Search for charged Higgs bosons in CMS
Part 1: 2HDM searches

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for the CMS Collaboration

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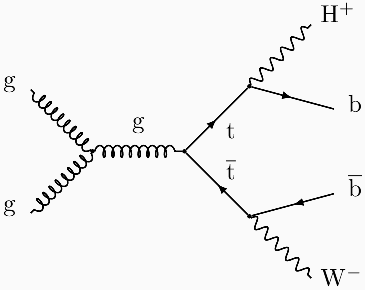
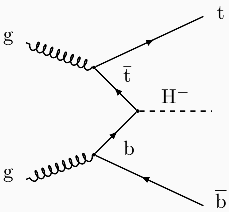
Beyond SM Higgs sector

- Simple extension to SM Higgs sector:
  add second complex doublet → 2HDM
  - e.g. Minimal Supersymmetric Standard Model (MSSM)
- 5 physical scalar Higgs bosons:
  - Neutral, CP-even h (light) and H (heavier)
  - Neutral, CP-odd A (pseudoscalar)
  - Charged Higgs bosons

Light $\mathrm{H}^+ \Leftrightarrow m_{\mathrm{H}^+} < m_\mathrm{t} - m_\mathrm{b}$



Heavy $\mathrm{H}^+ \Leftrightarrow m_{\mathrm{H}^+} > m_\mathrm{t} - m_\mathrm{b}$

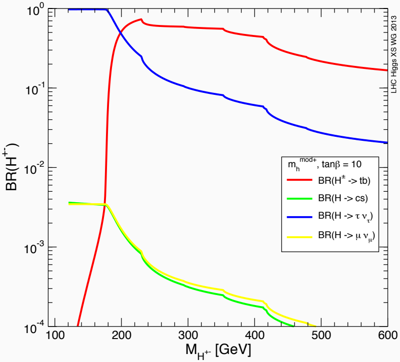


NB! Charge conjugation implied throughout the talk!

2HDM H^+ searches at CMS

Run I (7–8 TeV)

- $H^+ \to \tau\nu$ (HIG-14-023, Charged14)
  - τ_h+jets, $\mu\tau_h$, lepton+jets, dilepton
- $H^+ \to t\bar{b}$ (HIG-14-023, Charged14)
- $H^+ \to c\bar{s}$ (HIG-13-035, Charged14)



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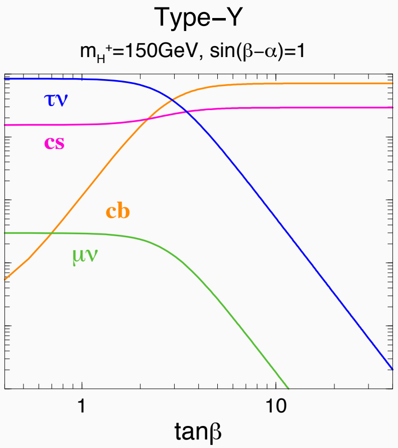
- NEW: $H^+ \to c\bar{b}$ (HIG-16-030)



arXiv:0902.4665

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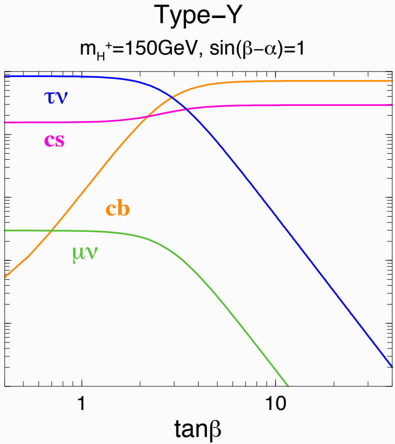
- NEW: $\mathrm{H}^+ \to \mathrm{c\bar{b}}$ (HIG-16-030)

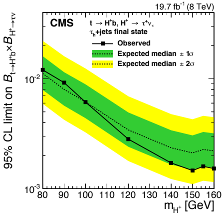
Run II (13 TeV)

- NEW: $\mathrm{H}^+ \to \tau_\mathrm{h}\nu$ with τ_h+jets (HIG-16-031)



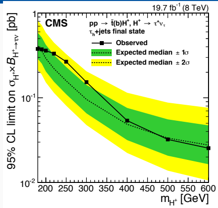
arXiv:0902.4665

Charged14 / Run I summary



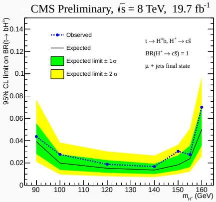
$H^+ \to \tau_h \nu$ 80–160 GeV

Observed: 1.2–0.15%



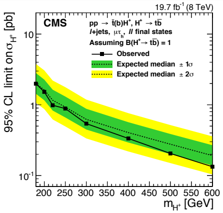
$H^+ \to \tau_h \nu$ 180-600 GeV

Observed: 0.38–0.025 pb



$H^+ \to c\bar{s}$ 90–160 GeV

Observed: 2–7%



$H^+ \to t\bar{b}$ 180-600 GeV

Observed: 2.0–0.13 pb

Run I: $H^+ \to c\bar{b}$ (HIG-16-030)

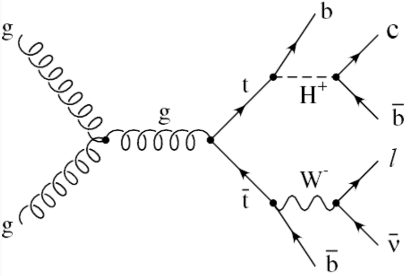
Analysis strategy

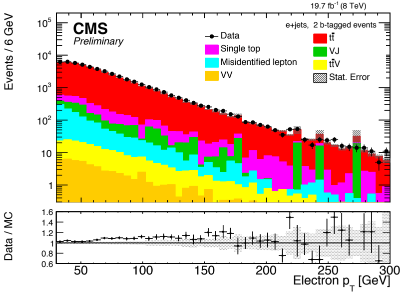
Event selection

- $\geq$ 4 jets ($p_T > 30$ GeV, $|\eta| < 2.4$)
- $\geq$ 2 b-jets
- 1 e ($p_T > 30$ GeV, $|\eta| < 2.5$) or 1 μ ($p_T > 26$ GeV, $|\eta| < 2.1$)
- $E_T^{\text{miss}} \geq 20$ GeV

Backgrounds

- $t\bar{t}$, single top, EWK
  - simulation + corrections
- QCD multijet BG
  - Using data from control region (looser lepton isolation)
  - Normalization from a 2nd control region ($E_T^{\text{miss}} < 20$ GeV)

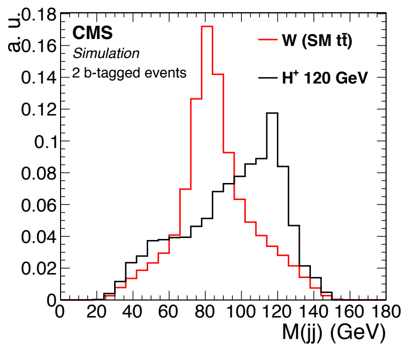




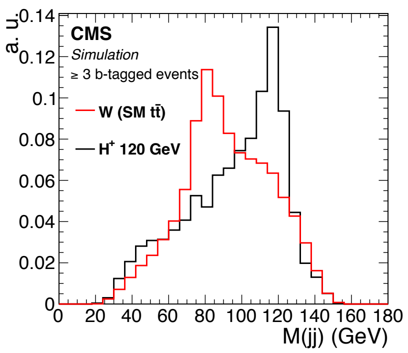
Analysis strategy: two cases

- Limits extracted from dijet invariant mass $M(jj)$
- Two event categories: 2 b jets and $\geq$ 3 b jets

2 b jets

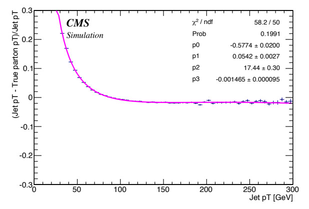


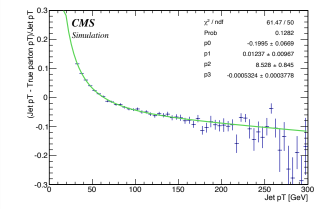
$\geq$ 3 b jets

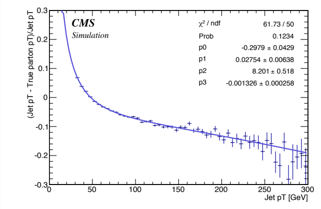


Jet corrections & kinematic fit

- In addition to standard jet energy corrections, parton specific corrections applied
  - Corrections from simulation as $\frac{p_T(\text{parton})-p_T(\text{jet})}{p_T(\text{jet})}$ + fit
  - Fitted results are different for b jets (left), c jets (middle) and light-flavour jets (right)
- Kinematic fit used to resolve jet combinatorics
  - matching four leading jets to four quarks
  - takes into account jet momenta, non-clustered energy, the W mass and the masses of both top quarks

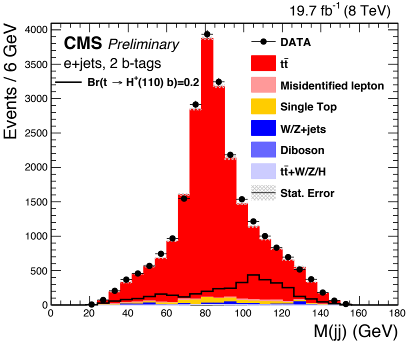




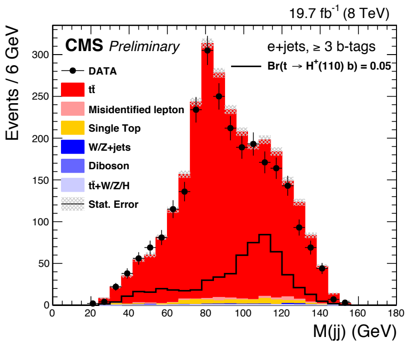


Dijet mass distributions

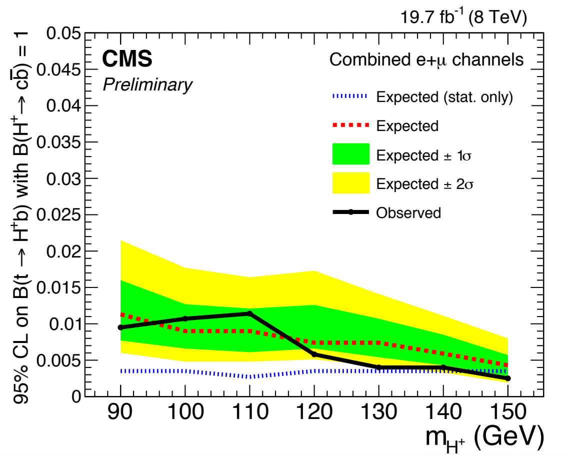
e+jets, 2 b jets



e+jets, ≥ 3 b jets



Exclusion limit



Observed limit: 1.1–0.4 %

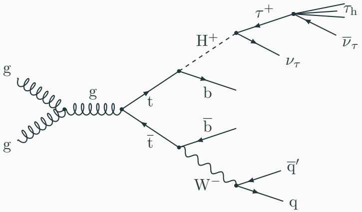
Limits from maximum likelihood fit using binned $M(\mathrm{jj})$ templates, assuming $\mathrm{H}^+ \to \mathrm{c}\bar{\mathrm{b}} = 1$

Run II: $\mathrm{H}^{+} \to \tau\nu$ with τ_{h}+jets (HIG-16-031)

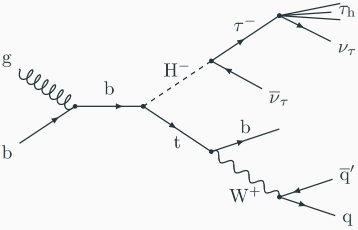
Fully hadronic final state

- Light and heavy H^+ have similar fully hadronic final state
  - $\rightarrow$ same analysis, but different selection thresholds
- All neutrinos in the event come from H^+ decay
  - $\rightarrow$ limits can be extracted from transverse mass

$$m_T \equiv \sqrt{2 p_T^{\tau \mathrm{jet}} E_t^{\mathrm{miss}} (1 - \cos \Delta\phi)}$$



Light



Heavy

Event selection

$\geq$ 1 tau lepton

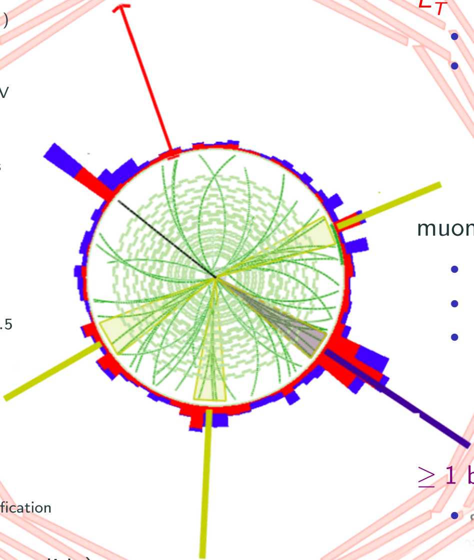
- $p_T > 60$ GeV (heavy H^+) or 50 GeV (light H^+)
- $|\eta| < 2.1$
- leading track $p_T > 30$ GeV
- 1 prong decay
- require isolation
- reject electrons and muons

$\geq$ 3 hadronic jets

- $p_T > 30$ GeV, $|\eta| < 4.7$
- jet energy corrections
- reject if $\Delta R(\mathrm{jet}, \tau_\mathrm{h}) < 0.5$

electron veto

- $p_T > 15$ GeV
- $|\eta| < 2.5$
- require isolation and identification



$E_T^{\mathrm{miss}} > 90$ / 100 GeV

- 90 GeV for light H^+
- Particle-flow E_T^{miss} + corrections

muon veto

- $p_T > 10$ GeV
- $|\eta| < 2.5$
- require isolation and identification

$\geq$ 1 b jet

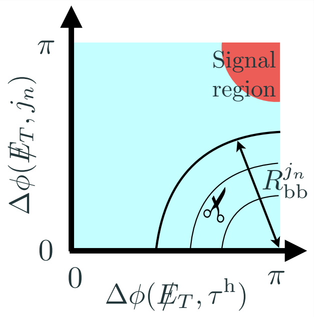
- b-tagged jet (combined secondary vertex algorithm)
- $|\eta| < 2.5$

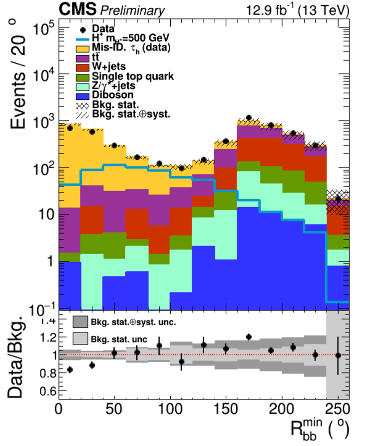
+ angular cuts (see next slide)

Angular cuts

Define $R_{\mathrm{bb}}^{\mathrm{min}} \equiv \min \sqrt{(180^o - \Delta\phi(\tau, E_T^{\mathrm{miss}}))^2 + \Delta\phi(\mathrm{jet}_n, E_T^{\mathrm{miss}})^2}$
where jet_N are the 3 highest-p_T jets

- Selection: $R_{\mathrm{bb}}^{\mathrm{min}} > 40^o$

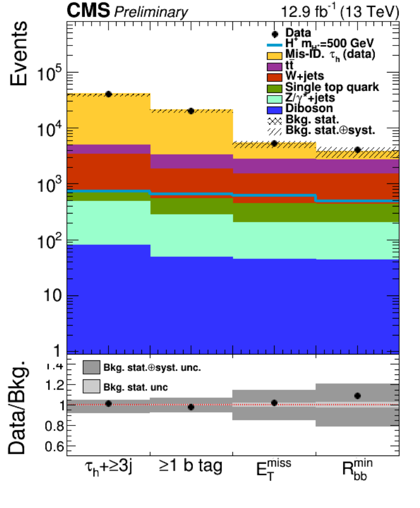




- To suppress QCD multijet BG after all other selections

Selection flow and backgrounds

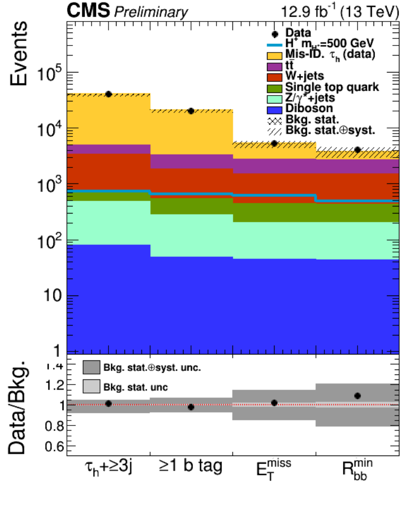
Event yields for heavy H^+



Selection flow and backgrounds

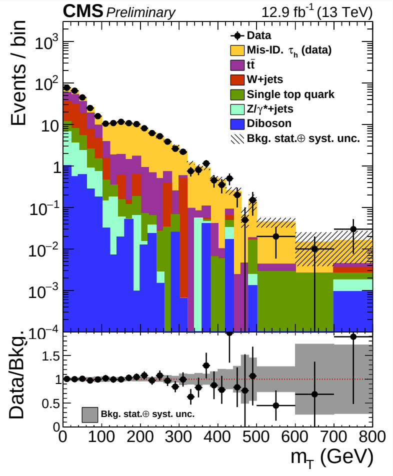
- EWK+$t\bar{t}$ genuine tau BG: from simulation
  - ttbar, W+jets, single top, Drell-Yan, diboson
- Fake tau BG: from data
  - Control sample from inverted tau selection
  - Data through the inverted tau selection + E_T^{miss} fit
  - Genuine tau BG through the signal selection + E_T^{miss} fit
  - Final fit assuming similar fake tau BG shape in signal and control regions

Event yields for heavy H^+

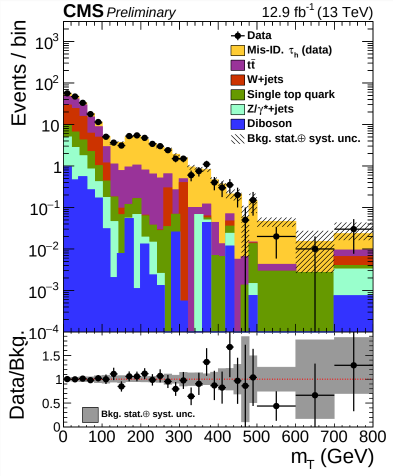


Transverse mass

Light H^+



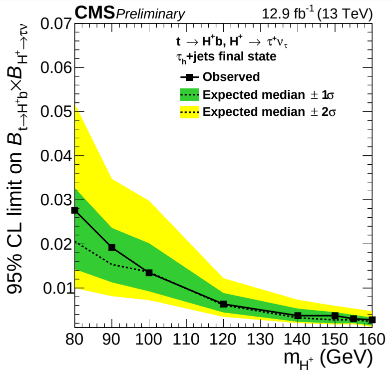
Heavy H^+



Data and backgrounds normalized to best ML fit values

Exclusion limits

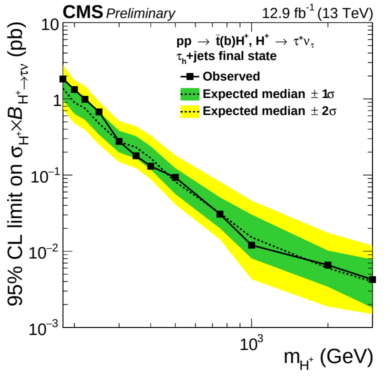
Light H^+



$m_{H^+} =$ 80–160 GeV

Observed limit: 2.8–0.28%

Heavy H^+



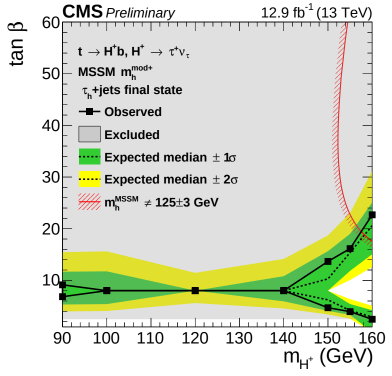
$m_{H^+} =$ 180–3000 GeV

Observed limit: 1.8–0.0042 pb

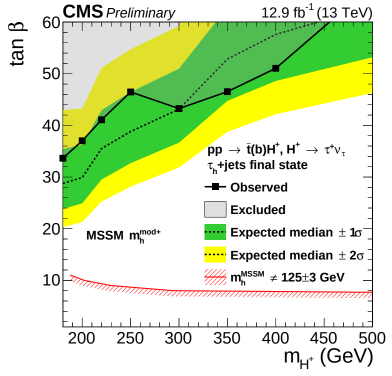
Obtained from maximum likelihood fit using binned m_T templates

Exclusion limits in MSSM m_h^{mod+}

Light H^+



Heavy H^+



Grey regions are excluded by the observed limit

Summary and outlook

Two recent results have been presented:

- 8 TeV search for $\mathrm{H}^{+} \to \mathrm{c}\bar{\mathrm{b}}$ with 19.7 fb^{-1} of data
  - First CMS result on this channel
- 13 TeV search for $\mathrm{H}^{+} \to \tau_{\mathrm{h}}\nu$ with τ_{h}+jets with 12.9 fb^{-1}
  - First CMS 13 TeV result on light H^{+} ,
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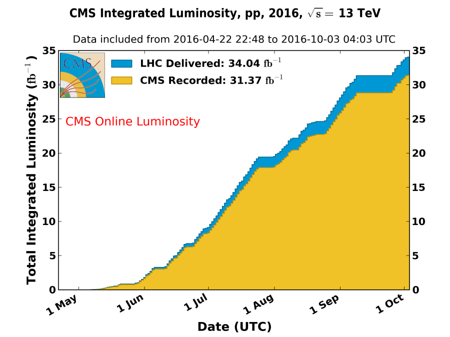
- CMS has recorded $>$30 fb^{-1} in 2016 and searches continue on many fronts



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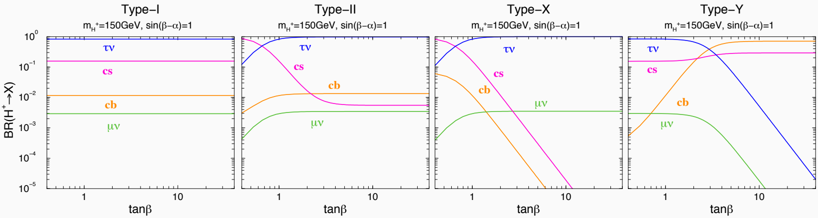
Back-up

2HDM models

Model	Type I	Type II	Lepton-specific	Flipped
Φ_1	–	d, ℓ	ℓ	d
Φ_2	u, d, ℓ	u	u, d	u, ℓ

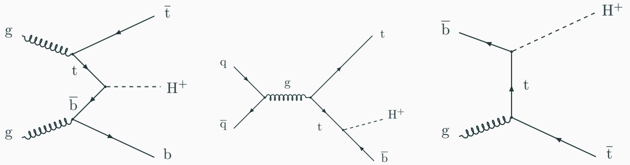
arXiv:1002.4916



arXiv:0902.4665

4FS vs. 5FS

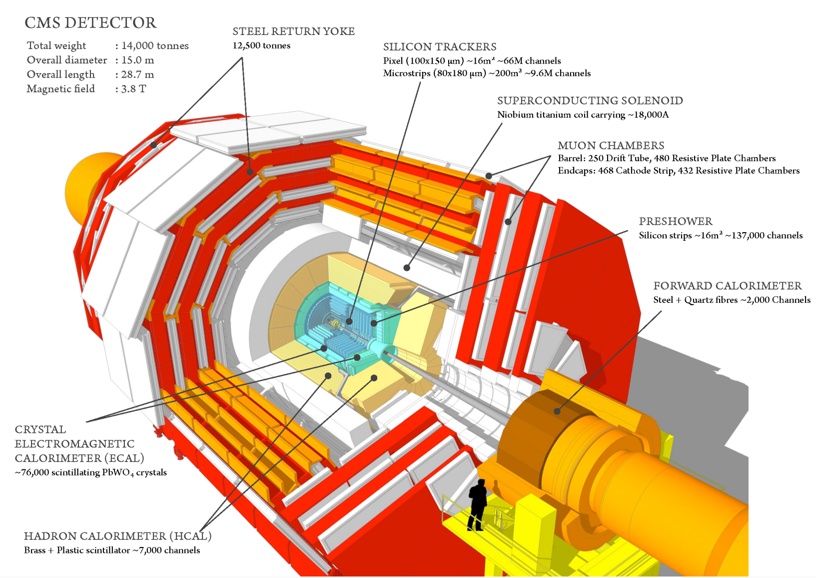
- 4FS: No b quarks in the initial state
  → Heavy H^+ (in LO) by gg → tbH^+ and and qq → tbH^+
- 5FS: Gluon splitting processes summed to all orders by introducing b parton densities
  →Heavy H^+ (in LO) by gb → t H^+ (right)



- Summing all orders, 4FS and 5FS yield identical results
  - different ordering → different results dierent at finite order
- 4FS and the 5FS NLO predictions combined with Santander matching

$$\sigma^{\text{matched}} = \frac{\sigma^{4\text{FS}} + w \times \sigma^{5\text{FS}}}{1+w} \text{ with } w = ln\frac{m_{\text{H}^\pm}}{m_{\text{b}}} - 2$$

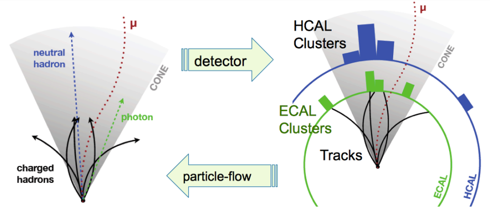
CMS detector



Particle flow algorithm

Particle flow algorighm combines information from various CMS subdetectors to reconstruct objects

- Muons by combining information from the tracker and the muon chambers
- Electrons by matching energy deposits in the ECAL with tracker tracks
- Jets using the anti-kT algorithm with R=0.4 (0.5 for Run I)
  - hadronic taus using hadron-plus-strips algorighm
  - b jets using combined secondary vertex
- E_T^{miss} as the negative vector sum of the of all objects



$H^+ \to c\bar{b}$: Kinematic fit

- Uses four leading jets with parton-spesific corrections
- Minimize

$$\chi^2 = \sum_{i=l,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{NE,fit} - p_j^{NE,meas})^2}{\sigma_{NE}^2}$$
$$+ \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bl\nu} - M_t)^2}{\Gamma_t^2} + \frac{(M_{bbc} - M_t)^2}{\Gamma_t^2}.$$

where non-clustered energy is

$$NE_{x,y} = -\mathrm{p_{x,y}}(\mathrm{lepton}) - \sum_{\mathrm{jets}(\mathrm{p_T}>10\,\mathrm{GeV})} \mathrm{p_{x,y}} - \mathrm{E_T^{miss}}_{\mathrm{x,y}}$$

- All p_T and non-clustered energy varied
  - top mass constrained to 172.5 GeV, W mass to 80.4 GeV
- E_T^{miss} recalculated from after the fit
- b jets assigned to top/W/H^+ decays a priori in some cases
  - e.g. in events with 2 b jets, both are assigned to top decays
- Goodness cuts to improve matching
  - $|p_T^{\mathrm{in}} - p_T^{\mathrm{fitted}}| < 20$ GeV for each jet
  - M(hadronic top before fit) < 200 GeV

$H^+ \to c\bar{b}$: Systematic uncertainties

Source of uncertainty	signal ($m_H = 120$)		$t\bar{t}$		non-$t\bar{t}$		QCD multijet	
	2 b-tag	3 b-tag	2 b-tag	3 b-tag	2 b-tag	3 b-tag	2 b-tag	3 b-tag
$t\bar{t}$ cross section	6.5	20	6.5	20				
Top quark mass	5 (s)	5 (s)	5 (s)	5 (s)				
$t\bar{t}$ p_T reweighting	(s)	(s)	(s)	(s)				
NLO-vs-LO shape (Powheg-vs-MadGraph)	8.5–9.0 (s)	7.6–8.8 (s)	8.3–8.5 (s)	8.0 (s)				
PYTHIA–MADGRAPH $p_T(t\bar{t})$ difference	(s)	(s)						
ME-PS matching			0.6–0.8 (s)	0.8–1.4 (s)				
Renormalization and factorization scales	4.0–4.2 (s)	6.8–7.2 (s)	1.3–1.7 (s)	1.3–2.0 (s)				
Jet energy scale (JES)	4.6–5.3 (s)	5.0–5.9 (s)	3.4 (s)	3.3 (s)	7.5–9.6 (s)	0.9–2.8 (s)		
Flavour-dependent JES (b quark)	0.3–0.4 (s)	0.2–0.6 (s)	0.1 (s)	9.0 (s)	0.1–0.7 (s)	0.5–0.9 (s)		
Flavour-dependent JES (udsc,g)	0.9–1.2 (s)	0.4–0.6 (s)	1.0 (s)	9.0 (s)	3.1–4.1 (s)	1.1–1.8 (s)		
Jet energy resolution	0.1–0.2 (s)	0.2–0.8 (s)	0.3 (s)	0.4 (s)	1.1 (s)	1.5 (s)		
B-tag scale factor for b/c quark jets	1.2–2.1	5.6–5.8	3.6	5.7	2.9–3.0	4.0–4.4		
Mis-tag scale factor for light quark jets	0.1–0.2	0.2–0.7	0.2	0.3–0.7	0.7–1.3	0.3–0.4		
Pileup reweighting	≈ 0.5							
Electron scale factor (e+jets)	2.0							
Muon scale factor (μ+jets)	2.0							
Luminosity	2.6							
Data driven prediction							Shift anti-Iso_{rel} region (s)	

- $t\bar{t}$ xsect: NNLO calculation $\to$ 6.5%, for ≥ 3 b jets case 20% (due to observed data-vs-simulation difference)
- Top mass: vary from 171.5 GeV to 173.5 GeV
- NLO-vs-LO for $t\bar{t}$: MadGraph (LO, in use), uncertainty by comparing to Powheg (NLO)
- Renormalization and factorization scales: vary up/down by a factor of 2 (to estimate beyond-LO contributions to $t\bar{t}$)
- Jet Energy Scale (see arXiv:1107.4277)

$H^+ \to c\bar{b}$: Physics model

Physics model used in limit calculation is

$$\mu_i = \mu_i(non - t\bar{t}) + (1 - BR)^2 \times \mu_i(t\bar{t} \to WbW^-\bar{b}) + 2 \times BR \times (1 - BR) \times \mu_i(t\bar{t} \to H^+bW^-\bar{b})$$

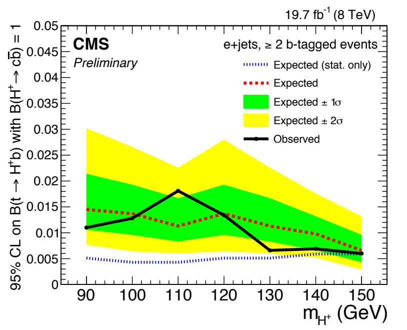
where

- BR is $B(t \to H^+ b)$
- μ_i is the number of events in dijet mass bin i

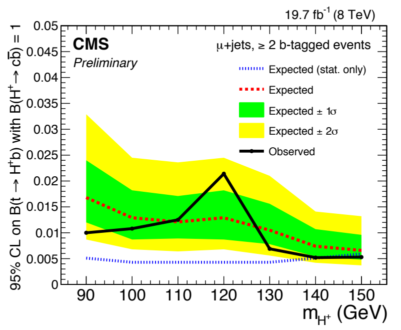
SM $t\bar{t}$ background is scaled down in case of non-zero signal!

$H^+ \to c\bar{b}$: Exclusion limits

e+jets



μ+jets



Limits from maximum likelihood fit using binned $M(\mathrm{jj})$ templates, assuming $H^+ \to c\bar{b} = 1$

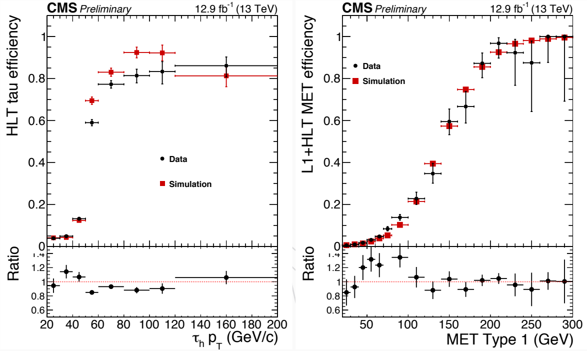
$H^+ \to \tau_h \nu$: Tau decays

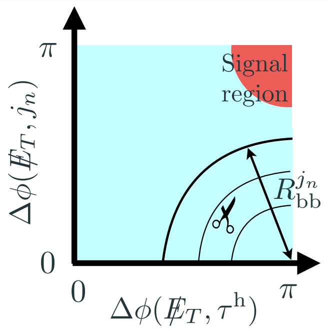
Final state	$\mathcal{B}$ (%)	$\Sigma\mathcal{B}$ (%)
leptonic modes		35.9
$\tau^- \to e + \overline{\nu}_e\ \nu_\tau$	17.9	
$\tau^- \to \mu + \overline{\nu}_\mu\ \nu_\tau$	17.4	
hadronic modes		
one-prong (excluding modes with K^0)		48.1
$\tau^- \to h^-\ \nu_\tau$	11.6	
$\tau^- \to \rho^-\ \nu_\tau \to h^-\ \pi^0\ \nu_\tau$	26.0	
$\tau^- \to a_1^-\ \nu_\tau \to h^-\ \pi^0\ \pi^0\ \nu_\tau$	9.3	
$\tau^- \to h^-\ \nu_\tau + \geq 3\pi^0$	1.3	
three-prong (excluding modes with K^0)		14.6
$\tau^- \to a_1^-\ \nu_\tau \to 2h^-h^+\ \nu_\tau$	9.7	
$\tau^- \to 2h^-h^+\ \nu_\tau + \geq 1\ \pi^0$	5.2	
five-prong (excluding modes with K^0)		0.1
$\tau^- \to 3h^-2h^+\ \nu_\tau \geq 0\ \pi^0$	0.1	
hadronic modes including K^0		2.0
$\tau^- \to K_S^0 + X$	0.9	
$\tau^- \to K_L^0 + X$	1.1	

Table 1: Final states and corresponding branching fractions of single τ lepton decays. The uncertainty of the branching fractions is 0.1 percent units or smaller. [14]

$H^+ \to \tau_h \nu$: Trigger

- Tau trigger: Hadronic tau with $p_T > 50$ GeV, $|\eta| < 2.1$ and leading charged hadron with $p_T > 30$ GeV
- E_T^{miss} trigger: calorimetric $E_T^{\text{miss}} > 90$ GeV
- Efficiency of the tau part (left) and E_T^{miss} part (right) of the trigger measured independently, MC samples corrected by scale factors





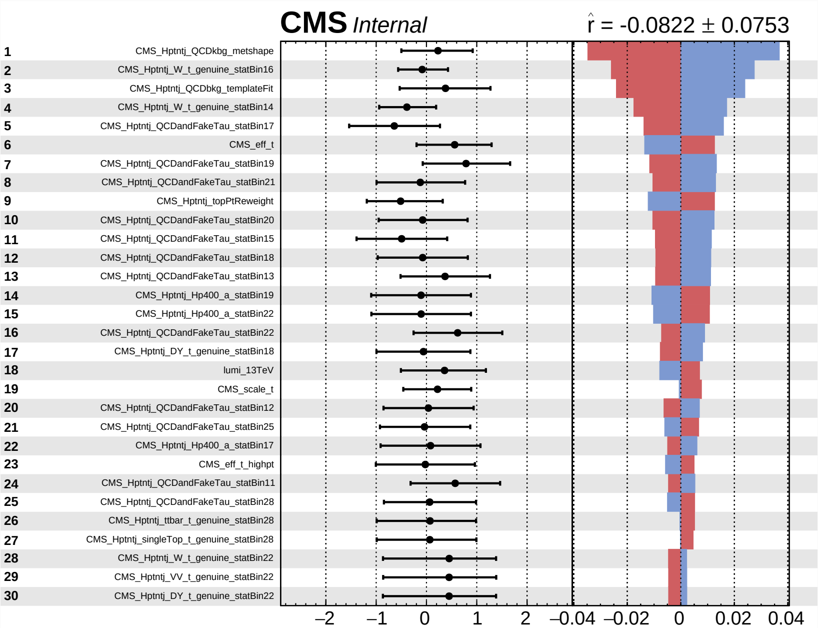
- Used to suppress QCD multijet background after all other selections
- Working principle:
    - tau $\bar{p}_T$ is typically back-to-back to $\bar{E}_T^{\mathrm{miss}}$
      $\to \Delta\phi(E_T^{\mathrm{miss}}, \tau) \approx 180^o$
      $\to$ large m_T
    - jet faking tau is typically back-to-back to another jet
      $\to \Delta\phi(E_T^{\mathrm{miss}}, \mathrm{jet}) \approx 0$

$$R_{\mathrm{bb}}^{\mathrm{min}} = \min\sqrt{(180^o - \Delta\phi(\tau, E_T^{\mathrm{miss}}))^2 + \Delta\phi(\mathrm{jet}_n, E_T^{\mathrm{miss}})^2}$$

where jet_N are the 3 highest-p_T jets

Selection: $R_{\mathrm{bb}}^{\mathrm{min}} > 40^o$

$H^+ \to \tau_h \nu$: Systematics



$\mathrm{H}^+ \rightarrow \tau_\mathrm{h}\nu$: Fake tau measurement

- Control sample from inverted tau selection
  $\rightarrow$ orthogonal sample dominated by fake taus
- Data processed through the inverted selection + E_T^{miss} fit
- EWK+ttbar BG through the signal selection + E_T^{miss} fit
- Done in tau p_T bins due to correlation of tau p_T and E_T^{miss}
- Final fit: use the E_T^{miss} templates obtained to estimate fake tau BG in the signal region
  - Assumes similar QCD shape in signal and control regions
- Transfer factors R_i from control region to signal region:

$$R_i = w_i R_i^{QCD} + (1 - w_i) R_i^{EWK+\ \mathrm{fake}\ \tau}$$

where $R_i^{QCD} \equiv \frac{N_{Baseline,i}^{QCD}}{N_{Inverted,i}^{QCD}}$,

$$R_i^{EWK+\ \mathrm{fake}\ \tau} \equiv \frac{N_{Baseline,i}^{EWK+\ \mathrm{fake}\ \tau}}{N_{Inverted,i}^{EWK+\ \mathrm{fake}\ \tau}},$$

$$w_i \equiv \frac{N_{Inverted,i}^{QCD}}{N_{Inverted,i}^{data}}$$

$\mathrm{H}^+ \to \tau_\mathrm{h}\nu$: Physics model

Physics model for light H^+ is

$$s_i(\mu, \mathbf{\Theta}) = \mu^2 \times s_{\mathrm{HH},i}(\mathbf{\Theta}) + 2\mu(1-\mu) \times s_{\mathrm{HW},i}(\mathbf{\Theta}) + (1-\mu^2) \times s_{\mathrm{WW},i}(\mathbf{\Theta}),$$

where μ is defined as

$$\mu = \mathcal{B}(\mathrm{t} \to \mathrm{bH}^+)\mathcal{B}(\mathrm{H}^\pm \to \tau^\pm \nu_\tau).$$

and for heavy H^+ it is

$$s_i(\mu, \mathbf{\Theta}) = \mu \times s_{\tau\nu,i}(\mathbf{\Theta}),$$

where μ is

$$\mu = \sigma_{\mathrm{pp}\to\mathrm{t(b)H}^\pm} \times \mathcal{B}(\mathrm{H}^\pm \to \tau^\pm \nu_\tau).$$

In equations, s_i is the total event yield (in m_T bin i) and $s_{process,i}$ are background yields due to different BG processes (in m_T bin i) .