t' (4^{th} Generation) Quark, Searches for

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

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>770	95	[1] AAD	15AR	ATLS	$B(t' \to W b) = 1$
>590	95	[2] AAD	15BY	ATLS	$W b$, $Z t$, $h t$ modes
>745	95	[3] KHACHATRY...	15AI	CMS	$B(t' \to h t) = 1$
>735	95	[4] AAD	14AZ	ATLS	
>700	95	[5] CHATRCHYAN	14A	CMS	$B(t' \to W b) = 1$
>706	95	[5] CHATRCHYAN	14A	CMS	$B(t' \to Z t) = 1$
>782	95	[5] CHATRCHYAN	14A	CMS	$B(t' \to h t) = 1$
>350	95	[6] AAD	12BC	ATLS	$B(t' \to W q)$=1 (q=d,s,b)
>420	95	[7] AAD	12C	ATLS	$t' \to X t$ ($m_X < 140$ GeV)
>685	95	[8] CHATRCHYAN	12BH	CMS	$m_{b'} = m_{t'}$
>557	95	[9] CHATRCHYAN	12P	CMS	$t'\overline{t}' \to W^+ b W^- \overline{b} \to b\ell^+ \nu \overline{b} \ell^- \overline{\nu}$

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

>656	95	[10] AAD	13F	ATLS	$B(t' \to W b) = 1$
>625	95	[11] CHATRCHYAN	13I	CMS	$B(t' \to Z t) = 1$
>404	95	[12] AAD	12AR	ATLS	$B(t' \to W b) = 1$
>570	95	[13] CHATRCHYAN	12BC	CMS	$t'\overline{t}' \to W^+ b W^- \overline{b}$
>400	95	[14] AALTONEN	11AH	CDF	$t' \to X t$ ($m_X < 70$ GeV)
>358	95	[15] AALTONEN	11AL	CDF	$t' \to W b$
>340	95	[15] AALTONEN	11AL	CDF	$t' \to W q$ (q=d,s,b)
>360	95	[16] AALTONEN	11O	CDF	$t' \to X t$ ($m_X < 100$ GeV)
>285	95	[17] ABAZOV	11Q	D0	$t' \to W q$ (q=d,s,b)
>256	95	[18,19] AALTONEN	08H	CDF	$t' \to W q$

[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 $B(t' \to H t)$ vs. $B(t' \to W b)$ from a combination of $t'\overline{t}' \to W b + X$ and $t'\overline{t}' \to H t + X$ 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 $\geq 2\ell + \not{E}_T + \geq$ 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 ($\geq$ 1 b-tag). If instead of $B(b' \to W t) = 1$ an electroweak singlet with $B(b' \to W t) \sim 0.45$ 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 $\sqrt{s} = 7$ 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 $\not{E}_T$, and ≥ 2 jets.

[7] Based on 1.04 fb^{-1} of data in pp collisions at 7 TeV. AAD 12C looked for $t'\overline{t}'$ 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 $t\overline{t}$ production gives the upper limit on $t'\overline{t}'$ production cross section as a function of $m_{t'}$ and m_X. The result is obtained for B($t' \rightarrow\ W\,t$) = 1.

[8] 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 4'th generation quarks that decay to $W\,b$ or $W\,t$. Absence of signal in events with one lepton, same-sign dileptons or tri-leptons gives the bound. With a mass difference of 25 GeV/c^2 between $m_{t'}$ and $m_{b'}$, the corresponding limit shifts by about $\pm$20 GeV/c^2.

[9] Based on 5.0 fb^{-1} of pp data at $\sqrt{s} = 7$ TeV. CHATRCHYAN 12P looked for $t'\overline{t}'$ production events with two isolated high p_T leptons, large $\not{E}_T$, 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.

[10] Based on 4.7 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 b quark in the events with a high p_T isolated lepton, large $\not{E}_T$ and at least 3 jets ($\geq$ 1 b-tag). Vector-like quark of charge 2/3 with $400 < m_{t'} < 550$ GeV and B($t' \rightarrow\ W\,b$) > 0.63 is excluded at 95% CL.

[11] Based on 5.0 fb^{-1} of pp data at $\sqrt{s} = 7$ TeV. CHATRCHYAN 13I looked for events with one isolated electron or muon, large $\not{E}_T$, 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 $\sqrt{s} = 7$ 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 $\not{E}_T$ and at least 3 jets (≥ 1 b-tag).

[13] Based on 5.0 fb^{-1} of pp data at $\sqrt{s} = 7$ TeV. CHATRCHYAN 12BC looked for $t'\overline{t}'$ production events with a single isolated high p_T lepton, large $\not{E}_T$ 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.

[14] Based on 5.7 fb^{-1} of data in $p\overline{p}$ collisions at 1.96 TeV. AALTONEN 11AH looked for $t'\overline{t}'$ production followed by t' decaying into a top quark and X, an invisible particle, in the all hadronic decay mode of $t\overline{t}$. No excess over the SM $t\overline{t}$ production gives the upper limit on $t'\overline{t}'$ production cross section as a function of $m_{t'}$ and m_X. The result is obtained for B($t' \rightarrow\ X\,t$) = 1.

[15] Based on 5.6 fb^{-1} of data in ppbar collisions at 1.96 TeV. AALTONEN 11AL looked for $\ell +\ \geq$ 4j events and set upper limits on $\sigma(t'\overline{t}')$ as functions of $m_{t'}$.

[16] Based on 4.8 fb^{-1} of data in $p\overline{p}$ collisions at 1.96 TeV. AALTONEN 11O looked for $t'\overline{t}'$ production signal when t' decays into a top quark and X, an invisible particle, in $\ell + \not{E}_T +$ jets channel. No excess over the SM $t\overline{t}$ production gives the upper limit on $t'\overline{t}'$ production cross section as a function of $m_{t'}$ and m_X. The result is obtained for B($t' \rightarrow\ X\,t$) = 1.

[17] Based on 5.3 fb^{-1} of data in $p\overline{p}$ collisions at 1.96 TeV. ABAZOV 11Q looked for $\ell +\ \not{E}_T +\ \geq$ 4j events and set upper limits on $\sigma(t'\overline{t}')$ 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($b' \rightarrow\ q\,Z$) = 1 for $q = u$, c which does not hold when $m_{b'} < m_{t'} - m_W$

or the mixing $\sin^2(\theta_{b\,t'})$ 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 $\sin^2(\theta_{b\,t'})$ and $m_{b'}$.

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

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>750	95	[1] AAD	15BY	ATLS	$t'(5/3) \to t\,W^+$
>840	95	[2] AAD	15Z	ATLS	$t'(5/3) \to t\,W^+$
>800	95	[3] CHATRCHYAN	14T	CMS	$t'(5/3) \to t\,W^+$

[1] 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 $W\,t$ is equal to one. Used events containing $\geq 2\ell + \not{E}_T + \geq 2$j (≥ 1 b) and including a same-sign lepton pair.

[2] AAD 15Z based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. Used events with $\ell + \not{E}_T + \geq 6$j (≥ 1 b) and at least one pair of jets from weak boson decay, sensitive to the final state $b\overline{b}\,W^+\,W^-\,W^+\,W^-$.

[3] 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 $b\overline{b}\,W^+\,W^-\,W^+\,W^-$.

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

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>950	95	[1] AAD	16AV	ATLS	$q\,g \to q'\,t'\,b$, B($t' \to W\,b$)=0.5
>403	95	[2] ABAZOV	11F	D0	$q\,d \to q'\,t' \to q'(W\,d)$ $\widetilde{\kappa}_{d\,t'}$=1, B($t' \to W\,d$)=1
>551	95	[2] ABAZOV	11F	D0	$q\,u \to q\,t' \to q(Z\,u)$ $\widetilde{\kappa}_{u\,t'}$=$\sqrt{2}$, B($t' \to Z\,u$)=1

[1] AAD 16AV 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 a fully reconstructed vector-like t' in the mode $\ell + \not{E}_T + \geq 2j$ ($\geq 1b$). A veto on massive large-radius jets is used to reject the $t\overline{t}$ background.

[2] Based on 5.4 fb^{-1} of data in ppbar 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 $p\overline{p} \to t'\,q \to (W\,d)q$, and $p\overline{p} \to t'\,q \to (Z\,d)q$ 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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AAD	15BY	JHEP 1510 150	G. Aad *et al.*	(ATLAS Collab.)
AAD	15Z	PR D91 112011	G. Aad *et al.*	(ATLAS Collab.)
KHACHATRY...	15AI	JHEP 1506 080	V. Khachatryan *et al.*	(CMS Collab.)
AAD	14AZ	JHEP 1411 104	G. Aad *et al.*	(ATLAS Collab.)
CHATRCHYAN	14A	PL B729 149	S. Chatrchyan *et al.*	(CMS Collab.)
CHATRCHYAN	14T	PRL 112 171801	S. Chatrchyan *et al.*	(CMS Collab.)
AAD	13F	PL B718 1284	G. Aad *et al.*	(ATLAS Collab.)
CHATRCHYAN	13I	JHEP 1301 154	S. Chatrchyan *et al.*	(CMS Collab.)
AAD	12AR	PRL 108 261802	G. Aad *et al.*	(ATLAS Collab.)
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AALTONEN	11AL	PRL 107 261801	T. Aaltonen *et al.*	(CDF Collab.)
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