

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

<sup>1</sup> AABOUD 18CE based on  $36.1 \text{ fb}^{-1}$  of proton-proton data taken at  $\sqrt{s} = 13$  TeV. Events including a same-sign lepton pair are used. The limit is for a singlet model, assuming the branching ratios of  $t'$  into  $Zt$ ,  $Wb$  and  $Ht$  as predicted by the model.

- 2 AABOUD 18CL based on  $36.1 \text{ fb}^{-1}$  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  $36.1 \text{ fb}^{-1}$  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  $36.1 \text{ fb}^{-1}$  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  $35.9 \text{ fb}^{-1}$  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.
- 10 SIRUNYAN 18Q based on  $19.7 \text{ fb}^{-1}$  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  $35.8 \text{ fb}^{-1}$  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  $36.1 \text{ fb}^{-1}$  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  $\geq 4$  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  $2.3\text{-}2.6 \text{ fb}^{-1}$  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.
- 14 AAD 15AR based on  $20.3 \text{ fb}^{-1}$  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  $20.3 \text{ fb}^{-1}$  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  $19.7 \text{ fb}^{-1}$  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  $20.3 \text{ fb}^{-1}$  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 ( $\geq 1 b$ -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.
- 18 Based on  $19.5 \text{ fb}^{-1}$  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  $1.04 \text{ fb}^{-1}$  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  $\geq 2$  jets.
- 20 Based on  $1.04 \text{ fb}^{-1}$  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  $B(t' \rightarrow Wt) = 1$ .
- 21 Based on  $5 \text{ fb}^{-1}$  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  $5.0 \text{ fb}^{-1}$  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  $B(t' \rightarrow Wb) = 1$ .
- 23 Based on  $4.7 \text{ fb}^{-1}$  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 ( $\geq 1$   $b$ -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.
- 24 Based on  $5.0 \text{ fb}^{-1}$  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  $1.04 \text{ fb}^{-1}$  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 ( $\geq 1$   $b$ -tag).
- 26 Based on  $5.0 \text{ fb}^{-1}$  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  $B(t' \rightarrow Wb) = 1$ .
- 27 Based on  $5.7 \text{ fb}^{-1}$  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  $B(t' \rightarrow Xt) = 1$ .
- 28 Based on  $5.6 \text{ fb}^{-1}$  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  $4.8 \text{ fb}^{-1}$  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  $B(t' \rightarrow Xt) = 1$ .
- 30 Based on  $5.3 \text{ fb}^{-1}$  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  $m_{t'}$ .

<sup>31</sup> 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.

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

<sup>1</sup> AABOUD 18AW based on  $36.1 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13 \text{ TeV}$ . 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  $\ell + \cancel{E}_T + \text{jets}$  ( $\geq 1 b$ -tagged).

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

<sup>3</sup> SIRUNYAN 17J based on  $2.3 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13 \text{ TeV}$ . 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  $4Ws$ ), along with jets, and no excess over the SM expectation is found.

<sup>4</sup> AAD 15BY based on  $20.3 \text{ fb}^{-1}$  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.

<sup>5</sup> AAD 15Z based on  $20.3 \text{ fb}^{-1}$  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  $b\bar{b}W^+W^-W^+W^-$ .

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

<sup>1</sup> AAD 16AV based on  $20.3 \text{ fb}^{-1}$  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.

<sup>2</sup>Based on  $5.4 \text{ fb}^{-1}$  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  $p\bar{p} \rightarrow t'q \rightarrow (Wd)q$ , 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.

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## 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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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.)
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