Physics Letters B 281 (1992) 383–393
North-Holland

PHYSICS LETTERS B

Measurement of the Z^0 branching fraction to b quark pairs using the boosted sphericity product

DELPHI Collaboration

P. Abreu [a], W. Adam [b], F. Adami [c], T. Adye [d], T. Akesson [c], G.D. Alekseev [f], P. Allen [g], S. Almehed [c], S.J. Alvsvaag [h], U. Amaldi [i], E.G. Anassontzis [j], P. Antilogus [k], W.-D. Apel [ℓ], R.J. Apsimon [d], B. Åsman [m], J.-E. Augustin [n], A. Augustinus [o], P. Baillon [i], P. Bambade [n], F. Barao [a], R. Barate [p], G. Barbiellini [q], D.Y. Bardin [f], A. Baroncelli [r], O. Barring [e], W. Bartl [b], M.J. Bates [s], M. Battaglia [t], M. Baubillier [u], K.-H. Becks [v], C.J. Beeston [s], M. Begalli [w], P. Beilliere [x], Yu. Belokopytov [y], P. Beltran [z], D. Benedic [aa], J.M. Benlloch [g], M. Berggren [n], D. Bertrand [ab], F. Bianchi [ac], M.S. Bilenky [f], P. Billoir [u], J. Bjarne [e], D. Bloch [aa], S. Blyth [s], V. Bocci [ad], P.N. Bogolubov [f], T. Bolognese [c], M. Bonesini [t], W. Bonivento [t], P.S.L. Booth [ae], P. Borgeaud [c], G. Borisov [y], H. Borner [i], C. Bosio [r], B. Bostjancic [i], O. Botner [af], B. Bouquet [n], C. Bourdarios [n], T.J.V. Bowcock [ae], M. Bozzo [w], S. Braibant [ab], P. Branchini [r], K.D. Brand [ag], R.A. Brenner [ah], H. Briand [u], C. Bricman [ab], R.C.A. Brown [i], N. Brummer [o], J.-M. Brunet [x], L. Bugge [ai], T. Buran [ai], H. Burmeister [i], J.A.M.A. Buytaert [i], M. Caccia [i], M. Calvi [t], A.J. Camacho Rozas [aj], T. Camporesi [i], V. Canale [ad], F. Cao [ab], F. Carena [i], L. Carroll [ae], C. Caso [w], E. Castelli [q], M.V. Castillo Gimenez [g], A. Cattai [i], F.R. Cavallo [ak], L. Cerrito [ad], A. Chan [aℓ], M. Chapkin [y], P. Charpentier [i], L. Chaussard [n], J. Chauveau [u], P. Checchia [ag], G.A. Chelkov [f], L. Chevalier [c], P. Chliapnikov [y], V. Chorowicz [u], R. Cirio [ac], M.P. Clara [ac], P. Collins [s], J.L. Contreras [am], R. Contri [w], G. Cosme [n], F. Couchot [n], H.B. Crawley [aℓ], D. Crennell [d], G. Crosetti [w], M. Crozon [x], J. Cuevas Maestro [aj], S. Czellar [ah], S. Dagoret [n], E. Dahl-Jensen [an], B. Dalmagne [n], M. Dam [ai], G. Damgaard [an], G. Darbo [w], E. Daubie [ab], P.D. Dauncey [s], M. Davenport [i], P. David [u], W. Da Silva [u], C. Defoix [x], D. Delikaris [i], S. Delorme [i], P. Delpierre [x], N. Demaria [ac], A. De Angelis [q], M. De Beer [c], H. De Boeck [ab], W. De Boer [ℓ], C. De Clercq [ab], M.D.M. De Fez Laso [g], N. De Groot [o], C. De La Vaissiere [u], B. De Lotto [q], A. De Min [t], H. Dijkstra [i], L. Di Ciaccio [ad], F. Djama [aa], J. Dolbeau [x], M. Donszelmann [i], K. Doroba [ao], M. Dracos [i], J. Drees [v], M. Dris [ap], Y. Dufour [x], L.-O. Eck [af], P.A.-M. Eerola [i], T. Ekelof [af], G. Ekspong [m], A. Elliot Peisert [ag], J.-P. Engel [aa], D. Fassouliotis [ap], M. Feindt [i], M. Fernandez Alonso [aj], A. Ferrer [g], T.A. Filippas [ap], A. Firestone [aℓ], H. Foeth [i], E. Fokitis [ap], P. Folegati [q], F. Fontanelli [w], K.A.J. Forbes [ae], B. Franek [d], P. Frenkiel [x], D.C. Fries [ℓ], A.G. Frodesen [h], R. Fruhwirth [b], F. Fulda-Quenzer [n], K. Furnival [ae], H. Furstenau [ℓ], J. Fuster [i], G. Galeazzi [ag], D. Gamba [ac], C. Garcia [g], J. Garcia [aj], C. Gaspar [i], U. Gasparini [ag], P. Gavillet [i], E.N. Gazis [ap], J.-P. Gerber [aa], P. Giacomelli [i], R. Gokieli [i], V.M. Golovatyuk [f], J.J. Gomez Y Cadenas [i], A. Goobar [m], G. Gopal [d], M. Gorski [ao], V. Gracco [w], A. Grant [i], F. Grard [ab], E. Graziani [r], G. Grosdidier [n], E. Gross [i], P. Grosse-Wiesmann [i], B. Grossetete [u], S. Gumenyuk [y], J. Guy [d], F. Hahn [i], M. Hahn [ℓ], S. Haider [o], Z. Hajduk [aq], A. Hakansson [c], A. Hallgren [af], K. Hamacher [v], G. Hamel De Monchenault [c], W. Hao [o], F.J. Harris [s], B.W. Heck [i], T. Henkes [i], J.J. Hernandez [g], P. Herquet [ab], H. Herr [i], T.L. Hessing [ac], I. Hietanen [ah], C.O. Higgins [ac], E. Higon [g], H.J. Hilke [i], S.D. Hodgson [s], T. Hofmokl [ao], R. Holmes [aℓ], S.-O. Holmgren [m], D. Holthuizen [o], P.F. Honore [x], J.E. Hooper [an], M. Houlden [ac], J. Hrubec [b], P.O. Hulth [m], K. Hultqvist [m], P. Ioannou [j], D. Isenhower [i], P.-S. Iversen [h], J.N. Jackson [ae],

P. Jalocha [aq], G. Jarlskog [e], P. Jarry [c], B. Jean-Marie [n], E.K. Johansson [m], D. Johnson [ae], M. Jonker [i], L. Jonsson [c], P. Juillot [aa], G. Kalkanis [j], G. Kalmus [d], F. Kapusta [u], M. Karlsson [i], E. Karvelas [z], S. Katsanevas [j], E.C. Katsoufis [ap], R. Keranen [ah], J. Kesteman [ab], B.A. Khomenko [f], N.N. Khovanski [f], B. King [ac], N.J. Kjaer [i], H. Klein [i], W. Klempt [i], A. Klovning [h], P. Kluit [o], J.H. Koehne [ℓ], B. Koene [o], P. Kokkinias [z], M. Kopf [ℓ], M. Koratzinos [ac], K. Korcyl [aq], A.V. Korytov [f], V. Kostioukhine [y], C. Kourkoumelis [j], P.H. Kramer [v], T. Kreuzberger [b], J. Krolikowski [ao], I. Kronkvist [c], J. Krstic [s], U. Kruener-Marquis [v], W. Krupinski [aq], W. Kucewicz [t], K. Kurvinen [ah], C. Lacasta [g], C. Lambropoulos [z], J.W. Lamsa [aℓ], L. Lanceri [q], V. Lapin [y], J.-P. Laugier [c], R. Lauhakangas [ah], G. Leder [b], F. Ledroit [p], R. Leitner [i], Y. Lemoigne [c], J. Lemonne [ab], G. Lenzen [v], V. Lepeltier [n], A. Letessier-Selvon [u], E. Lieb [v], D. Liko [b], E. Lillethun [h], J. Lindgren [ah], R. Lindner [v], A. Lipniacka [ao], I. Lippi [ag], R. Llosa [am], B. Loerstad [c], M. Lokajicek [f], J.G. Loken [s], A. Lopez-Fernandez [n], M.A. Lopez Aguera [aj], M. Los [o], D. Loukas [z], J.J. Lozano [g], P. Lutz [x], L. Lyons [s], G. Machlum [i], J. Maillard [x], A. Maltezos [z], F. Mandl [b], J. Marco [aj], M. Margoni [ag], J.-C. Marin [i], A. Markou [z], T. Maron [v], S. Marti [g], L. Mathis [aℓ], F. Matorras [aj], C. Matteuzzi [t], G. Matthiae [ad], M. Mazzucato [ag], M. Mc Cubbin [ac], R. Mc Kay [aℓ], R. Mc Nulty [ae], G. Meola [w], C. Meroni [t], W.T. Meyer [aℓ], M. Michelotto [ag], W.A. Mitaroff [b], G.V. Mitselmakher [f], U. Mjoernmark [e], T. Moa [m], R. Moeller [an], K. Moenig [i], M.R. Monge [w], P. Morettini [w], H. Mueller [ℓ], W.J. Murray [d], B. Muryn [n], G. Myatt [s], F. Naraghi [u], F.L. Navarria [ak], P. Negri [t], B.S. Nielsen [an], B. Nijjhar [ae], V. Nikolaenko [y], V. Obraztsov [y], K. Oesterberg [ah], A.G. Olshevski [f], R. Orava [ah], A. Ostankov [y], A. Ouraou [c], M. Paganoni [t], R. Pain [u], H. Palka [o], T. Papadopoulou [ap], L. Pape [i], A. Passeri [r], M. Pegoraro [ag], J. Pennanen [ah], V. Perevozchikov [y], M. Pernicka [b], A. Perrotta [ak], F. Pierre [c], M. Pimenta [a], O. Pingot [ab], M.E. Pol [i], G. Polok [aq], P. Poropat [q], P. Privitera [ℓ], A. Pullia [t], D. Radojicic [s], S. Ragazzi [t], P.N. Ratoff [ar], A.L. Read [ai], N.G. Redaelli [t], M. Regler [b], D. Reid [ac], P.B. Renton [s], L.K. Resvanis [j], F. Richard [n], M. Richardson [ae], J. Ridky [f], G. Rinaudo [ac], I. Roditi [i], A. Romero [ac], I. Roncagliolo [w], P. Ronchese [ag], C. Ronnqvist [ah], E.I. Rosenberg [aℓ], U. Rossi [ak], E. Rosso [i], P. Roudeau [n], T. Rovelli [ak], W. Ruckstuhl [o], V. Ruhlmann [c], A. Ruiz [aj], K. Rybicki [aq], H. Saarikko [ah], Y. Sacquin [c], G. Sajot [p], J. Salt [g], E. Sanchez [g], J. Sanchez [am], M. Sannino [w], S. Schael [ℓ], H. Schneider [ℓ], M.A.E. Schyns [v], F. Scuri [q], A.M. Segar [s], R. Sekulin [d], M. Sessa [q], G. Sette [w], R. Seufert [ℓ], R.C. Shellard [i], P. Siegrist [c], S. Simonetti [w], F. Simonetto [ag], A.N. Sissakian [f], T.B. Skaali [ai], G. Skjevling [ai], G. Smadja [c,k], G.R. Smith [d], R. Sosnowski [ao], T.S. Spassoff [p], E. Spiriti [r], S. Squarcia [w], H. Staeck [v], C. Stanescu [r], G. Stavropoulos [z], F. Stichelbaut [ab], A. Stocchi [n], J. Strauss [b], J. Straver [i], R. Strub [aa], M. Szczekowski [ao], M. Szeptycka [ao], P. Szymanski [ao], T. Tabarelli [t], S. Tavernier [ab], O. Tchikilev [y], G.E. Theodosiou [z], A. Tilquin [as], J. Timmermans [o], V.G. Timofeev [f], L.G. Tkatchev [f], T. Todorov [aa], D.Z. Toet [o], O. Toker [ah], E. Torassa [ac], L. Tortora [r], M.T. Trainor [s], D. Treille [i], U. Trevisan [w], W. Trischuk [i], G. Tristram [x], C. Troncon [t], A. Tsirou [i], E.N. Tsyganov [f], M. Turala [aq], M.-L. Turluer [c], T. Tuuva [ah], I.A. Tyapkin [f], M. Tyndel [d], S. Tzamarias [i], S. Ueberschaer [v], O. Ullaland [i], V. Uvarov [y], G. Valenti [ak], E. Vallazza [ac], J.A. Valls Ferrer [g], C. Vander Velde [ab], G.W. Van Apeldoorn [o], P. Van Dam [o], W.K. Van Doninck [ab], J. Varela [a], P. Vaz [i], G. Vegni [t], L. Ventura [ag], W. Venus [d], F. Verbeure [ab], L.S. Vertogradov [f], D. Vilanova [c], N. Vishnevsky [y], L. Vitale [q], E. Vlasov [y], S. Vlassopoulos [ap], A.S. Vodopyanov [f], M. Vollmer [v], S. Volponi [ak], G. Voulgaris [j], M. Voutilainen [ah], V. Vrba [r], H. Wahlen [v], C. Walck [m], F. Waldner [q], M. Wayne [aℓ], A. Wehr [v], M. Weierstall [v], P. Weilhammer [i], J. Werner [v], A.M. Wetherell [i], J.H. Wickens [ab], J. Wikne [ai], G.R. Wilkinson [s], W.S.C. Williams [s], M. Winter [aa], D. Wormald [ai], G. Wormser [n], K. Woschnagg [af], N. Yamdagni [m], P. Yepes [i], A. Zaitsev [y], A. Zalewska [aq], P. Zalewski [n], D. Zavrtanik [i], E. Zevgolatakos [z], G. Zhang [v], N.I. Zimin [f], M. Zito [c], R. Zitoun [u], R. Zukanovich Funchal [x], G. Zumerle [ag] and J. Zuniga [g]

[a] *LIP, Av. Elias Garcia 14 - 1e, P-1000 Lisbon Codex, Portugal*
[b] *Institut für Hochenergiephysik, Österreichische Akademie der Wissenschaften, Nikolsdorfergasse 18, A-1050 Vienna, Austria*
[c] *DPhPE, CEN-Saclay, F-91191 Gif-Sur-Yvette Cedex, France*
[d] *Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, UK*
[e] *Department of Physics, University of Lund, Sölvegatan 14, S-223 63 Lund, Sweden*
[f] *Joint Institute for Nuclear Research, Dubna, Head Post Office, P.O. Box 79, SU-101 000 Moscow, USSR*
[g] *Instituto de Fisica Corpuscular (IFIC), Centro Mixto Universidad de Valencia-CSIC, and Departamento de Fisica Atomica, Molecular y Nuclear, Universidad de Valencia, Avda. Dr. Moliner 50, E-46100 Burjassot (Valencia), Spain*
[h] *Department of Physics, University of Bergen, Allégaten 55, N-5007 Bergen, Norway*
[i] *CERN, CH-1211 Geneva 23, Switzerland*
[j] *Physics Laboratory, University of Athens, Solonos Street 104, GR-10680 Athens, Greece*
[k] *Université Claude Bernard de Lyon, 43 Boulevard du 11 Novembre 1918, F-69622 Villeurbanne Cedex, France*
[l] *Institut für Experimentelle Kernphysik, Universität Karlsruhe, Pf. 6980, W-7500 Karlsruhe 1, FRG*
[m] *Institute of Physics, University of Stockholm, Vanadisvägen 9, S-113 46 Stockholm, Sweden*
[n] *Laboratoire de l'Accélérateur Linéaire, Université de Paris-Sud, Bâtiment 200, F-91405 Orsay, France*
[o] *NIKHEF-H, Postbus 41882, NL-1009 DB Amsterdam, The Netherlands*
[p] *Institut des Sciences Nucléaires, Université de Grenoble 1, F-38026 Grenoble, France*
[q] *Dipartimento di Fisica, Università di Trieste and INFN, Via A. Valerio 2, I-34127 Trieste, Italy and Istituto di Fisica, Università di Udine, Via Larga 36, I-33100 Udine, Italy*
[r] *Istituto Superiore di Sanità, Istituto Nazionale di Fisica Nucleare (INFN), Viale Regina Elena 299, I-00161 Rome, Italy*
[s] *Nuclear Physics Laboratory, University of Oxford, Keble Road, Oxford OX1 3RH, UK*
[t] *Dipartimento di Fisica, Università di Milano and INFN, Via Celoria 16, I-20133 Milan, Italy*
[u] *LPNHE, Universités Paris VI et VII, Tour 33 (RdC), 4 place Jussieu, F-75230 Paris Cedex 05, France*
[v] *Fachbereich Physik, Universität Wuppertal, Pf. 100 127, W-5600 Wuppertal 1, FRG*
[w] *Dipartimento di Fisica, Università di Genova and INFN, Via Dodecaneso 33, I-16146 Genoa, Italy*
[x] *Laboratoire de Physique Corpusculaire, Collège de France, 11 place M. Berthelot, F-75231 Paris Cedex 5, France*
[y] *Institute for High Energy Physics, Serpukhov, P.O. Box 35, SU-142 284 Protvino (Moscow Region), USSR*
[z] *Institute of Nuclear Physics, N.C.S.R. Demokritos, P.O. Box 60228, GR-15310 Athens, Greece*
[aa] *Division des Hautes Energies, CRN-Groupe DELPHI and LEPSI, B.P. 20 CRO, F-67037 Strasbourg Cedex, France*
[ab] *Physics Department, Universitaire Instelling Antwerpen, Universiteitsplein 1, B-2610 Wilrijk, Belgium and IIHE, ULB-VUB, Pleinlaan 2, B-1050 Brussels, Belgium and Service de Physique des Particules Elémentaires, Faculté des Sciences, Université de l'Etat Mons, Av. Maistriau 19, B-7000 Mons, Belgium*
[ac] *Dipartimento di Fisica Sperimentale, Università di Torino and INFN, Via P. Giuria 1, I-10125 Turin, Italy*
[ad] *Dipartimento di Fisica, Università di Roma II and INFN, Tor Vergata, I-00173 Rome, Italy*
[ae] *Department of Physics, University of Liverpool, P.O. Box 147, Liverpool L69 3BX, UK*
[af] *Department of Radiation Sciences, University of Uppsala, P.O. Box 535, S-751 21 Uppsala, Sweden*
[ag] *Dipartimento di Fisica, Università di Padova and INFN, Via Marzolo 8, I-35131 Padua, Italy*
[ah] *Department of High Energy Physics, University of Helsinki, Siltavuorenpenger 20 C, SF-00170 Helsinki 17, Finland*
[ai] *Physics Department, University of Oslo, Blindern, N-1000 Oslo 3, Norway*
[aj] *Facultad de Ciencias, Universidad de Santander, av. de los Castros, E-39005 Santander, Spain*
[ak] *Dipartimento di Fisica, Università di Bologna and INFN, Via Irnerio 46, I-40126 Bologna, Italy*
[al] *Ames Laboratory and Department of Physics, Iowa State University, Ames IA 50011, USA*
[am] *Universidad Complutense, Avda. Complutense s/n, E-28040 Madrid, Spain*
[an] *Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark*
[ao] *Institute for Nuclear Studies, and University of Warsaw, Ul. Hoża 69, PL-00681 Warsaw, Poland*
[ap] *Physics Department, National Technical University, Zografou Campus, GR-15773 Athens, Greece*
[aq] *High Energy Physics Laboratory, Institute of Nuclear Physics, Ul. Kawiory 26 a, PL-30055 Cracow 30, Poland*
[ar] *School of Physics and Materials, University of Lancaster, Lancaster LA1 4YB, UK*
[as] *Université d'Aix - Marseille II, Case 907, 70, route Léon Lachamp, F-13288 Marseille Cedex 09, France*

Received 5 February 1992

From a sample of about 120 000 hadronic Z^0 decays, using a technique based on a separation of the different event categories in the boosted sphericity product, the fraction of $b\bar{b}$ decays has been measured to be 0.219 ± 0.014 (stat) $\pm$ 0.019 (syst). Using the DELPHI determination of the hadronic Z^0 width, this corresponds to a partial width $\Gamma_{b\bar{b}} = 378 \pm 42$ MeV (in good agreement with the standard model prediction of $\simeq 380$ MeV). Combining this measurement with the determinations based on events with high p_t leptons gives an estimate for the branching ratio of b into leptons at LEP of $(11.2 \pm 1.2)\%$, consistent with previous determinations.

1. Introduction

This letter presents a study of the branching ratio of the Z^0 into $b\bar{b}$ pairs, using a method based on the boosted sphericity product. The boosted sphericity product (BSP) is a shape variable that was originally used by the TASSO collaboration at PETRA to enrich data samples with $b\bar{b}$ events [1]. After selecting two jet events, the jets are boosted along their axes (defined by the direction of the sum of the momenta of their charged particles) towards their hypothetical B hadron rest frame by a boost β. The sphericities S_1 and S_2 of the two jets in their respective scaled reference frame are then calculated, and the boosted sphericity product is defined as the product of S_1 and S_2. Due to the large rest mass of the B hadrons, $b\bar{b}$ events have larger values for S_1 and S_2. The boost β is tuned via Monte Carlo simulations in order to optimize the separation between the $b\bar{b}$ events and the background. The final result should be independent of the precise value chosen for β, any residual dependence is taken as contribution to systematic uncertainties. The shape of the observed BSP distribution is then used to estimate the branching fraction of the Z^0 into $b\bar{b}$ pairs.

2. Experimental procedure and event sample

This analysis is based on the data collected by DELPHI in the period March 1990–August 1990, corresponding to $\simeq$ 120 000 hadronic Z^0 decays. The components of the DELPHI detector relevant for this analysis have already been described in ref. [2], as well as the trigger for the hadronic events. Tracks are measured in a 1.2 Tesla magnetic field by a set of three cylindrical tracking detectors: the Inner Detector (ID) (inner radius 12 cm, outer radius 28 cm, covering polar angles between 29° and 151°), the Time Projection Chamber (TPC) (inner radius = 30 cm, outer radius = 122 cm, covering polar angles between 21° and 159°) and the Outer Detector (OD) (inner radius = 198 cm, outer radius = 206 cm, covering polar angles between 42° and 138°). TPC, ID and OD provide complete coverage of the region between 35°) and 145° in the polar angle θ. The average momentum resolution is in the range $\Delta p/p \simeq (0.002\text{–}0.01)p$ (p in GeV/c). Only charged particles were used in the analysis and were required to fulfill the following criteria:

- impact parameter at the nominal primary vertex is less than 5 cm in radius from the beam axis and less than 10 cm along it;
- momentum p larger than 0.1 GeV/c;
- measured track length in the TPC greater than 50 cm;
- polar angle θ between 35° and 145°.

All particles were assumed to be pions. Hadronic events were then selected by imposing the following requirements:

- each of the two hemispheres $\cos\theta < 0$ and $\cos\theta > 0$ contained a total energy in charged particles $E_{ch} = \sum E_i$ larger than 3 GeV, where E_i are the particle energies;
- the total energy of the charged particles seen in both hemispheres together exceeded 15 GeV;
- there were at least 8 charged particles and among those at least 5 with momenta above 0.2 GeV/c;
- the polar angle θ of the sphericity axis was in the range $50° < \theta < 130°$.

In addition the events were required to be classified as two jet events by the JADE/E0 algorithm [3] with $y_{cut} = 0.08$, with at least 3 charged particles in each jet. The choice of $y_{cut} = 0.08$ was a compromise between the size and the quality of the two jet event sample. In this algorithm the scaled invariant mass $y_{kl} = M_{kl}^2/E_{vis}^2$ is computed (E_{vis} is the seen energy in the event) for all pairs of charged particles k, l of an event and the two particles (or clusters) with the smallest y_{kl} value are replaced by a "cluster" of 4-momentum $(p_k + p_l)$. This procedure is iterated until all y_{kl} exceed a threshold value y_{cut} and the result-

ing number of clusters is called the jet multiplicity of the event. The selected event sample has a negligible (< 0.3%) contamination from beam–gas scattering, $\gamma\gamma$ interactions and $\tau^+\tau^-$ events. A total of $\simeq 51\,000$ events were left after these cuts.

3. Analysis and results

The Lund Parton Shower Monte Carlo JETSET 7.2 [4] (JETSET PS) was used to generate a sample of 52 000 hadronic Z decays; the Peterson et al. fragmentation scheme [5] was selected for heavy quarks, assuming $\epsilon_b = 3\times10^{-3}$ and $\epsilon_c = 24\times10^{-3}$. The fragmentation function is defined as $D_Q^H(z) = N\times(1/z) \times[1 - (1/z) - \epsilon_Q/(1 - z)]^{-2}$, the normalization N is fixed by summing over all hadrons containing the heavy quark Q; z is the ratio between the values of the light cone variable $E + P_L$ for the heavy hadron and for the fragmenting $Q\bar{q}$ system. The axis along which P_L is defined is taken as the Q direction in the centre of mass of the fragmenting system. As the values used for ϵ_b and ϵ_c in the Monte Carlo simulation are not those that give a mean beam energy fraction taken by the B and the D hadrons – x_E – that agrees with actual measurements, a weighting procedure has been applied to the simulated events. This procedure allows one to vary ϵ_b and ϵ_c and is used to correct the previously mentioned discrepancy.

The events were then followed through the detailed detector simulation, (DELSIM [6]), which includes simulation of all secondary interactions and collection and digitization of all electronic signals; the simulated data were then processed through the same analysis chain as the real data. For all the two jet events in the Monte Carlo sample both jets were boosted along their axes. It was found that a boost value $\beta = 0.96$ resulted in maximum sensitivity for the determination of the $b\bar{b}$ branching fraction. Therefore this value was used in the analysis. The Monte Carlo distributions for $S_1\cdot S_2$ ($\beta = 0.96$) for $b\bar{b}$ and non-$b\bar{b}$ events are plotted in fig. 1. The BSP distribution of $c\bar{c}$ events is indistinguishable from those of light quark events and hence the cut on $S_1\cdot S_2$ is quite insensitive to the charm content of the events. The effects of selecting events with $S_1\cdot S_2$ above a cutoff value (for the data and the simulation described above) are summarized in table 1. The comparison between the fractions of

Table 1
Fractions (in percent) of data and Monte Carlo events for which $S_1\cdot S_2$ is larger than a given cut. The percentage of $b\bar{b}$ events in the Monte Carlo simulation remaining after the cut is also shown.

$S_1\cdot S_2$	Data fraction	Monte Carlo fraction	$b\bar{b}$ purity
0.025	75.0±0.2	75.5±0.3	25.6±0.5
0.050	56.2±0.2	56.4±0.3	28.9±0.6
0.075	42.3±0.2	42.6±0.3	31.4±0.7
0.100	32.3±0.2	32.4±0.3	33.2±0.8
0.125	25.0±0.2	25.0±0.3	35.6±1.0
0.150	19.4±0.2	19.2±0.3	37.3±1.1
0.175	15.0±0.2	14.5±0.2	39.4±1.3
0.200	11.5±0.1	11.0±0.2	41.4±1.6
0.225	8.7±0.1	8.4±0.2	41.7±1.8
0.250	6.6±0.1	6.3±0.2	42.8±2.2
0.275	5.0±0.1	4.6±0.1	44.6±2.6
0 300	3.7±0.1	3.4±0.1	44.7±3.0

real and Monte Carlo events passing the cut will be the subject of this analysis. From table 1 it can be noted that they agree reasonably well; the parameters used for the Monte Carlo simulation were those corresponding to the standard model. It is evident, however, that at LEP this discriminator does not select $b\bar{b}$ samples of high purity, the enrichment being lower than at PETRA where the B particles take a larger fraction of the available energy. The boosted sphericity depends not only on the mass of the fragmenting quark; it is also sensitive to the multiplicity and to the kinematic parameters (momentum and angle) of the particles inside the jet. For light quarks these variables depend mainly on the hadronization process, whereas for heavy quarks they are also governed by the decay properties of the heavy particles. The global properties of multihadronic final states have been found to be in well reproduced by the Monte Carlo simulations [7]. The value of the boosted sphericity is mainly sensitive to a subsample of kinematic variables, which need to be under control in the Monte Carlo simulation. Of particular importance are the distributions of the track momentum and of the transverse momentum relative to the jet axis: this is discussed in section 3.2.

3.1. The results of the fit

Fig. 2 and table 2 compare the observed $S_1\cdot S_2$ distribution with the prediction for pure $Z^0\to b\bar{b}$

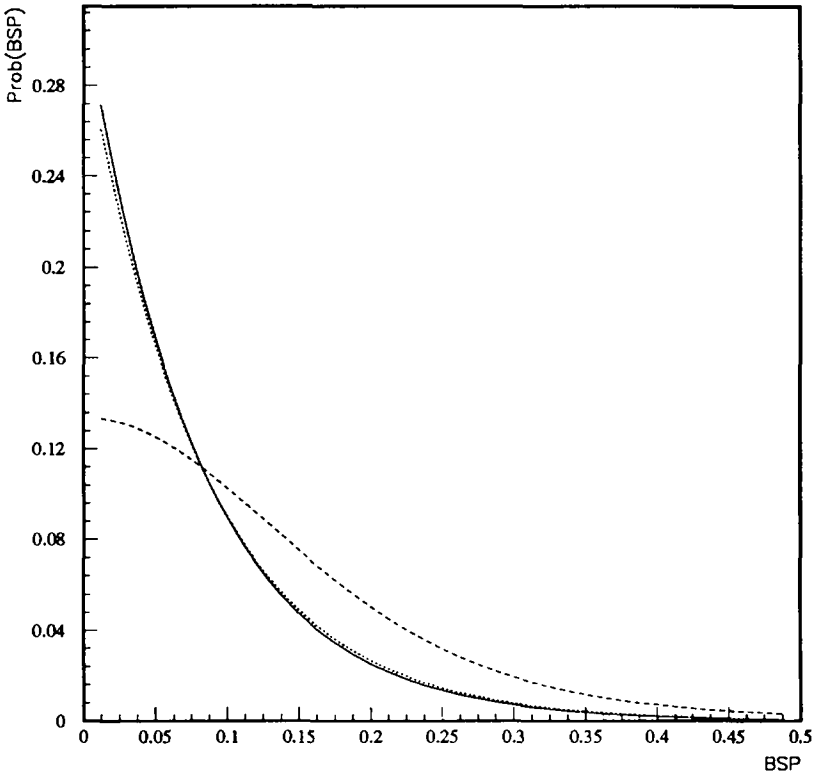

Fig. 1. Simulated $S_1 \cdot S_2$ distribution using JETSET PS for b (dashed line) and light quarks events (solid line), $\beta = 0.97$. The ordinate is the probability per event per bin of 0.025 in the BSP variable ($\equiv$ Prob(BSP)).

events, $(S_1 \cdot S_2)_{b\bar{b}}$, and for all other hadronic events, $(S_1 \cdot S_2)_{\text{non}-b\bar{b}}$. The observed $S_1 \cdot S_2$ distribution was fitted to the form

$$(S_1 \cdot S_2)_{\text{data}} = \alpha \times (S_1 \cdot S_2)_{b\bar{b}} + (1 - \alpha) \times (S_1 \cdot S_2)_{\text{non}-b\bar{b}}, \quad (3)$$

where the two Monte Carlo $S_1 \cdot S_2$ distributions, for $b\bar{b}$ and non-$b\bar{b}$ events, were normalized to unity and the branching fraction α was taken as an unknown parameter. The fit gave $\alpha = 0.217 \pm 0.014$ (stat) with a chi-squared value of 15.2 for 19 degrees of freedom. The value of α was corrected by 2%, to take into account the flavour dependent differences in the selection efficiency induced by the event cuts described previously. The $b\bar{b}$ branching ratio was determined to be:

$$R \equiv \frac{\Gamma(Z^0 \to b\bar{b})}{\Gamma(Z^0 \to \text{hadrons})} = 0.213 \pm 0.014(\text{stat}). \quad (4)$$

Repeating the same analysis using simulated events generated with the LUND 7.2 Matrix Element (ME) generator gave:

$$R \equiv \frac{\Gamma(Z^0 \beta \to b\bar{b})}{\Gamma(Z^0 \to \text{hadrons})} = 0.213 \pm 0.014(\text{stat}). \quad (5)$$

The fragmentation function for b quarks in the LUND-ME generator was tuned to give the same mean energy fraction for B hadrons as in the LUND Parton Shower generator.

3.2. *Study of systematic effects*

The main sources of systematic uncertainties are related to the modelling of the hadronization mechanism.

1. One of these sources is the uncertainty in the fragmentation function of the b quarks. Averaging the results from the LEP experiments [8–11] the mean value of the fraction of the beam energy taken by a

Table 2
Bin contents for Data and Monte Carlo events, as a percentage of the 2-jet events fulfilling the cuts given in section 2 (the bins have a common width of 0.025 and the first bin corresponds to the range 0–0.025).

$S_1 \cdot S_2$	Data	Monte Carlo $b\bar{b}$	Monte Carlo non-$b\bar{b}$
0.025	25.06±0.22	12.23±0.49	27.94±0.40
0.050	18.77±0.19	13.87±0.52	20.56±0.34
0.075	13.85±0.16	13.46±0.51	14.00±0.28
0.100	10.02±0.14	11.52±0.47	9.77±0.23
0.125	7.33±0.12	8.53±0.41	7.13±0.20
0.150	5.56±0.10	7.98±0.40	5.16±0.17
0.175	4.47±0.09	6.69±0.36	4.09±0.15
0.200	3.48±0.08	5.16±0.32	3.03±0.13
0.225	2.74±0.07	4.73±0.30	2.11±0.11
0.250	2.08±0.06	3.79±0.27	1.68±0.10
0.275	1.66±0.06	2.84±0.24	1.29±0.09
0.300	1.31±0.05	2.50±0.22	0.88±0.07
0.325	1.06±0.05	1.60±0.18	0.60±0.06
0.350	0.70±0.04	1.37±0.16	0.48±0.05
0.375	0.63±0.04	1.02±0.14	0.40±0.05
0.400	0.44±0.03	0.84±0.13	0.32±0.04
0.425	0.30±0.02	0.59±0.11	0.24±0.04
0.450	0.24±0.02	0.67±0.11	0.13±0.03
0.475	0.17±0.02	0.31±0.08	0.11±0.02
0.500	0.14±0.02	0.29±0.08	0.08±0.02

B hadron is $\langle x_B \rangle \equiv E_B/E_{beam} = 0.705 \pm 0.011$, the uncertainty of which corresponds to a variation in R of $\pm$ 0.009.

2. If the B particles are produced with different energy distributions in the data and in the Monte Carlo simulation, the measured value of R will depend on the choice of β. From the dispersion of the results for β varying in the range (0.95–0.98) a systematic uncertainty of $\pm$ 0.007 on R is evaluated. The limits of the considered range of variation for β are dictated by the reduced sensitivity for the determination of the $b\bar{b}$ branching fraction at the upper value of the range and by the dominant influence of soft hadroniza- tion effects at the lower end. The correlation between the uncertainties in ϵ_b and β is negligible.

3. The contribution from the uncertainty in the c quark fragmentation function is roughly one third of that from the b quark.

4. Another uncertainty concerns the knowledge of the $c\bar{c}$ fraction. A $c\bar{c}$ content larger than that predicted by the standard model could modify the $S_1 \cdot S_2$ shape for the background, but from fig. 1 it is clear that this effect is small as charm quarks and light quarks produce very similar distributions. The present knowledge of the $c\bar{c}$ branching fraction is, from the average of refs. [8,12,13]

$$\mathrm{Br}(Z^0 \to c\bar{c}) = 0.166 \pm 0.034.$$

This corresponds to a variation of $\pm$ 0.004 in the measured R.

5. A contribution to the error on R is expected from the modelling of the transverse momentum distribution of the hadrons relative to the jet axis. The corresponding distributions from Data and from Monte Carlo simulation should be equal, independent of p_t, if the following conditions are satisfied:
- the Monte Carlo generator gives a good description of the hadronic production mechanism,
- the decays of the B particles are correctly described,
- the detector simulation correctly models the track reconstruction,
- the rate of production of b quarks is the same in the data and in the Monte Carlo sample.

The first three points are independent of any a priori assumption on the coupling of the Z^0 to b quarks. There is good agreement between the Data and the Monte Carlo simulations for the charged particle multiplicity of the events and for the particle momentum

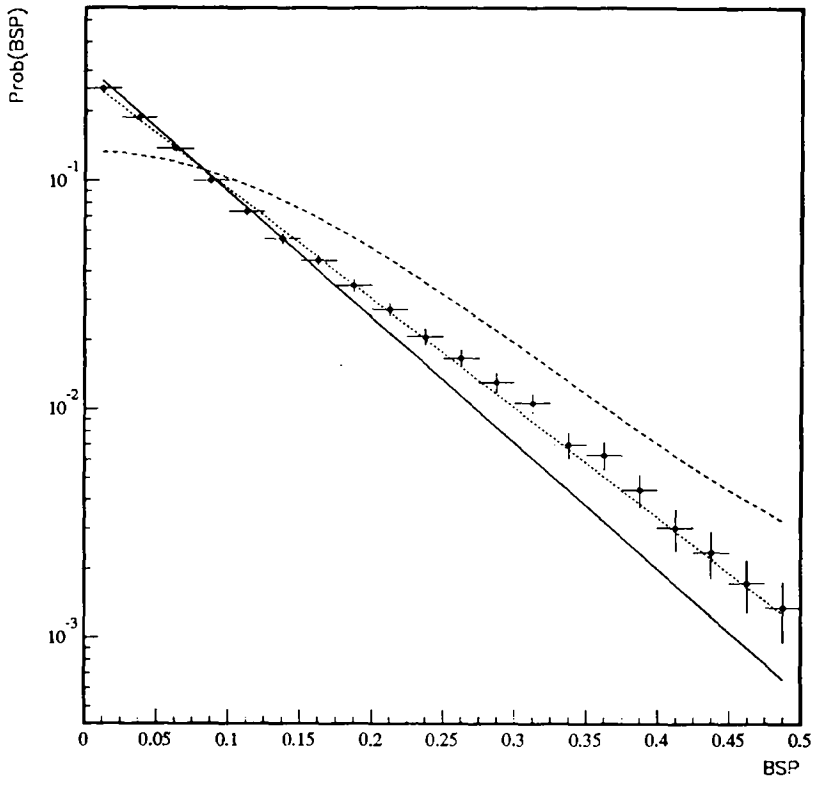

Fig. 2. Prob(BSP) distribution, for $\beta = 0.96$. The lines superimposed correspond to the predictions of JETSET PS for a $Z^0 \rightarrow b\bar{b}$ branching fraction of 1.0 (dashed line), 0.217, the standard model prediction (dotted line), 0.0 (solid line).

distribution. Noticeable differences are observed between the transverse momentum – p_t – distributions relative to the jet axis. These differences vary with p_t and their amplitude reaches 6–7% in a restricted region around 600 MeV/c. It was verified that the differences have nothing to do with the beauty content of the events by varying this parameter in the simulation. This variation in the $b\bar{b}$ fraction also changes the charged particle transverse momentum distribution but over a much larger range in p_t and with a much smaller amplitude, even for very unrealistic values for the $Z^0 \rightarrow b\bar{b}$ branching fraction. In order to evaluate the associated systematics, the transverse momentum distribution of individual particles in the Monte Carlo simulation was varied locally within the bounds of these differences. Then the $b\bar{b}$ fraction was changed in the Monte Carlo from 22% to 50%, and R was re-evaluated by fitting the corresponding BSP distribution. The result was compatible with a systematic contribution of < 0.004 to R.

Table 3
Different contributions to the systematic error.

Systematic source	Error
1) b fragmentation	± 0.009
2) Choice of β	± 0.007
3) c fragmentation	± 0.003
4) Br($Z^0 \rightarrow c\bar{c}$)	± 0.004
5) Modelling (systematic)	± 0.004
6) Modelling (statistics)	± 0.010
7) PS/ME Monte Carlo Simulations	± 0.009
8) Choice of Y_{cut}	± 0.004
Total	± 0.019

6. The contribution from the statistical error resulting from the correction 5) has been evaluated from the uncertainties on the fitted parameters used for the correction. This gives an uncertainty on R of ± 0.010.

Table 4
Check on the $b\bar{b}$ enriched sample.

p_t cut	% of $b\bar{b}$ events from BSP	% of $b\bar{b}$ events from muon spectrum
no cut	50.2±3.9	51±5
> 1.0 GeV/c	70.9±6.9	67±7

7. Another source of uncertainty comes from the difference in the results using different equally valid simulations. Averaging the results of the fits using the PS (eq. (4)) and the ME (eq. (5)) simulations, a central value of 0.219 is obtained for R together with a systematic error contribution of ± 0.009. (This is a conservative estimate because these two measurements are within the statistical uncertainties of the two Monte Carlo simulations).

8. Another source of systematic error arises from the choice of the jet resolution parameter y_{cut}. Considering a large range for the variation of this parameter [0.02–0.16] a systematic error of 0.004 to R is assigned although no trend of the fitted values as a function of y_{cut} is observed. The lower limit is dictated by statistical considerations (with $y_{cut} = 0.02$ only 40% are classified as two jet events) while the upper limit $y_{cut} = 0.16$ is well inside the region where the JADE/E0 algorithm gives mainly two jet events.

These contributions to the systematic uncertainty on the measurement of R are summarized in table 3. Other possible systematic errors, such as that coming from the differences in the efficiencies induced by the global event selection cuts, are negligible. This measurement of the branching fraction of the Z^0 to b quark pairs is based on the study of an event shape variable which uses comparisons between data and Monte Carlo simulated samples. Since the parameters governing the simulation have been tuned to reproduce several distributions of kinematical variables it can be argued [14] that an analysis used to find any of these parameters or any parameter dependent directly on them is bound to obtain the values introduced at the beginning in the simulation (circularity problem). But, in this analysis, the two samples of Monte Carlo simulated events – Parton Shower and Matrix Element – have been produced using sets of parameters tuned on TASSO data [15,16] where the influence of the Z^0 is negligible. Also, the fragmentation distributions of heavy particles – charm and beauty – have been chosen to reproduce the mean fraction of the beam energy taken by heavy hadrons, determined using inclusive distributions of high p_t leptons, and not the event shape distributions. Furthermore an approach has been presented which evaluates the correlation between the tuning of the Monte Carlo simulation on the data and the beauty content of the events used for this tuning. It can be stressed that this procedure is essentially Monte Carlo independent, once the set of variables which really influences the boosted jet sphericity has been identified.

3.3. Check on an enriched b sample

In order to check the separation in $S_1 \cdot S_2$ independently of the Monte Carlo simulations, the $S_1 \cdot S_2$ distribution was studied for the events with an identified muon in the final state. Such a sample is enriched in $b\bar{b}$ events [9]. Fig. 3 confirms that the BSP distribution of this sample approaches more closely that expected for a pure $b\bar{b}$ sample. When p_t, the transverse momentum of the muon with respect to the axis of the closest jet, is required to exceed 1 GeV/c, thus further increasing the purity of the sample, this trend continues but the statistical errors increase. Table 4 summarizes the results of these studies. (It was verified that there is no statistically significant difference between the BSP distributions for all $b\bar{b}$ events and for those in which a B decays semileptonically; comparing the two distributions gave a chisquared/(degree of freedom) of 16.5/19)

4. Results and conclusion

The Z^0 branching ratio fraction into $b\bar{b}$ pairs is found to be:

$$\frac{\Gamma(Z^0 \to b\bar{b})}{\Gamma(Z^0 \to \text{hadrons})} = 0.219 \pm 0.014(\text{stat}) \pm 0.019(\text{syst}). \quad (6)$$

Using our current experimental determination of the hadronic Z^0 width $\Gamma_{had} = 1726 \pm 19$ MeV [17], this gives:

$$\Gamma_{b\bar{b}} = 378 \pm 42 \text{ MeV}, \quad (7)$$

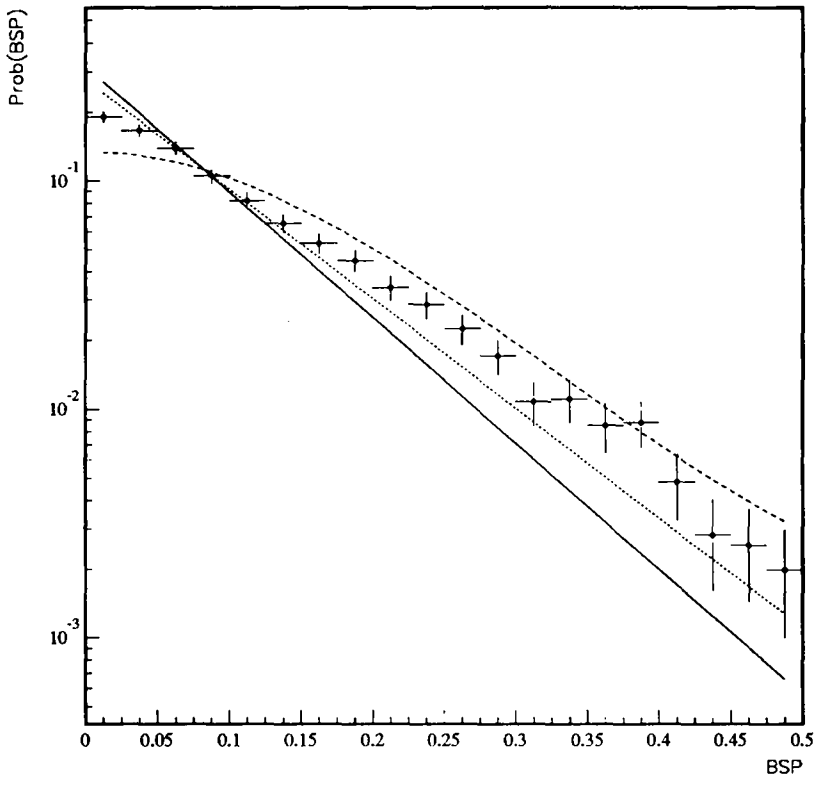

Fig. 3. Prob(BSP) distribution for the enriched b sample, for $\beta = 0.96$. The lines superimposed correspond to the predictions of JETSET PS for a $b\bar{b}$ branching fraction of 1.0 (dashed line), 0.217 (dotted line), 0. (solid line).

in good agreement with the standard model prediction of $\simeq 380$ MeV.

MARK II, ALEPH, DELPHI, L3 and OPAL have recently measured the product of the branching fraction of the Z^0 into $b\bar{b}$ pairs times the inclusive semileptonic branching fraction of the hadrons produced from the b quarks [8–11]. The average of their determinations is:

$$\mathrm{Br}(b\to\ell X)\times\frac{\Gamma(Z^0\to b\bar{b})}{\Gamma(Z^0\to\mathrm{hadrons})} = 0.0246 \pm 0.0006 \quad (8)$$

(where ℓ can be a muon or an electron; the branching fractions to muons and electrons are assumed to be equal). Determinations (6) and (8) give

$$\mathrm{Br}(b\to\ell X) = (11.2 \pm 1.2)\%. \quad (9)$$

This result can be compared with the lepton inclusive branching fraction measured at the $\Upsilon(4S)$, $\mathrm{Br}(b\to\ell X) = (10.6 \pm 0.4)\%$ [18]; with the measurements at higher energy colliders (PEP and PETRA), $\mathrm{Br}(b\to\ell X) = (11.9 \pm 0.7)\%$ [19]; and with the direct LEP measurement $\mathrm{Br}(b\to\ell X) = (11.3 \pm 1.2)\%$, using the ratio of double to single lepton events [20].

Acknowledgement

We are greatly indebted to our technical collaborators and to the funding agencies for their support in building and operating the DELPHI detector, and to the members of the CERN-SL Division for the excellent performance of the LEP collider.

References

[1] TASSO Collab., W. Braunschweig et al., Z. Phys. C 44 (1989) 1.

[2] DELPHI Collab., P. Aarnio et al., Phys. Lett. B 240 (1990) 271.

[3] JADE collab., W. Bartel et al., Z. Phys. C 33 (1986) 23.

[4] T. Sjostrand, Comput. Phys. Commun. 27 (1982) 243, 28 (1983) 229;
T. Sjostrand and M. Bengtsson, Comput. Phys. Commun. 43 (1987) 367.

[5] C. Peterson et al., Phys. Rev. D 27 (1983) 105.

[6] DELSIM User Manual, DELPHI 87-96 PROG-99, Geneva, July 1989; DELSIM Reference Manual, DELPHI 87-98 PROG-100, Geneva, July 1989.

[7] DELPHI Collab., P. Abreu et al., Phys. Lett. B 252 (1990) 149; B 247 (1990)167; Z. Phys. C 50 (1991) 185.

[8] ALEPH Collab., D. Decamp et al., Phys. Lett. B 244 (1990) 551;
updated results in: Measurement of the leptonic decay rates and fragmentation parameters for b and c states produced in Z decay (ALEPH Collaboration communication at the LP-HEP 91).

[9] Partial width of Z^0 into $b\bar{b}$ final states and mean semi-leptonic branching fraction (DELPHI Collaboration contributed paper to LP-HEP 91).

[10] L3 Collab., B. Adeva et al., Phys. Lett. B 241 (1990) 416.

[11] OPAL Collab. M.Z.Akrawy et al., Phys. Lett. B 263 (1991) 311.

[12] DELPHI Collab., P. Abreu et al., Phys. Lett. B 252 (1990) 140.

[13] OPAL Collab., G. Alexander et al., Phys. Lett B 262 (1990) 341.

[14] R. Barlow, J. Phys. G 17 (1991) 1579.

[15] TASSO Collab., W. Braunschweig et al., Z. Phys. C 41 (1988) 359.

[16] W. De Boer et al., Z. Phys. C 49 (1990) 141.

[17] DELPHI Collab., P. Abreu et al., Nucl. Phys. B 367 (1991) 511.

[18] ARGUS Collab., H. Albrecht et al., Phys. Lett. B 249 (1990) 35;
they obtained using both e and μ $Br(b\to\ell X) = (10.2 \pm 0.5 \pm 0.2)\%$;
CLEO Collab., R. Fulton et al., Cornell Preprint CLNS 90-989 (1990);
K. Berkelman and S. Stone, CLNS 91-1664 (1991);
they obtained using both e and μ $Br(b\to\ell X) = (10.5 \pm 0.3 \pm 0.4)\%$;
Crystal Ball Collab., K. Wachs et al., Z. Phys. C 42 (1989) 33;
they obtained using only e $Br(b\to\ell X) = (12.0 \pm 0.5 \pm 0.7)\%$.

[19] From the average of the references quoted in:
Particle Data Group, M. Aguilar-Benitez et al., Review of particle properties, Phys. Lett. B 239 (1990) 1.

[20] L3 Collab., B. Adeva et al., Phys. Lett. B 261 (1991) 177.