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# Search for decays of $B^0$ mesons into $e^+e^-$, $\mu^+\mu^-$ and $e^\pm\mu^\mp$ final states

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We present a search for the decays $B^0 \to e^+e^-$, $B^0 \to \mu^+\mu^-$, and $B^0 \to e^\pm\mu^\mp$ using data collected with the *BABAR* detector at the PEP-II $e^+e^-$ collider at SLAC. Using a data set corresponding to $384 \times 10^6$ $B\bar{B}$ pairs, we do not find evidence of any of the three decay modes. We obtain upper limit on the

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branching fractions, at 90% confidence level, of $\mathcal{B}(B^0 \to e^+e^-) < 11.3 \times 10^{-8}$, $\mathcal{B}(B^0 \to \mu^+\mu^-) < 5.2 \times 10^{-8}$, and $\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 9.2 \times 10^{-8}$.

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The standard model (SM) of particle physics does not allow flavor changing neutral currents at tree level, and decays of this kind are predicted to have very small branching fractions. This makes rare decays particularly interesting for the detection of possible new physics (NP) beyond the SM, such as supersymmetry [1]: loop contributions from heavy partners of the SM particles predicted in these models might induce, for certain decay modes, branching fractions significantly larger than the values predicted by the SM.

The leptonic decays $B^0 \to l^+l'^-$ (where $l^+l'^-$ stands for $e^+e^-$, $\mu^+\mu^-$, or $e^\pm\mu^\mp$; charge conjugation is implied throughout) are particularly interesting among rare decays, since a prediction of the decay rate in the context of the SM can be obtained with a relatively small error, due to the limited impact of long-distance hadronic corrections [2]. In the SM, $B^0 \to l^+l^-$ decays proceed through diagrams such as those shown in Fig. 1. These contributions are highly suppressed since they involve a $b \to d$ transition and require an internal quark annihilation within the $B$ meson. The decays are also helicity suppressed by factors of $(m_\ell/m_B)^2$, where $m_\ell$ is the mass of the lepton and $m_B$ the mass of the $B$ meson.

In addition, $B^0$ decays to leptons of two different flavors violate lepton flavor conservation, so they are forbidden in the SM. This feature provides a handle to discriminate among different NP models [3].

The $B^0 \to l^+l'^-$ decays are sensitive to NP also in a large set of models with minimal flavor violation [4] (MFV), in which the NP Lagrangian is flavor blind at the typical mass scale of new heavy states, with reduced effects on flavor physics at the $B$ mass scale [5]. In the context of MFV models, NP corrections to $B^0 \to l^+l'^-$ are characterized by interesting correlations with other rare decays for a particular choice of some fundamental parameters (as in the case of small [6] or large [7] $\tan\beta$ in supersymmetry models with MFV). A precise determination of the decay rate of $B^0 \to l^+l'^-$ would allow different NP scenarios to be disentangled.

As shown in Table I, the present experimental limits on $B^0 \to l^+l'^-$ are several orders of magnitude larger than SM expectations. Nevertheless, improved experimental bounds will restrict the allowed parameter space of several NP models.

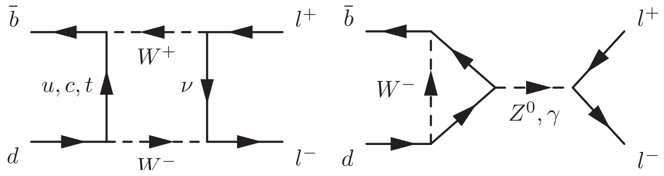

FIG. 1. Representative Feynman diagrams for $B^0 \to l^+l^-$ in the standard model.

The search for the $B^0 \to \tau^+\tau^-$ decay has been presented in a previous paper [12].

In this paper, we present a search for $B^0 \to l^+l'^-$ decay using data collected with the *BABAR* detector [13] at the PEP-II $e^+e^-$ storage rings at SLAC. The collider is operated at the $\Upsilon(4S)$ resonance with asymmetric beam energies, producing a boost ($\beta\gamma \approx 0.56$) of the $\Upsilon(4S)$ along the collision axis.

The data set used consists of $384 \times 10^6$ $B\bar{B}$ pairs accumulated at the $\Upsilon(4S)$ resonance ("on resonance"), equivalent to an integrated luminosity of 347 $\text{fb}^{-1}$, and 37 $\text{fb}^{-1}$ accumulated at a center-of-mass (CM) energy about 40 MeV below the $\Upsilon(4S)$ resonance ("off resonance"). The latter sample is used to characterize background contributions not originating from $B$ decays.

Hadronic two-body decays of $B$ mesons such as $B^0 \to \pi^+\pi^-$ and $B^0 \to K^\pm\pi^\mp$ have the same event topology as the leptonic ones and are therefore the main source of background from $B$ decays. We use Monte Carlo (MC) simulations [14] of $B^0 \to e^+e^-$, $B^0 \to \mu^+\mu^-$, $B^0 \to e^\pm\mu^\mp$ decays (signal) and $B^0 \to \pi^+\pi^-$ and $B^0 \to K^\pm\pi^\mp$ (background) of approximately $3 \times 10^5$ events each to optimize event selection criteria and to estimate efficiencies.

Charged particles are detected and their momenta measured by the combination of a silicon vertex tracker, consisting of five layers of double-sided silicon detectors, and a 40-layer central drift chamber, both operating in the 1.5-T magnetic field of a solenoid. The tracking system covers 92% of the solid angle in the CM frame. Identification of charged hadrons is provided by the average energy loss ($\mathrm{d}E/\mathrm{d}x$) in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector. For lepton identification, we also use the energy deposit in the electromagnetic calorimeter consisting of 6580 CsI(Tl) crystals and the pattern of hits in resistive plate chambers (partially upgraded to limited streamer tubes for a subset

TABLE I. The expected branching fractions in the standard model [2] and the available upper limits at 90% C.L.

| Decay mode | $B^0 \to e^+e^-$ | $B^0 \to \mu^+\mu^-$ | $B^0 \to e^\pm\mu^\mp$ |
|---|---|---|---|
| SM prediction | $1.9 \times 10^{-15}$ | $8.0 \times 10^{-11}$ | 0 |
| *BABAR* [8] | $6.1 \times 10^{-8}$ | $8.3 \times 10^{-8}$ | $18 \times 10^{-8}$ |
| Belle [9] | $1.9 \times 10^{-7}$ | $1.6 \times 10^{-7}$ | $1.7 \times 10^{-7}$ |
| CDF [10] | ⋯ | $2.3 \times 10^{-8}$ | ⋯ |
| CLEO [11] | $8.3 \times 10^{-7}$ | $6.1 \times 10^{-7}$ | $15 \times 10^{-7}$ |

of the data used in this analysis) interleaved with the passive material comprising the solenoid magnetic flux return.

We reconstruct $B^0$ meson candidates from two oppositely charged tracks originating from a common vertex. Signal events are characterized by two kinematic quantities:

$$m_{\mathrm{ES}} \equiv \sqrt{(s/2 + \mathbf{p_0} \cdot \mathbf{p_B})^2/E_0^2 - p_B^2}, \tag{1}$$

$$\Delta E \equiv E_B^* - \sqrt{s}/2, \tag{2}$$

where $\sqrt{s}/2$ is the beam energy in the CM frame, the subscripts 0 and $B$ refer to the initial $\Upsilon(4S)$ and to the $B$ candidate in the laboratory frame, respectively, and the asterisk denotes the $\Upsilon(4S)$ rest frame. The variables $s$, $\mathbf{p_0}$, and $E_0$ are calculated from the beam energies determined run by run. In Eq. (1), the variable $s$ is used as opposed to $E_B^*$ because $s$ is known with much greater precision and the resulting correlation between $m_{\mathrm{ES}}$ and $\Delta E$ is nearly zero.

For correctly reconstructed $B^0$ mesons, $m_{\mathrm{ES}}$ peaks at the mass of the $B^0$ meson with standard deviation of about 2.5 MeV$/c^2$, and $\Delta E$ peaks at zero with standard deviation of about 25 MeV. We require $|\Delta E| < 150$ MeV and $m_{\mathrm{ES}} > 5.2$ GeV$/c^2$.

Since we use the pion mass hypothesis for the reconstruction of tracks, the distribution of $\Delta E$ peaks near zero for the $\pi^+\pi^-$ and leptonic modes and at $-50$ MeV for $K^\pm\pi^\mp$. The mass hypothesis does not affect the distribution of $m_{\mathrm{ES}}$.

Energy loss by electrons due to final-state radiation or bremsstrahlung in detector material leads to tails in the $\Delta E$ and $m_{\mathrm{ES}}$ distributions, in particular for the $B^0 \to e^+e^-$ decay mode. We partially correct for this effect by adding the momentum of a photon emitted at a small angle from the track to the electron momentum.

We apply stringent requirements on particle identification (PID) to reduce the contamination from misidentified hadrons and leptons. In this way, we retain $\sim$93% ( $\sim$ 73%) of the electrons (muons), with a misidentification rate for pions of less than $\sim$0.1% ( $\sim$ 3%).

According to the information provided by the PID, we separate our data set into three samples, $2e$, $2\mu$, and $1\mu 1e$, containing events with two electrons, two muons, and one muon and one electron, respectively. The rest of the data set ($h^+h'^-$) comprises two oppositely charged hadrons and is used to characterize background contamination to the three signal samples.

Using MC simulations of the three leptonic and of the two hadronic decays, we expect cross feed of the order of $10^{-4}$ or less of the hadronic samples into the leptonic ones.

Contamination from nonresonant $q\bar{q}$ ($q = u, d, s, c$) and $\tau^+\tau^-$ production is reduced by exploiting their different event topology with respect of that of the signal events. In particular, we examine the distribution of final-state particles in the rest frame of the initial $e^+e^-$ system, in which the fragmentation of a $B\bar{B}$ pair (nonresonant event) produces an isotropic (jetlike) angular distribution of the particles.

Non-$B\bar{B}$ events are rejected by requiring the cosine of the sphericity angle [15] to be $|\cos\theta_S| < 0.8$, and the second normalized Fox-Wolfram moment [16] to be $R_2 < 0.95$, which is used to remove radiative Bhabhas and other QED events. In addition, we use a Fisher discriminant [17] ($\mathcal{F}$) in the maximum likelihood (ML) fit to separate the residual background from signal events. $\mathcal{F}$ is constructed from the CM momentum $p_i$ and angle $\theta_i$ of each particle $i$ in the rest of the event (ROE) with respect to the thrust axis [18] of the $B$ candidate.

$$\mathcal{F} \equiv 0.5319 - 0.6023 L_0 + 1.2698 L_2, \tag{3}$$

where $L_0 \equiv \sum_i^{\mathrm{ROE}} p_i$ and $L_2 \equiv \sum_i^{\mathrm{ROE}} p_i \cos^2\theta_i$. The coefficients of the linear combination have been optimized on samples of signal and background simulated events. Since the variable $\mathcal{F}$ depends only on the topology of the events, we use the same coefficients for the three leptonic decays in the ML fit.

The background from other $B\bar{B}$ events is found to be negligible after applying the PID requirements. Backgrounds originating from QED events (electrons and muons coming from $e^+e^-$ interactions) are rejected by requiring more than four charged tracks in the event.

We require more than five detected Cherenkov photons and a valid $\theta_c$ measurement in order to avoid tracks with a failed fit to extrapulate the Cherenkov angle. To reject protons, we require for pion and lepton candidates that $\theta_c$ is within $4\sigma$ of expected value for pions and for kaon candidates that $\theta_c$ is within $4\sigma$ of the expected value for kaons.

Applying the criteria described above, we select 67 events in the $2e$ sample, 56 in the $2\mu$ sample, 86 in the $1\mu 1e$ sample, and $\approx 94 \times 10^3$ in the $h^+h'^-$ sample.

Among these events, the three signal yields are independently determined by ML fits on the $2e$, $2\mu$, and $1\mu 1e$ samples. We expect that the background is composed only of nonresonant $q\bar{q}$ events.

Each likelihood function is based on the variables $m_{\mathrm{ES}}$, $\Delta E$, and $\mathcal{F}$. The probability density functions (PDFs) for the signal $m_{\mathrm{ES}}$ and $\Delta E$ distributions are parameterized as

$$f(x) = \exp\left(-\frac{(x-\mu)^2}{2 \cdot \sigma_{R/L}^2 + \alpha_{R/L} \cdot (x-\mu)^2}\right), \tag{4}$$

where $\mu$ is the maximum, $\sigma_{R/L}$ represent the standard deviation of the Gaussian component, and $\alpha_{R/L}$ describe the non-Gaussian tails of the PDF for $x > \mu$ (R) and $x < \mu$ (L). The $\mathcal{F}$ distribution for signal events is described by a Gaussian function with different standard deviation on the left and right side. The PDF of the background $m_{\mathrm{ES}}$ distribution is parameterized by an ARGUS [19] function, the background $\Delta E$ distribution by a second order polynomial, and the background $\mathcal{F}$ distribution by the sum of two Gaussian functions.

The PDF used in each likelihood function is the product of the PDFs of the variables $m_{\mathrm{ES}}$, $\Delta E$, and $\mathcal{F}$, for signal and background distributions separately. Figure 2 shows the estimated background distributions for the three subsamples (solid lines) and, just for comparison, the corresponding signal PDFs obtained from Monte Carlo (dotted lines) with arbitrary normalization.

We find that the residual background distributions of $m_{\mathrm{ES}}$, $\Delta E$, and $\mathcal{F}$ are the same in the three leptonic samples. This has been verified using data in the off-resonance sample and on-resonance events populating the kinematic sidebands ($m_{\mathrm{ES}} < 5.27\ \mathrm{GeV}/c^2$ or $|\Delta E| > 150$ MeV).

In the fit the shape parameters for the $B^0 \rightarrow l^+ l'^-$ (signal) PDFs are obtained from the MC simulation with a correction factor that accounts for differences between data and MC, while the background PDF shape parameters are determined on data with a procedure described below.

We determine the parameters of the background PDFs by fitting their distribution on the $h^+ h'^-$ sample, where we

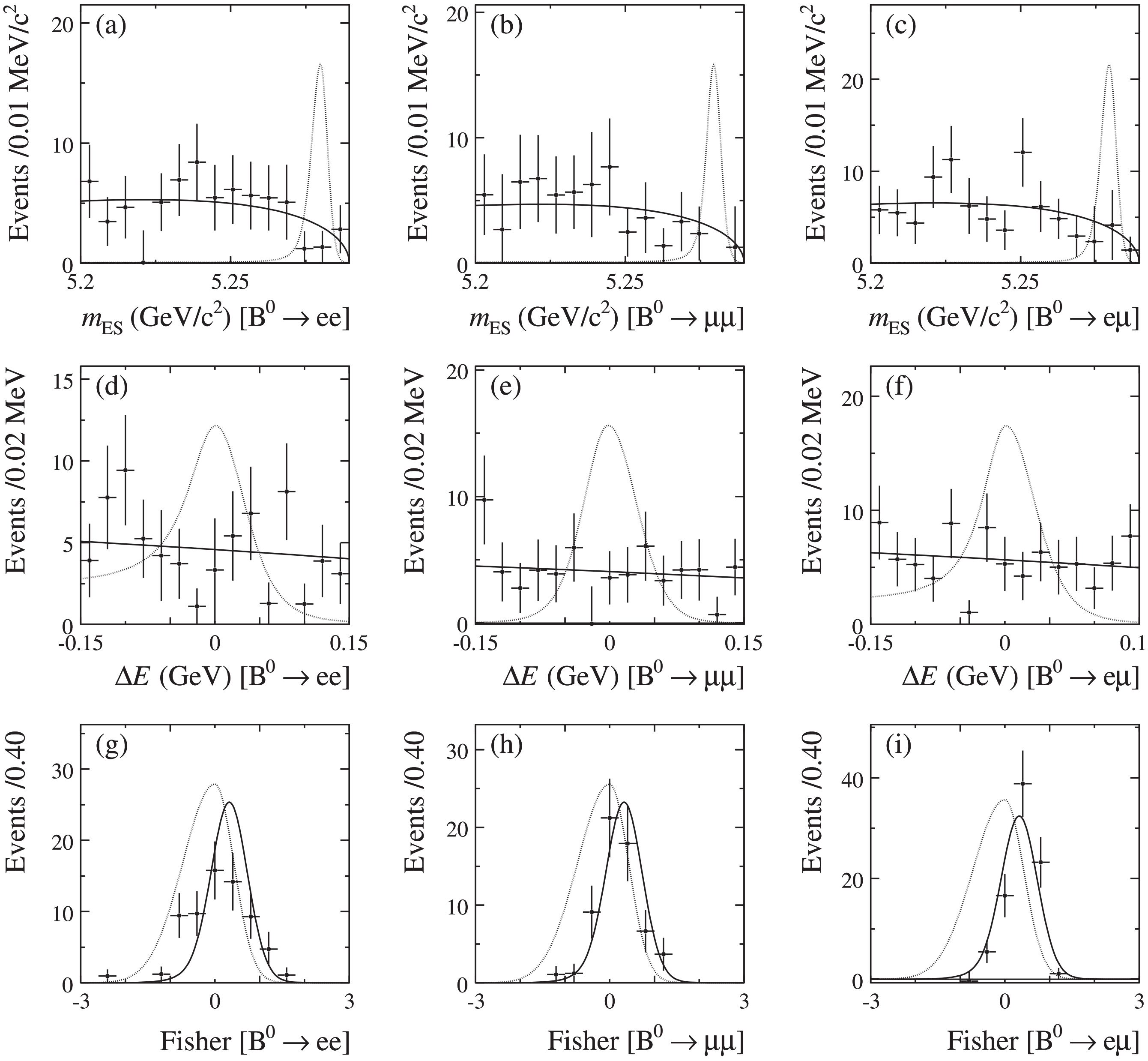

FIG. 2. Distribution of events in $m_{\mathrm{ES}}$ (a, b, c), $\Delta E$ (d, e, f), and $\mathcal{F}$ (g, h, i) for $B^0 \rightarrow e^+ e^-$ (left), $B^0 \rightarrow \mu^+ \mu^-$ (middle), and $B^0 \rightarrow e^\pm \mu^\mp$ (right). The overlaid solid curve in each plot is the background *s*Plot [22] distribution obtained by maximizing the likelihood not using the information from the corresponding component. The dotted line is the PDF obtained from signal Monte Carlo with arbitrary normalization.

use the Cherenkov angle to separate $B^0 \to \pi^+\pi^-$ and $B^0 \to K^\pm\pi^\mp$.

The yields of $B^0 \to \pi^+\pi^-$ and $K^\pm\pi^\mp$ in our $h^+h'^-$ sample are consistent with the results of the previous *BABAR* analysis [20]. We find ~600 signal and $\sim 3.5 \times 10^4$ background events for $\pi^+\pi^-$, ~2200 signal and $\sim 2.3 \times 10^4$ background events for $K^\pm\pi^\mp$.

The background shape parameters in the $B^0 \to l^+l'^-$ fit are fixed to the central values obtained in the fit to $B^0 \to \pi^+\pi^-$ and $B^0 \to K^\pm\pi^\mp$ samples, and their errors are used to estimate the associated systematic uncertainty on the leptonic yields.

We find no bias in the background shape parameters determined by the procedure described above on a large number of MC simulated $h^+h'^-$ event samples.

We correct for discrepancies between data and MC in the $B^0 \to l^+l'^-$ signal shape parameters by rescaling the PDF parameters obtained from the simulation by the ratio between the values of the $B^0 \to \pi^+\pi^-$ PDF parameters in data and MC.

The knowledge of the rescaled shapes is limited by the size of the $B^0 \to \pi^+\pi^-$ component in data, which causes a strong correlation among the parameters of each signal PDF. In order to avoid double counting of these effects, we take the largest observed deviation as the systematic error induced on the leptonic yields. The errors on the signal yields due to the PDF shapes are ~1.1, ~0.4, and ~0.2 events for the $e^+e^-$, $\mu^+\mu^-$, and $e^\pm\mu^\mp$ channels, respectively.

Our results are summarized in Table II. We find no evidence of signal in any of the three modes. Using a Bayesian approach, a 90% probability upper limit (UL) on the branching fraction ($BF$) is calculated as

$$\int_0^{\mathrm{UL}} \mathcal{L}(BF)dBF \Big/ \int_0^{\infty} \mathcal{L}(BF)dBF = 0.9. \qquad (5)$$

The $BF$ is calculated as

$$BF = \frac{N_{ll'}}{\epsilon_{ll'} N_{B\bar{B}}}, \qquad (6)$$

with $N_{ll'}$ indicating the signal yield, $\epsilon_{ll'}$ the reconstruction efficiency, and $N_{B\bar{B}}$ the number of $B\bar{B}$ pairs in the data set, $N_{B\bar{B}} = (383.6 \pm 4.2) \times 10^6$. We make the assumption that the $\Upsilon(4S)$ branching fractions to $B^+B^-$ and $B^0\bar{B}^0$ are equal.

TABLE II. Efficiency ($\epsilon_{ll'}$), number of signal events ($N_{ll'}$), and 90% C.L. upper limit on the $BF$ (UL($BF$)) for the three leptonic decays $B^0 \to e^+e^-$, $B^0 \to \mu^+\mu^-$, and $B^0 \to e^\pm\mu^\mp$.

| | $\epsilon_{ll'}(\%)$ | $N_{ll'}$ | UL($BF$) $\times 10^{-8}$ |
|---|---|---|---|
| $B^0 \to e^+e^-$ | $16.6 \pm 0.3$ | $0.6 \pm 2.1$ | 11.3 |
| $B^0 \to \mu^+\mu^-$ | $15.7 \pm 0.2$ | $-4.9 \pm 1.4$ | 5.2 |
| $B^0 \to e^\pm\mu^\mp$ | $17.1 \pm 0.2$ | $1.1 \pm 1.8$ | 9.2 |

The likelihood $\mathcal{L}(BF)$ is obtained by including in the likelihood function for the signal yield $\mathcal{L}(N_{ll'})$ the systematic errors on $N_{ll'}$ and the total number of $B\bar{B}$ pairs, and the statistical and systematic errors on the efficiency $\epsilon_{ll'}$. We use the relation of Eq. (6) and assume Gaussian shapes for the errors. Figure 3 shows the likelihood distributions of the three leptonic decays.

We evaluate the efficiencies for individual selection criteria from MC simulation and correct the results for small differences between the simulation and the data. We take these observed differences as a measure of the systematic uncertainties on the efficiencies.

The efficiency of PID requirements is calculated by using MC simulations of signal events. It is then corrected with efficiency ratios computed on data and MC, as func-

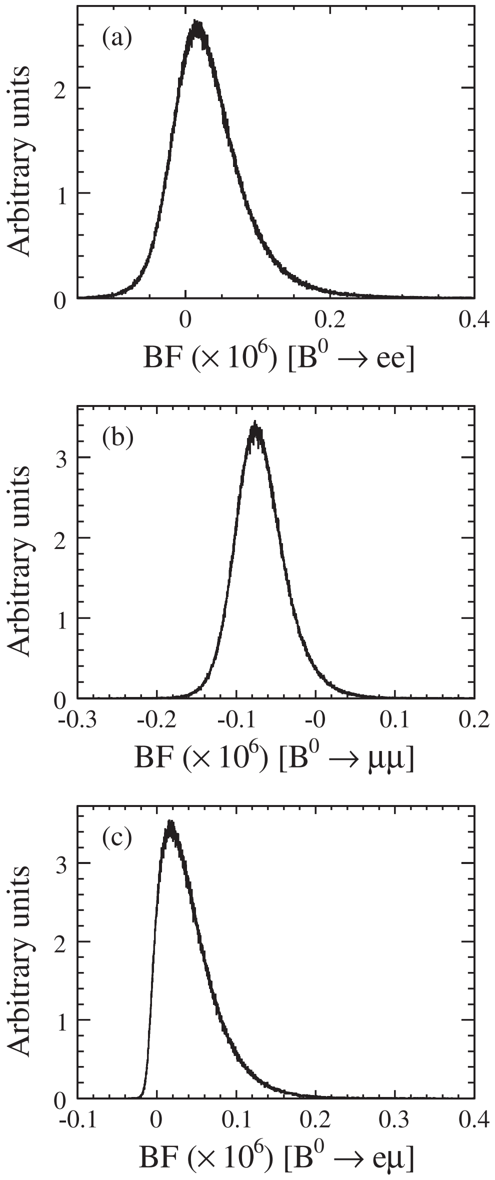

FIG. 3. Distribution of the likelihood as function of the $BF$ for $e^+e^-$ (a), $\mu^+\mu^-$ (b), and $e^\pm\mu^\mp$ (c) decays.

tion of track charge, momentum, and polar angle. We take into account the systematic error associated to this correction.

The total systematic error on the efficiencies is ~4%, calculated as the sum in quadrature of all these contributions.

We evaluate the expected UL in each of these modes by using MC simulations for a sample of the size of our data sample, and we find $7.4 \times 10^{-8}$, $5.9 \times 10^{-8}$, and $6.3 \times 10^{-8}$ for $B^0 \to e^+e^-$, $B^0 \to \mu^+\mu^-$, and $B^0 \to e^\pm\mu^\mp$, respectively.

Table II reports the efficiency, the number of signal events, and the UL in each of these modes.

The present result on $B^0 \to e^\pm\mu^\mp$ and $B^0 \to \mu^+\mu^-$ improve the previous *BABAR* upper limits [8] based on 111 $\text{fb}^{-1}$.

The upper limit reported here for $B^0 \to e^+e^-$ is higher than the value obtained in [8]. In our previous paper we used a largely frequentist approach [21] that does not explicitly require a non-negative signal. The present results supersede our previous results: the analysis has a higher sensitivity, estimated from the value of the expected UL, and is based on a larger data set that includes the sample used in [8].

In summary, we find no evidence of signal for $B^0 \to l^+l'^-$ and place 90% confidence level upper limits on the branching fractions of $B^0 \to e^+e^-$, $\mu^+\mu^-$, and $e^\pm\mu^\mp$.

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