

# $t'$ ( $4^{th}$ 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
>1530	95	1 AAD	24BP ATLS	$B(t' \rightarrow Wq) = 1$ ( $q=d,s$ )
>1700	95	2 AAD	24N ATLS	$B(t' \rightarrow Wb) = 1$
>1360	95	3 AAD	24N ATLS	$B(t' \rightarrow Wb : Ht : Zt) = 1/2 : 1/4 : 1/4$
>1600	95	4 AAD	23AV ATLS	$B(t' \rightarrow Zt) = 1$
> 960	95	5 TUMASYAN	23AX CMS	EW production, $t' \rightarrow Ht$ ( $H \rightarrow \gamma\gamma$ )
>1500	95	6 TUMASYAN	23V CMS	$B(t' \rightarrow ht) = 1$
> 980	95	7 AABOUD	18CE ATLS	$\geq 2\ell + \cancel{E}_T + \geq 1bj$
>1030	95	8,9 AABOUD	18CP ATLS	2,3 $\ell$ , singlet model
>1210	95	8,10 AABOUD	18CP ATLS	2,3 $\ell$ , doublet model
>1310	95	11,12 AABOUD	18CR ATLS	singlet $t'$ . ATLAS combination
>1370	95	11,13 AABOUD	18CR ATLS	$t'$ in a weak isospin doublet ( $t', b'$ ). ATLAS combination.
>1140	95	14 SIRUNYAN	18BM CMS	$Wb, Zt, ht$ modes
> 845	95	15 SIRUNYAN	18Q CMS	$B(t' \rightarrow Wq) = 1$ ( $q=d,s$ )
> 860	95	16 SIRUNYAN	17AU CMS	
> 735	95	17 AAD	14AZ ATLS	$B(b' \rightarrow Wt) = 1$
> 350	95	18 AAD	12BC ATLS	$B(t' \rightarrow Wq)=1$ ( $q=d,s,b$ )
> 420	95	19 AAD	12C ATLS	$t' \rightarrow Xt$ ( $m_X < 140$ GeV)
> 685	95	20 CHATRCHYAN	12BH CMS	$m_{b'} = m_{t'}$
> 557	95	21 CHATRCHYAN	12P CMS	$t'\bar{t}' \rightarrow W^+bW^-\bar{b} \rightarrow b\ell^+\nu b\ell^-\bar{\nu}$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>1470	95	22 AAD	23AG ATLS	$B(t' \rightarrow Zt) = 1$
>1280	95	23 SIRUNYAN	19AQ CMS	$B(t' \rightarrow Zt) = 1$
>1370	95	24 SIRUNYAN	19BWCMS	$B(t' \rightarrow ht) = 1$
>1010	95	25 AABOUD	18CL ATLS	$B(t' \rightarrow ht) = 1$
>1295	95	26 SIRUNYAN	18W CMS	$B(t' \rightarrow Wb) = 1$
>1160	95	27 AABOUD	17L ATLS	$B(t' \rightarrow Zt) = 1$
> 770	95	28 AAD	15AR ATLS	$B(t' \rightarrow Wb) = 1$
> 590	95	29 AAD	15BY ATLS	$Wb, Zt, ht$ modes
> 745	95	30 KHACHATRY...	15AI CMS	$B(t' \rightarrow ht) = 1$
> 700	95	31 CHATRCHYAN	14A CMS	$B(t' \rightarrow Wb) = 1$
> 706	95	31 CHATRCHYAN	14A CMS	$B(t' \rightarrow Zt) = 1$
> 782	95	31 CHATRCHYAN	14A CMS	$B(t' \rightarrow ht) = 1$
> 656	95	32 AAD	13F ATLS	$B(t' \rightarrow Wb) = 1$
> 625	95	33 CHATRCHYAN	13I CMS	$B(t' \rightarrow Zt) = 1$
> 404	95	34 AAD	12AR ATLS	$B(t' \rightarrow Wb) = 1$
> 570	95	35 CHATRCHYAN	12BC CMS	$t'\bar{t}' \rightarrow W^+bW^-\bar{b}$
> 400	95	36 AALTONEN	11AH CDF	$t' \rightarrow Xt$ ( $m_X < 70$ GeV)

> 358	95	37	AALTONEN	11AL CDF	$t' \rightarrow Wb$
> 340	95	37	AALTONEN	11AL CDF	$t' \rightarrow Wq$ ( $q=d,s,b$ )
> 360	95	38	AALTONEN	11O CDF	$t' \rightarrow Xt$ ( $m_X < 100$ GeV)
> 285	95	39	ABAZOV	11Q D0	$t' \rightarrow Wq$ ( $q=d,s,b$ )
> 256	95	40,41	AALTONEN	08H CDF	$t' \rightarrow Wq$

- <sup>1</sup> AAD 24BP based on  $140 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13$  TeV. Limit on pair-production of heavy vectorlike quarks where each decays into a  $W$  boson and a light quark. Used events with  $\ell + \cancel{E}_T + \text{multiple jets} + 1$  boosted- $W$ -jet.
- <sup>2</sup> AAD 24N based on  $140 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13$  TeV. Pair production of vector-like  $t'$  is searched for in the lepton+jets mode. The limit is for  $t'$  in a weak isospin doublet. The data are consistent with the SM background predictions and limits are obtained for different branching ratios. The same limits also apply to  $t'$  of charge  $-4/3$ .
- <sup>3</sup> AAD 24N based on  $140 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13$  TeV. Pair production of vector-like  $t'$  is searched for in the lepton+jets mode. The limit is for a singlet model. The data are consistent with the SM background predictions and limits are obtained for different branching ratios.
- <sup>4</sup> AAD 23AV based on  $139 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13$  TeV. Pair production of vector-like  $t'$  is searched for in the mode  $\ell^\pm \ell^\mp + \geq 2j$  ( $\geq 1b$ -tagged)  $+ \cancel{E}_T$  or with  $3\ell$ . The data are consistent with the SM background predictions and limits are obtained for different branching ratios.
- <sup>5</sup> TUMASYAN 23AX based on  $138 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13$  TeV. A vector-like  $t'$  is searched for in the  $t + H$  ( $H \rightarrow \gamma\gamma$ ) decay channel. EW production via a coupling to third-generation quarks of  $\kappa_T = 0.25$  is assumed. The branching fractions are assumed to be 50, 25, and 25%, respectively, for  $bW$ ,  $tZ$ , and  $tH$  decays.
- <sup>6</sup> TUMASYAN 23V based on  $138 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13$  TeV. Pair production of vector-like  $t'$  is searched for in the single-lepton, same-sign charge dilepton and multi-lepton channels. The data are consistent with the SM background predictions and limits are obtained for different branching ratios. Masses below 1.48 TeV are excluded for all decays to third generation quarks.
- <sup>7</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.
- <sup>8</sup> AABOUD 18CP based on  $36.1 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13$  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  $m_{t'} > 1340$  GeV.
- <sup>9</sup> The limit is for the singlet model, assuming that the branching ratios into  $Zt$ ,  $Wb$ , and  $Ht$  add up to one.
- <sup>10</sup> The limit is for the doublet model, assuming that the branching ratios into  $Zt$ ,  $Wb$ , and  $Ht$  add up to one.
- <sup>11</sup> AABOUD 18CR based on  $36.1 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13$  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  $m_{t'} > 1.31$  TeV, assuming that the branching ratios into  $Zt$ ,  $Wb$  and  $ht$  add up to one.
- <sup>12</sup> The limit is for the singlet  $t'$ .
- <sup>13</sup> The limit is for  $t'$  in a weak isospin doublet ( $t', b'$ ) and  $|V_{t'b}| \ll |V_{tb'}|$ .
- <sup>14</sup> SIRUNYAN 18BM based on  $35.9 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13$  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.
- <sup>15</sup> SIRUNYAN 18Q based on  $19.7 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 8$  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.

- <sup>16</sup> 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.
- <sup>17</sup> 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  $685\text{ GeV}$ .
- <sup>18</sup> 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.
- <sup>19</sup> Based on  $1.04\text{ fb}^{-1}$  of data in  $pp$  collisions at  $7\text{ TeV}$ . 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  $B(t' \rightarrow Wt) = 1$ .
- <sup>20</sup> 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  $\pm 20\text{ GeV}/c^2$ .
- <sup>21</sup> 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  $B(t' \rightarrow Wb) = 1$ .
- <sup>22</sup> AAD 23AG based on  $139\text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13\text{ TeV}$ . Pair production of vector-like top or  $b_s$  is searched for in the mode  $1\ell + \geq 4j$  ( $\geq 1b$ -tagged) +  $\cancel{E}_T$ . The data are consistent with the SM background predictions and limits are obtained for different branching ratios. Masses below  $1.59\text{ TeV}$  are excluded assuming a mass-degenerate vector-like doublet ( $t', b'$ ) model.
- <sup>23</sup> SIRUNYAN 19AQ based on  $35.9\text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13\text{ TeV}$ . 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  $t'$ .
- <sup>24</sup> SIRUNYAN 19BW 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  $t'$  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.
- <sup>25</sup> 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.
- <sup>26</sup> 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%. Generally the measurement sets upper limits on the product 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.
- <sup>27</sup> 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  $0.87$  ( $1.05$ )  $\text{TeV}$  is obtained for the singlet (doublet) model with other possible decay modes.

- <sup>28</sup> 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.
- <sup>29</sup> 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.
- <sup>30</sup> 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.
- <sup>31</sup> 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.
- <sup>32</sup> 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.
- <sup>33</sup> 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.
- <sup>34</sup> 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).
- <sup>35</sup> 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  $B(t' \rightarrow Wb) = 1$ .
- <sup>36</sup> 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  $B(t' \rightarrow Xt) = 1$ .
- <sup>37</sup> 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  $m_{t'}$ .
- <sup>38</sup> 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  $B(t' \rightarrow Xt) = 1$ .
- <sup>39</sup> 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>40</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>41</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
<b>&gt;1460</b>	95	<sup>1</sup> AAD	23AG ATLS	$t'(5/3) \rightarrow tW^+$
>1330	95	<sup>2</sup> SIRUNYAN	19T CMS	$t'_R(5/3) \rightarrow tW^+$
>1300	95	<sup>2</sup> SIRUNYAN	19T CMS	$t'_L(5/3) \rightarrow tW^+$
>1190	95	<sup>3</sup> AABOUD	18CE ATLS	$\geq 2\ell + \cancel{E}_T + \geq 1bj$
>1020	95	<sup>4</sup> SIRUNYAN	17J CMS	$t'_R(5/3) \rightarrow tW^+$
> 990	95	<sup>4</sup> SIRUNYAN	17J CMS	$t'_L(5/3) \rightarrow tW^+$
> 750	95	<sup>5</sup> AAD	15BY ATLS	$t'(5/3) \rightarrow tW^+$
> 840	95	<sup>6</sup> AAD	15Z ATLS	$t'(5/3) \rightarrow tW^+$
> 800	95	<sup>7</sup> CHATRCHYAN	14T CMS	$t'(5/3) \rightarrow tW^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>1350	95	<sup>8</sup> AABOUD	18AW ATLS	$t'(5/3) \rightarrow tW^+$

<sup>1</sup> AAD 23AG based on  $139 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13 \text{ TeV}$ . Pair production of vector-like top or  $b'$  is searched for in the mode  $1\ell + \geq 4j (\geq 1b\text{-tagged}) + \cancel{E}_T$ . The data are consistent with the SM background predictions and limits are obtained for different branching ratios.

<sup>2</sup> SIRUNYAN 19T based on  $35.9 \text{ fb}^{-1}$  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>3</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>4</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>5</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  $\geq 2\ell + \cancel{E}_T + \geq 2j (\geq 1b)$  and including a same-sign lepton pair.

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

<sup>7</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  $b\bar{b}W^+W^-W^+W^-$ .

<sup>8</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  $\ell + \cancel{E}_T + \text{jets} (\geq 1b\text{-tagged})$ .

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

VALUE (GeV)	CL%	EVTs	DOCUMENT ID	TECN	COMMENT
<b>&gt;2100</b>	95		<sup>1</sup> AAD	25I ATLS	$qg \rightarrow q't'b, t' \rightarrow Ht$ or $t' \rightarrow Zt$
<b>&gt;1800</b>	95		<sup>2</sup> AAD	24AK ATLS	$qg \rightarrow q't'b, B(t' \rightarrow Wb) = 0.5$
> 950	95		<sup>3</sup> AAD	16AV ATLS	$qg \rightarrow q't'b, B(t' \rightarrow Wb) = 0.5$

> 403	95		<sup>4</sup> ABAZOV	11F D0	$qd \rightarrow q't' \rightarrow q'(Wd)$ $\tilde{\kappa}_{d t'}=1, B(t' \rightarrow Wd)=1$
> 551	95		<sup>4</sup> ABAZOV	11F D0	$qu \rightarrow qt' \rightarrow q(Zu)$ $\tilde{\kappa}_{u t'}=\sqrt{2}, B(t' \rightarrow Zu)=1$

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

>1850	95	ATLS	<sup>5</sup> AAD	25BH ATLS	$t' \rightarrow Wb$
			<sup>6</sup> AAD	25S ATLS	$qg \rightarrow q't'b, t' \rightarrow Wb$
			<sup>7</sup> AAD	24V ATLS	$t' \rightarrow Zt$
			<sup>8</sup> HAYRAPETYAN	24AR CMS	$t' \rightarrow Zt, Ht$
			<sup>9</sup> AAD	22G ATLS	$t' \rightarrow Ht, \text{singlet } t'$
			<sup>10</sup> TUMASYAN	22X CMS	$t' \rightarrow Zt$

<sup>1</sup> AAD 25I based on  $139 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13 \text{ TeV}$ . No significant excess over SM expectation is found in the search for a vector-like  $t'$  decaying into  $tZ$  or  $tH$  in hadronic and semileptonic final states. The highest mass bound is obtained for the SU(2) singlet  $t'$  with electroweak coupling,  $\kappa$ , of 0.5, and  $\Gamma_{t'}/m_{t'} = 0.5$ .

<sup>2</sup> AAD 24AK based on  $139 \text{ fb}^{-1}$  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 events with a reconstructed boosted top quark and a large missing transverse momentum.  $B(t' \rightarrow Wb) + B(t' \rightarrow tZ) + B(t' \rightarrow tH) = 1$  and  $B(t' \rightarrow tZ) = B(t' \rightarrow tH) = 1/4$  are assumed.

<sup>3</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>4</sup> ABAZOV 11F based on  $5.4 \text{ fb}^{-1}$  of data in  $ppbar$  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.

<sup>5</sup> AAD 25BH based on  $140 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13 \text{ TeV}$ . No significant excess over SM expectation is found in the search for a vector-like  $t'$  decaying into  $bW$  in semileptonic final states. Upper limits are set on the cross section times branching ratio and on the coupling of  $t'$  to the SM sector. Also similar limits are set for  $t'$  with charge  $-4/3$ .

<sup>6</sup> AAD 25S based on  $139 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13 \text{ TeV}$ . No significant excess over SM expectation is found in the search for a vector-like  $t'$  decaying into  $bW$  in the fully hadronic final states using a highly boosted  $W$  jet. The mass bound is obtained for the global coupling parameter  $\kappa = 0.7$ . The corresponding mass bound for a vector-like quark  $Y$  with electric charge  $-4/3$  is 2.35 TeV.

<sup>7</sup> AAD 24V based on  $139 \text{ fb}^{-1}$  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, which consists of a pair of opposite-sign leptons from a  $Z$ -boson,  $b$ -tagged jets and forward jets. The mass range above 1 TeV is targeted and 95% CL limits on the mass and coupling strength of  $t'$  are set, in the singlet and doublet scenarios.

<sup>8</sup> HAYRAPETYAN 24AR based on  $138 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 13 \text{ TeV}$ . No deviation from the SM expectation is found in the search for a vector-like  $t'$  in the all-hadronic final state where the  $t'$  is reconstructed as five jets, with three of them being  $b$ -jets. 95% CL upper limits are set on the product of the  $t'$ -production cross section and the branching ratio  $B(t' \rightarrow tZ)$  or  $B(t' \rightarrow tH)$ .

- <sup>9</sup> AAD 22G based on  $139 \text{ fb}^{-1}$  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  $t'$ .
- <sup>10</sup> TUMASYAN 22X based on  $137 \text{ fb}^{-1}$  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. • • •

<sup>1</sup> SIRUNYAN 19AI CMS  $tW \rightarrow t'(5/3) \rightarrow tW$

<sup>1</sup> SIRUNYAN 19AI based on  $35.9 \text{ fb}^{-1}$  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.

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