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
>190	95	[1] ABAZOV	08X	D0	$c\tau$= 200mm
>268	95	[2,3] AALTONEN	07C	CDF	B($b' \rightarrow bZ$) = 1 assumed
>190	95	[4] ACOSTA	03	CDF	quasi-stable b'
>128	95	[5] ABACHI	95F	D0	$\ell\ell$ + jets, ℓ + jets
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>199	95	[6] AFFOLDER	00	CDF	NC: $b' \rightarrow bZ$
>148	95	[7] ABE	98N	CDF	NC: $b' \rightarrow bZ$ +decay vertex
> 96	95	[8] ABACHI	97D	D0	NC: $b' \rightarrow b\gamma$
> 75	95	[9] MUKHOPAD...	93	RVUE	NC: $b' \rightarrow b\ell\ell$
> 85	95	[10] ABE	92	CDF	CC: $\ell\ell$
> 72	95	[11] ABE	90B	CDF	CC: $e + \mu$
> 54	95	[12] AKESSON	90	UA2	CC: e + jets + missing E_T
> 43	95	[13] ALBAJAR	90B	UA1	CC: μ + jets
> 34	95	[14] ALBAJAR	88	UA1	CC: e or μ + jets

[1] 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 mm; see Fig. 3. 95% CL excluded region of b' lifetime and mass is shown in Fig. 4.

[2] 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 $\sigma(b'\overline{b}')$ [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.

[3] 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 GeV. The lower mass bound is given in the plane of $\sin^2(\theta_{tb'})$ and $m_{b'}$.

[4] ACOSTA 03 looked for long-lived fourth generation quarks in the data sample of 90 pb^{-1} of $\sqrt{s}$=1.8 TeV $p\overline{p}$ 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.

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

[6] 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).

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

[8] 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.

[9] 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.

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

[11] ABE 90B exclude the region 28–72 GeV.

[12] 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.

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

[14] 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' (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	[15] DECAMP	90F	ALEP	any decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 96–103	95	[16] ABDALLAH	07	DLPH	$b' \to bZ$, cW
		[17] 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	[18] ABREU	90D	DLPH	$b' \to cH^-$, $H^- \to \overline{c}s$, $\tau^-\nu$
>40.5	95	[19] ABREU	90D	DLPH	$\Gamma(Z \to$ hadrons)
>28.3	95	ADACHI	90	TOPZ	B(FCNC)=100%; isol. γ or 4 jets
>41.4	95	[20] AKRAWY	90B	OPAL	Any decay; acoplanarity
>45.2	95	[20] AKRAWY	90B	OPAL	B(CC) = 1; acoplanarity
>46	95	[21] AKRAWY	90J	OPAL	$b' \to \gamma +$ any
>27.5	95	[22] ABE	89E	VNS	B(CC) =1; μ, e
none 11.4–27.3	95	[23] ABE	89G	VNS	B($b' \to b\gamma$) > 10%; isolated γ
>44.7	95	[24] ABRAMS	89C	MRK2	B(CC)= 100%; isol. track
>42.7	95	[24] ABRAMS	89C	MRK2	B(bg)= 100%; event shape
>42.0	95	[24] ABRAMS	89C	MRK2	Any decay; event shape

>28.4	95	[25,26] ADACHI	89C	TOPZ	B($C\,C$) =1; μ
>28.8	95	[27] ENO	89	AMY	B($C\,C$) $\gtrsim$ 90%; μ, e
>27.2	95	[27,28] ENO	89	AMY	any decay; event shape
>29.0	95	[27] ENO	89	AMY	B($b' \to bg$) $\gtrsim$ 85%; event shape
>24.4	95	[29] IGARASHI	88	AMY	μ,e
>23.8	95	[30] SAGAWA	88	AMY	event shape
>22.7	95	[31] ADEVA	86	MRKJ	μ
>21		[32] ALTHOFF	84C	TASS	R, event shape
>19		[33] ALTHOFF	84I	TASS	Aplanarity

[15] 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.

[16] ABDALLAH 07 searched for b' pair production at $E_{\rm cm}$=196–209 GeV, with 420 pb^{-1}. No signal leads to the 95% CL upper limits on B($b' \to bZ$) and B($b' \to cW$) for $m_{b'}$ = 96 to 103 GeV.

[17] ADRIANI 93G search for vector quarkonium states near Z and give limit on quarkonium-Z mixing parameter δm^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.

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

[19] Superseded by ABREU 91F.

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

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

[22] ABE 89E search at $E_{\rm cm}$ = 56–57 GeV at TRISTAN for multihadron events with a spherical shape (using thrust and acoplanarity) or containing isolated leptons.

[23] ABE 89G search was at $E_{\rm cm}$ = 55–60.8 GeV at TRISTAN.

[24] 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.

[25] ADACHI 89C search was at $E_{\rm cm}$ = 56.5–60.8 GeV at TRISTAN using multi-hadron events accompanying muons.

[26] ADACHI 89C also gives limits for any mixture of $C\,C$ and bg decays.

[27] ENO 89 search at $E_{\rm cm}$ = 50–60.8 at TRISTAN.

[28] ENO 89 considers arbitrary mixture of the charged current, bg, and $b\gamma$ decays.

[29] 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.

[30] SAGAWA 88 set limit σ(top) $<$ 6.1 pb at CL=95% for top-flavored hadron production from event shape analyses at $E_{\rm cm}$ = 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.

[31] 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 $E_{\rm cm}$ = 45.4 GeV.

[32] 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%.

[33] 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

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HUANG	08	PR D77 037302	P.Q. Hung, M. Sher	(UVA, WILL)
AALTONEN	07C	PR D76 072006	T. Aaltonen *et al.*	(CDF Collab.)
ABDALLAH	07	EPJ C50 507	J. Abdallah *et al.*	(DELPHI Collab.)
ACOSTA	03	PRL 90 131801	D. Acosta *et al.*	(CDF Collab.)
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		PR D45 3921	F. Abe *et al.*	(CDF Collab.)
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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.)
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ABE	89E	PR D39 3524	K. Abe *et al.*	(VENUS Collab.)
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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)
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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.)