b' (4^{th} Generation) Quark, Searches for

MASS LIMITS for b' (4^{th} Generation) Quark or Hadron in $p\overline{p}$ Collisions

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>199	95	[1] AFFOLDER	00	CDF	NC: $b' \to bZ$
>128	95	[2] ABACHI	95F	D0	$\ell\ell$ + jets, ℓ + jets
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>148	95	[3] ABE	98N	CDF	NC: $b' \to bZ$ +decay vertex
> 96	95	[4] ABACHI	97D	D0	NC: $b' \to b\gamma$
> 75	95	[5] MUKHOPAD...	93	RVUE	NC: $b' \to b\ell\ell$
> 85	95	[6] ABE	92	CDF	CC: $\ell\ell$
> 72	95	[7] ABE	90B	CDF	CC: $e + \mu$
> 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 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($b' \to bZ$)= 100%. Between 100 GeV and 199 GeV, the 95%CL upper bound on $\sigma(b' \to \overline{b}')\times$B^2($b' \to bZ$) 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 $Z \to e^+e^-$ decays with displaced vertices. Quoted limit assumes B($b' \to bZ$)=1 and $c\tau_{b'}$=1 cm. The limit is lower than 96 GeV (m_Z+m_b) if $c\tau>$ 22 cm or $c\tau<$ 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($b'\overline{b}' \to \gamma$+ 3 jets) and B($b'\overline{b}' \to 2\gamma$+ 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($b' \to b\ell^+\ell^-$)=1%. For an exotic quark decaying only via virtual Z [B($b\ell^+\ell^-$) = 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, $|\eta|$ < 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 $b'\overline{b}'$ 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^{th} 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	$b' \to cH^-$, $H^- \to \overline{c}s$, $\tau^-\nu$
>40.5	95	[14] ABREU	90D	DLPH	$\Gamma(Z \to$ hadrons)
>28.3	95	ADACHI	90	TOPZ	B(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	$b' \to \gamma +$ any
>27.5	95	[17] ABE	89E	VNS	$B(CC) =1$; μ, e
none 11.4–27.3	95	[18] ABE	89G	VNS	$B(b' \to b\gamma) > 10\%$; 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	$B(b' \to bg) \gtrsim 85\%$; 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 $b' \to bg$ for $B(b' \to bg) > 65\%$ $b' \to b\gamma$ for $B(b' \to b\gamma) > 5\%$ 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) GeV^2 (95%CL) for the mass 88–94.5 GeV. Using Richardson potential, a 1S ($b'\overline{b}'$) state is excluded for the mass range 87.7–94.7 GeV. This range depends on the potential choice.

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

[14] Superseded by ABREU 91F.

[15] AKRAWY 90B search was restricted to data near the Z peak at $E_{cm} = 91.26$ 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.

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

[17] ABE 89E search at E_{cm} = 56–57 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_{cm} = 55–60.8 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 for Higgs decay ($b' \rightarrow cH^-$, $H^- \rightarrow \overline{c}s$) is 45.2 GeV.

[20] ADACHI 89C search was at E_{cm} = 56.5–60.8 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_{cm} = 50–60.8 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 σ(top) $<$ 6.1 pb at CL=95% for top-flavored hadron production from event shape analyses at E_{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_{cm} = 45.4 GeV.

[27] ALTHOFF 84C narrow state search sets limit $\Gamma(e^+e^-)$B(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 et al.	(CDF Collab.)
ABE	98N	PR D58 051102	F. Abe et al.	(CDF Collab.)
ABACHI	97D	PRL 78 3818	S. Abachi et al.	(D0 Collab.)
FROGGATT	97	ZPHY C73 333	C.D. Froggatt, D.J. Smith, H.B. Nielsen	(GLAS+)
ABACHI	95F	PR D52 4877	S. Abachi et al.	(D0 Collab.)
ADRIANI	93G	PL B313 326	O. Adriani et al.	(L3 Collab.)
ADRIANI	93M	PRPL 236 1	O. Adriani et al.	(L3 Collab.)
MUKHOPAD...	93	PR D48 2105	B. Mukhopadhyaya, D.P. Roy	(TATA)
ABE	92	PRL 68 447	F. Abe et al.	(CDF Collab.)
Also	92G	PR D45 3921	F. Abe et al.	(CDF Collab.)
ABE	92G	PR D45 3921	F. Abe et al.	(CDF Collab.)
ABREU	91F	NP B367 511	P. Abreu et al.	(DELPHI Collab.)
ABE	90B	PRL 64 147	F. Abe et al.	(CDF Collab.)
ABE	90D	PL B234 382	K. Abe et al.	(VENUS Collab.)
ABREU	90D	PL B242 536	P. Abreu et al.	(DELPHI Collab.)
ADACHI	90	PL B234 197	I. Adachi et al.	(TOPAZ Collab.)
AKESSON	90	ZPHY C46 179	T. Akesson et al.	(UA2 Collab.)
AKRAWY	90B	PL B236 364	M.Z. Akrawy et al.	(OPAL Collab.)
AKRAWY	90J	PL B246 285	M.Z. Akrawy et al.	(OPAL Collab.)
ALBAJAR	90B	ZPHY C48 1	C. Albajar et al.	(UA1 Collab.)
DECAMP	90F	PL B236 511	D. Decamp et al.	(ALEPH Collab.)
ABE	89E	PR D39 3524	K. Abe et al.	(VENUS Collab.)
ABE	89G	PRL 63 1776	K. Abe et al.	(VENUS Collab.)
ABRAMS	89C	PRL 63 2447	G.S. Abrams et al.	(Mark II Collab.)
ADACHI	89C	PL B229 427	I. Adachi et al.	(TOPAZ Collab.)

ENO	89	PRL 63 1910	S. Eno *et al.*	(AMY Collab.)
ALBAJAR	88	ZPHY C37 505	C. Albajar *et al.*	(UA1 Collab.)
ALTARELLI	88	NP B308 724	G. Altarelli *et al.*	(CERN, ROMA, ETH)
IGARASHI	88	PRL 60 2359	S. Igarashi *et al.*	(AMY Collab.)
SAGAWA	88	PRL 60 93	H. Sagawa *et al.*	(AMY Collab.)
ADEVA	86	PR D34 681	B. Adeva *et al.*	(Mark-J Collab.)
ALTHOFF	84C	PL 138B 441	M. Althoff *et al.*	(TASSO Collab.)
ALTHOFF	84I	ZPHY C22 307	M. Althoff *et al.*	(TASSO Collab.)