BABAR-CONF-08/001
SLAC-PUB-13325
arXiv:0807.4187
July, 2008

Search for $B^+ \to \mu^+\nu_\mu$ with inclusive reconstruction at BABAR

The BABAR Collaboration

July 25, 2008

Abstract

We search for the purely leptonic decay $B^\pm \to \mu^\pm\nu_\mu$ in the full BABAR dataset, having an integrated luminosity of approximately 426 fb^{-1}. We adopt a fully inclusive approach, where the signal candidate is identified by the highest momentum lepton in the event and the companion B is inclusively reconstructed without trying to identify its decay products. We set a preliminary upper limit on the branching fraction of $\mathcal{B}(B^\pm \to \mu^\pm\nu_\mu) < 1.3 \times 10^{-6}$ at the 90% confidence level, using a Bayesian approach.

Presented at the International Conference On High Energy Physics (ICHEP 2008),
7/29—8/5/2008, Philadelphia, USA

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

Work supported in part by Department of Energy contract DE-AC03-76SF00515.

The *BABAR* Collaboration,

B. Aubert, M. Bona, Y. Karyotakis, J. P. Lees, V. Poireau, E. Prencipe, X. Prudent, V. Tisserand
Laboratoire de Physique des Particules, IN2P3/CNRS et Université de Savoie, F-74941 Annecy-Le-Vieux, France

J. Garra Tico, E. Grauges
Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain

L. Lopez[ab], A. Palano[ab], M. Pappagallo[ab]
INFN Sezione di Bari[a]; Dipartmento di Fisica, Università di Bari[b], I-70126 Bari, Italy

G. Eigen, B. Stugu, L. Sun
University of Bergen, Institute of Physics, N-5007 Bergen, Norway

G. S. Abrams, M. Battaglia, D. N. Brown, R. N. Cahn, R. G. Jacobsen, L. T. Kerth, Yu. G. Kolomensky, G. Lynch, I. L. Osipenkov, M. T. Ronan,[1] K. Tackmann, T. Tanabe
Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA

C. M. Hawkes, N. Soni, A. T. Watson
University of Birmingham, Birmingham, B15 2TT, United Kingdom

H. Koch, T. Schroeder
Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

D. Walker
University of Bristol, Bristol BS8 1TL, United Kingdom

D. J. Asgeirsson, B. G. Fulsom, C. Hearty, T. S. Mattison, J. A. McKenna
University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

M. Barrett, A. Khan
Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

V. E. Blinov, A. D. Bukin, A. R. Buzykaev, 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

M. Bondioli, S. Curry, I. Eschrich, D. Kirkby, A. J. Lankford, P. Lund, M. Mandelkern, E. C. Martin, 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

J. W. Gary, F. Liu, O. Long, B. C. Shen,[1] G. M. Vitug, Z. Yasin, L. Zhang
University of California at Riverside, Riverside, California 92521, USA

[1]Deceased

V. Sharma

University of California at San Diego, La Jolla, California 92093, USA

C. Campagnari, T. M. Hong, D. Kovalskyi, M. A. Mazur, 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, A. J. Martinez, T. Schalk, B. A. Schumm, A. Seiden, M. G. Wilson, L. O. Winstrom

University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

C. H. Cheng, D. A. Doll, B. Echenard, F. Fang, D. G. Hitlin, I. Narsky, T. Piatenko, F. C. Porter

California Institute of Technology, Pasadena, California 91125, USA

R. Andreassen, G. Mancinelli, B. T. Meadows, K. Mishra, M. D. Sokoloff

University of Cincinnati, Cincinnati, Ohio 45221, USA

P. C. Bloom, W. T. Ford, A. Gaz, J. F. Hirschauer, M. Nagel, U. Nauenberg, J. G. Smith, K. A. Ulmer, S. R. Wagner

University of Colorado, Boulder, Colorado 80309, USA

R. Ayad,[2] A. Soffer,[3] W. H. Toki, R. J. Wilson

Colorado State University, Fort Collins, Colorado 80523, USA

D. D. Altenburg, E. Feltresi, A. Hauke, H. Jasper, M. Karbach, J. Merkel, A. Petzold, B. Spaan, K. Wacker

Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany

M. J. Kobel, W. F. Mader, R. Nogowski, K. R. Schubert, R. Schwierz, A. Volk

Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany

D. Bernard, G. R. Bonneaud, E. Latour, M. Verderi

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France

P. J. Clark, S. Playfer, J. E. Watson

University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

M. Andreotti[ab], D. Bettoni[a], C. Bozzi[a], R. Calabrese[ab], A. Cecchi[ab], G. Cibinetto[ab], P. Franchini[ab], E. Luppi[ab], M. Negrini[ab], A. Petrella[ab], L. Piemontese[a], V. Santoro[ab]

INFN Sezione di Ferrara[a]; Dipartimento di Fisica, Università di Ferrara[b], I-44100 Ferrara, Italy

R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, G. Finocchiaro, S. Pacetti, P. Patteri, I. M. Peruzzi,[4] M. Piccolo, M. Rama, A. Zallo

INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy

A. Buzzo[a], R. Contri[ab], M. Lo Vetere[ab], M. M. Macri[a], M. R. Monge[ab], S. Passaggio[a], C. Patrignani[ab], E. Robutti[a], A. Santroni[ab], S. Tosi[ab]

INFN Sezione di Genova[a]; Dipartimento di Fisica, Università di Genova[b], I-16146 Genova, Italy

[2]Now at Temple University, Philadelphia, Pennsylvania 19122, USA
[3]Now at Tel Aviv University, Tel Aviv, 69978, Israel
[4]Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy

K. S. Chaisanguanthum, M. Morii
Harvard University, Cambridge, Massachusetts 02138, USA

A. Adametz, J. Marks, S. Schenk, U. Uwer
Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany

V. Klose, H. M. Lacker
Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, Germany

D. J. Bard, P. D. Dauncey, J. A. Nash, M. Tibbetts
Imperial College London, London, SW7 2AZ, United Kingdom

P. K. Behera, X. Chai, M. J. Charles, U. Mallik
University of Iowa, Iowa City, Iowa 52242, USA

J. Cochran, H. B. Crawley, L. Dong, W. T. Meyer, S. Prell, E. I. Rosenberg, A. E. Rubin
Iowa State University, Ames, Iowa 50011-3160, USA

Y. Y. Gao, A. V. Gritsan, Z. J. Guo, C. K. Lae
Johns Hopkins University, Baltimore, Maryland 21218, USA

N. Arnaud, J. Béquilleux, A. D'Orazio, M. Davier, J. Firmino da Costa, G. Grosdidier, A. Höcker, V. Lepeltier, F. Le Diberder, A. M. Lutz, S. Pruvot, P. Roudeau, M. H. Schune, J. Serrano, V. Sordini,[5] A. Stocchi, 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

D. J. Lange, D. M. Wright
Lawrence Livermore National Laboratory, Livermore, California 94550, USA

I. Bingham, J. P. Burke, C. A. Chavez, J. R. Fry, E. Gabathuler, R. Gamet, D. E. Hutchcroft, D. J. Payne, C. Touramanis
University of Liverpool, Liverpool L69 7ZE, United Kingdom

A. J. Bevan, C. K. Clarke, K. A. George, F. Di Lodovico, R. Sacco, M. Sigamani
Queen Mary, University of London, London, E1 4NS, United Kingdom

G. Cowan, H. U. Flaecher, D. A. Hopkins, S. Paramesvaran, 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

A. G. Denig M. Fritsch, W. Gradl, G. Schott
Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany

[5]Also with Università di Roma La Sapienza, I-00185 Roma, Italy

K. E. Alwyn, D. Bailey, R. J. Barlow, Y. M. Chia, C. L. Edgar, G. Jackson, G. D. Lafferty, T. J. West, J. I. Yi

University of Manchester, Manchester M13 9PL, United Kingdom

J. Anderson, C. Chen, A. Jawahery, D. A. Roberts, G. Simi, J. M. Tuggle

University of Maryland, College Park, Maryland 20742, USA

C. Dallapiccola, X. Li, E. Salvati, S. Saremi

University of Massachusetts, Amherst, Massachusetts 01003, USA

R. Cowan, D. Dujmic, P. H. Fisher, G. Sciolla, M. Spitznagel, F. Taylor, R. K. Yamamoto, M. Zhao

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

P. M. Patel, S. H. Robertson

McGill University, Montréal, Québec, Canada H3A 2T8

A. Lazzaro[ab], V. Lombardo[a], F. Palombo[ab]

INFN Sezione di Milano[a]; Dipartimento di Fisica, Università di Milano[b], I-20133 Milano, Italy

J. M. Bauer, L. Cremaldi R. Godang,[6] R. Kroeger, D. A. Sanders, D. J. Summers, H. W. Zhao

University of Mississippi, University, Mississippi 38677, USA

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

G. De Nardo[ab], L. Lista[a], D. Monorchio[ab], G. Onorato[ab], C. Sciacca[ab]

INFN Sezione di Napoli[a]; Dipartimento di Scienze Fisiche, Università di Napoli Federico II[b], I-80126 Napoli, Italy

G. Raven, H. L. Snoek

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

C. P. Jessop, K. J. Knoepfel, J. M. LoSecco, W. F. Wang

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

G. Benelli, L. A. Corwin, K. Honscheid, H. Kagan, R. Kass, J. P. Morris, A. M. Rahimi, J. J. Regensburger, S. J. Sekula, 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

[6]Now at University of South Alabama, Mobile, Alabama 36688, USA

G. Castelli[ab], N. Gagliardi[ab], M. Margoni[ab], M. Morandin[a], M. Posocco[a], M. Rotondo[a], F. Simonetto[ab], R. Stroili[ab], C. Voci[ab]

INFN Sezione di Padova[a]; Dipartimento di Fisica, Università di Padova[b], I-35131 Padova, Italy

P. del Amo Sanchez, E. Ben-Haim, H. Briand, G. Calderini, J. Chauveau, P. David, L. Del Buono, O. Hamon, Ph. Leruste, J. Ocariz, A. Perez, J. Prendki, S. Sitt

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

University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

M. Biasini[ab], R. Covarelli[ab], E. Manoni[ab],

INFN Sezione di Perugia[a]; Dipartimento di Fisica, Università di Perugia[b], I-06100 Perugia, Italy

C. Angelini[ab], G. Batignani[ab], S. Bettarini[ab], M. Carpinelli[ab],[7] A. Cervelli[ab], F. Forti[ab], M. A. Giorgi[ab], A. Lusiani[ac], G. Marchiori[ab], M. Morganti[ab], N. Neri[ab], E. Paoloni[ab], G. Rizzo[ab], J. J. Walsh[a]

INFN Sezione di Pisa[a]; Dipartimento di Fisica, Università di Pisa[b]; Scuola Normale Superiore di Pisa[c], I-56127 Pisa, Italy

D. Lopes Pegna, C. Lu, J. Olsen, A. J. S. Smith, A. V. Telnov

Princeton University, Princeton, New Jersey 08544, USA

F. Anulli[a], E. Baracchini[ab], G. Cavoto[a], D. del Re[ab], E. Di Marco[ab], R. Faccini[ab], F. Ferrarotto[a], F. Ferroni[ab], M. Gaspero[ab], P. D. Jackson[a], L. Li Gioi[a], M. A. Mazzoni[a], S. Morganti[a], G. Piredda[a], F. Polci[ab], F. Renga[ab], C. Voena[a]

INFN Sezione di Roma[a]; Dipartimento di Fisica, Università di Roma La Sapienza[b], I-00185 Roma, Italy

M. Ebert, T. Hartmann, H. Schröder, R. Waldi

Universität Rostock, D-18051 Rostock, Germany

T. Adye, B. Franek, E. O. Olaiya, F. F. Wilson

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom

S. Emery, M. Escalier, L. Esteve, S. F. Ganzhur, G. Hamel de Monchenault, W. Kozanecki, G. Vasseur, Ch. Yèche, M. Zito

CEA, Irfu, SPP, Centre de Saclay, F-91191 Gif-sur-Yvette, France

X. R. Chen, H. Liu, W. Park, M. V. Purohit, R. M. White, J. R. Wilson

University of South Carolina, Columbia, South Carolina 29208, USA

M. T. Allen, D. Aston, R. Bartoldus, P. Bechtle, J. F. Benitez, R. Cenci, J. P. Coleman, M. R. Convery, J. C. Dingfelder, J. Dorfan, G. P. Dubois-Felsmann, W. Dunwoodie, R. C. Field, A. M. Gabareen, S. J. Gowdy, M. T. Graham, P. Grenier, C. Hast, W. R. Innes, J. Kaminski, M. H. Kelsey, H. Kim, P. Kim, M. L. Kocian, D. W. G. S. Leith, S. Li, B. Lindquist, S. Luitz, V. Luth, H. L. Lynch, D. B. MacFarlane, H. Marsiske, R. Messner, D. R. Muller, H. Neal, S. Nelson, C. P. O'Grady, I. Ofte, A. Perazzo, M. Perl, B. N. Ratcliff, A. Roodman, A. A. Salnikov, R. H. Schindler, J. Schwiening, A. Snyder, D. Su, M. K. Sullivan, K. Suzuki, S. K. Swain, J. M. Thompson, J. Va'vra, A. P. Wagner, M. Weaver, C. A. West, W. J. Wisniewski, M. Wittgen, D. H. Wright, H. W. Wulsin, A. K. Yarritu, K. Yi, C. C. Young, V. Ziegler

Stanford Linear Accelerator Center, Stanford, California 94309, USA

[7]Also with Università di Sassari, Sassari, Italy

P. R. Burchat, A. J. Edwards, S. A. Majewski, T. S. Miyashita, B. A. Petersen, L. Wilden
Stanford University, Stanford, California 94305-4060, USA

S. Ahmed, M. S. Alam, J. A. Ernst, B. Pan, M. A. Saeed, S. B. Zain
State University of New York, Albany, New York 12222, USA

S. M. Spanier, B. J. Wogsland
University of Tennessee, Knoxville, Tennessee 37996, USA

R. Eckmann, J. L. Ritchie, A. M. Ruland, C. J. Schilling, R. F. Schwitters
University of Texas at Austin, Austin, Texas 78712, USA

B. W. Drummond, J. M. Izen, X. C. Lou
University of Texas at Dallas, Richardson, Texas 75083, USA

F. Bianchi[ab], D. Gamba[ab], M. Pelliccioni[ab]
INFN Sezione di Torino[a]; Dipartimento di Fisica Sperimentale, Università di Torino[b], I-10125 Torino, Italy

M. Bomben[ab], L. Bosisio[ab], C. Cartaro[ab], G. Della Ricca[ab], L. Lanceri[ab], L. Vitale[ab]
INFN Sezione di Trieste[a]; Dipartimento di Fisica, Università di Trieste[b], I-34127 Trieste, Italy

V. Azzolini, N. Lopez-March, F. Martinez-Vidal, D. A. Milanes, A. Oyanguren
IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain

J. Albert, Sw. Banerjee, B. Bhuyan, H. H. F. Choi, K. Hamano, R. Kowalewski, M. J. Lewczuk, I. M. Nugent, J. M. Roney, R. J. Sobie
University of Victoria, Victoria, British Columbia, Canada V8W 3P6

T. J. Gershon, P. F. Harrison, J. Ilic, T. E. Latham, G. B. Mohanty
Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

H. R. Band, X. Chen, S. Dasu, K. T. Flood, Y. Pan, M. Pierini, R. Prepost, C. O. Vuosalo, S. L. Wu
University of Wisconsin, Madison, Wisconsin 53706, USA

1 INTRODUCTION

In the Standard Model (SM), the purely leptonic B decays $B^+ \to \ell^+\nu_\ell$ ($\ell = e, \mu, \tau$) (charge conjugation is implied troughout the paper) proceed through the annihilation of the two quarks in the meson to form a virtual W boson (Fig. 1). The branching ratio can be cleanly calculated in the SM,

$$\mathcal{B}(B^+ \to \ell^+\nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B, \tag{1}$$

where G_F is the Fermi coupling constant, m_ℓ and m_B are the lepton and B meson masses, and τ_B is the B^+ lifetime. The decay rate is sensitive to the Cabibbo Kobayashi Maskawa matrix element V_{ub} and the B decay constant f_B which describes the overlap of the quark wave functions within the meson. Currently, the uncertainty on f_B is one of the main factors limiting the determination of V_{td} from precision $B^0\bar{B}^0$ mixing measurements. Given a measurement of V_{ub} from semileptonic decays such as $B \to \pi\ell\nu$, f_B could be extracted from a measurement of the $B^+ \to \ell^+\nu_\ell$ branching ratio.

The SM estimate of the branching ratio for $B^+ \to \tau^+\nu_\tau$ is $(1.59 \pm 0.40) \times 10^{-4}$ assuming τ_B = 1.638±0.011 ps, V_{ub} = $(4.39 \pm 0.33) \times 10^{-3}$[1] determined from inclusive charmless semileptonic B decays and f_B = 216±22 MeV [2] from lattice QCD calculation. Due to helicity suppression, $B^+ \to \mu^+\nu_\mu$ and $B^\pm \to e^+\nu_e$ are suppressed by factors of 225 and 10^7 respectively, leading to branching ratios of $\mathcal{B}(B^\pm \to \mu^\pm\nu_\mu) \simeq 4.7 \times 10^{-7}$ and $\mathcal{B}(B^\pm \to e^\pm\nu_e) \simeq 1.1 \times 10^{-11}$.

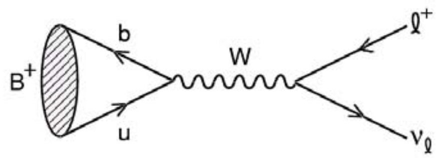

Figure 1: SM annihilation diagram for $B^\pm \to l^\pm\nu_\mu$.

Purely leptonic B decays are sensitive to physics beyond the SM due to possible insertion of New Physics (NP) heavy states in the annihilation process. Charged Higgs boson effects may greatly enhance or suppress the branching ratio in certain two Higgs doublet models [3]. Similarly, this decay may be enhanced through mediation by leptoquarks in the Pati-Salam model of quark-lepton unification [4].

Moreover, as in annihilation processes the longitudinal component of the vector boson is directly involved, this decay allows a direct test of Yukawa interactions in and beyond the SM. In particular, in a SUSY scenario at large $\tan\beta$ ($O(m_t/m_b) >> 1$), non-standard effects in helicity-suppressed charged current interactions are potentially observable, being strongly $\tan\beta$ dependent:

$$\mathcal{B}(B^\pm \to l^\pm\nu_l) \approx \mathcal{B}(B^\pm \to l^\pm\nu_l)_{\rm SM} \times \left(1 - \tan\beta^2 m_B^2/M_H^2\right)^2. \tag{2}$$

Recently, Belle had a first evidence of a purely leptonic B decay. With 414 fb^{-1}, Belle finds [5]

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \left(1.79^{+0.56}_{-0.49}(\text{stat})^{+0.46}_{-0.51}(\text{syst})\right) \times 10^{-4}, \tag{3}$$

at 3.5 σ significance. The most recent *BABAR* result on this channel uses an integrated luminosity of 346 fb^{-1}, corresponding to 383 million of $B\bar{B}$ pairs, and sets an upper limit (UL) at 90% of confidence level on the branching ratio of $\mathcal{B}(B^+ \to \tau^+\nu_\tau) < 1.7 \times 10^{-4}$[6] and a central value $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.2 \pm 0.4(\text{stat}) \pm 0.3(\text{bkg}) \pm 0.2(\text{syst})) \times 10^{-4}$[7].

BABAR has published a result on $\mathcal{B}(B^+ \to \mu^+\nu_\mu)$ with 81 fb^{-1} and set an UL at 90 % confidence level of $\mathcal{B}(B^+ \to \mu^+\nu_\mu) < 6.6 \times 10^{-6}$ [8]. The current best published upper limits at 90 % confidence level on $B^+ \to \mu^+\nu_\mu$ and $B^\pm \to e^+\nu_e$ are from Belle Collaboration on 235 fb^{-1} [9]

$$\begin{aligned} \mathcal{B}(B^+ \to \mu^+\nu_\mu) &< 1.7 \times 10^{-6}, \\ \mathcal{B}(B^+ \to e^+\nu_e) &< 9.8 \times 10^{-7}. \end{aligned} \tag{4}$$

2 THE *BABAR* DETECTOR AND DATASET

This analysis is based on the data collected with the *BABAR* detector [10] at the PEP-II storage ring. The sample corresponds to an integrated luminosity of 426 fb^{-1} at the $\Upsilon(4S)$ resonance, consisting of about 447 millions of $B\overline{B}$ pairs, and 44 fb^{-1} accumulated at a center-of-mass (CM) energy about 40 MeV below the $\Upsilon(4S)$ resonance. Off-resonance data are used as cross-checks for continuum $q\bar{q}$ ($q = u$, d, s, and c) and $\tau^+\tau^-$ on-resonance events. In particular, given the variation of muon identification in time due to detector differences and changes, we considered the total dataset divided into data-taking periods (runs).

Charged track reconstruction is provided by a Silicon Vertex Tracker (SVT) and a Drift Chamber (DCH) operating in a 1.5-T magnetic field. Particle identification is based on the energy loss dE/dx in the tracking system and the Cherenkov angle in an internally reflecting ring-imaging Cherenkov detector. Photon detection is provided by a CsI(Tl) Electromagnetic Calorimeter (EMC). Muons and neutral hadrons are identified by Resistive Plate Chambers and Limited Streamer Tubes in the Instrumented Flux Return (IFR) detector.

A GEANT4-based [11] Monte Carlo (MC) simulation is used to model the detector response and test the analysis technique. A sample of about 28 million simulated B^+B^- events where B^+ decays to $\mu^+\nu_\mu$ and the B^- decays generically is studied to evaluate the efficiency for the signal. Background sources considered include $e^+e^- \to B\overline{B}$, $e^+e^- \to q\overline{q}$ ($q = u$, d, s, and c), and $e^+e^- \to \tau^+\tau^-$ in quantities comparable to three times ($B\overline{B}$), twice ($c\bar{c}$) and once (uds,$\tau^+\tau^-$) the actual dataset luminosity.

3 ANALYSIS METHOD

$B^+ \to \mu^+\nu_\mu$ is a two-body decay so the muon must be mono-energetic in the B rest frame. The momentum p^* of the muon in the B rest frame is given by

$$p^* = \frac{m_B^2 - m_\mu^2}{2m_B} \approx \frac{m_B}{2} \approx 2.46\text{GeV}. \tag{5}$$

where m_B is the B mass and m_μ is the muon mass. At *BABAR* the CM frame is a good approximation to the B rest frame, so we initially select well-identified muon candidates with momentum p_{CM} between 2.4 and 3.2 GeV/c in the CM frame. Since the neutrino produced in the signal decay is not detected, any other charged tracks or neutral deposits in a signal event must have been produced by the decay of the companion (tag) B. Therefore, the tag B can be reconstructed from the remaining visible energy in the event. Signal decays can then be selected using the kinematic variables ΔE and energy-substituted mass, $m_{\rm ES}$, defined by

$$\Delta E = E_B - E_{\rm beam}, \tag{6}$$

and

$$m_{\rm ES} = \sqrt{E_{\rm beam}^2 - |\vec{p}_B|^{\,2}}, \tag{7}$$

where $\vec{p}_B$ and E_B are the momentum and energy of the reconstructed tag B candidate in the CM frame and $E_{\rm beam}$ is the beam energy in the CM frame. We include all neutral calorimeter clusters with cluster energy greater than 30 MeV. Particle identification is applied to the charged tracks to identify electrons, muons, kaons and protons in order to apply the most likely mass hypothesis to each track and thus improve the ΔE and $m_{\rm ES}$ resolution. Events with additional identified leptons are discarded to discriminate against events containing additional neutrinos. For signal events in which all decay products of the other B are reconstructed, we expect the ΔE distribution to peak near zero and $m_{\rm ES}$ to peak near m_B. In reality, due to the inclusive nature of our analysis, we often fail to reconstruct all the decay products so that the ΔE distribution develops a negative tail while the m_{ES} distribution exhibits a tail below the B mass. For uds and $c\bar{c}$ backgrounds, ΔE is shifted significantly greater than zero since we attribute too much energy to the opposite hemisphere decay. ΔE is negative for $\tau^+\tau^-$ decays due to missing neutrinos. Figure 2 shows the distributions of ΔE and $m_{\rm ES}$ for the on-peak data, background MC and signal MC after muon candidate selection.

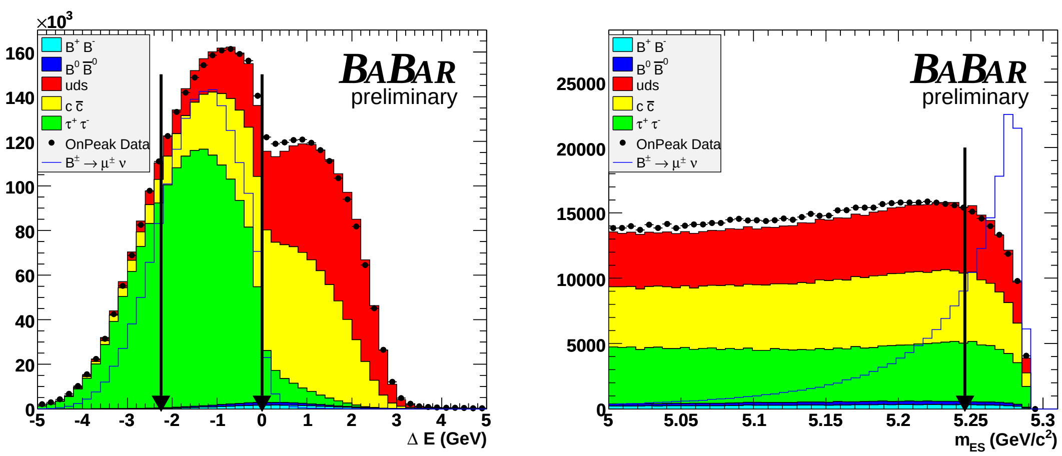

Figure 2: Distribution of ΔE and m_{ES} after the muon selection: signal in blue histogram, data in black dots and background events are stacked on top of each other: uds in red, $c\bar{c}$ in yellow, $\tau^+\tau^-$ in green, $B^0\bar{B}^0$ in dark blue and B^+B^- in light blue. The arrows indicate the requirements set on these variables.

In order to obtain data/MC agreement, we extract the uds, $c\bar{c}$ and $\tau^+\tau^-$ MC normalization coefficients from a fit to the ΔE data distribution, keeping the $b\bar{b}$ component fixed. The requirements on tag B kinematical variables is optimized with the figure of merit $\epsilon_{\rm sig}/\sqrt{N_{\rm bkg}}$ where $\epsilon_{\rm sig}$ is the signal efficiency and $N_{\rm bkg}$ the number of background events. We require the tag B ΔE and m_{ES} to be within -2.25 $< \Delta E <$ 0 GeV and $m_{ES} >$ 5.246 GeV/c^2.

Once the tag B is reconstructed, we refine the estimate of the muon momentum in the B rest frame (p^*). We use the momentum direction of the tag B and assume a total momentum of 320 MeV/c in the CM frame (from the decay of the $\Upsilon(4S) \rightarrow B\overline{B}$) to boost the muon candidate into the reconstructed B rest frame.

Backgrounds may arise from any process producing charged tracks in the momentum range of the signal, particularly if the charged tracks are muons. The two most significant backgrounds are B semileptonic decays involving $b \rightarrow u\mu\nu_\mu$ transitions where the endpoint of the muon spectrum approaches that of the signal, and non-resonant $q\overline{q}$ (continuum) events where a charged pion is mistakenly identified as a muon. In the continuum events, there must also be significant missing energy due to detector acceptance, neutral hadrons, or additional neutrinos that mimic the signature of the expected neutrino.

Continuum backgrounds are suppressed using event shape variables. The light-quark events tend to produce a jet-like event topology as opposed to $B\overline{B}$ events which tend to be more isotropically distributed in space. Several topological variables have been considered and five have been found to be the most discriminating, using an appropriate cocktail of different data-taking periods. These variables are combined in a Fisher discriminant [12]: the normalized second Fox-Wolfram moment R_2 [13], calculated using all charged tracks and neutral clusters in the event; the ratio of the second and zeroth Legendre Polynomials L_2/L_0, where all tag B daughters momenta in the CM frame are included and the angle is measured with respect to the lepton candidate momentum; the cosine of the angle of the expected signal neutrino in the lab frame (as determined from the lepton candidate); the lepton transverse momentum in $\Upsilon(4S)$ frame; the sphericity of the event. The Fisher coefficients are optimized run-by-run. A cut is applied on the Fisher discriminant and is thus optimized for each run separately in order to have better performance. The efficiency of this cut is in the range 16% to 32% for signal events , 5% to 16% for $b\bar{b}$ events and less than 0.5% for continuum events.

The two-body kinematics of this decay is now exploited by combining p^* and p_{CM} in a second Fisher discriminant in order to discriminate against the remaining semileptonic $b\bar{b}$ background events. Signal and background yields are obtained from a Maximuum Likelihood Fit using the Fisher output p_{FIT}. We parameterize signal MC with the sum of two Gaussians. As $b\bar{b}$ events and continuum $q\bar{q}$ and $\tau^+\tau^-$ events are two background samples with different p_{FIT} Probability Density Functions (PDFs), we parameterize them separately and construct a summed background PDF with relative normalizations fixed from simulated events. Both of them are parameterized with a Gaussian function with a different sigma for value above and below the peak (bifurcated Gaussians). Table 1 shows the fixed parameterization of signal and backgrounds PDFs, with purely statistical uncertainties arising from the size of the simulated datasets used to obtain the parameterizations. The p_{FIT} distributions for simulated signal and background events are shown in Figure 3. Only the signal yield and the yield of the sum of all backgrounds are free parameters in the fit.

4 SYSTEMATIC STUDIES

To set an upper limit on the $B^+ \rightarrow \mu^+\nu_\mu$ branching fraction we evaluate systematic uncertainties in the number of $B^\pm$ in the sample, the signal efficiency and the signal yield.

- The number of $B^\pm$ mesons in the on-peak data sample is estimated to be 447×10^6 with an uncertainty of 1.1% estimated studying $\mu\mu$ pairs events [14].

Table 1: p_{FIT} distribution parameterization for signal MC (left), $b\bar{b}$ (center) and $uds + c\bar{c} + \tau^+\tau^-$ (right). The two summed Gaussians have parameters (μ_{core},σ_{core}) and (μ_{tail},σ_{tail}) respectively and f_{core} is the relative fraction of the core Gaussian. The bifurcated Gaussian has μ_{core} as mean and σ_L and σ_R as left and right σ respectively.

Parameter	Signal MC	$b\bar{b}$	$uds + c\bar{c} + \tau^+\tau^-$
μ_{core}	5.32 ± 0.03	-2.2 ± 0.3	0.5 ± 1.1
$\sigma_{\mathrm{core(L)}}$	2.43 ± 0.04	0.7 ± 0.2	1.6 ± 0.7
μ_{tail}	4.91 ± 0.03	-	-
$\sigma_{\mathrm{tail(R)}}$	1.39 ± 0.04	3.6 ± 0.3	6.8 ± 0.9
f_{core}	0.54 ± 0.03	-	-

- The uncertainty in the signal efficiency includes the muon candidate selection (particle identification, tracking efficiency and Fisher requirement) as well as the reconstruction efficiency of the tag B. The muon identification efficiency systematic is evaluated using control samples derived from the BABAR data, which are weighted to reproduce the kinematic distribution of the muon signal candidate. Comparing the cumulative signal efficiency obtained with and without this weight, a total discrepancy of 2.9% is found and this value is taken as the muon ID systematic uncertainty.

  Charge conservation is imposed on τ decays, which must proceed via an odd number of tracks and thus the number of events with a missing track can be used to evaluate the uncertainty associated with the tracking efficiency and the relative correction factor. The systematic uncertainty per track and the correction factor are taken in quadrature to give the total tracking efficiency uncertainty of 0.4% per track.

  In order to evaluate the systematic uncertainty associated with the requirements on the Fisher discriminants, we take the ratio between data and simulated events Fisher discriminant distributions in the ΔE and m_{ES} sidebands $\Delta E > 0$ GeV and 5.2 GeV/c^2 $< m_{ES} <$ 5.246 GeV/c^2 for each different data-taking period. We fit the data/MC ratio for each run with a linear function. The mean weighted by the errors of slopes and intercepts returns a linear function consistent with a data/MC unitary ratio in the full Fisher range. We take the uncertainty of 1.5% on the averaged intercept as the systematic error on the Fisher discriminant cut.

  The tag B reconstruction has been studied with a control sample of $B^+ \to D^{(*)0}\pi^+$ events, where the D is reconstructed into $\bar{D}^0 \to K^+\pi^-$ and $D^0 \to K^-\pi^+$ and the D^* into $D^{*0} \to D^0\gamma$ or $D^{*0} \to D^0\pi^0$. This is also a two-body decay so it is topologically very similar to our signal. Once reconstructed, the pion can be treated as if it were the signal muon and the $D^{(*)0}$ decay products are ignored to simulate the neutrino. The tag B is then reconstructed in the control sample as it would be for signal. We compare the efficiencies for our tag B selection cuts in the $B^+ \to D^{(*)0}\pi^+$ data and MC to quantify any data/MC disagreements that may affect the signal efficiency. We find a data/MC discrepancy on $B^+ \to D^{(*)0}\pi^+$ control sample of 2.7% and assign this as the signal efficiency uncertainty arising from the tag B selection. A summary of the systematic uncertainties in the signal efficiency is given in Table 2. The final signal efficiency is thus 4.64 ± 0.19 %.

- The fit parameters are extracted from MC and are kept fixed in the final fit to extract the

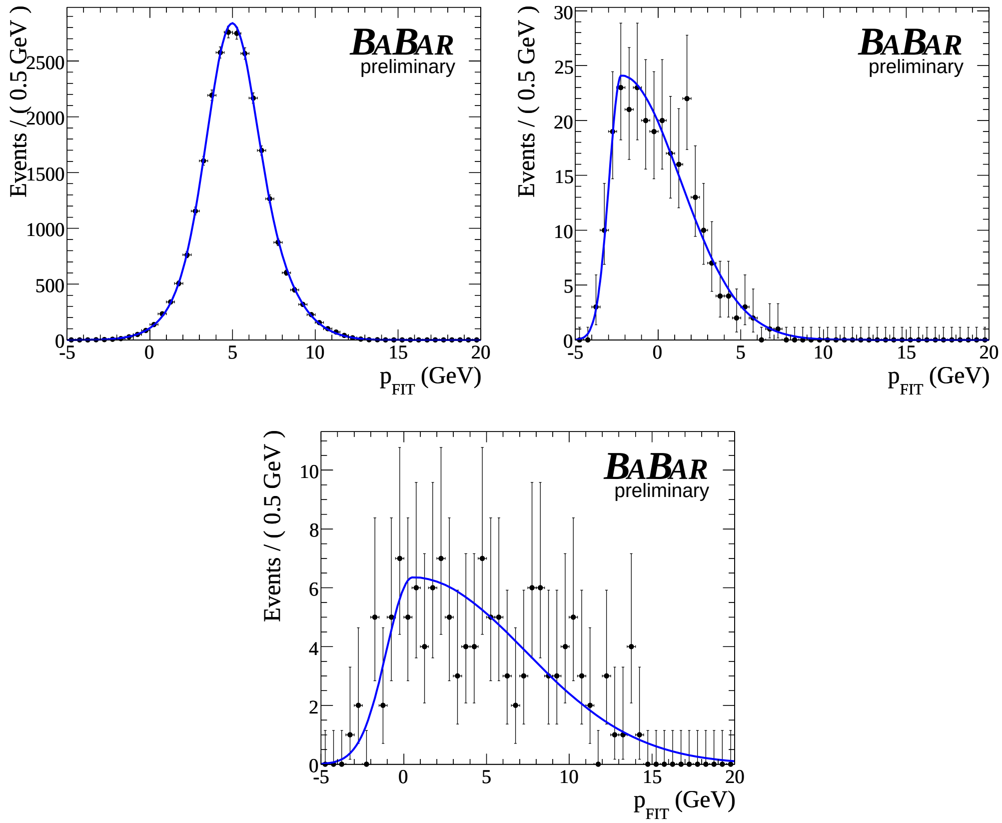

Figure 3: Distribution of p_{FIT} with the fit superimposed: signal (top left), $b\bar{b}$ (top right) and $c\bar{c}$ + uds + $\tau^+\tau^-$ (bottom).

Table 2: Contributions to the systematic uncertainty on the signal efficiency.

Source	Relative Error
muon identification	2.9%
tracking efficiency	0.4%
tag B reconstruction	2.7%
Fisher selection	1.5%
Total	4.2%

yields. These parameters are affected by an uncertainty due to the MC statistics, which is considered as a source of systematic uncertainty. In order to evaluate it, the final fit has been repeated 500 times for each background and signal PDF parameter. We randomly generate the PDF parameters assuming Gaussian errors and taking into account all the correlations between them. We perform a Gaussian fit to the distribution of the number of signal events for each parameter, take the fitted sigma as the systematic uncertainty and sum in quadrature. The total systematic uncertainty in the signal yield from all signal and background PDFs parameterization is 13 events.

We take into account possible discrepancies in the shape of the $p_{\rm FIT}$ background distribution in data and simulated events using again the simulated events over data ratio in the ΔE and m_{ES} sidebands $\Delta E > 0$ GeV and 5.2< m_{ES} < 5.246 GeV/c^2. Given the low statistics available for values of $p_{\rm FIT}$ above 5, we parameterize this ratio with a parabolic function in the region (-5;5) and take the constant value of the ratio in the region (5;20). The ratio with the parabolic fit superimposed is shown in Figure 4. We repeat the final fit to the data 500 times for each parabola parameter and the value of the constant. We generate each parameter according to a Gaussian distribution centered at its mean value and having a sigma equal to its error, taking into account all correlations between different parameters. We weight the dataset by the generated ratio and repeat the fit. A Gaussian fit to the distribution of number of fitted signal events for each parameter is performed and the sigma of the the Gaussian fit is taken as systematic uncertainty and summed in quarature. The total systematic uncertainty from this procedure is 7 events. A summary of all systematic uncertainties in the fitted signal yield is provided in Table 3.

The total systematic uncertainty is 1.1% on the number of B^+B^- pairs, 4.2 % on signal efficiency and 15 events on the signal yield.

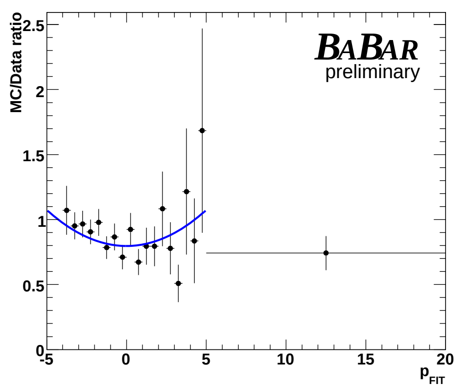

Figure 4: MC/Data ratio of p_{FIT} distribution on ΔE and m_{ES} sideband ($\Delta E > 0$ GeV and 5.2 GeV/c^2 < m_{ES} <5.246 GeV/c^2).

Table 3: Contributions to the systematic uncertainty on the signal yield.

Source	Total Error
PDF parameters	13
Data/MC agreement	7
Total	15

5 RESULTS

From the data we extract -12 ± 15 signal events and 600 ± 29 background events. We expect 10 events from MC assuming a SM branching fraction $\mathcal{B}(B^{\pm} \to \mu^{\pm}\nu_{\mu}) = 4.7 \times 10^{-7}$. The signal yield extracted corresponds to a central value $\mathcal{B}(B^{\pm} \to \mu^{\pm}\nu_{\mu}) = (-5.7 \pm 7.1(\text{stat}) \pm 6.8(\text{syst})) \times 10^{-7}$. Figure 5 shows the data points with the final fit superimposed.

Given the number of fitted signal events, the signal efficiency and including all systematic uncertainties, we find the Bayesian UL assuming a flat prior for the branching fraction up to a maximum of $\mathcal{B}(B^{\pm} \to \mu^{\pm}\nu_{\mu}) = 3 \times 10^{-6}$ to be

$$\mathcal{B}(B^{+} \to \mu^{+}\nu_{\mu}) < 1.3 \times 10^{-6}$$

at the 90% confidence level. The 95% Bayesian UL is $\mathcal{B}(B^{+} \to \mu^{+}\nu_{\mu}) < 1.6 \times 10^{-6}$. These results are more restrictive than previous measurements from *BABAR* [8] and Belle [9].

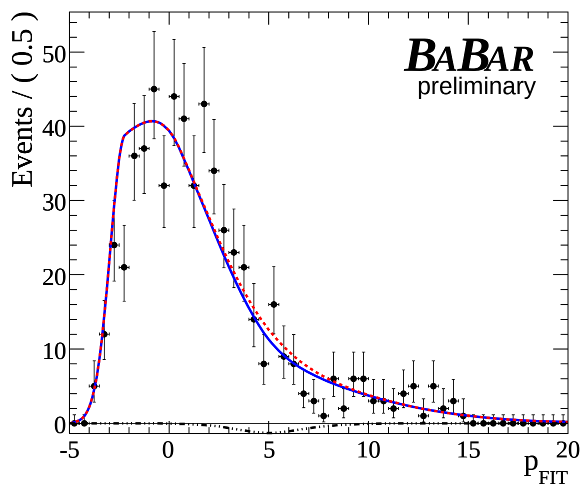

Figure 5: Final fit to the data p_{FIT} distribution: full blue line is the total distribution, dashed red line is background distribution, dashed-dotted black line is signal distribution.

6 ACKNOWLEDGMENTS

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), the Commissariat à l'Energie 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 Education and Science of the Russian Federation, Ministerio de Educación y Ciencia (Spain), and the Science and Technology Facilities 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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