

## A Search for the $B^0 \rightarrow e^+e^-\gamma$ and $B^0 \rightarrow \mu^+\mu^-\gamma$ Decays

The *BABAR* Collaboration

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### Abstract

With the *BABAR* detector at the PEP-II asymmetric  $B$  Factory at SLAC, we present the first search for the decays  $B^0 \rightarrow \ell^+\ell^-\gamma$  ( $\ell = e, \mu$ ). Using a data set of  $292 \text{ fb}^{-1}$  collected at the  $\Upsilon(4S)$  resonance, we find no significant signal and set the following branching fraction upper limits at 90% confidence level:  $\mathcal{B}(B^0 \rightarrow e^+e^-\gamma) < 0.7 \times 10^{-7}$  and  $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-\gamma) < 3.4 \times 10^{-7}$ .

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

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# 1 INTRODUCTION

Rare decays induced by flavor changing neutral currents occur at loop level in the Standard Model (SM) and they are sensitive to the flavor structure of the SM as well as to the new physics beyond the SM. Studying radiative  $B$  meson decays such as  $B^0 \rightarrow \ell^+\ell^-\gamma$ <sup>1</sup> can provide us essential information on the parameters of the SM, such as the elements of the Cabibbo-Kobayashi-Maskawa matrix and the leptonic decay constants. As explained below, the branching ratios that the SM predicts are much below the experimental sensitivity. Hence this paper presents a search for new physics.

The most important contribution to  $B^0 \rightarrow \ell^+\ell^-\gamma$  arises from radiative corrections to the pure leptonic processes  $B^0 \rightarrow \ell^+\ell^-$  which suffers from the helicity suppression. The short distance contributions to  $B^0 \rightarrow \ell^+\ell^-$  come from the box, Z-boson and photon-mediated diagrams. If a photon is emitted from the final charged lepton lines, the amplitude is proportional to the lepton mass  $m_\ell$  and is helicity suppressed. When a photon is attached to any charged internal line, the contributions are also significantly suppressed by a factor of  $m_b^2/m_W^2$ . Therefore, the main contribution is when a photon is radiated from the initial quark lines as shown in Fig. 1.

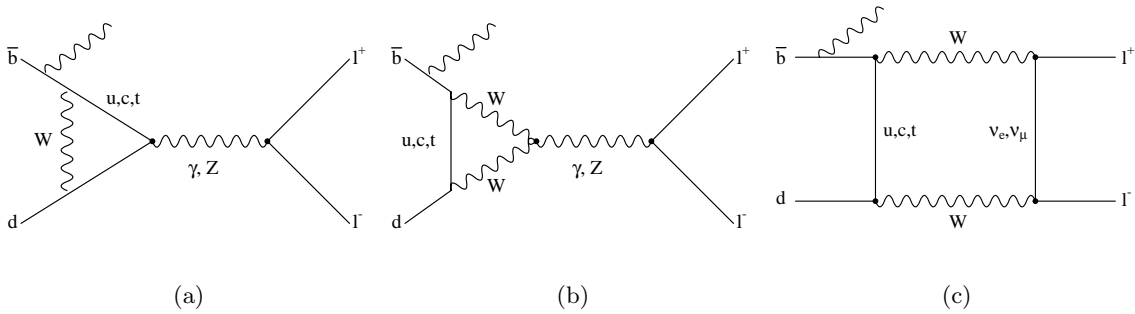


Figure 1: Feynman diagrams for the main contributions to  $B^0 \rightarrow \ell^+\ell^-\gamma$  decay. The signal photon can also be radiated from the initial  $d$  quark line.

The expected branching fractions are summarized in Table 1 for both radiative and non-radiative dilepton  $B$  decays[1]. This note presents the first search for  $B^0 \rightarrow \ell^+\ell^-\gamma$ .

Table 1: The predicted Standard Model branching fractions.

Channel	Branching Fraction
$B^0 \rightarrow e^+e^-\gamma$	$1.5 - 4 \times 10^{-10}$
$B^0 \rightarrow \mu^+\mu^-\gamma$	$1.2 - 3 \times 10^{-10}$
$B^0 \rightarrow e^+e^-$	$2.1 \times 10^{-15}$
$B^0 \rightarrow \mu^+\mu^-$	$9 \times 10^{-11}$

<sup>1</sup>Throughout the document,  $\ell$  denotes either  $e$  or  $\mu$ , and the charge conjugated states are implicitly included.

## 2 THE BABAR DETECTOR AND DATASET

The data used in this analysis were collected with the *BABAR* detector at the PEP-II storage ring at the Stanford Linear Accelerator Center and correspond to an integrated luminosity of  $292 \text{ fb}^{-1}$  accumulated at the  $\Upsilon(4S)$  resonance, which is equivalent to 320 million  $B\bar{B}$  events, and  $27 \text{ fb}^{-1}$  accumulated at a center-of-mass (CM) energy about 40 MeV below the  $\Upsilon(4S)$  resonance.

The *BABAR* detector is described elsewhere [2]. The 1.5 T superconducting solenoidal magnet contains a charged particle tracking system with a silicon vertex tracker (SVT) followed by a drift chamber (DCH), a ring imaging Cherenkov detector (DIRC) dedicated to charged-particle identification, and an electromagnetic CsI(Tl) calorimeter (EMC). The segmented flux return (IFR) is instrumented with resistive plate chambers. About 1/3 of these chambers have been replaced with limited streamer tubes which provide higher muon identification efficiency. This change affects the most recent  $77 \text{ fb}^{-1}$  of data.

A full *BABAR* detector Monte Carlo (MC) simulation based on GEANT4[3] is used to evaluate signal efficiencies and to identify and study background sources.

## 3 ANALYSIS METHOD

We reconstruct  $B^0$  candidates with two oppositely-charged leptons and a photon. The leptons are required to originate from a common vertex, and the  $B^0$  candidate is required to be consistent with coming from the beam interaction point. Since the signal events contain two neutral  $B$  mesons and no additional particles, the total energy of each  $B$  meson in the CM frame must be equal to half of the total beam energy in the CM frame. We define

$$m_{\text{ES}} = \sqrt{(E_{\text{beam}}^*)^2 - \left(\sum_i \mathbf{p}_i^*\right)^2} \quad (1)$$

$$\Delta E = \sum_i \sqrt{m_i^2 + (\mathbf{p}_i^*)^2} - E_{\text{beam}}^*, \quad (2)$$

where  $E_{\text{beam}}^*$  is the ( $e^+$  or  $e^-$ ) beam energy in the CM frame,  $\mathbf{p}_i^*$  and  $m_i$  are the momentum in the CM frame and the mass of the daughter particle  $i$  ( $i = \ell^+, \ell^-, \gamma$ ), respectively. In Eq. 1,  $E_{\text{beam}}^*$  is used instead of the  $B$  meson energy in the CM frame because  $E_{\text{beam}}^*$  is more precisely known. For correctly reconstructed  $B^0$  mesons,  $m_{\text{ES}}$  has a maximum at the nominal  $B^0$  mass with a resolution of about  $3 \text{ MeV}/c^2$  and  $\Delta E$  is near zero with a resolution of about 30 MeV.

The  $B^0 \rightarrow \ell^+ \ell^- \gamma$  candidates are selected in the  $-0.5 \leq \Delta E \leq 0.5 \text{ GeV}$  and  $5.2 \leq m_{\text{ES}} \leq 5.3 \text{ GeV}/c^2$  range. The size of the signal box is chosen to be approximately  $\pm 3\sigma$  of the  $\Delta E$  and  $m_{\text{ES}}$  distributions:  $|\Delta E| \leq 0.123 \text{ GeV}$  and  $5.27 \leq m_{\text{ES}} \leq 5.288 \text{ GeV}/c^2$ . The resolutions in  $\Delta E$  and  $m_{\text{ES}}$  are obtained from fits to the signal MC distributions assuming Crystal Ball function[4] shapes. A larger region which contains the signal box was blinded during the development of this analysis:  $|\Delta E| \leq 0.164 \text{ GeV}$  and  $5.267 \leq m_{\text{ES}} \leq 5.29 \text{ GeV}/c^2$ . The remaining region, the sideband area, is retained for background studies and data/MC comparison.

To minimize the number of mis-identified particles, the leptons are required to satisfy stringent electron and muon identification criteria. Electrons are identified using a likelihood method with EMC and DIRC information. The electron identification efficiency is about 93% and a pion fake rate is less than 0.1%. Muons are identified using a neural network method with IFR information.

The muon identification efficiency is about 70% and a pion fake rate is less than 3%. For photons, we require the shower lateral moment[5] to be less than 0.53(0.51) for the electron(muon) mode.

Leptons and photons are required to respect strict acceptance criteria. We have photon quality requirements on the number of crystals( $\geq 10$ ) and photon energy( $\geq 0.3$  GeV) for the electron mode only. These requirements help reject beam background, the initial state radiations, and higher order QED backgrounds which are not modeled in MC for the electron mode.

We apply vetoes on any leptons which may come from  $J/\psi$  or  $\psi(2S)$  decays. These vetoes are chosen in the 2-dimensional plane of  $\Delta E$  and the invariant mass of the two leptons,  $m_{DL}$ . The  $J/\psi$  veto region is the union of the following three regions in the  $\Delta E$ - $m_{DL}$  plane for electron(muon) mode:

- $2.90(3.00) < m_{DL} < 3.20$  GeV/ $c^2$ ,
- for  $m_{DL} > 3.20$  GeV/ $c^2$  region, a band in the  $\Delta E - m_{DL}$  plane defined by  $1.11c^2 \times m_{DL} - 3.58(3.53)$  GeV  $< \Delta E < 1.11c^2 \times m_{DL} - 3.25(3.31)$  GeV,
- for  $m_{DL} < 2.90(3.00)$  GeV/ $c^2$  region, a triangle in the  $\Delta E - m_{DL}$  plane defined by  $\Delta E < 1.11c^2 \times m_{DL} - 3.25(3.31)$  GeV.

Photon candidates whose invariant mass with other photons in the event are in the range of  $0.115 < m_{\gamma\gamma} < 0.155$  GeV/ $c^2$  are vetoed to remove photons from  $\pi^0$  decays. We studied the effect of an  $\eta$  veto and found it to be negligible.

We require that the invariant mass of dilepton system is between 0.3 and 4.9(4.7) GeV/ $c^2$  for the electron(muon) mode to reject non- $B\bar{B}$  background. Further suppression of background from non- $B\bar{B}$  background is provided by a series of topological requirements. We require  $|\cos \theta_T| \leq 0.8$ , where  $\theta_T$  is the angle in the CM frame between the thrust axis of the particles that form the reconstructed  $B^0$  candidate and the thrust axis of the remaining tracks and neutral clusters in the event. We have a requirement on the ratio of the second to zeroth Fox-Wolfram moment[6] of  $R_2 \leq 0.31$ . We define a Fisher discriminant based on the following variables: the angle between the  $B^0$  direction and the beam axis, the angle between the thrust axis of the  $B^0$  candidate and the beam axis, and the summed momentum of the rest of the event tracks and neutrals in nine non overlapping volumes delimited by cones centered around the thrust axis of the  $B^0$  candidate with half-angles in  $10^\circ$  steps. The distributions of the Fisher discriminants are shown in Fig. 2. The arrows show the allowed regions. If multiple  $B^0$  candidates pass all the selection requirements in an event, only the one with  $\Delta E$  closest to zero is retained. The average number of  $B^0$  candidates per event is 1 (1.05) for the electron(muon) mode.

To assess potential background contributions peaking like the signal in  $\Delta E$  and  $m_{ES}$ , we examined 32 exclusive hadronic and semileptonic decay modes, and found no significant contribution.

The requirement levels are optimized by minimizing the expected upper limit branching fraction at 90% confidence level (C.L.). The upper limit is calculated using the Feldman-Cousins method[7]. The normalizations and shapes of the data and MC distributions are compared at various requirement levels in the sideband area. They show reasonable agreement at all levels.

To estimate the background level in the signal box, three different sideband boxes are used, as indicated in Table 2. We perform an unbinned maximum likelihood fit on the  $m_{ES}$  distribution in the combined upper and lower sideband boxes with an Argus function[8], as shown in Fig. 3. The end-point of the Argus function is fixed at 5.29 GeV/ $c^2$ . We use this parameterization to extrapolate the background level found in the middle sideband (12 events for  $B^0 \rightarrow e^+e^-\gamma$  sample and 13 events for  $B^0 \rightarrow \mu^+\mu^-\gamma$  sample) into the signal box. The error on the expected number of background in

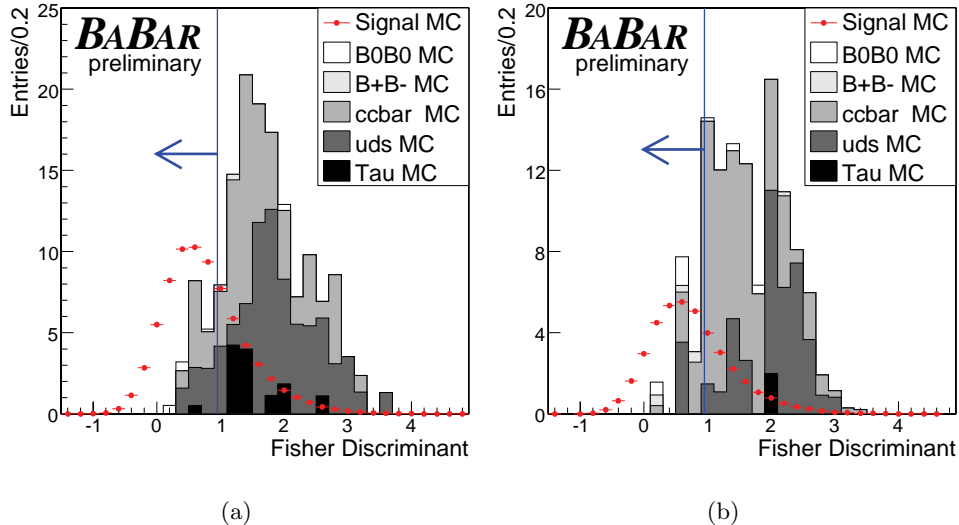


Figure 2: The distribution of the Fisher discriminant for selected events in the signal box for (a)  $B^0 \rightarrow e^+e^-\gamma$  and (b)  $B^0 \rightarrow \mu^+\mu^-\gamma$  sample. The points show the predicted distributions for signal events, the histograms show the various background contributions. The  $J/\psi$ ,  $\psi(2S)$  and  $\pi^0$  vetoes are applied. The signal distribution is normalized to the branching fraction of  $1 \times 10^{-6}$ .

the signal box from the fit is estimated by varying the Argus parameters by  $\pm 1\sigma$ . The background has been estimated with alternative methods, using sidebands in  $\Delta E$ , and repeating the fit after relaxing the selection requirements. The estimates obtained are in general compatible within errors. The fit to the  $m_{ES}$  sidebands was chosen as the preferred method because it yields the smallest statistical uncertainties.

Table 2: Definitions of the different sideband boxes used.

Sideband Box	span in $\Delta E$ (GeV)	span in $m_{ES}$ ( $\text{GeV}/c^2$ )
Upper Sideband	(0.164, 0.5)	(5.2, 5.3)
Lower Sideband	(-0.5, -0.164)	(5.2, 5.3)
Middle Sideband	(-0.123, 0.123)	(5.2, 5.26)

## 4 SYSTEMATIC STUDIES

Systematic uncertainties are evaluated using independent data control samples. The dominant systematic uncertainty is related to the reconstruction of the signal photon energy which is determined using  $e^+e^- \rightarrow \mu^+\mu^-\gamma$  decays. The uncertainty is 1.6% for both modes. The systematic uncertainty from the particle identification has been determined using an independent control sample of  $J/\psi$  decays. It is 0.7% and 1.3% for the electron and muon mode respectively. The uncertainty on the number of  $B\bar{B}$  events is 1.1%[9]. The tracking efficiency is determined from  $e^+e^- \rightarrow \tau^+\tau^-$  interac-

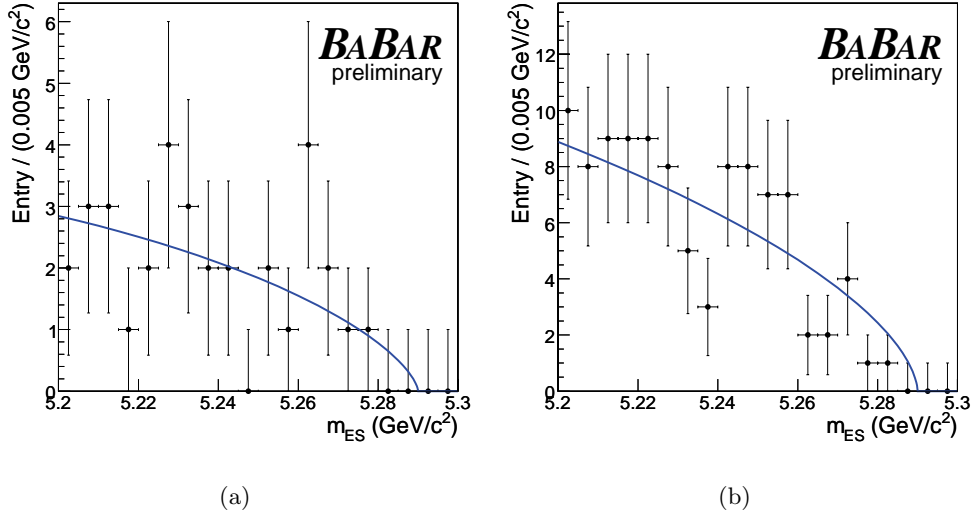


Figure 3: An unbinned maximum likelihood fit on  $m_{ES}$  distribution in the combined upper and lower sideband boxes, using an Argus function for (a)  $B^0 \rightarrow e^+e^-\gamma$  and (b)  $B^0 \rightarrow \mu^+\mu^-\gamma$  sample. The points represent data and the solid lines show the fit function.

tions, with one tau decaying leptonically and the other to three charged hadrons. The uncertainty is 0.94% for both electron and muon modes. All contributions to the systematics are added in quadrature to give a total relative systematic uncertainty of 2.3% for the electron mode and 2.5% for the muon mode on the branching fraction.

## 5 RESULTS

As shown in Fig. 4 and Table 3, zero and three events were found in the electron and muon modes, respectively. The number of events found in the signal box is compatible with the expected background for both modes.

An upper limit on the branching fraction is computed using

$$\mathcal{B}_{UL}(B^0 \rightarrow \ell^+\ell^-\gamma) = \frac{N_{UL}}{N_{B^0} \cdot \epsilon_{sig}} \quad (3)$$

where  $N_{UL}$  is the 90% C.L. upper limit for the signal yield as determined by the method described in [10] with both statistical and systematic errors,  $N_{B^0}$  is the number of the neutral  $B$  mesons and  $\epsilon_{sig}$  is the signal reconstruction efficiency from the signal MC sample.  $N_{B^0}$  is equal to the number of  $B\bar{B}$  events, as we are assuming  $\mathcal{B}(\Upsilon(4S) \rightarrow B^0\bar{B}^0) = \mathcal{B}(\Upsilon(4S) \rightarrow B^+B^-)$ . The obtained 90% C.L. branching fraction upper limits are  $\mathcal{B}(B^0 \rightarrow e^+e^-\gamma) < 0.7 \times 10^{-7}$  and  $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-\gamma) < 3.4 \times 10^{-7}$ .

## 6 CONCLUSION

A search for the  $B^0 \rightarrow \ell^+\ell^-\gamma$  ( $\ell = e$  or  $\mu$ ) modes has been performed based on 320 million  $B\bar{B}$  events. We obtain 90% C.L. upper limits for the branching fraction of  $\mathcal{B}(B^0 \rightarrow e^+e^-\gamma) <$

Table 3: Summary of the results where  $n_{obs}$  and  $n_{bg}^{exp}$  are the observed and expected number of background events in the signal box,  $\epsilon_{sig}$  is the efficiency,  $N_{UL}$  is the 90% C.L. upper limit for the signal yield, and  $\mathcal{B}_{UL}(B^0 \rightarrow \ell^+ \ell^- \gamma)$  is the upper limit on the branching fraction at the 90% C.L. Systematic uncertainties on  $n_{bg}^{exp}$  and  $\epsilon_{sig}$  are given.

Decay Mode	$n_{obs}$	$n_{bg}^{exp}$	$\epsilon_{sig}$ (%)	$N_{UL}$	$\mathcal{B}_{UL}(B^0 \rightarrow \ell^+ \ell^- \gamma)$
$e^+e^-$	0	$1.28 \pm 0.80$	$6.07 \pm 0.14$	1.33	$0.7 \times 10^{-7}$
$\mu^+\mu^-$	3	$1.40 \pm 0.42$	$4.93 \pm 0.12$	5.30	$3.4 \times 10^{-7}$

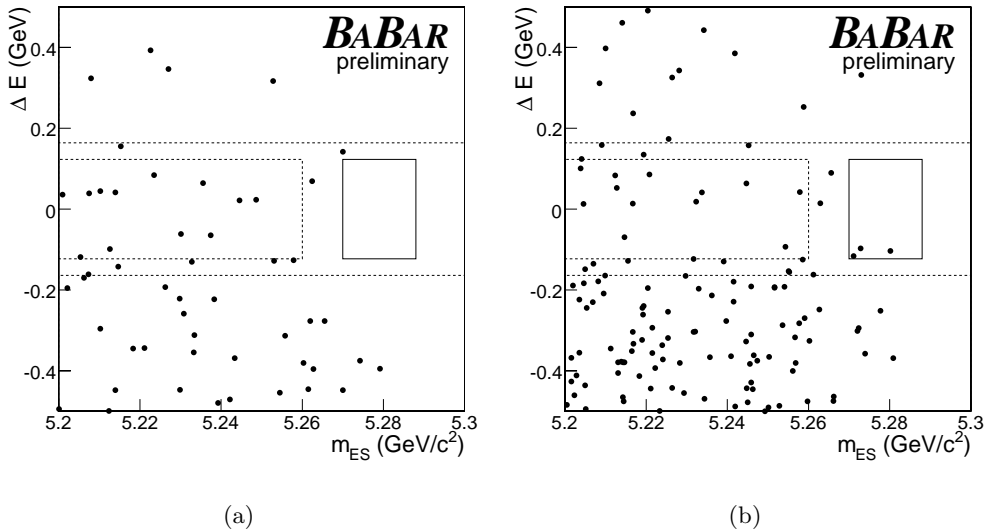


Figure 4: Distribution of events in  $m_{ES}$  and  $\Delta E$  for (a)  $B^0 \rightarrow e^+e^-\gamma$  and (b)  $B^0 \rightarrow \mu^+\mu^-\gamma$  sample. The solid box represents the signal box. The three dashed-lined area show the upper, middle, and lower sideband boxes from top to bottom.

$0.7 \times 10^{-7}$  and  $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-\gamma) < 3.4 \times 10^{-7}$ . These are the only limits currently available for these decay modes.

## 7 ACKNOWLEDGMENTS

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