# $t'$ ($4^{th}$ 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* |
|---|---|---|---|---|---|
| **>1600** | 95 | [1] AAD | 23AV | ATLS | $B(t' \to Zt) = 1$ |
| > 960 | 95 | [2] TUMASYAN | 23AX | CMS | EW production, $t' \to Ht$ ($H \to \gamma\gamma$) |
| **>1500** | 95 | [3] TUMASYAN | 23V | CMS | $B(t' \to ht) = 1$ |
| > 980 | 95 | [4] AABOUD | 18CE | ATLS | $\geq 2\ell + \not{E}_T + \geq 1$bj |
| >1030 | 95 | [5,6] AABOUD | 18CP | ATLS | 2,3$\ell$, singlet model |
| >1210 | 95 | [5,7] AABOUD | 18CP | ATLS | 2,3$\ell$, 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 | 18BM | CMS | $Wb$, $Zt$, $ht$ modes |
| > 845 | 95 | [12] SIRUNYAN | 18Q | CMS | $B(t' \to Wq) = 1$ ($q$=$d$,$s$) |
| **>1295** | 95 | [13] SIRUNYAN | 18W | CMS | $B(t' \to Wb) = 1$ |
| > 860 | 95 | [14] SIRUNYAN | 17AU | CMS | |
| > 735 | 95 | [15] AAD | 14AZ | ATLS | $B(b' \to Wt) = 1$ |
| > 350 | 95 | [16] AAD | 12BC | ATLS | $B(t' \to Wq)$=1 ($q$=$d$,$s$,$b$) |
| > 420 | 95 | [17] AAD | 12C | ATLS | $t' \to Xt$ ($m_X < 140$ GeV) |
| > 685 | 95 | [18] CHATRCHYAN | 12BH | CMS | $m_{b'} = m_{t'}$ |
| > 557 | 95 | [19] CHATRCHYAN | 12P | CMS | $t'\overline{t}' \to W^+ bW^- \overline{b} \to b\ell^+ \nu \overline{b}\ell^- \overline{\nu}$ |

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

| | | | | | |
|---|---|---|---|---|---|
| >1470 | 95 | [20] AAD | 23AG | ATLS | $B(t' \to Zt) = 1$ |
| >1280 | 95 | [21] SIRUNYAN | 19AQ | CMS | $B(t' \to Zt) = 1$ |
| >1370 | 95 | [22] SIRUNYAN | 19BW | CMS | $B(t' \to ht) = 1$ |
| >1010 | 95 | [23] AABOUD | 18CL | ATLS | $B(t' \to ht) = 1$ |
| >1160 | 95 | [24] AABOUD | 17L | ATLS | $B(t' \to Zt) = 1$ |
| > 770 | 95 | [25] AAD | 15AR | ATLS | $B(t' \to Wb) = 1$ |
| > 590 | 95 | [26] AAD | 15BY | ATLS | $Wb$, $Zt$, $ht$ modes |
| > 745 | 95 | [27] KHACHATRY... | 15AI | CMS | $B(t' \to ht) = 1$ |
| > 700 | 95 | [28] CHATRCHYAN | 14A | CMS | $B(t' \to Wb) = 1$ |
| > 706 | 95 | [28] CHATRCHYAN | 14A | CMS | $B(t' \to Zt) = 1$ |
| > 782 | 95 | [28] CHATRCHYAN | 14A | CMS | $B(t' \to ht) = 1$ |
| > 656 | 95 | [29] AAD | 13F | ATLS | $B(t' \to Wb) = 1$ |
| > 625 | 95 | [30] CHATRCHYAN | 13I | CMS | $B(t' \to Zt) = 1$ |
| > 404 | 95 | [31] AAD | 12AR | ATLS | $B(t' \to Wb) = 1$ |
| > 570 | 95 | [32] CHATRCHYAN | 12BC | CMS | $t'\overline{t}' \to W^+ bW^- \overline{b}$ |
| > 400 | 95 | [33] AALTONEN | 11AH | CDF | $t' \to Xt$ ($m_X < 70$ GeV) |
| > 358 | 95 | [34] AALTONEN | 11AL | CDF | $t' \to Wb$ |
| > 340 | 95 | [34] AALTONEN | 11AL | CDF | $t' \to Wq$ ($q$=$d$,$s$,$b$) |
| > 360 | 95 | [35] AALTONEN | 11O | CDF | $t' \to Xt$ ($m_X < 100$ GeV) |
| > 285 | 95 | [36] ABAZOV | 11Q | D0 | $t' \to Wq$ ($q$=$d$,$s$,$b$) |
| > 256 | 95 | [37,38] AALTONEN | 08H | CDF | $t' \to Wq$ |

[1] AAD 23AV based on 139 fb$^{-1}$ of $pp$ data at $\sqrt{s} = 13$ TeV. Pair production of vector-like $t'$ is searched for in the mode $\ell^{\pm}\ell^{\mp} + \geq 2$j ( $\geq$ 1b-tagged) + $\not{E}_T$ or with $3\ell$. The data are consistent with the SM background predictions and limits are obtained for different branching ratios.

[2] TUMASYAN 23AX based on 138 fb$^{-1}$ of $pp$ data at $\sqrt{s} = 13$ TeV. A vector-like $t'$ is seached 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.

[3] TUMASYAN 23V based on 138 fb$^{-1}$ of $pp$ data at $\sqrt{s} = 13$ TeV. Pair production of vector-like $t'$ is seached 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.

[4] 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 a singlet model, assuming the branching ratios of $t'$ into $Zt$, $Wb$ and $Ht$ as predicted by the model.

[5] AABOUD 18CP based on 36.1 fb$^{-1}$ of $pp$ data at $\sqrt{s} = 13$ TeV. Pair and single production of vector-like $t'$ are seached 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.

[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 $\sqrt{s} = 13$ 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.

[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 $\sqrt{s} = 13$ 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 $\sqrt{s} = 8$ 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 $\sqrt{s} = 13$ 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 100product of the production cross section and branching faction to $Wb$ for any new pair-produced heavy quark decaying to this channel as a narrow resonance.

[14] SIRUNYAN 17AU based on 2.3-2.6 fb$^{-1}$ of $pp$ data at $\sqrt{s} = 13$ 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 GeV. Other limits are also given in the paper.

[15] 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($b' \rightarrow Wt$) = 1 an electroweak singlet with B($b' \rightarrow Wt$) $\sim$ 0.45 is assumed, the limit reduces to 685 GeV.

[16] 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 $\geq 2$ jets.

[17] 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.

[18] 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$.

[19] 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.

[20] AAD 23AG based on 139 fb$^{-1}$ of $pp$ data at $\sqrt{s} = 13$ TeV. Pair production of vector-like top or bs is searched for in the mode $1\ell + \geq 4$j($\geq 1$b-tagged) + $\not{E}_T$. The data are consistent with the SM background predictions and limits are obtained for different branching ratios. Masses below 1.59 TeV are excluded assuming a mass-degenerate vector-like doublet ($t'$,$b'$) model.

[21] SIRUNYAN 19AQ based on 35.9 fb$^{-1}$ of $pp$ data at $\sqrt{s} = 13$ TeV. Pair production of vector-like $t'$ is seached for with one $t'$ decaying into $Z\,t$ and the other $t'$ decaying into $W\,b$, $Z\,t$, $h\,t$. 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 $t'$.

[22] SIRUNYAN 19BW based on 35.9 fb$^{-1}$ of $pp$ data at $\sqrt{s} = 13$ TeV. The limit is for the pair-produced vector-like $t'$ using all-hadronic final state. The analysis is made for the $W\,b$, $Z\,t$, $h\,t$ modes and mass limits are obtained for a variety of branching ratios.

[23] AABOUD 18CL based on 36.1 fb$^{-1}$ of $pp$ data at $\sqrt{s} = 13$ TeV. The limit is for the pair-produced vector-like $t'$ using all-hadronic final state. The analysis is also made for the $W\,b$, $Z\,t$, $h\,t$ modes and mass limits are obtained for a variety of branching ratios.

[24] AABOUD 17L based on 36.1 fb$^{-1}$ of $pp$ data at $\sqrt{s} = 13$ TeV. No signal is found in the search for heavy quark pair production that decay into $Z\,t$ followed by $Z \rightarrow \nu\nu$ in the events with one lepton, large $\not{E}_T$, 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.

[25] 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($t' \rightarrow H\,t$) vs. B($t' \rightarrow W\,b$) from a combination of $t'\overline{t}' \rightarrow W\,b + X$ and $t'\overline{t}' \rightarrow H\,t + X$ searches. Any branching ratio scenario is excluded for mass below 715 GeV.

[26] 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 $\geq 2\ell + \not{E}_T + \geq 2$j ($\geq 1$ $b$) and including a same-sign lepton pair.

[27] 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.

[28] 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.

[29] 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($t' \to W b$) $> 0.63$ is excluded at 95% CL.

[30] 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.

[31] 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 ( $\geq 1$ $b$-tag).

[32] 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($t' \to W b$) = 1.

[33] 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($t' \to X t$) = 1.

[34] 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 $m_{t'}$.

[35] 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($t' \to X t$) = 1.

[36] 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 $m_{t'}$.

[37] 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.

[38] HUANG 08 reexamined the $t'$ mass lower bound of 256 GeV obtained in AALTONEN 08H that assumes B($b' \to q Z$) = 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 |
|---|---|---|---|---|---|
| **>1460** | 95 | [1] AAD | 23AG | ATLS | $t'(5/3) \to t W^+$ |
| >1330 | 95 | [2] SIRUNYAN | 19T | CMS | $t'_R(5/3) \to t W^+$ |
| >1300 | 95 | [2] SIRUNYAN | 19T | CMS | $t'_L(5/3) \to t W^+$ |
| >1190 | 95 | [3] AABOUD | 18CE | ATLS | $\geq 2\ell + \not{E}_T + \geq 1b$j |
| >1020 | 95 | [4] SIRUNYAN | 17J | CMS | $t'_R(5/3) \to t W^+$ |
| > 990 | 95 | [4] SIRUNYAN | 17J | CMS | $t'_L(5/3) \to t W^+$ |
| > 750 | 95 | [5] AAD | 15BY | ATLS | $t'(5/3) \to t W^+$ |
| > 840 | 95 | [6] AAD | 15Z | ATLS | $t'(5/3) \to t W^+$ |
| > 800 | 95 | [7] CHATRCHYAN | 14T | CMS | $t'(5/3) \to t W^+$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >1350 | 95 | [8] AABOUD | 18AW | ATLS | $t'(5/3) \to t W^+$ |

[1] AAD 23AG based on 139 fb$^{-1}$ of $pp$ data at $\sqrt{s} = 13$ TeV. Pair production of vector-like top or $b'$ is seached for in the mode $1\ell + \geq 4$j( $\geq 1$b-tagged) + $\not{E}_T$. The data are consistent with the SM background predictions and limits are obtained for different branching ratios.

[2] 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 4$W$s), along with jets, and no excess over the SM expectation is found.

[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 $t' t W$ 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 4$W$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 $W t$ is equal to one. Used events containing $\geq 2\ell + \not{E}_T + \geq 2$j ( $\geq 1$ $b$) 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 $\ell + \not{E}_T + \geq 6$j ( $\geq 1$ $b$) and at least one pair of jets from weak boson decay, sensitive to the final state $b\overline{b}W^+W^-W^+W^-$.

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

[8] 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 $W t$ is equal to one. Lepton-plus-jets final state is used, characterized by $\ell + \not{E}_T$ + jets ( $\geq 1$ $b$-tagged).

## $t'(2/3)$ 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 | $qg \to q' t' b$, B($t' \to W b$)=0.5 |
| **>403** | 95 | [2] ABAZOV | 11F | D0 | $qd \to q' t' \to q'(W d)$ $\widetilde{\kappa}_{d t'}$=1, B($t' \to W d$)=1 |
| **>551** | 95 | [2] ABAZOV | 11F | D0 | $qu \to q t' \to q(Z u)$ $\widetilde{\kappa}_{u t'}$=$\sqrt{2}$, B($t' \to Z u$)=1 |

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

| | | | |
|---|---|---|---|
| [3] AAD | 22G | ATLS | $t' \to H t$, singlet $t'$ |
| [4] TUMASYAN | 22X | CMS | $t' \to Z t$ |

[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] ABAZOV 11F based on 5.4 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 $p\overline{p} \to t' q \to (W d)q$, 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.

[3] AAD 22G based on 139 fb$^{-1}$ of $pp$ data at $\sqrt{s} = 13$ 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 $\sqrt{s} = 13$ 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 $p\overline{p}$ and $pp$ collisions

| *VALUE* (GeV) | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|

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

[1] SIRUNYAN 19AI CMS $tW \rightarrow t'(5/3) \rightarrow tW$

[1] SIRUNYAN 19AI based on 35.9 fb$^{-1}$ of $pp$ data at $\sqrt{s} = 13$ 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 | 16AV | EPJ C76 442 | G. Aad *et al.* | (ATLAS Collab.) |
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| AAD | 14AZ | JHEP 1411 104 | G. Aad *et al.* | (ATLAS Collab.) |
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| AALTONEN | 11AH | PRL 107 191803 | T. Aaltonen *et al.* | (CDF Collab.) |
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