## Title
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# Search for the rare leptonic decays $B^+ \to l^+ \nu_l$ ($l = e, \mu$)

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

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In the standard model (SM), the purely leptonic $B$ meson decays $B^+ \to \ell^+ \nu_\ell$ [1] proceed at lowest order through the annihilation diagram shown in Fig. 1. The SM branching fraction can be calculated as [2]

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

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 $B^+ \to \tau^+ \nu_\tau$ 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 $B^+ \to \mu^+ \nu_\mu$ and $B^+ \to e^+ \nu_e$ decays, which are therefore suppressed by factors $m_{\mu,e}^2/m_\tau^2$ with respect to $B^+ \to \tau^+ \nu_\tau$, leading to expected branching fractions of $\mathcal{B}(B^+ \to \mu^+ \nu_\mu) = (5.6 \pm 0.4) \times 10^{-7}$ and $\mathcal{B}(B^+ \to e^+ \nu_e) = (1.3 \pm 0.4) \times 10^{-11}$. However, reconstruction of $B^+ \to \tau^+ \nu_\tau$ decays is experimentally more challenging than $B^+ \to \mu^+ \nu_\mu$ or $B^+ \to e^+ \nu_e$ 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 [7]

$$\frac{\mathcal{B}(B^+ \to l^+ \nu_l)_{\text{exp}}}{\mathcal{B}(B^+ \to l^+ \nu_l)_{\text{SM}}} \approx \left(1 - \tan^2\beta \frac{m_B^2}{M_H^2}\right)^2. \quad (2)$$

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 $\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (1.51 \pm 0.33) \times 10^{-4}$ [11]. The current best published upper limits on $B^+ \to \mu^+ \nu_\mu$ and $B^+ \to e^+ \nu_e$ are $\mathcal{B}(B^+ \to \mu^+ \nu_\mu) < 1.7 \times 10^{-6}$ and $\mathcal{B}(B^+ \to e^+ \nu_e) < 9.8 \times 10^{-7}$ 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 $\Upsilon(4S)$ resonance (“on resonance”), which consists of $468 \times 10^6$ $B\bar{B}$ pairs, corresponding to an integrated luminosity of 426 fb$^{-1}$. In order to study background from continuum events such as $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$ and $e^+e^- \to \tau^+\tau^-$, an additional sample of about 41 fb$^{-1}$ was collected at a center-of-mass (c.m.) energy about 40 MeV below the $\Upsilon(4S)$ 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

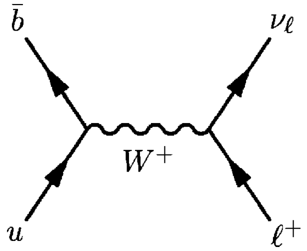


FIG. 1. Lowest order SM Feynman diagram for the purely leptonic decay $B^+ \to l^+ \nu_l$.

streamer tubes [14], in order to provide muon identification. A GEANT4-based [15] Monte Carlo (MC) simulation of generic $B\bar{B}$, $q\bar{q}$, $d$, $s$, $c$, 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 $p^* \approx m_B/2$. The $B$ mesons produced in $\Upsilon(4S)$ decays have a c.m. momentum of about 320 MeV/$c$, so we initially select lepton candidates with c.m. momentum $2.4 < p_{\mathrm{c.m.}} < 3.2$ 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 $B_{\mathrm{tag}}$ daughter and thus improve the reconstruction of the $B_{\mathrm{tag}}$. Events which have additional lepton candidates are discarded. These typically arise from semileptonic $B_{\mathrm{tag}}$ or charm decays and indicate the presence of additional neutrinos, for which the inclusive $B_{\mathrm{tag}}$ reconstruction is not expected to work well.

The signal lepton's momentum in the signal $B$ rest frame $p^*$ is refined using the $B_{\mathrm{tag}}$ 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 $B_{\mathrm{tag}}$ to boost the lepton candidate into the signal $B$ rest frame.

Signal events are selected using the kinematic variables $\Delta E = E_B - E_{\mathrm{beam}}$, where $E_B$ is the energy of the $B_{\mathrm{tag}}$ and $E_{\mathrm{beam}}$ is the beam energy, all in the c.m. frame. For signal events in which all decay products of the $B_{\mathrm{tag}}$ are reconstructed, we expect the $\Delta E$ distribution to peak near zero. However, we are often unable to reconstruct all $B_{\mathrm{tag}}$ 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 $B_{\mathrm{tag}}$ 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 $b \to ul\nu_l$ 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 $L_n = \Sigma_i|\vec{p}_i|\cos(\alpha)^n$, where the sum runs over all $B_{\mathrm{tag}}$ daughters having momenta $\vec{p}_i$ and $\alpha$ is the angle with respect to the lepton candidate momentum, both in the c.m. frame, and the sphericity $S = \frac{3}{2}\min\frac{\Sigma_j(p_{jT})^2}{\Sigma_j(p_j)^2}$, 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 $p_{\mathrm{c.m.}}$ in a second Fisher discriminant ($p_{\mathrm{FIT}}$) which discriminates against the remaining semileptonic $b\bar{b}$ and continuum background events which populate the end of the lepton spectrum in both frames. The $p^*$ and $p_{\mathrm{c.m.}}$ 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 $p_{\mathrm{FIT}}$ and the energy-substituted mass $m_{\mathrm{ES}}$, defined as $\sqrt{E_{\mathrm{beam}}^2 - |\vec{p}_B|^2}$, where $\vec{p}_B$ is the momentum of the reconstructed $B_{\mathrm{tag}}$ candidate in the c.m. frame.

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

Separately for $B^+ \to \mu^+\nu_\mu$ and $B^+ \to e^+\nu_e$, 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 $p_{\mathrm{FIT}}$ 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 $m_{\mathrm{ES}}$ and $p_{\mathrm{FIT}}$ distributions for $B^+ \to \mu^+\nu_\mu$ and $B^+ \to e^+\nu_e$, respectively, with the PDFs described above superimposed.

In the on-resonance data, the ML fit returns $1 \pm 15$ signal $B^+ \to \mu^+\nu_\mu$ candidate events and $18 \pm 14$ signal $B^+ \to e^+\nu_e$ 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 $B^+ \to \mu^+\nu_\mu$ and $B^+ \to e^+\nu_e$, respectively, projected on $m_{\mathrm{ES}}$ and $p_{\mathrm{FIT}}$.

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 $\Upsilon(4S)$ [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 $e^+e^- \to \mu^+\mu^-\gamma$, $e^+e^- \to e^+e^-\mu^+\mu^-$, 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 $B^+ \to \mu^+\nu_\mu$ and 2.3% for $B^+ \to e^+\nu_e$ 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 $B^+ \to \mu^+\nu_\mu$ sample and $(p_T + 0.529 \cdot \Delta E) > 0.2$ for the $B^+ \to e^+\nu_e$ sample. We fit the data/

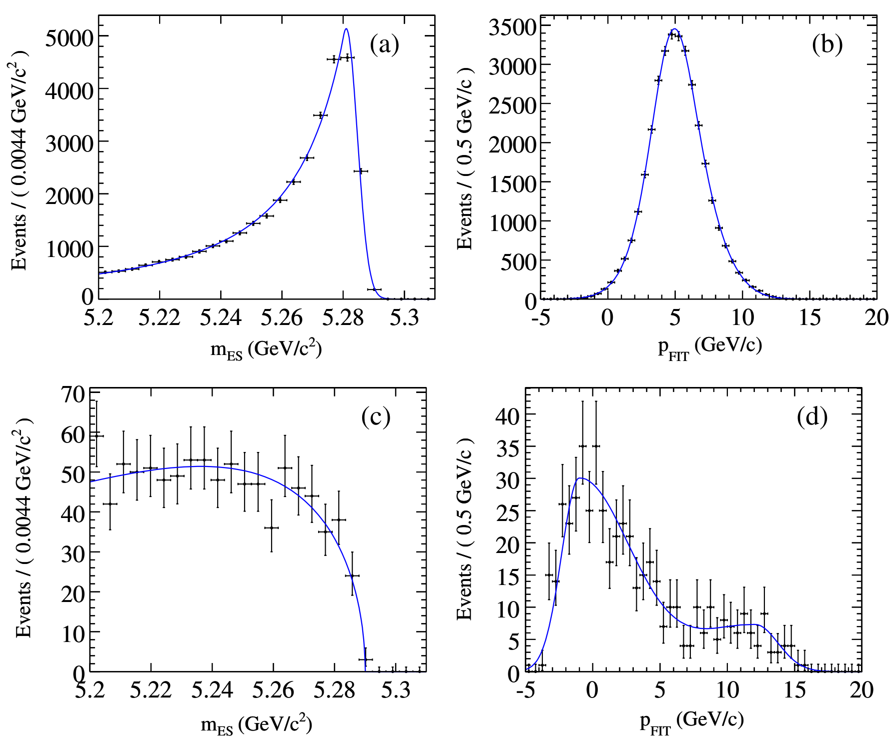


FIG. 2 (color online). Distributions of signal (a),(b) and background (c),(d) $m_{\mathrm{ES}}$ (left) and $p_{\mathrm{FIT}}$ (right) for $B^+ \to \mu^+\nu_\mu$ from MC simulation [(a)–(c)] and from $m_{\mathrm{ES}}$ sideband $5.17 < m_{\mathrm{ES}} < 5.2\ \mathrm{GeV}/c^2$ (d).

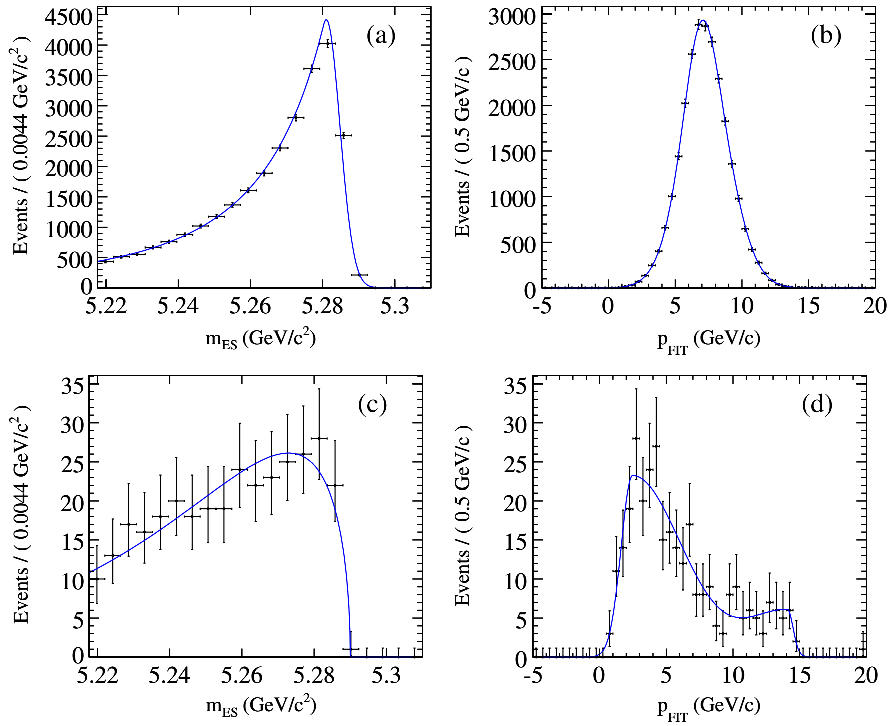


FIG. 3 (color online). Distributions of signal (a),(b) and background (c),(d) $m_{\rm ES}$ (left) and $p_{\rm FIT}$ (right) for $B^+ \to e^+ \nu_e$ from MC simulation.

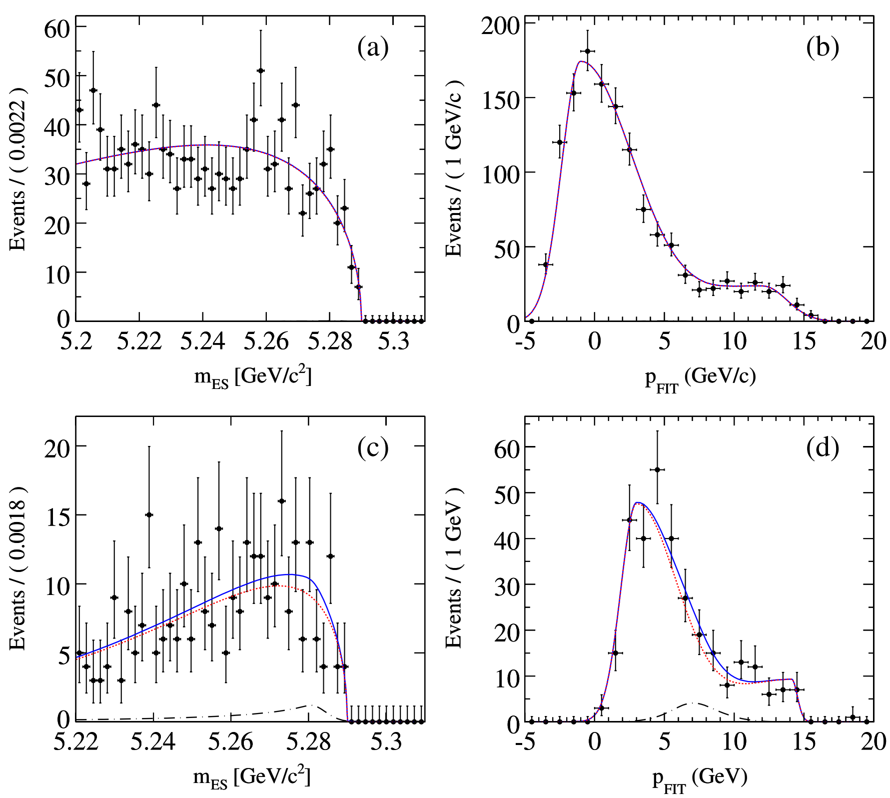


FIG. 4 (color online). Final fit to the data projected on $m_{\rm ES}$ (left) and $p_{\rm FIT}$ (right) distributions for $B^+ \to \mu^+ \nu_\mu$ events (a),(b) and $B^+ \to e^+ \nu_e$ events (c),(d): The solid blue line is the total PDF, the dashed red line is the background PDF, and the dashed-dotted 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 $B^+ \to \mu^+ \nu_\mu$ and 5.3% for $B^+ \to e^+ \nu_e$.

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 $D^{*0} \to D^0 \pi^0$. 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 $B^+ \to D^{(*)0} \pi^+$ data and MC to quantify any data/MC disagreements that may affect the signal efficiency. We find a data/MC discrepancy on the $B^+ \to D^{(*)0} \pi^+$ control sample of 3.0% for $B^+ \to \mu^+ \nu_\mu$ decays and 0.4% for $B^+ \to e^+ \nu_e$ 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 $B^+ \to \mu^+ \nu_\mu$ signal efficiency is $(6.1 \pm 0.2)\%$, and the $B^+ \to e^+ \nu_e$ 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 $p_{\rm FIT}$ and $m_{\rm ES}$ PDF parameters, which are kept fixed in the final fit and, in the $B^+ \to e^+ \nu_e$ 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 $B^+ \to \mu^+ \nu_\mu$ and 10 events for $B^+ \to e^+ \nu_e$.

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

| Source | $B^+ \to \mu^+ \nu_\mu$ | $B^+ \to e^+ \nu_e$ |
|---|---|---|
| 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% |

For the $B^+ \to e^+ \nu_e$ sample, an additional systematic uncertainty coming from possible discrepancies in the shape of the $p_{\rm FIT}$ background distribution in data and simulated events must be accounted for. The data/MC ratio of the $p_{\rm FIT}$ distribution in the $m_{\rm ES}$ sideband $5.16 < m_{\rm ES} < 5.22~{\rm GeV}/c^2$ is fit with a linear function. The background $p_{\rm FIT}$ 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:

$$\mathcal{B}(B \to l^+ \nu)_{UL} = \frac{N_{\rm sig}}{N_{B^\pm} \cdot \varepsilon}, \qquad (3)$$

where $N_{\rm sig}$ represents the observed signal yield, $N_{B^\pm}$ is the number of $B^+ B^-$ in the sample (where equal production of $B^+ B^-$ and $B^0 \bar{B}^0$ is assumed), and $\varepsilon$ 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 $\mathcal{B}$ 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:

$$\mathcal{B}(B^+ \to \mu^+ \nu_\mu) < 1.0 \times 10^{-6}, \qquad (4)$$

$$\mathcal{B}(B^+ \to e^+ \nu_e) < 1.9 \times 10^{-6}. \qquad (5)$$

The 95% upper limits are $\mathcal{B}(B^+ \to \mu^+ \nu_\mu) < 1.3 \times 10^{-6}$ and $\mathcal{B}(B^+ \to e^+ \nu_e) < 2.2 \times 10^{-6}$. This result improves the previous best published limit for $B^+ \to \mu^+ \nu_\mu$ branching fraction by nearly a factor of 2, to a value twice the SM prediction. The $B^+ \to e^+ \nu_e$ 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.

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