

b' (4th Generation) Quark, Searches for

MASS LIMITS for b' (4th Generation) Quark or Hadron in p-p̄ Collisions

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>199	95	¹ AFFOLDER	00 CDF	NC: b' → bZ
>128	95	² ABACHI	95F D0	ll + jets, l + jets
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>148	95	³ ABE	98N CDF	NC: b' → bZ + decay vertex
> 96	95	⁴ ABACHI	97D D0	NC: b' → bγ
> 75	95	⁵ MUKHOPAD...	93 RVUE	NC: b' → bll
> 85	95	⁶ ABE	92 CDF	CC: ll
> 72	95	⁷ ABE	90B CDF	CC: e + μ
> 54	95	⁸ AKESSON	90 UA2	CC: e + jets + missing E _T
> 43	95	⁹ ALBAJAR	90B UA1	CC: μ + jets
> 34	95	¹⁰ ALBAJAR	88 UA1	CC: e or μ + jets

¹ 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 μ⁺μ⁻ and the other Z decays hadronically. The bound assumes B(b' → bZ)=100%. Between 100 GeV and 199 GeV, the 95%CL upper bound on σ(b' → b̄') × B²(b' → bZ) is also given (see their Fig. 2).

² ABACHI 95F bound on the top-quark also applies to b' and t' quarks that decay predominantly into W. See FROGGATT 97.

³ ABE 98N looked for Z → e⁺e⁻ decays with displaced vertices. Quoted limit assumes B(b' → bZ)=1 and cτ_{b'}=1cm. The limit is lower than 96 GeV (m_Z+m_b) if cτ > 22 cm or cτ < 0.009 cm. See their Fig. 4.

⁴ ABACHI 97D searched for b' that decays mainly via FCNC. They obtained 95%CL upper bounds on B(b' b̄' → γ + 3 jets) and B(b' b̄' → 2γ + 2 jets), which can be interpreted as the lower mass bound m_{b'} > m_Z+m_b.

⁵ 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' → bℓ⁺ℓ⁻)=1%. For an exotic quark decaying only via virtual Z [B(bℓ⁺ℓ⁻) = 3%], the limit is 85 GeV.

⁶ ABE 92 dilepton analysis limit of >85 GeV at CL=95% also applies to b' quarks, as discussed in ABE 90B.

⁷ ABE 90B exclude the region 28–72 GeV.

⁸ 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, |η| < 2.2, and excluded m_{b'} between 30 and 69 GeV.

⁹ For the reduction of the limit due to non-charged-current decay modes, see Fig. 19 of ALBAJAR 90B.

¹⁰ ALBAJAR 88 study events at E_{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' b̄' production cross section and by assuming that it cannot be produced in W decays. The value quoted here is revised using the full O(α_s³) 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	¹¹ DECAMP	90F ALEP	any decay
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		¹² 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	¹³ ABREU	90D DLPH	$b' \rightarrow c H^-, H^- \rightarrow \bar{c}s, \tau^- \nu$
>40.5	95	¹⁴ 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	¹⁵ AKRAWY	90B OPAL	Any decay; acoplanarity
>45.2	95	¹⁵ AKRAWY	90B OPAL	$B(CC) = 1$; acoplanarity
>46	95	¹⁶ AKRAWY	90J OPAL	$b' \rightarrow \gamma + \text{any}$
>27.5	95	¹⁷ ABE	89E VNS	$B(CC) = 1$; μ, e
none 11.4–27.3	95	¹⁸ ABE	89G VNS	$B(b' \rightarrow b\gamma) > 10\%$; isolated γ
>44.7	95	¹⁹ ABRAMS	89C MRK2	$B(CC) = 100\%$; isol. track
>42.7	95	¹⁹ ABRAMS	89C MRK2	$B(bg) = 100\%$; event shape
>42.0	95	¹⁹ ABRAMS	89C MRK2	Any decay; event shape
>28.4	95	^{20,21} ADACHI	89C TOPZ	$B(CC) = 1$; μ
>28.8	95	²² ENO	89 AMY	$B(CC) \gtrsim 90\%$; μ, e
>27.2	95	^{22,23} ENO	89 AMY	any decay; event shape
>29.0	95	²² ENO	89 AMY	$B(b' \rightarrow bg) \gtrsim 85\%$; event shape
>24.4	95	²⁴ IGARASHI	88 AMY	μ, e
>23.8	95	²⁵ SAGAWA	88 AMY	event shape
>22.7	95	²⁶ ADEVA	86 MRKJ	μ
>21		²⁷ ALTHOFF	84C TASS	R , event shape
>19		²⁸ ALTHOFF	84I TASS	Aplanarity

¹¹ 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.

¹² 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.

¹³ ABREU 90D assumed $m_{H^-} < m_{b'} - 3 \text{ GeV}$.

¹⁴ Superseded by ABREU 91F.

¹⁵ AKRAWY 90B search was restricted to data near the Z peak at $E_{\text{cm}} = 91.26 \text{ GeV}$ 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.
- 16 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 $B(b' \rightarrow \gamma X) > 10\%$.
- 17 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.
- 18 ABE 89G search was at $E_{\text{cm}} = 55\text{--}60.8$ GeV at TRISTAN.
- 19 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.
- 20 ADACHI 89C search was at $E_{\text{cm}} = 56.5\text{--}60.8$ GeV at TRISTAN using multi-hadron events accompanying muons.
- 21 ADACHI 89C also gives limits for any mixture of CC and bg decays.
- 22 ENO 89 search at $E_{\text{cm}} = 50\text{--}60.8$ at TRISTAN.
- 23 ENO 89 considers arbitrary mixture of the charged current, bg , and $b\gamma$ decays.
- 24 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.
- 25 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.
- 26 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.
- 27 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%.
- 28 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

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.)
