Study of Exclusive $B$ Decays to Charmed Baryons

N. Gabyshev, H. Kichimi, K. Abe, T. Abe, I. Adachi, H. Aihara, M. Akatsu, Y. Asano, T. Aso, V. Aulchenko, T. Aushiw, A. M. Bakich, Y. Ban, E. Banas, A. Bay, P. K. Behera, I. Bizjak, A. Bondar, A. Bozek, M. Bracko, J. Brodzicka, T. E. Browder, B. C. K. Casey, P. Chang, Y. Chao, K.-F. Chen, B. G. Cheon, R. Chistov, S.-K. Choi, Y. Choi, K. Choi, M. Danilov, L. Y. Dong, A. Drutskoy, S. Eidelman, V. Eiges, Y. Enari, F. Fang, A. Garmash, T. Gershon, B. Golob, J. H. Har, H. Hayashii, M. Hazumi, E. M. Heenan, T. Higuchi, H. Hinz, T. Hojo, T. Hokue, Y. Hoshi, W.-S. Hou, H.-C. Huang, T. Igaki, Y. Igarashi, T. Iijima, K. Inami, A. Ishikawa, R. Itoh, H. Iwasaki, Y. Iwasaki, H. K. Jang, J. H. Kang, J. S. Kang, P. Kapusta, N. Katayama, H. Kawai, Y. Kawakami, T. Kawasaki, D. W. Kim, Heejong Kim, H. J. Kim, H. O. Kim, Hyunwoo Kim, S. K. Kim, K. Kinoshita, S. Kobayashi, S. Korpar, P. Križan, P. Krokovny, R. Kulasir, Y. J. Kwon, J. S. Lange, G. Leder, S. H. Lee, D. Liventsev, R.-S. Lu, J. MacNaughton, G. Majumber, F. Mandl, S. Matsumoto, T. Matsumoto, W. Mitaroff, K. Miyabayashi, H. Miyake, H. Miyata, G. R. Moloney, T. Mori, T. Nagamine, Y. Nagasaka, T. Nakadaira, E. Nakano, M. Nakao, H. Nakazawa, J. W. Nam, Z. Natacaniec, S. Nishida, O. Nitoh, S. Noguchi, S. Ogawa, T. Ohshima, T. Okabe, S. Okuno, S. Olsen, H. Ozaki, P. Pakhlov, H. Palka, C. W. Park, H. Park, K. S. Park, J.-P. Perraud, M. Peters, E. Piilonen, F. J. Ronga, N. Root, K. Rybicki, H. Sagawa, S. Saitoh, Y. Sakai, H. Sakamoto, M. Satapathy, A. Satpathy, O. Schneider, C. Schwanda, A. Schwartz, S. Semenov, K. Senyo, R. Seuster, M. E. Sevior, H. Shibuya, B. Shwartz, V. Sidorov, N. Soni, S. Stanic, M. Starić, A. Sugi, A. Sugiyama, K. Sumisawa, T. Sumiyoshi, K. Suzuki, T. Takahashi, F. Takasaki, N. Tamura, J. Tanaka, M. Tanaka, G. N. Taylor, Y. Teramoto, S. Tokuda, T. Tomura, T. Tsuboyama, T. Tsukamoto, S. Uehara, K. Ueno, S. Uno, Y. Ushiroda, S. E. Vahsen, G. Varner, K. E. Varvell, C. C. Wang, C. H. Wang, J. G. Wang, M.-Z. Wang, Y. Watanabe, E. Won, B. D. Yabsley, Y. Yamada, A. Yamaguchi, Y. Yamashita, H. Yanai, J. Yashima, Y. Yuan, Y. Yusa, C. C. Zhang, Z. P. Zhang, V. Zhilich, and D. Žontar

(The Belle Collaboration)

1 Budker Institute of Nuclear Physics, Novosibirsk
2 Chiba University, Chiba
3 Chuo University, Tokyo
4 University of Cincinnati, Cincinnati OH
5 University of Frankfurt, Frankfurt
6 Gyeongsang National University, Chinju
7 University of Hawaii, Honolulu HI
8 High Energy Accelerator Research Organization (KEK), Tsukuba
9 Hiroshima Institute of Technology, Hiroshima
10 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
11 Institute of High Energy Physics, Vienna
12 Institute for Theoretical and Experimental Physics, Moscow
13 J. Stefan Institute, Ljubljana
14 Kanagawa University, Yokohama
15 Korea University, Seoul
16 Kyoto University, Kyoto
17 Kyungpook National University, Taegu
18 Institut de Physique des Hautes Énergies, Université de Lausanne, Lausanne
19 University of Ljubljana, Ljubljana
20 University of Maribor, Maribor
21 University of Melbourne, Victoria
22 Nagoya University, Nagoya
23 Nara Women’s University, Nara
24 National Lien-Ho Institute of Technology, Miao Li
25 National Taiwan University, Taipei
26 H. Niewodniczanski Institute of Nuclear Physics, Krakow
27 Nihon Dental College, Niigata
28 Niigata University, Niigata
29 Osaka City University, Osaka
30 Osaka University, Osaka
31 Panjab University, Chandigarh
32 Princeton University, Princeton NJ
33 RIKEN BNL Research Center, Brookhaven NY
34 Saga University, Saga
35 University of Science and Technology of China, Hefei
36 Seoul National University, Seoul
37 Sungkyunkwan University, Suwon
38 University of Sydney, Sydney NSW
39 Tata Institute of Fundamental Research, Bombay
40 Toho University, Funabashi
41 Tohoku Gakuin University, Tagajo
42 Tohoku University, Sendai
43 University of Tokyo, Tokyo
44 Tokyo Institute of Technology, Tokyo
45 Tokyo Metropolitan University, Tokyo
46 Tokyo University of Agriculture and Technology, Tokyo
47 Toyama National College of Maritime Technology, Toyama
48 University of Tsukuba, Tsukuba
49 Utkal University, Bhubaneswar
50 Virginia Polytechnic Institute and State University, Blacksburg VA
51 Yonsei University, Seoul
52 Peking University, Beijing
(Dated: March 25, 2022)

Abstract

Using 29.1 fb$^{-1}$ of data accumulated at the $\Upsilon(4S)$ with the Belle detector at KEKB, we have studied the decay modes $\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^-$, $B^- \to \Lambda_c^+ \bar{p} \pi^-$, and $\bar{B}^0 \to \Lambda_c^+ \bar{p}$. We report branching fractions of exclusive $B$ decays to charmed baryons with four-, three- and two-body final states, including intermediate $\Sigma_c^{++}$ and $\Sigma_c^0$ states. We observed $\bar{B}^0 \to \Sigma_c(2455)^{++} \bar{p} \pi^-$ for the first time with a branching fraction of $(2.38^{+0.63}_{-0.55} \pm 0.41 \pm 0.62) \times 10^{-4}$ and observed evidence for the two-body decay $B^- \to \Sigma_c(2455)^0 \bar{p}$ with a branching fraction of $(0.45^{+0.26}_{-0.19} \pm 0.07 \pm 0.12) \times 10^{-4}$. We also set improved upper limits for the two-body decays $\bar{B}^0 \to \Lambda_c^+ \bar{p}$ and $B^- \to \Sigma_c(2520)^0 \bar{p}$.

PACS numbers: 13.25.Hw, 14.20.Lq

*on leave from Nova Gorica Polytechnic, Nova Gorica
Baryon production in flavored meson decays is unique to the $B$ meson system due to the heavy mass of the constituent $b$-quark. Several studies of inclusive charmed baryon production in $B$ meson decays have been made and a large branching fraction for $B \to \Lambda_c^+ X$ of $(6.4\pm1.1)\%$ has been reported. However, the mechanism is not well understood. The measured inclusive $\Lambda_c^+$ momentum spectra indicate that multi-body final states are dominant in baryonic $B$ decays. With a data sample of $2.39 \text{ fb}^{-1}$, CLEO has studied exclusive charmed baryonic decay modes and measured the branching fractions for $B^0 \to \Lambda_c^+ p \pi^+ \pi^-$ and $B^- \to \Lambda_c^+ \bar{p} \pi^-$. They found no evidence for $B^0 \to \Lambda_c^+ p$ and provided an upper limit. So far, no observations of two-body decays have been reported. On the other hand, there are theoretical predictions for branching fractions of two-body baryonic modes based on a pole model, a QCD sum rule, a diquark model, and a bag model. The predictions of the different models vary by an order of magnitude, and experimental measurement can be used to discriminate among them. We have made a systematic study of exclusive charmed baryonic decays of $\bar{B}^0$ and $B^-$ mesons into four-, three- and two-body final states including $\Sigma^{++}/0$, intermediate resonances, by analyzing the $\Lambda_c^+ p \pi^+ \pi^-$, $\Lambda_c^+ \bar{p} \pi^-$ and $\Lambda_c^+ \bar{p}$ final states. Charge conjugate modes are included unless otherwise mentioned. This analysis is based on a data sample of $29.1 \text{ fb}^{-1}$ corresponding to $3.17 \times 10^7 B\bar{B}$ pairs. The data were accumulated at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric collider of $3.5 \text{ GeV} e^+ e^-$ and $8.0 \text{ GeV} e^- e^-$.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector (SVD), a 50-layer cylindrical drift chamber (CDC), a mosaic of aerogel threshold Čerenkov counters (ACC), a barrel-like array of time-of-flight scintillation counters (TOF), and an array of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside the coil is instrumented to detect muons and $K_L$ mesons (KLM). The detector is described in detail elsewhere. We use a GEANT based Monte Carlo (MC) simulation to model the response of the detector and determine the acceptance.

In searches for the decay modes $\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-$, $B^- \to \Lambda_c^+ \bar{p} \pi^-$, and $\bar{B}^0 \to \Lambda_c^+ \bar{p}$, the $\Lambda_c^+ \to pK^-\pi^+$ decay mode is used. Particle identification information from the CDC $dE/dx$, ACC and TOF is used to provide a mass assignment for each track. A likelihood ratio $LR(A, B) = L_A/(L_A + L_B) > 0.6$ is required to identify a particle as type $A$, where $B$ is the other possible assignment among $\pi^\pm$, $K^\pm$ and $p(\bar{p})$. Electron and muon candidate tracks are removed if their probabilities from the ECL, CDC $dE/dx$ and KLM are greater than 95%. Candidate $\Lambda_c^+$’s are tagged if the invariant mass of the $p$, $K^-$ and $\pi^+$ track combination is within $0.010 \text{ GeV}/c^2$ of the $\Lambda_c^+$ mass; tagged events are then examined for the three search modes by adding $\bar{p}$, $\pi^-$, and $\pi^+$ tracks. The width $\sigma_{\Lambda_c^+}$ is found to be $4.9 \text{ MeV}/c^2$, consistent with the MC.

In order to select $B$ meson candidates, we use the beam energy-constrained mass and energy difference, which are defined as $M_{bc} = \sqrt{E_{beam}^2 - (\sum \bar{p}_i)^2}$ and $\Delta E = \sum E_i - E_{beam}$ in the center-of-mass (CM) frame of the $e^+e^-$ collision. $E_{beam}$ is the beam energy, and $E_i$ and $\bar{p}_i$ are the energy and momentum vector for the $i$-th daughter particle of a $B$ candidate. $B$ candidates are selected with a loose cut to retain sideband events by requiring $M_{bc} > 5.2 \text{ GeV}/c^2$ and $|\Delta E| < 0.2 \text{ GeV}$. A vertex-constrained fit for the three daughter tracks is carried out at the $\Lambda_c^+$ vertex. For each decay mode, the virtual $\Lambda_c^+$ track and additional tracks are required to form a good vertex. If there are multiple candidates for both $\Lambda_c^+$ and $B$, the candidate with the minimum $\chi^2 = \chi^2_{\Lambda_c^+} + \chi^2_{B} + (M_{bc} - 5.279)^2/\sigma_{M_{bc}}^2$ is selected. Here, $\chi^2_{\Lambda_c^+}$ and $\chi^2_{B}$ are the $\chi^2$’s from the fits for the $\Lambda_c^+$ and $B$ vertices, respectively, and $\sigma_{M_{bc}}$ is
the MC value of the $M_{bc}$ width (2.8 MeV/c^2). Loose cuts on $\chi^2_{A_s^c}$ and $\chi^2_{B}$ are applied to remove background from tracks arising from $K_S^0$ and $\Lambda$ decays.

Event selection requirements are optimized using signal MC events and continuum background MC events consisting of $u \bar{u}$, $d \bar{d}$, $s \bar{s}$, and $c \bar{c}$ quark-antiquark pairs generated with the expected fractions. To suppress the continuum background, we use a Fisher discriminant constructed from 10 variables: 8 modified Fox-Wolfram moments $[10]$, $\cos \Theta_B$, and $\cos \Theta_{A_s^c}$. Here, $\cos \Theta_{B}$ is the cosine of the direction of the $B$ meson with respect to the electron beam direction, and $\cos \Theta_{A_s^c}$ is the cosine of the direction of the daughter $A_s^c$ with respect to the thrust axis of the tracks not associated with the $B$ candidates. Both quantities are defined in the CM system. A set of 10 coefficients for each mode is optimized to maximize separation of the signal from the continuum background. The probability density functions for the signals and for the continuum, $P_{\text{sig}}$ and $P_{\text{con}}$, respectively, are parameterized with Gaussian functions for the three search modes and for the continuum events. A cut on the likelihood ratio $R_{\text{sfw}} = P_{\text{sig}}/(P_{\text{sig}} + P_{\text{con}}) > 0.6$ is applied to all decay modes. In the MC simulation this cut removed 76% of the continuum background while retaining 86% of the signal for $\Lambda_c^+ \bar{p} \pi^+ \pi^-$. Figure 1 shows the $M_{bc}$ and $\Delta E$ distributions for the three decay modes, after a tight cut is made in the $(\Delta E, M_{bc})$ variable not plotted. The $M_{bc}$ background distributions are parameterized by the ARGUS function $[11]$, while a Gaussian is used for the signal. The $\Delta E$ distributions are fitted with a second-order polynomial for the background and a double Gaussian for the signal. Here, the width parameters are fixed to the values fitted to the signal MC events. The mean and width of $M_{bc}$ in the data are found to be consistent with the MC values of 5.279 GeV/c^2 and 2.8 MeV/c^2, respectively. The width of $\Delta E$ is also consistent with the MC value (9.9 MeV) when fit to a single Gaussian. We obtain signal yields of 154$^{+17}_{-16}$ and 38.8$^{+7.6}_{-7.0}$ from the fits to the $M_{bc}$ distributions (a) and (c), and 141$^{+16}_{-15}$ and 30.2$^{+7.9}_{-6.4}$ from the fits to the $\Delta E$ distributions (b) and (d), respectively. Here, we choose the asymmetric range of $-0.100 < \Delta E < 0.200$ GeV to exclude feed-down from higher multiplicity modes with extra pions; these produce the structure observed in the region $\Delta E < -0.150$ GeV. Since $M_{bc}$ is used in the $\chi^2$ calculation for the best candidate selection as described previously, we use the yields resulting from the fits to the $\Delta E$ distributions to calculate branching fractions.

We observe $B^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$ and $B^- \rightarrow \Lambda_c^+ \bar{p} \pi^-$ signals. For $B^0 \rightarrow \Lambda_c^+ \bar{p}$ we find a statistical significance of only 1.9$\sigma$ from a fit to a Gaussian function for the signal with mean and width fixed to those from the signal MC, and a linear background function. We thus set an upper limit of 6.1 events at the 90% confidence level based on the likelihood function, using the Bayesian method with a prior uniform in the branching fraction.

Table 1 summarizes the observed yields and branching fractions. Here, the detection efficiencies are calculated assuming nonresonant decays and do not include the branching fraction $B(\Lambda_c^+ \rightarrow pK^- \pi^-) = (5.0 \pm 1.3)\%$ $[12]$. We assume the fractions of charged and neutral $B$ mesons to be equal in the branching fraction calculations. We include a correlated systematic error of 2% per track for tracking and particle identification. Systematics due to the $\chi^2_{A_s^c}$, $\chi^2_{B}$ and $R_{\text{sfw}}$ cuts are estimated by varying cut values. The signal shape systematic error is evaluated from the variation in fit results obtained with different-order polynomials used for the background and single and double Gaussians used for the signal. The resulting total systematic errors for $\Lambda_c^+ \bar{p} \pi^+ \pi^-$, $\Lambda_c^+ \bar{p} \pi^-$ and $\Lambda_c^+ \bar{p}$ are 17.2%, 14.8% and 13.3%, respectively. Table 1 shows the CLEO measurements renormalized to the same $B(\Lambda_c^+ \rightarrow pK^- \pi^+)$ for comparison. Our branching fraction for $B^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$ is consistent with their mea-
The CLEO results are renormalized to

TABLE I: Branching fractions for $B_c \rightarrow \Lambda_c^+ \bar{p}\pi^+$, $B_c \rightarrow \Lambda_c^+ \bar{p}\pi^-$, $B_c \rightarrow \Lambda_c^0 \bar{p}$, and $B_c \rightarrow \Lambda_c^+ \bar{p}$. The errors are statistical, systematic, and a common error due to the uncertainty in the value of $B(\Lambda_c^+ \rightarrow pK^-\pi^+)$. The CLEO results are renormalized to $B(\Lambda_c^+ \rightarrow pK^-\pi^+) = (5.0 \pm 1.3)\%$ [12] for comparison.

![](image)

**FIG. 1:** $M_{bc}$ distributions for $|\Delta E| < 0.030$ GeV and $\Delta E$ distributions for $M_{bc} > 5.270$ GeV/c$^2$: (a) and (b) for $B_c \rightarrow \Lambda_c^+ \bar{p}\pi^+\pi^-$, (c) and (d) for $B^- \rightarrow \Lambda_c^+ \bar{p}\pi^-$, and (e) and (f) for $B_c \rightarrow \Lambda_c^+ \bar{p}$. We also set a more restrictive upper limit on $B_c \rightarrow \Lambda_c^+ \bar{p}$.

Figure 2 shows the $\Lambda_c^+ \pi^\pm$ invariant mass distributions in the $B$ signal region, $|\Delta E| < 0.030$ GeV and $M_{bc} > 5.270$ GeV/c$^2$. Significant signals are observed for the $\Sigma_c(2455)$ and $\Sigma_c(2520)$. The shaded histograms are the distributions for events in the sideband region $0.040 < |\Delta E| < 0.100$ GeV, normalized to the signal region $|\Delta E| < 0.030$ GeV; these account for continuum $\Sigma_c$ background. The two curves indicate the results of separate fits to the distributions for the $B$ signal and the sideband regions, with $\Sigma_c$ masses and widths fixed to fit values for the signal MC events generated with PDG values for masses and widths [12]. The background shapes are taken from a nonresonant signal MC. To extract the $\Sigma_c$ yields, we performed a simultaneous likelihood fit to the distributions for the $B$ signal and sideband regions. We express the expected number $N_{\Sigma_c}$ of $B$ events as $N_{\Sigma_c} = N_{Bb} - r \cdot N_{sb}$, where $N_{Bb}$ is the yield in the $B$ signal region, $N_{sb}$ is the yield in the sideband region, and $r = 0.5$ is the normalization factor due to the ratio of their $\Delta E$ ranges, assuming a linear background shape.
Table II summarizes the observed signal yields and branching fractions. We observe the

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Mode & Efficiency (%) & Yield & Significance & \( \mathcal{B} \times 10^{-4} \) \\
\hline
\( \bar{B}^0 \to \Sigma_c(2455)^{++} \bar{p}\pi^- \) & 4.93 & 16.8^{+4.9}_{-4.3} & 5.3 & 2.38^{+0.63}_{-0.55} \pm 0.41 \pm 0.62 \\
\hline
\( B^0 \to \Sigma_c(2520)^{++} \bar{p}\pi^- \) & 6.38 & 16.5^{+5.2}_{-4.6} & 3.5 & 1.63^{+0.57}_{-0.51} \pm 0.28 \pm 0.42 \\
\hline
\( B^0 \to \Sigma_c(2455)^0 \bar{p}\pi^+ \) & 4.80 & 6.4^{+3.2}_{-2.7} & 2.6 & 0.84^{+0.42}_{-0.35} \pm 0.14 \pm 0.22 \\
& & & < 11.6 (90\% CL) & < 1.50 (90\% CL) \\
\hline
\( B^0 \to \Sigma_c(2520)^0 \bar{p}\pi^+ \) & 6.35 & 4.8^{+4.5}_{-4.0} & 1.2 & 0.48^{+0.45}_{-0.40} \pm 0.08 \pm 0.12 \\
& & & < 11.7 (90\% CL) & < 1.21 (90\% CL) \\
\hline
\( B^- \to \Sigma_c(2455)^0 \bar{p} \) & 6.00 & 4.3^{+2.5}_{-1.8} & 3.0 & 0.45^{+0.20}_{-0.19} \pm 0.07 \pm 0.12 \\
& & & < 8.5 (90\% CL) & < 0.93 (90\% CL) \\
\hline
\( B^- \to \Sigma_c(2520)^0 \bar{p} \) & 7.47 & 1.7^{+1.5}_{-1.1} & 1.8 & 0.14^{+0.15}_{-0.09} \pm 0.02 \pm 0.04 \\
& & & < 5.2 (90\% CL) & < 0.46 (90\% CL) \\
\hline
\end{tabular}
\caption{Efficiencies, yields, significances and branching fractions for decay modes with \( \Sigma_c^{++/0} \) resonances. The errors are statistical, systematic, and a common error due to the uncertainty in the value of \( \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) \).}
\end{table}

\( \bar{B}^0 \to \Sigma_c(2455)^{++} \bar{p}\pi^- \) decay for the first time with a statistical significance of 5.3 \( \sigma \). We also see 3.5 \( \sigma \) evidence for \( \bar{B}^0 \to \Sigma_c(2520)^{++} \bar{p}\pi^- \), 2.6 \( \sigma \) evidence for \( \bar{B}^0 \to \Sigma_c(2455)^0 \bar{p}\pi^+ \), and less evidence for \( \bar{B}^0 \to \Sigma_c(2520)^0 \bar{p}\pi^+ \). We see 3.0 \( \sigma \) evidence for the two-body decay \( B^- \to \Sigma_c(2455)^0 \bar{p} \), and less evidence for \( B^- \to \Sigma_c(2520)^0 \bar{p} \). For those modes with a significance of three sigmas or less, we set upper limits on their branching fractions.
Our results provide stringent constraints upon theoretical predictions [3, 4, 5, 6]. The predictions for $B^0 \rightarrow \Lambda_c^+ p$ in [3, 4, 5] were already much larger than the CLEO experimental upper limit [2]; here we set an even more restrictive upper limit. A recent study based on a bag model [6] gives predictions of branching fractions of $\leq (0.1 \sim 0.3) \times 10^{-4}$ for $B^0 \rightarrow \Lambda_c^+ p$ and $(4.3 \sim 15.1) \times 10^{-4}$ for $B^- \rightarrow \Lambda_c^+ p\pi^-$. Our upper limit for $B^0 \rightarrow \Lambda_c^+ p$ does not contradict this model, while our measured result for $B^- \rightarrow \Lambda_c^+ p\pi^-$ is much smaller than its predicted value.

In summary, we have observed the exclusive three-body decay $\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p}\pi^-$ for the first time and observed evidence for the exclusive two-body decay $B^- \rightarrow \Sigma_c(2455)^0 \bar{p}$. We make improved measurements of the branching fractions for $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p}\pi^+\pi^-$ and $B^- \rightarrow \Lambda_c^+ p\pi^-$, and also set a more restrictive upper limit on $\bar{B}^0 \rightarrow \Lambda_c^+ p$.

Acknowledgments

We wish to thank the KEKB accelerator group for the excellent operation of the KEKB accelerator. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology of Japan and the Japan Society for the Promotion of Science; the Australian Research Council and the Australian Department of Industry, Science and Resources; the National Science Foundation of China under Contract No. 10175071; the Department of Science and Technology of India; the BK21 program of the Ministry of Education of Korea and the CHEP SRC program of the Korea Science and Engineering Foundation; the Polish State Committee for Scientific Research under contract No. 2P03B 17017; the Ministry of Science and Technology of the Russian Federation; the Ministry of Education, Science and Sport of Slovenia; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy.

[1] H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. B 210, 263 (1988). G. Crawford et al. (CLEO Collaboration), Phys. Rev. D 45, 752 (1992), and M. Procario et al. (CLEO Collaboration), Phys. Rev. Lett. 73, 1472 (1994).
[2] X. Fu et al. (CLEO Collaboration), Phys. Rev. Lett. 79, 3125 (1997).
[3] M. Jarfi et al., Phys. Lett. B 237, 513 (1990); M. Jarfi et al., Phys. Rev. D 43, 1599 (1991); N. Deshpande, J. Trampetic and A. Soni, Mod. Phys. Lett. A 3, 749 (1988).
[4] V. Chernyak and I. Zhitnitsky, Nucl. Phys. B 345, 137 (1990).
[5] P. Ball and H.G. Dosch, Z. Phys. C 51, 445 (1991).
[6] H. Cheng and K. Yang, Phys. Rev. D 65, 054028 (2002).
[7] E. Kikutani ed., KEK preprint 2001-157(2001) to appear in Nucl. Instr. Meth. A (2002).
[8] A. Abashian et al. (Belle Collaboration), Nucl. Instr. Meth. A 479, 117 (2002).
[9] Events are generated with the CLEO QQ program [http://www.lns.cornell.edu/public/CLEO/soft/QQ]. The detector response is simulated using GEANT, R.Brun et al., GEANT 3.21, CERN Report DD/EE/84-1, 1984.
[10] The Fox-Wolfram moments are introduced in G.C. Fox and S. Wolfram, Phys. Rev. Lett. 41, 1581 (1978). The Fisher discriminant used by Belle is described in K. Abe et al. (Belle Collaboration), Phys. Rev. Lett. 87, 101801 (2001) and K. Abe et al. (Belle Collaboration), Phys. Lett. B 511, 151 (2001).
[11] H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. B 229, 304 (1989).
[12] D.E. Groom et al. (Particle Data Group), Eur. Phys. J. C 15, 636 (2000).