to e\nu\mu\nu$



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

- New heavy resonances X in the mass range **200-6000 GeV** from 5 different models:
  - ⇨ a Higgs-like narrow width scalar
  - ⇨ a Higgs boson in the Georgi–Machacek model
  - ⇨ a Radion particle arising in the bulk Randall-Sundrum model
  - ⇨ spin-1 heavy vector triplet
  - ⇨ a spin-2 Kaluza-Klein graviton
- Considering $W^+W^- \to e\nu\mu\nu$ channel



- Main backgrounds: Top, $qqWW$

4 CR categories defined for controlling $t\bar{t}/Wt$ and non-resonant WW background

3 SR categories targeting resonance production types:

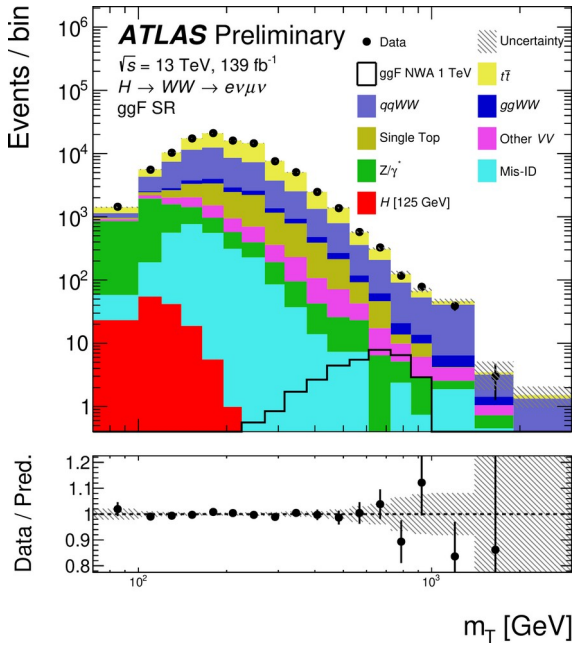
- 1 for ggF
- 2 for VBF: =1 jet and ≥2 jets

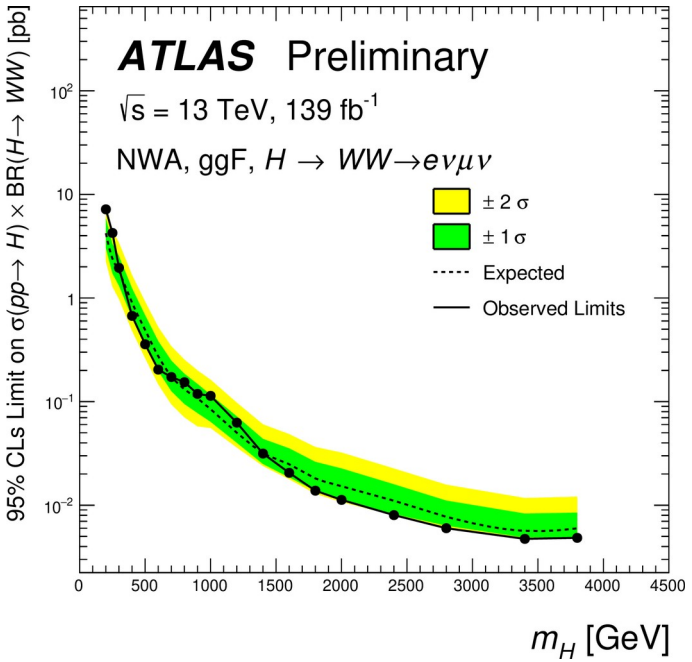
$X \to WW \to e\nu\mu\nu$

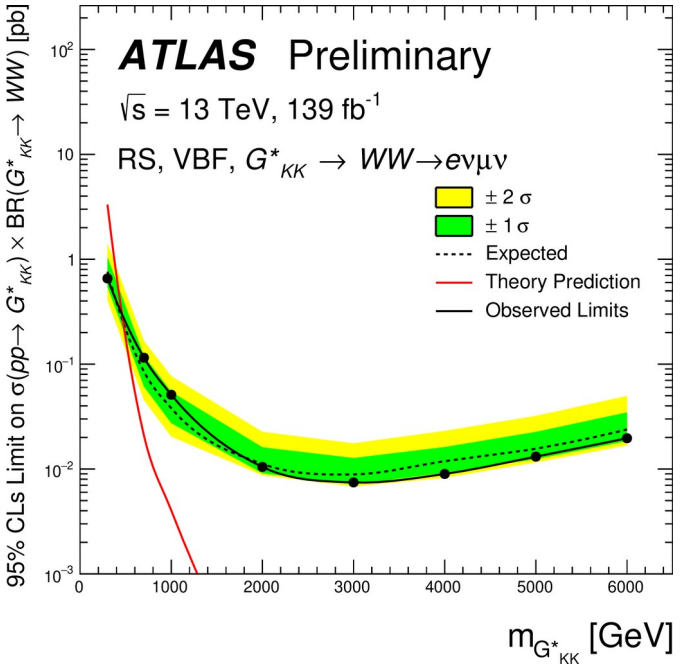
- Transverse mass m_T used as final discriminant variable in all SRs

$$m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{ll} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - |\vec{p}_{\mathrm{T}}^{\,ll} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}|^2}$$

$$\text{with } E_{\mathrm{T}}^{ll} = \sqrt{|\vec{p}_{\mathrm{T}}^{\,ll}|^2 + m_{ll}^2}$$



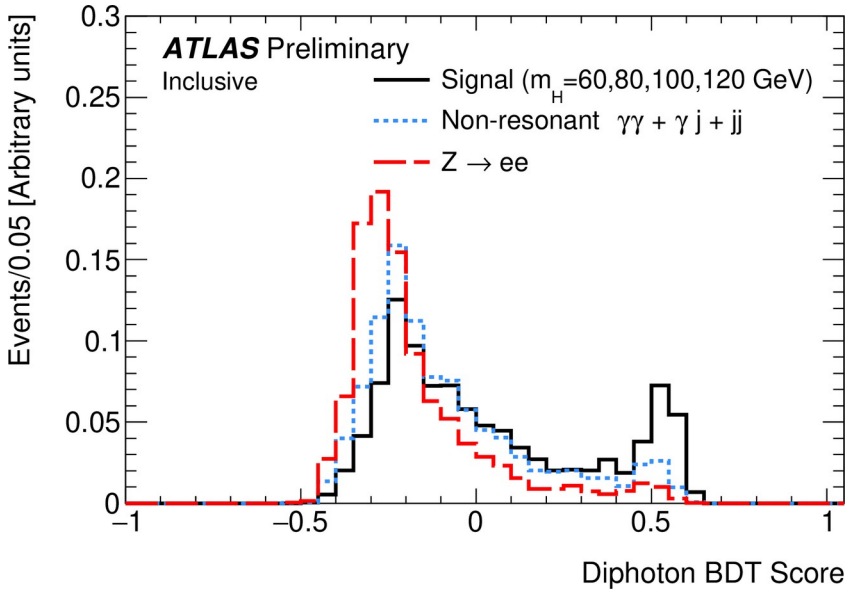




- No significant excess of events is seen
  - ⇨ Upper limits set on $\sigma X \times \mathrm{BR}(X \to WW)$ as function of m_X from fit of all SRs and CRs for the 5 models

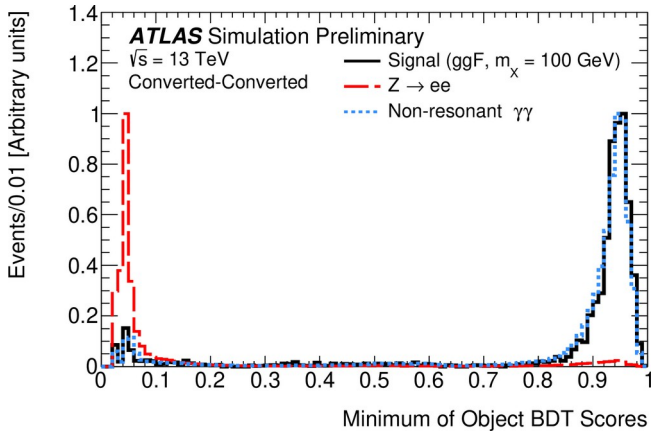
Low-mass $H \to \gamma\gamma$

Search for low-mass diphoton resonances in the 66 to 110 GeV mass range



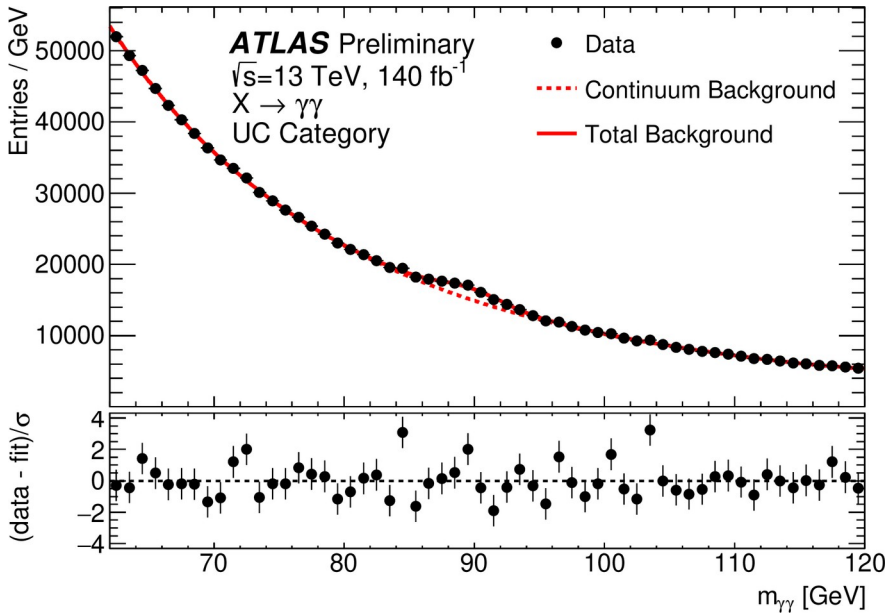
- Searches for general spin-0 boson (X) and additional low-mass Higgs (H)
- 2 main components of background:
  - ⇨ Non-resonant QCD-initiated $\gamma\gamma$, γj and jj continuum process
  - ⇨ Resonant Drell-Yan (DY) dielectron process (mainly $Z \to ee$)
  - ⇨ Both modelled by analytic functions derived from MC and data-driven methods
- Gradient BDT used for improved photon-electron discrimination

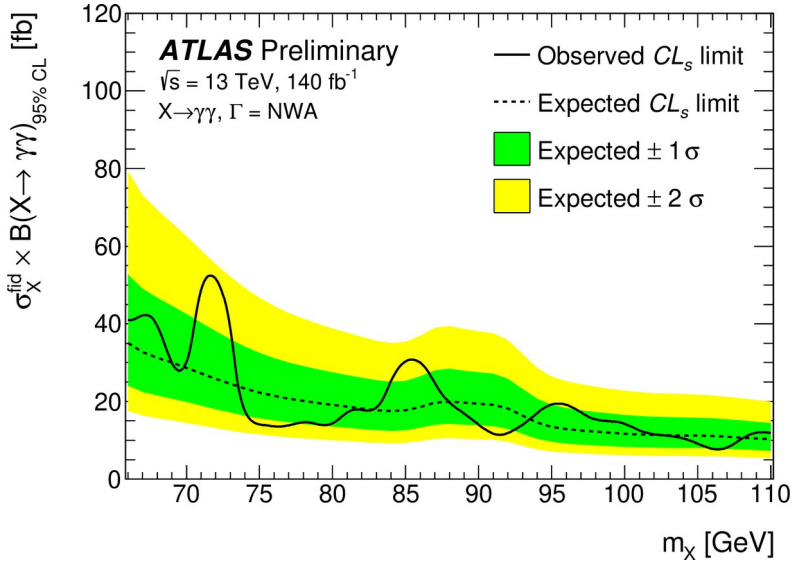
- **3 conversion categories** UU, UC, CC defined taking into account if photons are converted to electron pairs (C) or not (U)
- An **additional BDT** is used in the model-dependent search to enhance sensitivity (3 categories per conversion category, **9 total**)

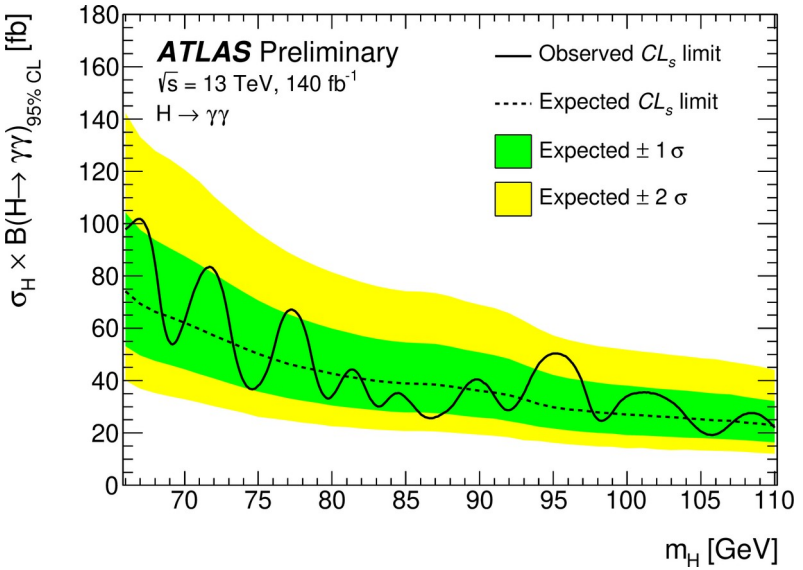


Low-mass $H \to \gamma\gamma$

- Using **diphoton invariant mass $m_{\gamma\gamma}$** as final discriminant variable in all SRs
  - ⇨ Considering a fit range of 62-120 GeV
  - ⇨ Signal modelled with analytic double-sided crystal ball function using parameters from MC simulations







- No significant excess above SM observed
  - ⇨ Upper limits set on **$\sigma_X^{fid} \times BR(X \to \gamma\gamma)$** and **$\sigma_H \times BR(H \to \gamma\gamma)$** as function of m_X/m_H of from fit in all SRs
  - ⇨ Most significant excess for $m_X = 71.8$ GeV with **2.2σ** local significance
  - ⇨ Most significant excess for $m_H = 95.4$ GeV with **1.7σ** local significance

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** & **broad mass range**
  - ⇨ Improved sensitivity 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!

Questions?

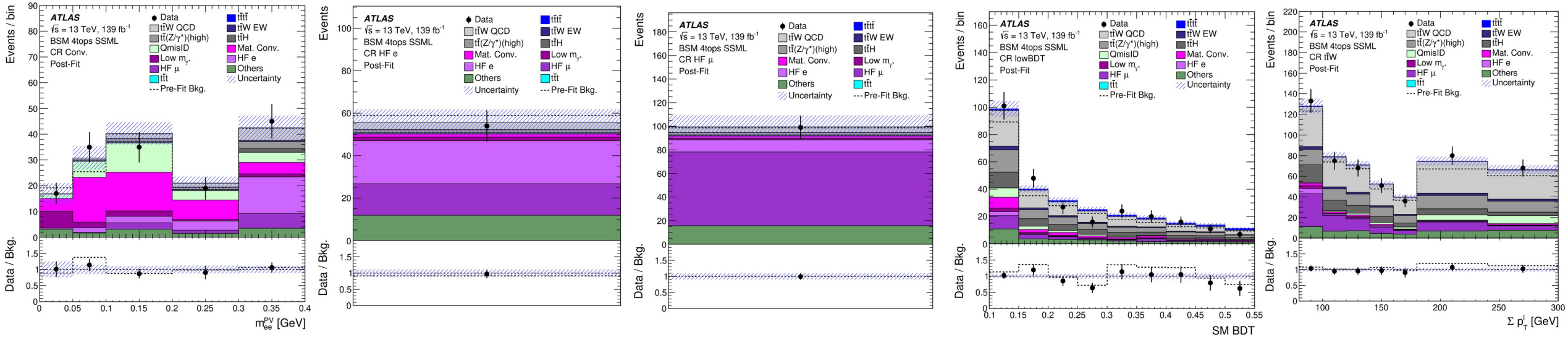
Backup

$t\bar{t}\,H/A \to t\bar{t}t\bar{t}$

JHEP 07 (2023) 203

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

- Boosted Decision Tree (BDT) classifier trained to distinguish the SM 4*t* events from other backgrounds (SM BDT)
  - ⇨ Used to define **BSM Signal Region (BSM SR)** and a **low-BDT Control Region (lowBDT CR)**
- **4 additional CR** categories for controlling HF non-prompt leptons, photon conversion and *ttW*
  - ⇨ Defined based on flavour and charge of leptons, number of jets and *b*-jets



$t\bar{t}\,H/A \rightarrow t\bar{t}t\bar{t}$

[JHEP 07 (2023) 203]

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

- Boosted Decision Tree (BDT) classifier trained to distinguish the SM 4*t* events from other backgrounds (SM BDT)
  - ⇨ Used to define **BSM Signal Region (BSM SR)** and a **low-BDT Control Region (lowBDT CR)**
- Mass-parametrized 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)
- H_T
- event shape variable associated with hadronic activity (sphericity)
- sphericity in the transverse plane
- DeltaR of two leptons for all possible pairs
- Sum of distances ΔR between two leptons for all possible pairs
- MET

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

$t\bar{t}\,H/A \rightarrow t\bar{t}t\bar{t}$

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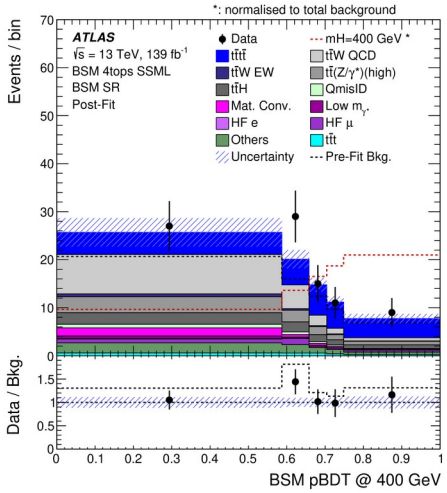
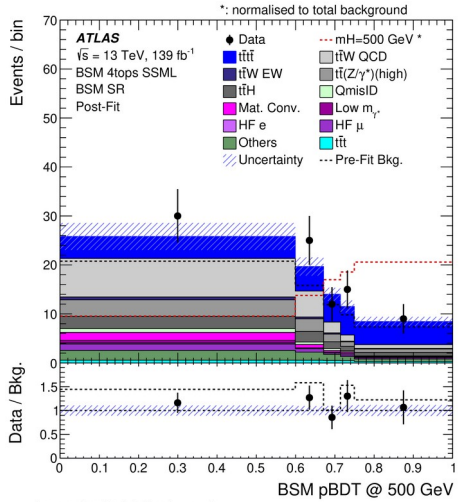
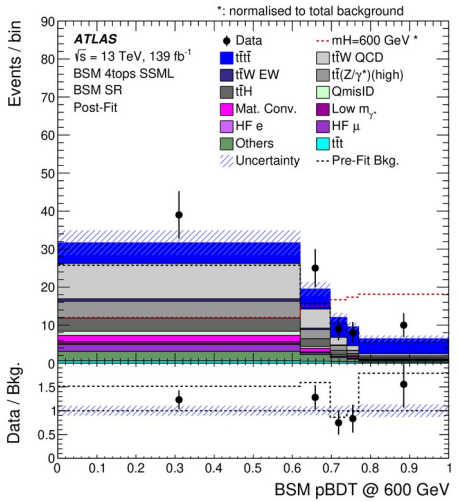
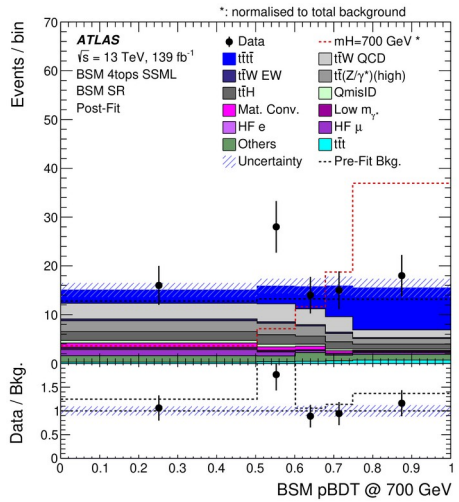
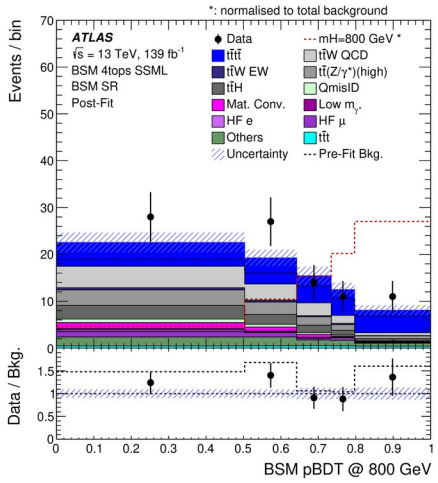
- Mass-parametrized BDT (BSM pBDT) trained in the SR to distinguish between the signal and all backgrounds and used as final discriminant variable in the SR

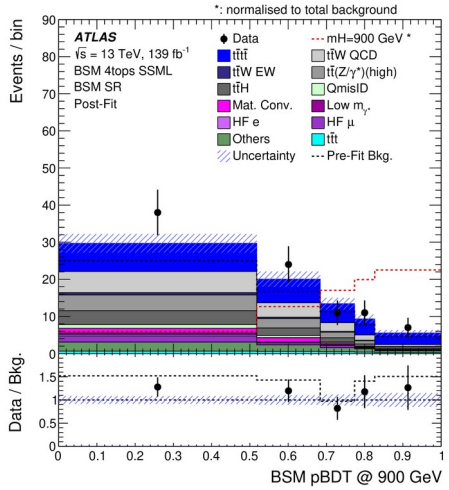


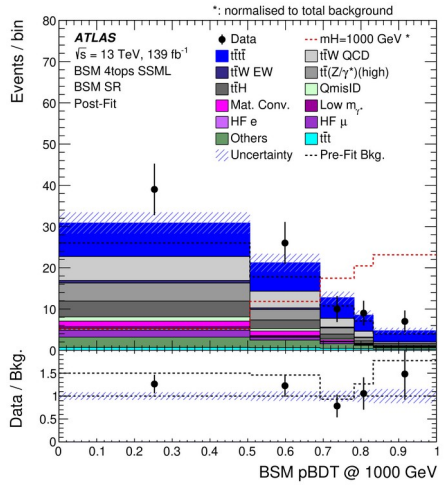








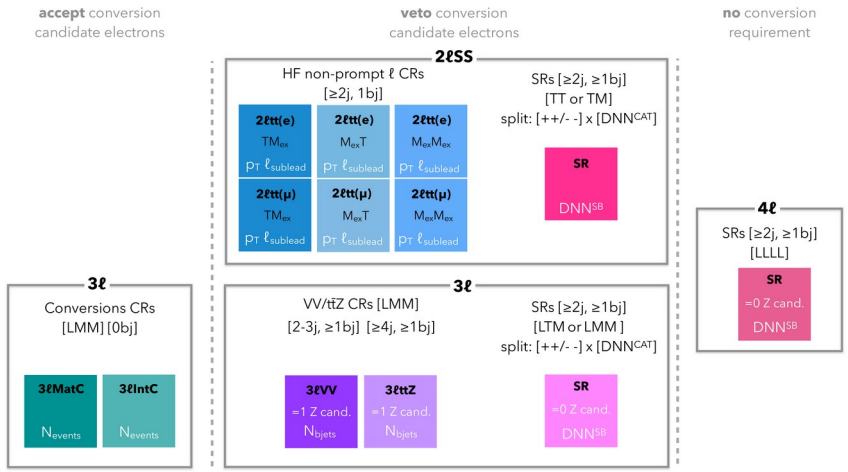




arXiv:2307.14759 (Sub. to JHEP)

Flavourful 2HDM multi-b multi-lepton

Search for heavy Higgs bosons in flavour-violating decays with multiple leptons and *b*-jets final states



17 Signal Region (SR) categories, based on:

- Number of leptons
- Charge sign of leptons
- Deep neural network (DNN) classifier trained to distinguish different production/decay modes

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

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

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)
$m^{OS-SF}_{\ell^+\ell^-}$ [GeV]	–	> 12	
$\lvert m^{OS-SF}_{\ell^+\ell^-} - m_Z\rvert$ [GeV]	–	> 10	
N_{jets}	≥ 2		
N_{b-jets}	$\geq 1\ b^{60\%}$ ‖ $\geq 2\ b^{77\%}$		
Region split	(ssst, ttq, ttt, tttq, tttt) × (Q^{++}, Q^{--})	(ttt, tttq, tttt) × (Q^{+}, Q^{-})	–
Region naming	2ℓSS ++ CAT sstt 2ℓSS ++ CAT ttq 2ℓSS ++ CAT ttt 2ℓSS ++ CAT tttq 2ℓSS ++ CAT tttt 2ℓSS −− CAT sstt 2ℓSS −− CAT ttq 2ℓSS −− CAT ttt 2ℓSS −− CAT tttq 2ℓSS −− CAT tttt	3ℓ ++ CAT ttt 3ℓ ++ CAT tttq 3ℓ ++ CAT tttt 3ℓ −− CAT ttt 3ℓ −− CAT tttq 3ℓ −− CAT tttt	4ℓ

Control regions	WZ	$t\bar{t}Z$	Conversions	HF non-prompt
N_{jets}	2 or 3	≥ 4	≥ 0	≥ 2
N_{b-jets}	$\geq 1\ b^{60\%}$ ‖ $\geq 2\ b^{77\%}$		$0\ b^{77\%}$	$1\ b^{77\%}$
Lepton requirement	3ℓ		$\mu\mu e^*$	2ℓSS
Lepton definition	(L,M,M)			(T, M_{ex}) ‖ (M_{ex}, T) ‖ (M_{ex}, M_{ex})
Lepton p_T [GeV]	(10, 20, 20)			(20, 20)
$m^{OS-SF}_{\ell^+\ell^-}$ [GeV]	> 12		> 12	–
$\lvert m^{OS-SF}_{\ell^+\ell^-} - m_Z\rvert$ [GeV]	< 10		> 10	–
$\lvert m_{\ell\ell\ell} - m_Z\rvert$ [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	$2\ell tt(e)_{(T,M_{ex})}$, $2\ell tt(e)_{(M_{ex},T)}$, $2\ell tt(e)_{(M_{ex},M_{ex})}$
			3ℓMatC	$2\ell tt(\mu)_{(T,M_{ex})}$, $2\ell tt(\mu)_{(M_{ex},T)}$, $2\ell tt(\mu)_{(M_{ex},M_{ex})}$

	e				*μ*			
Lepton categorization	*L*	*M*	M_{ex}	*T*	*L*	*M*	M_{ex}	*T*
Isolation	Yes				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 $\lvert d_0\rvert/\sigma_{d_0}$	< 5				< 3			
Longitudinal impact parameter $\lvert z_0 \sin\theta\rvert$	< 0.5 mm							

arXiv:2307.14759 (Sub. to JHEP)

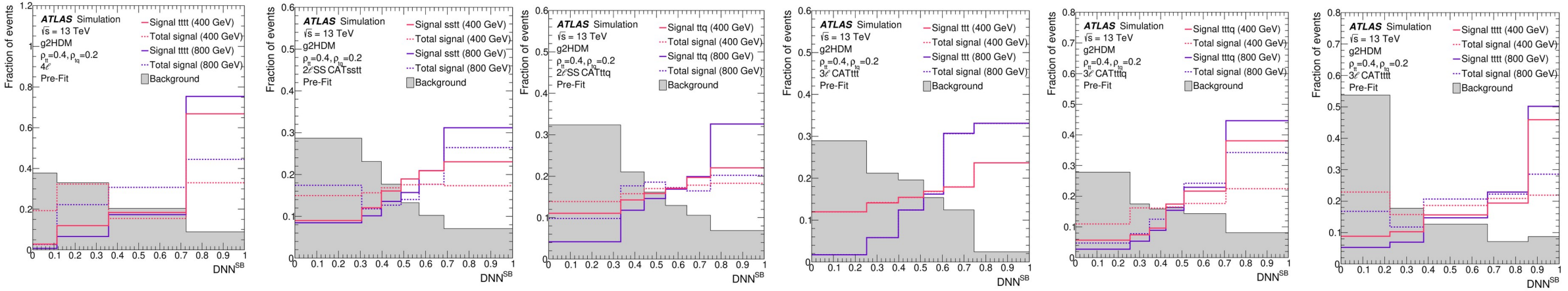
Flavourful 2HDM multi-b multi-lepton

Search for heavy Higgs bosons in flavour-violating decays with multiple leptons and *b*-jets final states

- Categorization 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)

DNN input variables

Variable	DNN^{cat}	DNN^{SB}
Number of jets (N_{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 ($H_{T,jets}$, $H_{T,lep}$)	✓	✓
Angular distance of leptons (sum in the case of 3ℓ and 4ℓ)	✓	✓
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)	-	✓



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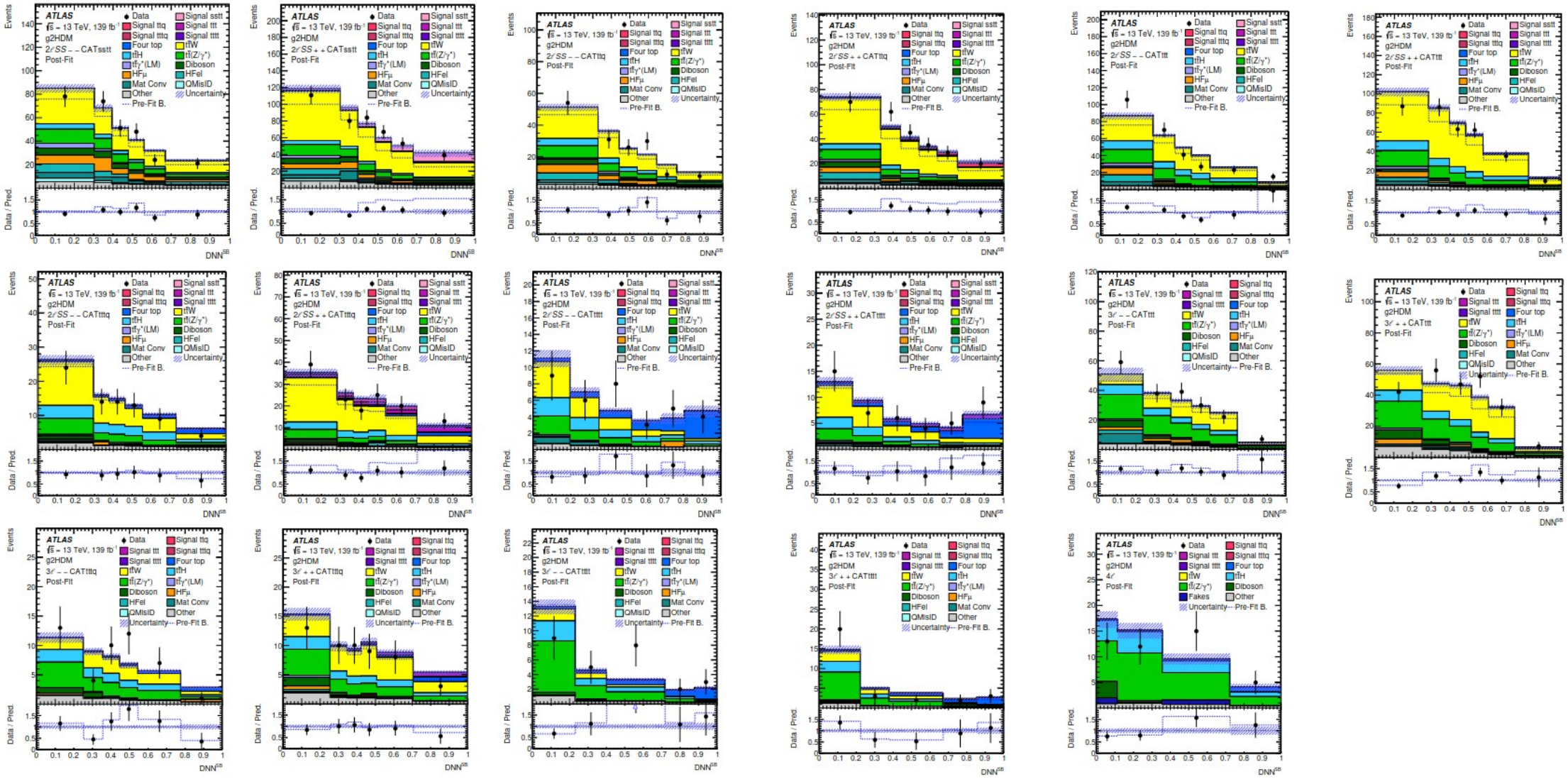
Flavourful 2HDM multi-b multi-lepton



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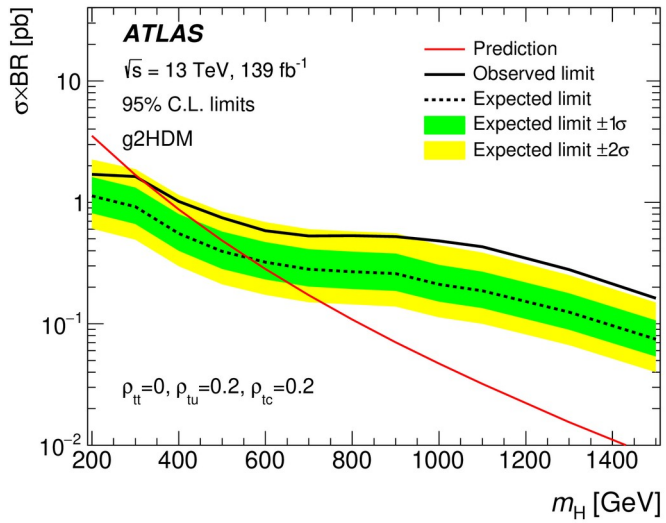

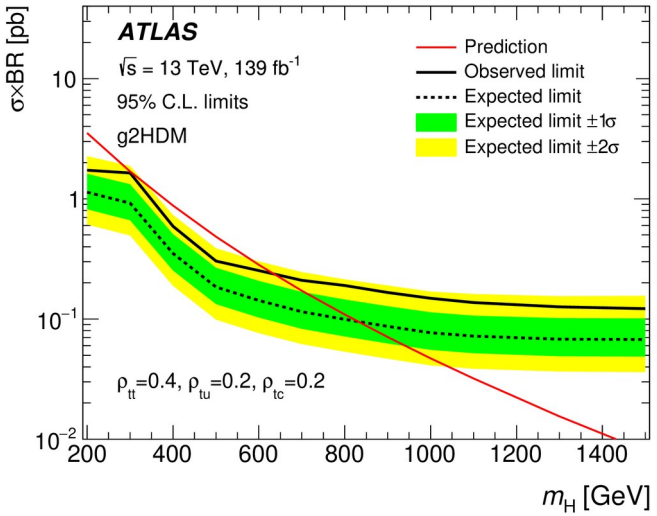

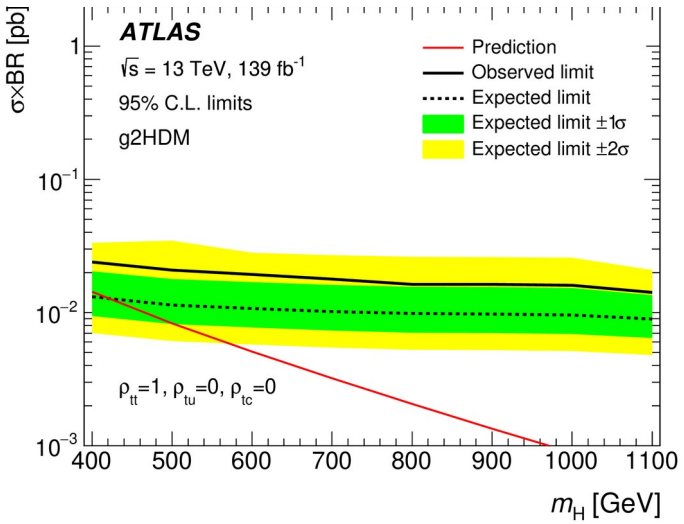

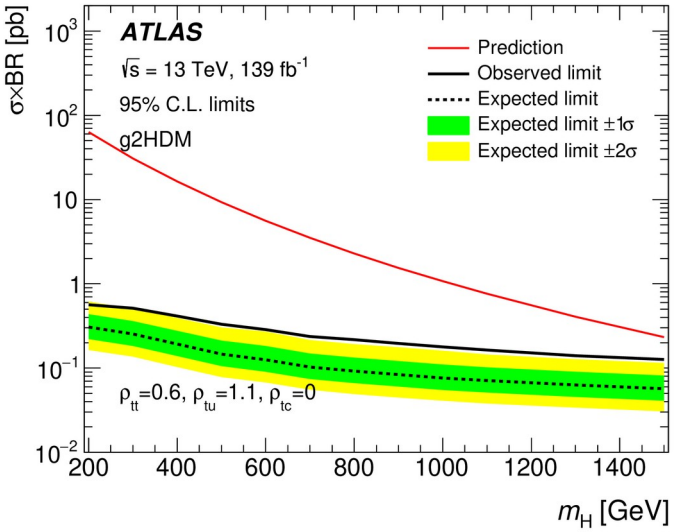

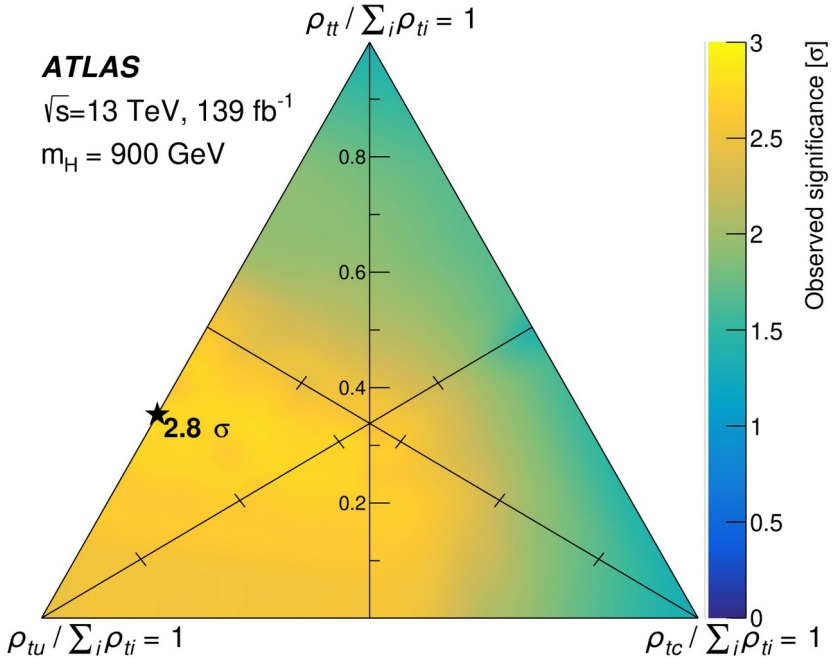

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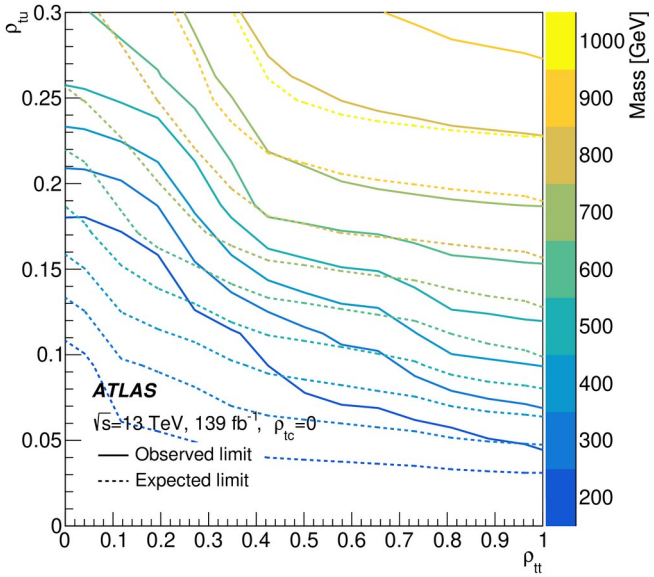
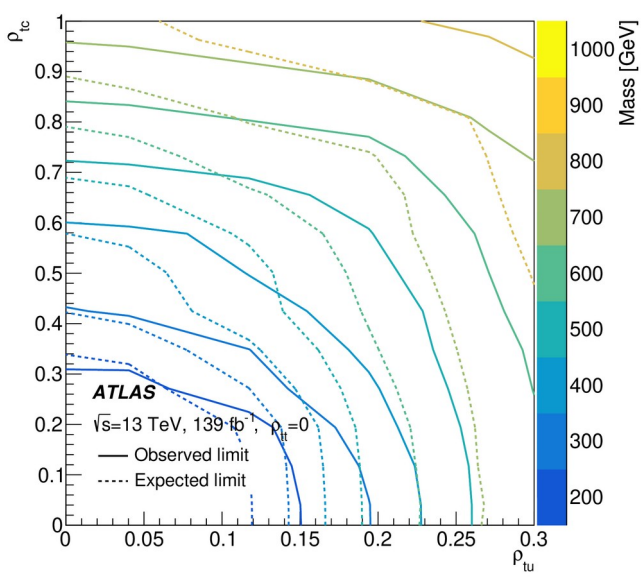
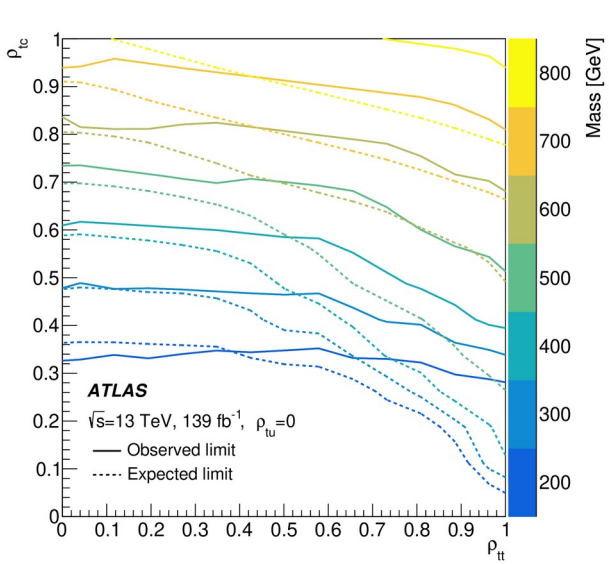
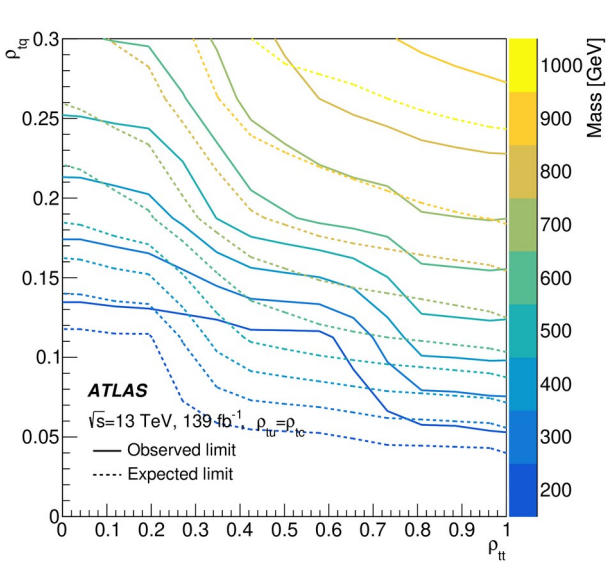








arXiv:2311.04033 (Sub. to JHEP)

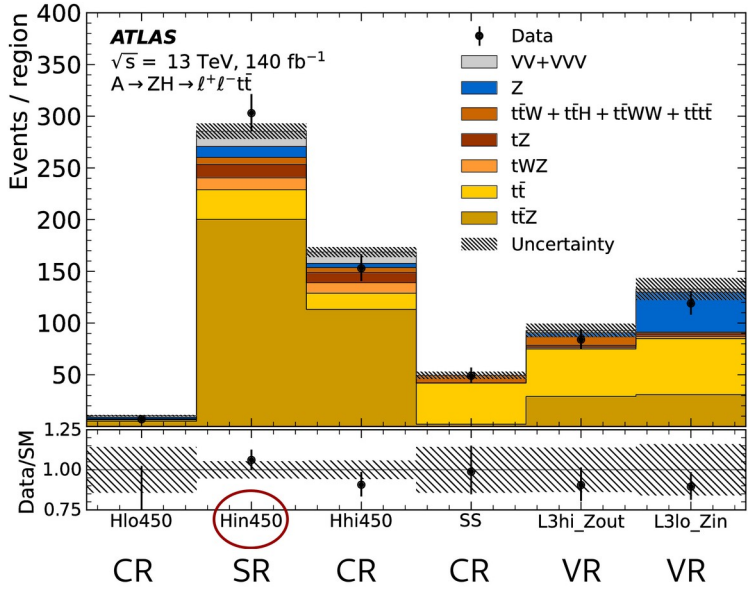
A → ZH → *llt$\bar{t}$* / *vv$\bar{b}\bar{b}$*

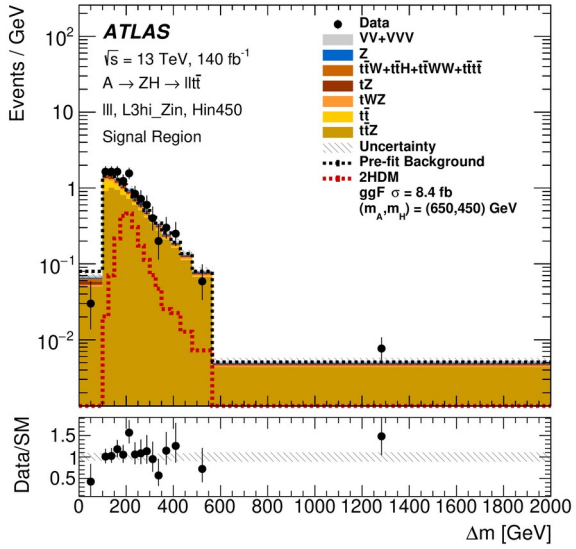
Search for a heavy CP-odd Higgs boson (*A*) decaying to a heavy CP-even Higgs Boson (*H*) and a *Z* in the *llt$\bar{t}$* / *vv$\bar{b}\bar{b}$* channels

3 SR categories, based on number of leptons, jets, *b*-jets, MET, reconstructed *Z* and *H* boson masses:
- 1 *lltt* SR: 3*l*, ≥4 jets and 2 *b*-jets

11 CR categories for controlling:
- *ttZ* and *t$\bar{t}$* in the *lltt* channel (3 CRs)

Requirement	Regions				
	ss (CR)	L3hi_Zout (VR)	L3hi_Zin		L3lo_Zin (VR)
			Hlo / Hhi (CR)	Hin (SR)	
Number of leptons	3				
$p_T(\ell_1)$	> 27 GeV				
Number of jets	≥ 4				
Number of b-jets	2				
$\lvert\eta^{ZH\text{-r.fr.}}_{H\text{-cand}}\rvert$	$< 2.2 + 0.0004 \cdot m(t\bar{t})\,[\text{GeV}] - 0.0011 \cdot m(\ell^+\ell^- t\bar{t})\,[\text{GeV}]$				
$p_T(\ell_3)$	> 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	≥ 1			
$\lvert m_Z^{\text{cand}} - m_Z\rvert$	< 20 GeV	> 10 GeV & < 20 GeV	< 10 GeV		
$\lvert m(t\bar{t}) - m_H\rvert$ m_H < 500 GeV	-		$> 0.32 \cdot m_H$	$< 0.32 \cdot m_H$	-
$m_H \geq 500$ GeV			$> 0.24 \cdot m_H$	$< 0.24 \cdot m_H$	





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A → ZH → *llt̄t̄* / *νν̄bb̄*

Search for a heavy CP-odd Higgs boson (*A*) decaying to a heavy CP-even Higgs Boson (*H*) and a *Z* in the *llt̄t̄* / *νν̄bb̄* channels

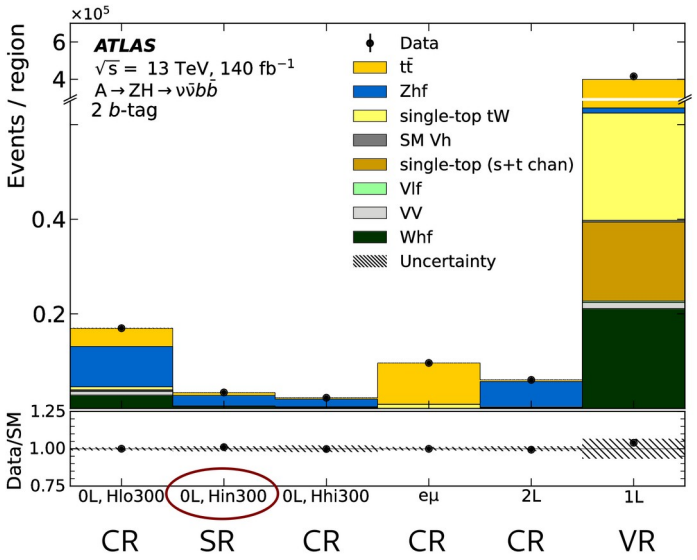
3 SR categories, based on number of leptons, jets, *b*-jets, MET, reconstructed *Z* and *H* boson masses:

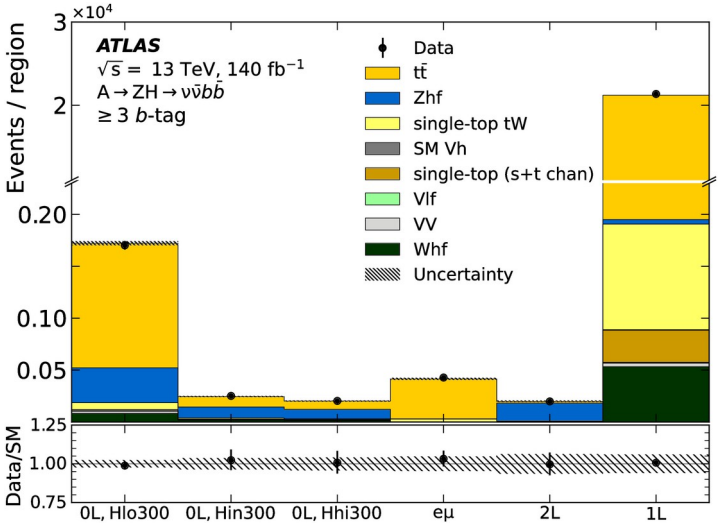
- 2 *νvbb* SRs: 0*l*, MET, 2 *b*-jets and ≥3 *b*-jets

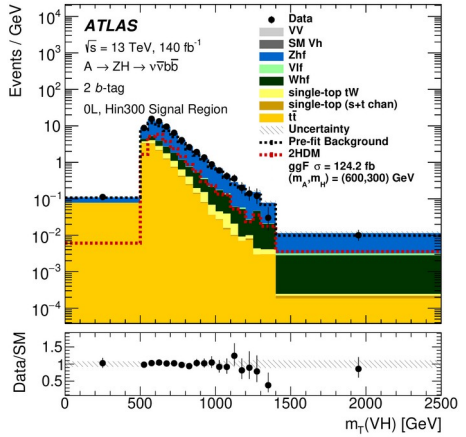
11 CR categories for controlling:

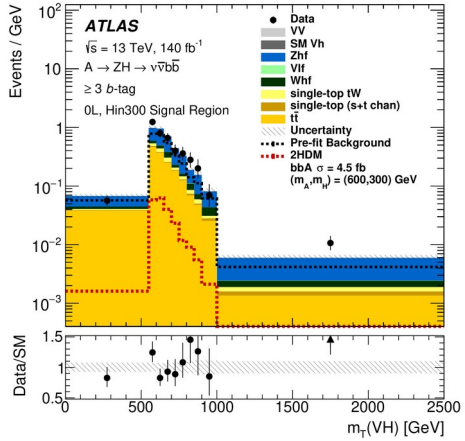
- *Z*+HF and *tt̄* in the *νvbb* channel (8 CRs)

Requirement	Regions				
	2L (CR)	eμ (CR)	1L (VR)	0L	
				Hlo / Hhi (CR)	Hin (SR)
Number of jets	2–5				
Number of b-jets	≥ 2				
$m(b\bar{b})$	> 50 GeV				
Number of τ^{had}	0				
$p_{\text{T}}(V)$	> 150 GeV				
$\min_i \Delta\phi(\vec{E}_{\text{T}}^{\text{miss}}, \vec{p}_i^{\text{jet}})$	> $\pi/10$				
$\Delta R(b_1, b_2)$	< 3.3 (2 b-jets) < 3.5 (≥ 3 b-jets)				
Number of leptons	2		1	0	
Lepton flavour	$ee/\mu\mu$	$e\mu$	e/μ	-	
$p_{\text{T}}(\ell_1)$	> 27 GeV			-	
$\lvert m_Z^{\text{cand}} - m_Z \rvert$	< 10 GeV	-			
$\mathcal{S}_{\text{MET}}$	< 5	-	> 3	> 10	
$m_{\text{top}}^{\text{near}}$	-			> 180 GeV	
$m_{\text{top}}^{\text{far}}$	-			> 200 GeV	
$\lvert m(b\bar{b}) - m_H \rvert$	-			> $0.2 \cdot m_H$	< $0.2 \cdot m_H$









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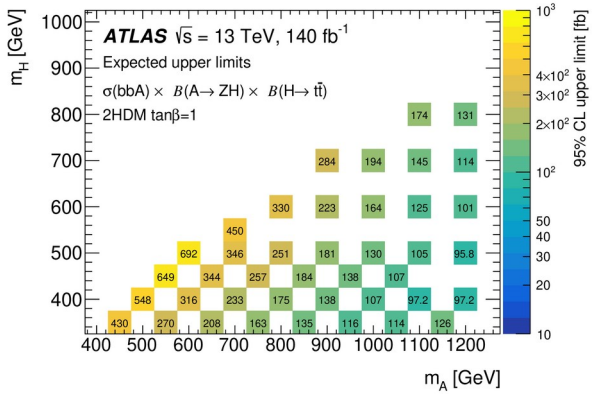

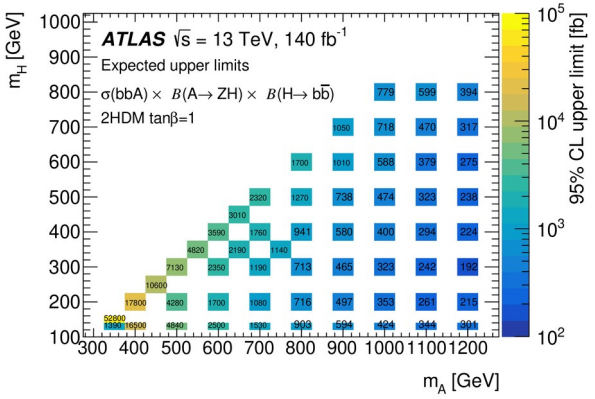

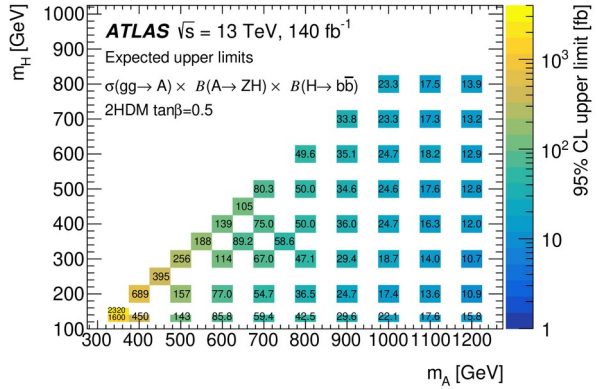

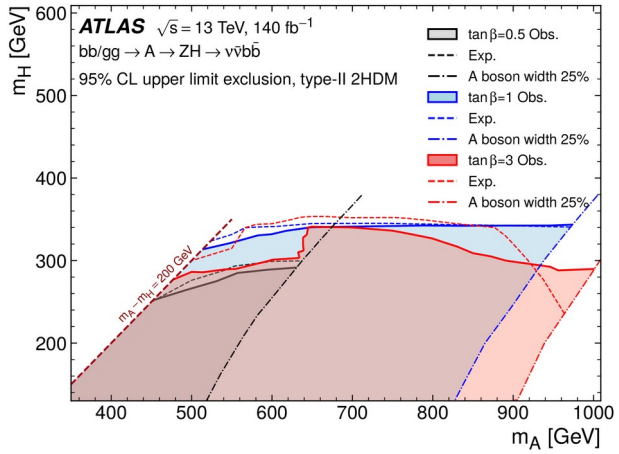

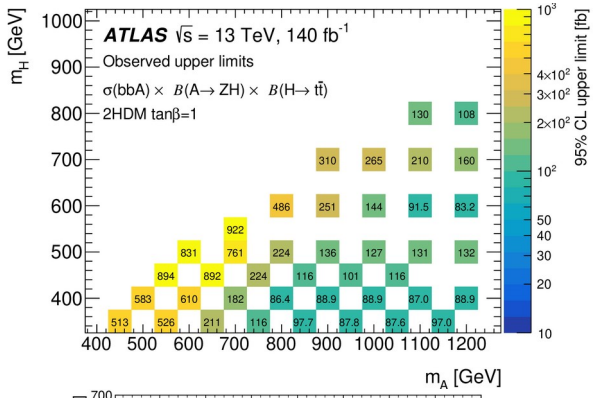

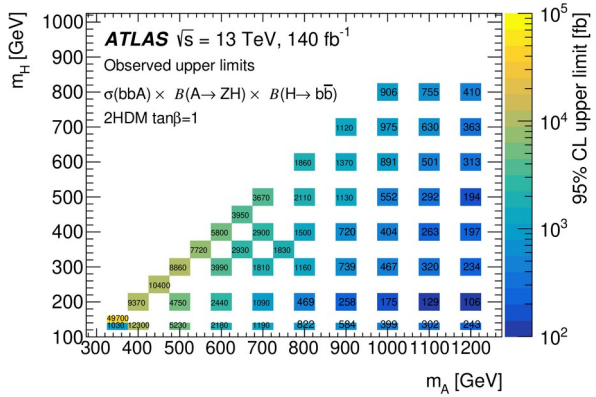

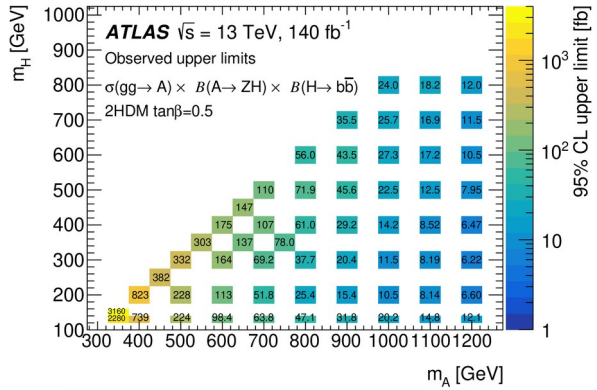

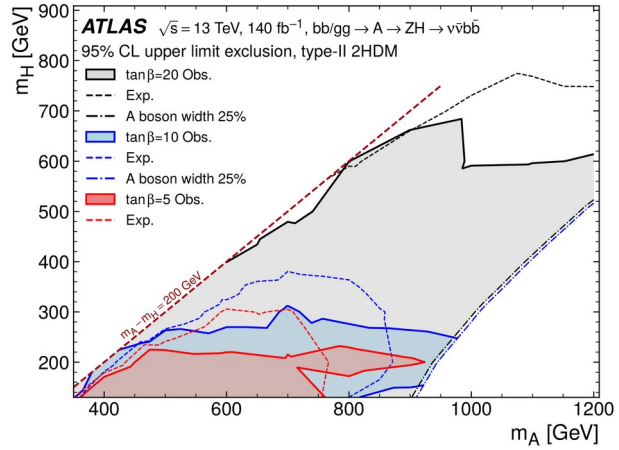

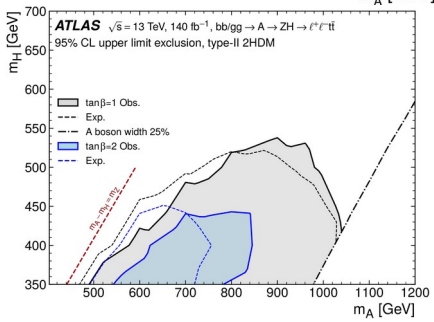

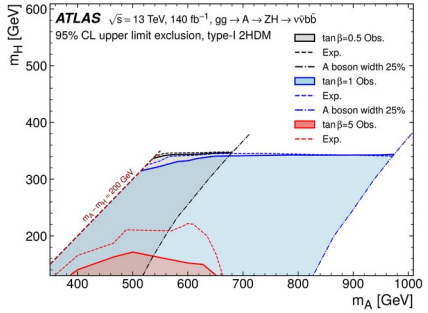

$t \to qX,\ X \to b\bar{b}$

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

Input variables for the pNN:

- Pt, eta and phi of the jets
- Pseudo-continuous b-tagging score of the *b*-jets
- Pt 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

$t \to qX,\ X \to b\bar{b}$

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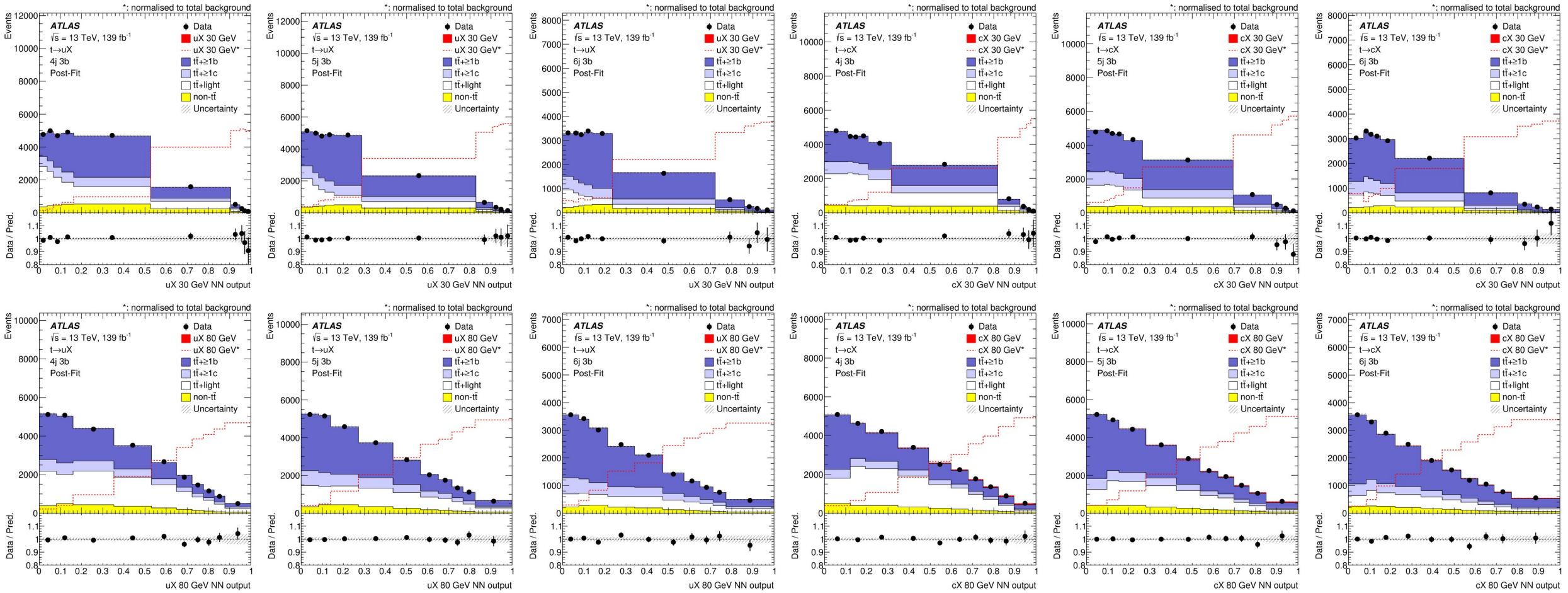
- **Mass-parametrized Neural Network** (pNN) classifier trained to separate signal and background, separately for *cX* and *uX* channels, pNN output used as final discriminant variable in all SRs



$X \to WW \to e\nu\mu\nu$

Search for heavy resonances (X) in the decay channel $W^+W^- \to e\nu\mu\nu$

4 CR categories defined for controlling $t\bar{t}$/Wt and non-resonant WW background based on

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

Pre-Selection			
Two Different Flavour, Opposite Sign Leptons, $p_T^{\ell} > 25$ GeV Third lepton veto, $p_T^{\ell} > 15$ GeV			
WW CR_{ggF}	Top CR_{ggF}	WW CR_{VBF1J}	Top CR_{VBF}
$N_{b-\text{tag}} = 0$	$N_{b-\text{tag}} = 1$	$N_{b-\text{tag}} = 0$	$N_{b-\text{tag}} \geq 1$
$\lvert\Delta\eta_{\ell\ell}\rvert > 1.8$	$\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$	($\lvert\Delta\eta_{\ell\ell}\rvert > 1.8$ or	$\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$
$m_{\ell\ell} > 55$ GeV		10 GeV $< m_{\ell\ell} <$ 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 GeV^{-1}	–		–
Excluding VBF1/2J phase space		VBF1J phase space	VBF1/2J phase space

3 SR categories targeting resonance production types:

- 2 for VBF: =1 jet and ≥2 jets
- 1 for ggF (all events not going into VBF regions)

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

$X \to WW \to e\nu\mu\nu$

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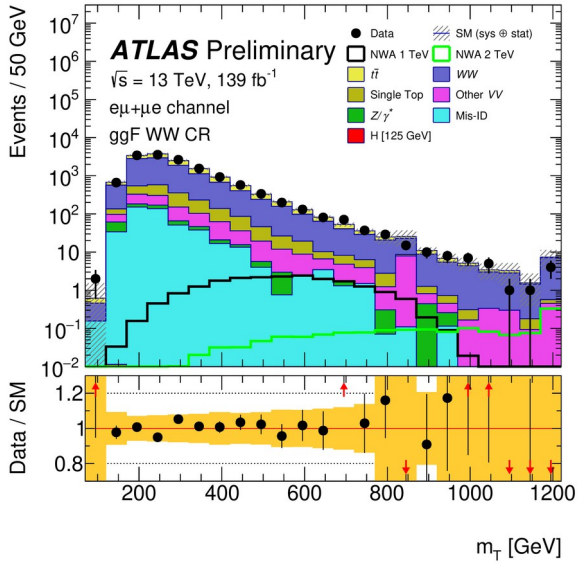

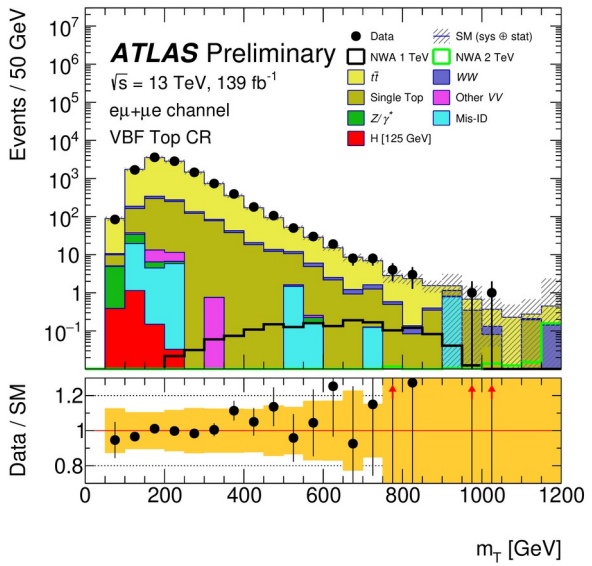

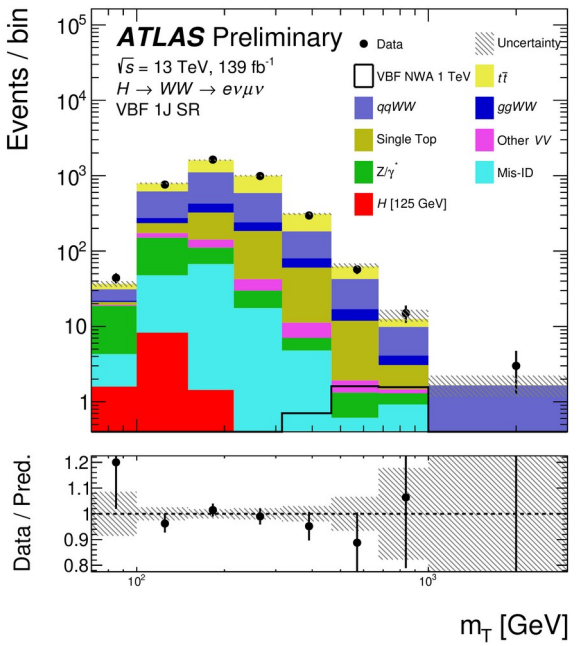

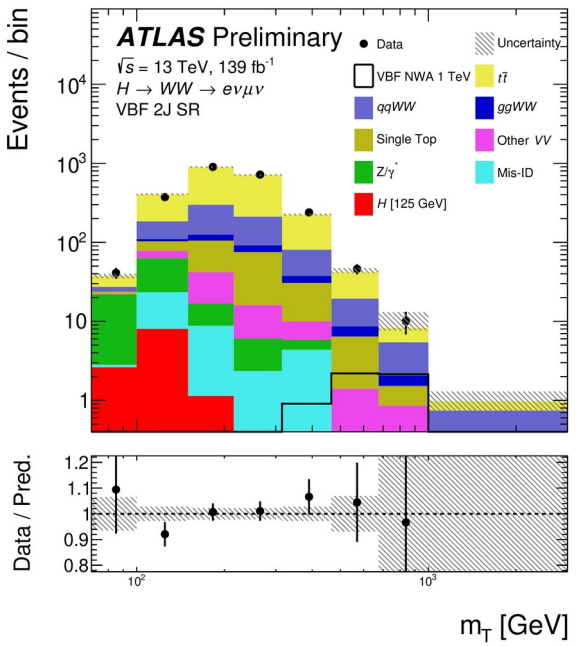

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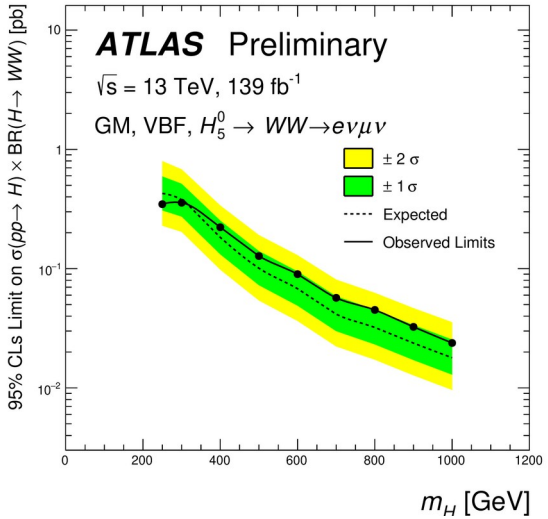
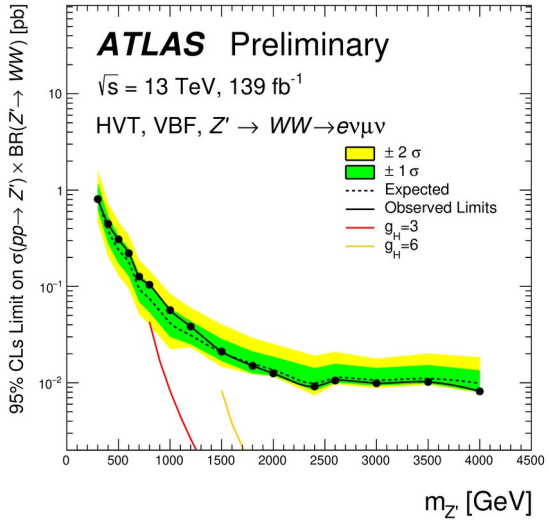
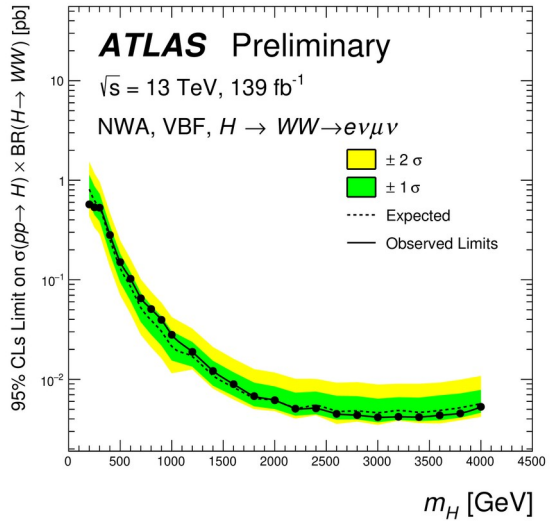
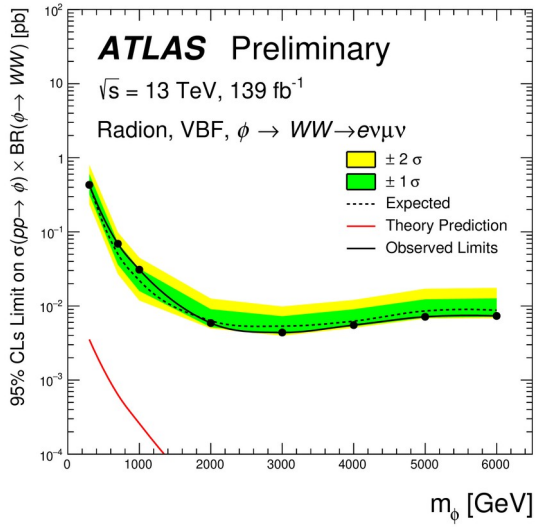
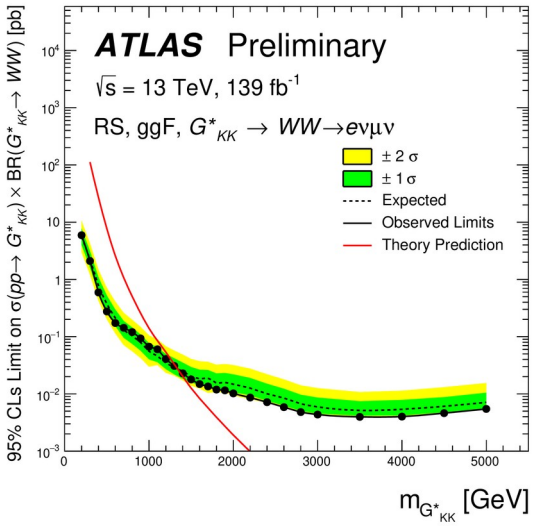
$X \to WW \to e\nu\mu\nu$

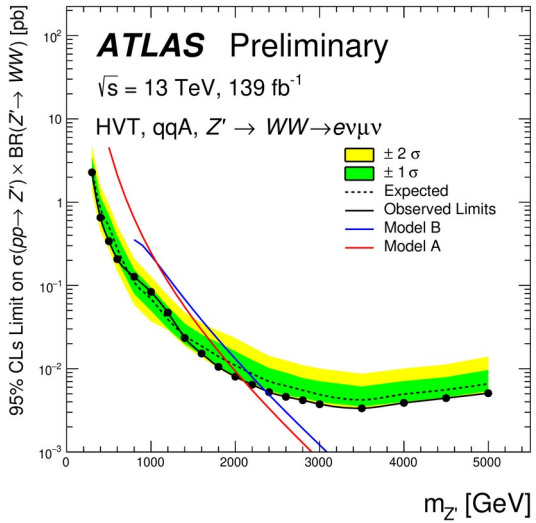


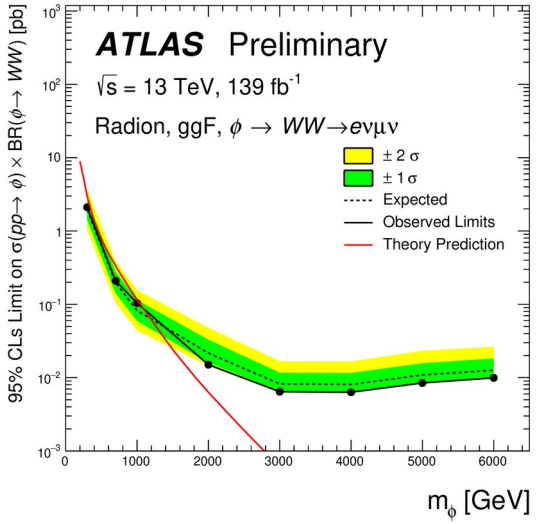












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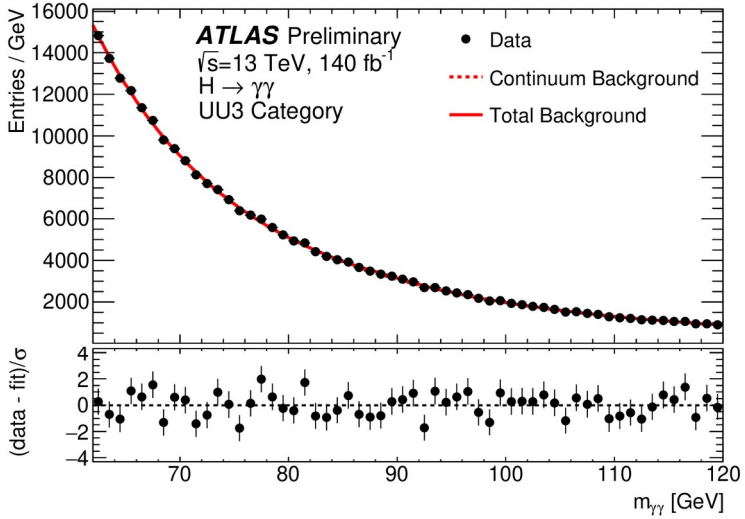
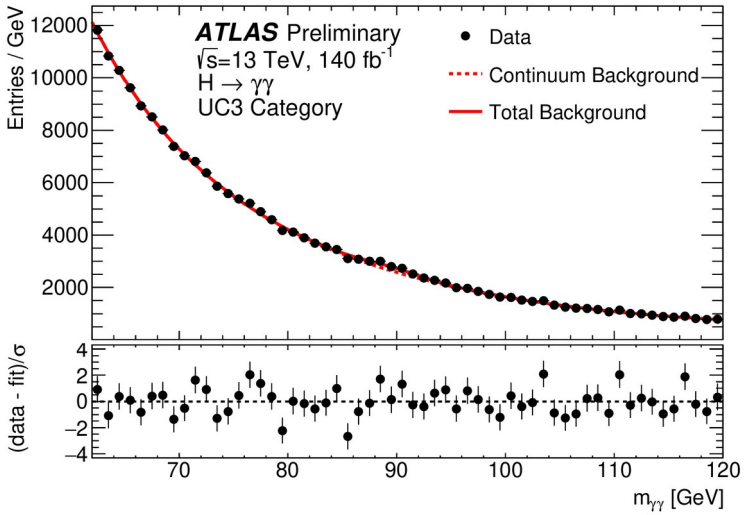
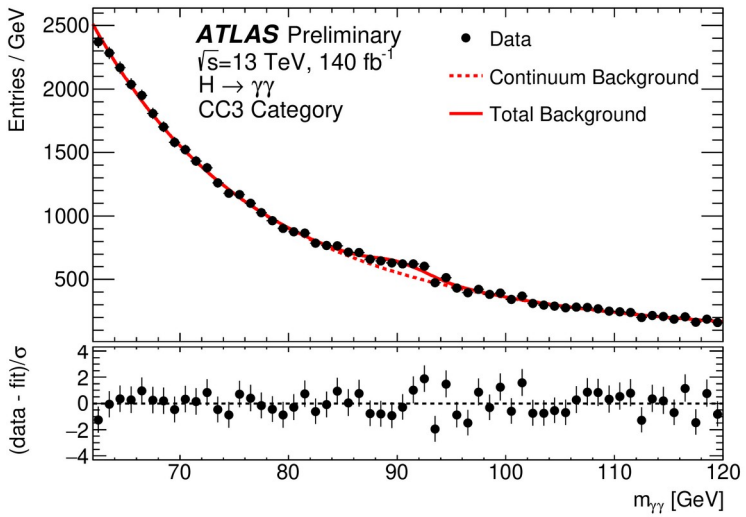
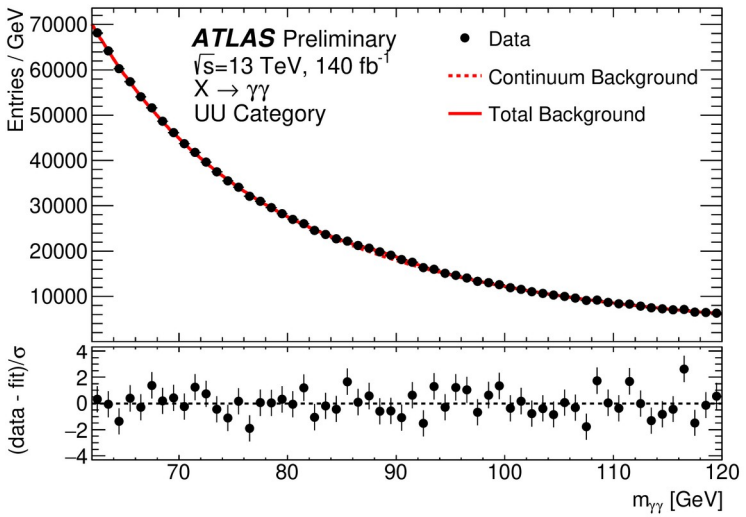
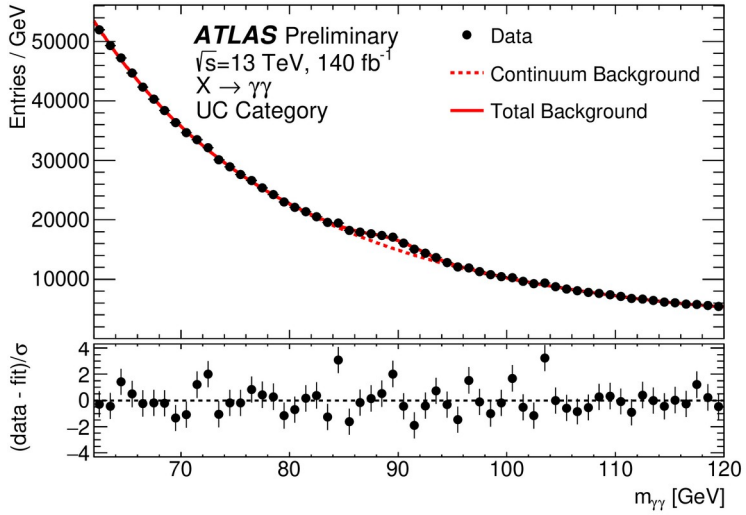
Low-mass $H \to \gamma\gamma$

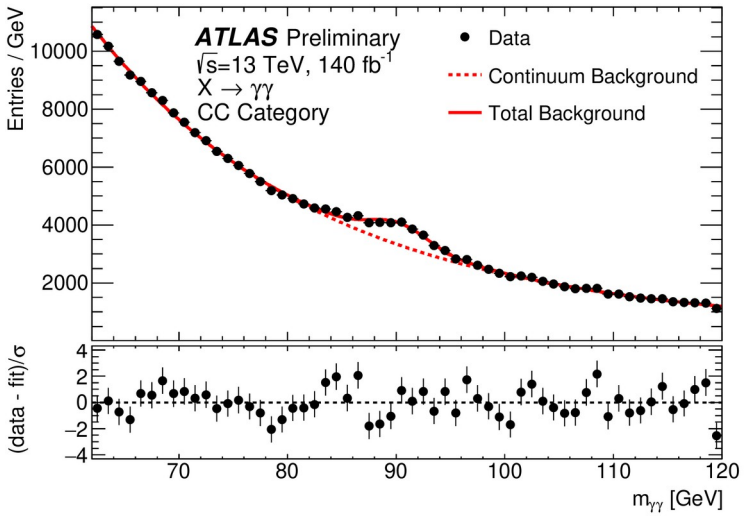












Low-mass $H \to \gamma\gamma$