Search for heavy charged Higgs bosons decaying into top and bottom quarks in the ATLAS detector

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on behalf of the ATLAS collaboration

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Higgs Hunting 2021

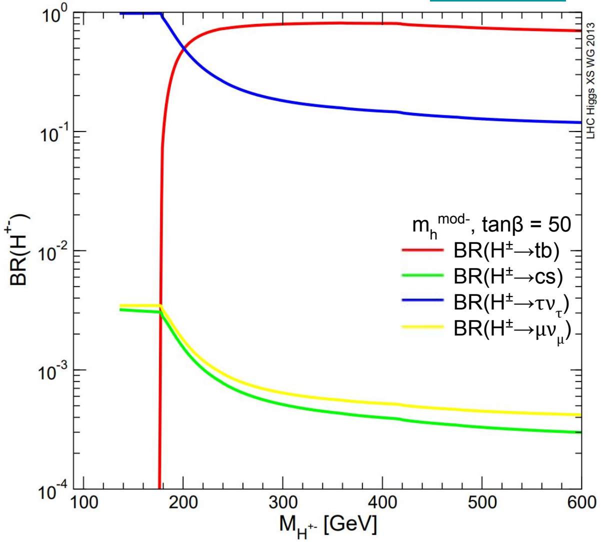
Motivation

➔Several BSM theories include an extended Higgs sector with at least one pair of charged Higgs bosons.

➔In the 2HDM models:

- A total of 5 scalar bosons are predicted: h, H, A, **H^+**, **H^-**
- The $H^\pm$ decay mainly depends on:
  - $H^\pm$ mass
  - $\tan\beta$: vacuum expectation values ratio of the two Higgs doublets.
  - α: mixing angle of the CP-even Higgs bosons.
- In the Type-II 2HDM, the $H^+ \rightarrow tb$ decay dominates for:
  - H^+ mass > 200 GeV
  - $\cos(\beta-\alpha) \sim 0$ limit (the light neutral scalar is SM-like)

arXiv:1307.1347



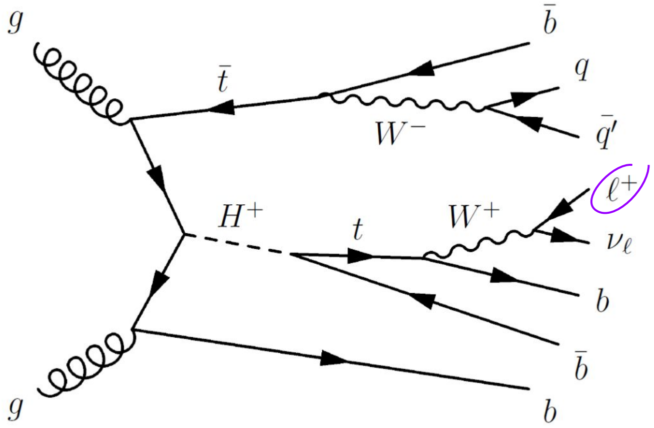
Analysis overview

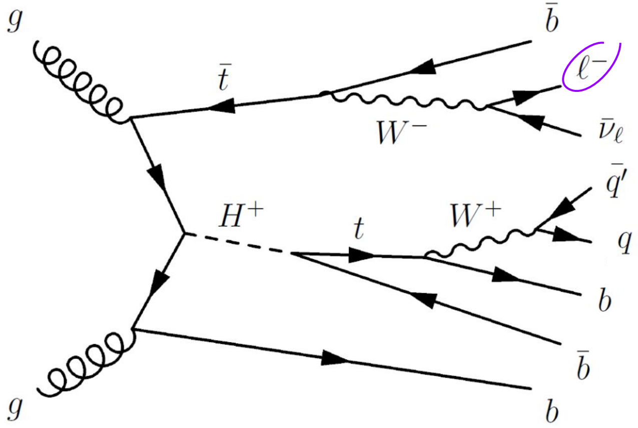
➔Use LHC Run-2 139 fb^{-1} pp collisions recorded with the ATLAS detector.

- ◆10.1007/JHEP06(2021)145
- ◆Previous publication based on 2015+2016 (36 fb^{-1}). 10.1007/JHEP11(2018)085

➔Search in the 200 - 2000 GeV H^+ mass range.

➔Focused on the single lepton channel since it provides the best significance.

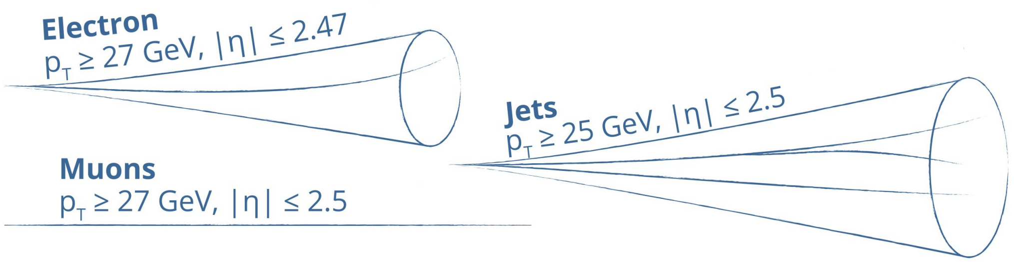




Analysis strategy

➔ Select events with:

- ◆ Exactly one lepton: $e^{\pm}$ or $\mu^{\pm}$.
- ◆ ≥5 jets, ≥2 b-tagged at 70% efficiency.



➔ Classify events according to jet and b-jet multiplicities.

- ◆ Four signal regions: 5j3b, 5j≥4b, ≥6j3b, ≥6j≥4b.
- ◆ $t\bar{t}$+jets is the main background.
  - ● Especially $t\bar{t}+\geq 1b$ in the most signal-sensitive regions.
  - ● Modelling improved by applying Data/MC-based corrections.

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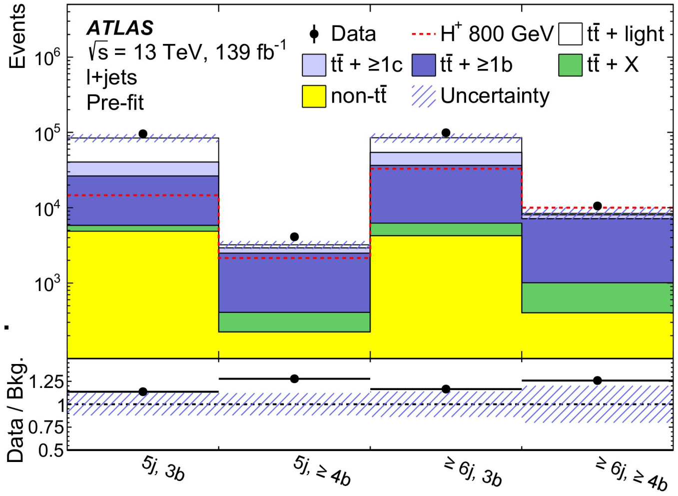

$t\bar{t}$+jets MC correction

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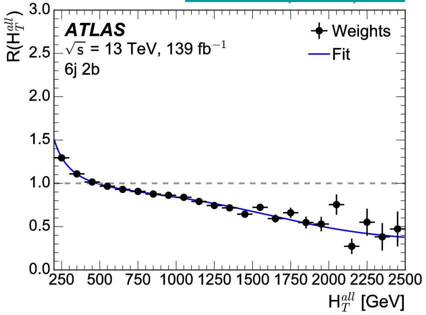


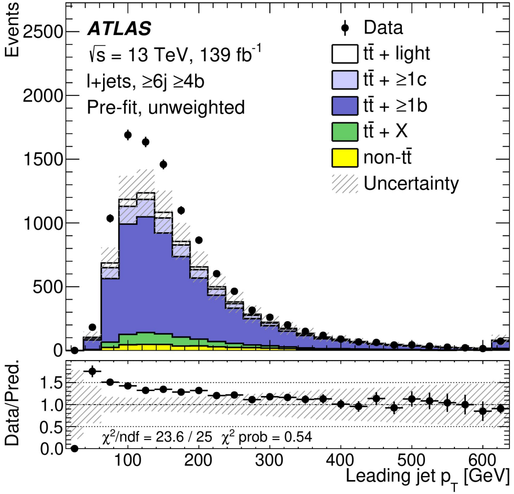
➔ Mitigate differences observed in data/MC distributions due to $t\bar{t}$+jets mismodelling.

➔ Data/MC-based factors extracted from 2b control regions:

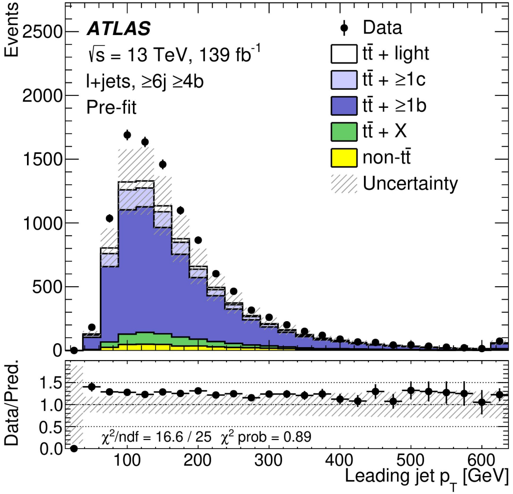
- Dependent on jet multiplicity and $\sum p_T^{jet} + p_T^{lep}$ distributions.

➔ Corrections applied appropriately to the SRs improve pre-fit agreement:

Uncorrected



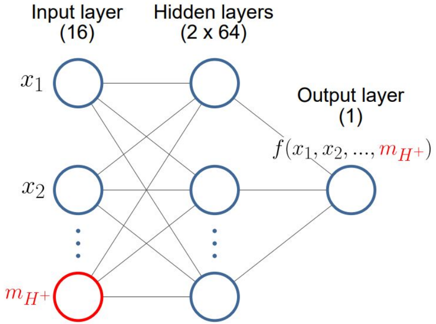
Corrected



Parameterised Neural Network

→Use of multivariate techniques to separate signal and background in the signal regions.

→Description:
- A single training performed for each signal region.
- Based on high-level kinematic variables:
  - $\sum p_T^{jet}$, leading jet p_T, kinematic discriminant...
- Input parameter: H^+ mass hypothesis
- All H^+ mass samples included in a single training.
  - Simplifies training, benefits from continuity, effectively more signal statistics and allows interpolation.



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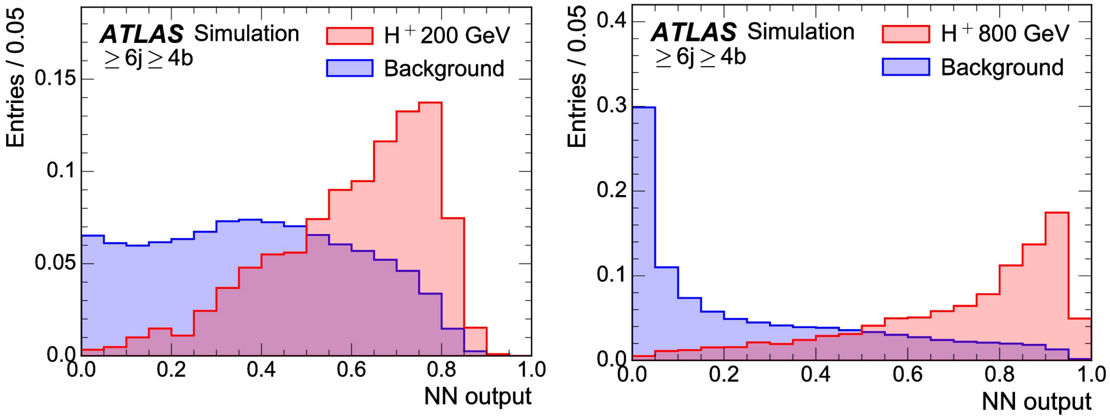
→Better signal and background separation at higher masses.



Fit results

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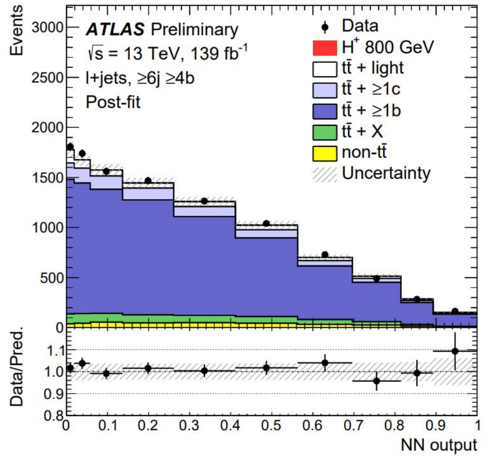
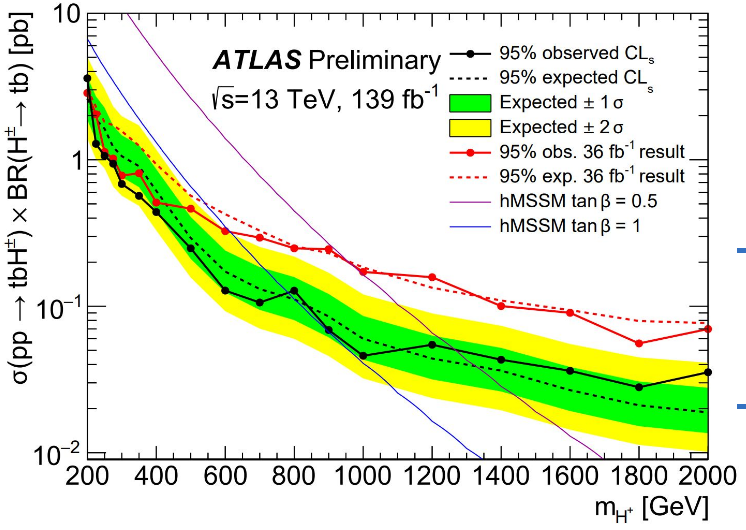
➔ Simultaneous binned profile likelihood fit to mass-parameterised NN output in the four signal regions.

- One fit for each H^+ mass hypothesis.
- Normalisation of $t\bar{t}$+≥1b and $t\bar{t}$+≥1c backgrounds allowed to vary freely.
- Systematic uncertainties included as nuisance parameters.



➔ Produced model-independent σ x BR limits.



➔ Improved exclusion limits at 95% CL with respect to the 36 fb^{-1} publication, especially at high H^+ masses.

➔ Limited by systematics, especially $t\bar{t}$+≥1b modelling.

Exclusion limits

- ➔ Results interpreted in context of different benchmark models
  - ◆ hMSSM, M_h^{125}
  - ◆ $M_h^{125}(\tilde{\chi})$, $M_h^{125}(\tilde{\tau})$, M_h^{125}(align), M_h^{125}(CPV)

- ➔ Exclusion limits on hMSSM improved especially at high H^+ masses with respect to the previous publication.

- ➔ tanβ exclusion summary from direct and indirect ATLAS searches.

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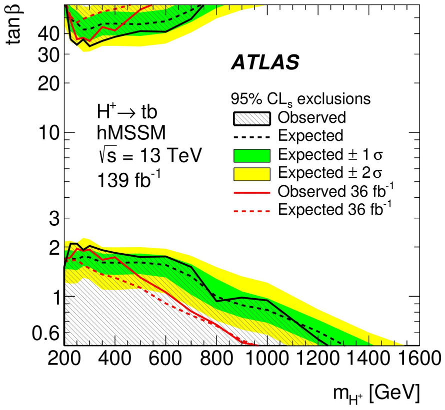

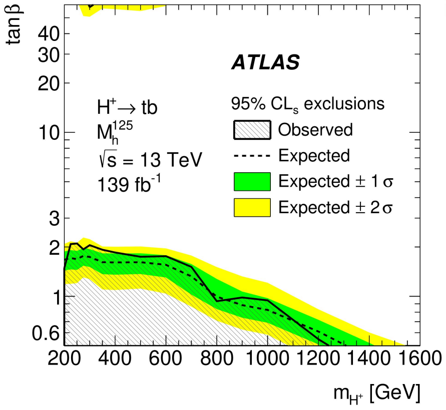

Additional results in backup

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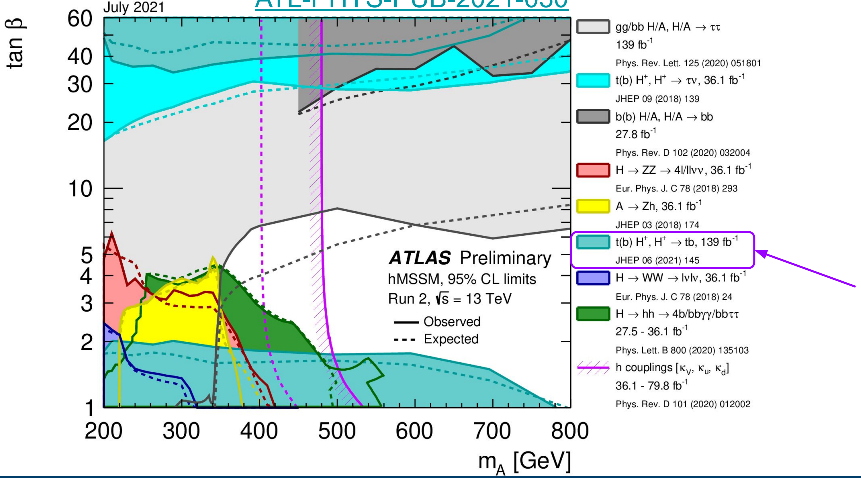
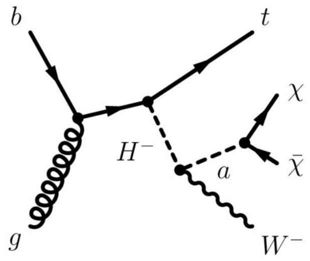


2HDM+a interpretation

➔The 2HDM+a is the simplest extension of the simplified pseudoscalar model.

- 2HDM scalars (h, H, A, $H^{\pm}$), pseudoscalar a and DM Dirac fermion χ.
- Extra parameter: mixing angle θ between pseudoscalars.



➔Interpreted the H±→tb results in the context of the 2HDM+a model.

- Exclusion limits set on m_a, mχ, tanβ, sinθ

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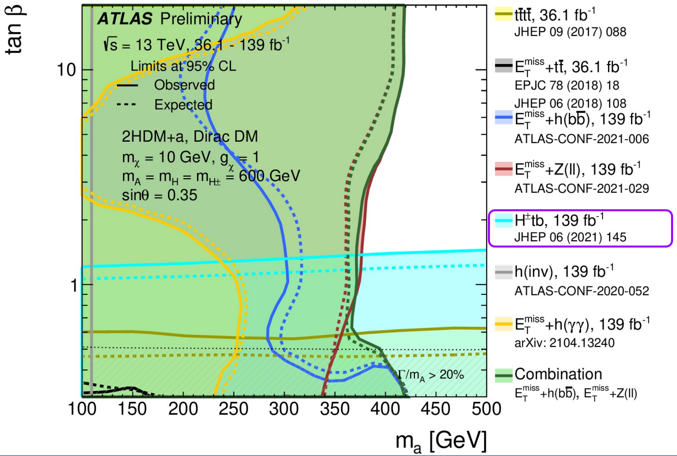
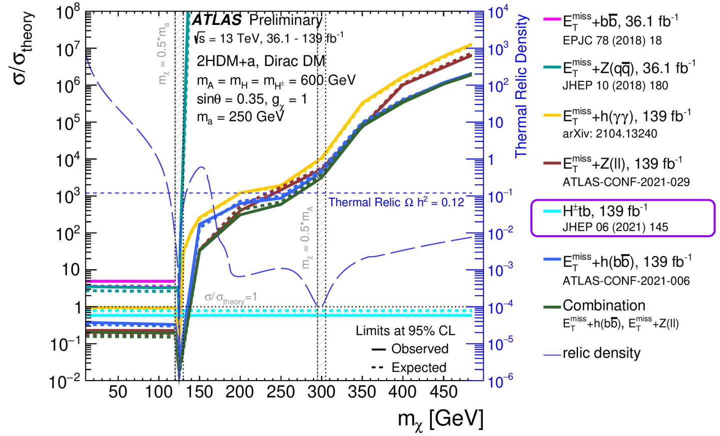




Additional results in backup

Summary

➔ Performed a $H^+ \rightarrow tb$ search using the full Run-2 dataset in the single lepton channel.
- Implemented a PNN to separate signal and background.
- No significant excess above the expected SM background found.
- Improved 95% CL_s limits on $\sigma \times BR$ obtained with respect to previous analysis.
- Obtained $\tan\beta$ exclusion limits for various benchmark scenarios.

➔ Interpreted results in the 2HDM+a dark matter model.
- Good complementarity with other dark matter searches.

Thank you for you attention!

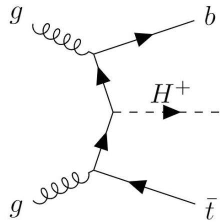
Backup

Signal sample details

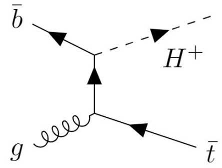
- Four flavor scheme (4FS):
  - No b quarks in the initial state.
  - LO: Direct production $gg \to tbH^+$ and $qq \to tbH^+$ + NLO corrections.
- Five flavor scheme (5FS):
  - Introducing b quark parton density functions.
  - LO: $gb \to tH^+$ + NLO corrections.
- 4FS and 5FS yield differences at finite order.
- Strategy used:
  - Signal sample simulated using 4FS.
  - 4FS and 5FS NLO cross-sections combined with Santander matching:

$$\sigma = \frac{\sigma^{4\mathrm{FS}} + w\sigma^{5\mathrm{FS}}}{1+w} \qquad w = \log\frac{M_{H^+}}{m_b} - 2$$

4FS



5FS



Background composition and yields

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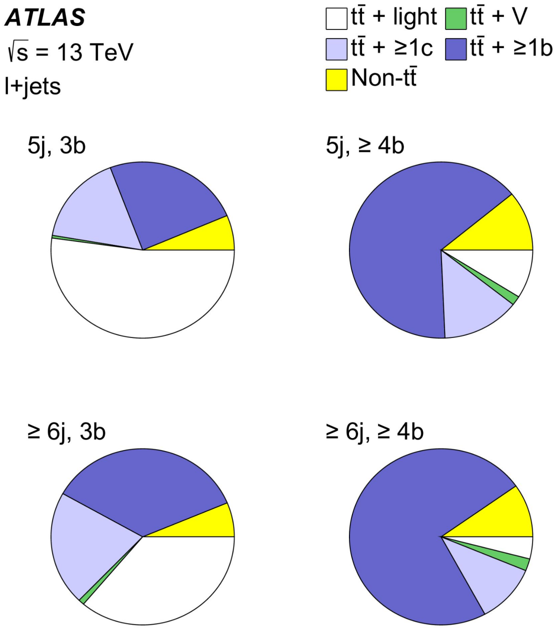

m_{H^+} = 200 GeV hypothesis				
	5j, 3b	5j, ≥ 4b	≥ 6j, 3b	≥ 6j, ≥ 4b
$t\bar{t}$ + light	45000 ± 4000	310 ± 110	32000 ± 4000	340 ± 140
$t\bar{t}$ + ≥1b	29600 ± 2900	2940 ± 220	40200 ± 3300	8000 ± 500
$t\bar{t}$ + ≥1c	14000 ± 4000	440 ± 140	19000 ± 6000	1010 ± 290
$t\bar{t}$ + W	110 ± 15	3.2 ± 0.6	236 ± 35	16.2 ± 2.7
$t\bar{t}$ + Z	300 ± 40	51 ± 6	670 ± 90	174 ± 23
Single-top Wt-channel	2300 ± 600	80 ± 50	1900 ± 800	150 ± 90
Single-top t-channel	740 ± 300	51 ± 20	500 ± 400	60 ± 50
Other top-quark sources	128 ± 16	17.5 ± 3.2	180 ± 70	58 ± 24
VV & V + jets	1600 ± 600	65 ± 23	1600 ± 600	120 ± 40
$t\bar{t}H$	530 ± 60	127 ± 19	1140 ± 120	430 ± 60
H^+	600 ± 900	70 ± 90	700 ± 1000	160 ± 230
Total	95700 ± 2900	4150 ± 140	98400 ± 2900	10500 ± 400
Data	95852	4109	98929	10552

m_{H^+} = 800 GeV hypothesis				
	5j, 3b	5j, ≥ 4b	≥ 6j, 3b	≥ 6j, ≥ 4b
$t\bar{t}$ + light	46000 ± 4000	330 ± 120	33000 ± 4000	500 ± 200
$t\bar{t}$ + ≥1b	29600 ± 3100	2920 ± 210	41000 ± 4000	8100 ± 400
$t\bar{t}$ + ≥1c	14000 ± 6000	440 ± 190	17000 ± 7000	870 ± 330
$t\bar{t}$ + W	108 ± 15	3.3 ± 0.6	233 ± 35	16.0 ± 2.7
$t\bar{t}$ + Z	300 ± 40	50 ± 7	660 ± 90	171 ± 23
Single-top Wt-channel	2000 ± 500	56 ± 33	1400 ± 500	100 ± 60
Single-top t-channel	740 ± 300	53 ± 21	600 ± 500	70 ± 50
Other top-quark sources	130 ± 16	17.7 ± 3.2	190 ± 70	61 ± 24
VV & V + jets	1900 ± 700	73 ± 25	1700 ± 600	130 ± 50
$t\bar{t}H$	520 ± 60	125 ± 19	1130 ± 120	420 ± 60
H^+	30 ± 80	4 ± 10	70 ± 180	20 ± 50
Total	94700 ± 2800	4070 ± 140	97800 ± 2800	10400 ± 400
Data	95852	4109	98929	10552

Kinematic discriminant description

➔ Variable reflecting the probability of an event being compatible with the $H^+ \rightarrow tb$ and the $t\bar{t}$ hypotheses:

$$D = \frac{P_{H^+}(\mathbf{x})}{P_{H^+}(\mathbf{x}) + P_{t\bar{t}}(\mathbf{x})}$$

➔ $P_{H^+}(\mathbf{x})$ defined as the product of a pdf for each of the reconstructed invariant masses in the event:

- Mass of the semileptonically decaying top quark.
- Mass of the hadronically decaying W boson.
- Mass of the hadronically top quark minus the mass of its W.
- Mass of the H^+ minus the mass of the top quark of the $H^+ \rightarrow tb$ decay.
- For events with ≥6 jets, mass of the H^+ recoil system minus the corresponding top quark.

➔ $P_{t\bar{t}}(\mathbf{x})$ defined similarly:

- For events with 5 jets, same invariant masses described before.
- For events with ≥6 jets, mass of the two highest p_T jets not used in the rest of the reconstructed objects.

Systematic uncertainties

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→ Systematic uncertainties impact on H^+ σ x BR:
  - ◆ Largest contribution from $t\bar{t}$+≥1b modelling systematics.

Uncertainty source	$\Delta\mu(H^+_{200})$ [pb]	$\Delta\mu(H^+_{800})$ [pb]
$t\bar{t}+\geq 1b$ modelling	1.01	0.025
Jet energy scale and resolution	0.35	0.009
$t\bar{t}+\geq 1c$ modelling	0.32	0.006
Jet flavour tagging	0.20	0.025
Reweighting	0.22	0.007
$t\bar{t}$ + light modelling	0.33	0.009
Other background modelling	0.19	0.011
MC statistics	0.11	0.008
JVT, pile-up modelling	<0.01	0.001
Luminosity	<0.01	0.002
Lepton ID, isolation, trigger, E_T^{miss}	<0.01	<0.001
H^+ modelling	0.05	0.002
Total systematic uncertainty	1.35	0.049
$t\bar{t}+\geq 1b$ normalisation	0.23	0.007
$t\bar{t}+\geq 1c$ normalisation	0.045	0.015
Total statistical uncertainty	0.43	0.025
Total uncertainty	1.42	0.055

→ $t\bar{t}$+jets modelling uncertainties summary:

Uncertainty source	Description		Components
$t\bar{t}$ cross-section	Up or down by 6%		$t\bar{t}$ + light
$t\bar{t}$ reweighting	Statistical uncertainties of fitted function (six) parameters		All $t\bar{t}$ and Wt
$t\bar{t}+\geq 1b$ modelling	4FS vs 5FS		$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ normalisation	Free-floating		$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1c$ normalisation	Free-floating		$t\bar{t}+\geq 1c$
NLO matching	MadGraph5_aMC@NLO+Pythia	vs PowhegBox+Pythia	All $t\bar{t}$
PS & hadronisation	PowhegBox+Herwig	vs PowhegBox+Pythia	All $t\bar{t}$
ISR	Varying α_S^{ISR}	in PowhegBox+Pythia	All $t\bar{t}$
μ_f	Scaling by 0.5 (2.0)	in PowhegBox+Pythia	All $t\bar{t}$
μ_r	Scaling by 0.5 (2.0)	in PowhegBox+Pythia	All $t\bar{t}$
FSR	Varying α_S^{FSR}	in PowhegBox+Pythia	All $t\bar{t}$

Exclusion limits

- ➔ $\tan\beta$ vs $m(H^+)$ exclusion limits:
  - ◆ M_h^{125} ($\tilde{\chi}$), M_h^{125} ($\tilde{\tau}$), M_h^{125}(alignment), M_h^{125}(CPV)

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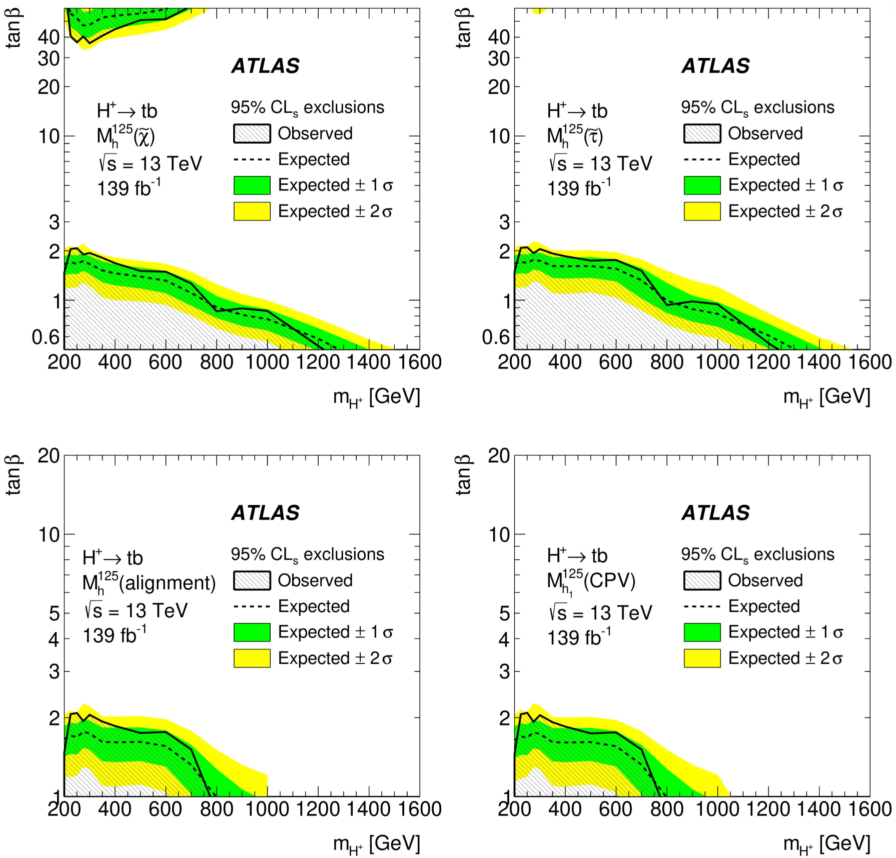

2HDM+a limits

➔ Interpreted the $H^{\pm} \to tb$ results in the context of the 2HDM+a model:
- ◆ Exclusion limits set on m_a, mχ, tanβ, sinθ

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