

b' (4th Generation) Quark, Searches for

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

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>1350	95	1 AABOUD	18AW ATLS	$B(b' \rightarrow W t) = 1$
>1000	95	2 AABOUD	18CE ATLS	$\geq 2\ell + \cancel{E}_T + \geq 1b_j$
> 950	95	3 AABOUD	18CL ATLS	$W t, Z b, h b$ modes
>1010	95	4,5 AABOUD	18CP ATLS	2,3 ℓ , singlet model
>1140	95	3,6 AABOUD	18CP ATLS	2,3 ℓ , doublet model
>1220	95	7,8 AABOUD	18CR ATLS	singlet b'. ATLAS Combination
>1370	95	7,9 AABOUD	18CR ATLS	b' in a weak isospin doublet (t', b'). ATLAS combination.
> 910	95	10 SIRUNYAN	18BM CMS	$W t, Z b, h b$ modes
> 845	95	11 SIRUNYAN	18Q CMS	$B(b' \rightarrow W u) = 1$
> 730	95	12 SIRUNYAN	17AU CMS	
> 880	95	13 KHACHATRY...	16AN CMS	$B(b' \rightarrow W t) = 1$
> 620	95	14 AAD	15BY ATLS	$W t, Z b, h b$ modes
> 730	95	15 AAD	15BY ATLS	$B(b' \rightarrow W t) = 1$
> 810	95	16 AAD	15Z ATLS	
> 755	95	17 AAD	14AZ ATLS	$B(b' \rightarrow W t) = 1$
> 675	95	18 CHATRCHYAN	13I CMS	$B(b' \rightarrow W t) = 1$
> 190	95	19 ABAZOV	08X D0	$c\tau = 200\text{mm}$
> 190	95	20 ACOSTA	03 CDF	quasi-stable b'
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
<350, 580–635, >700	95	21 AAD	15AR ATLS	$B(b' \rightarrow H b) = 1$
> 690	95	22 AAD	15CN ATLS	$B(b' \rightarrow W q) = 1$ (q=u)
> 480	95	23 AAD	12AT ATLS	$B(b' \rightarrow W t) = 1$
> 400	95	24 AAD	12AU ATLS	$B(b' \rightarrow Z b) = 1$
> 350	95	25 AAD	12BC ATLS	$B(b' \rightarrow W q) = 1$ (q=u,c)
> 450	95	26 AAD	12BE ATLS	$B(b' \rightarrow W t) = 1$
> 685	95	27 CHATRCHYAN	12BH CMS	$m_{t'} = m_{b'}$
> 611	95	28 CHATRCHYAN	12X CMS	$B(b' \rightarrow W t) = 1$
> 372	95	29 AALTONEN	11J CDF	$b' \rightarrow W t$
> 361	95	30 CHATRCHYAN	11L CMS	Repl. by CHATRCHYAN 12X
> 338	95	31 AALTONEN	10H CDF	$b' \rightarrow W t$
> 380–430	95	32 FLACCO	10 RVUE	$m_{b'} > m_{t'}$
> 268	95	33,34 AALTONEN	07C CDF	$B(b' \rightarrow Z b) = 1$
> 199	95	35 AFFOLDER	00 CDF	NC: $b' \rightarrow Z b$
> 148	95	36 ABE	98N CDF	NC: $b' \rightarrow Z b + \text{vertex}$
> 96	95	37 ABACHI	97D D0	NC: $b' \rightarrow b\gamma$
> 128	95	38 ABACHI	95F D0	$\ell\ell + \text{jets}, \ell + \text{jets}$
> 75	95	39 MUKHOPAD...	93 RVUE	NC: $b' \rightarrow b\ell\ell$

> 85	95	40 ABE	92	CDF	CC: $\ell\ell$
> 72	95	41 ABE	90B	CDF	CC: $e + \mu$
> 54	95	42 AKESSON	90	UA2	CC: $e + \text{jets} + \cancel{E}_T$
> 43	95	43 ALBAJAR	90B	UA1	CC: $\mu + \text{jets}$
> 34	95	44 ALBAJAR	88	UA1	CC: e or $\mu + \text{jets}$

- ¹ AABOUD 18AW based on 36.1 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. 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.
- ² AABOUD 18CE based on 36.1 fb^{-1} of proton-proton data taken at $\sqrt{s} = 13 \text{ TeV}$. 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.
- ³ AABOUD 18CL, AABOUD 18CP based on 36.1 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. The limit is for the pair-produced vector-like b' using all-hadronic final state. The analysis is particularly powerful for the $b' \rightarrow hb$ mode. Assuming the pure decay only in this mode sets a limit $m_{b'} > 1010 \text{ GeV}$.
- ⁴ AABOUD 18CP based on 36.1 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. Pair and single production of vector-like b' are searched for with at least one b' decaying into Zb . In the case of $B(b' \rightarrow Zb) = 1$, the limit is $m_{b'} > 1220 \text{ GeV}$.
- ⁵ The limit is for the singlet model, assuming that the branching ratios into Wt , Zb , hb add up to one.
- ⁶ The limit is for the doublet model, assuming that the branching ratios into Wt , Zb , hb add up to one.
- ⁷ AABOUD 18CR based on 36.1 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. A combination of searches for the pair-produced vector-like b' in various decay channels ($b' \rightarrow Wt$, Zb , hb). Also a model-independent limit is obtained as $m_{b'} > 1.03 \text{ TeV}$, assuming that the branching ratios into Zb , Wt , and hb add up to one.
- ⁸ The limit is for the singlet b' .
- ⁹ 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 $m_{b'} > 1.14 \text{ TeV}$ is obtained.
- ¹⁰ SIRUNYAN 18BM based on 35.9 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. 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 .
- ¹¹ SIRUNYAN 18Q based on 19.7 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. 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.
- ¹² SIRUNYAN 17AU based on $2.3\text{--}2.6 \text{ fb}^{-1}$ of pp data at $\sqrt{s} = 13 \text{ TeV}$. 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.
- ¹³ KHACHATRYAN 16AN based on 19.7 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. 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.
- ¹⁴ AAD 15BY based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. Limit on pair-produced vector-like b' assuming the branching fractions to W , Z , and h modes of the singlet model. Used events containing $\geq 2\ell + \cancel{E}_T + \geq 2j$ ($\geq 1 b$) and including a same-sign lepton pair.

- ¹⁵ AAD 15BY based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. Limit on pair-produced chiral b' -quark. Used events containing $\geq 2\ell + \cancel{E}_T + \geq 2j$ ($\geq 1 b$) and including a same-sign lepton pair.
- ¹⁶ AAD 15Z based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. Used events with $\ell + \cancel{E}_T + \geq 6j$ ($\geq 1 b$) and at least one pair of jets from weak boson decay, primarily designed to select the signature $b'\bar{b}' \rightarrow WWt\bar{t} \rightarrow WWWWb\bar{b}$. This is a limit on pair-produced vector-like b' . The lower mass limit is 640 GeV for a vector-like singlet b' .
- ¹⁷ Based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. 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.
- ¹⁸ Based on 5.0 fb^{-1} of pp data at $\sqrt{s} = 7 \text{ TeV}$. CHATRCHYAN 13I looked for events with one isolated electron or muon, large \cancel{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.
- ¹⁹ 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 $2 < c\tau < 7000 \text{ mm}$; see Fig. 3. 95% CL excluded region of b' lifetime and mass is shown in Fig. 4.
- ²⁰ ACOSTA 03 looked for long-lived fourth generation quarks in the data sample of 90 pb^{-1} of $\sqrt{s}=1.8 \text{ TeV } p\bar{p}$ 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.
- ²¹ AAD 15AR based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. 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 $b'\bar{b}' \rightarrow Hb + X$ searches.
- ²² AAD 15CN based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. Limit on pair-production of chiral b' -quark. Used events with $\ell + \cancel{E}_T + \geq 4j$ (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.
- ²³ Based on 1.04 fb^{-1} of pp data at $\sqrt{s} = 7 \text{ TeV}$. 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 \cancel{E}_T , and at least 6 jets in which one, two or more dijets are from W .
- ²⁴ Based on 2.0 fb^{-1} of pp data at $\sqrt{s} = 7 \text{ TeV}$. 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.
- ²⁵ Based on 1.04 fb^{-1} of pp data at $\sqrt{s} = 7 \text{ TeV}$. 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 \cancel{E}_T , and ≥ 2 jets.
- ²⁶ Based on 1.04 fb^{-1} of pp data at $\sqrt{s} = 7 \text{ TeV}$. AAD 12BE looked for events with two isolated like-sign leptons and at least 2 jets, large \cancel{E}_T and $H_T > 350 \text{ GeV}$.
- ²⁷ Based on 5 fb^{-1} of pp data at $\sqrt{s} = 7 \text{ TeV}$. 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 tripletons gives the bound. With a mass difference of $25 \text{ GeV}/c^2$ between $m_{t'}$ and $m_{b'}$, the corresponding limit shifts by about $\pm 20 \text{ GeV}/c^2$.
- ²⁸ Based on 4.9 fb^{-1} of pp data at $\sqrt{s} = 7 \text{ TeV}$. CHATRCHYAN 12X looked for events with tripletons or same-sign dileptons and at least one b jet.

- ²⁹ Based on 4.8 fb^{-1} of data in $p\bar{p}$ collisions at 1.96 TeV. AALTONEN 11J looked for events with $\ell + \cancel{E}_T + \geq 5j$ (≥ 1 b or c). No signal is observed and the bound $\sigma(b'\bar{b}') < 30 \text{ fb}$ for $m_{b'} > 375 \text{ GeV}$ is found for $B(b' \rightarrow Wt) = 1$.
- ³⁰ 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 $B(b' \rightarrow Wt) = 1$.
- ³¹ Based on 2.7 fb^{-1} of data in $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$. 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^+ , $m_{T_{5/3}} > 365 \text{ GeV}$ (95% CL) is found when it has the charge $-1/3$ partner B of the same mass.
- ³² FLACCO 10 result is obtained from AALTONEN 10H result of $m_{b'} > 338 \text{ GeV}$, by relaxing the condition $B(b' \rightarrow Wt) = 100\%$ when $m_{b'} > m_{t'}$.
- ³³ 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 $\sigma(b'\bar{b}') [1-(1-B(b' \rightarrow Zb))^2]$ and the LO estimate of the b' pair production cross section shown in Fig. 38 of the article.
- ³⁴ 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 $m_{b'} > 255 \text{ GeV}$. The lower mass bound is given in the plane of $\sin^2(\theta_{tb'})$ and $m_{b'}$.
- ³⁵ AFFOLDER 00 looked for b' that decays into $b+Z$. 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 $\sigma(b' \rightarrow \bar{b}') \times B^2(b' \rightarrow Zb)$ is also given (see their Fig. 2).
- ³⁶ ABE 98N looked for $Z \rightarrow e^+e^-$ decays with displaced vertices. Quoted limit assumes $B(b' \rightarrow Zb) = 1$ and $c\tau_{b'} = 1 \text{ cm}$. The limit is lower than $m_Z + m_b$ ($\sim 96 \text{ GeV}$) if $c\tau > 22 \text{ cm}$ or $c\tau < 0.009 \text{ cm}$. See their Fig. 4.
- ³⁷ ABACHI 97D searched for b' that decays mainly via FCNC. They obtained 95%CL upper bounds on $B(b'\bar{b}' \rightarrow \gamma + 3 \text{ jets})$ and $B(b'\bar{b}' \rightarrow 2\gamma + 2 \text{ jets})$, which can be interpreted as the lower mass bound $m_{b'} > m_Z + m_b$.
- ³⁸ ABACHI 95F bound on the top-quark also applies to b' and t' quarks that decay predominantly into W . See FROGGATT 97.
- ³⁹ 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.
- ⁴⁰ ABE 92 dilepton analysis limit of $>85 \text{ GeV}$ at CL=95% also applies to b' quarks, as discussed in ABE 90B.
- ⁴¹ ABE 90B exclude the region 28–72 GeV.
- ⁴² AKESSON 90 searched for events having an electron with $p_T > 12 \text{ GeV}$, missing momentum $> 15 \text{ GeV}$, and a jet with $E_T > 10 \text{ GeV}$, $|\eta| < 2.2$, and excluded $m_{b'}$ between 30 and 69 GeV.
- ⁴³ For the reduction of the limit due to non-charged-current decay modes, see Fig. 19 of ALBAJAR 90B.
- ⁴⁴ ALBAJAR 88 study events at $E_{\text{cm}} = 546$ 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 $b'\bar{b}'$ 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 $p\bar{p}$ and pp collisions

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>1500	95	¹ AAD	16AH ATLS	$gb \rightarrow b' \rightarrow tW, B(b' \rightarrow tW)=1$
>1390	95	² KHACHATRY...16I	CMS	$gb \rightarrow b' \rightarrow tW, B(b' \rightarrow tW)=1$
>1430	95	³ KHACHATRY...16I	CMS	$gb \rightarrow b' \rightarrow tW, B(b' \rightarrow tW)=1$
> 1530	95	⁴ KHACHATRY...16I	CMS	$gb \rightarrow b' \rightarrow tW, B(b' \rightarrow tW)=1$
> 693	95	⁵ ABAZOV	11F D0	$qu \rightarrow q'b' \rightarrow q'(Wu)$ $\tilde{\kappa}_{ub'}=1, B(b' \rightarrow Wu)=1$
> 430	95	⁵ ABAZOV	11F D0	$qd \rightarrow qb' \rightarrow q(Zd)$ $\tilde{\kappa}_{db'}=\sqrt{2}, B(b' \rightarrow Zd)=1$

¹ 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.

² 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.

³ 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.

⁴ 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.

⁵ Based on 5.4 fb^{-1} of data in $p\bar{p}$ 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 $p\bar{p} \rightarrow b'q \rightarrow Wuq$, and $p\bar{p} \rightarrow b'q \rightarrow Zdq$ 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	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	$b' \rightarrow bZ, cW$
		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	$b' \rightarrow cH^-, H^- \rightarrow \bar{c}s, \tau^- \nu$
>40.5	95	⁵ ABREU	90D DLPH	$\Gamma(Z \rightarrow \text{hadrons})$
>28.3	95	ADACHI	90 TOPZ	$B(\text{FCNC})=100\%$; 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	$b' \rightarrow \gamma + \text{any}$
>27.5	95	8 ABE	89E VNS	$B(CC) = 1$; μ, e
none 11.4–27.3	95	9 ABE	89G VNS	$B(b' \rightarrow b\gamma) > 10\%$; 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	$B(b' \rightarrow bg) \gtrsim 85\%$; 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 $b' \rightarrow bg$ for $B(b' \rightarrow bg) > 65\%$ $b' \rightarrow b\gamma$ for $B(b' \rightarrow b\gamma) > 5\%$ are excluded. Charged Higgs decay were not discussed.

² ABDALLAH 07 searched for b' pair production at $E_{\text{cm}} = 196\text{--}209$ GeV, with 420 pb^{-1} . No signal leads to the 95% CL upper limits on $B(b' \rightarrow bZ)$ and $B(b' \rightarrow cW)$ 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 $\delta m^2 < (10\text{--}30) \text{ GeV}^2$ (95%CL) for the mass 88–94.5 GeV. Using Richardson potential, a 1S ($b'\bar{b}'$) 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 $E_{\text{cm}} = 91.26$ 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 $(m_{H^+} + 1.5 \text{ GeV})$ and 45.5 GeV.

⁷ AKRAWY 90J search for isolated photons in hadronic Z decay and derive $B(Z \rightarrow b'\bar{b}') \cdot B(b' \rightarrow \gamma X) / B(Z \rightarrow \text{hadrons}) < 2.2 \times 10^{-3}$. Mass limit assumes $B(b' \rightarrow \gamma X) > 10\%$.

⁸ ABE 89E search at $E_{\text{cm}} = 56\text{--}57$ GeV at TRISTAN for multihadron events with a spherical shape (using thrust and acoplanarity) or containing isolated leptons.

⁹ ABE 89G search was at $E_{\text{cm}} = 55\text{--}60.8$ GeV at TRISTAN.

¹⁰ If the photonic decay mode is large ($B(b' \rightarrow b\gamma) > 25\%$), the ABRAMS 89C limit is 45.4 GeV. The limit for Higgs decay ($b' \rightarrow cH^-$, $H^- \rightarrow \bar{c}s$) is 45.2 GeV.

¹¹ ADACHI 89C search was at $E_{\text{cm}} = 56.5\text{--}60.8$ 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 $E_{\text{cm}} = 50\text{--}60.8$ 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 $E_{\text{cm}} = 52$ 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 $E_{\text{cm}} = 45.4$ GeV.
- ¹⁸ 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%.
- ¹⁹ 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

AABOUD	18AW	JHEP 1808 048	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18CE	JHEP 1812 039	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18CL	PR D98 092005	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18CP	PR D98 112010	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18CR	PRL 121 211801	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
SIRUNYAN	18BM	JHEP 1808 177	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	18Q	PR D97 072008	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	17AU	JHEP 1711 085	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
AAD	16AH	JHEP 1602 110	G. Aad <i>et al.</i>	(ATLAS Collab.)
KHACHATRY...	16AN	PR D93 112009	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	16I	JHEP 1601 166	V. Khachatryan <i>et al.</i>	(CMS Collab.)
AAD	15AR	JHEP 1508 105	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15BY	JHEP 1510 150	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15CN	PR D92 112007	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15Z	PR D91 112011	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	14AZ	JHEP 1411 104	G. Aad <i>et al.</i>	(ATLAS Collab.)
CHATRCHYAN	13I	JHEP 1301 154	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
AAD	12AT	PRL 109 032001	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12AU	PRL 109 071801	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12BC	PR D86 012007	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12BE	JHEP 1204 069	G. Aad <i>et al.</i>	(ATLAS Collab.)
CHATRCHYAN	12BH	PR D86 112003	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	12X	JHEP 1205 123	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
AALTONEN	11J	PRL 106 141803	T. Aaltonen <i>et al.</i>	(CDF Collab.)
ABAZOV	11F	PRL 106 081801	V.M. Abazov <i>et al.</i>	(D0 Collab.)
CHATRCHYAN	11L	PL B701 204	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
AALTONEN	10H	PRL 104 091801	T. Aaltonen <i>et al.</i>	(CDF Collab.)
FLACCO	10	PRL 105 111801	C.J. Flacco <i>et al.</i>	(UCI, HAIF)
ATRE	09	PR D79 054018	A. Atre <i>et al.</i>	
ABAZOV	08X	PRL 101 111802	V.M. Abazov <i>et al.</i>	(D0 Collab.)
HUANG	08	PR D77 037302	P.Q. Hung, M. Sher	(UVA, WILL)
AALTONEN	07C	PR D76 072006	T. Aaltonen <i>et al.</i>	(CDF Collab.)
ABDALLAH	07	EPJ C50 507	J. Abdallah <i>et al.</i>	(DELPHI Collab.)
ACOSTA	03	PRL 90 131801	D. Acosta <i>et al.</i>	(CDF Collab.)
AFFOLDER	00	PRL 84 835	A. Affolder <i>et al.</i>	(CDF Collab.)
ABE	98N	PR D58 051102	F. Abe <i>et al.</i>	(CDF Collab.)
ABACHI	97D	PRL 78 3818	S. Abachi <i>et al.</i>	(D0 Collab.)
FROGGATT	97	ZPHY C73 333	C.D. Froggatt, D.J. Smith, H.B. Nielsen	(GLAS+)
ABACHI	95F	PR D52 4877	S. Abachi <i>et al.</i>	(D0 Collab.)
ADRIANI	93G	PL B313 326	O. Adriani <i>et al.</i>	(L3 Collab.)
ADRIANI	93M	PRPL 236 1	O. Adriani <i>et al.</i>	(L3 Collab.)
MUKHOPAD...	93	PR D48 2105	B. Mukhopadhyaya, D.P. Roy	(TATA)
ABE	92	PRL 68 447	F. Abe <i>et al.</i>	(CDF Collab.)
Also		PR D45 3921	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	92G	PR D45 3921	F. Abe <i>et al.</i>	(CDF Collab.)
ABREU	91F	NP B367 511	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ABE	90B	PRL 64 147	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	90D	PL B234 382	K. Abe <i>et al.</i>	(VENUS Collab.)

ABREU	90D	PL B242 536	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ADACHI	90	PL B234 197	I. Adachi <i>et al.</i>	(TOPAZ Collab.)
AKESSON	90	ZPHY C46 179	T. Akesson <i>et al.</i>	(UA2 Collab.)
AKRAWY	90B	PL B236 364	M.Z. Akrawy <i>et al.</i>	(OPAL Collab.)
AKRAWY	90J	PL B246 285	M.Z. Akrawy <i>et al.</i>	(OPAL Collab.)
ALBAJAR	90B	ZPHY C48 1	C. Albajar <i>et al.</i>	(UA1 Collab.)
DECAMP	90F	PL B236 511	D. Decamp <i>et al.</i>	(ALEPH Collab.)
ABE	89E	PR D39 3524	K. Abe <i>et al.</i>	(VENUS Collab.)
ABE	89G	PRL 63 1776	K. Abe <i>et al.</i>	(VENUS Collab.)
ABRAMS	89C	PRL 63 2447	G.S. Abrams <i>et al.</i>	(Mark II Collab.)
ADACHI	89C	PL B229 427	I. Adachi <i>et al.</i>	(TOPAZ Collab.)
ENO	89	PRL 63 1910	S. Eno <i>et al.</i>	(AMY Collab.)
ALBAJAR	88	ZPHY C37 505	C. Albajar <i>et al.</i>	(UA1 Collab.)
ALTARELLI	88	NP B308 724	G. Altarelli <i>et al.</i>	(CERN, ROMA, ETH)
IGARASHI	88	PRL 60 2359	S. Igarashi <i>et al.</i>	(AMY Collab.)
SAGAWA	88	PRL 60 93	H. Sagawa <i>et al.</i>	(AMY Collab.)
ADEVA	86	PR D34 681	B. Adeva <i>et al.</i>	(Mark-J Collab.)
ALTHOFF	84C	PL 138B 441	M. Althoff <i>et al.</i>	(TASSO Collab.)
ALTHOFF	84I	ZPHY C22 307	M. Althoff <i>et al.</i>	(TASSO Collab.)
