EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Search for Rare Charmless B Decays at LEP

The L3 Collaboration

Abstract

A search for rare charmless decays of B_d^0 and B_s^0 mesons has been performed in the exclusive channels $B^0_{d(s)} \to \eta\eta$, $B^0_{d(s)} \to \eta\pi^0$ and $B^0_{d(s)} \to \pi^0\pi^0$. More than three million hadronic Z decays collected by the L3 experiment at LEP in the years from 1991 through 1994 have been used. No candidate events have been observed and the following upper limits at 90% confidence level on the branching ratios have been set:

$$\mathrm{Br}(B_d^0 \to \eta\eta) < 4.8 \times 10^{-4},\ \mathrm{Br}(B_s^0 \to \eta\eta) < 1.3 \times 10^{-3},$$

$$\mathrm{Br}(B_d^0 \to \eta\pi^0) < 2.8 \times 10^{-4},\ \mathrm{Br}(B_s^0 \to \eta\pi^0) < 8.9 \times 10^{-4},$$

$$\mathrm{Br}(B_d^0 \to \pi^0\pi^0) < 7.6 \times 10^{-5},\ \mathrm{Br}(B_s^0 \to \pi^0\pi^0) < 1.4 \times 10^{-4}.$$

The $B_d^0 \to \eta\eta$ and all the B_s^0 limits are the first experimental limits, while the $B_d^0 \to \eta\pi^0$ limit improves the existing one by ARGUS.

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Introduction

The high statistics data collected by the LEP experiments allow the study of rare B physics such as rare decays with branching ratios in the $10^{-4} \div 10^{-5}$ range. Moreover, $\mathrm{B_s^0}$'s mesons are produced at the centre-of-mass energy $\sqrt{s} \approx m_{\mathrm{Z}}$, while they are not available at the $\Upsilon(4\mathrm{S})$ centre-of-mass energy. ALEPH, DELPHI and OPAL experiments at LEP have recently searched for decays of B mesons to charmless final states [1] such as:

$$\mathrm{B_d^0} \to \pi^+\pi^-,\ \mathrm{B_d^0} \to \mathrm{K}^+\pi^-,\ \mathrm{B_d^0} \to \mathrm{K}^+\mathrm{K}^-,\ \mathrm{B_s^0} \to \pi^+\pi^-,\ \mathrm{B_s^0} \to \mathrm{K}^+\pi^-,\ \mathrm{B_s^0} \to \mathrm{K}^+\mathrm{K}^-,$$

and charge-conjugate modes. The CLEO experiment at the $\mathrm{e^+e^-}$ collider CESR running at the $\Upsilon(4\mathrm{S})$ centre-of-mass energy has reported on the search for severals $\mathrm{B_d^0}$ decays modes [2], observing such charmless decays in the sum of the two modes $\mathrm{B_d^0} \to \pi^+\pi^-$ and $\mathrm{B_d^0} \to \mathrm{K}^+\pi^-$ [3].

This paper describes the search for rare charmless hadronic decays of $\mathrm{B_d^0}$ and $\mathrm{B_s^0}$ mesons[1)] in the neutral exclusive final states:

$$\mathrm{B_d^0} \to \eta\eta,\ \mathrm{B_d^0} \to \eta\pi^0,\ \mathrm{B_d^0} \to \pi^0\pi^0,\ \mathrm{B_s^0} \to \eta\eta,\ \mathrm{B_s^0} \to \eta\pi^0,\ \mathrm{B_s^0} \to \pi^0\pi^0.$$

The high resolution of the L3 detector for electromagnetic clusters has been exploited in detecting η's and π^0's by means of their decays into pairs of photons.

In the Standard Model [4] these decays can occur through a Cabibbo-suppressed $b \to u$ transition [5] with a further color suppression [6]. One loop diagrams with a heavy quark and a virtual $\mathrm{W}^\pm$ boson are also possible [6, 7]. Contributions can also arise from electroweak penguins [8]. A complete set of diagrams, following Reference [7], is shown in Figure 1.

These decay modes can open a window on new physics beyond the Standard Model. In models with two Higgs doublets additional diagrams with a charged Higgs boson are allowed and can be constructively added to the $\mathrm{W}^\pm$ boson loop [9]. Minimal Supersymmetric extensions of the Standard Model predict superpartners that could affect the expected decay rates [10]. In Table 1 the theoretical prediction of Buccella *et al.* [11], Chau *et al.* [6] and Deandrea *et al.* [12] for the branching ratios of the rare charmless decays of $\mathrm{B_d^0}$, together with the ARGUS [13] limit on $\mathrm{B_d^0} \to \eta\pi^0$ and the preliminary CLEO [2] limit on $\mathrm{B_d^0} \to \pi^0\pi^0$ are quoted. No previous limits exists for $\mathrm{B_s^0}$ decays, nor are there any predictions in extension to the Standard Model.

The search has been performed in 3 088 053 hadronic decays of the Z collected in the years from 1991 through 1994.

Process	Buccella *et al.*	Chau *et al.*	Deandrea *et al.*	Exp. limit (90% C.L.)
$\mathrm{B_d^0} \to \eta\eta$	2.7×10^{-6}	1.4×10^{-5}	$(6.1 \pm 3.0) \times 10^{-8}$	-
$\mathrm{B_d^0} \to \eta\pi^0$	-	4.1×10^{-6}	-	$< 1.8 \times 10^{-3}$
$\mathrm{B_d^0} \to \pi^0\pi^0$	2.6×10^{-6}	1.0×10^{-6}	$(6.4 \pm 3.2) \times 10^{-7}$	$< 1.0 \times 10^{-5}$

Table 1: Theoretical predictions and experimental limits for $\mathrm{B_d^0}$ branching ratios.

The L3 Detector

The L3 detector consists of a central tracking chamber, a high resolution crystals electromagnetic calorimeter, a ring of plastic scintillation counters, a uranium and brass hadron calorimeter

[1)]Throughout this paper all charge conjugate modes are also considered.

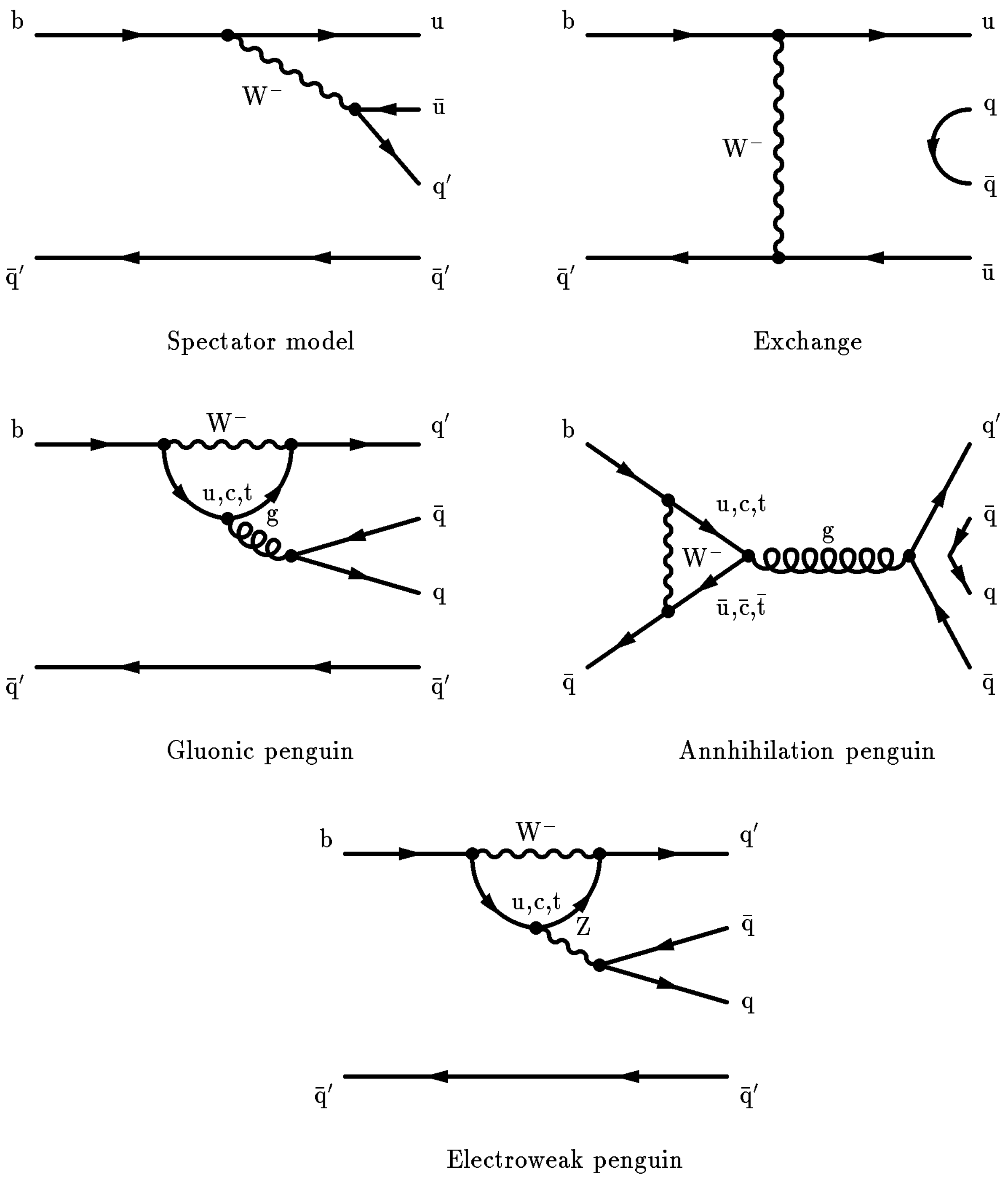

Figure 1: Diagrams involved in $B^0_{d(s)} \to \eta\eta$, $B^0_{d(s)} \to \eta\pi^0$ and $B^0_{d(s)} \to \pi^0\pi^0$ decays. q stands for a u, d or s quark while q′ is either a d or a s quark.

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. Luminosity is measured with forward BGO arrays on each side of the detector. A detailed description of each detector subsystem and its performance is given in Reference [14]. The subdetectors relevant for this analysis are the central tracking chamber and the electromagnetic calorimeter. The central tracking chamber is a time expansion chamber (TEC) which consists of two cylindrical layers of 12 and 24 sectors, with a total of 62 wires measuring the R-ϕ coordinate in a plane normal to the beam direction. The $z-$coordinate is measured by a Z-chamber mounted just outside the TEC.

The electromagnetic calorimeter, placed around the TEC, consists of about 11000 bismuth germanium oxide (BGO) crystals arranged in two half barrels with polar angle coverage $42.3^\circ \leq \theta \leq 137.7^\circ$ (where θ is defined with respect to the beam axis) and two endcaps covering $10.2^\circ \leq \theta \leq 38.2^\circ$ and $141.8^\circ \leq \theta \leq 169.8^\circ$. The energy resolution of the BGO calorimeter is $\simeq 5\%$ for photons and electron of energy around 100 MeV and is less than 2% for energies above 1 GeV. The angular resolution of electromagnetic clusters is better than 0.5° for energies above 1 GeV.

Event simulation

JETSET 7.4 [15] Monte Carlo, based on the Lund parton shower model, was used to generate a total of 30 000 $Z \rightarrow b\bar{b}$ events, 5 000 events in each of the exclusive decay modes:

$$B_d^0 \rightarrow \eta\eta,\ B_d^0 \rightarrow \eta\pi^0,\ B_d^0 \rightarrow \pi^0\pi^0,\ B_s^0 \rightarrow \eta\eta,\ B_s^0 \rightarrow \eta\pi^0,\ B_s^0 \rightarrow \pi^0\pi^0.$$

The b quark on the other side of the event was left free to hadronize and decay according to the JETSET 7.4 tables. The masses of the generated B_d^0 and B_s^0 mesons were respectively 5.279 GeV and 5.373 GeV. The events were then passed through the full L3 simulation[2)] which takes into account the effects of energy loss, multiple scattering, interactions and decays in the detector materials. Also the inefficiencies of TEC and BGO obtained from the data were simulated. The events were then reconstructed with the same program used for the data. These events were used to tune the analysis procedure and calculate the efficiency of the rare decays selection criteria.

The background processes were studied by means of 1.7 million hadronic decays of the Z generated with JETSET 7.3 Monte Carlo and passed through the detector simulation and reconstruction chain already described. In this generation the Standard Model value $\frac{\Gamma_{b\bar{b}}}{\Gamma_{had}} = 0.217$ was used for the fraction of Z decaying to $b\bar{b}$ with respect to the hadronic decays of the Z. The hadronization of the light quarks was described by the Lund symmetric fragmentation function [15] while the Peterson fragmentation function was used to describe the fragmentation of c and b quarks.

Analysis strategy

The hard fragmentation of the b quark gives on average 70% of the beam energy to the B_d^0 or B_s^0 mesons. The decay product η's and π^0's are thus likely to have high momentum and

[2)]The L3 simulation program is based on the GEANT package [16] with the GHEISHA [17] program for the simulation of hadronic interactions.

the photon pairs originating from their decay have a small opening angle. As a conseguence of this the light meson can give a single energy deposition, called *bump* in the following, in the electromagnetic calorimeter. The rare decay modes of B^0_d and B^0_s were thus searched for in four different final configurations, giving the best acceptance and background rejection capability

- $B^0_{d(s)} \to \eta\eta$:
  - four detected photons in the final state,
  - an η giving two detected photons and the other one giving a single bump,
- $B^0_{d(s)} \to \eta\pi^0$:
  - the η detected as two photons and the π^0 as single bump,
- $B^0_{d(s)} \to \pi^0\pi^0$:
  - both π^0 searched for as bumps in the final state.

Two classes of variables are relevant for this analysis: the former concerns the identification of photons and electromagnetic bumps, studying both their purity and kinematics; the latter is the description of the global kinematics of the $B^0_{d(s)}$ meson candidate. The background in the former selection consists of charged tracks with energy deposition in the BGO calorimeter or minimum ionizing particles, while in the latter random combinations of electromagnetic clusters have to be rejected. The photons were selected from clusters in the full BGO angular coverage with lateral shower shapes consistent with electromagnetic energy depositions as expected from test beam studies. A cut on the opening angle between the electromagnetic cluster and the closest track in the TEC was also used. A minimum energy and a minimum number of crystals in the cluster were required. Similar criteria were used for the selection of the single bump from high energy mesons; these bumps are indeed expected to have high energies since the opening angle between the two photons is quite small. Some global kinematic variables give a powerful rejection of the background:

- The opening angle of the two light mesons (Figure 2a) is expected to be small, while for random combinations it is peaked toward large angles.
- The hard fragmentation of the b quark gives high energy to the $B^0_{d(s)}$ meson candidate (Figure 2b), whereas backgroung tends to low energies.
- The angle between the direction of the decay mesons in the $B^0_{d(s)}$ candidate rest frame and the $B^0_{d(s)}$ candidate flight direction is small for the background, while it is expected to be isotropic for the signal.
- In decay mode where the η is detected as a photon pair, a cut on the invariant mass of these photons can be set. A flat invariant mass spectrum is expected for random combinations of electromagnetic clusters (Figure 2c).
- A constrained fit to the $B^0_{d(s)}$ mass, taking into account the electromagnetic calorimeter energetic and angular resolutions has been performed for the $B^0_{d(s)} \to \pi^0\pi^0$ search. The χ^2 of this fit shows high values for background and low ones for signal (Figure 2d).

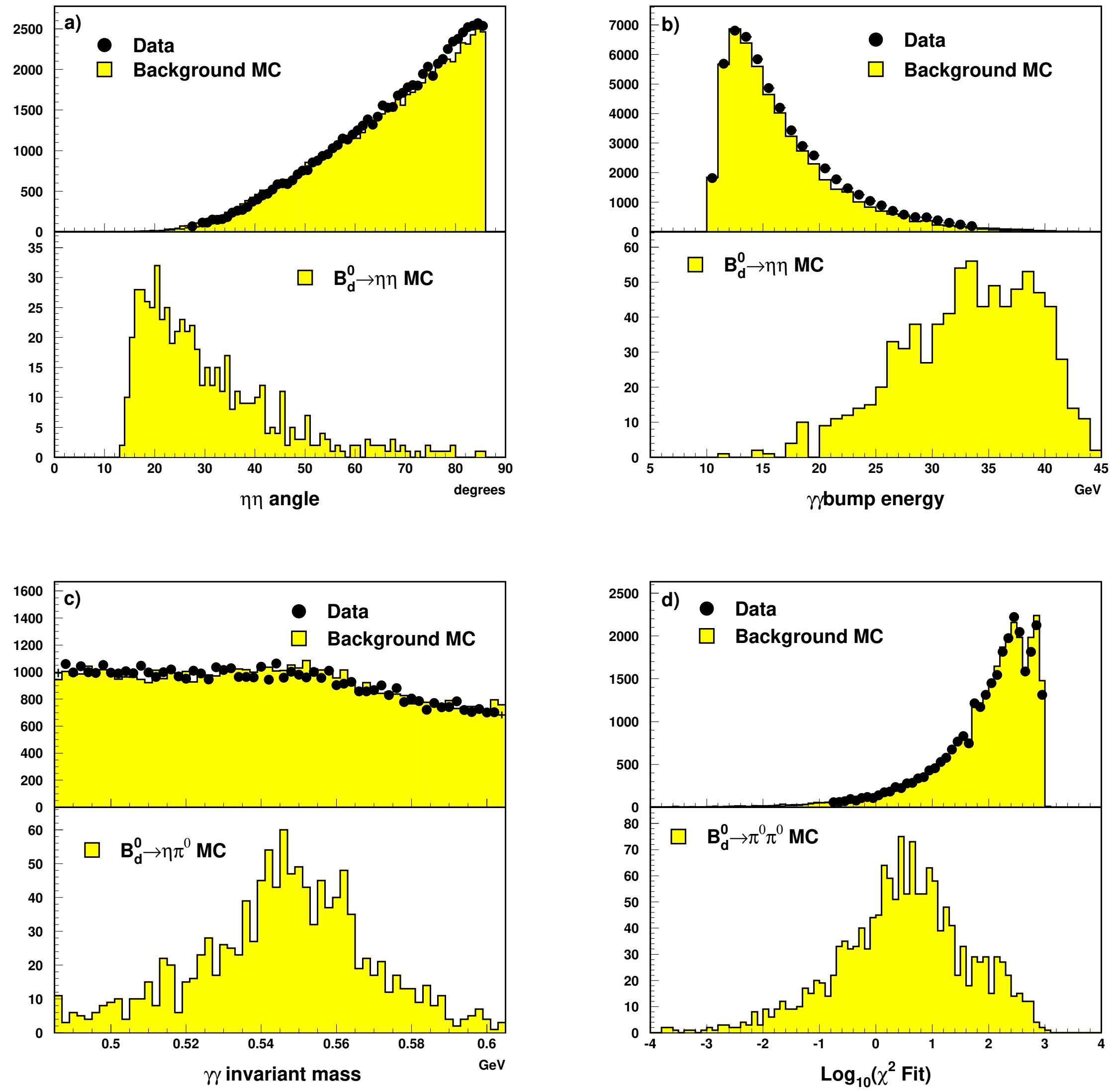

Figure 2: Some selection variables for rare B_d^0 decays for Monte Carlo of the signal, data collected in years from 1991 to 1993 and one equivalent amount of Monte Carlo event. Some preselection cuts are applied. a) Opening angle of the two reconstructed η's of $B_d^0 \to \eta\eta$ in four detected photon final state, b) energy of the B_d^0 candidate in $B_d^0 \to \eta\eta$ decay where one of the η's is detected as a single bump (this requirement chooses high energy B_d^0 events in Monte Carlo), c) invariant mass of the photon pair from the η candidate decay in $B_d^0 \to \eta\pi^0$, d) logarithm of the χ^2 of a costrained fit to the B_d^0 mass for the two bumps in $B_d^0 \to \pi^0\pi^0$.

These cut were optimized for each decay mode. The same procedure was used for the tuning of the cuts for any of the eight exclusive modes studied. After a preselection on the photons and bump variables some loose cuts were fixed and applied on all the variables but one in order to choose its cut.

The energies and the angles of photons from η's decays have been rescaled in order to minimize the χ^2 of a constrained fit to the η mass (547.45 MeV [18]). The invariant mass of all the photons and/or bumps is then studied. A gaussian fit to this invariant mass in the signal Monte Carlo, after the application of the cuts, was performed obtaining the gaussian width σ of the distribution. Then events were counted for data, background Monte Carlo and signal Monte Carlo in a $\pm 2\sigma$ window around the fitted mass of the B meson.

Results

No candidate event was found in data for any of the eight decay modes, so upper limit at 90% confidence level were set as:

$$\mathrm{Br}(\mathrm{B}^0_{\mathrm{d(s)}} \to \eta\eta) < \frac{2.3}{\varepsilon \mathrm{N}_{\mathrm{Hadrons}} \frac{\mathrm{N}_{\mathrm{B}^0_{\mathrm{d(s)}}}}{\mathrm{N}_{\mathrm{Hadrons}}} \mathrm{Br}(\eta \to \gamma\gamma)^2},$$

$$\mathrm{Br}(\mathrm{B}^0_{\mathrm{d(s)}} \to \eta\pi^0) < \frac{2.3}{\varepsilon \mathrm{N}_{\mathrm{Hadrons}} \frac{\mathrm{N}_{\mathrm{B}^0_{\mathrm{d(s)}}}}{\mathrm{N}_{\mathrm{Hadrons}}} \mathrm{Br}(\eta \to \gamma\gamma)\mathrm{Br}(\pi^0 \to \gamma\gamma)},$$

$$\mathrm{Br}(\mathrm{B}^0_{\mathrm{d(s)}} \to \pi^0\pi^0) < \frac{2.3}{\varepsilon \mathrm{N}_{\mathrm{Hadrons}} \frac{\mathrm{N}_{\mathrm{B}^0_{\mathrm{d(s)}}}}{\mathrm{N}_{\mathrm{Hadrons}}} \mathrm{Br}(\pi^0 \to \gamma\gamma)^2},$$

where $\mathrm{N}_{\mathrm{Hadrons}}$ =3 088 053 is the number of Z decaying to hadron selected as described elsewhere [19], ε is the efficiency as calculated from the event counting in signal Monte Carlo, $\mathrm{Br}(\eta \to \gamma\gamma) = 38.8\%$ and $\mathrm{Br}(\pi^0 \to \gamma\gamma) = 98.8\%$ [18], and

$$\frac{\mathrm{N}_{\mathrm{B}^0_{\mathrm{d(s)}}}}{\mathrm{N}_{\mathrm{Hadrons}}} = 2 \times \frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma_{\mathrm{had}}} \times f(\mathrm{b} \to \mathrm{B}^0_{\mathrm{d(s)}})$$

is the $\mathrm{B}^0_{\mathrm{d(s)}}$ yield for hadronic events. In the last formula the following numerical values are used: $\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma_{\mathrm{had}}} = 0.222$ [20], $f(\mathrm{b} \to \mathrm{B}^0_{\mathrm{d}}) = 39.5\%$ and $f(\mathrm{b} \to \mathrm{B}^0_{\mathrm{s}}) = 12.0\%$.
For the $\mathrm{B}^0_{\mathrm{d(s)}} \to \eta\eta$ search the efficiencies for the two final states, one with four detected photons and the other with a photon pair plus a single bump, were added.
The σ of the gaussian fit to the signal Monte Carlo, the efficiency obtained from event counting in $\pm 2\sigma$ window in the same Monte Carlo and the upper limit set with the procedure described in this paper are reported in Table 2.

Conclusions

A search for rare charmless decays of $\mathrm{B}^0_{\mathrm{d}}$ and $\mathrm{B}^0_{\mathrm{s}}$ mesons has been performed in the exclusive modes $\mathrm{B}^0_{\mathrm{d(s)}} \to \eta\eta$, $\mathrm{B}^0_{\mathrm{d(s)}} \to \eta\pi^0$ and $\mathrm{B}^0_{\mathrm{d(s)}} \to \pi^0\pi^0$. No candidate events have been found and upper limits on the branching ratios at 90% confidence level were set as:

$$\mathrm{Br}(\mathrm{B}^0_{\mathrm{d}} \to \eta\eta) < 4.8 \times 10^{-4}, \ \mathrm{Br}(\mathrm{B}^0_{\mathrm{s}} \to \eta\eta) < 1.3 \times 10^{-3},$$

Process	Resolution	Efficiency	Upper limit 90% C.L.
$B_d^0 \to \eta\eta$ (I)	107 MeV	2.5%	
$B_d^0 \to \eta\eta$ (II)	110 MeV	3.3%	
$B_d^0 \to \eta\eta$ (total)		5.8%	$< 4.8 \times 10^{-4}$
$B_d^0 \to \eta\pi^0$	110 MeV	4.1%	$< 2.8 \times 10^{-4}$
$B_d^0 \to \pi^0\pi^0$	126 MeV	5.8%	$< 7.6 \times 10^{-5}$
$B_s^0 \to \eta\eta$ (I)	101 MeV	2.4%	
$B_s^0 \to \eta\eta$ (II)	129 MeV	4.8%	
$B_s^0 \to \eta\eta$ (total)		7.2%	$< 1.3 \times 10^{-3}$
$B_s^0 \to \eta\pi^0$	81 MeV	4.3%	$< 8.9 \times 10^{-4}$
$B_s^0 \to \pi^0\pi^0$	99 MeV	8.3%	$< 1.4 \times 10^{-4}$

Table 2: Resolution (sigma of a gaussian fit to the signal Monte Carlo invariant mass distribution), efficiency and experimental limits for B_d^0 and B_s^0 branching ratios. The (I) and (II) modes refer respectively to the search for a four photon final state or one with a photon pair for one η and a single bump for the other one

$$\mathrm{Br}(B_d^0 \to \eta\pi^0) < 2.8 \times 10^{-4}, \ \mathrm{Br}(B_s^0 \to \eta\pi^0) < 8.9 \times 10^{-4},$$
$$\mathrm{Br}(B_d^0 \to \pi^0\pi^0) < 7.6 \times 10^{-5}, \ \mathrm{Br}(B_s^0 \to \pi^0\pi^0) < 1.4 \times 10^{-4}.$$

In calculating these limits the values $\frac{\Gamma_{b\bar{b}}}{\Gamma_{had}} = 0.222$, $f(b \to B_d^0) = 39.5\%$ and $f(b \to B_s^0) = 12.0\%$ were assumed respectively for the partial decay width of Z in $b\bar{b}$ with respect to hadrons and the fraction of B_d^0 and B_s^0 produced in fragmentation of b quarks at LEP.
The $B_d^0 \to \eta\eta$ and B_s^0 limits are the first ones set, while the $B_d^0 \to \eta\pi^0$ limit improves the existing one.

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