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Search for $B^0 \to \gamma\gamma$ using the L3 detector

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Abstract

A search for $B^0_{d,s} \to \gamma\gamma$ decays in 2.95 million hadronic Z decays has been performed using the L3 detector at LEP. No candidates are found in the signal region and upper limits has been set on the branching ratios: $Br(B^0_d \to \gamma\gamma) < 3.8 \times 10^{-5}$ and $Br(B^0_s \to \gamma\gamma) < 11.4 \times 10^{-5}$ at the 90% CL. These are the first limits set on these exclusive rare decays.

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Introduction

Rare B hadron decays are important discriminators for the finer details (higher order structures) of the Standard Model (SM) as well as physics beyond. Of particular interest are the decays $B^0_{d,s} \rightarrow \gamma\gamma$ for which there has been no experimental effort as yet. The decay corresponds to a second order weak transition including gluonic penguins followed by annihilation, often referred to as an "effective" flavor-changing weak neutral current process, as shown by some simple diagrams in Figure 1. The expected branching ratio for this decay mode is $\sim 10^{-7}$ in SM, however there are large theoretical uncertainties [1–4]. As pointed out in reference [5] exclusive decay rates are extremely difficult to compute reliably. In contrast to the theoretical situation, experimentally $B^0 \rightarrow \gamma\gamma$ is a relatively clean channel to study.

It is believed that for some non-standard scenarios, such as minimal supersymmetric and two-Higgs-doublet models, the $B^0 \rightarrow \gamma\gamma$ decay rate can be enhanced significantly [1]. Thus any observation of the decay $B^0 \rightarrow \gamma\gamma$ at an unusual rate could be an indication of new physics.

The present work is an effort to look for this decay mode exploiting the high resolution BGO electromagnetic calorimeter of the L3 detector which is particularly well suited for this purpose. As will be demonstrated later in this paper, the resolution of the detector is appropriate to reconstruct exclusively this decay mode. The analysis is performed on data recorded in 1991,1992,1993 and 1994 at $\sqrt{s} \approx M_Z$. This data corresponds to a sample of 2.95 million $e^+e^- \rightarrow$ hadron events.

The mixed sample of B hadrons available in Z decays, provides opportunity to study B^0_s meson decays, not available at the $\Upsilon(4S)$ center-of-mass energy.

The L3 Detector

The L3 detector is described in detail in Ref. [6]. It consists of a central tracking chamber, a high resolution electromagnetic calorimeter composed of bismuth germanium oxide (BGO) crystals, a ring of plastic scintillation counters, a uranium and brass hadron calorimeter with proportional wire chamber readout, and an accurate muon chamber system. These detectors are installed in a 12 m diameter magnet which provides a uniform field of 0.5 T along the beam direction.

The central tracking chamber (TEC) is a time expansion chamber with high spatial resolution in the plane normal to the beam. A Z-chamber, mounted just outside the TEC, supplements the r/ϕ measurements with z-coordinates.

The material preceding the barrel part of the electromagnetic calorimeter amounts to less than 10% of a radiation length. In this region the energy resolution of the BGO calorimeter is 5% for photons and electrons of energy around 100 MeV, and is better than 2% for energies above 1 GeV. The angular resolution of electromagnetic clusters is better than 0.5° for energies above 1 GeV.

For this analysis, we use the data collected in the following polar angle ranges: for the central tracking chamber $40^\circ < \theta < 140^\circ$; for the electromagnetic calorimeter $42^\circ < \theta < 138^\circ$; and for the hadron calorimeter $5^\circ < \theta < 175^\circ$.

Event Selection

Hadronic events selected with the standard cuts [7] are used for this analysis. In an event photons are selected with $|cos\theta| \leq 0.75$, where θ is the polar angle. The candidate photons in the electromagnetic calorimeter are recognized as isolated energy clusters with a narrow shower shape consistent with that of electromagnetic particles. For this purpose the ratio of the energy measured in a 3×3 crystal array centered at the most energetic crystal to the energy measured in 5×5 array i.e. $\frac{E_9}{E_{25}}$ is required to be greater than 0.95. To ensure that the electromagnetic cluster corresponds to a photon, there should be no charged track within 10 mrad of the electromagnetic cluster in the plane transverse to the beam.

Due to the hard fragmentation and high mass of the b mass, the energy carried by the two photons from a B^0 decay is large. The sum of the two photon energies was required to be more than 25 GeV as shown in Figure 2(a), where combinatorial background is peaked in the backward direction in contrast to the $\mathrm{B}^0 \rightarrow \gamma\gamma$ Monte Carlo events. In addition it was required that the opening angle between the two photons be less than 40° as shown in Figure 2(b). In this case combinatorial background is peaked at the large angles in contrast to the $\mathrm{B}^0 \rightarrow \gamma\gamma$ Monte Carlo events. These cuts reduce the combinatorial background either from the low energy photons or from the opposite hemisphere. The invariant mass of the $\gamma\gamma$ system is reconstructed with photons having a minimum energy of 2 GeV.

Finally in order to identify the $\mathrm{b\bar{b}}$ events from other hadronic events, use of the multidimensional analysis based on a neural network approach described elsewhere [8] was used. Requiring a large value of network response, an enriched sample of $\mathrm{b\bar{b}}$ events can be obtained ($\approx 35\%$ efficiency with $\approx 60\%$ b - purity). It has been checked that the neural network response for $\mathrm{B}^0 \rightarrow \gamma\gamma$ has the same shape as other $\mathrm{b\bar{b}}$ events.

The acceptance calculation is based on a full simulation of the L3 detector [9] allowing for the effect of energy loss, multiple scattering, interactions and decays in the detector material as well as time-dependent detector effects. We use JETSET 7.4 [10] Monte Carlo b-flavor events, requiring the decay chain $\mathrm{B}^0_{\mathrm{d,s}} \rightarrow \gamma\gamma$, for one of the $\mathrm{B}^0_{\mathrm{d,s}}$ mesons. The mass of the $\mathrm{B}^0_{\mathrm{d}}$ and $\mathrm{B}^0_{\mathrm{s}}$ generated in the Monte Carlo are 5279 MeV/c^2 and 5373 MeV/c^2 respectively. The modified Peterson fragmentation function [11] was used as a function of $x_e = 2E_{hadron}/\sqrt{s}$ with the parameter $\epsilon_b = 0.05$. For the background studies a sample of approximately 2.1 million hadronic Z events were generated and simulated using JETSET 7.3 Monte Carlo.

Figure 3(a) shows the $\gamma\gamma$ invariant mass of the $\mathrm{B}^0_{\mathrm{d,s}}$ Monte Carlo events. The gaussian fit is performed to the invariant mass distributions. The mass resolutions obtained are $\sim$ 72 MeV ,where mass difference $\mathrm{M}_{\mathrm{B}^0_{\mathrm{s}}} - \mathrm{M}_{\mathrm{B}^0_{\mathrm{d}}} = 93$ MeV. The acceptance for this process within the mass window of $\mathrm{B}^0_{\mathrm{d,s}}$ is calculated to be $0.23 \pm 0.007 \pm 0.006$ using all preselected events and $0.12 \pm 0.005 \pm 0.007$ with the additional $\mathrm{b\bar{b}}$ selection requirement,where the first error is statistical and the second is systematic. The systematic uncertainties are evaluated by varying the selection criteria as shown in Table 1

Results

Figure 3 shows the invariant mass distribution of the $\gamma\gamma$ system for all events and for the $\mathrm{b\bar{b}}$ enriched sample in data and five flavor $\mathrm{q\bar{q}}$ Monte Carlo events. No candidates are observed within the mass window of $\mathrm{B}^0_{\mathrm{d,s}}$. As one can see from Figure 3(b) the shape of the background

Source	Variation	$\Delta\epsilon_{\mathrm{B^0}\to\gamma\gamma}$
$\frac{E_9}{E_{25}}$	$\pm 1\%$	± 0.0033
Matching Veto	$\pm 20\%$	± 0.0028
Opening Angle	$\pm 10\%$	± 0.0005
Energy sum of two photons	$\pm 5\%$	± 0.0018
$\mathrm{b\bar{b}}$ Selection	$\pm 2\%$	± 0.0035

Table 1: Systematic Uncertainties on the acceptance for $\mathrm{B^0} \to \gamma\gamma$ Monte Carlo events.

is well reproduced by the five flavor $\mathrm{q\bar{q}}$ Monte Carlo events.

Upper limits on the exclusive branching ratio for the $\mathrm{B^0_d}$ and $\mathrm{B^0_s}$ mesons decaying into two photons were obtained using a binned likelihood fit to the $\gamma\gamma$ invariant mass distribution. The background was estimated from the shape of the invariant mass distribution in the data shown in figure 3(c). An exponential function is fitted to the invariant mass distribution in the range 4.4 $\mathrm{GeV/c^2}$ to 6.0 $\mathrm{GeV/c^2}$ and excluding the $\mathrm{B^0_{d,s}}$ mass window. For the signal there are two components, corresponding to $\mathrm{B^0_d}$ and $\mathrm{B^0_s}$, which take into account the overlapping region of $\mathrm{B^0_d}$ and $\mathrm{B^0_s}$ by using the Monte Carlo $\gamma\gamma$ mass distributions. The total likelihood function, is given by:

$$\mathcal{L}(\mu_\mathrm{d}, \mu_\mathrm{s}) = \prod_{\mathrm{i}=1}^{\mathrm{n}} \frac{\mathrm{e}^{-(\mu_\mathrm{b}+\mu_\mathrm{d}+\mu_\mathrm{s})_\mathrm{i}} (\mu_\mathrm{b} + \mu_\mathrm{d} + \mu_\mathrm{s})_\mathrm{i}^{\mathrm{N_i}}}{\mathrm{N_i}!}$$

Where i (i= 1,n) is the number of bins; $\mathrm{N_i}$ are the number of observed events in i bins; μ_b is the background component and μ_d, μ_s are the $\mathrm{B^0_d}$ and $\mathrm{B^0_s}$ signal components respectively. The signal components are given by:

$$\mu_\mathrm{q} = \sum^{\mathrm{q=d,s}} \mathrm{Br(B^0_q} \to \gamma\gamma) \times \mathrm{N_h} \times 2 \times \mathrm{R_{b\bar{b}}} \times \mathrm{f_{b\to q}} \times \epsilon_{\mathrm{B^0_q}\to\gamma\gamma}$$

Where $\mathrm{N_h}$ is the total number of hadronic Z decays, $\mathrm{R_{b\bar{b}}}$ is taken from the L3 measurement [8]. $\mathrm{f_{b\to d,s}}$ is the fraction of $\mathrm{b \to d} = 39.5\%$ and $\mathrm{b \to s} = 12.0\%$ [10], while $\epsilon_{\mathrm{B^0_q}\to\gamma\gamma}$ indicates the selection efficiency of $\mathrm{B^0}$.

The likelihood is mapped as a function of branching ratios $\mathrm{Br(B^0_d} \to \gamma\gamma)$, $\mathrm{Br(B^0_s} \to \gamma\gamma)$ taking in account errors on the acceptance and $\mathrm{R_{b\bar{b}}}$. Varying simultaneously $\mathrm{Br(B^0_d} \to \gamma\gamma)$ and $\mathrm{Br(B^0_s} \to \gamma\gamma)$, gives two dimensional contours for different confidence levels as shown in the figure 4. The one dimensional 90% confidence level upper limits on the $\mathrm{B^0_d}$ ($\mathrm{B^0_s}$) branching ratios are obtained by integrating the likelihood over all the values of $\mathrm{B^0_s}$ ($\mathrm{B^0_d}$) branching ratios. The 90% confidence level limits obtained are

$$\mathrm{Br(B^0_d} \to \gamma\gamma) < 3.8 \times 10^{-5} \qquad \text{at } 90\% \text{ CL.}$$

$$\mathrm{Br(B^0_s} \to \gamma\gamma) < 11.4 \times 10^{-5} \qquad \text{at } 90\% \text{ CL.}$$

A complementary analysis using a multi-dimensional approach has been performed. The $\mathrm{b\bar{b}}$ selection by neural network has been neglected while two more variables were used: the cosine of rest frame angle between the most energetic photon and the $\mathrm{B^0_{d,s}}$ candidate flight direction;

the χ^2 of a constrained fit of the photons pair invariant mass to the $\mathrm{B}^0_{\mathrm{d,s}}$ mass, this fit takes into account the energetic and angular resolutions of the BGO calorimeter.

Probability distributions for each variable were built from a sub-sample of signal and background Monte Carlo. Each event was then given a total probability to be signal or to be background taking the product of the probabilities for each variable. The ratio of these total probabilities has been taken as a discriminating function. The monte Carlo sub-samples used in the training phase and the ones used for the following analysis were different and randomly extracted many times. Two different criteria for choosing the cut on the discriminating function were used, the former setting an *a priori* cut on the number of expected event and the latter from the position of the last event in data, both giving compatible results with the analysis described in this paper.

Conclusion

A search for the exclusive rare decays $\mathrm{B}^0_{\mathrm{d,s}} \to \gamma\gamma$ in 2.95 million hadronic Z decays has been performed. No candidates were observed in data within the mass window of $\mathrm{B}^0_{\mathrm{d,s}}$. Upper limit on these decay modes have been set:

$$\mathrm{Br}(\mathrm{B}^0_{\mathrm{d}} \to \gamma\gamma) < 3.8 \times 10^{-5} \qquad \text{at} \;\; 90\% \;\; \text{CL.}$$

$$\mathrm{Br}(\mathrm{B}^0_{\mathrm{s}} \to \gamma\gamma) < 11.4 \times 10^{-5} \qquad \text{at} \;\; 90\% \;\; \text{CL.}$$

It is noted that there are very few theoretical calculations within the Standard Model. On general considerations large enhancements in these branching fractions are expected from new physics, however there is hardly any reliable quantitative calculation. The present results are the first limits set on the above branching ratios.

Acknowledgments

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Figure 1. Example diagrams responsible for the $B^0 \to \gamma\gamma$ decay. In these diagrams q = u, c, t.

Figure 2. Comparison of a) E_{Total} , where E_{Total} is the total energy of the two photons and b) $\theta_{\gamma\gamma}$, the opening angle between two photons; for combintorial background from data and five flavor $q\bar{q}$ Monte Carlo in contrast with exclusive $B^0 \to \gamma\gamma$ Monte Carlo Events.

Figure 3. The measured $\gamma\gamma$ invariant mass distribution after all the selection cuts for exclusive Monte Carlo a) $B^0_d \to \gamma\gamma$ and $B^0_s \to \gamma\gamma$ decays fiited with gaussain.

The measured $\gamma\gamma$ invariant mass distribution for b) all events and c) $b\bar{b}$ enriched sample,in data and Monte Carlo. The $b\bar{b}$ enriched sample is fitted with an exponential function excluding the $B^0_{d,s}$ mass window shown with dot lines.

Figure 4. Two dimensional conservative contours for different confidence levels for $Br(B^0_d \to \gamma\gamma)$ versus $Br(B^0_s \to \gamma\gamma)$.

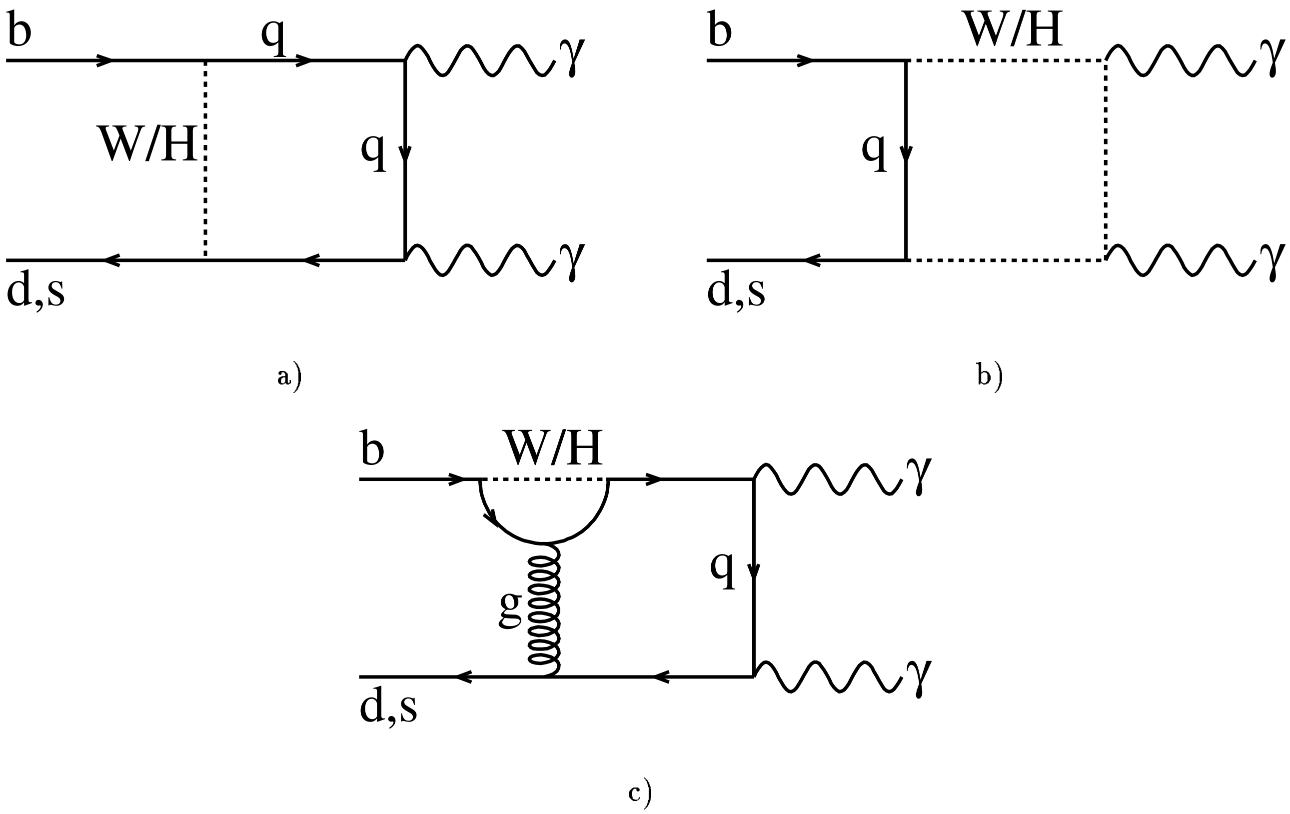
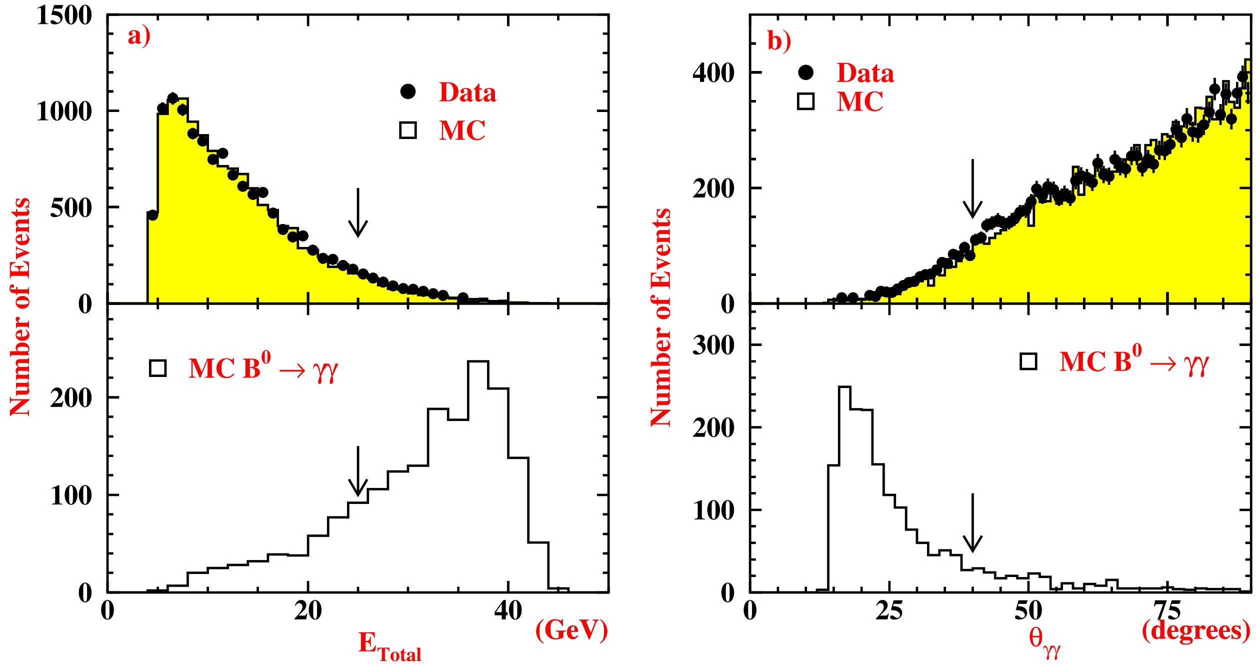
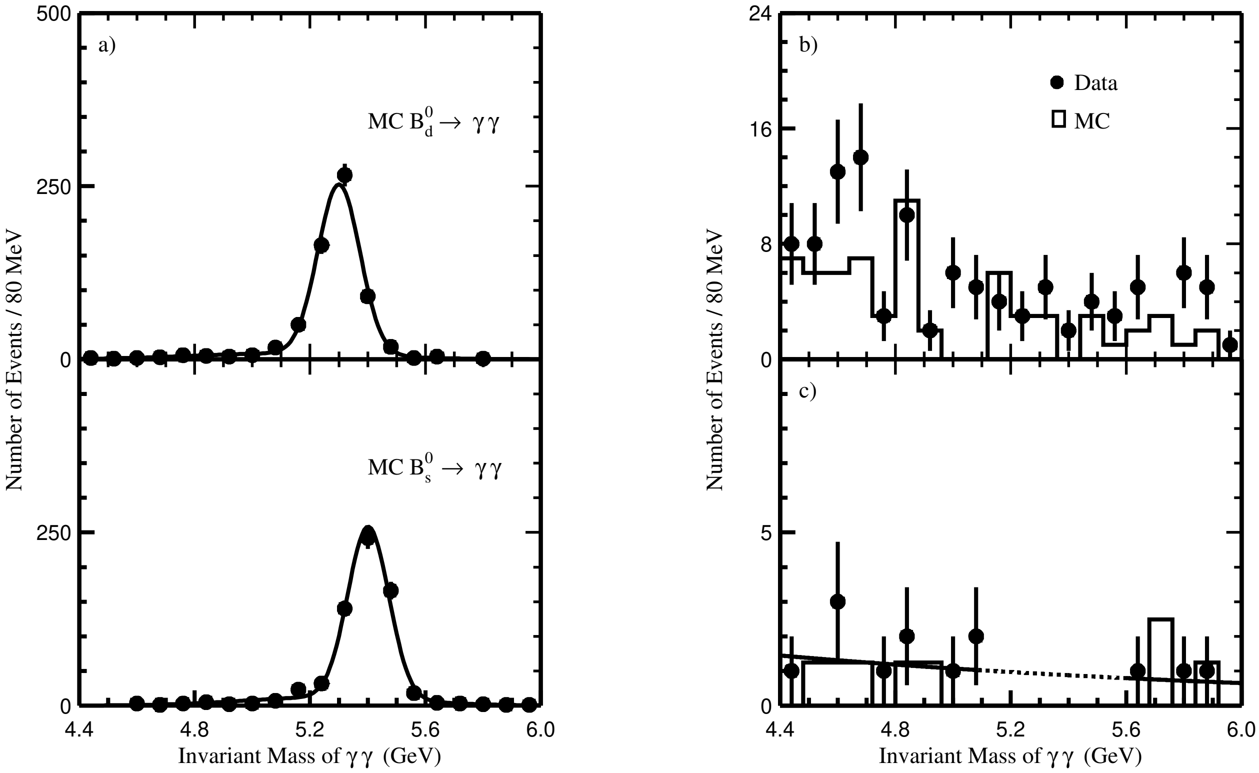


Figure 1



a)
Data
MC
Number of Events
MC $B^0 \to \gamma\gamma$
E_{Total}
(GeV)
b)
Data
MC
Number of Events
MC $B^0 \to \gamma\gamma$
$\theta_{\gamma\gamma}$
(degrees)

Figure 2



a)
MC $B_d^0 \to \gamma\gamma$
MC $B_s^0 \to \gamma\gamma$
b)
Data
MC
c)
Number of Events / 80 MeV
Invariant Mass of $\gamma\gamma$ (GeV)

Figure 3

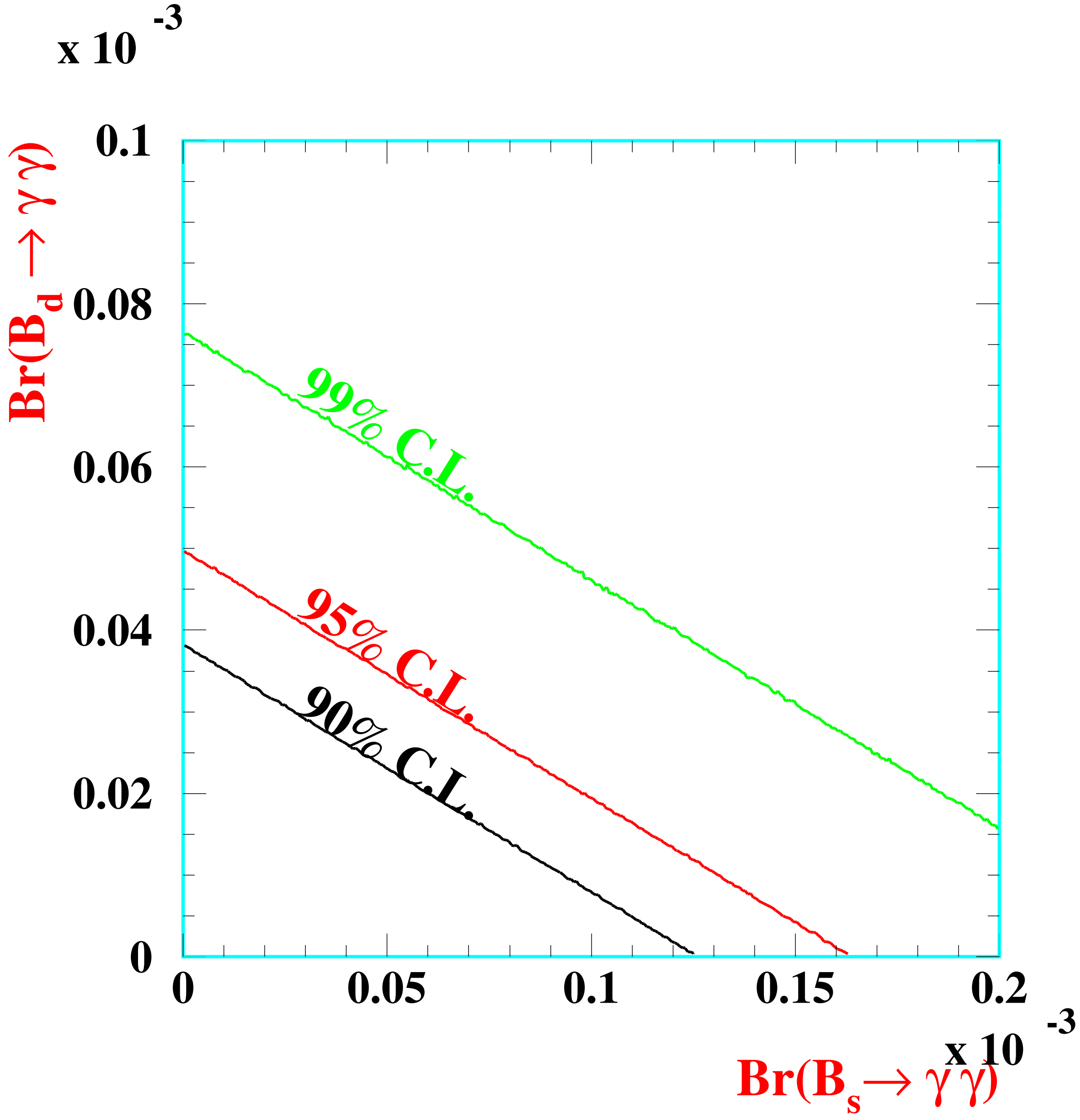

x 10 -3
0.1
0.08
0.06
0.04
0.02
0
$Br(B_d \to \gamma\gamma)$
99% C.L.
95% C.L.
90% C.L.
0
0.05
0.1
0.15
0.2
x 10 -3
$Br(B_s \to \gamma\gamma)$

Figure 4