

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
>770	95	¹ AAD	15AR ATLS	$B(t' \rightarrow Wb) = 1$
>590	95	² AAD	15BY ATLS	Wb, Zt, ht modes
>745	95	³ KHACHATRYAN...15AI	CMS	$B(t' \rightarrow ht) = 1$
>735	95	⁴ AAD	14AZ ATLS	
>700	95	⁵ CHATRCHYAN 14A	CMS	$B(t' \rightarrow Wb) = 1$
>706	95	⁵ CHATRCHYAN 14A	CMS	$B(t' \rightarrow Zt) = 1$
>782	95	⁵ CHATRCHYAN 14A	CMS	$B(t' \rightarrow ht) = 1$
>350	95	⁶ AAD	12BC ATLS	$B(t' \rightarrow Wq)=1$ ($q=d,s,b$)
>420	95	⁷ AAD	12C ATLS	$t' \rightarrow Xt$ ($m_X < 140$ GeV)
>685	95	⁸ CHATRCHYAN 12BH	CMS	$m_{b'} = m_{t'}$
>557	95	⁹ 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	¹⁰ AAD	13F ATLS	$B(t' \rightarrow Wb) = 1$
>625	95	¹¹ CHATRCHYAN 13I	CMS	$B(t' \rightarrow Zt) = 1$
>404	95	¹² AAD	12AR ATLS	$B(t' \rightarrow Wb) = 1$
>570	95	¹³ CHATRCHYAN 12BC	CMS	$t'\bar{t}' \rightarrow W^+bW^-\bar{b}$
>400	95	¹⁴ AALTONEN	11AH CDF	$t' \rightarrow Xt$ ($m_X < 70$ GeV)
>358	95	¹⁵ AALTONEN	11AL CDF	$t' \rightarrow Wb$
>340	95	¹⁵ AALTONEN	11AL CDF	$t' \rightarrow Wq$ ($q=d,s,b$)
>360	95	¹⁶ AALTONEN	11O CDF	$t' \rightarrow Xt$ ($m_X < 100$ GeV)
>285	95	¹⁷ ABAZOV	11Q D0	$t' \rightarrow Wq$ ($q=d,s,b$)
>256	95	^{18,19} AALTONEN	08H CDF	$t' \rightarrow Wq$

¹ AAD 15AR based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. Used lepton-plus-jets final state. See Fig. 20 for mass limits in the plane of $B(t' \rightarrow Ht)$ vs. $B(t' \rightarrow Wb)$ from a combination of $t'\bar{t}' \rightarrow Wb + X$ and $t'\bar{t}' \rightarrow Ht + X$ searches. Any branching ratio scenario is excluded for mass below 715 GeV.

² AAD 15BY based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. Limit on pair-produced vector-like t' assuming the branching fractions to W , Z , and h modes of the singlet model. Used events containing $\geq 2\ell + \cancel{E}_T + \geq 2j$ (≥ 1 b) and including a same-sign lepton pair.

³ KHACHATRYAN 15AI based on 19.7 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. The search exploits all-hadronic final states by tagging boosted Higgs boson using jet substructure and b -tagging.

⁴ 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). If instead of $B(b' \rightarrow Wt) = 1$ an electroweak singlet with $B(b' \rightarrow Wt) \sim 0.45$ is assumed, the limit reduces to 685 GeV.

⁵ 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.

- ⁶ Based on 1.04 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 quark in the events with dileptons, large \cancel{E}_T , and ≥ 2 jets.
- ⁷ 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 $B(t' \rightarrow Wt) = 1$.
- ⁸ Based on 5 fb^{-1} of pp data at $\sqrt{s} = 7 \text{ TeV}$. CHATRCHYAN 12BH searched for QCD and EW production of single and pair of degenerate 4'th generation quarks that decay to Wb or Wt . Absence of signal in events with one lepton, same-sign dileptons or tri-leptons 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 $\pm 20 \text{ GeV}/c^2$.
- ⁹ Based on 5.0 fb^{-1} of pp data at $\sqrt{s} = 7 \text{ TeV}$. 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 $B(t' \rightarrow Wb) = 1$.
- ¹⁰ 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.
- ¹¹ 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.
- ¹² 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).
- ¹³ 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 $B(t' \rightarrow Wb) = 1$.
- ¹⁴ 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 $B(t' \rightarrow Xt) = 1$.
- ¹⁵ 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 $m_{t'}$.
- ¹⁶ 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 $B(t' \rightarrow Xt) = 1$.
- ¹⁷ 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 $m_{t'}$.
- ¹⁸ 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.
- ¹⁹ 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
>750	95	¹ AAD	15BY ATLS	$t'(5/3) \rightarrow tW^+$
>840	95	² AAD	15Z ATLS	$t'(5/3) \rightarrow tW^+$
>800	95	³ CHATRCHYAN	14T CMS	$t'(5/3) \rightarrow tW^+$

¹ AAD 15BY based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. Limit on $t'(5/3)$ in pair and single production assuming its coupling to Wt is equal to one. Used events containing $\geq 2\ell + \cancel{E}_T + \geq 2j (\geq 1 b)$ and including a same-sign lepton pair.

² AAD 15Z based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. Used events with $\ell + \cancel{E}_T + \geq 6j (\geq 1 b)$ and at least one pair of jets from weak boson decay, sensitive to the final state $b\bar{b}W^+W^-W^+W^-$.

³ 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	¹ ABAZOV	11F D0	$qd \rightarrow q't' \rightarrow q'(Wd)$ $\tilde{\kappa}_{dt'}=1, B(t' \rightarrow Wd)=1$
>551	95	¹ ABAZOV	11F D0	$qu \rightarrow qt' \rightarrow q(Zu)$ $\tilde{\kappa}_{ut'}=\sqrt{2}, B(t' \rightarrow Zu)=1$

¹ 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

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