

# $b'$ (4<sup>th</sup> Generation) Quark, Searches for

## MASS LIMITS for $b'$ (4<sup>th</sup> Generation) Quark or Hadron in $p\bar{p}$ Collisions

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>190	95	1 ACOSTA	03 CDF	quasi-stable $b'$
>199	95	2 AFFOLDER	00 CDF	NC: $b' \rightarrow bZ$
>128	95	3 ABACHI	95F D0	$l\bar{l} + \text{jets}, l + \text{jets}$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>148	95	4 ABE	98N CDF	NC: $b' \rightarrow bZ + \text{decay vertex}$
> 96	95	5 ABACHI	97D D0	NC: $b' \rightarrow b\gamma$
> 75	95	6 MUKHOPAD...	93 RVUE	NC: $b' \rightarrow bll$
> 85	95	7 ABE	92 CDF	CC: $l\bar{l}$
> 72	95	8 ABE	90B CDF	CC: $e + \mu$
> 54	95	9 AKESSON	90 UA2	CC: $e + \text{jets} + \text{missing } E_T$
> 43	95	10 ALBAJAR	90B UA1	CC: $\mu + \text{jets}$
> 34	95	11 ALBAJAR	88 UA1	CC: $e \text{ or } \mu + \text{jets}$

<sup>1</sup> ACOSTA 03 looked for long-lived fourth generation quarks in the data sample of 90 pb<sup>-1</sup> of  $\sqrt{s}=1.8$  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>2</sup> AFFOLDER 00 looked for  $b'$  that decays in to  $b+Z$ . 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  $B(b' \rightarrow bZ)=100\%$ . Between 100 GeV and 199 GeV, the 95%CL upper bound on  $\sigma(b' \rightarrow \bar{b}') \times B^2(b' \rightarrow bZ)$  is also given (see their Fig. 2).

<sup>3</sup> ABACHI 95F bound on the top-quark also applies to  $b'$  and  $t'$  quarks that decay predominantly into  $W$ . See FROGGATT 97.

<sup>4</sup> ABE 98N looked for  $Z \rightarrow e^+e^-$  decays with displaced vertices. Quoted limit assumes  $B(b' \rightarrow bZ)=1$  and  $c\tau_{b'}=1$  cm. The limit is lower than  $m_Z+m_b$  ( $\sim 96$  GeV) if  $c\tau > 22$  cm or  $c\tau < 0.009$  cm. See their Fig. 4.

<sup>5</sup> 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  $m_{b'} > m_Z + m_b$ .

<sup>6</sup> 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.

<sup>7</sup> ABE 92 dilepton analysis limit of  $>85$  GeV at CL=95% also applies to  $b'$  quarks, as discussed in ABE 90B.

<sup>8</sup> ABE 90B exclude the region 28–72 GeV.

<sup>9</sup> AKESSON 90 searched for events having an electron with  $p_T > 12$  GeV, missing momentum  $> 15$  GeV, and a jet with  $E_T > 10$  GeV,  $|\eta| < 2.2$ , and excluded  $m_{b'}$  between 30 and 69 GeV.

<sup>10</sup> For the reduction of the limit due to non-charged-current decay modes, see Fig. 19 of ALBAJAR 90B.

<sup>11</sup> 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.

## 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
<b>&gt;46.0</b>	95	<sup>12</sup> DECAMP	90F ALEP	any decay
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		<sup>13</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>14</sup> ABREU	90D DLPH	$b' \rightarrow cH^-, H^- \rightarrow \bar{c}s, \tau^- \nu$
>40.5	95	<sup>15</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>16</sup> AKRAWY	90B OPAL	Any decay; acoplanarity
>45.2	95	<sup>16</sup> AKRAWY	90B OPAL	$B(CC) = 1$ ; acoplanarity
>46	95	<sup>17</sup> AKRAWY	90J OPAL	$b' \rightarrow \gamma + \text{any}$
>27.5	95	<sup>18</sup> ABE	89E VNS	$B(CC) = 1$ ; $\mu, e$
none 11.4–27.3	95	<sup>19</sup> ABE	89G VNS	$B(b' \rightarrow b\gamma) > 10\%$ ; isolated $\gamma$
>44.7	95	<sup>20</sup> ABRAMS	89C MRK2	$B(CC) = 100\%$ ; isol. track
>42.7	95	<sup>20</sup> ABRAMS	89C MRK2	$B(bg) = 100\%$ ; event shape
>42.0	95	<sup>20</sup> ABRAMS	89C MRK2	Any decay; event shape
>28.4	95	<sup>21,22</sup> ADACHI	89C TOPZ	$B(CC) = 1$ ; $\mu$
>28.8	95	<sup>23</sup> ENO	89 AMY	$B(CC) \gtrsim 90\%$ ; $\mu, e$
>27.2	95	<sup>23,24</sup> ENO	89 AMY	any decay; event shape
>29.0	95	<sup>23</sup> ENO	89 AMY	$B(b' \rightarrow bg) \gtrsim 85\%$ ; event shape
>24.4	95	<sup>25</sup> IGARASHI	88 AMY	$\mu, e$
>23.8	95	<sup>26</sup> SAGAWA	88 AMY	event shape
>22.7	95	<sup>27</sup> ADEVA	86 MRKJ	$\mu$
>21		<sup>28</sup> ALTHOFF	84C TASS	$R$ , event shape
>19		<sup>29</sup> ALTHOFF	84I TASS	Aplanarity

<sup>12</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>13</sup> ADRIANI 93G search for vector quarkonium states near  $Z$  and give limit on quarkonium- $Z$  mixing parameter  $\delta m^2 < (10-30) \text{ GeV}^2$  (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.

- 14 ABREU 90D assumed  $m_{H^-} < m_{b'} - 3$  GeV.
- 15 Superseded by ABREU 91F.
- 16 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  $(m_{H^+} + 1.5$  GeV) and 45.5 GeV.
- 17 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  $B(b' \rightarrow \gamma X) > 10\%$ .
- 18 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.
- 19 ABE 89G search was at  $E_{\text{cm}} = 55\text{--}60.8$  GeV at TRISTAN.
- 20 If the photonic decay mode is large ( $B(b' \rightarrow b\gamma) > 25\%$ ), the ABRAMS 89C limit is 45.4 GeV. The limit for for Higgs decay ( $b' \rightarrow cH^-, H^- \rightarrow \bar{c}s$ ) is 45.2 GeV.
- 21 ADACHI 89C search was at  $E_{\text{cm}} = 56.5\text{--}60.8$  GeV at TRISTAN using multi-hadron events accompanying muons.
- 22 ADACHI 89C also gives limits for any mixture of  $CC$  and  $bg$  decays.
- 23 ENO 89 search at  $E_{\text{cm}} = 50\text{--}60.8$  at TRISTAN.
- 24 ENO 89 considers arbitrary mixture of the charged current,  $bg$ , and  $b\gamma$  decays.
- 25 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.
- 26 SAGAWA 88 set limit  $\sigma(\text{top}) < 6.1$  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.
- 27 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.
- 28 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%.
- 29 ALTHOFF 84I exclude heavy quark pair production for  $7 < m < 19$  GeV ( $1/3$  charge) using aplanarity distributions (CL = 95%).

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

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	92G	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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