

# $b'$ ( $4^{\text{th}}$ Generation) Quark, Searches for

## $b'(-1/3)$ -quark/hadron mass limits in $p\bar{p}$ and $pp$ collisions

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>620	95	1 AAD	15BY ATLS	$Wt, Zb, hb$ modes
>730	95	2 AAD	15BY ATLS	$B(b' \rightarrow Wt) = 1$
>810	95	3 AAD	15Z ATLS	
<b>&gt;755</b>	95	4 AAD	14AZ ATLS	
<b>&gt;675</b>	95	5 CHATRCHYAN13I	CMS	$B(b' \rightarrow Wt) = 1$
<b>&gt;190</b>	95	6 ABAZOV	08X D0	$c\tau = 200\text{mm}$
<b>&gt;190</b>	95	7 ACOSTA	03 CDF	quasi-stable $b'$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
<350, 580–635, >700	95	8 AAD	15AR ATLS	$B(b' \rightarrow Hb) = 1$
>690	95	9 AAD	15CN ATLS	$B(b' \rightarrow Wq) = 1$ ( $q=u$ )
>480	95	10 AAD	12AT ATLS	$B(b' \rightarrow Wt) = 1$
>400	95	11 AAD	12AU ATLS	$B(b' \rightarrow Zb) = 1$
>350	95	12 AAD	12BC ATLS	$B(b' \rightarrow Wq) = 1$ ( $q=u,c$ )
>450	95	13 AAD	12BE ATLS	$B(b' \rightarrow Wt) = 1$
>685	95	14 CHATRCHYAN12BH	CMS	$m_{t'} = m_{b'}$
>611	95	15 CHATRCHYAN12X	CMS	$B(b' \rightarrow Wt) = 1$
>372	95	16 AALTONEN	11J CDF	$b' \rightarrow Wt$
>361	95	17 CHATRCHYAN11L	CMS	Repl. by CHATRCHYAN12X
>338	95	18 AALTONEN	10H CDF	$b' \rightarrow Wt$
> 380–430	95	19 FLACCO	10 RVUE	$m_{b'} > m_{t'}$
>268	95	20,21 AALTONEN	07C CDF	$B(b' \rightarrow Zb) = 1$
>199	95	22 AFFOLDER	00 CDF	NC: $b' \rightarrow Zb$
>148	95	23 ABE	98N CDF	NC: $b' \rightarrow Zb + \text{vertex}$
> 96	95	24 ABACHI	97D D0	NC: $b' \rightarrow b\gamma$
>128	95	25 ABACHI	95F D0	$\ell\ell + \text{jets}, \ell + \text{jets}$
> 75	95	26 MUKHOPAD...	93 RVUE	NC: $b' \rightarrow b\ell\ell$
> 85	95	27 ABE	92 CDF	CC: $\ell\ell$
> 72	95	28 ABE	90B CDF	CC: $e + \mu$
> 54	95	29 AKESSON	90 UA2	CC: $e + \text{jets} + \cancel{E}_T$
> 43	95	30 ALBAJAR	90B UA1	CC: $\mu + \text{jets}$
> 34	95	31 ALBAJAR	88 UA1	CC: $e$ or $\mu + \text{jets}$

<sup>1</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  $b'$  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>2</sup> AAD 15BY based on  $20.3 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 8 \text{ TeV}$ . Limit on pair-produced chiral  $b'$ -quark. Used events containing  $\geq 2\ell + \cancel{E}_T + \geq 2j$  ( $\geq 1 b$ ) and including a same-sign lepton pair.

- <sup>3</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, primarily designed to select the signature  $b'\bar{b}' \rightarrow WWt\bar{t} \rightarrow WWWWb\bar{b}$ . This is a limit on pair-produced vector-like  $b'$ . The lower mass limit is 640 GeV for a vector-like singlet  $b'$ .
- <sup>4</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  $b'$  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.
- <sup>5</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>6</sup> Result is based on  $1.1 \text{ fb}^{-1}$  of data. No signal is found for the search of long-lived particles which decay into final states with two electrons or photons, and upper bound on the cross section times branching fraction is obtained for  $2 < c\tau < 7000 \text{ nm}$ ; see Fig. 3. 95% CL excluded region of  $b'$  lifetime and mass is shown in Fig. 4.
- <sup>7</sup> ACOSTA 03 looked for long-lived fourth generation quarks in the data sample of  $90 \text{ pb}^{-1}$  of  $\sqrt{s}=1.8 \text{ TeV } p\bar{p}$  collisions by using the muon-like penetration and anomalously high ionization energy loss signature. The corresponding lower mass bound for the charge  $(2/3)e$  quark ( $t'$ ) is 220 GeV. The  $t'$  bound is higher than the  $b'$  bound because  $t'$  is more likely to produce charged hadrons than  $b'$ . The 95% CL upper bounds for the production cross sections are given in their Fig. 3.
- <sup>8</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. 24 for mass limits in the plane of  $B(b' \rightarrow Wt)$  vs.  $B(b' \rightarrow Hb)$  from  $b'\bar{b}' \rightarrow Hb + X$  searches.
- <sup>9</sup> AAD 15CN based on  $20.3 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 8 \text{ TeV}$ . Limit on pair-production of chiral  $b'$ -quark. Used events with  $\ell + \cancel{E}_T + \geq 4j$  (non- $b$ -tagged). Limits on a heavy vector-like quark, which decays into  $Wq$ ,  $Zq$ ,  $hq$ , are presented in the plane  $B(Q \rightarrow Wq)$  vs.  $B(Q \rightarrow hq)$  in Fig. 12.
- <sup>10</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  $t$  quark in the events with a high  $p_T$  isolated lepton, large  $\cancel{E}_T$ , and at least 6 jets in which one, two or more dijets are from  $W$ .
- <sup>11</sup> Based on  $2.0 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 7 \text{ TeV}$ . No  $b' \rightarrow Zb$  invariant mass peak is found in the search of heavy quark pair production that decay into  $Z$  and a  $b$  quark in events with  $Z \rightarrow e^+e^-$  and at least one  $b$ -jet. The lower mass limit is 358 GeV for a vector-like singlet  $b'$  mixing solely with the third SM generation.
- <sup>12</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>13</sup> Based on  $1.04 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 7 \text{ TeV}$ . AAD 12BE looked for events with two isolated like-sign leptons and at least 2 jets, large  $\cancel{E}_T$  and  $H_T > 350 \text{ GeV}$ .
- <sup>14</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<sup>th</sup> generation quarks that decay to  $bW$  or  $tW$ . Absence of signal in events with one lepton, same-sign dileptons or tripleptons 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>15</sup> Based on  $4.9 \text{ fb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 7 \text{ TeV}$ . CHATRCHYAN 12X looked for events with tripleptons or same-sign dileptons and at least one  $b$  jet.
- <sup>16</sup> Based on  $4.8 \text{ fb}^{-1}$  of data in  $p\bar{p}$  collisions at 1.96 TeV. AALTONEN 11J looked for events with  $\ell + \cancel{E}_T + \geq 5j$  ( $\geq 1 b$  or  $c$ ). No signal is observed and the bound  $\sigma(b'\bar{b}') < 30 \text{ fb}$  for  $m_{b'} > 375 \text{ GeV}$  is found for  $B(b' \rightarrow Wt) = 1$ .

- 17 Based on  $34 \text{ pb}^{-1}$  of data in  $pp$  collisions at 7 TeV. CHATRCHYAN 11L looked for multi-jet events with trileptons or same-sign dileptons. No excess above the SM background excludes  $m_{b'}$  between 255 and 361 GeV at 95% CL for  $B(b' \rightarrow Wt) = 1$ .
- 18 Based on  $2.7 \text{ fb}^{-1}$  of data in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$ . AALTONEN 10H looked for pair production of heavy quarks which decay into  $tW^-$  or  $tW^+$ , in events with same sign dileptons ( $e$  or  $\mu$ ), several jets and large missing  $E_T$ . The result is obtained for  $b'$  which decays into  $tW^-$ . For the charge 5/3 quark ( $T_{5/3}$ ) which decays into  $tW^+$ ,  $m_{T_{5/3}} > 365 \text{ GeV}$  (95% CL) is found when it has the charge  $-1/3$  partner B of the same mass.
- 19 FLACCO 10 result is obtained from AALTONEN 10H result of  $m_{b'} > 338 \text{ GeV}$ , by relaxing the condition  $B(b' \rightarrow Wt) = 100\%$  when  $m_{b'} > m_{t'}$ .
- 20 Result is based on  $1.06 \text{ fb}^{-1}$  of data. No excess from the SM  $Z$ +jet events is found when  $Z$  decays into  $ee$  or  $\mu\mu$ . The  $m_{b'}$  bound is found by comparing the resulting upper bound on  $\sigma(b'\bar{b}') [1-(1-B(b' \rightarrow Zb))^2]$  and the LO estimate of the  $b'$  pair production cross section shown in Fig. 38 of the article.
- 21 HUANG 08 reexamined the  $b'$  mass lower bound of 268 GeV obtained in AALTONEN 07C that assumes  $B(b' \rightarrow Zb) = 1$ , which does not hold for  $m_{b'} > 255 \text{ GeV}$ . The lower mass bound is given in the plane of  $\sin^2(\theta_{tb'})$  and  $m_{b'}$ .
- 22 AFFOLDER 00 looked for  $b'$  that decays into  $b+Z$ . The signal searched for is  $bbZZ$  events where one  $Z$  decays into  $e^+e^-$  or  $\mu^+\mu^-$  and the other  $Z$  decays hadronically. The bound assumes  $B(b' \rightarrow Zb) = 100\%$ . Between 100 GeV and 199 GeV, the 95%CL upper bound on  $\sigma(b' \rightarrow \bar{b}') \times B^2(b' \rightarrow Zb)$  is also given (see their Fig. 2).
- 23 ABE 98N looked for  $Z \rightarrow e^+e^-$  decays with displaced vertices. Quoted limit assumes  $B(b' \rightarrow Zb) = 1$  and  $c\tau_{b'} = 1 \text{ cm}$ . The limit is lower than  $m_Z + m_b$  ( $\sim 96 \text{ GeV}$ ) if  $c\tau > 22 \text{ cm}$  or  $c\tau < 0.009 \text{ cm}$ . See their Fig. 4.
- 24 ABACHI 97D searched for  $b'$  that decays mainly via FCNC. They obtained 95%CL upper bounds on  $B(b'\bar{b}' \rightarrow \gamma + 3 \text{ jets})$  and  $B(b'\bar{b}' \rightarrow 2\gamma + 2 \text{ jets})$ , which can be interpreted as the lower mass bound  $m_{b'} > m_Z + m_b$ .
- 25 ABACHI 95F bound on the top-quark also applies to  $b'$  and  $t'$  quarks that decay predominantly into  $W$ . See FROGGATT 97.
- 26 MUKHOPADHYAYA 93 analyze CDF dilepton data of ABE 92G in terms of a new quark decaying via flavor-changing neutral current. The above limit assumes  $B(b' \rightarrow b\ell^+\ell^-) = 1\%$ . For an exotic quark decaying only via virtual  $Z$  [ $B(b\ell^+\ell^-) = 3\%$ ], the limit is 85 GeV.
- 27 ABE 92 dilepton analysis limit of  $>85 \text{ GeV}$  at CL=95% also applies to  $b'$  quarks, as discussed in ABE 90B.
- 28 ABE 90B exclude the region 28–72 GeV.
- 29 AKESSON 90 searched for events having an electron with  $p_T > 12 \text{ GeV}$ , missing momentum  $> 15 \text{ GeV}$ , and a jet with  $E_T > 10 \text{ GeV}$ ,  $|\eta| < 2.2$ , and excluded  $m_{b'}$  between 30 and 69 GeV.
- 30 For the reduction of the limit due to non-charged-current decay modes, see Fig. 19 of ALBAJAR 90B.
- 31 ALBAJAR 88 study events at  $E_{\text{cm}} = 546$  and 630 GeV with a muon or isolated electron, accompanied by one or more jets and find agreement with Monte Carlo predictions for the production of charm and bottom, without the need for a new quark. The lower mass limit is obtained by using a conservative estimate for the  $b'\bar{b}'$  production cross section and by assuming that it cannot be produced in  $W$  decays. The value quoted here is revised using the full  $O(\alpha_s^3)$  cross section of ALTARELLI 88.

### $b'(-1/3)$ mass limits from single production in $p\bar{p}$ and $pp$ collisions

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>1390	95	<sup>1</sup> KHACHATRY...16I	CMS	$gb \rightarrow b' \rightarrow tW$ , $B(b' \rightarrow tW)=1$
>1430	95	<sup>2</sup> KHACHATRY...16I	CMS	$gb \rightarrow b' \rightarrow tW$ , $B(b' \rightarrow tW)=1$
>1530	95	<sup>3</sup> KHACHATRY...16I	CMS	$gb \rightarrow b' \rightarrow tW$ , $B(b' \rightarrow tW)=1$
> 693	95	<sup>4</sup> ABAZOV 11F	D0	$qu \rightarrow q' b' \rightarrow q'(Wu)$ $\tilde{\kappa}_{ub'}=1$ , $B(b' \rightarrow Wu)=1$
> 430	95	<sup>4</sup> ABAZOV 11F	D0	$qd \rightarrow q b' \rightarrow q(Zd)$ $\tilde{\kappa}_{db'}=\sqrt{2}$ , $B(b' \rightarrow Zd)=1$

<sup>1</sup> Based on  $19.7 \text{ fb}^{-1}$  of data in  $pp$  collisions at 8 TeV. Limit on left-handed  $b'$  assuming 100% decay to  $tW$  and using all-hadronic, lepton + jets, and dilepton final states.

<sup>2</sup> Based on  $19.7 \text{ fb}^{-1}$  of data in  $pp$  collisions at 8 TeV. Limit on right-handed  $b'$  assuming 100% decay to  $tW$  and using all-hadronic, lepton + jets, and dilepton final states.

<sup>3</sup> Based on  $19.7 \text{ fb}^{-1}$  of data in  $pp$  collisions at 8 TeV. Limit on vector-like  $b'$  assuming 100% decay to  $tW$  and using all-hadronic, lepton+jets, and dilepton final states.

<sup>4</sup> Based on  $5.4 \text{ fb}^{-1}$  of data in  $p\bar{p}$  collisions at 1.96 TeV. ABAZOV 11F looked for single production of  $b'$  via the  $W$  or  $Z$  coupling to the first generation up or down quarks, respectively. Model independent cross section limits for the single production processes  $p\bar{p} \rightarrow b'q \rightarrow Wuq$ , and  $p\bar{p} \rightarrow b'q \rightarrow Zdq$  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.

### MASS LIMITS for $b'$ (4<sup>th</sup> Generation) Quark or Hadron in $e^+e^-$ Collisions

Search for hadrons containing a fourth-generation  $-1/3$  quark denoted  $b'$ .

The last column specifies the assumption for the decay mode ( $CC$  denotes the conventional charged-current decay) and the event signature which is looked for.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>46.0	95	<sup>1</sup> DECAMP	90F	ALEP any decay
• • •		We do not use the following data for averages, fits, limits, etc. • • •		
none 96–103	95	<sup>2</sup> ABDALLAH	07	DLPH $b' \rightarrow bZ, cW$
		<sup>3</sup> ADRIANI	93G	L3 Quarkonium
>44.7	95	ADRIANI	93M	L3 $\Gamma(Z)$
>45	95	ABREU	91F	DLPH $\Gamma(Z)$
none 19.4–28.2	95	ABE	90D	VNS Any decay; event shape
>45.0	95	ABREU	90D	DLPH $B(CC) = 1$ ; event shape
>44.5	95	<sup>4</sup> ABREU	90D	DLPH $b' \rightarrow cH^-, H^- \rightarrow \bar{c}s, \tau^- \nu$
>40.5	95	<sup>5</sup> ABREU	90D	DLPH $\Gamma(Z \rightarrow \text{hadrons})$
>28.3	95	ADACHI	90	TOPZ $B(\text{FCNC})=100\%$ ; isol. $\gamma$ or 4 jets
>41.4	95	<sup>6</sup> AKRAWY	90B	OPAL Any decay; acoplanarity
>45.2	95	<sup>6</sup> AKRAWY	90B	OPAL $B(CC) = 1$ ; acoplanarity
>46	95	<sup>7</sup> AKRAWY	90J	OPAL $b' \rightarrow \gamma + \text{any}$
>27.5	95	<sup>8</sup> ABE	89E	VNS $B(CC) = 1$ ; $\mu, e$

none 11.4–27.3	95	<sup>9</sup> ABE	89G	VNS	$B(b' \rightarrow b\gamma) > 10\%$ ; isolated $\gamma$
>44.7	95	<sup>10</sup> ABRAMS	89C	MRK2	$B(CC) = 100\%$ ; isol. track
>42.7	95	<sup>10</sup> ABRAMS	89C	MRK2	$B(bg) = 100\%$ ; event shape
>42.0	95	<sup>10</sup> ABRAMS	89C	MRK2	Any decay; event shape
>28.4	95	<sup>11,12</sup> ADACHI	89C	TOPZ	$B(CC) = 1$ ; $\mu$
>28.8	95	<sup>13</sup> ENO	89	AMY	$B(CC) \gtrsim 90\%$ ; $\mu, e$
>27.2	95	<sup>13,14</sup> ENO	89	AMY	any decay; event shape
>29.0	95	<sup>13</sup> ENO	89	AMY	$B(b' \rightarrow bg) \gtrsim 85\%$ ; event shape
>24.4	95	<sup>15</sup> IGARASHI	88	AMY	$\mu, e$
>23.8	95	<sup>16</sup> SAGAWA	88	AMY	event shape
>22.7	95	<sup>17</sup> ADEVA	86	MRKJ	$\mu$
>21		<sup>18</sup> ALTHOFF	84C	TASS	$R$ , event shape
>19		<sup>19</sup> ALTHOFF	84I	TASS	Aplanarity

<sup>1</sup> DECAMP 90F looked for isolated charged particles, for isolated photons, and for four-jet final states. The modes  $b' \rightarrow bg$  for  $B(b' \rightarrow bg) > 65\%$   $b' \rightarrow b\gamma$  for  $B(b' \rightarrow b\gamma) > 5\%$  are excluded. Charged Higgs decay were not discussed.

<sup>2</sup> ABDALLAH 07 searched for  $b'$  pair production at  $E_{\text{cm}} = 196\text{--}209$  GeV, with  $420 \text{ pb}^{-1}$ . No signal leads to the 95% CL upper limits on  $B(b' \rightarrow bZ)$  and  $B(b' \rightarrow cW)$  for  $m_{b'} = 96$  to 103 GeV.

<sup>3</sup> ADRIANI 93G search for vector quarkonium states near  $Z$  and give limit on quarkonium- $Z$  mixing parameter  $\delta m^2 < (10\text{--}30) \text{ GeV}^2$  (95%CL) for the mass 88–94.5 GeV. Using Richardson potential, a 1S ( $b'\bar{b}'$ ) state is excluded for the mass range 87.7–94.7 GeV. This range depends on the potential choice.

<sup>4</sup> ABREU 90D assumed  $m_{H^-} < m_{b'} - 3$  GeV.

<sup>5</sup> Superseded by ABREU 91F.

<sup>6</sup> AKRAWY 90B search was restricted to data near the  $Z$  peak at  $E_{\text{cm}} = 91.26$  GeV at LEP. The excluded region is between 23.6 and 41.4 GeV if no  $H^+$  decays exist. For charged Higgs decays the excluded regions are between  $(m_{H^+} + 1.5 \text{ GeV})$  and 45.5 GeV.

<sup>7</sup> AKRAWY 90J search for isolated photons in hadronic  $Z$  decay and derive  $B(Z \rightarrow b'\bar{b}') \cdot B(b' \rightarrow \gamma X) / B(Z \rightarrow \text{hadrons}) < 2.2 \times 10^{-3}$ . Mass limit assumes  $B(b' \rightarrow \gamma X) > 10\%$ .

<sup>8</sup> ABE 89E search at  $E_{\text{cm}} = 56\text{--}57$  GeV at TRISTAN for multihadron events with a spherical shape (using thrust and acoplanarity) or containing isolated leptons.

<sup>9</sup> ABE 89G search was at  $E_{\text{cm}} = 55\text{--}60.8$  GeV at TRISTAN.

<sup>10</sup> If the photonic decay mode is large ( $B(b' \rightarrow b\gamma) > 25\%$ ), the ABRAMS 89C limit is 45.4 GeV. The limit for Higgs decay ( $b' \rightarrow cH^-$ ,  $H^- \rightarrow \bar{c}s$ ) is 45.2 GeV.

<sup>11</sup> ADACHI 89C search was at  $E_{\text{cm}} = 56.5\text{--}60.8$  GeV at TRISTAN using multi-hadron events accompanying muons.

<sup>12</sup> ADACHI 89C also gives limits for any mixture of  $CC$  and  $bg$  decays.

<sup>13</sup> ENO 89 search at  $E_{\text{cm}} = 50\text{--}60.8$  at TRISTAN.

<sup>14</sup> ENO 89 considers arbitrary mixture of the charged current,  $bg$ , and  $b\gamma$  decays.

<sup>15</sup> IGARASHI 88 searches for leptons in low-thrust events and gives  $\Delta R(b') < 0.26$  (95% CL) assuming charged current decay, which translates to  $m_{b'} > 24.4$  GeV.

<sup>16</sup> SAGAWA 88 set limit  $\sigma(\text{top}) < 6.1 \text{ pb}$  at CL=95% for top-flavored hadron production from event shape analyses at  $E_{\text{cm}} = 52$  GeV. By using the quark parton model cross-section formula near threshold, the above limit leads to lower mass bounds of 23.8 GeV for charge  $-1/3$  quarks.

- 17 ADEVA 86 give 95%CL upper bound on an excess of the normalized cross section,  $\Delta R$ , as a function of the minimum c.m. energy (see their figure 3). Production of a pair of 1/3 charge quarks is excluded up to  $E_{\text{cm}} = 45.4$  GeV.
- 18 ALTHOFF 84C narrow state search sets limit  $\Gamma(e^+e^-)B(\text{hadrons}) < 2.4$  keV CL = 95% and heavy charge 1/3 quark pair production  $m > 21$  GeV, CL = 95%.
- 19 ALTHOFF 84I exclude heavy quark pair production for  $7 < m < 19$  GeV (1/3 charge) using aplanarity distributions (CL = 95%).

## REFERENCES FOR Searches for (Fourth Generation) $b'$ Quark

KHACHATRY...	16I	JHEP 1601 166	V. Khachatryan <i>et al.</i>	(CMS Collab.)
AAD	15AR	JHEP 1508 105	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15BY	JHEP 1510 150	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15CN	PR D92 112007	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15Z	PR D91 112011	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	14AZ	JHEP 1411 104	G. Aad <i>et al.</i>	(ATLAS Collab.)
CHATRCHYAN	13I	JHEP 1301 154	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
AAD	12AT	PRL 109 032001	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12AU	PRL 109 071801	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12BC	PR D86 012007	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12BE	JHEP 1204 069	G. Aad <i>et al.</i>	(ATLAS Collab.)
CHATRCHYAN	12BH	PR D86 112003	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	12X	JHEP 1205 123	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
AALTONEN	11J	PRL 106 141803	T. Aaltonen <i>et al.</i>	(CDF Collab.)
ABAZOV	11F	PRL 106 081801	V.M. Abazov <i>et al.</i>	(D0 Collab.)
CHATRCHYAN	11L	PL B701 204	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
AALTONEN	10H	PRL 104 091801	T. Aaltonen <i>et al.</i>	(CDF Collab.)
FLACCO	10	PRL 105 111801	C.J. Flacco <i>et al.</i>	(UCI, HAIF)
ATRE	09	PR D79 054018	A. Atre <i>et al.</i>	
ABAZOV	08X	PRL 101 111802	V.M. Abazov <i>et al.</i>	(D0 Collab.)
HUANG	08	PR D77 037302	P.Q. Hung, M. Sher	(UVA, WILL)
AALTONEN	07C	PR D76 072006	T. Aaltonen <i>et al.</i>	(CDF Collab.)
ABDALLAH	07	EPJ C50 507	J. Abdallah <i>et al.</i>	(DELPHI Collab.)
ACOSTA	03	PRL 90 131801	D. Acosta <i>et al.</i>	(CDF Collab.)
AFFOLDER	00	PRL 84 835	A. Affolder <i>et al.</i>	(CDF Collab.)
ABE	98N	PR D58 051102	F. Abe <i>et al.</i>	(CDF Collab.)
ABACHI	97D	PRL 78 3818	S. Abachi <i>et al.</i>	(D0 Collab.)
FROGGATT	97	ZPHY C73 333	C.D. Froggatt, D.J. Smith, H.B. Nielsen	(GLAS+)
ABACHI	95F	PR D52 4877	S. Abachi <i>et al.</i>	(D0 Collab.)
ADRIANI	93G	PL B313 326	O. Adriani <i>et al.</i>	(L3 Collab.)
ADRIANI	93M	PRPL 236 1	O. Adriani <i>et al.</i>	(L3 Collab.)
MUKHOPAD...	93	PR D48 2105	B. Mukhopadhyaya, D.P. Roy	(TATA)
ABE	92	PRL 68 447	F. Abe <i>et al.</i>	(CDF Collab.)
Also		PR D45 3921	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	92G	PR D45 3921	F. Abe <i>et al.</i>	(CDF Collab.)
ABREU	91F	NP B367 511	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ABE	90B	PRL 64 147	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	90D	PL B234 382	K. Abe <i>et al.</i>	(VENUS Collab.)
ABREU	90D	PL B242 536	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ADACHI	90	PL B234 197	I. Adachi <i>et al.</i>	(TOPAZ Collab.)
AKESSON	90	ZPHY C46 179	T. Akesson <i>et al.</i>	(UA2 Collab.)
AKRAWY	90B	PL B236 364	M.Z. Akrawy <i>et al.</i>	(OPAL Collab.)
AKRAWY	90J	PL B246 285	M.Z. Akrawy <i>et al.</i>	(OPAL Collab.)
ALBAJAR	90B	ZPHY C48 1	C. Albajar <i>et al.</i>	(UA1 Collab.)
DECAMP	90F	PL B236 511	D. Decamp <i>et al.</i>	(ALEPH Collab.)
ABE	89E	PR D39 3524	K. Abe <i>et al.</i>	(VENUS Collab.)
ABE	89G	PRL 63 1776	K. Abe <i>et al.</i>	(VENUS Collab.)
ABRAMS	89C	PRL 63 2447	G.S. Abrams <i>et al.</i>	(Mark II Collab.)
ADACHI	89C	PL B229 427	I. Adachi <i>et al.</i>	(TOPAZ Collab.)
ENO	89	PRL 63 1910	S. Eno <i>et al.</i>	(AMY Collab.)
ALBAJAR	88	ZPHY C37 505	C. Albajar <i>et al.</i>	(UA1 Collab.)
ALTARELLI	88	NP B308 724	G. Altarelli <i>et al.</i>	(CERN, ROMA, ETH)
IGARASHI	88	PRL 60 2359	S. Igarashi <i>et al.</i>	(AMY Collab.)
SAGAWA	88	PRL 60 93	H. Sagawa <i>et al.</i>	(AMY Collab.)
ADEVA	86	PR D34 681	B. Adeva <i>et al.</i>	(Mark-J Collab.)

ALTHOFF	84C	PL 138B 441	M. Althoff <i>et al.</i>	(TASSO Collab.)
ALTHOFF	84I	ZPHY C22 307	M. Althoff <i>et al.</i>	(TASSO Collab.)

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