

b' (4th Generation) Quark, Searches for

b'-quark/hadron mass limits in p \bar{p} and pp collisions

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>372	95	¹ AALTONEN 11J	CDF	$b' \rightarrow tW$
>361	95	² CHATRCHYAN 11L	CMS	$b' \rightarrow tW$
>190	95	³ ABAZOV 08X	D0	$c\tau = 200\text{mm}$
>268	95	^{4,5} AALTONEN 07C	CDF	$B(b' \rightarrow bZ) = 1$ assumed
>190	95	⁶ ACOSTA 03	CDF	quasi-stable b'
>128	95	⁷ ABACHI 95F	D0	$\ell\ell + \text{jets}, \ell + \text{jets}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>338	95	⁸ AALTONEN 10H	CDF	$b' \rightarrow tW$
> 380–430	95	⁹ FLACCO 10	RVUE	$m_{b'} > m_{t'}$
>199	95	¹⁰ AFFOLDER 00	CDF	NC: $b' \rightarrow bZ$
>148	95	¹¹ ABE 98N	CDF	NC: $b' \rightarrow bZ$ +decay vertex
> 96	95	¹² ABACHI 97D	D0	NC: $b' \rightarrow b\gamma$
> 75	95	¹³ MUKHOPAD... 93	RVUE	NC: $b' \rightarrow b\ell\ell$
> 85	95	¹⁴ ABE 92	CDF	CC: $\ell\ell$
> 72	95	¹⁵ ABE 90B	CDF	CC: $e + \mu$
> 54	95	¹⁶ AKESSON 90	UA2	CC: $e + \text{jets} + \text{missing } E_T$
> 43	95	¹⁷ ALBAJAR 90B	UA1	CC: $\mu + \text{jets}$
> 34	95	¹⁸ ALBAJAR 88	UA1	CC: e or $\mu + \text{jets}$

¹ Based on 4.8 fb^{-1} of data in $p\bar{p}$ collisions at 1.96 TeV. AALTONEN 11J looked for events with $\ell + \cancel{E}_T + \geq 5j$ (≥ 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 $B(b' \rightarrow tW) = 1$.

² Based on 34 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 $B(b' \rightarrow tW) = 1$.

³ Result is based on 1.1 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 $2 < c\tau < 7000 \text{ mm}$; see Fig. 3. 95% CL excluded region of b' lifetime and mass is shown in Fig. 4.

⁴ Result is based on 1.06 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 $\sigma(b'\bar{b}') [1 - (1 - B(b' \rightarrow bZ))^2]$ and the LO estimate of the b' pair production cross section shown in Fig. 38 of the article.

⁵ HUANG 08 reexamined the b' mass lower bound of 268 GeV obtained in AALTONEN 07C that assumes $B(b' \rightarrow bZ) = 1$, 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 $m_{b'}$.

⁶ ACOSTA 03 looked for long-lived fourth generation quarks in the data sample of 90 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.

- ⁷ ABACHI 95F bound on the top-quark also applies to b' and t' quarks that decay predominantly into W . See FROGGATT 97.
- ⁸ Based on 2.7 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 μ), 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.
- ⁹ FLACCO 10 result is obtained from AALTONEN 10H result of $m_{b'} > 338 \text{ GeV}$, by relaxing the condition $B(b' \rightarrow tW) = 100\%$ when $m_{b'} > m_{t'}$.
- ¹⁰ 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 $B(b' \rightarrow bZ) = 100\%$. 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).
- ¹¹ ABE 98N looked for $Z \rightarrow e^+e^-$ decays with displaced vertices. Quoted limit assumes $B(b' \rightarrow bZ) = 1$ and $c\tau_{b'} = 1 \text{ cm}$. 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.
- ¹² 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 $m_{b'} > m_Z + m_b$.
- ¹³ 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.
- ¹⁴ ABE 92 dilepton analysis limit of $>85 \text{ GeV}$ at CL=95% also applies to b' quarks, as discussed in ABE 90B.
- ¹⁵ ABE 90B exclude the region 28–72 GeV.
- ¹⁶ 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.
- ¹⁷ For the reduction of the limit due to non-charged-current decay modes, see Fig. 19 of ALBAJAR 90B.
- ¹⁸ 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' mass limits from single production in $p\bar{p}$ and pp collisions

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>693	95	¹⁹ ABAZOV	11F D0	$qu \rightarrow q'b' \rightarrow q'(Wu)$ $\tilde{\kappa}_{ub'} = 1, B(b' \rightarrow Wu) = 1$
>430	95	¹⁹ ABAZOV	11F D0	$qd \rightarrow qb' \rightarrow q(Zd)$ $\tilde{\kappa}_{db'} = \sqrt{2}, B(b' \rightarrow Zd) = 1$

¹⁹Based on 5.4 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 $p\bar{p} \rightarrow b'q \rightarrow W uq$, and $p\bar{p} \rightarrow b'q \rightarrow Z d q$ 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.

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	20 DECAMP	90F ALEP	any decay
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
none 96–103	95	21 ABDALLAH	07 DLPH	$b' \rightarrow bZ, cW$
		22 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	23 ABREU	90D DLPH	$b' \rightarrow cH^-, H^- \rightarrow \bar{c}s, \tau^- \nu$
>40.5	95	24 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	25 AKRAWY	90B OPAL	Any decay; acoplanarity
>45.2	95	25 AKRAWY	90B OPAL	$B(CC) = 1$; acoplanarity
>46	95	26 AKRAWY	90J OPAL	$b' \rightarrow \gamma + \text{any}$
>27.5	95	27 ABE	89E VNS	$B(CC) = 1$; μ, e
none 11.4–27.3	95	28 ABE	89G VNS	$B(b' \rightarrow b\gamma) > 10\%$; isolated γ
>44.7	95	29 ABRAMS	89C MRK2	$B(CC) = 100\%$; isol. track
>42.7	95	29 ABRAMS	89C MRK2	$B(bg) = 100\%$; event shape
>42.0	95	29 ABRAMS	89C MRK2	Any decay; event shape
>28.4	95	30,31 ADACHI	89C TOPZ	$B(CC) = 1$; μ
>28.8	95	32 ENO	89 AMY	$B(CC) \gtrsim 90\%$; μ, e
>27.2	95	32,33 ENO	89 AMY	any decay; event shape
>29.0	95	32 ENO	89 AMY	$B(b' \rightarrow bg) \gtrsim 85\%$; event shape
>24.4	95	34 IGARASHI	88 AMY	μ, e
>23.8	95	35 SAGAWA	88 AMY	event shape
>22.7	95	36 ADEVA	86 MRKJ	μ
>21		37 ALTHOFF	84C TASS	R , event shape
>19		38 ALTHOFF	84I TASS	Aplanarity

- ²⁰ 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.
- ²¹ ABDALLAH 07 searched for b' pair production at $E_{\text{cm}}=196\text{--}209$ GeV, with 420 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.
- ²² ADRIANI 93G search for vector quarkonium states near Z and give limit on quarkonium- Z mixing parameter $\delta m^2 < (10\text{--}30)$ GeV² (95%CL) for the mass $88\text{--}94.5$ GeV. Using Richardson potential, a $1S$ ($b'\bar{b}'$) state is excluded for the mass range $87.7\text{--}94.7$ GeV. This range depends on the potential choice.
- ²³ ABREU 90D assumed $m_{H^-} < m_{b'} - 3$ GeV.
- ²⁴ Superseded by ABREU 91F.
- ²⁵ 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.
- ²⁶ 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 $B(b' \rightarrow \gamma X) > 10\%$.
- ²⁷ 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.
- ²⁸ ABE 89G search was at $E_{\text{cm}} = 55\text{--}60.8$ GeV at TRISTAN.
- ²⁹ 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.
- ³⁰ ADACHI 89C search was at $E_{\text{cm}} = 56.5\text{--}60.8$ GeV at TRISTAN using multi-hadron events accompanying muons.
- ³¹ ADACHI 89C also gives limits for any mixture of CC and bg decays.
- ³² ENO 89 search at $E_{\text{cm}} = 50\text{--}60.8$ at TRISTAN.
- ³³ ENO 89 considers arbitrary mixture of the charged current, bg , and $b\gamma$ decays.
- ³⁴ 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.
- ³⁵ 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.
- ³⁶ 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.
- ³⁷ 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%.
- ³⁸ 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

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.)