# BSM Higgs searches in final states with top quarks

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**Higgs potential and BSM opportunity**

# Outline

*SM 4tops meeting | 04 October, 2018, CERN*

- Introduction

  - The **Higgs**, the **top** and **BSM**

- Canonical (high mass) 2HDM / MSSM "inspired" searches

  - Why are they relevant, where do we stand, what's next?

- Other signatures: top quark decays mediated by BSM interactions

- Summary

  - What we learned, unexplored channels, ..

# Introduction

# (Extended) Higgs sector(s)

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \implies \langle H_1 \rangle \sim \begin{pmatrix} 0 \\ v_1 \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \qquad \langle H_2 \rangle \sim \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

$$\tan\beta = \frac{v_2}{v_1}$$

**Particle spectrum:**
**h, H, A, H±**

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}$$

$$\alpha = 0 \implies \text{alignment}$$

Depending on the **Higgs potential** structure the **masses of the BSM Higgs bosons** maybe related with each other (and other SM particles)

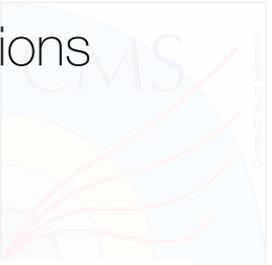|      | 2HDM I | 2HDM II | 2HDM III | 2HDM IV |
|------|--------|---------|----------|---------|
| $hVV$ | $\sin(\beta - \alpha)$ | $\sin(\beta - \alpha)$ | $\sin(\beta - \alpha)$ | $\sin(\beta - \alpha)$ |
| $hQu$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ |
| $hQd$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ |
| $hLe$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $-\sin\alpha/\cos\beta$ | $\cos\alpha/\sin\beta$ |
| $HVV$ | $\cos(\beta - \alpha)$ | $\cos(\beta - \alpha)$ | $\cos(\beta - \alpha)$ | $\cos(\beta - \alpha)$ |
| $HQu$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ |
| $HQd$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ |
| $HLe$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ | $\cos\alpha/\cos\beta$ | $\sin\alpha/\sin\beta$ |
| $AVV$ | $0$ | $0$ | $0$ | $0$ |
| $AQu$ | $\cot\beta$ | $\cot\beta$ | $\cot\beta$ | $\cot\beta$ |
| $AQd$ | $-\cot\beta$ | $\tan\beta$ | $-\cot\beta$ | $\tan\beta$ |
| $ALe$ | $-\cot\beta$ | $\tan\beta$ | $\tan\beta$ | $-\cot\beta$ |

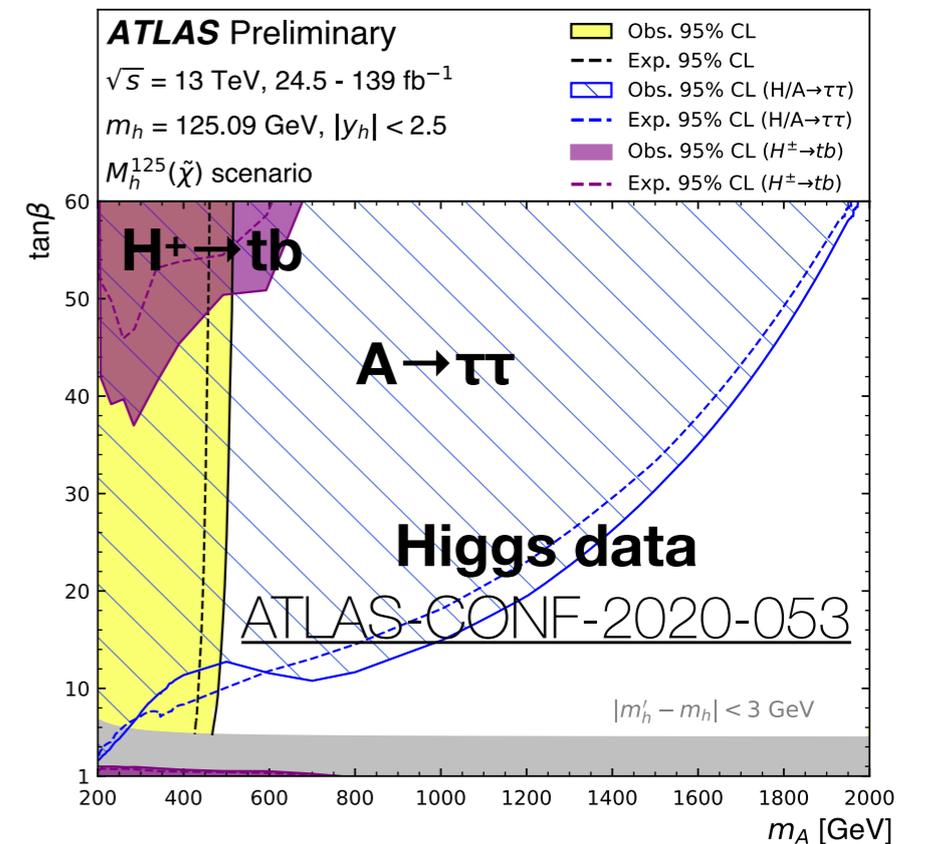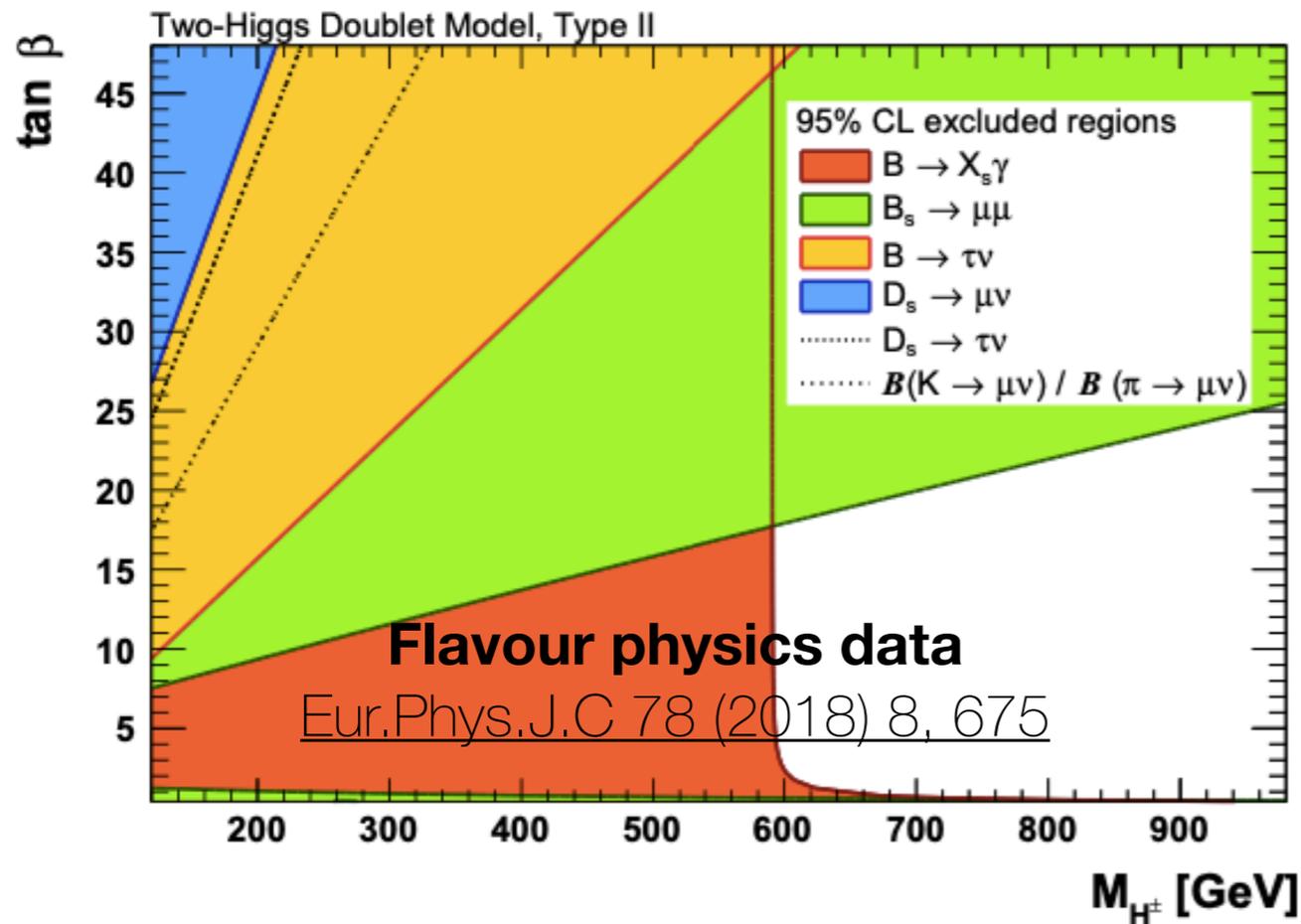Measuring couplings of the SM particles (e.g. SM H) strongly constrain "BSM couplings"

# Why the top quark?

- Constraints from flavour and LHC data favour scenarios with BSM Higgs bosons having masses ~0.5 TeV or above

  - Large branching ratios of decay channels involving the top quark

- Low-energy data constrain couplings of BSM Higgs bosons to first and second generation fermions

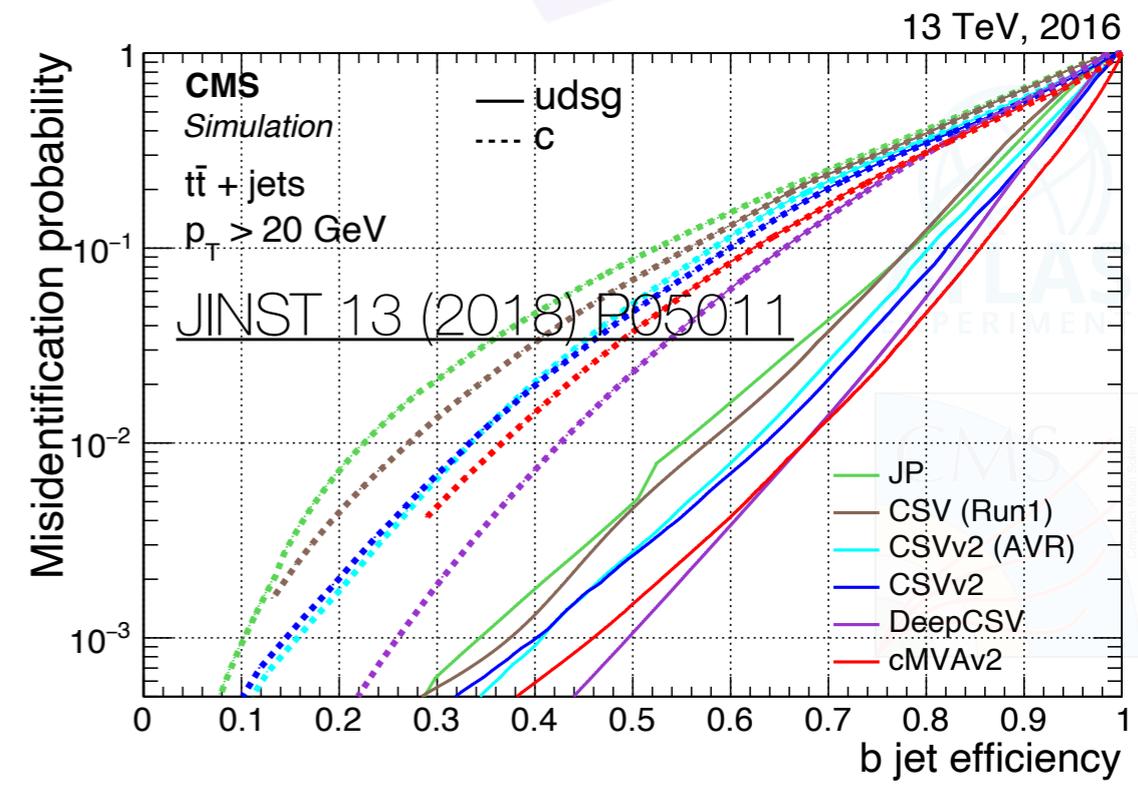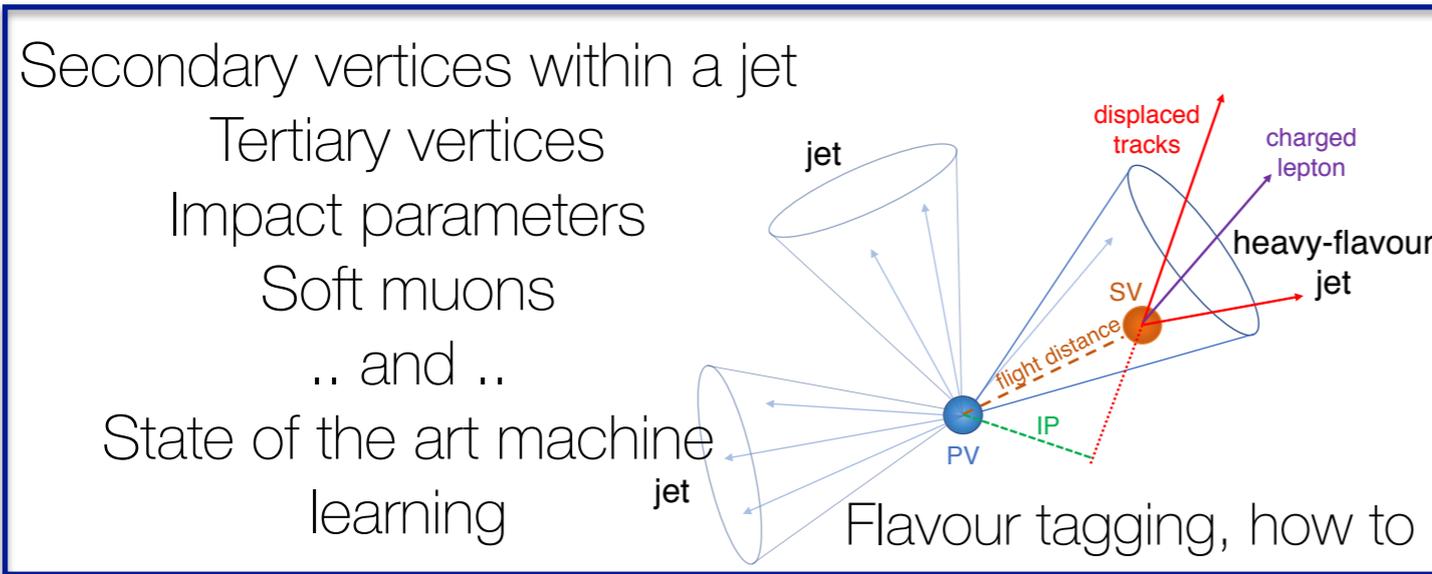- **None of two points above is true in general** (rely on model assumptions)



Two-Higgs Doublet Model, Type II

95% CL excluded regions
- $B \to X_s \gamma$
- $B_s \to \mu\mu$
- $B \to \tau\nu$
- $D_s \to \mu\nu$
- $D_s \to \tau\nu$
- $B(K \to \mu\nu) / B(\pi \to \mu\nu)$

**Flavour physics data**
Eur.Phys.J.C 78 (2018) 8, 675

$M_{H^\pm}$ [GeV]



**ATLAS** Preliminary
$\sqrt{s}$ = 13 TeV, 24.5 - 139 fb$^{-1}$
$m_h$ = 125.09 GeV, $|y_h|$ < 2.5
$M_h^{125}(\tilde{\chi})$ scenario

- Obs. 95% CL
- Exp. 95% CL
- Obs. 95% CL (H/A→ττ)
- Exp. 95% CL (H/A→ττ)
- Obs. 95% CL (H$^\pm$→tb)
- Exp. 95% CL (H$^\pm$→tb)

**H$^+$→tb**

**A→ττ**

**Higgs data**
ATLAS-CONF-2020-053

$|m'_h - m_h|$ < 3 GeV

$m_A$ [GeV]

# How to: flavour tagging

Secondary vertices within a jet
Tertiary vertices
Impact parameters
Soft muons
.. and ..
State of the art machine
learning



Flavour tagging, how to
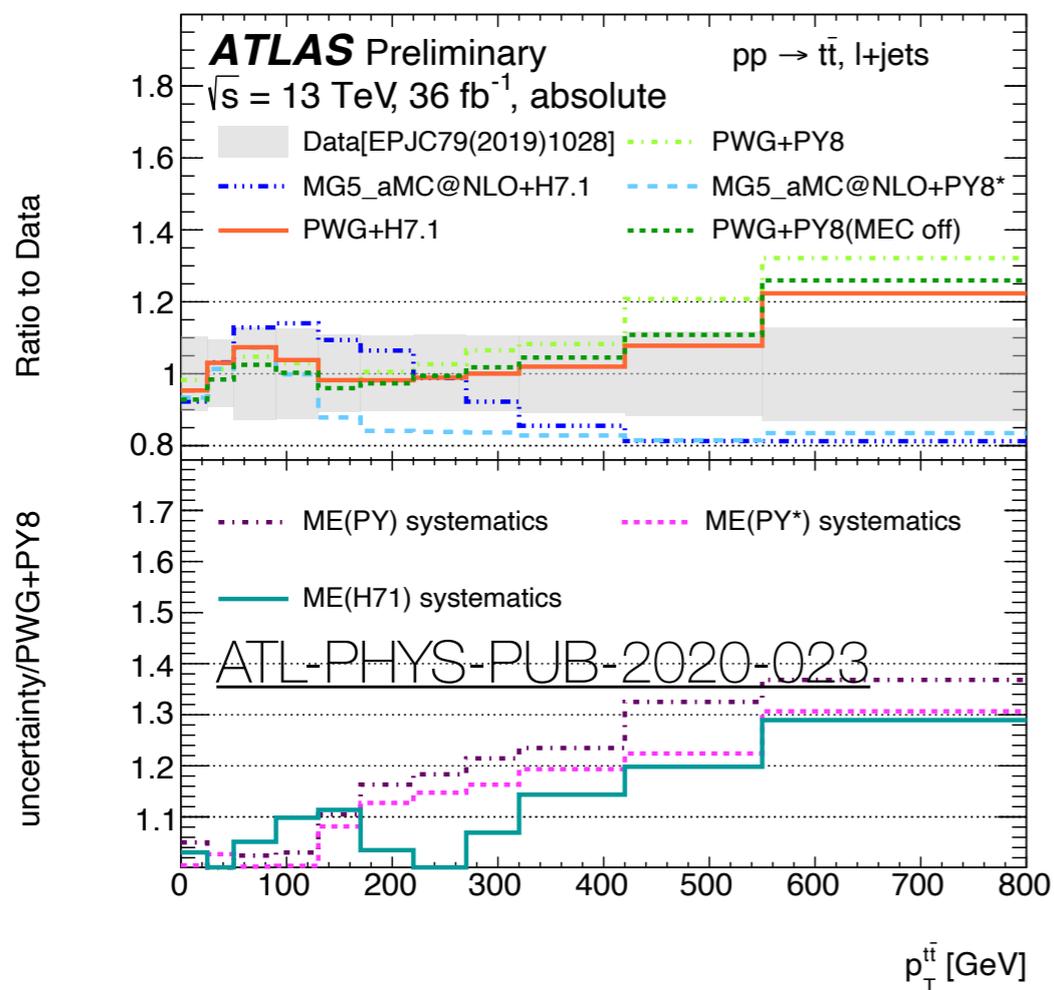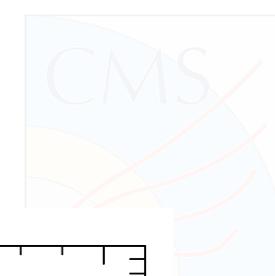


JINST 13 (2018) P05011

- Critical aspect of searches with top-quark

  - Capabilities of the taggers

  - Precision of the calibration

- Unprecedented level of performance
  → **greater discovery potential**



Eur. Phys. J. C 79 (2019) 970
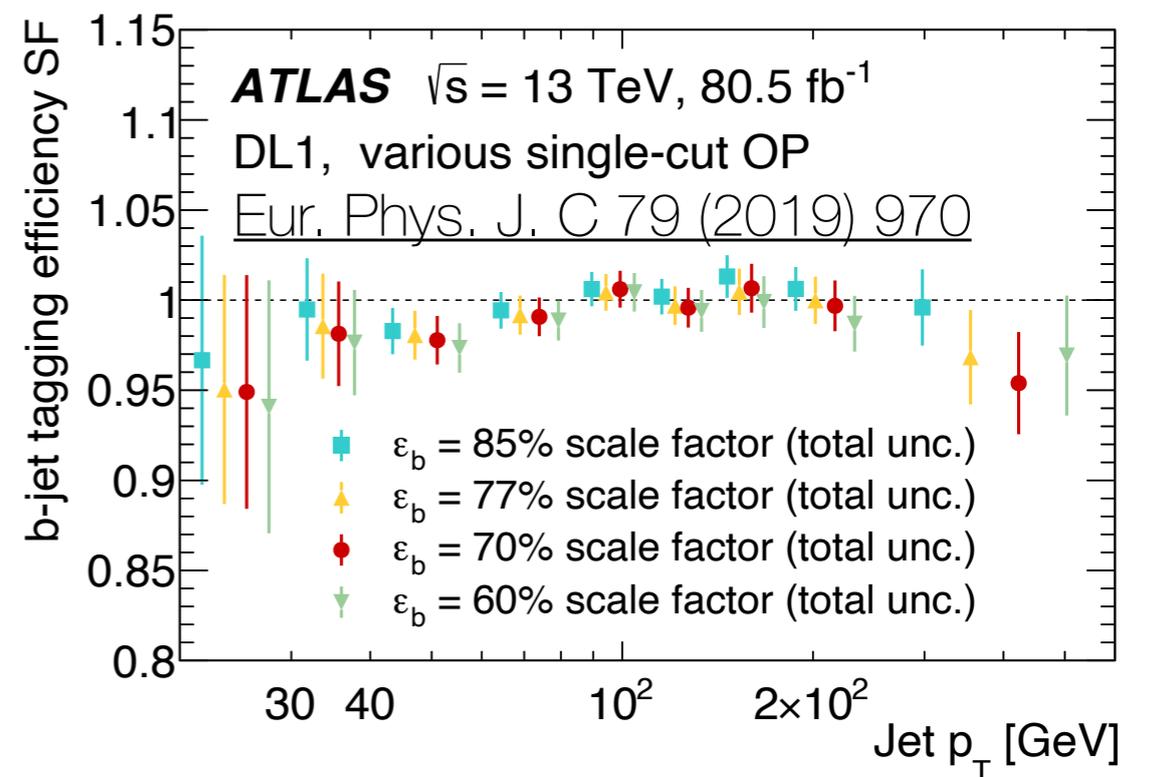
# How to: modelling of top-quark processes

*SM 4tops meeting* | *04 October, 2018, CERN*

- Modelling of **top-quark pair** production is of critical importance

  - Sophisticated background models to describe **event hardness, jet multiplicity, ..**

  - Modelling of **top-quark pair production in association with heavy flavour** is also a bottleneck, not enough measurements available

- Modelling of **ttW** is relevant for signatures with at least three top quarks

  - **EW corrections** play a role in describing high jets multiplicity (affects 3top and 4tops signatures)
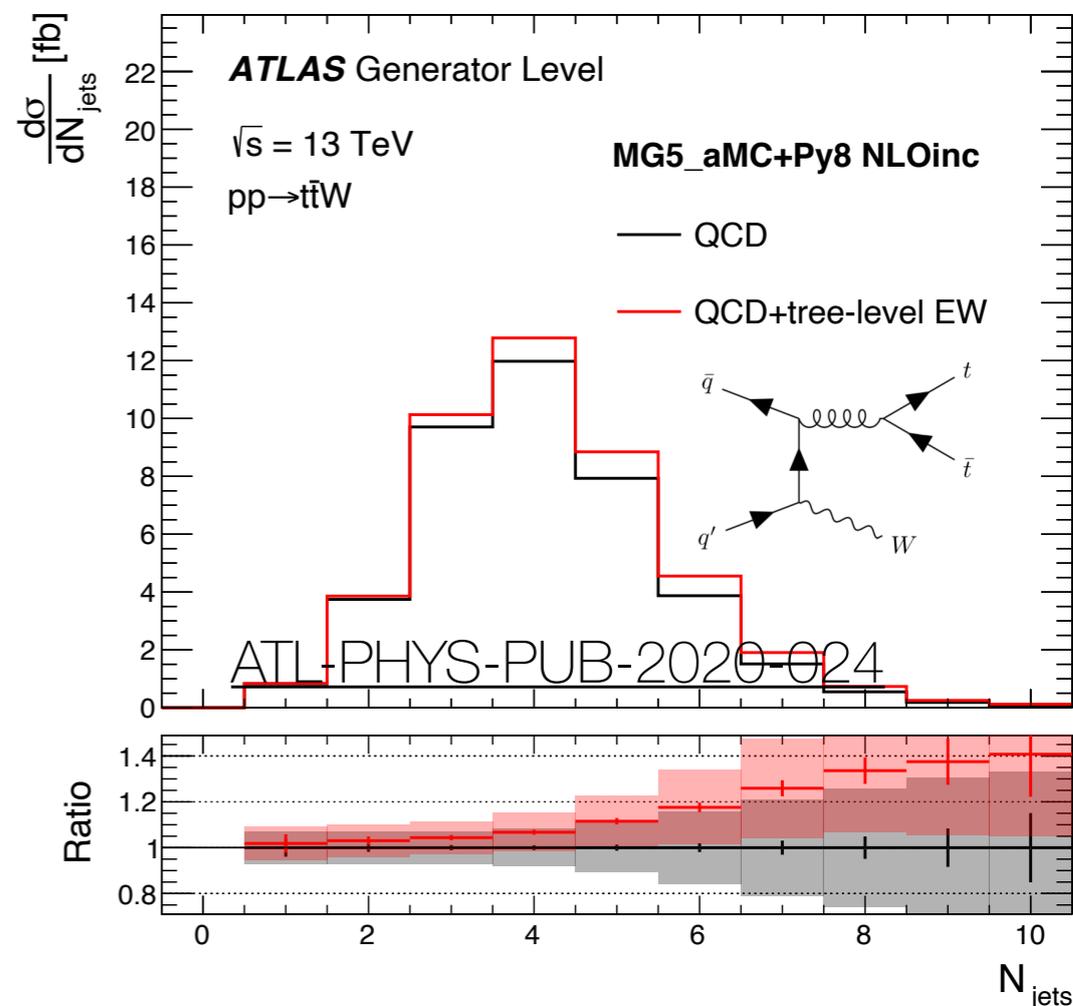


ATL-PHYS-PUB-2020-023



ATL-PHYS-PUB-2020-024

**Higgs potential and BSM opportunity** | *27-31 August 2021, Nanjing (China) + online*

# 2HDM / MSSM "inspired" searches

$H^+ \rightarrow tb$
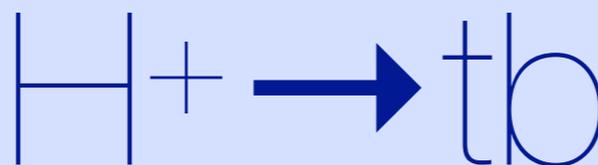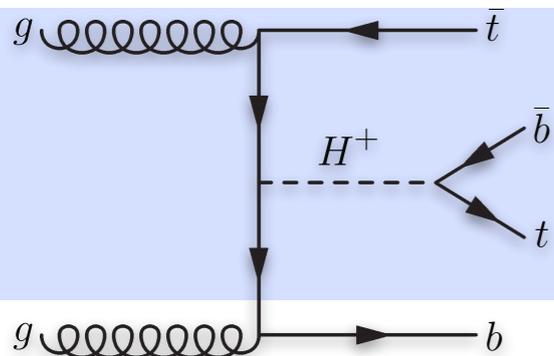
- Challenging search: high jets and b-jets multiplicities (6 jets, 4 b-jets)

  - Top-quark pair production in association with b-jets is the main background

- Deploys a complex event reconstruction method (based on combinatorial likelihood) and a neural network analysis

- **Leads collider exclusion in large class of 2HDM models at high mass**

# Neutral Higgs, associated production

BSM signal
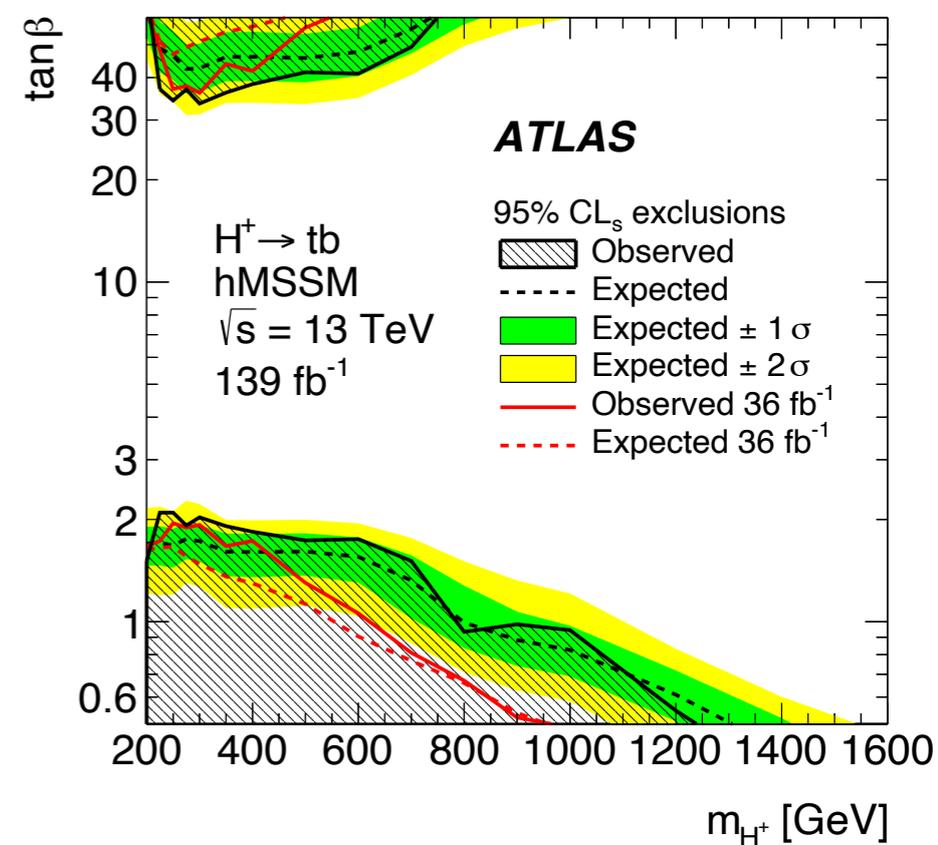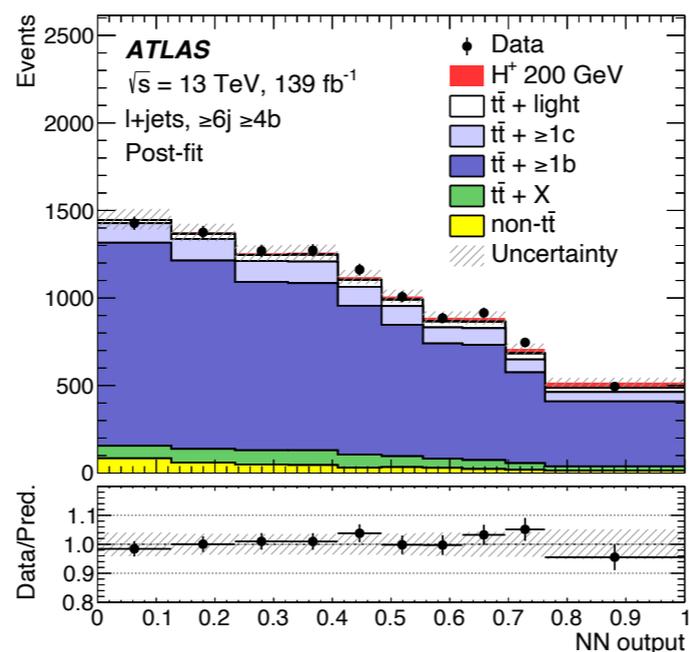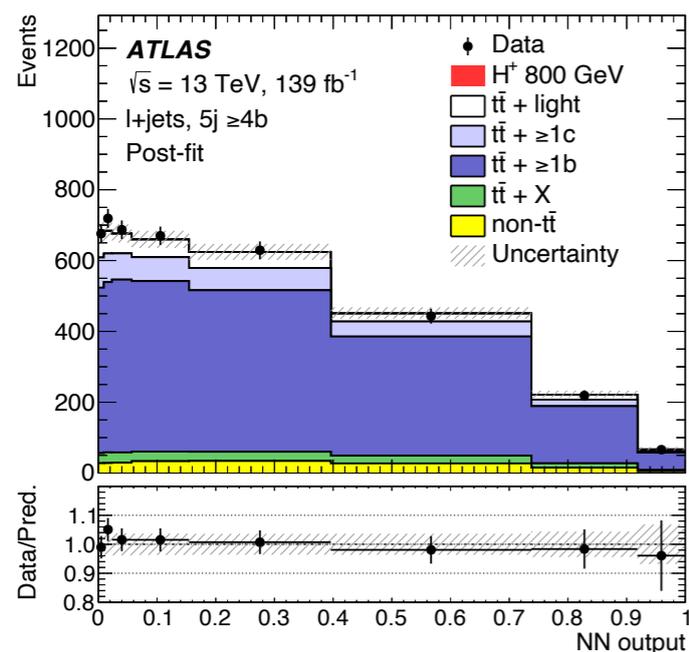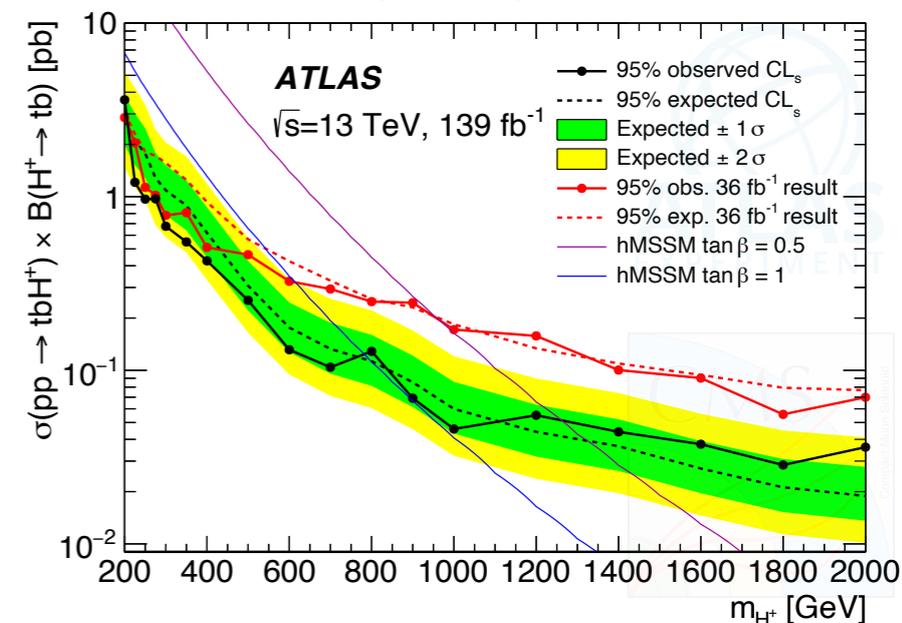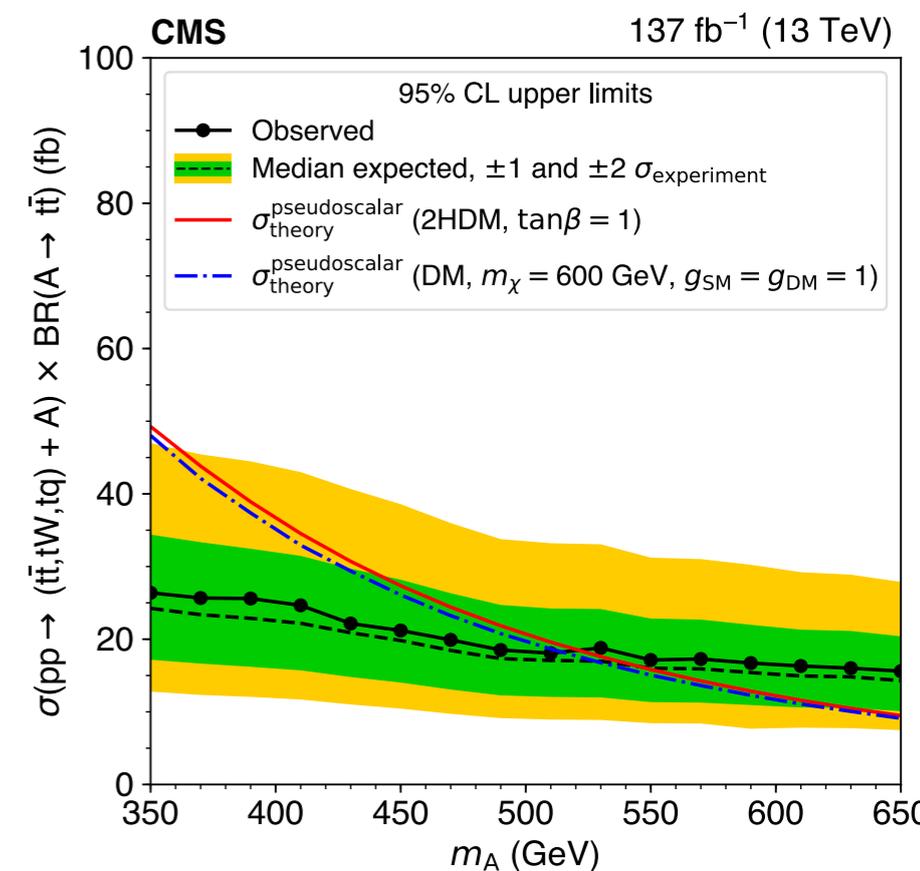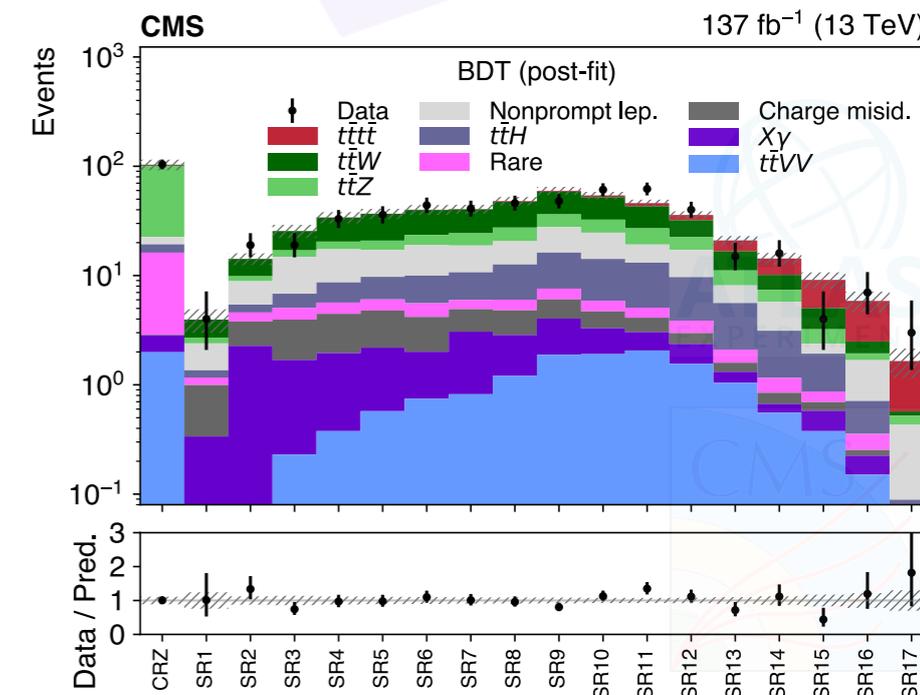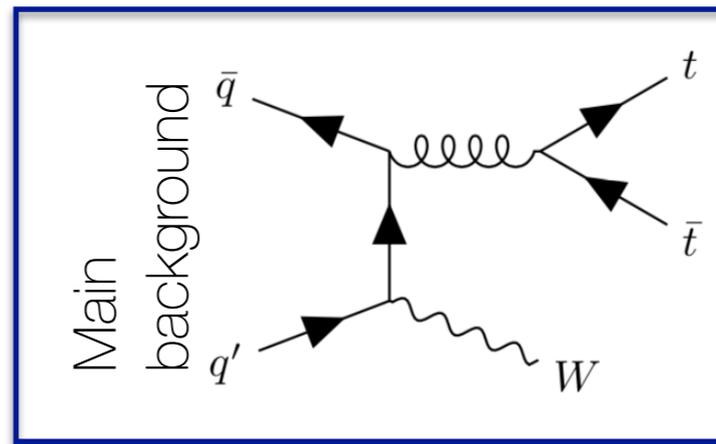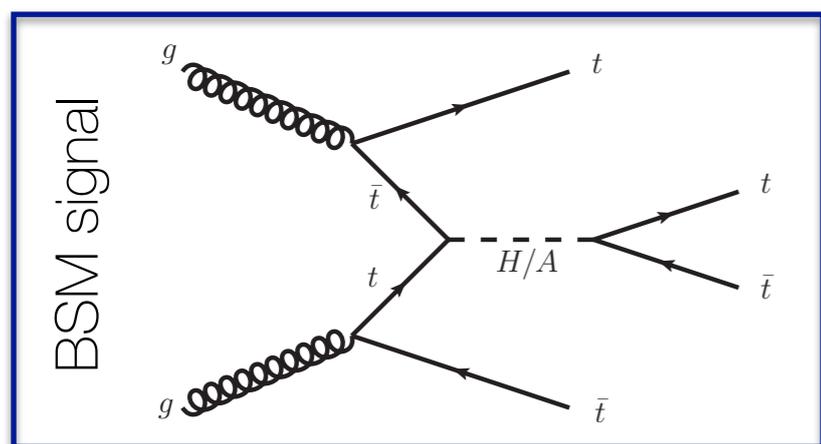
Main background



- Most prominent channel to probe low tanβ 2HDM scenarios

- Spin-off of other searches (SM 4top quark in CMS, VLQ in ATLAS)

- Multi-region search using a BDT, ttW is the main background

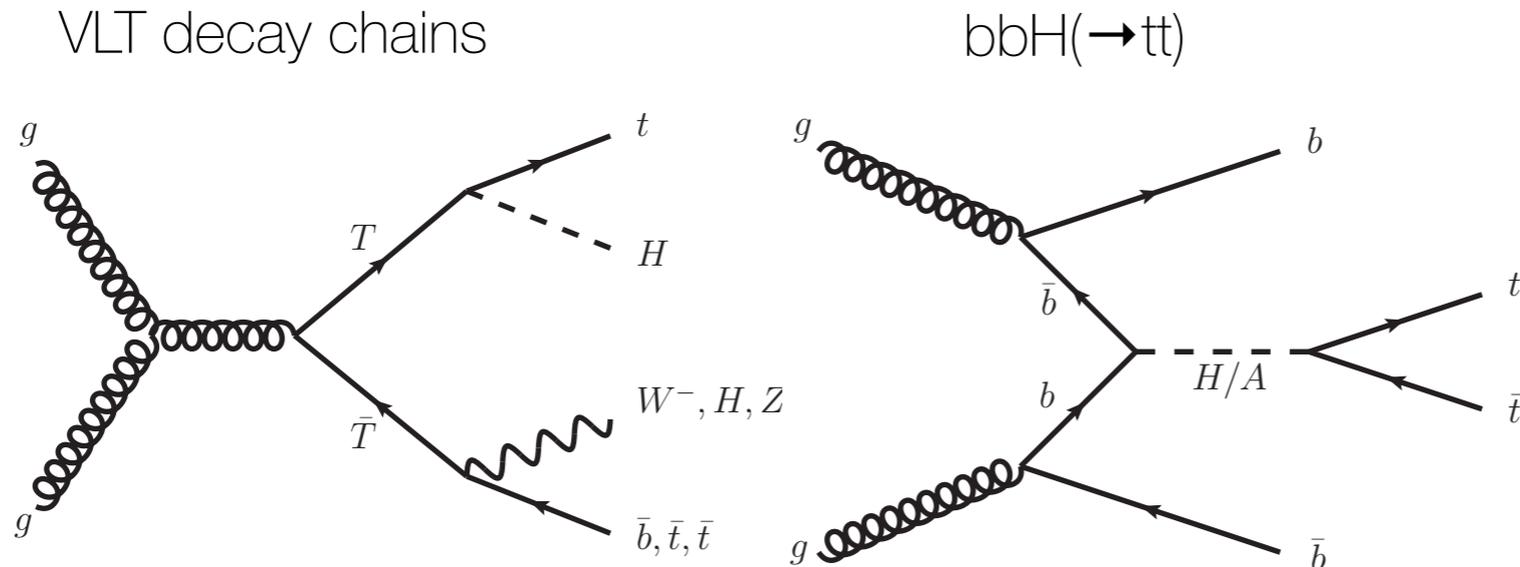- **Growing interest driven by 4tops excess observed in ATLAS**

ATLAS JHEP 12 (2018) 039
CMS Eur. Phys. J. C 80 (2020) 75

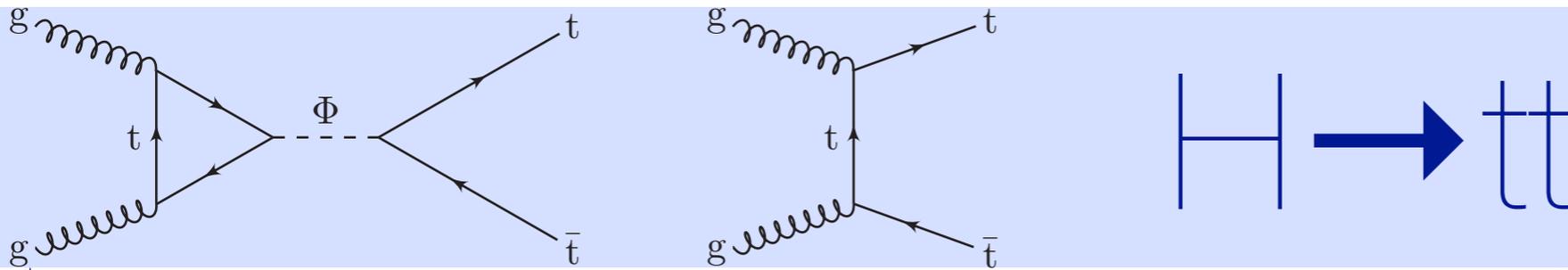# Neutral Higgs, associated production

VLT decay chains



bbH(→tt)



- Production of top-quarks in association with heavy flavour → very rich signature

- **BSM Higgs processes with a neutral Higgs are not covered in a satisfactory way**

- VLQs with BSM Higgs bosons in their decay chains to be explored

- Target performance is **not a mirage**

$H \rightarrow t\bar{t}$
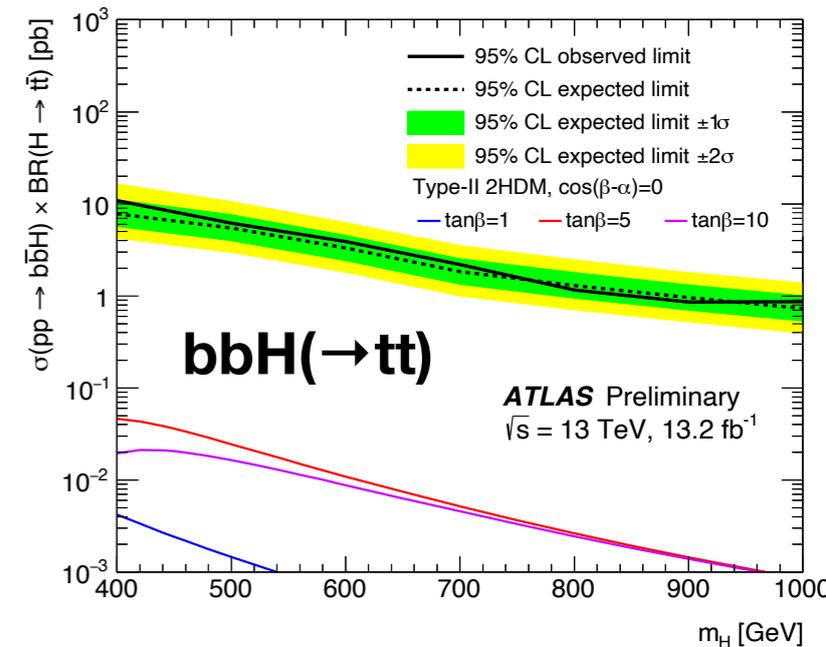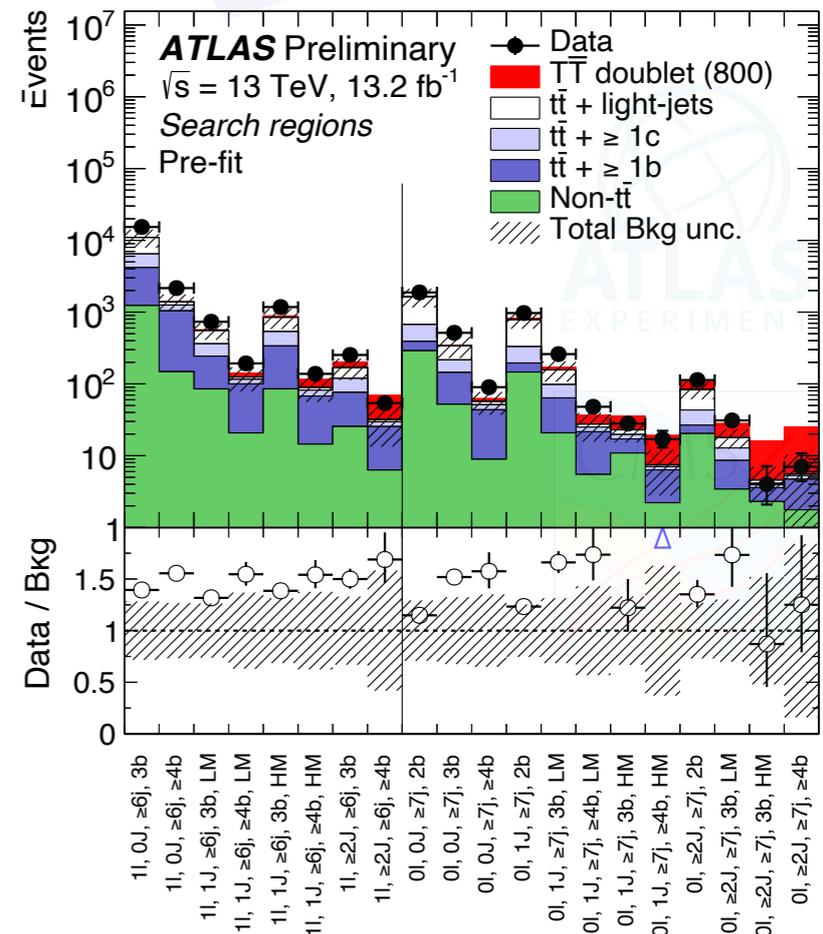
- Search for inclusive H→tt, main challenge: **signal and background interference**

  - Size and sign of the interference depends on details of considered BSM models

  - Can be parametrised as a function of coupling strength and H width

- Complex analysis of the top-quark pair invariant mass spectrum as a function of angular correlations

  - **Sensitive to CP quantum numbers** of the signal

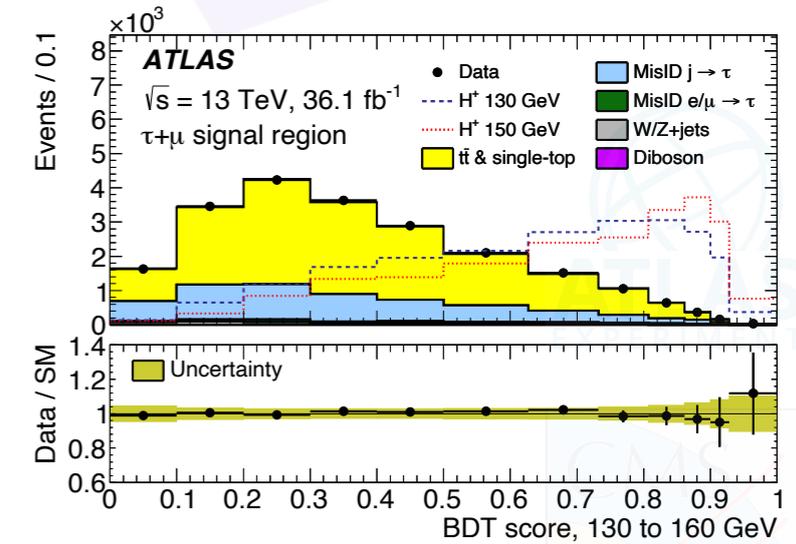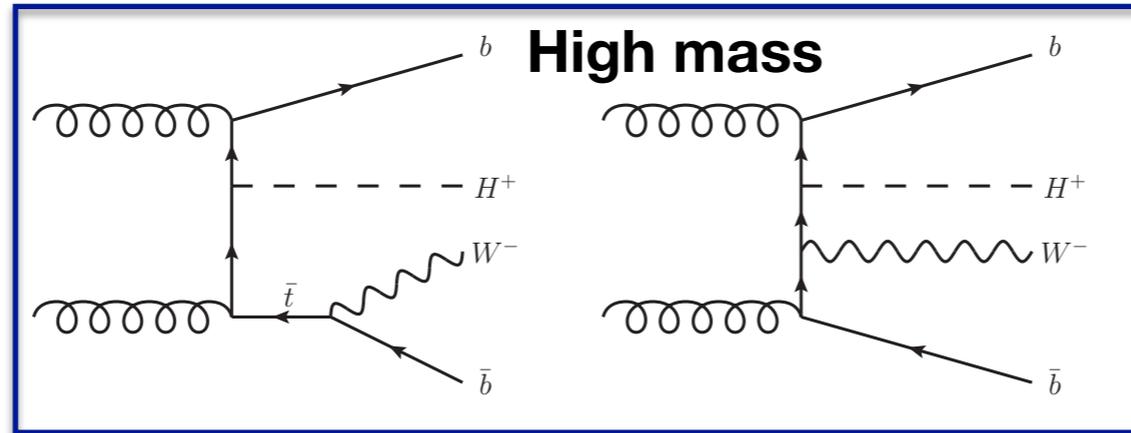- **Deviation from SM prediction at low mass (400 GeV), with global (local) significance of 1.9σ (3.5σ)**
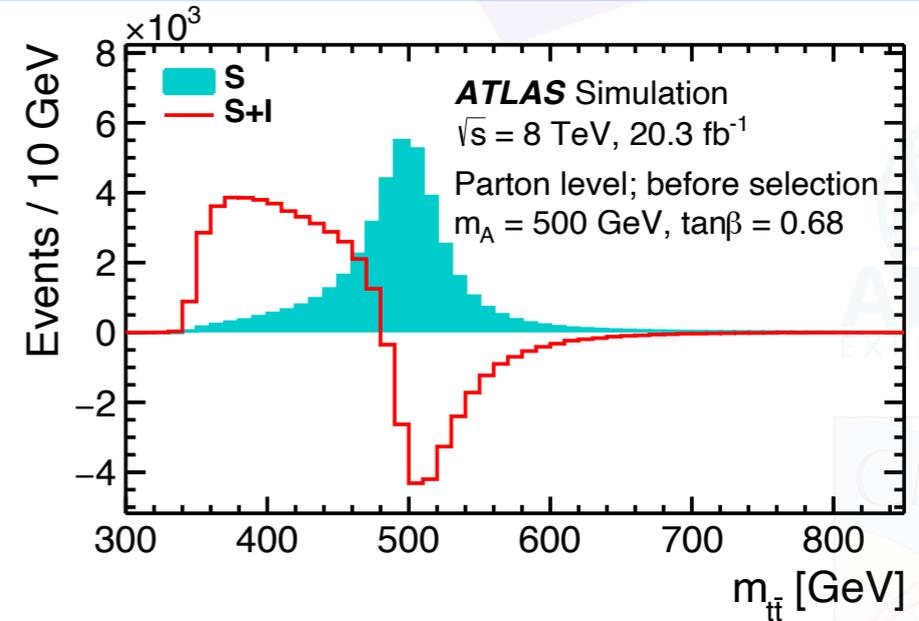
# H⁺ → τν
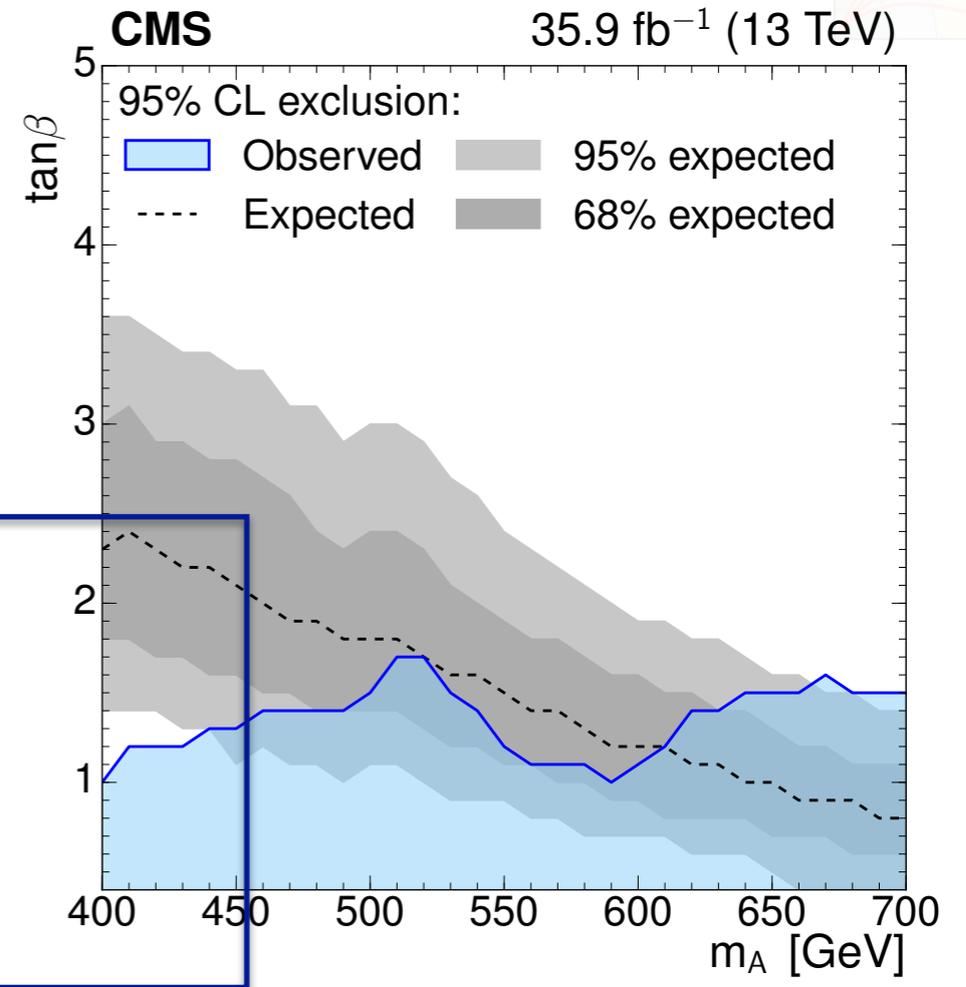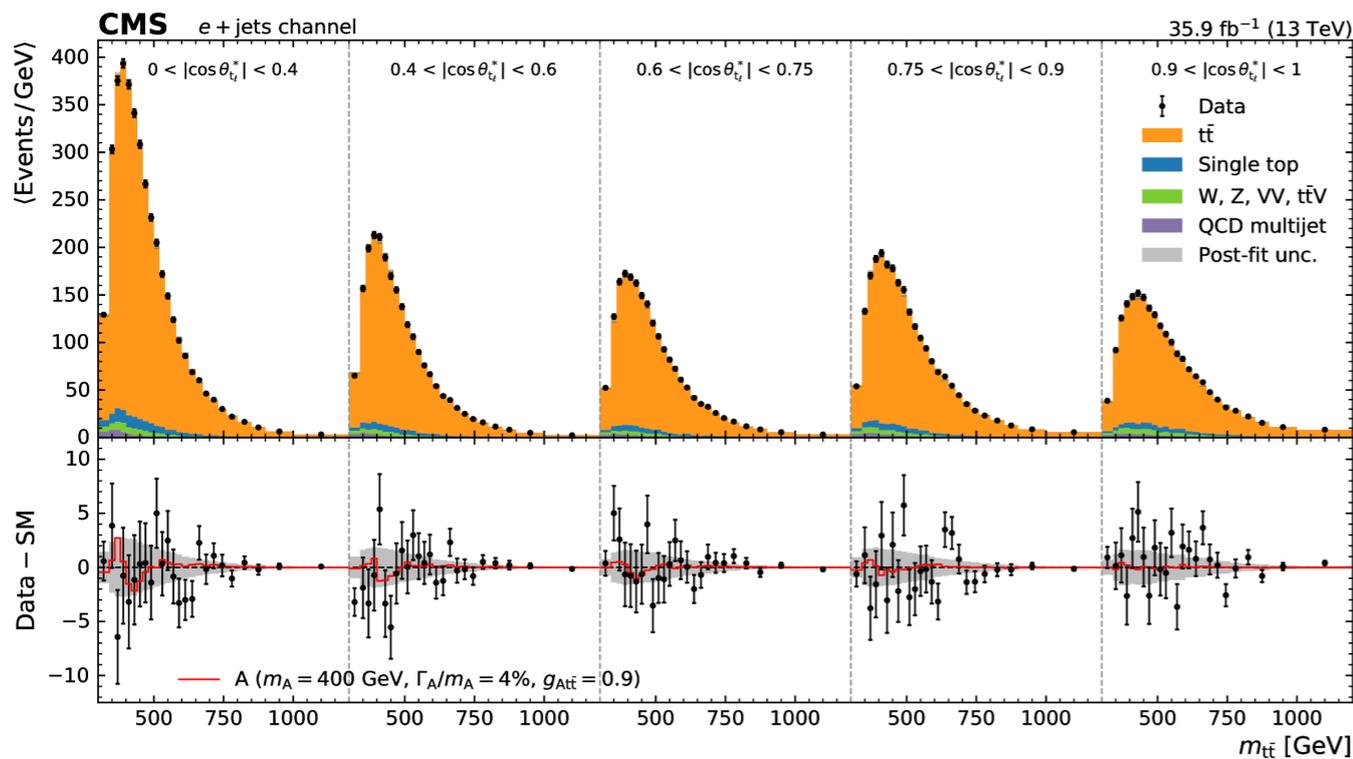
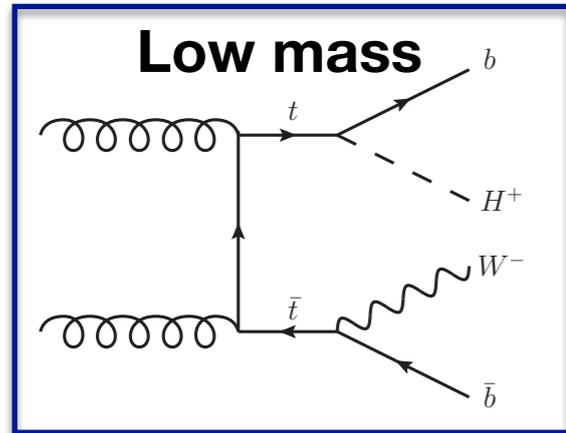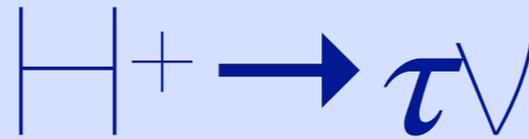**Low mass**

**High mass**



ATLAS [JHEP 09 (2018) 139](#)
CMS [JHEP 07 (2019) 142](#)

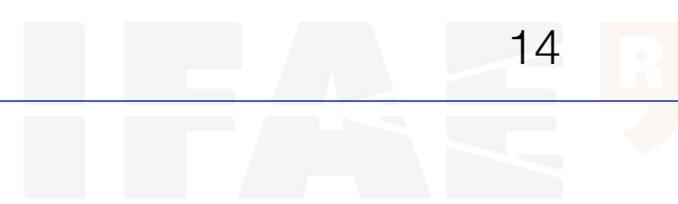- **Simultaneous search for high mass and low mass charged Higgs in the H⁺→τν channel**

  - ATLAS uses a BDT, CMS transverse mass

- Covers associated production with top-quarks and production from top-quark decays

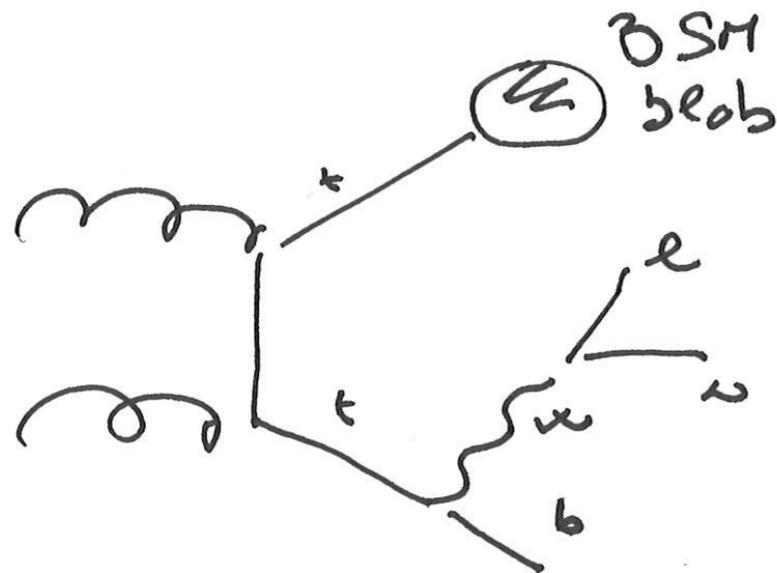- **No excess above SM background prediction**
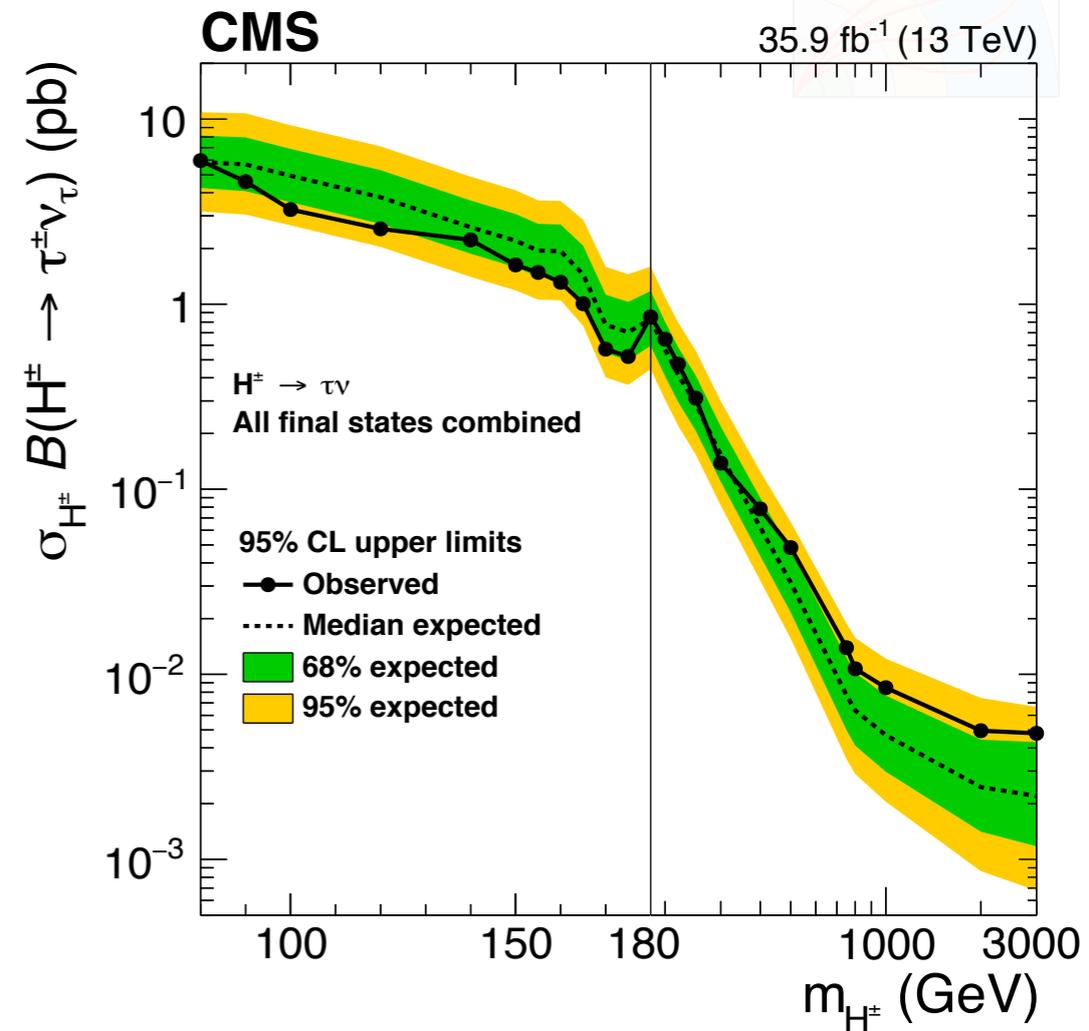
Higgs potential and BSM opportunity | 27-31 August 2021, Nanjing (China) + online

# Top quark decays mediated by BSM interactions

# Introduction

**Charged Higgs boson**

$H^+ \rightarrow cb$

$H^+ \rightarrow cs$

$H^+ \rightarrow \tau \nu$

**Anomalous top-quark decays (flavour violating)**

$t \rightarrow qH$ (q=c, u)

- Top-quark pair production is a **prime source for light degrees of freedom** coupling to the top quark

  - Tremendous amount of SM background and poor signal-to-background separation

  - Yet strong discovery potential

- **Not only source of charged Higgs bosons** !

- **Low mass is still viable? → Yes !** e.g. constraints can be evaded in the Higgs sector is richer than what available in models with two Higgs doubles

# BSM with SM: top-Higgs FCNC couplings

Standard Model
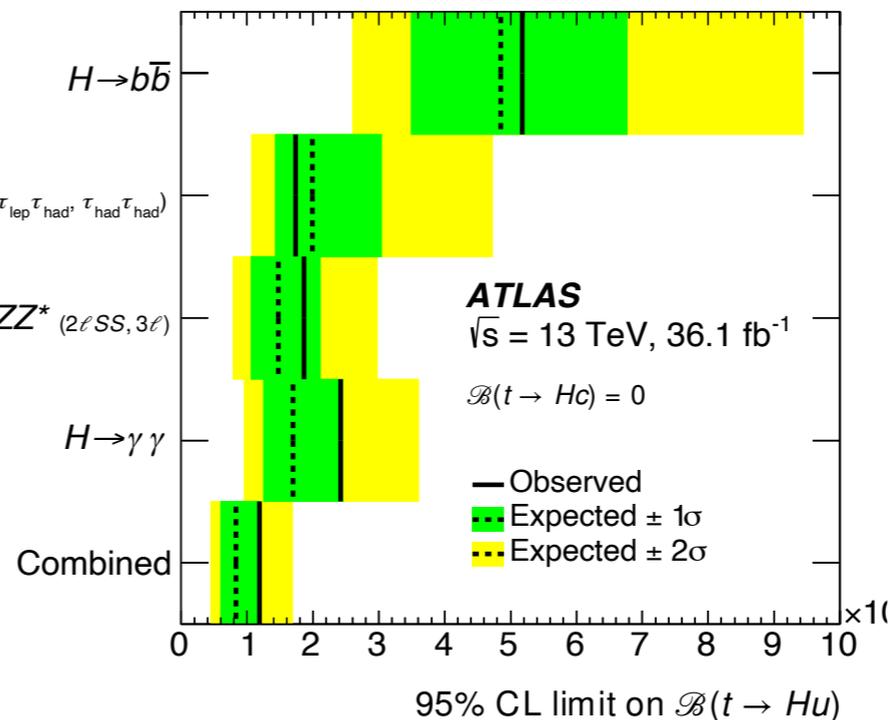
Beyond Standard Model (examples)
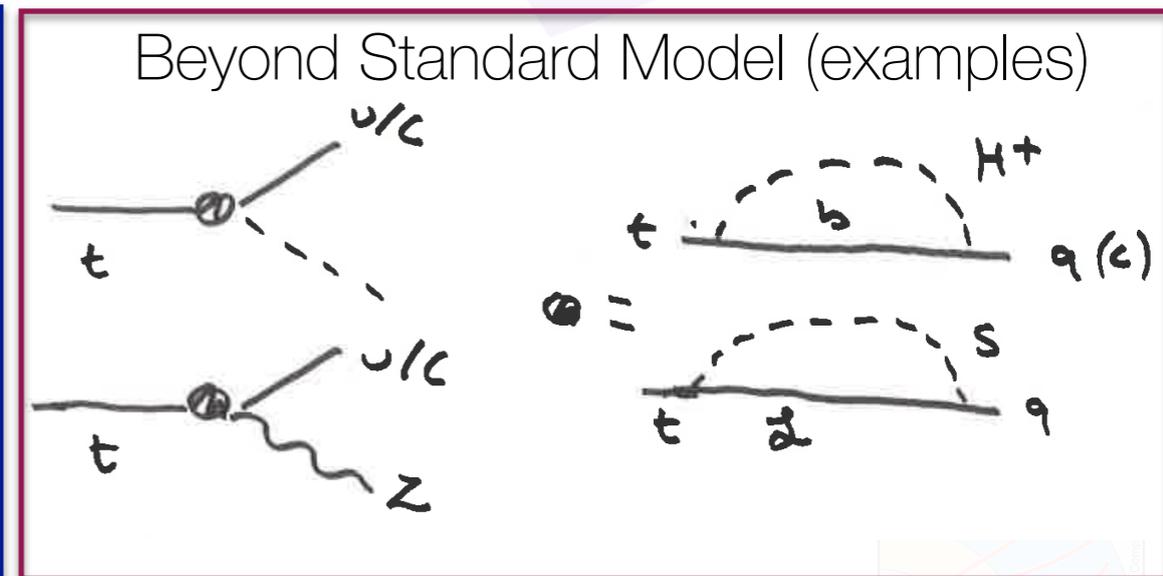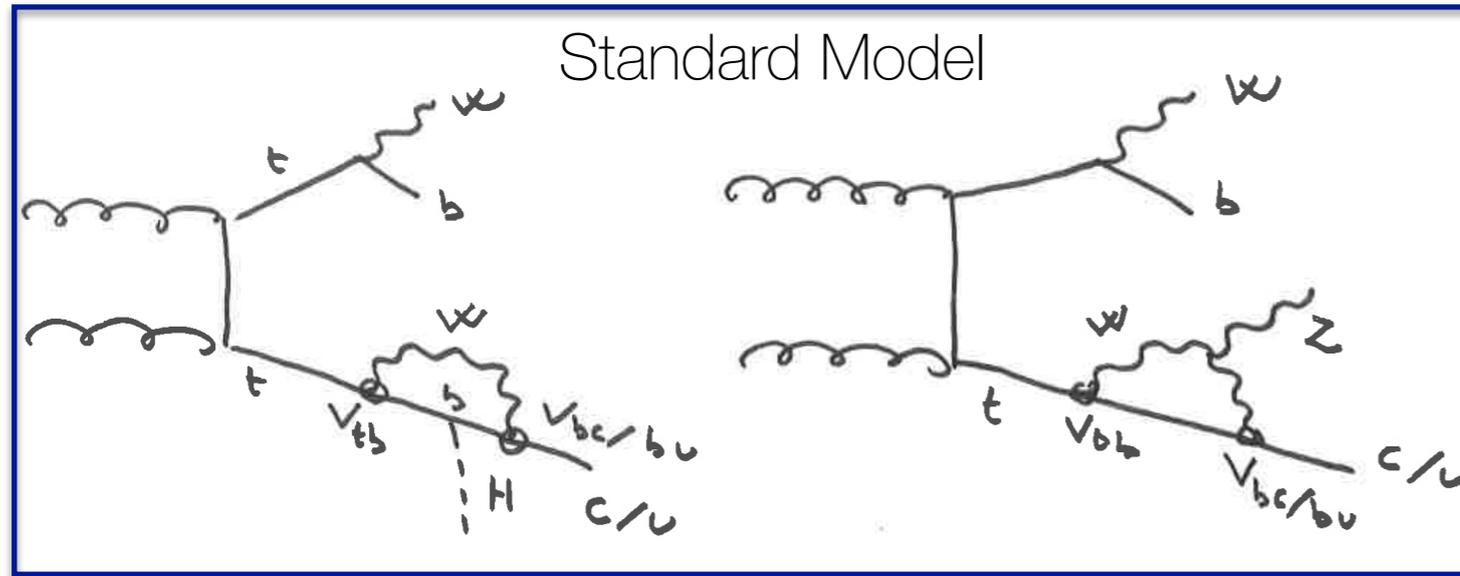
- Search for flavour violating decays of the top into a Higgs boson and a quark → **Sensitive to a wide set of BSM scenarios**
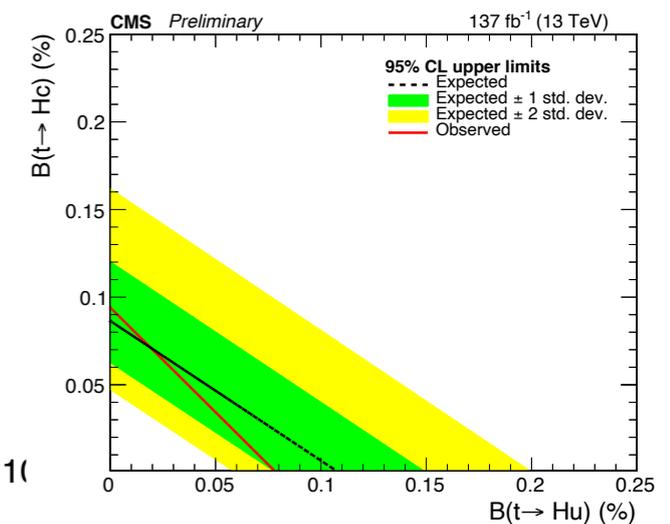
  - Very complex searches exploiting multiple Higgs boson decay channels

- Analyses start to approach per-mille level branching fraction → **Just starting to probe expected BSM branching fraction !**
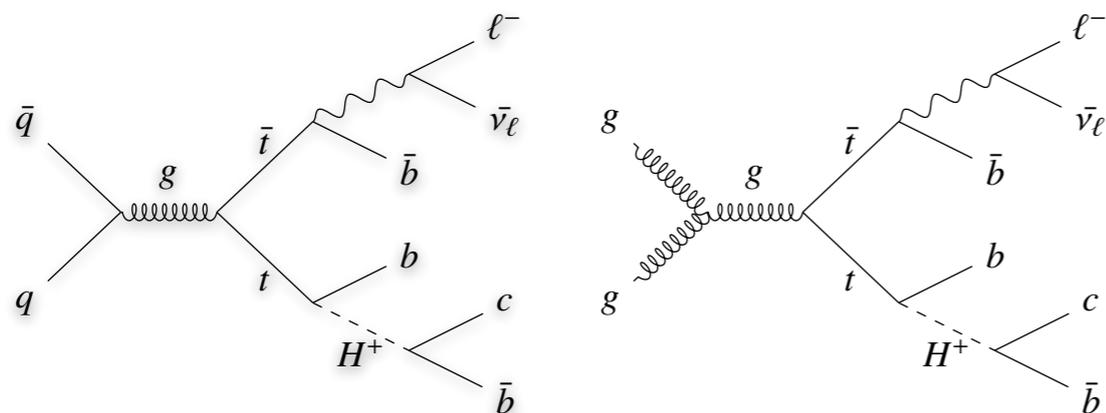
ATLAS combination



$H \rightarrow b\bar{b}$

$H \rightarrow \tau\tau$ ($\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$)

$H \rightarrow WW^*, \tau\tau, ZZ^*$ ($2\ell SS, 3\ell$)

$H \rightarrow \gamma\gamma$

Combined

**ATLAS**
$\sqrt{s}$ = 13 TeV, 36.1 fb$^{-1}$

$\mathcal{B}(t \rightarrow Hc) = 0$

— Observed
Expected ± 1σ
Expected ± 2σ

95% CL limit on $\mathcal{B}(t \rightarrow Hu)$

$H \rightarrow bb$, **5 times better exclusion**



**CMS** *Preliminary* 137 fb$^{-1}$ (13 TeV)

**95% CL upper limits**
Expected
Expected ± 1 std. dev.
Expected ± 2 std. dev.
Observed

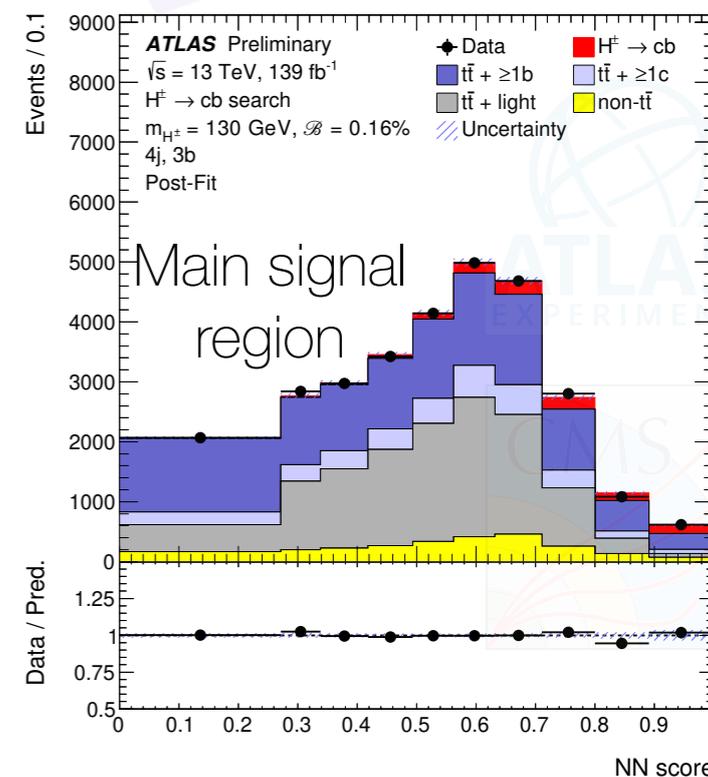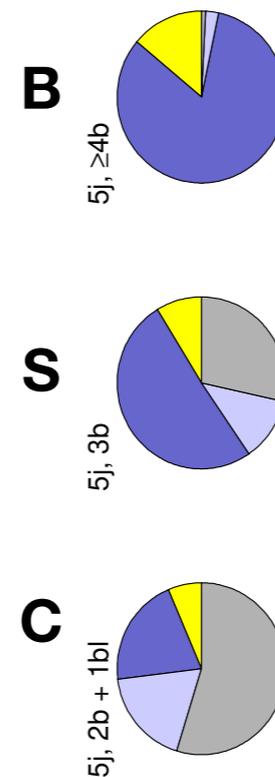ATLAS JHEP 05 (2019) 123
CMS CMS-PAS-TOP-19-002

# Light charged Higgs boson

ATLAS-CONF-2021-037



B= background rich
S= signal region
C= background correction

- Search using categories with at least three b-jets and four jets

- Using a neural network classifier for signal extraction

- Background modelling improved with **data-based corrections** derived in loose analysis regions

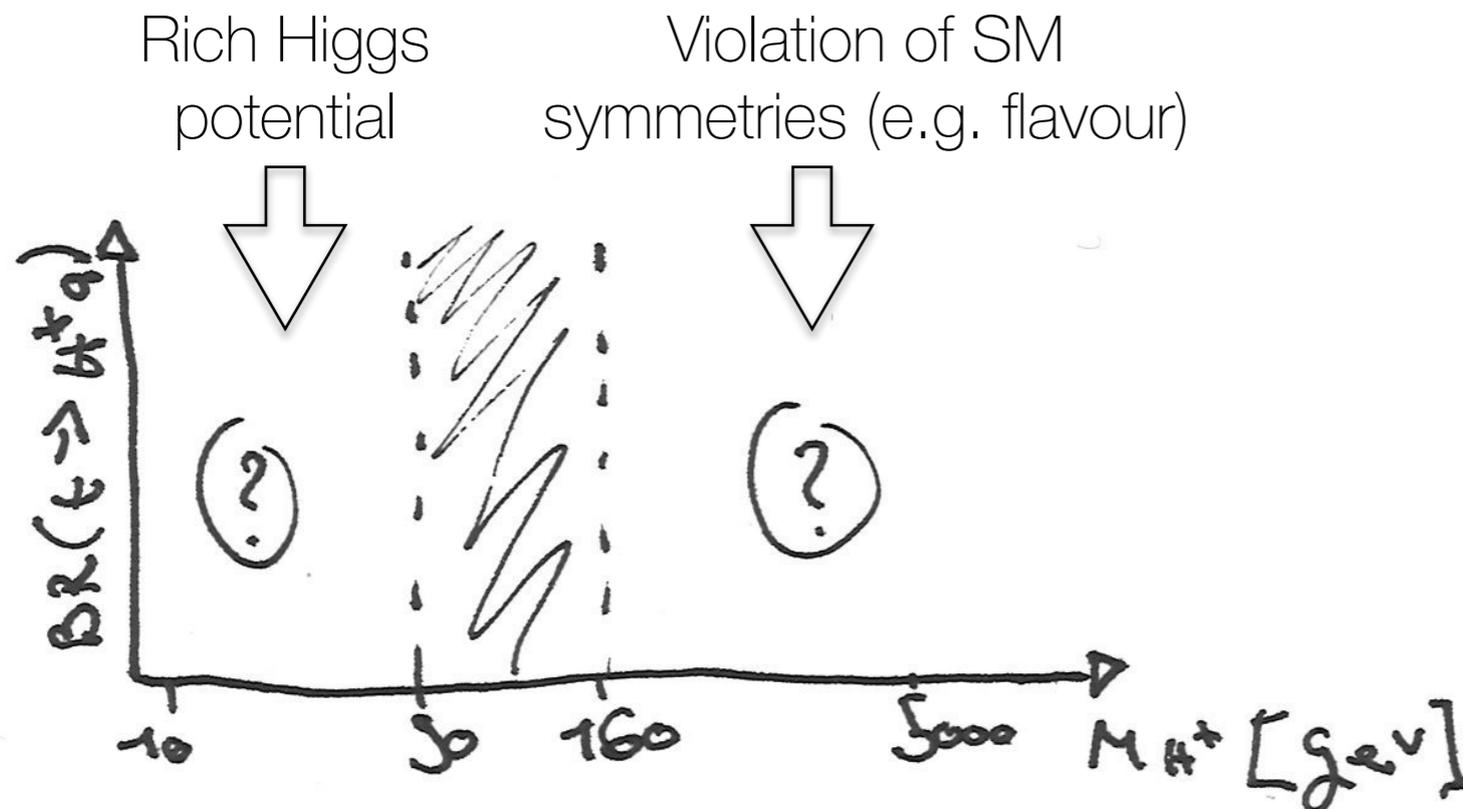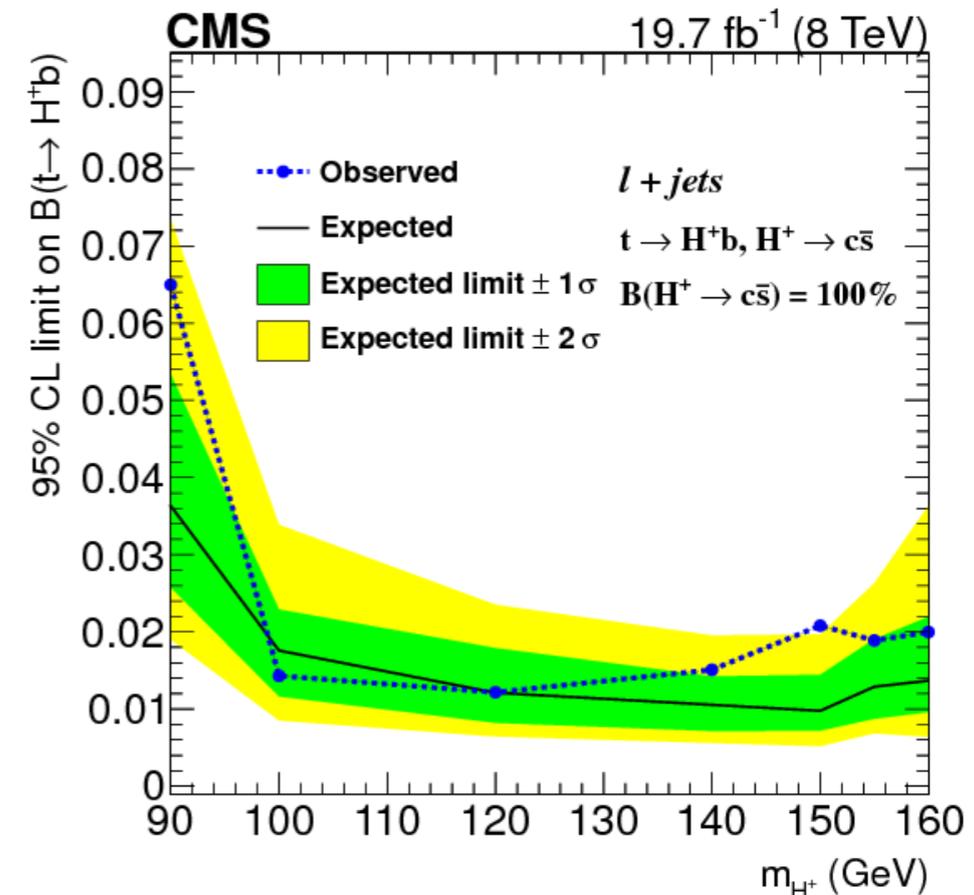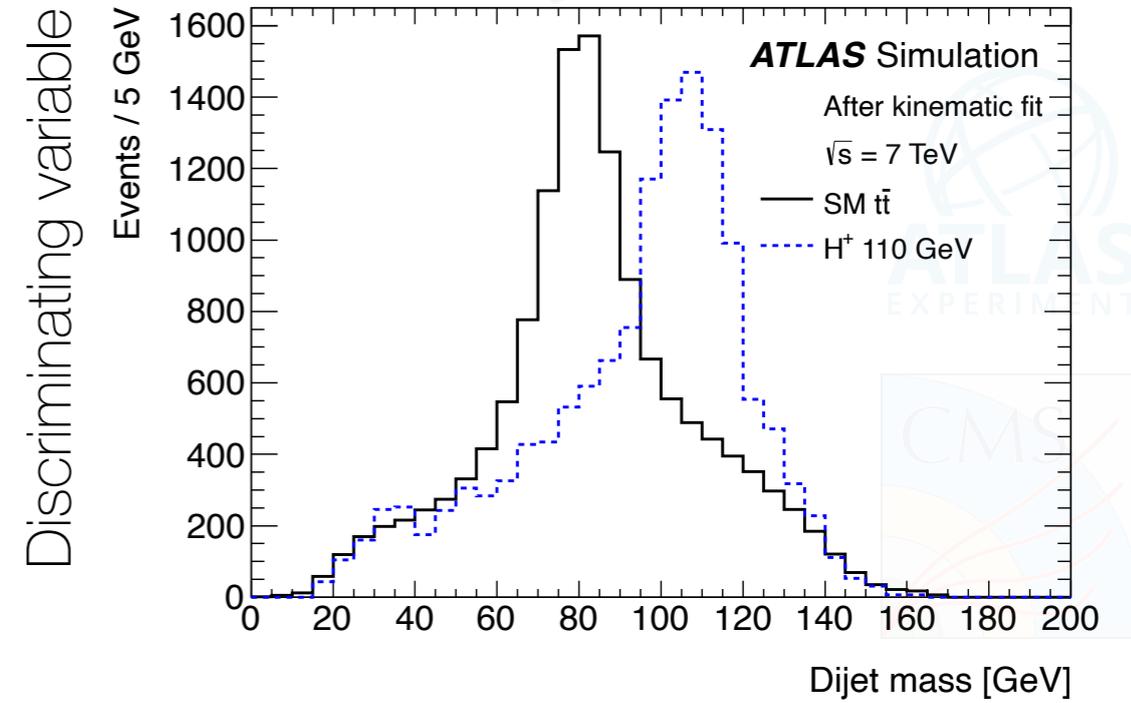- Data marginally consistent with background expectation

- **Excess of events with a global (local) significance of 2σ (3σ)**

  - Consistent with the expected mass resolution
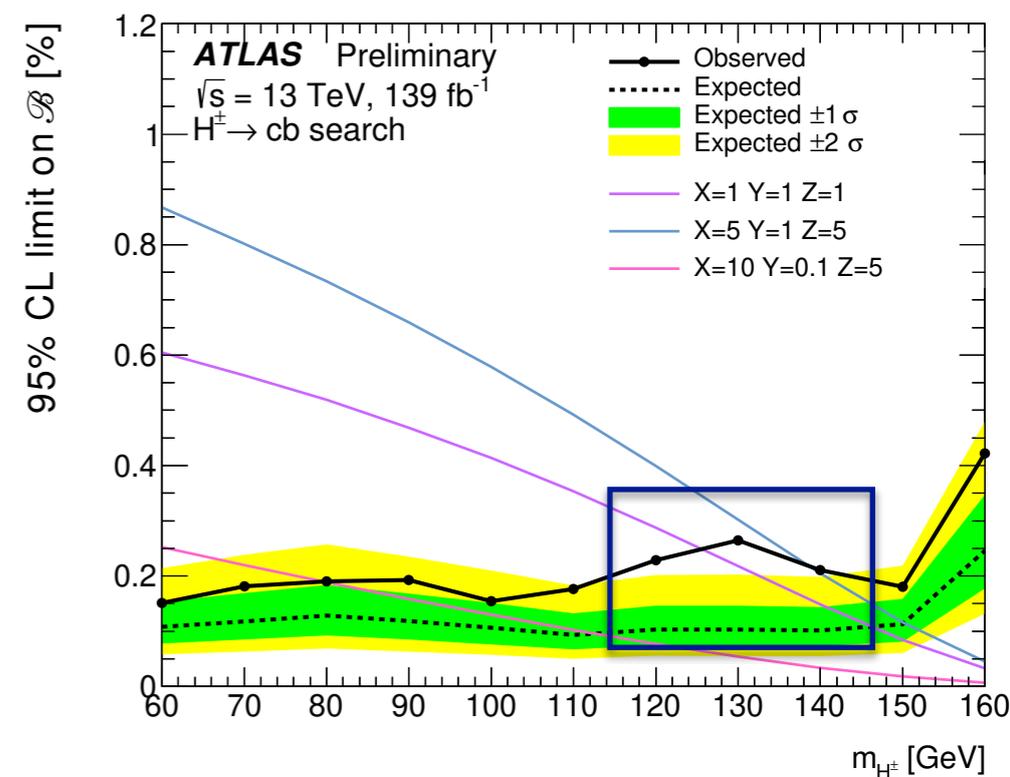
# Forgotten channel: H⁺ ➙ cs

- Two searches for H⁺→cs performed at LHC by ATLAS and CMS

  - Based on small datasets from Run 1

- **Just starting to probe percent-level BSM top branching ratio**

  - Analyses with a limited level of sophistication

    - Signal extraction based on a fit to di-jet invariant mass

Rich Higgs potential

Violation of SM symmetries (e.g. flavour)

**Higgs potential and BSM opportunity** | *27-31 August 2021, Nanjing (China) + online*
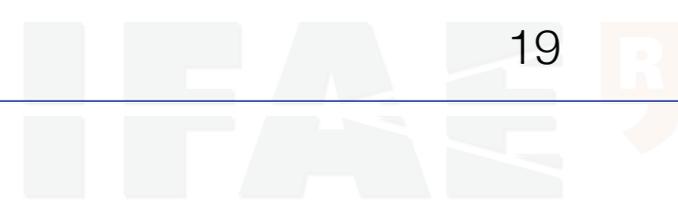
# Summary

# MSSM interpretation

July 2021

$\tan \beta$

$m_A$ [GeV]

**ATLAS** Preliminary
hMSSM, 95% CL limits
Run 2, $\sqrt{s}$ = 13 TeV
— Observed
-- - Expected

gg/bb H/A, H/A → ττ
139 fb⁻¹
Phys. Rev. Lett. 125 (2020) 051801

t(b) H⁺, H⁺ → τν, 36.1 fb⁻¹
JHEP 09 (2018) 139

b(b) H/A, H/A → bb
27.8 fb⁻¹
Phys. Rev. D 102 (2020) 032004

H → ZZ → 4l/llνν, 36.1 fb⁻¹
Eur. Phys. J. C 78 (2018) 293

A → Zh, 36.1 fb⁻¹
JHEP 03 (2018) 174

t(b) H⁺, H⁺ → tb, 139 fb⁻¹
JHEP 06 (2021) 145

H → WW → lνlν, 36.1 fb⁻¹
Eur. Phys. J. C 78 (2018) 24

H → hh → 4b/bbγγ/bbττ
27.5 - 36.1 fb⁻¹
Phys. Lett. B 800 (2020) 135103

h couplings [$\kappa_V$, $\kappa_u$, $\kappa_d$]
36.1 - 79.8 fb⁻¹
Phys. Rev. D 101 (2020) 012002

ATL-PHYS-PUB-2021-030
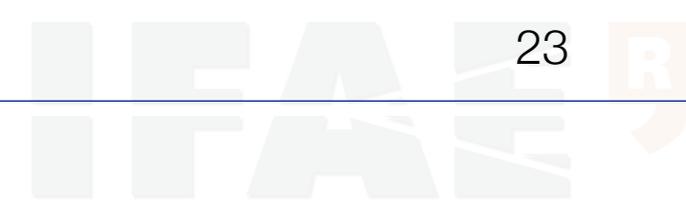
# BSM Higgs and Dark Matter
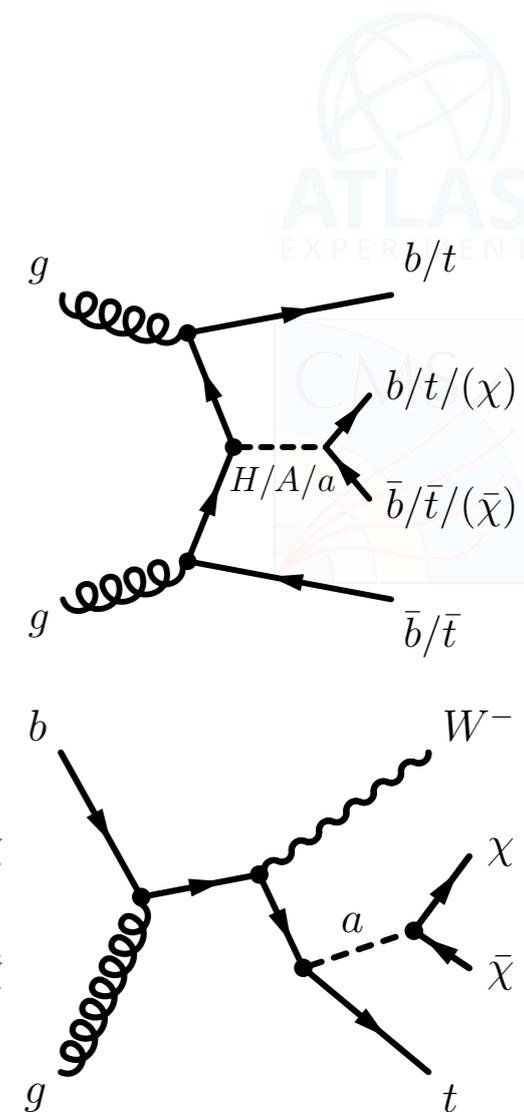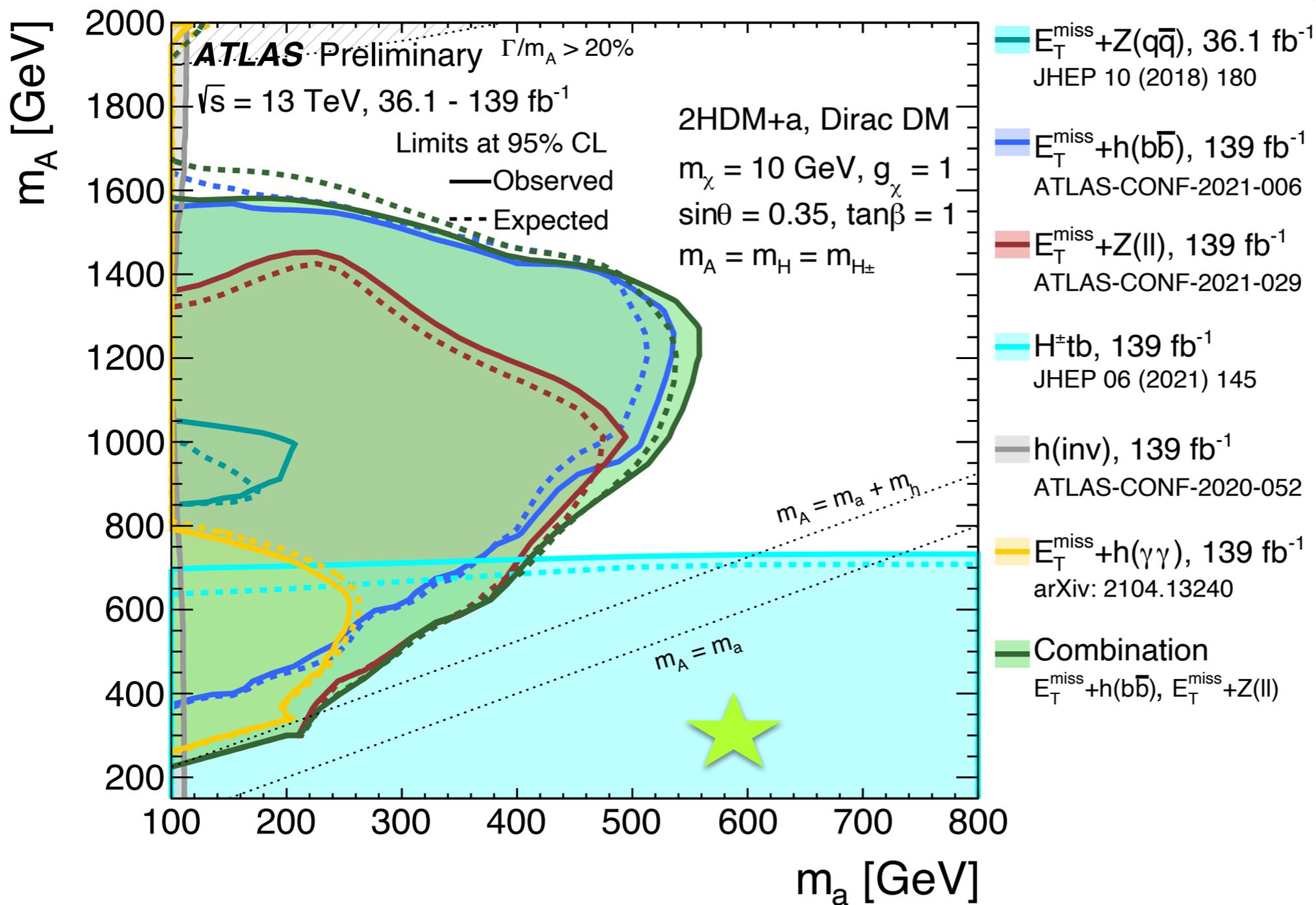


**Direct constraints on DM mediators or indirect from searches of other BSM particles**
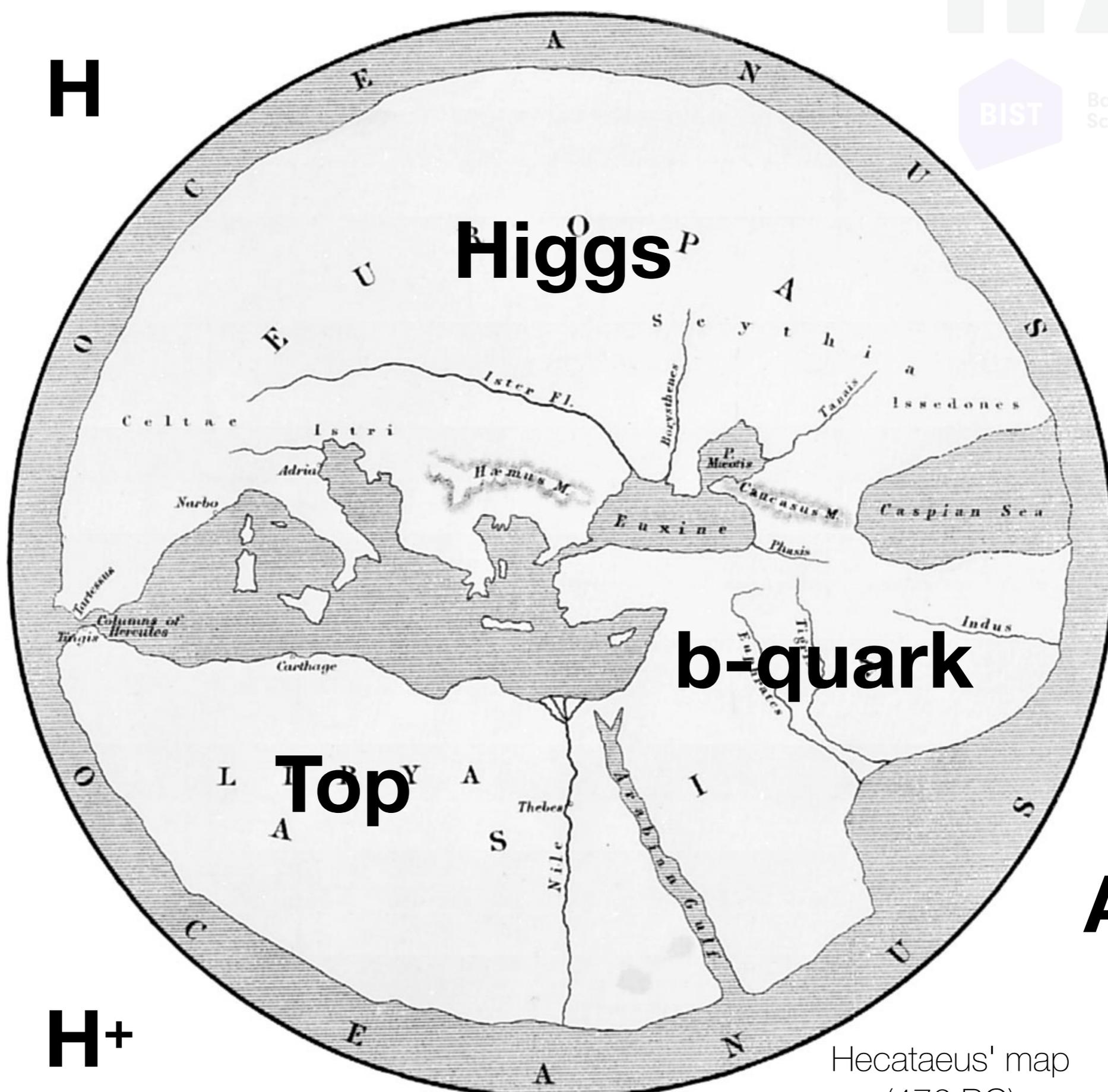
# Conclusions

- Searches for heavy Higgs bosons coupling to top quarks are really just at the beginning

  - Large amount of signatures are yet to be probed

    - Very limited scope searches considered (e.g. assuming flavour conservation)

- Searches for light BSM Higgs bosons coupling to top quarks are equally (un-)probed and compelling

- Each search (even with unsuccessful discovery) has a deep consequence on our way of seen our universe

  - DM constraints, richer Higgs sectors, ..

H

H

H

Higgs

b-quark

Top

H+

H+

H+

A     A

A

Hecataeus' map
(476 BC)