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Rare B Decays at LEP

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Abstract

The study of the B-hadrons Rare Decays is a very important tool to understand the mechanisms of the weak interactions. Recently, the CLEO collaboration has reported evidence for charmless B-hadron decays measuring a branching ratio of the order of 10^{-5}. The four LEP experiments have collected of the order of two million Z^0 decays each, already in the data taken between 1990 and 1993 at $\sqrt{s} = 91.2\ GeV$, meaning 3.2 million B-hadron decays available in the total. Therefore ALEPH, DELPHI, L3 and OPAL are a good place to search for rare B decays since their data is of very high quality and at an energy which allows the production of not only the B_d and B_u mesons but also of the B_s mesons and of the B-baryons as well. The actual situation for the various searches and measurements of the B-hadrons Rare Decays, as given by the four LEP collaborations, is presented in this contribution.

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1 Introduction

The study of the rare decays of b-hadrons is a very important tool to test the Standard Model (SM) and its loop structure, as well as the effective role of Flavour Changing Neutral Currents (FCNC). Figure 1 shows the Feynman diagrams related to those decays. One of the most interesting of them is the channel $b \to s\gamma$[2], which is prohibited at tree level and occurs in FCNC on the loop level through penguin diagrams involving the exchange of a W boson and a t quark[3], as can be seen in figures 1a and 1b. Therefore, the experimental measurement of this branching ratio is also a direct measurement of the penguin diagram. If a definite discrepancy with the SM prediction is found, it will provide a window to physics beyond the SM since in supersymmetry (SUSY) there are additional penguin diagrams involving the exchange of the charged Higgs, the charginos, the gluinos and the neutralinos. It is already known that a significant contribution can arise from the charged Higgs[1]. Predicted branching ratios at the quark level, $b \to s\gamma$, and also at the hadronic level, $B^0 \to K^*\gamma$, $B^s \to \phi\gamma$, $\Lambda_b \to \Lambda^0\gamma$, have been published recently[1],[2]. For the SM it is of the order of 10^{-4} at the quark level and 10^{-5}, with 50% theoretical uncertainties, at the hadronic level. The uncertainties are mainly due to the variations found when using different hadronisation mechanisms.

Charmless decays of beauty hadrons can occur both through tree level diagrams involving $b \to u$ transitions, figures 1c and 1e, and loop diagrams known as *hadronic penguin* diagrams, figures 1d and 1f. In the special cases $B^0 \to \eta\eta$ and $B^0 \to \eta\pi^0$ we also have W exchange diagrams, as can be seen in figures 1g and 1h. In this case, the tree level diagram is colour supressed.

Tree level dominated decays confirm the non zero value of the CKM matrix element V_{ub} while those induced by penguin processes give an indirect measurement of V_{tb}, V_{ts}, V_{td} and provide a clean and sensitive measurement of the physics predicted by the SM and beyond it. The interference term between the penguin and the tree level amplitudes in hadronic charmless b-hadron decays provides a mean to analyse the final state strong interactions[3]. Charmless final states may also originate from rescattering through double charm production. The size of this contribution to the charmless final states can be estimated by studying decays that do not originate from any of the above mentioned diagrams, as $B_d^0 \to K^+K^-$. This is of special relevance for the studies and the interpretation of CP asymmetries in b-hadron decays. Predicted branching ratios for a large number of two body decay modes have been published recently[4].

The CLEO collaboration has reported evidence for charmless b-hadron decays in the talk given by P. Avery in this workshop. They give a branching ratio both for the radiative channel, $BR(B \to K^*\gamma) = (4.5 \pm 1.5 \pm 0.9) \times 10^{-5}$, and for the two body hadronic decays, $BR(B \to \pi\pi) < 2.2 \times 10^{-5}$ and $BR(B \to K\pi) < 1.9 \times 10^{-5}$.

A detailed theoretical review on rare b-hadron decays can be found in the talk given by G. Burdman in the session B of LISHEP95.

[2]Except when mentioned explicitly, all decays given in this paper also include the charge conjugate ones.

[3]In reality there is also a contribution coming from a W boson and a c quark exchange, as well as from a W boson and a u quark exchange, but they are too small compared to the t quark contribution since they depend on the mass of the quark involved in the loop.

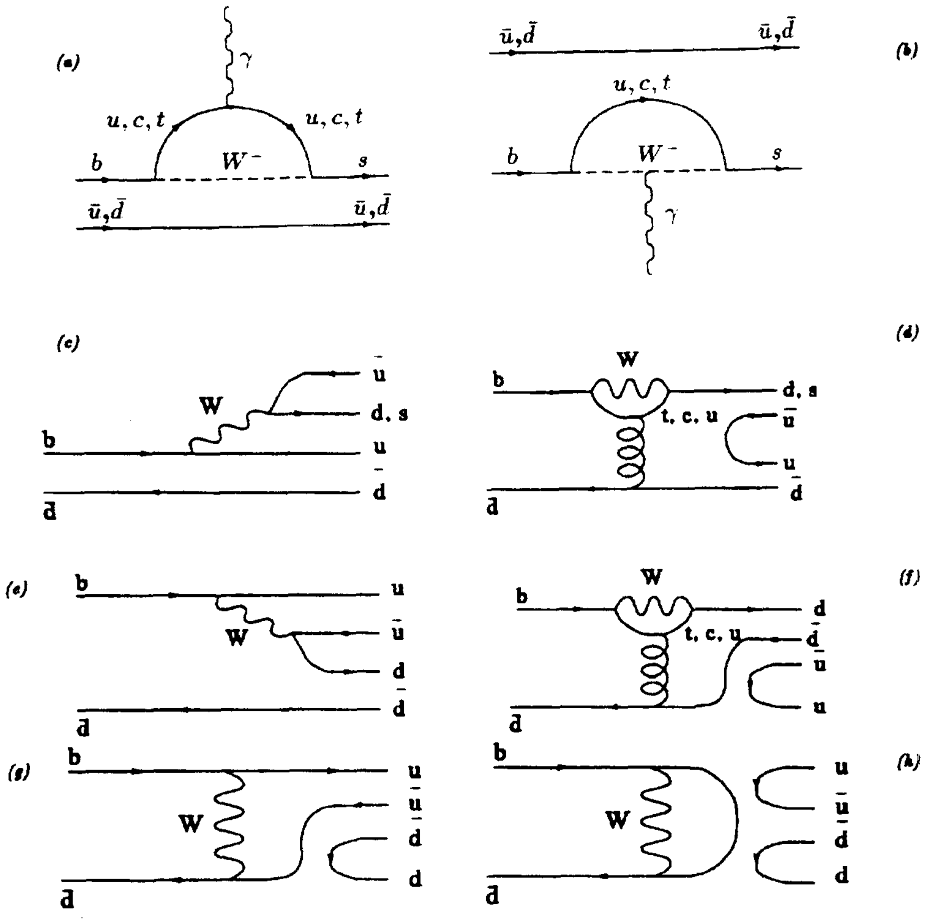

Figure 1: Some Feynmann diagrams involved in the rare decays of b-hadrons. The penguin diagrams from the $b \rightarrow s\gamma$ decay, *(a)*, *(b)*, or the FCNC diagrams with the exchange of a W boson and a u, c, or t quark where the photon can be emitted from the W or one of the quarks in the loop. The tree level diagrams involving $b \rightarrow u$ transitions, *(c)*, *(e)*, the first represents the diagram of the charged decays and the second represents the neutral ones. The hadronic penguin diagram involved in the charged and neutral charmless decays, respectively, *(d)*, *(f)*. The W exchange diagrams involved in the neutral charmless decays, *(g)*, *(h)*.

2 The Experiments

LEP, the Large Electron Positron ring at CERN, is a very good place to search for rare decays of heavy quarks. Between 1990 and 1993 the four experiments, namely, ALEPH, DELPHI, L3 and OPAL, running at the Z^0 mass peak (91.2 GeV center of mass energy), have collected of the order of 2×10^6 Z^0 hadronic decays per experiment or 8×10^5 b-hadron decays per experiment reaching the necessary statistics required by the predictions of the SM. The data cc ied in 1994 plus the one being collected in 1995 shall double this statistics.

The four LEP experiments are delivering not only high statistics data, but also high quality data. Good track detection using ionization chambers (TPC in ALEPH and DELPHI, a jet chamber - TEC - in L3 and drift chambers in OPAL) and silicon microvertices, all attached to a careful reconstruction through a high quality software, developed by the teams of physicists in each the experiment, allow the reconstruction of the interaction point and of the secondary decays present in the event together with a good particle identification using dE/dx measurements. All experiments are covered by muon chambers in the 4π solid angle, therefore muon identification, and $\pi - \mu$ sepparation, is assured as well as the b-tagging via a high p_t muon. Electrons and photons are measured in the eletromagnetic calorimeters (EMC), also covering the 4π solid angle except for the cracks due to cabling and mechanical support. Each experiment has contructed its EMC using a very different technique. The ones from DELPHI and L3 are the first of its type constructed in the world. Again the b-tagging via a high p_t electron is assured and the good energy measurement and electron-photon separation allows the study of the channel $b \to s\gamma$, so interesting to us in this subject. Adding to all of this, DELPHI has a ring imaging Cĕrenkov (RICH) detector divided in two parts, one filled with a gas radiator and the other with a liquid radiator. The gas radiator detector gives the $\pi - K - p$ separation in the momentum range 3 GeV/c to 20 GeV/c and the liquid one the $\pi - K - p$ separation in the range 20 GeV/c to 50 GeV/c, covering, together with the dE/dx information from the TPC, the full momentum range of the particles produced in the e^+e^- interactions. Details of each detector, for each experiment, can be found in reference [5].

Each experiment has its own criteria to separate, first, the Z^0 hadronic decays from the $Z^0 \to e^+e^-$, $Z^0 \to \mu^+\mu^-$, $Z^0 \to \tau^+\tau^-$ ones, beam gas and cosmic ray events, and then select the b-decays among them. Such criteria mixes quality cuts, like requiring a minimum momentum for the charged tracks in order to have a high detection efficiency, and event characteristics cuts, like minimum multiplicity for the hadronic selection and event shape variables (thrust, oblateness, acoplanarity) for the b-selection. The secondary vertex reconstruction is also very important in the selection of the b-hadron events. A detailed description of all cuts used in the different analysis presented here can be found in references [6] a [13]. The background has always been calculated using the LUND Monte Carlo generator[14], including either the full detector simulation or corrections and smearing to reproduce the real data set. Several studies have been made, channel per channel, in order to assure the Monte Carlo events agree and reproduce well the data. In cases where it did not happen, special corrections were applied. All simulated events passed through the full reconstruction chain and selection criteria of the corresponding experiment. They where then taken to study the cuts, the vertex fitting procedure, the selection efficiencies for each decay channel of the B hadrons we are analysing here, and also to lead to a decision of which is the best selection criteria to be applied to each data sample. Details on the simulation used by each experiment can again be found in references [6] a [13].

3 The Search for the Channel $b \to s\gamma$

When making theoretical calculations it is "*easy*" to calculate the branching ratio for $b \to s\gamma$ but since we can not detect free quarks, experimentalists have to deal with decays like

$$B^0 \to K^*\gamma \qquad B_s \to \phi\gamma \qquad \Lambda_b \to \Lambda\gamma .$$

To reach the $b \to s\gamma$ level, it is necessary to measure the branching ratio of all b-hadrons going to any hadron formed by one or more strange quark(s) plus a photon and this is the goal the four LEP experiments want to reach. On the other side, theorists are working hard to understand the hadronisation mechanisms involved in building a hadron from a given quark to have results which can be compared directly to each branching ratio measurement of each b-hadron decaying into a photon plus anything having at least one strange quark. The situation of such calculations nowadays shows that results can differ by 50% depending on the hadronisation model applied to it. In other words, we have a lot to learn from the measurement of the rare b-hadron decays.

Here we will separate the branching ratio measurements per decay type and will describe shortly the selection criteria used to emphasize the signal and suppress the enormous background.

The decay $B_s \to \phi\gamma$, where the ϕ decays as $\phi \to K^+K^-$, was studied by ALEPH and DELPHI.

ALEPH[7] uses both photons detected by their EMC, named ECAL, and reconstructed from their conversion electrons detected in the TPC. The photon must be in the region fully covered by ECAL and TPC, namely $16^0 < \theta_\gamma < 164^0$ or $|\cos\theta_\gamma| < 0.96$, where θ_γ is the angle the photon has with respect to the beam axis (the z direction). If a converted photon is used, it is required that at least one of the electrons is well identified and its trajectory in the TPC has left at least 4 ionization points. For a photon measured by ECAL an algorithm based on the information of the 12 modules, each made of the 45 lead plates interspaced with planes of proportional tubes, is used[15]. Only clusters selected as single photons are taken.

The photon energy, E_γ, must be larger than 3 GeV because the B_s is expected to have a momentum of the order of 40 GeV/c. The ϕ is reconstructed from its decay channel $\phi \to K^+K^-$, where at least one of the kaons must be well identified from the dE/dx information and the momentum of each kaon must be larger than 250 MeV/c to assure a good detection and reconstruction in the TPC. The mass of the reconstructed ϕ meson is taken from the Particle Data Group (PDG) with a window of 6 MeV/c^2, or $\Delta m = \pm 6\ MeV/c^2$. The efficiency recontruction obtained is $\epsilon_\phi = (50 \pm 1)\%$.

To reconstruct the B_s a combination of the ϕ candidates with the photons is performed. A cut on θ_{boost}, $|\cos\theta_{boost}| \leq 0.7$ ($\theta_{boost} \geq 45^0$), where θ_{boost} is the angle of the kaon with respect to the B_s direction on the ϕ rest frame, is used in order to cut the combinatorial background taking into account that the decay channel being analysed is the decay of a pseudoscalar meson into a vector meson and a gamma ray, with the subsequent decay of the vector into two pseudoscalar particles. A further cut on the angle between the ϕ and the γ in the lab-frame is done, $\cos\theta_{(\phi,\gamma)} \geq 0.85$ and the reconstructed B_s momentum to be above 25 GeV/c. An algorithm is used to check if the decay in the other hemisphere of the event was also originated from a b-hadron. Since the LEP experiments work on the Center of Mass frame, the reaction $e^+e^- \rightarrow Z^0 \rightarrow b\bar{b}$ originates two back-to-back jets with a b-hadron in each of them, therefore if e divide the event into two hemispheres by a line perpendicular to the *thrust axis* (the direction of the b and the $\bar{b}$ when they are produced from the Z^0 decay) and a B hadron decay is found in one of these hemispheres, we are sure we have another one in the other hemisphere. The B_s candidates are taken from combinations with invariant mass between 5 GeV/c^2 and 5.7 GeV/c^2 (2.5σ). The overall B_s reconstruction efficiency is $(17 \pm 1)\%$. A sample of about 1.8×10^6 hadronic Z^0 decays together with about 2×10^6 $Z^0 \rightarrow q\bar{q}$ Monte Carlo decays were analysed. As it can be seen in figure 2, no candidate in both data and Monte Carlo samples survived in the region of interest. The upper limit for the branching ratio for this decay was calculated by the following formula:

$$BR(B_s \rightarrow \phi\gamma) = \frac{N_{obs}}{N_{Z^0} * \frac{\Gamma(Z^0 \rightarrow b\bar{b})}{\Gamma(Z^0 \rightarrow hadrons)} * 2 * f_s * BR(\phi \rightarrow K^+K^-) * \epsilon_{B_s}} \qquad (1)$$

where:

- $N_{obs} < 2.3$ is the upper limit on the number of candidates in the signal mass region at 90% Confidence Level (CL).
- $N_{Z^0} = 1,836,687$ is the number of Z^0 events analysed,
- $\frac{\Gamma(Z^0 \rightarrow b\bar{b})}{\Gamma(Z^0 \rightarrow hadrons)} = 0.217$
- the factor 2 comes from the fact that we have two b-hadron decays per Z^0 event,
- $f_{B_s} = 0.12$ takes into account the production rate for B_s^0
- $BR(\phi \rightarrow K^+K^-) = (49.1 \pm 1.1)\%$
- $\epsilon_{B_s} = (17 \pm 1)\%$ is the Monte Carlo efficiency for the considered decay.

Thus, the upper limit for the branching ratio is calculated to be:

$$BR(B_s \rightarrow \phi\gamma) < 2.9 \times 10^{-4} \qquad at \quad 90\% \; C.L.$$

DELPHI[9] has used only the region given by $45^0 < \theta_\gamma < 135^0$ corresponding to the region covered by the High Projection Chamber (HPC), their barrel EMC. The gas sampling technique used in the HPC provides a three-dimensional charge distribution measurement with high granularity. An algorithm[16] is used in order to combine all shower(s) information from the HPC with the information from the TPC+OD+RICH. The TPC register the charged tracks in the event, being essencial to disantangle electrons from photons. Photons can pre-shower in the RICH or before it due to the material represented by the walls of the detectors plus the liquid in the RICH. The electrons produced in this pre-shower process leave a signal in the OD (Outer Detector, a wire

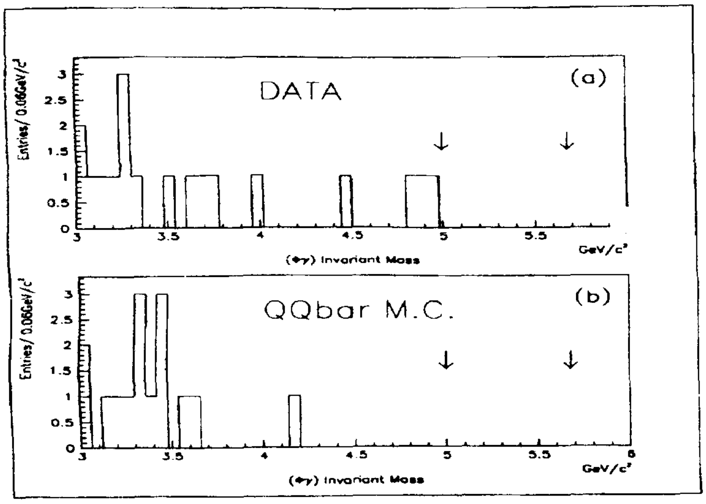

Figure 2: The ALEPH $\phi\gamma$ invariant mass for *(a)* the data and *(b)* the $q\bar{q}$ Monte Carlo events. The arrows show the mass signal region for the B_s.

chamber just before the HPC) giving a very characteristic cluster of signals. The TPC also register the electrons coming from converted photons. Thus this algorithm, called PXPHOT, combines all these giving as output the reconstructed and identified photon and its energy and coordinate points. It also reconstructs and identifies electrons and π^0.

The ϕ was reconstructed through the decay channel $\phi \rightarrow K^+K^-$ where each kaon was identified by a combination of the dE/dx measurement, the RICH identification and the veto from HPC and from the Muon Chambers. Each kaon was required to have a momentum above 2 GeV/c. The decay vertex was fitted by a special algorithm[17] to reconstruct V0 decays in DELPHI. The angle between the two kaons was required to be larger than 0.08 radians in order to suppress the combinatorial background. Only decays with a length larger than 3 cm and with its reconstructed mass 1.5 σ far from the nominal PDG value, at most, were taken.

The invariant mass of the $\phi\gamma$ pair was computed by tracking the photon from the center of gravity of the reconstructed shower to the ϕ vertex. The energy of the $\phi\gamma$ system was required to be larger than 25 GeV and not to exceed the beam energy[4]. Figure 3a shows the invariant mass for the $\phi\gamma$ system. The histograms of real data and Monte Carlo were normalized to the same total number of real hadronic events. Only events with an angle between the ϕ and γ smaller than 35^0 and in the mass window $4.9\ GeV/c^2 < m_{B_s} < 5.6\ GeV/c^2$ were accepted. One million Z^0 hadronic events and two million simulated ones were used in this analysis[5]. It can be seen that no excess of events was found in the signal region. The upper limit for the branching ratio is calculated using the equation (1) with

- $N_{obs} < 2.3$

[4]LEP runs at the Z^0 mass peak, namely 45.6 GeV of energy per beam, but there is also a scan around the Z^0 peak which means, sometimes the beam energy can vary between 42.6 GeV and 48.6 GeV.

[5]Only the data taken in 1991 and 1992.

- $N_{Z^0} = 10^6$
- $\frac{\Gamma(Z^0 \to b\bar{b})}{\Gamma(Z^0 \to hadrons)} = 0.221$
- $f_{B_s} = 0.12$
- $BR(\phi \to K^+K^-) = (49.1 \pm 0.9)\%$
- $\epsilon_{B_s} = 4\%$

Thus, the upper limit for the branching ratio is calculated to be:

$$BR(B_s \to \phi\gamma) < 13.0 \times 10^{-4} \qquad at \quad 90\% \; C.L.$$

DELPHI[9] used the same analysis described above to search also for the decays

$$B^0 \to K^{*^0}(892)\gamma \qquad K^{*^0} \to K^{\pm}\pi^{\mp}$$

$$B^- \to K_1^-(1270)\gamma \qquad K_1^- \to K^-\rho$$

$$B^0 \to K_2^{*^0}(1430)\gamma \qquad K_2^{*^0} \to K^{\pm}\pi^{\mp}$$

profiting all the information delivered by the RICH and the V0 reconstruction tool. Figure 3b-3d show the invariant mass distribution for the combinations $K^{*^0} \to K^{\pm}\pi^{\mp}$, $K_1^- \to K^-\rho$ and $K_2^{*^0} \to K^{\pm}\pi^{\mp}$. Again an opening angle of 35^0 was required for the decay products of the B mesons given above. The same mass region as for the B_s was taken. The results, for the decay $B^0 \to K^{*^0}(892)\gamma$ are:

- $N_{obs} < 2.9$ (from figure 3b)
- $N_{Z^0} = 10^6$
- $\frac{\Gamma(Z^0 \to b\bar{b})}{\Gamma(Z^0 \to hadrons)} = 0.221$
- $f_{B^0} = 0.39$
- $BR(K^{*^0}(892) \to K^{\pm}\pi^{\mp}) =\approx 100\%$
- $\epsilon_{B_s} = 4\%$

Thus, the upper limit for the branching ratio is calculated to be:

$$BR(B^0 \to K^{*^0}(892)\gamma) < 3.0 \times 10^{-4} \qquad at \quad 90\% \; C.L.$$

For the decay $B^- \to K_1^-(1270)\gamma$:

- $N_{obs} < 3.5$ (from figure 3c)
- $N_{Z^0} = 10^6$
- $\frac{\Gamma(Z^0 \to b\bar{b})}{\Gamma(Z^0 \to hadrons)} = 0.221$
- $f_{B^-} = 0.39$
- $BR(K_1^-(1270) \to K^-\rho) = (42 \pm 6)\%$
- $\epsilon_{B_s} = 4\%$

Thus, the upper limit for the branching ratio is calculated to be:

$$BR(B^- \to K_1^-(1270)\gamma) < 21.0 \times 10^{-4} \qquad at \quad 90\% \ C.L.$$

For the decay $B^0 \to K_2^{*0}(1430)\gamma$:

- $N_{obs} < 8.1$ (from figure 3d)
- $N_{Z^0} = 10^6$
- $\frac{\Gamma(Z^0 \to bb)}{\Gamma(Z^0 \to hadrons)} = 0.221$
- $f_{B^0} = 0.39$
- $BR(K_2^{*0}(1430) \to K^{\pm}\pi^{\mp}) = (93 \pm 10)\%$
- $\epsilon_{B_s} = 4\%$

Thus, the upper limit for the branching ratio is calculated to be:

$$BR(B^0 \to K_2^{*0}(1430)\gamma) < 18.0 \times 10^{-4} \qquad at \quad 90\% \ C.L.$$

ALEPH[7] has also repeated the analysis done for the decay $B_s \to \phi\gamma$ to search for a b-baryon decay, namely the $\Lambda_b \to \Lambda^0\gamma$. A Λ^0 reconstruction was done with a JADE algorithm. A veto identification was used for the proton and the pion coming for the Λ^0. All combinations with momentum above 5 GeV/c, whose decay products had an angle of 18^0 or more in the Λ^0 center of mass, were taken. A mass window of 5σ around the nominal PDG value for the Λ^0 mass was used. The Λ_b reconstruction followed the B_s selection. In this case, the momentum was accepted to be a bit smaller, $p_{\Lambda_b} > 20\ GeV/c$, instead of the 25 GeV/c required for the B_s and, of course, the mass window was different, $5.3\ GeV/c^2 < m_{\Lambda_b} < 6.0\ GeV/c^2$. Figure 4 shows the mass distribution for this decay. Again no candidate was found and the results are:

- $N_{obs} < 2.3$
- $N_{Z^0} = 1.836,687$
- $\frac{\Gamma(Z^0 \to b\bar{b})}{\Gamma(Z^0 \to hadrons)} = 0.217$
- $f_{\Lambda_b} = 0.08$
- $BR(\Lambda^0 \to p\pi) = 64.1\%$ $\qquad \epsilon_{\Lambda^0} = (32 \pm 1)\%$
- $\epsilon_{B_s} = (10.1 \pm 1.1)\%$

Thus, the upper limit for the branching ratio is calculated to be:

$$BR(\Lambda_b \to \Lambda^0\gamma) < 5.6 \times 10^{-4} \qquad at \quad 90\% \ C.L.$$

L3[11] has done a very different analysis compared to DELPHI and ALEPH. They have looked for the *inclusive decay* $b \to s\gamma$. In other words, they select all b-hadron decays which goes to any particle having at least one strange quark plus a photon. Since they have the barrel EMC made of BGO crystals and capable to measeure photons in the energy range $100\ MeV < E_\gamma < 100\ GeV$ and with a very high spatial resolution, all their

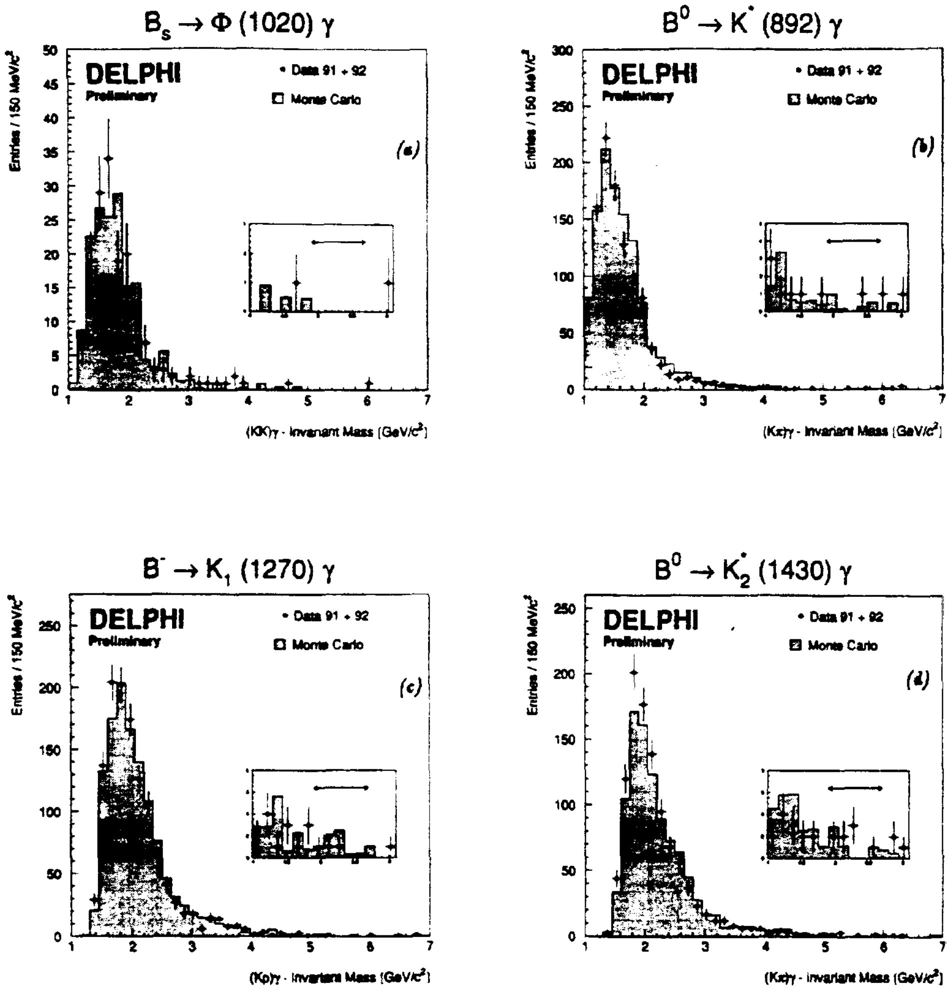

Figure 3: The DELPHI invariant mass distribution for the channels *(a)* $\phi\gamma$, *(b)* $K^*(892)\gamma$, *(c)* $K_1(1270)\gamma$ and *(d)* $K_2^*(1430)\gamma$. The histograms of real data and Monte Carlo were normalized to the same total number of hadronic events.

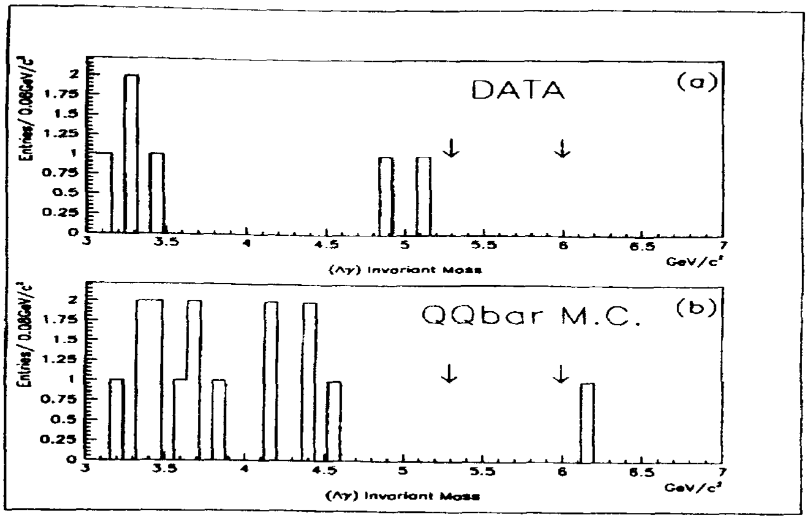

Figure 4: The ALEPH $\Lambda\gamma$ invariant mass for *(a)* the data and *(b)* the $q\bar{q}$ Monte Carlo events. The arrows show the mass signal region for the Λ_b.

hadronic selection is based in the information delivered by this detector. Details of this selection can be found in reference [11].

The angular region taken was the barrel, $44^0 < \theta_\gamma < 136^0$. The photon was select following the L3 algorithm to compare the energy deposited in each BGO crystal with the predicted energy of an eletromagnetic shower. The behavior of the distribution of the energy in the BGO crystals hit by the shower was also considered. To select the b-hadron decay, the thrust axis of the event was required to be 45^0 or more far from the beam axis, assuring the event is full contained in the barrel region. The nearest jet to the photon was asked to have a multiplicity smaller than 5. The direction of the b-hadron was taken to be the direction of the thrust axis, simulation studies showed this implies in an error of (30.1 ± 0.1) $mrad$. The mass of the b-hadron was calculated by the formula

$$m_b^2 = 2E_\gamma^2 \left(\frac{\sin\theta_1}{\sin\theta_2}\right)(1 - \cos(\theta_1 + \theta_2))$$

where θ_1 is the angle between the photon and the thrust axis, θ_2 is the angle between the nearest jet to the photon and the thrust axis. The direction of flight of this jet is calculated by $\vec{p}_J = (m_B\sqrt{\gamma^2 - 1})\vec{n}_{thr} - \vec{p}_\gamma$, with $m_B = 5.3\ GeV/c^2$, the Lorentz factor $\gamma = 6.6$ and $\vec{n}_{thr}$ the unitary vector indicating the thrust direction. Since the photon should be emitted isotropically in the b-hadron rest frame and the b-hadron mass is expected to be centered at $5.3\ GeV/c^2$, two further cuts where applied:

$$-0.8 < \cos\theta_\gamma^* < 0.5 \qquad\qquad 1.8\ GeV < E_\gamma^* < 3.8\ GeV$$

together with a cut on the p_t of the photon with respect to the thrust axis to eliminate final state radiation events:

$$p_t < 3.4\ GeV/c.$$

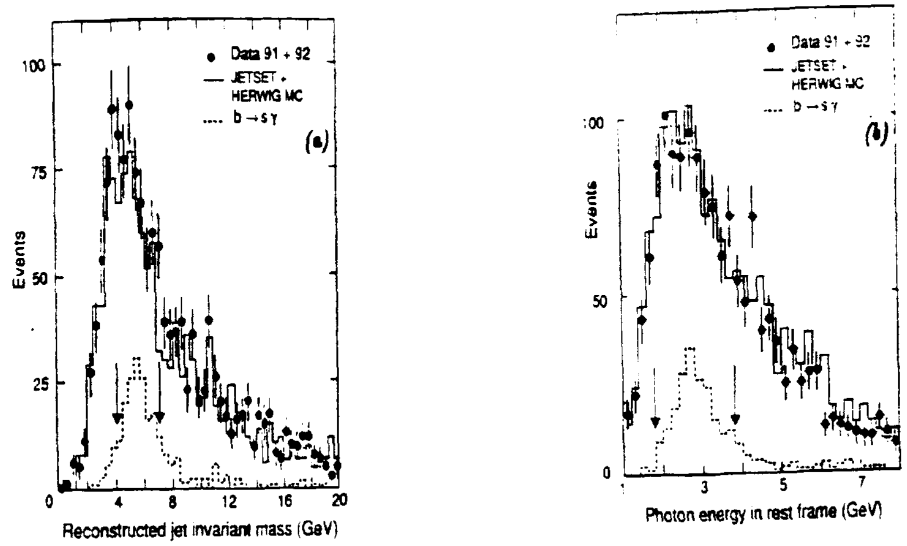

Figure 5: The L3 reconstructed photon energy in the b-hadron rest frame *(a)* and invariant mass distribution for the b-hadron candidate *(b)*, together with the expected background and signal events. The candidates are the events contained between the arrows in both histograms.

The reconstructed photon energy in the b-hadron rest frame and the invariant mass distribution for the b-hadron candidate are shown in figure 5 together with the expected background and signal events. 88 events were found in the data sample where (85.9 ± 9.0) events were expected from background. The upper limit for the branching ratio was calculated by

$$BR(b \to s\gamma) = \frac{N_{obs}}{N_B * \epsilon_b}$$

where

- $N_{obs} < 20.80$ is the upper limit on the number of candidates in the signal mass region at 90% Confidence Level (CL)
- $N_B = 2 * BR(b \to B^0, B^{\pm}, B_s, b - baryon) * \frac{\Gamma_{b\bar{b}}}{\Gamma_{hadrons}} * N_{hadrons} = (394508 \pm 17009)$ is the number of b-hadron decays
- $\epsilon_b = (5.2 \pm 0.7)\%$ is the signal detection efficiency, giving

$$BR(b \to s\gamma) < 1.20 \times 10^{-3} \qquad at \quad 90\% \ C.L.$$

A summary of all upper limits obtained in the search for the channel $b \to s\gamma$ is given in table 1.

Decay Channel	Experiment	BR ($\times$ 10^{-4})
$B_s^0 \to \phi\gamma$	ALEPH[7]	< 2.9 *at* 90% $C.L.$
	DELPHI[9]	$< 13.$ *at* 90% $C.L.$
$B^0 \to K^{*^0}(892)\gamma$	DELPHI[9]	< 3.0 *at* 90% $C.L.$
$B^- \to K_1^-(1270)\gamma$	DELPHI[9]	$< 21.$ *at* 90% $C.L.$
$B^0 \to K_2^{*^0}(1430)\gamma$	DELPHI[9]	$< 18.$ *at* 90% $C.L.$
$\Lambda_b \to \Lambda^0\gamma$	ALEPH[7]	< 5.6 *at* 90% $C.L.$
$b \to s\gamma$ *(inclusive)*	L3[11]	$< 12.$ *at* 90% $C.L.$
$B^0 \to K^{*^0}(892)\gamma$	CLEO[18]	$0.40 \pm 0.17 \pm 0.08$
$B^- \to K^{*^-}(892)\gamma$	CLEO[18]	$0.57 \pm 3.1 \pm 1.1$
$b \to s\gamma$	CLEO[19]	$2.32 \pm 0.57 \pm 0.35$
$b \to s\gamma$	theory[1],[2]	2 – 5

Table 1 - Upper limits for radiative FCNC processes in b-hadron decays, except for L3, CLEO and the theoretical calculations. All results are preliminary.

4 The Search for $b \to u(d)$ transitions

The search for $b \to u(d)$ transitions was done via many different b-hadron decay channels. Each experiment looked for two or more decay channels in the same analysis and, most of the time, they were different for different experiments. The selection criteria used had many things in common with the selection done in the search for $b \to s\gamma$ type decays. The upper limit for branching ratios was calculated in the same way. Therefore, we will describe, shortly, the analysis done, experiment per experiment, and give the limits for each branching ratio in table 5, at the end of all descriptions.

L3[12] has search for the decays $B^0 \to \eta\eta$ and $B^0 \to \eta\pi^0$. Figures 1e-1h show the penguin and other diagrams which can give a significant contribution to these decays. Figures 1c-1d show the diagrams involved in the charged decays of the B^0. A comparisson between those figures easily shows the $B^0 \to \eta\eta$ and $B^0 \to \eta\pi^0$ decays are color suppressed with respect to the channel $B^0 \to \pi^+\pi^-$ and L3 has taken advantage of the high resolution their EMC offers to reconstruct π^0 and η to look for such decays. A candidate event for the channel $B^0 \to \eta\eta$ was selected if it had 4 photons with a minimum energy of $0.2\ GeV$ each and were isolated, at least, by 1.7^0 from the most neighbouting charged track. The η were taken as a combination of the 2 photons where $0.51\ GeV/c^2 < M_{\gamma\gamma} < 0.58 GeV/c^2$ and with an angle between them shorter than 57^0. Its signal should be registered by at least 3 crystals in the BGO calorimeter and the χ^2 of the fit was required to be less than 10. The B^0 was taken if its energy was above 17 GeV and the angle between the two η was smaller than 86^0. To be sure the two η were full contained in the calorimeter region, another cut was imposed, namely, the angle between the η in the

B^0 rest frame and the B^0 flight direction to be larger than 45^0. At the end, a so called *purity cut*, $(\cos\theta_{\eta B^0} - 0.7) * (E_{B^0} - 17.). -0.95\ GeV$. was applied. Figure 6a shows the mass distribution obtained for the Monte Carlo events generated with 5 quark flavours in order to study the background. Figure 6b shows the same distribution obtained from the 1.194527 hadronic Z^0 analysed. Figure 6c shows the expected signal obatined from a special Monte Carlo for the decay $B^0 \to \eta\eta$. No event was found.

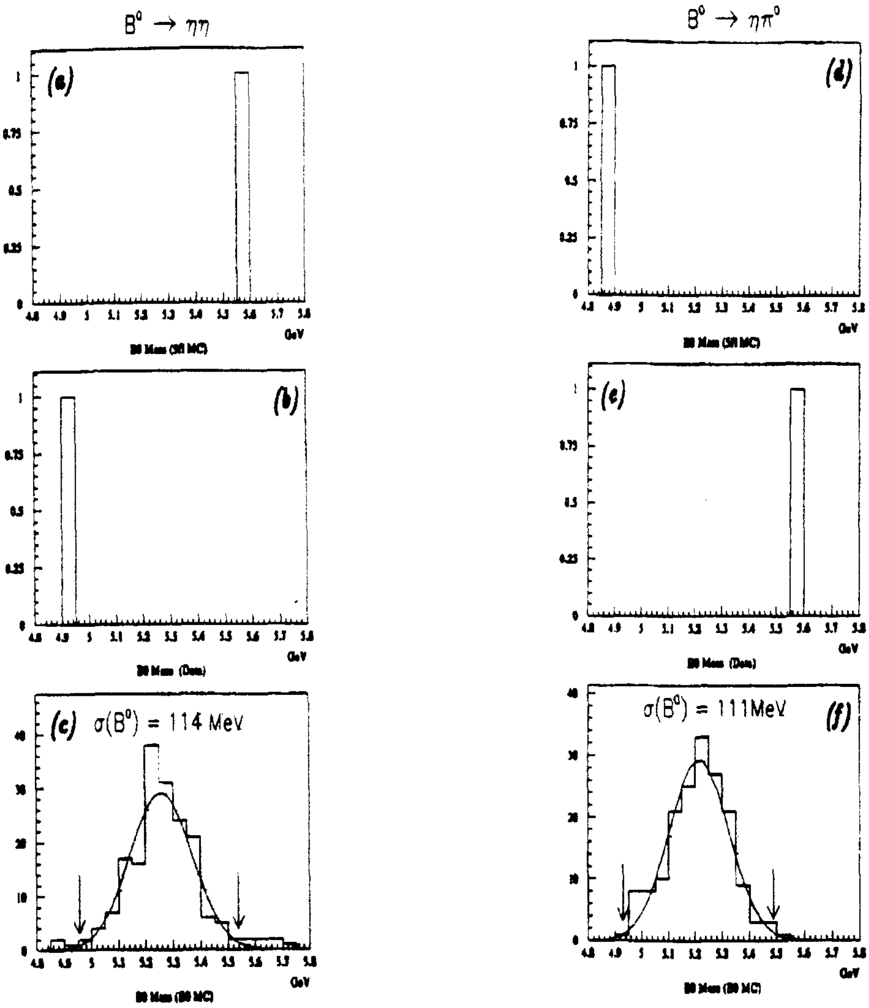

Figure 6: The L3 invariant mass spectrum for $B^0 \to \eta\eta$, *(a)*, *(b)* and *(c)*, and $B^0 \to \eta\pi^0$, *(d)*, *(e)* and *(f)*. The Monte Carlo, *(a)* and *(d)*, the data events, *(b)* and *(e)*, and the expected signal distributions, *(c)* and *(f)*, are shown.

Roughly the same cuts were applied when they searched for the decay $B^0 \to \eta\pi^0$. In order to cut the combinatorial background in the π^0, the energy of the photons was required to be a bit higher, $E_\gamma > 0.5\ GeV$, and the photons coming from the η to leave a signal in at least 6 BGO crystals. The same mass window was used for them together with $0.12\ GeV/c^2 < M_{\gamma\gamma} < 0.15\ GeV/c^2$ for the π^0. the energy of the B^0 was accepted to be smaller, $E_{B^0} > 13.\ GeV$. The purity cut used was $(\cos\theta_{\pi^0 B^0} + 0.85) * (E_{B^0} - 13.) < -1.2\ GeV$. Figures 6d-6f show the same as figures 6a-6c but for the $\eta\pi^0$ combination. Again no event was found. The especific Monte Carlo simulations for both decay channels gave an efficiency of 3.5%. The branching rations used for η and π^0 into 2 photons were $BR(\eta \rightarrow \gamma\gamma) = 38.9\%$ and $BR(\pi^0 \rightarrow \gamma\gamma) = 100\%$.

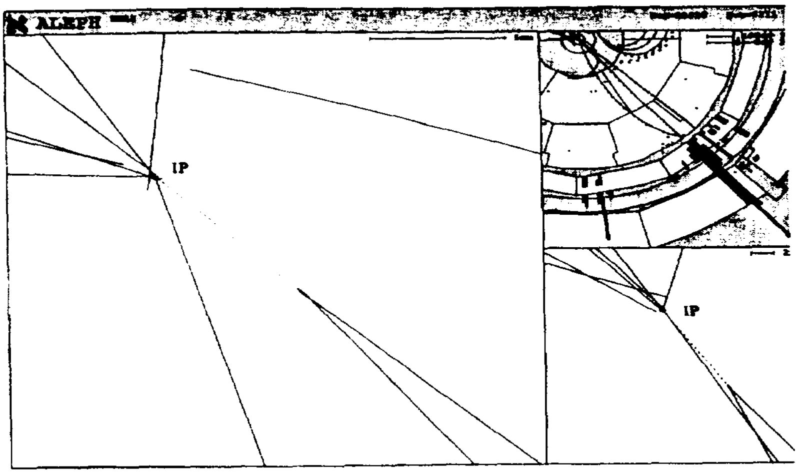

Figure 7: Two orthogonal views showing the region close to the interaction point and one $R\phi$ view of the hemisphere for the ALEPH event 22026/6311. The positions of the reconstructed vertex of the beauty candidate and the interaction point (IP) are indicated together with their 3σ error elipses.

ALEPH[7] used 1.5×10^6 hadronic Z^0 decays to search for any b-hadron charmless decay into 2 charged particles and putting limits on each channel at the end of the analysis. Each charged particle with momentum above 3 GeV/c was taken as long as it was not identified as a lepton. A pair of particles was taken if the sum of their momentum exceeded 20 GeV/c, the impact parameter of each track was inconsistent by more than 3σ with the interaction point and each of them had at least a hit in the vertex detector in order to reconstruct the decay vertex. If the χ^2 probability of this fit was higher than 1% and the distance between the primary and the secondary vertex, namely, the b-hadron decay vertex, was larger than 6σ of the interaction point the decay was taken. Each b-hadron was searched in an invariant mass window of $3\sigma_b$ around the nominal value of the b-hadron mass given by the PDG. Here σ_b is the error in the invariant mass calculation. Table 2 shows the 4 candidate events they have found. The fourth event is clarly a background one since it has the wrong sign combination. Figure 7 shows one of them with a detailed view of the vertex region.

Sign	Run/Event	$M_{\pi\pi}$	P_b	P_1	P_2	b_1/σ_1	b_2/σ_2	L	L/σ_L
+ −	13366/13[illegible]	5.34 ± 0.04	38	9	30	38	14	0.60	40
+ −	16936/312	5.25 ± 0.04	24	21	3	6	15	0.23	17
+ −	22026/6311	5.34 ± 0.05	40	10	30	67	27	0.95	73
− −	17600/3034	5.73 ± 0.03	23	5	18	13	3	0.12	11

Table 2 - Some properties of the 4 events with $M_{\pi\pi}$ significantly above 5 GeV/c^2. The masses ($M_{\pi\pi}$) are given in GeV/c^2, and the momenta of the beauty candidates (P_b) and of the individual tracks (P_1, P_2) are given GeV/c. b_1/σ_1 and b_2/σ_2 are the impact parameter significances of the two tracks. The decay length L is given in cm together with its significance (L/σ_L).

OPAL[13] did a similar search with 1.92×10^6 hadronic Z^0 decays, adding the dE/dx information to identify kaons and pions. The event was divided by in two hemispheres by an axis perpendicular to the thrust axis and all charged tracks with momentum above 0.15 GeV/c and far from the beam axis by an angle larger than 26^0 were combined in pairs. Only tracks with hit(s) in the vertex detector and with an impact parameter to the average beam spot, in the transverse plane, less than 3 mm were used. Once fitted, the decay was selected if it was less than 5 cm far from the interaction point and this distance was larger than twice its error, in order to reduce the enourmous background from $K_s^0 \to \pi\pi$, $\Lambda^0 \to p\pi$ and from spurious two track combinations, its energy was more than 60% the beam energy, the angle between the $K^+(\pi^+)$ in the B^0 rest frame and the B^0 flight direction to be larger than 41^0 and the opening angle between the decay products of the B^0 was less than 29^0. The decay was then classified as a B_d^0 or B_s^0, according to the mass window, 5.1 $GeV/c^2 < m_{B_d} <$ 5.5 GeV/c^2 and 5.2 $GeV/c^2 < m_{B_s} <$ 5.6 GeV/c^2. Figures 8a-8d show the invariant mass distribution for B_d^0 and B_s^0 from real data and background. The solid line indicates the fit done by a Gaussian to the expected combinatorial background. The region between the arrows shows where the signal is expected to be. No real excess above the background is seen. The expected mass resolutions for the B_d^0 and the B_s^0, from specific Monte Carlo simulations, are 0.137 GeV/c^2 for the $\pi^+\pi^-$ and the K^+K^- channels and 0.152 GeV/c^2 for the $K^\pm\pi^\mp$ channels. Table 3 shows the number of candidates and respective background found for each channel.

Decay Channel	Number of Candidates	Number of Background Events
$B_d^0 \to \pi^+\pi^-$	7	10.7 ± 2.5
$B_d^0 \to K^+\pi^-$	13	14.4 ± 2.6
$B_s^0 \to \pi^+K^-$	11	12.4 ± 2.7
$B_s^0 \to K^+K^-$	4	7.0 ± 1.9

Table 3 - Number of rare decay candidates and background events predicted from the fit after all cuts.

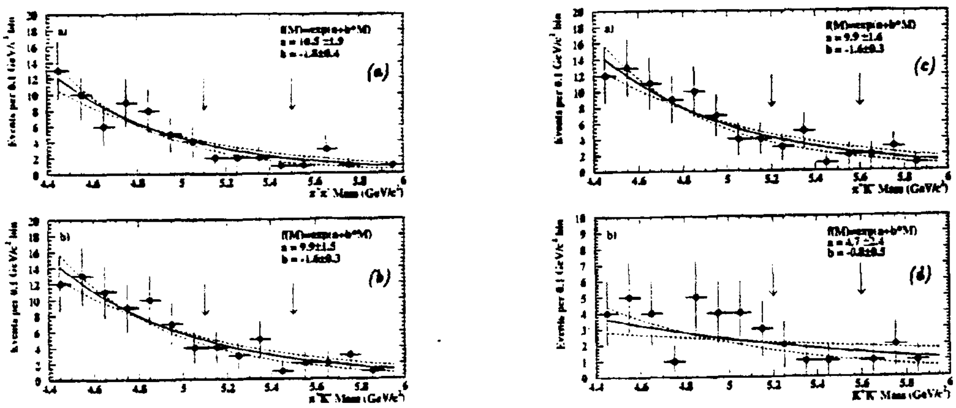

Figure 8: The invariant mass distributions for the OPAL data in the decay channels *(a)* $B_d^0 \to \pi^+\pi^-$, *(b)* $B_d^0 \to \pi^+K^-$, *(c)* $B_s^0 \to \pi^+K^-$ and *(d)* $B_s^0 \to K^+K^-$. The solid lines are the result of the fit to the combinatorial background, the arrows indicate the mass range 5.1 GeV/c^2 to 5.5 GeV/c^2 which is excluded from this fit, and the dotted lines are the 1 standard deviation errors on the background.

DELPHI[10] analysed about 1.7×10^6 Z^0 hadronic decays. The events passed, first of all, through the standard hadronic selection[8]. The event was then divided in two hemispheres by an axis perpendicular to the thrust axis. The largest momentum track in each of them was used to start the secondary vertex reconstruction and the other tracks were them added in an interactive way. Only tracks with at least 1 hit in the vertex detector and momentum above 1 GeV/c were taken. Particle tracks with an impact parameter with respect to the primary vertex larger than 0.5 cm were rejected, because they could be due to a long lived particle decay or to a problem in the pattern recognition. Vertices with a fit probability below 10^{-5} were discarded. Because of the high amount of combinatorial background the secondary vertex was taken only when it was separated from the primary by a distance larger than 2.5σ in the $R\phi$ plane[6] and, at the same time, be smaller than 2.0 cm in space. This last cut eliminated the long lived particles. Further on, the b-tagging algorithm[8] was applied to the decay in the other hemisphere of the event. The decay was considered a charmless b-decay candidate if it was the only one in its hemisphere and had a multiplicity smaller than 5.

In order to have a full reconstructed b-decay, it was removed if the invariant mass was below 4.5 GeV/c^2. Taking into account that the beam energy is around 45.6 GeV and the b-quark carries about 40 GeV of energy, two more cuts were applied in order to profit the hard b-quark fragmentation, namely, the leading track should have momentum above 10(8) GeV/c and the other one(s) momentum above 1.0(0.8) GeV for decays with two (or more) prong topology. Decays having ressonant intermediate states were accepted only if the ressonance mass was far from the mass of any charmed particle by 2σ. A detailed simulation study showed that 99%, 98% and 94% of the selected two, three and four prong vertices belong to b-decays while 2%, 12% and 32% of these have one or more primary tracks wrongly assigned to the secondary vertex.

The efficiency to reconstruct the two prong decays was evaluated to be 16%, for the three prong 6% and for four prong 4%. The b-decay candidates were accepted in the invariant mass region $5.15\ GeV/c^2 < m < 5.55\ GeV/c^2$ and $5.20\ GeV/c^2 < m < 5.50\ GeV/c^2$ for two and more than two prongs respectively. The mass resolution was found to be $(90 \pm 6)\ MeV/c^2$, $(60 \pm 5)\ GeV/c^2$ and $(45 \pm 8)\ GeV/c^2$ for each decay channel in the two, three and four prongs topologies. Figures 9a-9c show the invariant mass distribution obtained for the data and for the expected background in the different two, three and four body decay channels.

Decay Channel	**Mass** $[GeV/c^2]$	E_B $[GeV]$	d/σ_d	τ_B $[ps]$	$\lvert\cos\theta^*\rvert$	Δm_B in $[\sigma]$
$B^0_{d,s} \to K^+\pi^-$	5.47 ± 0.10	43.7	8.5	1.5	-	-
$B^-_u \to \rho\pi^-$	5.40 ± 0.09	38.1	70.4	5.1	0.68	+0.95
$B^-_u \to K^*\pi^-$	5.21 ± 0.06	40.0	17.6	1.2	0.59	+0.78

Table 4 - Characteristics of the candidate events. The mass, the energy of the b-meson, E_B, the distance significance between the primary and the decay vertex, d/σ_d, the lifetime of the b-meson, τ_B, the cosine of the angle between the pion in the b-meson rest frame and the b-meson direction of flight, $\lvert\cos\theta^*\rvert$, and the distance in σ from the ressonant mass, Δm_B, where the central value for the ressonant mass was taken from the PDG.

Three candidate events were found in the two body modes with an estimated background of 0.29 ± 0.07 events. The characteristics of each candidate are given in table 4. Figure 10a shows in detail the primary and secondary vertices reconstruction of one of those events. Figure 10b shows the particle identification, given by the RICH and by

[6]The plane perpendicular to the beam axis.

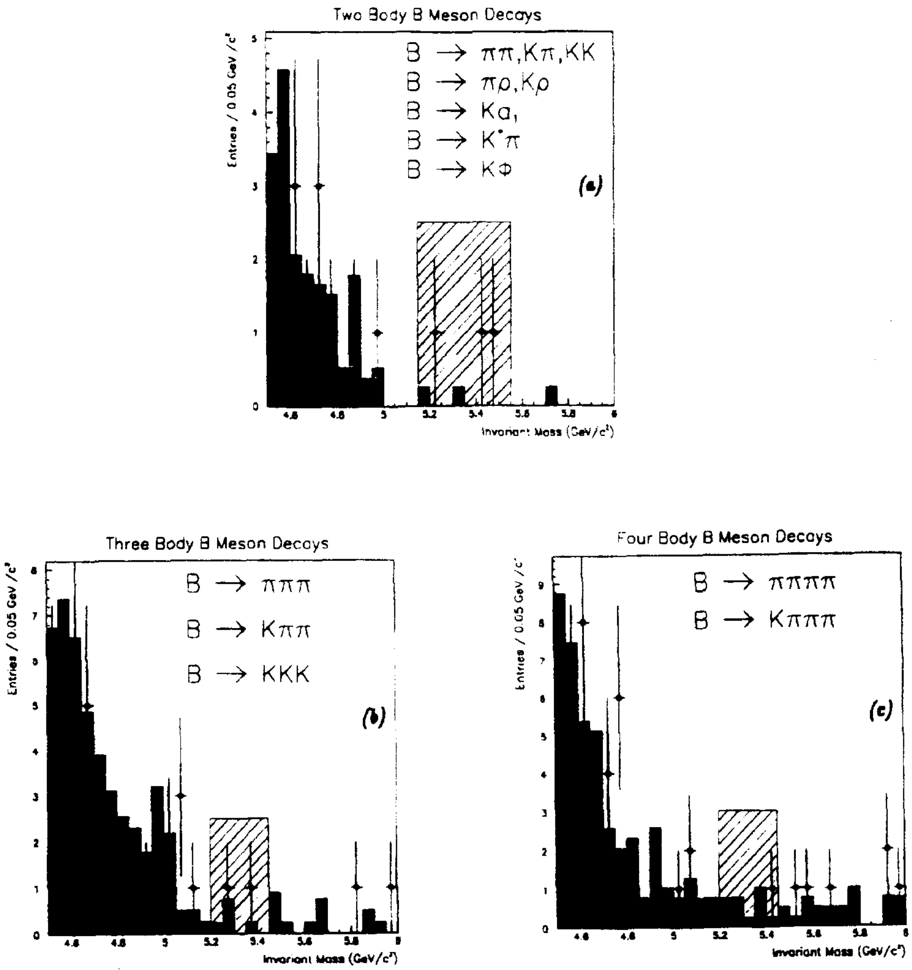

Figure 9: DELPHI invariant mass distribution for *(a)* two, *(b)* three, *(c)* and four, body decays. Real data events are indicated by the dot while simulated data is shown by the histogram. The normalization is given by the equivalent number of Z^0 hadronic decays.

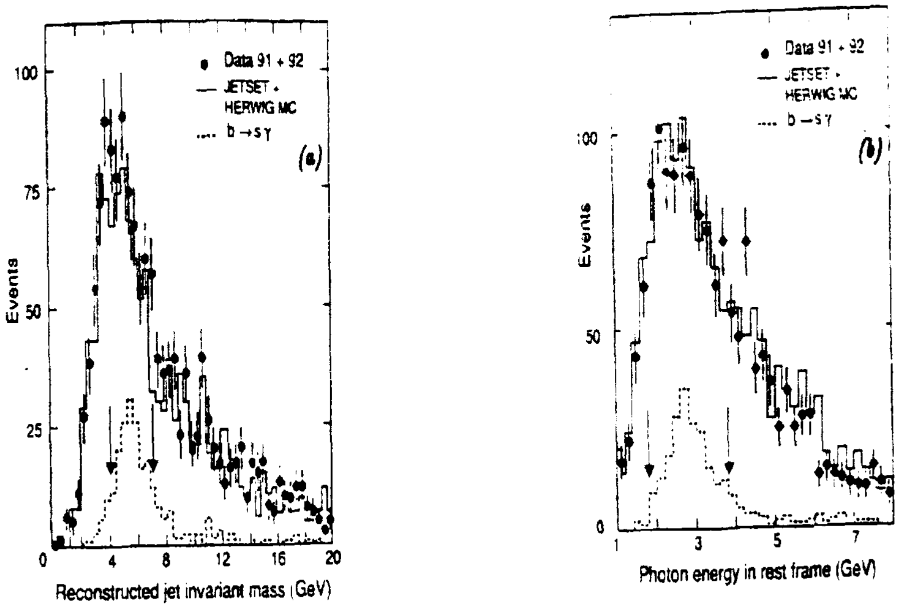

Figure 10: Display of the vertex region for the DELPHI candidate event of the decay $B \to K^*(892)\pi$, *(a)*. The error elipses for the primary and secondary vertex indicate a 1.5σ region. Display of the hadron identification properties for the same event, *(b)*.

the dE/dx measured in the TPC, for the decay products of the decay in figure 10a. The probability for all the three events to originate from a background fluctuation was found to be 6×10^{-3}. Figure 11 shows the mass distribution for some of the possible two body decays of a b-hadron. With the number of events analysed until now, no significance can be reached in order to say from which specific decay channel each of those 3 candidates come from. Looking, for example, at figure 11a, we see they can fulfill more than one decay channel. In this case, we must keep in mind DELPHI has 3 signal events, with a 30% probability one of them comes from a background combination, and clearly more statistics is nedded to reach the the level where they can measure the branching ratio channel per channel. Therefore, at this moment, only the upper limits can be given.

Except for OPAL all these analyse are preliminary. The four experiments are working in order to add the data collected in 1994, of the order of $3 - 4 \times 10^6$ hadronic Z^0 decays per experiment or $\sim 1.5 \times 10^6$ b-hadron decays per experiment. Adding the data we will get this year we shall have of the order of 2.5×10^6 b-hadron decays per experiment to add to the data already analysed, reaching the accuracy needed to check the Standard Model calculations. Table 5 gives a summary of the upper limit for the branching ratios, for the different b-hadron charmless decay channels, obtained by each experiment.

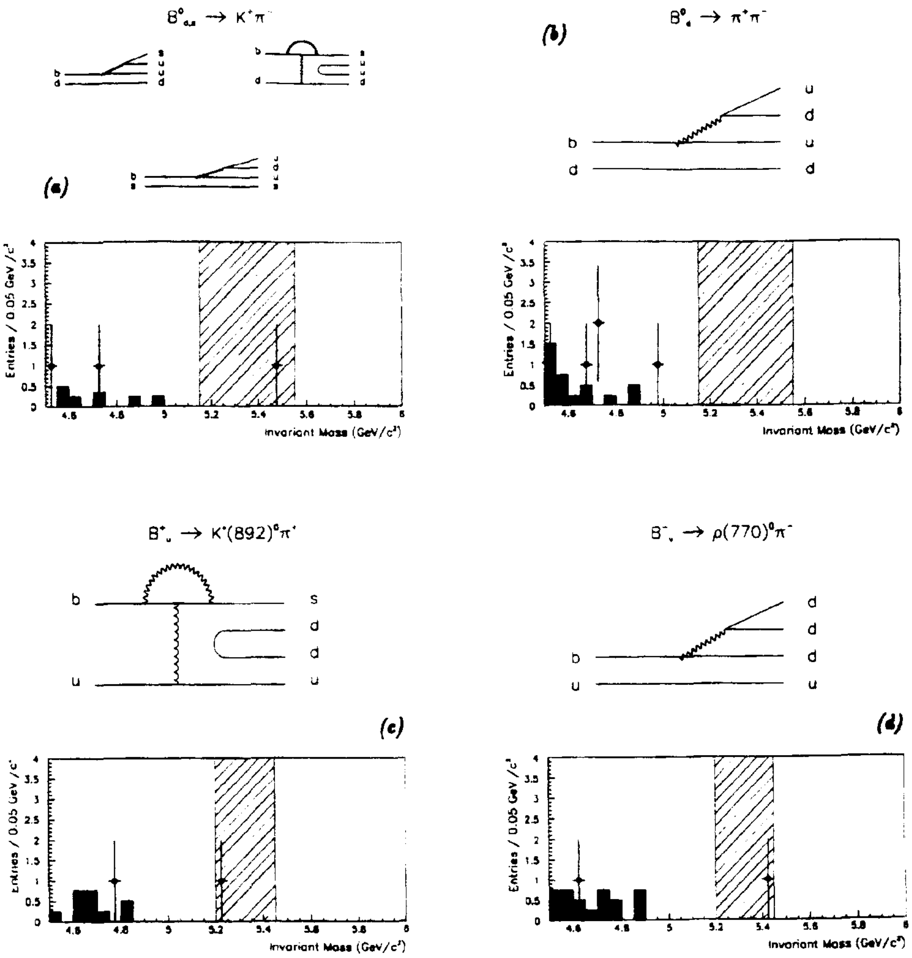

Figure 11: Some possible decay modes of the DELPHI *signal* events, *(a)* $B^0_{d,s} \rightarrow K^+\pi^-$, *(b)* $B^0_d \rightarrow \pi^+\pi^-$, *(c)* $B^+_u \rightarrow K^*(892)\pi^-$, and *(d)* $B^-_u \rightarrow \rho(770)^0\pi^-$. Together with the invariant mass distribution it is also shown the Feynmann diagrams involved in the specific decay.

Decay Channel	Experiment	BR ($\times 10^{-5}$)
$B^0 \to \eta\eta$	L3[12]	< 21 *at* 90% $C.L.$
$B^0 \to \eta\pi^0$	L3[12]	< 8.4 *at* 90% $C.L.$
$B^0_d \to \pi^+\pi^-$	ALEPH[7]	< 7.5 *at* 90% $C.L.$
	DELPHI[10]	< 5.5 *at* 90% $C.L.$
	OPAL[13]	< 4.7 *at* 90% $C.L.$
	CLEO[19]	$1.3 {}^{+0.8}_{-0.6} \pm 0.2$
	CLEO[19]	< 2.2 *at* 90% $C.L.$
$B^0_d \to K^+\pi^-$	ALEPH[7]	< 7.5 *at* 90% $C.L.$
	DELPHI[10]	< 9 *at* 90% $C.L.$
	OPAL[13]	< 8.1 *at* 90% $C.L.$
	CLEO[19]	$1.1 {}^{+0.7}_{-0.6} \pm 0.2$
	CLEO[19]	< 2.0 *at* 90% $C.L.$
$B^0_d \to K^+K^-$	ALEPH[7]	< 3.2 *at* 90% $C.L.$
	DELPHI[10]	< 12 *at* 90% $C.L.$
	CLEO[19]	$0.0 {}^{+0.2}_{-0.0}$
$B^0_d \to p\bar{p}$	ALEPH[7]	< 3.2 *at* 90% $C.L.$
	DELPHI[10]	< 35 *at* 90% $C.L.$
$B^0_s \to \pi^+\pi^-$	ALEPH[7]	< 25 *at* 90% $C.L.$
$B^0_s \to K^+\pi^-$	ALEPH[7]	< 25 *at* 90% $C.L.$
	DELPHI[10]	< 9 *at* 90% $C.L.$
	OPAL[13]	< 26 *at* 90% $C.L.$
$B^0_s \to K^+K^-$	ALEPH[7]	< 11 *at* 90% $C.L.$
	DELPHI[10]	< 12 *at* 90% $C.L.$
	OPAL[13]	< 14 *at* 90% $C.L.$
$B^0_s \to p\bar{p}$	ALEPH[7]	< 11 *at* 90% $C.L.$
$B^-_u \to \rho^0\pi^-$	DELPHI[10]	< 26 *at* 90% $C.L.$
$B^-_u \to K^{*0}\pi^-$	DELPHI[10]	< 48 *at* 90% $C.L.$
$B^-_u \to K^-\rho^0$	DELPHI[10]	< 19 *at* 90% $C.L.$
$B^-_u \to K^-\phi$	DELPHI[10]	< 44 *at* 90% $C.L.$
$B^0_d \to K^+a_1$	DELPHI[10]	< 39 *at* 90% $C.L.$
$B^0_s \to K^+a_1$	DELPHI[10]	< 39 *at* 90% $C.L.$
$\Lambda^0_b \to p\pi^-$	ALEPH[7]	< 16 *at* 90% $C.L.$
$\Lambda^0_b \to pK^-$	ALEPH[7]	< 16 *at* 90% $C.L.$
$B^-_u \to \pi^+\pi^-\pi^-$	DELPHI[10]	< 22 *at* 90% $C.L.$
$B^-_u \to K^-\pi^+\pi^-$	DELPHI[10]	< 40 *at* 90% $C.L.$
$B^-_u \to K^+K^-K^-$	DELPHI[10]	< 31 *at* 90% $C.L.$
$B^-_u \to p\bar{p}\pi^-$	DELPHI[10]	< 50 *at* 90% $C.L.$
$B^0_d \to \pi^+\pi^+\pi^-\pi^-$	DELPHI[10]	< 28 *at* 90% $C.L.$
$B^0_d \to K^+\pi^+\pi^-\pi^-$	DELPHI[10]	< 21 *at* 90% $C.L.$
$B^0_d \to p\bar{p}\pi^+\pi^-$	DELPHI[10]	< 95 *at* 90% $C.L.$
$B^0_s \to K^+\pi^+\pi^-\pi^-$	DELPHI[10]	< 21 *at* 90% $C.L.$

Table 5 - Summary of the results for the seach $b \to$ charmless decay.

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