Citation: K. Hagiwara *et al.* (Particle Data Group), Phys. Rev. D **66**, 010001 (2002) and 2003 partial update for edition 2004 (URL: http://pdg.lbl.gov)

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: $b' \rightarrow bZ$
>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: $b' \rightarrow bZ$ +decay vertex
> 96	95	[4] ABACHI	97D	D0	NC: $b' \rightarrow b\gamma$
> 75	95	[5] MUKHOPAD...	93	RVUE	NC: $b' \rightarrow b\ell\ell$
> 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($b' \rightarrow bZ$)= 100%. Between 100 GeV and 199 GeV, the 95%CL upper bound on $\sigma(b' \rightarrow \overline{b}') \times B^2(b' \rightarrow bZ)$ 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 $Z \rightarrow e^+e^-$ 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.

[4] ABACHI 97D searched for b' that decays mainly via FCNC. They obtained 95%CL upper bounds on B($b'\overline{b}' \rightarrow \gamma$+ 3 jets) and B($b'\overline{b}' \rightarrow 2\gamma$+ 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($b' \rightarrow b\ell^+\ell^-$)=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 $E_{\text{cm}} = 91.26$ 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.

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

[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 ($B(b' \to b\gamma) > 25\%$), the ABRAMS 89C limit is 45.4 GeV. The limit for for Higgs decay ($b' \to cH^-$, $H^- \to \overline{c}s$) 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 $\sigma(\text{top}) < 6.1$ 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(\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 *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.)