Charged Higgs boson searches at the LHC

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On behalf of the

ATLAS and CMS experiments

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Outline

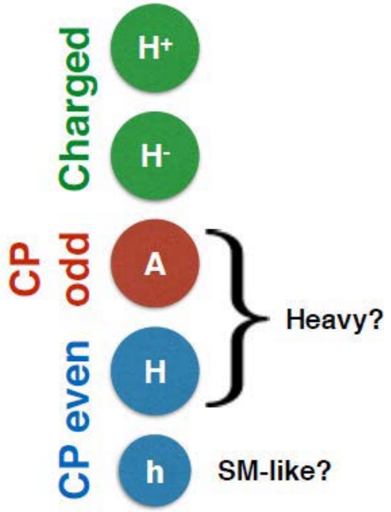
- Motivation
- Phenomenology
  - Basic postulates and parameters
  - Couplings and decay characteristics
  - Production at the LHC
- Experimental search
  - Strategies for various production and decay channels: signal characteristics, background, challenges
  - Results
- Summary and outlook

Motivation

- Discovery of ***a*** Higgs boson prompts further investigations into the scalar sector – it may well be richer in structure than the minimum required by the SM.
- Charged Higgs bosons appear in many extensions of the SM.
- A "Type 2" two-Higgs doublet model (2HDM) is an essential feature of the MSSM.
- It is strategically straightforward to look for deviations from SM-predicted fermion-mass-independence in charged-current couplings, especially in top quark production and decay.

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^0, H^0),
  - one neutral pseudoscalar (A),
  - one charge-conjugate scalar pair (H^+, H^-).



- In "Type 2" 2HDM, one complex doublet couples with up-type quarks (and neutrinos), the other with down-type quarks and charged leptons.
- The two parameters of the model are commonly chosen as the ratio of the two vacuum expectation values and the mass of either A or H^+.

H^+ coupling with fermions in Type 2 2HDM

- $\tan\beta = \frac{v_2}{v_1}$; $m_W^2 = (v_1^2 + v_2^2)$

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

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

- Current H^+ searches at LHC are focused on production and decay via interactions with SM fermions.

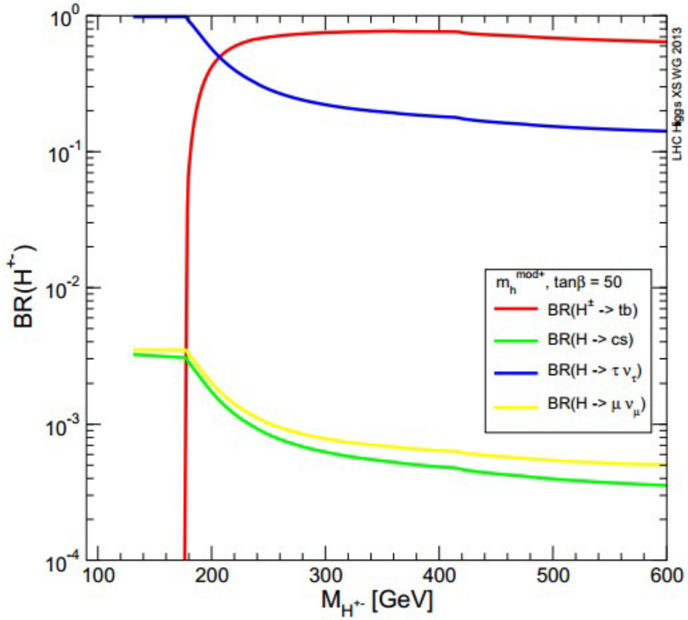
- H^+tb coupling is the strongest of all irrespective of $(m_{H^+}, \tan\beta) \rightarrow$ Production most likely in decay of top quarks if $m_{H^+} < m_t$, otherwise in association with the top quark.

- Decay driven by phase space (m_{H^+}) and $\tan\beta$.

H^+ decay branching fractions

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

$$\Gamma_{H^\pm} = \Gamma^{FH}_{H^\pm\to\tau\nu_\tau} + \Gamma^{FH}_{H^\pm\to\mu\nu_\mu} + \Gamma^{FH}_{H^\pm\to hW} + \Gamma^{FH}_{H^\pm\to HW} + \Gamma^{FH}_{H^\pm\to AW}$$
$$+ \Gamma^{HD}_{H^\pm\to tb} + \Gamma^{HD}_{H^\pm\to ts} + \Gamma^{HD}_{H^\pm\to td} + \Gamma^{HD}_{H^\pm\to cb} + \Gamma^{HD}_{H^\pm\to cs} + \Gamma^{HD}_{H^\pm\to cd}$$
$$+ \Gamma^{HD}_{H^\pm\to ub} + \Gamma^{HD}_{H^\pm\to us} + \Gamma^{HD}_{H^\pm\to ud} ,$$



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

Previous results

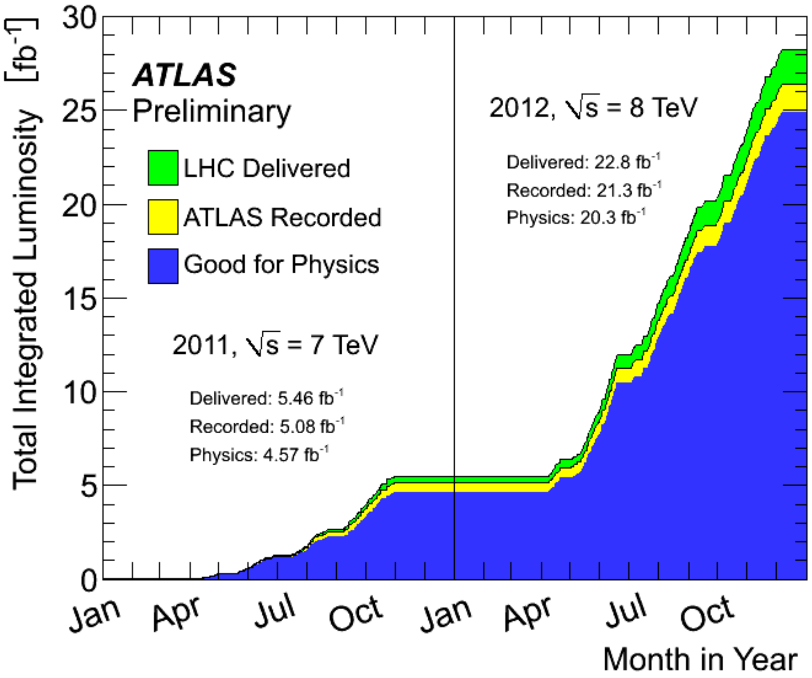
No evidence of H^+ production found so far. 95% CL limits:

- 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):
  - $B(t \to H^+b) < [0.15 - 0.20]$ depending on m_{H^+}, $\tan\beta$, Type 2 2HDM assumed.

The LHC

pp collider designed for $\sqrt{s} = 14$ TeV.
Delivered so far:

- $\sim 5.4\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ TeV (2011)
- $\sim 23\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8$ TeV (2012)



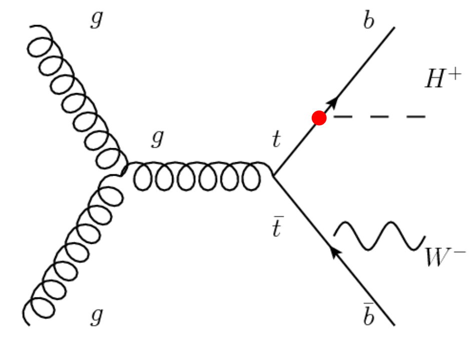
- Peak lumi $\sim 7.7 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- On avg, ~21 interactions/crossing in 2012 $\rightarrow$ large pile-up

H^+ production at the LHC: processes

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

If $m_{H^+} < m_t$

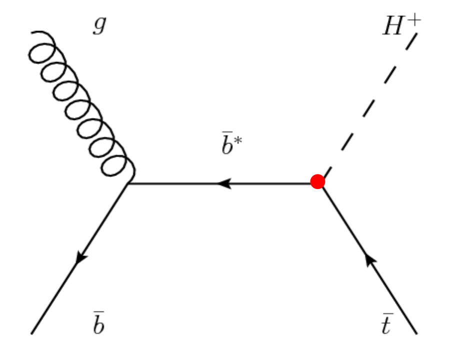
Primary contribution from decays of top quarks



- Production cross section:

  $\sigma(pp \to t\bar{t}) \times B(t \to H^+ b)$ [dominant at LHC]

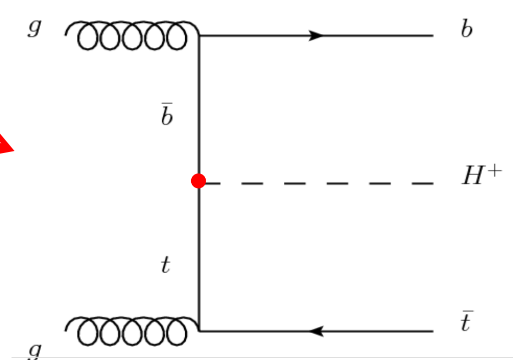
  The first factor is calculated and measured with precision better than 10%. There are several options to measure the latter.



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.

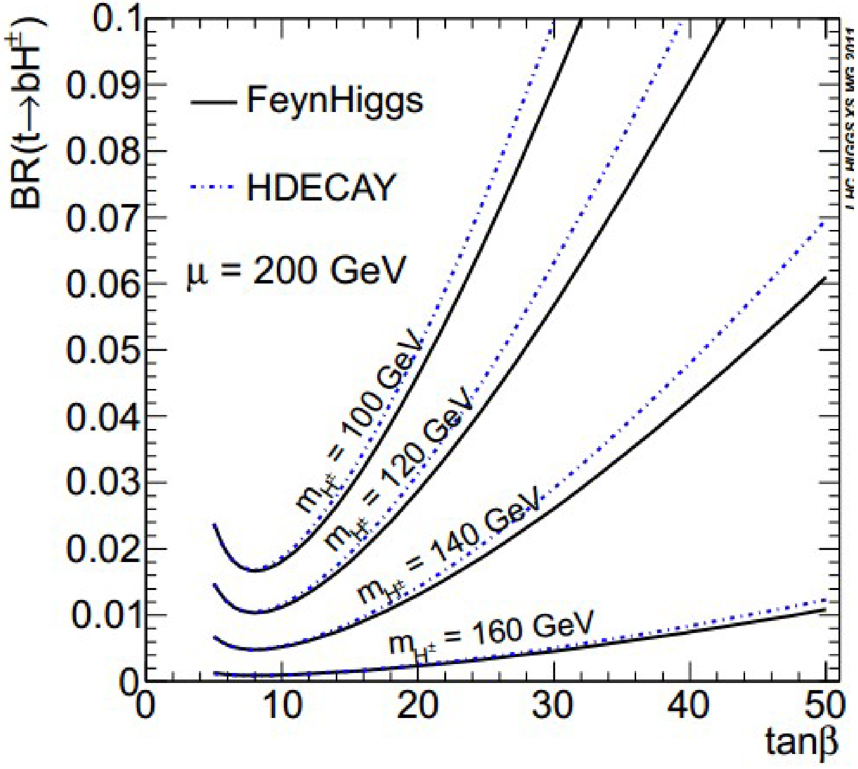
- Production cross section is much smaller.

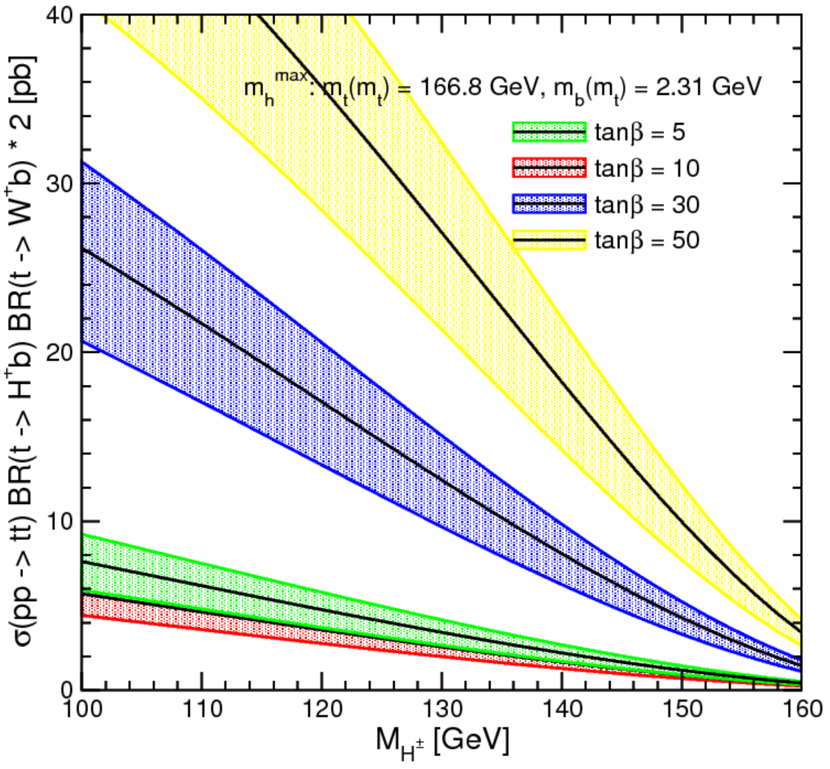


H+ production at the LHC: cross section, $m_{H^+} < m_t$

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

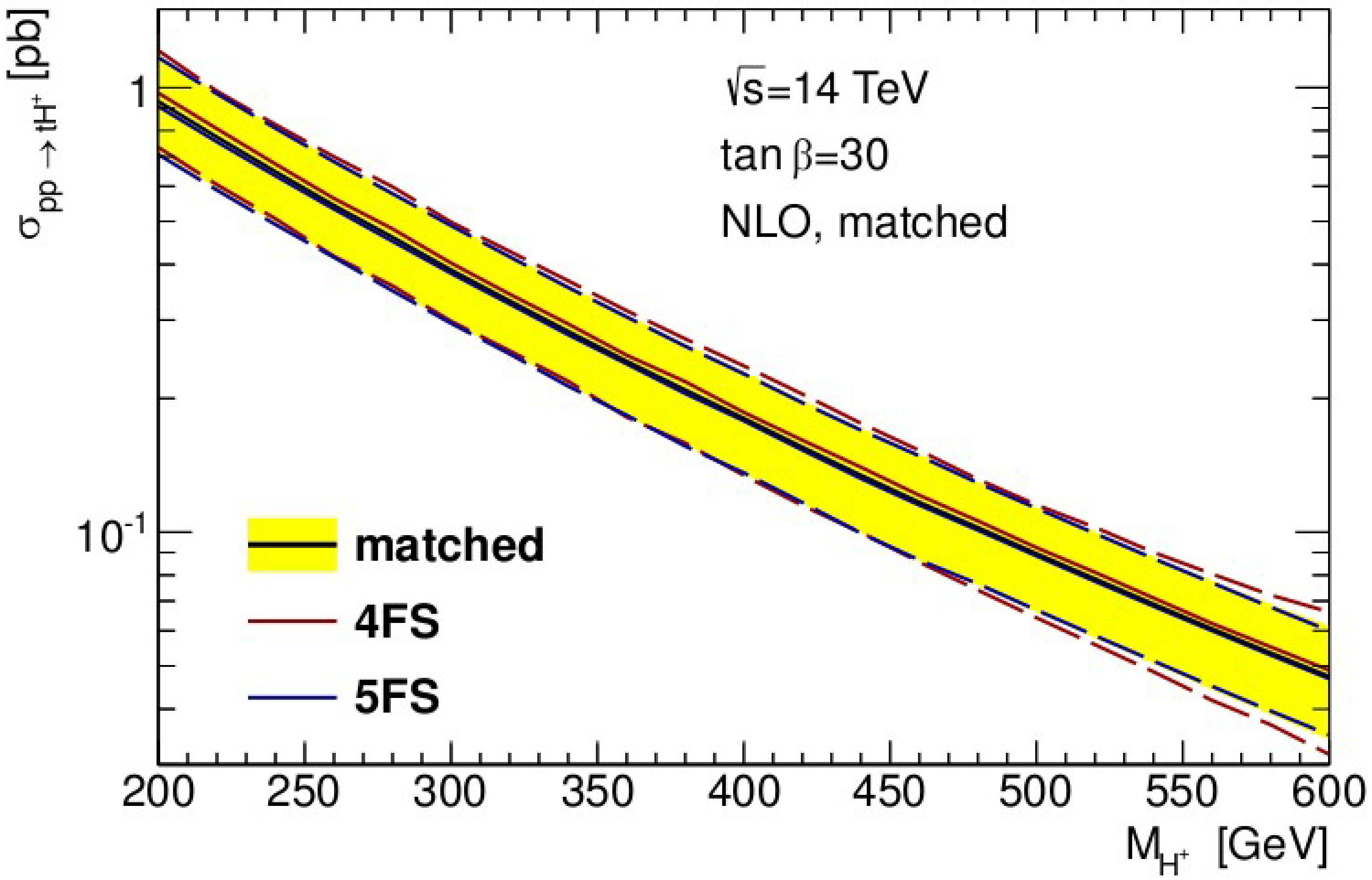
$\sqrt{s} = 14$ TeV





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

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



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/MSSMCharged

H^+ search strategies at the LHC

For $m_{H^+} < m_t$

- Look for $t \to H^+ b$ followed by
  - $H^+ \to \tau^+ \nu_\tau$ for $\tan\beta > \sim 1$
  - $H^+ \to c\bar{s}$ for $\tan\beta < \sim 1$
- $B(t \to H^+ b) \approx 0$ at $\tan\beta \approx \sqrt{\frac{m_t}{m_b}} \approx 7$: sensitivity is at minimum

For $m_{H^+} > m_t$

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

$H^+ \to W^+ b\bar{b}$ 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 $t\bar{t}$.

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

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.

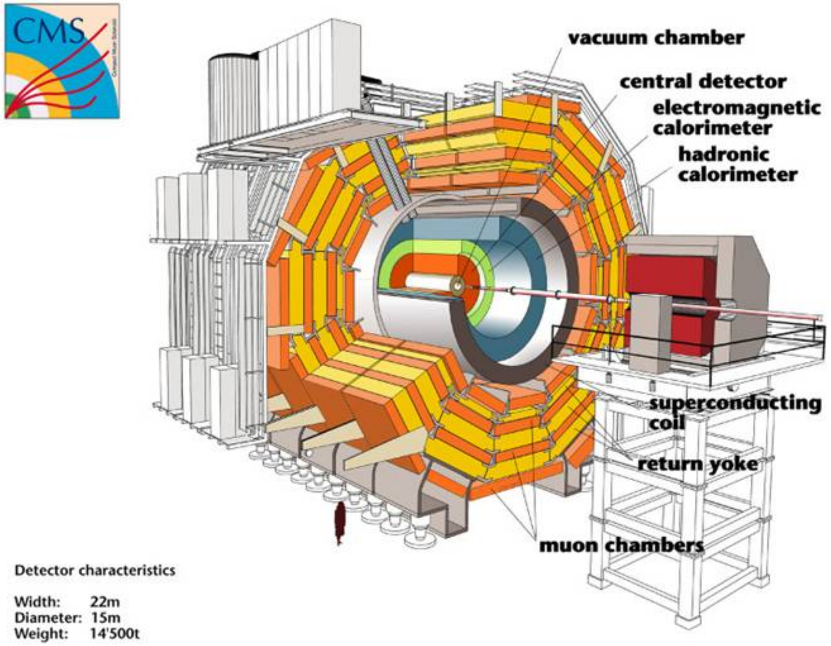
Other search strategies

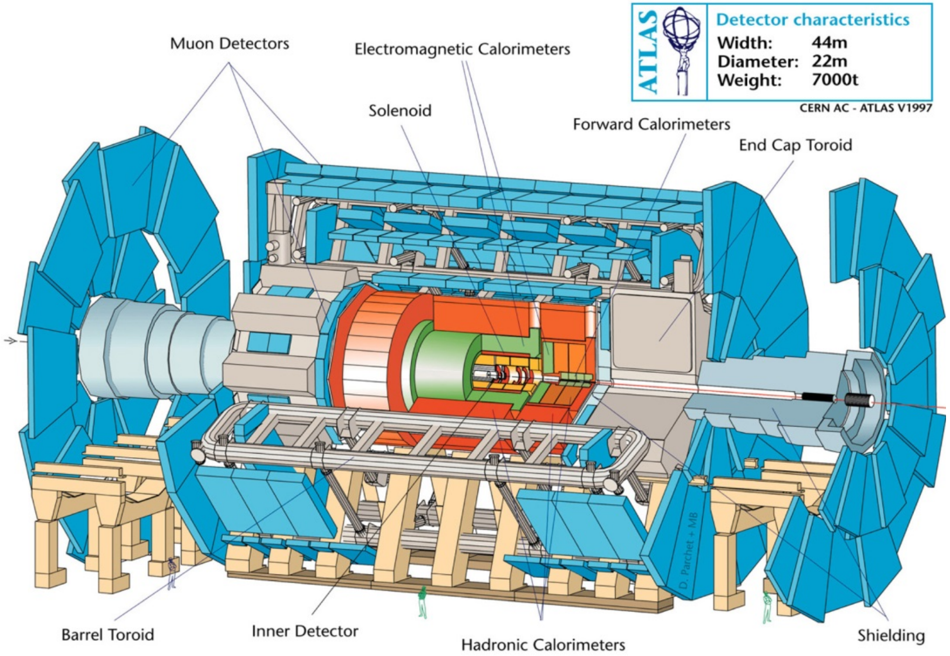
- Look for tell-tale violation of lepton universality in charged current interactions among $t\bar{t}$ event candidates,
- Look for $H^0 \to H^\pm W^\mp$ (Higgs "cascade" decays),
- Look for $H^+ \to t\bar{b}$,
- Other all-bosonic vertices,
- Vertices involving BSM particles.

(Results are available from the first three of these)

ATLAS and CMS

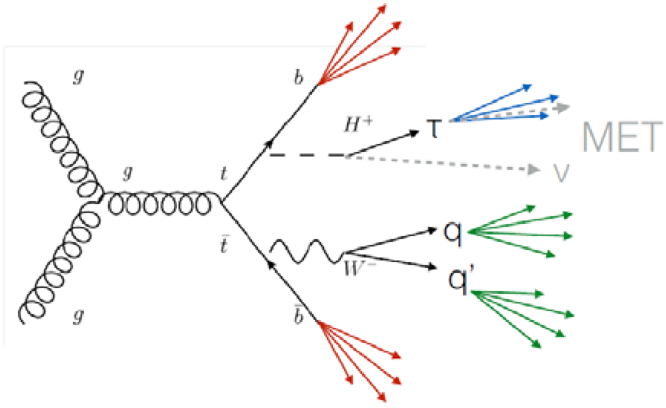
Two general-purpose detectors for the LHC





- 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.

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



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

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

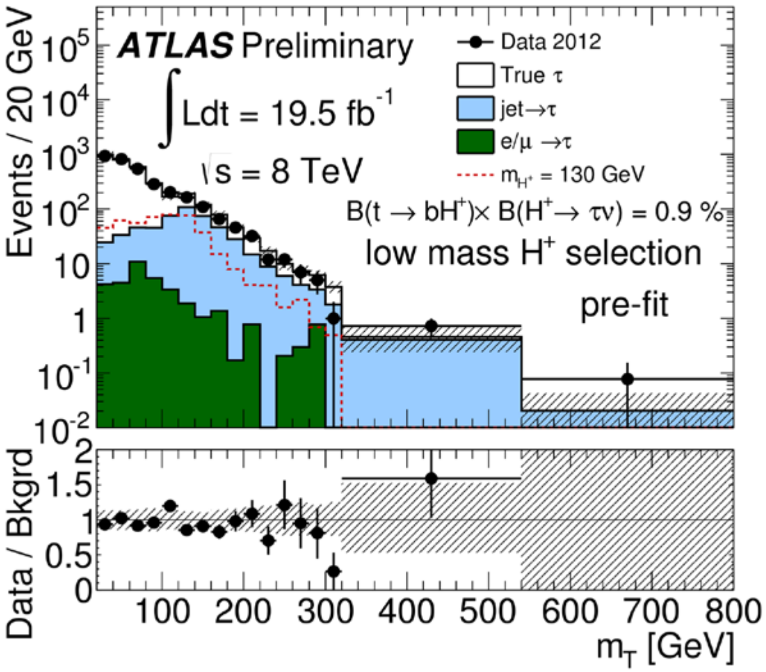
- Dominant background: SM $t\bar{t}$, QCD multi-jet.

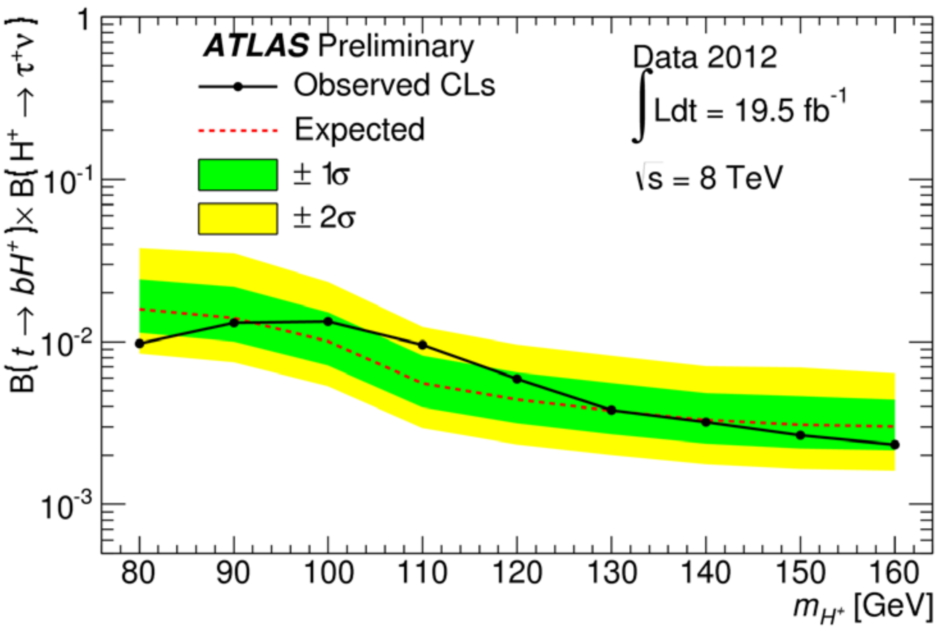
- For $m_{H^+} < m_t$ search, assume $B(H^+ \rightarrow \tau^+\nu_\tau) = 1$ to derive limits on $B(t \rightarrow H^+ b)$.
- For $m_{H^+} > m_t$, use similar event selection, but allow other decay modes to derive limits on

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

ATLAS-CONF-2014-050

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

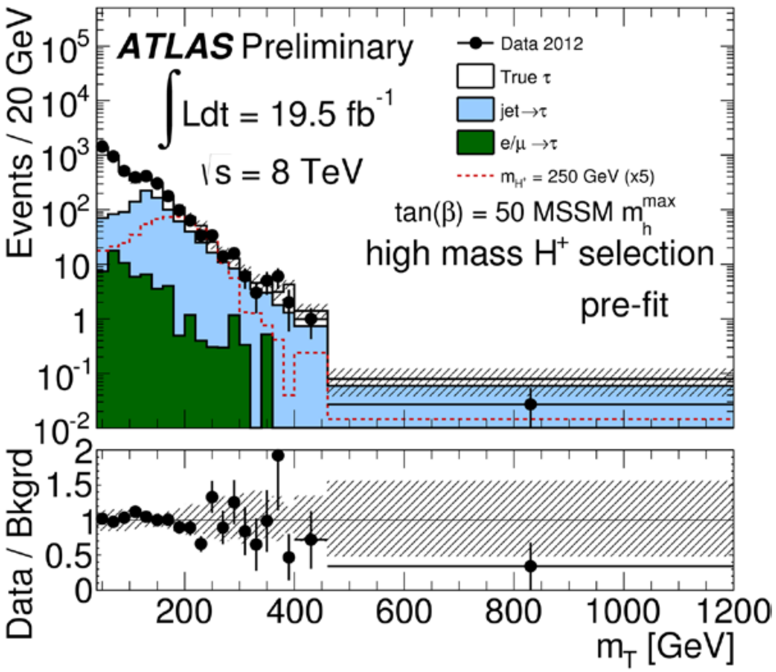


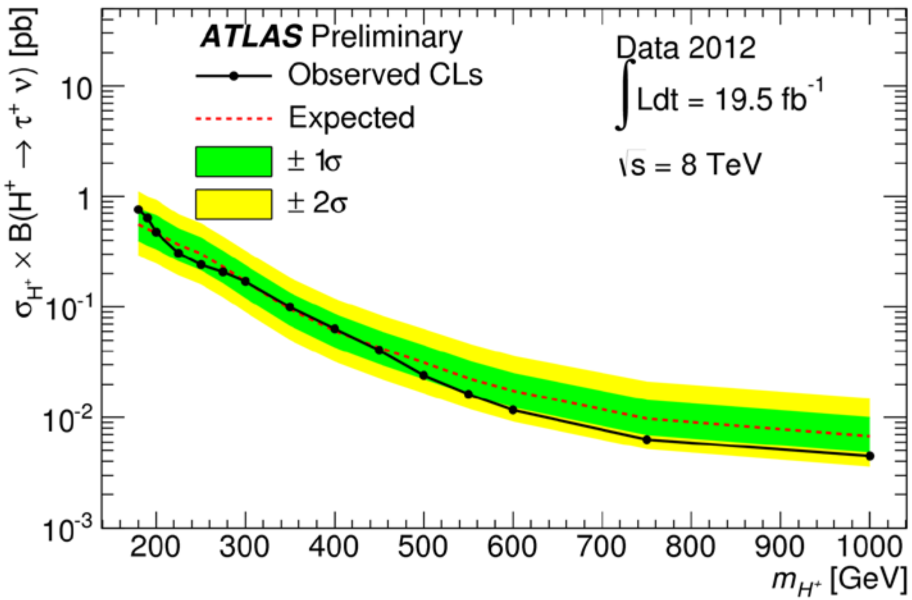


$B(t \to\ H^+b)$ < 0.0023 – 0.013 at 95% CL for $80\text{ GeV} < m_{H^+} < 160\text{ GeV}$

ATLAS-CONF-2014-050

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





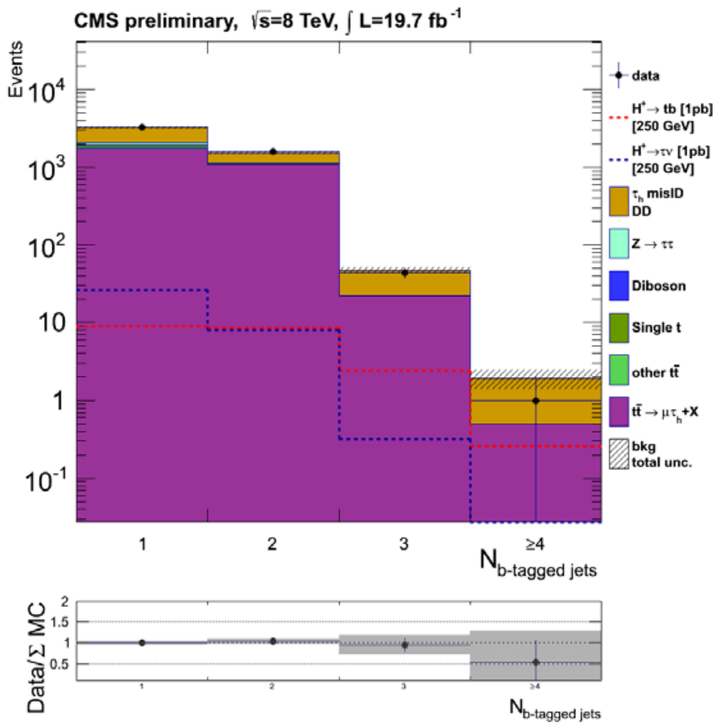
$\sigma(pp \to H^\pm) \times B(H^+ \to \tau^+\nu_\tau)$ < 0.004 - 0.76 pb at 95% CL

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

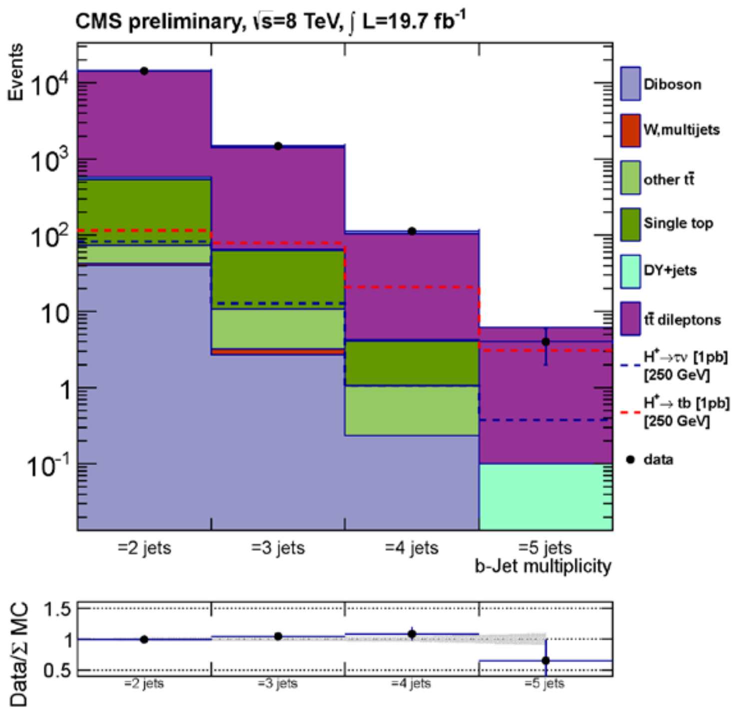
ATLAS-CONF-2014-050

$H^+ \to \tau^+\nu_\tau$ 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.



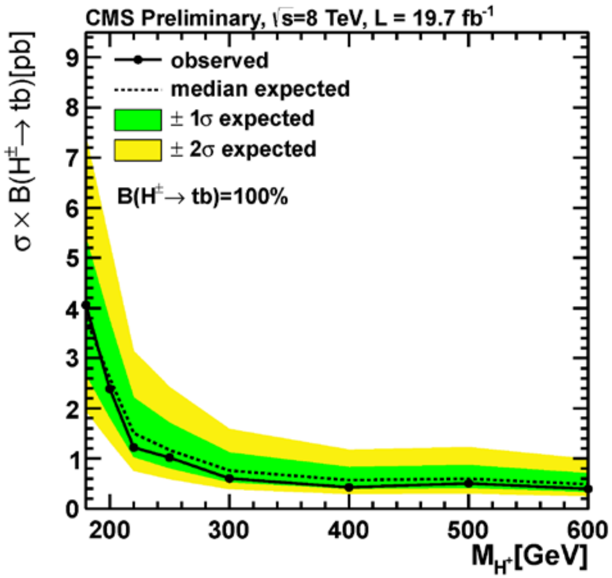
$H^{\pm} \to \tau_h l$

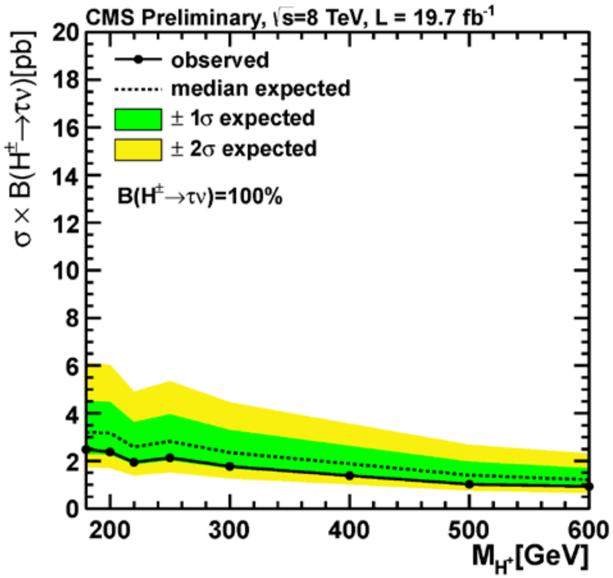


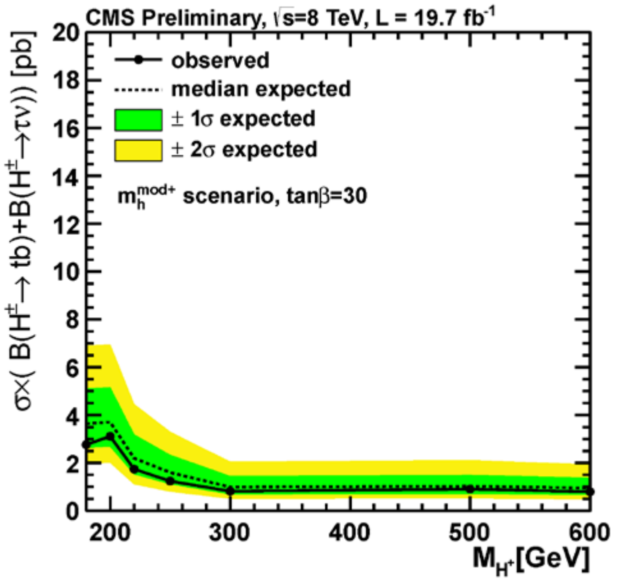
$H^{\pm} \to l_1 l_2$

CMS PAS-HIG-13-026

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







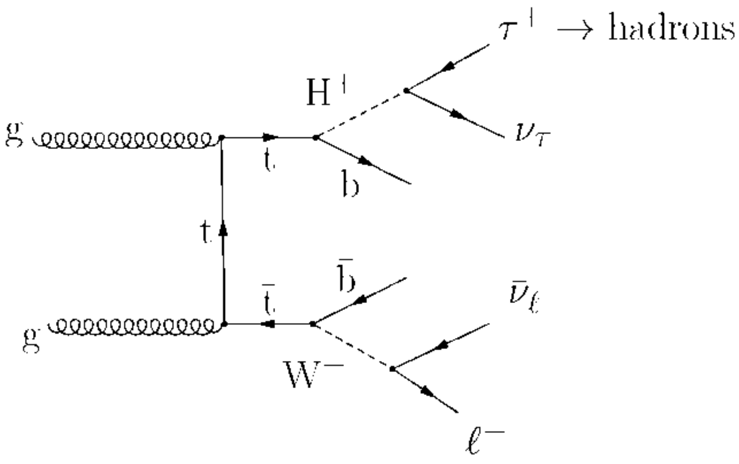
$\sigma(pp \rightarrow H^\pm) \times B\left(H^+ \rightarrow t\bar{b}\right) <\sim 1 - 2$ pb,

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

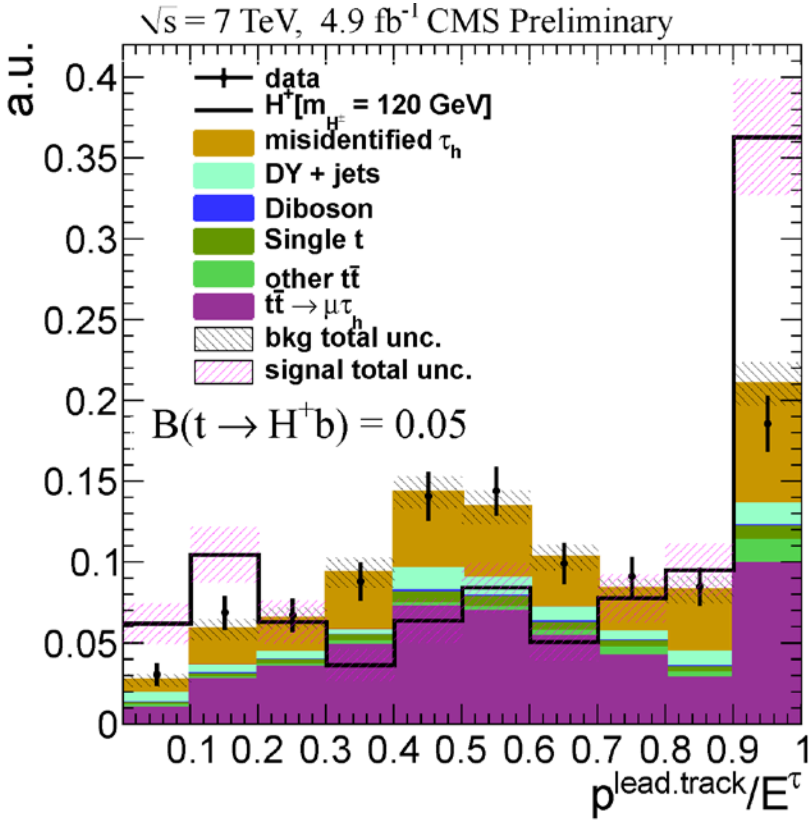
at 95% CL for $180\text{ GeV} < m_{H^+} < 600\text{ GeV}$

CMS PAS-HIG-13-026

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



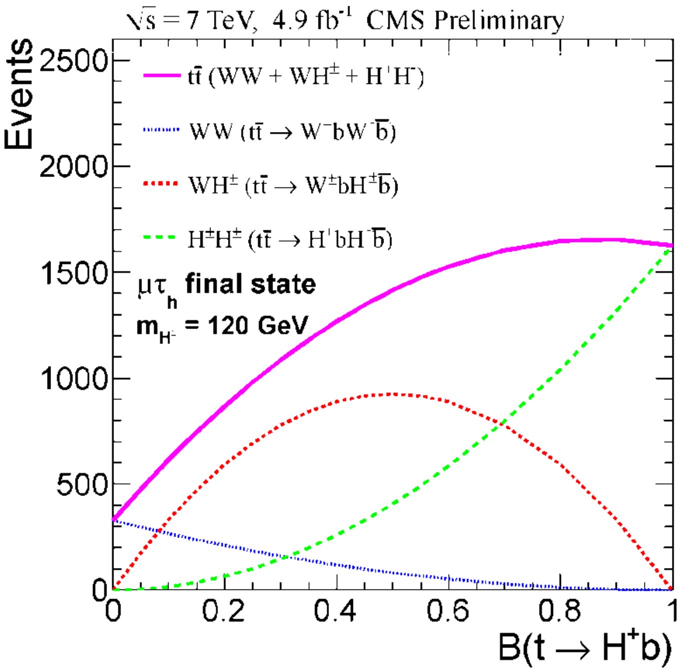
- Search in the $\tau_h l$ final state $l = e, \mu$
- Binned maximum likelihood fit to $R = p^{lead.track}/E_\tau$ distribution. This quantity is sensitive to τ polarization, which is different between τ's from H^+ and W^+ decays.

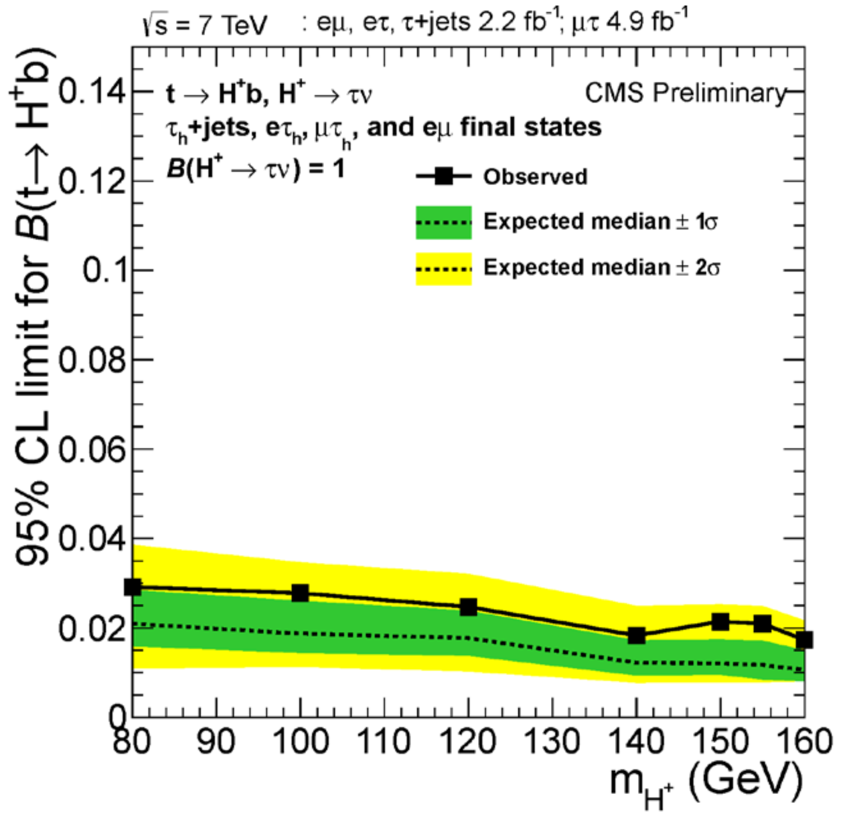


CMS PAS-HIG-12-052

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



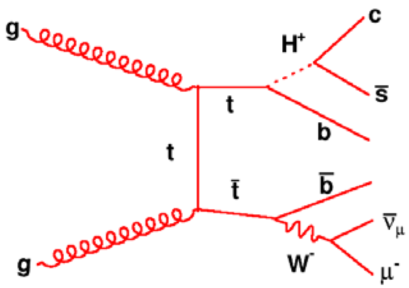


$B(t \to H^+b) < 0.03 - 0.02$ at 95% CL

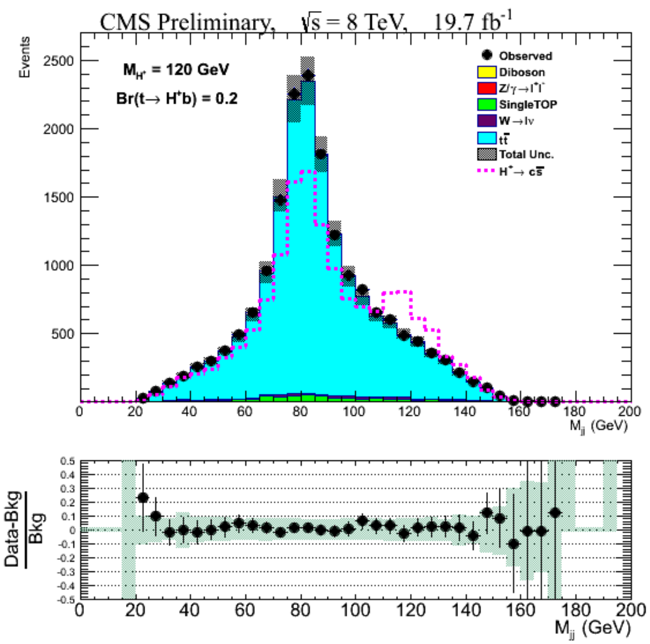
for $80\ \text{GeV} < m_{H^+} < 160\ \text{GeV}$

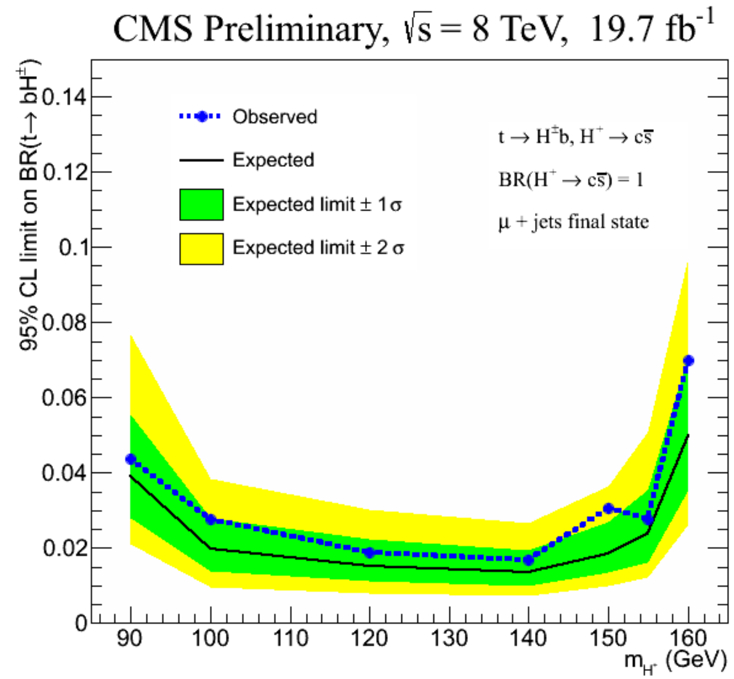
CMS PAS-HIG-12-052

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

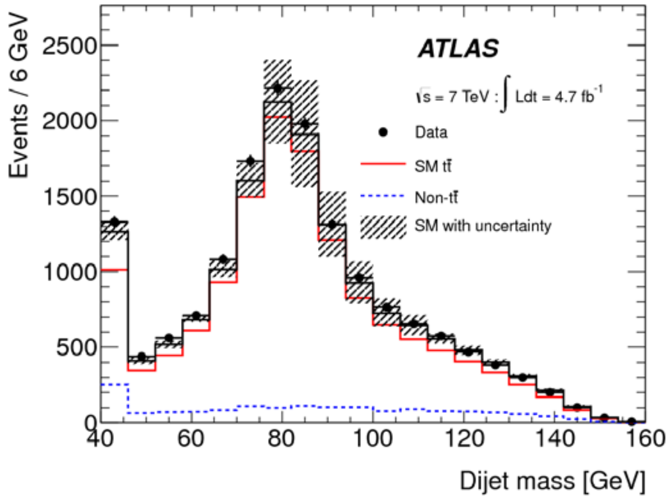




$B(t \to H^+ b)$ < 0.017 – 0.07 at 95% CL for 90 GeV $< m_{H^+} <$ 160 GeV

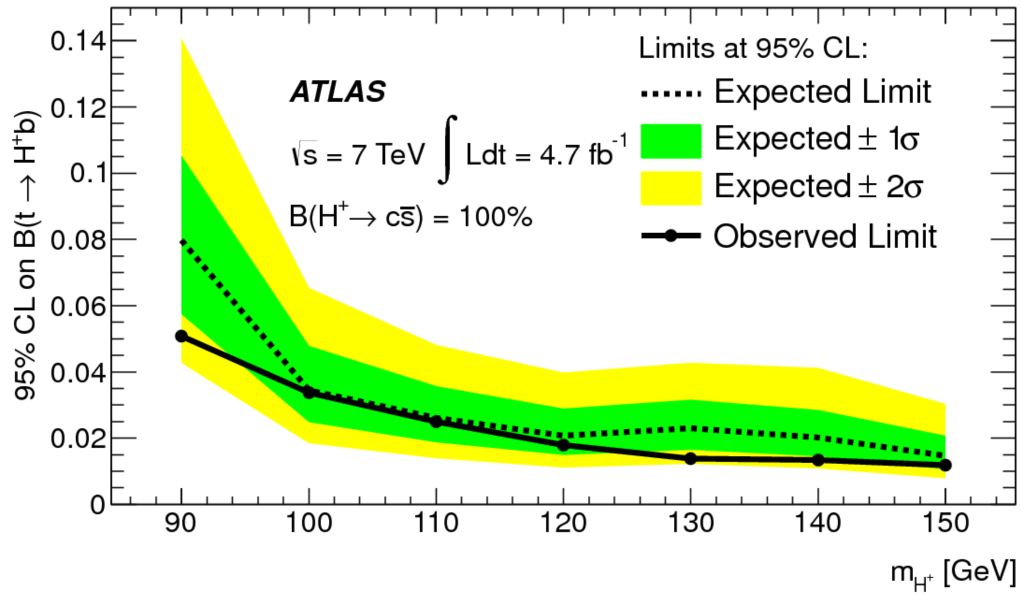
CMS PAS-HIG-13-035

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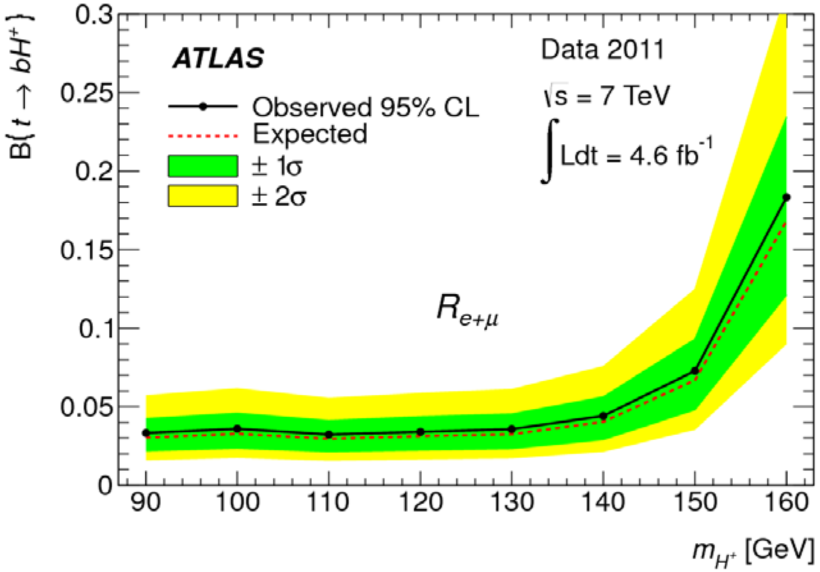
lepton universality; $m_{H^+} < m_t$ (ATLAS)

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

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



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

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

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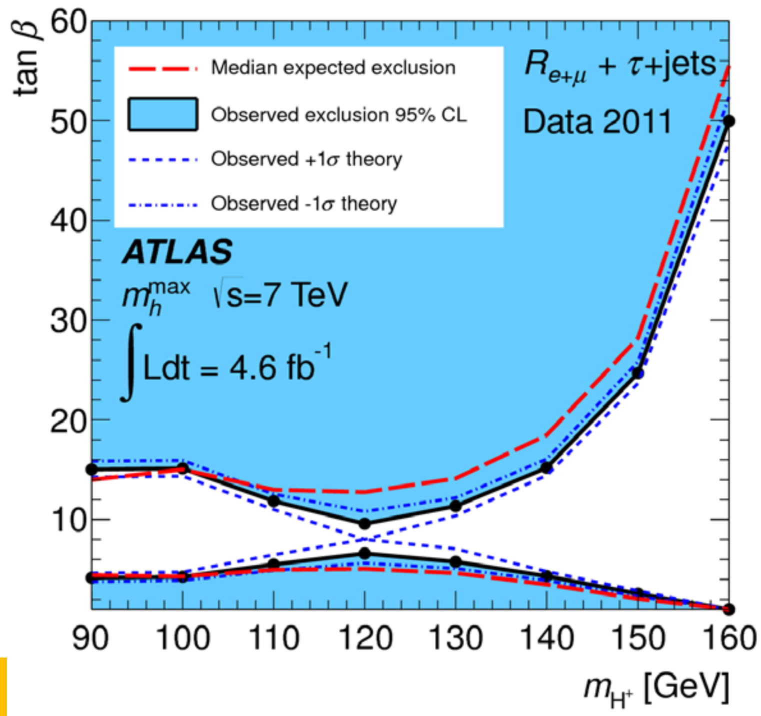
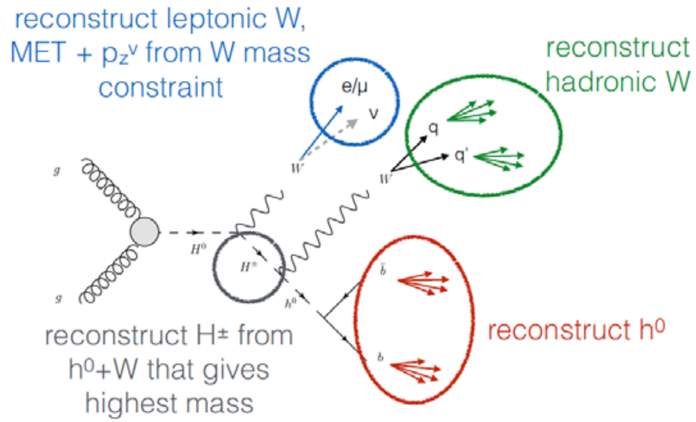
- Combined with τ_h + jets, gave best results for $\sqrt{s} = 7$ TeV.

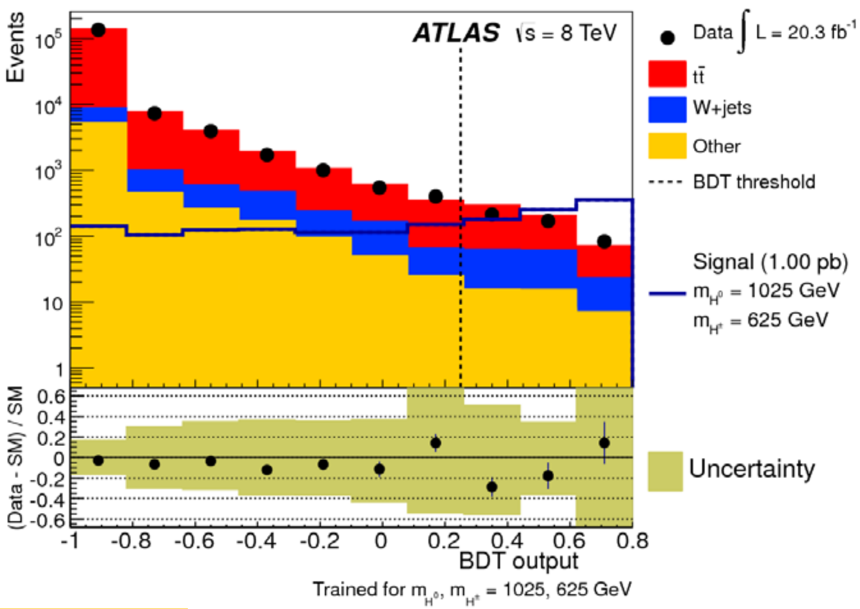


$H^0 \to H^{\pm}W^{\mp} \to h^0W^+W^-$ (ATLAS)

- 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.

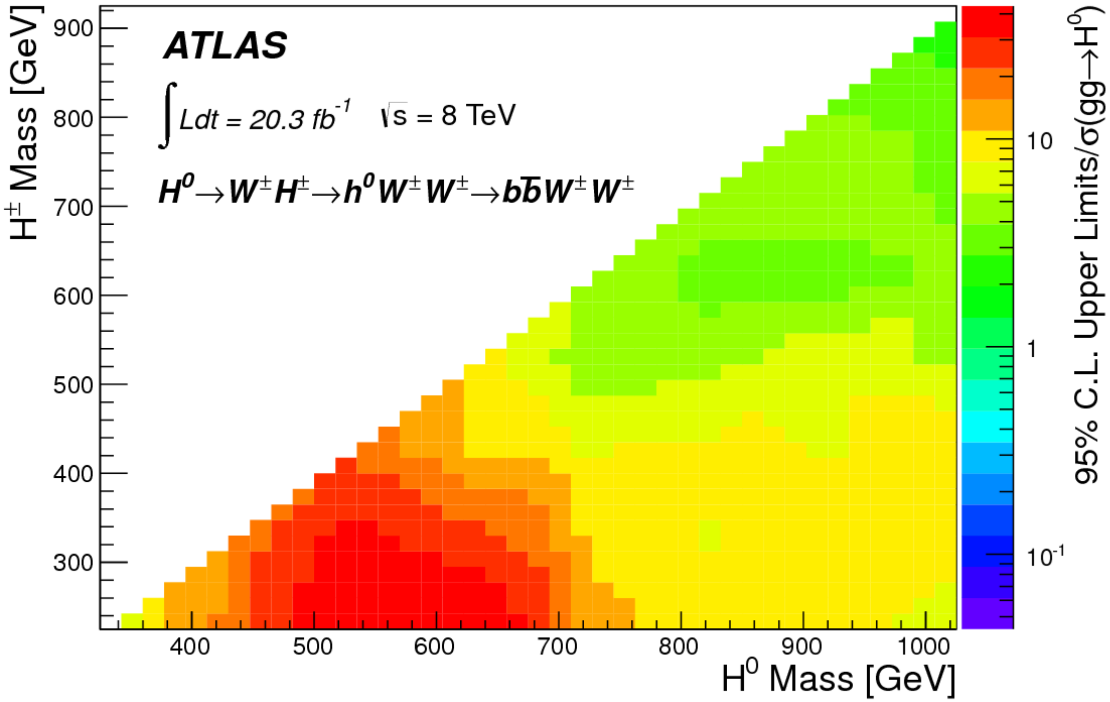




PRD 89 (2014) 032002

$H^0 \rightarrow H^\pm W^\mp \rightarrow h^0 W^+ W^-$ (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.

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Summary and outlook

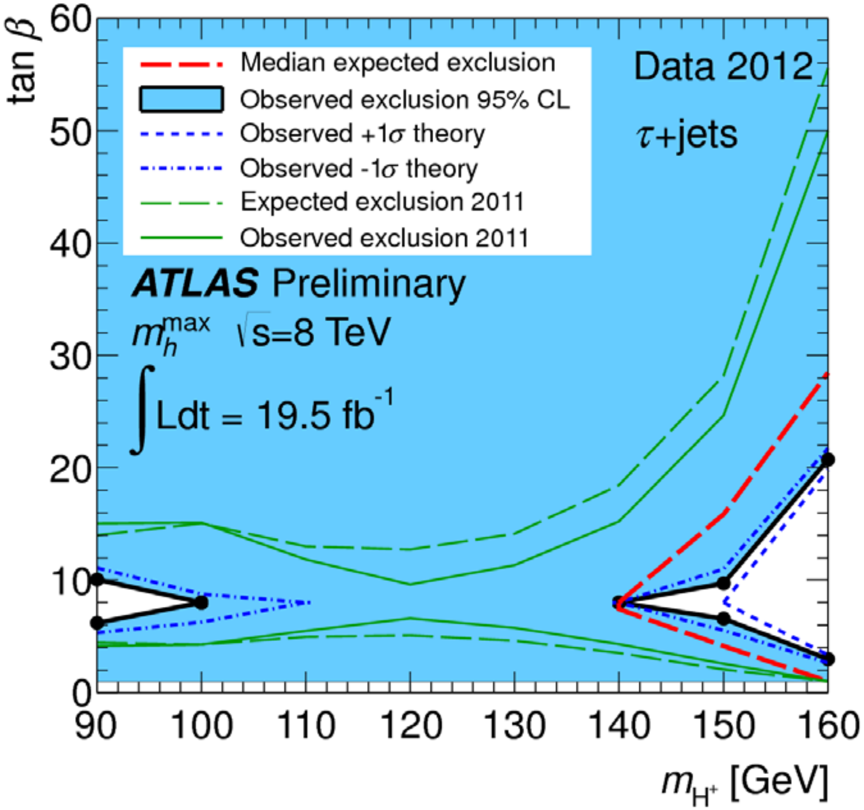
- Both ATLAS and CMS experiments have searched for production of charged Higgs bosons in pp collisions up to 20 (5) fb^{-1} of data at $\sqrt{s} = 8$ (7) TeV.
- Mostly via $H^{+}tb$ vertices so far, but investigations into alternatives have started.
- In the absence of evidence of signal, limits have been set on cross sections and/or branching fractions, interpreted to exclusion in $(m_{H^+}, \tan\beta)$ space.
- All previous direct results have been drastically improved.
- More (improved) results are expected soon.
- Close collaboration with theorists/phenomenologists to improve modeling.
- Higher production cross section and larger volume of data are expected to further improve results in Run 2.

BACK-UP SLIDES

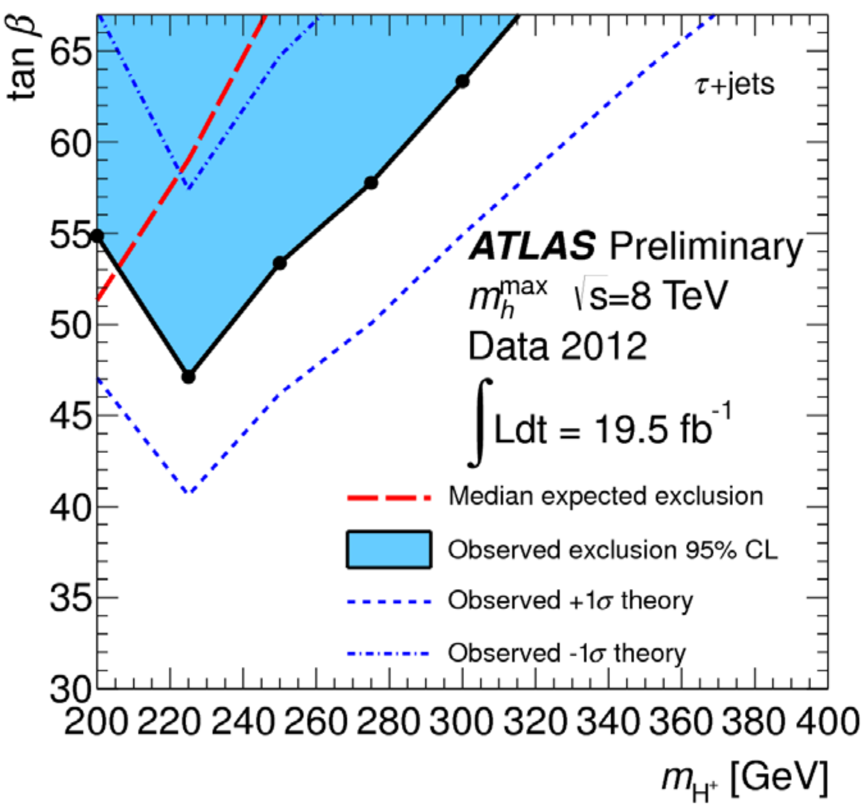
Older result: $H^+ \rightarrow \tau^+\nu_\tau$ (ATLAS)

Interpretation in MSSM m_h^{max} scenario

$m_{H^+} < m_t$



$m_{H^+} > m_t$



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