Search for the rare leptonic decays $B^+ \rightarrow l^+ \nu l$ ($l=e,\mu$)

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

| Citation       | BABAR Collaboration et al. "Search for the rare leptonic decays $B^+ \rightarrow l^+ \nu l$ ($l=e,\mu$)." Physical Review D 79.9 (2009): 091101. © 2009 American Physical Society. |
|----------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| As Published   | http://dx.doi.org/10.1103/PhysRevD.79.091101                                                                                                                                                        |
| Publisher      | American Physical Society                                                                                                                                                                          |
| Version        | Final published version                                                                                                                                                                             |
| Citable link   | http://hdl.handle.net/1721.1/55363                                                                                                                                                                 |
| Terms of Use   | Article is made available in accordance with the publisher’s policy and may be subject to US copyright law. Please refer to the publisher’s site for terms of use.                                        |
Search for the rare leptonic decays $B^+ \to l^+ \nu_l$ ($l = e, \mu$)
M. R. Convery, J. C. Dingfelder, J. Dorfan, G. P. Dubois-Felsmann, W. Dunwoodie, R. C. Field, A. M. Gabareen, 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, D. B. MacFarlane, H. Marsiske, R. Messner, D. R. Muller, H. Neal, S. Nelson, C. P. O’Grady, I. Ofte, M. Perl, B. N. Ratcliff, 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, C. A. West, W. J. Wisniewski, M. Wittgen, D. H. Wright, H. W. Wulsin, A. K. Yarritt, K. Yi, C. C. Young, V. Ziegler, X. R. Chen, H. Liu, W. Park, M. V. Purohit, R. M. White, P. R. Burchat, A. J. Edwards, T. S. Miyashita, S. Ahmed, M. S. Alam, J. A. Ernst, B. Pan, M. A. Saeed, S. B. Zain, S. M. Spanier, B. J. Wogsland, R. Eckmann, J. L. Ritchie, M. Ruland, C. J. Schilling, R. F. Schwitters, B. C. Wray, B. W. Drummond, J. M. Izen, X. C. Lou, F. Bianchi, D. Gamba, M. Pelliccioni, L. Bosio, C. Cartaro, G. Della Ricca, L. Lanceri, L. Vitale, V. Azzolini, N. Lopez-March, F. Martinez-Vidal, D. A. Milanes, O. Oyanguren, J. Albert, Sw. Banerjee, B. Bhuyan, H. H. F. Choi, K. Hamano, G. J. King, R. Kowalewski, M. J. Lewczuk, I. M. Nugent, J. M. Roney, R. J. Sobie, T. J. Gershon, P. F. Harrison, T. E. Latham, G. B. Mohanty, E. M. T. Puccio, H. R. Band, X. Chen, S. Dasu, K. T. Flood, Y. Pan, R. Prepost, C. O. Vuosalo, S. L. Wu

(BABAR Collaboration)

1Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France
2Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain
3aINFN Sezione di Bari, I-70126 Bari, Italy; 3bDipartimento di Fisica, Università di Bari, I-70126 Bari, Italy
4University of Bergen, Institute of Physics, N-5007 Bergen, Norway
5Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
6University of Birmingham, Birmingham, B15 2TT, United Kingdom
7Ruhr Universitaet Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany
8University of British Columbia, Vancouver; British Columbia, Canada V6T 1Z1
9Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom
10Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
11University of California at Irvine, Irvine, California 92697, USA
12University of California at Los Angeles, Los Angeles, California 90024, USA
13University of California at Riverside, Riverside, California 92521, USA
14University of California at San Diego, La Jolla, California 92093, USA
15University of California at Santa Barbara, Santa Barbara, California 93106, USA
16University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA
17California Institute of Technology, Pasadena, California 91125, USA
18University of Cincinnati, Cincinnati, Ohio 45221, USA
19University of Colorado, Boulder, Colorado 80309, USA
20Colorado State University, Fort Collins, Colorado 80523, USA
21Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany
22Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
23Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France
24University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
25aINFN Sezione di Ferrara, I-44100 Ferrara, Italy; 25bDipartimento di Fisica, Università di Ferrara, I-44100 Ferrara, Italy
26INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
27aINFN Sezione di Genova, I-16146 Genova, Italy; 27bDipartimento di Fisica, Università di Genova, I-16146 Genova, Italy
28Harvard University, Cambridge, Massachusetts 02138, USA
29Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
30Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, Germany
31Imperial College London, London, SW7 2AZ, United Kingdom
32University of Iowa, Iowa City, Iowa 52242, USA
33Iowa State University, Ames, Iowa 50011-3160, USA
34Johns Hopkins University, Baltimore, Maryland 21218, USA

091101-2
SEARCH FOR THE RARE LEPTONIC DECAYS . . .

PHYSICAL REVIEW D 79, 091101(R) (2009)

35Laboratoire de l’Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d’Orsay, B.P. 34, F-91898 Orsay Cedex, France
36Lawrence Livermore National Laboratory, Livermore, California 94550, USA
37University of Liverpool, Liverpool L69 7ZE, United Kingdom
38Queen Mary, University of London, London, E1 4NS, United Kingdom
39University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
40University of Louisville, Louisville, Kentucky 40292, USA
41Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany
42University of Manchester, Manchester M13 9PL, United Kingdom
43University of Maryland, College Park, Maryland 20742, USA
44University of Massachusetts, Amherst, Massachusetts 01003, USA
45Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
46McGill University, Montréal, Québec, Canada H3A 2T8
47aINFN Sezione di Milano, I-20133 Milano, Italy;
47bDipartimento di Fisica, Università di Milano, I-20133 Milano, Italy
48University of Mississippi, University, Mississippi 38677, USA
49Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7
50Mount Holyoke College, South Hadley, Massachusetts 01075, USA
51aINFN Sezione di Napoli, I-80126 Napoli, Italy;
51bDipartimento di Scienze Fisiche, Università di Napoli Federico II, I-80126 Napoli, Italy
52NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
53University of Notre Dame, Notre Dame, Indiana 46556, USA
54Ohio State University, Columbus, Ohio 43210, USA
55University of Oregon, Eugene, Oregon 97403, USA
56aINFN Sezione di Padova, I-35131 Padova, Italy;
56bDipartimento di Fisica, Università di Padova, I-35131 Padova, Italy
57Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France
58University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
59aINFN Sezione di Perugia, I-06100 Perugia, Italy;
59bDipartimento di Fisica, Università di Perugia, I-06100 Perugia, Italy
60aINFN Sezione di Pisa, I-56127 Pisa, Italy;
60bDipartimento di Fisica, Università di Pisa, I-56127 Pisa, Italy;
61Princeton University, Princeton, New Jersey 08544, USA
62aINFN Sezione di Roma, I-00185 Roma, Italy;
62bDipartimento di Fisica, Università di Roma La Sapienza, I-00185 Roma, Italy
63Universität Rostock, D-18051 Rostock, Germany
64Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
65CEA, Ifri, SPP, Centre de Saclay, F-91191 Gif-sur-Yvette, France
66SLAC National Accelerator Laboratory, Stanford, California 94309 USA
67University of South Carolina, Columbia, South Carolina 29208, USA
68Stanford University, Stanford, California 94305-4060, USA
69State University of New York, Albany, New York 12222, USA
70University of Tennessee, Knoxville, Tennessee 37996, USA
71University of Texas at Austin, Austin, Texas 78712, USA
72University of Texas at Dallas, Richardson, Texas 75083, USA
73aINFN Sezione di Torino, I-10125 Torino, Italy;
73bDipartimento di Fisica Sperimentale, Università di Torino, I-10125 Torino, Italy
74aINFN Sezione di Trieste, I-34127 Trieste, Italy;
74bDipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy

*Deceased.
†Now at Tel Aviv University, Tel Aviv, 69978, Israel.
‡Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy.
§Also with Università di Roma La Sapienza, I-00185 Roma, Italy.
‖Also at Tel Aviv University, Tel Aviv, 69978, Israel.
‖Also with University of South Alabama, Mobile, AL 36688, USA.
**Also with Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6.
††Also with Università di Sassari, Sassari, Italy.

091101-3
We have performed a search for the rare leptonic decays $B^+ \rightarrow \ell^+ \nu_\ell (\ell = e, \mu)$, using data collected at the Y(4S) resonance by the BABAR detector at the PEP-II storage ring. In a sample of $468 \times 10^6 \bar{B}B$ pairs we find no evidence for a signal and set an upper limit on the branching fractions $\mathcal{B}(B^+ \rightarrow \mu^+ \nu_\mu) < 1.0 \times 10^{-6}$ and $\mathcal{B}(B^+ \rightarrow e^+ \nu_e) < 1.9 \times 10^{-6}$ at the 90% confidence level, using a Bayesian approach.

In the standard model (SM), the purely leptonic $B$ meson decays $B^+ \rightarrow \ell^+ \nu_\ell$ [1] proceed at lowest order through the annihilation diagram shown in Fig. 1. The SM branching fraction can be calculated as

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

where $G_F$ is the Fermi coupling constant, $m_\ell$ and $m_B$ are, respectively, the lepton and $B$ meson masses, and $\tau_B$ is the $B^+$ lifetime. The decay rate is sensitive to the Cabibbo-Kobayashi-Maskawa matrix element $|V_{ub}|$ [3] and the $B$ decay constant $f_B$ that describes the overlap of the quark wave functions within the meson.

The SM estimate of the branching fraction for $B^+ \rightarrow \tau^+ \nu_\tau$ is $(1.59 \pm 0.40) \times 10^{-4}$ assuming $\tau_B = 1.638 \pm 0.011$ ps [4], $V_{ub} = (4.39 \pm 0.33) \times 10^{-3}$ determined from inclusive charmless semileptonic $B$ decays [5], and $f_B = 216 \pm 22$ MeV from lattice QCD calculation [6]. To a very good approximation, helicity is conserved in $B^+ \rightarrow \mu^+ \nu_\mu$ and $B^+ \rightarrow e^+ \nu_e$ decays, which are therefore suppressed by factors $m_{\mu,e}^2/m_B^2$ with respect to $B^+ \rightarrow \tau^+ \nu_\tau$, leading to expected branching fractions of $\mathcal{B}(B^+ \rightarrow \mu^+ \nu_\mu) = (5.6 \pm 0.4) \times 10^{-7}$ and $\mathcal{B}(B^+ \rightarrow e^+ \nu_e) = (1.3 \pm 0.4) \times 10^{-11}$. However, reconstruction of $B^+ \rightarrow \tau^+ \nu_\tau$ decays is experimentally more challenging than $B^+ \rightarrow \mu^+ \nu_\mu$ or $B^+ \rightarrow e^+ \nu_e$ due to the large missing momentum from multiple neutrinos in the final state.

Purely leptonic $B$ decays are sensitive to physics beyond the SM, where additional heavy virtual particles contribute to the annihilation processes. Charged Higgs boson effects may greatly enhance or suppress the branching fraction in some two-Higgs-doublet models [7]. Similarly, there may be enhancements through mediation by leptoquarks in the Pati-Salam model of quark-lepton unification [8]. Direct tests of Yukawa interactions in and beyond the SM are possible in the study of these decays, as annihilation processes proceed through the longitudinal component of the intermediate vector boson. In particular, in a supersymmetry scenario at large $\tan\beta$, nonstandard effects in helicity-suppressed charged current interactions are potentially observable, being strongly $\tan\beta$-dependent and leading to

$$\frac{\mathcal{B}(B^+ \rightarrow l^+ \nu_l)_{\text{exp}}}{\mathcal{B}(B^+ \rightarrow l^+ \nu_l)_{\text{SM}}} = \left(1 - \tan^2\beta \frac{m_\ell^2}{M_H^2}\right)^2.$$

Evidence for the first purely leptonic $B$ decays has recently been presented by both the BABAR and Belle Collaborations. The latest HFAG world average of the BABAR [9] and Belle [10] results is $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau) = (1.51 \pm 0.33) \times 10^{-4}$ [11]. The current best published upper limits on $B^+ \rightarrow \mu^+ \nu_\mu$ and $B^+ \rightarrow e^+ \nu_e$ are $\mathcal{B}(B^+ \rightarrow \mu^+ \nu_\mu) < 1.7 \times 10^{-6}$ and $\mathcal{B}(B^+ \rightarrow e^+ \nu_e) < 9.8 \times 10^{-7}$ at 90% confidence level from Belle using a data sample of 235 fb$^{-1}$ [12].

The analysis described herein is based on the entire data set collected with the BABAR detector [13] at the PEP-II storage ring at the $Y(4S)$ resonance (“on resonance”), which consists of $468 \times 10^6 \bar{B}B$ pairs, corresponding to an integrated luminosity of 426 fb$^{-1}$. In order to study background from continuum events such as $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) and $e^+e^- \rightarrow \tau^+\tau^-$, an additional sample of about 41 fb$^{-1}$ was collected at a center-of-mass (c.m.) energy about 40 MeV below the $Y(4S)$ resonance (“off resonance”).

In the BABAR detector, charged particle trajectories are measured with a 5-layer double-sided silicon vertex tracker and a 40-layer drift chamber, which are contained in the 1.5 T magnetic field of a superconducting solenoid. A detector of internally reflected Cherenkov radiation provides identification of charged kaons and pions. The energies and trajectories of neutral particles are measured by an electromagnetic calorimeter consisting of 6580 CsI(Tl) crystals. The flux return of the solenoid is instrumented with resistive plate chambers and, more recently, limited

---

**FIG. 1.** Lowest order SM Feynman diagram for the purely leptonic decay $B^+ \rightarrow l^+ \nu_l$. 

B. AUBERT et al.

75 IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
76 University of Victoria, Victoria, British Columbia, Canada V8W 3P6
77 Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
78 University of Wisconsin, Madison, Wisconsin 53706, USA

(Received 8 April 2009; published 28 May 2009)
streamer tubes [14], in order to provide muon identification. A GEANT4-based [15] Monte Carlo (MC) simulation of generic $\bar{B}B$, $q\bar{q}$, $d$, $s$, $c$, and $\tau^+\tau^-$ events as well as $B^+ \to \mu^+\nu_\mu$ and $B^+ \to e^+\nu_e$ signal events is used to model the detector response and test the analysis technique.

The $B^+ \to \ell^+\nu_\ell$ decay produces a monoenergetic charged lepton in the $B$ rest frame with a momentum $p^* = m_B/2$. The $B$ mesons produced in $Y(4S)$ decays have a c.m. momentum of about 320 MeV/$c$, so we initially select lepton candidates with c.m. momentum $2.4 < p_{c.m.} < 3.2$ GeV/$c$, to take into account the smearing due to the motion of the $B$. A tight particle identification requirement is applied to the candidate lepton in order to discard fake muons or electrons.

Since the neutrino produced in the signal decay is not detected, all charged tracks besides the signal lepton and all neutral energy deposits in the calorimeter are combined to reconstruct the companion (tag) $B$. 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, pions, kaons, and protons in order to assign the most likely mass hypothesis to each $B_{tag}$ daughter and thus improve the reconstruction of the $B_{tag}$ events which have additional lepton candidates are discarded. These typically arise from semileptonic $B_{tag}$ or charm decays and indicate the presence of additional neutrinos, for which the inclusive $B_{tag}$ reconstruction is not expected to work well.

The signal lepton’s momentum in the signal $B$ rest frame $p^*$ is refined using the $B_{tag}$ momentum direction. We assume that the signal $B$ has a c.m. momentum of 320 MeV/$c$ and choose its direction as opposite that of the reconstructed $B_{tag}$ to boost the lepton candidate into the signal $B$ rest frame.

Signal events are selected using the kinematic variables $\Delta E = E_B - E_{beam}$, where $E_B$ is the energy of the $B_{tag}$ and $E_{beam}$ is the beam energy, all in the c.m. frame. Since for signal events in which all decay products of the $B_{tag}$ are reconstructed, we expect the $\Delta E$ distribution to peak near zero. However, we are often unable to reconstruct all $B_{tag}$ decay products, which biases the $\Delta E$ distribution toward negative values. For continuum backgrounds, $\Delta E$ is shifted toward relatively large positive values since too much energy is attributed to the nominal $B_{tag}$ decay, while there is a negative bias in $\tau^+\tau^-$ events due to the unreconstructed neutrinos.

We require the tag $B$ to satisfy $-2.25 < \Delta E < 0$ GeV for $B^+ \to \mu^+\nu_\mu$ decays. For $B^+ \to e^+\nu_e$ decays, we require a linear combination of $\Delta E$ and the tag $B$ transverse momentum $p_T$ to satisfy $(p_T + 0.529 \cdot \Delta E) < 0.2$ and $(p_T - 0.529 \cdot \Delta E) < 1.5$. This selection rejects background events arising from two-photon process $e^+e^- \to e^+e^-\gamma^+\gamma^-$, $\gamma^+\gamma^- \to$ hadrons, with one of the final electrons scattered at a large angle and detected. The coefficient of the $\Delta E$ term is extracted from the data.

Backgrounds may arise from any process producing charged tracks in the momentum range of the signal, particularly if the charged tracks are leptons. The two most significant backgrounds are $B$ semileptonic decays involving $b \to u\ell\nu_\ell$ transitions in which the momentum of the leptons at the end point of the spectrum approaches that of the signal and from continuum and $\tau^+\tau^-$ events in which a charged pion is mistakenly identified as a muon or an electron.

Continuum events tend to produce a jetlike event topology, while $B\bar{B}$ events tend to be more isotropically distributed in the c.m. frame and are suppressed using event shape parameters. Five different spatial and kinematical variables, considered separately for $B^+ \to \mu^+\nu_\mu$ and $B^+ \to e^+\nu_e$, are combined in Fisher discriminants [16]. The most effective discriminating parameters are the ratio of the second $L_2$ and the zeroth $L_0$ monomial $L_0 = \Sigma (\tilde{p}_j \cos (\alpha))^n$, where the sum runs over all $B_{tag}$ daughters having momenta $\tilde{p}_j$ and $\alpha$ is the angle with respect to the lepton candidate momentum, both in the c.m. frame, and the sphericity $S = \frac{1}{2} \min \Sigma (\tilde{p}_j \rho)^2$, where the $T$ subscript denotes the momentum component transverse to the sphericity axis, which is the axis that minimizes $S$. $S$, in fact, tends to be closer to 1 for spherical events and 0 for jetlike events. In order to take into account the changes in detector performance throughout the years, in particular, in muon identification, the data sample is divided into six different data taking periods, and the Fisher discriminants and selection criteria are optimized separately with the algorithm described in Ref. [17] for each period.

The two-body kinematics of the signal decay is exploited by combining the signal lepton momentum in the $B$ rest frame $p^*$ and $p_{c.m.}$ in a second Fisher discriminant ($p_{FIT}$) which discriminates against the remaining semileptonic $bb$ and continuum background events which populate the end of the lepton spectrum in both frames. The $p^*$ and $p_{c.m.}$ coefficients in the linear combination are determined separately for $B^+ \to \mu^+\nu_\mu$ and $B^+ \to e^+\nu_e$ with Ref. [17].

We employ an extended maximum likelihood (ML) fit to extract signal and background yields using simultaneously the distributions of the Fisher output $p_{FIT}$ and the energy-substituted mass $m_{ES}$, defined as $\sqrt{E_{beam}^2 - |\mathbf{p}_B|^2}$, where $\mathbf{p}_B$ is the momentum of the reconstructed $B_{tag}$ candidate in the c.m. frame.

Signal $m_{ES}$ and $p_{FIT}$ probability density functions (PDFs) are fixed in the final fit and are parameterized from simulated events, respectively, with a Crystal Ball function [18] and the sum of two Gaussians (double Gaussian) for both $B^+ \to \mu^+\nu_\mu$ and $B^+ \to e^+\nu_e$.

The background $m_{ES}$ distribution is described by an ARGUS function whose slope is determined in the fit to
the yields [19]. To parameterize the background \( \rho_{\text{FIT}} \) distributions, we studied the possibility of using the \( m_{\text{ES}} \) sideband of on-resonance data. We found the \( B^+ \rightarrow \mu^+ \nu_\mu \) sideband suited for this purpose, while the \( B^+ \rightarrow e^+ \nu_e \) sideband is not sufficiently populated. We use the region \( 5.17 < m_{\text{ES}} < 5.2 \text{ GeV}/c^2 \) to parameterize the \( B^+ \rightarrow \mu^+ \nu_\mu \) background \( \rho_{\text{FIT}} \) distribution and simulated events for the background \( B^+ \rightarrow e^+ \nu_e \rho_{\text{FIT}} \) distribution.

Separately for \( B^+ \rightarrow \mu^+ \nu_\mu \) and \( B^+ \rightarrow e^+ \nu_e \), the sum of two Gaussians with different sigmas on the right and the left of the mean (bifurcated Gaussians) is used to parameterize the background \( \rho_{\text{FIT}} \) distribution, and the relative fraction of the two bifurcated Gaussians is determined from the fit to the data. Figures 2 and 3 show background and signal \( m_{\text{ES}} \) and \( \rho_{\text{FIT}} \) distributions for \( B^+ \rightarrow \mu^+ \nu_\mu \) and \( B^+ \rightarrow e^+ \nu_e \), respectively, with the PDFs described above superimposed.

In the on-resonance data, the ML fit returns \( 1 \pm 15 \) signal \( B^+ \rightarrow \mu^+ \nu_\mu \) candidate events and \( 18 \pm 14 \) signal \( B^+ \rightarrow e^+ \nu_e \) candidate events. Distributions of the fit data events with the final fit superimposed, as well as the signal and background PDFs, are shown in Fig. 4 for \( B^+ \rightarrow \mu^+ \nu_\mu \) and \( B^+ \rightarrow e^+ \nu_e \), respectively, projected on \( m_{\text{ES}} \) and \( \rho_{\text{FIT}} \).

We next evaluate systematic uncertainties on the number of \( B^\pm \) in the sample, the signal efficiency, and the signal yield. The number of \( B^\pm \) mesons in the on-resonance data sample is estimated to be \( 468 \times 10^6 \) with an uncertainty of 1.1% [20], assuming equal \( B^+ \) and \( B^0 \) production at the \( Y(4S) \) [21].

The uncertainty in the signal efficiency includes the lepton candidate selection (particle identification, tracking efficiency, and event selection Fisher requirement) as well as the reconstruction efficiency of the tag \( B \). The systematic uncertainty on the particle identification efficiency is evaluated using \( e^+ e^- \rightarrow \mu^+ \mu^- \gamma \), \( e^+ e^- \rightarrow e^+ e^- \mu^+ \mu^- \), and Bhabha event control samples derived from the data, which are weighted to reproduce the kinematic distribution of the lepton signal candidate. By comparing the cumulative signal efficiency obtained with and without these weights, a total discrepancy of 1.9% for \( B^+ \rightarrow \mu^+ \nu_\mu \) and 2.3% for \( B^+ \rightarrow e^+ \nu_e \) is found, and this value is taken as the particle identification systematic uncertainty. Tracking efficiency is studied employing \( \tau \) decays, which must produce an odd number of final state charged tracks because of charge conservation. Thus, one can determine an absolute efficiency because the number of events with a missing track can be measured. The uncertainty associated with the tracking efficiency and the data/MC discrepancy evaluated with this method are taken in quadrature for a 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 compare data and MC Fisher distributions in the sidebands \( \Delta E > 0 \) for the \( B^+ \rightarrow \mu^+ \nu_\mu \) sample and \( (p_T + 0.529 \cdot \Delta E) > 0.2 \) for the \( B^+ \rightarrow e^+ \nu_e \) sample. We fit the data/
FIG. 3 (color online). Distributions of signal (a),(b) and background (c),(d) $m_{ES}$ (left) and $p_{FIT}$ (right) for $B^+ \rightarrow e^+ \nu_e$ from MC simulation.

FIG. 4 (color online). Final fit to the data projected on $m_{ES}$ (left) and $p_{FIT}$ (right) distributions for $B^+ \rightarrow \mu^+ \nu_\mu$ events (a),(b) and $B^+ \rightarrow e^+ \nu_e$ events (c),(d): The solid blue line is the total PDF, the dashed red line is the background PDF, and the dashed-dotted black line is the signal PDF.
MC ratio with a linear function, with results consistent with a unitary ratio in the whole Fisher range. We take the error on the intercept as the systematic uncertainty on the Fisher discriminants, that is, 1.4% for $B^+ \rightarrow \mu^+ \nu_\mu$ and 5.3% for $B^+ \rightarrow e^+ \nu_e$.

The tag $B$ reconstruction has been studied with a control sample of $B^+ \rightarrow D^{(*)0} \pi^+$ events, where the $D$ is reconstructed into $\bar{D}^0 \rightarrow K^+ \pi^-$ and $D^0 \rightarrow K^- \pi^+$ and the $D^*$ into $D^{*0} \rightarrow D^{0} \gamma$ or $D^{*0} \rightarrow D^{0} \pi^0$. These two-body decays are topologically very similar to our signal, as the charged pion can be treated as the signal lepton and the $D^{(*)0}$ decays products ignored to simulate the missing neutrino. The tag $B$ reconstructed in the control sample thus simulates the tag $B$ reconstruction in the nominal data sample. We compare the efficiencies for our tag $B$ selection cuts in the $B^+ \rightarrow D^{(*)0} \pi^+$ data and MC to quantify any data/MC disagreements that may affect the signal efficiency. We find a data/MC discrepancy on the $B^+ \rightarrow D^{(*)0} \pi^+$ control sample of 3.0% for $B^+ \rightarrow \mu^+ \nu_\mu$ decays and 0.4% for $B^+ \rightarrow e^+ \nu_e$ decays and assign these 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 I. The final $B^+ \rightarrow \mu^+ \nu_\mu$ signal efficiency is $(6.1 \pm 0.2)%$, and the $B^+ \rightarrow e^+ \nu_e$ signal efficiency is $(4.7 \pm 0.3)%$, where the errors are the sum in quadrature of statistical and systematic uncertainties. The systematic uncertainty in the yields comes from the $p_{\text{FIT}}$ and $m_{\text{ES}}$ PDF parameters, which are kept fixed in the final fit and, in the $B^+ \rightarrow e^+ \nu_e$ case, from the use of MC simulation to extract the PDF shapes. The fit parameters extracted from MC are affected by an uncertainty due to MC statistics. In order to evaluate the systematic uncertainty associated with the parameterization, the final fit has been repeated 500 times for each background and signal PDF parameter which is kept fixed in the final fit. We randomly generate the PDF parameters assuming Gaussian errors and taking into account all of 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 on the signal yield from all signal and background PDF parameters is 8 events for $B^+ \rightarrow \mu^+ \nu_\mu$ and 10 events for $B^+ \rightarrow e^+ \nu_e$.

| Source                  | $B^+ \rightarrow \mu^+ \nu_\mu$ | $B^+ \rightarrow e^+ \nu_e$ |
|-------------------------|---------------------------------|-------------------------------|
| Particle identification | 1.9%                            | 2.3%                          |
| Tracking efficiency     | 0.4%                            | 0.4%                          |
| Tag $B$ reconstruction  | 3.0%                            | 0.4%                          |
| Fisher selection        | 1.4%                            | 5.3%                          |
| Total                   | 3.8%                            | 5.8%                          |

 TABLE I. Contributions to the systematic uncertainty on the signal efficiency. Total systematic represents the sum in quadrature of the table entries.

For the $B^+ \rightarrow e^+ \nu_e$ sample, an additional systematic uncertainty coming from possible discrepancies in the shape of the $p_{\text{FIT}}$ background distribution in data and simulated events must be accounted for. The data/MC ratio of the $p_{\text{FIT}}$ distribution in the $m_{\text{ES}}$ sideband $5.16 < m_{\text{ES}} < 5.22$ GeV/$c^2$ is fit with a linear function. The background $p_{\text{FIT}}$ distribution shape is varied according to the fitted linear function and its associated statistical uncertainties; the total systematic contribution from this procedure is 4 events.

To evaluate the branching fraction, we use the following expression:

$$B(B \rightarrow l^+ \nu_{l})_{UL} = \frac{N_{\text{sig}}}{N_{B^+} \times e}, \quad (3)$$

where $N_{\text{sig}}$ represents the observed signal yield, $N_{B^+}$ is the number of $B^+ B^-$ in the sample (where equal production of $B^+ B^-$ and $B^0 \bar{B}^0$ is assumed), and $e$ is the signal efficiency.

As we did not find evidence for signal events, we employ a Bayesian approach to set upper limits on the branching fractions. Flat priors in the branching fractions are assumed for positive values of the branching fractions, and Gaussian likelihoods are adopted for the observed signal yield, related to $B$ by Eq. (3). The Gaussian widths are fixed to the sum in quadrature of the statistical and systematic yield errors. The effect of systematic uncertainties associated with the efficiencies, modeled by Gaussian PDFs, is taken into account as well. We extract the following 90% confidence level upper limits on the branching fractions:

$$B(B \rightarrow \mu^+ \nu_\mu) < 1.0 \times 10^{-6}, \quad (4)$$

$$B(B \rightarrow e^+ \nu_e) < 1.9 \times 10^{-6}. \quad (5)$$

The 95% upper limits are $B(B \rightarrow \mu^+ \nu_\mu) < 1.3 \times 10^{-6}$ and $B(B \rightarrow e^+ \nu_e) < 2.2 \times 10^{-6}$. This result improves the previous best published limit for $B^+ \rightarrow \mu^+ \nu_\mu$ branching fraction by nearly a factor of 2, to a value twice the SM prediction. The $B^+ \rightarrow e^+ \nu_e$ result is consistent with previous measurements. It should be noted that the results in Ref. [12] are obtained using a different statistical approach to interpret the observed number of signal events. The results show no deviation from the SM expectations.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MES (Russia), MEC (Spain), and STFC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A.P. Sloan Foundation.
[1] Charge conjugation is implied throughout this paper.
[2] D. Silverman and H. Yao, Phys. Rev. D 38, 214 (1988).
[3] N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).
[4] C. Amsler et al., Phys. Lett. B 667, 1 (2008).
[5] E. Barberio et al. [Heavy Flavor Averaging Group (HFAG)], arXiv:hep-ex/0603003.
[6] A. Gray et al. (HPQCD Collaboration), Phys. Rev. Lett. 95, 212001 (2005).
[7] W. S. Hou, Phys. Rev. D 48, 2342 (1993).
[8] G. Valencia and S. Willenbrock, Phys. Rev. D 50, 6843 (1994).
[9] B. Aubert et al. (BABAR Collaboration), Phys. Rev. D 77, 011107 (2008).
[10] I. Adachi et al. (Belle Collaboration), arXiv:0809.3834.
[11] Heavy Flavor Averaging Group (HFAG), http://www.slac.stanford.edu/xorg/hfag/index.html.
[12] N. Satoyama et al. (Belle Collaboration), Phys. Lett. B 647, 67 (2007).
[13] B. Aubert et al. (BABAR Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 479, 1 (2002).
[14] G. Benelli, K. Honscheid, E. A. Lewis, J. J. Regensburger, and D. S. Smith, IEEE Nucl. Sci. Symp. Conf. Rec. 2, 1145 (2006).
[15] S. Agostinelli et al. (GEANT4 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 506, 250 (2003).
[16] R. A. Fisher, Ann. Eugenics 7, 179 (1936); G. Cowan, Statistical Data Analysis (Oxford University Press, New York, 1998), p. 51.
[17] I. Narsky, arXiv:physics/0507143.
[18] J. Gaiser et al., Phys. Rev. D 34, 711 (1986).
[19] H. Albrecht et al. (ARGUS Collaboration) Phys. Lett. B 241, 278 (1990).
[20] B. Aubert et al. (BABAR Collaboration), Phys. Rev. D 67, 032002 (2003).
[21] B. Aubert et al. (BABAR Collaboration), Phys. Rev. Lett. 95, 042001 (2005).