Search for a fourth-generation quark with |Q|=e/3 in e+e- collisions at √s =56-57 GeV

著者	Abe K., et al., VENUS Collaboration
journal or publication title	Physical Review. D
volume	39
number	11
page range	3524-3527
year	1989
URL	http://hdl.handle.net/10097/53665

doi: 10.1103/PhysRevD.39.3524

RAPID COMMUNICATIONS

PHYSICAL REVIEW D VOLUME 39, NUMBER 3 1 JUNE 1989

Search for a fourth-generation quark with $|Q| = e/3$ in e^+e^- collisions at $\sqrt{s} = 56-57$ GeV

K. Abe,[a] K. Amako,[b] Y. Arai,[b] Y. Asano,[c] M. Chiba,[d] Y. Chiba,[e] M. Daigo,[f] T. Emura,[g] I. Endo,[e] M. Fukawa,[b] T. Fukui,[d] Y. Fukushima,[b] J. Haba,[h] D. Haidt,[b,*] I. Hayashibara,[e,†] Y. Hemmi,[i] M. Higuchi,[j] T. Hirose,[d] Y. Hojyo,[k] Y. Homma,[l] Y. Hoshi,[j] Y. Ikegami,[m] N. Ishihara,[b] T. Kamitani,[h] N. Kanematsu,[h] J. Kanzaki,[b] R. Kikuchi,[i] T. Kondo,[b] T. Koseki,[c] H. Kurashige,[i] T. Matsui,[b] M. Minami,[d] K. Miyake,[i] S. Mori,[c] Y. Nagashima,[h] T. Nakamura,[o] I. Nakano,[m] Y. Narita,[d] S. Odaka,[b] K. Ogawa,[b] T. Ohama,[b] T. Ohsugi,[e] A. Okamoto,[i] A. Ono,[n] H. Osabe,[h] T. Oyama,[d] H. Saito,[d,‡] H. Sakae,[k,§] H. Sakamoto,[b] S. Sakamoto,[h] M. Sakano,[c,**] M. Sakuda,[b] N. Sasao,[i] M. Sato,[j] M. Shioden,[p] J. Shirai,[b] S. Sugimoto,[h] T. Sumiyoshi,[b] Y. Suzuki,[h] Y. Takada,[c] F. Takasaki,[b] A. Taketani,[e] N. Tamura,[i] R. Tanaka,[e] N. Terunuma,[e] K. Tobimatsu,[q] T. Tsuboyama,[b] A. Tsukamoto,[h,††] S. Uehara,[b] Y. Unno,[b] M. Utsumi,[d] M. Wakai,[d] T. Watanabe,[d] Y. Watase,[b] Y. Yamada,[b] T. Yamagata,[d] T. Yamashita,[h] Y. Yonezawa,[c] and H. Yoshida[r]

[a]*Department of Physics, Tohoku University, Sendai 980, Japan*
[b]*KEK, National Laboratory for High Energy Physics, Tsukuba 305, Japan*
[c]*Institute of Applied Physics, University of Tsukuba, Tsukuba 305, Japan*
[d]*Department of Physics, Tokyo Metropolitan University, Tokyo 158, Japan*
[e]*Department of Physics, Hiroshima University, Hiroshima 730, Japan*
[f]*Wakayama Medical College, Wakayama 649-63, Japan*
[g]*Faculty of Engineering, Tokyo University of Agriculture and Technology, Koganei 184, Japan*
[h]*Department of Physics, Osaka University, Toyonaka 560, Japan*
[i]*Department of Physics, Kyoto University, Kyoto 606, Japan*
[j]*Department of Applied Physics, Tohoku-Gakuin University, Tagajo 985, Japan*
[k]*Graduate School of Science and Technology, Kobe University, Kobe 657, Japan*
[l]*School of Allied Medical Science, Kobe University, Kobe 654-01, Japan*
[m]*Institute of Physics, University of Tsukuba, Tsukuba 305, Japan*
[n]*College of Liberal Arts, Kobe University, Kobe 657, Japan*
[o]*Faculty of Engineering, Miyazaki University, Miyazaki 889-21, Japan*
[p]*Department of Electronic and Computer Engineering, Ibaraki College of Technology, Ibaraki 312, Japan*
[q]*Faculty of General Education, Meiji-Gakuin University, Yokohama 244, Japan*
[r]*Faculty of Engineering, Fukui University, Fukui 910, Japan*

(VENUS Collaboration)
(Received 23 December 1988)

A search for a fourth-generation quark with $|Q| = e/3$ has been made with the VENUS detector at the KEK e^+e^- collider TRISTAN. Multihadron events with a spherical shape or containing isolated leptons were studied. There is no evidence for an excess production of such events in e^+e^- collisions at $\sqrt{s} = 56-57$ GeV, and a lower limit on the mass is 27.5 GeV/c^2 at the 95% C.L.

It is now widely believed that the standard model can describe most of the known phenomena in particle physics. The model however is not considered as the ultimate theory. For example, it can neither explain the origin of the generations of quarks and leptons nor predict how many generations should exist. Constraints on the number of generations come from neutrino-counting experiments using cosmological arguments on ^{4}He abundance,[1] as well as recent results from $\bar{p}p$ and e^+e^- colliders.[2] Such arguments indicate that the number of light neutrinos should not exceed five, therefore not excluding the possible existence of a fourth generation.[3]

In the present study, we have made a direct search for the fourth-generation quark with $|Q| = e/3$, hereafter called b', in e^+e^- collisions. The data analyzed here were taken with the VENUS detector at the KEK collider TRISTAN at $\sqrt{s} = 56$, 56.5, and 57 GeV. The integrated luminosity was $9.8 \pm 0.2(\text{stat}) \pm 0.3(\text{sys})$ pb^{-1}. A description of the VENUS detector can be found elsewhere.[4]

The cross section for the pair production of b' quarks in e^+e^- annihilations is given by the standard electroweak theory. The threshold behavior of the cross section, which is represented in terms of the b' velocity and radiative corrections of $O(\alpha)$ in the initial state, was also considered.[5] An enhancement from QCD corrections or from possible effects of quarkonium resonances were ignored.

Two signatures are expected to characterize $b'\bar{b}'$ production: (1) multihadron events with a spherical shape, and (2) multihadron events with energetic isolated leptons.

We first selected a multihadron-event sample as follows.[4]

(a) Total calorimeter energy ($E_{\rm cal}$), which is the sum of the energy deposited in the lead-glass (LG) barrel calorimeter and in part ($|\cos\theta| < 0.91$) of the liquid-argon (LA) end-cap calorimeter, must be greater than 5.0 GeV.

(b) At least five good tracks must be detected in the central drift chamber (CDC) with $|\cos\theta| < 0.85$.

(c) The total visible energy ($E_{\rm vis}$) must exceed the beam energy ($\sqrt{s}/2$).

(d) The absolute value of the longitudinal-momentum balance ($P_{\rm bal} \equiv |\sum p_z| / E_{\rm vis}$) must be less than 0.4.

These cuts yielded a multihadron-event sample of 1301 events to study the above signatures.

Signature (1): Event shape. In general, the production of a heavy-quark pair in e^+e^- annihilations near threshold leads to an event with a spherical shape. In the present analysis, the event shape was studied in terms of thrust (T) and acoplanarity (A), which are defined as

$$T = \max \frac{\sum_i |\mathbf{p}_{iL}|}{\sum_i |\mathbf{p}_i|}$$

and

$$A = 4 \min \left(\frac{\sum_i |\mathbf{p}_{iT,\rm out}|}{\sum_i |\mathbf{p}_i|} \right)^2 .$$

The thrust axis is defined in such a way that the longitudinal momenta $\mathbf{p}_{iL}$ with respect to this axis is maximal. Similarly, for the acoplanarity A, the transverse momentum $\mathbf{p}_{iT,\rm out}$ is measured in such a way that A is minimal with respect to a plane. For this measurement, we further required that $P_{\rm bal} < 0.2$ in order to suppress events with hard-photon emission in the initial state. Such events tend to have a large acoplanarity even in the three-jet topology. The requirement that $|\cos\Theta_T| < 0.7$, where Θ_T is the angle between the thrust and beam axes, was also applied to ensure that most of the final-state particles were detected.

For the 918 selected events, a scatter plot of T vs A is shown in Fig. 1(a). A scatter plot of simulated events from the productions of the five known quarks is shown in Fig. 1(b). The similarity with the data is evident. Figure 1(c) shows the simulated distribution for $e^+e^- \to b'\bar{b}'$ events with a b' mass of 26 GeV/c^2. To enhance the contribution of b' events, highly spherical events with $T < 0.75$ and $A > 0.15$ were selected, as shown in Fig. 1 by the solid lines. In this region there remained 6 events in our data, consistent with the 11 ± 7 events expected from production of the five known quarks. The corresponding number expected from the $b'\bar{b}'$ was 15 ± 2 for a b' mass of 26 GeV/c^2.

In the multihadron-event simulation, LUND 6.3, a model incorporating a parton-shower scheme, was used to generate and fragment the quarks.[6] The initial-state radiation was also included.[5] The large error in the expected number of events from the five known quarks is due to the fact that the fraction of multijet final states, which is small but

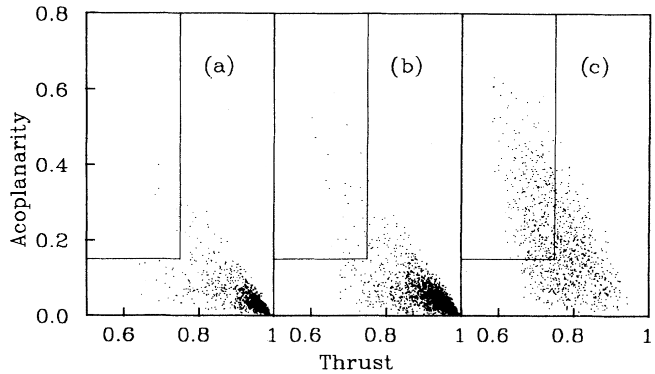

FIG. 1. Scatter plots of T vs A. (a) The data sample, (b) the simulated events for the five known quarks, and (c) those for b'. For the simulation, the normalizations (number of generated events) are arbitrarily chosen. Solid lines indicated the cuts of $T < 0.75$ and $A > 0.15$.

significant in the above selection, is quite dependent on the choice of the model scheme. In contrast, the uncertainty in the b' detection efficiency ϵ of ($28 \pm 4\%$) is comparatively small. This error has several contributions: the choice of fragmentation model and its parameters ($\Delta\epsilon/\epsilon \sim 10\%$), uncertainties in the detector calibration (1%), statistics in the simulation (5%), uncertainty of the b' decay chain (7%),[7] and uncertainty in the luminosity measurement (4%). The total error is 14% if these uncertainties are combined in quadrature.

Comparing the 95% upper limit of the 6 events in the data with the number of expected b' events, which is estimated as a function of the mass of the b', gives a 95%-C.L. lower limit for the mass of the b' quark. Taking the above errors into consideration, we set the limit at 26.1 GeV/c^2. No attempt was made to subtract the expected background from the production of the five known quarks.

Signature (2): Energetic isolated leptons. Heavy quarks like the b' can be detected by tagging "prompt" leptons coming directly from the decay of the primary quark. Such leptons are distinguished from those originating from the five known quarks by the fact that they have higher momenta and are isolated from the hadron jets. As a measure of the isolation of those leptons, we defined a minimum half angle θ_c of the cone around the direction of the lepton momentum, which contained a visible energy of more than 1 GeV excluding the energy of the lepton itself. For example, the scatter plots of the momentum p vs θ_c are shown in Fig. 2 for muons satisfying the conditions described in the following paragraph. Figure 2(b) is a plot of p vs θ_c for simulated muons from production of the five known quarks while Fig. 2(c) shows that expected from the $b'\bar{b}'$ production. These events were simulated with the LUND 6.3 event generator, in which the mass of b' was assumed to be 26 GeV/c^2. As is clear from these figures, the cuts of $\theta_c > 30°$ and $p > 4$ GeV/c efficiently identify prompt leptons from b' ($\bar{b}'$) production.

We now describe the effect of these cuts on the muon and electron candidates in our multihadron event sample. Prior to the lepton study, we restricted our sample to $T < 0.9$ in order to reduce events from the pair production

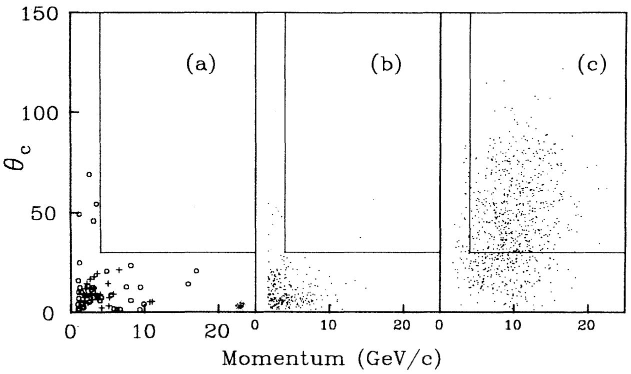

FIG. 2. Scatter plots of momentum p vs θ_c of the leptons. (a) For muon (+) and electron (0) in our multihadron-event sample, (b) for muons in the simulated events for the five known quarks production, and (c) those for $b'\bar{b}'$ production. Solid lines indicate the cuts of $\theta_c > 30°$ and $p > 4$ GeV/c. As described in the text, the restriction of $T < 0.9$ and the conditions of our lepton identifications were applied beforehand.

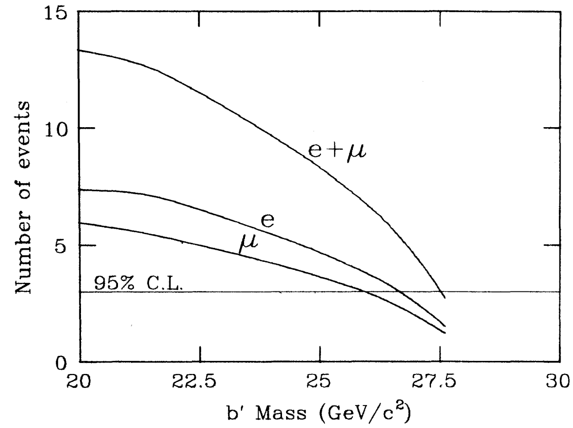

FIG. 3. The expected number of the $b'\bar{b}'$ events selected by the lepton signature as a function of the b' mass. Curves are drawn for the lower bounds of the systematic uncertainties.

of τ leptons or light quarks.

Muons were identified as penetrating tracks in the muon detector, which consists of 2 layers of muon filter (20-cm-thick iron) and 8 layers of proportional drift tubes[8] outside the return yoke (30-cm-thick iron) of the superconducting magnet. A muon candidate was defined as follows.

(1) It had a charged track ($p > 2.0$ GeV/c) detected in the CDC with $|\cos\theta| < 0.7$.

(2) It also had four or more hits in the six inner layers of the drift tubes within the expected extrapolation of the CDC track.

(3) At least one good track should be reconstructed from the above selected hits. The track's position and direction should agree within errors with the CDC extrapolation.

(4) The depth penetrated by the track must exceed 5.3 absorption lengths, which is equal to the total thickness of the yoke and the filters.

The efficiency for the muon identification is estimated with a detailed detector simulation to be 93% for $p > 4$ GeV/c with $|\cos\theta| < 0.55$ and to decrease gradually to 50% at $|\cos\theta| = 0.7$ because of the geometry of the muon detector, which covers the barrel region in not a cylindrical but a rectangular shape. These values were checked independently using cosmic-ray muons. The cuts on θ_c and p described above were applied to the muon candidates selected in our multihadron sample.[9] No candidate event was found in our data, as shown in Fig. 2(a). The detection efficiency ϵ for the $b'\bar{b}'$ events was estimated to be $7.5 \pm 1.0\%$ including the branching fraction. The errors considered were the uncertainties in the efficiency of muon identification ($\Delta\epsilon/\epsilon \sim 6\%$), the branching fraction of b' (9%),[10] the event simulation (7%), and in the luminosity measurement (4%). The expected number of events from $b'\bar{b}'$ are plotted as a function of the b' mass in Fig. 3, where the curves use the lower bound 6.5% of the quoted efficiency. The horizontal line shows the 95%-C.L. upper limit of the null observation. We set a lower limit on the b' mass of 25.9 GeV/c^2 using this isolated muon signature.

Electrons were identified by their E/p ratio, the ratio of the energy deposited in the LG to the momentum measured in the CDC. An electron candidate was defined as follows.

(1) It had a charged track ($p > 1$ GeV/c) detected in the CDC with $|\cos\theta| < 0.74$.

(2) It also had a shower cluster in the LG at the extrapolated point of the CDC track within the expected deviation.

(3) The ratio E/p was between 0.8 and 1.3.

The efficiency for the electron identification was 85% for $p > 4$ GeV/c, which was estimated with isolated electrons from the reactions of $e^+e^- \to e^+e^-e^+e^-$ or $e^+e^-\gamma$. Of the electron candidates selected in our multihadron-event sample, none were found with $\theta_c > 30°$ and $p > 4$ GeV/c, as shown in Fig. 2(a). The detection efficiency ϵ of $b'\bar{b}'$ events was estimated to be $(8.5 \pm 1.1)\%$. The errors considered here are the systematic uncertainties in the efficiency of electron identification ($\Delta\epsilon/\epsilon \sim 6\%$), the branching fraction of b' (9%), the event simulation (7%), and in the luminosity measurement (4%). A conservative estimate for the number of expected events is shown in Fig. 3. We set a lower limit on b' mass of 26.6 GeV/c^2 at the 95% C.L. using the isolated-electron signature as shown in Fig. 3.

In summary, we have searched for a fourth-generation quark with $|Q| = e/3$ in multihadron events from e^+e^- annihilations. Studies both on the event shape of the final-state particles and on energetic isolated leptons show no evidence for $b'\bar{b}'$ production. The 95%-C.L. lower limits on the b' mass are calculated as 26.1, 25.9, and 26.6 GeV/c^2 from the event-shape, isolated-muon, and isolated-electron signatures, respectively. If we combine the results from the muon- and the electron-signature analyses, we can set a lower limit of 27.5 GeV/c^2 on the b' mass at the 95% C.L.

The authors are grateful to the KEK accelerator operating crew for their skillful operation. The experiment was made possible by the support of the technical staffs at KEK and Universities. Thanks also go to them.

---

*On leave from DESY, D-2000 Hamburg, Federal Republic of Germany.

†Present address: Institute for Nuclear Study, Tanashi, Tokyo 188, Japan.

‡Present address: IBM Japan Co. Ltd., Yamato, Kanagawa 242, Japan.

§Present address: Ishikawajima Harima Heavy Industry Inc., Chiyoda-ku, Tokyo 100, Japan.

**Present address: The Furukawa Electric Co. Ltd., Chiyodaku, Tokyo 100, Japan.

††Present address: Matsushita Electronics Industrial Co. Ltd., Kadoma, Osaka 571 Japan.

[1]J. Ellis, K. Enqvist, and D. V. Nanopoulous, Phys. Lett. **167B**, 457 (1986).

[2]P. Colas, D. Denegri, and C. Stubenrauch, Z. Phys. C **40**, 527 (1988), and references therein.

[3]The AMY group at TRISTAN has rejected $m_{b'} < 23.8$ GeV/c^2 at 95% C.L. in e^+e^- collisions [H. Sagawa *et al.*, Phys. Rev. Lett. **60**, 93 (1988)]. A recent publication of UA1 at CERN set the limit at 32 GeV/c^2 in $\bar{p}p$ collisions [C. Albajar *et al.*, Z. Phys. C **37**, 505 (1988)].

[4]H. Yoshida *et al.*, Phys. Lett. B **198**, 570 (1987); K. Abe *et al.*, Phys. Rev. Lett. **61**, 915 (1988).

[5]R. Berends, R. Kleiss, and S. Jadach, Nucl. Phys. **B202**, 63 (1987).

[6]M. Bengtsson and T. Sjöstrand, Nucl. Phys. **B289**, 810 (1987); Comput. Phys. Commun. **43**, 367 (1987). For comparison, we also used the LUND model with the matrix element scheme.

[7]Two possibilities for the decay of $b' \to u + W^-$ and $b' \to c + W^-$ were considered. They showed a small difference in the efficiencies of the event selection within 7%. Note that the present search is not sensitive to a b' whose lifetime is longer than the order of 10^{-10} sec.

[8]Y. Asano *et al.*, Nucl. Instrum. Methods **A259**, 430 (1987).

[9]The data samples used in the muon analysis are part of those used in the event-shape or the electron analysis. The integrated luminosity of the data samples used in the muon analysis was 8.8 ± 0.4 pb^{-1} and the "multihadron sample" contains 1177 events.

[10]The decay branching ratio of $b' \to l^- \nu q$ was assumed as 11% according to the standard calculations with the error of $\pm 1\%$.