Searches for singly- and doubly-charged Higgs bosons in ATLAS

Otilia Ducu, on behalf of ATLAS Collaboration

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Charged Higgs bosons

Well studied Higgs Sector extensions (CERN-EP-2024-094):

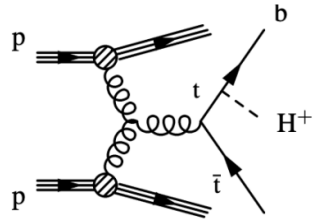
- Two-Higgs-doublet models (2HDMs):
  - Five physical scalar states: CP-even h^0 and H^0, CP-odd pseudo-scalar A, and $H^{\pm}$
  - Such models can be described with 6 physical parameters:
    - Higgs masses: m_h, m_H, m_A and $m_{H^{\pm}}$
    - tanβ, the ratio of the vacuum expectation values of the two doublets
    - α, that describes the mixing between the CP-even states
- **The CP-conserving 2HDMs are categorized into four types:**
  - Type-I, type-II, lepton-specific, and flipped
  - They differ in the way the Higgs fields couple to the SM particles:

2HDM Type	Up-type quarks couple to	Down-type quarks couple to	Charged leptons couple to
Type-I	Φ_2	Φ_2	Φ_2
Type-II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

- Three-Higgs-doublet models, 3HDMs that extends the SM by adding two more doublets
- The Georgi–Machacek (GM) model that extends the SM by adding two triplets – or even higher multiplets in its most general form
- The type-II seesaw mechanism → an attractive model since it can predict massive neutrinos

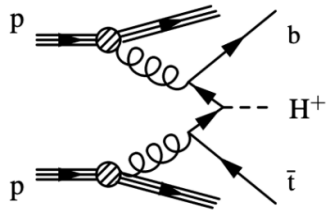
Three mass ranges usually studied (link):

Light: $m_{H^\pm} < m_t - m_b$



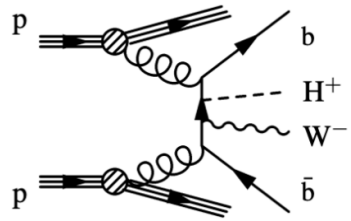
double-resonant t

Heavy: $m_{H^\pm} > m_t - m_b$



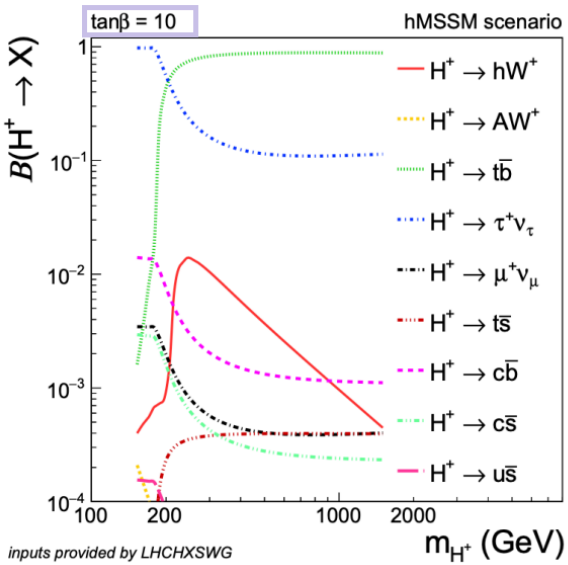
single-resonant t

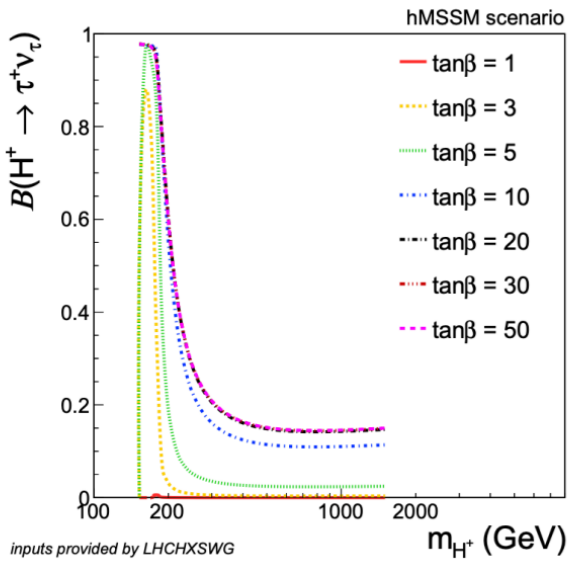
Intermediate: $m_{H^\pm} \approx m_t$

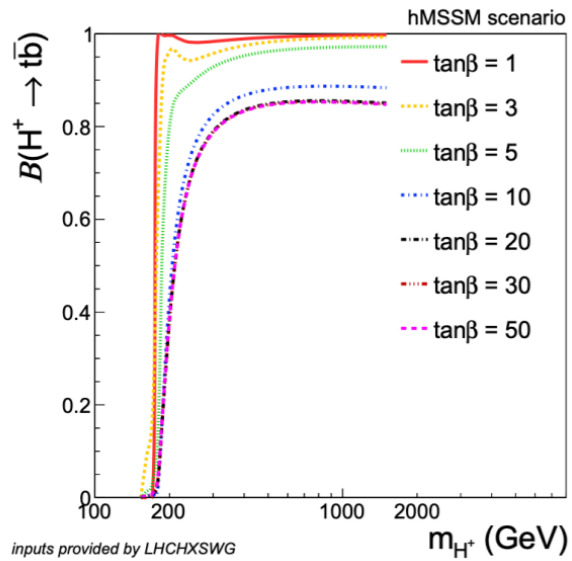


non-resonant t

- $H^\pm$ (as well as $H^{\pm\pm}$) BRs are highly model dependent







- In 2HDM type II, below 200 GeV the $H^\pm \to \tau\nu_\tau$ decay is dominant, with $H^\pm \to cs$ or cb becoming more important at low tanβ
- Above 200 GeV, the dominant decay is $H^\pm \to tb$

Charged Higgs bosons searches in ATLAS

Many charged Higgs boson searches performed in ATLAS, the latest being (link):

Run-2

Charge	Coupling	Decay	Mass range	Integrated $\mathcal{L}$
Singly-charged	Fermions	$H^{\pm} \to \tau\nu$	90–2000 GeV	36 fb^{-1}
		$H^{\pm} \to tb$	200–2000 GeV	139 fb^{-1}
		$H^{\pm} \to cb$	60–160 GeV	139 fb^{-1}
		$H^{\pm} \to cs$	60–168 GeV	140 fb^{-1}
	Bosons	$H^{\pm} \to W^{\pm}Z$	200–1000 GeV	139 fb^{-1}
		$H^{\pm} \to W^{\pm}a$	120–160 GeV	139 fb^{-1}
Doubly-charged	Fermions	$H^{\pm\pm} \to \ell\ell'$	400–1300 GeV	139 fb^{-1}
	Bosons	$H^{\pm\pm} \to W^{\pm}W^{\pm}$	200–600 GeV	139 fb^{-1}

- In this talk, only a selected set of analyses discussed

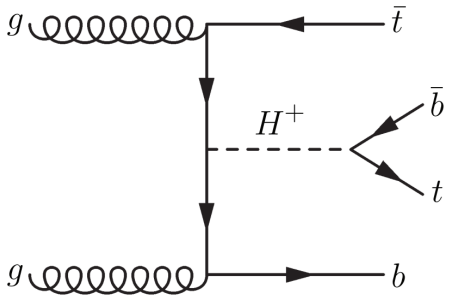
ATLAS $H^{\pm} \to tb$ SEARCH (JHEP 06 (2021) 145)

Search for singly charged Higgs $H^{\pm}$ in association with a t and b, using 139 fb^{-1} of data

- Considered decay mode: $H^{\pm} \to tb$

→ Intermediate states with two tops and two bottoms

- Analysis looking for final states with jets and one electron or muon



- Event selection: exactly one electron or muon ($p_T > 27$ GeV), at least five **j**ets with at least three of them being **b**-tagged

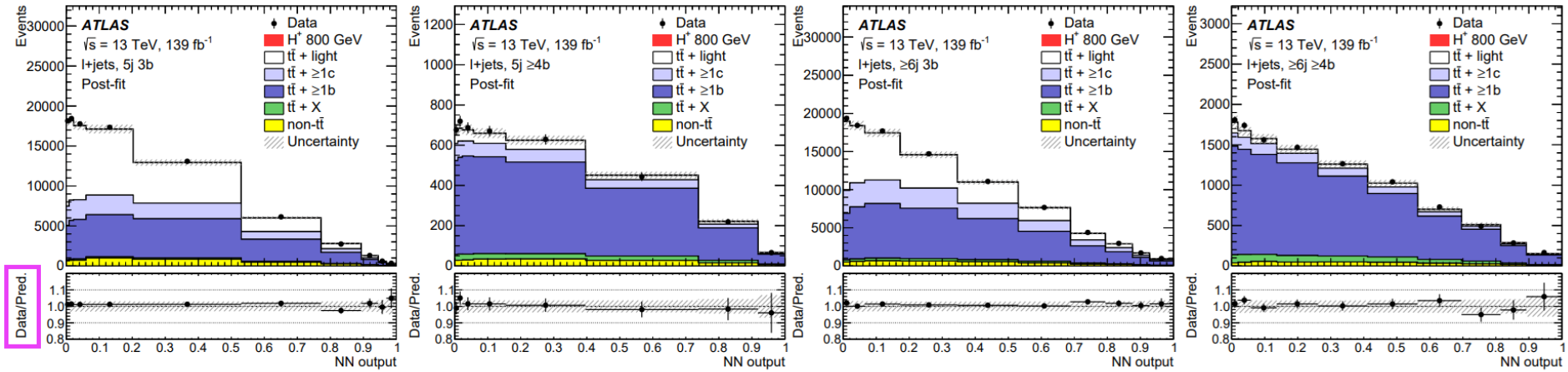
→ Signal regions defined with $5j3b$, $5j \geq 4b$, $\geq 6j3b$ and $\geq 6j \geq 4b$ event categories, using a neural network algorithm

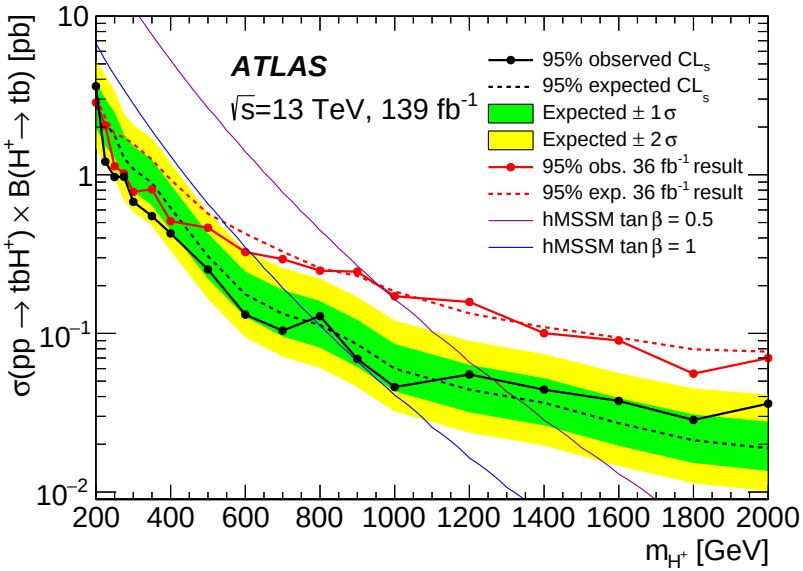
  - **All** signal samples are used in the training against all background samples (weighted according to their x-sections)

- Background sources:
  - tt+jets the main bkg; categorized according to the flavour of the jets in the event

  → Estimated using data-based corrections

Overall, very good agreement between data and the final bkg estimation:

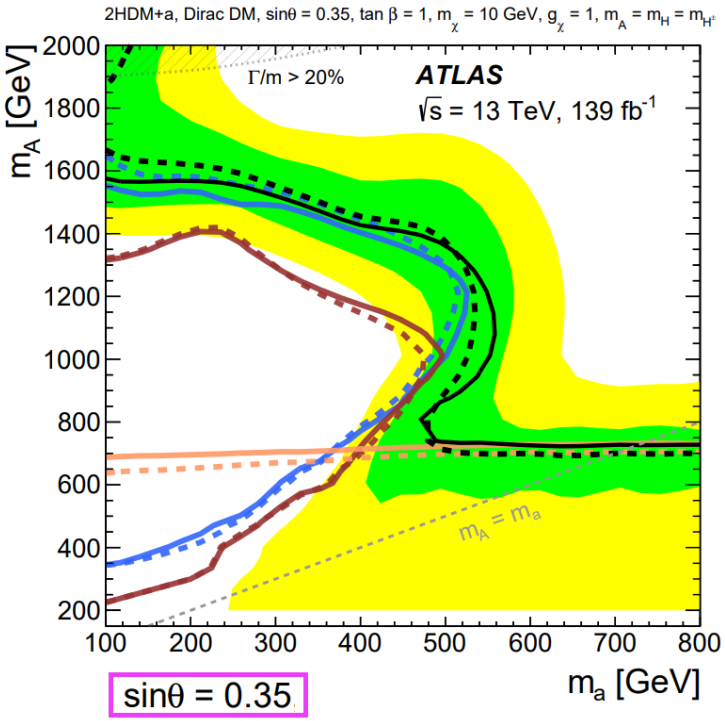


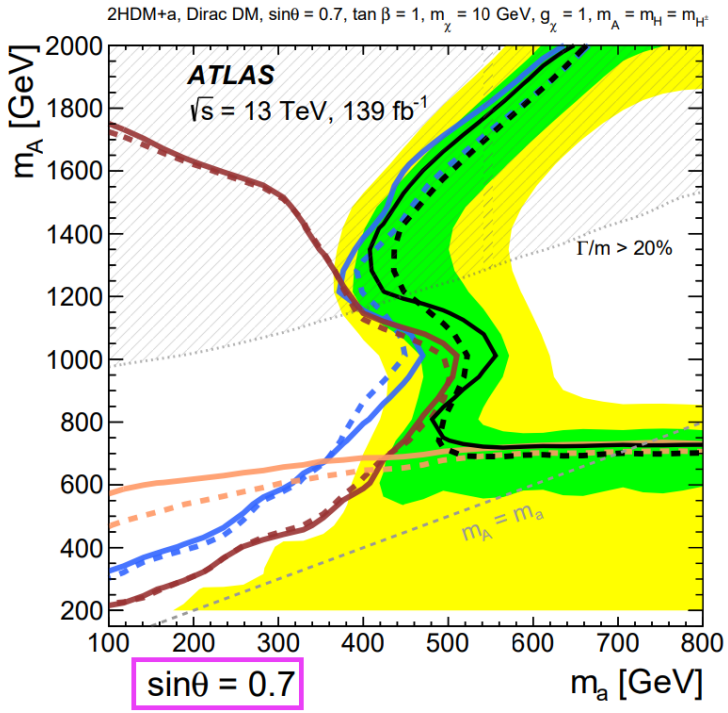


- The observed (expected) limits range from $\sigma \times \mathrm{B} = 3.6$ (2.6) pb at $m_{H^\pm} = 200$ GeV to $\sigma \times \mathrm{B} = 0.036$ (0.019) pb at $m_{H^\pm} = 2$ TeV

Results included in a Dark Matter interpretation (2HDM+a), [Sci.Bull. 69 (2024) 19, 3005-3035]

→ *a* being a pseudo-scalar mediator that couples to dark matter particles

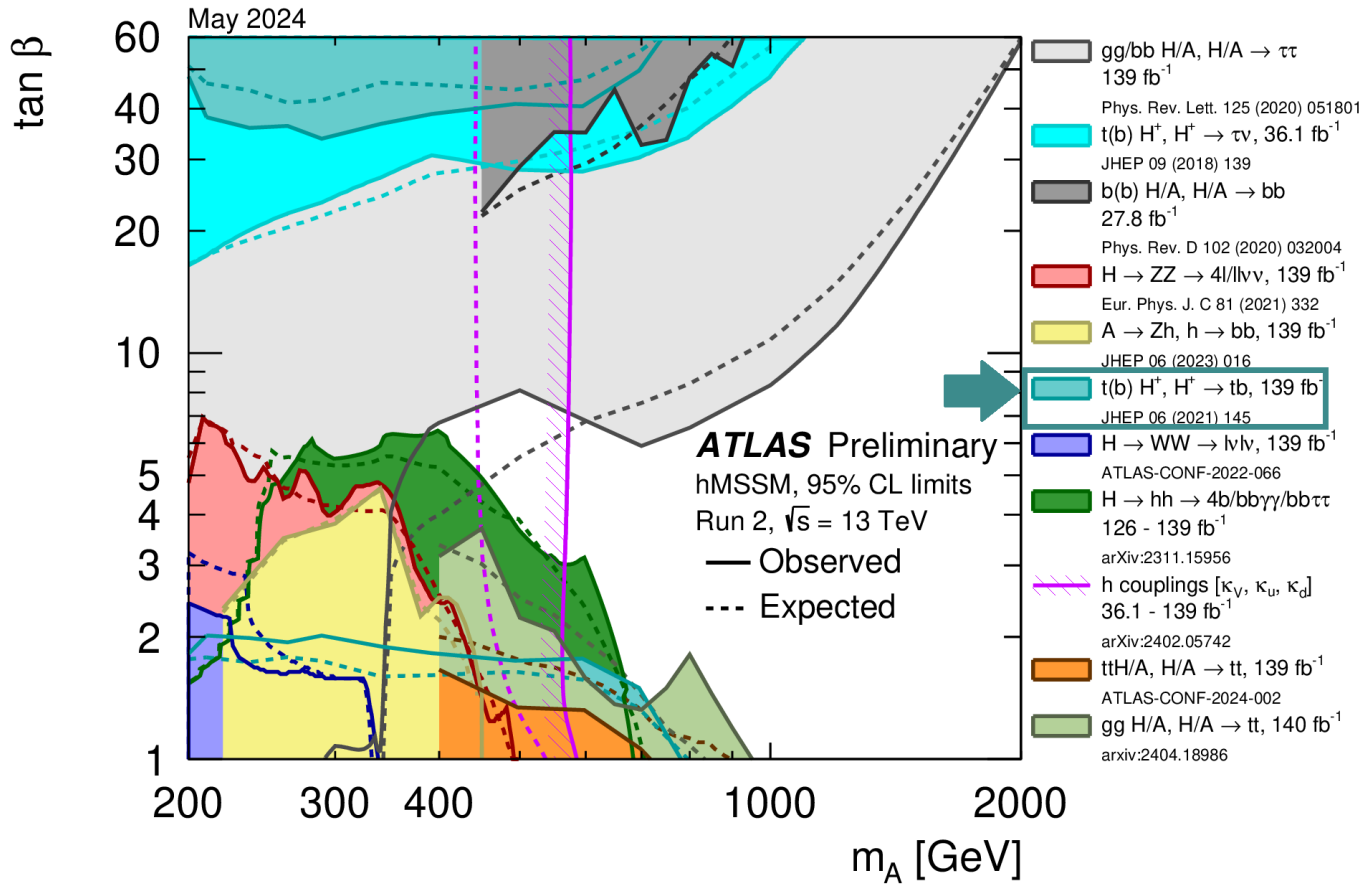




- *Dashed gray reg: indicate the region where the width of any of the Higgs bosons exceeds 20% of its mass*

Results used also for constraints in the m_A and tanβ plane, in hMSSM (ATL-PHYS-PUB-2024-008)

- The masses of charged bosons $H^{\pm}$ at tree-level can be obtained from: $m_{H^{\pm}} = m_A^2 + m_{W^{\pm}}^2$



- At high tanβ, $H^{\pm} \to tb$ search competitive with the $H^{\pm} \to \tau\nu$ search, especially in the low m_A region (< 500 GeV)

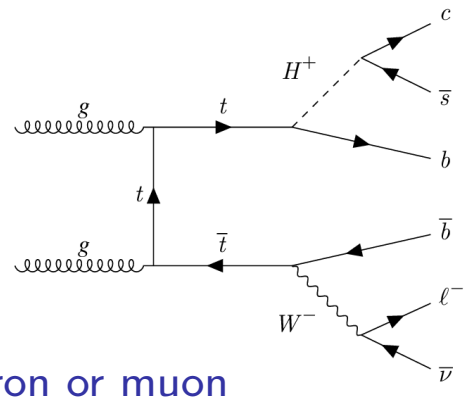
ATLAS $H^{\pm} \to cs$ SEARCH (CERN-EP-2024-185)

Search for light charged Higgs $H^{\pm}$ produced in the decay of a t quark, using 140 fb^{-1} of data

- Considered process: top pair production

→ Considered decay mode: $H^{\pm} \to cs$

- Intermediate states with $W^{\mp}b$ $H^{\pm}b$



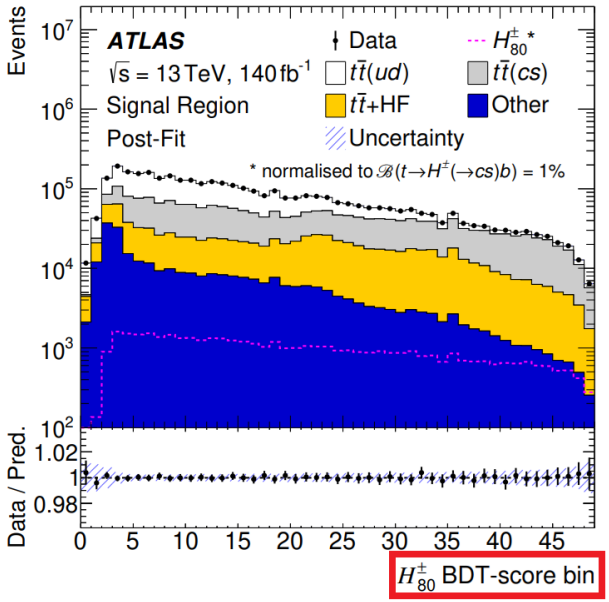
- Analysis looking for final states with b-jets and one electron or muon
  - Leptons produced via leptonically decaying τ-leptons are also included
  - Flavour-tagging algorithms used to tag jets as b-jets, c-jets or light-flavour jets

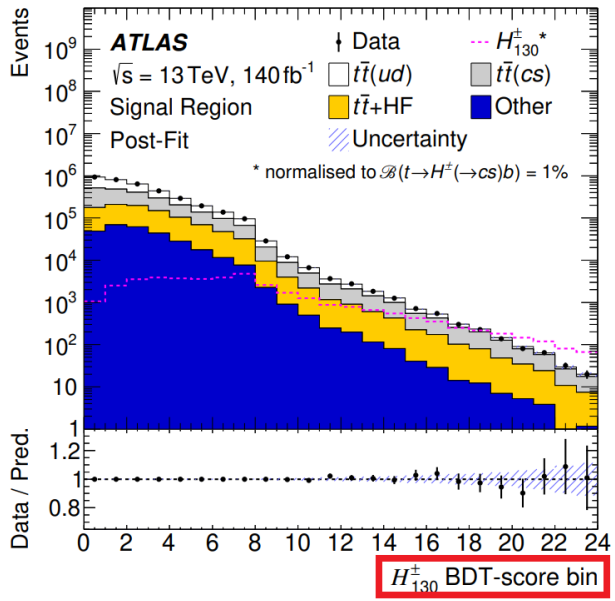
  → Dedicated flavour-tagging scheme with simultaneous tagging of b-jets and c-jets used

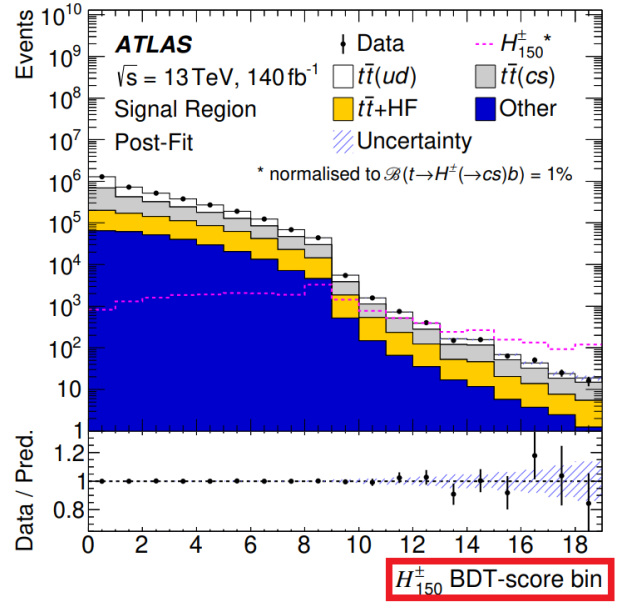
- Signal regions defined with multivariate techniques (BDTs)

- $t\bar{t}$+jets processes are the main background sources: same data-based corrections applied to both $t\bar{t}$ and signal samples
  - MC $t\bar{t}$ events separated in Heavy Flavor ($t\bar{t}$+b/c), and Light Flavor further split in $t\bar{t}(ud)$ and $t\bar{t}(cs)$, according to the W decays to ud or cs
- Multijet (MJ) processes – when jets are misidentified as leptons or when real non-prompt leptons are produced in the decays of heavy-flavour hadrons – can also contribute

Overall, very good agreement between data and the final bkg estimation:



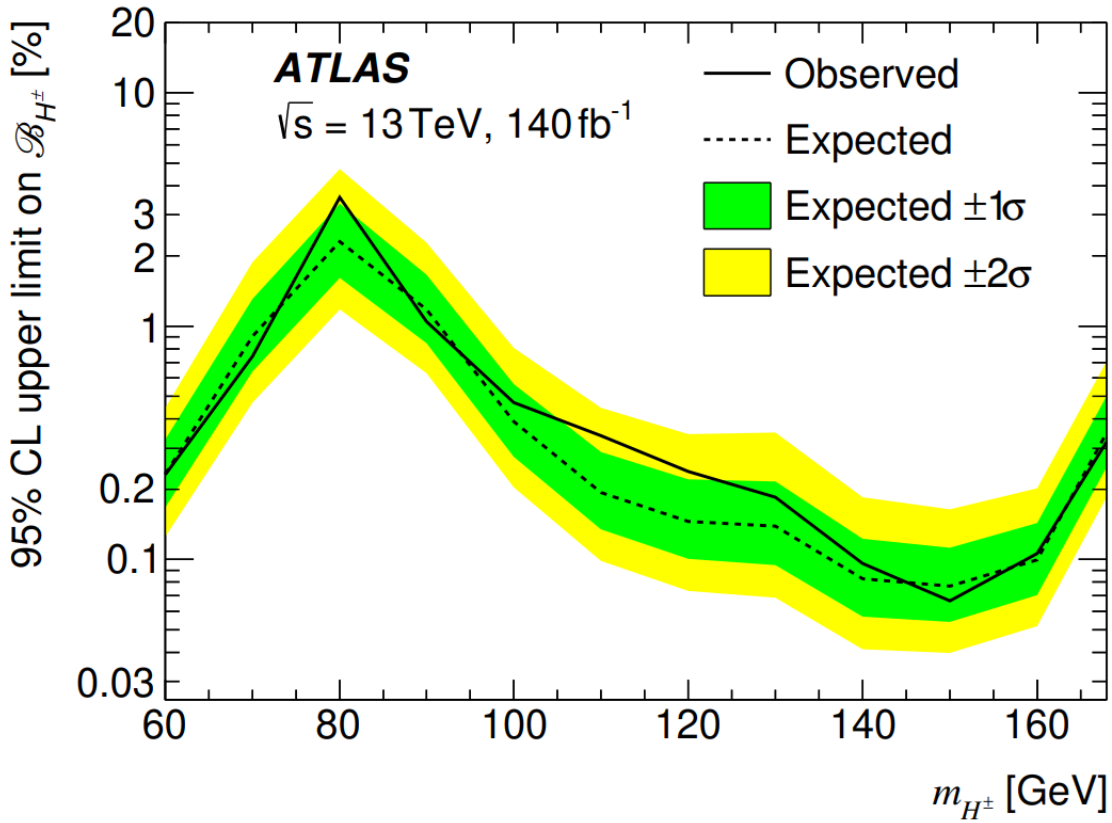




$H^{\pm}_{80}$		$H^{\pm}_{150}$	
Category	Relative contribution	Category	Relative contribution
Data statistical	6%	**Data statistical**	38%
Systematic	99.8%	**Systematic**	93%
Flavour-tagging	64%	$t\bar{t}$ modelling	72%
MC statistical	64%	MC statistical	35%
$t\bar{t}$ modelling	50%	Weak-boson & MJ modelling	27%
$\mu_{t\bar{t}}$ & f_{LF}	21%	Single-top-quark modelling	25%
Jet	19%	$\mu_{t\bar{t}}$ & f_{LF}	24%
Single-top-quark modelling	16%	Jet	23%
Luminosity & pile-up	15%	Flavour-tagging	20%
Weak-boson & MJ modelling	12%	Lepton & $E_{\mathrm{T}}^{\mathrm{miss}}$	8%
Signal modelling	8%	Luminosity & pile-up	7%
Lepton & $E_{\mathrm{T}}^{\mathrm{miss}}$	7%	Signal modelling	5%

→ MC statistics and $t\bar{t}$ modelling: among the main unc sources

- Observed and expected 95% CL upper limits on the branching fraction $\mathcal{B}(t \to H^{\pm} b)$
  - → Assumption: $\mathcal{B}(t \to Wb) + \mathcal{B}(t \to H^{\pm}(\to cs)b)$ is 100%

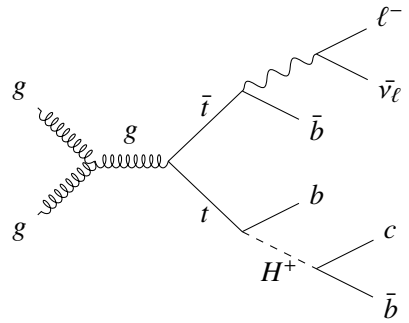


- Observed (expected) limits set between 0.066% (0.077%) and 3.6% (2.3%), in the 60 - 168 GeV mass range

ATLAS $H^{\pm} \to cb$ SEARCH (JHEP 09 (2023) 004)

Search for light charged Higgs $H^{\pm}$ produced in the decay of a t quark, using 139 fb^{-1} of data

- Considered process: top pair production
- Considered decay mode: $H^{\pm} \to cb$, $W^{\mp} \to \ell\nu$
- Signal generation: $H^{\pm}$ total width assumed to be 1 GeV, and its mass in the [60, 160] GeV interval
- Signal normalization: x-sec as for $t\bar{t}$ SM processes, assuming $\mathscr{B}(t \to H^{\pm} b) \times \mathscr{B}(H^{\pm} \to cb) = 1\%$



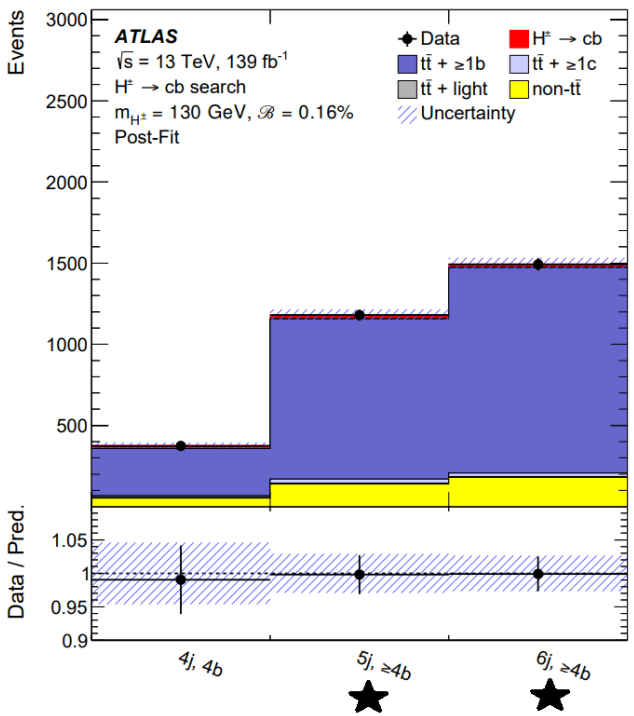
N_j \ N_b	**2b + 1bl:** exactly two b-tagged jets (60% OP) plus one loose b- tagged jet (70% OP)	**3b:** exactly three b-tagged jets (60% OP)	**≥4b:** at least four b-tagged jets (60% OP)
4j: exactly four jets	**4j, 2b + 1bl** (data-based $t\bar{t}$ corrections, 10 bins)	★ **4j, 3b** (signal region, 10 bins)	**4j, 4b** ($t\bar{t}$ + ≥ 1b background control region and large S/B region, 1 bin)
5j: exactly five jets	**5j, 2b + 1bl** (data-based $t\bar{t}$ corrections, 10 bins)	★ **5j, 3b** (signal region, 10 bins)	**5j,≥ 4b** ★ ($t\bar{t}$ + ≥ 1b background control region and large S/B region, 1 bin)
6j: exactly six jets	**6j, 2b + 1bl** (data-based $t\bar{t}$ corrections, 10 bins)	**6j, 3b** (signal region, shape correction for the NN discriminant in low S/B bins, 10 bins)	★ **6j,≥ 4b** ($t\bar{t}$ + ≥ 1b background control region, 1 bin)

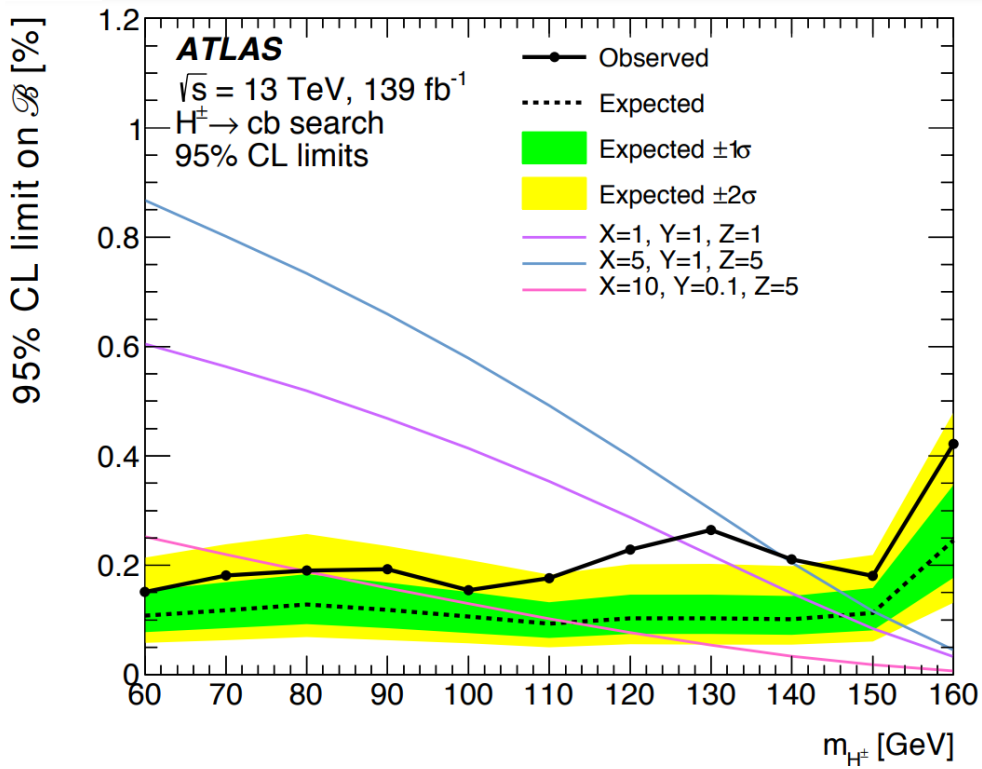
A total of nine analysis – bkg and signal – regions considered

- Signal regions defined with a neural network; main ones: (4j, 3b) and (5j, 3b)
- (5j, ≥4b) and (6j, ≥4b) control regions highly enriched in $t\bar{t} + 1b$ bkg
- Main bkg sources in all regions: $t\bar{t}$ processes ($> 80\%$)

- Good data - bkg expectation agreement in all regions of interest

→ No excess in data in any of the signal regions





- Observed (expected) 95% CL upper limits on the branching fraction $\mathscr{B}$ ($\mathscr{B}(t \to H^{\pm} b) \times \mathscr{B}(H^{\pm} \to cb)$) as a function of $H^{\pm}$ mass

→ they range from 0.15% (0.09%) up to 0.42% (0.25%), depending on the $H^{\pm}$ mass

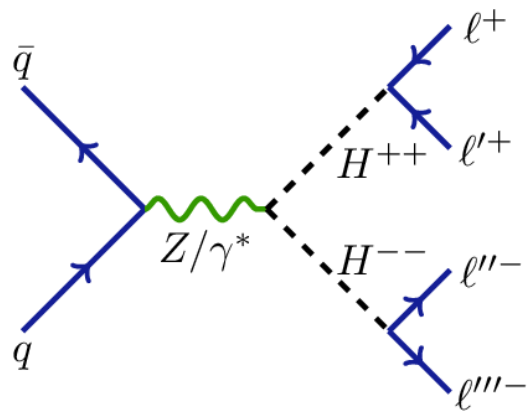
- Superimposed are also predictions from the 3HDM, corresponding to three benchmark values for the parameters X, Y, and Z

$H^{\pm\pm} \rightarrow$ MULTI-ℓ SEARCH (EPJC 83 (2023) 7, 605)

Search for Drell-Yan production of heavy charged Higgs $H^{\pm\pm}$, using 139 fb^{-1} of data

$\rightarrow$ Using left-right symmetric type-II seesaw (LRSMs) and Zee–Babu models

- $H^{\pm\pm}$ decay modes depend on the vacuum expectation value of the Higgs triplet
- In this analysis set to be $< 10^{-8}$ GeV $\rightarrow$ only leptonic decays relevant (WW ones suppressed)
- Lepton-flavour-violating decays (e.g $H^{\pm\pm} \rightarrow e^{\pm}\mu^{\pm}$) also allowed in the model



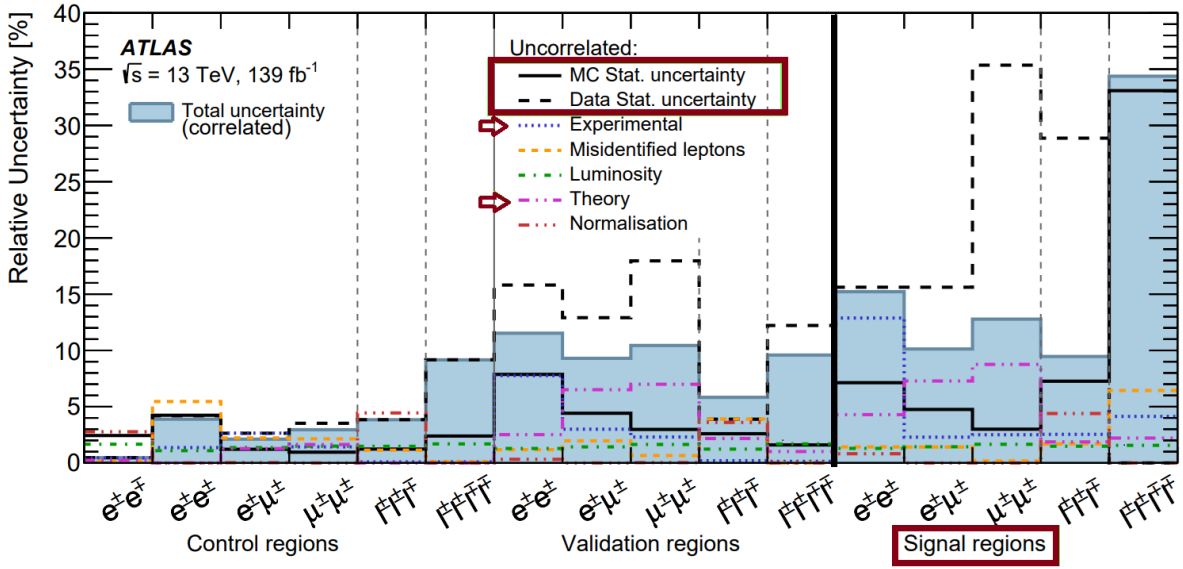
Signal regions defined per lepton multiplicity/flavor:

- SR2L: $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$
- SR3L: $\ell^{\pm}\ell^{\pm}\ell^{\mp}$
- SR4L: $\ell^{+}\ell^{+}\ell^{-}\ell^{-}$

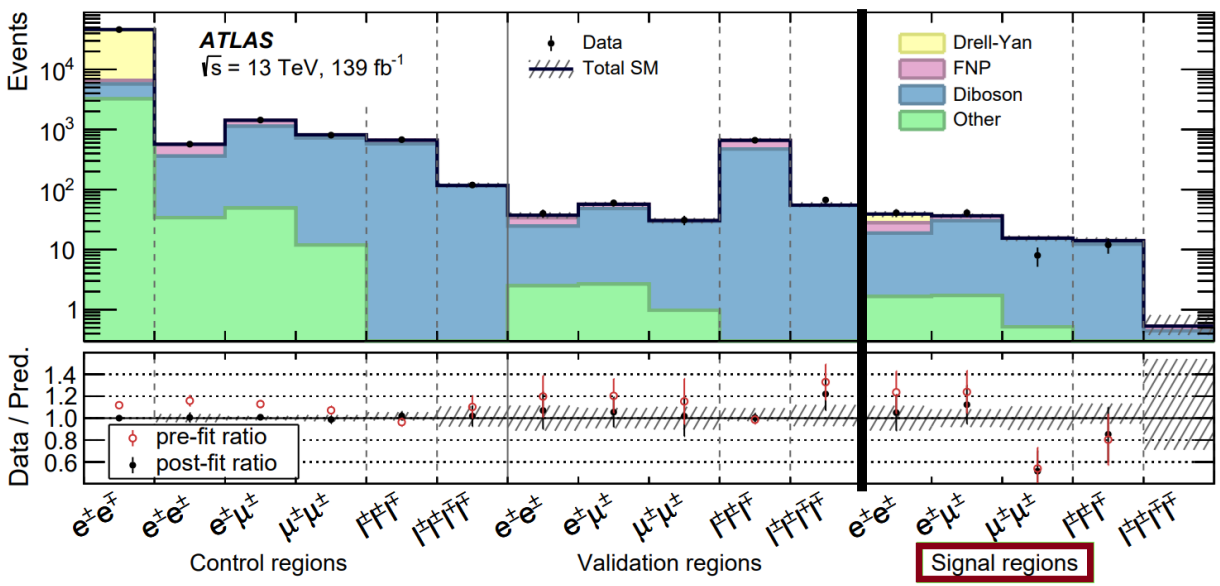
Background sources

- Electron charge flip
- Fake/non-prompt leptons
- SM irreducible processes

- Uncertainty sources breakdown:

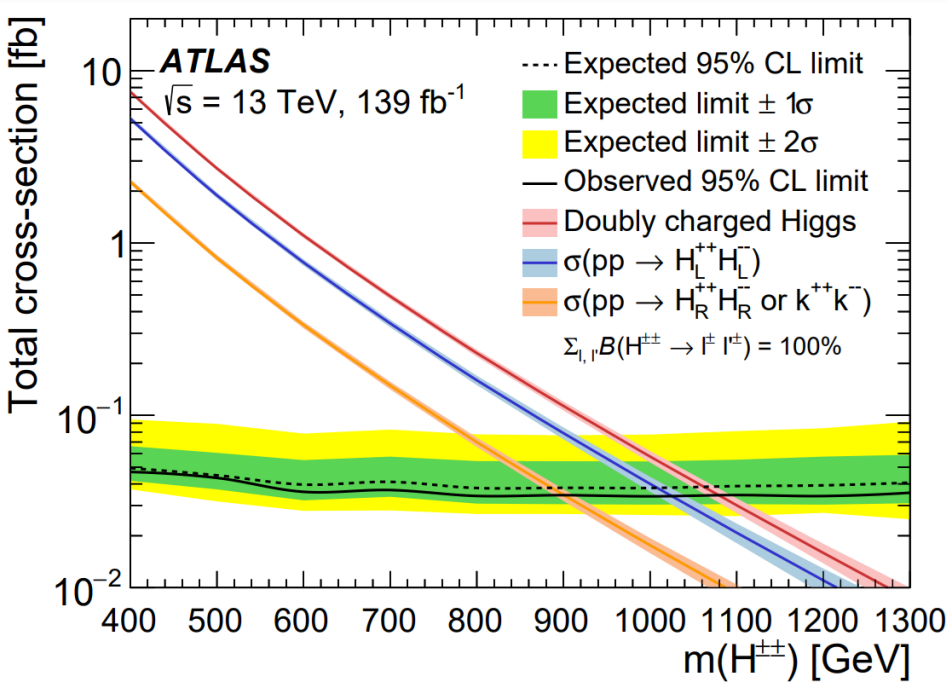


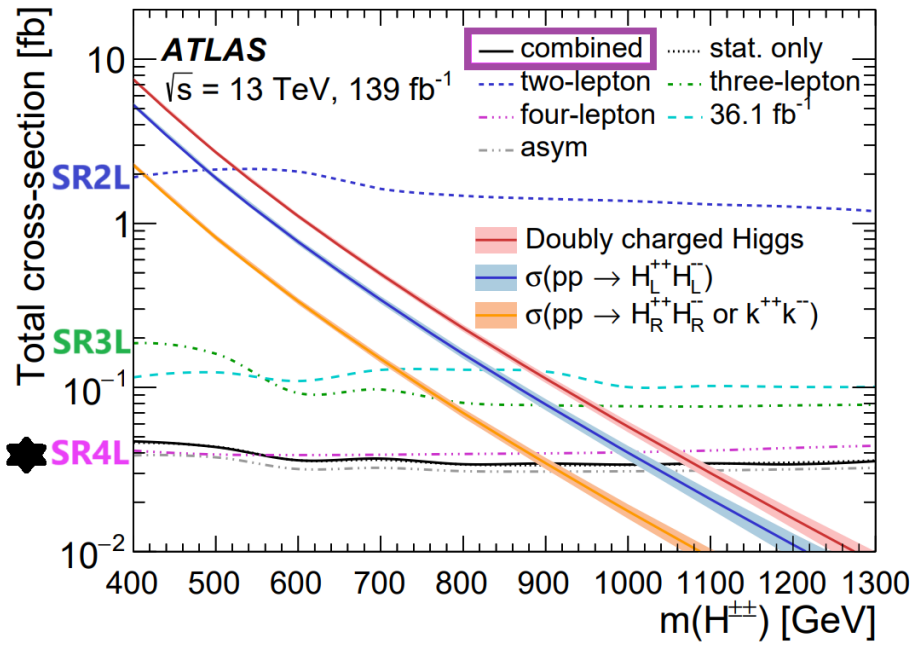
- Observed and expected events in the defined regions:



- Observed (expected) 95% CL upper limits on the production x-section

→ assuming $\sum_{\ell\ell'} \mathscr{B}(H^{\pm\pm} \to \ell^{\pm}\ell'^{\pm}) = 100\%$, with $\ell = e,\ \mu,\ \tau$





- Depending on the lepton multiplicity channel, the excl limits vary between 520 GeV and 1050 GeV for LRSMs, and between 410 GeV and 880 GeV for the Zee–Babu model

→ SR with the highest sensitivity the 4-lepton one

Conclusions

- Several analyses finalized or ongoing in ATLAS targeting $H^{\pm}$ or $H^{\pm\pm}$ BSM bosons

→ Using both 13 TeV Run-2 data, as well as 13.6 TeV Run-3 data

- No significant excess over the SM expectation found in any published analysis

→ Stringent limits were set on the production cross section $\times$ BR

- **More results to come!**

Thank you!