CMS H^+ searches, part 2:

H+ → $\tau^+\nu_\tau$ in fully hadronic final state*

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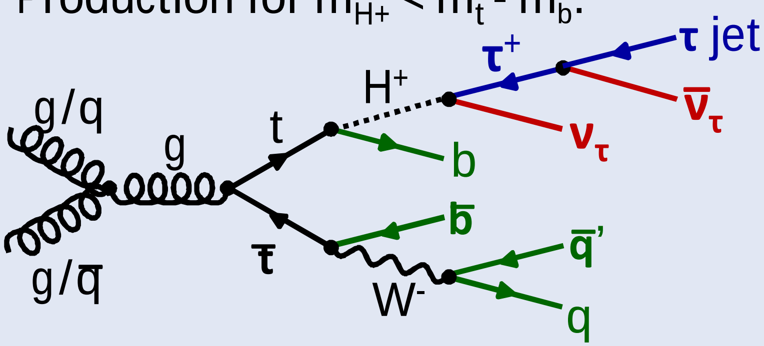
Overview of the latest CMS H+ analyses:

- H+ → $\tau^+\nu_\tau$ and H+ → tb in leptonic final states, $m_{H+}>m_t-m_b$ (see talk by P. Vischia)
- H+ → $\tau^+\nu_\tau$ in fully hadronic final state, $m_{H+}<m_t-m_b$ and $m_{H+}>m_t-m_b$ (this talk)
- H+ → csbar, $m_{H+}<m_t-m_b$ (see talk by G. Kole)
- Data-driven background measurements in the H+ searches (see talk by M.Kortelainen)

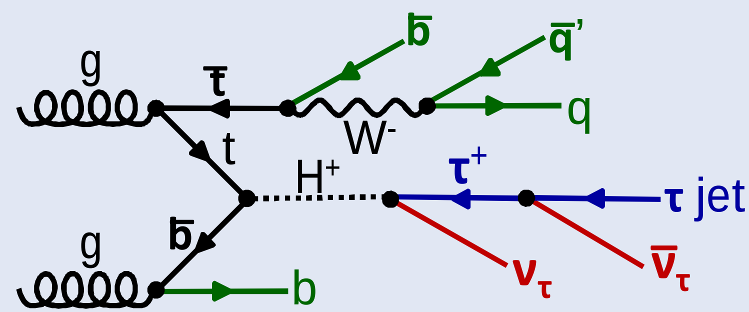
* Charge conjugation is implied throughout this talk

Overview of the $H^+ \rightarrow \tau^+\nu_\tau$ (fully hadr.) analysis

Production for $m_{H+} < m_t - m_b$:



Production for $m_{H+} > m_t - m_b$ (5FS):

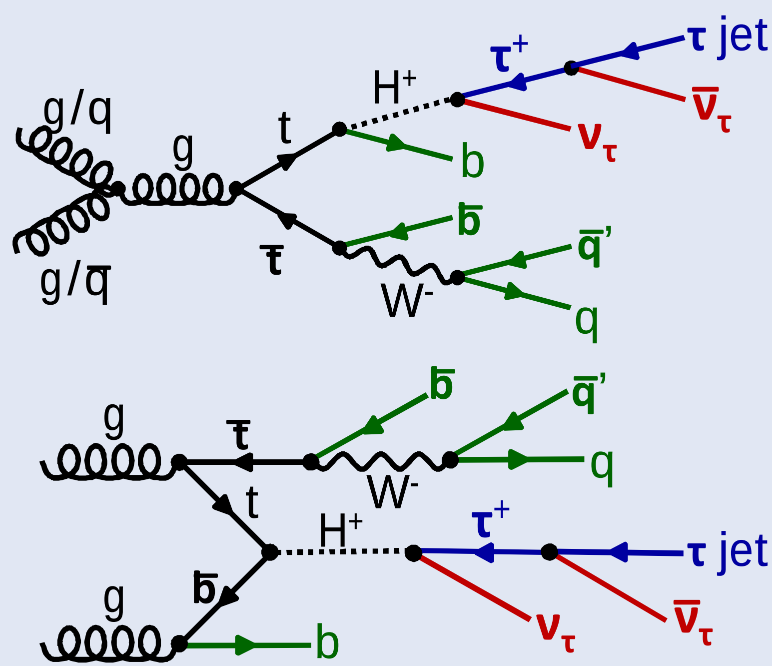


- For $H^+ \rightarrow \tau^+\nu_\tau$ decay mode, the final state is the same for light and heavy H+
  - Same methods can be used and only the thresholds need to be optimized
- Main backgrounds: QCD multijet, $t\bar{t}$, and single top
  - Multijet background (reducible): shape and normalization measured from data
  - EWK+ttbar with τ_h : shape and normalization measured from data
  - EWK+ttbar no τ_h: small background, mainly jet→τ misid., estimated from simulation

  (More in talk by M. Kortelainen — for the first two items)
- Speciality of the fully hadronic final state:
  - All neutrinos in the event come from H^+ decay
    - I.e. can separate EWK+$t\bar{t}$ from signal with transverse mass, $m_T(\tau_h, E_t^{miss})$
    - This feature makes the fully hadr. final state for $H^+ \rightarrow \tau^+\nu_\tau$ the most sensitive final state!
  - In this analysis, we are able to separate the $H^+ \rightarrow \tau^+\nu_\tau$ signal from other possible H^+ signals since in the other H^+ signals the tau always comes from W decay and they are measured as part of EWK+ttbar with τ_h
- In this talk, results are shown for 2012 data for both light and heavy H^+

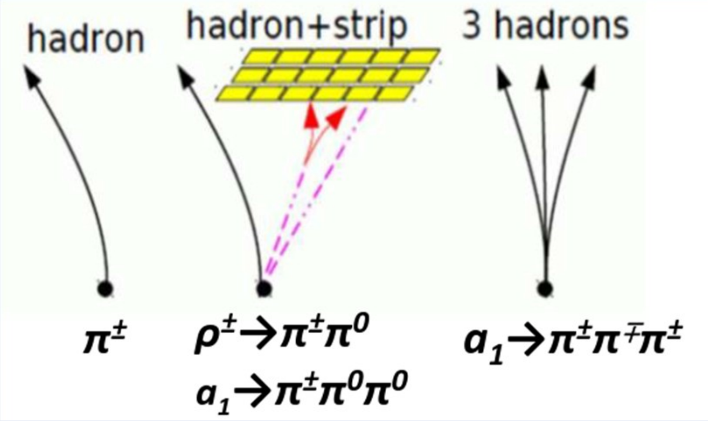
Event selection overview

- Trigger: Single tau + E_T^{miss}
- Require one hadronically decaying τ
- Apply veto on isolated and identified e/μ
  - To select fully hadr. final state
- Require at least 3 jets (in addition to τ_h), out of which at least one is a b jet
  - To select ttbar-like event topology
  - Supresses DY, W+jets, and multijet backgrounds
- Require large E_T^{miss}
  - To supress multijet background
- Apply angular cuts on τ, jets and E_T^{miss}
  - To supress multijet background in the signal region
- After these selections, ttbar is the dominant background
- Shape analysis conducted on the transverse mass from τ_h and E_T^{miss}
- More detailed event selection in following slides



Event selections in more detail (1)

- Single tau + E_T^{miss} trigger
  - τ $p_T > 35$ GeV, loose isolation on τ, and calorimetric $E_T^{miss} > 70$ GeV
- Particle-flow (PF) technique used
  - Combine the CMS subdetector information in an optimal way to identify electrons, muons, photons, charged hadrons and neutral hadrons
  - Construct composite objects such as taus, jets, and E_T^{miss} from these particles
- Primary vertex: choose vertex with highest $\mathbf{\Sigma}_{tracks}(p_T)^2$
- Taus with hadron-plus-strips (HPS) algorithm
  - τ candidates are required to match to the trigger τ object
  - $p_T > 41$ GeV, $|\eta| < 2.1$, and p_T(leading ch. particle) > 20 GeV
  - Reject electrons and muons
  - Require isolation isolation
  - 1 charged particle associated to the τ object
  - Helicity cut: R_τ ($p_{\text{leading ch. particle}}$ / $p_{\tau\ \text{jet}}$) > 0.7



- Electrons and muons for vetoing:
  - Require $p_T > 15$ GeV (10 GeV for muons) and $|\eta| < 2.5$
  - Require isolation and identification

Event selections in more detail (2)

- Jets:
  - Ignore jets overlapping with selected with τ, i.e. $\Delta R(\text{jet}, \tau_h) < 0.5$
  - Require jet $p_T > 30$ GeV and $|\eta| < 2.4$
  - Jet energy corrections are applied
  - Require at least 3 jets passing above criteria
- b tag:
  - Discriminator based on secondary vertices and track impact parameter information
  - 0.1 % rate for udsg→b (30-60 % efficiency for identifying b jets)
  - Require at least 1 of the selected jets passes b tagging
- E_T^{miss}:
  - PF E_T^{miss} used with jet energy corrections propagated to it
  - Require $E_T^{miss} > 60$ GeV
- Pile-up mitigation:
  - Correct for the presence of charged and neutral particles from pile-up vertices in electron/muon/tau isolation and jet energy and identification

Angular cuts on τ, jets and E_T^{miss} (1)

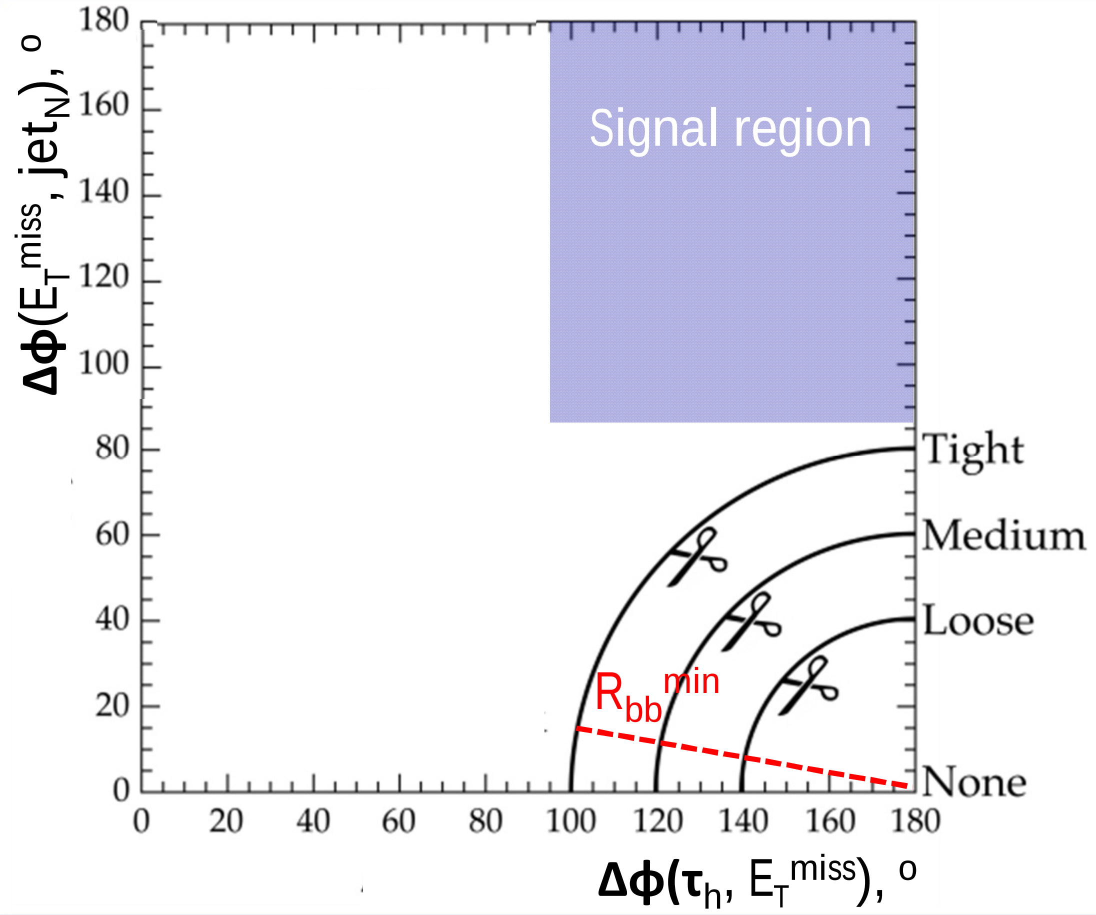
- In QCD multijet events:
  - The E_T^{miss} comes typically from overestimation of the τ_h energy
  - The p_T vector of the misidentified τ_h is typically almost back-to-back to E_T^{miss} vector in ϕ
    - This configuration maximizes the m_T and contaminates therefore the signal region
  - The p_T vector of the misidentified τ_h is typically almost back-to-back to a jet (recoiling jet) in ϕ
    - I.e. $\Delta\phi(E_T^{miss}, \tau_h) \sim 180^o$ and $\min(\Delta\phi(E_T^{miss}, jet_N)) \sim 0^o$

Angular cuts on τ, jets and E_T^{miss} (2)

- In QCD multijet events:
  - The E_T^{miss} comes typically from overestimation of the τ_h energy
  - The p_T vector of the misidentified τ_h is typically almost back-to-back to E_T^{miss} vector in ϕ
    - This configuration maximizes the m_T and contaminates therefore the signal region
  - The p_T vector of the misidentified τ_h is typically almost back-to-back to a jet (recoiling jet) in ϕ
    - I.e. $\Delta\phi(E_T^{miss}, \tau_h) \sim 180^o$ and $\min(\Delta\phi(E_T^{miss}, jet_N)) \sim 0^o$
- This feature can be used to supress multijet events by cut on:

$R_{bb}^{min} = \min\{\mathrm{sqrt}\{ \boldsymbol{\Delta\phi}_{MET,jet\_N}{}^2 + (180^o - \boldsymbol{\Delta\phi}_{\tau,MET})^2 \}\}$

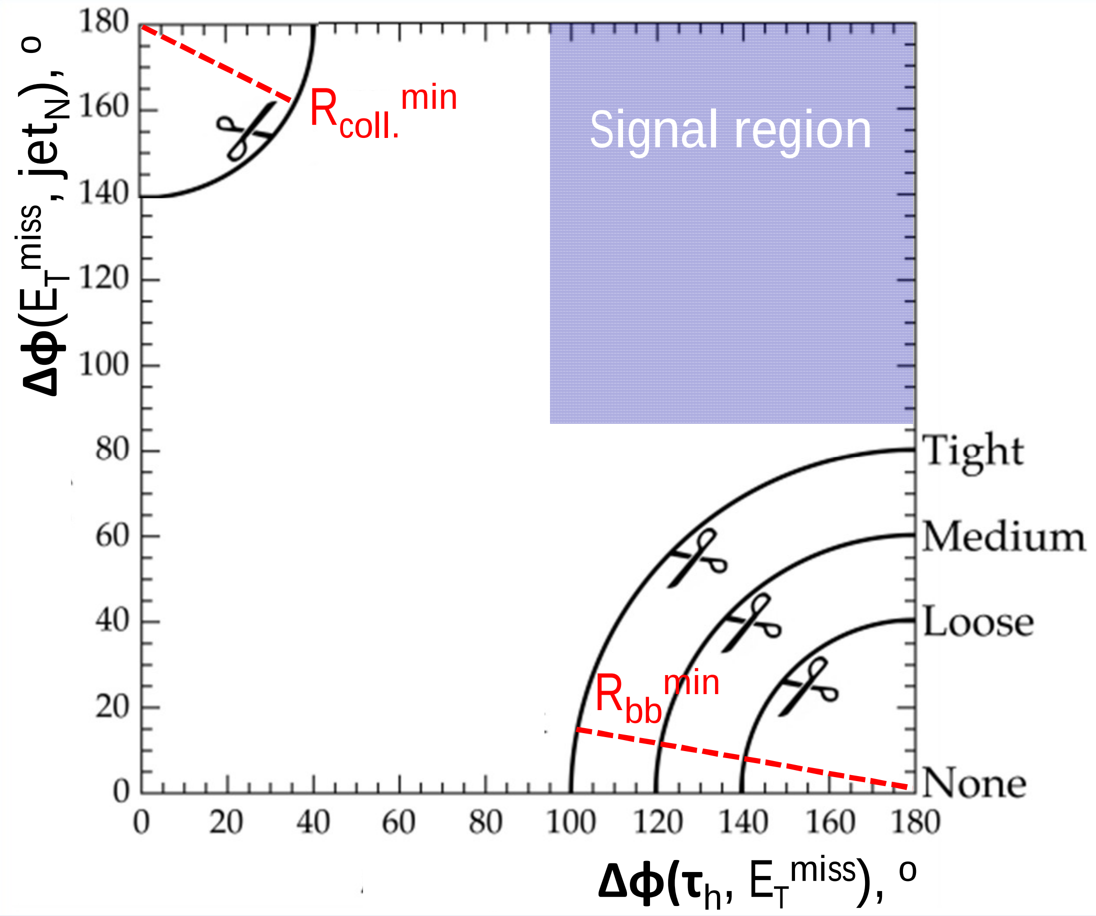
where N = 1..3 highest-p_T jet in the event



$m_T = \mathrm{sqrt}\{ 2\, E_T^{miss}\, p_T^{\tau} (1-\cos \Delta\phi(E_T^{miss}, \tau_h)) \}$

Angular cuts on τ, jets and E_T^{miss} (3)

- Additionally:
  - The E_T^{miss} can also come from the from underestimation of the τ_h energy
  - The p_T vector of the misidentified τ_h is almost collinear to E_T^{miss} vector in ϕ
    - This configuration minimizes the m_T, i.e. It does not contaminate the signal region, but causes a small correlation in the multijet measurement if a cut on R_{bb}^{min} is applied
  - The p_T vector of the misidentified τ_h is typically almost back-to-back to a jet (recoiling jet) in ϕ
    - I.e. $\Delta\phi(E_T^{miss}, \tau_h) \sim 0^o$ and $\min(\Delta\phi(E_T^{miss}, jet_N)) \sim 180^o$
- This feature can be used to make a cut on:



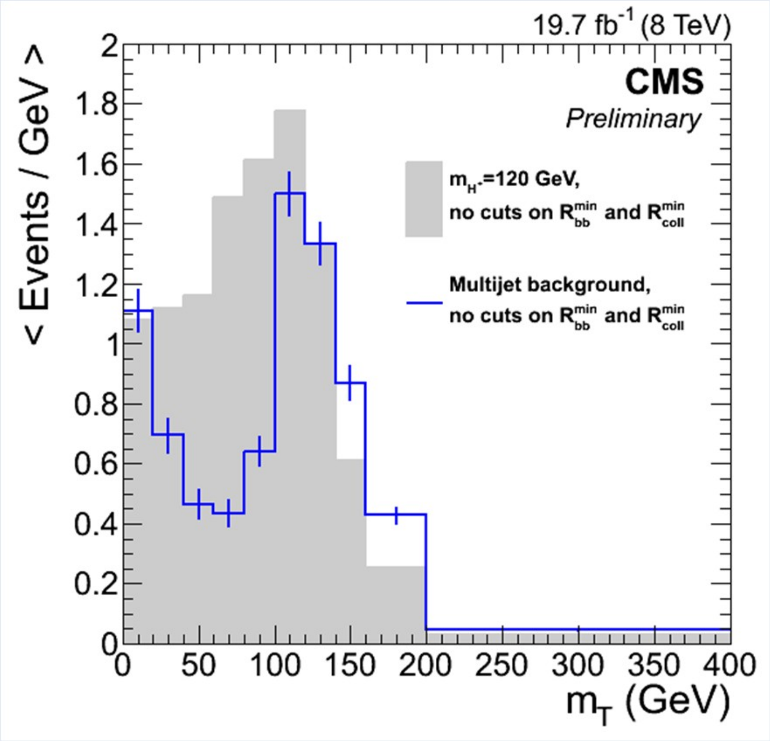
$R_{coll.}^{min} = \min\{\text{sqrt}\{ (180^o - \mathbf{\Delta\phi}_{MET, jet\_N})^2 + \mathbf{\Delta\phi}_{\tau,MET}^2 \}\}$

where n = 1..3 highest-p_T jet in the event

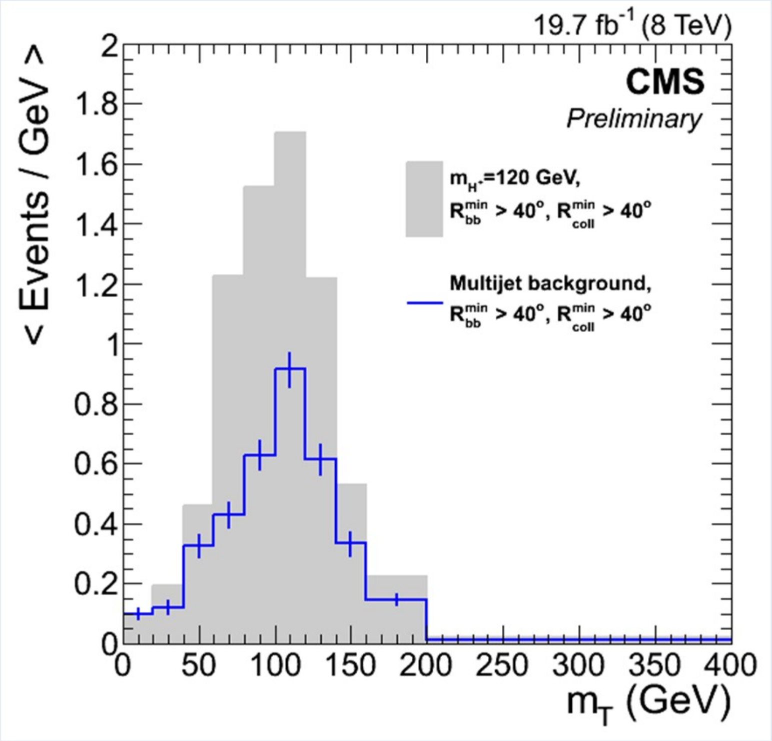
$m_T = \text{sqrt}\{ 2 E_T^{miss} p_T^{\tau} (1-\cos \mathbf{\Delta\phi}(E_T^{miss}, \tau_h)) \}$

Angular cuts on τ, jets and E_T^{miss} (4)

Number of selected events from signal and multijet background with no angular cuts applied



Number of selected events from signal and multijet background with $R_{coll.}^{min} > 40^o$ and $R_{bb}^{min} > 40^o$ applied



- $R_{coll.}^{min} > 40^o$ and $R_{bb}^{min} > 40^o$ used in the analysis

Systematic uncertainties

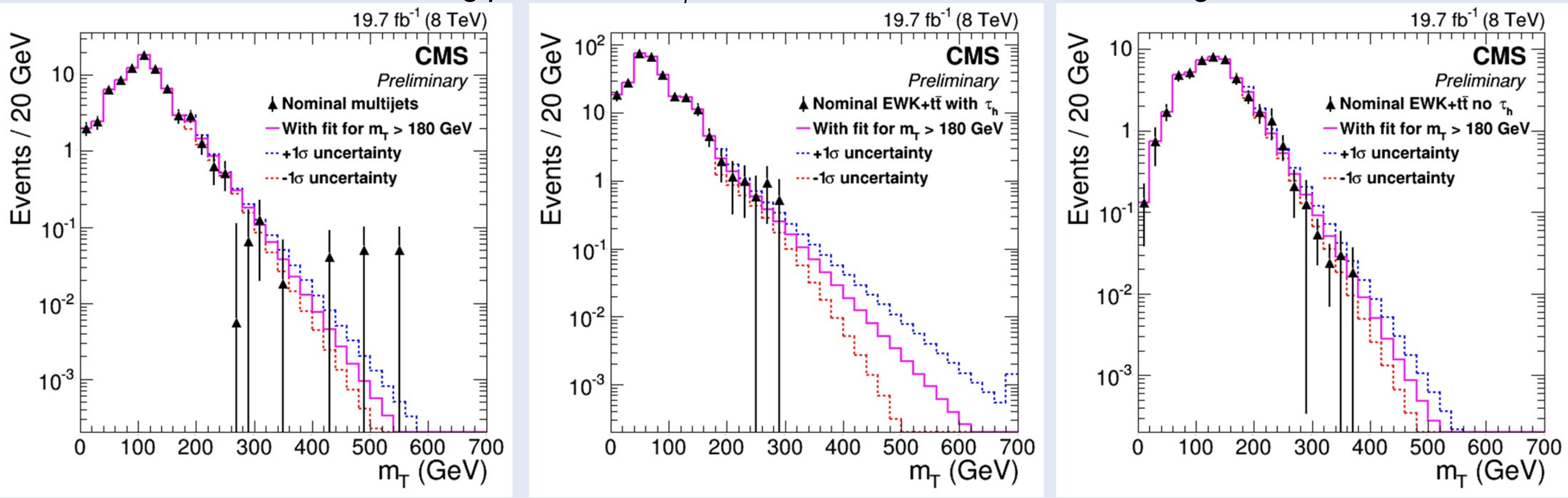
	Signal H^+H^-	Signal H^+W^-	Signal H^+	Multi-jets	EWK+$t\bar{t}$ with τ_h	EWK+$t\bar{t}$ no τ_h
Trigger τ part, data (S)	1.5–1.8	1.3–1.5	1.8–3.0	0.5	1.2	1.4
Trigger τ part, sim. (S)	0.7–0.8	0.6–0.7	0.8–1.1	0.2		0.8
Trigger E_T^{miss} part, data (S)	2.6–3.3	2.5–2.8	2.9–4.2	1.2	2.5	2.8
Trigger E_T^{miss} part, sim. (S)	0.1	0.1	0.1	0.1		0.4
Trigger, approximation in E_T^{miss}					12	
Trigger, single μ (S)					0.1	
τ_h identification (S)	6.0	6.0	5.9–6.0	0.8	6.0	
$e \rightarrow \tau_h$ misident. (S)	< 0.1	< 0.1	< 0.1	0.1		3.3
$\mu \rightarrow \tau_h$ misident. (S)	< 0.1	< 0.1	< 0.1	< 0.1		1.1
Jet$\rightarrow \tau_h$ misident. (S)	0.1	0.1–0.3	0.1	6.9		17
Veto of events with e/μ	0.4–0.5	0.6–0.7	0.5–0.6	< 0.1		1.6
τ energy scale (S)	0.3–2.6	2.7–5.2	0.3–2.7	1.8	5.8	2.0
Jet energy scale (S)	2.6–5.2	2.0–3.0	1.6–2.1	1.4		3.2
Jet energy resolution (S)	1.1–1.8	0.5–1.3	0.7–1.5	1.4		3.2
Unclustered E_T^{miss} ES (S)	0.1–0.4	0.1–0.9	0.1–0.4	0.5		1.5
b tagging (S)	5.9–20	4.7–5.3	4.6–5.4	3.5		5.0
Probabilistic m_T in single top						6.8
Top p_T reweighting (S)				$^{+5.6}_{-6.8}$		$^{+11}_{-6.6}$
Multijet m_T distribution shape (S)				4.6		
Multijet template fit				3.0		
μ identification (S)					< 0.1	
Multijet contamination					2.0	
$W \rightarrow \tau\nu_\tau \rightarrow \mu\nu_\mu\nu_\tau$ frac. (S)					1.2	
Non-emb./emb. difference					$^{+14}_{-12}$	
Pileup modelling (S)	0.1–0.9	0.1–0.8	0.1–0.6	0.1		2.9
$t\bar{t}$ cross section	$^{+5.2}_{-6.0}$	$^{+5.2}_{-6.0}$		$^{+1.8}_{-1.5}$		$^{+4.5}_{-5.2}$
Single top cross section						1.0
W+jets, DY, VV cross section						0.1
Luminosity	2.6	2.6	2.6	0.8		2.6

- Note that some of the backgrounds include simulation related uncertainties
  - Multijets: through subtraction of impurity from simulated EWK+tt (subtraction causes these uncertainies to be anti-correlated with other samples)
  - EWK+ttbar with taus: simulation of tau decay
- Most uncertainties change the mT shape and are therefore treated as shape nuisances denoted by (S)
- Correlation is implied on the same line
- Dominating uncertainties:
  - Signal (tt→bbH^+H^-, tt→bbH^+W^-, pp->t(b)H^+)
    - τ ID and b tag
  - QCD multijets:
    - Jet→τ mis-ID
    - top p_T reweighting
    - shape difference between non-isol./isol. sample
  - EWK+tt genuine taus:
    - Approximation in E_T^{miss} part of trigger
    - shape difference between non-emb./emb. sample
  - EWK+tt mis-ID taus:
    - jet→τ mis-ID
    - top p_T reweighting

Treatment of statistical uncertainties on m_T templates

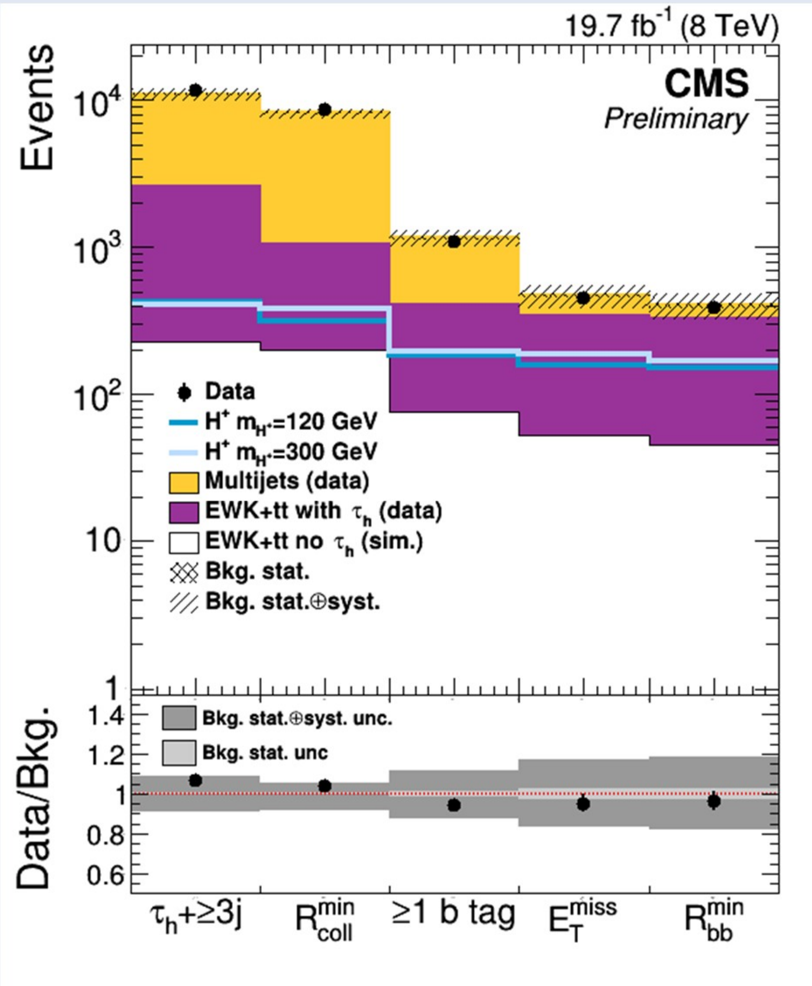
- In the signal or background distributions, an uncorrelated nuisance parameter is assigned for each bin of the m_T templates
- In addition, for m_{H+}=180-600 GeV, the falling part of the m_T distribution in the backgrounds is fitted to p_0*exp{ -p_1*(m_T - 180 GeV) }
  - The relative syst. uncertainties are kept constant
  - The stat. uncertainties in the fit region are given by the uncertainties on the fit parameters

Fit on the falling part of the m_T distributions for the different backgrounds



N_{events} as function of cut flow

Number of events after each selection step



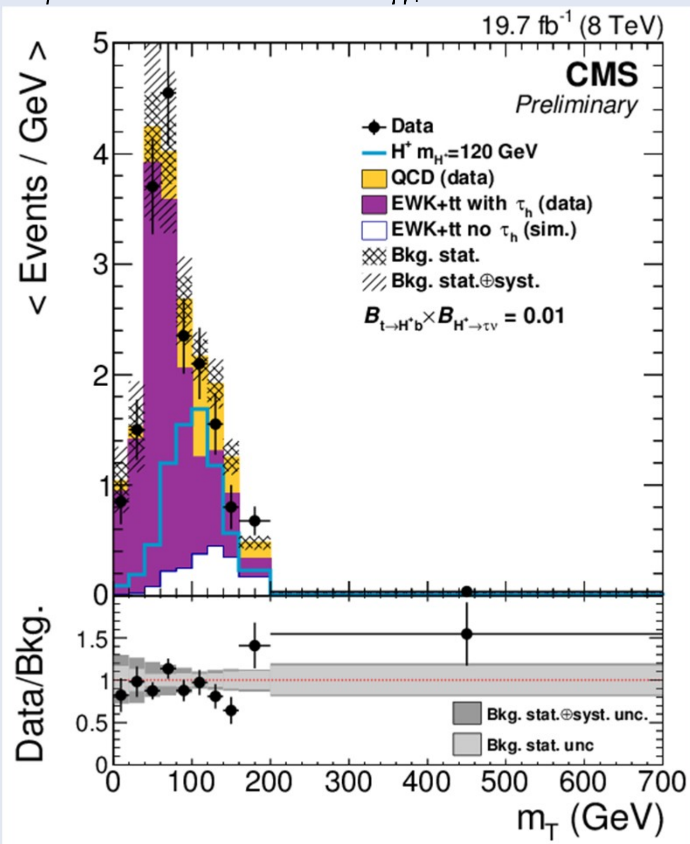
Number of selected events after all selections

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

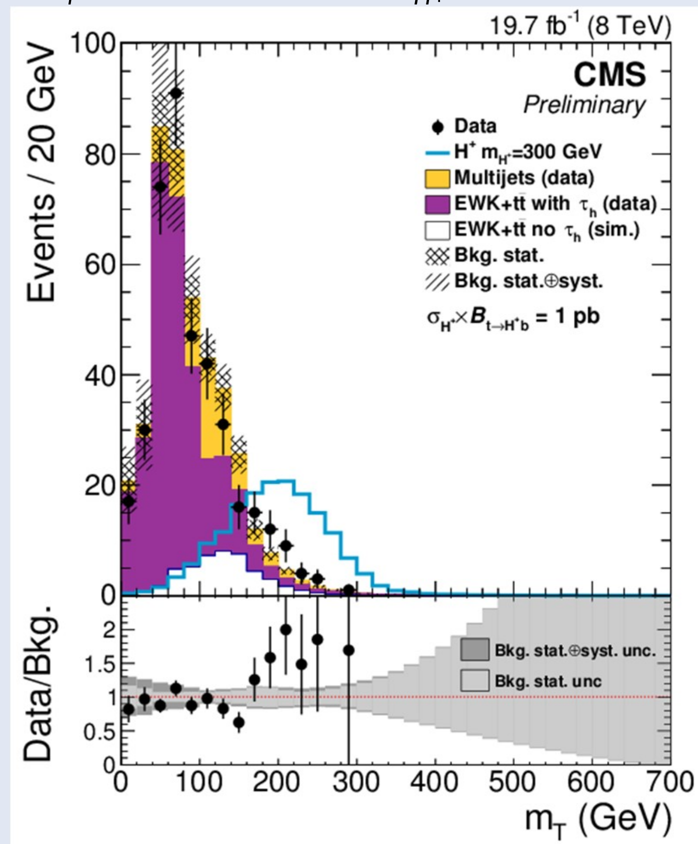
- Signal is normalized here for illustration purposes to:
  $B(t \rightarrow bH^+) * B(H^+ \rightarrow \tau^+\nu_\tau) = 0.01$
  or
  $\sigma(pp \rightarrow t(b)H^+) * B(H^+ \rightarrow \tau^+\nu_\tau) = 1$ pb

Transverse mass distributions

m_T distributions for m_{H+}=80-160 GeV



m_T distributions for m_{H+}=180-600 GeV

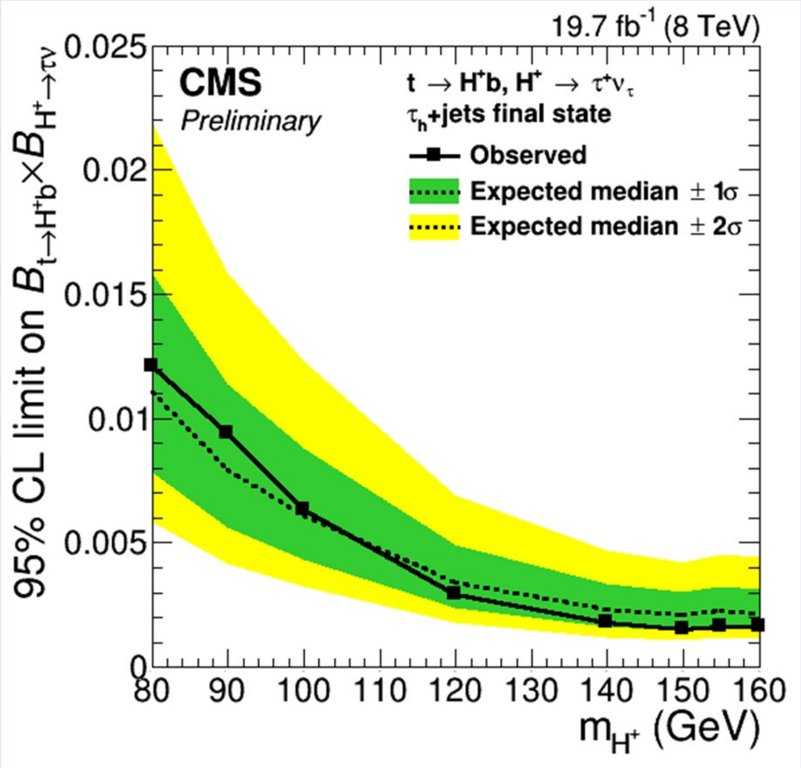


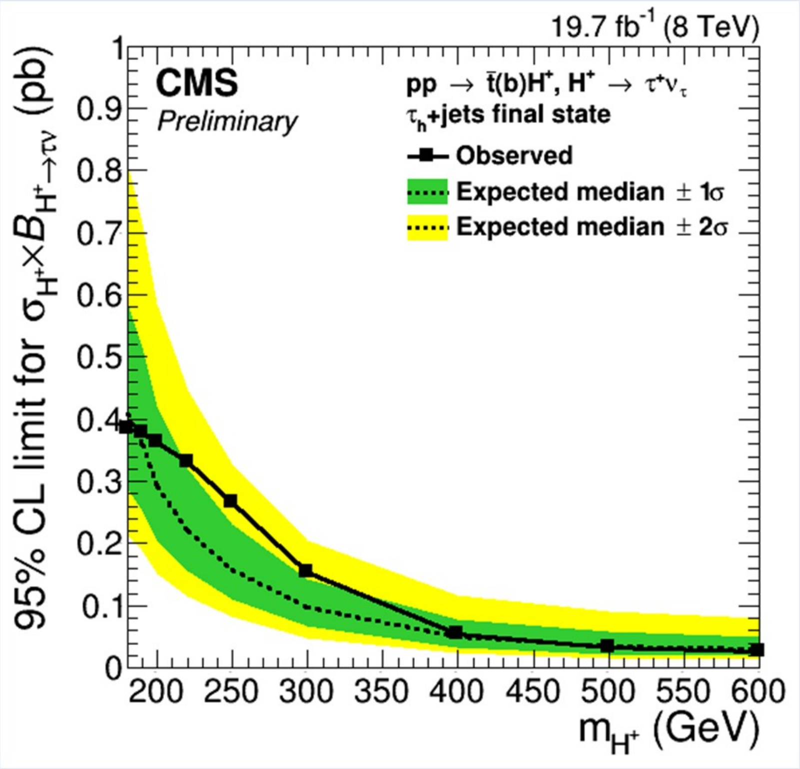
- Signal is normalized here for illustration purposes to $B(t \rightarrow bH^+)*B(H^+ \rightarrow \tau^+\nu_\tau) = 0.01$ or $\sigma(pp \rightarrow t(b)H^+)*B(H^+ \rightarrow \tau^+\nu_\tau) = 1$ pb
- For m_{H+}=180-600 GeV, the fit on the m_T tail is used
- Signal separation from backgrounds improves as a function of m_{H+}

About setting limits

- The statistical analysis is done with a binned maximum-likelihood fit
- The 95 % CL limits are derived with modified frequentist CL_s criterion
- Model-indepenent limits:
  - $B(t \rightarrow bH^+) * B(H^+ \rightarrow \tau^+\nu_\tau)$ for m_{H+}=80-160 GeV
  - $\sigma(pp \rightarrow t(b)H^+) * B(H^+ \rightarrow \tau^+\nu_\tau)$ for m_{H+}=180-600 GeV
- Model-dependent limits:
  - Calculated for MSSM benchmark scenarios [LHCHXSWG YR3 CERN-2013-004, Carena et al., EPJ C 73 (2013) 2552]
    - Updated m_h^{max}, m_h^{mod+}, m_h^{mod-}, light stop, light stau, τ-phobic, and low m_H
  - Theoretical uncertainties of 21 % used for m_{H+}=80-160 GeV and 32 % for m_{H+}=180-600 GeV
    - Includes uncertainty from higher order ttbar corrections for ttbar production and 30 % uncertainty for $pp \rightarrow t(b)H^+$ production
    - Includes uncertainty on one-loop EWK diagrams, missing two-loop QCD diagrams, and Δ_b corrections for $B(t \rightarrow bH^+)$ and $B(H^+ \rightarrow \tau^+\nu_\tau)$ [LHCHXSWG YR2 CERN-2012-002]

Model-independent limits

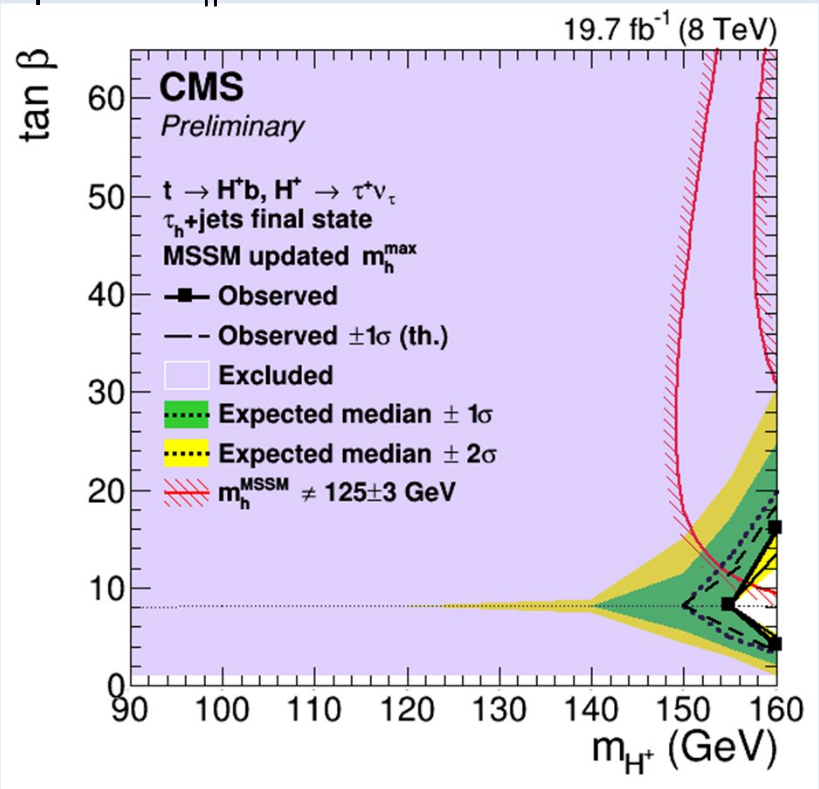




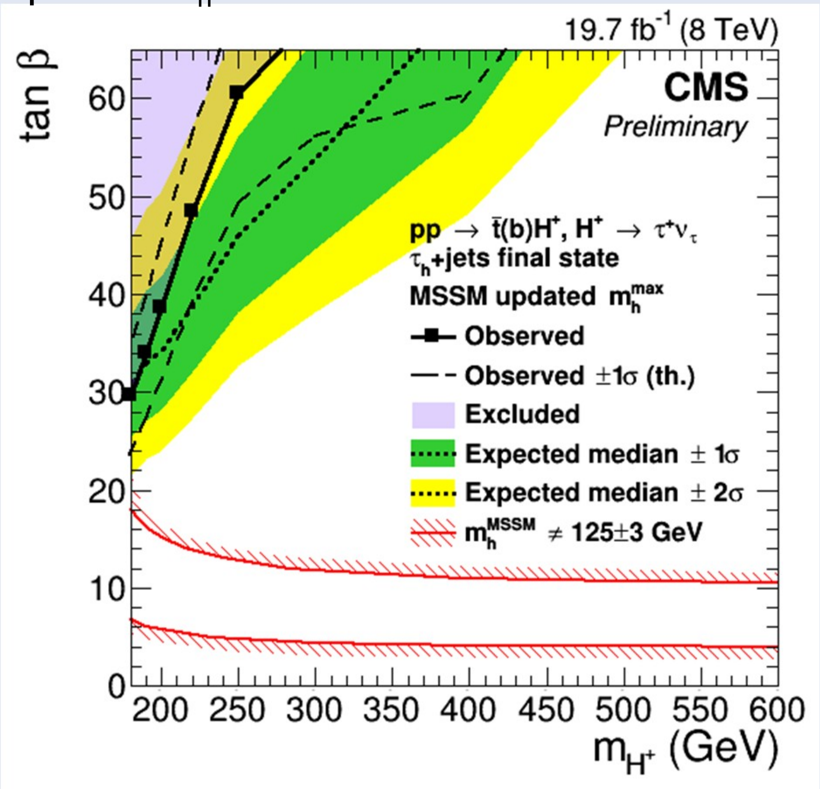
- 95 % CL upper limit on $B(t \rightarrow bH^+)*B(H^+ \rightarrow \tau^+ \nu_\tau)$: 1.2–0.16 % for m_{H+} = 80-160 GeV
- 95 % CL upper limit on $\sigma(pp \rightarrow tbH^+)*B(H^+ \rightarrow \tau^+ \nu_\tau)$: 0.38–0.026 pb for m_{H+} = 180-600 GeV

Limits for updated MSSM m_h^{max} scenario

Updated m_h^{max}



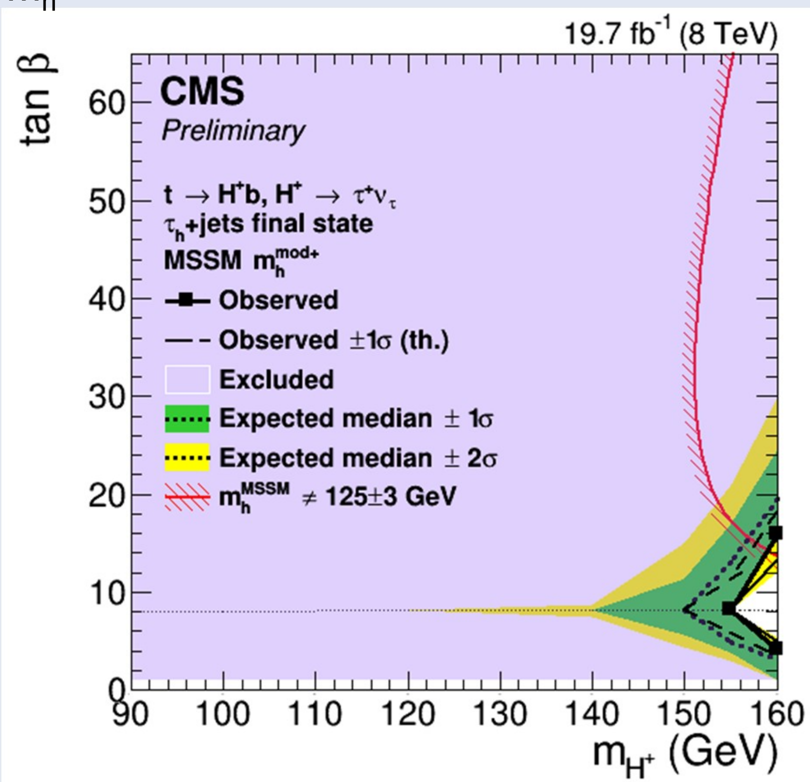
Updated m_h^{max}



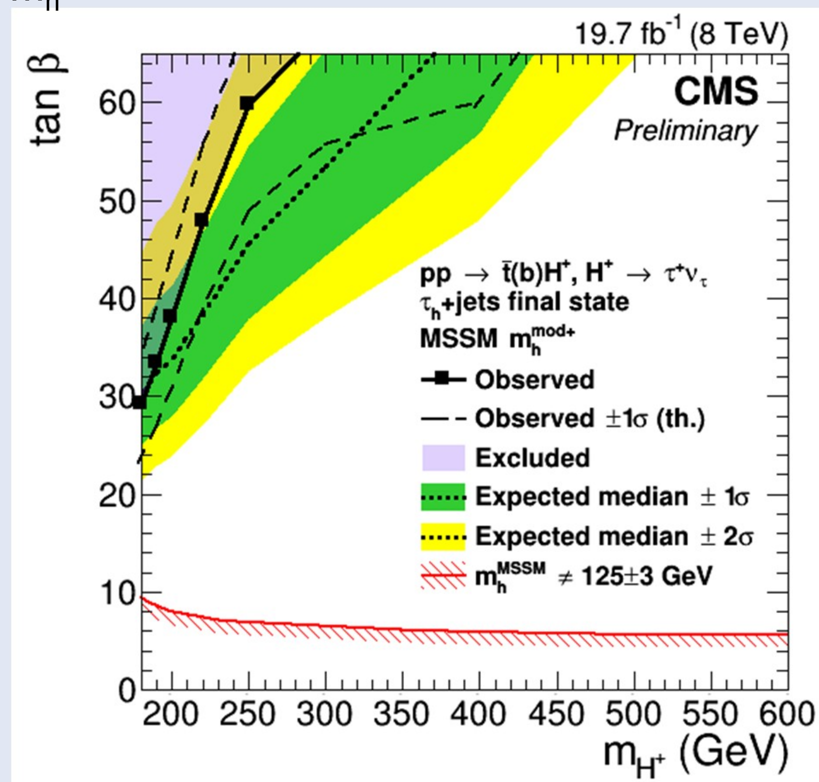
- In this scenario, the X_t value is chosen to maximize m_h at large values of m_A
- The area between the red lines is the (m_{H+}, tan **β**) area, where m_h = 125.0 ± 3.0 GeV
- m_{H+} excluded for m_{H+}<155 GeV

Limits for MSSM m_h^{mod+} scenario

m_h^{mod-}



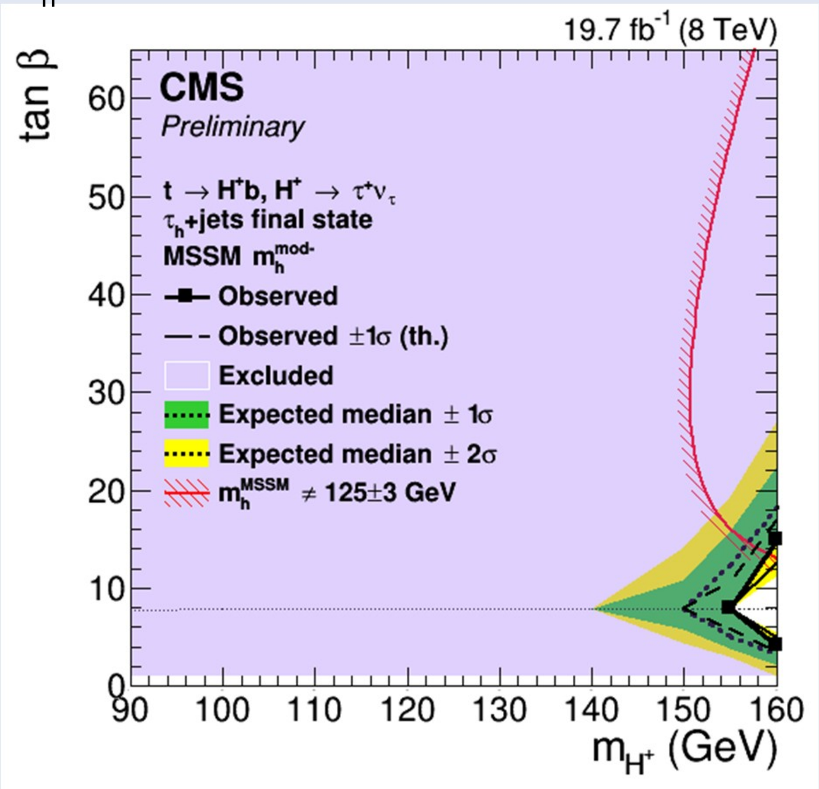
m_h^{mod-}



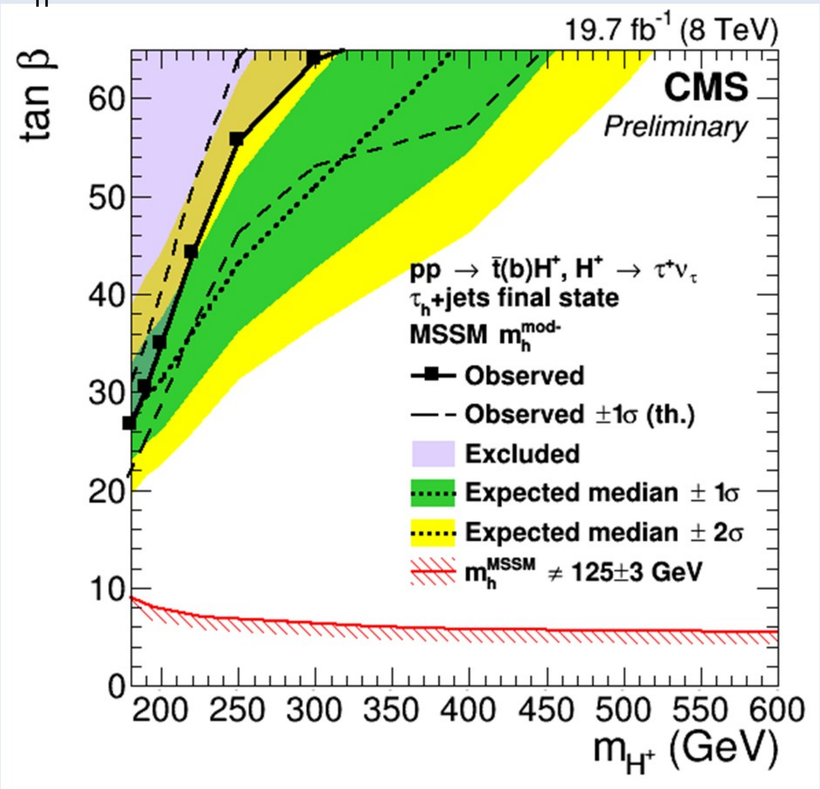
- In this scenario, $|X_t/M_{SUSY}|$ is reduced compared to the m_h^{max} scenario and $X_t > 0$
- The area above the red line is the (m_{H+}, tan **β**) area, where $m_h = 125.0 \pm 3.0$ GeV
- m_{H+} almost completely excluded for m_{H+}<160 GeV

Limits for MSSM m_h^{mod-} scenario

m_h^{mod+}



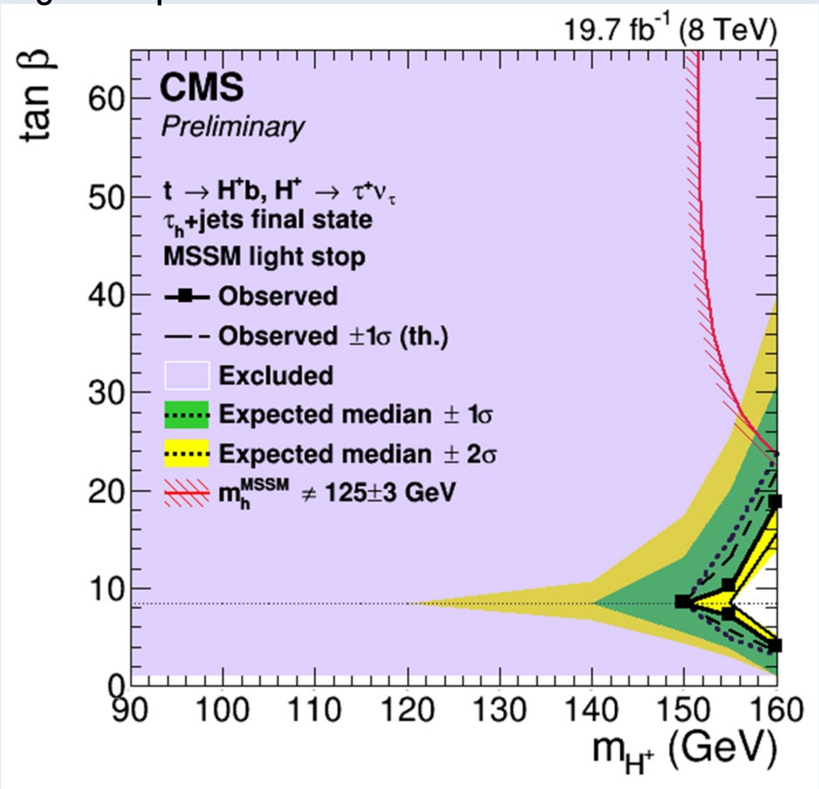
m_h^{mod+}



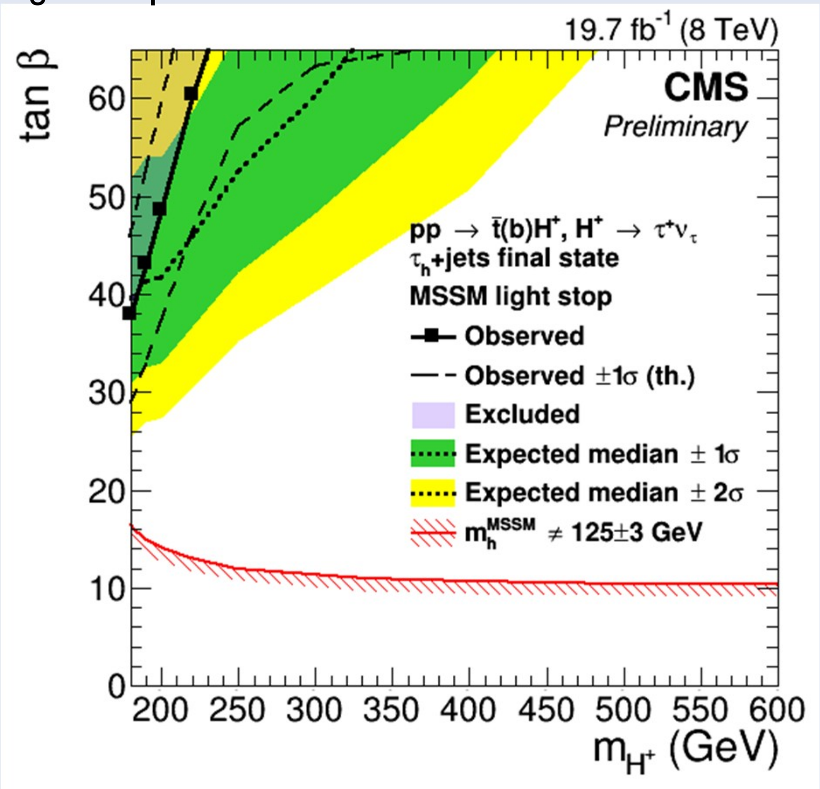
- In this scenario, $|X_t/M_{SUSY}|$ is reduced compared to the m_h^{max} scenario and $X_t < 0$
- The area above the red line is the (m_{H+}, tan **β**) area, where $m_h = 125.0 \pm 3.0$ GeV
- m_{H+} almost completely excluded for m_{H+}<160 GeV

Limits for MSSM light stop scenario

Light stop



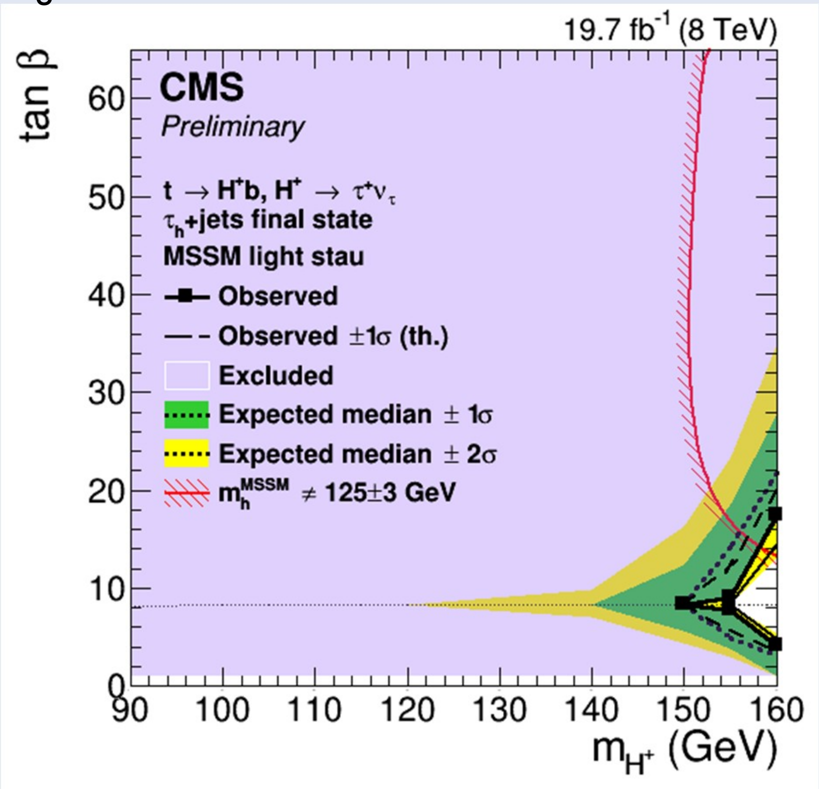
Light stop



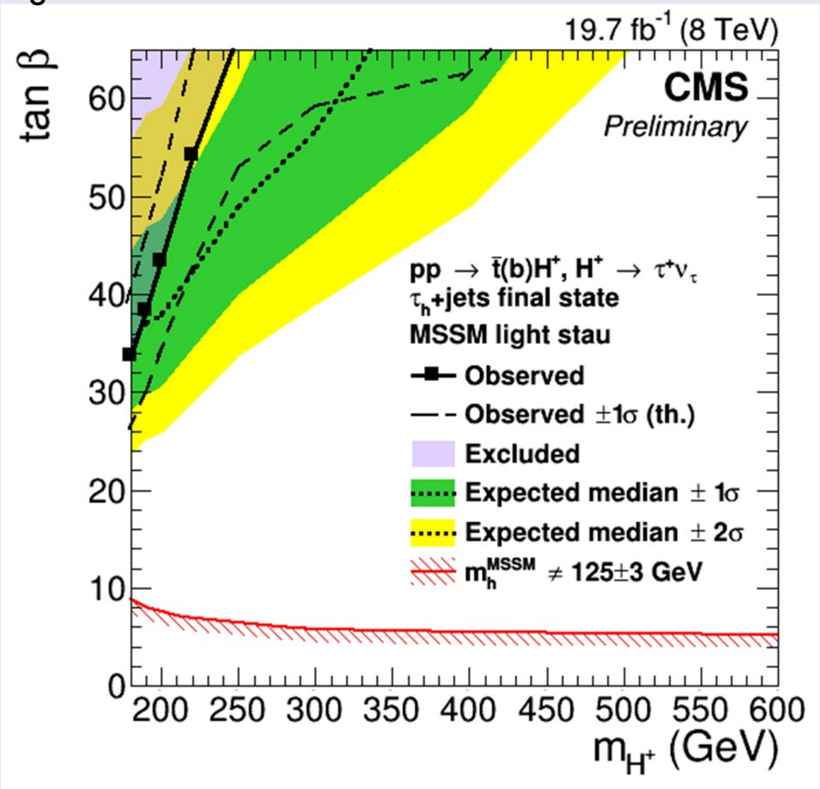
- In this scenario, the gluon-gluon fusion Higgs boson production is suppressed
- The area above the red line is the (m_{H+}, tan **β**) area, where m_h = 125.0 ± 3.0 GeV
- m_{H+} excluded for m_{H+}<160 GeV

Limits for MSSM light stau scenario

Light stau



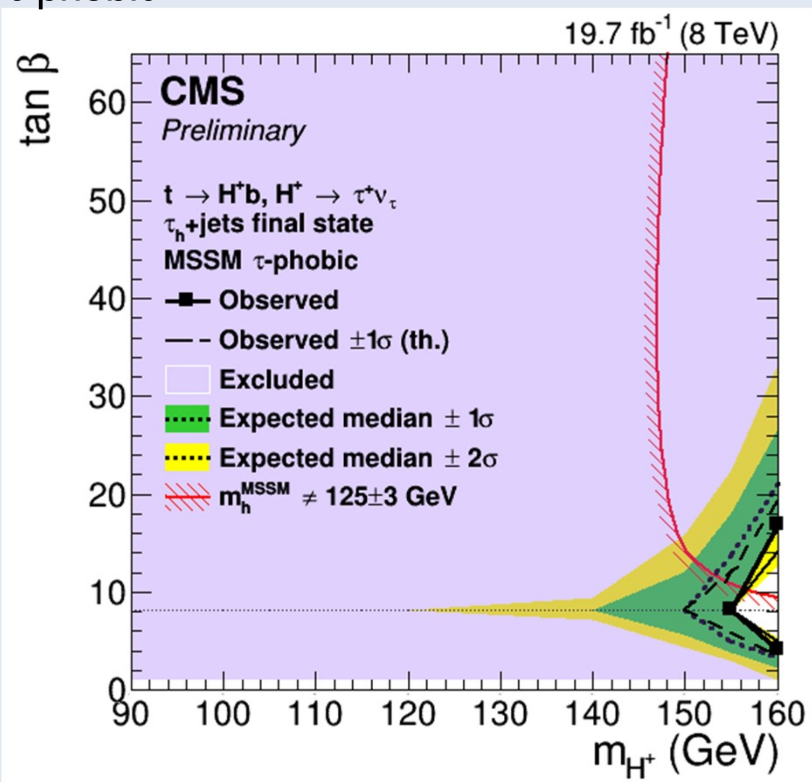
Light stau



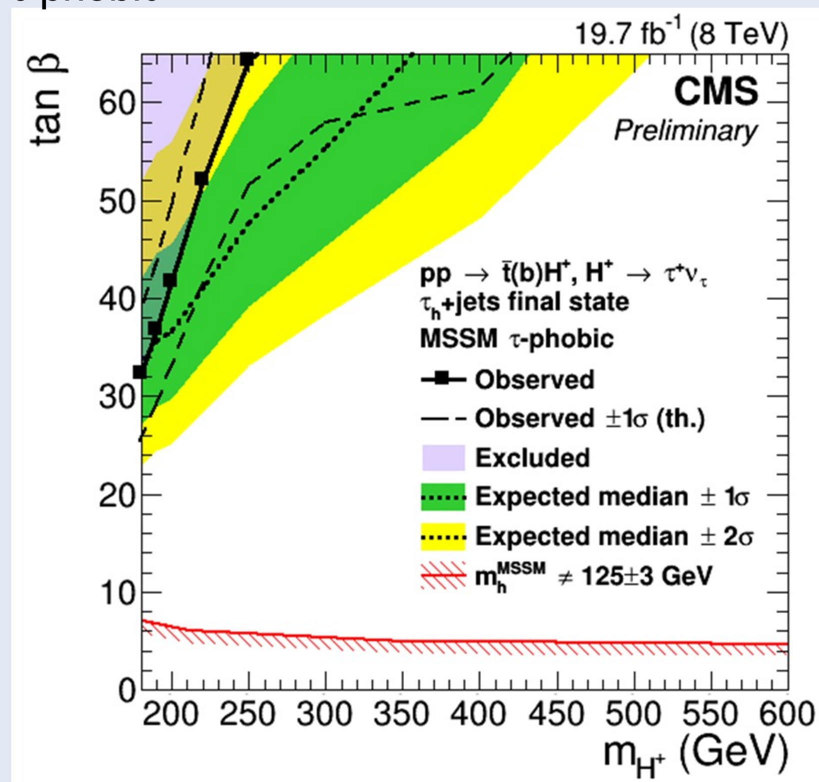
- In this scenario, the rate for h→**γγ** decays is enhanced
- The area above the red line is the (m_{H+}, tan **β**) area, where m_h = 125.0 ± 3.0 GeV
- m_{H+} almost completely excluded for m_{H+}<160 GeV

Limits for MSSM τ-phobic scenario

τ-phobic



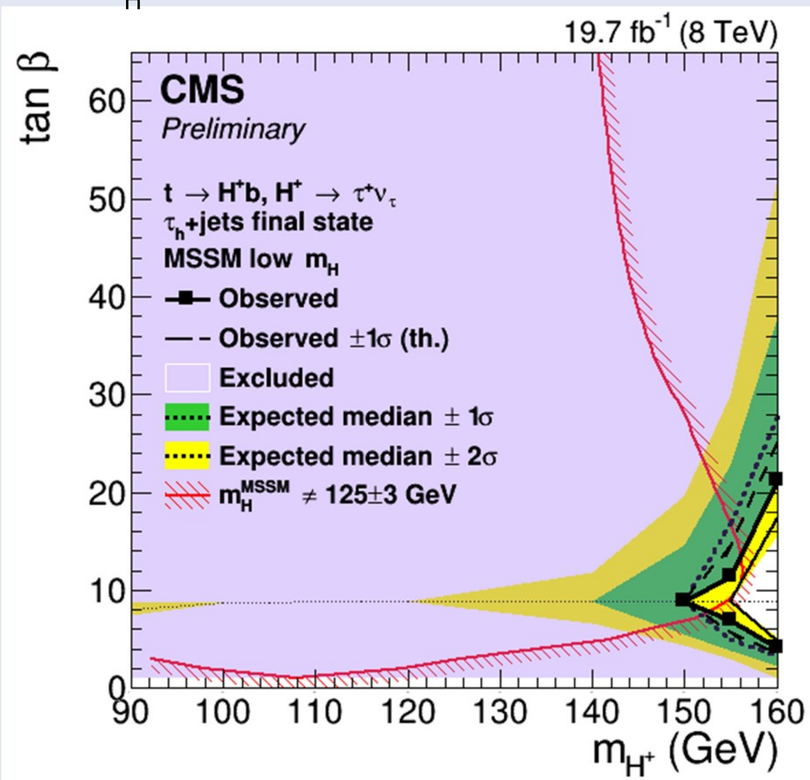
τ-phobic



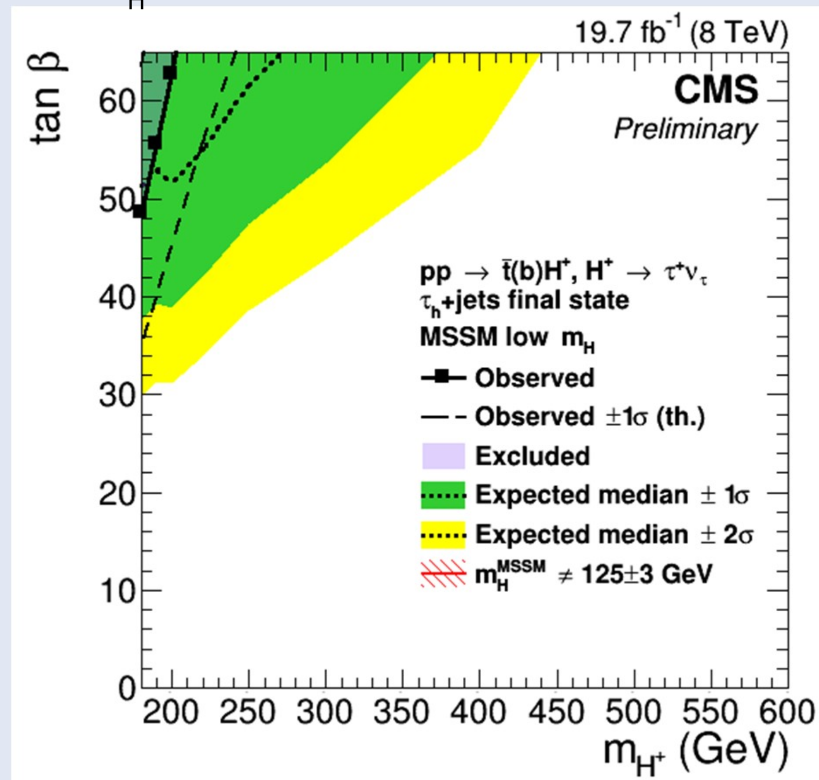
- In this scenario, the couplings to down-type fermions are suppressed
- The area above the red line is the (m_{H+}, tan **β**) area, where m_h = 125.0 ± 3.0 GeV
- m_{H+} excluded for m_{H+}<155 GeV

Limits for MSSM low m_H scenario

Low m_H



Low m_H



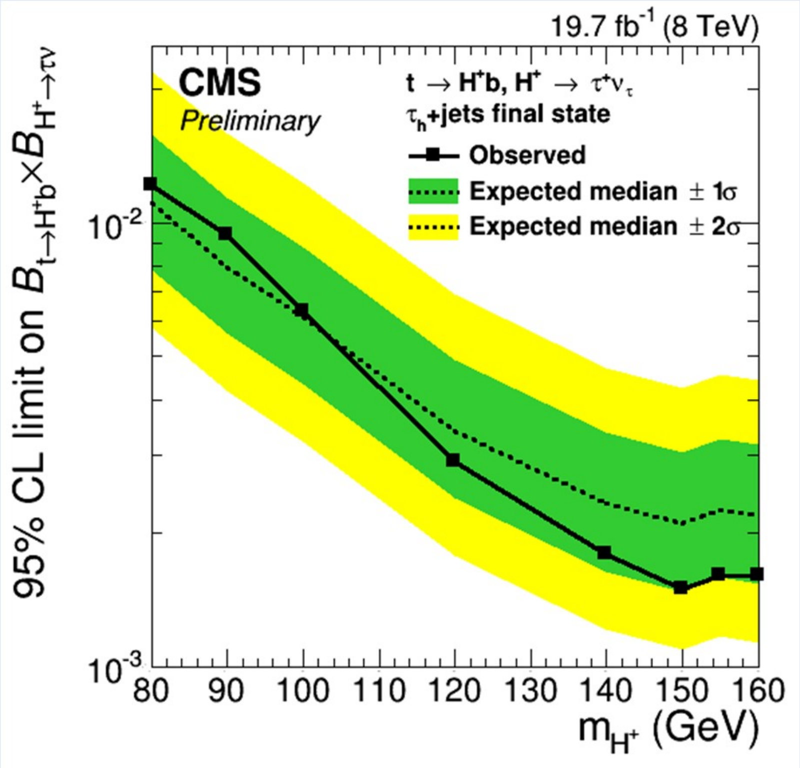
- In this scenario, the discovered Higgs boson is the heavy CP-even Higgs boson
- The area between the red lines is the (m_{H+}, tan **β**) area, where m_h = 125.0 ± 3.0 GeV
- m_{H+} excluded except for a tiny area between m_{H+}=150-155 GeV at tan **β** ~ 10

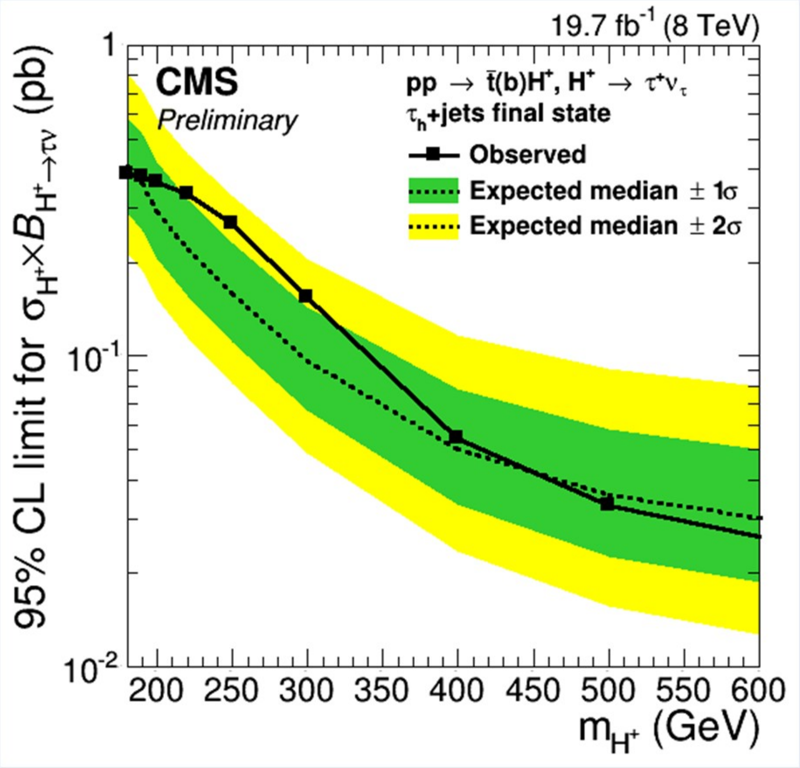
Summary

- Presented the search for charged Higgs bosons with $H^+ \rightarrow \tau^+\nu_\tau$ in fully hadronic final state and 20 fb^{-1} of sqrt(s)=8 TeV data
  - Majority of backgrounds are measured in data-driven way
  - Enhanced selection on angular cuts w.r.t. previous public results
  - First CMS public result on this final state for $m_{H+} > m_t - m_b$
  - Falling part of m_T distribution fitted to account better for low number of events
  - Set new model-independent limits:
    - 95 % CL upper limit on $B(t \rightarrow bH^+) * B(H^+ \rightarrow \tau^+\nu_\tau)$: 1.2 - 0.16 % for m_{H+} = 80..160 GeV
    - 95 % CL upper limit on $\sigma(pp \rightarrow tbH^+) * B(H^+ \rightarrow \tau^+\nu_\tau)$: 0.38 - 0.026 pb for m_{H+} = 180..600 GeV
  - Limits also calculated in the MSSM benchmark scenarios
    - In all scenarios, light H+ almost excluded (m_{H+}>150 GeV or m_{H+}>155 GeV)
    - Low m_H scenario almost completely excluded
- Documentation for the preliminary results is available in CMS PAS HIG-14-020

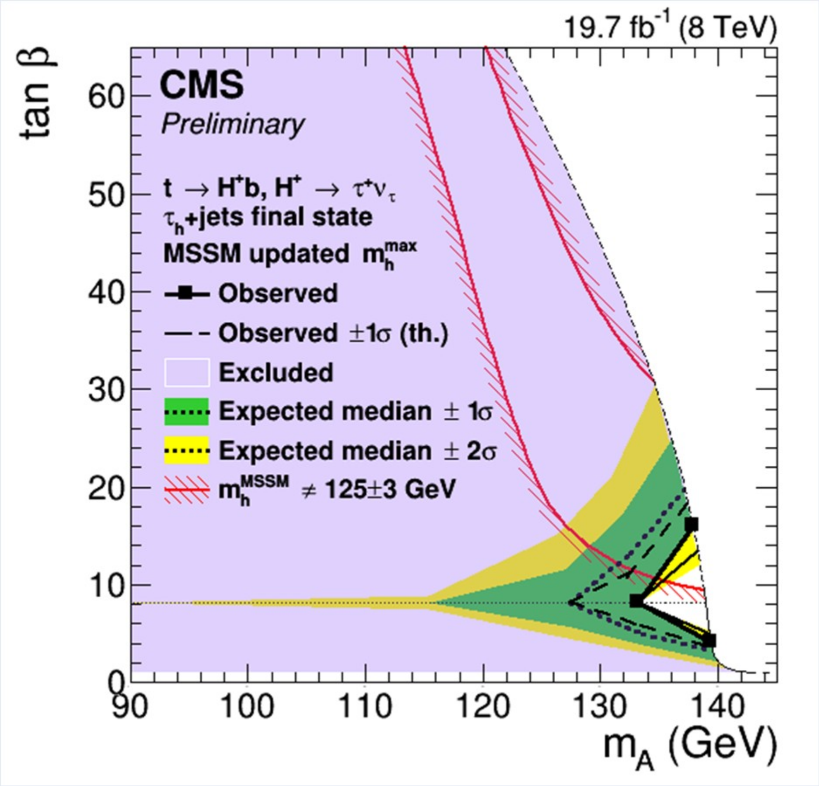
Additional slides

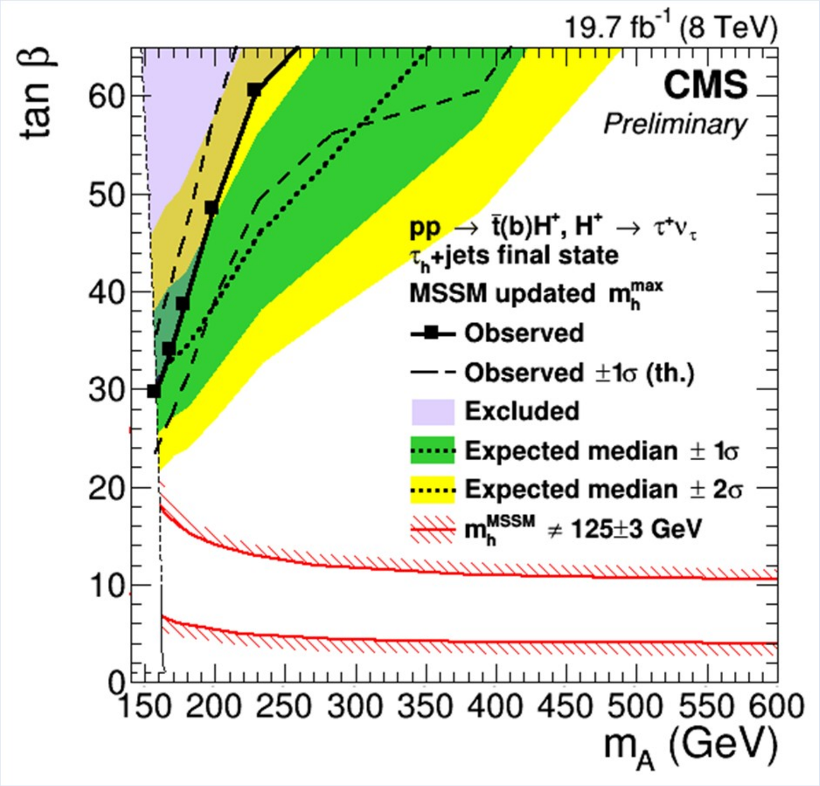
Model-independent limits on log scale





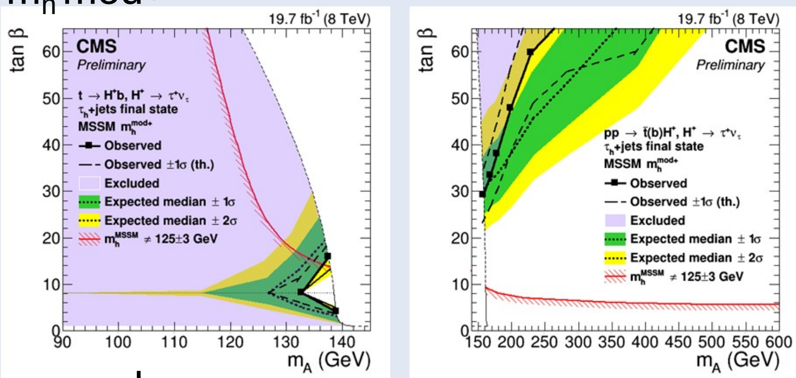
Limits for updated m_h^{max} scenario in m_A



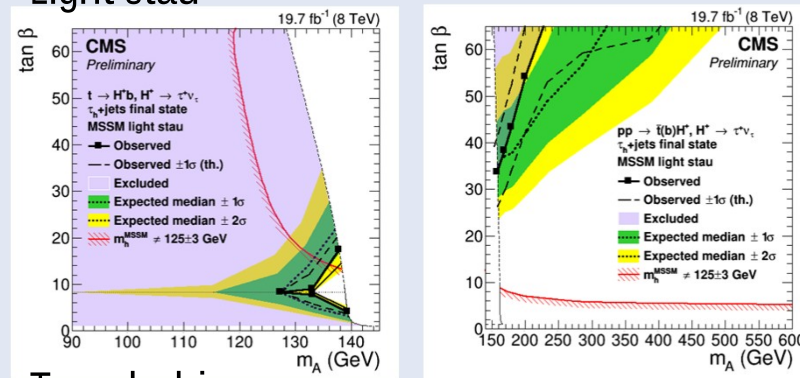


Limits for other MSSM scenarios in m_A

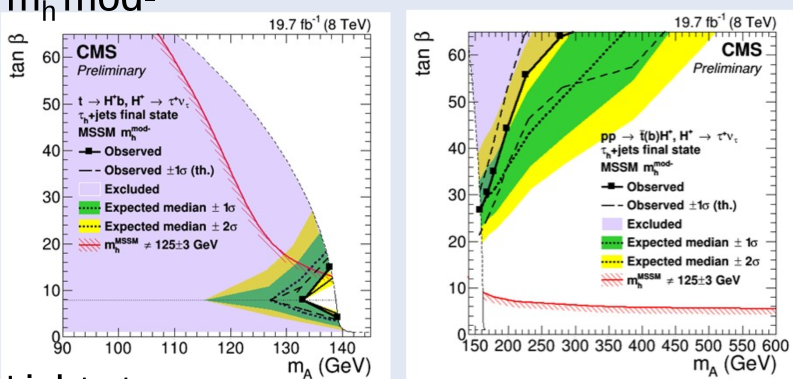
m_h mod+



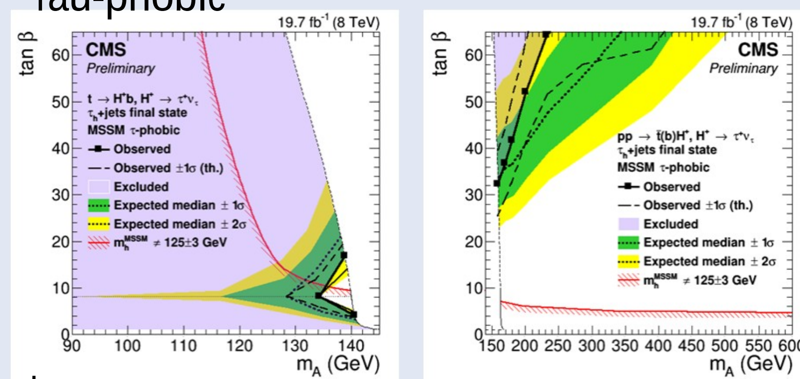
Light stau



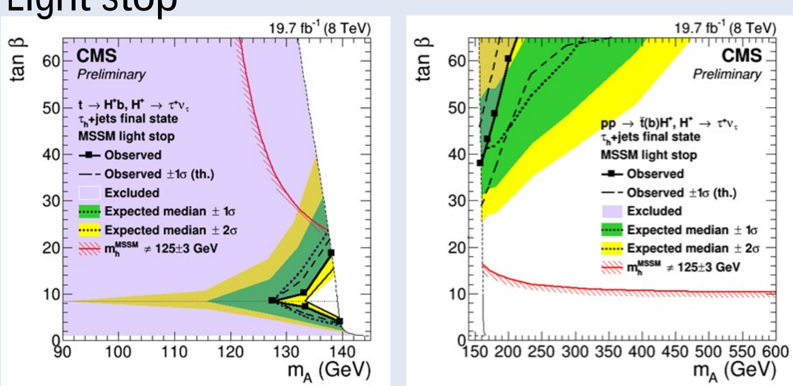
m_h mod-



Tau-phobic



Light stop



Low m_H