

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

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We present results of a search for the decays  $B^0 \rightarrow \ell^+ \ell^- \gamma$  ( $\ell = e, \mu$ ). The search is performed using  $320 \times 10^6$   $B\bar{B}$  pairs collected at the  $\Upsilon(4S)$  resonance with the *BABAR* detector at the PEP-II *B* Factory at SLAC. We find no significant signal and set the following branching fraction upper limits at the 90% confidence level:  $\mathcal{B}(B^0 \rightarrow e^+ e^- \gamma) < 1.2 \times 10^{-7}$  and  $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^- \gamma) < 1.5 \times 10^{-7}$ .

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Radiative leptonic decays of neutral  $B$  mesons,  $B^0 \rightarrow \ell^+ \ell^- \gamma$  with  $\ell = e, \mu$  [1], are flavor-changing neutral-current transitions that are forbidden at the tree level in the standard model (SM). In the SM, such processes are described by penguin and box diagrams to leading order, as shown in Fig. 1. The expected branching fractions for these processes are of order of  $10^{-10}$  [2]. A measured branching fraction bigger than this would be an evidence for new physics. The largest contributions arise from processes in which a photon is emitted from one of the initial quarks, thus avoiding the helicity suppression of the purely leptonic decay  $B^0 \rightarrow \ell^+ \ell^-$ . A search for the processes  $B^0 \rightarrow \ell^+ \ell^-$  has been performed by the *BABAR* collaboration and others [3], but there is no previous search for the  $B^0 \rightarrow \ell^+ \ell^- \gamma$  decays.

The analysis described in this Letter uses a sample of  $320 \times 10^6$   $B\bar{B}$  pairs recorded with the *BABAR* detector at the PEP-II asymmetric energy  $e^+e^-$  storage rings. This corresponds to an integrated luminosity of  $292 \text{ fb}^{-1}$  collected at the  $\Upsilon(4S)$  resonance.

A detailed description of the *BABAR* detector can be found elsewhere [4]. Charged-particle trajectories are measured by a five-layer silicon vertex tracker and a 40-layer drift chamber operating in a 1.5 T magnetic field. A detector of internally reflected Cherenkov light is used for charged hadron identification. Surrounding this is an electromagnetic calorimeter (EMC) consisting of 6580 CsI(Tl) crystals, and the instrumented flux return for the solenoid, which consists of layers of steel interspersed with resistive plate chambers or limited streamer tubes.

A full *BABAR* Monte Carlo (MC) simulation using *GEANT4* [5] is used to evaluate signal efficiencies and to identify and study background sources. The signal MC sample is based on a calculation where the  $B^0 \rightarrow \ell^+ \ell^- \gamma$  transition depends on three Wilson coefficients  $C_7$ ,  $C_9$ , and  $C_{10}$  at leading order [6].

We reconstruct the  $B^0$  signal candidates by combining two oppositely-charged leptons and a photon. The  $B^0$  vertex is fitted using a Kalman Filter method [7]. 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.

To minimize the number of misidentified particles, the leptons are required to satisfy stringent particle identification criteria [8]. For the electron candidates, the energy loss due to bremsstrahlung is recovered whenever possible, by looking for the energy deposits (clusters) in the EMC close to the intersection of their tracks with the EMC. For photon clusters, the transverse shower shape is

required to be consistent with an electromagnetic shower. Leptons and photons are required to reside fully in the geometric acceptance of the detector.

Since the signal event contains two neutral  $B$  mesons and no additional particles, the total energy of each  $B$  meson in the center-of-mass (CM) frame must be equal to half of the total beam energy in the CM frame. We define  $m_{\text{ES}} = \sqrt{(E_{\text{beam}}^*)^2 - (\sum_i \mathbf{p}_i^*)^2}$  and  $\Delta E = \sum_i \sqrt{m_i^2 + (\mathbf{p}_i^*)^2} - E_{\text{beam}}^*$ , where  $E_{\text{beam}}^*$  is the beam energy in the CM frame,  $\mathbf{p}_i^*$  and  $m_i$  are the momenta in the CM frame and the masses of the daughter particles  $i$  ( $i = \ell^+, \ell^-, \gamma$ ), respectively.  $E_{\text{beam}}^*$  is used instead of the measured  $B$  meson energy in the CM frame because  $E_{\text{beam}}^*$  is more precisely known. For correctly reconstructed  $B^0$  mesons, the  $m_{\text{ES}}$  distribution has a maximum at the  $B^0$  mass with a standard deviation of about  $3 \text{ MeV}/c^2$  and the  $\Delta E$  distribution has a maximum near zero with a standard deviation of about  $30 \text{ MeV}$ .

The  $B^0 \rightarrow \ell^+ \ell^- \gamma$  candidates are selected by requiring  $-0.5 \leq \Delta E \leq 0.5 \text{ GeV}$  and  $5.0 \leq m_{\text{ES}} \leq 5.3 \text{ GeV}/c^2$ . These ranges include both background- and signal-dominated regions. As shown in Fig. 2, five background-dominated regions (sideband areas) are used for the background estimation. To avoid experimenter's bias, the events in the signal-dominated region (signal box) and in the shaded area covering the signal box are not included in the analysis until the final selection criteria have been optimized and the background estimation has been finalized. The shapes of the  $m_{\text{ES}}$  and  $\Delta E$  distributions of the signal MC are parameterized by the Crystal Ball function [9] to allow for the asymmetric shape of the signal peak due to energy loss in the EMC. The size of the signal box is chosen to be approximately  $\pm 3 \times \text{FWHM}$  for  $\Delta E$  and  $m_{\text{ES}}$ :  $-0.146(-0.112) \leq \Delta E \leq 0.082 \text{ GeV}$  for the  $e^+e^- \gamma$  ( $\mu^+ \mu^- \gamma$ ) mode, and  $5.270 \leq m_{\text{ES}} \leq 5.289 \text{ GeV}/c^2$  for both modes.

The dominant backgrounds are: 1) unmodeled higher-order QED and hadronic two-photon processes for the  $e^+e^- \gamma$  mode; 2)  $B$  decays where the photon comes from a  $\pi^0$  decay, or the lepton is from a  $J/\psi$  or  $\psi(2S)$  decay; and 3) continuum background from  $e^+e^- \rightarrow f\bar{f}$  (where  $f = u, d, s, c, \text{ or } \tau$ ) processes at the parton level.

To take into account higher-order QED and hadronic two-photon processes, we introduce additional selection criteria for the  $e^+e^- \gamma$  candidates: we require the cosine of the polar angle of  $e^-$  ( $\gamma$ ) to be between  $-0.743$  ( $-0.618$ ) and  $0.81$  ( $0.8$ ), the energy of the photon to be  $\geq 0.3 \text{ GeV}$ , the number of charged tracks (EMC clusters) in the event to be  $\geq 5$  ( $10$ ), and the ratio of the second-to-zeroth order

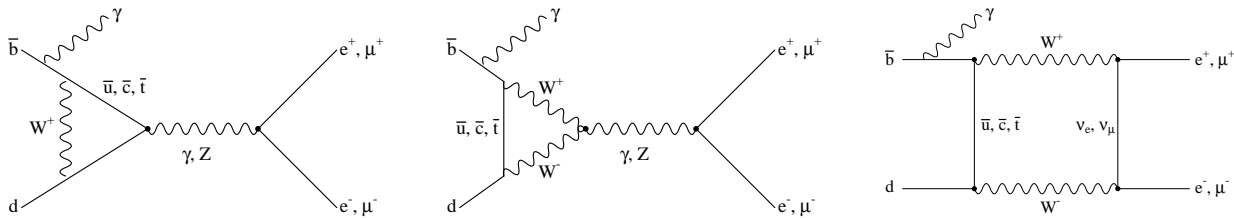


FIG. 1: The penguin (left and middle) and box (right) Feynman diagrams for  $B^0 \rightarrow \ell^+ \ell^- \gamma$  ( $\ell = e, \mu$ ) decays. The photon can be emitted from any of the quarks or leptons, but the amplitudes are largest if the photon is emitted from one of the initial quarks.

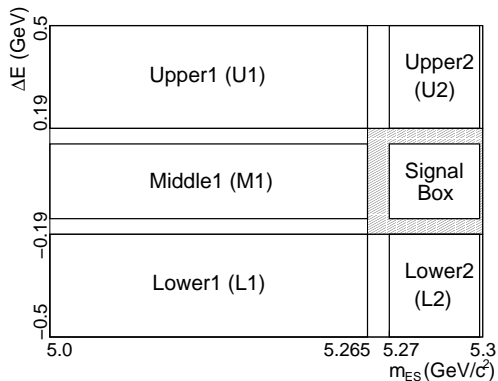


FIG. 2: Definitions of the signal box, blinded area (equal to the sum of the signal box and of the shaded area), and sideband areas in the  $\Delta E$  vs.  $m_{ES}$  plot: Upper1 (U1), Upper2 (U2), Lower1 (L1), Lower2 (L2), and Middle1 (M1). The signal box has the same  $\Delta E$  range as the M1 box (different for each mode), and the same  $m_{ES}$  limits as the U2 and L2 boxes. The figure is not drawn to scale.

Fox-Wolfram moments ( $R_2$ ) [10], which is calculated with the charged tracks and neutral clusters in the rest of the event (ROE), to be  $\leq 0.7$ .

To reduce the number of events where the photon is from a  $\pi^0$  decay, we veto photon candidates that can be combined with any other photon in the event to form a  $\pi^0$  candidate with a mass within three standard deviations ( $\sim 20 \text{ MeV}/c^2$ ) of the nominal  $\pi^0$  mass.

We veto lepton candidates that form a suitable  $J/\psi$  or  $\psi(2S)$ , as described in Ref. [11].

To suppress the continuum background, we require  $R_2$ , calculated from all charged tracks and neutral clusters, to be less than 0.35, and the absolute value of the cosine of the angle between the thrust axis of the  $B^0$  candidate and that of the ROE to be less than 0.8. These variables are used in a neural network combined with the following variables: 1) the absolute value of the cosine of the angle between the  $B^0$  direction and the beam axis, 2) the absolute value of the cosine of the angle between the thrust axis of the  $B^0$  candidate's decay products and the beam

axis, 3) the ratio of second order to zeroth order Legendre moments of all charged tracks and neutral clusters, and 4) the invariant mass of the dileptons. The neural network rejects 20(36)% of the background while keeping 95(89)% of the signal, for the  $e^+e^- \gamma$  ( $\mu^+ \mu^- \gamma$ ) mode. All the selection criteria are optimized with MC samples to discriminate signal from background.

After all requirements are applied, there are on average 1.01(1.07) candidates per event for the  $e^+e^- \gamma$  ( $\mu^+ \mu^- \gamma$ ) mode. In events with multiple candidates, the one with the highest probability for the vertex fit is retained. The signal efficiency is 7.4(5.2)% for the  $e^+e^- \gamma$  ( $\mu^+ \mu^- \gamma$ ) mode. The  $e^+e^- \gamma$  mode has higher efficiency because electrons have higher detection efficiency than muons.

To assess possible background contributions that peak in the signal box, we examined 32 exclusive hadronic and semileptonic  $B$  decays using MC, including events where both  $B$  mesons decay semileptonically, and found no significant contribution.

A variety of methods to estimate the background in the signal box have been tried, including fitting and counting methods in various  $m_{ES}$  and  $\Delta E$  sideband areas with different conditions. All studies yield results that are compatible within uncertainties.

The chosen method is model-independent, is based on data only, and has a small systematic uncertainty. To estimate the background level in the signal box, five different sideband areas are used, as indicated in Fig. 2. The ratio  $R_{est}^M$  is the estimated ratio of the yield in the signal box to the yield in the M1 box. The expected background in the signal box ( $n_{bg}^{exp}$ ) is calculated by multiplying  $R_{est}^M$  by the yield in the M1 box. We estimate  $R_{est}^M$  as the mean of two ratios  $R^U$  and  $R^L$ , where  $R^{U(L)} = N^{U2(L2)} / N^{U1(L1)}$ , and where  $N^X$  is the yield in box  $X$ . This assumes that the changes in the ratio  $R^L$ ,  $R_{est}^M$  and  $R^U$  are linear in  $\Delta E$ .

To test our assumption of this linearity, we use MC samples and calculate the ratio  $R^M$  by dividing the yield in the signal box by the yield in the M1 box. The relative difference between  $R^M$  and  $R_{est}^M$  in MC samples is assigned as a systematic uncertainty. The estimated background is  $1.75 \pm 1.38 \pm 0.36$  ( $2.66 \pm 1.40 \pm 1.58$ ) events

for the  $e^+e^- \gamma$  ( $\mu^+\mu^- \gamma$ ) mode, where the stated errors represent the statistical and systematic uncertainties, respectively.

The dominant source of systematic uncertainty on the signal yield is the calculation used for the signal MC [6]. The three theoretical input parameters, the Wilson coefficients  $C_7$ ,  $C_9$ , and  $C_{10}$ , used in the calculation are varied by  $\pm 10\%$ , as recommended by the authors of [6]. This variation changes the kinematics of the signal events and can thereby impact the detection efficiency. The largest relative change in signal efficiency by this variation is assigned as a systematic uncertainty.

We have studied  $e^+e^- \rightarrow \mu^+\mu^- \gamma$  decays in data to assess the systematic uncertainty in photon reconstruction.

The systematic uncertainty from the lepton identification has been determined using an independent control sample of  $J/\psi$  decays.

The uncertainty on the number of  $B\bar{B}$  events is 1.1% [12].

The systematic uncertainty related to an imperfect detector simulation is studied using a control sample of  $B^0 \rightarrow J/\psi K_s^0$  events. The same continuum background suppression requirements are applied on this sample and the signal efficiency is calculated. The relative difference in the signal efficiencies between data and MC samples is assigned as a systematic uncertainty.

The systematic uncertainty related to the tracking efficiency is determined from  $e^+e^- \rightarrow \tau^+\tau^-$  interactions, with one  $\tau$  decaying leptonically and the other to three charged hadrons. All the contributions to the systematic uncertainties are added in quadrature and summarized in Table I.

TABLE I: Summary of the systematic uncertainties on the signal yields.

	$e^+e^- \gamma$ (%)	$\mu^+\mu^- \gamma$ (%)
Signal Calculation	2.3	3.8
Photon Reconstruction	1.6	1.6
Lepton Identification	0.7	1.3
Number of $B\bar{B}$ Pairs	1.1	1.1
Data/MC comparison	1.3	0.4
Tracking Efficiency	0.9	0.9
Total	3.5	4.6

After applying the selection criteria we find one event in the signal box for each mode, as shown in Fig. 3 and Table II. These numbers are compatible with the expected background for both modes.

An upper limit on the branching fraction is computed from

$$\mathcal{B}_{UL}(B^0 \rightarrow \ell^+\ell^-\gamma) = \frac{N_{UL}}{N_{B^0} \cdot \epsilon_{sig}}, \quad (1)$$

where  $N_{UL}$  is the 90% confidence level (C.L.) upper limit for the signal yield, determined by taking into account

the one observed event in the signal box and the estimated background, using the frequentist method described in Ref. [13] including both statistical and systematic uncertainties,  $N_{B^0}$  is the number of neutral  $B$  mesons and  $\epsilon_{sig}$  is the signal reconstruction efficiency. The systematic uncertainties are included in  $\epsilon_{sig}$ . It is assumed that  $\mathcal{B}(\Upsilon(4S) \rightarrow B^0\bar{B}^0) = \mathcal{B}(\Upsilon(4S) \rightarrow B^+B^-)$ , and so  $N_{B^0}$  is equal to the number of  $B\bar{B}$  events. The 90% C.L. branching fraction upper limits obtained are  $\mathcal{B}(B^0 \rightarrow e^+e^- \gamma) < 1.2 \times 10^{-7}$  and  $\mathcal{B}(B^0 \rightarrow \mu^+\mu^- \gamma) < 1.5 \times 10^{-7}$ .

TABLE II: Summary of the results where  $n_{obs}$  ( $n_{bg}^{exp}$ ) is the number of observed (expected 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  $\mathcal{B}_{UL}$  is the upper limit on the branching fraction at the 90% C.L. The stated uncertainties on  $n_{bg}^{exp}$  are statistical and systematic, and the uncertainty on  $\epsilon_{sig}$  is systematic.

Mode	$n_{obs}$	$n_{bg}^{exp}$	$\epsilon_{sig}$ (%)	$N_{UL}$	$\mathcal{B}_{UL}$
$e^+e^- \gamma$	1	$1.75 \pm 1.38 \pm 0.36$	$7.4 \pm 0.3$	2.82	$1.2 \times 10^{-7}$
$\mu^+\mu^- \gamma$	1	$2.66 \pm 1.40 \pm 1.58$	$5.2 \pm 0.2$	2.55	$1.5 \times 10^{-7}$

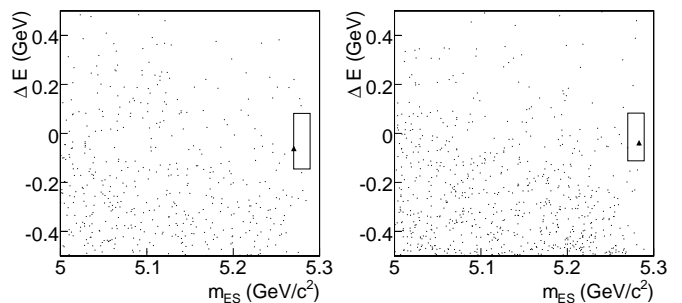


FIG. 3: Distribution of events in  $m_{ES}$  and  $\Delta E$ . The left plot is for the  $e^+e^- \gamma$  mode and the right plot is for the  $\mu^+\mu^- \gamma$  mode. The dots are the events outside the signal box (rectangular region), and the triangles are the events inside the signal box.

In summary, a search for  $B^0 \rightarrow \ell^+\ell^-\gamma$  ( $\ell = e$  or  $\mu$ ) decays has been performed based on  $320 \times 10^6$   $B\bar{B}$  events. We obtain 90% C.L. upper limits for the branching fractions of  $\mathcal{B}(B^0 \rightarrow e^+e^- \gamma) < 1.2 \times 10^{-7}$  and  $\mathcal{B}(B^0 \rightarrow \mu^+\mu^- \gamma) < 1.5 \times 10^{-7}$ , which represent the first limits placed on these decay channels. These are well above the SM expectations.

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The Crystal Ball function can be written as:

$$CB(m) = \begin{cases} \exp\left(-\frac{(m-\mu)^2}{2\sigma^2}\right) & m > \mu - \alpha\sigma \\ \frac{(n/\alpha)^n \exp(-\alpha^2/2)}{((\mu-m)/\sigma + n/\alpha - \alpha)^n} & m < \mu - \alpha\sigma, \end{cases}$$

where  $\mu$  is the mean value,  $\sigma$  is a measure of the width, and  $n$  and  $\alpha$  are parameters describing the tail.

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