Search for a low-mass charged Higgs boson at CMS

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(on behalf of CMS collaboration)

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Outline

- Physics motivation
- Signal and background
- Selection criteria
- Signal sensitivity
- Estimation of QCD background
- Measurement uncertainties
- Explicit charm tagging
- Upper limit
- Summary and Outlook

Physics Motivation - I

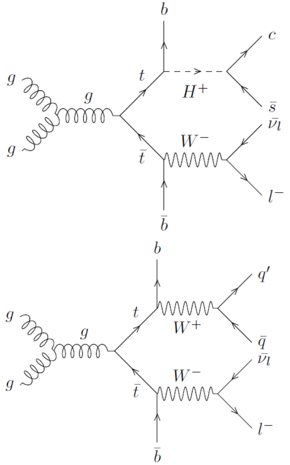
- Limitations of SM
  - $m_\nu \neq 0$
  - Matter-antimatter asymmetry
  - No explanation of dark matter
  - Does not include gravity
- Two Higgs Doublet Model (2HDM)
  - A minimal extension of one Higgs doublet to two Higgs doublets $\rightarrow$ Eight scalar fields
  - Three of eight fields participate in SSB leaving five.
    - Two neutral CP-even Higgs fields (h, H)
    - One pseudoscalar (CP-odd) Higgs field A
    - Two charged Higgs $H^{\pm}$
- Four types of 2HDM based on coupling to quarks and leptons
  - Type I, II, X, Y
  - Our concern is Type II, where up-type quark interact with second Higgs doublet (ϕ_2) and down-type and leptons interact with the ϕ_1
  - MSSM corresponds type-II of 2HDM and can answer the first three limitations of SM [NPB 887 (2014) 338, RMP 76 (2004) 1, JOP Conf 689(2016) 012001]

Physics Motivation - II

- The physical free parameters of the theory includes
  - The masses of four Higgs $[m_h, m_H, m_A, m_{H^\pm}]$
  - Combined Vacuum Expectation Value (VEV) $[\nu = \sqrt{\nu_1^2 + \nu_2^2}]$
  - Ratio of VEVs $[tan\beta = \nu_1/\nu_2]$
  - Mixing angle α
- Current study
  - SM studies do not entirely exclude the possibility of $t \rightarrow H^\pm q$
  - The $H^\pm$ has non-zero decay possibility to heavy quarks and leptons
- Previous limit by our group : JHEP12 (2015) 178
  - $Br(t \rightarrow H^\pm b) < (1.2 - 6.5)\%$ for m_{H^+} (90 – 160) GeV in pp collisions at $\sqrt{s} = 8$ TeV with $\mathcal{L}_{\text{int}} = 19.7$ fb^{-1}
- Current limit results : PRD 102 (2020) 072001
  - $Br(t \rightarrow H^\pm b)$ calculation for m_{H^+} (80 – 160) GeV in pp collisions at $\sqrt{s} = 13$ TeV with $\mathcal{L}_{\text{int}} = 35.9$ fb^{-1} of 2016

Signal and Backgrounds

- Signal : $t\bar{t} \to H^+W^-b\bar{b}$; $H^+ \to c\bar{s}$, $W^- \to l^-\bar{\nu}_l$
  - Minimal event topology : Two b-tagged jets, two light jets (one of which is tagged as c-jet), one lepton and $\not{E}_T$
  - Additional constrain through kinematic fitting
  - The m_{jj} distribution is the observable for this search
- Backgrounds
  - SM $t\bar{t}$ + jets: [94.7% (e) or 93.6% (μ) of total background]
    - $t\bar{t} \to W^+W^-b\bar{b}$; $H^+ \to c\bar{s}$, $W^- \to l^-\bar{\nu}_l$
  - Single top quark : [3.3% (e) or 3.4% (μ)]
  - QCD multijet [0.2% (e) or 1.4% (μ)]
  - W + jets (upto 4 jets) [1.2% (e) or 1.3% (μ)]
  - Z/γ + jets (upto 4 jets) [0.4% (e) or 0.2% (μ)]
  - VV : Vector Boson Fusion [0.1% (e) or 0.1% (μ)]



Signal(above) and SM $t\bar{t}$ background (below).

Object and event selection

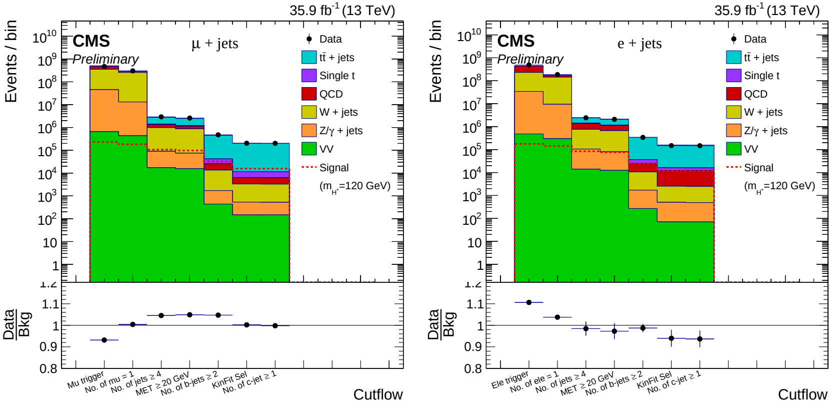
Channel	Cut type	Cut values
Event	MET filter	yes
	PV	$N^{dof} > 4$, $\rho = \sqrt{x^2+y^2} < 2$ cm, $|z| < 24$ cm
$\mu(e)$	HLT	IsoMu24 or IsoTkMu24 (Ele27_WPTight_Gsf)
	vertex	$|d_{xy}| < 0.05$ cm, $|d_z| < 0.2$ cm ($|d_{xy}| < 0.05[0.1]$, $|d_z| < 0.1[0.2]$ cm EB[EE])
	selection : $p_T, |\eta|$	> 26 GeV, < 2.4 (> 35 GeV, < 2.4)
	selection : ID	mediumId equivalent[eqv.] (mediumId eqv.)
	selection : I_{rel}	< 0.15 ($< 0.0821[0.0695]$ EB[EE])
	selection : N^{lepton}	1 (1)
	veto : $p_T, |\eta|$	> 15 GeV, < 2.4 (> 15 GeV, < 2.4)
	veto : ID	looseId eqv. (looseId eqv.)
	veto : I_{rel}	< 0.25 (0.175[0.159] for EB[EE])
	veto : N^{lepton}	≥ 1 (≥ 1)
Jet/MET	$p_T, \eta, \Delta R$	$p_T > 25$ GeV, $|\eta| < 2.4$, $\Delta R(\mathrm{lepton, jet}) > 0.4$, loose JetID eqv.
	(N^{jet}, N^{b-jet}, $\not{E}_T$)	($N^{jet} \geq 4$, $N^{b-jet} \geq 2$, $\not{E}_T \geq 20$ GeV)
	b_{tag} (CSVV2)	(M:0.8484)
	c_{tag} (CSVV2)	see the table below
Kinematic Fitting	$\epsilon_\chi = [\chi^2(n-1) - \chi^2(n)]/\mathrm{NDF}$	$\epsilon_\chi < 5 \times 10^{-5}$
	$\epsilon_c = m_{inv}[b^{jet}(q\bar{q}/l\nu_l)] - m_t$	$\epsilon_c < 0.0001$, $m_t = 172.5$ GeV and $m_W = 80.379$ GeV for ($W \to l\nu_l$)
	N_{iter}	$N_{iter} < 500$

charm tagging efficiency and working points (WP)

WP	ϵ^c (%)	ϵ^b (%)	ϵ^{udsg} (%)	CvsL	CvsB
c-tagger L	88	36	91	> -0.48	> -0.17
c-tagger M	40	17	19	> -0.1	> 0.08
c-tagger T	19	20	1.2	> 0.69	> -0.45

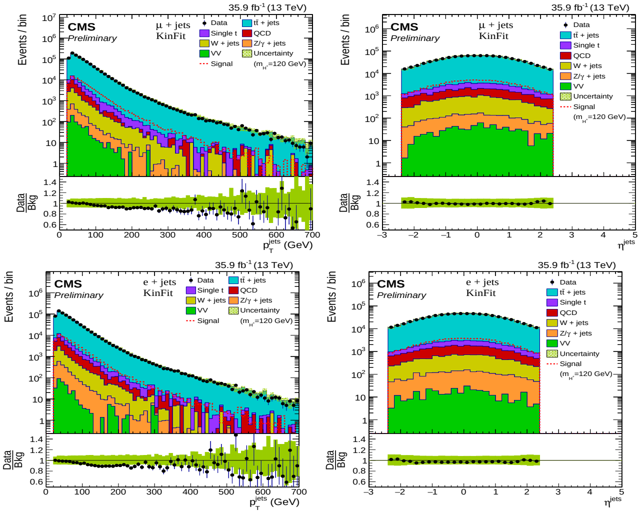
Event → Trigger → Lepton → JET → MET → b-jet → KinFit → QCD multijet → c tagging → Limit

Cutflow and signal sensitivity



- A better sig/bkg ratio after the selection of kinematic fitting (See Fig. 7.1 of link of Ravindra's Ph.D. thesis).
- The signal event yields are scaled by twice the maximum observed upper limit on $Br(t \to H^{\pm} b)$ obtained at 8 TeV

Comparison of data/MC after Kinematic Fitting: p_T^{jets}, η^{jets} dist^n



- The p_T^{jet} and η^{jet} distribution of μ+jets and e + jets are shown at top and the bottom plots (Fig. 7.2 and 7.3 of link).
- A good agreement is observed has been observed at the pre-fit level.

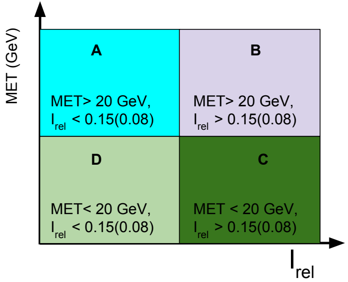
Estimation of QCD estimation background

- The simulation of full QCD multijet events demands high CPU consumption.
- Hence a data driven method is applied to estimate the QCD multijet background.
- Calculate the scale factor in C and D as

$$\mathrm{SF_{qcd}} = \frac{\mathrm{N^{D}_{Data-knownMC}}}{\mathrm{N^{C}_{Data-knownMC}}}$$

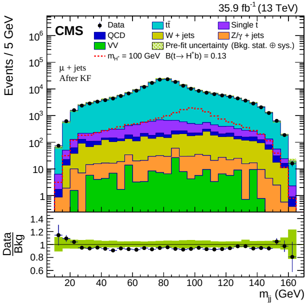
- Then estimate the data driven QCD background in region A as,

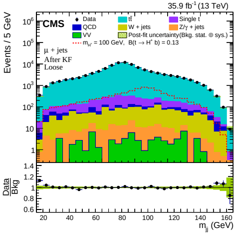
$$\mathrm{(QCD)^{A} = SF_{qcd} \times (Data - knownMC)^{B}}$$

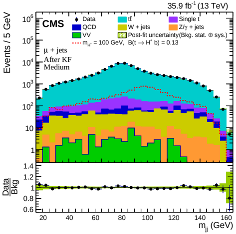


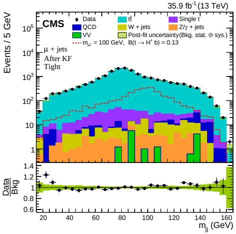
In case of A and D, the upper limits for I^{μ}_{rel} and I^{e}_{rel} are 0.15 and 0.0821(0.0695) for $e+$ jets in barrel(endcap), respectively. Similarly, for B and C, the upper limits for I^{μ}_{rel} and I^{e}_{rel} are 0.25 and 0.175(0.159) for $e+$ jets in barrel(endcap), respectively.

Categorization of Events : m_{jj} distribution









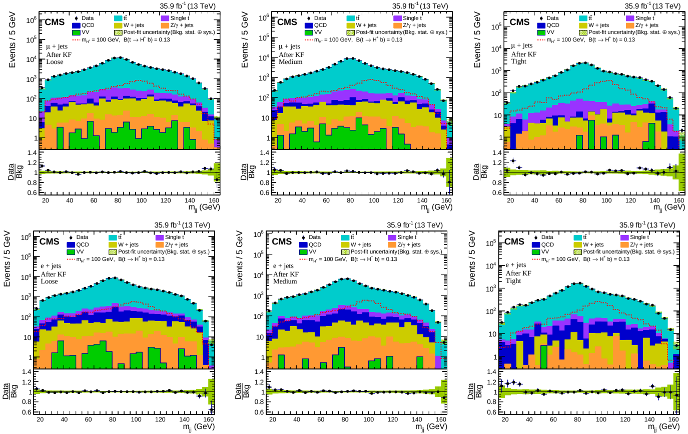
- The m_{jj} distribution at KinFit (top) and for excl. loose c-tagging (left), medium c-tagging (middle) and tight c-tagging (right) are shown.
- The final results are obtained for m_{jj} distribution after exclusive categorization.

Systematic and statistical uncertainties

Category	Process	Pileup	jet & $\not{E}_T$	b & c jets	Normalization	Statistical	p_{T} (t)
Loose	$m_{H^+} = 100$ GeV	0.6 (1.1)	4.2 (3.5)	6.1 (6.1)	6.1 (6.1)	1.0 (1.2)	1.4 (1.8)
	SM $t\bar{t}$ + jets	0.9 (1.1)	3.6 (3.6)	5.8 (5.8)	6.1 (6.1)	0.2 (0.2)	1.5 (1.9)
	Single t quark	0.6 (0.8)	4.9 (5.4)	6.5 (6.6)	5.0 (5.0)	0.7 (0.8)	···
	W + jets	2.3 (0.4)	13 (6.9)	10 (10)	5.0 (5.0)	3.9 (4.5)	···
	Z/γ + jets	1.8 (2.4)	11 (8.4)	9.2 (9.0)	4.5 (4.5)	5.7 (4.2)	···
	VV	1.5 (7.9)	19 (13)	7.2 (7.0)	4.0 (4.0)	19 (22)	···
	QCD multijet	···	···	···	10 (10)	20 (7.3)	···
Medium	$m_{H^+} = 100$ GeV	0.4 (0.3)	3.5 (2.0)	6.7 (6.8)	6.1 (6.1)	1.1 (1.3)	1.6 (1.9)
	SM $t\bar{t}$ + jets	0.3 (0.4)	3.0 (3.0)	7.3 (7.3)	6.1 (6.1)	0.2 (0.3)	1.5 (2.0)
	Single t quark	0.3 (0.1)	4.4 (4.1)	8.1 (8.1)	5.0 (5.0)	0.9 (1.0)	···
	W + jets	2.9 (1.6)	14 (6.8)	12 (11)	5.0 (5.0)	4.8 (5.7)	···
	Z/γ + jets	0.7 (3.4)	9.0 (11)	12 (11)	4.5 (4.5)	5.9 (5.9)	···
	VV	0.6 (4.4)	15 (49)	10 (9.4)	4.0 (4.0)	20 (36)	···
	QCD multijet	···	···	···	10 (10)	19 (9.4)	···
Tight	$m_{H^+} = 100$ GeV	1.2 (1.3)	2.2 (3.0)	9.2 (9.2)	6.1 (6.1)	1.6 (1.9)	1.4 (1.8)
	SM $t\bar{t}$ + jets	0.9 (1.0)	2.7 (3.1)	9.4 (9.4)	6.1 (6.1)	0.4 (0.5)	1.4 (1.8)
	Single t quark	0.4 (0.5)	4.3 (4.5)	9.8 (9.8)	5.0 (5.0)	1.8 (2.1)	···
	W + jets	1.1 (2.8)	23 (3.4)	13 (13)	5.0 (5.0)	12 (14)	···
	Z/γ + jets	3.7 (2.7)	7.5 (10)	13 (12)	4.5 (4.5)	9.1 (15)	···
	VV	2.3 (8.9)	36 (0.3)	11 (10)	4.0 (4.0)	38 (100)	···
	QCD multijet	···	···	···	10 (10)	47 (17)	···

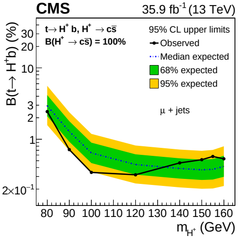
- Systematic and statistical uncertainties in the event yield for the different processes in percent, when they differ from process to process, prior to the fit to data, for the exclusive charm categories in the muon (electron) channel.
- The "···" indicates that the corresponding uncertainties are either not considered for the given process or too small to be measured.

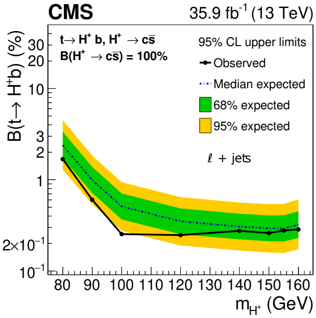
Event Yields

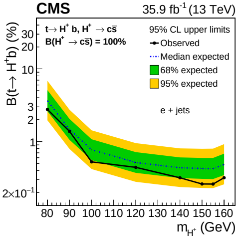


- The m_{jj} distribution with exclusive loose (left), medium (middle) and tight (right) charm tagging are shown for muon+jets (top) and electron+jets (bottom).
- The results are shown with statistical and systematic uncertainties after a background-only fit to the data.
- The total uncertainty in the background process is calculated by taking into account all the positive as well as negative correlations among the fit parameters.
- The signal event yields are scaled by twice the maximum observed upper limit on $Br(t \rightarrow H^{\pm} b)$ obtained at 8 TeV.

Calculation of upper limit







m_{H^+} (GeV)	Expected					Observed
	-2σ	-1σ	median	$+1\sigma$	$+2\sigma$	
80	1.29	1.72	2.39	3.36	4.50	1.68
90	0.54	0.72	0.99	1.38	1.84	0.60
100	0.28	0.37	0.51	0.71	0.94	0.25
120	0.19	0.25	0.35	0.49	0.64	0.25
140	0.17	0.22	0.31	0.42	0.56	0.28
150	0.16	0.21	0.29	0.41	0.54	0.26
155	0.16	0.21	0.29	0.41	0.54	0.28
160	0.17	0.23	0.32	0.45	0.61	0.29

- Expected and observed 95% CL exclusion limits on $Br(t \to H^{\pm} b)$ are shown for muon+jets (left) electron+jets (right) and after combining the two channels (middle).
- Table : Expected and observed 95% CL exclusion limits in percent on $Br(t \to H^{\pm} b)$ in the lepton+jets after combining muon+jets and electron+jets channel.
- The first results from the LHC at $\sqrt{s} = 13$ TeV for the above final states and represent an improvement by a factor of approximately 4 over the previous results at $\sqrt{s} = 8$ TeV.

Summary and Outlook

- A search for a light charged Higgs boson produced by top has been performed in muon+jets and electron+jets channels at $\sqrt{s} = 13$ TeV [see PRD 102 (2020) 072001].
- The observed and predicted number of events from standard model processes are in agreement within the uncertainties.
- The observed exclusion limits on $Br(t \to H^{\pm} b)$ [assuming $Br(H^{\pm} \to cs) = 100\%$] for a charged Higgs boson mass between 80 and 160 GeV, 2.44%–0.32%, 2.77%–0.26% and 1.68%–0.25% for the muon+jets, electron+jets, and the combination of the two channels, respectively.
- The first results from the LHC at $\sqrt{s} = 13$ TeV for the above final states and represent an improvement by a factor of approximately 4 over the previous results at $\sqrt{s} = 8$ TeV.
- We are in process to finalize the charged Higgs analysis on Run2 data of LHC.

Thank You

Cutflow and signal sensitivity

Event yields for the μ + jets							
Process	Trigger	$N_{muon} = 1$	$N_{jets} \geq 4$	$\not{E}_T \geq 20GeV$	$\geq$ 2 b-jets	KinFit Sel.	$\geq$1 c-jet
MC signal	232076	195177	116921	106839	35050.5	16932.3	16995.4
SM $t\bar{t}$ + jets	4.02823e+06	2.84791e+06	1.4925e+06	1.37212e+06	449363	205678	204577
Single t	589360	455794	92348.6	84612	18402.3	5738.97	5692.71
W + jets	3.0976e+08	2.60782e+08	1.11136e+06	992060	13768.1	2979.1	2931.53
Z/γ + jets	4.48471e+07	1.38263e+07	92247.8	74957.5	1527.75	440.68	423.088
MC QCD	1.44528e+08	4.33387e+07	454277	340874	14787.7	3159.25	3108.99
VV	653644	462752	21110.8	19097.7	515.918	155.957	156.093
Bkg	5.04407e+08	3.21714e+08	3.26384e+06	2.88373e+06	498365	218152	216890
Data	4.69926e+08	3.02859e+08	2.91118e+06	2.58404e+06	475120	203180	201332
Data/Bkg	0.931641	0.941392	0.891948	0.896078	0.953358	0.931368	0.92827

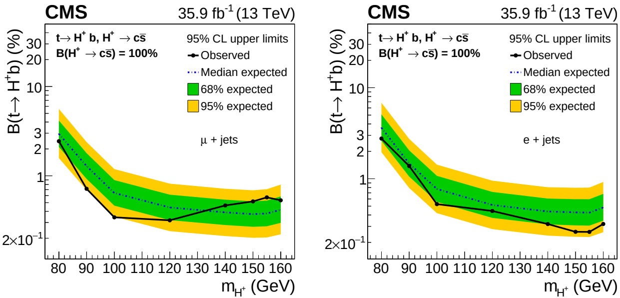
Event yields for the e + jets							
Process	Trigger	$N_{ele} = 1$	$N_{jets} \geq 4$	$\not{E}_T \geq 20GeV$	$\geq$ 2 b-jets	KinFit Sel.	$\geq$1 c-jet
MC signal	176707	142579	85553.5	77733.4	24927.6	11958.6	11989.3
SM $t\bar{t}$ + jets	3.00506e+06	2.02494e+06	1.06093e+06	972693	313133	143178	142432
Single t	436965	312490	66953.2	61092.8	13159.7	4030.43	3995.41
W + jets	1.95738e+08	1.33639e+08	760254	675272	9814.24	2115.41	2074.13
Z/γ + jets	3.38253e+07	9.14985e+06	105837	79926	1568.69	453.363	438.934
MC QCD	2.04408e+08	3.23709e+07	685990	524208	13850.2	9798.04	9734.67
VV	479876	297512	15953.1	14091.4	281.626	67.4654	67.2817
Bkg	4.37893e+08	1.77795e+08	2.69591e+06	2.32728e+06	351807	159643	158742
Data	4.85205e+08	1.84925e+08	2.42496e+06	2.07011e+06	338836	148500	147210
Data/Bkg	1.10804	1.0401	0.899494	0.889495	0.96313	0.9302	0.927354

Event Yields

Process	Loose		Medium		Tight	
	μ + jets	e + jets	μ + jets	e + jets	μ + jets	e + jets
m_{H^+} = 80 GeV	7690 ± 550	5430 ± 380	6560 ± 490	4700 ± 370	2670 ± 270	1860 ± 180
m_{H^+} = 90 GeV	7710 ± 550	5620 ± 400	6770 ± 510	4860 ± 380	2630 ± 260	1870 ± 190
m_{H^+} = 100 GeV	7950 ± 590	5550 ± 400	7070 ± 540	4950 ± 360	2770 ± 270	2000 ± 200
m_{H^+} = 120 GeV	7620 ± 570	5360 ± 400	6870 ± 510	4780 ± 360	2650 ± 260	1960 ± 190
m_{H^+} = 140 GeV	6160 ± 500	4370 ± 360	5420 ± 420	3840 ± 310	2010 ± 210	1500 ± 150
m_{H^+} = 150 GeV	4530 ± 390	3230 ± 280	3850 ± 330	2800 ± 250	1340 ± 140	1030 ± 120
m_{H^+} = 155 GeV	3700 ± 340	2560 ± 250	2980 ± 270	2230 ± 220	1020 ± 120	766 ± 86
m_{H^+} = 160 GeV	2780 ± 270	2080 ± 200	2370 ± 230	1710 ± 180	728 ± 83	510 ± 59
SM $t\bar{t}$ + jets	100540 ± 410	71800 ± 470	73210 ± 320	52340 ± 290	18760 ± 130	13380 ± 130
Single t quark	2750 ± 220	1970 ± 160	1940 ± 160	1400 ± 110	421 ± 35	302 ± 26
QCD multijet	520 ± 130	2120 ± 470	498 ± 98	1460 ± 210	88 ± 28	346 ± 39
W + jets	1360 ± 140	1061 ± 90	950 ± 110	681 ± 58	127 ± 23	102 ± 9
Z/γ + jets	189 ± 18	240 ± 25	132 ± 13	132 ± 14	56 ± 7	31 ± 4
VV	61 ± 9	43 ± 6	56 ± 8	11 ± 4	15 ± 5	3 ± 1
All background	105410 ± 500	77240 ± 690	76780 ± 390	56020 ± 380	19470 ± 140	14160 ± 140
Data	105474	77244	76807	56051	19437	14179

- Expected event yields for different signal mass scenarios and backgrounds in each of the channels and event categories.
- The number of events is shown along with its uncertainty, including statistical and systematic effects.
- The yields of the background processes are obtained after a background-only fit to the data.
- The total uncertainty in the background process is calculated by taking into account all the positive as well as negative correlations among the fit parameters.
- The signal event yields are scaled by twice the maximum observed upper limit on $Br(t \to H^{\pm} b)$ obtained at 8 TeV.

Calculation of upper limit



m_{H^+} (GeV)	Expected					Observed
	-2σ	-1σ	median	$+1\sigma$	$+2\sigma$	
80	1.58 (1.96)	2.10 (2.61)	2.95 (3.63)	4.16 (5.10)	5.61 (6.84)	2.44 (2.77)
90	0.69 (0.79)	0.92 (1.06)	1.28 (1.47)	1.79 (2.05)	2.39 (2.74)	0.72 (1.38)
100	0.35 (0.42)	0.46 (0.56)	0.64 (0.77)	0.90 (1.08)	1.19 (1.43)	0.34 (0.53)
120	0.24 (0.28)	0.32 (0.37)	0.44 (0.52)	0.61 (0.72)	0.82 (0.95)	0.32 (0.44)
140	0.21 (0.24)	0.28 (0.32)	0.39 (0.44)	0.54 (0.61)	0.72 (0.81)	0.47 (0.32)
150	0.20 (0.23)	0.27 (0.31)	0.37 (0.43)	0.52 (0.60)	0.69 (0.80)	0.52 (0.26)
155	0.20 (0.23)	0.27 (0.31)	0.38 (0.42)	0.53 (0.60)	0.71 (0.80)	0.57 (0.26)
160	0.22 (0.26)	0.30 (0.35)	0.42 (0.48)	0.59 (0.68)	0.80 (0.92)	0.53 (0.32)

- Left table : Expected and observed 95% CL exclusion limits in percent on $Br(t \to H^{\pm}b)$ in the muon+jets (electron+jets) channel, after combining the individual charm tagging categories.