BABAR-CONF-06/014
SLAC-PUB-11974
hep-ex/0607040

Search for the Baryon and Lepton Number Violating Decays $\tau \rightarrow \Lambda h$

The *BABAR* Collaboration

August 18, 2006

Abstract

We have searched for the violation of baryon number B and lepton number L in the $(B-L)$-conserving modes $\tau^- \rightarrow \bar{\Lambda}^0\pi^-$ and $\tau^- \rightarrow \bar{\Lambda}^0 K^-$ as well as the $(B-L)$-violating modes $\tau^- \rightarrow \Lambda^0\pi^-$ and $\tau^- \rightarrow \Lambda^0 K^-$ using 237 fb^{-1} of data collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage ring. We do not observe any signal and determine preliminary upper limits on the branching fractions $\mathcal{B}(\tau^- \rightarrow \bar{\Lambda}^0\pi^-) < 5.9 \times 10^{-8}$, $\mathcal{B}(\tau^- \rightarrow \Lambda^0\pi^-) < 5.8 \times 10^{-8}$, $\mathcal{B}(\tau^- \rightarrow \bar{\Lambda}^0 K^-) < 7.2 \times 10^{-8}$, and $\mathcal{B}(\tau^- \rightarrow \Lambda^0 K^-) < 15 \times 10^{-8}$ at 90% confidence level.

Submitted to the 33$^{\text{rd}}$ International Conference on High-Energy Physics, ICHEP 06,
26 July—2 August 2006, Moscow, Russia.

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Work supported in part by the US Department of Energy contract DE-AC02-76SF00515

The *BABAR* Collaboration,

B. Aubert, R. Barate, M. Bona, D. Boutigny, F. Couderc, Y. Karyotakis, J. P. Lees, V. Poireau, V. Tisserand, A. Zghiche

Laboratoire de Physique des Particules, IN2P3/CNRS et Université de Savoie, F-74941 Annecy-Le-Vieux, France

E. Grauges

Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain

A. Palano

Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy

J. C. Chen, N. D. Qi, G. Rong, P. Wang, Y. S. Zhu

Institute of High Energy Physics, Beijing 100039, China

G. Eigen, I. Ofte, B. Stugu

University of Bergen, Institute of Physics, N-5007 Bergen, Norway

G. S. Abrams, M. Battaglia, D. N. Brown, J. Button-Shafer, R. N. Cahn, E. Charles, M. S. Gill, Y. Groysman, R. G. Jacobsen, J. A. Kadyk, L. T. Kerth, Yu. G. Kolomensky, G. Kukartsev, G. Lynch, L. M. Mir, T. J. Orimoto, M. Pripstein, N. A. Roe, M. T. Ronan, W. A. Wenzel

Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA

P. del Amo Sanchez, M. Barrett, K. E. Ford, A. J. Hart, T. J. Harrison, C. M. Hawkes, S. E. Morgan, A. T. Watson

University of Birmingham, Birmingham, B15 2TT, United Kingdom

T. Held, H. Koch, B. Lewandowski, M. Pelizaeus, K. Peters, T. Schroeder, M. Steinke

Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

J. T. Boyd, J. P. Burke, W. N. Cottingham, D. Walker

University of Bristol, Bristol BS8 1TL, United Kingdom

D. J. Asgeirsson, T. Cuhadar-Donszelmann, B. G. Fulsom, C. Hearty, N. S. Knecht, T. S. Mattison, J. A. McKenna

University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

A. Khan, P. Kyberd, M. Saleem, D. J. Sherwood, L. Teodorescu

Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

V. E. Blinov, A. D. Bukin, V. P. Druzhinin, V. B. Golubev, A. P. Onuchin, S. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, K. Yu Todyshev

Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

D. S. Best, M. Bondioli, M. Bruinsma, M. Chao, S. Curry, I. Eschrich, D. Kirkby, A. J. Lankford, P. Lund, M. Mandelkern, R. K. Mommsen, W. Roethel, D. P. Stoker

University of California at Irvine, Irvine, California 92697, USA

S. Abachi, C. Buchanan

University of California at Los Angeles, Los Angeles, California 90024, USA

S. D. Foulkes, J. W. Gary, O. Long, B. C. Shen, K. Wang, L. Zhang
University of California at Riverside, Riverside, California 92521, USA

H. K. Hadavand, E. J. Hill, H. P. Paar, S. Rahatlou, V. Sharma
University of California at San Diego, La Jolla, California 92093, USA

J. W. Berryhill, C. Campagnari, A. Cunha, B. Dahmes, T. M. Hong, D. Kovalskyi, J. D. Richman
University of California at Santa Barbara, Santa Barbara, California 93106, USA

T. W. Beck, A. M. Eisner, C. J. Flacco, C. A. Heusch, J. Kroseberg, W. S. Lockman, G. Nesom, T. Schalk, B. A. Schumm, A. Seiden, P. Spradlin, D. C. Williams, M. G. Wilson
University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

J. Albert, E. Chen, A. Dvoretskii, F. Fang, D. G. Hitlin, I. Narsky, T. Piatenko, F. C. Porter, A. Ryd, A. Samuel
California Institute of Technology, Pasadena, California 91125, USA

G. Mancinelli, B. T. Meadows, K. Mishra, M. D. Sokoloff
University of Cincinnati, Cincinnati, Ohio 45221, USA

F. Blanc, P. C. Bloom, S. Chen, W. T. Ford, J. F. Hirschauer, A. Kreisel, M. Nagel, U. Nauenberg, A. Olivas, W. O. Ruddick, J. G. Smith, K. A. Ulmer, S. R. Wagner, J. Zhang
University of Colorado, Boulder, Colorado 80309, USA

A. Chen, E. A. Eckhart, A. Soffer, W. H. Toki, R. J. Wilson, F. Winklmeier, Q. Zeng
Colorado State University, Fort Collins, Colorado 80523, USA

D. D. Altenburg, E. Feltresi, A. Hauke, H. Jasper, J. Merkel, A. Petzold, B. Spaan
Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany

T. Brandt, V. Klose, H. M. Lacker, W. F. Mader, R. Nogowski, J. Schubert, K. R. Schubert, R. Schwierz, J. E. Sundermann, A. Volk
Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany

D. Bernard, G. R. Bonneaud, E. Latour, Ch. Thiebaux, M. Verderi
Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France

P. J. Clark, W. Gradl, F. Muheim, S. Playfer, A. I. Robertson, Y. Xie
University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

M. Andreotti, D. Bettoni, C. Bozzi, R. Calabrese, G. Cibinetto, E. Luppi, M. Negrini, A. Petrella, L. Piemontese, E. Prencipe
Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy

F. Anulli, R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, G. Finocchiaro, S. Pacetti, P. Patteri, I. M. Peruzzi,[1] M. Piccolo, M. Rama, A. Zallo
Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy

[1]Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy

A. Buzzo, R. Capra, R. Contri, M. Lo Vetere, M. M. Macri, M. R. Monge, S. Passaggio, C. Patrignani, E. Robutti, A. Santroni, S. Tosi

Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy

G. Brandenburg, K. S. Chaisanguanthum, M. Morii, J. Wu

Harvard University, Cambridge, Massachusetts 02138, USA

R. S. Dubitzky, J. Marks, S. Schenk, U. Uwer

Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany

D. J. Bard, W. Bhimji, D. A. Bowerman, P. D. Dauncey, U. Egede, R. L. Flack, J. A. Nash, M. B. Nikolich, W. Panduro Vazquez

Imperial College London, London, SW7 2AZ, United Kingdom

P. K. Behera, X. Chai, M. J. Charles, U. Mallik, N. T. Meyer, V. Ziegler

University of Iowa, Iowa City, Iowa 52242, USA

J. Cochran, H. B. Crawley, L. Dong, V. Eyges, W. T. Meyer, S. Prell, E. I. Rosenberg, A. E. Rubin

Iowa State University, Ames, Iowa 50011-3160, USA

A. V. Gritsan

Johns Hopkins University, Baltimore, Maryland 21218, USA

A. G. Denig, M. Fritsch, G. Schott

Universität Karlsruhe, Institut für Experimentelle Kernphysik, D-76021 Karlsruhe, Germany

N. Arnaud, M. Davier, G. Grosdidier, A. Höcker, F. Le Diberder, V. Lepeltier, A. M. Lutz, A. Oyanguren, S. Pruvot, S. Rodier, P. Roudeau, M. H. Schune, A. Stocchi, W. F. Wang, G. Wormser

Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, B.P. 34, F-91898 ORSAY Cedex, France

C. H. Cheng, D. J. Lange, D. M. Wright

Lawrence Livermore National Laboratory, Livermore, California 94550, USA

C. A. Chavez, I. J. Forster, J. R. Fry, E. Gabathuler, R. Gamet, K. A. George, D. E. Hutchcroft, D. J. Payne, K. C. Schofield, C. Touramanis

University of Liverpool, Liverpool L69 7ZE, United Kingdom

A. J. Bevan, F. Di Lodovico, W. Menges, R. Sacco

Queen Mary, University of London, E1 4NS, United Kingdom

G. Cowan, H. U. Flaecher, D. A. Hopkins, P. S. Jackson, T. R. McMahon, S. Ricciardi, F. Salvatore, A. C. Wren

University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom

D. N. Brown, C. L. Davis

University of Louisville, Louisville, Kentucky 40292, USA

J. Allison, N. R. Barlow, R. J. Barlow, Y. M. Chia, C. L. Edgar, G. D. Lafferty, M. T. Naisbit, J. C. Williams, J. I. Yi

University of Manchester, Manchester M13 9PL, United Kingdom

C. Chen, W. D. Hulsbergen, A. Jawahery, C. K. Lae, D. A. Roberts, G. Simi

University of Maryland, College Park, Maryland 20742, USA

G. Blaylock, C. Dallapiccola, S. S. Hertzbach, X. Li, T. B. Moore, S. Saremi, H. Staengle

University of Massachusetts, Amherst, Massachusetts 01003, USA

R. Cowan, G. Sciolla, S. J. Sekula, M. Spitznagel, F. Taylor, R. K. Yamamoto

Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA

H. Kim, S. E. Mclachlin, P. M. Patel, S. H. Robertson

McGill University, Montréal, Québec, Canada H3A 2T8

A. Lazzaro, V. Lombardo, F. Palombo

Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy

J. M. Bauer, L. Cremaldi, V. Eschenburg, R. Godang, R. Kroeger, D. A. Sanders, D. J. Summers, H. W. Zhao

University of Mississippi, University, Mississippi 38677, USA

S. Brunet, D. Côté, M. Simard, P. Taras, F. B. Viaud

Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7

H. Nicholson

Mount Holyoke College, South Hadley, Massachusetts 01075, USA

N. Cavallo,[2] G. De Nardo, F. Fabozzi,[3] C. Gatto, L. Lista, D. Monorchio, P. Paolucci, D. Piccolo, C. Sciacca

Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy

M. A. Baak, G. Raven, H. L. Snoek

NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands

C. P. Jessop, J. M. LoSecco

University of Notre Dame, Notre Dame, Indiana 46556, USA

T. Allmendinger, G. Benelli, L. A. Corwin, K. K. Gan, K. Honscheid, D. Hufnagel, P. D. Jackson, H. Kagan, R. Kass, A. M. Rahimi, J. J. Regensburger, R. Ter-Antonyan, Q. K. Wong

Ohio State University, Columbus, Ohio 43210, USA

N. L. Blount, J. Brau, R. Frey, O. Igonkina, J. A. Kolb, M. Lu, R. Rahmat, N. B. Sinev, D. Strom, J. Strube, E. Torrence

University of Oregon, Eugene, Oregon 97403, USA

[2]Also with Università della Basilicata, Potenza, Italy
[3]Also with Università della Basilicata, Potenza, Italy

A. Gaz, M. Margoni, M. Morandin, A. Pompili, M. Posocco, M. Rotondo, F. Simonetto, R. Stroili, C. Voci
Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy

M. Benayoun, H. Briand, J. Chauveau, P. David, L. Del Buono, Ch. de la Vaissière, O. Hamon, B. L. Hartfiel, M. J. J. John, Ph. Leruste, J. Malclès, J. Ocariz, L. Roos, G. Therin
Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France

L. Gladney, J. Panetta
University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

M. Biasini, R. Covarelli
Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy

C. Angelini, G. Batignani, S. Bettarini, F. Bucci, G. Calderini, M. Carpinelli, R. Cenci, F. Forti, M. A. Giorgi, A. Lusiani, G. Marchiori, M. A. Mazur, M. Morganti, N. Neri, E. Paoloni, G. Rizzo, J. J. Walsh
Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy

M. Haire, D. Judd, D. E. Wagoner
Prairie View A&M University, Prairie View, Texas 77446, USA

J. Biesiada, N. Danielson, P. Elmer, Y. P. Lau, C. Lu, J. Olsen, A. J. S. Smith, A. V. Telnov
Princeton University, Princeton, New Jersey 08544, USA

F. Bellini, G. Cavoto, A. D'Orazio, D. del Re, E. Di Marco, R. Faccini, F. Ferrarotto, F. Ferroni, M. Gaspero, L. Li Gioi, M. A. Mazzoni, S. Morganti, G. Piredda, F. Polci, F. Safai Tehrani, C. Voena
Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy

M. Ebert, H. Schröder, R. Waldi
Universität Rostock, D-18051 Rostock, Germany

T. Adye, N. De Groot, B. Franek, E. O. Olaiya, F. F. Wilson
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom

R. Aleksan, S. Emery, A. Gaidot, S. F. Ganzhur, G. Hamel de Monchenault, W. Kozanecki, M. Legendre, G. Vasseur, Ch. Yèche, M. Zito
DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France

X. R. Chen, H. Liu, W. Park, M. V. Purohit, J. R. Wilson
University of South Carolina, Columbia, South Carolina 29208, USA

M. T. Allen, D. Aston, R. Bartoldus, P. Bechtle, N. Berger, R. Claus, J. P. Coleman, M. R. Convery, M. Cristinziani, J. C. Dingfelder, J. Dorfan, G. P. Dubois-Felsmann, D. Dujmic, W. Dunwoodie, R. C. Field, T. Glanzman, S. J. Gowdy, M. T. Graham, P. Grenier,[4] V. Halyo, C. Hast, T. Hryn'ova, W. R. Innes, M. H. Kelsey, P. Kim, D. W. G. S. Leith, S. Li, S. Luitz, V. Luth, H. L. Lynch, D. B. MacFarlane, H. Marsiske, R. Messner, D. R. Muller, C. P. O'Grady, V. E. Ozcan, A. Perazzo, M. Perl, T. Pulliam, B. N. Ratcliff, A. Roodman, A. A. Salnikov, R. H. Schindler, J. Schwiening, A. Snyder, J. Stelzer, D. Su, M. K. Sullivan, K. Suzuki, S. K. Swain, J. M. Thompson, J. Va'vra, N. van

[4]Also at Laboratoire de Physique Corpusculaire, Clermont-Ferrand, France

Bakel, M. Weaver, A. J. R. Weinstein, W. J. Wisniewski, M. Wittgen, D. H. Wright, A. K. Yarritu, K. Yi, C. C. Young

Stanford Linear Accelerator Center, Stanford, California 94309, USA

P. R. Burchat, A. J. Edwards, S. A. Majewski, B. A. Petersen, C. Roat, L. Wilden

Stanford University, Stanford, California 94305-4060, USA

S. Ahmed, M. S. Alam, R. Bula, J. A. Ernst, V. Jain, B. Pan, M. A. Saeed, F. R. Wappler, S. B. Zain

State University of New York, Albany, New York 12222, USA

W. Bugg, M. Krishnamurthy, S. M. Spanier

University of Tennessee, Knoxville, Tennessee 37996, USA

R. Eckmann, J. L. Ritchie, A. Satpathy, C. J. Schilling, R. F. Schwitters

University of Texas at Austin, Austin, Texas 78712, USA

J. M. Izen, X. C. Lou, S. Ye

University of Texas at Dallas, Richardson, Texas 75083, USA

F. Bianchi, F. Gallo, D. Gamba

Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy

M. Bomben, L. Bosisio, C. Cartaro, F. Cossutti, G. Della Ricca, S. Dittongo, L. Lanceri, L. Vitale

Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy

V. Azzolini, N. Lopez-March, F. Martinez-Vidal

IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain

Sw. Banerjee, B. Bhuyan, C. M. Brown, D. Fortin, K. Hamano, R. Kowalewski, I. M. Nugent, J. M. Roney, R. J. Sobie

University of Victoria, Victoria, British Columbia, Canada V8W 3P6

J. J. Back, P. F. Harrison, T. E. Latham, G. B. Mohanty, M. Pappagallo

Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

H. R. Band, X. Chen, B. Cheng, S. Dasu, M. Datta, K. T. Flood, J. J. Hollar, P. E. Kutter, B. Mellado, A. Mihalyi, Y. Pan, M. Pierini, R. Prepost, S. L. Wu, Z. Yu

University of Wisconsin, Madison, Wisconsin 53706, USA

H. Neal

Yale University, New Haven, Connecticut 06511, USA

1 INTRODUCTION

One of the important unresolved questions of our time is the presence of a large baryon asymmetry in today's universe. According to A. Sakharov [1] three conditions must be satisfied in order for a baryon asymmetry to arise from an initial state with zero baryon number: baryon number violation, C and CP symmetry violation, and a departure from thermal equilibrium. No baryon number violating processes have yet been observed [2]. Though we know that the baryon number was violated in the early universe we do not know how it came about. Conservation of angular momentum requires that the spin 1/2 of a nucleon that is decaying to a lepton be transferred to the lepton: $\Delta B = \pm\Delta L$. Therefore there are two types of baryon instabilities $|\Delta(B-L)| = 0, 2$. In the Standard Model (SM), and in most of its extensions, it is required that $\Delta(B-L) = 0$. The second possibility of $|\Delta(B-L)| = 2$ allows transitions with $\Delta B = -\Delta L$, or $|\Delta B| = 2$ and $|\Delta L| = 0$, or $|\Delta L| = 2$ and $|\Delta B| = 0$. It follows that the conservation or violation of $(B-L)$ determines the mechanism of baryon instability.

It has been shown that, in baryogenesis, nonperturbative Standard Model effects at the electroweak energy scale will erase any baryon excess generated by $(B-L)$-conserving processes at the earliest moments of the universe ($T >> 1$ TeV) [3]. In addition, generating a baryon excess through electroweak effects alone does not seem to be adequate to account for the observed baryon asymmetry [4]. A component with $\Delta(B-L) = 2$ might be necessary to explain baryogenesis.

Most existing searches for $(B–L)$ violation have been restricted to experiments with nucleons [2]. In this analysis we search for the decays $\tau \to \Lambda\pi$ and $\tau \to \Lambda K$, in the $(B-L)$-conserving modes $\tau^- \to \bar{\Lambda}^0\pi^-(K^-)$ as well as the $(B–L)$-violating modes $\tau^- \to \Lambda^0\pi^-(K^-)$. Charge conjugate modes are always included if not mentioned otherwise. A similar analysis of the modes $\tau \to \Lambda\pi$ published recently by the Belle Collaboration [5] finds the upper limits $\mathcal{B}(\tau^- \to \bar{\Lambda}^0\pi^-) < 14 \times 10^{-8}$ and $\mathcal{B}(\tau^- \to \Lambda^0\pi^-) < 7.2 \times 10^{-8}$ at 90% confidence level (C.L.).

Experimental limits on the proton lifetime imply that the expected branching fraction for $\tau \to (\bar{p} + \text{anything})$ is not observable in the Standard Model: $\mathcal{B}(\tau \to \bar{p} + X) < 10^{-40}$ [6]. The Λ^0 baryon couples weakly to the proton. We would then expect similar but approximately 10^8 times weaker [6] constraints from the proton lifetime for $\tau \to \Lambda\pi(K)$. A recent theoretical paper [7] studied dimension-6 operators and concludes that baryon number violation in decays involving higher generations, assuming proton stability, will not be observable. However such a model may not be adequate to describe the apparent baryon asymmetry in the first place. Models with dimension-9 operators and yet unknown mechanisms that generate baryon number violation or enhance the coupling to higher generations may be able to accomplish this [8].

With the advent of the B factories, that also produce large quantities of τ leptons, we are now able to experimentally study such decays with greatly improved precision.

2 THE *BABAR* DETECTOR AND DATASET

This measurement was performed using data collected by the *BABAR* detector at the PEP-II storage ring. Charged particles are detected and their momenta measured by a combination of a silicon vertex tracker (SVT), consisting of 5 layers of double-sided detectors, and a 40-layer central drift chamber (DCH), both operating in a 1.5-T axial magnetic field. Charged particle identification is provided by the energy loss in the tracking devices and by the measured Cherenkov angle from an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region. Photons and electrons are detected by a CsI(Tl) electromagnetic calorimeter (EMC). The EMC is surrounded by an instrumented flux return (IFR). Electrons are identified using measurements from the DCH, EMC, and DIRC. The average identification efficiency is approximately 97%, whereas the pion (kaon) misidentification rate is less than 2% (1%). Kaons are identified using the SVT, DCH, and DIRC. The average identification efficiency for the tight kaon selection is approximately 80%, whereas the pion misidentification rate is less than 1%. The average identification efficiency for the loose kaon selection is approximately 90%, whereas the pion misidentification rate is less than 4%. Protons are identified with a likelihood based algorithm using measurements from all described detector components. The proton identification efficiency ranges from approximately 90% to 96% depending on polar angle and momentum, whereas the average pion (kaon) misidentification rate is 5% (12%). Details of the detector are described elsewhere [9].

The data sample used corresponds to an integrated luminosity of 237 fb^{-1} collected from e^+e^- collisions at, or 40 MeV below, the $\Upsilon(4S)$ resonance. Production and decay of the tau leptons are simulated with the kk2f [10, 11] and tauola [12, 13] Monte Carlo (MC) event generators, according to two-body phase space, and taking spin correlations into account for the signal mode. B meson decays are simulated with the EvtGen generator [14], and $q\bar{q}$ events, where $q = u, d, s$, or c quark, with the JETSET [15] generator. The detector is fully modelled using the GEANT4 simulation package [16].

3 ANALYSIS METHOD

We reconstruct candidate events $e^+e^- \to \tau^+\tau^-$ with one τ decaying to $\Lambda\pi(K)$ and $\Lambda \to p\pi$. The other tau in each event is required to be a one-prong decay. Decays that conserve $(B-L)$ are recognized by opposite sign charge of the pion or kaon from the τ decay and the pion from the Λ^0 decay. In decays where $(B-L)$ is violated the two charges have the same sign.

Each event must have exactly four well reconstructed tracks in the fiducial volume of the DCH with a total charge of zero. We divide the events into two hemispheres defined by the thrust axis of the event. The thrust axis is calculated using tracks in the drift chamber and calorimeter energy depositions without an associated track. We require that the three signal tracks are contained in one hemisphere and that there is exactly one remaining track in the other hemisphere, which we will refer to as the tagging hemisphere.

One of the signal tracks must be identified as a proton and, when combined with an oppositely charged signal track, must give a $p\pi^-$ invariant mass within 5 MeV/c^2 of the nominal Λ^0 mass [2]. The set of signal tracks are subjected to a topological fit to the decay tree $\tau \to \Lambda\pi(K)$, which must converge and return a χ^2 probability greater than 2.5%.

We require that the center-of-mass (CM) momentum of the Λ^0 is greater than the lower kinematic limit of 1.8 GeV/c for $\tau^- \to \Lambda^0\pi^-$ decays. A requirement on the Λ^0 flight distance $L_{\Lambda^0} > 1$ cm and the signed flight length significance $L_{\Lambda^0}/\sigma_{\Lambda^0} > 0$ removes $\tau^+\tau^-$ (88%) and $q\bar{q}$ (22%) events that do not contain true Λ particles. The remaining backgrounds are mostly from $q\bar{q}$ events and to a lesser degree $\tau^+\tau^-$ events that contain K^0_s decays and photon conversions $\gamma \to e^+e^-$. None of approximately 800 million MC $B\bar{B}$ events survive the selection criteria.

Figure 1 shows a comparison of the MC simulation with our data. Note that the Λ^0 momentum spectrum shown in Figure 1 (a,b) is not very well described by our MC simulation. This is most likely due to imperfections of the $q\bar{q}$ MC event generator. For this reason the final background will be determined from the data. All other variables that were studied show better agreement between data and MC.

We require that the pion track from the Λ^0 decay as well as the tagging track from the other

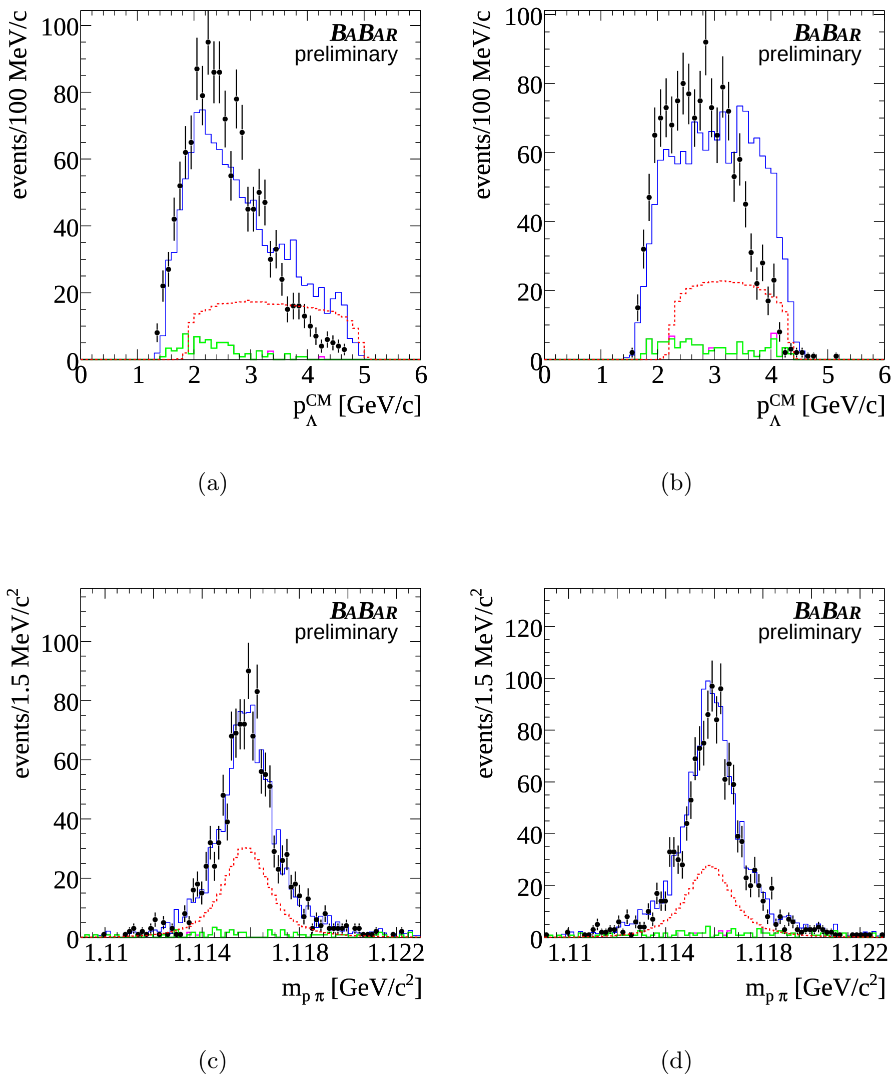


Figure 1: The Λ^0 candidate momentum in the e^+e^- rest frame for (a) $\tau \to \Lambda\pi$ and (b) $\tau \to \Lambda K$ and the Λ^0 invariant mass spectrum for (c) $\tau \to \Lambda\pi$ and (d) $\tau \to \Lambda K$. The solid stacked histograms are from top to bottom: uds backgrounds (blue), and $\tau^+\tau^-$ (green). The $c\bar{c}$ component is too small to be seen in these figures. The signal Monte Carlo distributions are shown with the dashed red histogram. The points correspond to events in the data sidebands.

τ lepton do not pass tight kaon identification requirements. In the mode $\tau \to \Lambda\pi$ we require that the π is not identified as a kaon. In the mode $\tau \to \Lambda K$ we require that the kaon track be identified with loose kaon identification requirements. To suppress candidates that include tracks from photon conversions, we require that the pion or kaon from the τ decay and the pion from the Λ^0 decay must not be identified as an electron. The pion or kaon from the τ decay must not be identified as a proton.

We study events in the two dimensional plane $m_{\Lambda\pi(K)}$ versus $\Delta E_{\Lambda\pi(K)}$, where $m_{\Lambda\pi(K)}$ is the invariant mass of the Λ and the pion (or kaon) candidate, and $\Delta E_{\Lambda\pi(K)} = E_{\Lambda\pi(K)} - \sqrt{s}/2$ is the reconstructed energy $E_{\Lambda\pi(K)}$ of the signal tracks minus the expected τ energy, which is half the known e^+e^- center-of-mass energy $\sqrt{s}$. A rectangular region that includes the signal region was blinded during the development of this analysis. Signal candidates are counted in an elliptical signal region with a half width of 10 MeV in $m_{\Lambda\pi(K)}$ and 90 MeV in $\Delta E_{\Lambda\pi(K)}$ centered around the nominal τ mass [2] and $\Delta E_{\Lambda\pi(K)} = 0$. In the case of $\tau \to \Lambda K$ the width in $m_{\Lambda\pi(K)}$ is reduced to 7 MeV because of the better resolution in this mode. The elliptical signal region is slightly tilted to reflect the small correlation between the two variables. The tilt is $\approx 3^\circ$, which can also be expressed as a correlation coefficient between the two variables: $\rho = 0.42$ for $\tau \to \Lambda\pi$ and $\rho = 0.56$ for $\tau \to \Lambda K$. The definition of the signal region as well as the other selection requirements applied in this analysis have been optimized using MC simulation, to obtain the lowest average upper limit for the signal modes under the assumption that no signal will be observed.

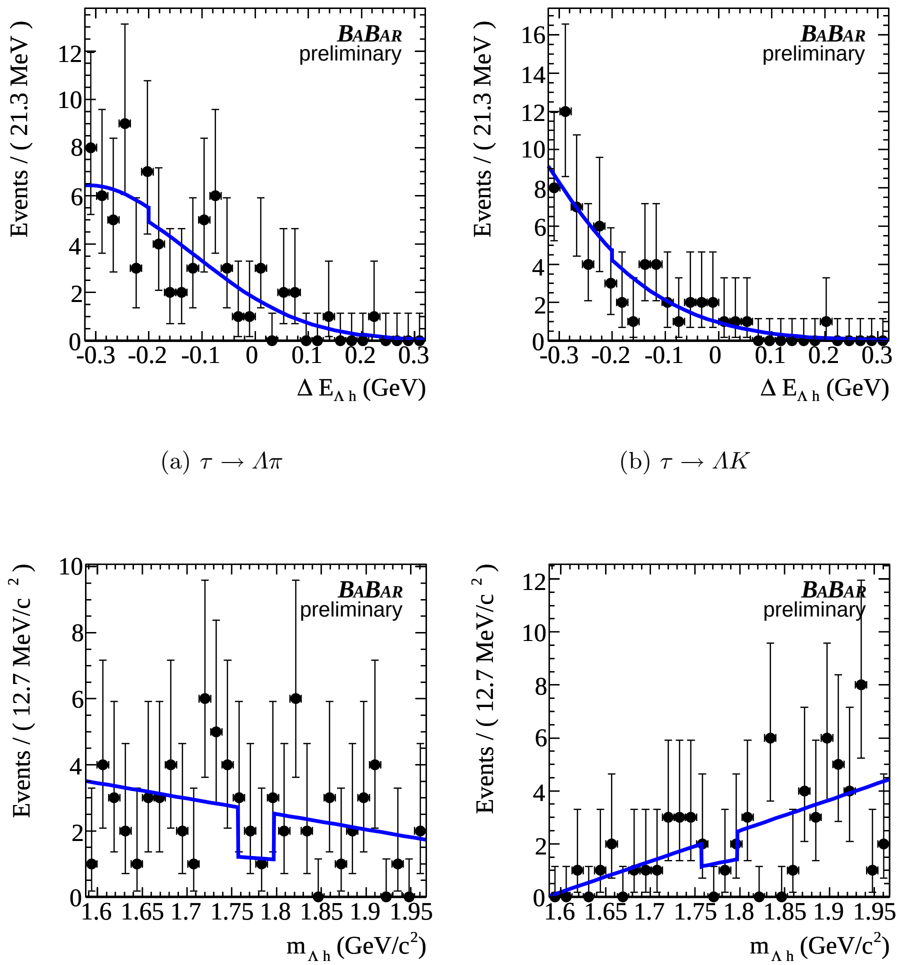
We estimate the number of background events in the signal region with a 2D unbinned maximum likelihood fit of the $m_{\Lambda\pi(K)}$ and $\Delta E_{\Lambda\pi(K)}$ distributions outside the blinded region. We try a number of functional forms that describe both the data and MC distributions. The default fit uses a simple parametrization that describes the data well and results in a background estimate that is in the center of the possible range of values. A first-order polynomial is fitted to the $m_{\Lambda\pi(K)}$ distribution and a Gaussian function to the $\Delta E_{\Lambda\pi(K)}$ distribution. The blinded region is excluded from the fit and the probability density function is set to zero within the blinded region. The parametrizations obtained are shown in Figure 2. The elliptical signal regions and the blinded region are also indicated in Figure 3. Due to the uncertainties of the background parametrization and the possibility of correlations among the fit variables, we take a conservative 100% error on the number of estimated background events in the signal region.

4 SELECTION EFFICIENCY

The signal efficiencies have been obtained from Monte Carlo simulations. Systematic uncertainties have been studied using independent control samples of real data; a summary is presented in Table 1. The largest contributions are from uncertainties related to the tracking efficiency, and Λ reconstruction. The latter has been estimated by comparing lifetime distributions of long lived particles in data and Monte Carlo. The uncertainty on the branching fraction $\mathcal{B}(\Lambda^0 \to p\pi^-)$ has been taken from the Review of Particle Physics [2]. Contributions to the systematic uncertainty are added in quadrature to give a total systematic uncertainty of 6.9% in the mode $\tau \to \Lambda\pi$ and 7.0% for $\tau \to \Lambda K$.

5 RESULTS

The data distributions in the $\Delta E_{\Lambda\pi(K)}$ versus $m_{\Lambda\pi(K)}$ plane after all selection requirements are shown in Figure 3. No signal candidate events are observed in the $\tau \to \Lambda\pi$ mode. We observe one candidate event in the $(B-L)$-violating mode $\tau^- \to \Lambda^0 K^-$. We determine upper limits on branching fractions at 90% C.L. using the method described in Ref. [17]. This method considers uncertainties both on the signal efficiency as well as the number of expected background events in the signal region. The number of expected background events and number of observed events in the signal region, the signal efficiency, and the upper limit that has been determined are shown separately for the $(B-L)$-violating and $(B-L)$-conserving cases in Table 2. The upper limit on



(a) $\tau \to \Lambda\pi$ (b) $\tau \to \Lambda K$

(c) $\tau \to \Lambda\pi$ (d) $\tau \to \Lambda K$

Figure 2: Projections of the background parametrization as derived from a 2D unbinned maximum likelihood fit. The top row shows the ΔE projection, and the bottom row the $m_{\Lambda h}$ projection. The $\tau \to \Lambda\pi$ mode is shown in the left column and the $\tau \to \Lambda K$ mode in the right column. The fitted probability density function (PDF) is indicated by a line. The PDF was required to be zero in the blinded region, which causes the apparent drop around the signal regions in these projections. The points with error bars correspond to $\tau \to \Lambda\pi(K)$ candidates in data, outside the blinded region.

the branching fraction is given by

$$\mathcal{B}_{U.L.}(\tau \to \Lambda\pi(K)) = \frac{\ell}{2\sigma_{\tau\tau}\mathcal{L}\mathcal{B}(\Lambda \to p\pi)\varepsilon} \ , \quad (1)$$

where ℓ is the 90% C.L. upper limit for the signal yield, $\sigma_{\tau\tau} = 0.89$ nb is the assumed cross section for production of τ pairs, $\mathcal{L} = 237\ \text{fb}^{-1}$ is the total luminosity of our dataset, $\mathcal{B}(\Lambda \to p\pi) = 0.639$ is the Λ branching fraction taken from the RPP [2], and ε is the signal efficiency.

Table 1: Summary of systematic uncertainties on the signal efficiency, and the luminosity and cross section.

source	uncertainty (%)
Λ reconstruction	5.0
tracking efficiency	4.0
proton identification	1.0
kaon identification ($\tau \to \Lambda K$ only)	1.0
$\mathcal{B}(\Lambda \to p\pi)$	0.8
luminosity and cross section	2.3
total $\tau \to \Lambda\pi$	6.9
total $\tau \to \Lambda K$	7.0

Table 2: The number of expected background events in the signal region, signal efficiency, number of observed events, 90% C.L. upper limit for the signal yield (ℓ), and the upper limit branching fraction for each mode.

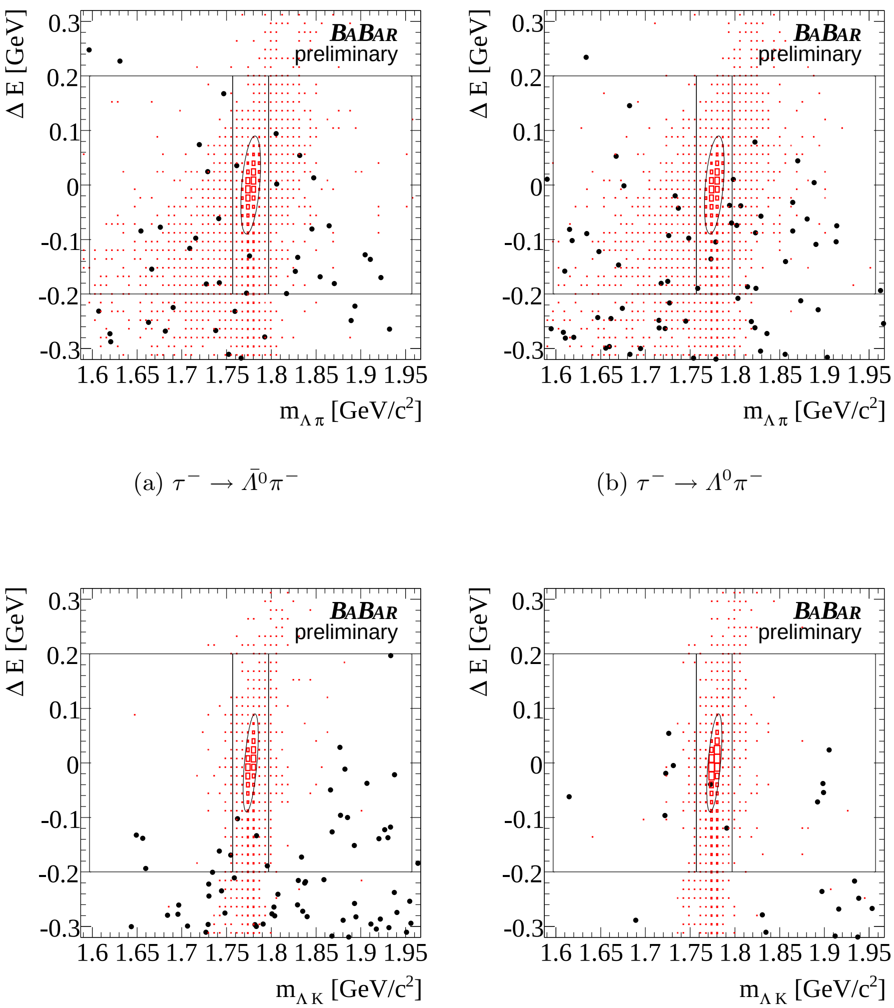
mode	$(B-L)$	expected background	efficiency %	observed events	ℓ	upper limit on $\mathcal{B}$ @ 90% C.L.
$\tau^- \to \bar{\Lambda}^0\pi^-$	conserving	0.42 ± 0.42	12.28	0	1.97	5.9×10^{-8}
$\tau^- \to \Lambda^0\pi^-$	violating	0.56 ± 0.56	12.21	0	1.90	5.8×10^{-8}
$\tau^- \to \bar{\Lambda}^0 K^-$	conserving	0.26 ± 0.26	10.63	0	2.08	7.2×10^{-8}
$\tau^- \to \Lambda^0 K^-$	violating	0.12 ± 0.12	9.47	1	3.78	15×10^{-8}

6 SUMMARY

A search for the $(B-L)$-conserving modes $\tau^- \to \bar{\Lambda}^0\pi^-$ and $\tau^- \to \bar{\Lambda}^0 K^-$ as well as the $(B-L)$-violating modes $\tau^- \to \Lambda^0\pi^-$ and $\tau^- \to \Lambda^0 K^-$ has been performed using 237 fb^{-1} of e^+e^- data. No signal is observed and we obtain preliminary upper limits on the branching fractions at 90% C.L. of $\mathcal{B}(\tau^- \to \bar{\Lambda}^0\pi^-) < 5.9 \times 10^{-8}$, $\mathcal{B}(\tau^- \to \Lambda^0\pi^-) < 5.8 \times 10^{-8}$, $\mathcal{B}(\tau^- \to \bar{\Lambda}^0 K^-) < 7.2 \times 10^{-8}$, and $\mathcal{B}(\tau^- \to \Lambda^0 K^-) < 15 \times 10^{-8}$. This analysis is the first measurement of the mode $\tau \to \Lambda K$, and it improves over earlier measurements of the mode $\tau \to \Lambda\pi$.

7 ACKNOWLEDGMENTS

We would like to thank Yury Kamishkov for his insights and useful discussions around baryon and lepton number violation in tau decays. We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the US Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), Institute of High Energy Physics (China), the Commissariat à l'Energie



(a) $\tau^- \to \bar{\Lambda}^0\pi^-$

(b) $\tau^- \to \Lambda^0\pi^-$

(c) $\tau^- \to \bar{\Lambda}^0 K^-$

(d) $\tau^- \to \Lambda^0 K^-$

Figure 3: $\Delta E_{\Lambda\pi(K)}$ versus $m_{\Lambda\pi(K)}$ data distributions for the $(B-L)$-conserving modes (left) and the $(B-L)$-violating modes (right). The top row shows the mode $\tau \to \Lambda\pi$; the mode $\tau \to \Lambda K$ is shown in the bottom row. The expected signal distribution (taken from Monte Carlo) is shown with red squares; data events are shown as dots. The large rectangles in each plot are from left to right: left sideband, blinded region, and right sideband. The elliptical signal region is also shown.

Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung and Deutsche Forschungsgemeinschaft (Germany), the Istituto Nazionale di Fisica Nucleare (Italy), the Foundation for Fundamental Research on Matter (The Netherlands), the Research Council of Norway, the Ministry of Science and Technology of the Russian Federation, and the Particle Physics and Astronomy Research Council (United Kingdom). Individuals have received support from the Marie-Curie IEF program (European Union) and the A. P. Sloan Foundation.

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