

t' (4^{th} 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
>1160 (CL = 95%) OUR LIMIT				
> 980	95	¹ AABOUD	18CE ATLS	$\geq 2\ell + \cancel{E}_T + \geq 1bj$
>1010	95	² AABOUD	18CL ATLS	$B(t' \rightarrow ht) = 1$
>1030	95	^{3,4} AABOUD	18CP ATLS	$2,3\ell$, singlet model
>1210	95	^{3,5} AABOUD	18CP ATLS	$2,3\ell$, doublet model
>1310	95	^{6,7} AABOUD	18CR ATLS	singlet t' . ATLAS combination
>1370	95	^{6,8} AABOUD	18CR ATLS	t' in a weak isospin doublet (t', b'). ATLAS combination.
>1140	95	⁹ SIRUNYAN	18BM CMS	Wb, Zt, ht modes
> 845	95	¹⁰ SIRUNYAN	18Q CMS	$B(t' \rightarrow Wq) = 1$ ($q=d,s$)
>1295	95	¹¹ SIRUNYAN	18W CMS	$B(t' \rightarrow Wb) = 1$
>1160	95	¹² AABOUD	17L ATLS	$B(t' \rightarrow Zt) = 1$
> 860	95	¹³ SIRUNYAN	17AU CMS	
> 770	95	¹⁴ AAD	15AR ATLS	$B(t' \rightarrow Wb) = 1$
> 590	95	¹⁵ AAD	15BY ATLS	Wb, Zt, ht modes
> 745	95	¹⁶ KHACHATRY...	15AI CMS	$B(t' \rightarrow ht) = 1$
> 735	95	¹⁷ AAD	14AZ ATLS	$B(b' \rightarrow Wt) = 1$
> 700	95	¹⁸ CHATRCHYAN 14A	CMS	$B(t' \rightarrow Wb) = 1$
> 706	95	¹⁸ CHATRCHYAN 14A	CMS	$B(t' \rightarrow Zt) = 1$
> 782	95	¹⁸ CHATRCHYAN 14A	CMS	$B(t' \rightarrow ht) = 1$
> 350	95	¹⁹ AAD	12BC ATLS	$B(t' \rightarrow Wq)=1$ ($q=d,s,b$)
> 420	95	²⁰ AAD	12C ATLS	$t' \rightarrow Xt$ ($m_X < 140$ GeV)
> 685	95	²¹ CHATRCHYAN 12BH	CMS	$m_{b'} = m_{t'}$
> 557	95	²² CHATRCHYAN 12P	CMS	$t'\bar{t}' \rightarrow W^+ b W^- \bar{b} \rightarrow b\ell^+ \nu \bar{b}\ell^- \bar{\nu}$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
> 656	95	²³ AAD	13F ATLS	$B(t' \rightarrow Wb) = 1$
> 625	95	²⁴ CHATRCHYAN 13I	CMS	$B(t' \rightarrow Zt) = 1$
> 404	95	²⁵ AAD	12AR ATLS	$B(t' \rightarrow Wb) = 1$
> 570	95	²⁶ CHATRCHYAN 12BC	CMS	$t'\bar{t}' \rightarrow W^+ b W^- \bar{b}$
> 400	95	²⁷ AALTONEN	11AH CDF	$t' \rightarrow Xt$ ($m_X < 70$ GeV)
> 358	95	²⁸ AALTONEN	11AL CDF	$t' \rightarrow Wb$
> 340	95	²⁸ AALTONEN	11AL CDF	$t' \rightarrow Wq$ ($q=d,s,b$)
> 360	95	²⁹ AALTONEN	11O CDF	$t' \rightarrow Xt$ ($m_X < 100$ GeV)
> 285	95	³⁰ ABAZOV	11Q D0	$t' \rightarrow Wq$ ($q=d,s,b$)
> 256	95	^{31,32} AALTONEN	08H CDF	$t' \rightarrow Wq$

- ¹ AABOUD 18CE based on 36.1 fb^{-1} of proton-proton data taken at $\sqrt{s} = 13 \text{ TeV}$. Events including a same-sign lepton pair are used. The limit is for a singlet model, assuming the branching ratios of t' into Zt , Wb and Ht as predicted by the model.
- ² AABOUD 18CL based on 36.1 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. The limit is for the pair-produced vector-like t' using all-hadronic final state. The analysis is also made for the Wb , Zt , ht modes and mass limits are obtained for a variety of branching ratios.
- ³ AABOUD 18CP based on 36.1 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. Pair and single production of vector-like t' are searched for with at least one t' decaying into Zt . In the case of $B(t' \rightarrow Zt) = 1$, the limit is $m_{t'} > 1340 \text{ GeV}$.
- ⁴ The limit is for the singlet model, assuming that the branching ratios into Zt , Wb , and Ht add up to one.
- ⁵ The limit is for the doublet model, assuming that the branching ratios into Zt , Wb , and Ht add up to one.
- ⁶ AABOUD 18CR based on 36.1 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. A combination of searches for the pair-produced vector-like t' in various decay channels ($t' \rightarrow Wb$, Zt , ht). Also a model-independent limit is obtained as $m_{t'} > 1.31 \text{ TeV}$, assuming that the branching ratios into Zt , Wb and ht add up to one.
- ⁷ The limit is for the singlet t' .
- ⁸ The limit is for t' in a weak isospin doublet (t', b') and $|V_{t'b}| \ll |V_{tb'}|$.
- ⁹ SIRUNYAN 18BM based on 35.9 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. The limit is for the pair-produced vector-like t' . Three channels (single lepton, same-charge 2 leptons, or at least 3 leptons) are considered for various branching fraction combinations. Assuming $B(t'H) = 1$, the limit is 1270 GeV and for $B(t'Z) = 1$ it is 1300 GeV.
- ¹⁰ SIRUNYAN 18Q based on 19.7 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. The limit is for the pair-produced vector-like t' that couple only to light quarks. Constraints for other decay channels (Zq and Hq) are also given in the paper.
- ¹¹ SIRUNYAN 18W based on 35.8 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. The limit is for the vector-like t' pair-produced by strong interaction using lepton-plus-jets mode and assuming that $B(t' \rightarrow Wb)$ is 100% of the production cross section and branching fraction to Wb for any new pair-produced heavy quark decaying to this channel as a narrow resonance.
- ¹² AABOUD 17L based on 36.1 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. No signal is found in the search for heavy quark pair production that decay into Zt followed by $Z \rightarrow \nu\nu$ in the events with one lepton, large \cancel{E}_T , and ≥ 4 jets. The lower mass limit 0.87 (1.05) TeV is obtained for the singlet (doublet) model with other possible decay modes.
- ¹³ SIRUNYAN 17AU based on 2.3-2.6 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. Limit on pair-produced singlet vector-like t' using one lepton and several jets. The mass bound is given for a t' transforming as a singlet under the electroweak symmetry group, assumed to decay through W , Z or Higgs boson (which decays to jets) and to a third generation quark. For a doublet, the limit is $>830 \text{ GeV}$. Other limits are also given in the paper.
- ¹⁴ AAD 15AR based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. 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.
- ¹⁵ AAD 15BY based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. Limit on pair-produced vector-like t' assuming the branching fractions to W , Z , and h modes of the singlet model. Used events containing $\geq 2\ell + \cancel{E}_T + \geq 2j$ ($\geq 1 b$) and including a same-sign lepton pair.
- ¹⁶ KHACHATRYAN 15AI based on 19.7 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. The search exploits all-hadronic final states by tagging boosted Higgs boson using jet substructure and b -tagging.

- 17 Based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. 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 $B(b' \rightarrow W t) = 1$ an electroweak singlet with $B(b' \rightarrow W t) \sim 0.45$ is assumed, the limit reduces to 685 GeV .
- 18 Based on 19.5 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. 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.
- 19 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.
- 20 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 $B(t' \rightarrow W t) = 1$.
- 21 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 $\pm 20 \text{ GeV}/c^2$.
- 22 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 $B(t' \rightarrow W b) = 1$.
- 23 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 $B(t' \rightarrow W b) > 0.63$ is excluded at 95% CL.
- 24 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.
- 25 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).
- 26 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 $B(t' \rightarrow W b) = 1$.
- 27 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 $B(t' \rightarrow X t) = 1$.
- 28 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 $m_{t'}$.
- 29 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 $B(t' \rightarrow X t) = 1$.

- ³⁰ 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 $m_{t'}$.
- ³¹ 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.
- ³² 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
>1350	95	¹ AABOUD	18AW ATLS	$t'(5/3) \rightarrow tW^+$
>1190	95	² AABOUD	18CE ATLS	$\geq 2\ell + \cancel{E}_T + \geq 1bj$
>1020	95	³ SIRUNYAN	17J CMS	$t'_R(5/3) \rightarrow tW^+$
> 990	95	³ SIRUNYAN	17J CMS	$t'_L(5/3) \rightarrow tW^+$
> 750	95	⁴ AAD	15BY ATLS	$t'(5/3) \rightarrow tW^+$
> 840	95	⁵ AAD	15Z ATLS	$t'(5/3) \rightarrow tW^+$
> 800	95	⁶ CHATRCHYAN	14T CMS	$t'(5/3) \rightarrow tW^+$

¹ AABOUD 18AW based on 36.1 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. Limit on $t'(5/3)$ in pair production assuming its coupling to Wt is equal to one. Lepton-plus-jets final state is used, characterized by $\ell + \cancel{E}_T + \text{jets}$ (≥ 1 b -tagged).

² AABOUD 18CE based on 36.1 fb^{-1} of proton-proton data taken at $\sqrt{s} = 13$ TeV. Events including a same-sign lepton pair are used. The limit is for the pair-produced vector-like t' . With single t' production included, assuming $t'tW$ coupling of one, the limit is $m_{t'} > 1.6$ TeV.

³ SIRUNYAN 17J based on 2.3 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. Signals are searched in the final states of t' pair production, with same-sign leptons (which come from a t' decay) or a single lepton (which comes from a W out of $4W$ s), along with jets, and no excess over the SM expectation is found.

⁴ AAD 15BY based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. Limit on $t'(5/3)$ in pair and single production assuming its coupling to Wt is equal to one. Used events containing $\geq 2\ell + \cancel{E}_T + \geq 2j$ (≥ 1 b) and including a same-sign lepton pair.

⁵ AAD 15Z based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. Used events with $\ell + \cancel{E}_T + \geq 6j$ (≥ 1 b) and at least one pair of jets from weak boson decay, sensitive to the final state $b\bar{b}W^+W^-W^+W^-$.

⁶ CHATRCHYAN 14T based on 19.5 fb^{-1} of pp data at $\sqrt{s} = 8$ 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
>950	95	¹ AAD	16AV ATLS	$qg \rightarrow q't'b, B(t' \rightarrow Wb)=0.5$
>403	95	² ABAZOV	11F D0	$qd \rightarrow q't' \rightarrow q'(Wd)$ $\tilde{\kappa}_{dt'}=1, B(t' \rightarrow Wd)=1$
>551	95	² ABAZOV	11F D0	$qu \rightarrow qt' \rightarrow q(Zu)$ $\tilde{\kappa}_{ut'}=\sqrt{2}, B(t' \rightarrow Zu)=1$

- ¹ AAD 16AV based on 20.3 fb^{-1} of $p\bar{p}$ data at $\sqrt{s} = 8 \text{ TeV}$. No significant excess over SM expectation is found in the search for a fully reconstructed vector-like t' in the mode $\ell + \cancel{E}_T + \geq 2j$ ($\geq 1b$). A veto on massive large-radius jets is used to reject the $t\bar{t}$ background.
- ² 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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SIRUNYAN	18Q	PR D97 072008	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
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SIRUNYAN	17J	JHEP 1708 073	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
AAD	16AV	EPJ C76 442	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15AR	JHEP 1508 105	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15BY	JHEP 1510 150	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15Z	PR D91 112011	G. Aad <i>et al.</i>	(ATLAS Collab.)
KHACHATRY...	15AI	JHEP 1506 080	V. Khachatryan <i>et al.</i>	(CMS Collab.)
AAD	14AZ	JHEP 1411 104	G. Aad <i>et al.</i>	(ATLAS Collab.)
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