

b' (4th Generation) Quark, Searches for

MASS LIMITS for b' (4th 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	$\ell\ell + \text{jets}, \ell + \text{jets}$
● ● ● 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: $b' \rightarrow b\ell\ell$
> 85	95	⁷ ABE 92	CDF	CC: $\ell\ell$
> 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: $e \text{ or } \mu + \text{jets}$

¹ ACOSTA 03 looked for long-lived fourth generation quarks in the data sample of 90 pb^{-1} 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.

² 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).

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

⁴ 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 (~ 96 GeV) if $c\tau > 22$ cm or $c\tau < 0.009$ cm. See their Fig. 4.

⁵ 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 $m_{b'} > m_Z+m_b$.

⁶ 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.

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

⁸ ABE 90B exclude the region 28–72 GeV.

⁹ 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.

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

¹¹ 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' (4th 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	¹² DECAMP	90F ALEP	any decay
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		¹³ 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	¹⁴ ABREU	90D DLPH	$b' \rightarrow cH^-, H^- \rightarrow \bar{c}s, \tau^- \nu$
>40.5	95	¹⁵ ABREU	90D DLPH	$\Gamma(Z \rightarrow \text{hadrons})$
>28.3	95	ADACHI	90 TOPZ	$B(\text{FCNC})=100\%$; isol. γ or 4 jets
>41.4	95	¹⁶ AKRAWY	90B OPAL	Any decay; acoplanarity
>45.2	95	¹⁶ AKRAWY	90B OPAL	$B(CC) = 1$; acoplanarity
>46	95	¹⁷ AKRAWY	90J OPAL	$b' \rightarrow \gamma + \text{any}$
>27.5	95	¹⁸ ABE	89E VNS	$B(CC) = 1$; μ, e
none 11.4–27.3	95	¹⁹ ABE	89G VNS	$B(b' \rightarrow b\gamma) > 10\%$; isolated γ
>44.7	95	²⁰ ABRAMS	89C MRK2	$B(CC) = 100\%$; isol. track
>42.7	95	²⁰ ABRAMS	89C MRK2	$B(bg) = 100\%$; event shape
>42.0	95	²⁰ ABRAMS	89C MRK2	Any decay; event shape
>28.4	95	^{21,22} ADACHI	89C TOPZ	$B(CC) = 1$; μ
>28.8	95	²³ ENO	89 AMY	$B(CC) \gtrsim 90\%$; μ, e
>27.2	95	^{23,24} ENO	89 AMY	any decay; event shape
>29.0	95	²³ ENO	89 AMY	$B(b' \rightarrow bg) \gtrsim 85\%$; event shape
>24.4	95	²⁵ IGARASHI	88 AMY	μ, e
>23.8	95	²⁶ SAGAWA	88 AMY	event shape
>22.7	95	²⁷ ADEVA	86 MRKJ	μ
>21		²⁸ ALTHOFF	84C TASS	R , event shape
>19		²⁹ ALTHOFF	84I TASS	Aplanarity

¹² 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.

¹³ 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 $E_{\text{cm}} = 56$ –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 $E_{\text{cm}} = 55$ –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 Higgs decay ($b' \rightarrow cH^-, H^- \rightarrow \bar{c}s$) is 45.2 GeV.
- 21 ADACHI 89C search was at $E_{\text{cm}} = 56.5$ –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 $E_{\text{cm}} = 50$ –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, ΔR , 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%).

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		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.)
