

t' (4th Generation) Quark, Searches for

$t'(2/3)$ -quark/hadron mass limits in $p\bar{p}$ and pp collisions

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>735	95	¹ AAD 14AZ	ATLS	$B(t' \rightarrow Zt) = 1$
>700	95	² CHATRCHYAN 14A	CMS	$B(t' \rightarrow Wb) = 1$
>706	95	² CHATRCHYAN 14A	CMS	$B(t' \rightarrow Zt) = 1$
>782	95	² CHATRCHYAN 14A	CMS	$B(t' \rightarrow ht) = 1$
>350	95	³ AAD 12BC	ATLS	$B(t' \rightarrow Wq)=1$ ($q=d,s,b$)
>420	95	⁴ AAD 12C	ATLS	$t' \rightarrow Xt$ ($m_X < 140$ GeV)
>685	95	⁵ CHATRCHYAN 12BH	CMS	$m_{b'} = m_{t'}$
>557	95	⁶ CHATRCHYAN 12P	CMS	$t'\bar{t}' \rightarrow W^+bW^-\bar{b} \rightarrow b\ell^+\nu\bar{b}\ell^-\bar{\nu}$

• • • We do not use the following data for averages, fits, limits, etc. • • •

>656	95	⁷ AAD 13F	ATLS	$B(t' \rightarrow Wb) = 1$
>625	95	⁸ CHATRCHYAN 13I	CMS	$B(t' \rightarrow Zt) = 1$
>404	95	⁹ AAD 12AR	ATLS	$B(t' \rightarrow Wb) = 1$
>570	95	¹⁰ CHATRCHYAN 12BC	CMS	$t'\bar{t}' \rightarrow W^+bW^-\bar{b}$
>400	95	¹¹ AALTONEN 11AH	CDF	$t' \rightarrow Xt$ ($m_X < 70$ GeV)
>358	95	¹² AALTONEN 11AL	CDF	$t' \rightarrow Wb$
>340	95	¹² AALTONEN 11AL	CDF	$t' \rightarrow Wq$ ($q=d,s,b$)
>360	95	¹³ AALTONEN 11O	CDF	$t' \rightarrow Xt$ ($m_X < 100$ GeV)
>285	95	¹⁴ ABAZOV 11Q	D0	$t' \rightarrow Wq$ ($q=d,s,b$)
>256	95	^{15,16} AALTONEN 08H	CDF	$t' \rightarrow Wq$

¹ Based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. No significant excess over SM expectation is found in the search for pair production or single production of t' in the events with dilepton from a high p_T Z and additional jets (≥ 1 b -tag). The lower mass limit is 655 GeV for a vector-like singlet t' mixing solely with the third SM generation.

² Based on 19.5 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. The t' quark is pair produced and is assumed to decay into three different final states of bW , tZ , and th . The search is carried out using events with at least one isolated lepton.

³ Based on 1.04 fb^{-1} of pp data at $\sqrt{s} = 7$ TeV. No signal is found for the search of heavy quark pair production that decay into W and a quark in the events with dileptons, large \cancel{E}_T , and ≥ 2 jets.

⁴ Based on 1.04 fb^{-1} of data in pp collisions at 7 TeV. AAD 12C looked for $t'\bar{t}'$ production followed by t' decaying into a top quark and X , an invisible particle, in a final state with an isolated high- p_T lepton, four or more jets, and a large missing transverse energy. No excess over the SM $t\bar{t}$ production gives the upper limit on $t'\bar{t}'$ production cross section as a function of $m_{t'}$ and m_X . The result is obtained for $B(t' \rightarrow Wt) = 1$.

⁵ Based on 5 fb^{-1} of pp data at $\sqrt{s} = 7$ TeV. CHATRCHYAN 12BH searched for QCD and EW production of single and pair of degenerate 4th generation quarks that decay to Wb or Wt . Absence of signal in events with one lepton, same-sign dileptons or tripletons gives the bound. With a mass difference of $25 \text{ GeV}/c^2$ between $m_{t'}$ and $m_{b'}$, the corresponding limit shifts by about $\pm 20 \text{ GeV}/c^2$.

⁶ Based on 5.0 fb^{-1} of pp data at $\sqrt{s} = 7$ TeV. CHATRCHYAN 12P looked for $t'\bar{t}'$ production events with two isolated high p_T leptons, large \cancel{E}_T , and 2 high p_T jets with

- b*-tag. The absence of signal above the SM background gives the limit for $B(t' \rightarrow Wb) = 1$.
- 7 Based on 4.7 fb^{-1} of pp data at $\sqrt{s} = 7 \text{ TeV}$. No signal is found for the search of heavy quark pair production that decay into W and a b quark in the events with a high p_T isolated lepton, large \cancel{E}_T and at least 3 jets (≥ 1 *b*-tag). Vector-like quark of charge $2/3$ with $400 < m_{t'} < 550 \text{ GeV}$ and $B(t' \rightarrow Wb) > 0.63$ is excluded at 95% CL.
 - 8 Based on 5.0 fb^{-1} of pp data at $\sqrt{s} = 7 \text{ TeV}$. CHATRCHYAN 13I looked for events with one isolated electron or muon, large \cancel{E}_T , and at least four jets with large transverse momenta, where one jet is likely to originate from the decay of a bottom quark.
 - 9 Based on 1.04 fb^{-1} of pp data at $\sqrt{s} = 7 \text{ TeV}$. No signal is found in the search for pair produced heavy quarks that decay into W boson and a b quark in the events with a high p_T isolated lepton, large \cancel{E}_T and at least 3 jets (≥ 1 *b*-tag).
 - 10 Based on 5.0 fb^{-1} of pp data at $\sqrt{s} = 7 \text{ TeV}$. CHATRCHYAN 12BC looked for $t'\bar{t}'$ production events with a single isolated high p_T lepton, large \cancel{E}_T and at least 4 high p_T jets with a *b*-tag. The absence of signal above the SM background gives the limit for $B(t' \rightarrow Wb) = 1$.
 - 11 Based on 5.7 fb^{-1} of data in $p\bar{p}$ collisions at 1.96 TeV. AALTONEN 11AH looked for $t'\bar{t}'$ production followed by t' decaying into a top quark and X , an invisible particle, in the all hadronic decay mode of $t\bar{t}$. No excess over the SM $t\bar{t}$ production gives the upper limit on $t'\bar{t}'$ production cross section as a function of $m_{t'}$ and m_X . The result is obtained for $B(t' \rightarrow Xt) = 1$.
 - 12 Based on 5.6 fb^{-1} of data in $p\bar{p}$ collisions at 1.96 TeV. AALTONEN 11AL looked for $\ell + \geq 4j$ events and set upper limits on $\sigma(t'\bar{t}')$ as functions of $m_{t'}$.
 - 13 Based on 4.8 fb^{-1} of data in $p\bar{p}$ collisions at 1.96 TeV. AALTONEN 11O looked for $t'\bar{t}'$ production signal when t' decays into a top quark and X , an invisible particle, in $\ell + \cancel{E}_T + \text{jets}$ channel. No excess over the SM $t\bar{t}$ production gives the upper limit on $t'\bar{t}'$ production cross section as a function of $m_{t'}$ and m_X . The result is obtained for $B(t' \rightarrow Xt) = 1$.
 - 14 Based on 5.3 fb^{-1} of data in $p\bar{p}$ collisions at 1.96 TeV. ABAZOV 11Q looked for $\ell + \cancel{E}_T + \geq 4j$ events and set upper limits on $\sigma(t'\bar{t}')$ as functions of $m_{t'}$.
 - 15 Searches for pair production of a new heavy top-like quark t' decaying to a W boson and another quark by fitting the observed spectrum of total transverse energy and reconstructed t' mass in the lepton + jets events.
 - 16 HUANG 08 reexamined the t' mass lower bound of 256 GeV obtained in AALTONEN 08H that assumes $B(b' \rightarrow qZ) = 1$ for $q = u, c$ which does not hold when $m_{b'} < m_{t'} - m_W$ or the mixing $\sin^2(\theta_{bt'})$ is so tiny that the decay occurs outside of the vertex detector. Fig. 1 gives that lower bound on $m_{t'}$ in the plane of $\sin^2(\theta_{bt'})$ and $m_{b'}$.

$t'(5/3)$ -quark/hadron mass limits in $p\bar{p}$ and pp collisions

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>800	95	17 CHATRCHYAN14T	CMS	$t'(5/3) \rightarrow tW^+$

- 17 Based on 19.5 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. Non-observation of anomaly in H_T distribution in the same sign dilepton events leads to the limit when pair produced $t'(5/3)$ quark decays exclusively into t and W^+ , resulting in the final state with $b\bar{b}W^+W^-W^+W^-$.

$t'(2/3)$ mass limits from single production in $p\bar{p}$ and pp collisions

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>403	95	¹⁸ ABAZOV	11F D0	$qd \rightarrow q' t' \rightarrow q'(Wd)$ $\tilde{\kappa}_{d t'}=1, B(t' \rightarrow Wd)=1$
>551	95	¹⁸ ABAZOV	11F D0	$qu \rightarrow q t' \rightarrow q(Zu)$ $\tilde{\kappa}_{u t'}=\sqrt{2}, B(t' \rightarrow Zu)=1$

¹⁸ Based on 5.4 fb^{-1} of data in $p\bar{p}$ collisions at 1.96 TeV. ABAZOV 11F looked for single production of t' via the Z or E coupling to the first generation up or down quarks, respectively. Model independent cross section limits for the single production processes $p\bar{p} \rightarrow t' q \rightarrow (Wd)q$, and $p\bar{p} \rightarrow t' q \rightarrow (Zd)q$ are given in Figs. 3 and 4, respectively, and the mass limits are obtained for the model of ATRE 09 with degenerate bi-doublets of vector-like quarks.

REFERENCES FOR Searches for (Fourth Generation) t' Quark

AAD	14AZ	JHEP 1411 104	G. Aad <i>et al.</i>	(ATLAS Collab.)
CHATRCHYAN	14A	PL B729 149	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	14T	PRL 112 171801	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
AAD	13F	PL B718 1284	G. Aad <i>et al.</i>	(ATLAS Collab.)
CHATRCHYAN	13I	JHEP 1301 154	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
AAD	12AR	PRL 108 261802	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12BC	PR D86 012007	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12C	PRL 108 041805	G. Aad <i>et al.</i>	(ATLAS Collab.)
CHATRCHYAN	12BC	PL B718 307	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	12BH	PR D86 112003	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	12P	PL B716 103	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
AALTONEN	11AH	PRL 107 191803	T. Aaltonen <i>et al.</i>	(CDF Collab.)
AALTONEN	11AL	PRL 107 261801	T. Aaltonen <i>et al.</i>	(CDF Collab.)
AALTONEN	11O	PRL 106 191801	T. Aaltonen <i>et al.</i>	(CDF Collab.)
ABAZOV	11F	PRL 106 081801	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	11Q	PRL 107 082001	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ATRE	09	PR D79 054018	A. Atre <i>et al.</i>	
AALTONEN	08H	PRL 100 161803	T. Aaltonen <i>et al.</i>	(CDF Collab.)
HUANG	08	PR D77 037302	P.Q. Hung, M. Sher	(UVA, WILL)