

t' (4th Generation) Quark, Searches for

t'(2/3)-quark/hadron mass limits in p-p̄ and pp collisions

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>1280	95	¹ SIRUNYAN	19AQ CMS	B(t' → Zt) = 1
>1370	95	² SIRUNYAN	19BWCMS	B(t' → ht) = 1
> 980	95	³ AABOUD	18CE ATLS	≥ 2ℓ + E _T + ≥ 1bj
>1010	95	⁴ AABOUD	18CL ATLS	B(t' → ht) = 1
>1030	95	^{5,6} AABOUD	18CP ATLS	2,3ℓ, singlet model
>1210	95	^{5,7} AABOUD	18CP ATLS	2,3ℓ, doublet model
>1310	95	^{8,9} AABOUD	18CR ATLS	singlet t'. ATLAS combination
>1370	95	^{8,10} AABOUD	18CR ATLS	t' in a weak isospin doublet (t', b'). ATLAS combination.
>1140	95	¹¹ SIRUNYAN	18BMCMS	Wb, Zt, ht modes
> 845	95	¹² SIRUNYAN	18Q CMS	B(t' → Wq) = 1 (q=d,s)
>1295	95	¹³ SIRUNYAN	18W CMS	B(t' → Wb) = 1
>1160	95	¹⁴ AABOUD	17L ATLS	B(t' → Zt) = 1
> 860	95	¹⁵ SIRUNYAN	17AU CMS	
> 770	95	¹⁶ AAD	15AR ATLS	B(t' → Wb) = 1
> 590	95	¹⁷ AAD	15BY ATLS	Wb, Zt, ht modes
> 745	95	¹⁸ KHACHATRYAN	15AI CMS	B(t' → ht) = 1
> 735	95	¹⁹ AAD	14AZ ATLS	B(b' → Wt) = 1
> 700	95	²⁰ CHATRCHYAN	14A CMS	B(t' → Wb) = 1
> 706	95	²⁰ CHATRCHYAN	14A CMS	B(t' → Zt) = 1
> 782	95	²⁰ CHATRCHYAN	14A CMS	B(t' → ht) = 1
> 350	95	²¹ AAD	12BC ATLS	B(t' → Wq)=1 (q=d,s,b)
> 420	95	²² AAD	12C ATLS	t' → Xt (m _χ < 140 GeV)
> 685	95	²³ CHATRCHYAN	12BH CMS	m _{b'} = m _{t'}
> 557	95	²⁴ CHATRCHYAN	12P CMS	t't' → W ⁺ bW ⁻ b̄ → bℓ ⁺ νb̄ℓ ⁻ ν̄

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

> 656	95	²⁵ AAD	13F ATLS	B(t' → Wb) = 1
> 625	95	²⁶ CHATRCHYAN	13I CMS	B(t' → Zt) = 1
> 404	95	²⁷ AAD	12AR ATLS	B(t' → Wb) = 1
> 570	95	²⁸ CHATRCHYAN	12BC CMS	t't' → W ⁺ bW ⁻ b̄
> 400	95	²⁹ AALTONEN	11AH CDF	t' → Xt (m _χ < 70 GeV)
> 358	95	³⁰ AALTONEN	11AL CDF	t' → Wb
> 340	95	³⁰ AALTONEN	11AL CDF	t' → Wq (q=d,s,b)
> 360	95	³¹ AALTONEN	11O CDF	t' → Xt (m _χ < 100 GeV)
> 285	95	³² ABAZOV	11Q D0	t' → Wq (q=d,s,b)
> 256	95	^{33,34} AALTONEN	08H CDF	t' → Wq

¹ SIRUNYAN 19AQ based on 35.9 fb⁻¹ of pp data at √s = 13 TeV. Pair production of vector-like t' is searched for with one t' decaying into Zt and the other t' decaying into Wb, Zt, ht. Events with an opposite-sign lepton pair consistent with coming from Z and jets are used. Mass limits are obtained for a variety of branching ratios of t'.

- ² SIRUNYAN 19BW 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' using all-hadronic final state. The analysis is made for the Wb , Zt , ht modes and mass limits are obtained for a variety of branching ratios.
- ³ 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.
- ⁴ 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.
- ⁵ 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 $m_{t'} > 1340 \text{ GeV}$.
- ⁶ The limit is for the singlet model, assuming that the branching ratios into Zt , Wb , and Ht add up to one.
- ⁷ The limit is for the doublet model, assuming that the branching ratios into Zt , Wb , and Ht add up to one.
- ⁸ 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.
- ⁹ The limit is for the singlet t' .
- ¹⁰ The limit is for t' in a weak isospin doublet (t', b') and $|V_{t'b}| \ll |V_{tb'}|$.
- ¹¹ 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 $B(tH) = 1$, the limit is 1270 GeV and for $B(tZ) = 1$ it is 1300 GeV .
- ¹² 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.
- ¹³ 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.
- ¹⁴ 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.
- ¹⁵ SIRUNYAN 17AU based on $2.3\text{-}2.6 \text{ fb}^{-1}$ 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.
- ¹⁶ 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 .
- ¹⁷ 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.

- ¹⁸ 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.
- ¹⁹ 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 $B(b' \rightarrow Wt) = 1$ an electroweak singlet with $B(b' \rightarrow Wt) \sim 0.45$ is assumed, the limit reduces to 685 GeV .
- ²⁰ 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.
- ²¹ 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.
- ²² 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 $B(t' \rightarrow Wt) = 1$.
- ²³ 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 $\pm 20 \text{ GeV}/c^2$.
- ²⁴ 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 $B(t' \rightarrow Wb) = 1$.
- ²⁵ 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.
- ²⁶ 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.
- ²⁷ 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).
- ²⁸ 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 $B(t' \rightarrow Wb) = 1$.
- ²⁹ 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 $B(t' \rightarrow Xt) = 1$.
- ³⁰ 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 $m_{t'}$.
- ³¹ 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_χ . The result is obtained for $B(t' \rightarrow X t) = 1$.

³² 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 $m_{t'}$.

³³ 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.

³⁴ 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
>1330	95	¹ SIRUNYAN	19T CMS	$t'_R(5/3) \rightarrow tW^+$
>1300	95	¹ SIRUNYAN	19T CMS	$t'_L(5/3) \rightarrow tW^+$
>1350	95	² AABOUD	18AW ATLS	$t'(5/3) \rightarrow tW^+$
>1190	95	³ AABOUD	18CE ATLS	$\geq 2\ell + \cancel{E}_T + \geq 1bj$
>1020	95	⁴ SIRUNYAN	17J CMS	$t'_R(5/3) \rightarrow tW^+$
> 990	95	⁴ SIRUNYAN	17J CMS	$t'_L(5/3) \rightarrow tW^+$
> 750	95	⁵ AAD	15BY ATLS	$t'(5/3) \rightarrow tW^+$
> 840	95	⁶ AAD	15Z ATLS	$t'(5/3) \rightarrow tW^+$
> 800	95	⁷ CHATRCHYAN	14T CMS	$t'(5/3) \rightarrow tW^+$

¹ SIRUNYAN 19T based on 35.9 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.

² 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).

³ 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.

⁴ 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.

⁵ 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.

⁶ 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 $b\bar{b}W^+W^-W^+W^-$.

⁷ 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	$qu \rightarrow q t' \rightarrow q(Zu)$ $\tilde{\kappa}_{ut'}=\sqrt{2}, B(t' \rightarrow Zu)=1$

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

³ AAD	22G ATLS	$t' \rightarrow Ht$, singlet t'
⁴ TUMASYAN	22X CMS	$t' \rightarrow Zt$

¹ AAD 16AV 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 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 ABAZOV 11F based on 5.4 fb^{-1} of data in $p\bar{p}$ collisions at 1.96 TeV. It 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.

³ AAD 22G based on 139 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. No significant excess over SM expectation is found in the search for a vector-like t' in the Ht decay channel, where H and t are reconstructed as single jets. The mass range between 1.0 and 2.3 TeV is targeted and 95% CL limits on the production section times the decay branching fraction are set depending on the coupling and mass of t' .

⁴ TUMASYAN 22X based on 137 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. No significant excess over SM expectation is found in the search for a vector-like t' in the Zt decay channel, where Z decays to neutrinos and t decays hadronically. The 95% CL limits on the production section times the decay branching fraction are set depending on the coupling and mass of t' .

$t'(5/3)$ mass limits from single production in $p\bar{p}$ and pp collisions

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
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• • • We do not use the following data for averages, fits, limits, etc. • • •

¹ SIRUNYAN	19AI CMS	$tW \rightarrow t'(5/3) \rightarrow tW$
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¹ SIRUNYAN 19AI based on 35.9 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. Exclusion limits are set on the product of the production cross section and branching fraction for the $b'(-1/3) + t$ and $t'(5/3) + t$ modes as a function of the vector-like quark mass in Fig. 8 and Tab. 2 for relative vector-like quark widths between 1 and 30% for left- and right-handed vector-like quark couplings. No significant deviation from the SM prediction is observed.

REFERENCES FOR Searches for (Fourth Generation) t' Quark

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AAD	15BY	JHEP 1510 150	G. Aad <i>et al.</i>	(ATLAS Collab.)
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