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

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- **One doublet of complex scalar fields** is **the minimal content of the Higgs sector** for spontaneous symmetry breaking.

- **Several theories beyond the SM** predict a **non-minimal Higgs sector** and introduce **charged scalar fields**.

ATLAS Run 2

$\kappa_c = \kappa_t$

κ_c is a free parameter

— SM prediction

$\frac{m_F}{vev}$ or $\sqrt{\kappa_V \frac{m_V}{vev}}$

κ_F or κ_V

Particle mass [GeV]

Leptons			Quarks		
ν_e	ν_μ	ν_τ	u	c	t
e	μ	τ	d	s	b

Force carriers				Higgs boson
g	γ	Z	W	H

Nature 607, 52–59 (2022)
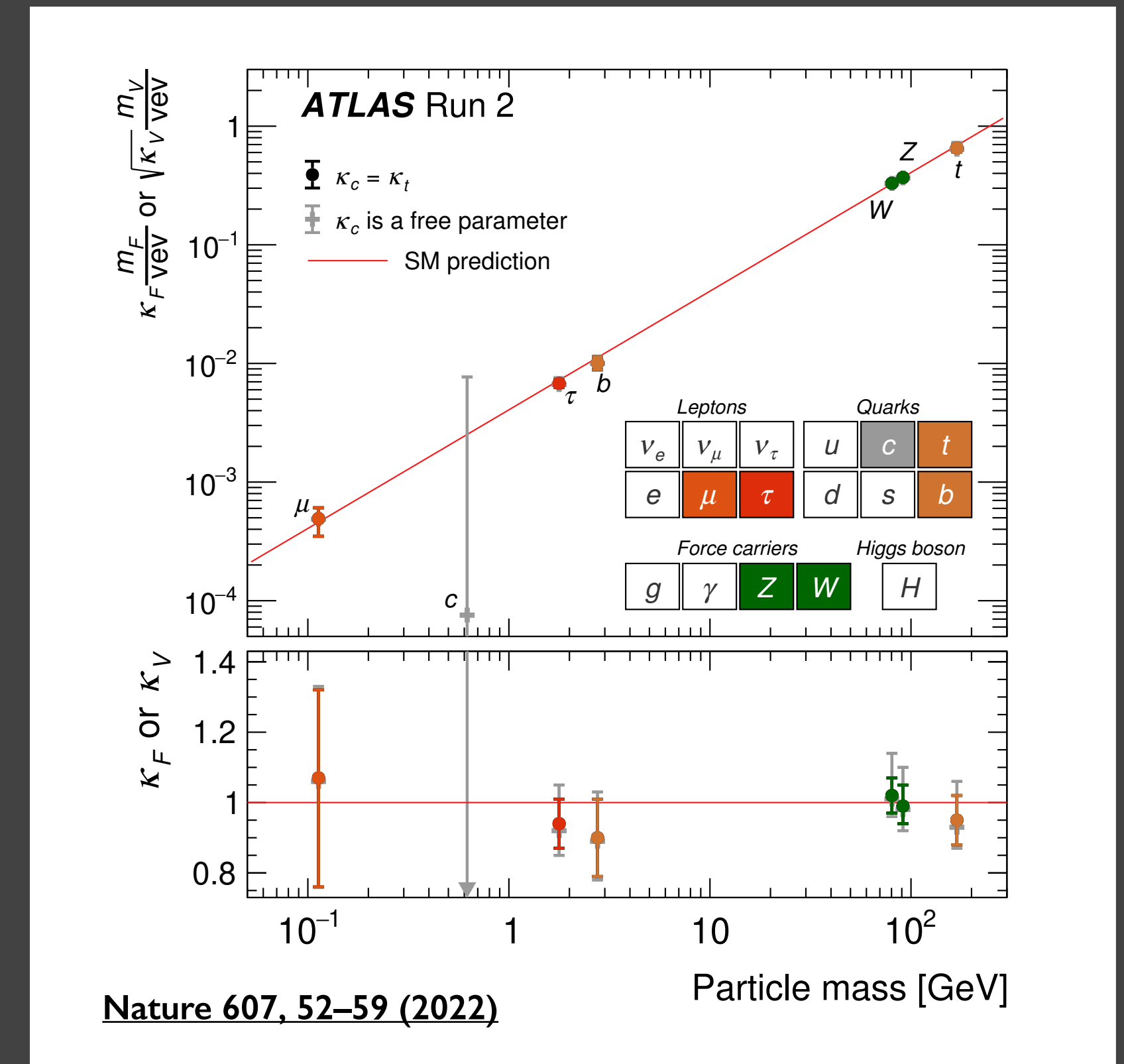
H± H±± ?

Extended Higgs Sector and Charged Higgs

- **Widely investigated extension:** two-Higgs-doublet models (2HDMs)
  - **Five Higgs bosons**: CP-even h^0, H^0, CP-odd A, $H^\pm$
  - **Four types** depending on the coupling (Φ_1, Φ_2: Higgs doublets)

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

← MSSM

CERN-EP-2024-094

- **hMSSM**: type-II, m_h = 125 GeV, described with the parameters entering the tree-level expressions for masses and mixing ("model independent")
- **Many other extensions:** three-Higgs doublet models (3HDMs) allowing light $H^\pm$, the Georgi–Machacek (GM) model and type-II seesaw model both including Higgs triplet and doubly charged Higgs $H^{\pm\pm}$, …
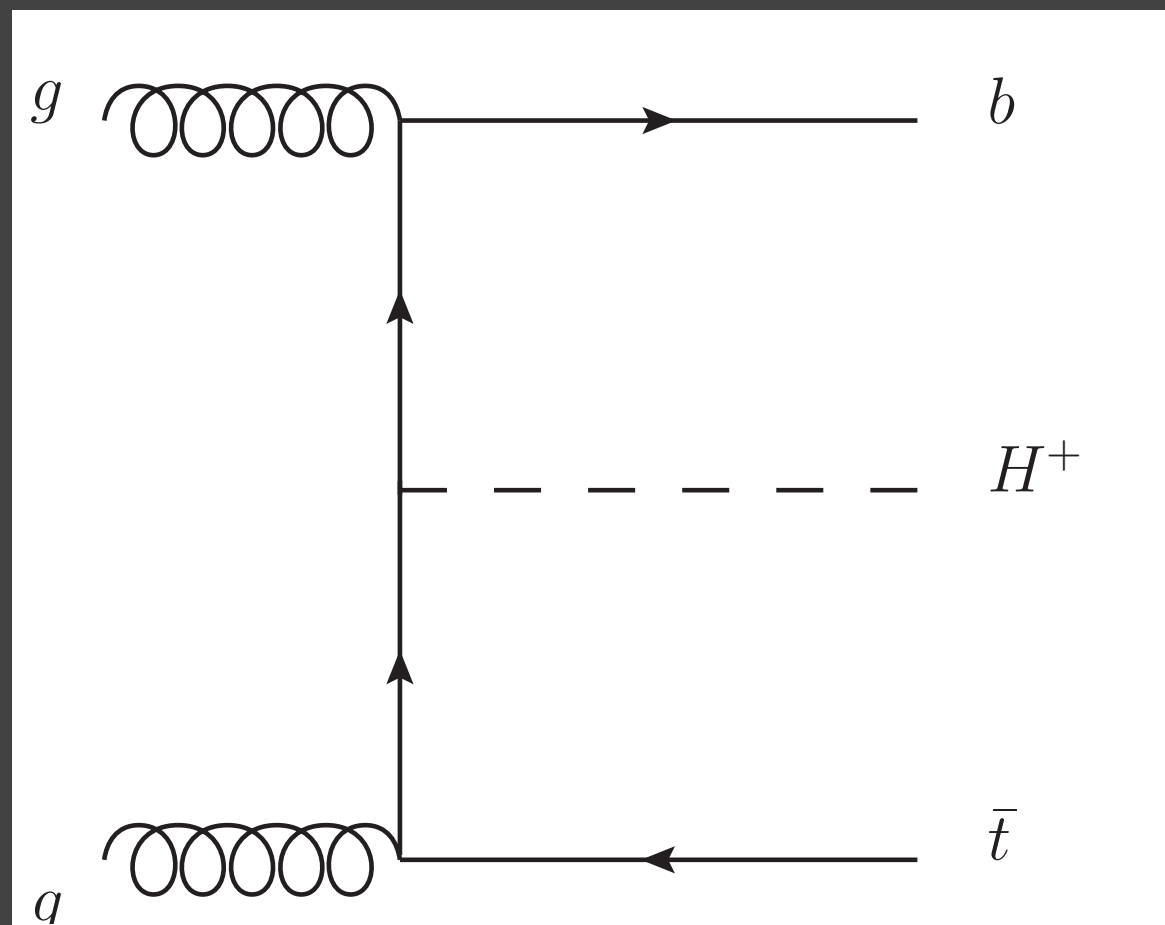
Concept for the Charged Higgs Searches

- Experimental signatures defined by the charge, coupling, and mass of H⁺/H⁺⁺.
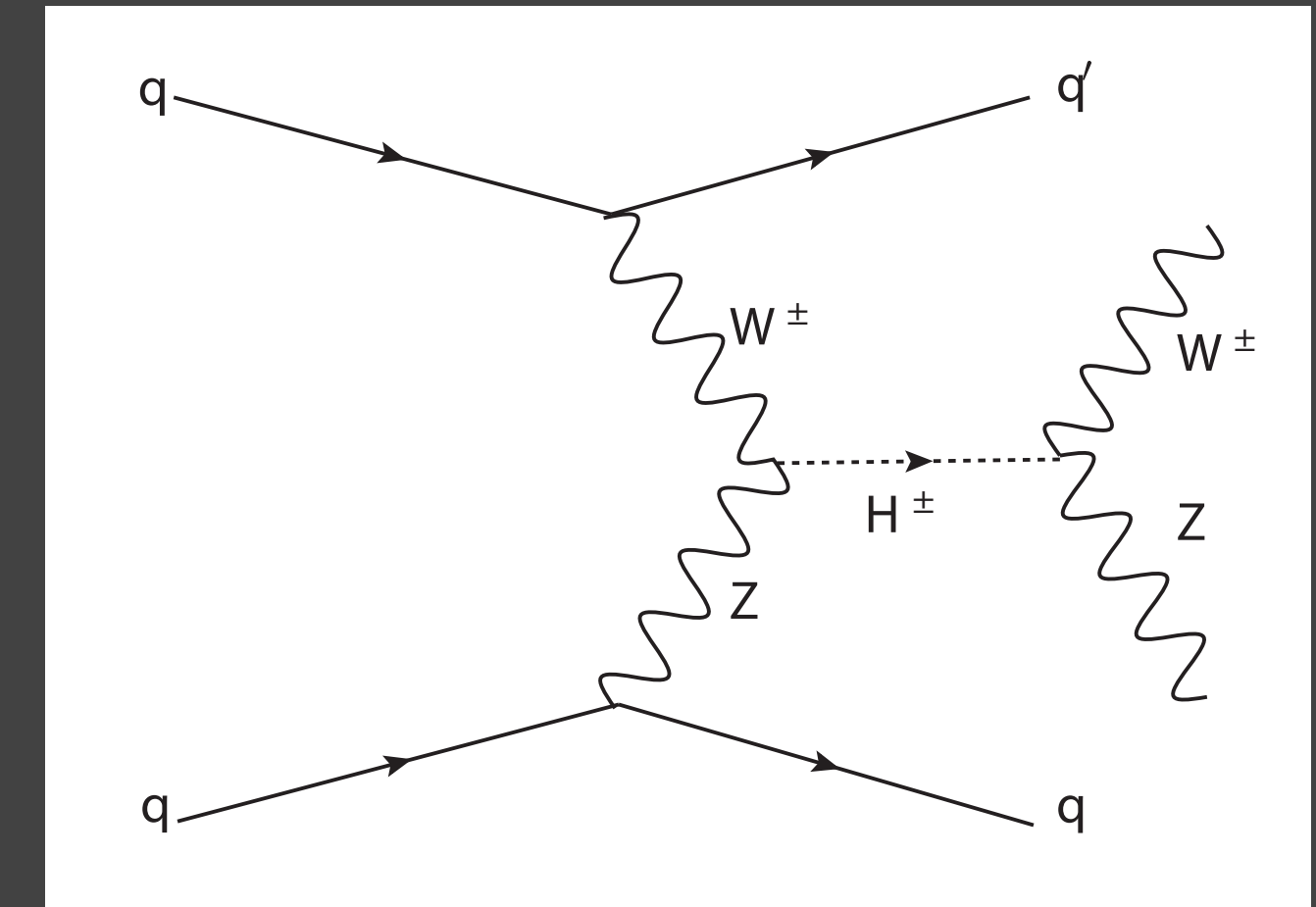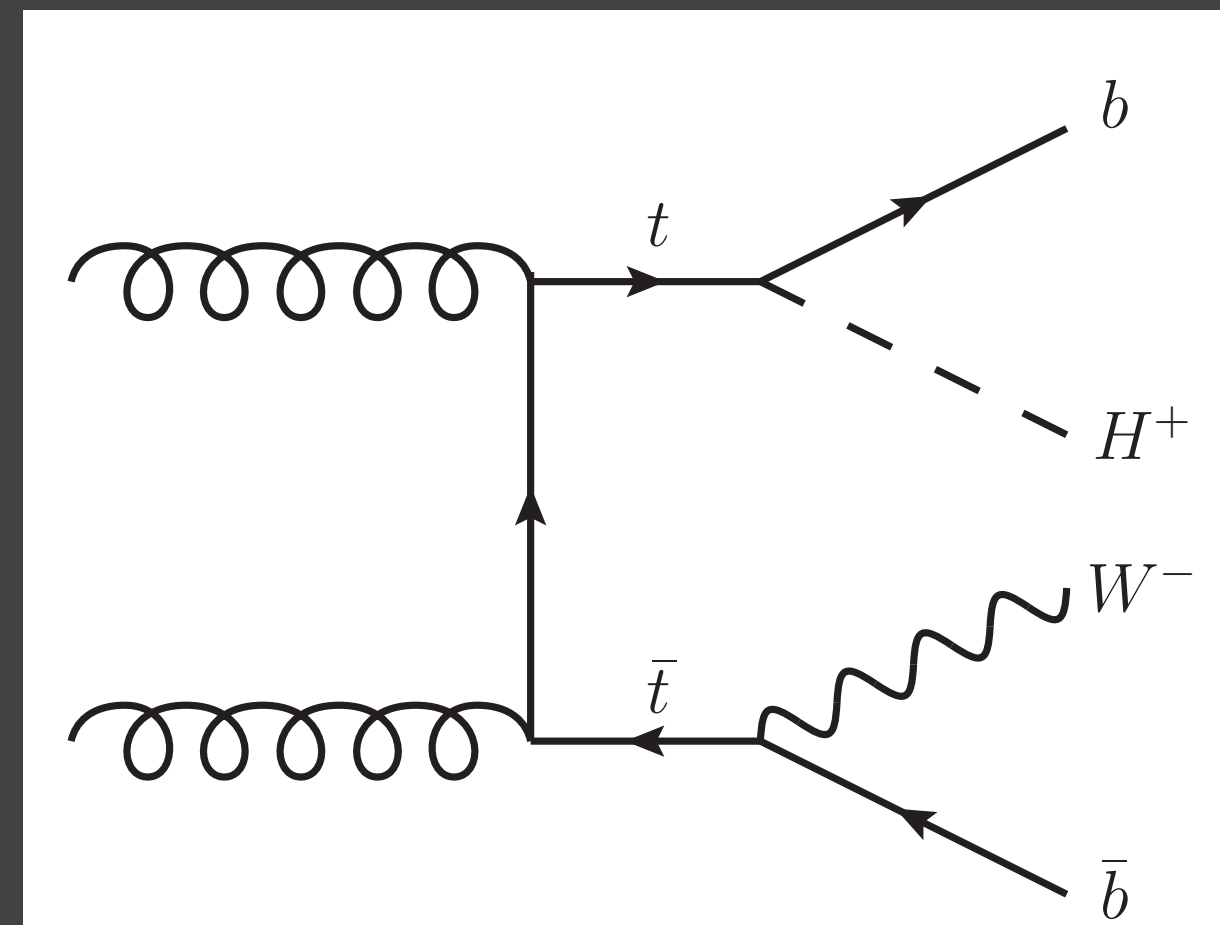
H⁺ coupling to fermions

H⁺ coupling to bosons

High mass H⁺ production

Low mass H⁺ production

- The searches are designed to enrich one or several signal regions in events with the expected signal signature. Multivariate analyses used in most searches.

Latest Results from ATLAS

1) Singly charged Higgs bosons decaying into fermions

Target decay	Integrated L	Reference
$H^+ \to \tau^+ \nu$	36 fb^{-1}	JHEP 09 (2018) 139
$H^+ \to t\, b$	139 fb^{-1}	JHEP 06 (2021) 145
$H^+ \to c\, b$	139 fb^{-1}	JHEP 09 (2023) 004
$H^+ \to c\, s$	140 fb^{-1}	Submitted to EPJC New!

2) Singly charged Higgs bosons decaying into bosons

$H^+ \to W^+ Z$	139 fb^{-1}	EPJC 83, 633 (2023), JHEP 06 (2021) 146
$H^+ \to W^+ a$	139 fb^{-1}	PRD 108, 092007 (2023)

3) Doubly charged Higgs bosons decaying into fermions/bosons

$H^{++} \to l^+ l'^+$	139 fb^{-1}	EPJC 83, 605 (2023)
$H^{++} \to W^+ W^+$	139 fb^{-1}	JHEP 06 (2021) 146

- **H⁺ produced either in top-quark decays (low mass H⁺) or in association with a top quark (high mass H⁺).**
- **The search targets τ+jets and τ+lepton final states, in both cases with a hadronically decaying τ-lepton.**

BDT score fitted.
No H⁺ evidence found.

Limit set to σ x B
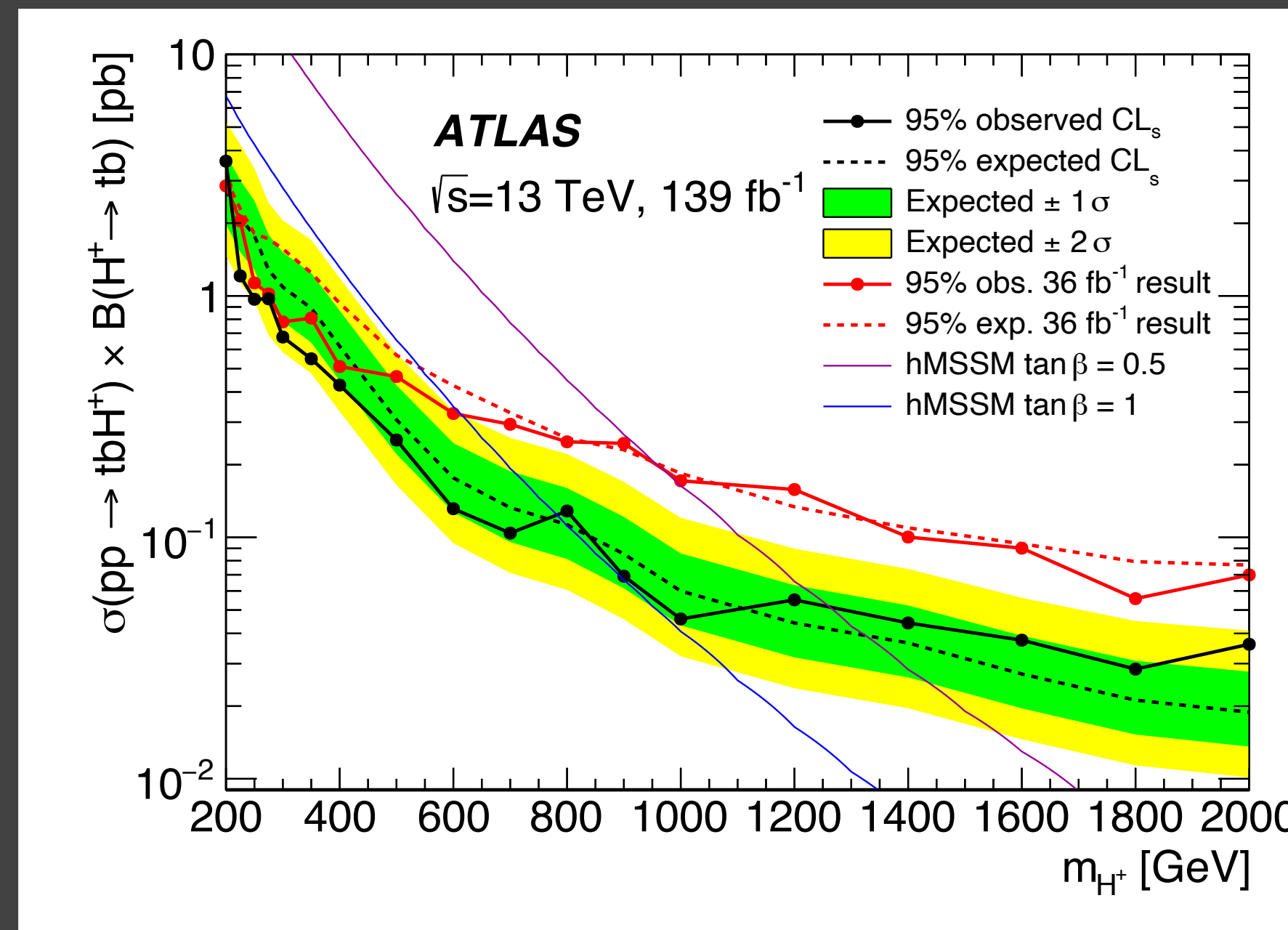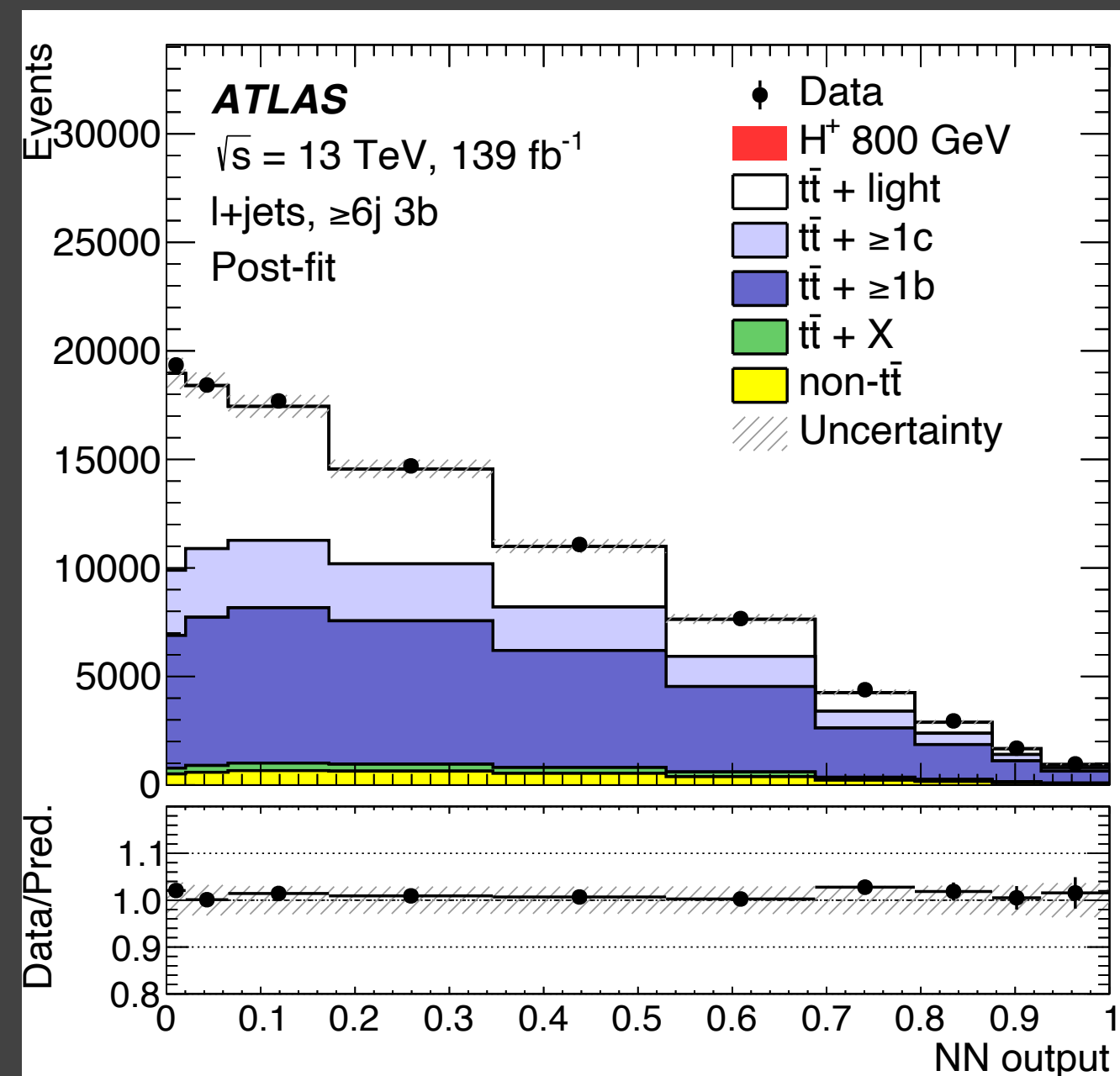for m_{H+} = 90-2000 GeV

Constraints on hMSSM
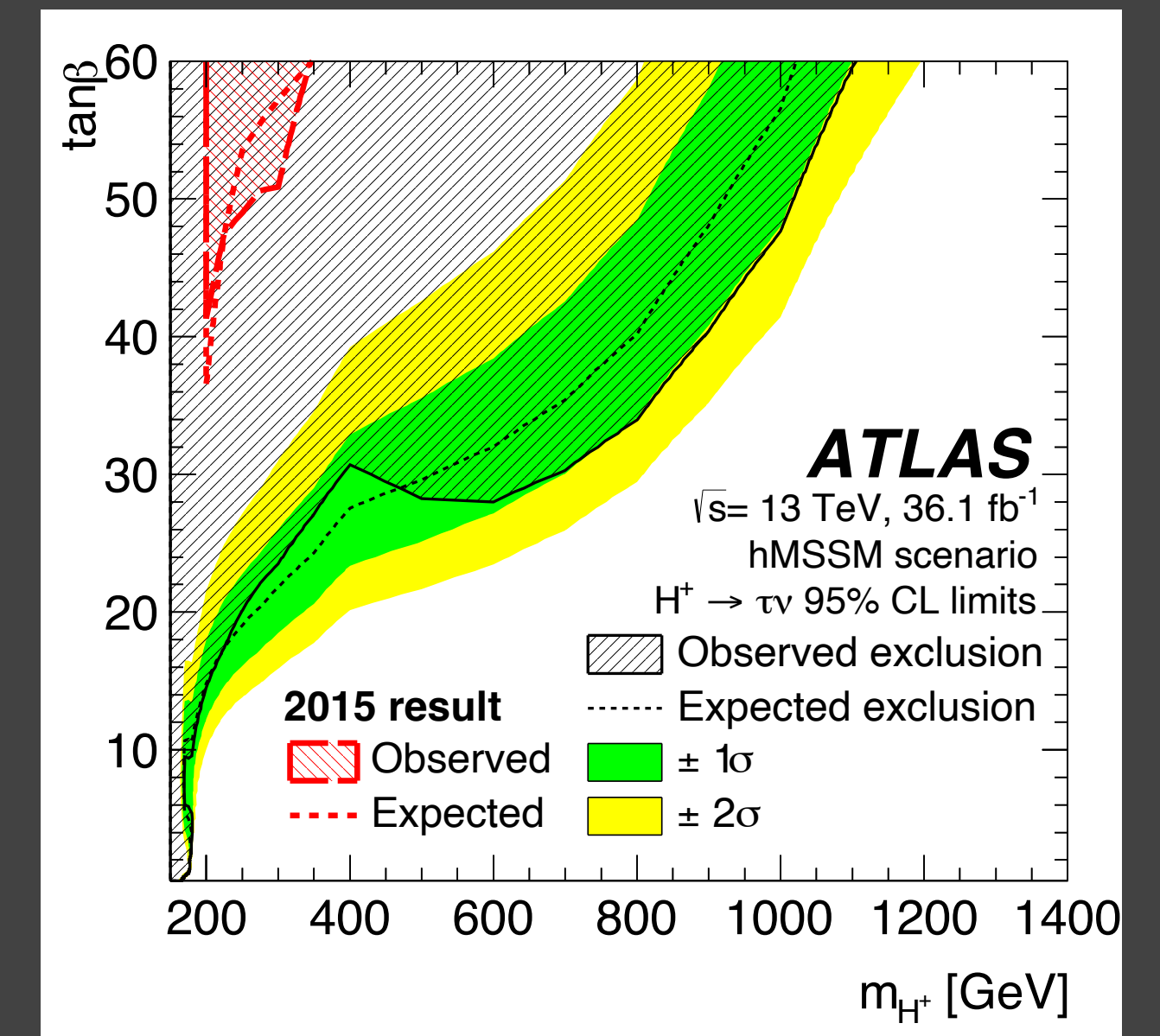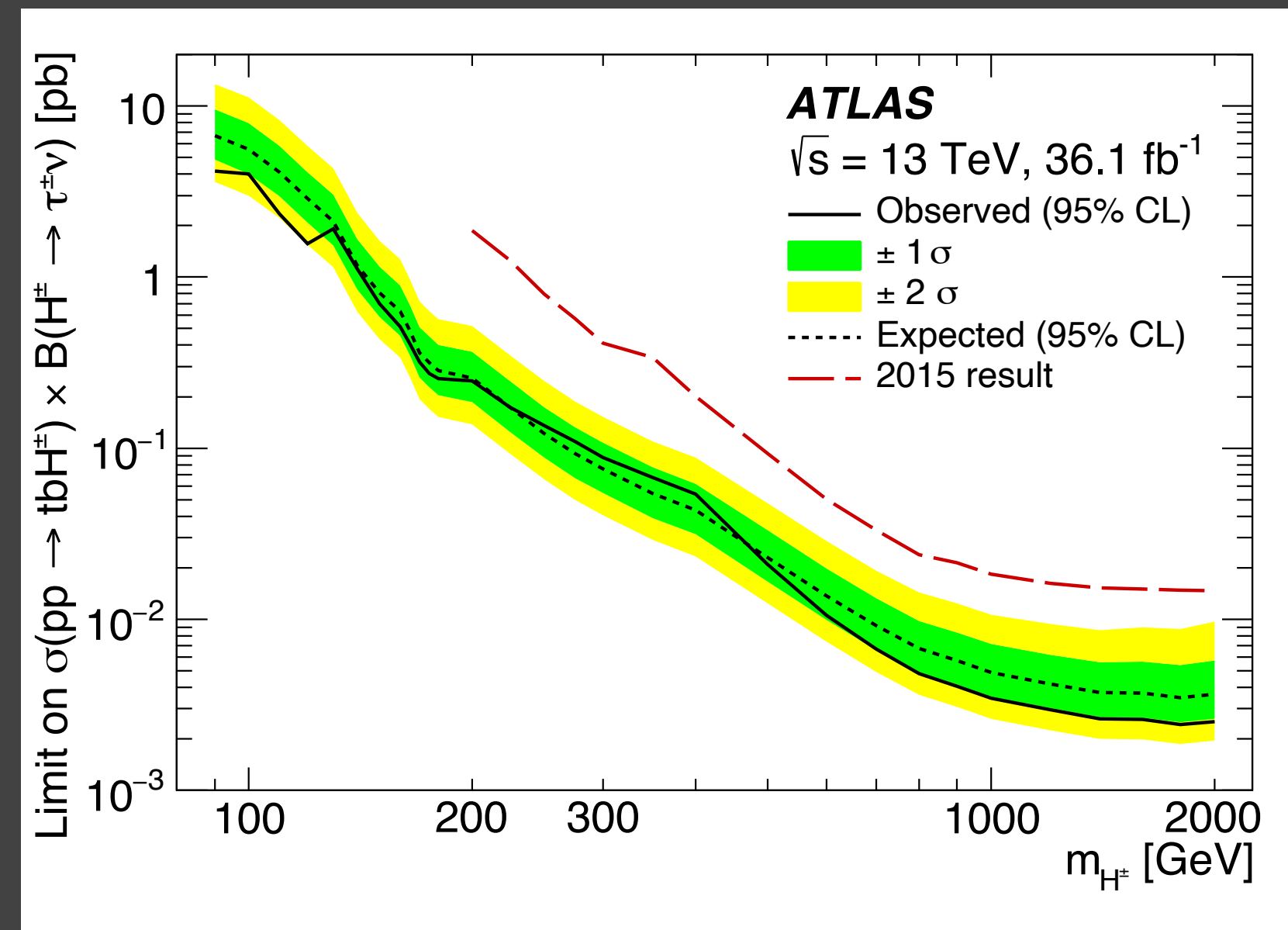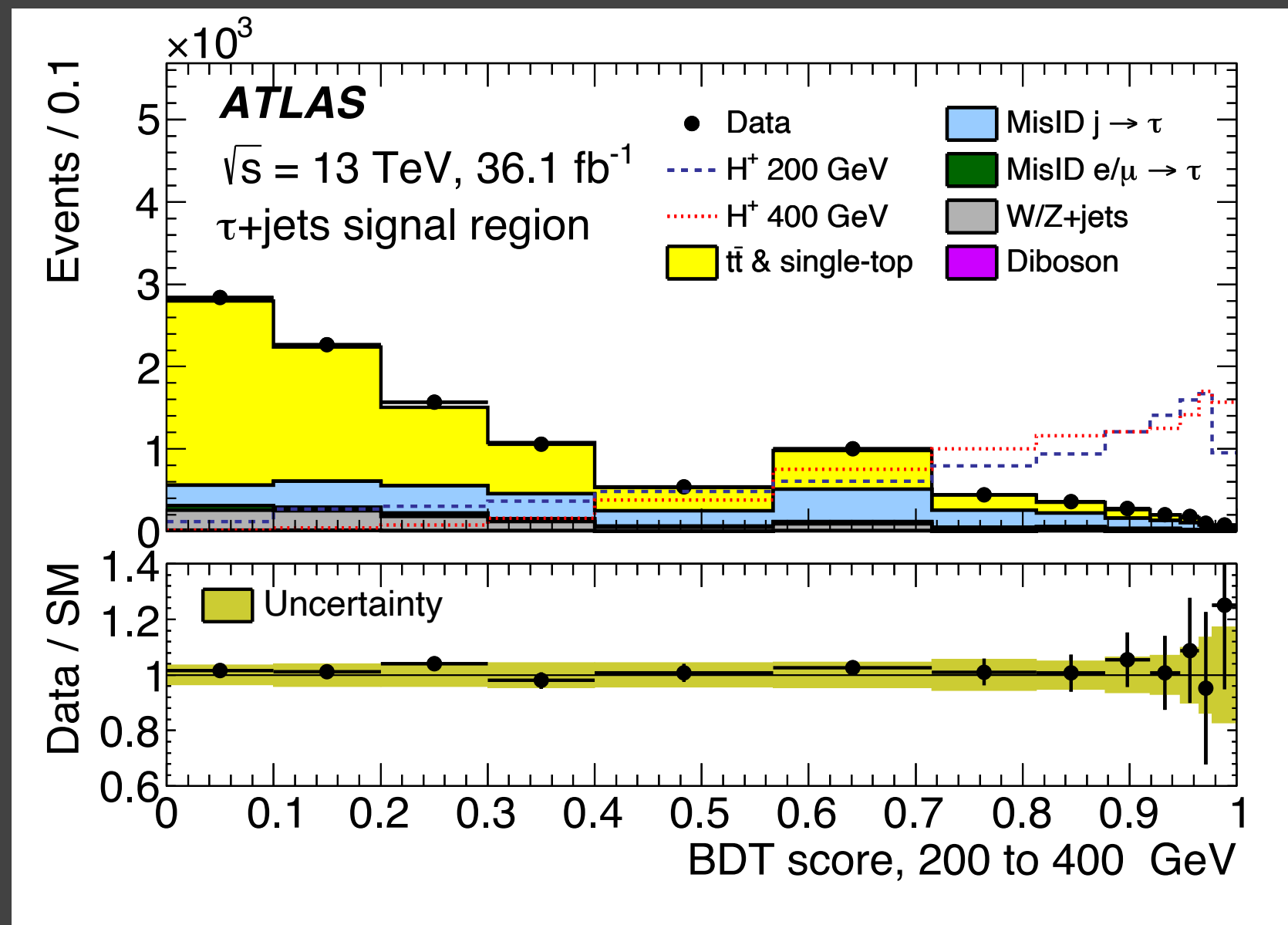
H+ to Fermions: H+ → t b

- **H+ produced in association with a top quark (high mass H+).**
- **Final states with jets and one electron or muon.**
- **Events are categorised according to the multiplicity of jets and b-tagged jets.**

NN output fitted.
No H+ evidence found.

Limit set to σ x B
for m_{H+} = 200-2000 GeV

Constraints on hMSSM
(and other MSSM scenarios)
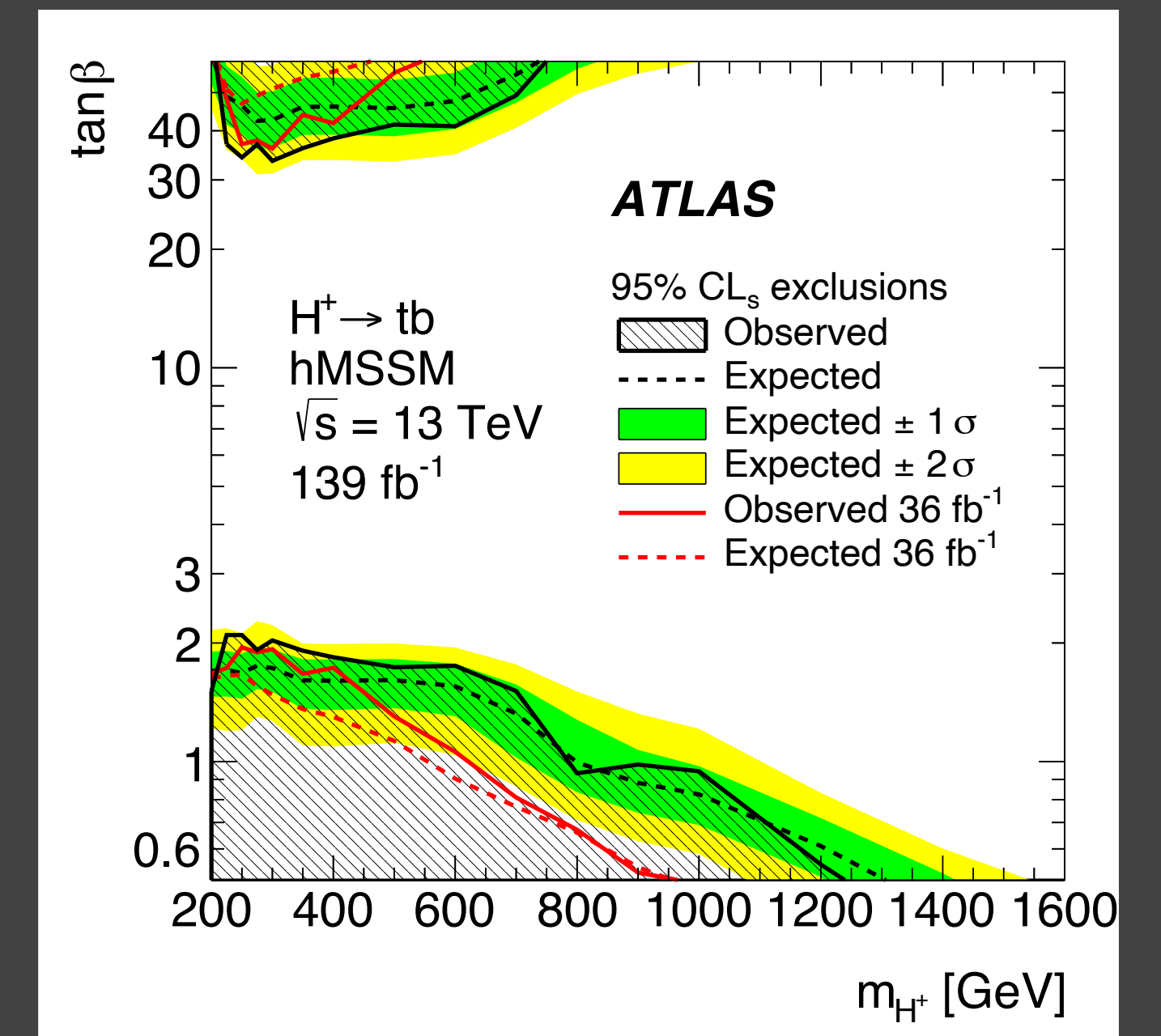
In **MSSM**, tree-level

H± mass is given by:

$$m_{H^\pm}^2 = m_A^2 + m_{W^\pm}^2$$

The **H⁺ → τ⁺ ν** and

H⁺ → t b results

were used to **constrain**

m_A and tanβ for hMSSM.

ATL-PHYS-PUB-2024-008
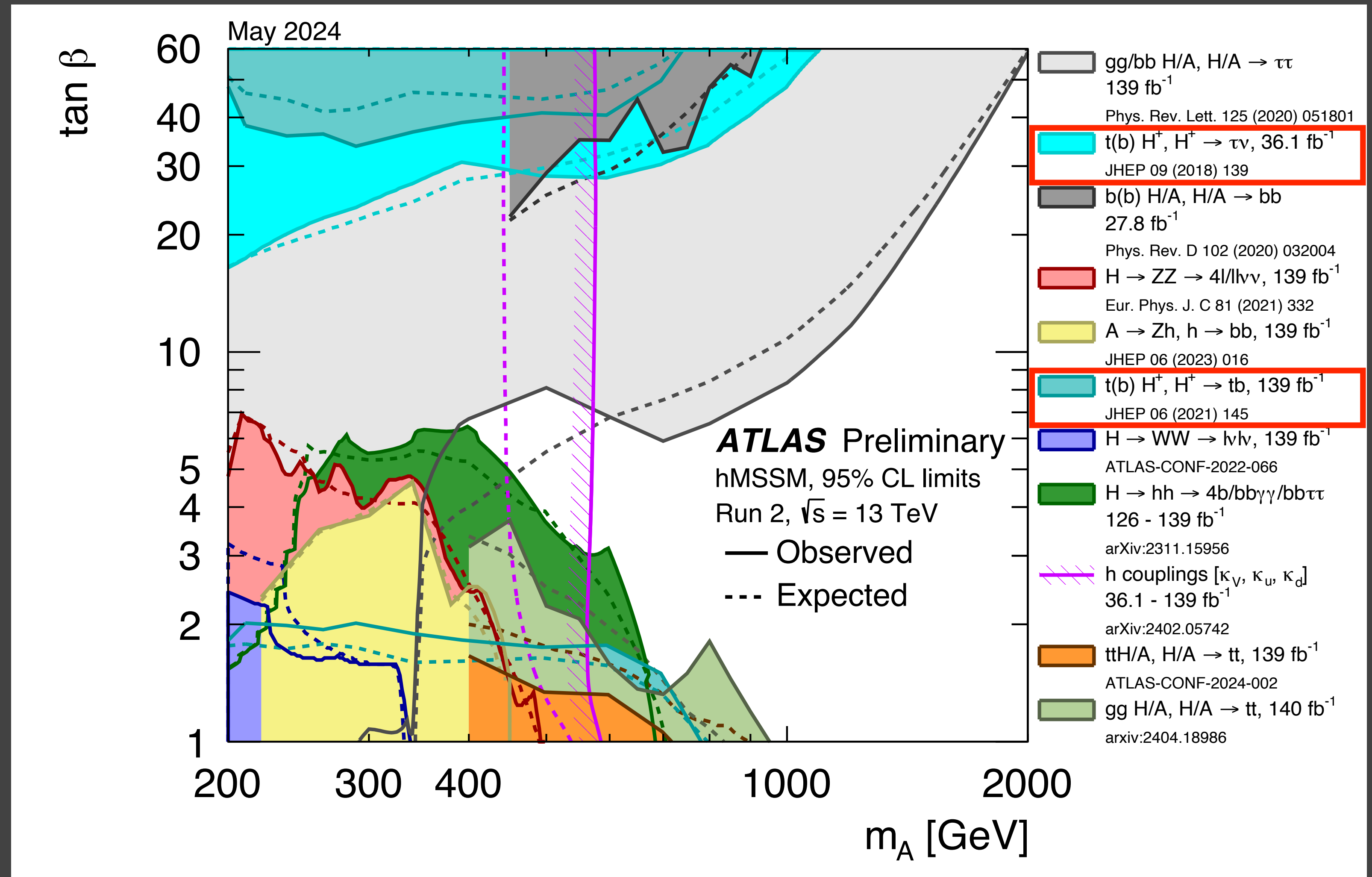
H⁺ to Fermions: H⁺ → c b

- **H⁺ produced in t-quark decays (low mass H⁺)**
- **Lepton plus jets state**

- **NN score fitted.**
- **No evidence of a H⁺ boson.**

- **Limit set for m_{H+} = 60-160 GeV.**
- **3HDM predictions shown for three benchmark parameters.**
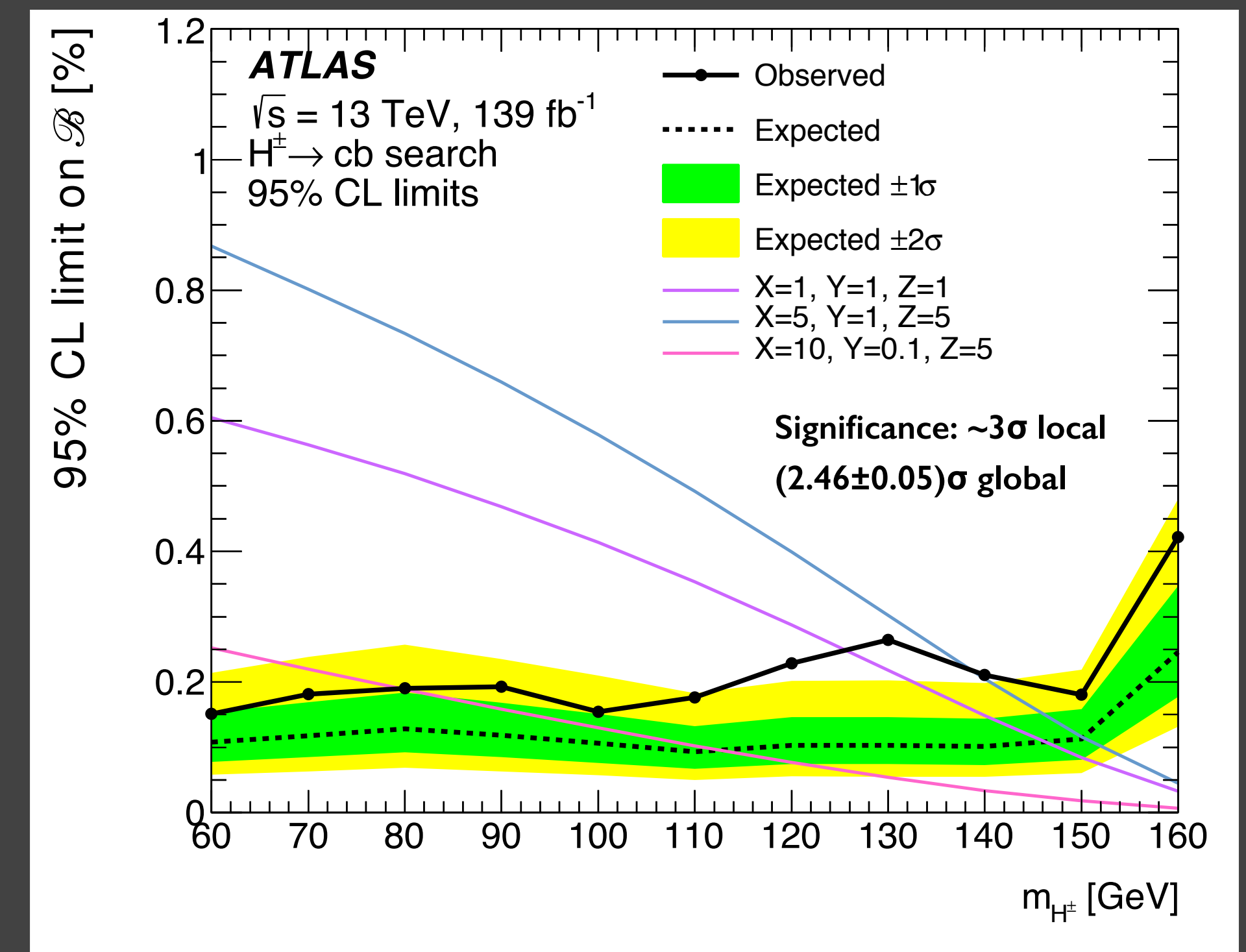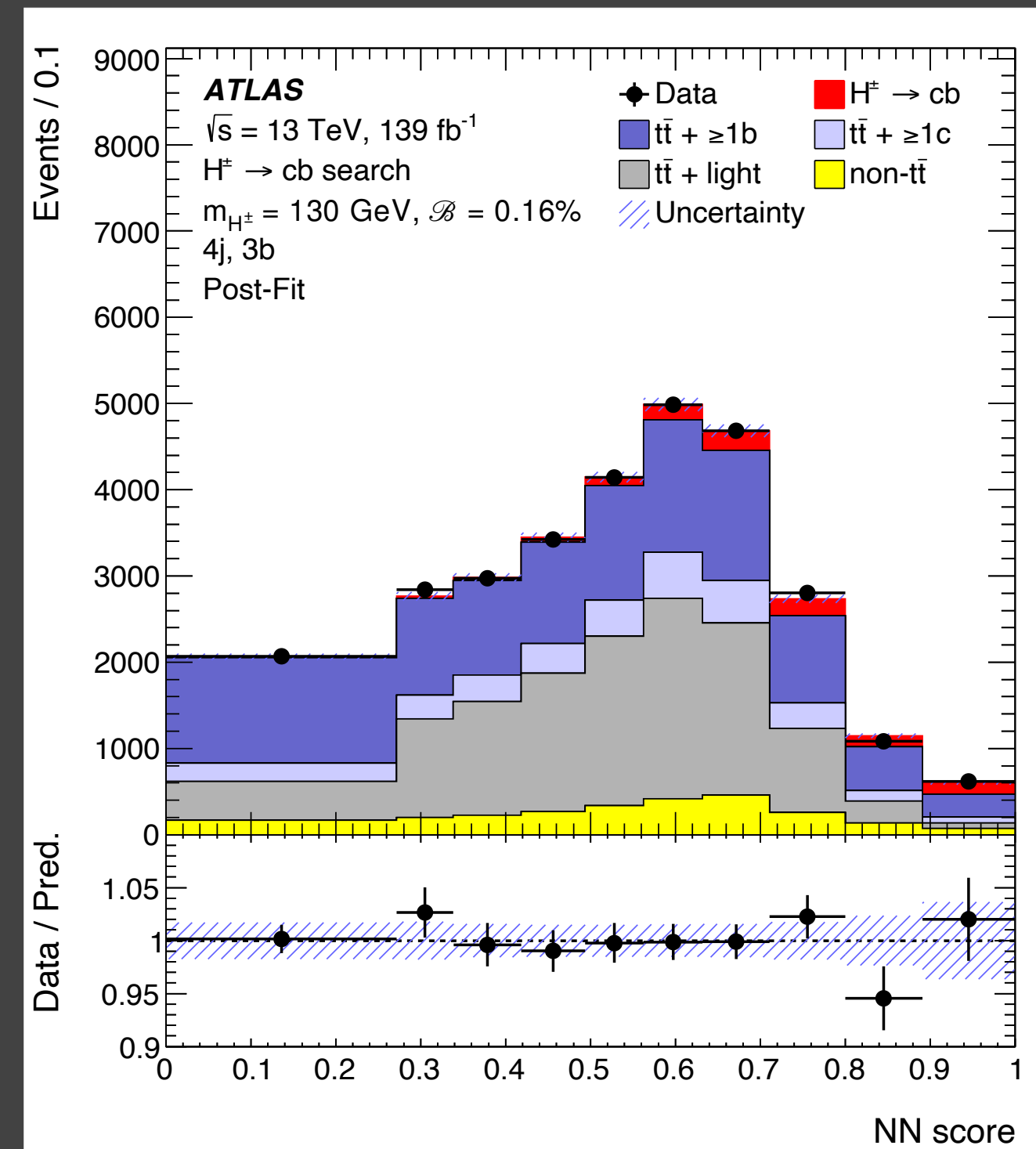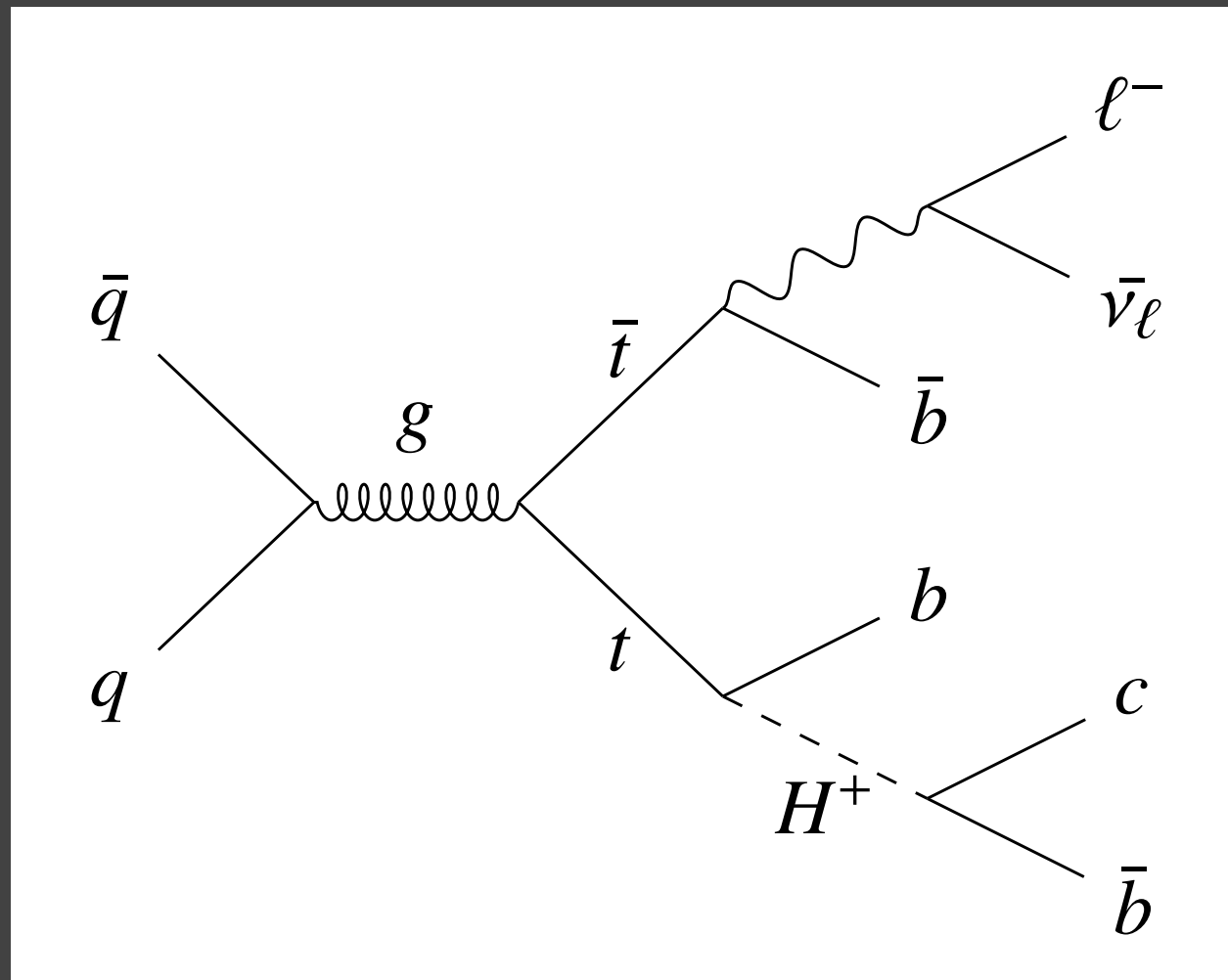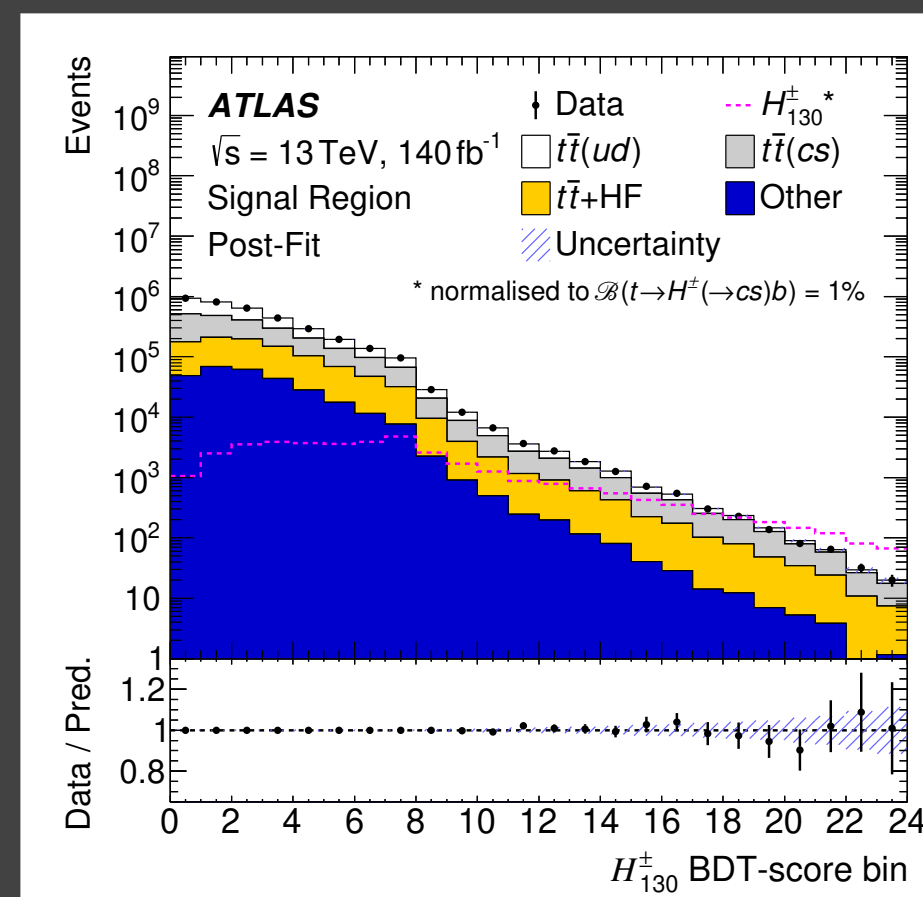
H⁺ produced in t-quark decays

BDT training depending on H⁺ mass

No excess on the BDT score

Low mass H⁺

Lepton + jets

Upper limit set for

m$_{H+}$ = 60-168 GeV
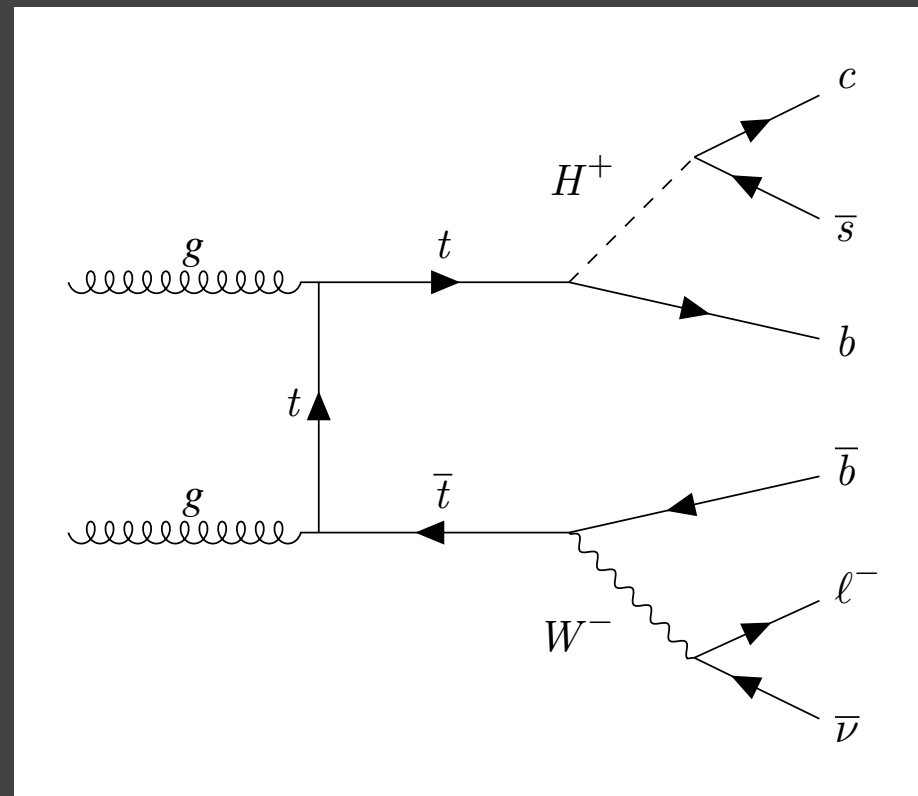
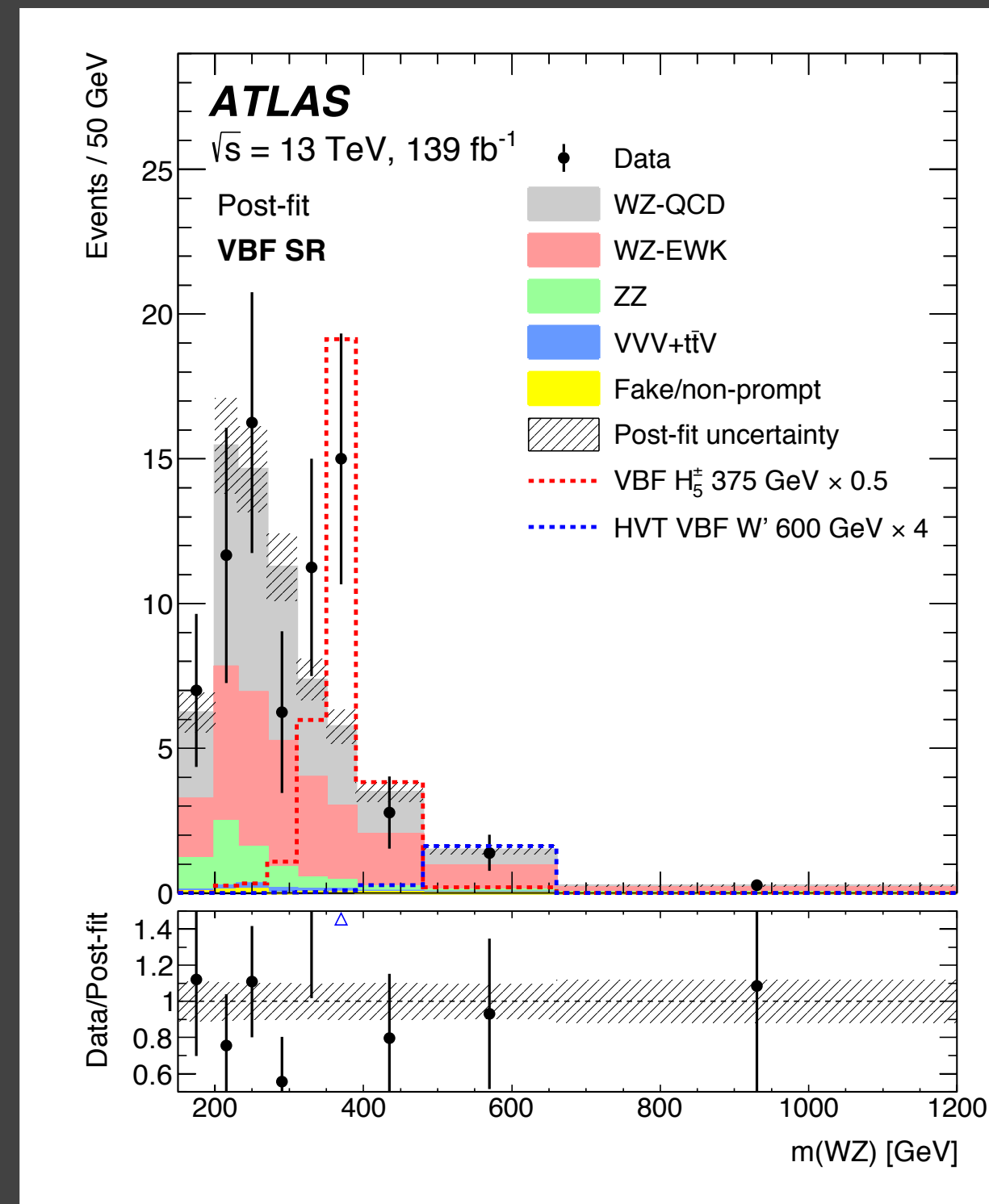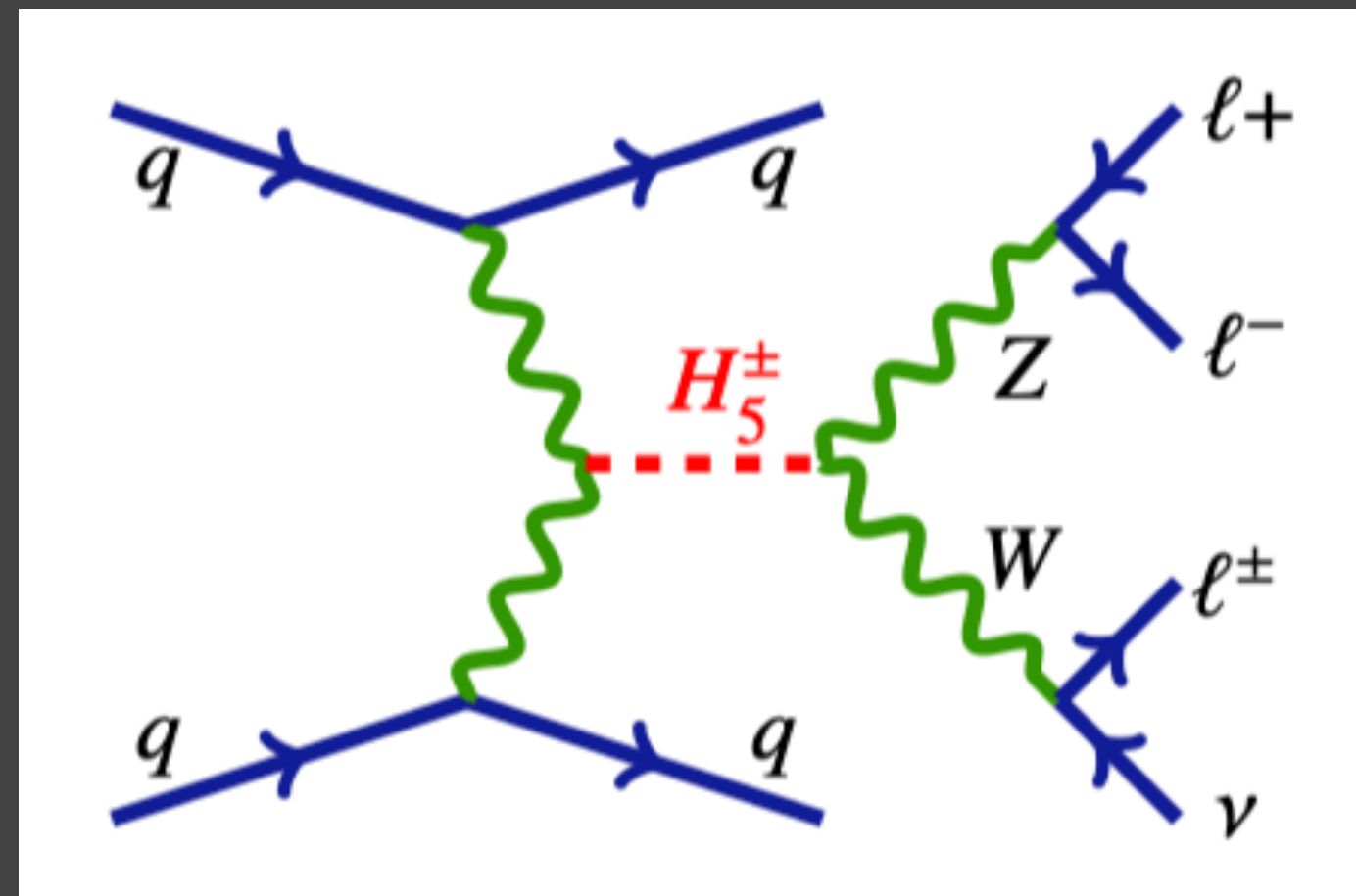## BDT inputs: dijet mass, b p$_T$, …
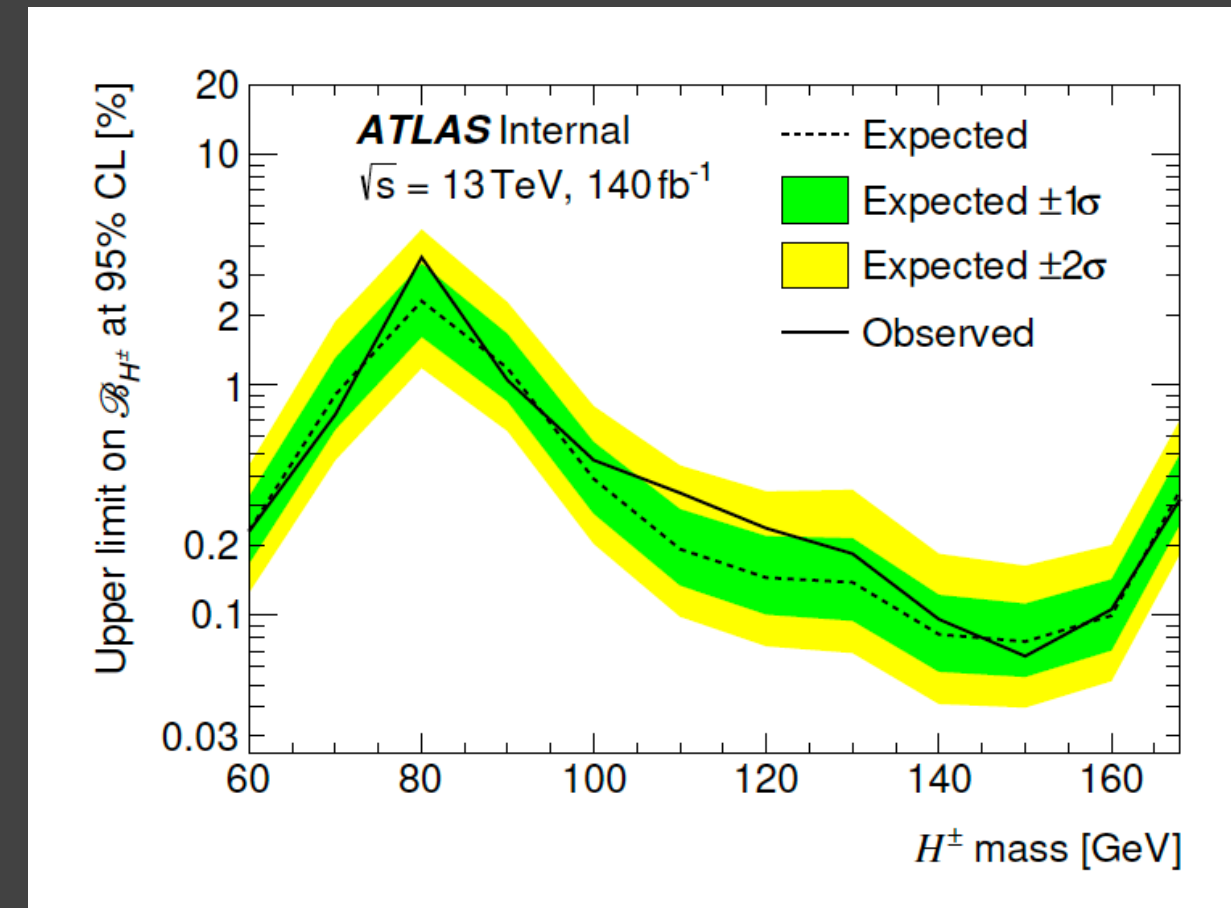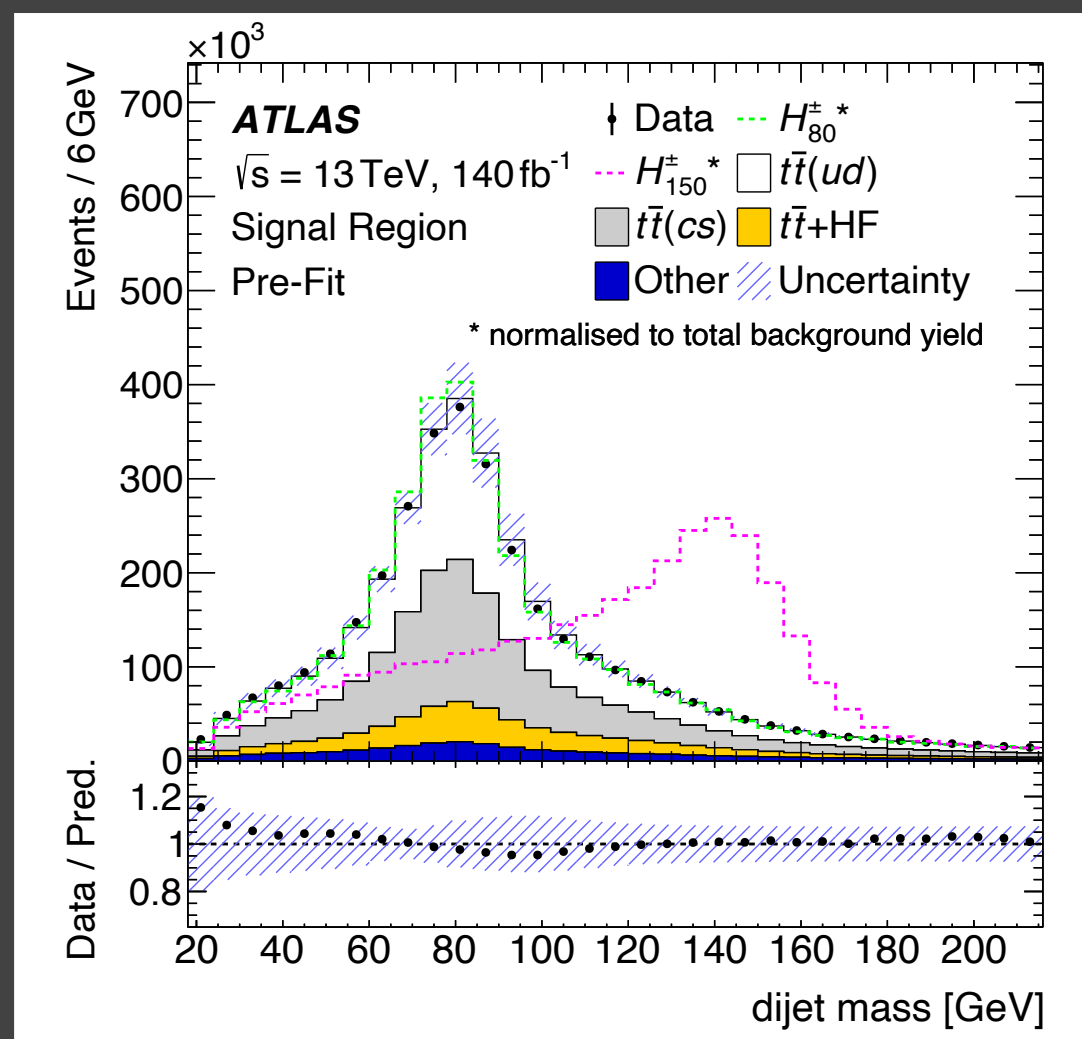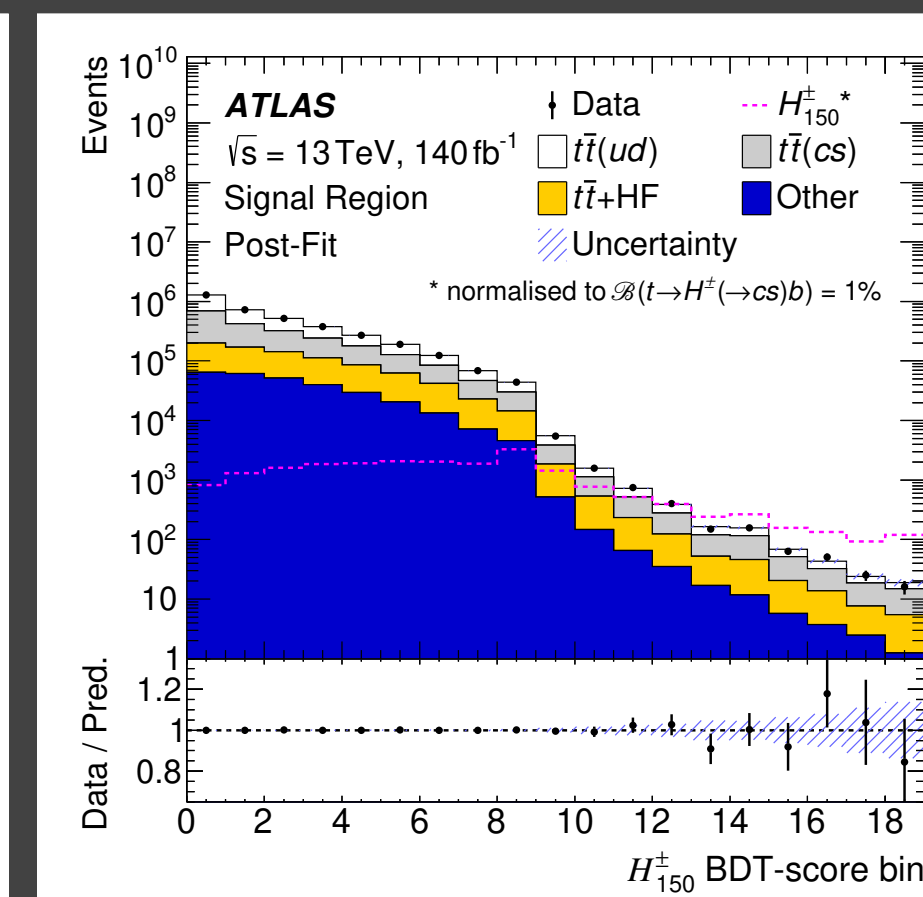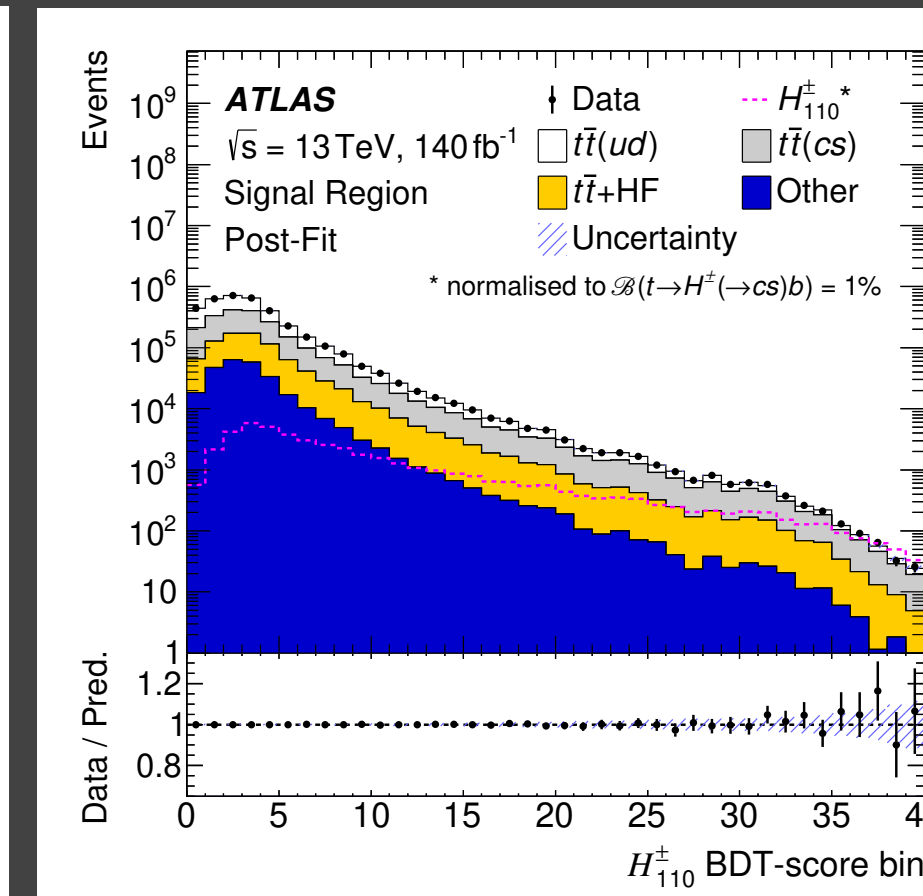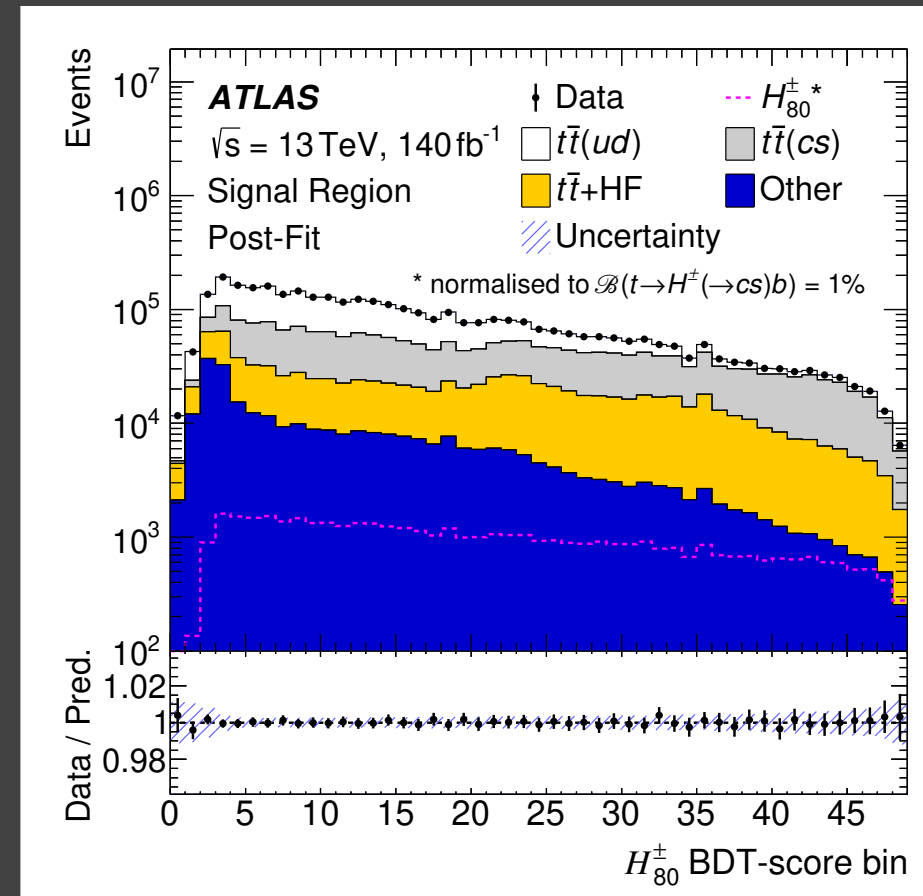
m$_W$ = 80 GeV

H⁺ to Bosons: H⁺ → W⁺ Z → l⁺ v l⁺ l⁻

Fully leptonic final state.

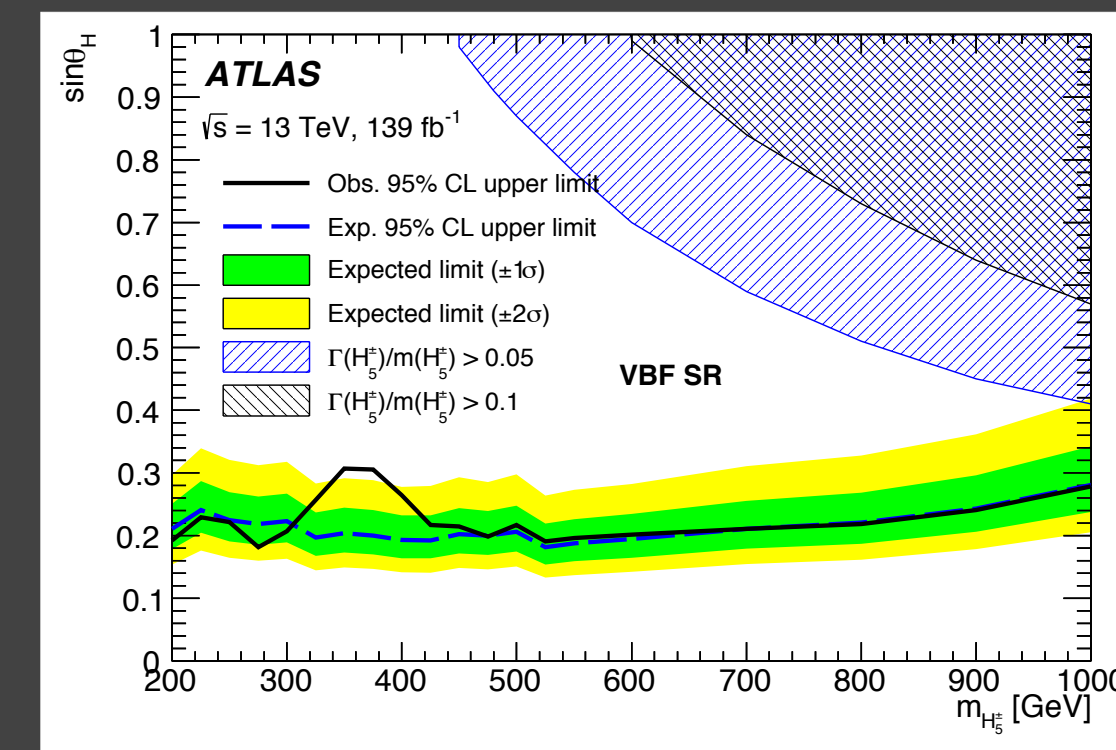**Signal region defined with the NN output.**

Signal extraction by the fit to m(WZ).

No excess observed.

Limits set for m_{H+} = 200-1000 GeV
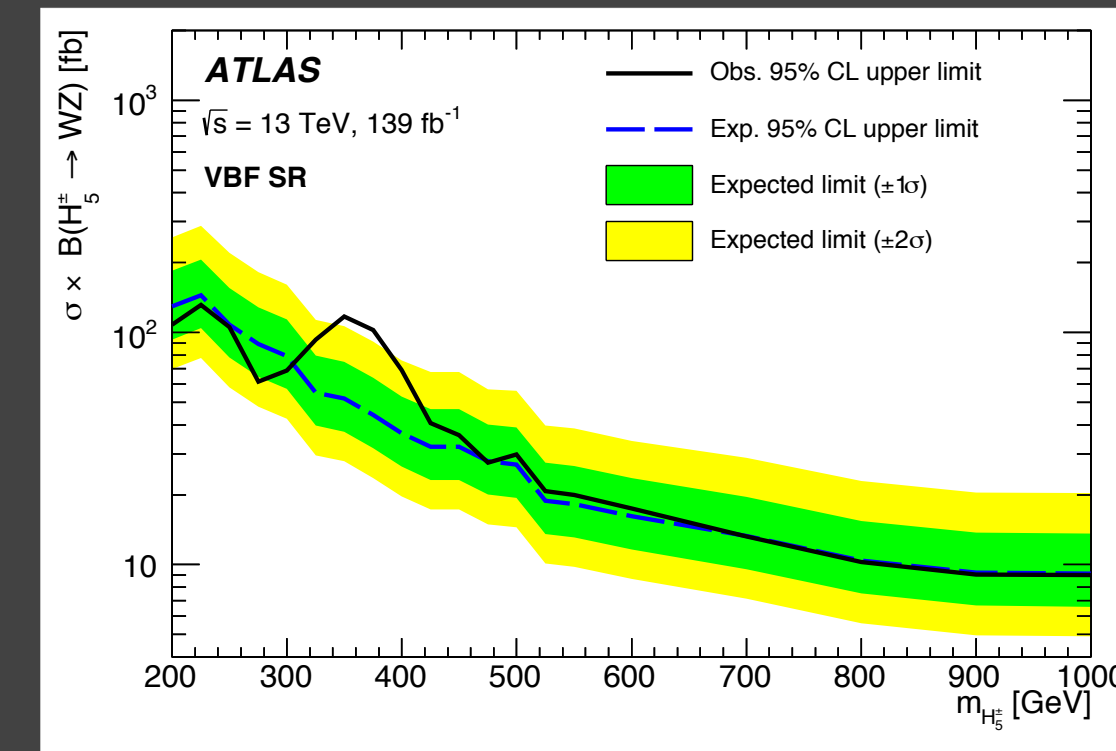
2.8σ local

1.6σ global

significance

at 375 GeV

EPJC 83, 633 (2023)

Interpreted in the GM model

$\sinθ_H$ determines the contribution of the triplets to the masses of W and Z

The search targets the final state with **eµµ or µµµ**.

Fit to m_µµ distribution
No significant excess observed.

Limit set to branching ratio for **m_H+ = 120-160 GeV**.

PRD 108, 092007 (2023)
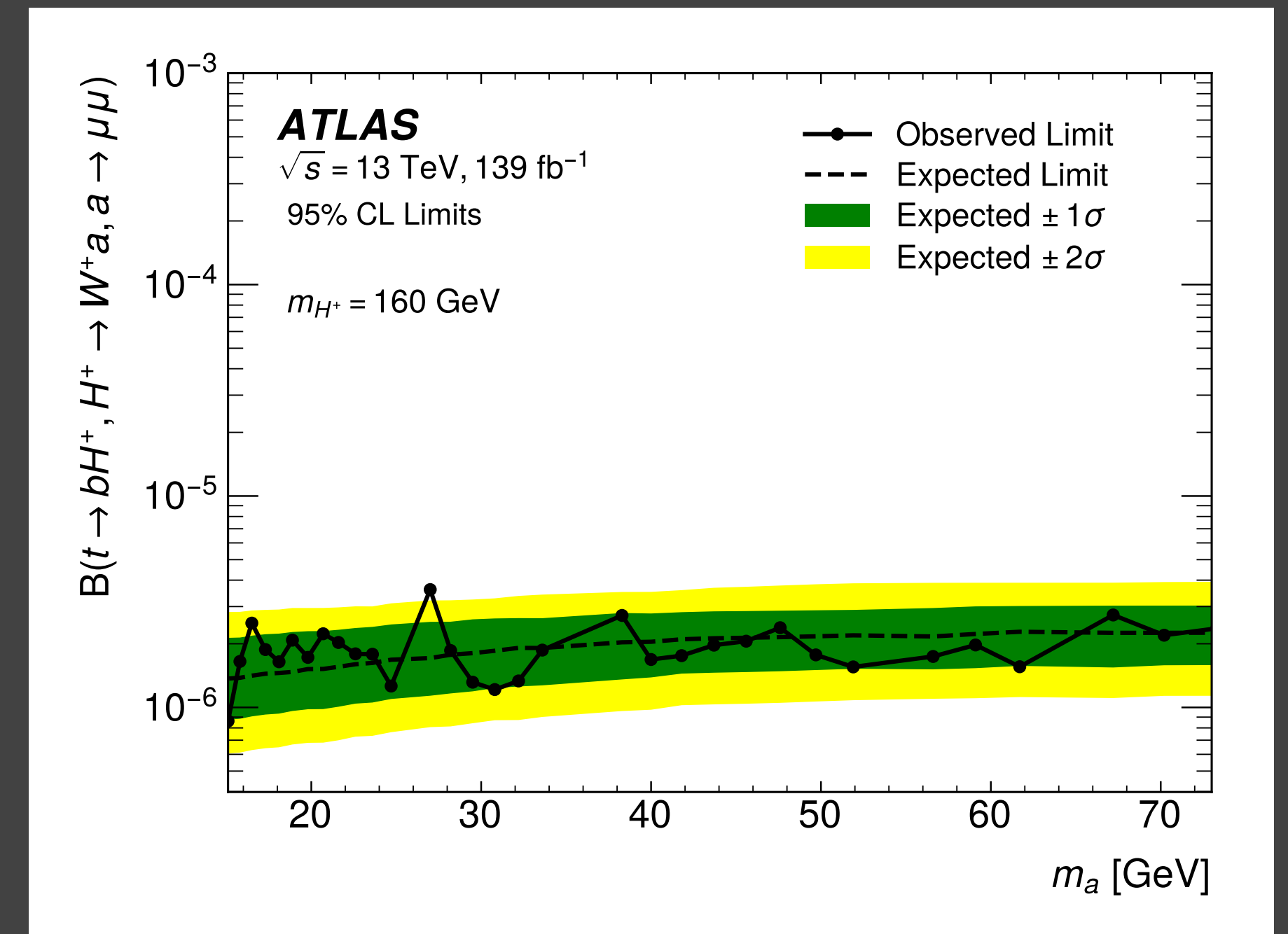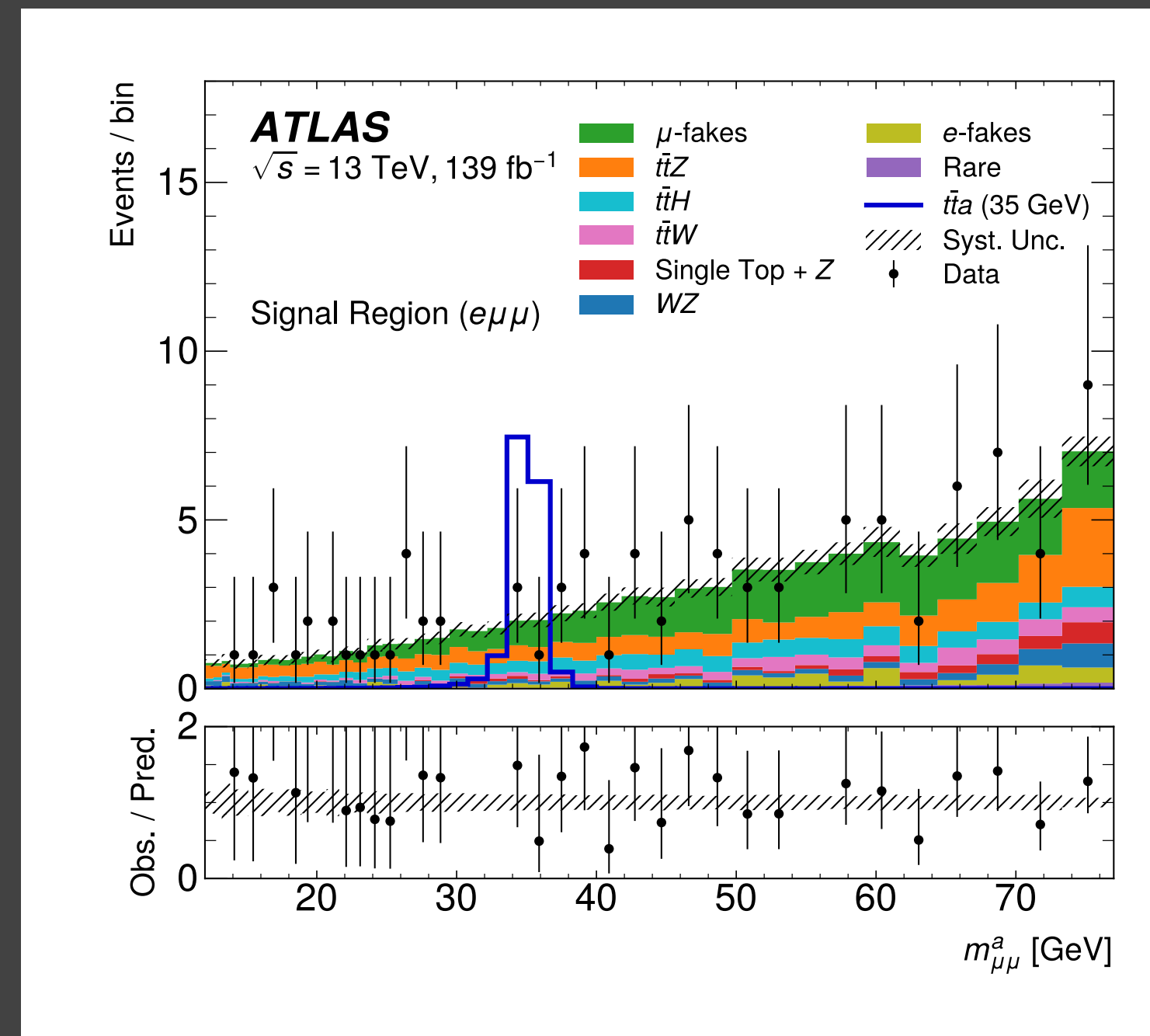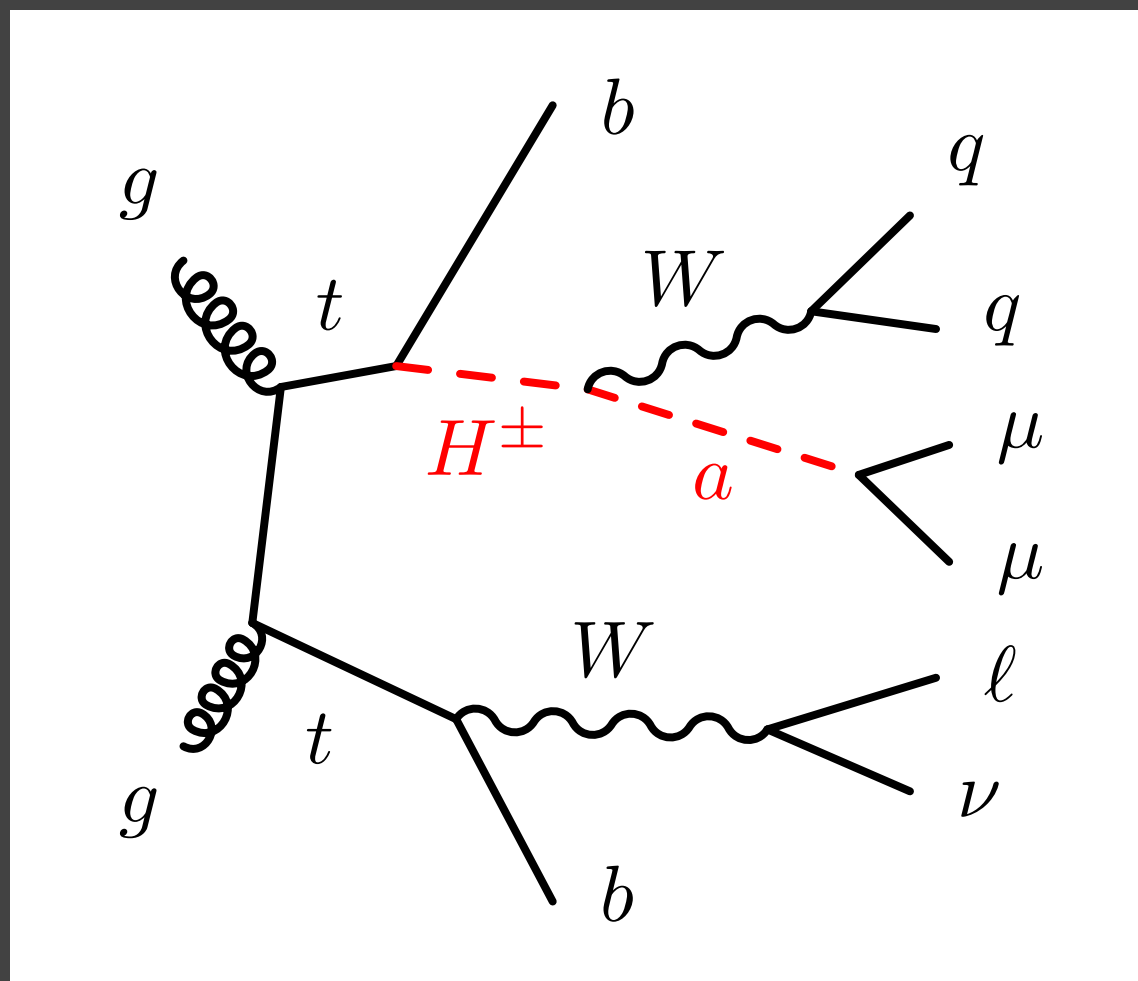
H++ to Fermions: H++ → l+ l'+

- **Search for pair production of H++** decaying into **two leptons**.
- LFV decays **H++ → e+μ+/μ+τ+/e+τ+ allowed**.
- Regions depending on **light lepton (e, μ) multiplicity**.
- **No excess** observed. Limit set to cross section.
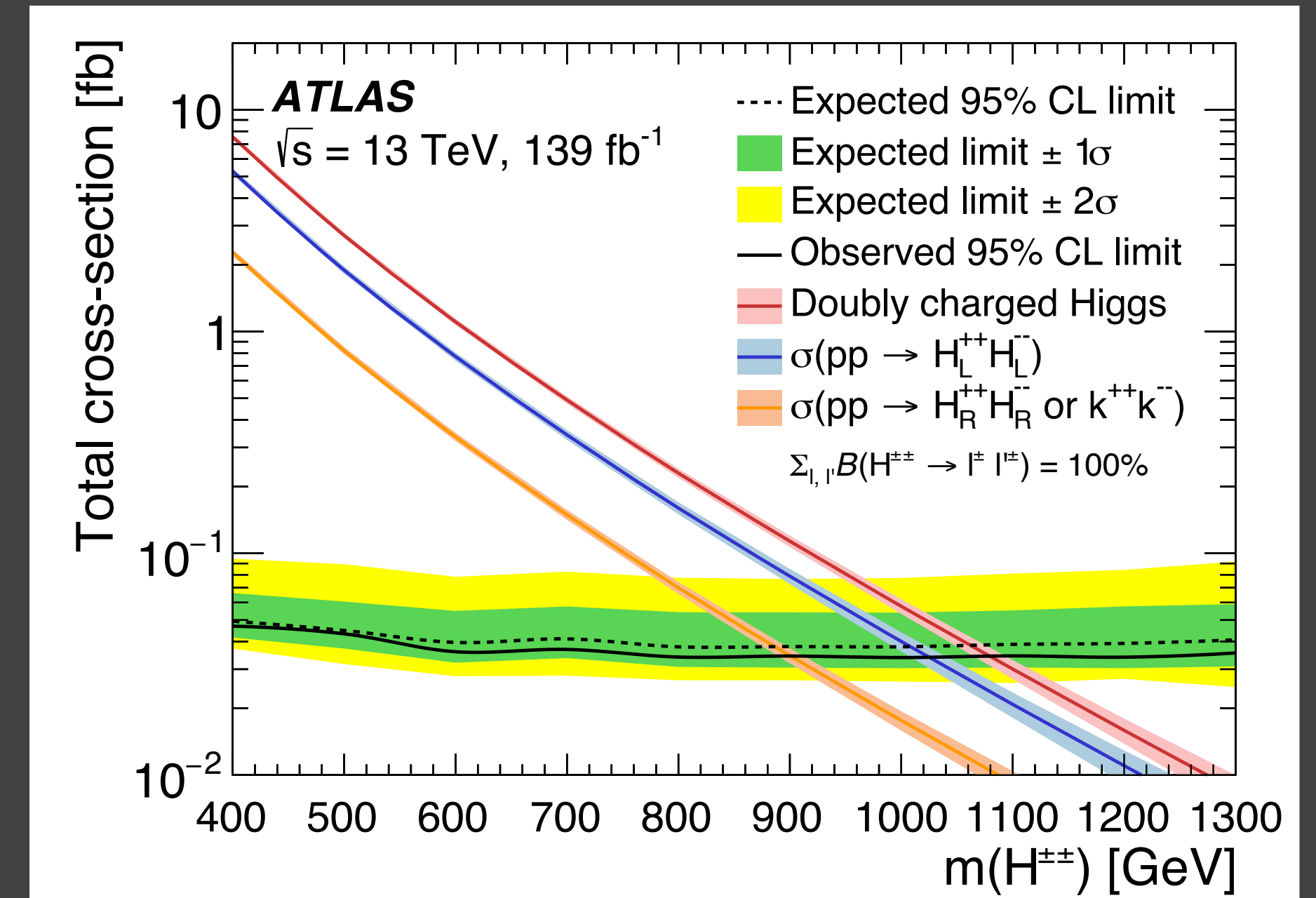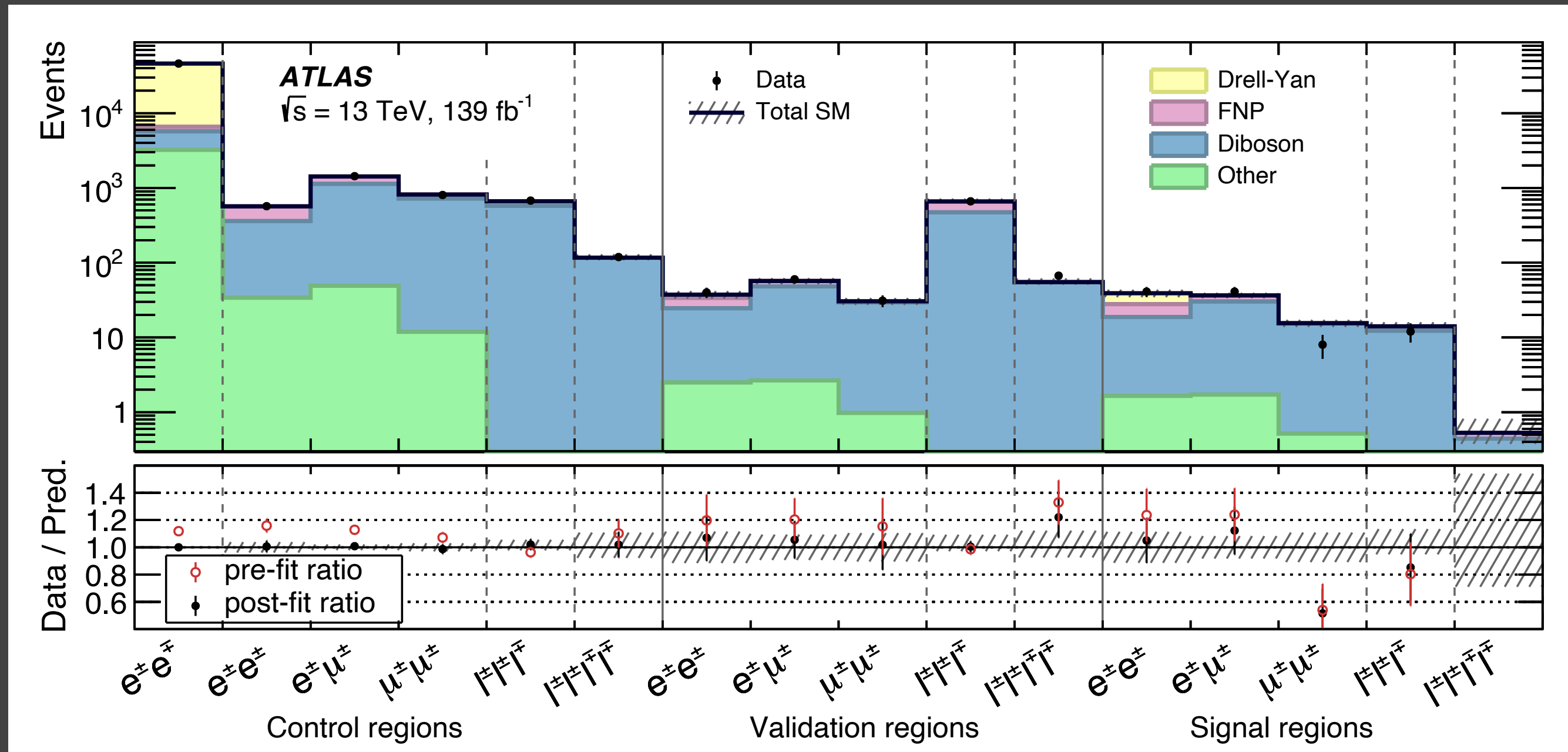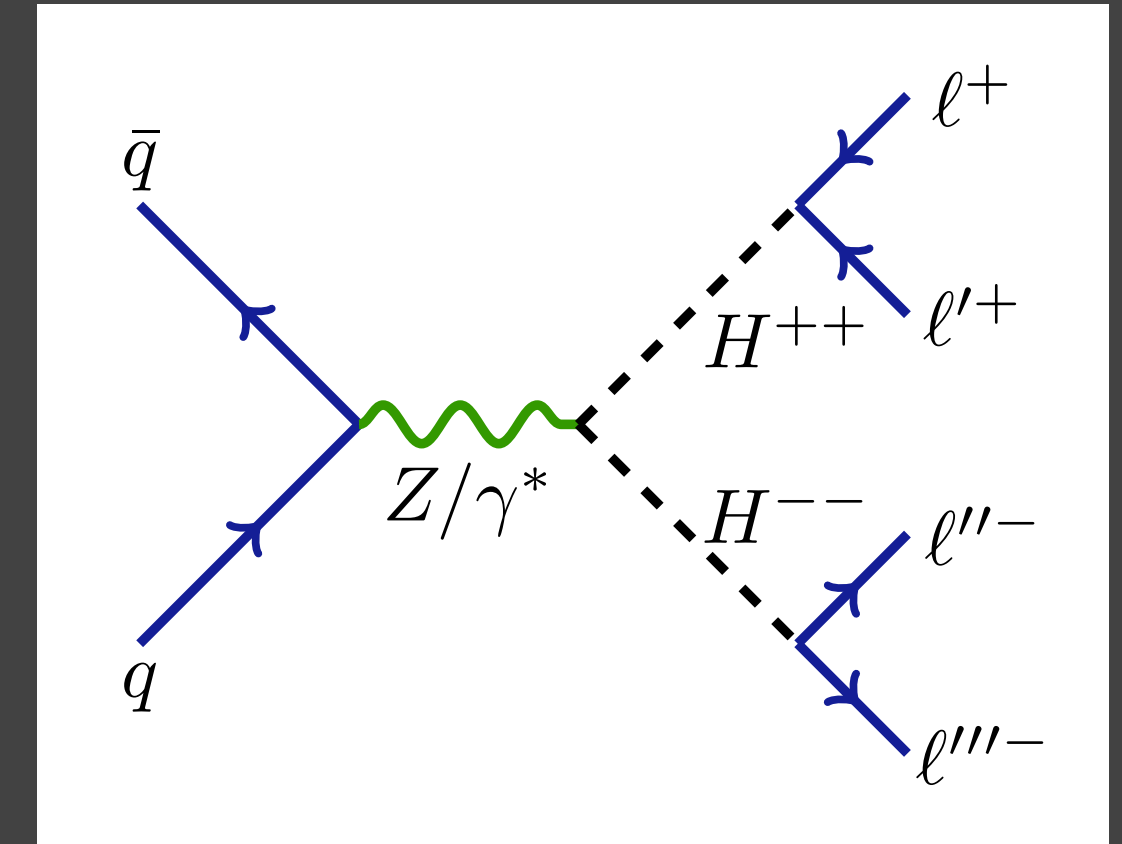
H++ to Bosons: H++ → W+ W+

- Target: **pair production of H++** decaying into **W+W+**.

- Channels: **two same-charge leptons**, **three leptons**, and **four leptons**.

- Note: H+ → W+Z in the H+H-- production also searched for.

- Cut-and-count method. **No excess** observed.

- Upper limit (95% CL) in **a type-II seesaw model: m_{H++} < 350 GeV**
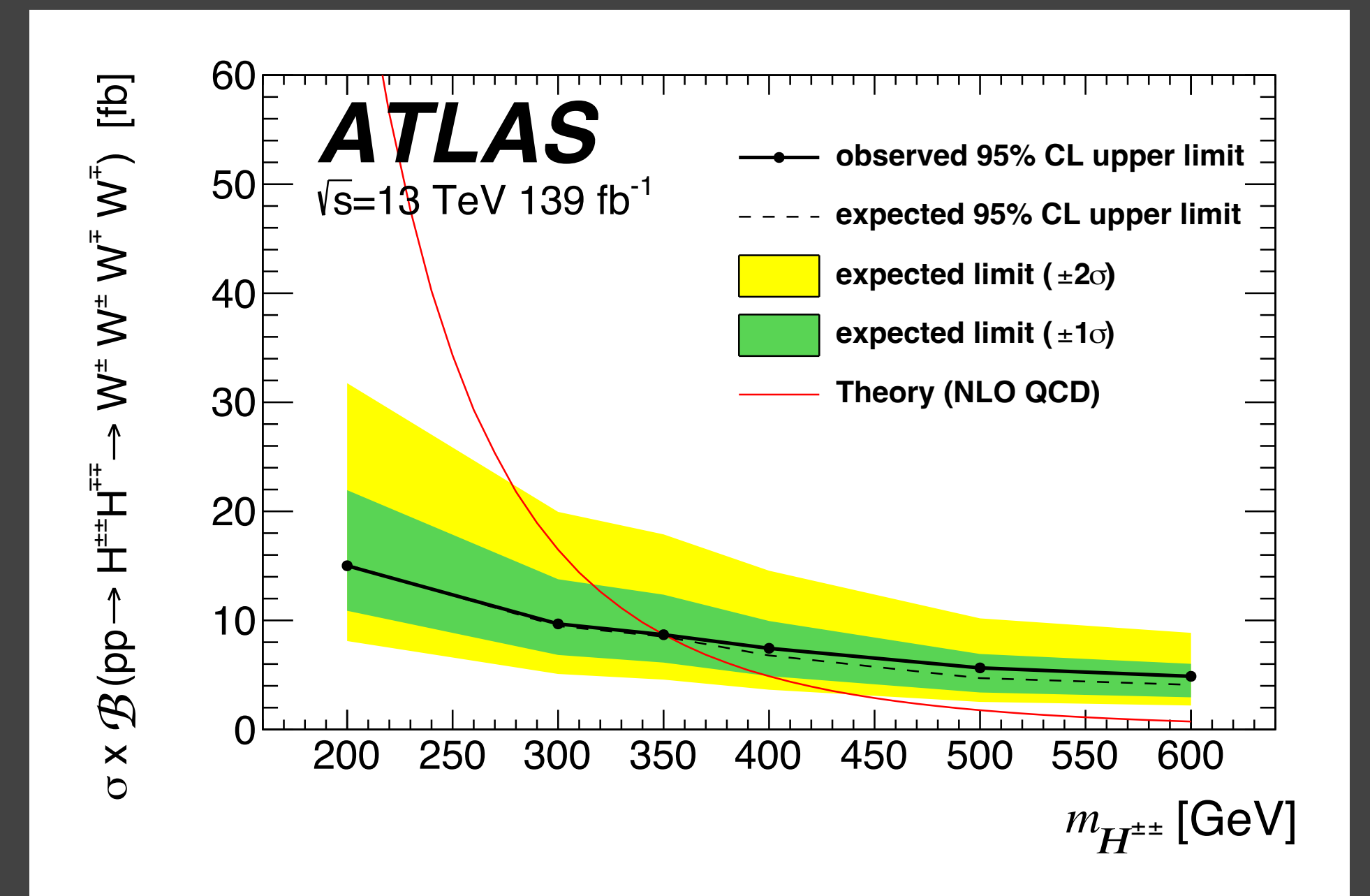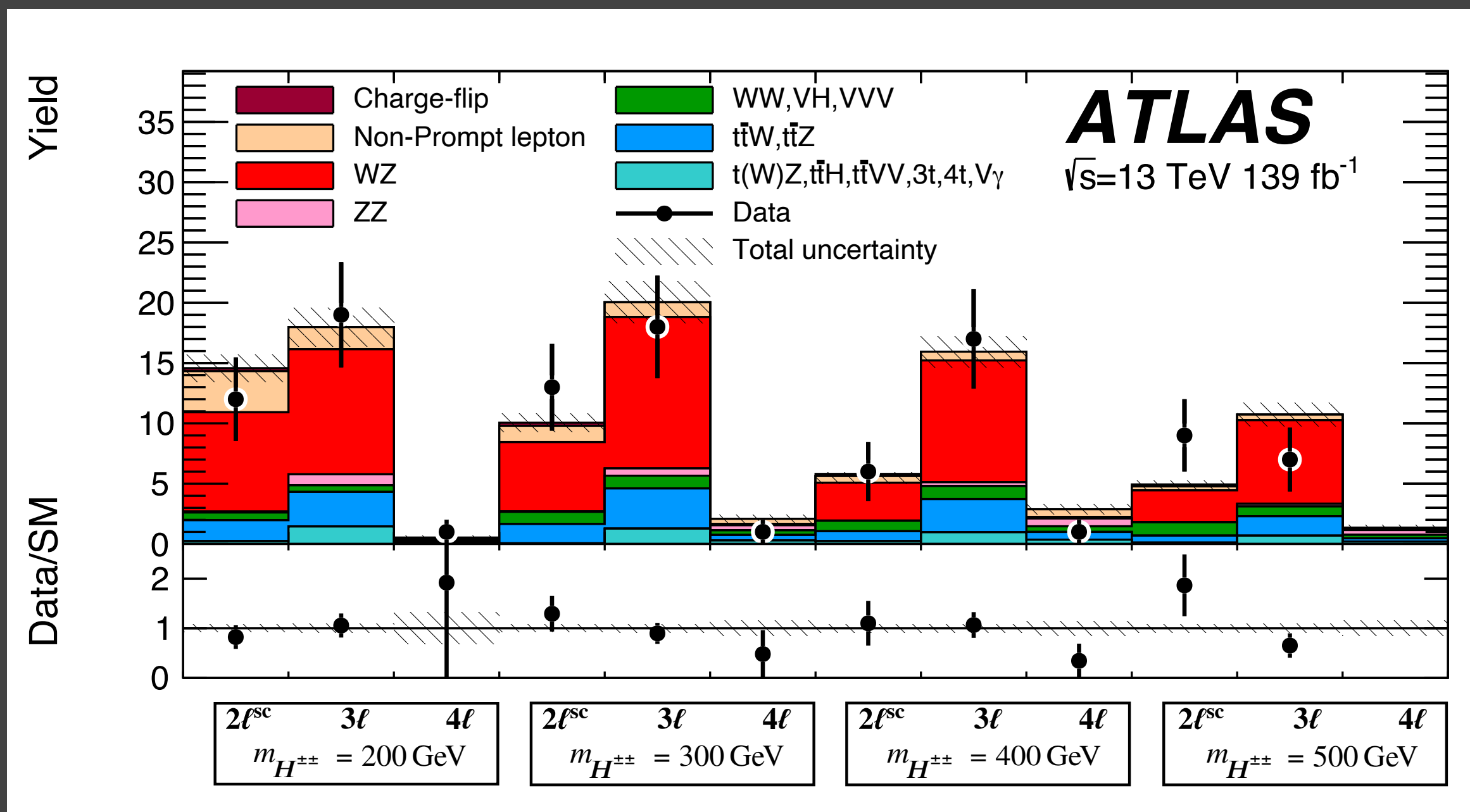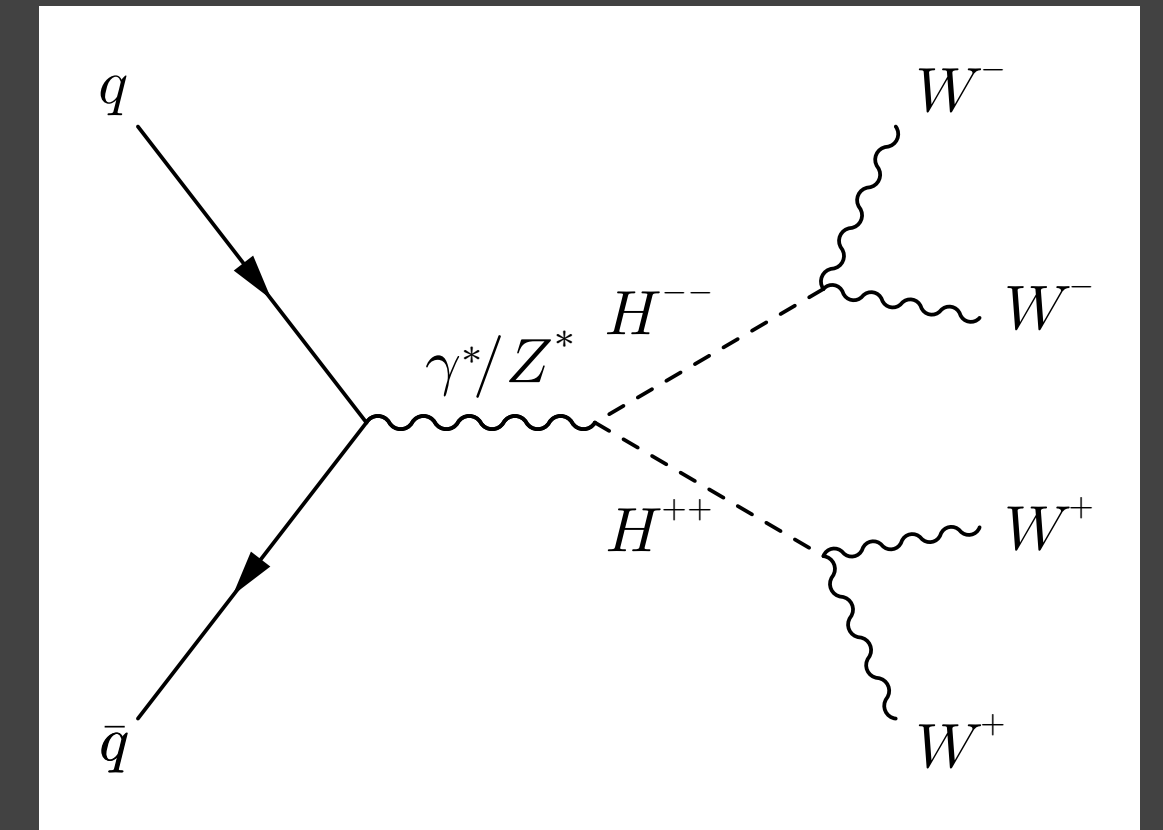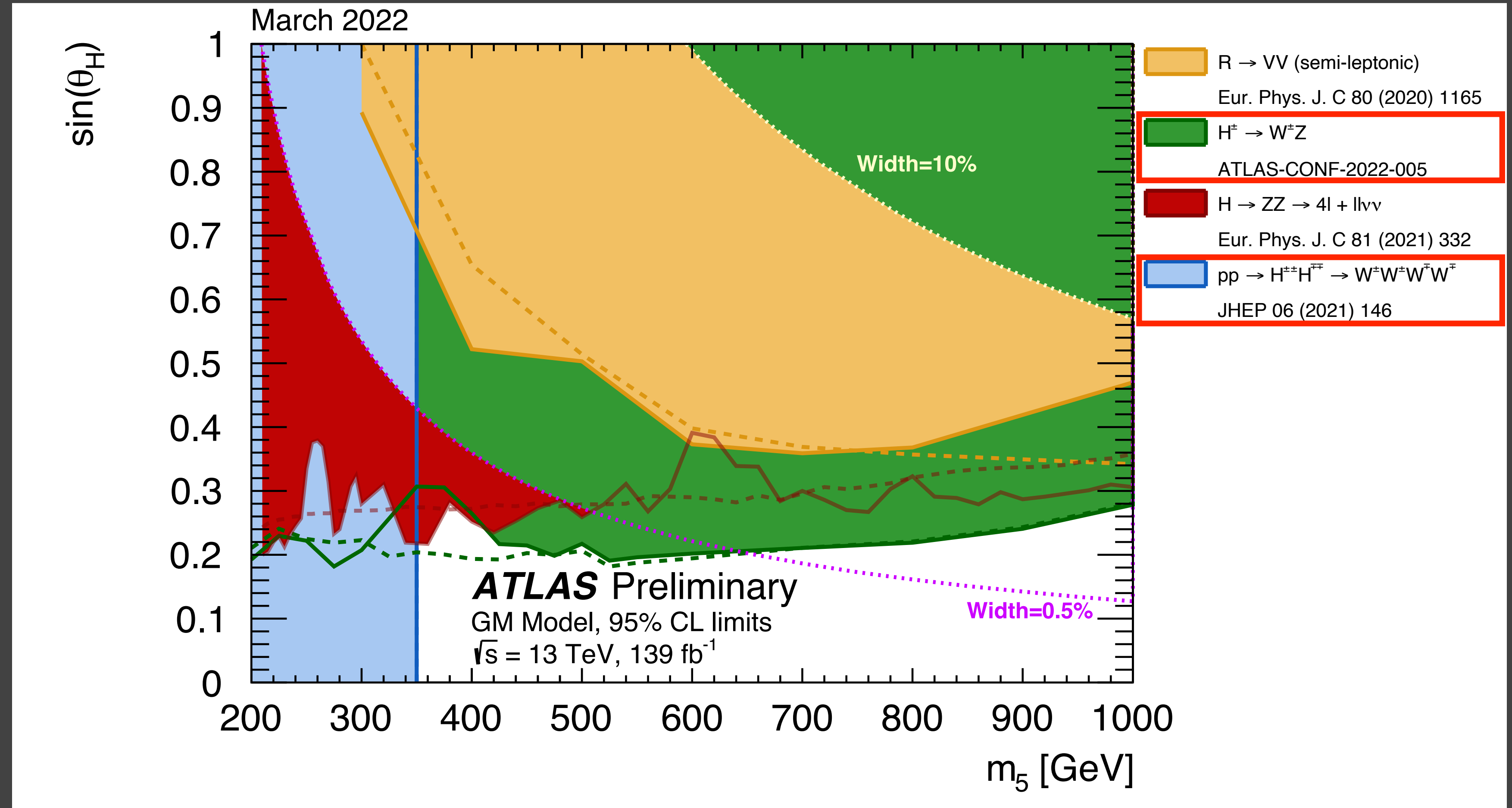
The $H^+ \to W^+ Z$ and $H^{++} \to W^+ W^+$ results were used to constrain the H5 plane benchmark of the GM model.

$\sin\theta_H$: determines the contribution of the triplets to the masses of W and Z.

m_5: a single mass scale.

Conclusion

- Despite its tremendous success, the SM cannot be the final theory; various models extend the Higgs sector, involving charged Higgs bosons.

- Searches were performed with 13 TeV pp collision data at ATLAS Run 2.
  - Singly charged Higgs bosons: $H^+ \to \tau^+\nu$, tb, cb, cs, W^+Z, W^+A
  - Doubly charged Higgs bosons: $H^{++} \to l^+l'^+$, W^+W^+

- No significant excess over the SM expectation was found.

- Limits on the cross section and the branching ratio were set, and the parameters of extended models were constrained: hMSSM, 3HDM, the GM model, the type-II seesaw model, …