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

$b'(-1/3)$-quark/hadron mass limits in $p\overline{p}$ and pp collisions

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>1530	95	[1] AAD	24BP	ATLS	$B(b' \to Wu) = 1$
>1540	95	[2] HAYRAPETY...	24AQ	CMS	$B(b' \to Zb) = 1$
>1570	95	[2] HAYRAPETY...	24AQ	CMS	$B(b' \to Hb) = 1$
>1560	95	[3] TUMASYAN	23V	CMS	$B(b' \to Wt) = 1$
>1570	95	[4] SIRUNYAN	20BI	CMS	$B(b' \to Hb) = 1$
>1000	95	[5] AABOUD	18CE	ATLS	$\geq 2\ell + \not{E}_T + \geq 1bj$
> 950	95	[6] AABOUD	18CL	ATLS	Wt, Zb, hb modes
>1010	95	[7,8] AABOUD	18CP	ATLS	2,3ℓ, singlet model
>1140	95	[6,9] AABOUD	18CP	ATLS	2,3ℓ, doublet model
>1220	95	[10,11] AABOUD	18CR	ATLS	singlet b'. ATLAS Combination
>1370	95	[10,12] AABOUD	18CR	ATLS	b' in a weak isospin doublet (t',b'). ATLAS combination.
> 730	95	[13] SIRUNYAN	17AU	CMS	
> 810	95	[14] AAD	15Z	ATLS	
> 190	95	[15] ABAZOV	08X	D0	$c\tau$= 200mm
> 190	95	[16] ACOSTA	03	CDF	quasi-stable b'
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>1460	95	[17] AAD	23AG	ATLS	$B(b' \to Wt) = 1$
>1420	95	[18] AAD	23AV	ATLS	$B(b' \to Zb) = 1$
>1390	95	[4] SIRUNYAN	20BI	CMS	$B(b' \to Zb) = 1$
>1130	95	[19] SIRUNYAN	19AQ	CMS	$B(b' \to Zb) = 1$
>1230	95	[20] SIRUNYAN	19BW	CMS	$B(b' \to Wt) = 1$
>1350	95	[21] AABOUD	18AW	ATLS	$B(b' \to Wt) = 1$
> 910	95	[22] SIRUNYAN	18BM	CMS	Wt, Zb, hb modes
> 845	95	[23] SIRUNYAN	18Q	CMS	$B(b' \to Wu) = 1$
> 880	95	[24] KHACHATRY...	16AN	CMS	$B(b' \to Wt) = 1$
<350, 580–635, >700	95	[25] AAD	15AR	ATLS	$B(b' \to Hb) = 1$
> 620	95	[26] AAD	15BY	ATLS	Wt, Zb, hb modes
> 730	95	[27] AAD	15BY	ATLS	$B(b' \to Wt) = 1$
> 690	95	[28] AAD	15CN	ATLS	$B(b' \to Wq) = 1$ (q=u)
> 755	95	[29] AAD	14AZ	ATLS	$B(b' \to Wt) = 1$
> 675	95	[30] CHATRCHYAN	13I	CMS	$B(b' \to Wt) = 1$
> 480	95	[31] AAD	12AT	ATLS	$B(b' \to Wt) = 1$
> 400	95	[32] AAD	12AU	ATLS	$B(b' \to Zb) = 1$
> 350	95	[33] AAD	12BC	ATLS	$B(b' \to Wq) = 1$ (q=u,c)
> 450	95	[34] AAD	12BE	ATLS	$B(b' \to Wt) = 1$
> 685	95	[35] CHATRCHYAN	12BH	CMS	$m_{t'} = m_{b'}$
> 611	95	[36] CHATRCHYAN	12X	CMS	$B(b' \to Wt) = 1$
> 372	95	[37] AALTONEN	11J	CDF	$b' \to Wt$

$>$ 361	95	[38] CHATRCHYAN	11L	CMS	Repl. by CHATRCHYAN 12X
$>$ 338	95	[39] AALTONEN	10H	CDF	$b' \to Wt$
$>$ 380–430	95	[40] FLACCO	10	RVUE	$m_{b'} > m_{t'}$
$>$ 268	95	[41,42] AALTONEN	07C	CDF	$B(b' \to Zb) = 1$
$>$ 199	95	[43] AFFOLDER	00	CDF	NC: $b' \to Zb$
$>$ 148	95	[44] ABE	98N	CDF	NC: $b' \to Zb$ + vertex
$>$ 96	95	[45] ABACHI	97D	D0	NC: $b' \to b\gamma$
$>$ 128	95	[46] ABACHI	95F	D0	$\ell\ell$ + jets, ℓ + jets
$>$ 75	95	[47] MUKHOPAD...	93	RVUE	NC: $b' \to b\ell\ell$
$>$ 85	95	[48] ABE	92	CDF	CC: $\ell\ell$
$>$ 72	95	[49] ABE	90B	CDF	CC: $e + \mu$
$>$ 54	95	[50] AKESSON	90	UA2	CC: e + jets + $\not{E}_T$
$>$ 43	95	[51] ALBAJAR	90B	UA1	CC: μ + jets
$>$ 34	95	[52] ALBAJAR	88	UA1	CC: e or μ + jets

[1] AAD 24BP based on 140 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. Limit on pair-production of heavy vectorlike quarks where each decays into a W boson and a light quark. Used events with $\ell + \not{E}_T$ + multiple jets + 1 boosted-W-jet.

[2] HAYRAPETYAN 24AQ based on 138 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. Pair production of vector-like b' is searched for in the fully hadronic final states and those containing $\ell^+\ell^-$ from a Z boson. The data are consistent with the SM background predictions and limits are obtained for different branching ratios $B(b' \to Hb)$, $B(b' \to Zb)$, $B(b' \to Wt)$.

[3] TUMASYAN 23V based on 138 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. Pair production of vector-like b' is seached for in the single-lepton, same-sign charge dilepton and multi-lepton channels. The data are consistent with the SM background predictions and limits are obtained for different branching ratios.

[4] SIRUNYAN 20BI based on 137 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. Pair production of vector-like b' is seached for with each b' decaying into Zb or hb. Analysis focuses on final states consisting of jets from six quarks. Mass limits are obtained for a variety of branching ratios of b' decays.

[5] AABOUD 18CE based on 36.1 fb^{-1} of proton-proton data taken at $\sqrt{s} = 13$ TeV. Events including a same-sign lepton pair are used. The limit is for a singlet model, assuming the branching ratios of b' into Zb, Wt and Hb as predicted by the model.

[6] AABOUD 18CL, AABOUD 18CP based on 36.1 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. The limit is for the pair-produced vector-like b' using all-hadronic final state. The analysis is particularly powerful for the $b' \to hb$ mode. Assuming the pure decay only in this mode sets a limit $m_{b'} > 1010$ GeV.

[7] AABOUD 18CP based on 36.1 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. Pair and single production of vector-like b' are seached for with at least one b' decaying into Zb. In the case of $B(b' \to Zb) = 1$, the limit is $m_{b'} > 1220$ GeV.

[8] The limit is for the singlet model, assuming that the branching ratios into Wt, Zb, hb add up to one.

[9] The limit is for the doublet model, assuming that the branching ratios into Wt, Zb, hb add up to one.

[10] AABOUD 18CR based on 36.1 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. A combination of searches for the pair-produced vector-like b' in various decay channels ($b' \to Wt$, Zb, hb). Also a model-independent limit is obtained as $m_{b'} > 1.03$ TeV, assuming that the branching ratios into Zb, Wt, and hb add up to one.

[11] The limit is for the singlet b'.

[12] The limit is for b' in a weak isospin doublet (t',b') and $|V_{t'b}| \ll |V_{tb'}|$. For a b' in a doublet with a charge $-4/3$ vector-like quark, the limit $m_{b'} > 1.14$ TeV is obtained.

[13] SIRUNYAN 17AU based on 2.3–2.6 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. Limit on pair-produced singlet vector-like b' using one lepton and several jets. The mass bound is given for a b' transforming as a singlet under the electroweak symmetry group, assumed to decay through W, Z or Higgs boson (which decays to jets) and to a third generation quark.

[14] AAD 15Z based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. Used events with $\ell + \not{E}_T + \geq 6$j (≥ 1 b) and at least one pair of jets from weak boson decay, primarily designed to select the signature $b'\overline{b}' \to WWt\overline{t} \to WWWWb\overline{b}$. This is a limit on pair-produced vector-like b'. The lower mass limit is 640 GeV for a vector-like singlet b'.

[15] 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.

[16] 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.

[17] AAD 23AG based on 139 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. Pair production of vector-like top or bs is searched for in the mode $1\ell + \geq 4$j($\geq$ 1b-tagged) + $\not{E}_T$. The data are consistent with the SM background predictions and limits are obtained for different branching ratios. Masses below 1.59 TeV are excluded assuming a mass-degenerate vector-like doublet (t',b') model.

[18] AAD 23AV based on 139 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. Pair production of vector-like b' is searched for in the mode $\ell^{\pm}\ell^{\mp} + \geq 2$j ($\geq$ 1b-tagged) + $\not{E}_T$ or with 3ℓ. The data are consistent with the SM background predictions and limits are obtained for different branching ratios.

[19] SIRUNYAN 19AQ based on 35.9 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. Pair production of vector-like b' is seached for with one b' decaying into Zb and the other b' decaying into Wt, Zb, hb. Events with an opposite-sign lepton pair consistent with coming from Z and jets are used. Mass limits are obtained for a variety of branching ratios of b'.

[20] SIRUNYAN 19BW based on 35.9 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. The limit is for the pair-produced vector-like b' using all-hadronic final state. The analysis is made for the Zb, Wt, hb modes and mass limits are obtained for a variety of branching ratios.

[21] AABOUD 18AW based on 36.1 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. The limit is for the pair-produced vector-like b' using lepton-plus-jets final state. The search is also sensitive to the decays into Zb and Hb final states.

[22] SIRUNYAN 18BM based on 35.9 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. The limit is for the pair-produced vector-like b'. Three channels (single lepton, same-charge 2 leptons, or at least 3 leptons) are considered for various branching fraction combinations. Assuming $B(tW) = 1$, the limit is 1240 GeV and for $B(bZ) = 1$ it is 960 GeV.

[23] SIRUNYAN 18Q based on 19.7 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. The limit is for the pair-produced vector-like b' that couple only to light quarks. Upper cross section limits on the single production of a b' and constraints for other decay channels (Zq and Hq) are also given in the paper.

[24] KHACHATRYAN 16AN based on 19.7 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. Limit on pair-produced vector-like b' using 1, 2, and >2 leptons as well as fully hadronic final states. Other limits depending on the branching fractions to tW, bZ, and bH are given in Table IX.

[25] AAD 15AR based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. Used lepton-plus-jets final state. See Fig. 24 for mass limits in the plane of B($b' \rightarrow Wt$) vs. B($b' \rightarrow Hb$) from $b'\overline{b}' \rightarrow Hb + X$ searches.

[26] AAD 15BY based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. Limit on pair-produced vector-like b' assuming the branching fractions to W, Z, and h modes of the singlet model. Used events containing $\geq 2\ell + \not{E}_T + \geq 2$j (≥ 1 b) and including a same-sign lepton pair.

[27] AAD 15BY based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. Limit on pair-produced chiral b'-quark. Used events containing $\geq 2\ell + \not{E}_T + \geq 2$j (≥ 1 b) and including a same-sign lepton pair.

[28] AAD 15CN based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. Limit on pair-production of chiral b'-quark. Used events with $\ell + \not{E}_T + \geq 4$j (non-$b$-tagged). Limits on a heavy vector-like quark, which decays into Wq, Zq, hq, are presented in the plane B($Q \rightarrow Wq$) vs. B($Q \rightarrow hq$) in Fig. 12.

[29] Based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. No significant excess over SM expectation is found in the search for pair production or single production of b' in the events with dilepton from a high p_T Z and additional jets ($\geq$ 1 b-tag). If instead of B($b' \rightarrow Wt$) $= 1$ an electroweak singlet with B($b' \rightarrow Wt$) $\sim$ 0.45 is assumed, the limit reduces to 685 GeV.

[30] 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.

[31] 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.

[32] Based on 2.0 fb^{-1} of pp data at $\sqrt{s} = 7$ TeV. No $b' \rightarrow Zb$ invariant mass peak is found in the search of heavy quark pair production that decay into Z and a b quark in events with $Z \rightarrow e^+e^-$ 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.

[33] 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 ≥ 2 jets.

[34] 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.

[35] 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 trileptons gives the bound. With a mass difference of 25 GeV/c^2 between $m_{t'}$ and $m_{b'}$, the corresponding limit shifts by about ± 20 GeV/c^2.

[36] 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.

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

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

[39] 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.

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

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

[42] HUANG 08 reexamined the b' mass lower bound of 268 GeV obtained in AALTONEN 07C that assumes B($b' \to Zb$) = 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 $m_{b'}$.

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

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

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

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

[47] 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.

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

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

[50] 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.

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

[52] 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.

$b'(-1/3)$ mass limits from single production in $p\overline{p}$ and pp collisions

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>3000	95	[1] TUMASYAN	22O	CMS	$gb \to b' \to tW$, B($b' \to tW$)=1
> 693	95	[2] ABAZOV	11F	D0	$qu \to q'b' \to q'(Wu)$ $\widetilde{\kappa}_{ub'}$=1, B($b' \to Wu$)=1
> 430	95	[2] ABAZOV	11F	D0	$qd \to qb' \to q(Zd)$ $\widetilde{\kappa}_{db'}=\sqrt{2}$, B($b' \to Zd$)=1

• • • We do not use the following data for averages, fits, limits, etc. • • •

		[3] AAD	23CQ	ATLS	$b' \to b h$ ($h \to b\overline{b}$)
>2600	95	[4] SIRUNYAN	21AG	CMS	$g b \to b' \to t W$, B($b' \to t W$)=1
		[5] SIRUNYAN	19AI	CMS	$b Z / t W \to b' \to t W$
>1500	95	[6] AAD	16AH	ATLS	$g b \to b' \to t W$, B($b' \to t W$)=1
>1390	95	[7] KHACHATRY...	16I	CMS	$g b \to b'_L \to t W$, B($b'_L \to t W$)=1
>1430	95	[8] KHACHATRY...	16I	CMS	$g b \to b'_R \to t W$, B($b'_R \to t W$)=1
>1530	95	[9] KHACHATRY...	16I	CMS	$g b \to b' \to t W$, B($b' \to t W$)=1

[1] TUMASYAN 22O based on 138 fb^{-1} of data in pp collisions at 13 TeV. No significant excess over SM expectation is found in the search for a left-handed b' assuming 100% decay to tW using a t-tagged jet and a lepton from W. The model assumes that the b' has the excited quark couplings. The bound is from a statistical combination with an earlier analysis by SIRUNYAN 21AG. The 95% CL bounds are also set as 3.0, 3.0, and 3.2 TeV, respectively, for left-handed, right-handed, and vector-like couplings.

[2] ABAZOV 11F 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 $p\overline{p} \to b' q \to W u q$, and $p\overline{p} \to b' q \to Z d q$ 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.

[3] AAD 23CQ based on 139 fb^{-1} of data in pp collisions at 13 TeV. No significant excess over SM expectation is found. Limits on mass and production cross section of a vector-like b' are obtained in several theoretical scenarios determined by the couplings betwen b' and W, Z, h.

[4] SIRUNYAN 21AG based on 137 fb^{-1} of data in pp collisions at 13 TeV. No significant excess over SM expectation is found in the search for a left-handed b' assuming 100% decay to tW using all hadronic final states, where t and W are tagged as single jets, respectively. The model assumes that the b' has the excited quark couplings. The 95% CL bounds are also set as 2.8 and 3.1 TeV, respectively, for the right-handed and vector-like couplings.

[5] SIRUNYAN 19AI based on 35.9 fb^{-1} of pp data at $\sqrt{s} = 13$ TeV. Exclusion limits are set on the product of the production cross section and branching fraction for the $b'(-1/3) +\ b$ and $b'(-1/3) +\ t$ modes as a function of the vector-like quark mass in Figs. 7 and 8 and in Tab. 2 for relative vector-like quark widths between 1 and 30% for left- and right-handed vector-like quark couplings. No significant deviation from the SM prediction is observed.

[6] AAD 16AH based on 20.3 fb^{-1} of data in pp collisions at 8 TeV. No significant excess over SM expectation is found in the search for a vector-like b' in the single-lepton and dilepton channels (ℓ or $\ell\ell$) + 1,2,3 j ($\geq 1b$). The model assumes that the b' has the excited quark couplings.

[7] Based on 19.7 fb^{-1} of data in pp collisions at 8 TeV. Limit on left-handed b' assuming 100% decay to tW and using all-hadronic, lepton + jets, and dilepton final states.

[8] Based on 19.7 fb^{-1} of data in pp collisions at 8 TeV. Limit on right-handed b' assuming 100% decay to tW and using all-hadronic, lepton + jets, and dilepton final states.

[9] Based on 19.7 fb^{-1} of data in pp collisions at 8 TeV. Limit on vector-like b' assuming 100% decay to tW and using all-hadronic, lepton+jets, and dilepton final states.

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	[1]	DECAMP	90F	ALEP	any decay
• • • We do not use the following data for averages, fits, limits, etc. • • •						
none 96–103	95	[2]	ABDALLAH	07	DLPH	$b' \to bZ$, cW
		[3]	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	[4]	ABREU	90D	DLPH	$b' \to cH^-$, $H^- \to \overline{c}s$, $\tau^-\nu$
>40.5	95	[5]	ABREU	90D	DLPH	$\Gamma(Z \to \text{hadrons})$
>28.3	95		ADACHI	90	TOPZ	B(FCNC)=100%; isol. γ or 4 jets
>41.4	95	[6]	AKRAWY	90B	OPAL	Any decay; acoplanarity
>45.2	95	[6]	AKRAWY	90B	OPAL	$B(CC) = 1$; acoplanarity
>46	95	[7]	AKRAWY	90J	OPAL	$b' \to \gamma + \text{any}$
>27.5	95	[8]	ABE	89E	VNS	$B(CC)=1$; μ, e
none 11.4–27.3	95	[9]	ABE	89G	VNS	$B(b' \to b\gamma) > 10\%$; isolated γ
>44.7	95	[10]	ABRAMS	89C	MRK2	$B(CC)= 100\%$; isol. track
>42.7	95	[10]	ABRAMS	89C	MRK2	$B(bg)= 100\%$; event shape
>42.0	95	[10]	ABRAMS	89C	MRK2	Any decay; event shape
>28.4	95	[11,12]	ADACHI	89C	TOPZ	$B(CC)=1$; μ
>28.8	95	[13]	ENO	89	AMY	$B(CC) \gtrsim 90\%$; μ, e
>27.2	95	[13,14]	ENO	89	AMY	any decay; event shape
>29.0	95	[13]	ENO	89	AMY	$B(b' \to bg) \gtrsim 85\%$; event shape
>24.4	95	[15]	IGARASHI	88	AMY	μ,e
>23.8	95	[16]	SAGAWA	88	AMY	event shape
>22.7	95	[17]	ADEVA	86	MRKJ	μ
>21		[18]	ALTHOFF	84C	TASS	R, event shape
>19		[19]	ALTHOFF	84I	TASS	Aplanarity

[1] 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.

[2] 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 $B(b' \to bZ)$ and $B(b' \to cW)$ for $m_{b'} = 96$ to 103 GeV.

[3] 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.

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

[5] Superseded by ABREU 91F.

[6] 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.

[7] 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 $B(b' \to \gamma X) > 10\%$.

[8] 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.

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

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

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

[12] ADACHI 89C also gives limits for any mixture of CC and bg decays.

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

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

[15] 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.

[16] 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.

[17] 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.

[18] 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%.

[19] ALTHOFF 84I exclude heavy quark pair production for 7 < m <19 GeV (1/3 charge) using aplanarity distributions (CL = 95%).

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