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

## MASS LIMITS for $b'$ ($4^{th}$ Generation) Quark or Hadron in $p\overline{p}$ Collisions

These experiments (except for MUKHOPADHYAYA 93) assume that no two-body modes such as $b' \to b\gamma$, $b' \to bg$, or $b' \to cH^+$ are available.

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>85** | 95 | [1] ABE | 92 | CDF | $\ell\ell$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >75 | 95 | [2] MUKHOPAD... | 93 | RVUE | FCNC |
| >72 | 95 | [3] ABE | 90B | CDF | $e + \mu$ |
| >54 | 95 | [4] AKESSON | 90 | UA2 | $e$ + jets + missing $E_T$ |
| >43 | 95 | [5] ALBAJAR | 90B | UA1 | $\mu$ + jets |
| >34 | 95 | [6] ALBAJAR | 88 | UA1 | $e$ or $\mu$ + jets |

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

[2] 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.

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

[4] 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.

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

[6] 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.

## 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 ($C$ $C$ denotes the conventional charged-current decay) and the event signature which is looked for.

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>46.0** | 95 | [7] DECAMP | 90F | ALEP | any decay |

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

| | | | | | |
|---|---|---|---|---|---|
| | | [8] 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($C\,C$) = 1; event shape |
| >44.5 | 95 | [9] ABREU | 90D | DLPH | $b' \to c H^-$, $H^- \to \overline{c}s$, $\tau^-\nu$ |
| >40.5 | 95 | [10] ABREU | 90D | DLPH | $\Gamma(Z \to$ hadrons) |
| >28.3 | 95 | ADACHI | 90 | TOPZ | B(FCNC)=100%; isol. $\gamma$ or 4 jets |
| >41.4 | 95 | [11] AKRAWY | 90B | OPAL | Any decay; acoplanarity |
| >45.2 | 95 | [11] AKRAWY | 90B | OPAL | B($C\,C$) = 1; acoplanarity |
| >46 | 95 | [12] AKRAWY | 90J | OPAL | $b' \to \gamma$ + any |
| >27.5 | 95 | [13] ABE | 89E | VNS | B($C\,C$) =1; $\mu$, $e$ |
| none 11.4–27.3 | 95 | [14] ABE | 89G | VNS | B($b' \to b\gamma$) > 10%; isolated $\gamma$ |
| >44.7 | 95 | [15] ABRAMS | 89C | MRK2 | B($C\,C$)= 100%; isol. track |
| >42.7 | 95 | [15] ABRAMS | 89C | MRK2 | B($bg$)= 100%; event shape |
| >42.0 | 95 | [15] ABRAMS | 89C | MRK2 | Any decay; event shape |
| >28.4 | 95 | [16,17] ADACHI | 89C | TOPZ | B($C\,C$) =1; $\mu$ |
| >28.8 | 95 | [18] ENO | 89 | AMY | B($C\,C$) $\gtrsim$ 90%; $\mu$, $e$ |
| >27.2 | 95 | [18,19] ENO | 89 | AMY | any decay; event shape |
| >29.0 | 95 | [18] ENO | 89 | AMY | B($b' \to bg$) $\gtrsim$ 85%; event shape |
| >24.4 | 95 | [20] IGARASHI | 88 | AMY | $\mu$,$e$ |
| >23.8 | 95 | [21] SAGAWA | 88 | AMY | event shape |
| >22.7 | 95 | [22] ADEVA | 86 | MRKJ | $\mu$ |
| >21 | | [23] ALTHOFF | 84C | TASS | $R$, event shape |
| >19 | | [24] ALTHOFF | 84I | TASS | Aplanarity |

[7] 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.

[8] 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.

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

[10] Superseded by ABREU 91F.

[11] AKRAWY 90B search was restricted to data near the $Z$ peak at $E_{\rm cm} = 91.26$ 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.

[12] AKRAWY 90J search for isolated photons in hadronic $Z$ decay and derive B($Z \to b'\overline{b}'$)·B($b' \to \gamma$X)/B($Z \to$ hadrons) < $2.2 \times 10^{-3}$. Mass limit assumes B($b' \to \gamma$X) > 10%.

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

[14] ABE 89G search was at $E_{\rm cm}$ = 55–60.8 GeV at TRISTAN.

[15] 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.

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

[17] ADACHI 89C also gives limits for any mixture of $C\,C$ and $bg$ decays.

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

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

[20] 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.

[21] SAGAWA 88 set limit $\sigma$(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.

[22] ADEVA 86 give 95%CL upper bound on an excess of the normalized cross section, $\Delta R$, 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.

[23] 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%.

[24] 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


| | | | | |
|---|---|---|---|---|
| ADRIANI | 93G | PL B313 326 | +Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+ | (L3 Collab.) |
| ADRIANI | 93M | PRPL 236 1 | +Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+ | (L3 Collab.) |
| MUKHOPAD... | 93 | PR D48 2105 | Mukhopadhyaya, Roy | (TATA) |
| ABE | 92 | PRL 68 447 | +Amidei, Apollinari, Atac, Auchincloss+ | (CDF Collab.) |
| Also | 92G | PR D45 3921 | Abe, Amidei, Apollinari, Atac, Auchincloss+ | (CDF Collab.) |
| ABE | 92G | PR D45 3921 | +Amidei, Apollinari, Atac, Auchincloss+ | (CDF Collab.) |
| ABREU | 91F | NP B367 511 | +Adam, Adami, Adye, Akesson+ | (DELPHI Collab.) |
| ABE | 90B | PRL 64 147 | +Amidei, Apollinari, Atac, Auchincloss+ | (CDF Collab.) |
| ABE | 90D | PL B234 382 | +Amako, Arai, Asano+ | (VENUS Collab.) |
| ABREU | 90D | PL B242 536 | +Adam, Adami, Adye, Alekseev, Allaby+ | (DELPHI Collab.) |
| ADACHI | 90 | PL B234 197 | +Aihara, Doser, Enomoto+ | (TOPAZ Collab.) |
| AKESSON | 90 | ZPHY C46 179 | +Alitti, Ansari, Ansorge, Bagnaia+ | (UA2 Collab.) |
| AKRAWY | 90B | PL B236 364 | +Alexander, Allison, Allport, Anderson+ | (OPAL Collab.) |
| AKRAWY | 90J | PL B246 285 | +Alexander, Allison, Allport, Anderson+ | (OPAL Collab.) |
| ALBAJAR | 90B | ZPHY C48 1 | +Albrow, Allkofer, Andrieu, Ankoviak+ | (UA1 Collab.) |
| DECAMP | 90F | PL B236 511 | +Deschizeaux, Lees, Minard+ | (ALEPH Collab.) |
| ABE | 89E | PR D39 3524 | +Amako, Arai, Asano, Chiba, Chiba+ | (VENUS Collab.) |
| ABE | 89G | PRL 63 1776 | +Amako, Arai, Asano, Chiba+ | (VENUS Collab.) |
| ABRAMS | 89C | PRL 63 2447 | +Adolphsen, Averill, Ballam+ | (Mark II Collab.) |
| ADACHI | 89C | PL B229 427 | +Aihara, Doser, Enomoto, Fujii+ | (TOPAZ Collab.) |
| ENO | 89 | PRL 63 1910 | +Auchincloss, Blanis, Bodek, Budd+ | (AMY Collab.) |
| ALBAJAR | 88 | ZPHY C37 505 | +Albrow, Allkofer+ | (UA1 Collab.) |
| ALTARELLI | 88 | NP B308 724 | +Diemoz, Martinelli, Nason | (CERN, ROMA, ETH) |
| IGARASHI | 88 | PRL 60 2359 | +Myung, Chiba, Hanaoka+ | (AMY Collab.) |
| SAGAWA | 88 | PRL 60 93 | +Mori, Abe+ | (AMY Collab.) |
| ADEVA | 86 | PR D34 681 | +Ansari, Becker, Becker-Szendy+ | (Mark-J Collab.) |
| ALTHOFF | 84C | PL 138B 441 | +Braunschweig, Kirschfink+ | (TASSO Collab.) |
| ALTHOFF | 84I | ZPHY C22 307 | +Braunschweig, Kirschfink+ | (TASSO Collab.) |