

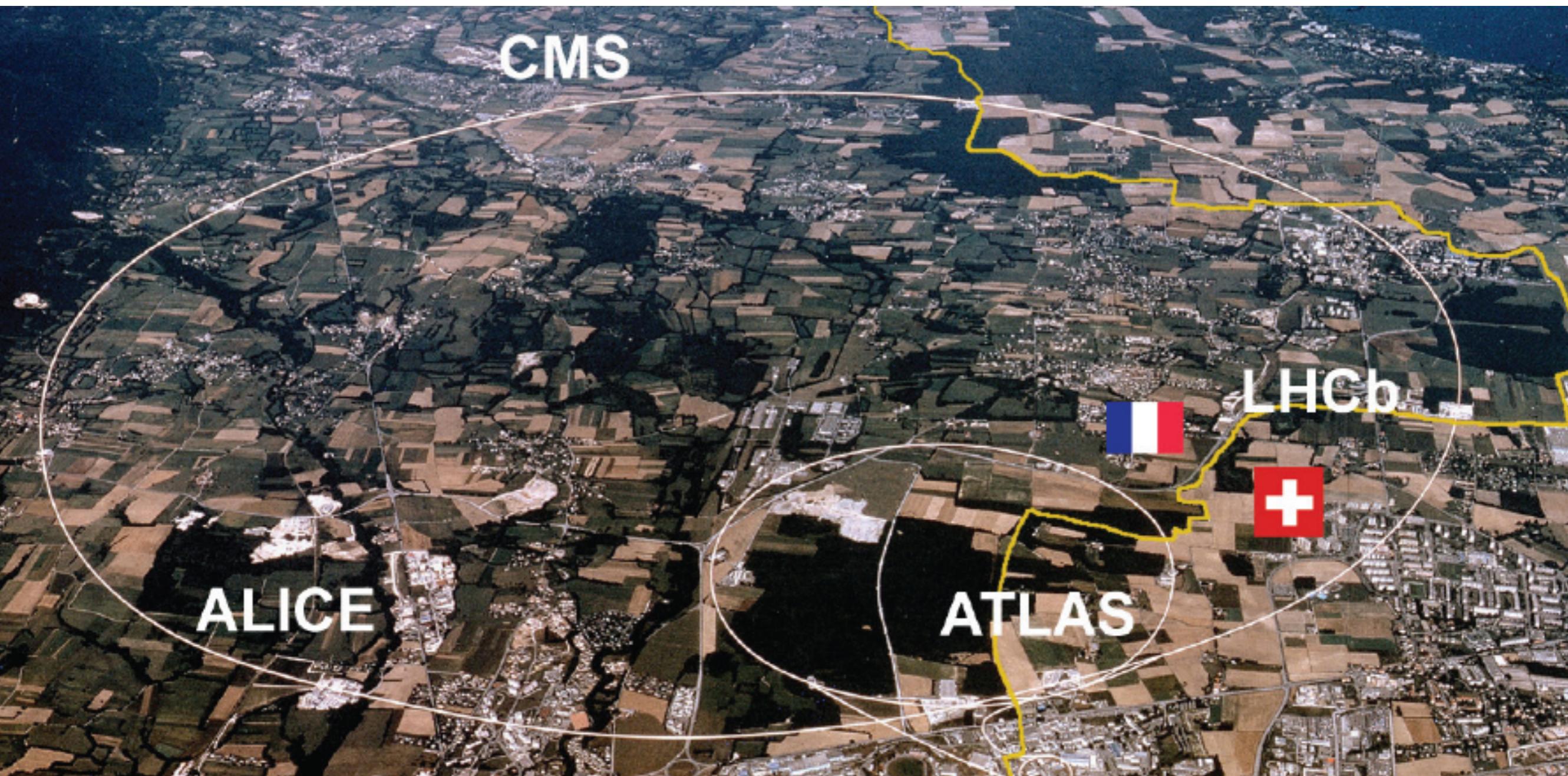
H^+ searches at LHC

Geum Bong Yu
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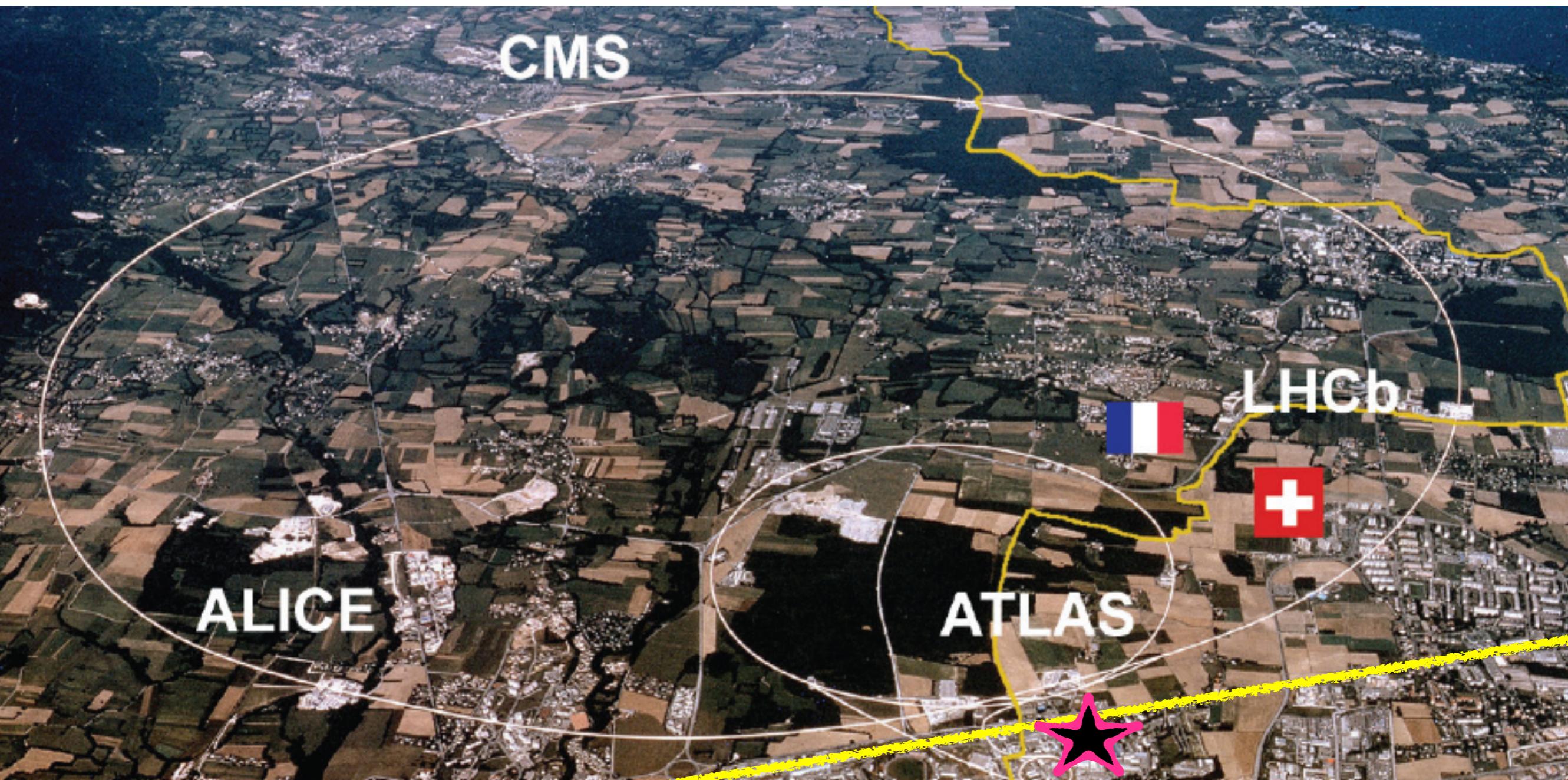
Intro.. to the H^+ searches

- May not need to introduce theory basis of the extended Higgs sector here
- Trends ever since the discovery of the H boson at a mass of 125.09 GeV are:
 - BSM searches get more active (boom! in exotica group)
 - H^+ gets more attention than before judging by the number of people involved in the analysis
 - So far no strong anomalies/excess/deficit observed either from CMS or ATLAS (except LHCb in LFU)
 - May keep looking for anomalies like the recent ATLAS $t\bar{t}$ spin-correlation
 - Keep searching for new particles in different point of view: trying to find in various channels with alternative models

Large Hadron Collider



Large Hadron Collider



Route de Meyrin
Tram 18

gate B to
CERN Meyrin site

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
T2AU iron

SILICON TRACKERS
Zsol (190x30 μm) - 1 m^2 - 604 channels
Microstrip (8x380 μm) - 200 m^2 - 9,604 channels

SUPERCONDUCTING SLENOID
Nickel-titanium coil carrying ~18,000A

MUON CHAMBERS
Base: 250 Drift Tube, 480 Resistive Plate Chambers
Endcap: 458 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16 m^2 = 157,000 channels

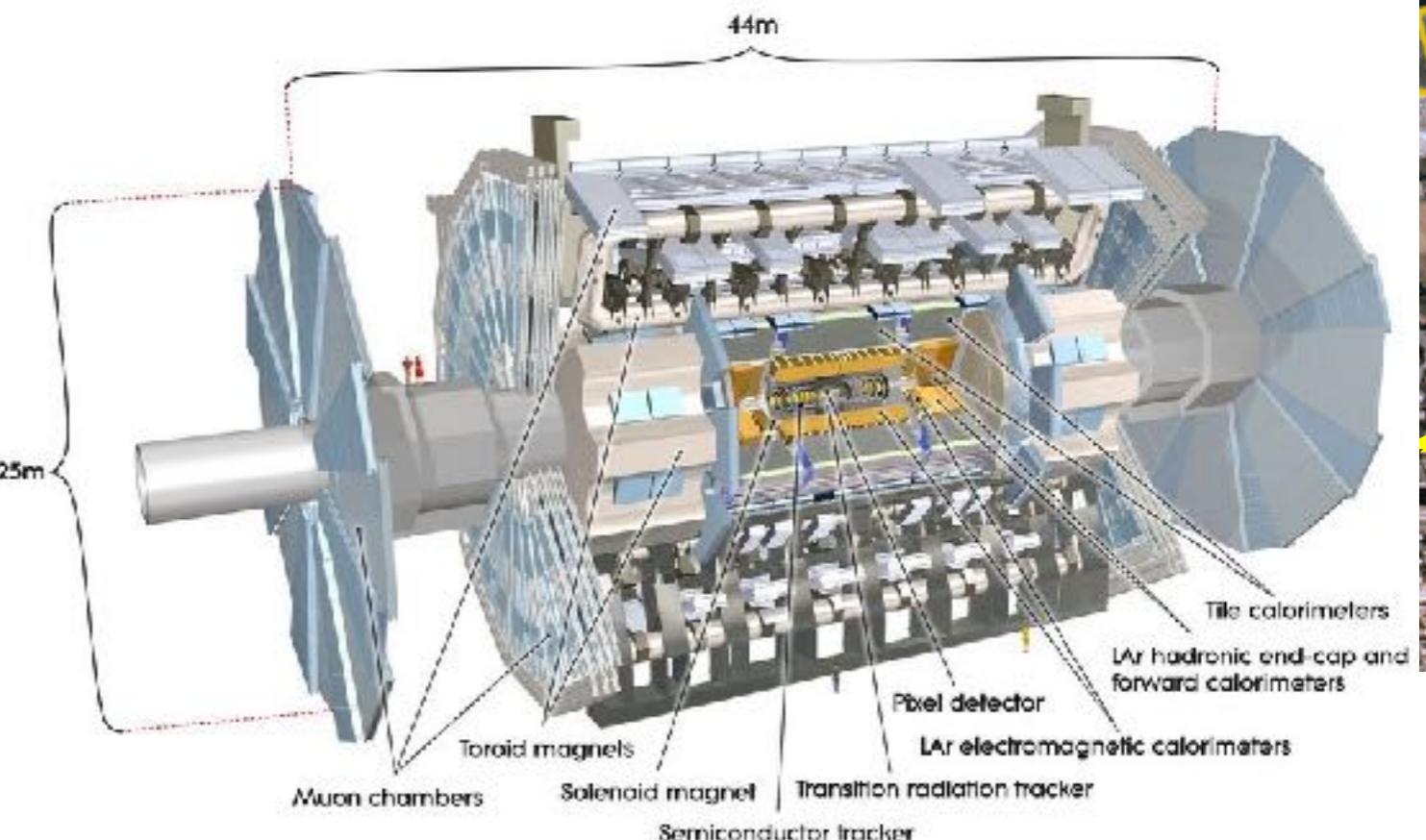
CALORIMETERS
Lead + Quartz Glass < 100 GeV

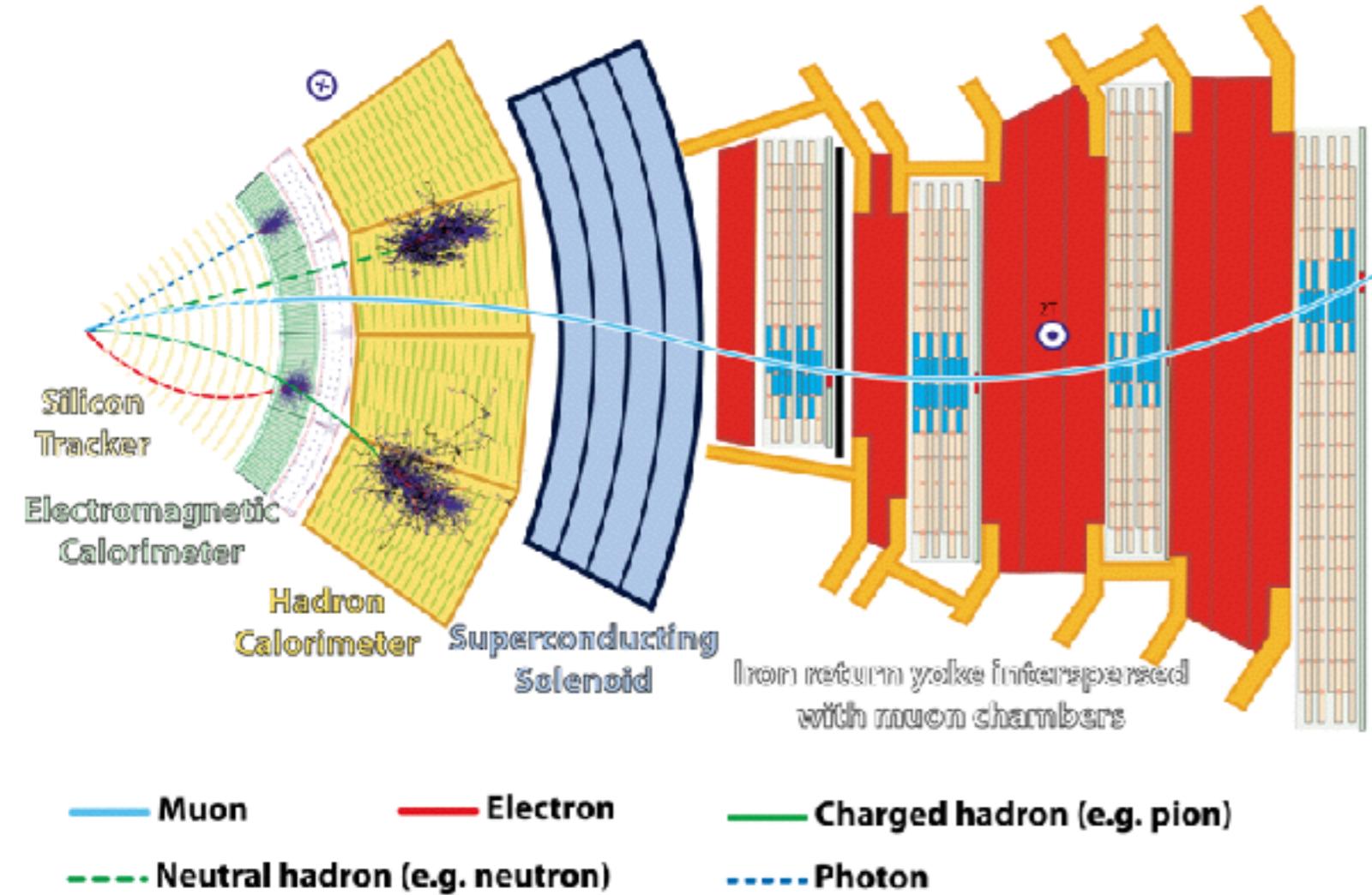
CRYSTAL
ELECTRON AGGREGATE
CALORIMETER
- 20,000 crystal elements
- 100 GeV resolution

LIQUID ARGON CALORIMETER
- 100 GeV resolution, < 10% energy loss

HELIUM CRYOGENIC SYSTEM

ALICE

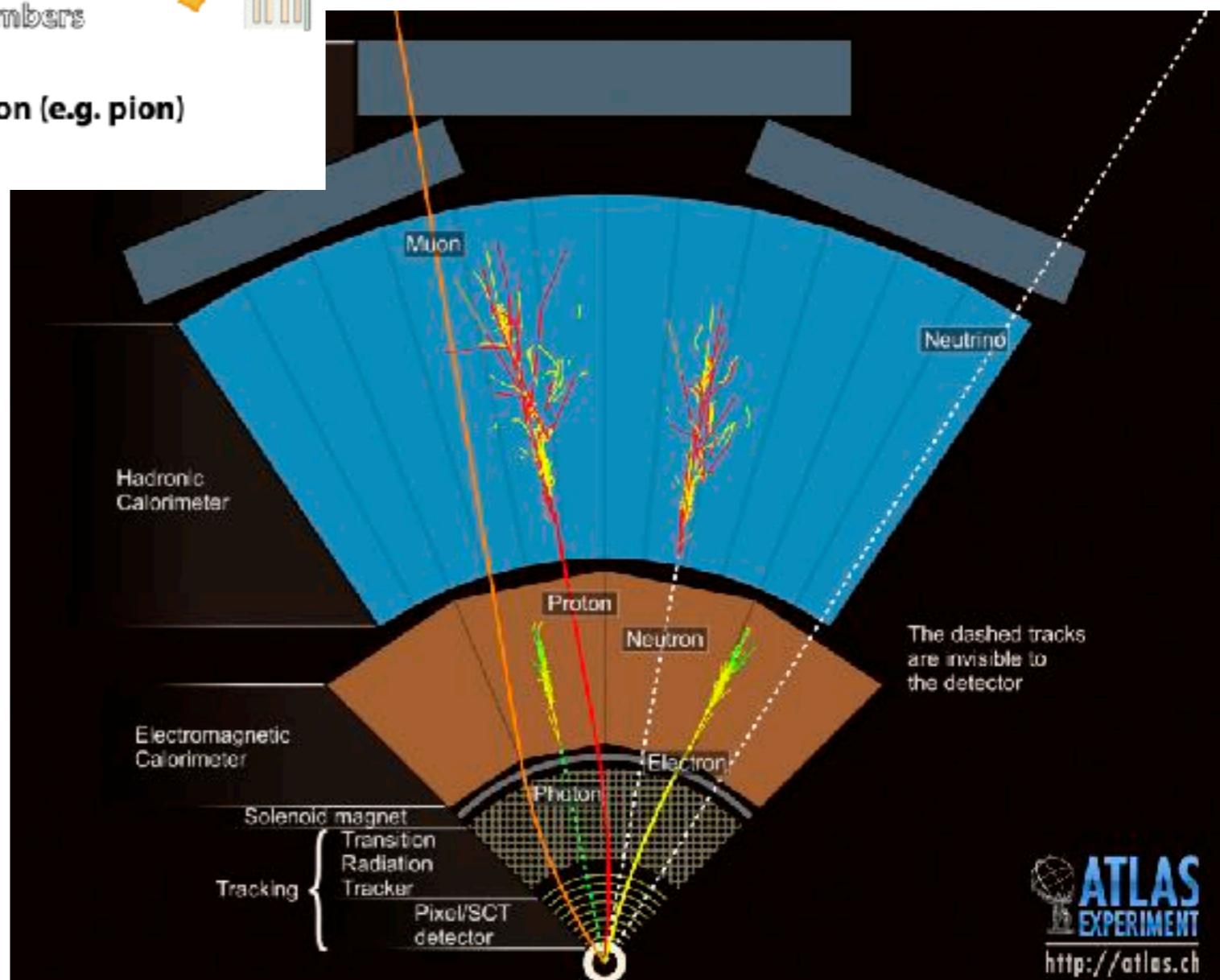




CMS vs ATLAS Detector Characteristics

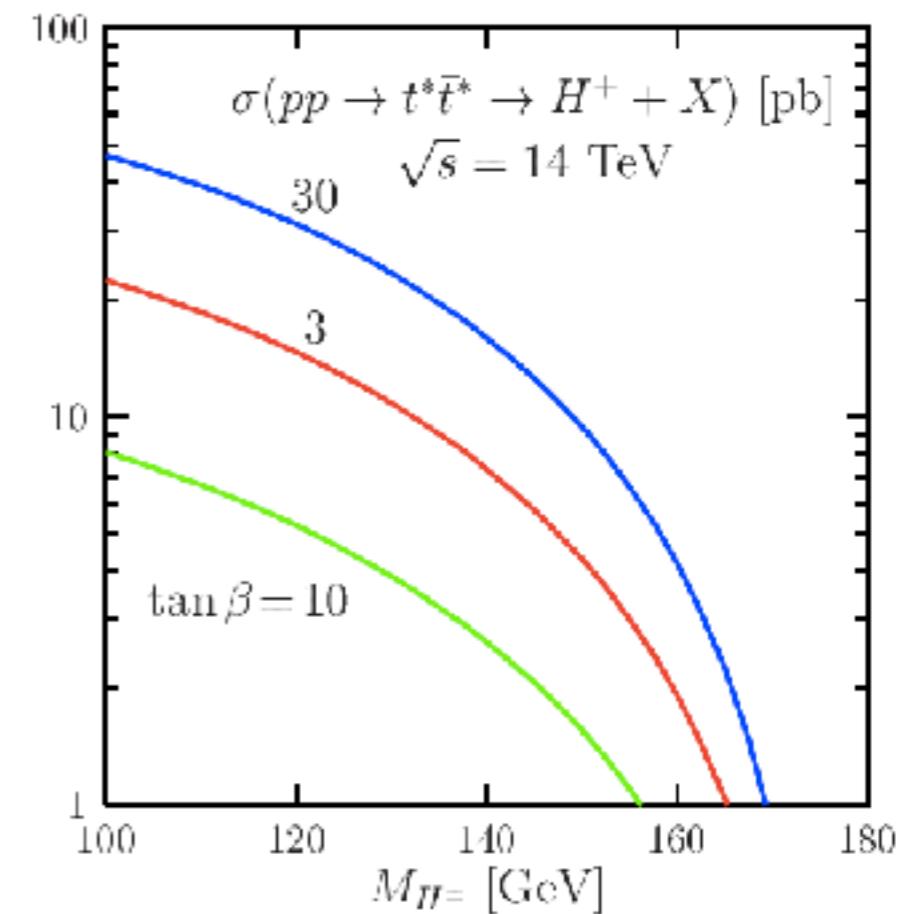
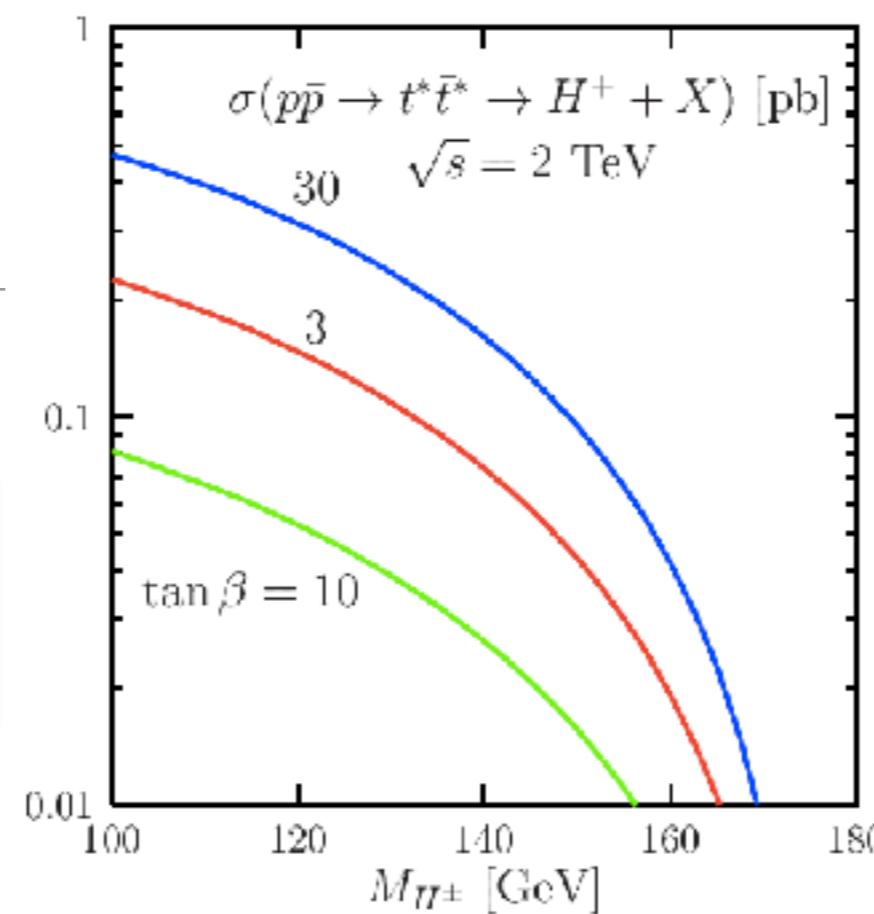
CMS:
Magnet: $3.8\text{T}\otimes, 2.0\text{T}\odot$
Calorimeters inside solenoids

ATLAS:
2T Magnet & toroids for muon
General detectors

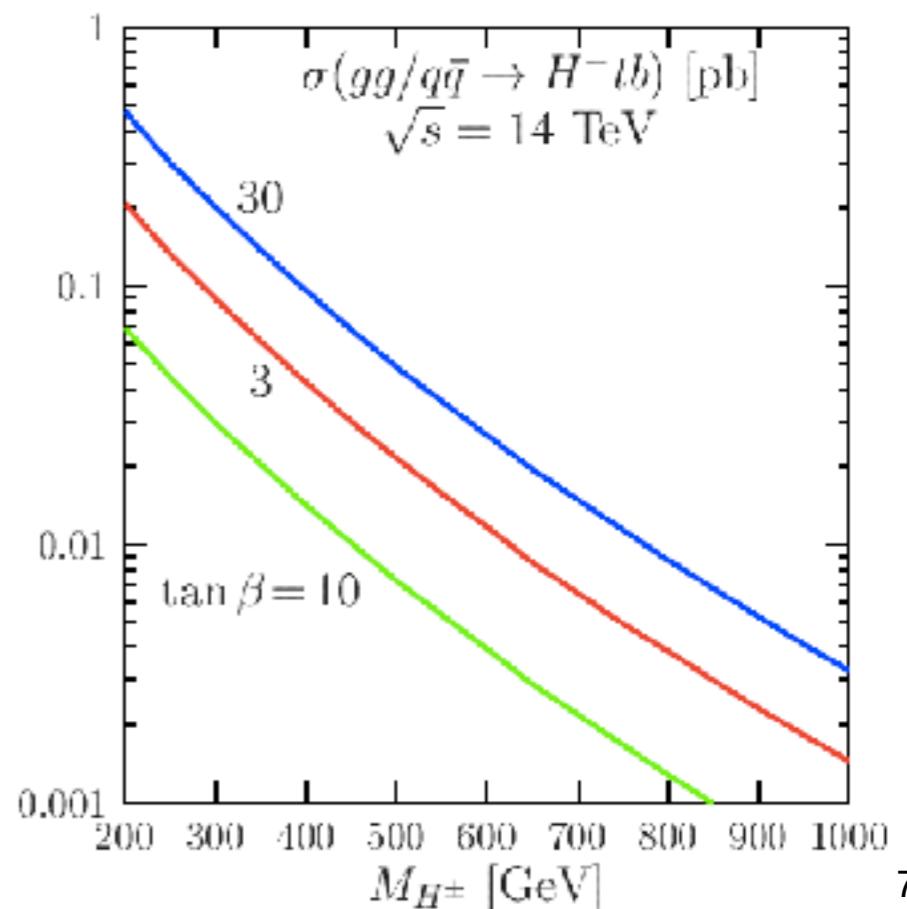
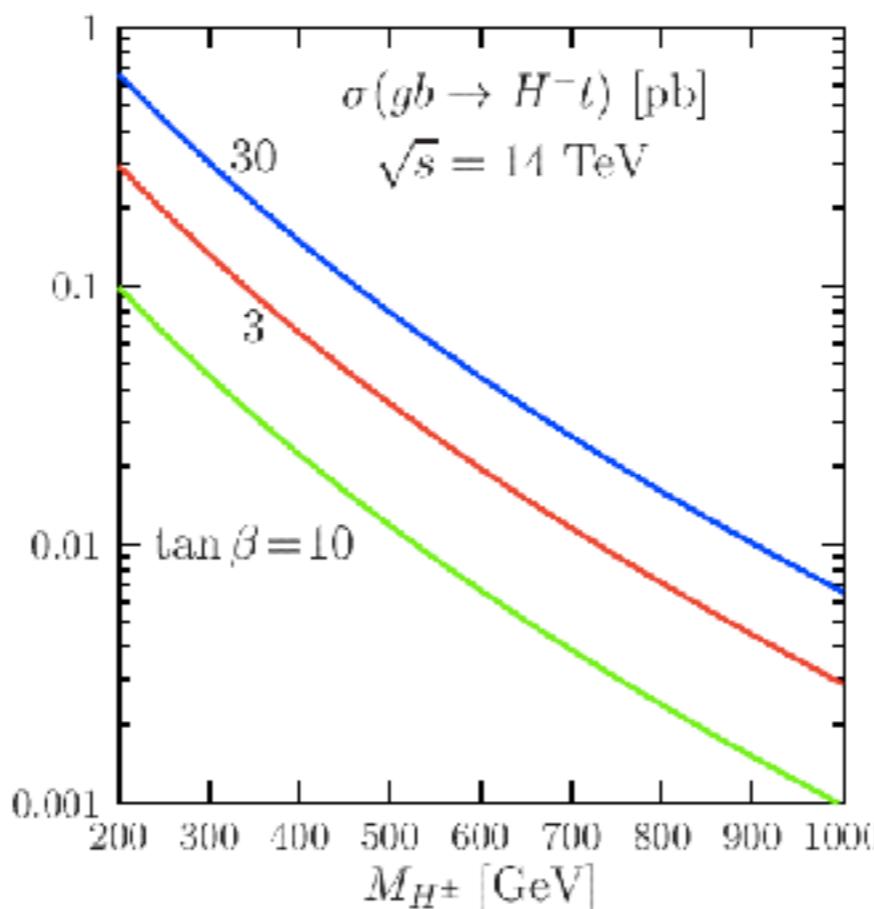


H^+ Production

$m(H^+) < m(t)$
Light H^+

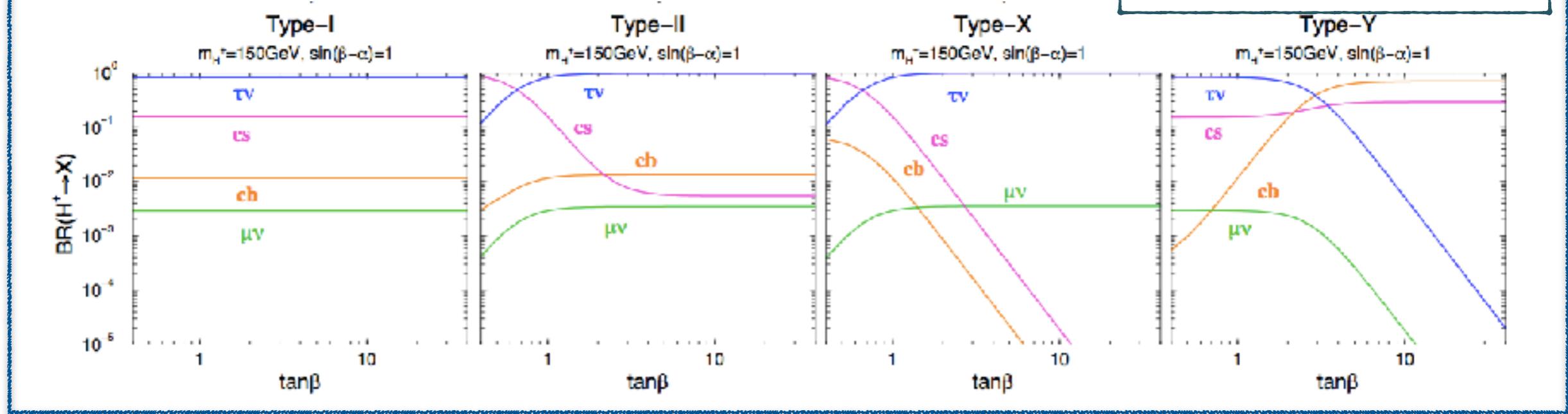


$m(H^+) > m(t)$
Heavy H^+

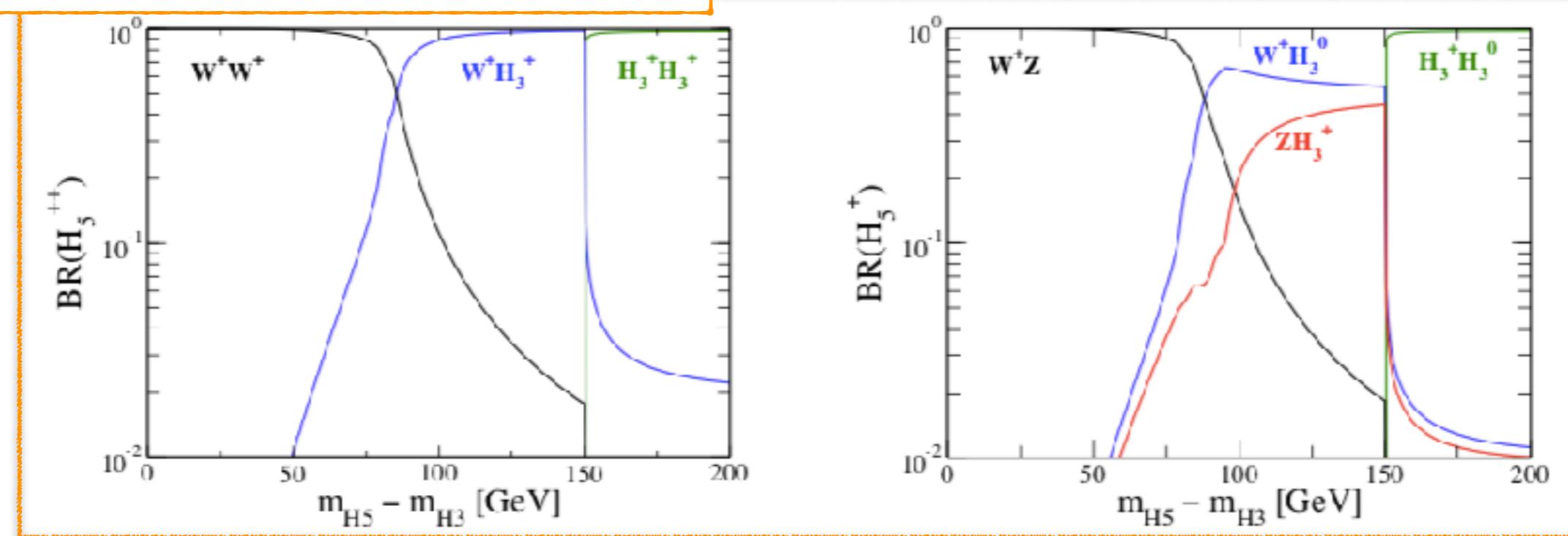


H^+ Decays for various models

2HDM, arXiv: 0902.4665



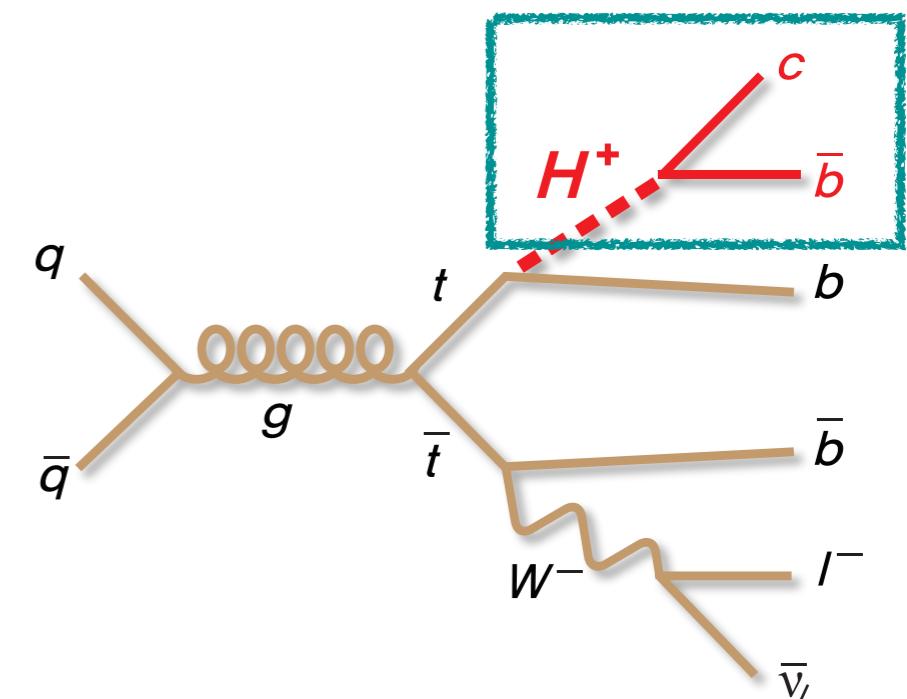
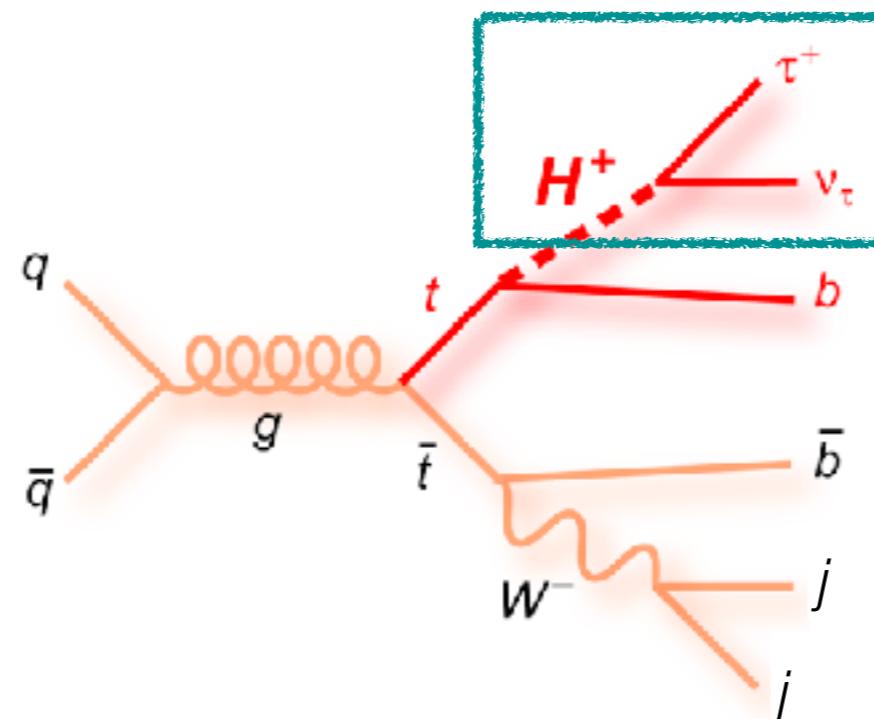
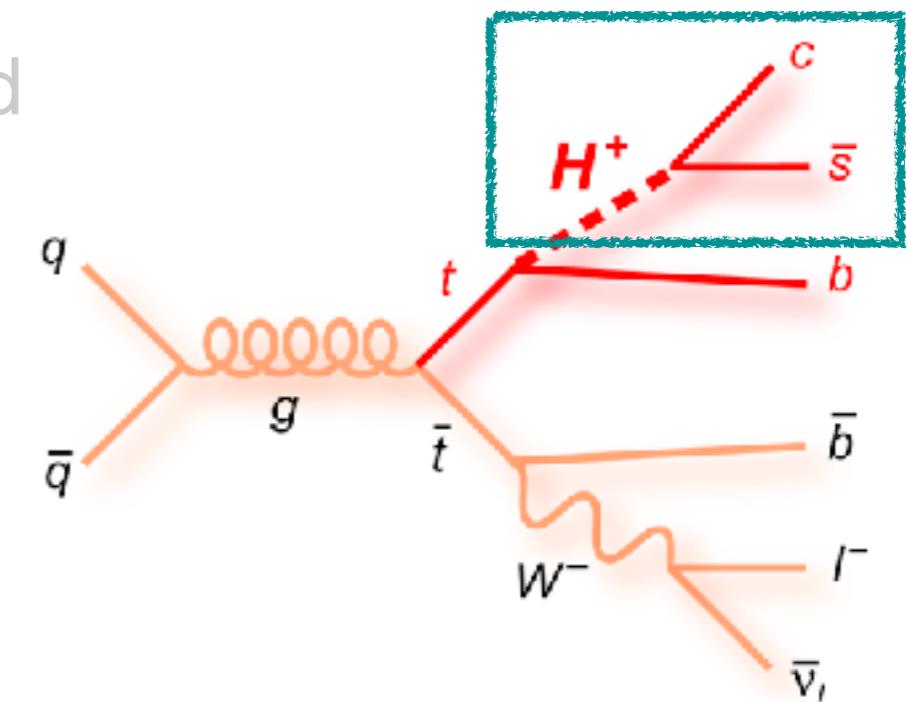
Georgi-Machacek model, arXiv: 1510.06297v2



Light H⁺ Searches: $90 \leq m(H^+) \leq m(t) - m(b)$

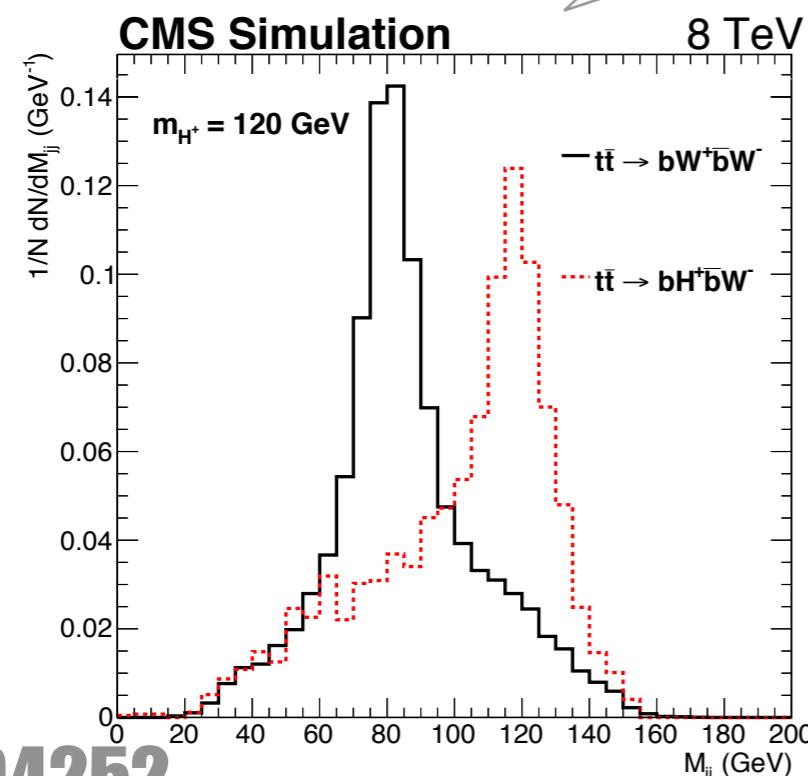
Mass below W boson excluded by LEP

Model independent search has performed



$H^+ \rightarrow cs$ @ 8 TeV

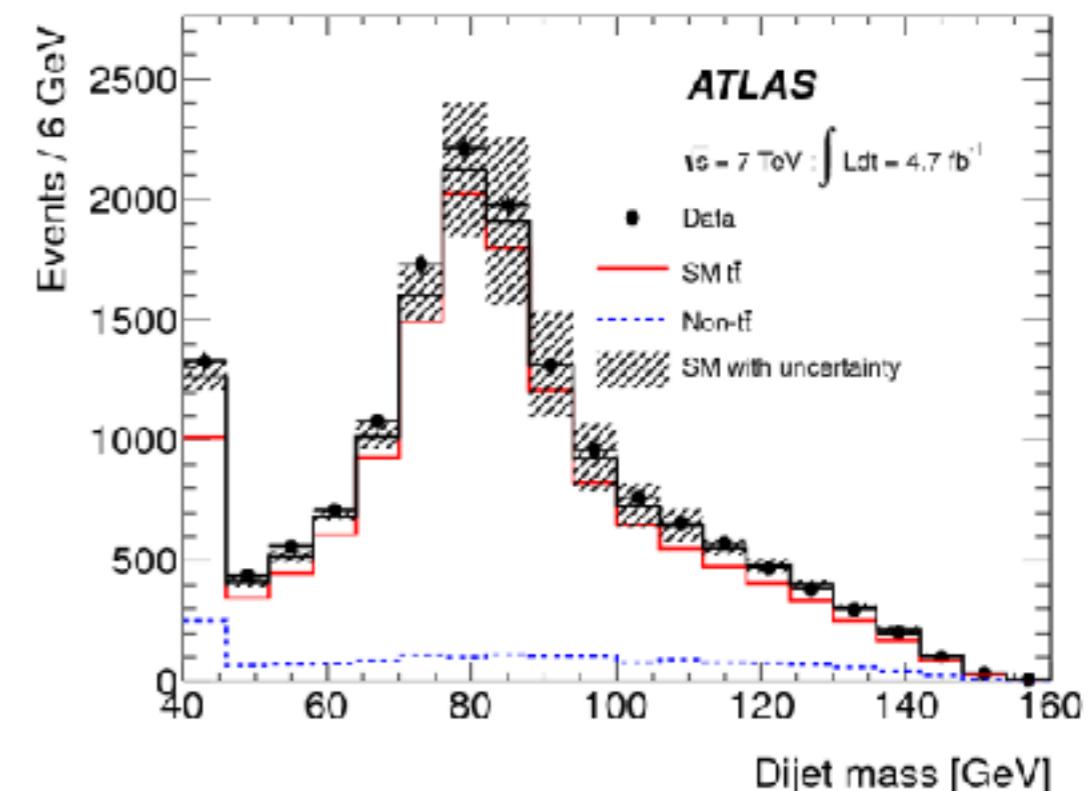
CMS



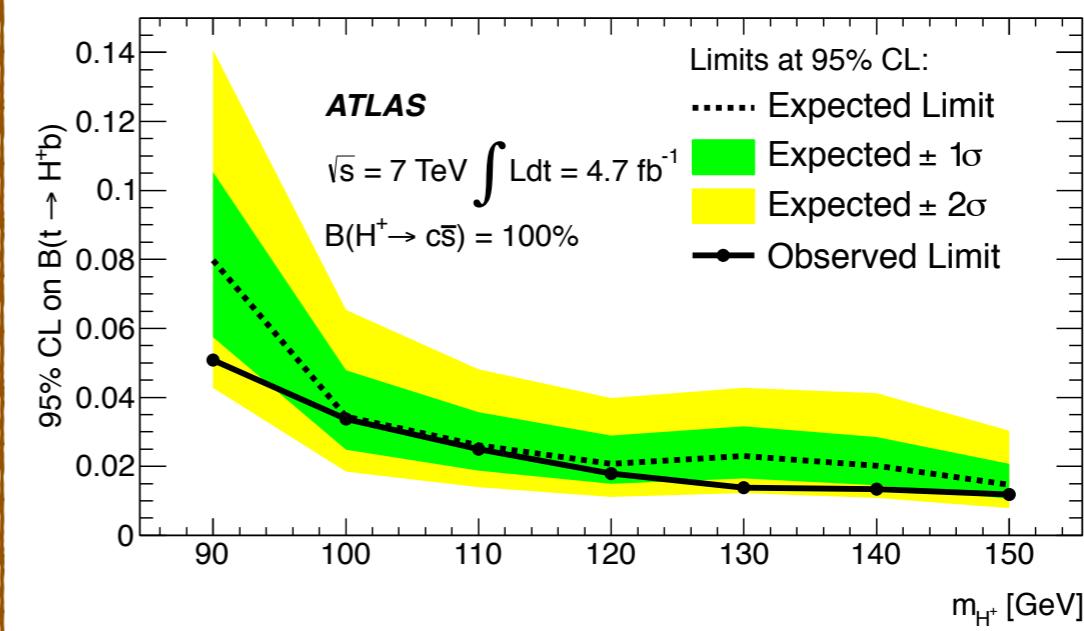
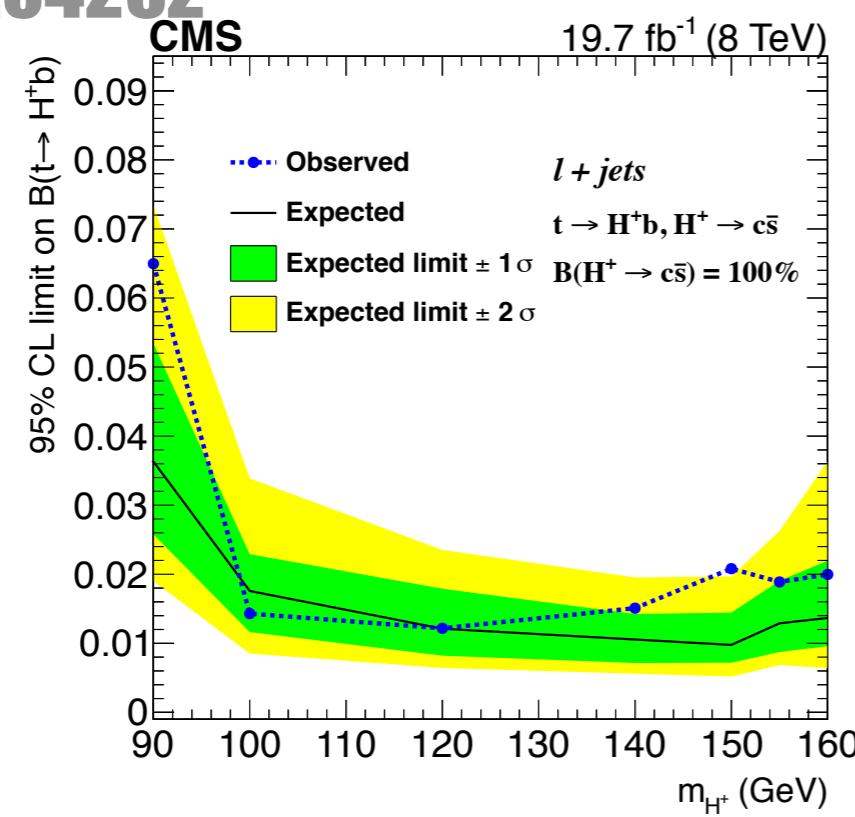
arXiv:1510.04252

$H^+ \rightarrow cs$ @ 7 TeV

ATLAS



arXiv:1302.3694

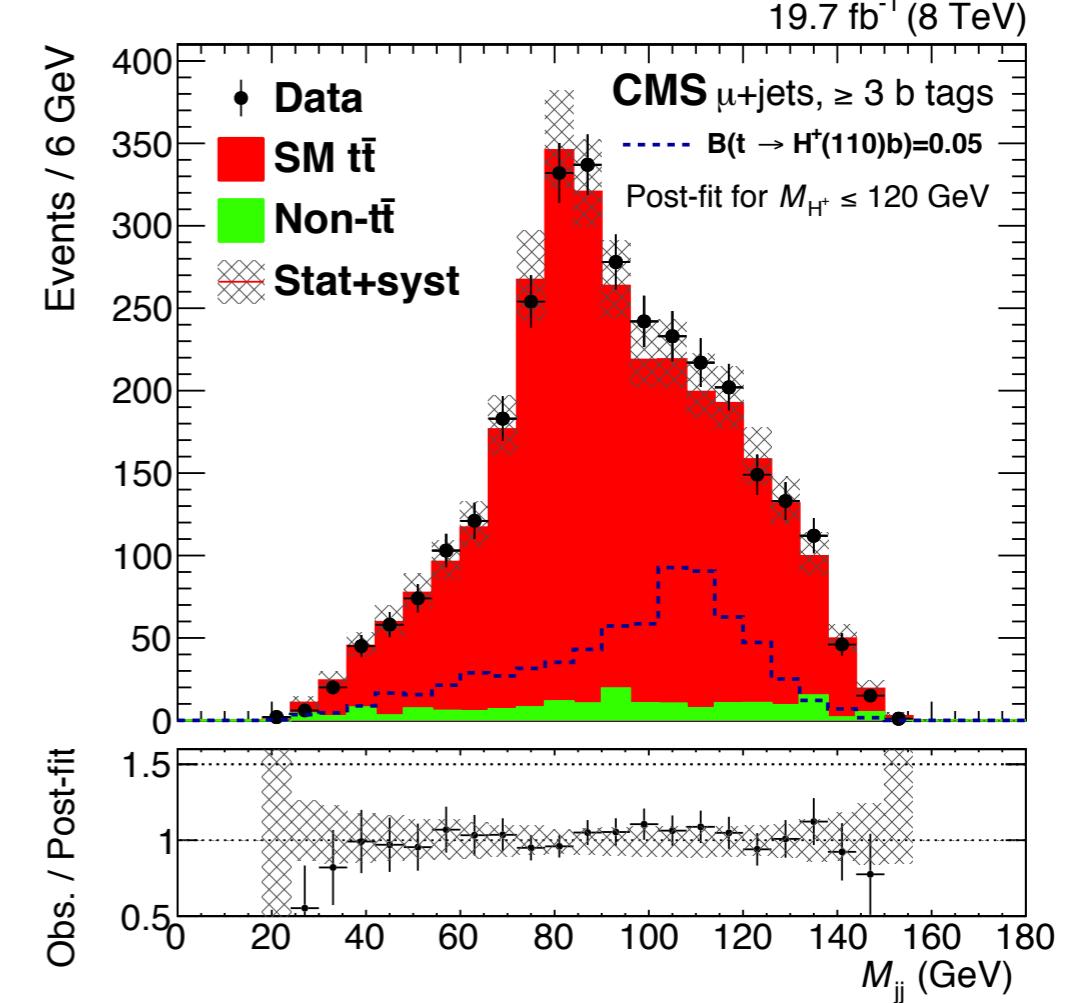
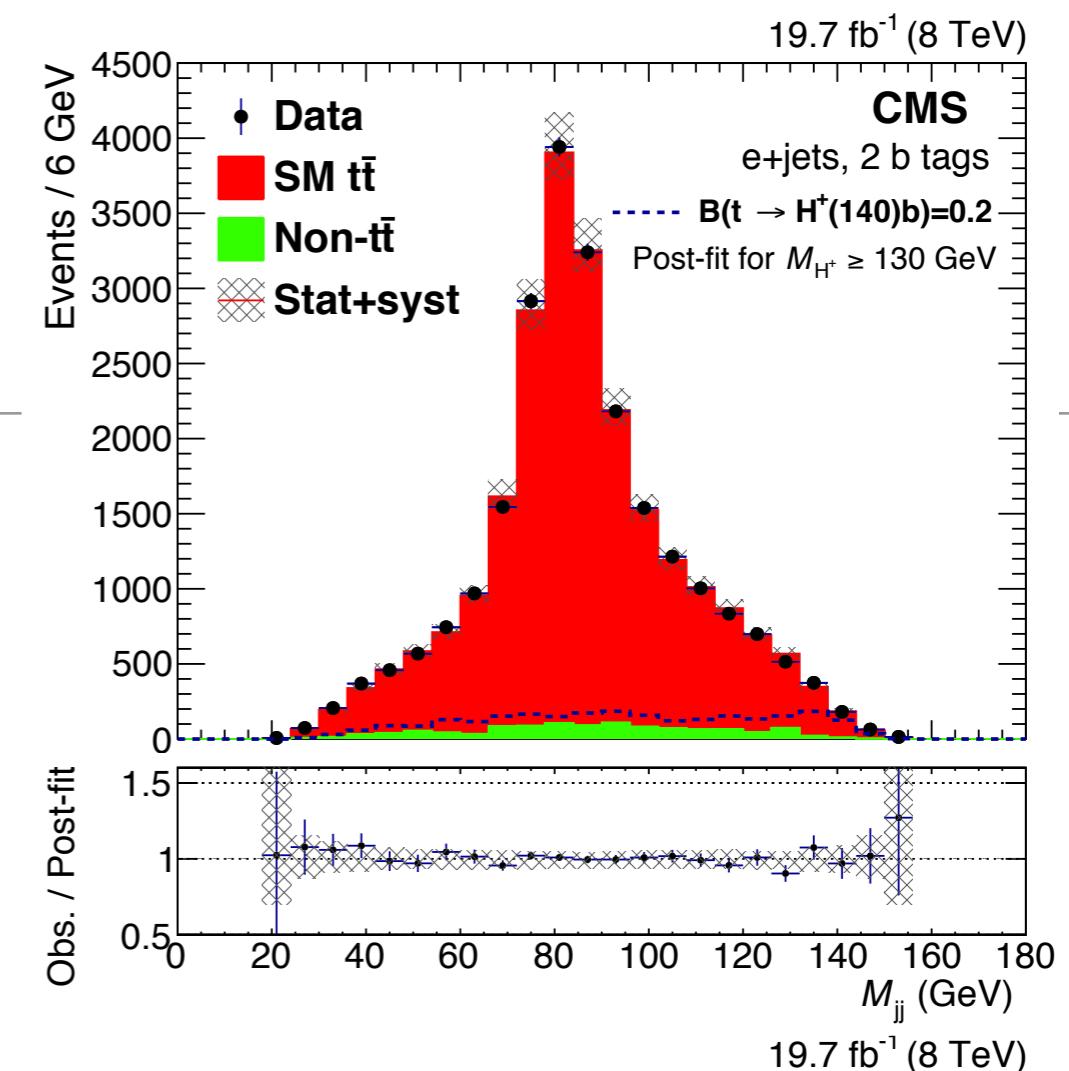
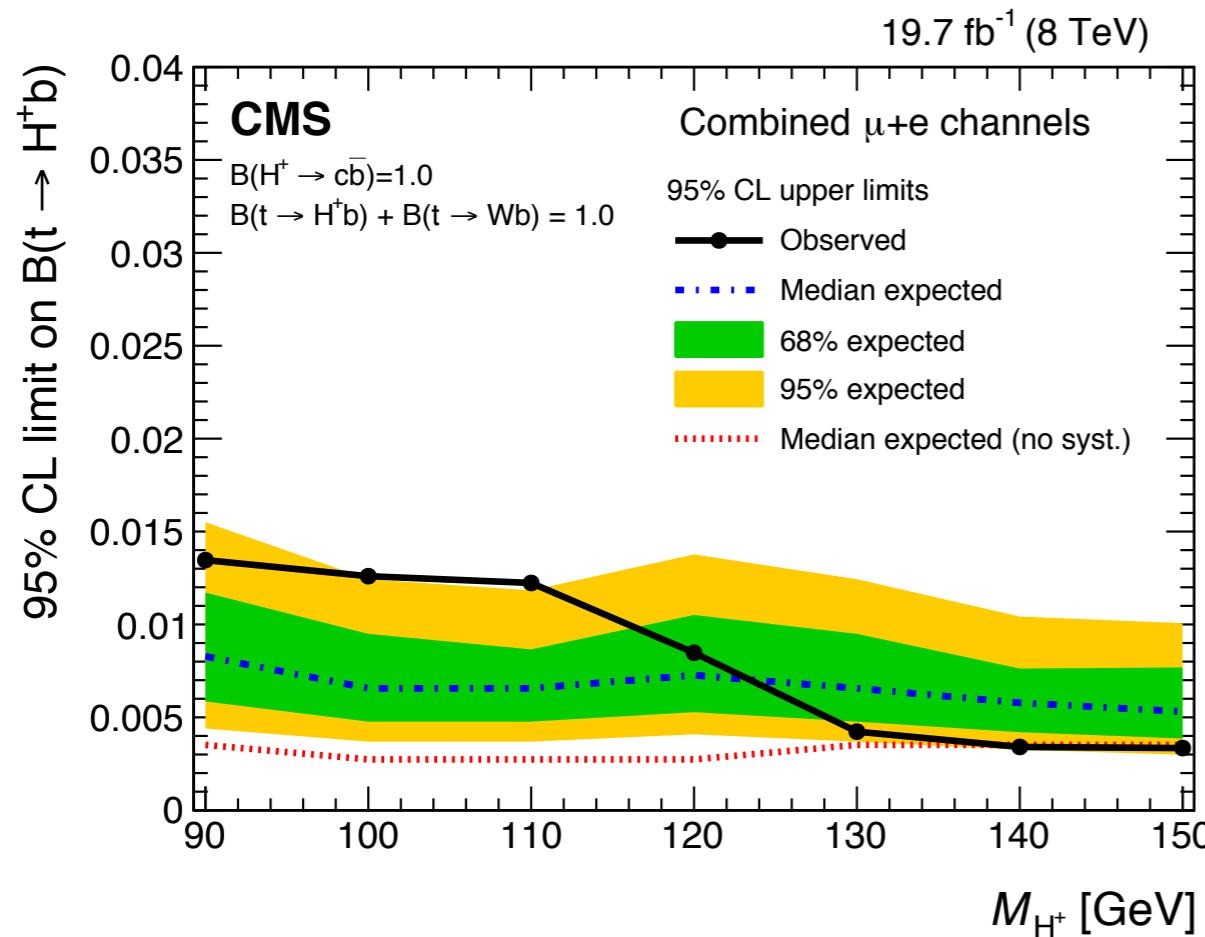


Use dijet mass discrepancy between W and H+ in fully reconstructed tt events¹⁰

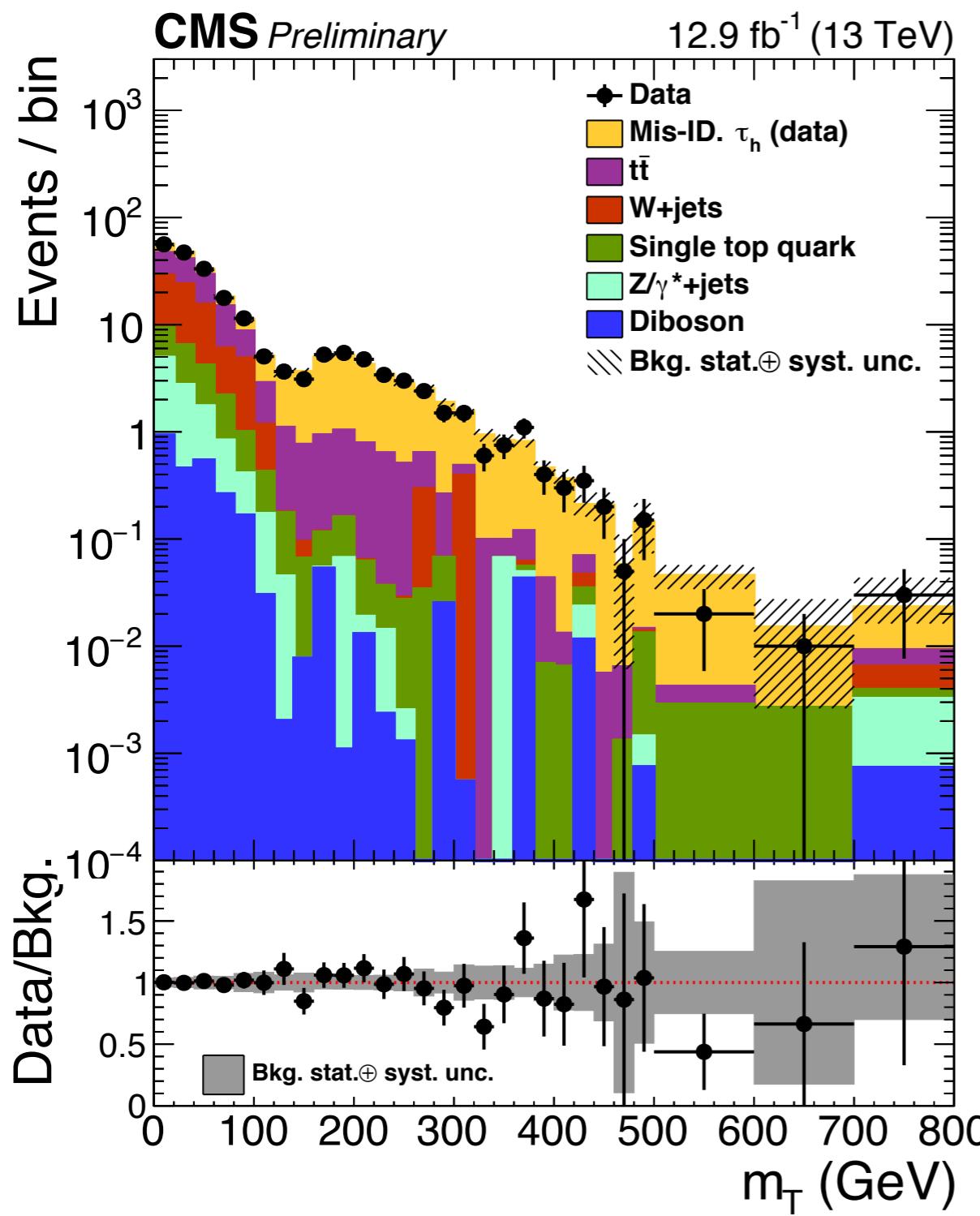
$H^+ \rightarrow cb @ 8 \text{ TeV}$

CMS
only

- Dominant in type-Y of 2HDM
- First measurement of this channel
- Simultaneous fit on both 2b-tags & ≥ 3 b-tags dijet mass distributions

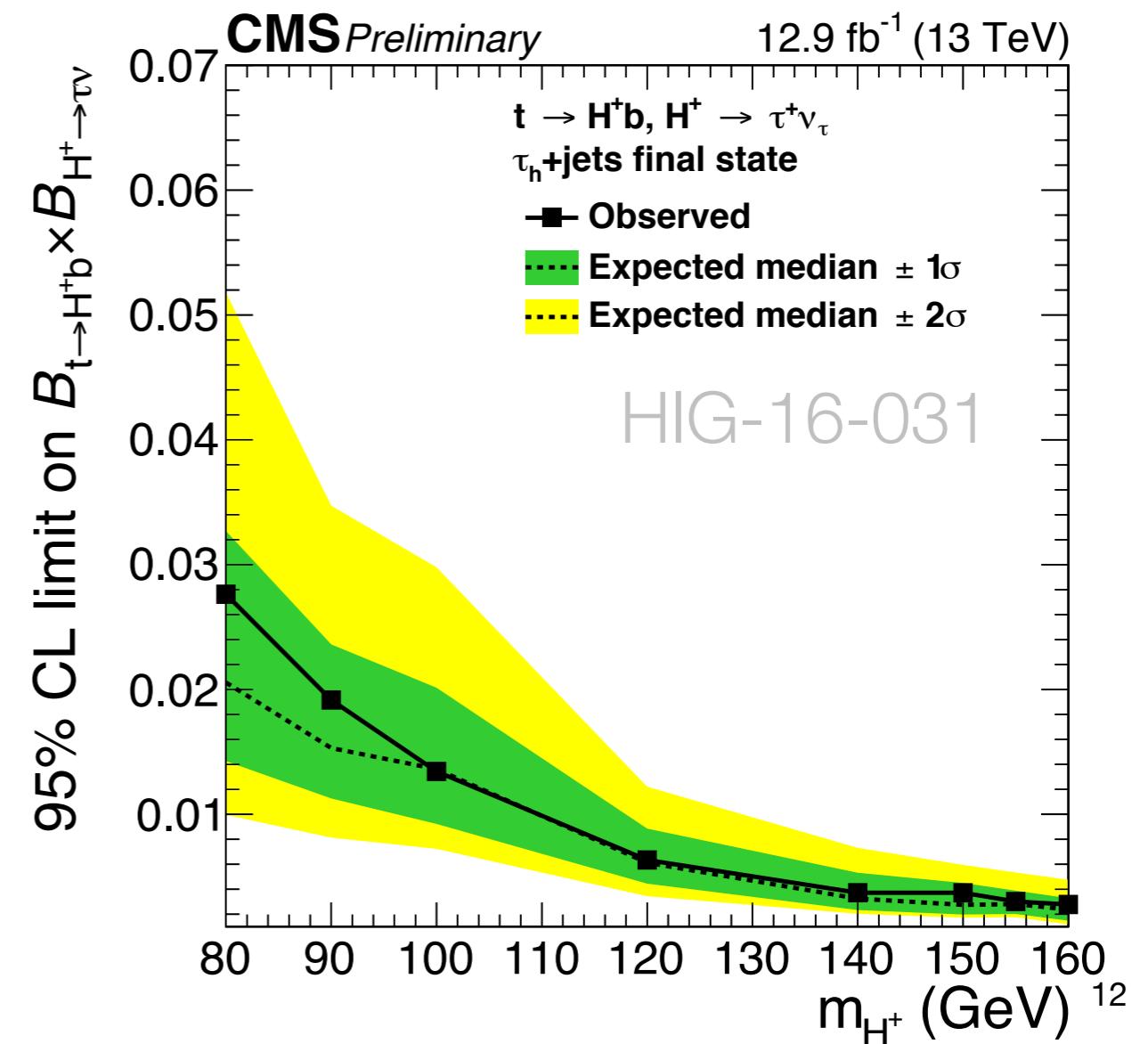


$H^+ \rightarrow \tau\nu$ @ 13 TeV



Reconstruct the transverse mass & extract the charged Higgs boson signal

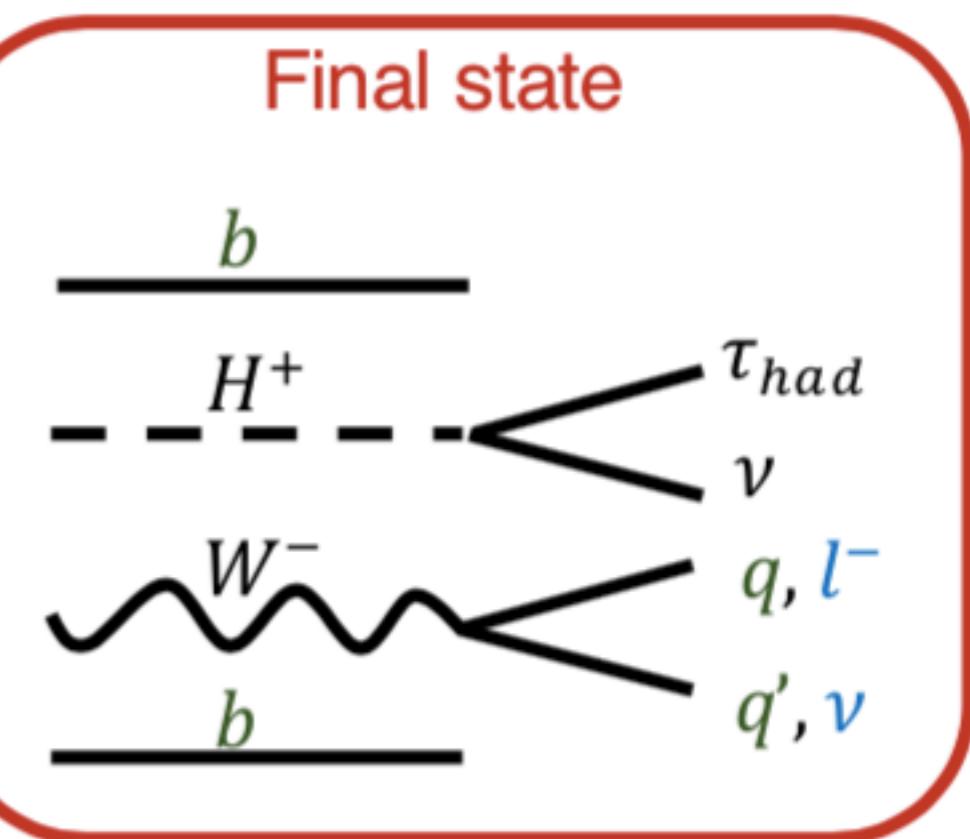
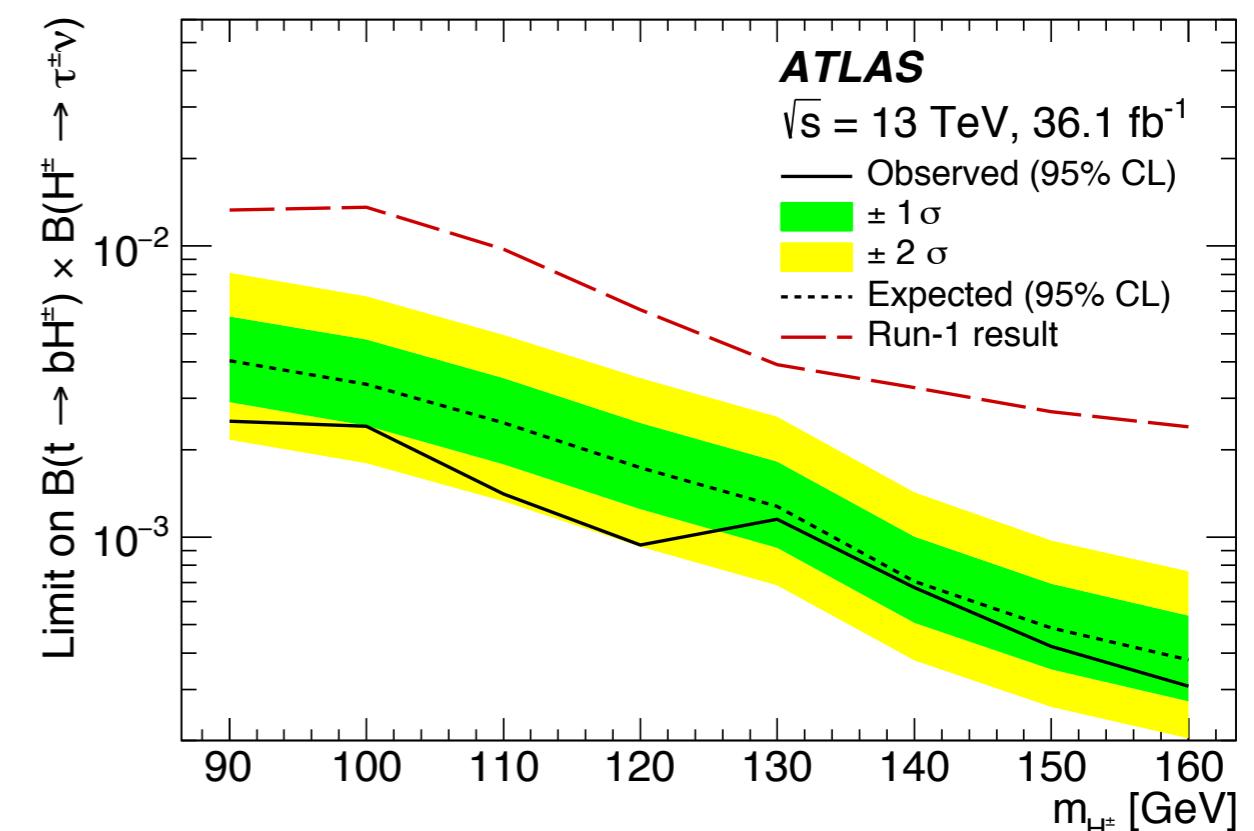
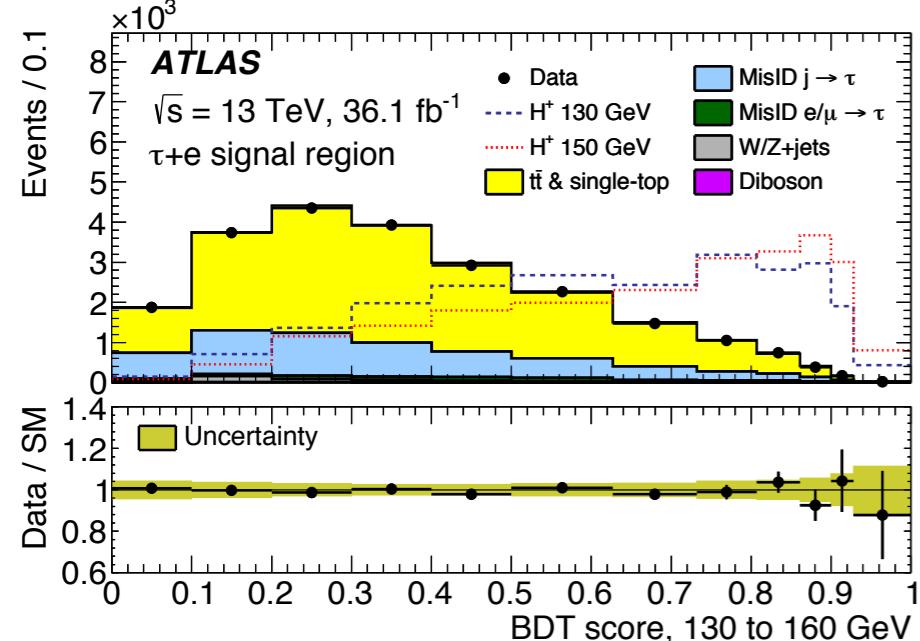
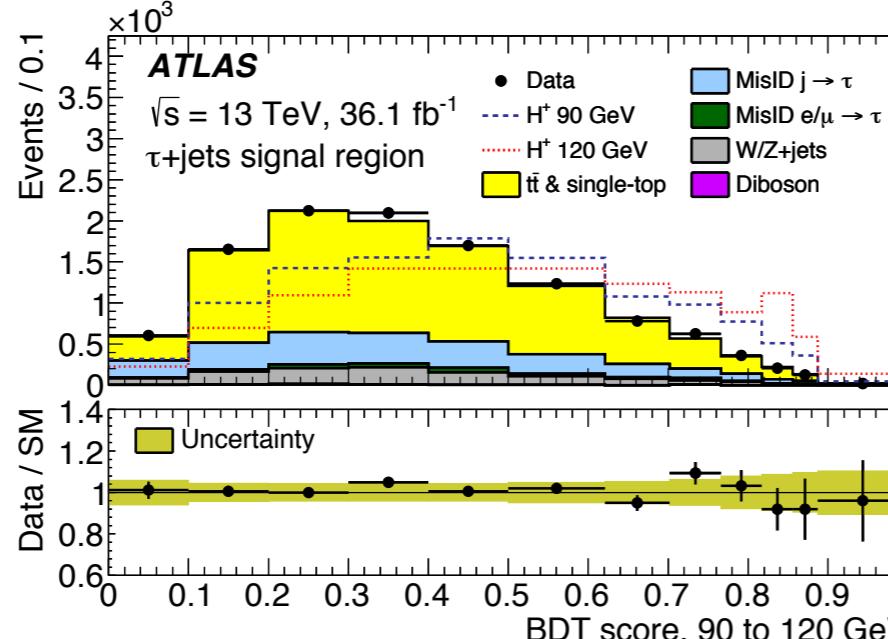
$$m_T^2 = 2 \cdot p_T^{\tau^h} |\vec{E}_T| (1 - \cos \Delta\phi(\vec{E}_T, \tau^h))$$



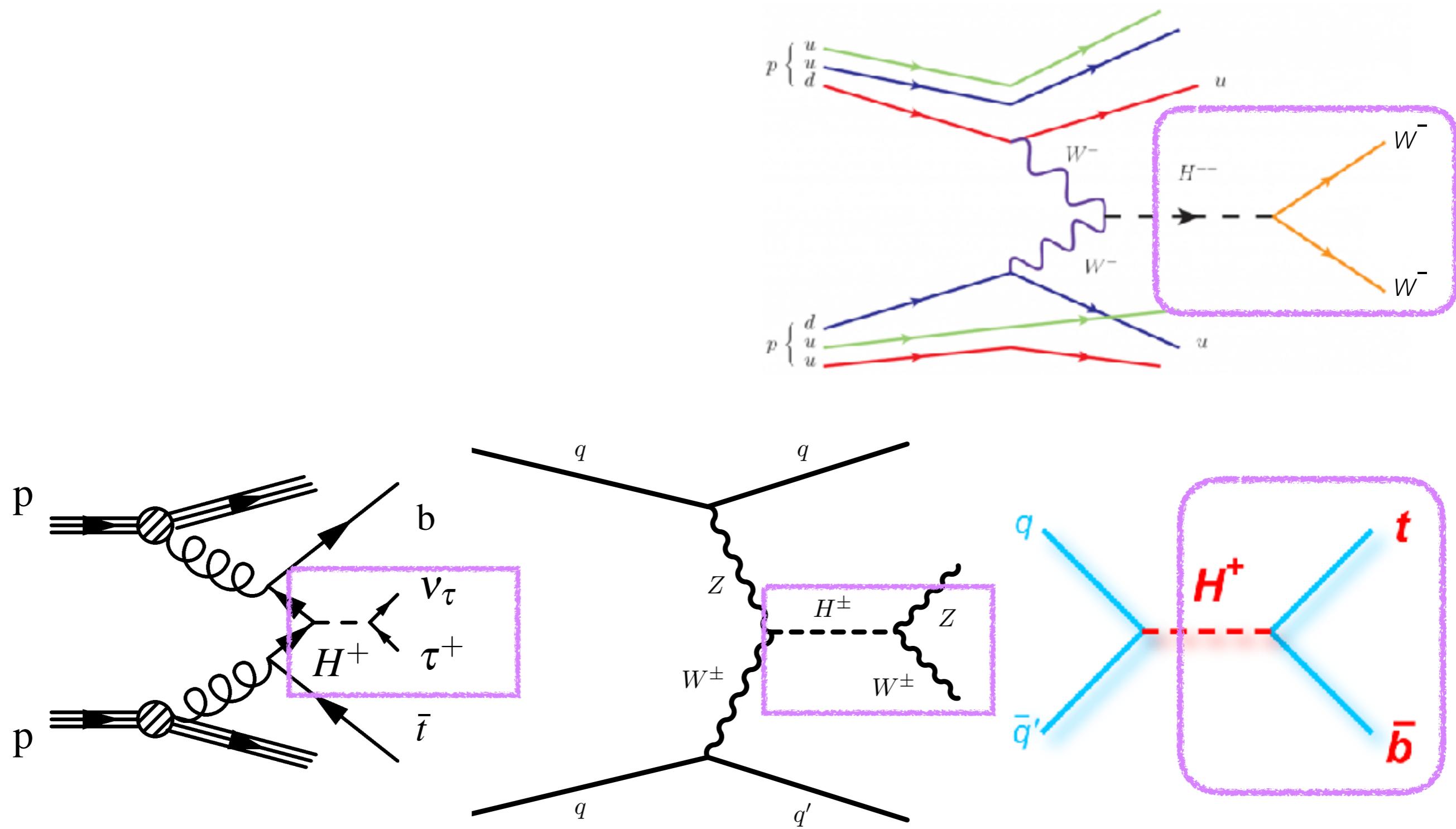
ATLAS

 $H^+ \rightarrow \tau\nu$ @ 13 TeV

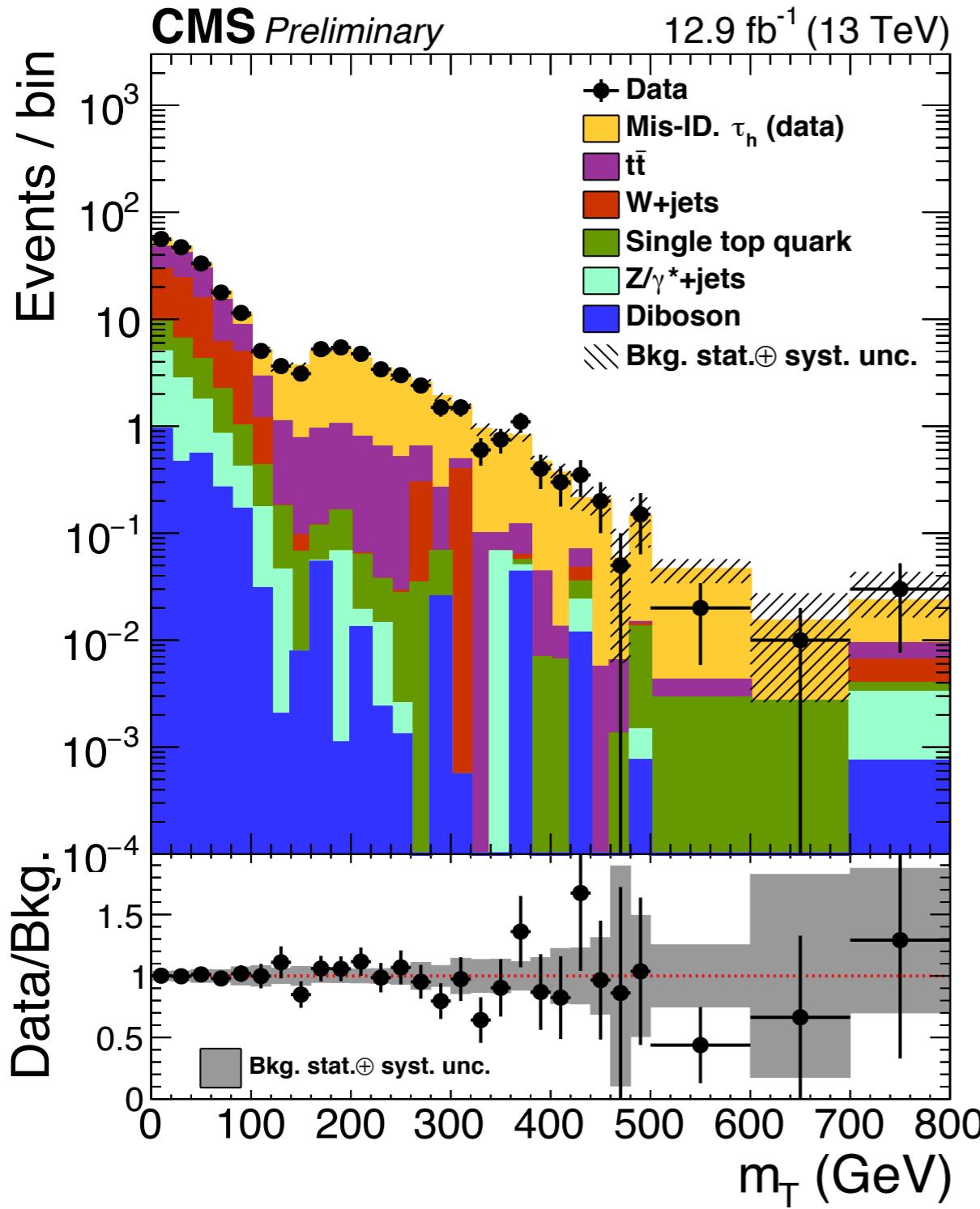
- Select events with $\tau_{\text{had}} + \geq 3 \text{ jets} \& \tau_{\text{had}} + \text{lepton}$
- In mass range 90–160 GeV, H^+ produced in $t\bar{t}$
- Multivariate technique used for signal extraction



Heavy H⁺ Searches: $m(H^+) \geq m(t)$

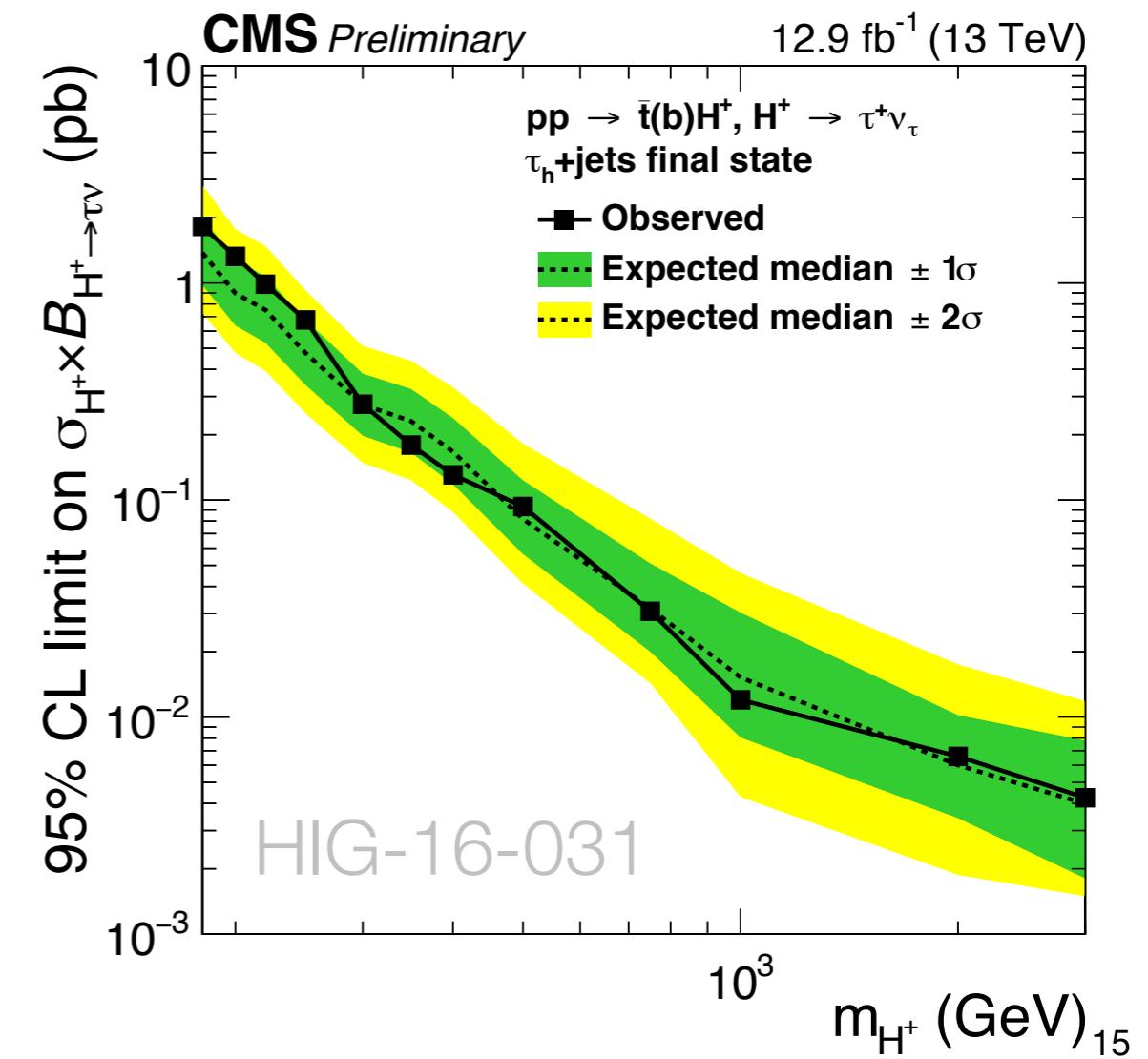


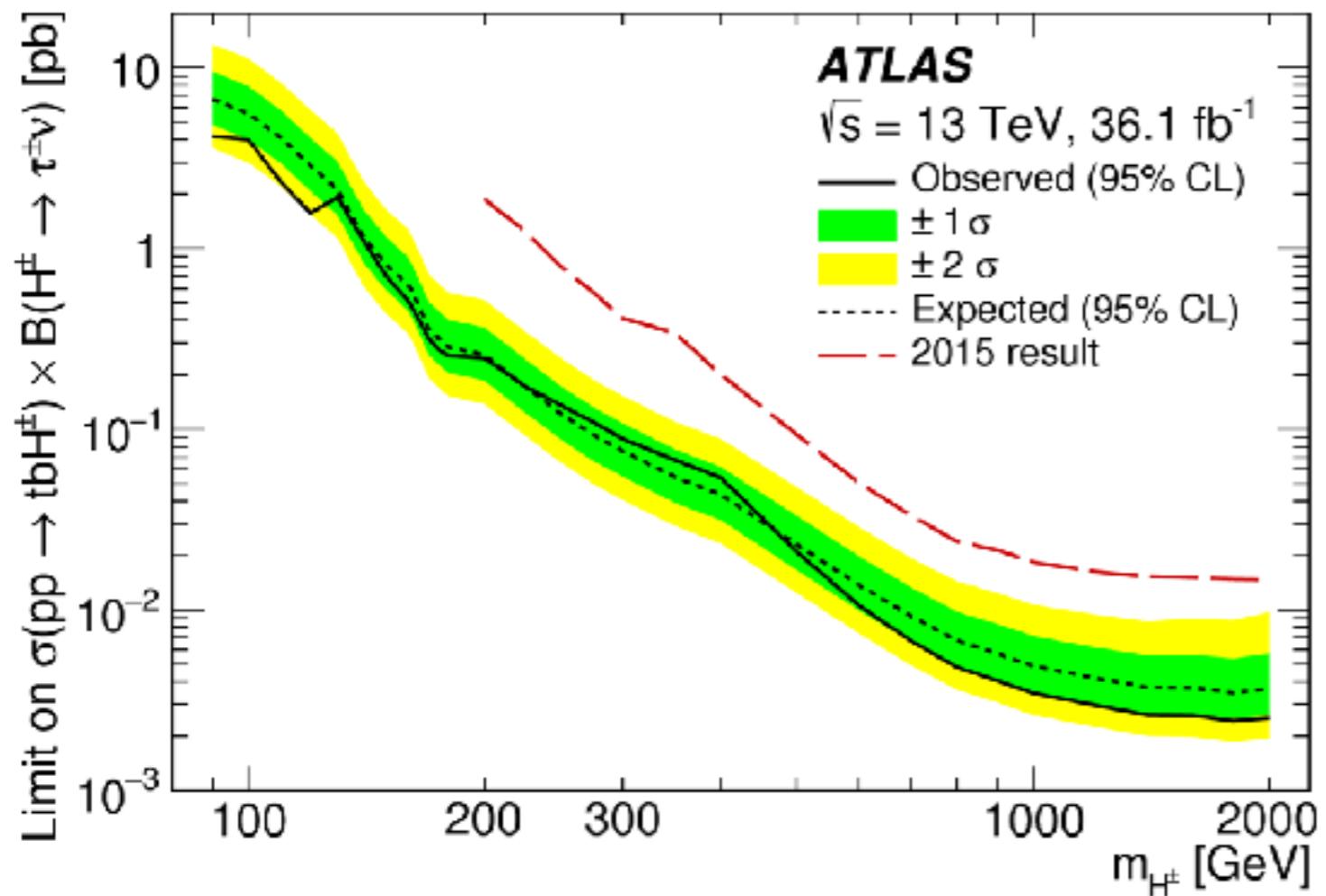
$H^+ \rightarrow \tau\nu$ @ 13 TeV



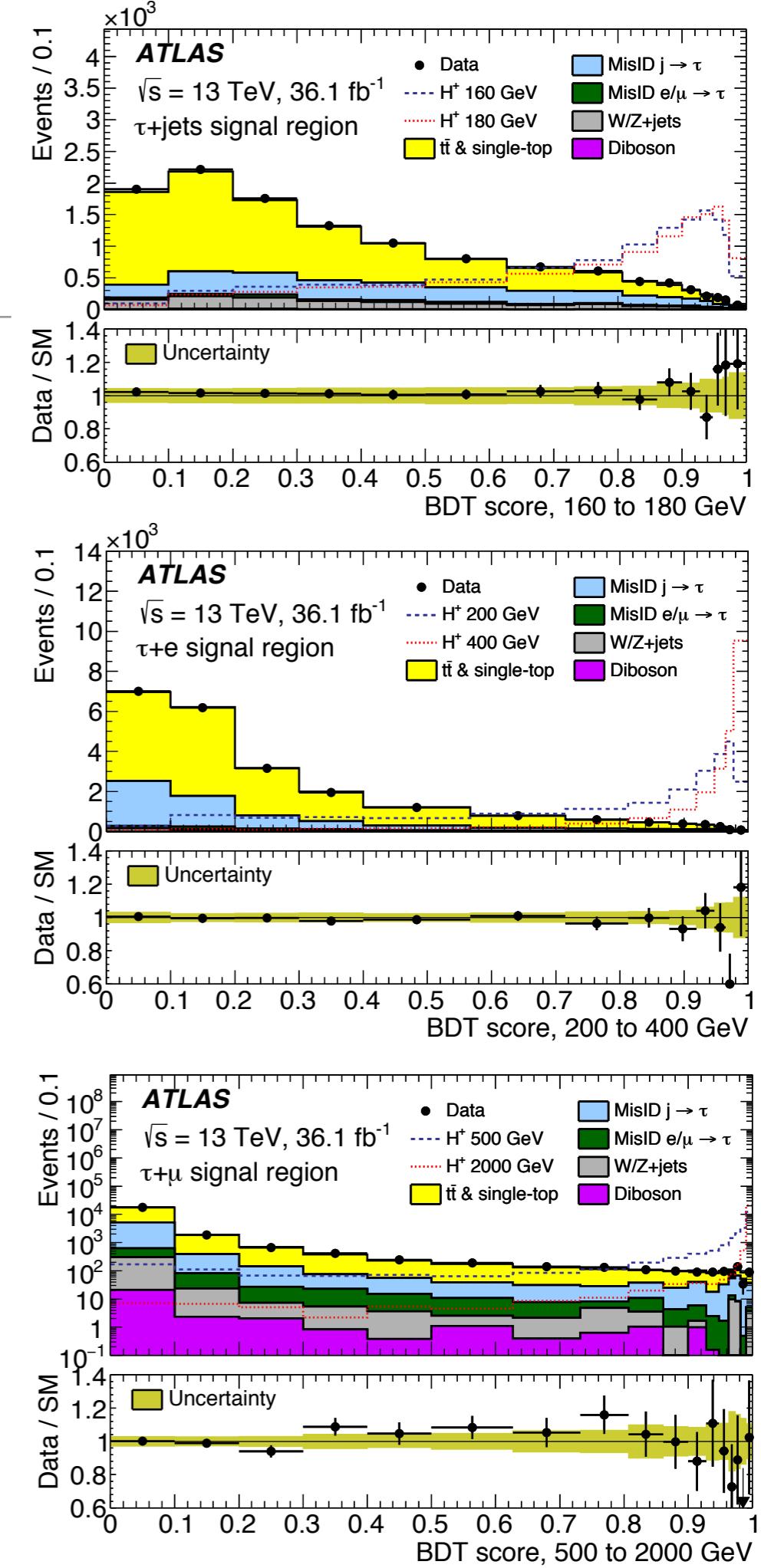
Reconstruct the transverse mass & extract the charged Higgs boson signal

$$m_T^2 = 2 \cdot p_T^{\tau^h} |\vec{E}_T| (1 - \cos \Delta\phi(\vec{E}_T, \tau^h))$$



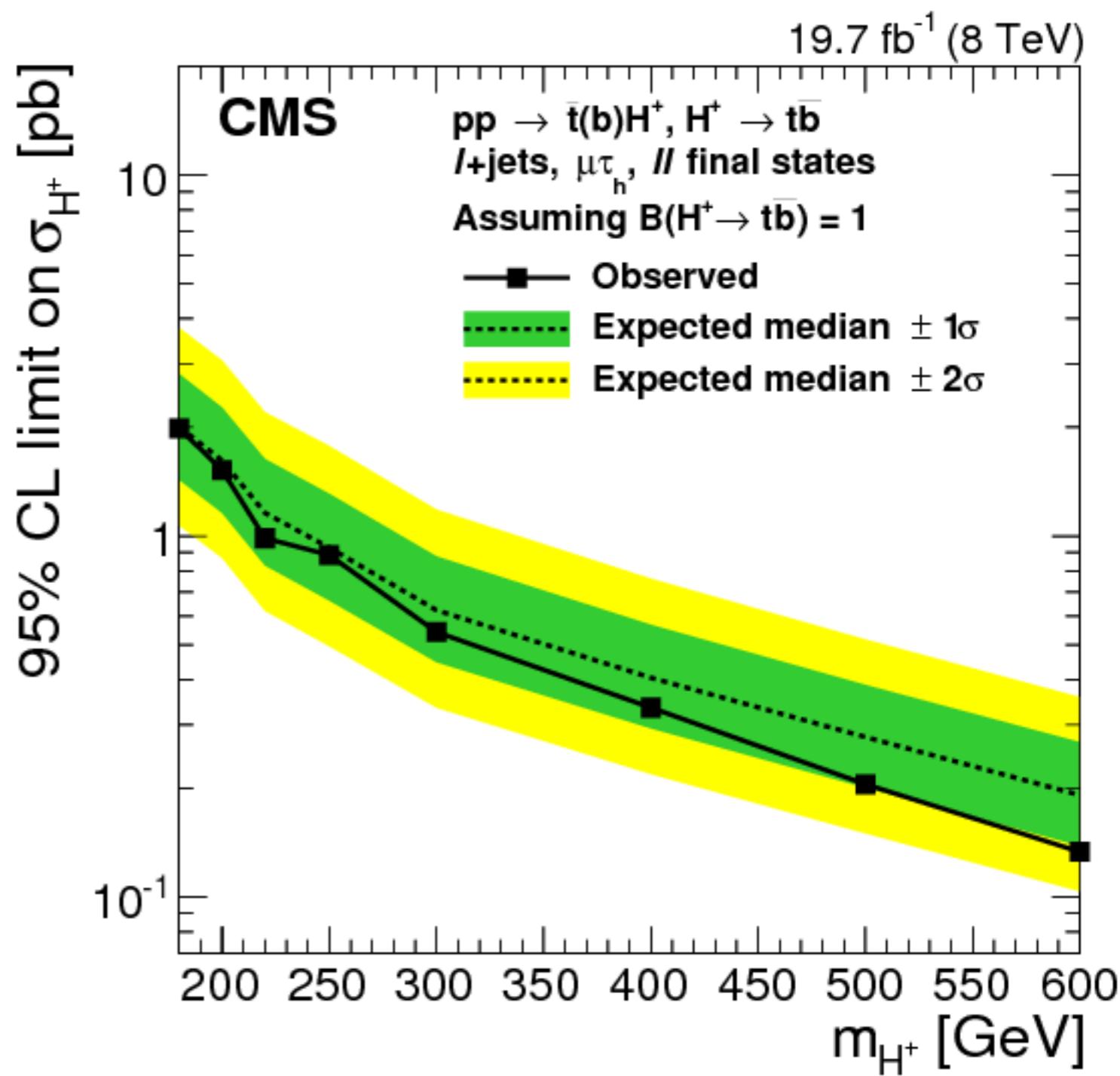
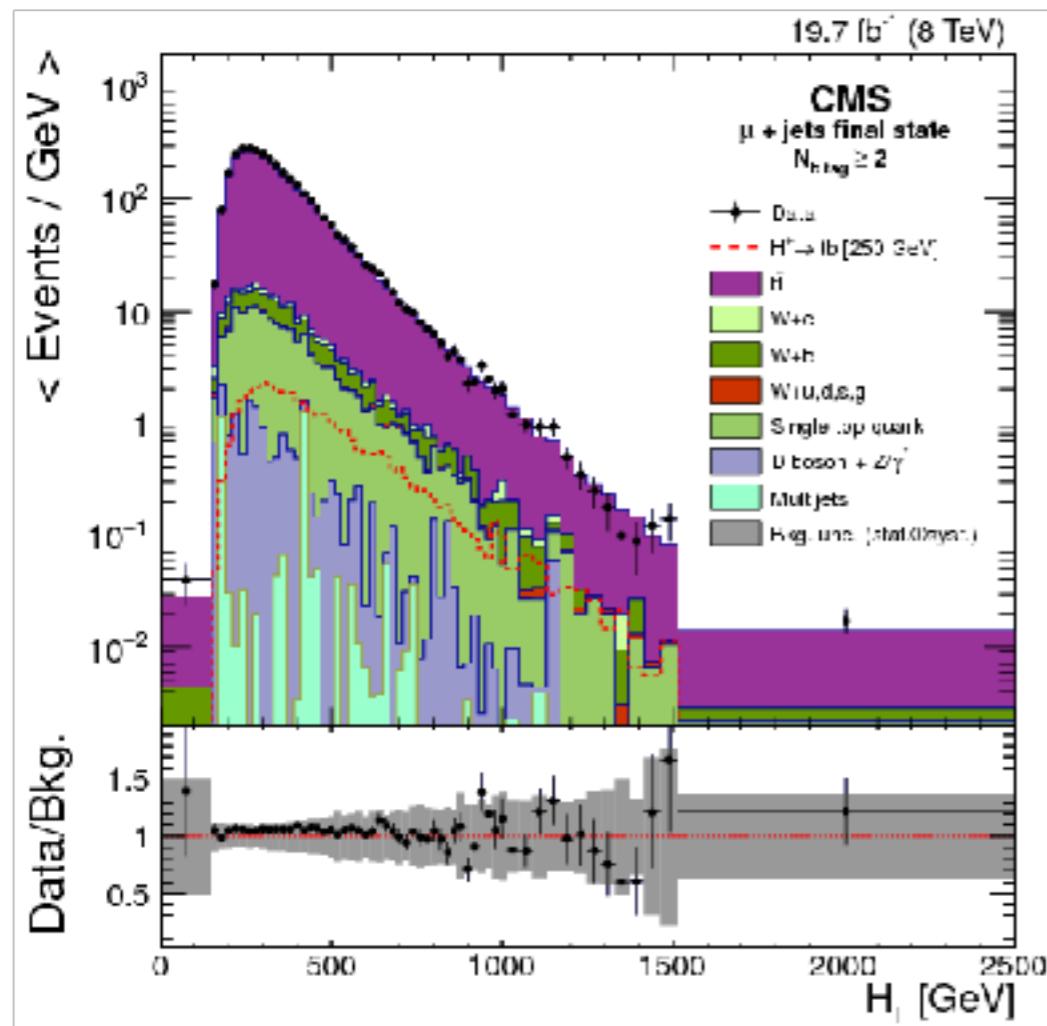
$H^+ \rightarrow \tau\nu @ 13 \text{ TeV}$ 

- Select events with $\tau_{\text{had}} + \geq 3 \text{ jets} \& \tau_{\text{had}} + \text{lepton}$
- First measurement in the intermediate mass range 160–180 GeV, H^+ produced in non-resonant $t\bar{t}$
- Multivariate technique used for signal extraction



$H^+ \rightarrow tb$ @ 8 TeV

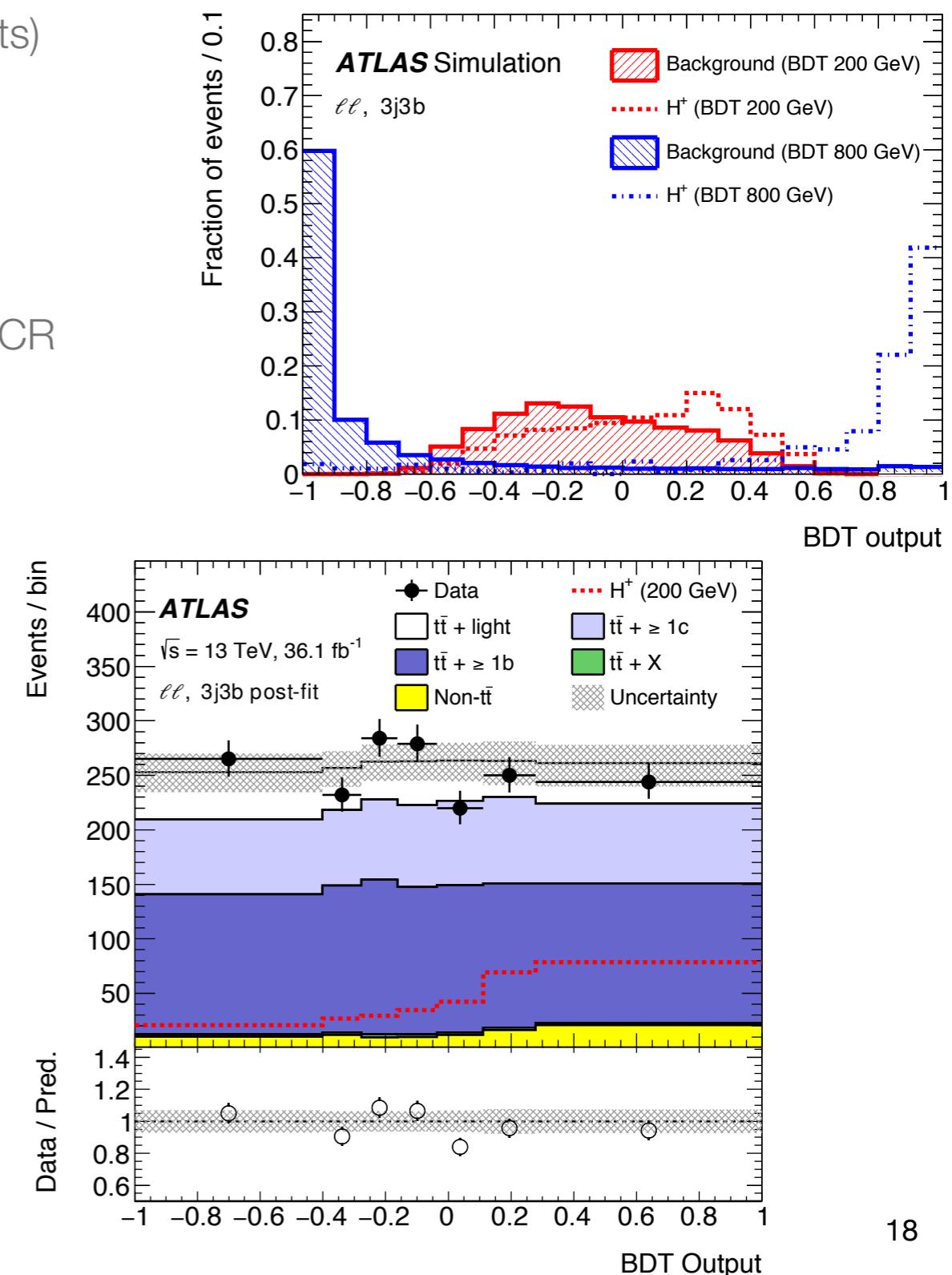
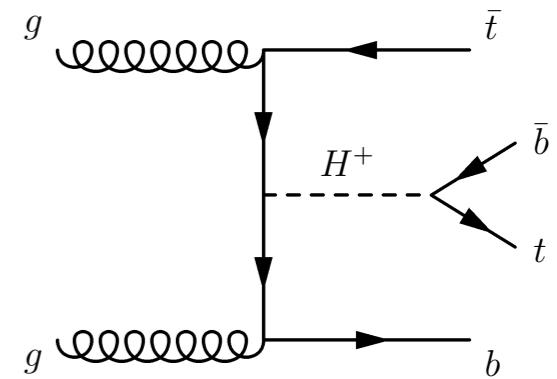
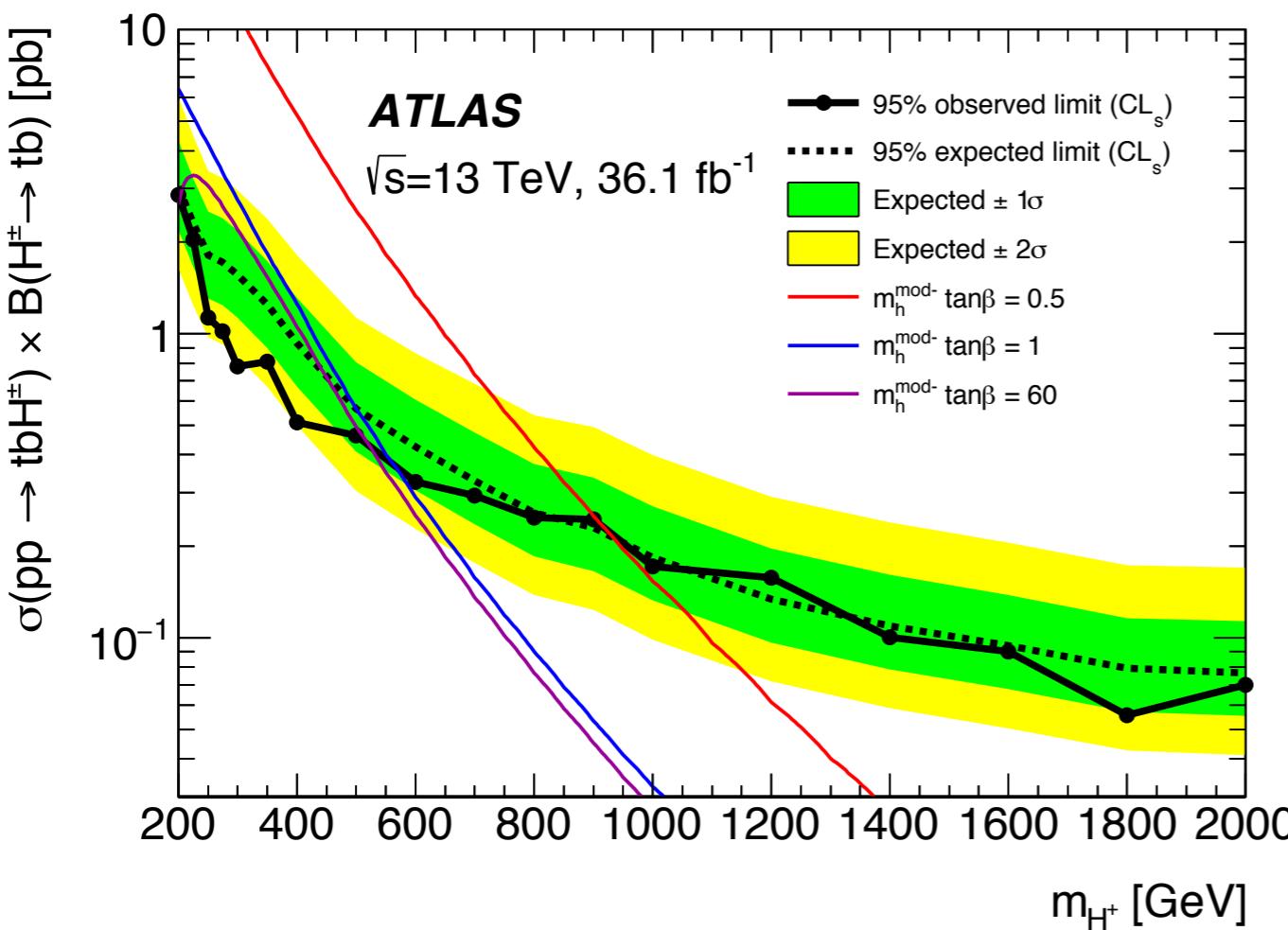
- Combining the results obtained from three different final states
- H^+ signal is extracted based on the kinematic distributions of each channel





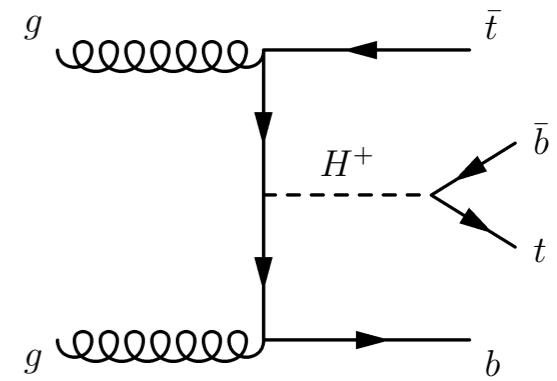
$H^+ \rightarrow tb$ @ 13 TeV

- Two OS leptons + ≥ 3 jets (≥ 2 b-jets) || lepton + ≥ 5 jets (≥ 3 b-jets)
- Search in $m(H^+)$ 200–2000 GeV
- Use multivariate techniques to separate S/B
- Simultaneous fit to BDT output in SR & number of events in CR

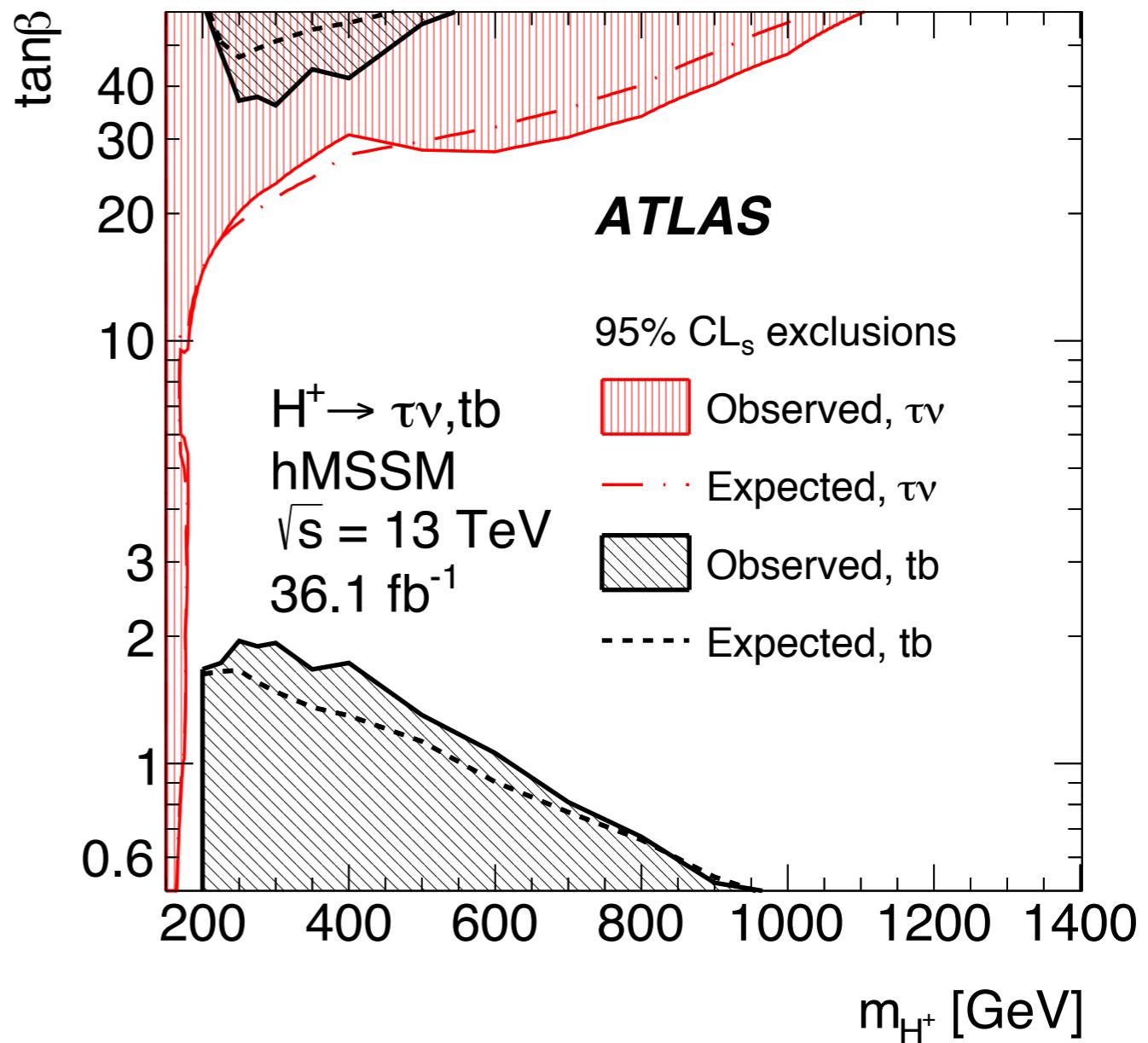
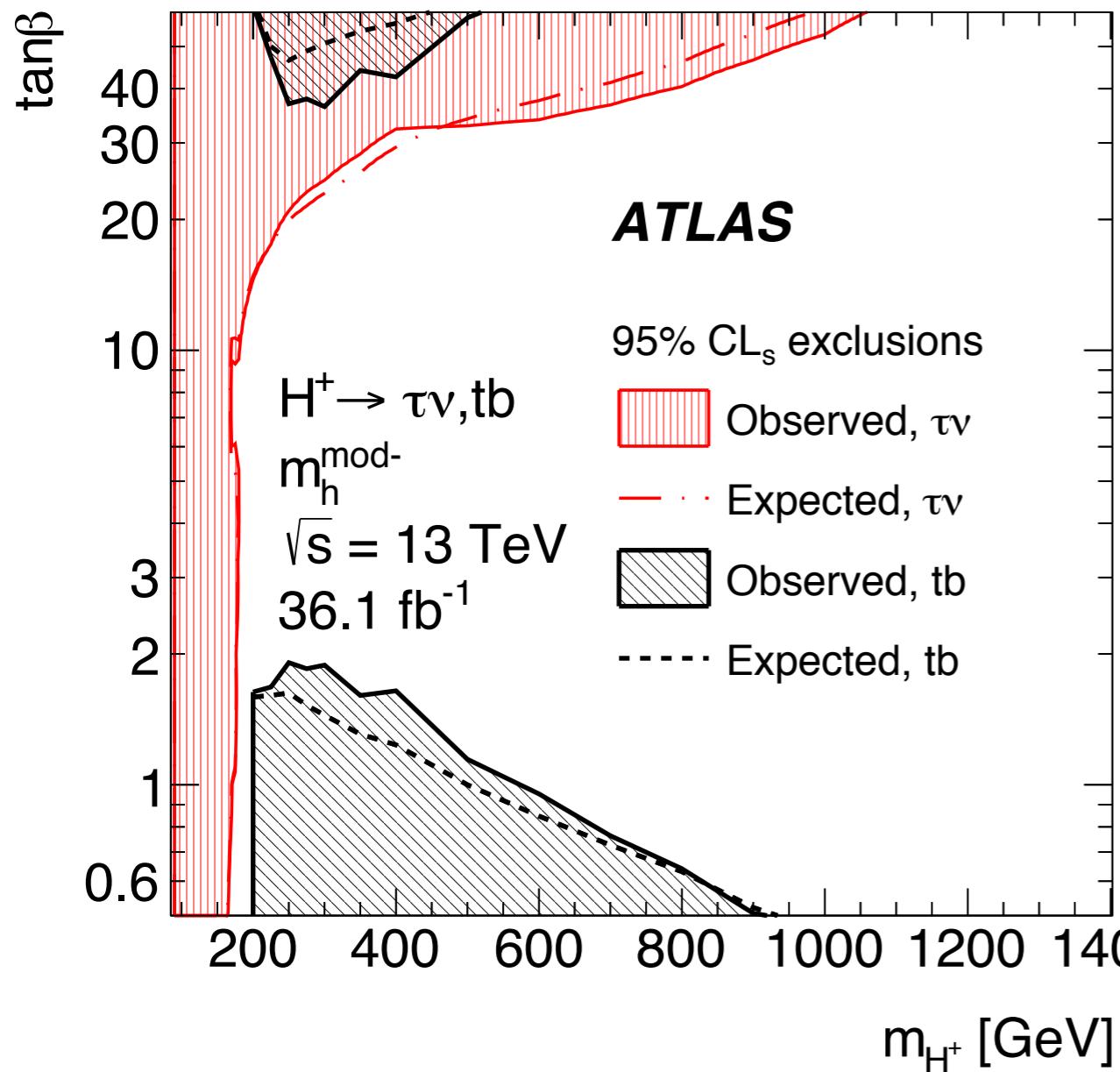




$H^+ \rightarrow tb$ @ 13 TeV



Interpretation in the MSSM: $m_h^{\text{mod-}}$ and hMSSM scenario

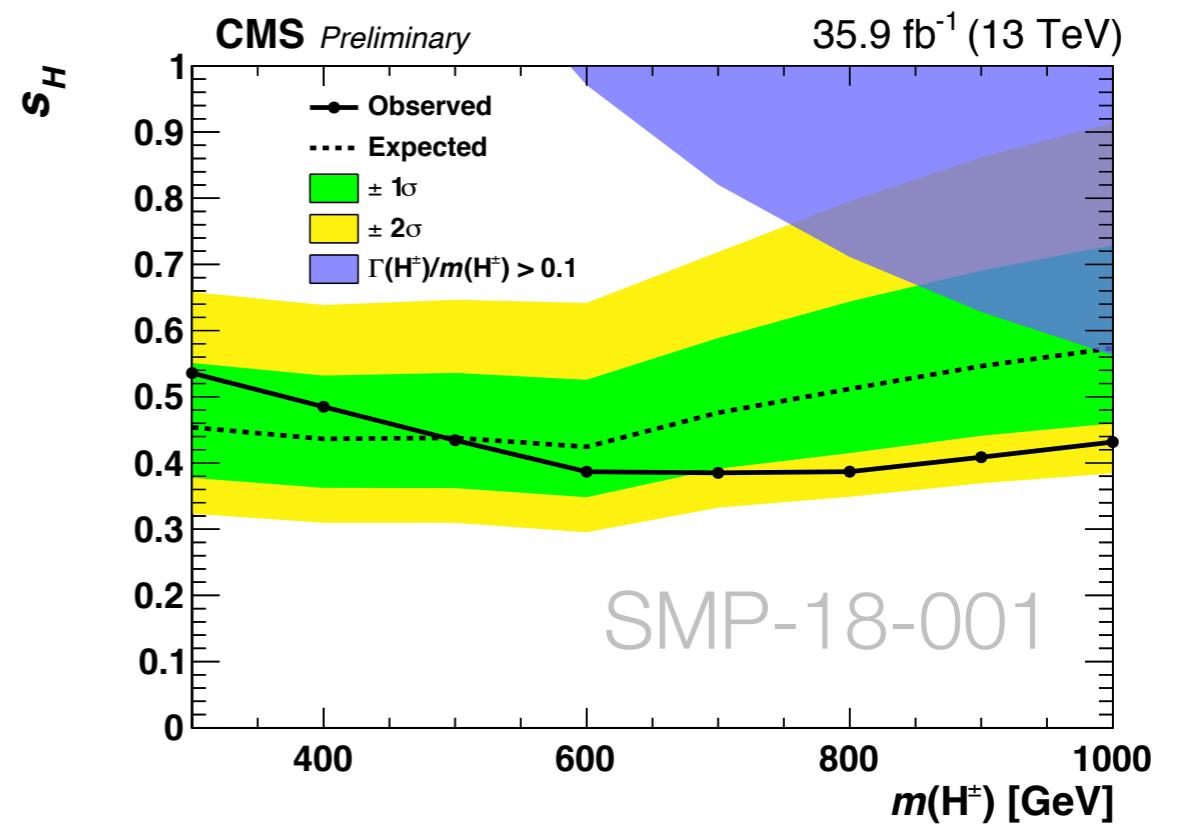
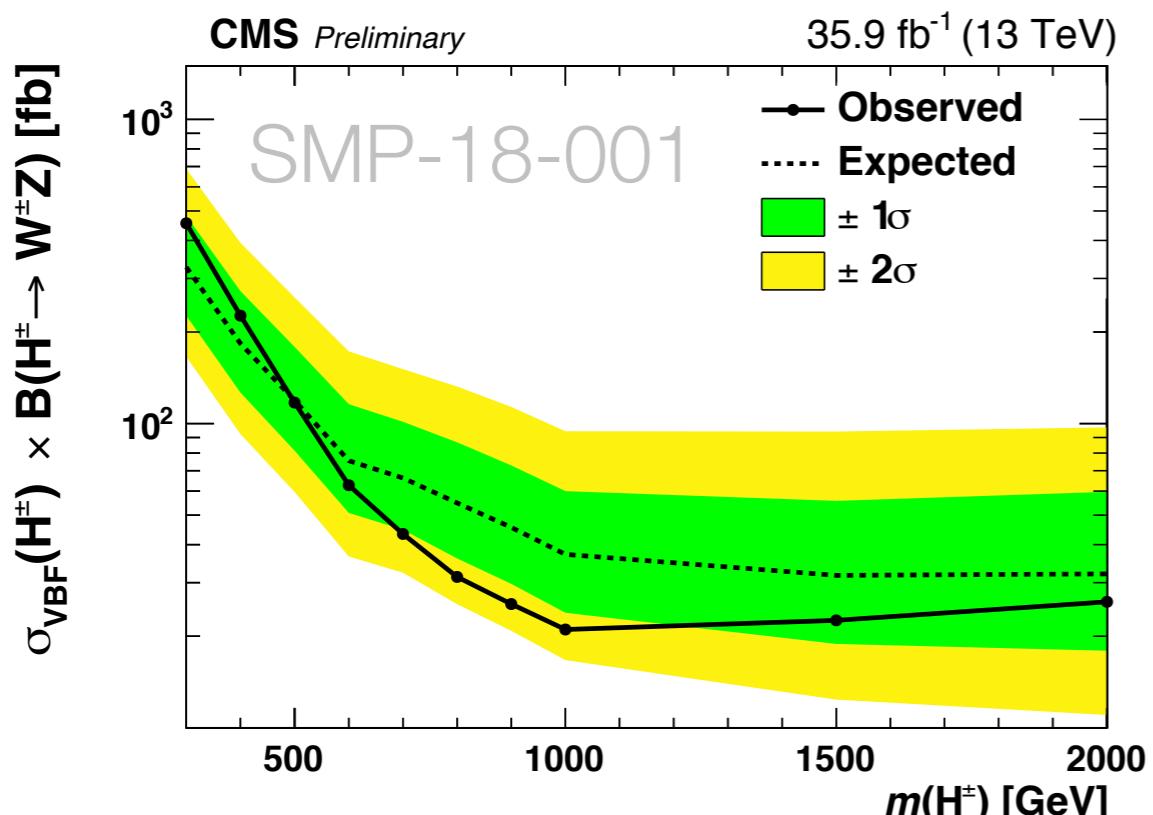
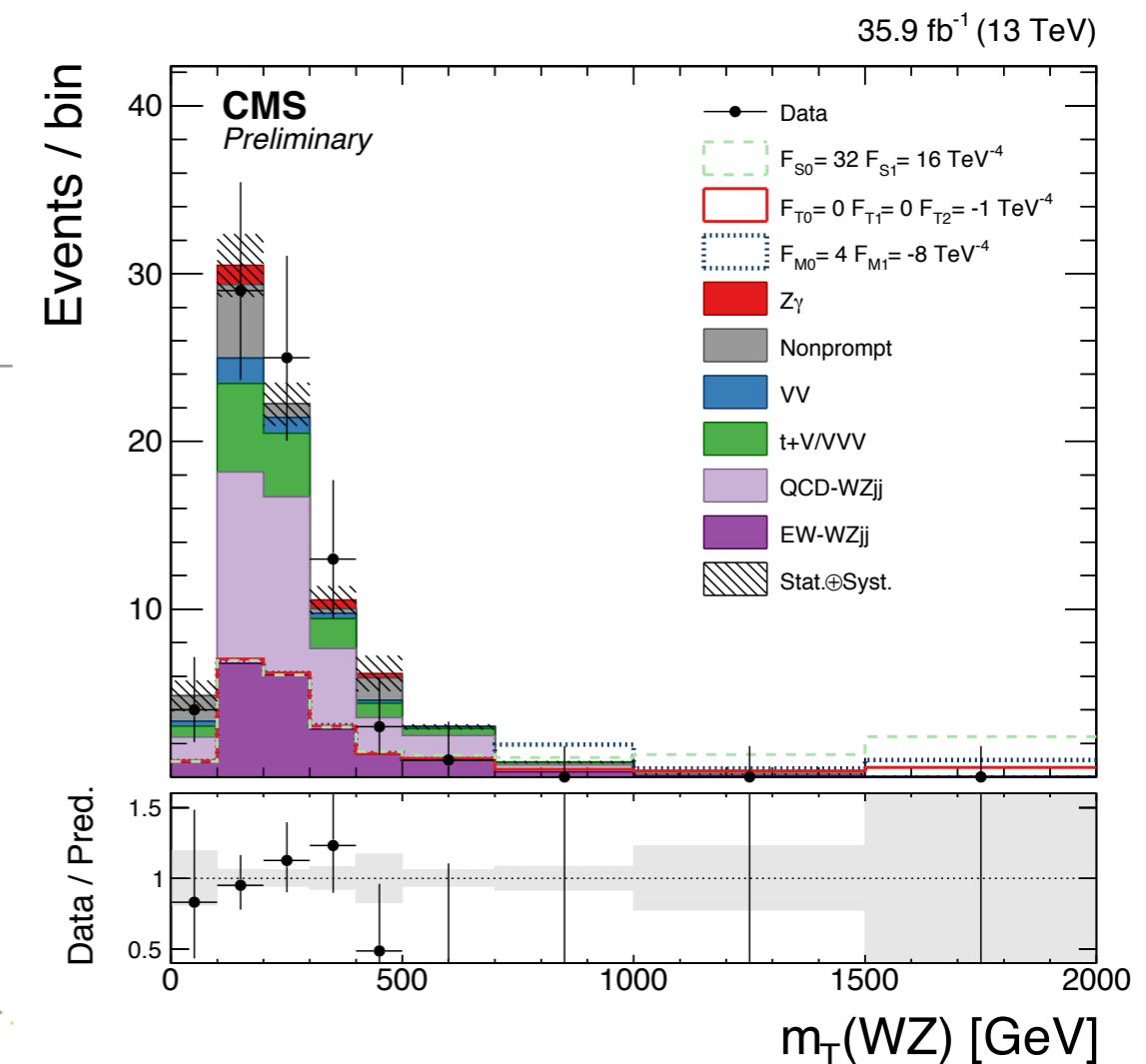


$H^+ \rightarrow WZ @ 13 \text{ TeV}$

- $WZ \rightarrow 3\text{leptons} \& \text{two jets with large } \Delta\eta$
- Reconstruct transverse mass of WZ and extract the signal

$$m_T(WZ) = \sqrt{(E_T(W) + E_T(Z))^2 - (\mathbf{p}_T(W) + \mathbf{p}_T(Z))^2}$$

$$\sigma(\text{VBF} \rightarrow H_5) = s_H^2 \sigma_1(\text{VBF} \rightarrow H_5), \quad s_H \equiv \sin \theta_H = \frac{2\sqrt{2} v_\chi}{v}$$

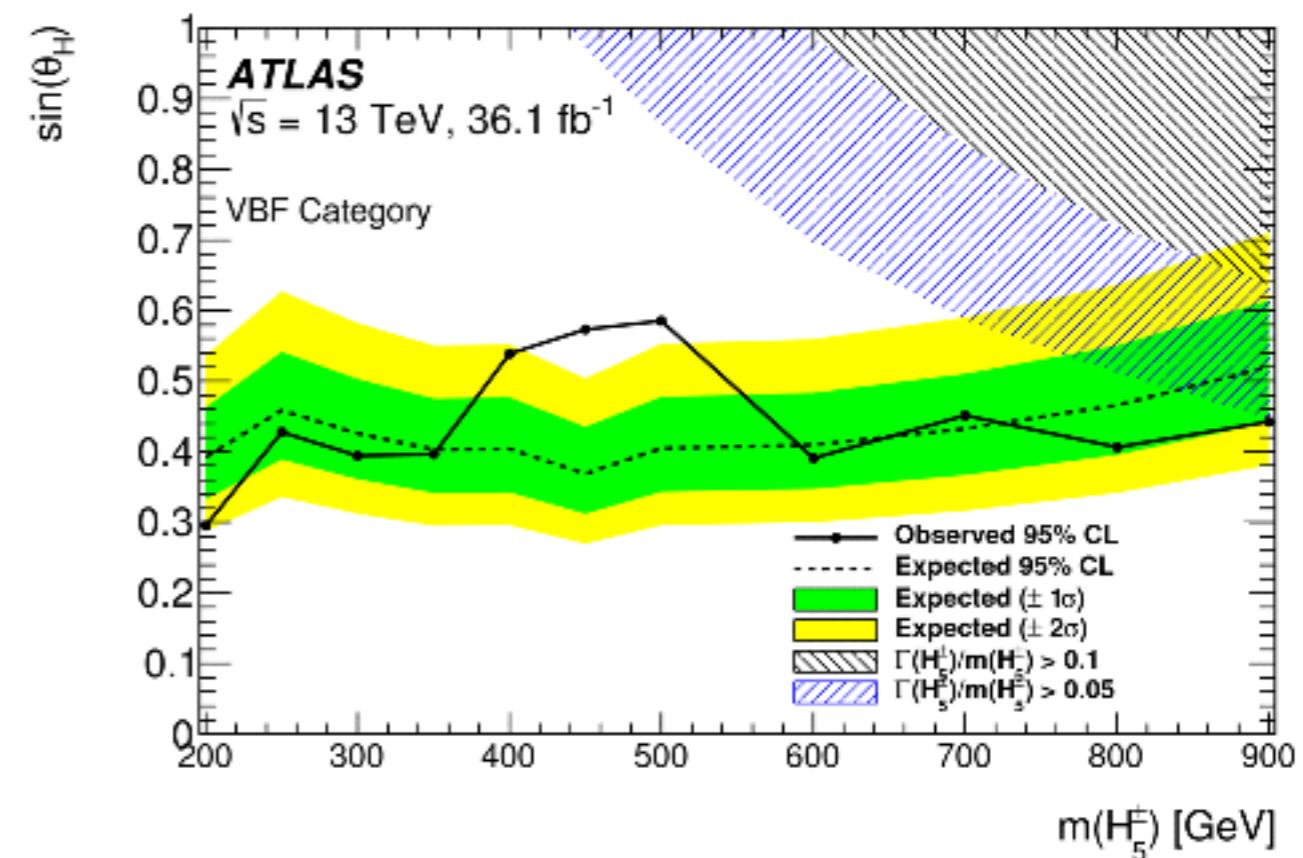
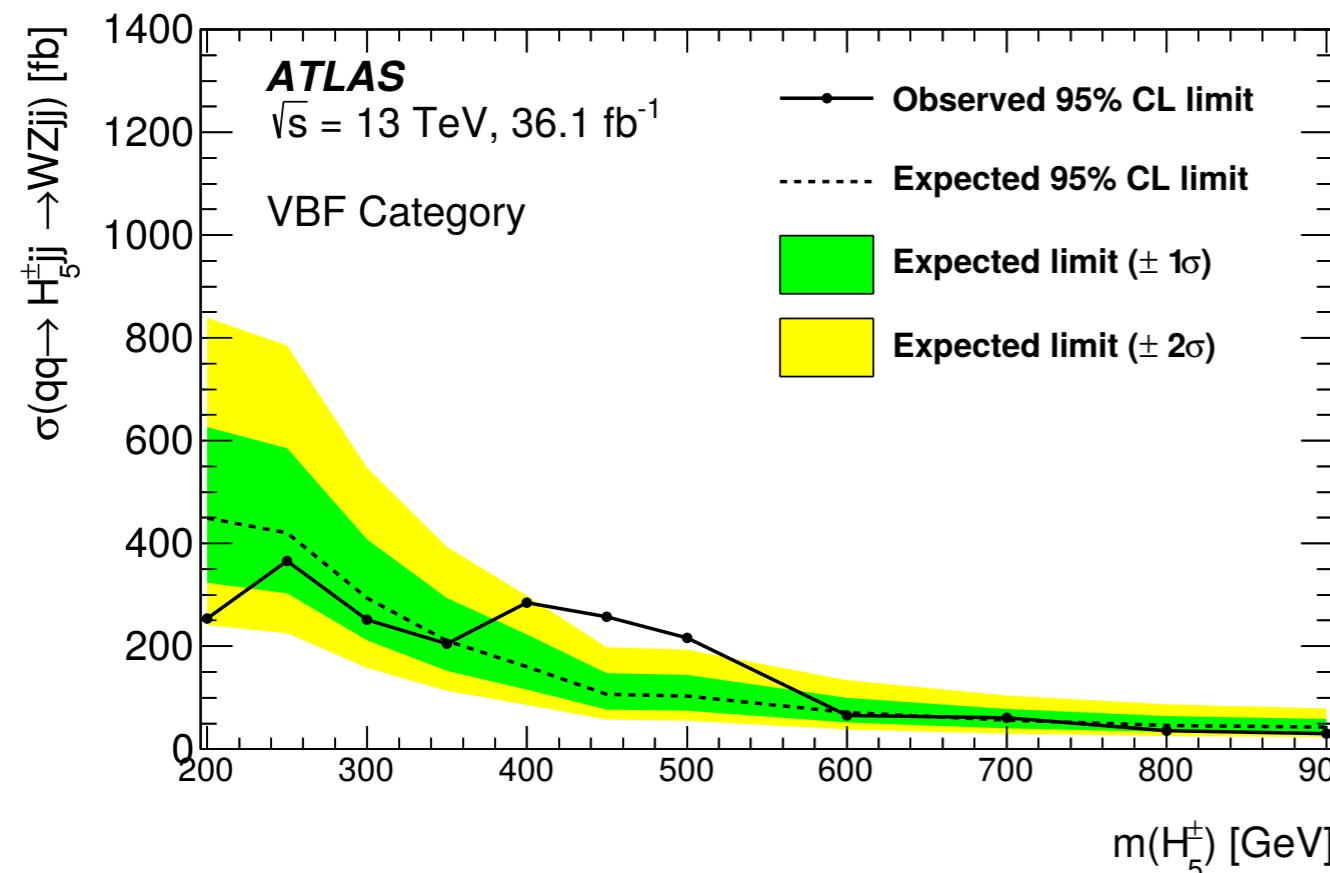
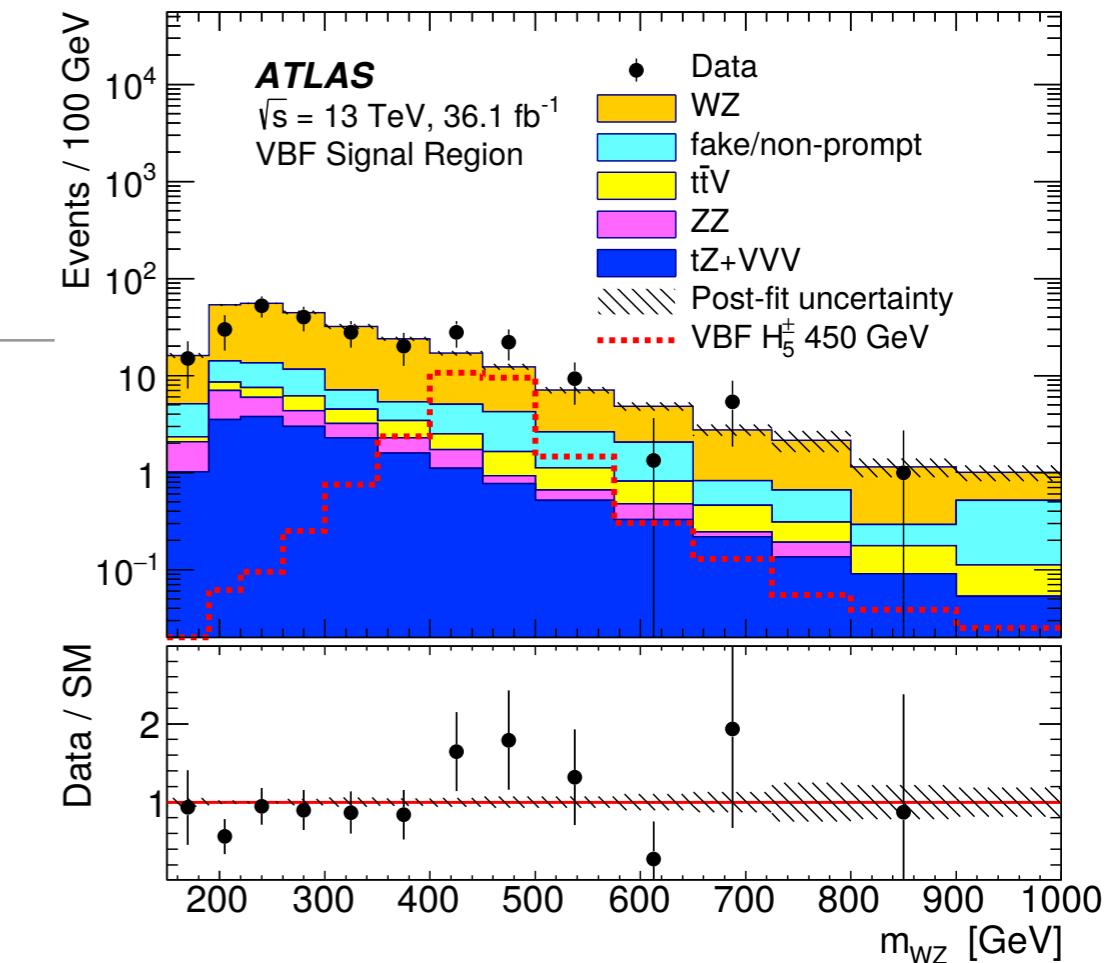


Georgi-Machacek model interpretation

$H^+ \rightarrow WZ @ 13 \text{ TeV}$

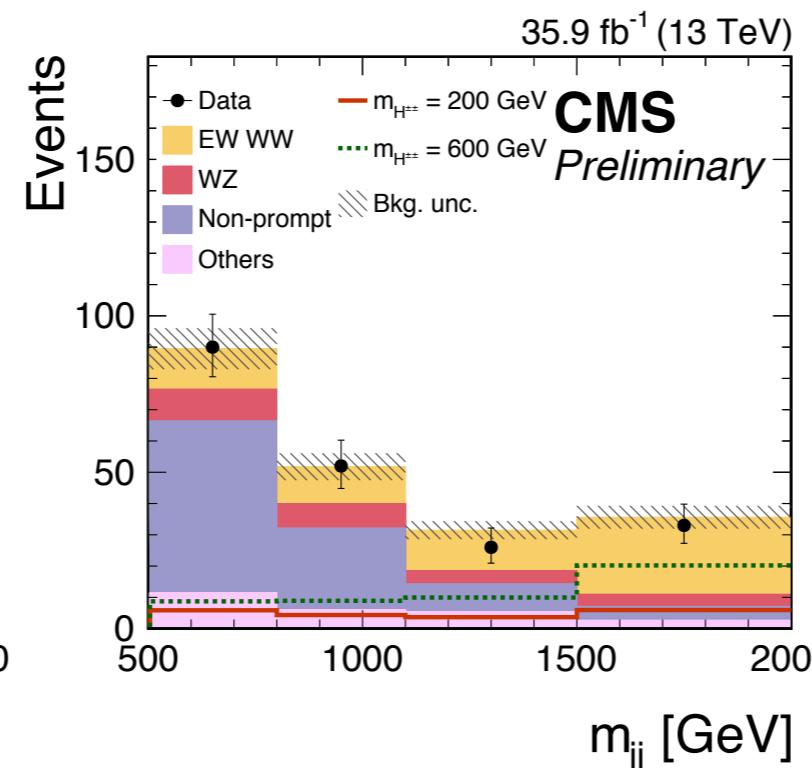
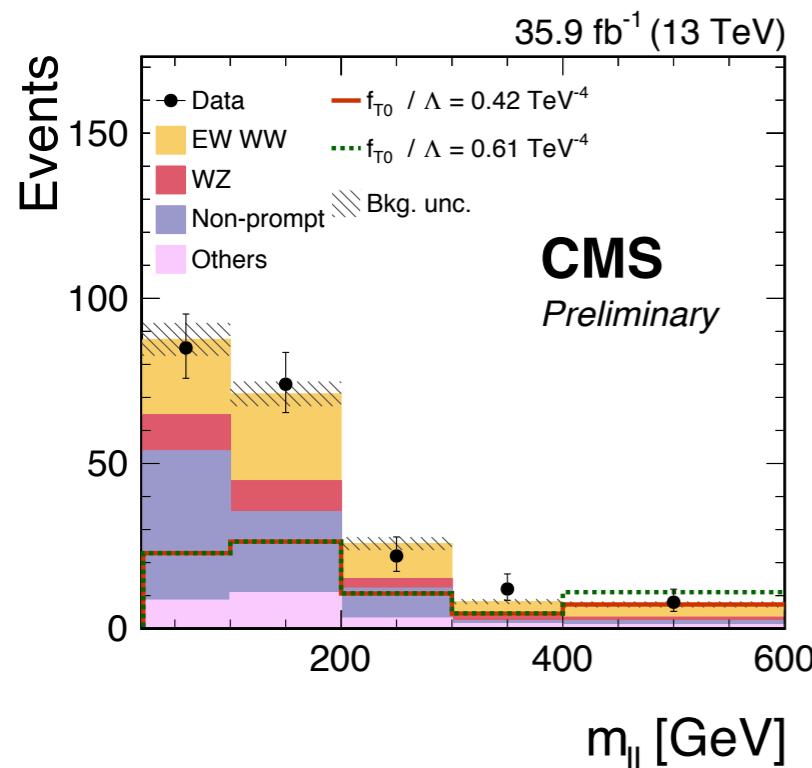
- $WZ \rightarrow 3\text{leptons} \& \text{two jets with large } \Delta\eta$
- Constrained fit on M_{WZ} , derived from lepton momenta and MET

$$\sigma(\text{VBF} \rightarrow H_5) = s_H^2 \sigma_1(\text{VBF} \rightarrow H_5), \quad s_H \equiv \sin \theta_H = \frac{2\sqrt{2} v_\chi}{v}$$

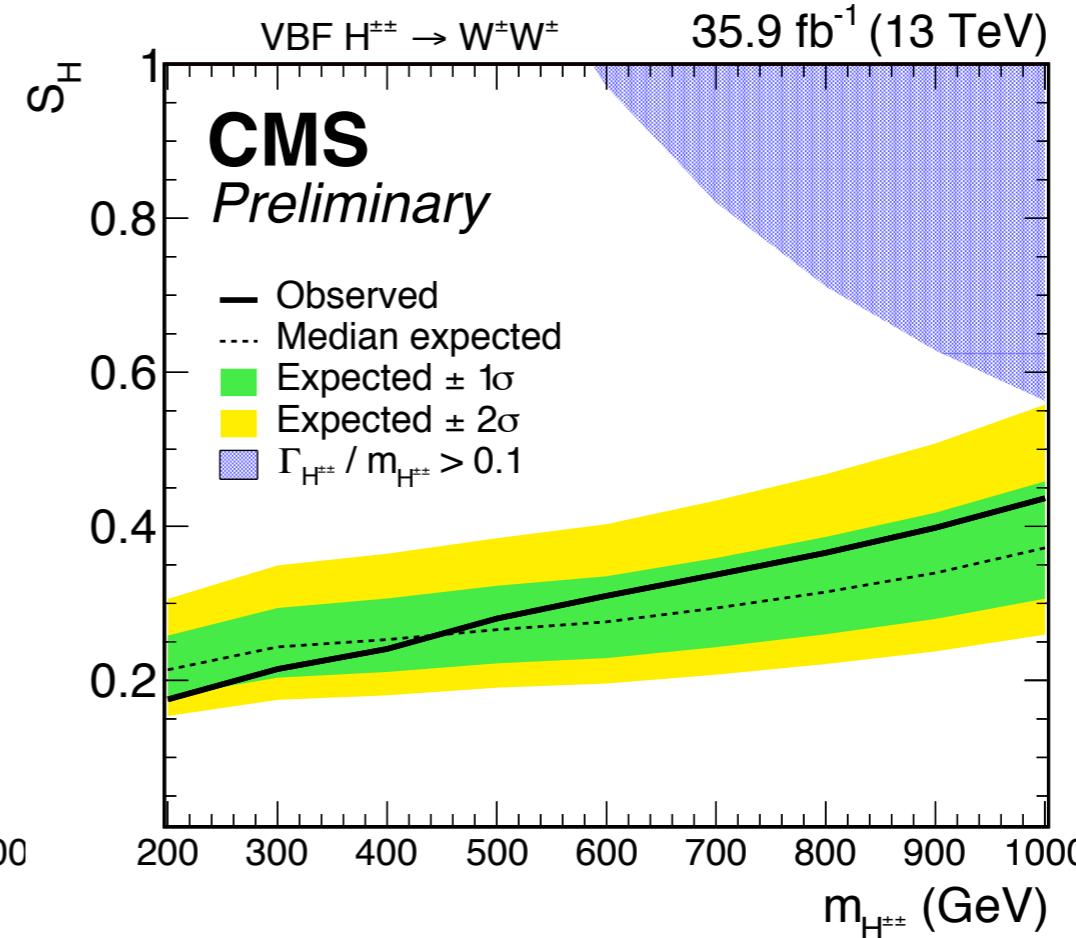
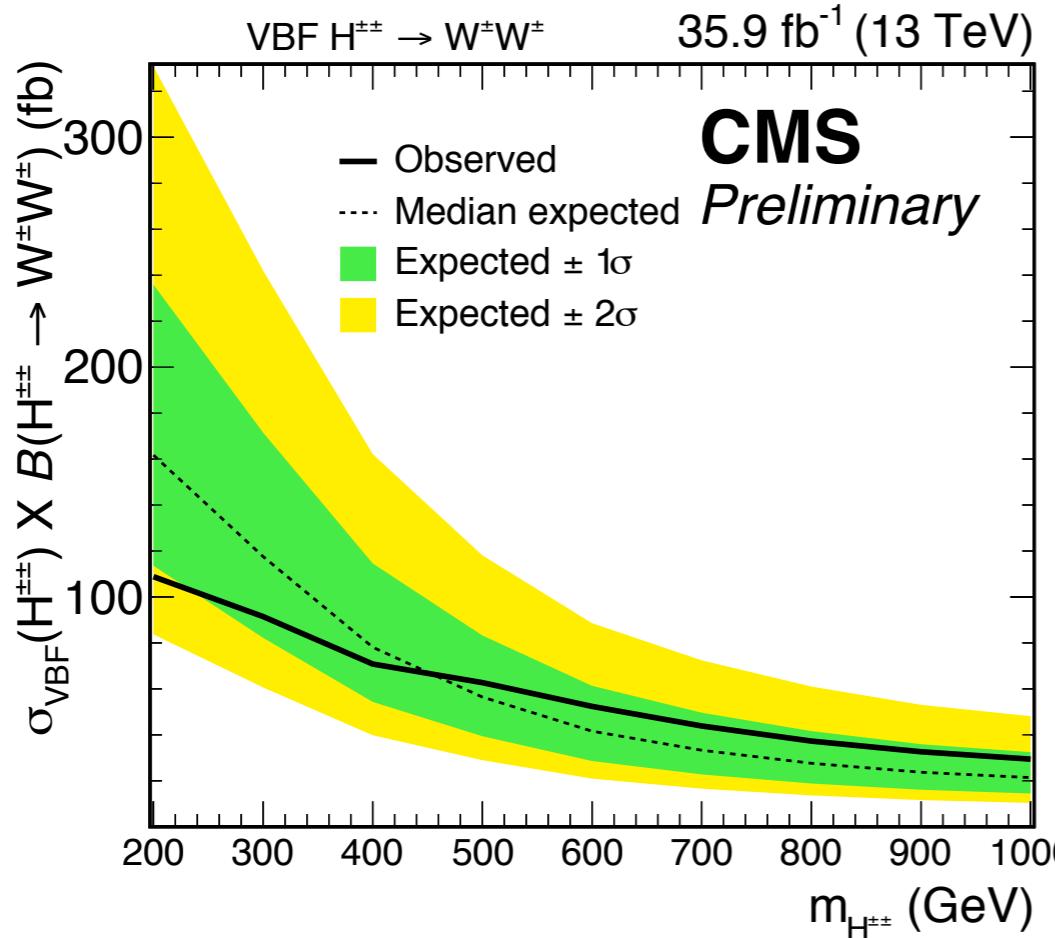


$H^{++} \rightarrow WW @ 13 \text{ TeV}$

CMS



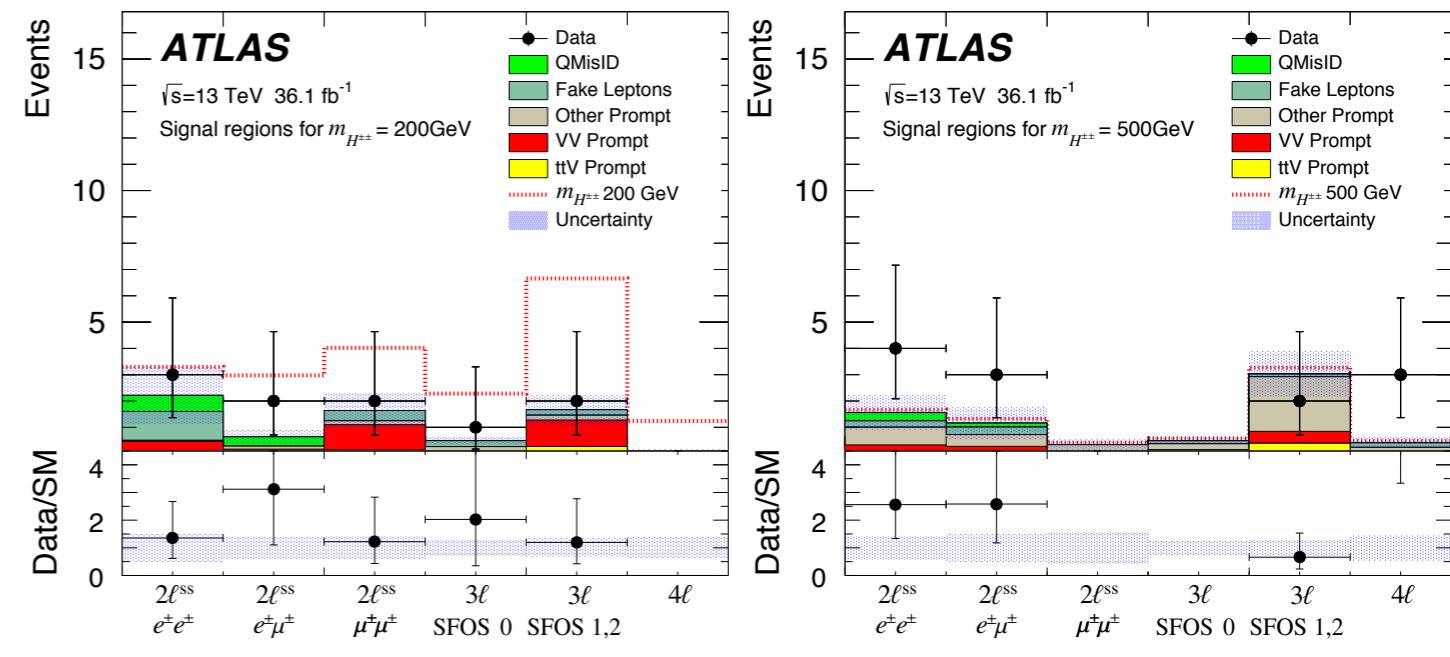
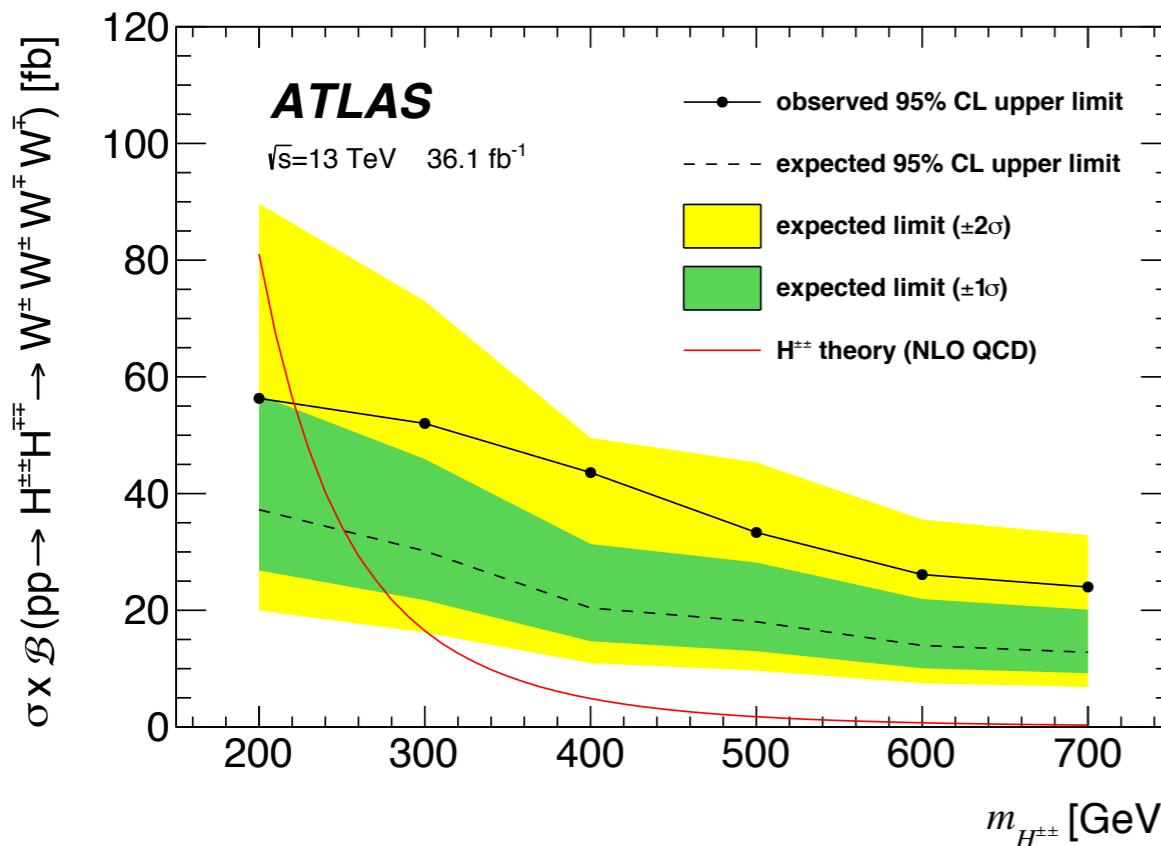
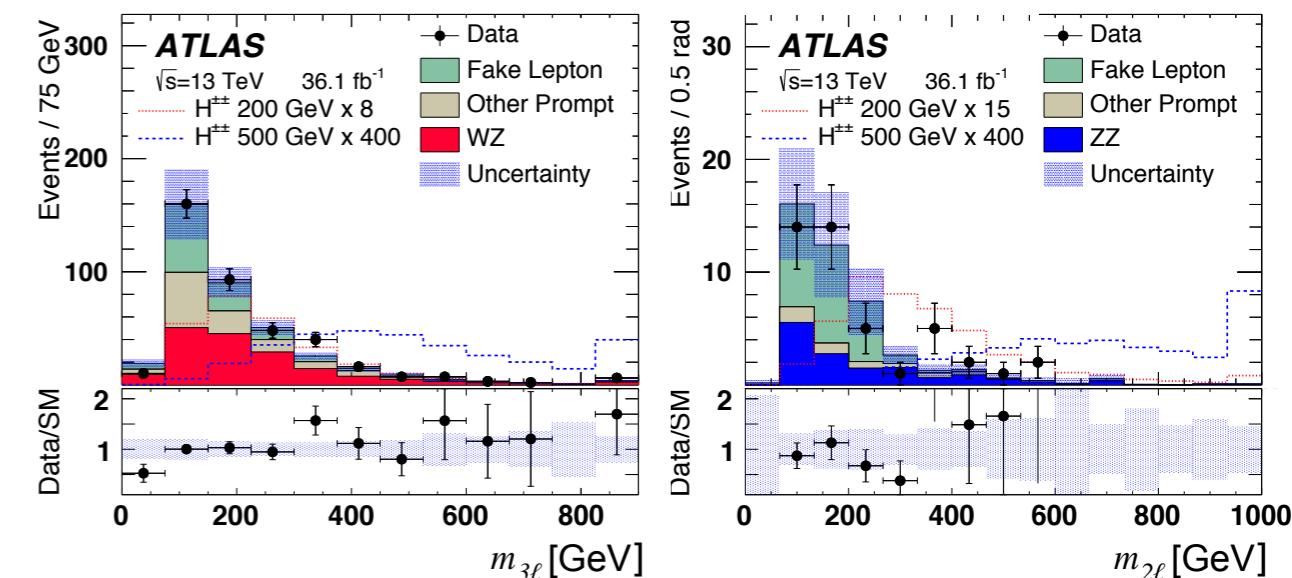
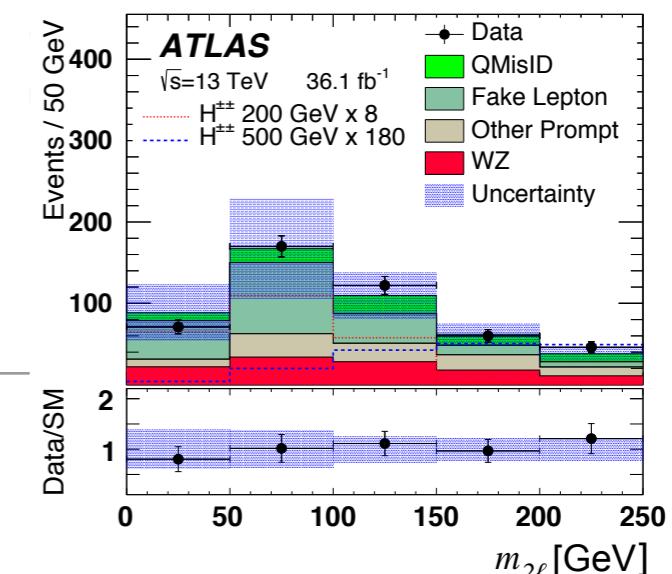
- Two isolated same-sign leptons, $p_T^{\text{miss}} > 40 \text{ GeV}$, two ak4 jets with large $\Delta\eta$
- Simultaneous fits on $m_{||}$ & m_{jj} and m_{jj} in WZ control region for H^+ signal extraction
- Limits interpreted in the Georgi-Machacek model



$H^{++} \rightarrow WW @ 13\text{ TeV}$

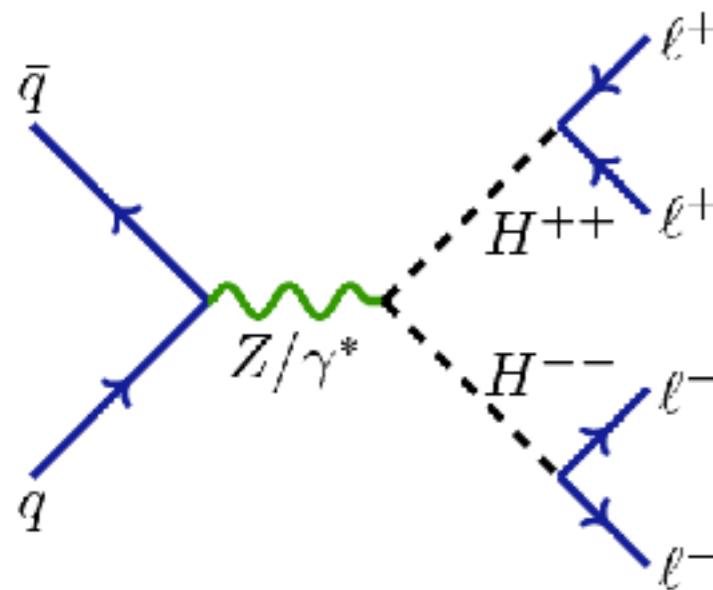


- Type-II seesaw comprising the scalar sector of a $Y=2$ scalar triplet with SM scalar doublet
- $\text{pp} \rightarrow H^{\pm\pm} H^{\mp\mp} \rightarrow W^\pm W^\pm W^\mp W^\mp$ for $m(H^{\pm\pm})$ of 200–700 GeV
- two SS leptons+two hadronic Ws ($n\text{jets} \geq 3$)
- three leptons+one hadronic W & fully leptonic Ws
- Selection optimized for each signal using TMVA

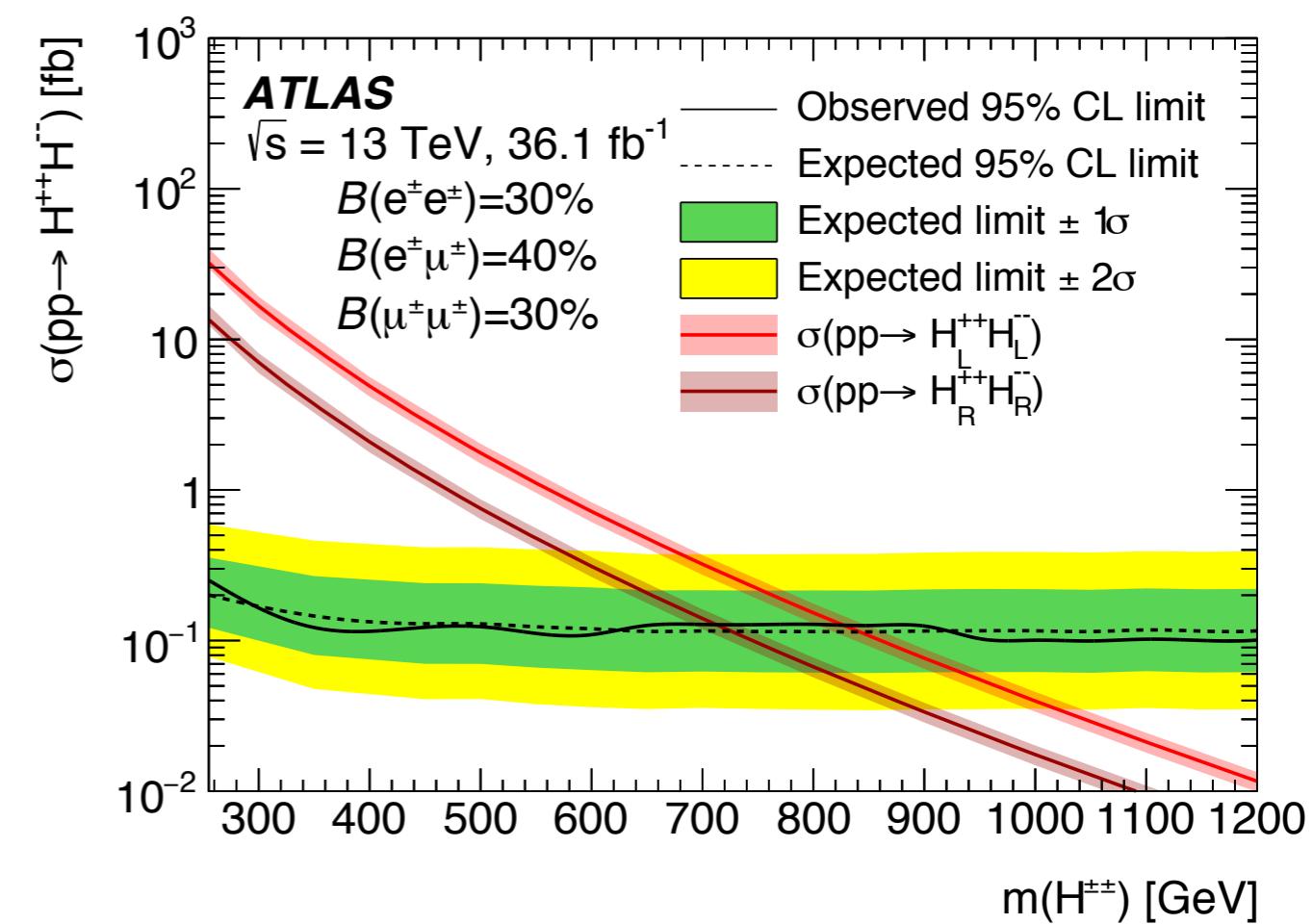
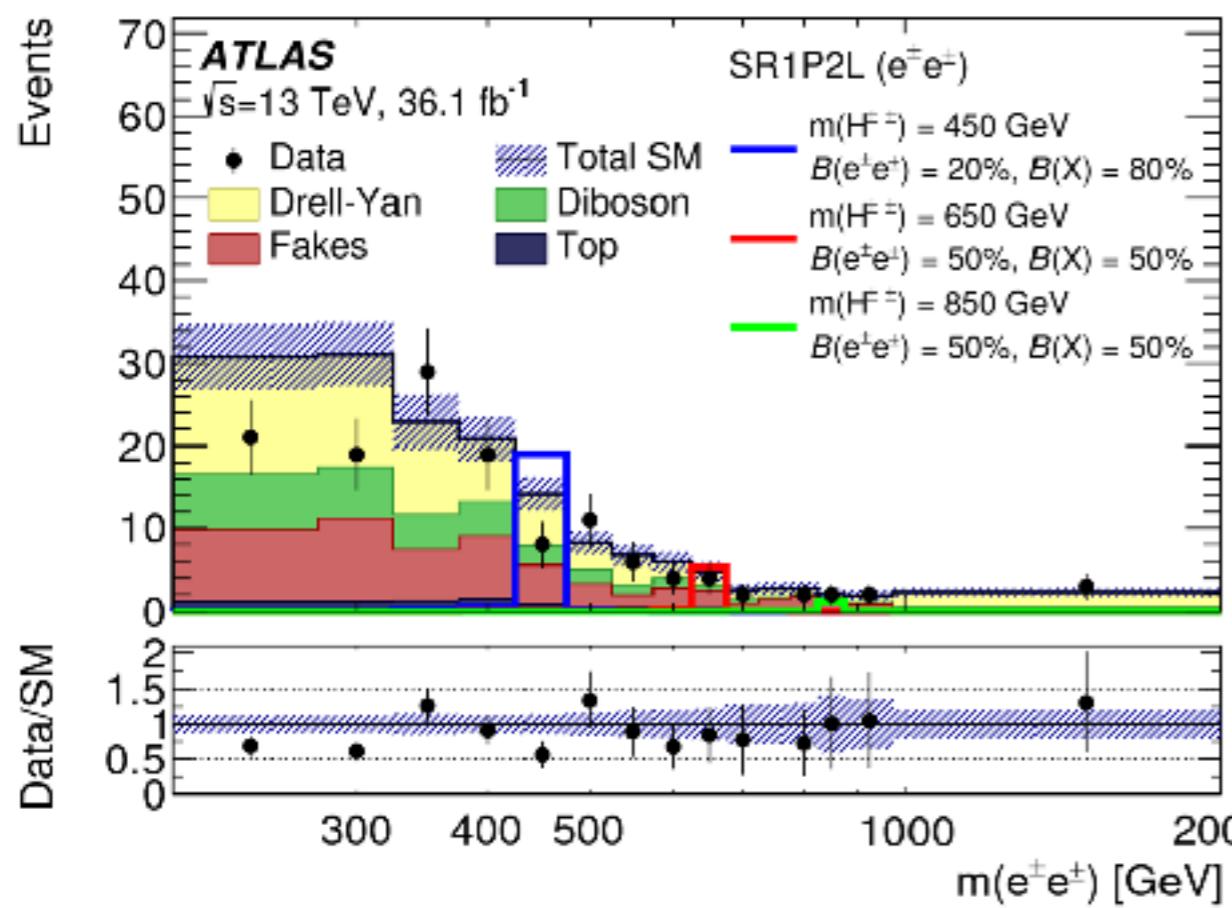




$H^{++}H^{-}\rightarrow|+|+|-|-$ @ 13 TeV



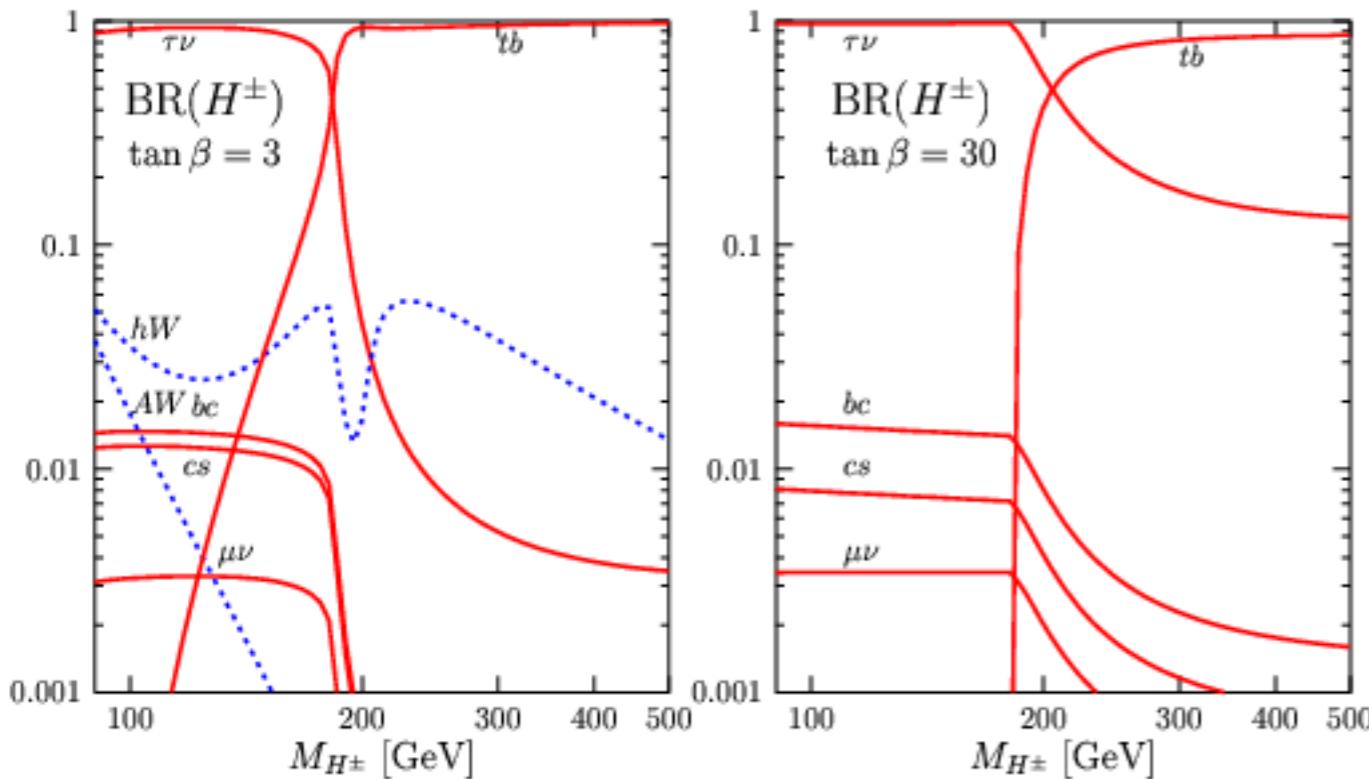
- Consider doubly charged Higgs pair predicted from a left-right symmetric model with additional triplets
 - targets the lepton decays → set triplet vev to exclude $H^{++}\rightarrow WW$
 - $200 \leq m(H^{\pm\pm}) \leq 1300$ GeV
- Fit on same charge pair distributions for nleptons ≥ 2 , $M=(m^{++}+m^{- -})/2$ for four leptons



Summary

- H^+ searches has been active since the discovery of the SM-like Higgs boson
- Yet any hints of H^+ boson has been reported from all the experiments
 - However, the H^+ must exist in most BSM theories
- Interaction between phenomenologists and experimentalists becomes important and drives the direction of the search
 - CH⁺arged workshop (late Sep. this year) becomes very active place to exchange the status of global researches - promote your ideas to the field!
 - Due to the consuming time for analysis finishing-up experimentally (2~3 yrs), co-work becomes more important at the beginning of the analysis
 - Not many people work on the H^+ in spite of the potential and importance of the discovery - May need a promotion especially among KCMS people

H^+ Decays & Widths (MSSM)



- Various scenarios available for the 2HDM under BSM hypotheses such as minimal supersymmetric standard model
- The properties of the H^+ , such as width and decays, depend on the parameters, $m(H^+)$ and $\tan\beta$

