

b' (4^{th} 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
>1420	95	1 AAD	23AV ATLS	$B(b' \rightarrow Z b) = 1$
>1560	95	2 TUMASYAN	23V CMS	$B(b' \rightarrow W t) = 1$
>1570	95	3 SIRUNYAN	20BI CMS	$B(b' \rightarrow H b) = 1$
>1000	95	4 AABOUD	18CE ATLS	$\geq 2\ell + \cancel{E}_T + \geq 1b_j$
> 950	95	5 AABOUD	18CL ATLS	$W t, Z b, h b$ modes
>1010	95	6,7 AABOUD	18CP ATLS	2,3 ℓ , singlet model
>1140	95	5,8 AABOUD	18CP ATLS	2,3 ℓ , doublet model
>1220	95	9,10 AABOUD	18CR ATLS	singlet b' . ATLAS Combination
>1370	95	9,11 AABOUD	18CR ATLS	b' in a weak isospin doublet (t', b'). ATLAS combination.
> 845	95	12 SIRUNYAN	18Q CMS	$B(b' \rightarrow W u) = 1$
> 730	95	13 SIRUNYAN	17AU CMS	
> 810	95	14 AAD	15Z ATLS	
> 190	95	15 ABAZOV	08X D0	$c\tau = 200\text{mm}$
> 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	$B(b' \rightarrow W t) = 1$
>1390	95	3 SIRUNYAN	20BI CMS	$B(b' \rightarrow Z b) = 1$
>1130	95	18 SIRUNYAN	19AQ CMS	$B(b' \rightarrow Z b) = 1$
>1230	95	19 SIRUNYAN	19BWCMS	$B(b' \rightarrow W t) = 1$
>1350	95	20 AABOUD	18AW ATLS	$B(b' \rightarrow W t) = 1$
> 910	95	21 SIRUNYAN	18BM CMS	$W t, Z b, h b$ modes
> 880	95	22 KHACHATRY...	16AN CMS	$B(b' \rightarrow W t) = 1$
<350, 580–635, >700	95	23 AAD	15AR ATLS	$B(b' \rightarrow H b) = 1$
> 620	95	24 AAD	15BY ATLS	$W t, Z b, h b$ modes
> 730	95	25 AAD	15BY ATLS	$B(b' \rightarrow W t) = 1$
> 690	95	26 AAD	15CN ATLS	$B(b' \rightarrow W q) = 1$ ($q=u$)
> 755	95	27 AAD	14AZ ATLS	$B(b' \rightarrow W t) = 1$
> 675	95	28 CHATRCHYAN	13I CMS	$B(b' \rightarrow W t) = 1$
> 480	95	29 AAD	12AT ATLS	$B(b' \rightarrow W t) = 1$
> 400	95	30 AAD	12AU ATLS	$B(b' \rightarrow Z b) = 1$
> 350	95	31 AAD	12BC ATLS	$B(b' \rightarrow W q) = 1$ ($q=u, c$)
> 450	95	32 AAD	12BE ATLS	$B(b' \rightarrow W t) = 1$
> 685	95	33 CHATRCHYAN	12BH CMS	$m_{t'} = m_{b'}$
> 611	95	34 CHATRCHYAN	12X CMS	$B(b' \rightarrow W t) = 1$
> 372	95	35 AALTONEN	11J CDF	$b' \rightarrow W t$
> 361	95	36 CHATRCHYAN	11L CMS	Repl. by CHATRCHYAN 12X
> 338	95	37 AALTONEN	10H CDF	$b' \rightarrow W t$

> 380–430	95	38	FLACCO	10	RVUE	$m_{b'} > m_{t'}$
> 268	95	39,40	AALTONEN	07C	CDF	$B(b' \rightarrow Zb) = 1$
> 199	95	41	AFFOLDER	00	CDF	NC: $b' \rightarrow Zb$
> 148	95	42	ABE	98N	CDF	NC: $b' \rightarrow Zb + \text{vertex}$
> 96	95	43	ABACHI	97D	D0	NC: $b' \rightarrow b\gamma$
> 128	95	44	ABACHI	95F	D0	$\ell\ell + \text{jets}, \ell + \text{jets}$
> 75	95	45	MUKHOPAD...	93	RVUE	NC: $b' \rightarrow b\ell\ell$
> 85	95	46	ABE	92	CDF	CC: $\ell\ell$
> 72	95	47	ABE	90B	CDF	CC: $e + \mu$
> 54	95	48	AKESSON	90	UA2	CC: $e + \text{jets} + \cancel{E}_T$
> 43	95	49	ALBAJAR	90B	UA1	CC: $\mu + \text{jets}$
> 34	95	50	ALBAJAR	88	UA1	CC: $e \text{ or } \mu + \text{jets}$

¹ AAD 23AV based on 139 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. Pair production of vector-like b' is searched for in the mode $\ell^\pm \ell^\mp + \geq 2j$ ($\geq 1b$ -tagged) + \cancel{E}_T or with 3ℓ . The data are consistent with the SM background predictions and limits are obtained for different branching ratios.

² TUMASYAN 23V based on 138 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. Pair production of vector-like b' is searched 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.

³ SIRUNYAN 20BI based on 137 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. Pair production of vector-like b' is searched 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.

⁴ 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.

⁵ 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 $m_{b'} > 1010 \text{ GeV}$.

⁶ 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 $m_{b'} > 1220 \text{ GeV}$.

⁷ The limit is for the singlet model, assuming that the branching ratios into Wt , Zb , hb add up to one.

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

⁹ 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.

¹⁰ The limit is for the singlet b' .

¹¹ 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.

¹² 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.

- 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 $\ell + \cancel{E}_T + \geq 6j$ ($\geq 1 b$) 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' .
- 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 $p\bar{p}$ 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.
- ¹⁷ AAD 23AG based on 139 fb⁻¹ of pp data at $\sqrt{s} = 13$ TeV. Pair production of vector-like top or b_s is searched for in the mode $1\ell + \geq 4j$ ($\geq 1b$ -tagged) + \cancel{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 SIRUNYAN 19AQ based on 35.9 fb⁻¹ of pp data at $\sqrt{s} = 13$ TeV. Pair production of vector-like b' is searched 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' .
- ¹⁹ 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.
- ²⁰ 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.
- ²¹ 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.
- ²² 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.
- ²³ 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 $b'\bar{b}' \rightarrow Hb + X$ searches.
- ²⁴ 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 $\geq 2\ell + \cancel{E}_T + \geq 2j$ ($\geq 1 b$) and including a same-sign lepton pair.
- ²⁵ 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 $\geq 2\ell + \cancel{E}_T + \geq 2j$ ($\geq 1 b$) and including a same-sign lepton pair.

- ²⁶ 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.
- ²⁷ 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 (≥ 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 .
- ²⁸ 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.
- ²⁹ 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 .
- ³⁰ 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.
- ³¹ 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.
- ³² 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 $H_T > 350 \text{ GeV}$.
- ³³ 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 tripleptons 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 $\pm 20 \text{ GeV}/c^2$.
- ³⁴ Based on 4.9 fb^{-1} of pp data at $\sqrt{s} = 7 \text{ TeV}$. CHATRCHYAN 12X looked for events with tripleptons or same-sign dileptons and at least one b jet.
- ³⁵ 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 $B(b' \rightarrow Wt) = 1$.
- ³⁶ Based on 34 pb^{-1} of data in pp collisions at 7 TeV . CHATRCHYAN 11L looked for multi-jet events with tripleptons or same-sign dileptons. No excess above the SM background excludes $m_{b'}$ between 255 and 361 GeV at 95% CL for $B(b' \rightarrow Wt) = 1$.
- ³⁷ 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.
- ³⁸ 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 $m_{b'} > m_{t'}$.
- ³⁹ 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.

- 40 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 $m_{b'}$.
- 41 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).
- 42 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 $m_Z + m_b$ (~ 96 GeV) if $c\tau > 22$ cm or $c\tau < 0.009$ cm. See their Fig. 4.
- 43 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 $m_{b'} > m_Z + m_b$.
- 44 ABACHI 95F bound on the top-quark also applies to b' and t' quarks that decay predominantly into W . See FROGGATT 97.
- 45 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.
- 46 ABE 92 dilepton analysis limit of >85 GeV at CL=95% also applies to b' quarks, as discussed in ABE 90B.
- 47 ABE 90B exclude the region 28–72 GeV.
- 48 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.
- 49 For the reduction of the limit due to non-charged-current decay modes, see Fig. 19 of ALBAJAR 90B.
- 50 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
>3000	95	1 TUMASYAN	220 CMS	$gb \rightarrow b' \rightarrow tW, B(b' \rightarrow tW) = 1$
> 693	95	2 ABAZOV	11F D0	$qu \rightarrow q'b' \rightarrow q'(Wu)$ $\tilde{\kappa}_{ub'} = 1, B(b' \rightarrow Wu) = 1$
> 430	95	2 ABAZOV	11F D0	$qd \rightarrow qb' \rightarrow q(Zd)$ $\tilde{\kappa}_{db'} = \sqrt{2}, B(b' \rightarrow Zd) = 1$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>2600	95	3 AAD	23CQ ATLS	$b' \rightarrow bh (h \rightarrow b\bar{b})$
		4 SIRUNYAN	21AG CMS	$gb \rightarrow b' \rightarrow tW, B(b' \rightarrow tW) = 1$
		5 SIRUNYAN	19AI CMS	$bZ/tW \rightarrow b' \rightarrow tW$
>1500	95	6 AAD	16AH ATLS	$gb \rightarrow b' \rightarrow tW, B(b' \rightarrow tW) = 1$

>1390	95	⁷ KHACHATRY...16I	CMS	$gb \rightarrow b'_L \rightarrow tW, B(b'_L \rightarrow tW)=1$
>1430	95	⁸ KHACHATRY...16I	CMS	$gb \rightarrow b'_R \rightarrow tW, B(b'_R \rightarrow tW)=1$
>1530	95	⁹ KHACHATRY...16I	CMS	$gb \rightarrow b' \rightarrow tW, B(b' \rightarrow tW)=1$

¹ TUMASYAN 220 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 $p\bar{p} \rightarrow b'q \rightarrow Wuq$, 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.

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 between 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 $(\ell \text{ or } \ell\ell) + 1,2,3 j (\geq 1b)$. 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' (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

AAD	23AG EPJ C83 719	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	23AV PL B843 138019	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	23CQ JHEP 2311 168	G. Aad <i>et al.</i>	(ATLAS Collab.)
TUMASYAN	23V JHEP 2307 020	A. Tumasyan <i>et al.</i>	(CMS Collab.)
TUMASYAN	22O JHEP 2204 048	A. Tumasyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	21AG JHEP 2112 106	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	20BI PR D102 112004	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	19AI EPJ C79 90	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	19AQ EPJ C79 364	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	19BW PR D100 072001	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
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.)