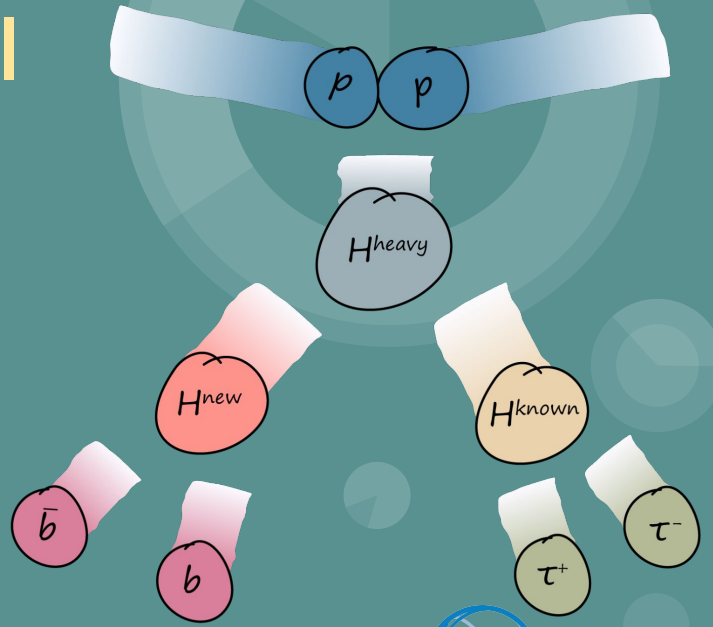
The XXXI International Workshop on Deep Inelastic Scattering [DIS2024]
8–12 Apr 2024, Grenoble, FRANCE

Searching for additional Higgs bosons at ATLAS

ASMA HADEF [TU Dresden, Germany]

on behalf of the ATLAS Collaboration



Bundesministerium für Bildung und Forschung

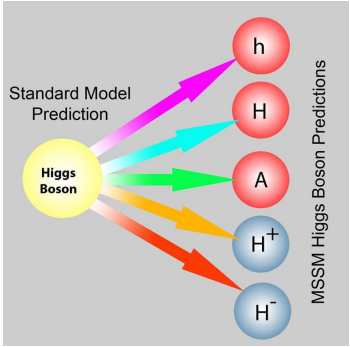
FSP ATLAS
Erforschung von Universum und Materie

TECHNISCHE UNIVERSITÄT DRESDEN

ATLAS EXPERIMENT

Introduction

- Discovery of a **neutral CP-even scalar** particle of **mass 125 GeV** at the LHC confirmed the predicted electroweak symmetry breaking mechanism of the SM.
- Experimental results are consistent with the **SM Higgs Boson**.
- The discovery has completed the SM particle content.



- Some questions remained open:
  - Neutrino oscillations/Neutrino masses
  - Hierarchy/Naturalness problem
  - Matter-antimatter asymmetry
  - Dark Matter
- Can be addressed in some BSM scenarios that extend the Higgs sector.

- Various BSM models predict **additional Higgs bosons**:

SM Higgs doublet + Additional field = h + Additional Higgs bosons

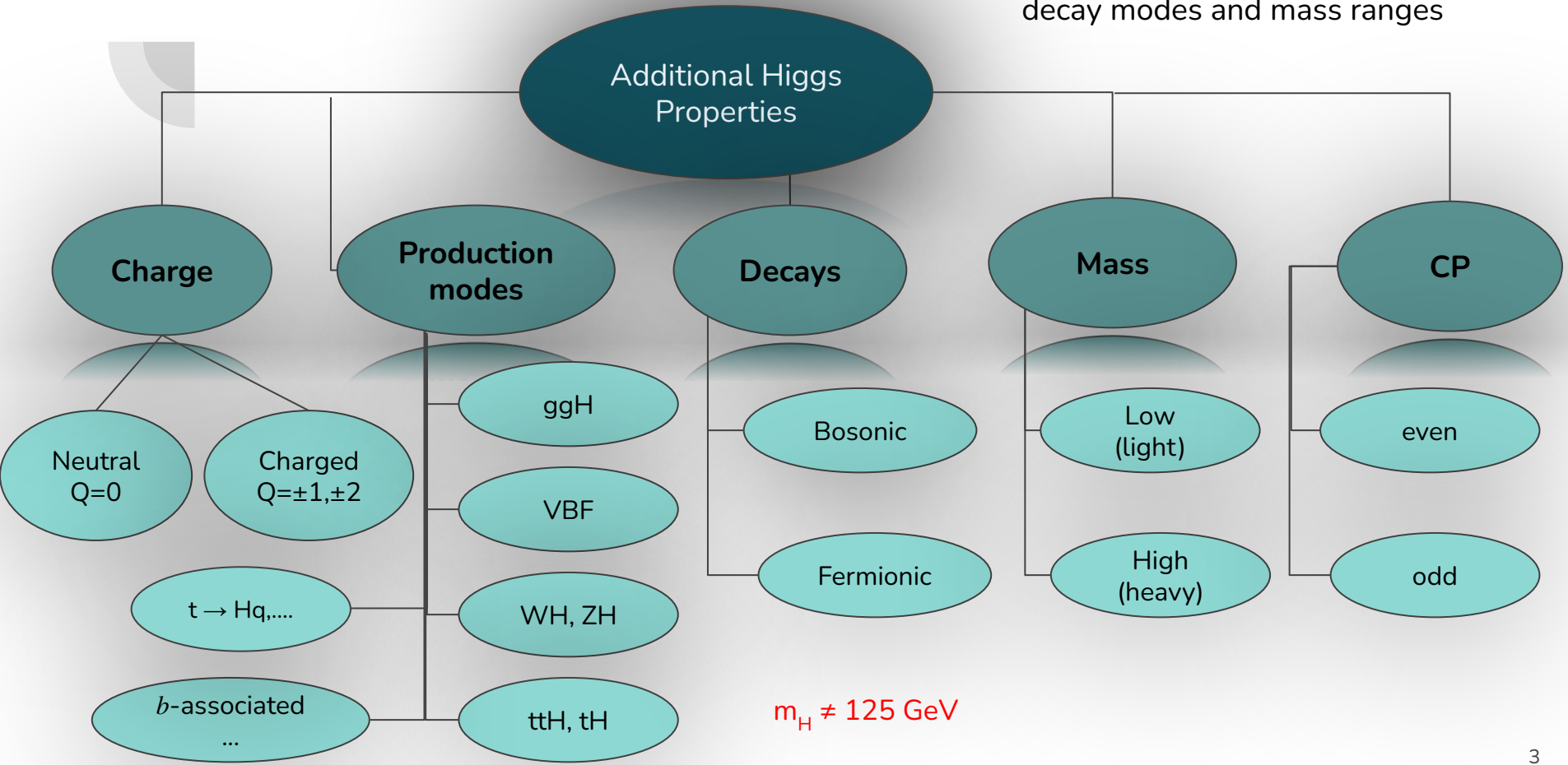
↓

125 GeV Higgs boson

Model	Additional field	Additional Higgs
EWS	Scalar EW singlet	H (CP-even)
2HDM	Higgs doublet	H, A (CP-odd), $H^{\pm}$
2HDM + singlet (complex)	Higgs doublet + singlet	H, A, $H^{\pm}$, s (CP-even), a (CP-odd)
Higgs triplet model	Higgs triplet	H, A, $H^{\pm}$, $H^{\pm\pm}$
Georgi-Machacek model	2 Higgs triplets	a_5, a_3, H_1, H'_1, H_3^0, H_3^+, H_5^0, H_5^+, H_5^{++}

Searches of Additional Higgs in ATLAS

Many searches in ATLAS targeting different charges, production and decay modes and mass ranges

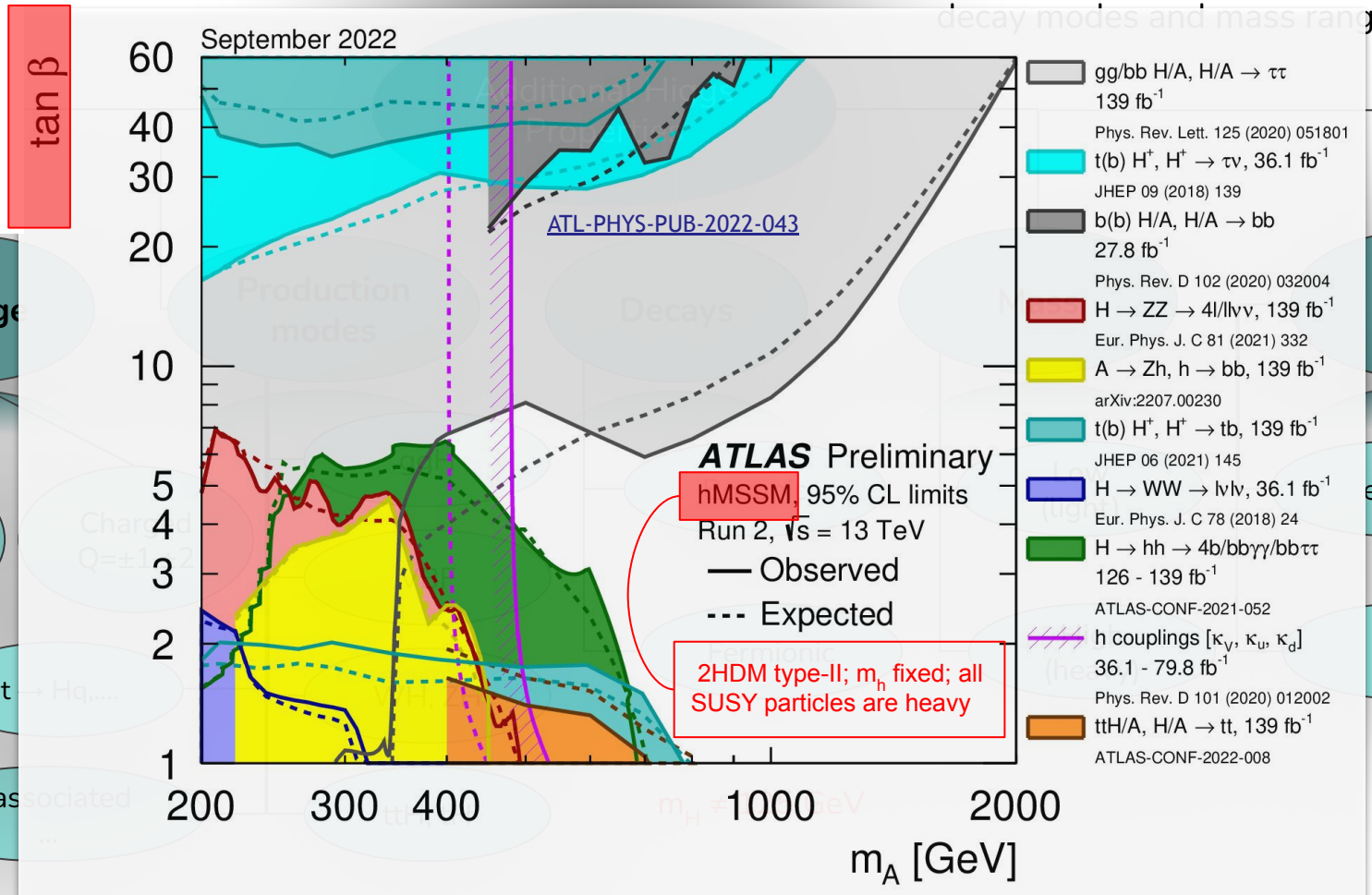


$m_H \neq 125$ GeV

Searches of Additional Higgs in ATLAS

Many searches in ATLAS targeting different charges, production and decay modes and mass ranges

Ratios of the 2 vacuum expectation values



What's covered in this talk

Latest results and most recent searches in ATLAS from LHC Run-2 during last year!!

1. Bosonic Decays

   1.1. $H \to \gamma\gamma$ (low mass: 10-3000 GeV): JHEP 07 (2023) 155 || ATLAS-CONF-2023-035 || Phys. Lett. B 822 (2021) 136651 → neutral Higgs

   1.2. $A \to ZH\ (H \to ZZ) \to ZZZ \to 4\ell + MET$ (high mass <1.3 TeV): arXiv:2401.04742 → heavy neutral Higgs

2. Fermionic decays

   2.1. $A \to ZH\ (H \to tt\ ) \to \ell\ell tt\ /\ vvbb$ (high mass <1.2 TeV): ATLAS-CONF-2023-034 → heavy neutral Higgs

   2.2. $H/A \to tt$ (high mass: 400-1400 GeV): ATLAS-CONF-2024-001 → heavy neutral Higgs

   2.3. ttH/A ($H/A \to tt$) → 4-top → multi-leptons (high mass: 400-1000 GeV): ATLAS-CONF-2024-002 → heavy neutral Higgs

   2.4. $H \to$ multi leptons + b-jets, (high mass: 200-1500 GeV): JHEP 12 (2023) 081 → heavy neutral Higgs

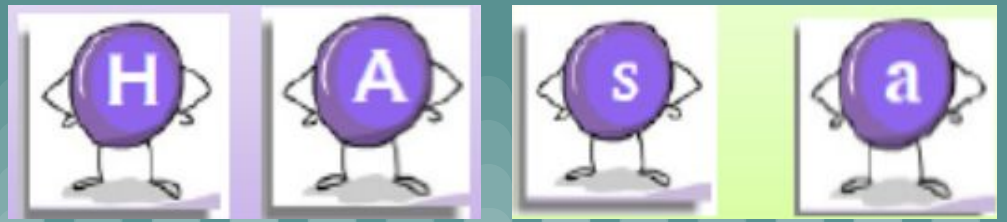
   2.5. $t \to qX$, $X \to bb$ (low mass 20-160 GeV): JHEP 07 (2023) 199 → light neutral Higgs

   2.6. $t \to H^{\pm}\ (H^{\pm} \to cb) + b \to cbb$ (low mass: 60-160 GeV): JHEP 09 (2023) 004 → light charged Higgs

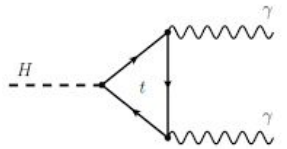
   2.7. $H^{\pm\pm} \to \ell^{\pm}\ell'^{\pm}$ (high mass: 300-1300 GeV): Eur. Phys. J C 83 (2023) 605 → heavy charged Higgs

Neutral Higgs

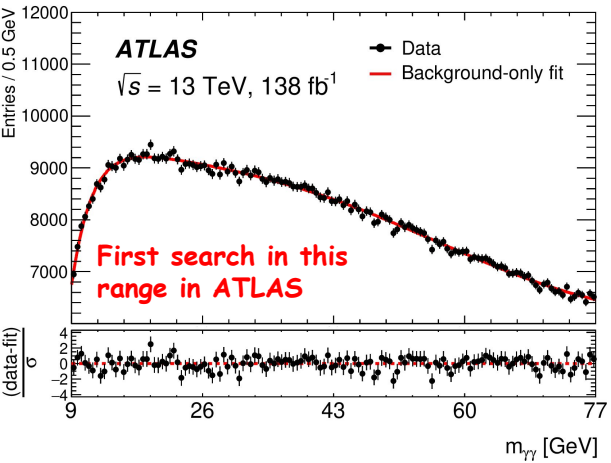
H, A, s, a



$H \rightarrow \gamma\gamma$



Low mass
10-70 GeV

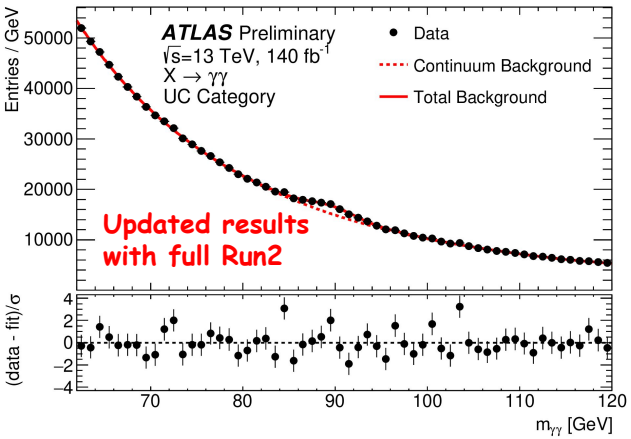


Challenging! Diphoton trigger with $E_T > 22$ GeV

➔ Trigger deforms the background shape.

➔ Requiring $p_T^{\gamma\gamma} > 50$ GeV reduces shape distortion but decreases data statistics.

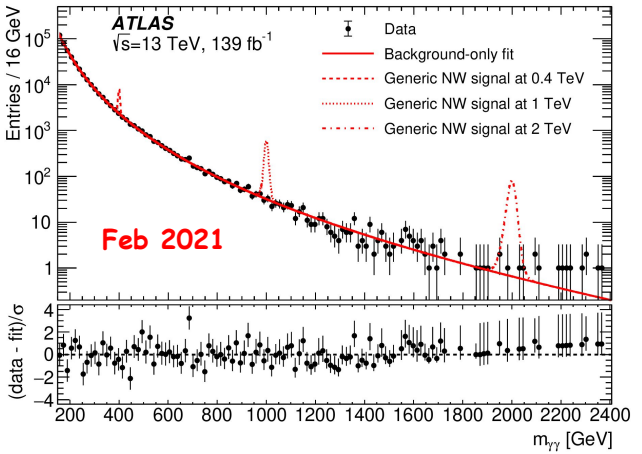
Intermediate mass
66-110 GeV



Hot topic! Several CMS analyses have excess at 95 GeV (γγ, ττ, bbγγ)

➔ Challenging due to proximity to Z→ee faking γγ peak → BDT reduces such ee fakes.

High mass
160-3000 GeV

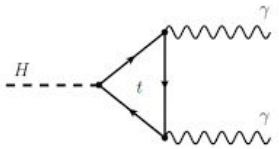


Inclusive search for spin-0/2 particle

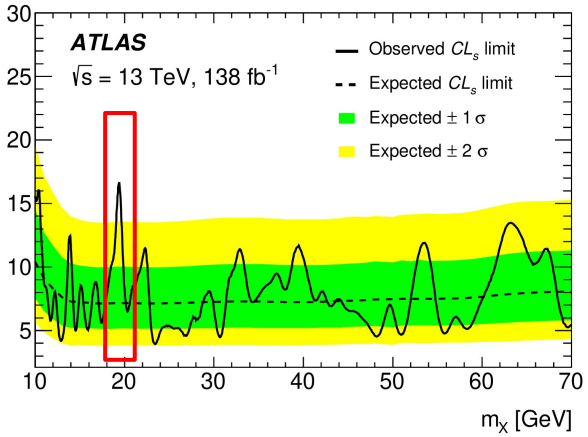
➔ Larger widths tested in the fit.

Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
H	0	even	ggF, VBF, ttH, WH, ZH	H→ $\gamma\gamma$	10 - 3000 GeV	140 fb^{-1}

$H \rightarrow \gamma\gamma$

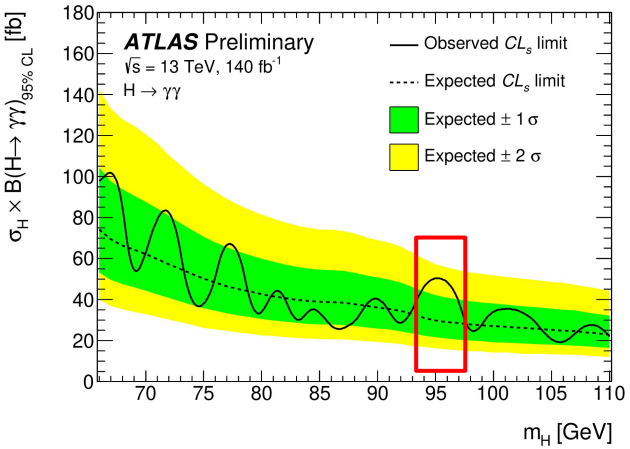


Low mass
10-70 GeV



- **3.1σ** local (1.5σ global) excess at **19.4 GeV.**

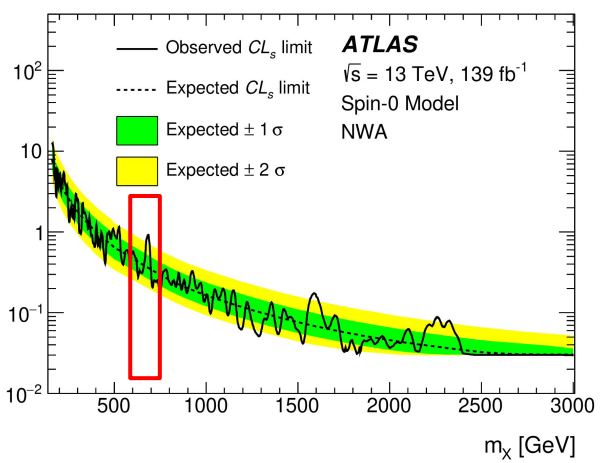
Intermediate mass
66-110 GeV



- **1.7σ** local deviation at **95.4 GeV**.

Competitive result without any significant deviation wrt SM bkg

High mass
160-3000 GeV

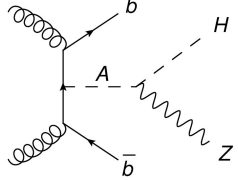


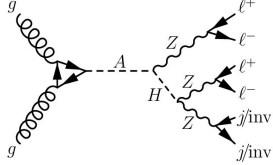
- Largest excess at **684 GeV** with **3.29σ**

local significance (1.30σ global).

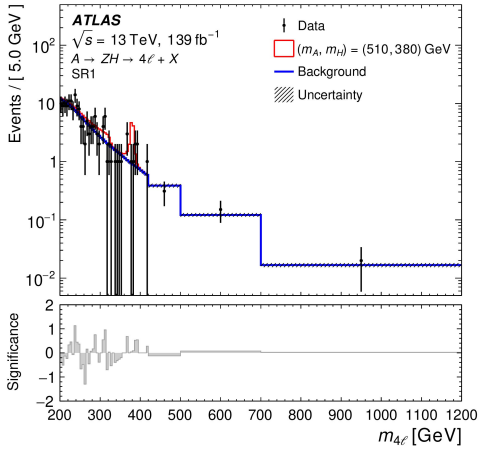
Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
H	0	even	ggF, VBF, ttH, WH, ZH	H→ $\gamma\gamma$	10 - 3000 GeV	140 fb^{-1}

$A \rightarrow ZH$





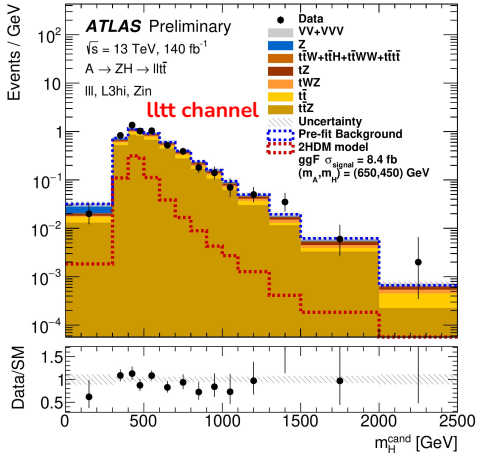
$A \rightarrow ZH \rightarrow 4l+2j/E_T^{miss}$

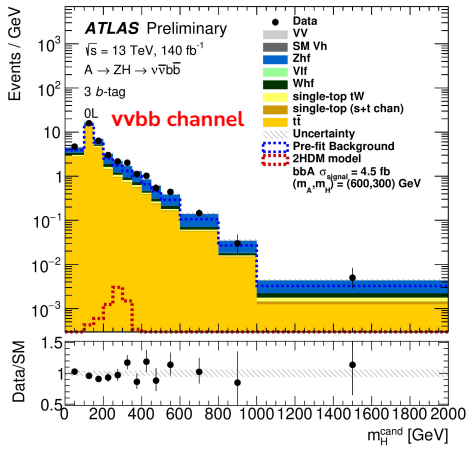


❑ $H \rightarrow ZZ \rightarrow 4\ell$ or $2\ell+2j/2\nu$, $Z \rightarrow 2\ell/2j/2\nu$.

- ❑ 7 categories based on the number of jets, *b*-jets, $p_T^{4\ell}$, E_T^{miss} significance.
- ❑ 72 signal mass points generated;
- ❑ Linear interpolation to obtain signal shapes between different masses.
- ❑ Main background: leptonic decay of $qq(gg) \rightarrow ZZ$.

$A \rightarrow ZH \rightarrow lltt$ / vvbb





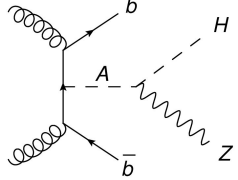
❑ $H \rightarrow tt$ or $H \rightarrow bb$; $Z \rightarrow 2\ell/2\nu$.

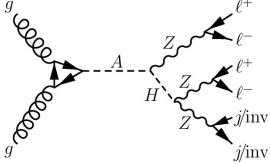
- ❑ 3 categories based on number of leptons, jets, b-jets, MET, reconstructed *Z* and *H* boson masses.
- ❑ Main background:

ttZ (**lltt channel**); *Z*+heavy flavour (Zhf) / tt^- (**vvbb channel**).

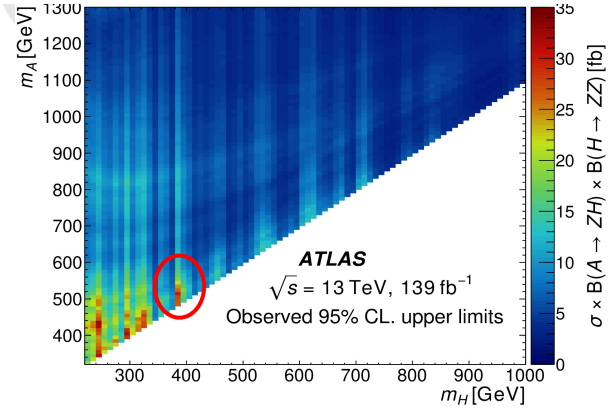
Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
A, H	0	Odd, even	ggH	A → ZH, H→ ZZ, *tt*, *bb*	320 - 1300, 130 - 1000 GeV	140 fb^{-1}

$A \rightarrow ZH$

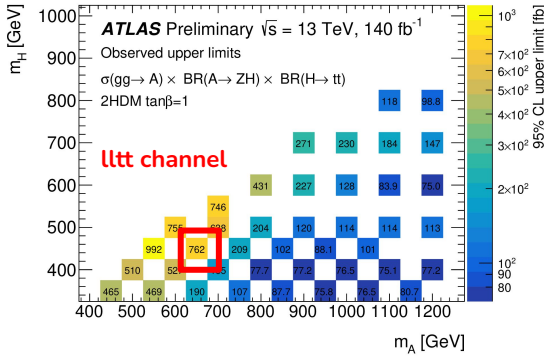


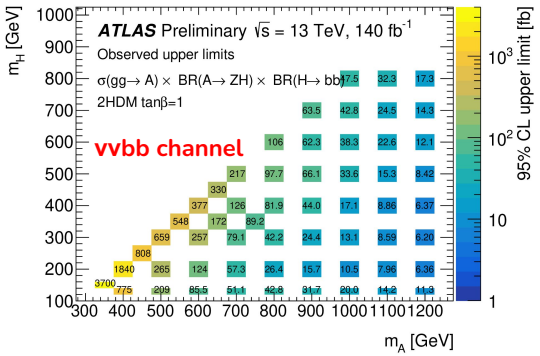


$A \rightarrow ZH \rightarrow 4l+2j/E_T^{miss}$



$A \rightarrow ZH \rightarrow lltt$ / vvbb





No significant deviation wrt SM bkg

- $H \rightarrow ZZ \rightarrow 4\ell$ or $2\ell+2j/2\nu$, $Z \rightarrow 2\ell/2j/2\nu$.
- $H \rightarrow tt$ or $H \rightarrow bb$; $Z \rightarrow 2\ell/2\nu$.

Mild excess observed at (m_A, m_H) = **(510, 380) GeV** with local significance of **2.5σ**.

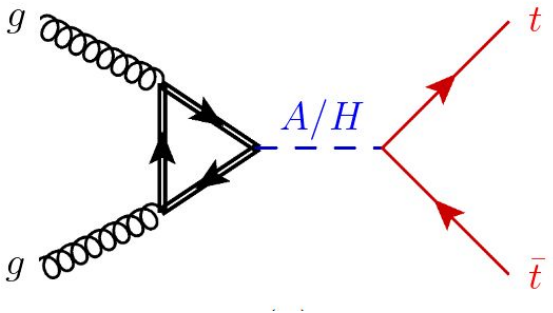
Mild excess observed at (m_A, m_H) = **(650, 450) GeV** in the lltt channel with local significance of **2.85σ**

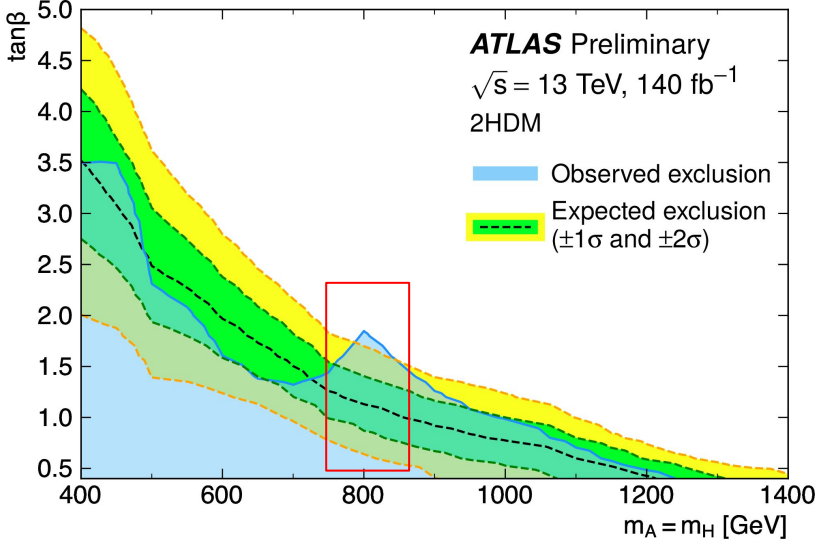
Other channels published in ATLAS: A → ZH → ll+bb, A → ZH → ll+WW → ll+qqqq, $A \rightarrow ZH \rightarrow \ell\ell\,\tau\tau$

Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
A, H	0	Odd, even	ggH	A → ZH, H→ ZZ, *tt*, *bb*	320 - 1300, 130 - 1000 GeV	140 fb^{-1}

$H/A \rightarrow tt$

- Final states includes only 1 or 2 leptons.
- Interference effects between the signal process and Standard Model (SM) $t\bar{t}$ production are taken into account.
- No significant excess above the SM predictions observed.
- A deviation of **2.3 σ** local significance for m_A = **800 GeV,** Γ_{A/m_A} = **10%,** and a best-fit value $\sqrt{\mu}$ = **4.0**,



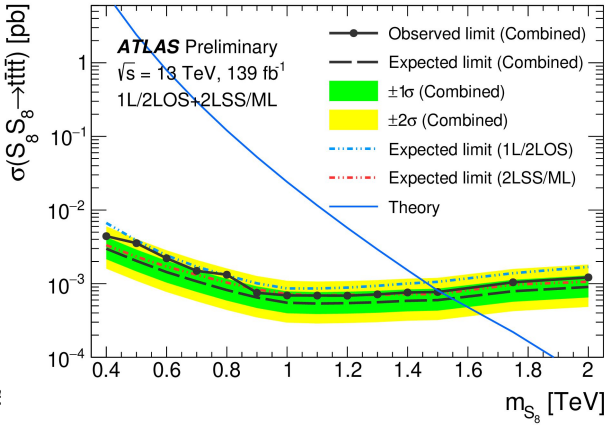


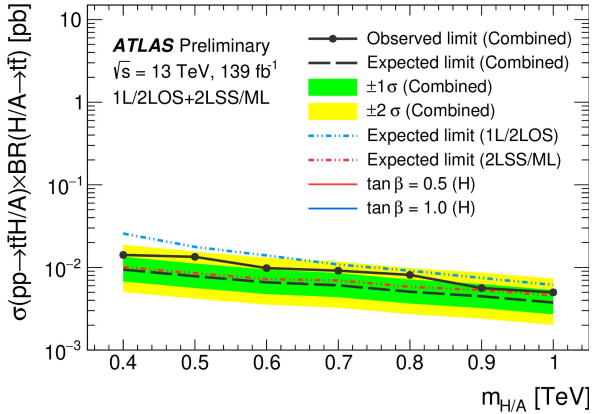
- **tanβ < 3.49 (3.16)** are observed to be excluded for m_A=m_H=**400 GeV** in the 2HDM (hMSSM).
- Masses up to **1240 (950) GeV** are observed to be excluded for **tanβ = 0.4 (1.0)** in the **2HDM** (**hMSSM**).
- Generic exclusion limits are derived separately.

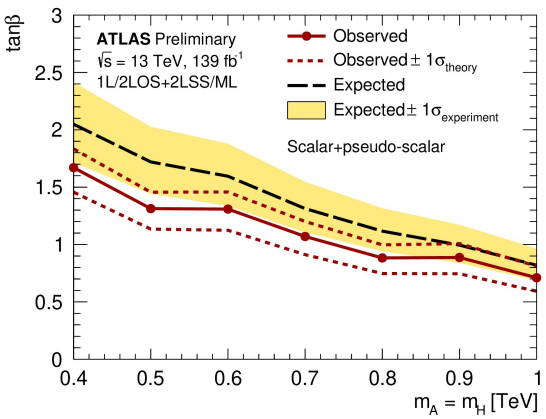
Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
H, A	0	even, odd	ggF	H → tt, A → tt	400 - 1400 GeV	139 fb^{-1}

ttH/A → 4-top → multi-lepton

- Final states (combination): 1l, 2l (OS+SS), 3l
- Multivariate techniques are employed to distinguish signal from background.
- Better expected sensitivity for 2l SS and 3l by a **factor of 4** w.r.t. previous result.
- Limits on **σ × BR (with $m_H = m_A$)**: **14.2-5 fb**
- Translated to limits on **tanβ: 1.7-0.7** are excluded for **400-1000 GeV** mass range





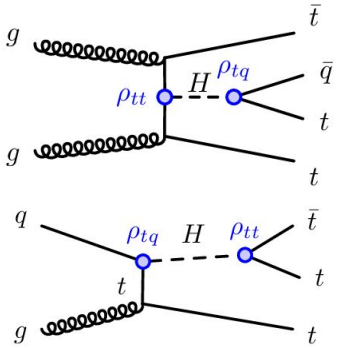


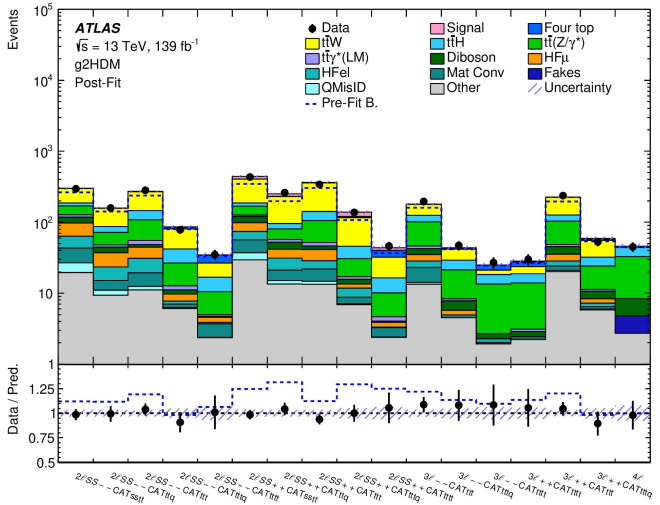
- The results are also used to constrain a model predicting the pair production of a colour-octet scalar, with the scalar decaying to a $t\bar{t}$ pair.

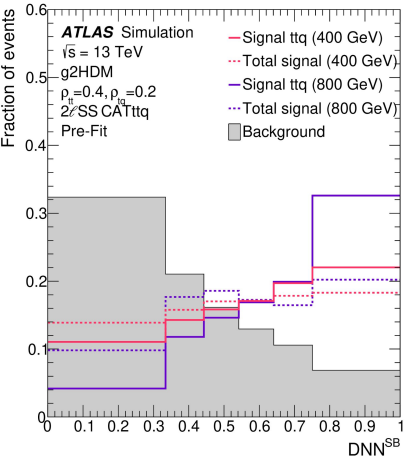
Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
H, A	0	even, odd	ttH, ttA	H → tt, A → tt	400 - 1000 GeV	139 fb^{-1}

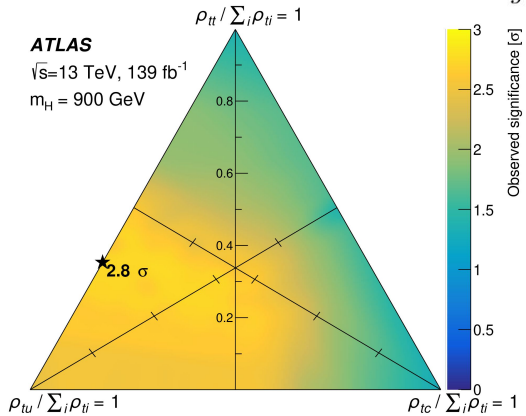
$H \rightarrow$ multi leptons + b-jets

- pp→ H → tt, pp→ tH → ttq(t), pp-> ttH -> tttq(t)
- The first search targeting: 3 top BSM production; 2HDM with flavour violation.
- 17 signal regions: based on lepton multiplicities, total lepton charge and a Deep Neural Network DNN-based categorisation.
- Another DNN trained to separate signal and background.







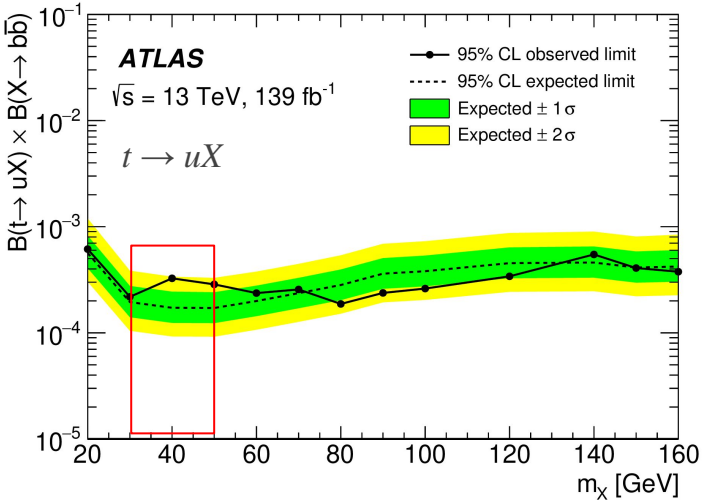


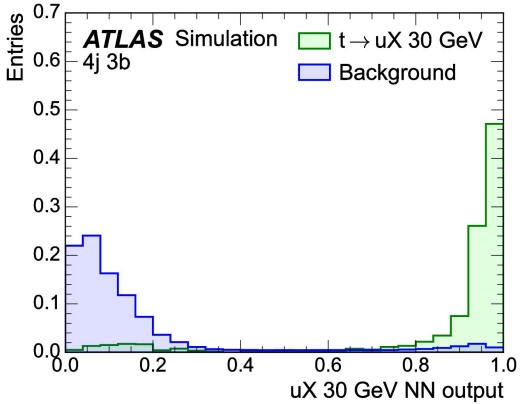
- No significant excess above the SM predictions observed.
- Mild excess observed at **m_H = 900 GeV** for **(ρ_{tt}, ρ_{tc}, ρ_{tu}) = (0.6, 0.0, 1.1)** with local significance of **2.8σ.**
- **200 < m_H< 630 GeV** is excluded with **(ρ_{tt}, ρ_{tc}, ρ_{tu}) = (0.4, 0.2, 0.2)** at 95% CLs.

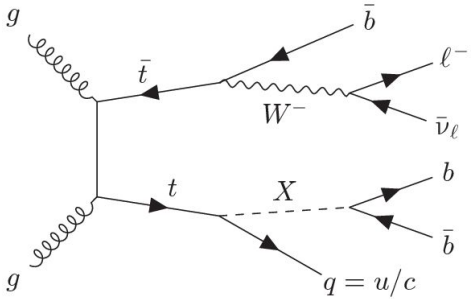
Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
H	0	even	ggF, tH, ttH	H→ tt, H→ tq	200 - 1500 GeV	139 fb^{-1}

$t \to qX,\ X \to bb$

- Search for neutral scalars X decaying to bb and produced in the flavour-changing neutral-current (FCNC) decay of a top-quark.
- "$t \to uX$" or "$t \to cX$" processes are considered.
- Events are categories according to jets' and b-tagged jets' multiplicity
- Main background: $t\bar{t}$+jets, reweighted from CR
- A discriminant Neutral Network (NN) is employed to distinguish signal from background





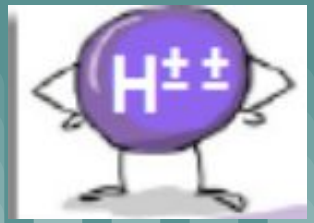


- Better expected limits by **a factor of ~3** w.r.t. previous results, scaled to the same luminosity at $m_X = 120$ GeV
- A deviation of **1.8σ** local significance in $t \to uX$ channel at m_X **= 40 GeV**

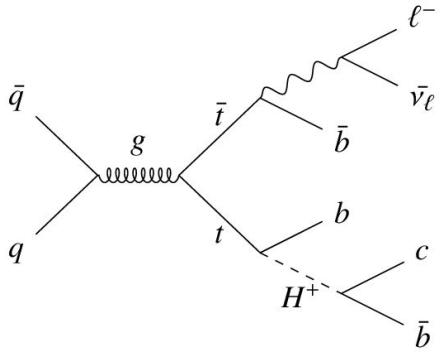
Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
H	0	even	gg→tt, t→Hu(d)	H→ bb	20 - 160 GeV	139 fb^{-1}

Charged Higgs

$H^{\pm}$, $H^{\pm\pm}$

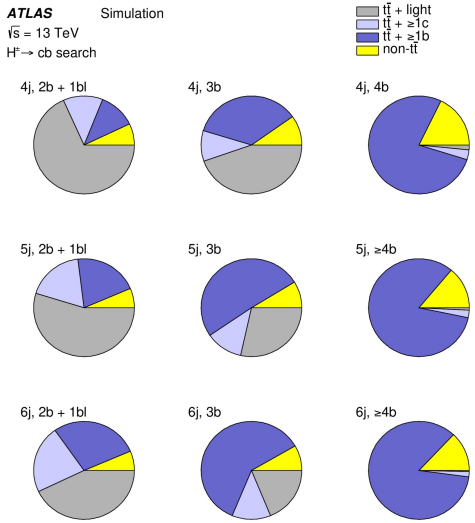


$t \rightarrow H^+ b \rightarrow cb\,b$



low mass $H^\pm$ production via the top decays $t \rightarrow H^\pm b$ with $H^\pm \rightarrow cb$

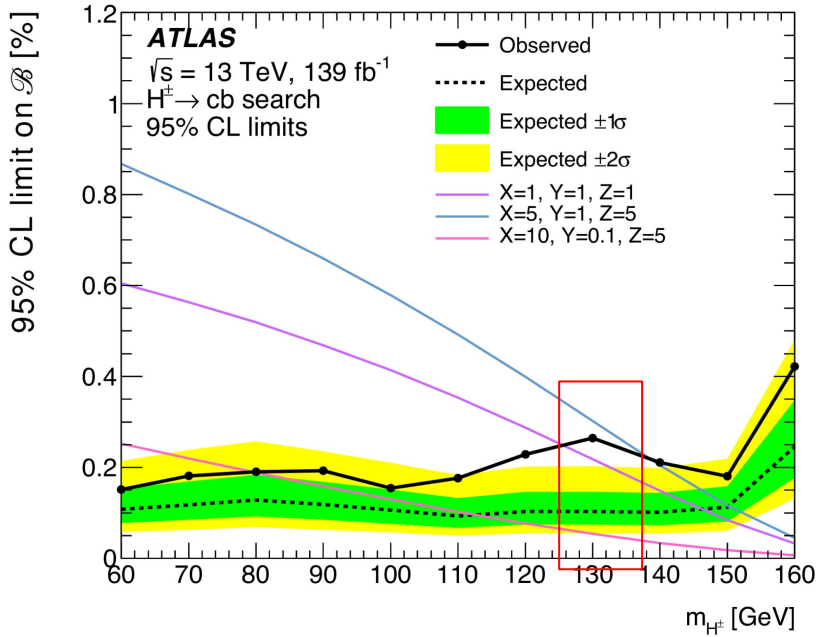
Final state: 1 lepton, 3 b-jets, 1 c-jet



Categories based on number of jets and b-jets

Use mass-parameterized NN to discriminate signal from background

→ **Factor of 5** improvement wrt previous ATLAS result



Small excess corresponds to a local (global) significance **3 σ** (2.5 σ) at **m(H±)= 130 GeV**

Upper limits on BR: **0.15%-0.42%**

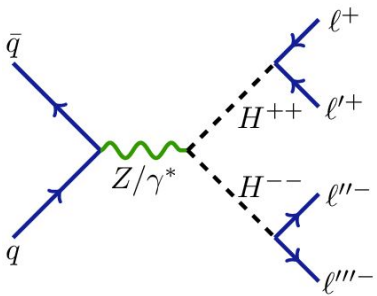
Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
$H^\pm$	±1	-	qq→tt	$H^\pm \rightarrow cb$	60 - 160 GeV	139 fb^{-1}

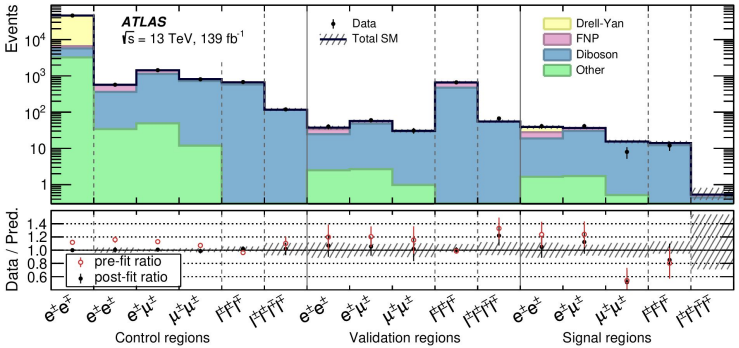
$H^{\pm\pm} \rightarrow \ell^{\pm}\ell'^{\pm}$

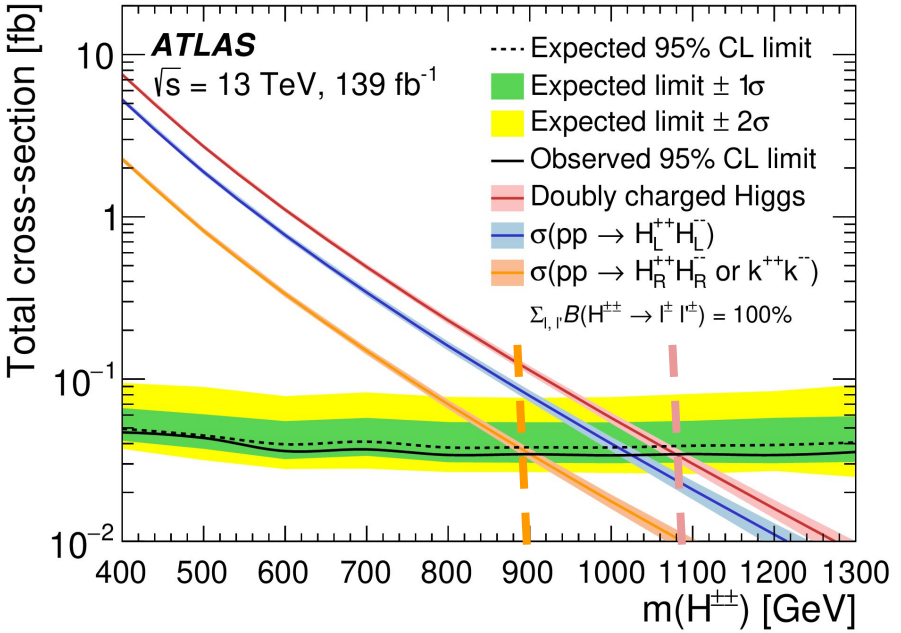
$H^{\pm\pm}$ predicted by Left-Right Symmetric Models (LRSM), type-II seesaw, Zee-Babu and Georgi–Machacek models

First direct test of the Zee-Babu model at the LHC

Categories based on lepton multiplicities (2/3/4L)







Factor of **2 improvement** in sensitivity wrt previous ATLAS result

Doubly charged Higgs **excluded** for masses **below 1080 (900) GeV** within LRSMs (Zee–Babu model)

Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
$H^{\pm\pm}$	±2	-	DY: pp → H^{++} H^{--}	$H^{\pm\pm} \rightarrow \ell^{\pm}\ell'^{\pm}$	400 - 1300 GeV	139 fb^{-1}

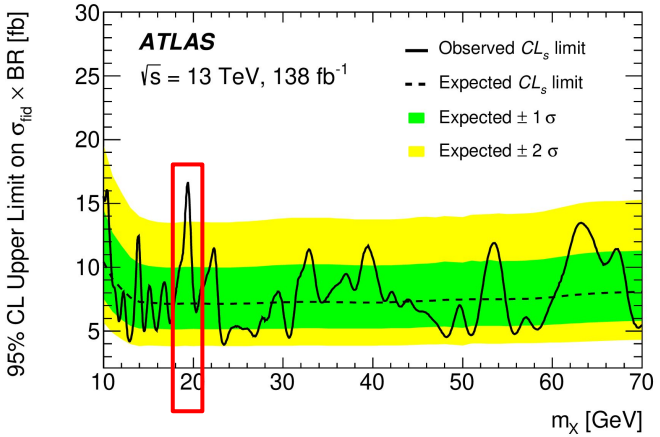
Conclusion

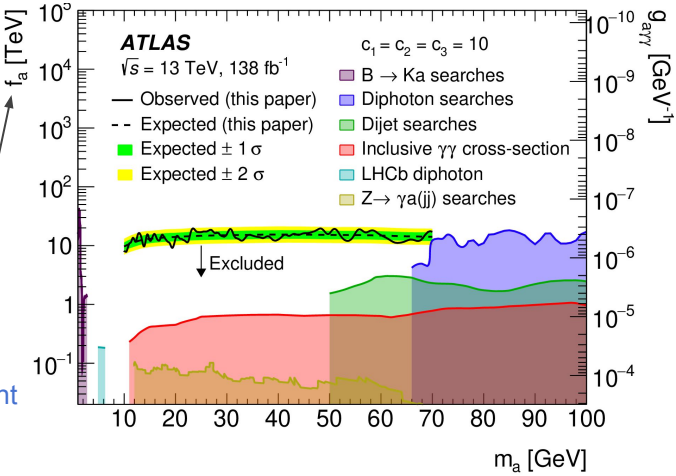
- Broad comprehensive programme targeting signatures of new scalars, pseudo-scalars and beyond the Standard Model Higgs decays is ongoing in ATLAS.
- **Searches** with **full LHC Run 2 dataset** covering **several production modes** and **final states** & **broad mass range** under **different spin** assumptions**.**
- **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. But there are several small deviations that have to be followed up..
- Many more exciting results to come using the full Run 2 dataset.
- Soon to have new results using Run 3 dataset..

Back Up

Low mass $H \rightarrow \gamma\gamma$

- Search for a light axion-like particle (ALP) , coupling to gluons in spectrum in mass range [10-70] GeV → Closely spaced photons pairs (boosted)!
- The signal is modeled using Double Sided Crystal Ball.
- Background estimation:
  - Irreducible (γγ) from MC.
  - Reducible (γj,jγ,jj) from data driven methods.
  - Mixed according to data-driven purities.
  - Fluctuations suppressed using the Gaussian Processes fit.
- Template fit to $m_{\gamma\gamma}$ distribution.
- No significant excess above SM observed.
- Exclusion limits set on the σ **x B(X→ γγ)** at the 95% CLs: **17-4 fb**
- Largest excess at **19.4 GeV** with **3.1σ** local significance (1.5σ global).
- Results interpreted as limits in the plane spanned by ALP mass (m_a) and decay constant (f_a).
- Covers previously unexplored phase space!



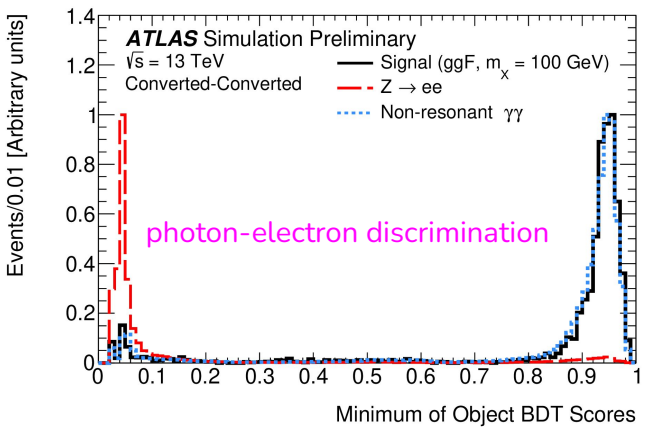


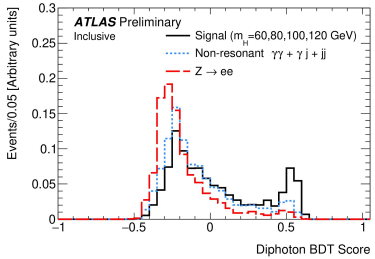
Lower limit on ALP decay constant

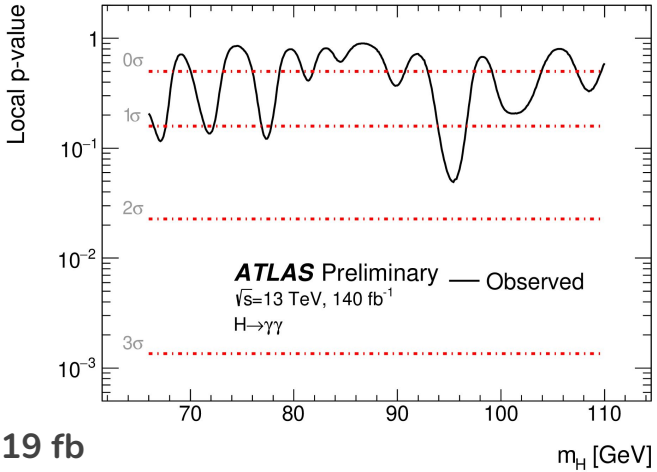
Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
H (Light ALP)	0	even	ggF	H→ $\gamma\gamma$	10-70 GeV	138 fb^{-1}

Intermediate mass $H \rightarrow \gamma\gamma$

- Searches for general spin-0 boson (X) and additional Higgs (H) in mass range [66, 110] GeV.
- Similar techniques to the low-mass H→$\gamma\gamma$ analysis.
- Additional background:
  - Resonant Drell-Yan (DY) dielectron process (mainly Z → ee).
  - Gradient BDT used to improve photon-electron discrimination.
- 9 signal categories based on photons conversion and additional BDT to enhance the sensitivity.
- No significant excess above SM observed.
- Largest deviation at **95.4 GeV** with **1.7σ** local significance.
- Upper limits on the fiducial **σ x B(H→ γγ)** are set at the 95% CLs : **102 - 19 fb**



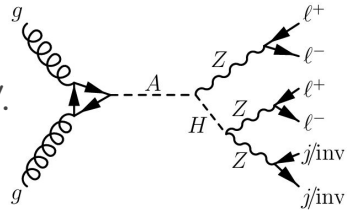


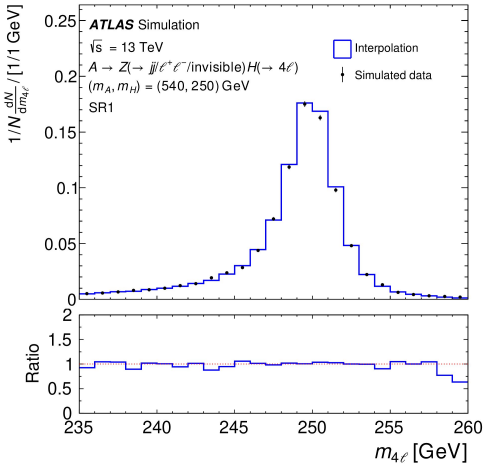


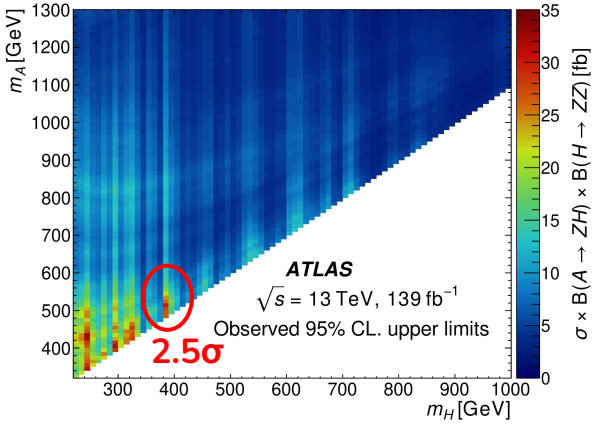
Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
H	0	even	ggF, VBF, ttH, WH, ZH	H→ $\gamma\gamma$	66-110 GeV	140 fb^{-1}

$A \rightarrow ZH\ (H \rightarrow ZZ) \rightarrow 4\ell + 2j/E_T^{miss}$

- Search for heavy resonances that decay to 4 leptons and missing transverse momentum or jets, with $m_{4\ell} > 200$ GeV.
- Events are divided into 7 categories based on the number of jets, b-jets, $p_T^{4\ell}$, E_T^{miss} significance.
- 72 signal mass points are generated; a linear interpolation to obtain signal shapes between different masses.
- Main background from the leptonic decay of two Z bosons (qq(gg) → ZZ)
- No significant excess above SM observed.
- Upper limits on the fiducial $\sigma \times B(A \rightarrow ZH) \times B(H \rightarrow ZZ)$ are set at the 95% CLs : **2.1–32.3 fb** for $(m_A, m_H) = (320, 220)$ **GeV** to $(m_A, m_H) = (1300, 1000)$ **GeV.**



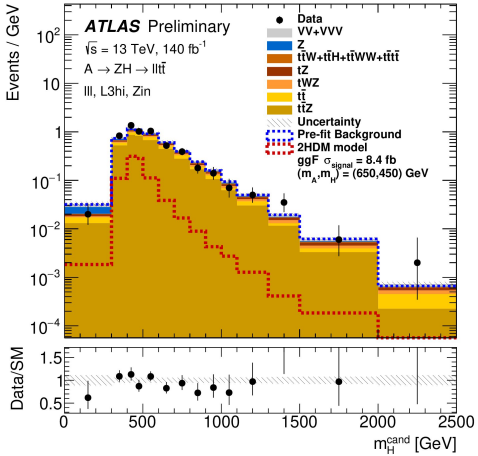


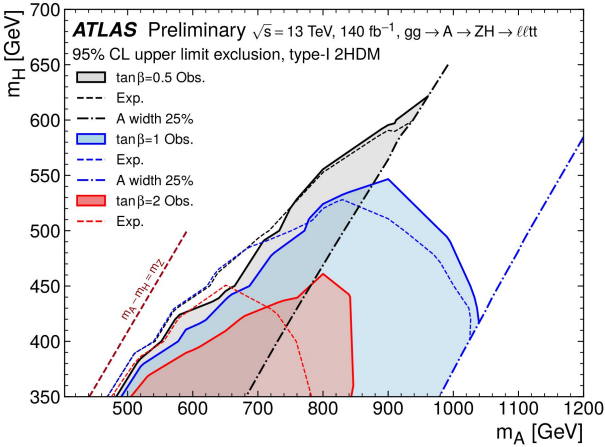


Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
A, H	0	Odd, even	ggH	A → ZH, H→ ZZ	320 - 1300, 220 - 1000 GeV	139 fb^{-1}

$A \rightarrow ZH \rightarrow \ell\ell tt$ / $vvbb$

- $Z \rightarrow 2\ell$ or $2v$ and $H \rightarrow tt$ or bb, leading to "$\ell\ell tt$" and "$vvbb$" final states.
- Events are divided into 3 categories based on number of leptons, jets, b-jets, MET, reconstructed Z and H boson masses.
- Main background: ttZ ($lltt$ channel); Z+heavy flavour + tt^- ($vvbb$ channel).
- No significant excess above SM observed.
- Largest deviation at the (m_A, m_H) = **(650, 450) GeV** with local significance of **2.85σ**.
- Upper limits on the fiducial σ **x B(A→ ZH)xB(H→ tt)** are set at the 95% CLs:
  - $\ell\ell tt$ channel : **992-75 fb** for (m_A, m_H) = **(550, 450) GeV** to (m_A, m_H) = **(1200, 600) GeV**.
  - $vvbb$ channel: **3700-6.2 fb** for (m_A, m_H) = **(350, 150) GeV** to (m_A, m_H) = **(1200, 300) GeV**.
- Constraints set on the **2HDM Type-I** and **Type-II** in the m_H-m_A plane for different ratios of the two vacuum expectation values **tanβ**.





Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
A, H	0	Odd, even	ggH, b-associated	A → ZH, H→ tt	350 - 1200, 130 - 800 GeV	139 fb^{-1}

ttH/A → 4-top 2lSS/3

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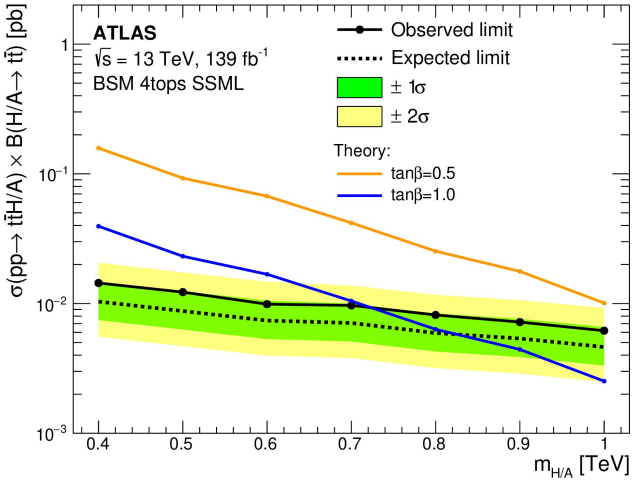
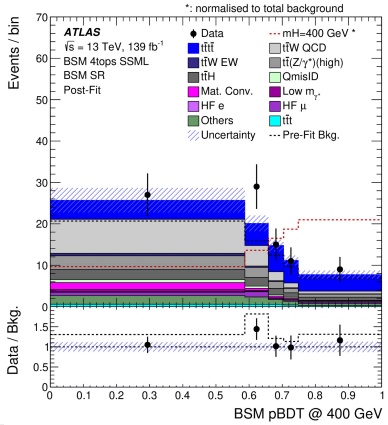
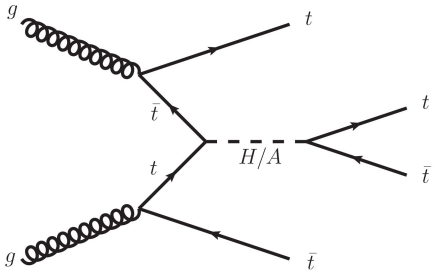
- Search for heavy additional neutral Higgs scalar (H) and pseudoscalar (A) in 4 top processes in mass range [0.4, 1] TeV.
- Only multi-lepton events are selected (2 same sign (2LSS) or 3 leptons) with at least 6 jets and at least 2b-tagged jets, H_T> 500 GeV.
- A multivariate discriminant BDT is employed to distinguish signal from background.
- Better expected sensitivity by a **factor of 4** w.r.t. previous result.



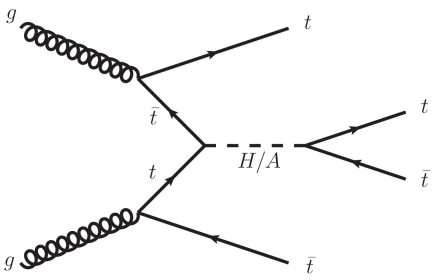




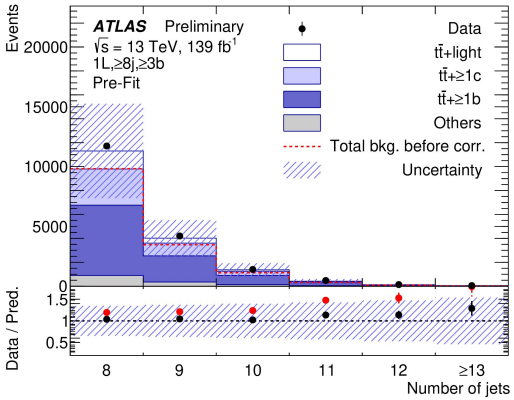
- No excess above the SM predictions observed.
- Interpreted in 2HDM type-II
- Limits on **σ × BR (with $m_H = m_A$)**: **14-6 fb**
- Translated to limits on **tanβ: < 1.6 (<0.6)** are excluded for a mass of **400 (1000) GeV**.

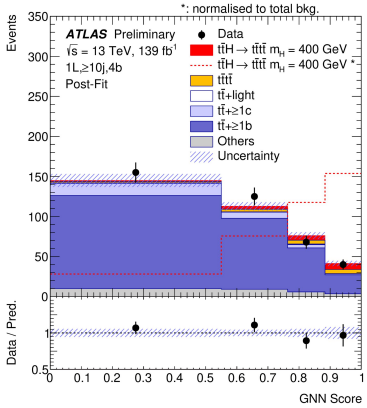
Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
H, A	0	even, odd	ttH, ttA	H → tt, A → tt	400 - 1000 GeV	139 fb^{-1}

ttH/A → 4-top 1l/2lOS



- To complete the previous analysis, events with one lepton or 2 OS leptons final are selected and studied.
- Main background: tt+jets → reweighted using data-driven corrections.
- A/H mass parametrised graph neural network (GNN) is trained to optimise the signal-to-background discrimination.





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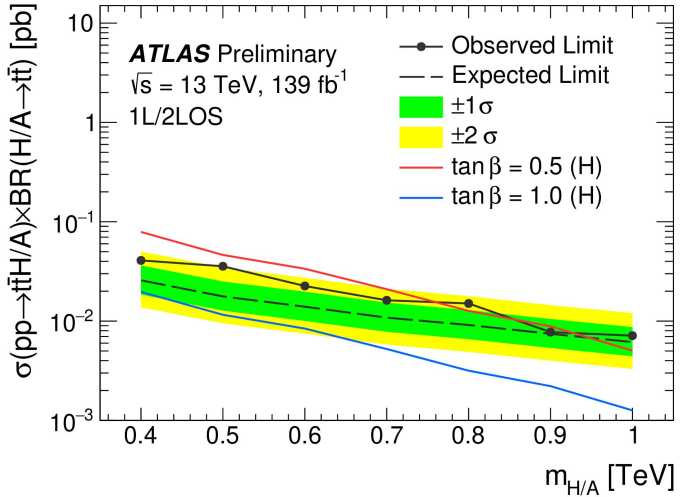
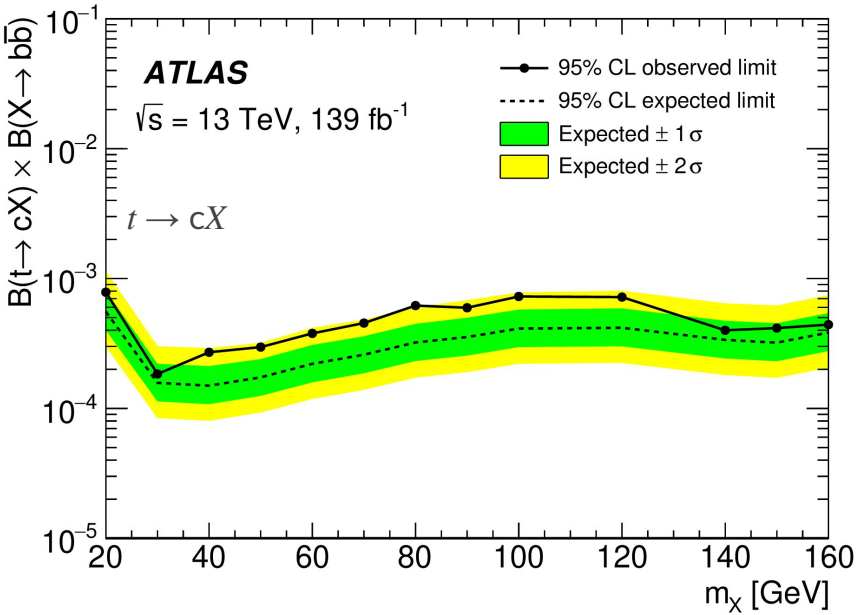
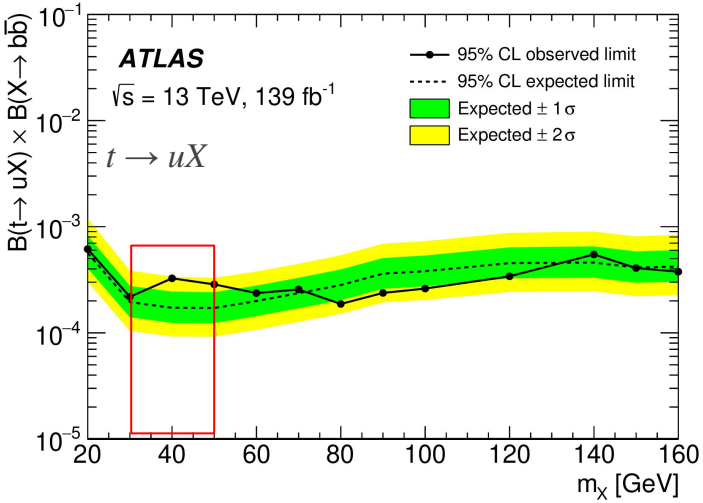


Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
H, A	0	even, odd	ttH, ttA	H → tt, A → tt	400 - 1000 GeV	139 fb^{-1}

$t \to qX,\ X \to bb$





- Better expected limits by **a factor of ~3** w.r.t. previous results, scaled to the same luminosity at m_X = 120 GeV
- A deviation of **1.8σ** local significance in $t \to uX$ channel at m_X **= 40 GeV**
- ~ **2σ** local excess in $t \to cX$ over almost the entire mass range → X is expected to be much narrower.

Additional Higgs	Charge	CP	Production modes	Decays	Mass range	Run-2 Luminosity
H	0	even	gg→tt, t→Hu(d)	H→ bb	20 - 160 GeV	139 fb^{-1}