

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

NODE=Q008

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

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>1530	95	1 AAD	24BP ATLS	$B(b' \rightarrow W u) = 1$
>1540	95	2 HAYRAPETY...24AQ CMS		$B(b' \rightarrow Z b) = 1$
>1570	95	2 HAYRAPETY...24AQ CMS		$B(b' \rightarrow H b) = 1$
>1560	95	3 TUMASYAN	23v CMS	$B(b' \rightarrow W t) = 1$
>1570	95	4 SIRUNYAN	20BI CMS	$B(b' \rightarrow H b) = 1$
>1000	95	5 AABOUD	18CE ATLS	$\geq 2\ell + \cancel{E}_T + \geq 1bj$
> 950	95	6 AABOUD	18CL ATLS	Wt, Zb, hb modes
>1010	95	7,8 AABOUD	18CP ATLS	2,3 ℓ , singlet model
>1140	95	6,9 AABOUD	18CP ATLS	2,3 ℓ , 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	$c\tau = 200\text{mm}$
> 190	95	16 ACOSTA	03 CDF	quasi-stable b'

NODE=Q008BPP

NODE=Q008BPP;CHECK LIMITS

OCCUR=2

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

>1460	95	17 AAD	23AG ATLS	$B(b' \rightarrow W t) = 1$
>1420	95	18 AAD	23AV ATLS	$B(b' \rightarrow Z b) = 1$
>1390	95	4 SIRUNYAN	20BI CMS	$B(b' \rightarrow Z b) = 1$
>1130	95	19 SIRUNYAN	19AQ CMS	$B(b' \rightarrow Z b) = 1$
>1230	95	20 SIRUNYAN	19BWCMS	$B(b' \rightarrow W t) = 1$
>1350	95	21 AABOUD	18AW ATLS	$B(b' \rightarrow W t) = 1$
> 910	95	22 SIRUNYAN	18BMCMS	Wt, Zb, hb modes
> 845	95	23 SIRUNYAN	18Q CMS	$B(b' \rightarrow W u) = 1$
> 880	95	24 KHACHATRY...16AN CMS		$B(b' \rightarrow W t) = 1$
<350, 580–635, >700	95	25 AAD	15AR ATLS	$B(b' \rightarrow H b) = 1$
> 620	95	26 AAD	15BY ATLS	Wt, Zb, hb modes
> 730	95	27 AAD	15BY ATLS	$B(b' \rightarrow W t) = 1$
> 690	95	28 AAD	15CN ATLS	$B(b' \rightarrow W q) = 1$ ($q=u$)
> 755	95	29 AAD	14AZ ATLS	$B(b' \rightarrow W t) = 1$
> 675	95	30 CHATRCHYAN 13I	CMS	$B(b' \rightarrow W t) = 1$
> 480	95	31 AAD	12AT ATLS	$B(b' \rightarrow W t) = 1$
> 400	95	32 AAD	12AU ATLS	$B(b' \rightarrow Z b) = 1$
> 350	95	33 AAD	12BC ATLS	$B(b' \rightarrow W q) = 1$ ($q=u,c$)
> 450	95	34 AAD	12BE ATLS	$B(b' \rightarrow W t) = 1$
> 685	95	35 CHATRCHYAN 12BH	CMS	$m_{t'} = m_{b'}$
> 611	95	36 CHATRCHYAN 12X	CMS	$B(b' \rightarrow W t) = 1$
> 372	95	37 AALTONEN	11J CDF	$b' \rightarrow W t$
> 361	95	38 CHATRCHYAN 11L	CMS	Repl. by CHATRCHYAN 12X
> 338	95	39 AALTONEN	10H CDF	$b' \rightarrow W t$
> 380–430	95	40 FLACCO	10 RVUE	$m_{b'} > m_{t'}$
> 268	95	41,42 AALTONEN	07C CDF	$B(b' \rightarrow Z b) = 1$
> 199	95	43 AFFOLDER	00 CDF	NC: $b' \rightarrow Z b$
> 148	95	44 ABE	98N CDF	NC: $b' \rightarrow Z b + \text{vertex}$
> 96	95	45 ABACHI	97D D0	NC: $b' \rightarrow b\gamma$
> 128	95	46 ABACHI	95F D0	$\ell\ell + \text{jets}, \ell + \text{jets}$
> 75	95	47 MUKHOPAD...	93 RVUE	NC: $b' \rightarrow b\ell\ell$
> 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: $e + \text{jets} + \cancel{E}_T$
> 43	95	51 ALBAJAR	90B UA1	CC: $\mu + \text{jets}$
> 34	95	52 ALBAJAR	88 UA1	CC: $e \text{ or } \mu + \text{jets}$

OCCUR=2

OCCUR=2

- 1 AAD 24BP based on 140 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. Limit on pair-production of heavy vectorlike quarks where each decays into a W boson and a light quark. Used events with $\ell + \cancel{E}_T + \text{multiple jets} + 1 \text{ boosted-}W\text{-jet}$.
NODE=Q008BPP;LINKAGE=JA
- 2 HAYRAPETYAN 24AQ 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 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 $B(b' \rightarrow Hb)$, $B(b' \rightarrow Zb)$, $B(b' \rightarrow Wt)$.
NODE=Q008BPP;LINKAGE=KA
- 3 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.
NODE=Q008BPP;LINKAGE=EA
- 4 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.
NODE=Q008BPP;LINKAGE=DA
- 5 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.
NODE=Q008BPP;LINKAGE=Y
- 6 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 $m_{b'} > 1010 \text{ GeV}$.
NODE=Q008BPP;LINKAGE=Q
- 7 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 $m_{b'} > 1220 \text{ GeV}$.
NODE=Q008BPP;LINKAGE=R
- 8 The limit is for the singlet model, assuming that the branching ratios into Wt , Zb , hb add up to one.
NODE=Q008BPP;LINKAGE=T
- 9 The limit is for the doublet model, assuming that the branching ratios into Wt , Zb , hb add up to one.
NODE=Q008BPP;LINKAGE=S
- 10 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.
NODE=Q008BPP;LINKAGE=V
- 11 The limit is for the singlet b' .
NODE=Q008BPP;LINKAGE=W
- 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 $m_{b'} > 1.14 \text{ TeV}$ is obtained.
NODE=Q008BPP;LINKAGE=X
- 13 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.
NODE=Q008BPP;LINKAGE=M
- 14 AAD 15Z based on 20.3 fb^{-1} of pp data at $\sqrt{s} = 8 \text{ TeV}$. Used events with $\ell + \cancel{E}_T + \geq 6j$ ($\geq 1b$) and at least one pair of jets from weak boson decay, primarily designed to select the signature $b' \bar{b}' \rightarrow W W t \bar{t} \rightarrow W W W W b \bar{b}$. This is a limit on pair-produced vector-like b' . The lower mass limit is 640 GeV for a vector-like singlet b' .
NODE=Q008BPP;LINKAGE=K
- 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 $2 < c\tau < 7000 \text{ nm}$; see Fig. 3. 95% CL excluded region of b' lifetime and mass is shown in Fig. 4.
NODE=Q008BPP;LINKAGE=AA
- 16 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.
NODE=Q008BPP;LINKAGE=CS
- 17 AAD 23AG based on 139 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. Pair production of vector-like top or bs 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.
NODE=Q008BPP;LINKAGE=FA
- 18 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.
NODE=Q008BPP;LINKAGE=IA
- 19 SIRUNYAN 19AQ based on 35.9 fb^{-1} of pp data at $\sqrt{s} = 13 \text{ TeV}$. 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' .
NODE=Q008BPP;LINKAGE=Z

- 20 SIRUNYAN 19BW 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' 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. NODE=Q008BPP;LINKAGE=BA
- 21 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. NODE=Q008BPP;LINKAGE=O
- 22 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. NODE=Q008BPP;LINKAGE=N
- 23 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. NODE=Q008BPP;LINKAGE=P
- 24 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. NODE=Q008BPP;LINKAGE=L
- 25 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. NODE=Q008BPP;LINKAGE=G
- 26 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 $\geq 2\ell + \cancel{E}_T + \geq 2j$ ($\geq 1b$) and including a same-sign lepton pair. NODE=Q008BPP;LINKAGE=H
- 27 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 $\geq 2\ell + \cancel{E}_T + \geq 2j$ ($\geq 1b$) and including a same-sign lepton pair. NODE=Q008BPP;LINKAGE=I
- 28 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. NODE=Q008BPP;LINKAGE=J
- 29 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 ($\geq 1b$ -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. NODE=Q008BPP;LINKAGE=E
- 30 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. NODE=Q008BPP;LINKAGE=B
- 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 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 . NODE=Q008BPP;LINKAGE=GD
- 32 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. NODE=Q008BPP;LINKAGE=DG
- 33 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. NODE=Q008BPP;LINKAGE=GA
- 34 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 $H_T > 350 \text{ GeV}$. NODE=Q008BPP;LINKAGE=AD
- 35 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 4th 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 $\pm 20 \text{ GeV}/c^2$. NODE=Q008BPP;LINKAGE=CT
- 36 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. NODE=Q008BPP;LINKAGE=CA
- 37 Based on 4.8 fb^{-1} of data in $p\bar{p}$ collisions at 1.96 TeV . AALTONEN 11J looked for events with $\ell + \cancel{E}_T + \geq 5j$ ($\geq 1b$ 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 $B(b' \rightarrow Wt) = 1$. NODE=Q008BPP;LINKAGE=AO
- 38 Based on 34 pb^{-1} of data in pp collisions at 7 TeV . CHATRCHYAN 11L looked for multi-jet events with tripletons or same-sign dileptons. No excess above the SM background excludes $m_{b'}$ between 255 and 361 GeV at 95% CL for $B(b' \rightarrow Wt) = 1$. NODE=Q008BPP;LINKAGE=CH
- 39 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^+ , NODE=Q008BPP;LINKAGE=AT

- $m_{T_{5/3}} > 365$ 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 $B(b' \rightarrow Wt) = 100\%$ 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 $\sigma(b'\bar{b'}) [1-(1-B(b' \rightarrow Zb))^2]$ and the LO estimate of the b' pair production cross section shown in Fig. 38 of the article.
- 42 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 $m_{b'}$.
- 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 $B(b' \rightarrow Zb) = 100\%$. 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).
- 44 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 (~ 96 GeV) if $c\tau > 22 \text{ cm}$ or $c\tau < 0.009 \text{ cm}$. See their Fig. 4.
- 45 ABACHI 97D searched for b' that decays mainly via FCNC. They obtained 95%CL upper bounds on $B(b'\bar{b'} \rightarrow \gamma + 3 \text{ jets})$ and $B(b'\bar{b'} \rightarrow 2\gamma + 2 \text{ jets})$, which can be interpreted as the lower mass bound $m_{b'} > m_Z+m_b$.
- 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 $B(b' \rightarrow b\ell^+\ell^-)=1\%$. 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 $E_{\text{cm}} = 546$ 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.

NODE=Q008BPP;LINKAGE=FL

NODE=Q008BPP;LINKAGE=AL

NODE=Q008BPP;LINKAGE=HU

NODE=Q008BPP;LINKAGE=EB

NODE=Q008BPP;LINKAGE=AN

NODE=Q008BPP;LINKAGE=K2

NODE=Q008BPP;LINKAGE=1K

NODE=Q008BPP;LINKAGE=C

NODE=Q008BPP;LINKAGE=U

NODE=Q008BPP;LINKAGE=AB

NODE=Q008BPP;LINKAGE=F

NODE=Q008BPP;LINKAGE=A

NODE=Q008BPP;LINKAGE=D

$b'(-1/3)$ 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	$gb \rightarrow b' \rightarrow tW, B(b' \rightarrow tW)=1$
>1500	95	5 SIRUNYAN 19AI	CMS	$bZ/tW \rightarrow b' \rightarrow tW$
		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	$gb \rightarrow b' \rightarrow tW, B(b' \rightarrow tW)=1$

NODE=Q008BPS
NODE=Q008BPS

OCCUR=2

OCCUR=2

OCCUR=3

- 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 $\sqrt{s} = 13 \text{ TeV}$. 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.

NODE=Q008BPS;LINKAGE=F

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NODE=Q008BPS;LINKAGE=H

NODE=Q008BPS;LINKAGE=G

NODE=Q008BPS;LINKAGE=E

NODE=Q008BPS;LINKAGE=D

NODE=Q008BPS;LINKAGE=A

NODE=Q008BPS;LINKAGE=B

NODE=Q008BPS;LINKAGE=C

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	$B(CC)=1; \mu, e$
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

NODE=Q008BPE

NODE=Q008BPE

NODE=Q008BPE

OCCUR=2

OCCUR=3

OCCUR=2

OCCUR=2

>42.0	95	¹⁰ ABRAMS	89C	MRK2	Any decay; event shape	OCCUR=3
>28.4	95	^{11,12} ADACHI	89C	TOPZ	$B(C C) = 1; \mu$	
>28.8	95	¹³ ENO	89	AMY	$B(C C) \gtrsim 90\%; \mu, e$	
>27.2	95	^{13,14} ENO	89	AMY	any decay; event shape	OCCUR=2
>29.0	95	¹³ ENO	89	AMY	$B(b' \rightarrow bg) \gtrsim 85\%;$ event shape	OCCUR=3
>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.						NODE=Q008BPE;LINKAGE=DC
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 $B(b' \rightarrow bZ)$ and $B(b' \rightarrow cW)$ for $m_{b'} = 96$ to 103 GeV.						NODE=Q008BPE;LINKAGE=DA
³ ADRIANI 93G search for vector quarkonium states near Z and give limit on quarkonium- Z mixing parameter $\delta m^2 < (10-30) \text{ GeV}^2$ (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.						NODE=Q008BPE;LINKAGE=TB
⁴ ABREU 90D assumed $m_{H^-} < m_{b'} - 3 \text{ GeV}$.						NODE=Q008BPE;LINKAGE=AB
⁵ Superseded by ABREU 91F.						NODE=Q008BPE;LINKAGE=AF
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 $(m_{H^+} + 1.5 \text{ GeV})$ and 45.5 GeV.						NODE=Q008BPE;LINKAGE=AK
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 $B(b' \rightarrow \gamma X) > 10\%$.						NODE=Q008BPE;LINKAGE=T
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.						NODE=Q008BPE;LINKAGE=A
⁹ ABE 89G search was at $E_{cm} = 55-60.8$ GeV at TRISTAN.						NODE=Q008BPE;LINKAGE=B
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 for Higgs decay ($b' \rightarrow cH^-, H^- \rightarrow \bar{c}s$) is 45.2 GeV.						NODE=Q008BPE;LINKAGE=G
¹¹ ADACHI 89C search was at $E_{cm} = 56.5-60.8$ GeV at TRISTAN using multi-hadron events accompanying muons.						NODE=Q008BPE;LINKAGE=C
¹² ADACHI 89C also gives limits for any mixture of CC and bg decays.						NODE=Q008BPE;LINKAGE=F
¹³ ENO 89 search at $E_{cm} = 50-60.8$ at TRISTAN.						NODE=Q008BPE;LINKAGE=D
¹⁴ ENO 89 considers arbitrary mixture of the charged current, bg , and $b\gamma$ decays.						NODE=Q008BPE;LINKAGE=E
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.						NODE=Q008BPE;LINKAGE=S
¹⁶ SAGAWA 88 set limit $\sigma(\text{top}) < 6.1 \text{ pb}$ at $\text{CL}=95\%$ 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.						NODE=Q008BPE;LINKAGE=Q
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.						NODE=Q008BPE;LINKAGE=J
¹⁸ ALTHOFF 84C narrow state search sets limit $\Gamma(e^+e^-)B(\text{hadrons}) < 2.4 \text{ keV}$ CL = 95% and heavy charge $1/3$ quark pair production $m > 21$ GeV, CL = 95%.						NODE=Q008BPE;LINKAGE=K
¹⁹ ALTHOFF 84I exclude heavy quark pair production for $7 < m < 19$ GeV ($1/3$ charge) using aplanarity distributions (CL = 95%).						NODE=Q008BPE;LINKAGE=L

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HAYRAPETY...	24AQ	PR D110 052004	A. Hayrapetyan <i>et al.</i>	(CMS Collab.)	REFID=63077
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AAD	23AV	PL B843 138019	G. Aad <i>et al.</i>	(ATLAS Collab.)	REFID=62364
AAD	23CQ	JHEP 2311 168	G. Aad <i>et al.</i>	(ATLAS Collab.)	REFID=62612
TUMASYAN	23V	JHEP 2307 020	A. Tumasyan <i>et al.</i>	(CMS Collab.)	REFID=62165
TUMASYAN	22O	JHEP 2204 048	A. Tumasyan <i>et al.</i>	(CMS Collab.)	REFID=61788
SIRUNYAN	21AG	JHEP 2112 106	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)	REFID=61565
SIRUNYAN	20BI	PR D102 112004	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)	REFID=60740
SIRUNYAN	19AI	EPJ C79 90	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)	REFID=59702
SIRUNYAN	19AQ	EPJ C79 364	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)	REFID=59721
SIRUNYAN	19BW	PR D100 072001	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)	REFID=60010
AABOUD	18AW	JHEP 1808 048	M. Aaboud <i>et al.</i>	(ATLAS Collab.)	REFID=59145
AABOUD	18CE	JHEP 1812 039	M. Aaboud <i>et al.</i>	(ATLAS Collab.)	REFID=59369
AABOUD	18CL	PR D98 092005	M. Aaboud <i>et al.</i>	(ATLAS Collab.)	REFID=59472
AABOUD	18CP	PR D98 112010	M. Aaboud <i>et al.</i>	(ATLAS Collab.)	REFID=59500
AABOUD	18CR	PRL 121 211801	M. Aaboud <i>et al.</i>	(ATLAS Collab.)	REFID=59532
SIRUNYAN	18BM	JHEP 1808 177	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)	REFID=59137

NODE=Q008

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SIRUNYAN	17AU	JHEP 1711 085	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)	REFID=58344
AAD	16AH	JHEP 1602 110	G. Aad <i>et al.</i>	(ATLAS Collab.)	REFID=57318
KHACHATRY...	16AN	PR D93 112009	V. Khachatryan <i>et al.</i>	(CMS Collab.)	REFID=57295
KHACHATRY...	16I	JHEP 1601 166	V. Khachatryan <i>et al.</i>	(CMS Collab.)	REFID=57141
AAD	15AR	JHEP 1508 105	G. Aad <i>et al.</i>	(ATLAS Collab.)	REFID=56648
AAD	15BY	JHEP 1510 150	G. Aad <i>et al.</i>	(ATLAS Collab.)	REFID=56863
AAD	15CN	PR D92 112007	G. Aad <i>et al.</i>	(ATLAS Collab.)	REFID=57013
AAD	15Z	PR D91 112011	G. Aad <i>et al.</i>	(ATLAS Collab.)	REFID=56592
AAD	14AZ	JHEP 1411 104	G. Aad <i>et al.</i>	(ATLAS Collab.)	REFID=56201
CHATRCHYAN	13I	JHEP 1301 154	S. Chatrchyan <i>et al.</i>	(CMS Collab.)	REFID=54941
AAD	12AT	PRL 109 032001	G. Aad <i>et al.</i>	(ATLAS Collab.)	REFID=54229
AAD	12AU	PRL 109 071801	G. Aad <i>et al.</i>	(ATLAS Collab.)	REFID=54230
AAD	12BC	PR D86 012007	G. Aad <i>et al.</i>	(ATLAS Collab.)	REFID=54358
AAD	12BE	JHEP 1204 069	G. Aad <i>et al.</i>	(ATLAS Collab.)	REFID=54458
CHATRCHYAN	12BH	PR D86 112003	S. Chatrchyan <i>et al.</i>	(CMS Collab.)	REFID=54772
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AALTONEN	11J	PRL 106 141803	T. Aaltonen <i>et al.</i>	(CDF Collab.)	REFID=16439
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ABACHI	95F	PR D52 4877	S. Abachi <i>et al.</i>	(D0 Collab.)	REFID=44482
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ADACHI	89C	PL B229 427	I. Adachi <i>et al.</i>	(TOPAZ Collab.)	REFID=40952
ENO	89	PRL 63 1910	S. Eno <i>et al.</i>	(AMY Collab.)	REFID=40953
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