Searches for 2HDM at the LHC

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On behalf of the

ATLAS and CMS experiments

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Outline

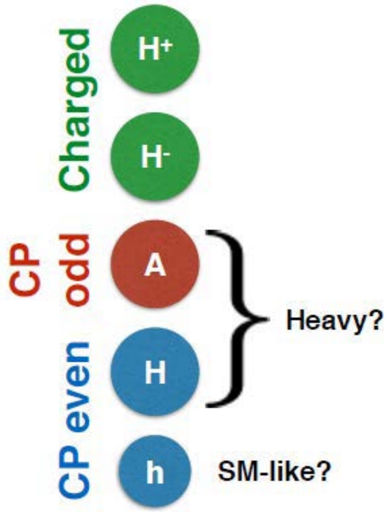
- Motivation
- Phenomenology
  - Basic postulates and parameters
  - Couplings and decay characteristics
  - Production at the LHC
- Experimental search
  - CP-even heavier neutral Higgs (H)
  - Charged Higgs bosons $(H^{\pm})$
- Summary and outlook

Motivation

- Discovery of ***a*** Higgs boson prompts further investigations into the scalar sector – it may well have a richer structure than the minimum required in SM.
- Two-Higgs doublet models (2HDM) are the simplest extension.
- 2HDM's can help explain the extent of baryon-antibaryon asymmetry in the universe - CPV allowed in SM is not enough.
- A "Type II" 2HDM is an essential feature of the MSSM, which also has an excellent candidate, the LSP, to constitute dark matter.
- Searches at LHC – through additional neutral or charged Higgs bosons - are strategically straightforward.

The two-Higgs-doublet model (2HDM)

- Two complex doublet scalar (Higgs) fields with opposite hypercharge.
- Of the 8 degrees of freedom, 3 are expended in giving mass to $W^{\pm}$, Z.
- The remaining 5 are manifested as physical particles:
    - two neutral scalars (h, H),
    - one neutral pseudoscalar (A),
    - one charge-conjugate scalar pair (H^{+}, H^{-}).



- The free parameters of the model are usually chosen as the ratio of the two VEVs, the mixing angle of CP-even fields, and the mass of H, A or H^{+}.
- Four different types are defined based on how members of the fermion family couple with those of the Higgs doublets.

Type I and Type II 2HDMs

Type	u_R	d_R	e_R
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

← $\sim$ MSSM (Type II)

- $\tan\beta = \frac{v_2}{v_1}$; $\quad m_W^2 = \frac{g^2}{2}(v_1^2 + v_2^2)$;
- $\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$

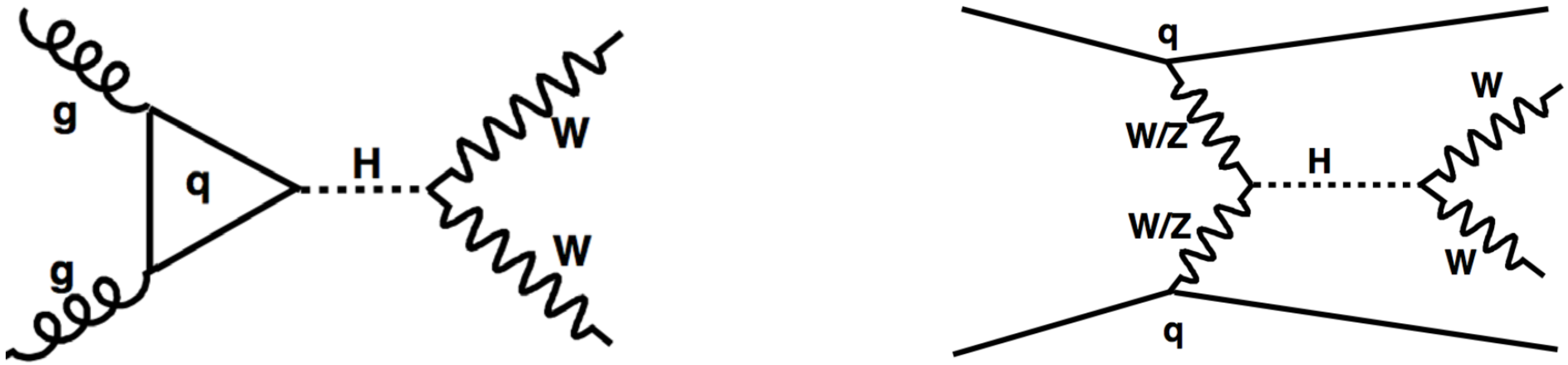
ψ_1, ψ_2: CP-even fields

- Relevant couplings:

Coupling	Type I	Type II
ξ_h^V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\sin\beta$
ξ_H^V	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

Search for the heavier CP-even Higgs boson

- Include h as a "known" part of the signal hypothesis, i.e. assume that the 125 GeV scalar boson discovered is the h of the 2HDM.
- Ensure consistent treatment of h and H w.r.t. the parameters of the model.
- Strategy: Look for $H \to WW^{(*)} \to e\nu\mu\nu$



0-jet bin **2-jet bin**

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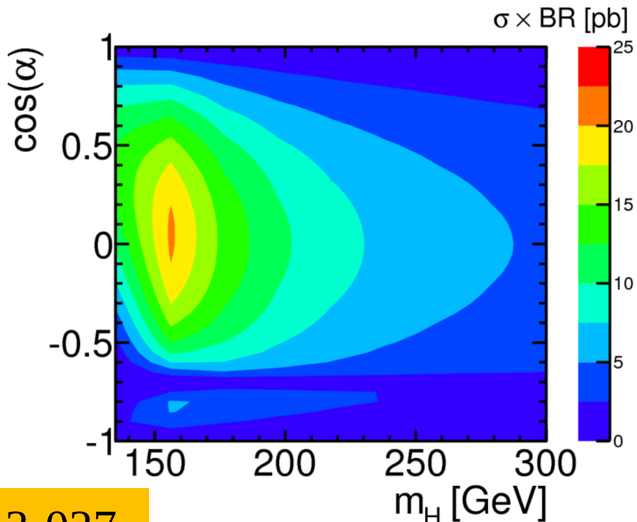
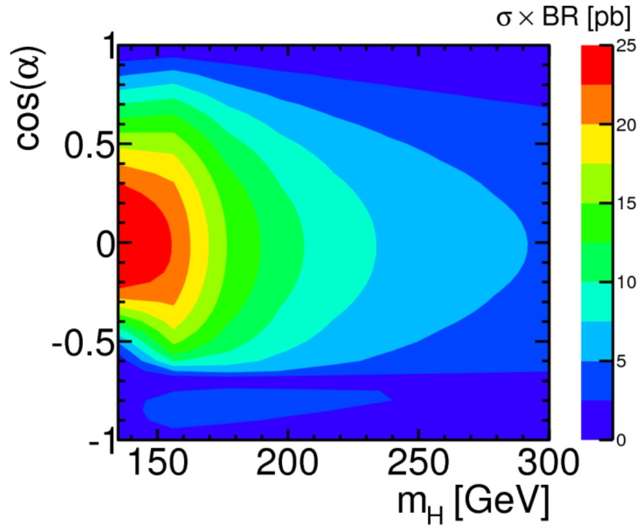
$\sigma(pp \to H) \times B(H \to WW^{(*)} \to e\nu\mu\nu)$

$\tan\beta = 1$

Type 1 | **Type 2**

***gg* fusion**





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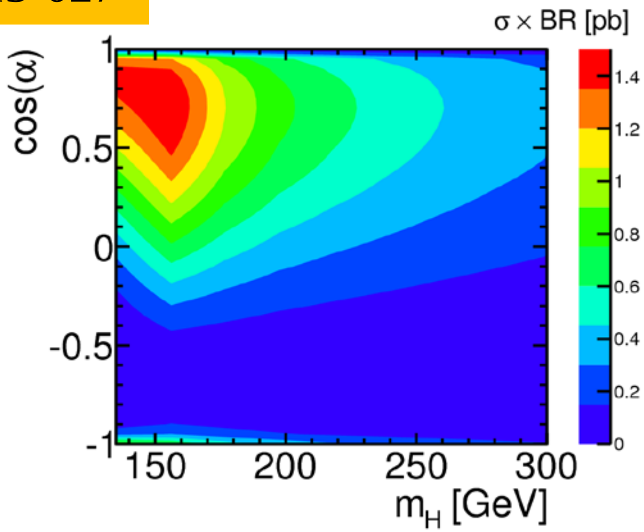
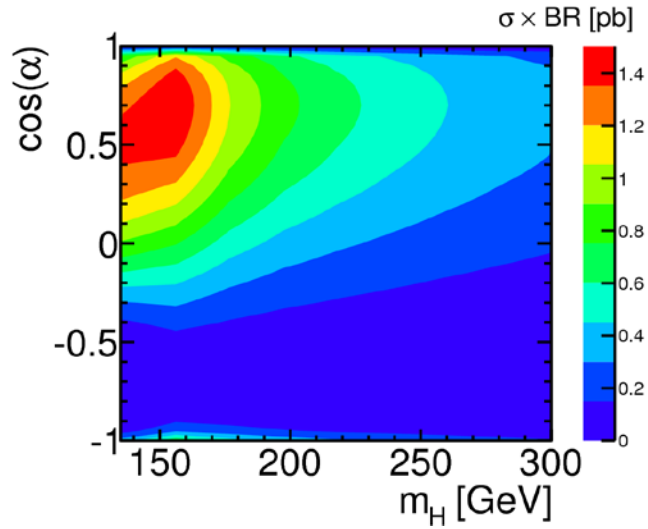
VB fusion





Search for $H \to WW^{(*)} \to e\nu\mu\nu$ (ATLAS)

- Isolated e, μ with $p_T(l_1) > 25$ GeV, $p_T(l_2) > 15$ GeV,
- $E_T{}^{miss} > 25$ GeV (with special consideration w.r.t. nearest lepton)
- Neural Network with 6 (9) inputs for the 0 (2) jet bin.

Process	0 jet	2 jet	Top control region	WW control region
Signal (m_h = 125 GeV)	2.55 ± 0.50	5.52 ± 0.71	1.35 ± 0.19	0.76 ± 0.13
Signal (m_H = 150 GeV)	470 ± 140	76 ± 19	20.9 ± 5.7	16.1 ± 3.9
$WW/WZ/ZZ/W\gamma/W\gamma*$	1140 ± 290	63 ± 18	22.1 ± 6.2	1170 ± 310
Z/γ^* + jets	41 ± 15	194 ± 72	84 ± 31	15.7 ± 6.4
W+jets	135 ± 58	23.4 ± 9.7	18.3 ± 7.6	78 ± 32
$t\bar{t}/tW/tb/tqb$	175 ± 49	168 ± 77	1760 ± 440	313 ± 97
Total background	1490 ± 420	450 ± 180	1890 ± 480	1580 ± 450
S/B	0.31	0.18	–	–
Observed	1815	483	1986	1725

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Search for $H \to WW^{(*)} \to e\nu\mu\nu$ (ATLAS)

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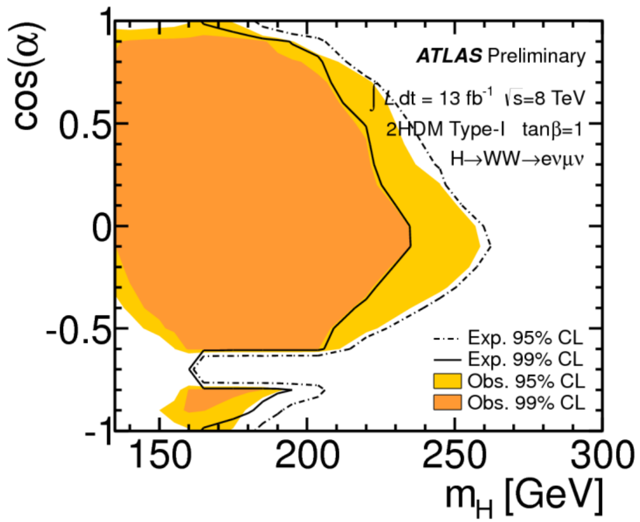
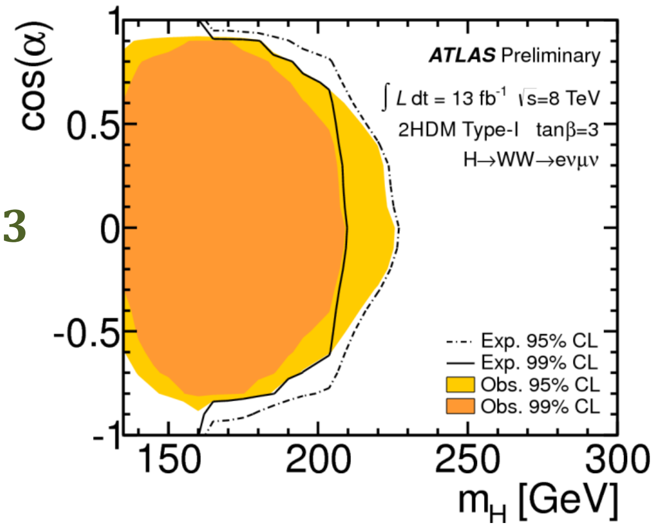
Result for Type I 2HDM

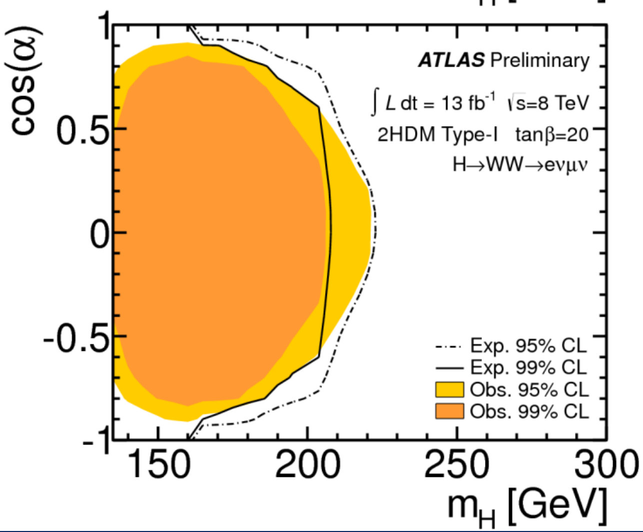
y_{2HDM}/y_{SM}	Type I	Type II
ξ_h^V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\sin\beta$
ξ_H^V	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$



$\tan\beta = 1$

$\tan\beta = 3$





$\tan\beta = 20$

Search for $H \to WW^{(*)} \to e\nu\mu\nu$ (ATLAS)

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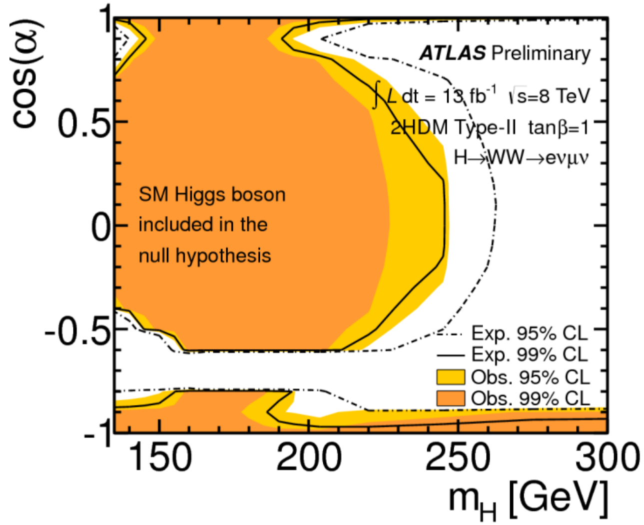
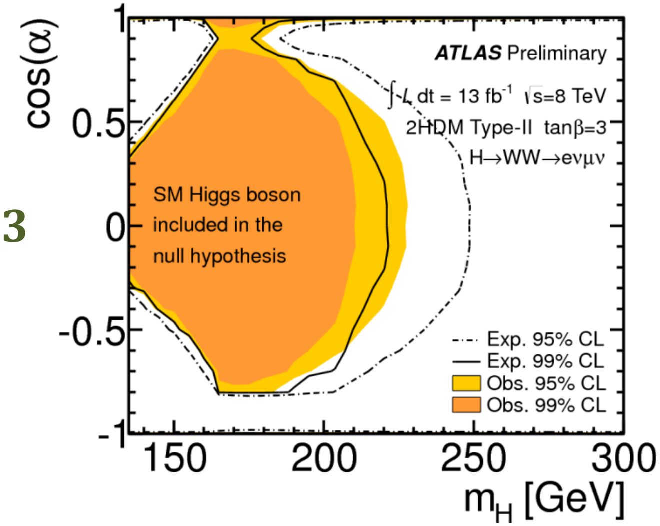
Result for Type II 2HDM

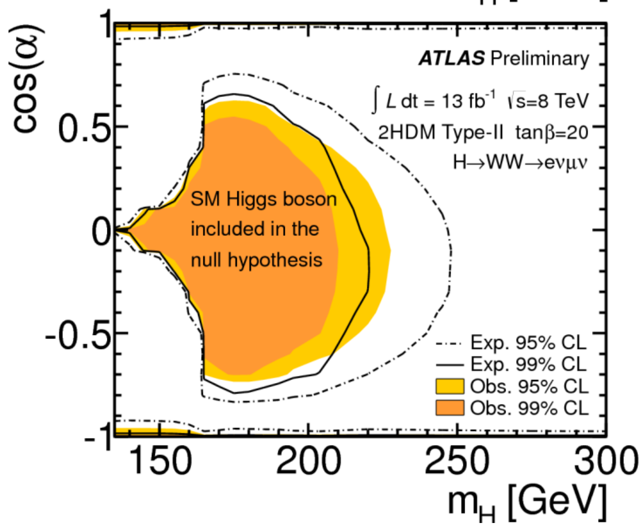
y_{2HDM}/y_{SM}	Type I	Type II
ξ_h^V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\sin\beta$
ξ_H^V	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$



$\tan\beta = 1$



$\tan\beta = 3$

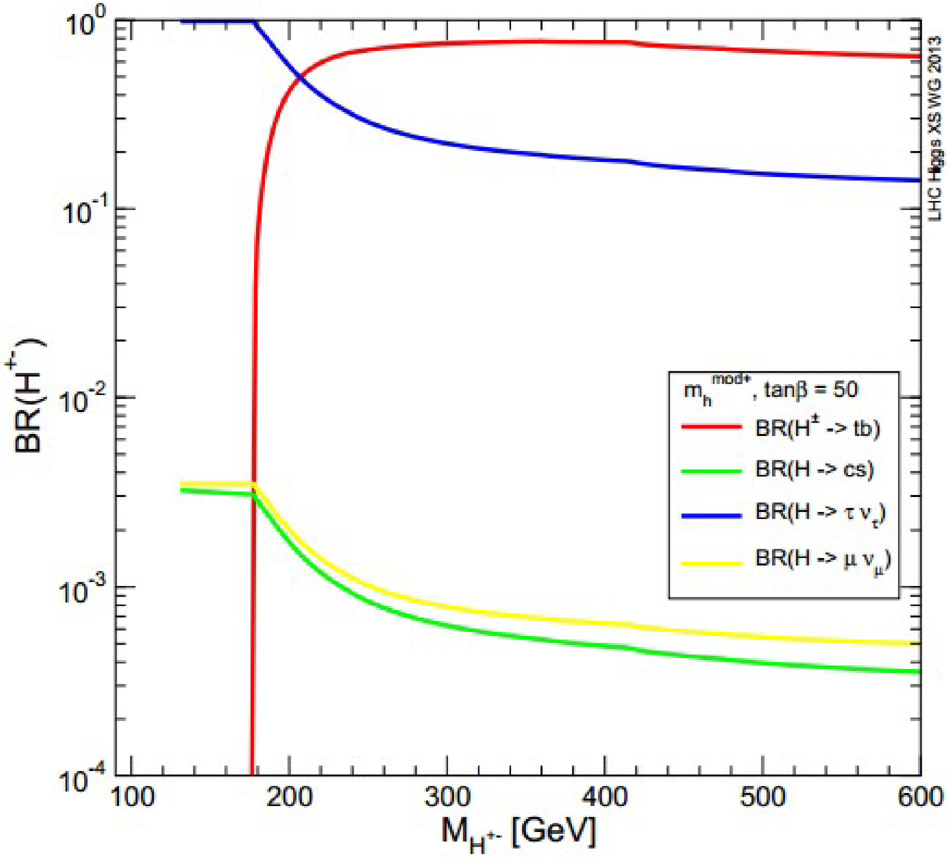


$\tan\beta = 20$

H^+ decay branching fractions

Partial decay widths calculated with FeynHiggs and HDecay (using MSSM input parameters provided by FeynHiggs)

$$\Gamma_{H^+} = \Gamma_{H^+\to\tau\nu} + \Gamma_{H^+\to\mu\nu} + \Gamma_{H^+\to hW} + \Gamma_{H^+\to HW} + \Gamma_{H^+\to AW} + \Gamma_{H^+\to tb} + \Gamma_{H^+\to ts} + \Gamma_{H^+\to td} + \Gamma_{H^+\to cb} + \Gamma_{H^+\to cs} + \Gamma_{H^+\to cd} + \Gamma_{H^+\to ub} + \Gamma_{H^+\to us} + \Gamma_{H^+\to ud}$$



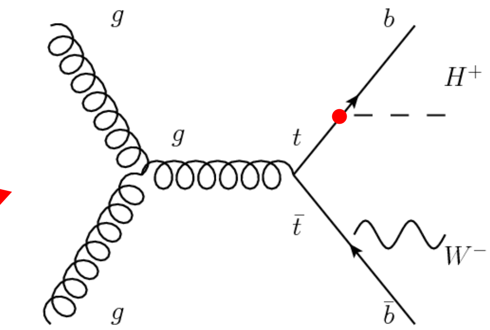
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/BRs#YR3_numbers

H^+ production at the LHC: processes

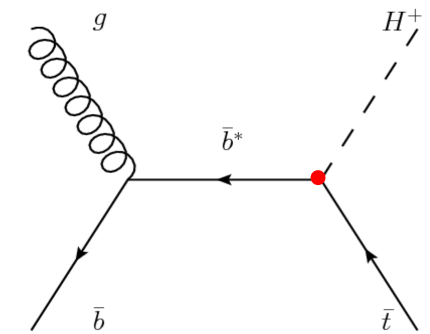
Relevant coupling: $g(tbH^+) \sim (m_t \cot\beta + m_b \tan\beta)$

If $m_{H^+} < m_t$

Primary contribution from decays of top quarks



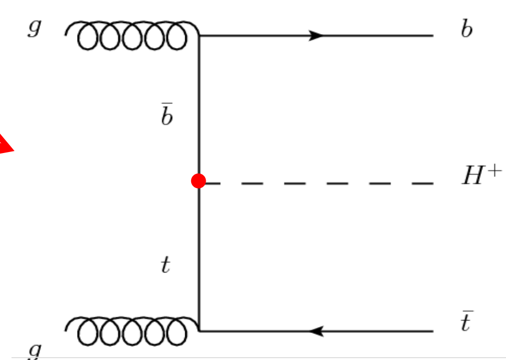
- Production cross section:
  $\sigma(pp \to t\bar{t}) \times B(t \to H^+ b)$ [dominant at LHC]
  The first factor is calculated and measured with precision better than 10%. There are several options to measure the latter.



If $m_{H^+} > m_t$

Production is expected to occur primarily in association with single top quarks – replace W^+ with H^+ in SM single top production.

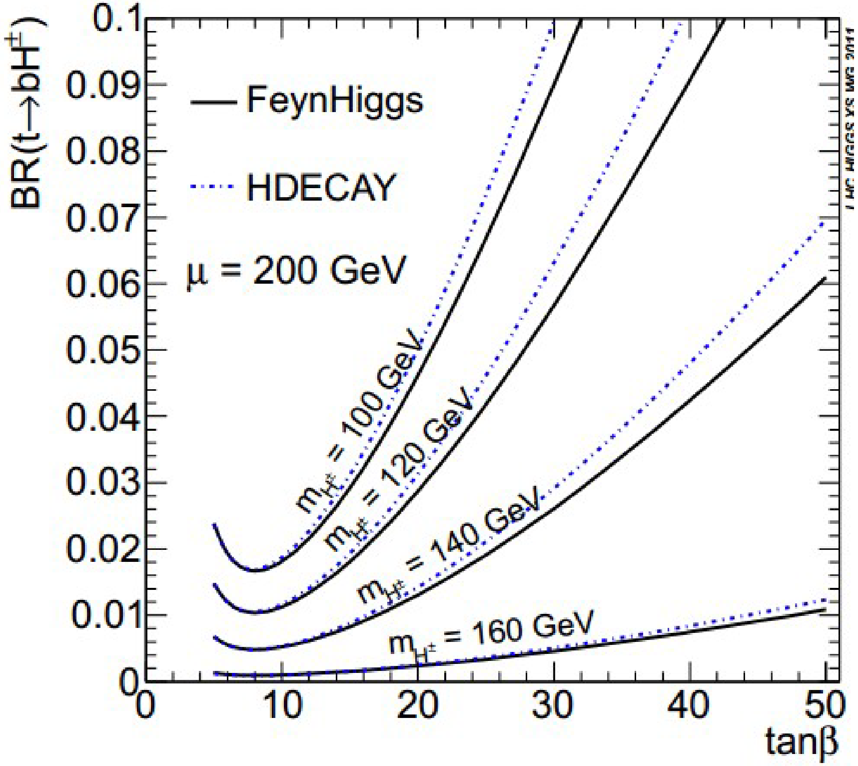
- Production cross section is much smaller.

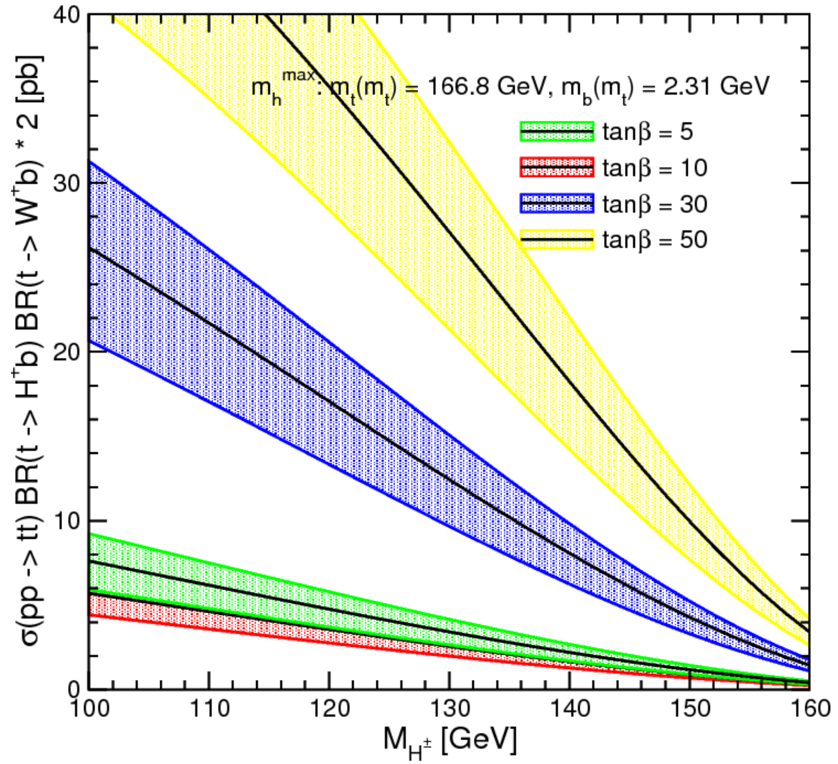


H+ production at the LHC: cross section, $m_{H^+} < m_t$

Partial decay widths calculated with FeynHiggs and HDecay
(using MSSM input parameters provided by FeynHiggs)

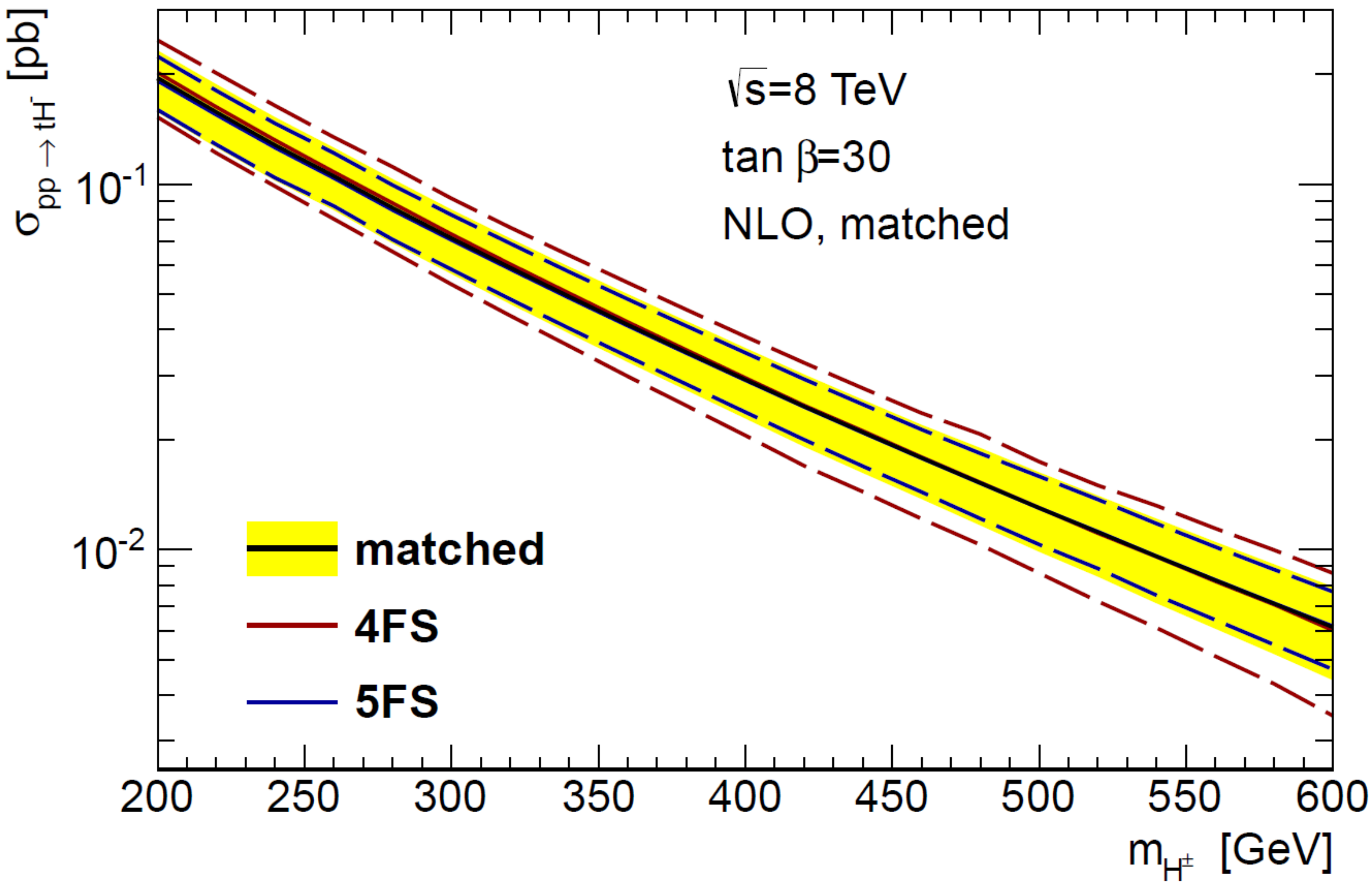
$\sqrt{s} = 14$ TeV





https://twiki.cern.ch/twiki/pub/LHCPhysics/MSSMCharged/mhmax-tb.tar.gz

H⁺ production at the LHC: cross section, $m_{H^+} > m_t$



http://arxiv.org/abs/1409.5615

H^+ search strategies at the LHC

For $\boldsymbol{m_{H^+} < m_t}$

- Look for $t \rightarrow H^+ b$ followed by
  - $H^+ \rightarrow \tau^+ \nu_\tau$ for $\tan\beta > \sim 1$
  - $H^+ \rightarrow c\bar{s}$ for $\tan\beta < \sim 1$
- $B(t \rightarrow H^+ b) \approx 0$ at $\tan\beta \approx \sqrt{\frac{m_t}{m_b}} \approx 8$: sensitivity is at minimum

For $\boldsymbol{m_{H^+} > m_t}$

- $H^+ \rightarrow tb \rightarrow W^+ b\bar{b}$ dominates, but $H^+ \rightarrow \tau^+ \nu_\tau$ is cleaner with a branching fraction of ~ 0.2 if $\tan\beta > \sim 3$.

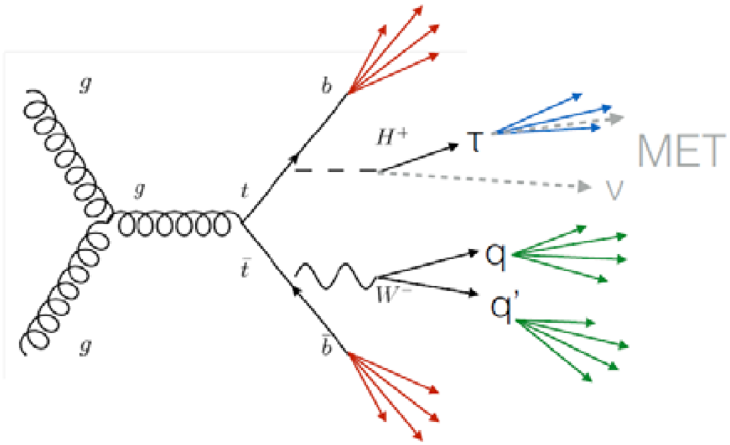
$H^+ \rightarrow W^+ b\bar{b}$ is significant even for $\tan\beta < \sim 1$ if $m_t - m_{H^+}$ is small. However, it is very difficult to extact from the SM decay of $t\bar{t}$.

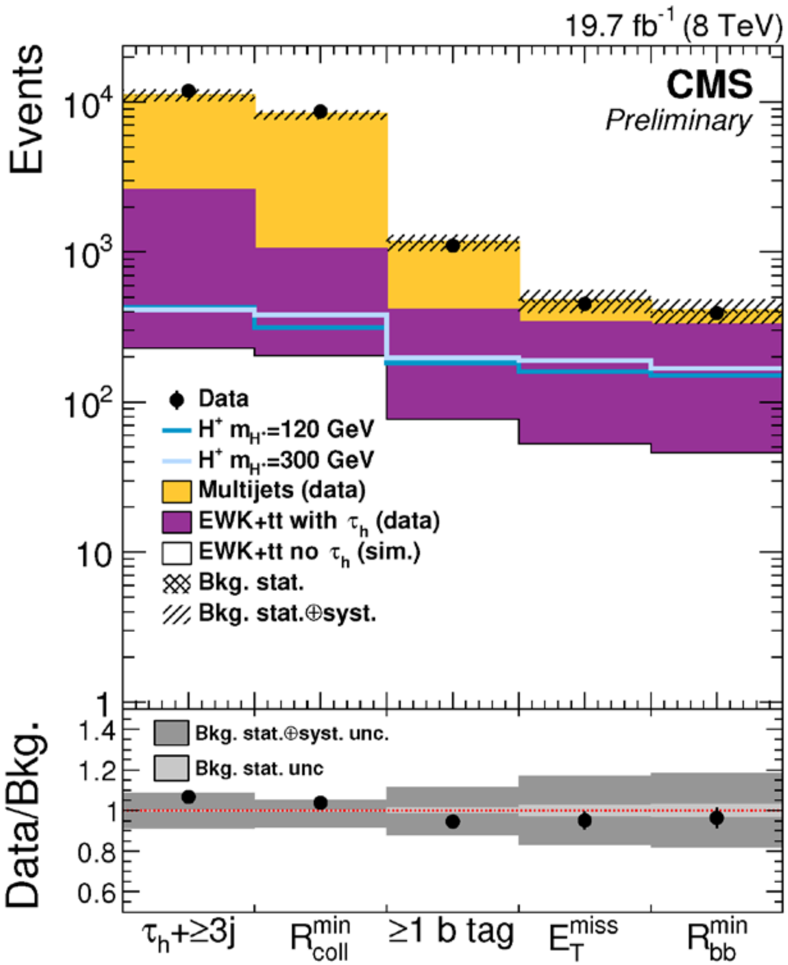
Other search strategies

- Look for tell-tale violation of lepton universality in charged current interactions among $t\bar{t}$ event candidates,
- Look for $H^0 \rightarrow H^{\pm}W^{\mp}$ (Higgs "cascade" decays),
- Look for $H^+ \rightarrow t\bar{b}$,
- Other all-bosonic vertices,
- Vertices involving BSM particles.

(Results are available from the first three of these)

$H^+ \to \tau^+ \nu_\tau$ (CMS)





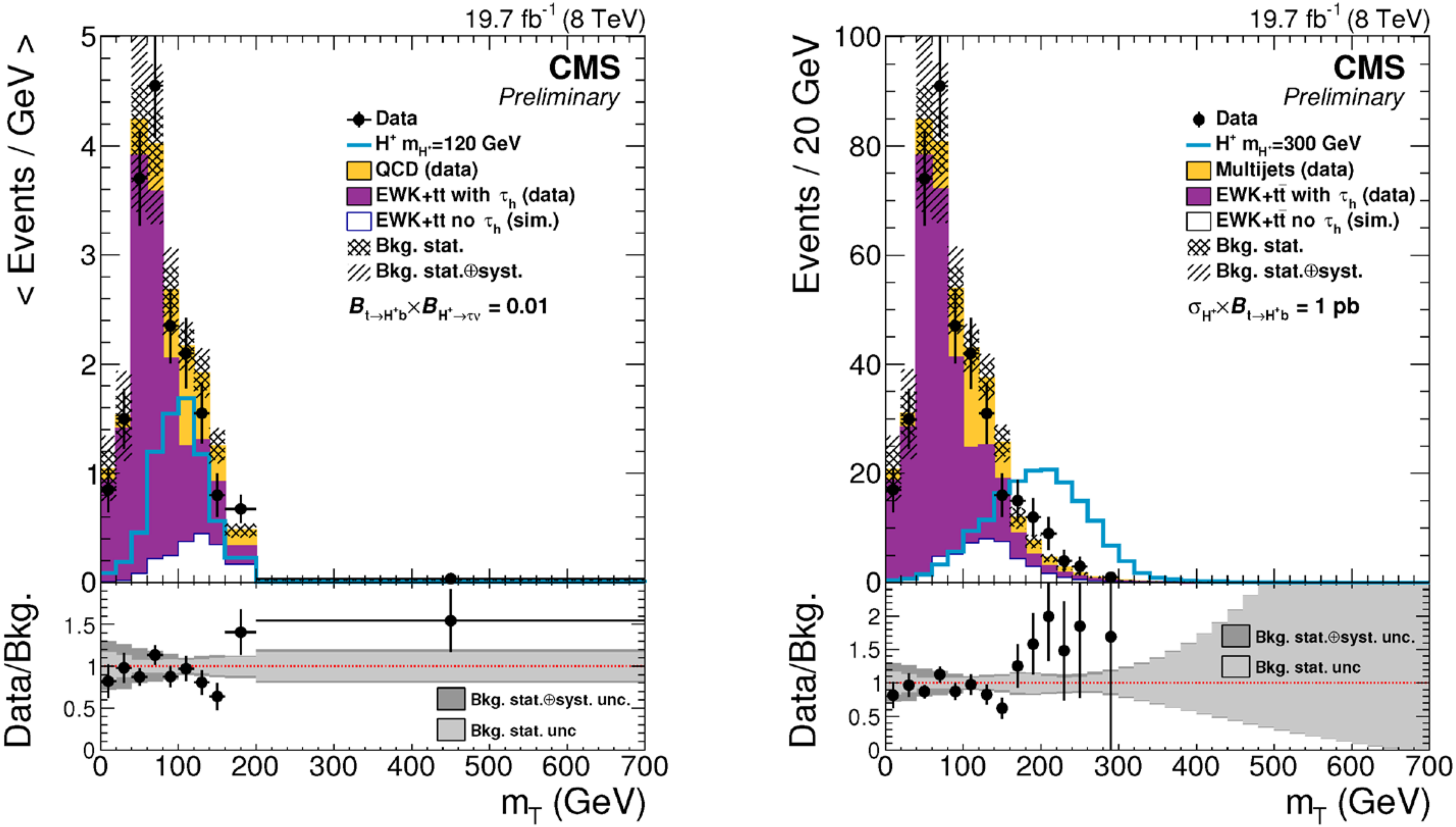
- Use $\tau_h + E_T{}^{miss}$ trigger.
- Shape analysis using

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\tau_h} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi(\vec{p}_{\mathrm{T}}^{\tau_h}, \vec{E}_T^{\mathrm{miss}}))}$$

- Dominant background: QCD multi-jet, EWK + $t\bar{t}$ (with or without a τ_h).

CMS PAS-HIG-14-020

$H^+ \to \tau^+ \nu_\tau$ (CMS)



CMS PAS-HIG-14-020

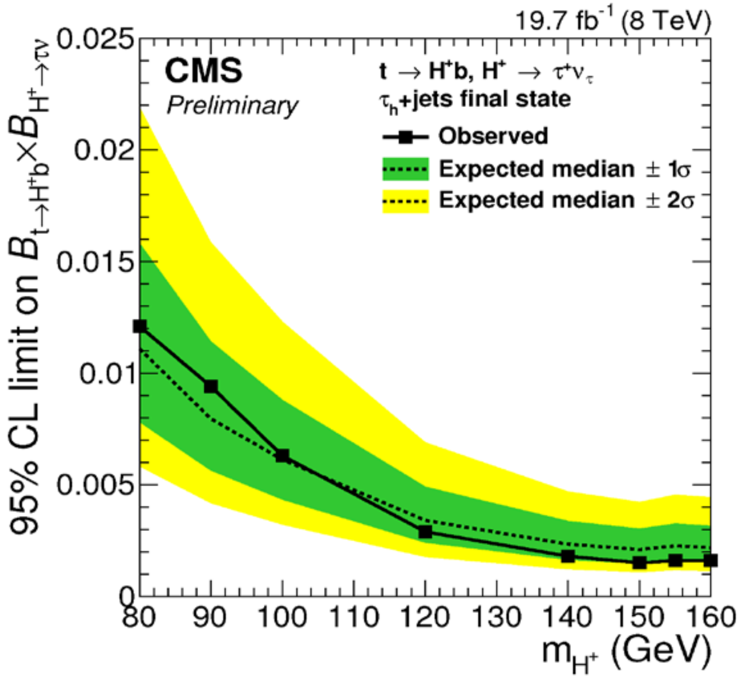
$H^+ \to \tau^+ \nu_\tau$ (CMS)

	$N_{events} \pm$ stat. $\pm$ syst.
Signal, $m_{H^+} = 120\,\mathrm{GeV}$	$151 \pm 4\,^{+17}_{-18}$
Signal, $m_{H^+} = 300\,\mathrm{GeV}$	$168 \pm 2 \pm 16$
Multijet background (data)	$78 \pm 3 \pm 17$
EWK+$\mathrm{t\bar{t}}$ with τ_h (data)	$283 \pm 12\,^{+55}_{-54}$
EWK+$\mathrm{t\bar{t}}$ no τ_h (sim.)	$47 \pm 2\,^{+11}_{-10}$
Total expected from the SM	$407 \pm 12\,^{+59}_{-58}$
Observed:	392

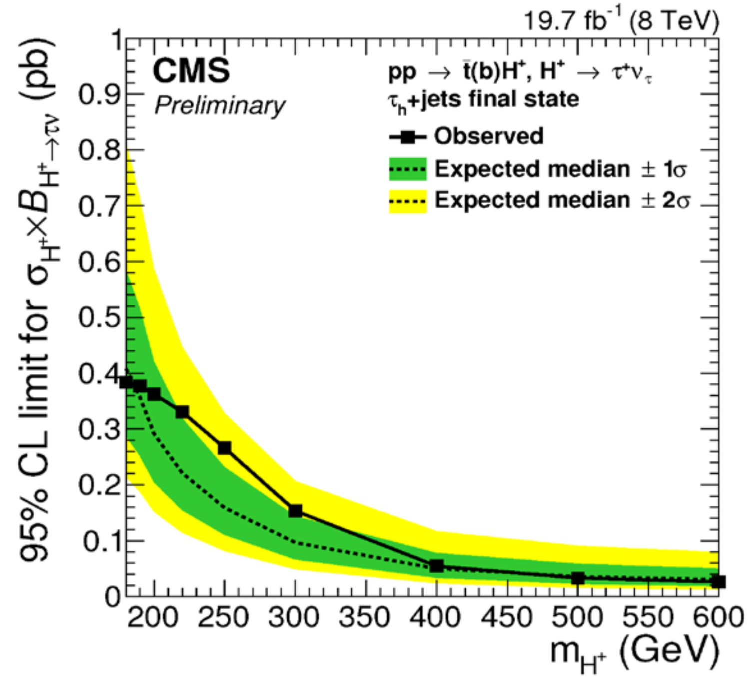
CMS PAS-HIG-14-020

$H^+ \to \tau^+ \nu_\tau$ (CMS)

$m_{H^+} < m_t$



$m_{H^+} > m_t$



- $B(t \to H^+ b) \times B(H^+ \to \tau^+ \nu_\tau)$< 0.002 – 0.012 at 95% CL

  for 80 GeV $< m_{H^+} <$ 160 GeV
- $\sigma(pp \to H^\pm) \times B(H^+ \to \tau^+ \nu_\tau)$ < 0.03 - 0.38 pb at 95% CL

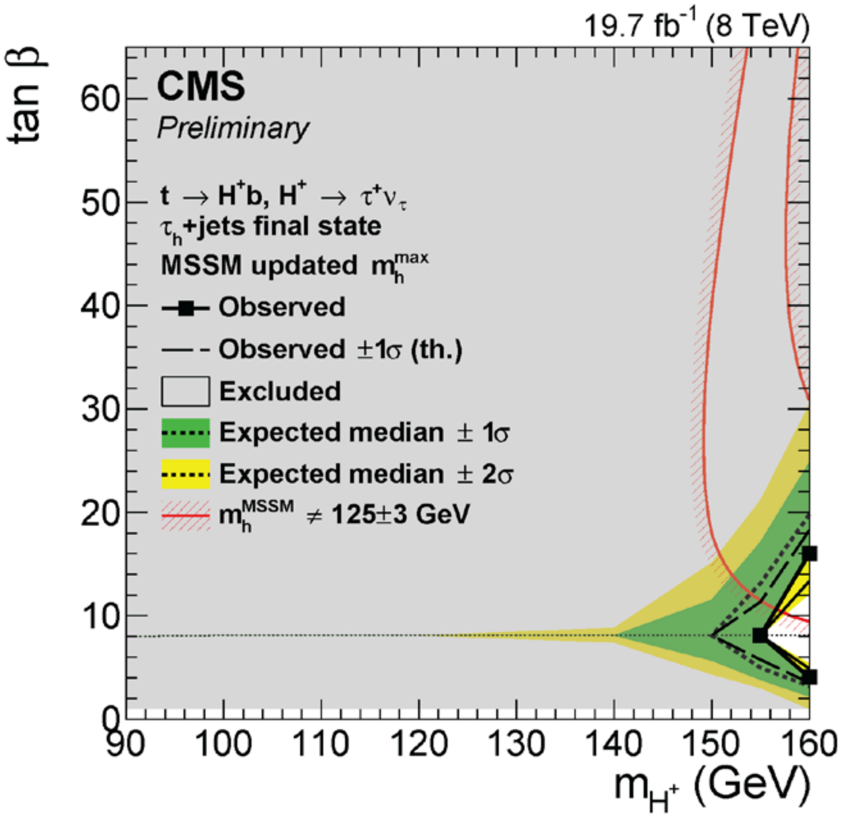
  for 180 GeV $< m_{H^+} <$ 600 GeV

CMS PAS-HIG-14-020

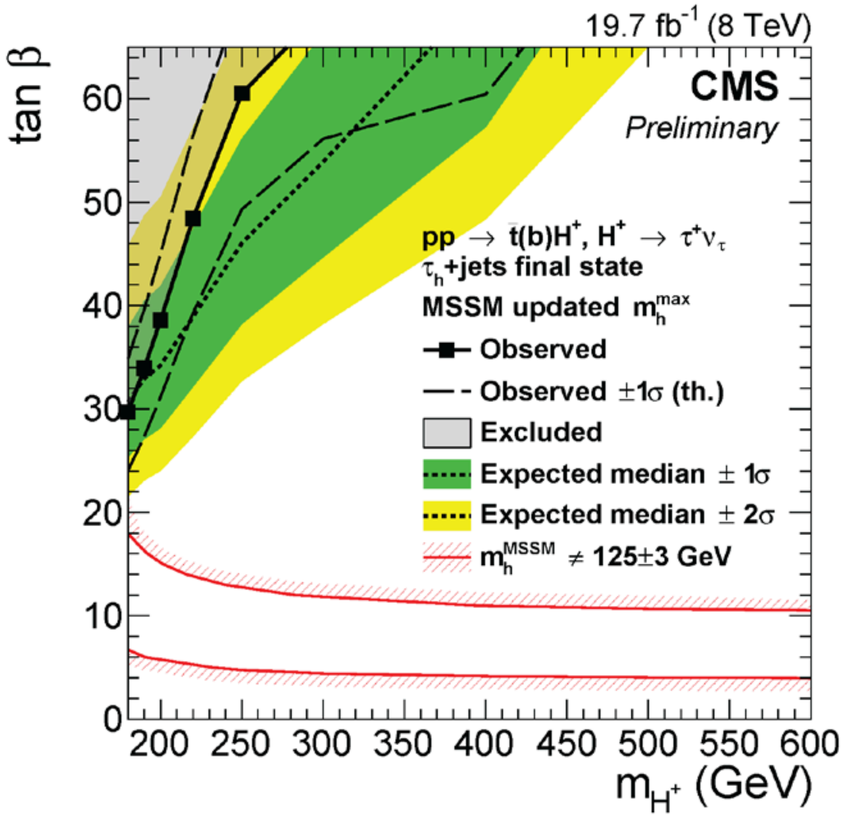
$H^+ \to \tau^+\nu_\tau$ (CMS)

Interpretation in MSSM m_h^{max} scenario

$m_{H^+} < m_t$



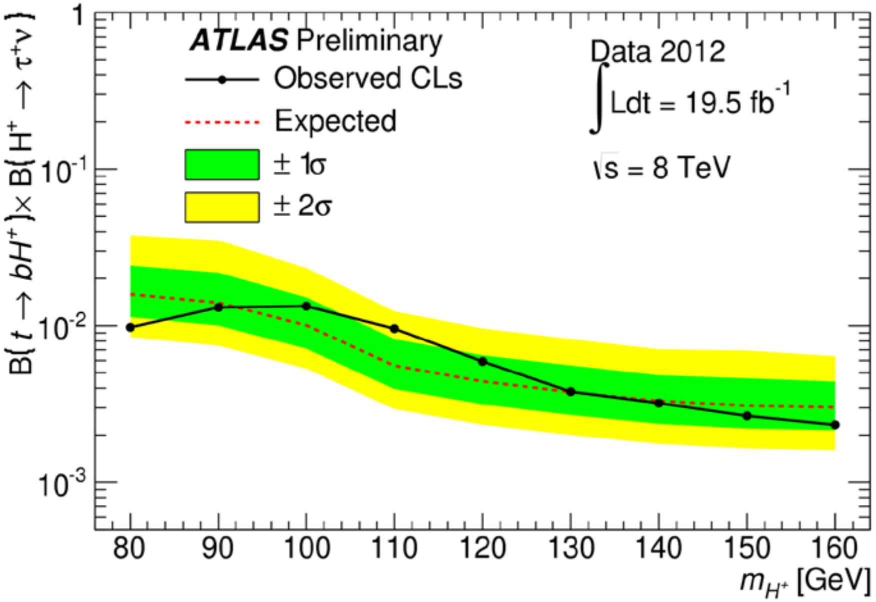
$m_{H^+} > m_t$



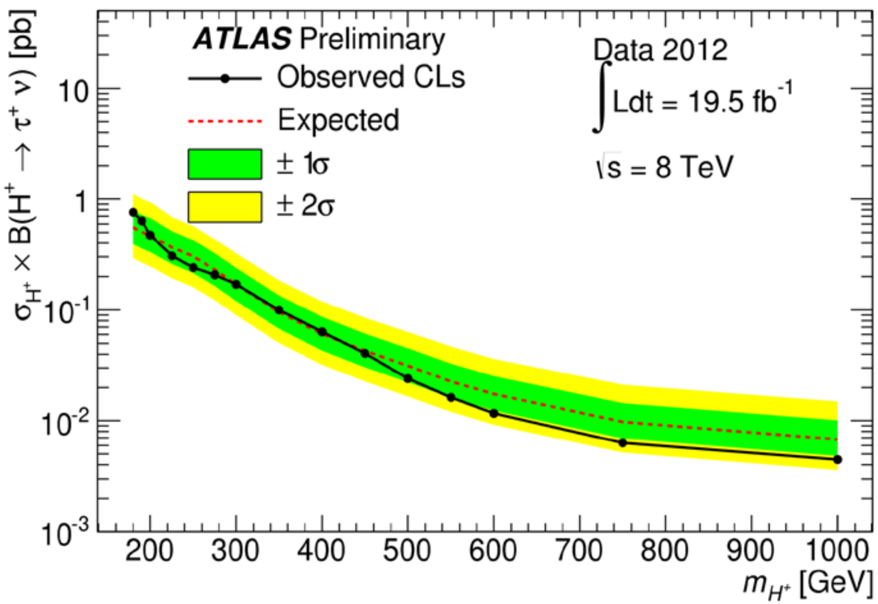
CMS PAS-HIG-14-020

$H^+ \rightarrow \tau^+ \nu_\tau$ (ATLAS)

$m_{H^+} < m_t$



$m_{H^+} > m_t$



- $B(t \rightarrow H^+ b) \times B(H^+ \rightarrow \tau^+ \nu_\tau)$ < 0.0023 – 0.013 at 95% CL

  for 80 GeV $< m_{H^+} <$ 160 GeV

- $\sigma(pp \rightarrow H^\pm) \times B(H^+ \rightarrow \tau^+ \nu_\tau)$ < 0.004 - 0.76 pb at 95% CL

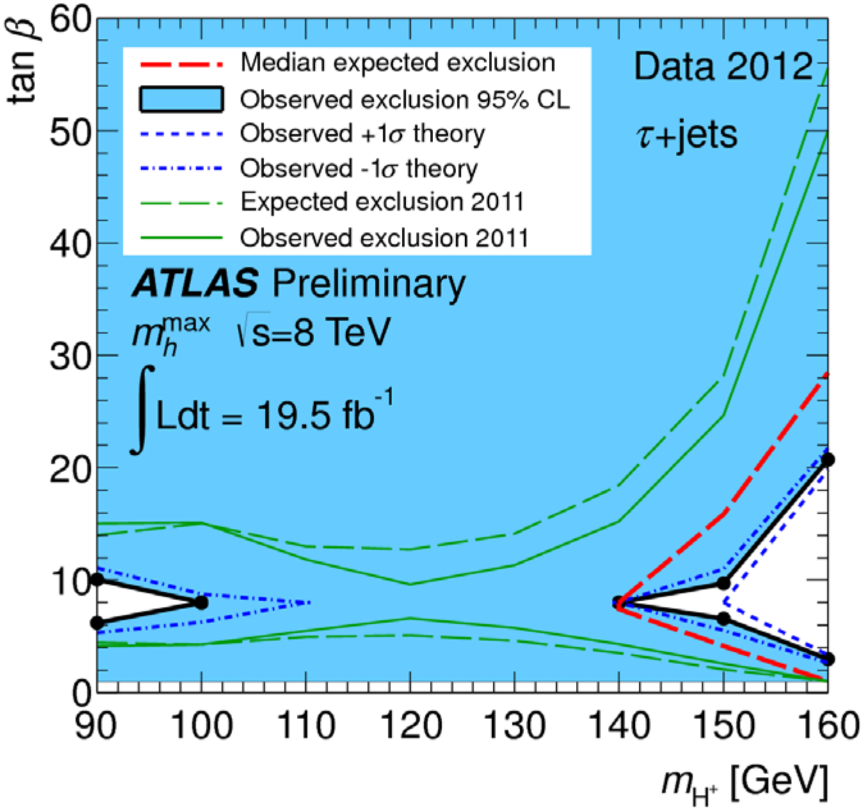
  for 180 GeV $< m_{H^+} <$ 1000 GeV

ATLAS-CONF-2014-050

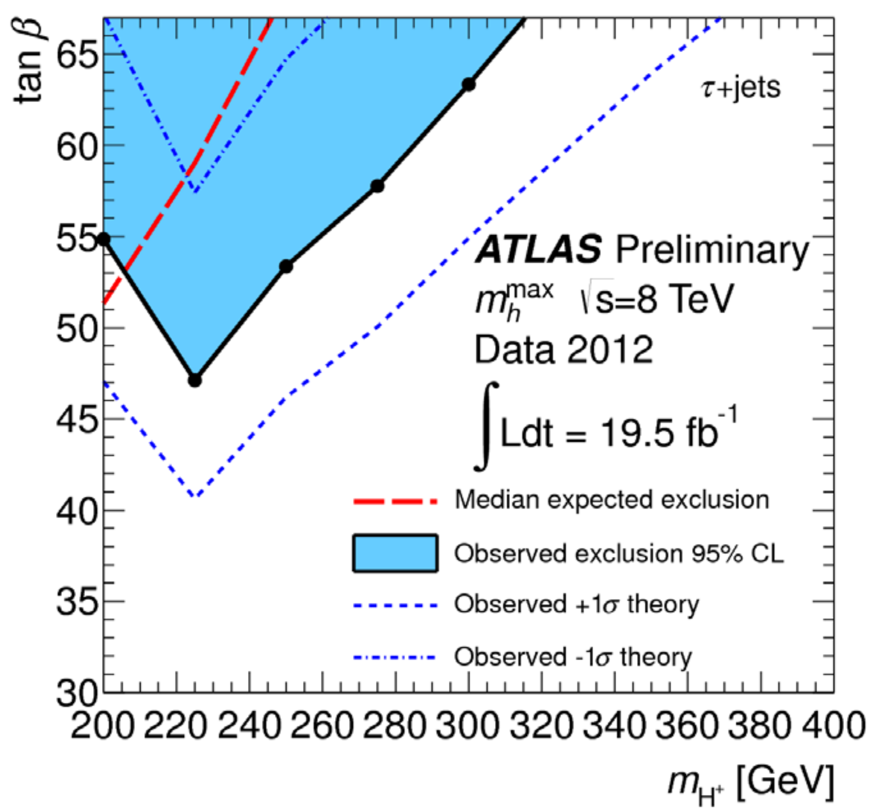
Older result: $H^+ \rightarrow \tau^+ \nu_\tau$ (ATLAS)

Interpretation in MSSM $m_h{}^{max}$ scenario

$m_{H^+} < m_t$



$m_{H^+} > m_t$



ATLAS-CONF-2013-090

Summary and outlook

- Both ATLAS and CMS experiments have searched for 2HDM scenarios in pp collisions up to 20 (5) fb^{-1} of data at $\sqrt{s} = 8$ (7) TeV.
- In the absence of evidence of signal, limits have been set on cross sections and/or branching fractions, interpreted to exclusion in 2HDM parameter space.
- All previous direct results have been drastically improved.
- More (improved) results are expected soon.
- Higher production cross section and larger volume of data are expected to further improve results in Run 2.

BACK-UP SLIDES

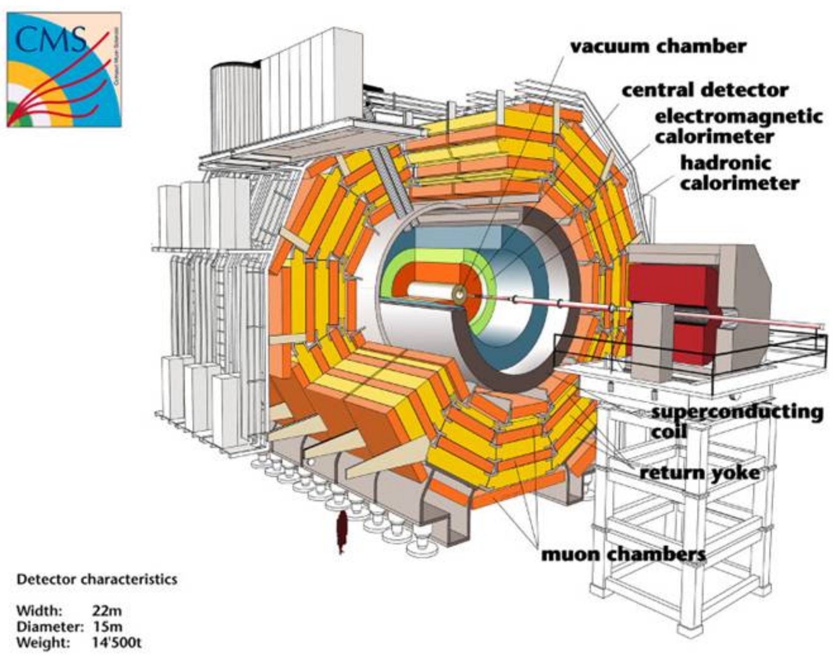
Previous H^+ search results

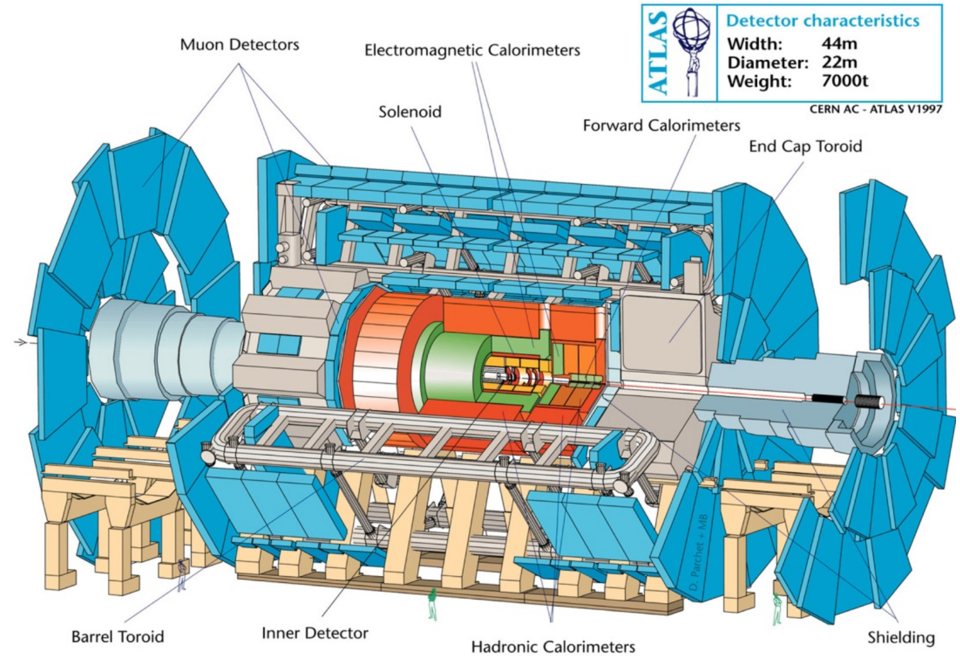
No evidence of H^+ production found so far. 95% CL limits:

- LEP combined:
  - $m_{H^+} > 78.6$ GeV irrespective of model.
  - $m_{H^+} > 90$ GeV assuming Type 2 2HDM, $B(H^+ \to \tau^+ \nu_\tau) = 1$.
- Tevatron (D0, CDF):
  - $B(t \to H^+ b) < [0.15\text{–}0.20]$ depending on m_{H^+}, $\tan\beta$, Type 2 2HDM assumed.

ATLAS and CMS

Two general-purpose detectors for the LHC





- Optimized to identify and measure electrons, photons, muons, taus, jets (q/g), missing p_T with excellent resolution & hermeticity.
- For offline analysis, multi-level triggering system select ~200 out of ~40 million bunch crossings every second.

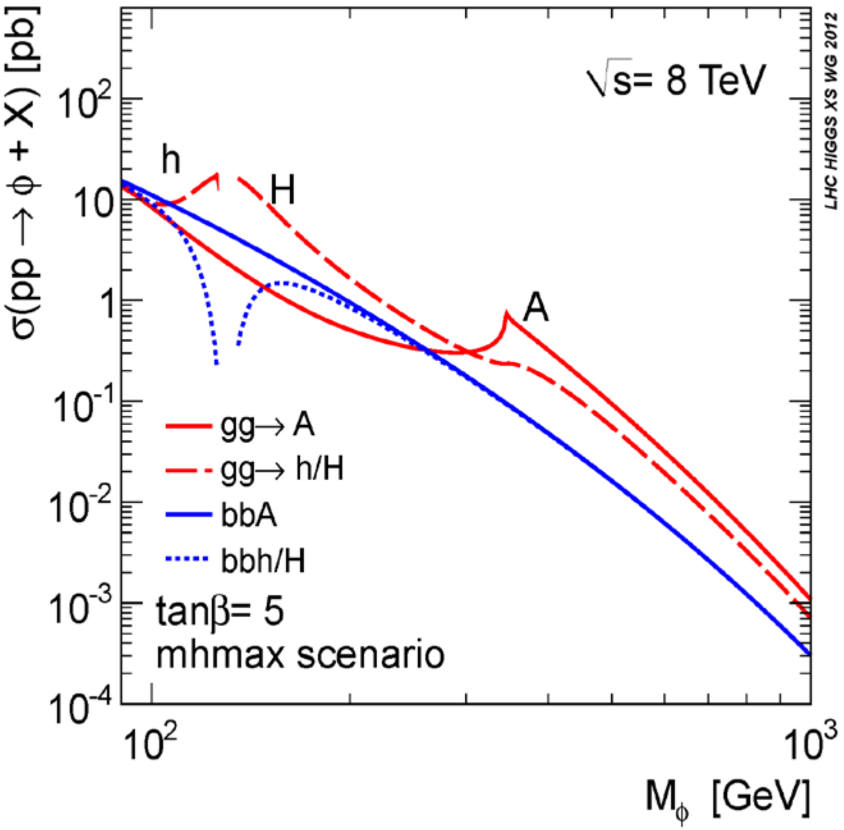
Type I and Type II 2HDMs

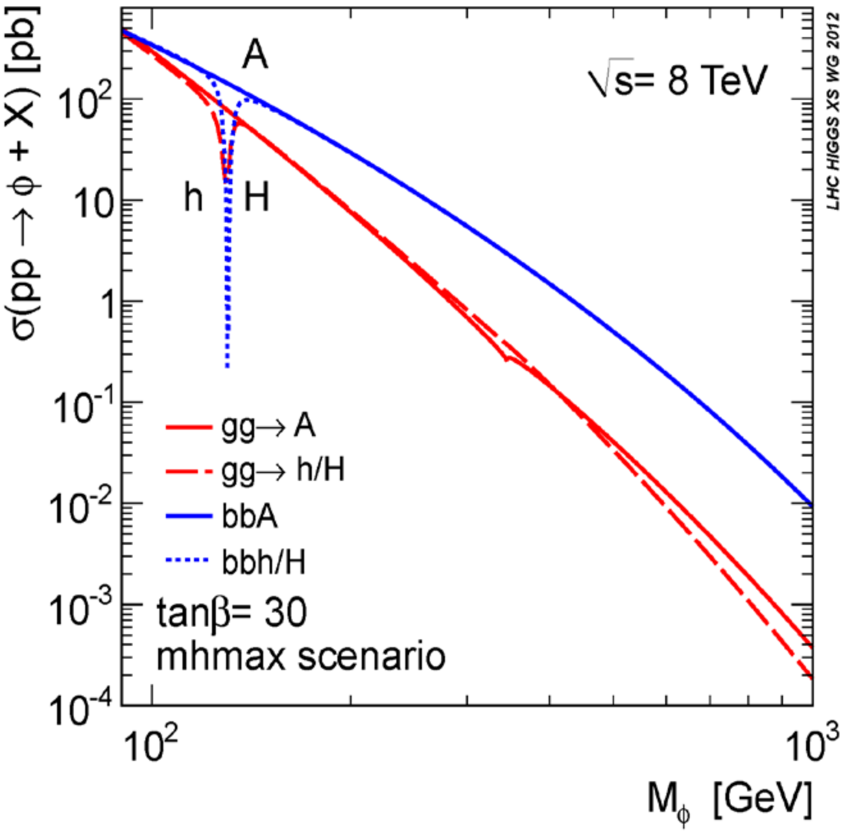
- FCNC naturally suppressed in both.
- Type I: all fermions couple to only one of the two Higgs doublets.
- Type II: u-types couple to one Higgs doublet, d-types to the other.
- $\tan\beta = \frac{v_2}{v_1}$; $\quad m_W^2 = (v_1^2 + v_2^2)$;
- $\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} -\sin\alpha & \cos\alpha \\ \cos\alpha & \sin\alpha \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$ $\quad \psi_1, \psi_2$: CP-even fields
- Relevant couplings:

Coupling	Type I	Type II
ξ_h^{v}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\sin\beta$
ξ_H^{v}	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

Search for the heavier CP-even Higgs boson

Production cross section

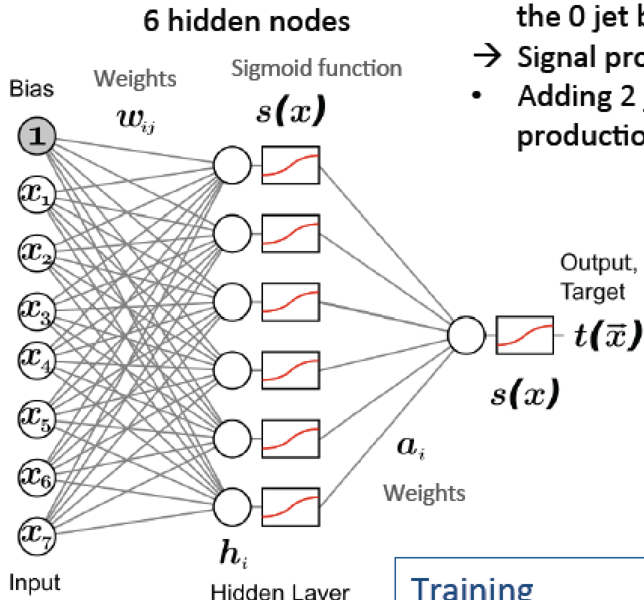




Neural Network

Implementation with NeuroBayes

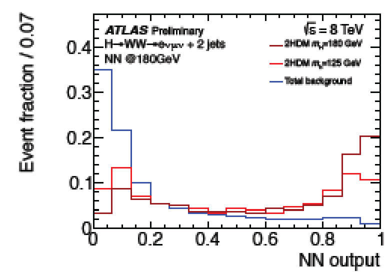
0 jet bin	2 jet bin
$\mathrm{m_T}$	$\mathrm{m}(jj)$
$\mathrm{m}(ll)$	$\mathrm{m}(ll)$
$p_\mathrm{T}(ll)$	$\mathrm{m_T}$
$\lvert\Delta\mathrm{Y}(ll)\rvert$	$p_\mathrm{T}^\mathrm{tot}$
$\mathrm{E_{T,rel}^{miss}}$	$p_\mathrm{T}(l_2)$
$\lvert\eta(l_1)\rvert$	$\lvert\eta(l_1)\rvert$
	$p_\mathrm{T}(j_1)$
	$\mathrm{m}(j_1)$
	$\cos\theta(l_1,l_2)$



- The contribution of VBF is very low in the 0 jet bin

→ Signal production mainly through ggH

- Adding 2 jet bin to include the VBF production and gain sensitivity.



Training in 0 jet bin:
ggH as signal
VBF not included

Training in 2 jet bin:
VBF as signal
ggH not included

$$p_\mathrm{T}^\mathrm{tot} = |\mathbf{p}_\mathrm{T}^\mathrm{tot}| = |\mathbf{p}_\mathrm{T}^{\ell 1} + \mathbf{p}_\mathrm{T}^{\ell 2} + \mathbf{p}_\mathrm{T}^{j1} + \mathbf{p}_\mathrm{T}^{j2} + \mathbf{p}_\mathrm{T}^\mathrm{miss}|$$

$$m_\mathrm{T} = \sqrt{(E_\mathrm{T}(\ell\ell) + E_\mathrm{T}(\nu\nu))^2 - (\mathbf{p}_\mathrm{T}(\ell\ell) + \mathbf{p}_\mathrm{T}^\mathrm{miss})^2} \quad \text{with} \quad E_\mathrm{T}(\ell\ell) = \sqrt{\mathbf{p}_\mathrm{T}^2(\ell\ell) + m^2(\ell\ell)}$$

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Searches for charged Higgs bosons

- $\mathcal{L}(H^{+}UD) =$

$$\frac{g}{2\sqrt{2}\,m_W}\left(H^{+}UK(m_U \cot\beta\,(1-\gamma_5) + m_D \tan\beta\,(1+\gamma_5)D\right) + \text{ h.c.}$$

- Current H+ searches at LHC are focused on production and decay via interactions with SM fermions.
- $H^{+}tb$ coupling is the strongest of all irrespective of $(m_{H^+}, \tan\beta) \rightarrow$ Production most likely in decay of top quarks if $m_{H^+} < m_t$, otherwise in association with the top quark.
- Decay driven by phase space (m_{H^+}) and $\tan\beta$.

Search strategies : $H^+ \rightarrow \tau^+ \nu_\tau$

Look for a high-p_T τ decaying into hadrons

- $B(\tau_h) \approx 0.65$ with ~ 0.5 to "1-prong", ~ 0.15 to "3-prong".
- Collimated energy deposits with low track-multiplicity, often with identifiable EM contribution from π^0's in τ decay.

Challenges:

- A good fraction of the τ momentum is carried away by the ν_τ in decay. Only the remaining part is directly visible (τ_{vis}).
- Multiple ν's in the event weakens the usefulness of E_T^{miss} .
- Large QCD background (quark- and gluon-initiated jets being misidentified as τ's). Hurts efficiency, especially at the trigger level, unless the event also features a high-p_T e or μ.

Search strategies : $H^+ \to c\bar{s}$

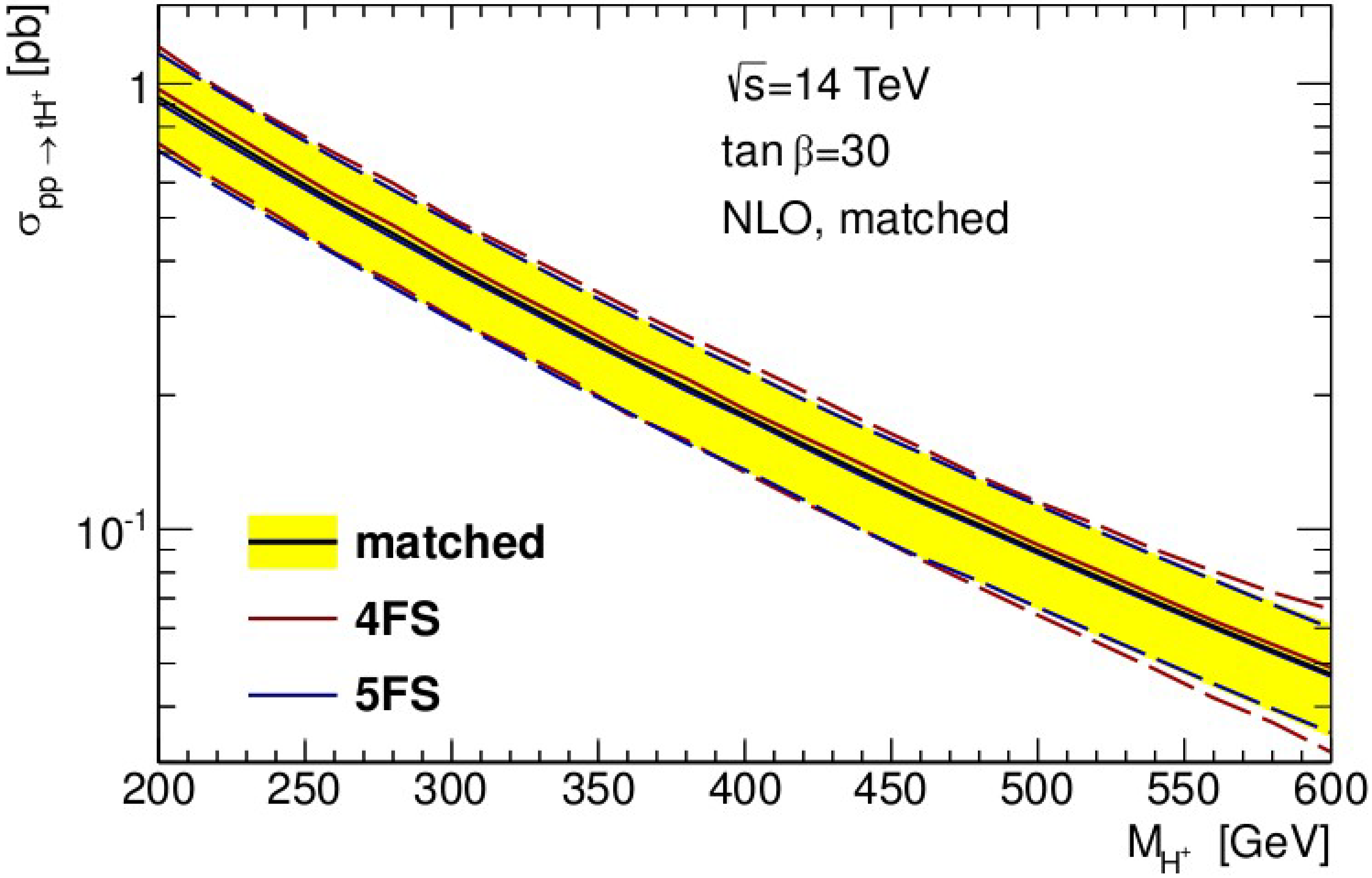
Look for $t\bar{t}$ events with one top decaying into 3 jets: $t \to H^+ b \to c\bar{s}b$

- $m_{j_1 j_2} = m_{H^+}$;
- $m_{j_1 j_2 j_3} = m_t$, possibly with $j_3 = b$.

Challenges:

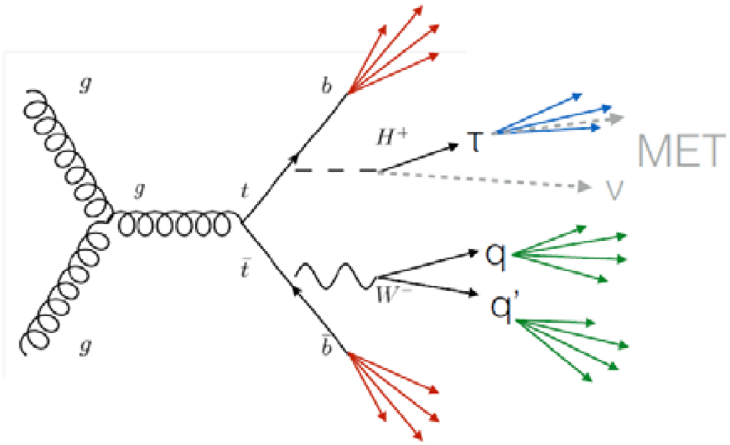
- In order to have any hope against the enormous QCD background, especially at the trigger level, the other top must decay into a high-p_T e or μ.
- Loss of discrimination if m_{H^+} is close to m_{W^+}.
- Competition from $H^+ \to W^+ b\bar{b}$ as m_{H^+} approaches m_t.
- Serious combinatorics from ISR, FSR, pile-up jets.

H^+ production at the LHC: cross section, $m_{H^+} > m_t$



http://arxiv.org/abs/1409.5615

$H^+ \to \tau^+ \nu_\tau$ (ATLAS)



- Use $\tau + E_T{}^{miss}$ trigger.
- Look for excess in $m_T(\tau, E_T^{miss})$ distribution.

$$m_T = \sqrt{2 p_T^\tau E_T^{miss}(1 - \cos \Delta\phi_{\tau_{had-vis},miss})}$$

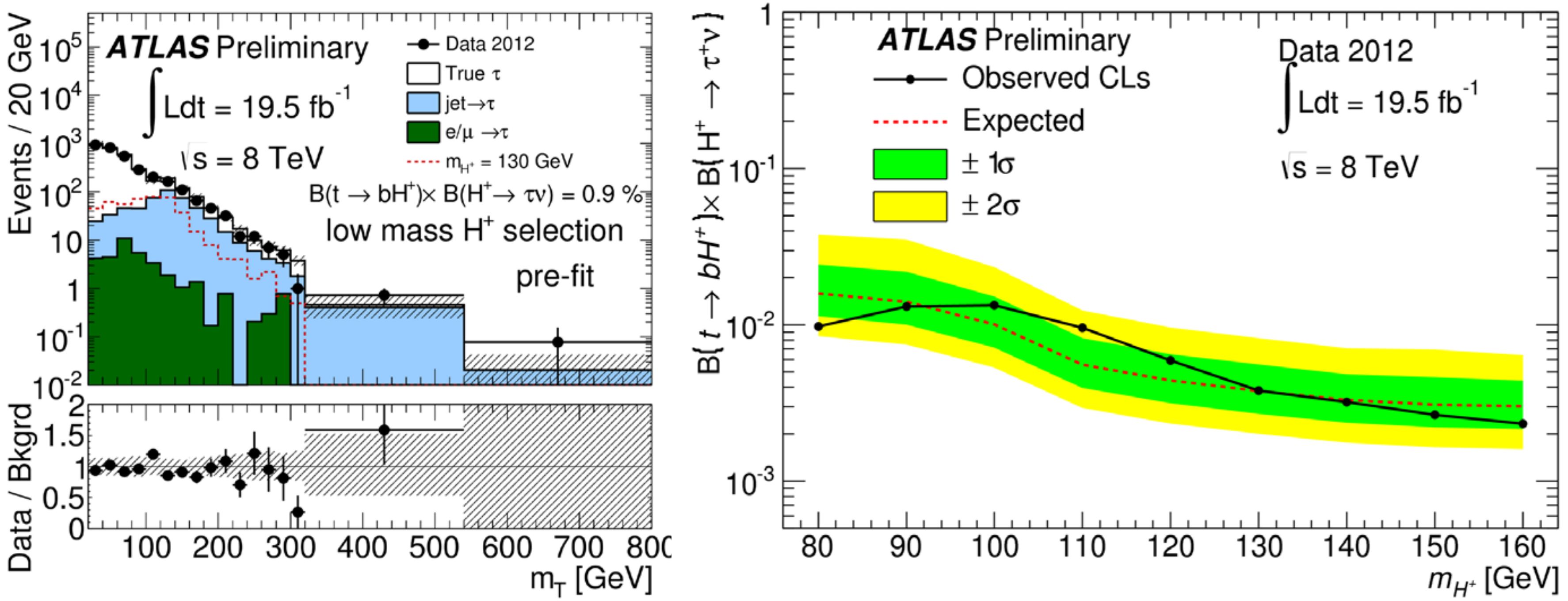
- Dominant background: SM $t\bar{t}$, QCD multi-jet.

- For $m_{H^+} < m_t$ search, assume $B(H^+ \to \tau^+\nu_\tau) = 1$ to derive limits on $B(t \to H^+ b)$.
- For $m_{H^+} > m_t$, use similar event selection, but allow other decay modes to derive limits on

$$\sigma(pp \to H^\pm) \times B(H^+ \to \tau^+\nu_\tau).$$

ATLAS-CONF-2014-050

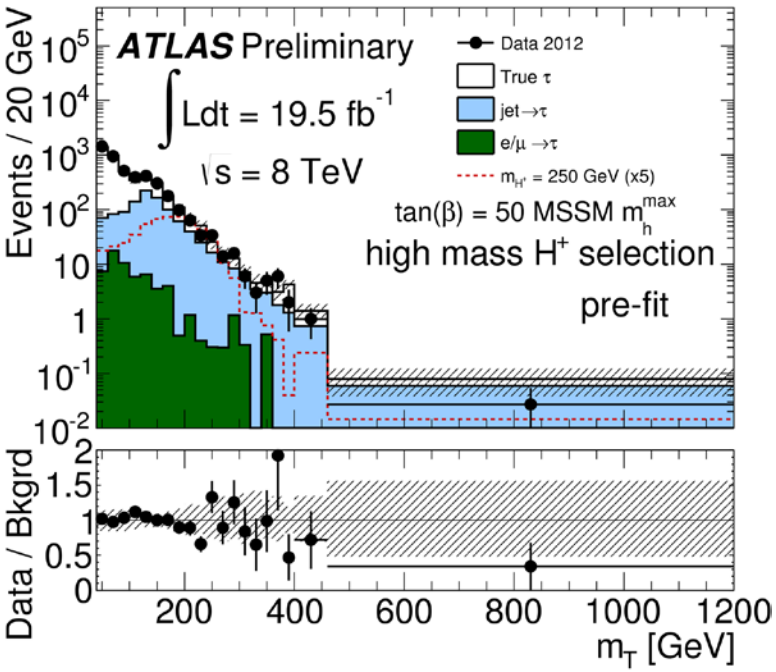
$H^+ \to \tau^+\nu_\tau;\ m_{H^+} < m_t$ (ATLAS)

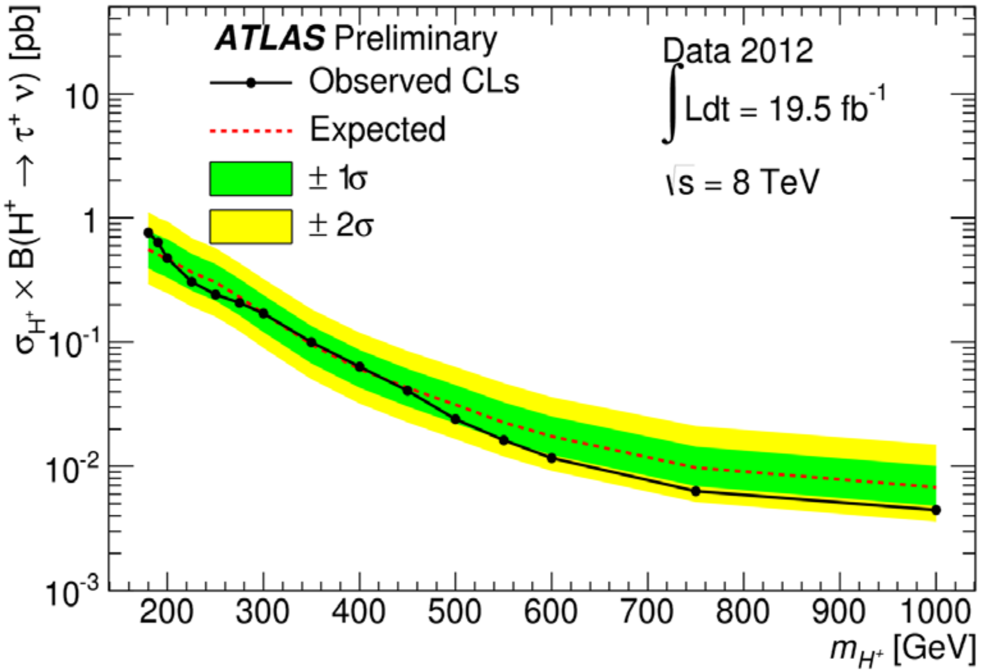


$B(t \to H^+b)$ < 0.0023 – 0.013 at 95% CL for $80\ \text{GeV} < m_{H^+} < 160\ \text{GeV}$

ATLAS-CONF-2014-050

$H^+ \to \tau^+ \nu_\tau;\ m_{H^+} > m_t$ (ATLAS)





$\sigma(pp \to H^{\pm}) \times B(H^+ \to \tau^+ \nu_\tau) < 0.004 - 0.76$ pb at 95% CL

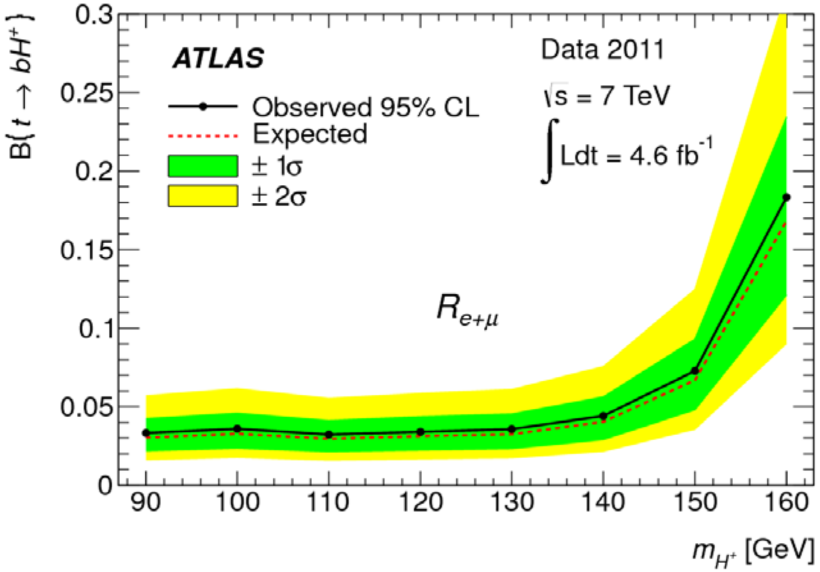
for $180\ \text{GeV} < m_{H^+} < 1000\ \text{GeV}$

ATLAS-CONF-2014-050

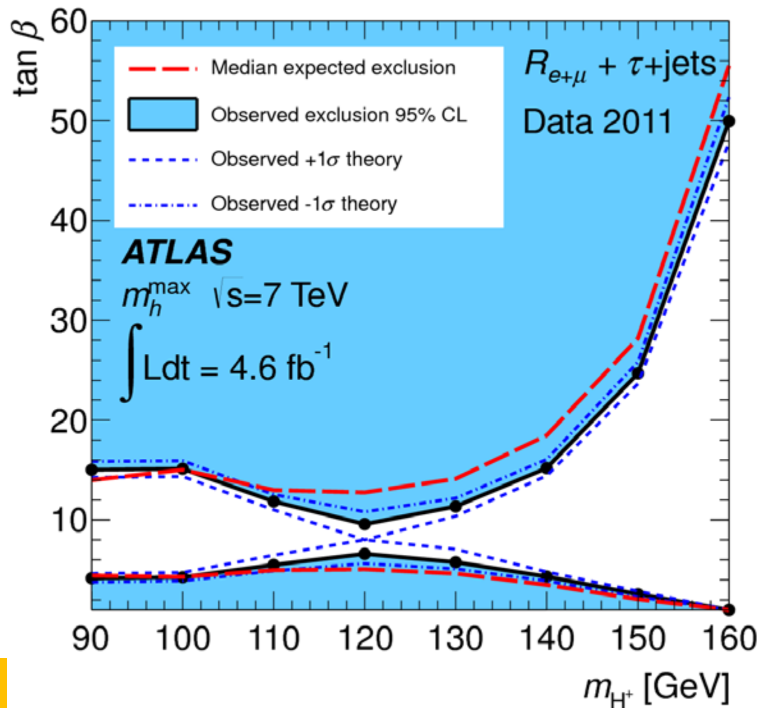
lepton universality; $m_{H^+} < m_t$ (ATLAS)

- Assume $B(H^+ \to \tau^+ \nu_\tau) = 1$
- Compare $e + \tau_h$, $\mu + \tau_h$ yields to that of $e + \mu$

$$R_{e+\mu} = \frac{\mathcal{N}(e + \tau_{\rm had}) + \mathcal{N}(\mu + \tau_{\rm had})}{\mathcal{N}(e + \mu) + \mathcal{N}_{\rm OR}(\mu + e)}$$



- Combined with τ_h + jets, gave best results for $\sqrt{s} = 7$ TeV.



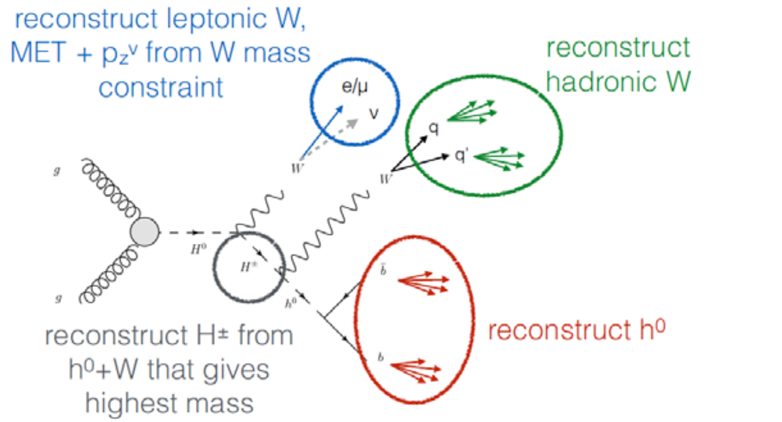
$B(t \to H^+ b)$ < 0.033 – 0.044 at 95% CL

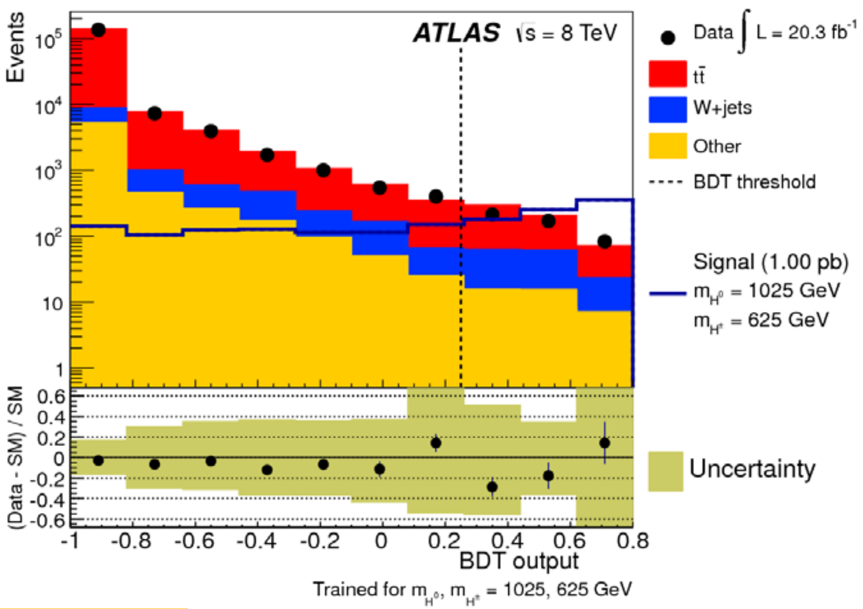
for 90 GeV $< m_{H^+} <$ 140 GeV

JHEP03 (2013) 076

$H^0 \to H^{\pm}W^{\mp} \to h^0W^+W^-$ (ATLAS)

- Look for $H^0 \to H^{\pm}W^{\mp} \to h^0W^{\pm}W^{\mp} \to b\bar{b}l\nu jj$
- Fairly model-independent (A too heavy to appear in decay chain).
- Exploit $m_{bb} = m_{h^0} = 125$ GeV.
- Same final state as semileptonic decay of $t\bar{t}$ in SM.
- BDT trained at 36 mass points of H^0 to discriminate against SM $t\bar{t}$ events.

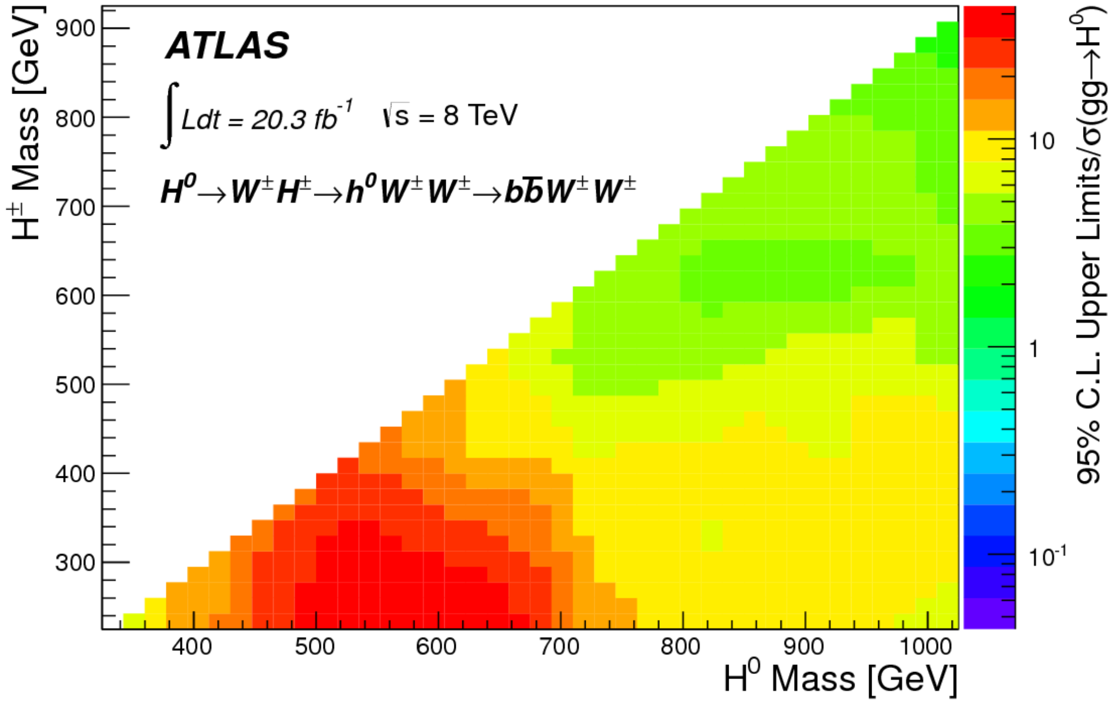




PRD 89 (2014) 032002

$H^0 \rightarrow H^{\pm}W^{\mp} \rightarrow h^0 W^+ W^-$ (ATLAS) [contd.]

The ratio of the observed 95% CL upper limits on the cross section to the theoretical cross section for $gg \rightarrow H^0 \rightarrow H^{\pm}W^{\mp} \rightarrow h^0 W^{\pm}W^{\mp} \rightarrow W^{\pm}W^{\mp}b\bar{b}$ on the $[m_{H^0}, m_{H^+}]$ plane.

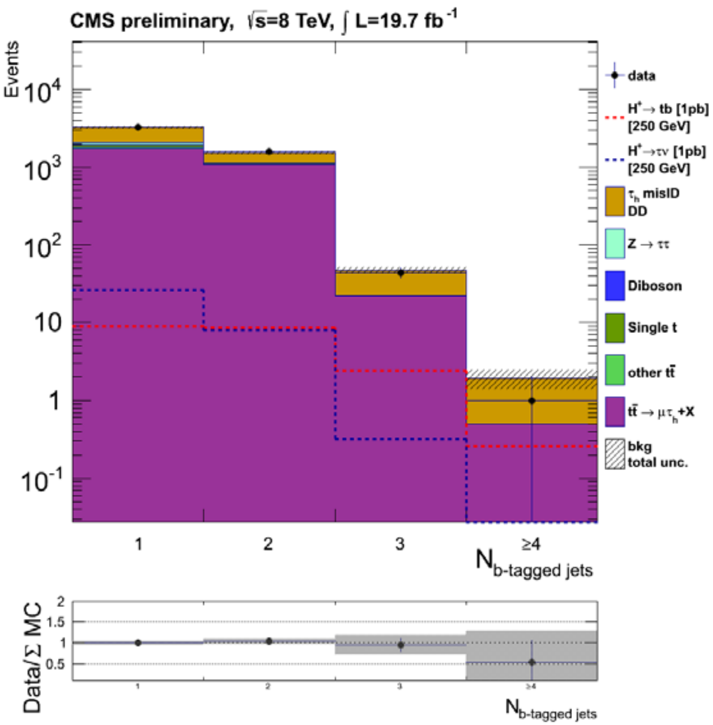


Observed upper limits are higher than theoretical expectation, but approaching it for larger H^0 masses.

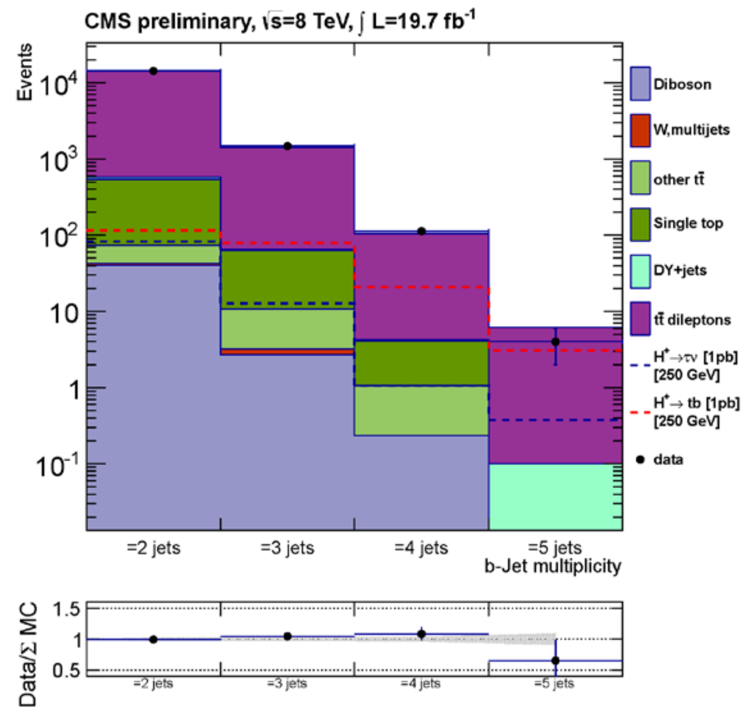
PRD 89 (2014) 032002

$H^+ \to \tau^+\nu_\tau$ or $t\bar{b}$; $m_{H^+} > m_t$ (CMS)

- Combined search in the $\tau_h l$ and $l_1 l_2$ final state $l_{(1,2)} = e, \mu$.
- Trigger on the isolated lepton (e, μ).
- Binned maximum likelihood fit to the number of b-tagged jets.



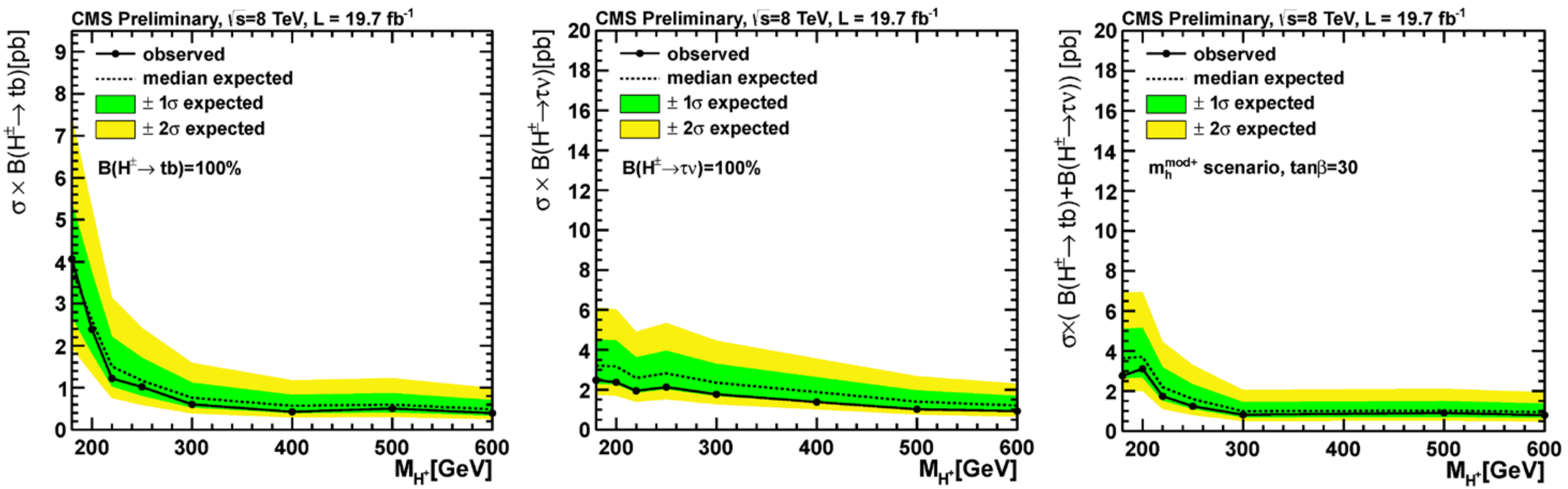
$H^{\pm} \to \tau_h l$



$H^{\pm} \to l_1 l_2$

CMS PAS-HIG-13-026

$H^+ \rightarrow \tau^+\nu_\tau$ or $t\bar{b}$; $m_{H^+} > m_t$ (CMS) [contd.]



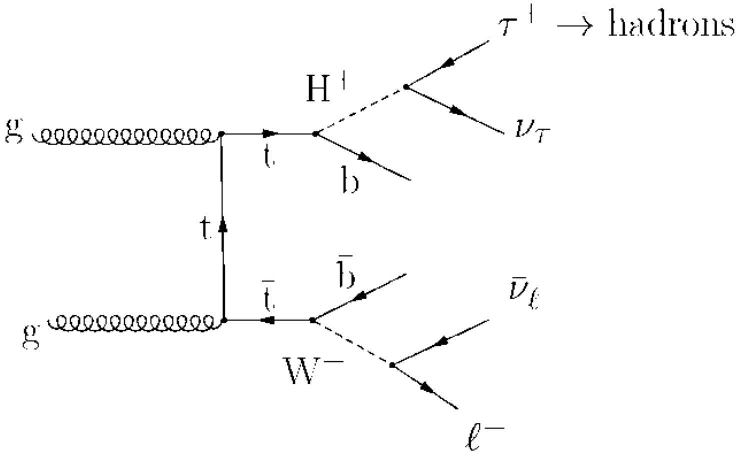
$$\sigma(pp \rightarrow H^{\pm}) \times B\left(H^+ \rightarrow t\bar{b}\right) < \sim 1 - 2 \text{ pb},$$

$$\sigma(pp \rightarrow H^{\pm}) \times B(H^+ \rightarrow \tau^+\nu_\tau) < \sim 4 - 5 \text{ pb},$$

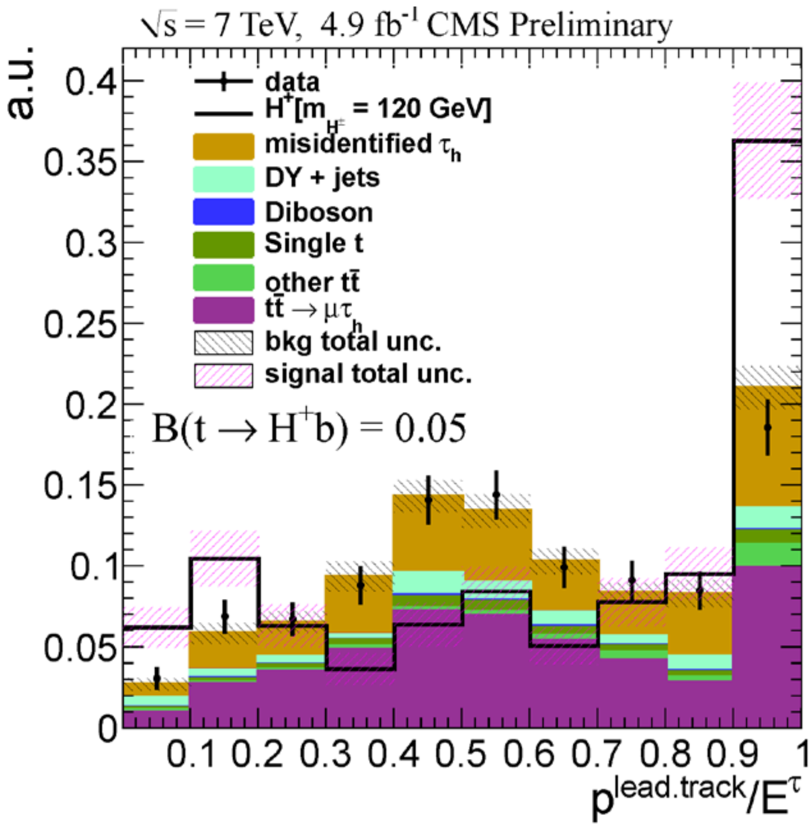
at 95% CL for $180 \text{ GeV} < m_{H^+} < 600 \text{ GeV}$

CMS PAS-HIG-13-026

$H^+ \to \tau^+\nu_\tau;\ m_{H^+} < m_t$ (CMS)



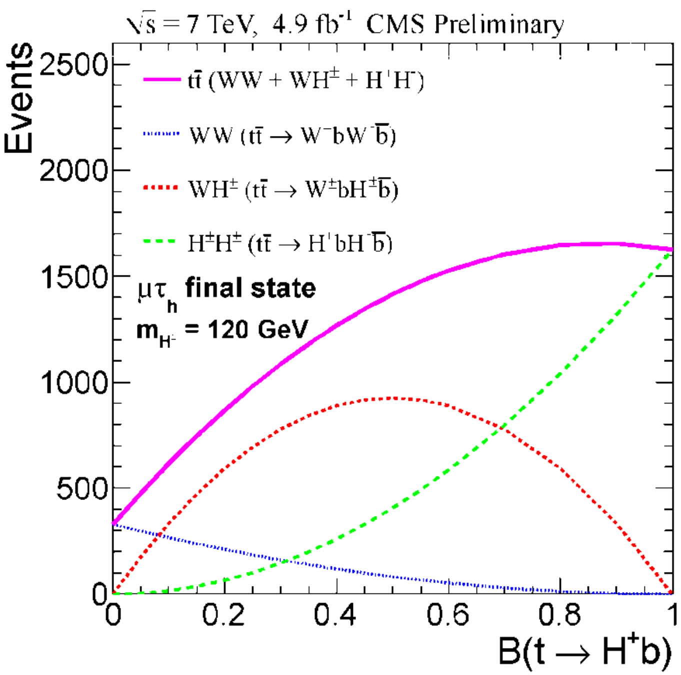
- Search in the $\tau_h l$ final state $l = e, \mu$
- Binned maximum likelihood fit to $R = p^{lead.track}/E_\tau$ distribution. This quantity is sensitive to τ polarization, which is different between τ's from H^+ and W^+ decays.

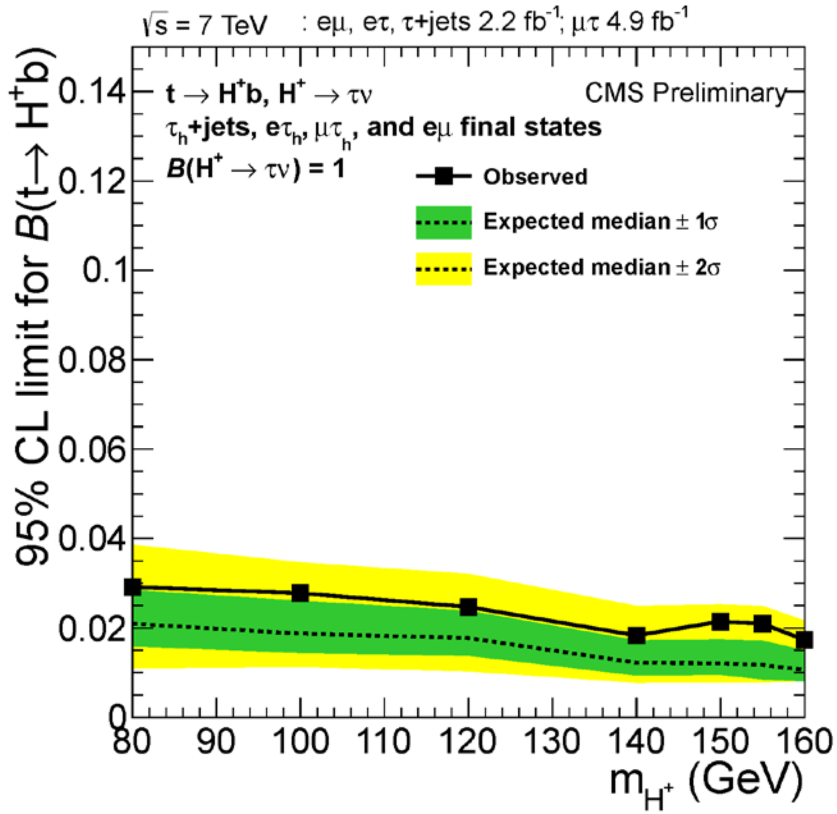


CMS PAS-HIG-12-052

$H^+ \to \tau^+ \nu_\tau$; $m_{H^+} < m_t$ (CMS) [contd.]

Source	N_{events} (± stat. ± syst.)
HH+HW, m_{H^+}=120 GeV, $\mathcal{B}(t \to H^+ b)$=0.05	179.3 ± 8.7 ± 22.1
τ fakes (from data)	222.0 ± 11.4
$t\bar{t} \to WbWb \to (\mu\nu b)\ (\tau_h \nu b)$	304.7 ± 2.8 ± 25.9
$t\bar{t} \to WbWb \to (\ell\nu b)\ (\ell\nu b)$	21.4 ± 0.7 ± 6.9
$Z/\gamma^* \to ee, \mu\mu$	0.4 ± 0.4 ± 0.1
$Z/\gamma^* \to \tau\tau$	50.6 ± 17.6 ± 20.7
Single top	26.6 ± 1.2 ± 3.3
VV	4.4 ± 0.5 ± 0.7
Total expected from SM	630.1 ± 17.9 ± 46.9
Data	620



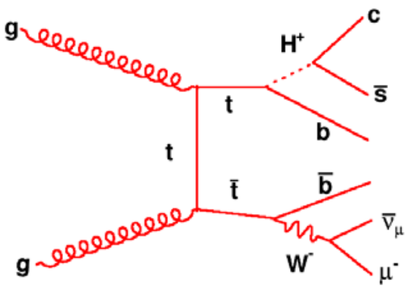


$B(t \to H^+ b) < 0.03 - 0.02$ at 95% CL

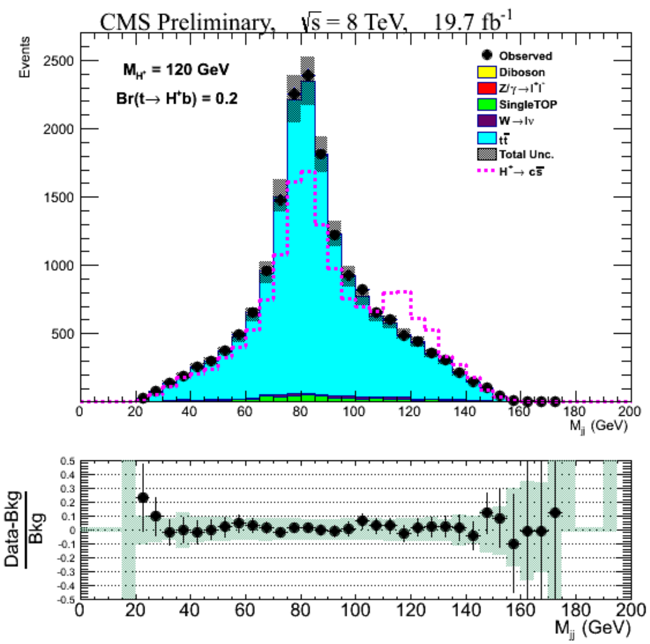
for $80\ \text{GeV} < m_{H^+} < 160\ \text{GeV}$

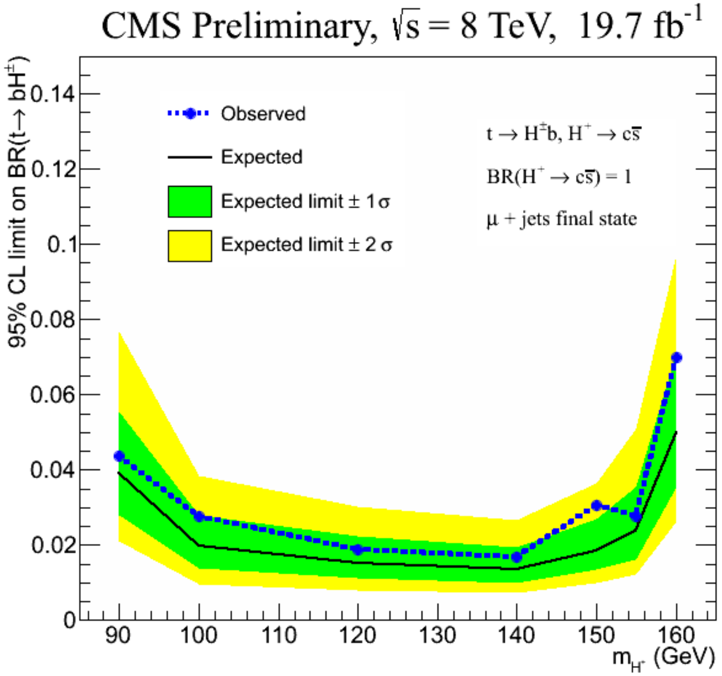
CMS PAS-HIG-12-052

$H^+ \to c\bar{s};\ m_{H^+} < m_t$ (CMS)



- Assume $B(H^+ \to c\bar{s}) = 1$.
- Same final state as semileptonic decay of $t\bar{t}$ in SM
- Kinematic fit to both top candidates

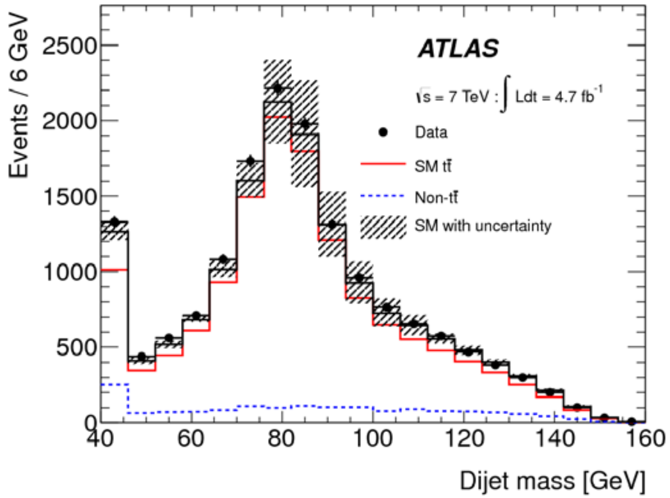




$B(t \to H^+ b) < 0.017 - 0.07$ at 95% CL for $90\ \text{GeV} < m_{H^+} < 160\ \text{GeV}$

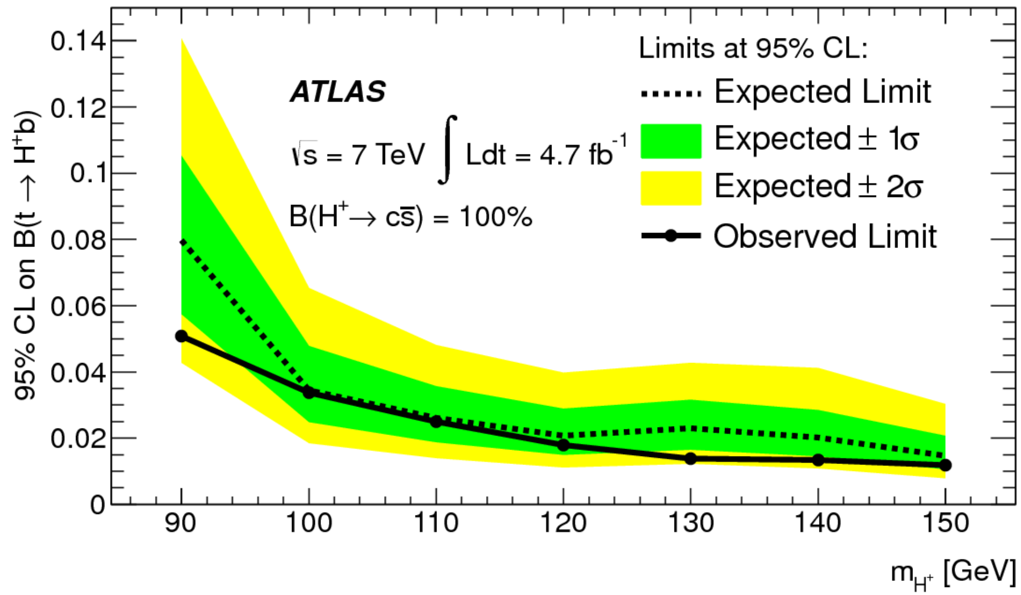
CMS PAS-HIG-13-035

$H^+ \to c\bar{s};\ m_{H^+} < m_t$ (ATLAS)



Channel	Muon	Electron
Data	10107	5696
SM $t\bar{t} \to W^+bW^-\bar{b}$	8700 ± 1800	5000 ± 1000
W/Z + jets	420 ± 120	180 ± 50
Single top quark + Diboson	370 ± 60	210 ± 30
QCD multi-jet	300 ± 150	130 ± 60
Total expected (SM)	9800 ± 1800	5500 ± 1000
$m_{H^+} = 110$ GeV		
$\mathcal{B}(t \to H^+b) = 10\,\%$:		
$t\bar{t} \to H^+bW^-\bar{b}$	1400 ± 280	800 ± 160
$t\bar{t} \to W^+bW^-\bar{b}$	7000 ± 1400	4000 ± 800
Total expected ($\mathcal{B} = 10\,\%$)	9500 ± 1700	5300 ± 1000

- Assume $B(H^+ \to c\bar{s}) = 1$.
- Same final state as semileptonic decay of $t\bar{t}$ in SM
- Likelihood fit to dijet mass for H^+candidate.



$B(t \to\ H^+b)$ < 0.01 – 0.05 at 95% CL for

$90\text{ GeV} < m_{H^+} < 150\text{ GeV}$

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