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

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

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>675	95	[1] CHATRCHYAN	13I	CMS	B($b' \to Wt$) = 1
>400	95	[2] AAD	12AU	ATLS	B($b' \to Zb$) = 1
>350	95	[3] AAD	12BC	ATLS	B($b' \to Wq$) = 1 (q=u,c)
>685	95	[4] CHATRCHYAN	12BH	CMS	$m_{t'} = m_{b'}$
>190	95	[5] ABAZOV	08X	D0	$c\tau$= 200mm
>190	95	[6] ACOSTA	03	CDF	quasi-stable b'
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>480	95	[7] AAD	12AT	ATLS	B($b' \to Wt$) = 1
>450	95	[8] AAD	12BE	ATLS	B($b' \to Wt$) = 1
>611	95	[9] CHATRCHYAN	12X	CMS	B($b' \to Wt$) = 1
>372	95	[10] AALTONEN	11J	CDF	$b' \to Wt$
>361	95	[11] CHATRCHYAN	11L	CMS	Repl. by CHATRCHYAN 12X
>338	95	[12] AALTONEN	10H	CDF	$b' \to Wt$
> 380–430	95	[13] FLACCO	10	RVUE	$m_{b'} > m_{t'}$
>268	95	[14,15] AALTONEN	07C	CDF	B($b' \to Zb$) = 1 assumed
>199	95	[16] AFFOLDER	00	CDF	NC: $b' \to Zb$
>148	95	[17] ABE	98N	CDF	NC: $b' \to Zb$ +decay vertex
> 96	95	[18] ABACHI	97D	D0	NC: $b' \to b\gamma$
>128	95	[19] ABACHI	95F	D0	$\ell\ell$ + jets, ℓ + jets
> 75	95	[20] MUKHOPAD...	93	RVUE	NC: $b' \to b\ell\ell$
> 85	95	[21] ABE	92	CDF	CC: $\ell\ell$
> 72	95	[22] ABE	90B	CDF	CC: $e + \mu$
> 54	95	[23] AKESSON	90	UA2	CC: e + jets + missing E_T
> 43	95	[24] ALBAJAR	90B	UA1	CC: μ + jets
> 34	95	[25] ALBAJAR	88	UA1	CC: e or μ + jets

[1] Based on 5.0 fb^{-1} of pp data at $\sqrt{s}$ = 7 TeV. CHATRCHYAN 13I looked for events with one isolated electron or muon, large $\not{E}_T$, and at least four jets with large transverse momenta, where one jet is likely to originate from the decay of a bottom quark.

[2] Based on 2.0 fb^{-1} of pp data at $\sqrt{s}$ = 7 TeV. No $b' \to Zb$ invariant mass peak is found in the search of heavy quark pair production that decay into Z and a b quark in events with $Z \to e^+e^-$ and at least one b-jet. The lower mass limit is 358 GeV for a vector-like singlet b' mixing solely with the third SM generation.

[3] Based on 1.04 fb^{-1} of pp data at $\sqrt{s}$ = 7 TeV. No signal is found for the search of heavy quark pair production that decay into W and a quark in the events with dileptons, large $\not{E}_T$, and $\geq$ 2 jets.

[4] Based on 5 fb^{-1} of pp data at $\sqrt{s}$ = 7 TeV. CHATRCHYAN 12BH searched for QCD and EW production of single and pair of degenerate 4'th generation quarks that decay to bW or tW. Absence of signal in events with one lepton, same-sign dileptons or tri-leptons gives the bound. With a mass difference of 25 GeV/c^2 between $m_{t'}$ and $m_{b'}$, the corresponding limit shifts by about $\pm$20 GeV/c^2.

[5] 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.

[6] 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.

[7] Based on 1.04 fb^{-1} of pp data at $\sqrt{s} = 7$ TeV. No signal is found for the search of heavy quark pair production that decay into W and a t quark in the events with a high p_T isolated lepton, large $\not{E}_T$, and at least 6 jets in which one, two or more dijets are from W.

[8] Based on 1.04 fb^{-1} of pp data at $\sqrt{s} = 7$ TeV. AAD 12BE looked for events with two isolated like-sign leptons and at least 2 jets, large $\not{E}_T$ and $H_T > 350$ GeV.

[9] Based on 4.9 fb^{-1} of pp data at $\sqrt{s} = 7$ TeV. CHATRCHYAN 12X looked for events with trileptons or same-sign dileptons and at least one b jet.

[10] Based on 4.8 fb^{-1} of data in $p\overline{p}$ collisions at 1.96 TeV. AALTONEN 11J looked for events with $\ell + \not{E}_T + \geq 5$j (≥ 1 b or c). No signal is observed and the bound $\sigma(b'\overline{b}')$ < 30 fb for $m_{b'} > 375$ GeV is found for $B(b' \rightarrow Wt) = 1$.

[11] 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 $B(b' \rightarrow Wt) = 1$.

[12] Based on 2.7 fb^{-1} of data in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ 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^+, $m_{T_{5/3}} > 365$ GeV (95% CL) is found when it has the charge $-1/3$ partner B of the same mass.

[13] FLACCO 10 result is obtained from AALTONEN 10H result of $m_{b'} > 338$ GeV, by relaxing the condition $B(b' \rightarrow Wt) = 100\%$ when $m_{b'} > m_{t'}$.

[14] 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($b' \rightarrow Zb$))^2] and the LO estimate of the b' pair production cross section shown in Fig. 38 of the article.

[15] HUANG 08 reexamined the b' mass lower bound of 268 GeV obtained in AALTONEN 07C that assumes $B(b' \rightarrow Zb) = 1$, which does not hold for $m_{b'} > 255$ GeV. The lower mass bound is given in the plane of $\sin^2(\theta_{tb'})$ and $m_{b'}$.

[16] 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 $B(b' \rightarrow Zb)$= 100%. Between 100 GeV and 199 GeV, the 95%CL upper bound on $\sigma(b' \rightarrow \overline{b}') \times B^2(b' \rightarrow Zb)$ is also given (see their Fig. 2).

[17] ABE 98N looked for $Z \rightarrow e^+e^-$ decays with displaced vertices. Quoted limit assumes $B(b' \rightarrow Zb)$=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.

[18] 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 $m_{b'} > m_Z + m_b$.

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

[20] 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.
[21] ABE 92 dilepton analysis limit of >85 GeV at CL=95% also applies to b' quarks, as discussed in ABE 90B.
[22] ABE 90B exclude the region 28–72 GeV.
[23] 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.
[24] For the reduction of the limit due to non-charged-current decay modes, see Fig. 19 of ALBAJAR 90B.
[25] 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.

b' mass limits from single production in $p\overline{p}$ and pp collisions

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>693	95	[26] ABAZOV	11F	D0	$qu \to q'b' \to q'(Wu)$ $\widetilde{\kappa}_{ub'}$=1, B($b' \to Wu$)=1
>430	95	[26] ABAZOV	11F	D0	$qd \to qb' \to q(Zd)$ $\widetilde{\kappa}_{db'}=\sqrt{2}$, B($b' \to Zd$)=1

[26] Based on 5.4 fb^{-1} of data in ppbar 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 $p\overline{p} \to b'q \to Wuq$, and $p\overline{p} \to b'q \to Zdq$ 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	[27] DECAMP	90F	ALEP	any decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 96–103	95	[28] ABDALLAH	07	DLPH	$b' \to bZ$, cW
		[29] ADRIANI	93G	L3	Quarkonium
>44.7	95	ADRIANI	93M	L3	Γ(Z)
>45	95	ABREU	91F	DLPH	Γ(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	[30] ABREU	90D	DLPH	$b' \to cH^-$, $H^- \to \overline{c}s$, $\tau^-\nu$
>40.5	95	[31] ABREU	90D	DLPH	Γ($Z \to$ hadrons)
>28.3	95	ADACHI	90	TOPZ	B(FCNC)=100%; isol. γ or 4 jets

>41.4	95	[32] AKRAWY	90B	OPAL	Any decay; acoplanarity
>45.2	95	[32] AKRAWY	90B	OPAL	B($C C$) = 1; acoplanarity
>46	95	[33] AKRAWY	90J	OPAL	$b' \rightarrow \gamma +$ any
>27.5	95	[34] ABE	89E	VNS	B($C C$) =1; μ, e
none 11.4–27.3	95	[35] ABE	89G	VNS	B($b' \rightarrow b\gamma$) > 10%; isolated γ
>44.7	95	[36] ABRAMS	89C	MRK2	B($C C$)= 100%; isol. track
>42.7	95	[36] ABRAMS	89C	MRK2	B($b g$)= 100%; event shape
>42.0	95	[36] ABRAMS	89C	MRK2	Any decay; event shape
>28.4	95	[37,38] ADACHI	89C	TOPZ	B($C C$) =1; μ
>28.8	95	[39] ENO	89	AMY	B($C C$) $\gtrsim$ 90%; μ, e
>27.2	95	[39,40] ENO	89	AMY	any decay; event shape
>29.0	95	[39] ENO	89	AMY	B($b' \rightarrow b g$) $\gtrsim$ 85%; event shape
>24.4	95	[41] IGARASHI	88	AMY	μ,e
>23.8	95	[42] SAGAWA	88	AMY	event shape
>22.7	95	[43] ADEVA	86	MRKJ	μ
>21		[44] ALTHOFF	84C	TASS	R, event shape
>19		[45] ALTHOFF	84I	TASS	Aplanarity

[27] DECAMP 90F looked for isolated charged particles, for isolated photons, and for four-jet final states. The modes $b' \rightarrow b g$ for B($b' \rightarrow b g$) > 65% $b' \rightarrow b\gamma$ for B($b' \rightarrow b\gamma$) > 5% are excluded. Charged Higgs decay were not discussed.

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

[29] 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.

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

[31] Superseded by ABREU 91F.

[32] 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.

[33] 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) < 2.2×10^{-3}. Mass limit assumes B($b' \rightarrow \gamma$X) > 10%.

[34] 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.

[35] ABE 89G search was at E_{cm} = 55–60.8 GeV at TRISTAN.

[36] 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 ($b' \rightarrow c H^-$, $H^- \rightarrow \overline{c} s$) is 45.2 GeV.

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

[38] ADACHI 89C also gives limits for any mixture of $C C$ and $b g$ decays.

[39] ENO 89 search at E_{cm} = 50–60.8 at TRISTAN.

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

[41] 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.

[42] 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.

[43] 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.

[44] 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%.

[45] 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

CHATRCHYAN	13I	JHEP 1301 154	S. Chatrchyan *et al.*	(CMS Collab.)
AAD	12AT	PRL 109 032001	G. Aad *et al.*	(ATLAS Collab.)
AAD	12AU	PRL 109 071801	G. Aad *et al.*	(ATLAS Collab.)
AAD	12BC	PR D86 012007	G. Aad *et al.*	(ATLAS Collab.)
AAD	12BE	JHEP 1204 069	G. Aad *et al.*	(ATLAS Collab.)
CHATRCHYAN	12BH	PR D86 112003	S. Chatrchyan *et al.*	(CMS Collab.)
CHATRCHYAN	12X	JHEP 1205 123	S. Chatrchyan *et al.*	(CMS Collab.)
AALTONEN	11J	PRL 106 141803	T. Aaltonen *et al.*	(CDF Collab.)
ABAZOV	11F	PRL 106 081801	V.M. Abazov *et al.*	(D0 Collab.)
CHATRCHYAN	11L	PL B701 204	S. Chatrchyan *et al.*	(CMS Collab.)
AALTONEN	10H	PRL 104 091801	T. Aaltonen *et al.*	(CDF Collab.)
FLACCO	10	PRL 105 111801	C.J. Flacco *et al.*	(UCI, HAIF)
ATRE	09	PR D79 054018	A. Atre *et al.*	
ABAZOV	08X	PRL 101 111802	V.M. Abazov *et al.*	(D0 Collab.)
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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.)
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.)