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Search for FCNC in the process $Z \to b\bar{q}$, $q = d, s$

Preliminary

DELPHI Collaboration

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Abstract

From 1992 to 1995 the DELPHI detector at LEP has collected about 3.5 million hadronic Z decays from which over a half were recorded with a double-sided microvertex detector. The accurate and efficient tracking devices of DELPHI enabled an efficient hadronic flavour tag with high purity allowing the present search for flavour violating Z decays in the process $e^+e^- \to b\bar{q}$, $q = d, s$ at the M_Z energy scale. No signal for such events was found on data and a preliminary upper limit of 1.7×10^{-3} at 95% CL has been derived to the quantity

$$R_{FCNC} = \frac{\sum\limits_{q=d,s} \Gamma(e^+e^- \to b\bar{q})}{\Gamma(e^+e^- \to hadrons)} \; .$$

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1 Introduction

Flavor Changing Neutral Current processes (FCNC) are governed in the Standard Model (SM) by the Glashow-Iliopoulus-Maini (GIM) mechanism [1]. In this scenario these transitions are forbidden at tree level and the leading contributions which can produce these processes only result from the one-loop diagrams known as the penguin and box diagrams which then contain suppression factors in the order of $10^{-6} - 10^{-9}$ with respect to the allowed tree level SM reactions [2]. The experimental search of such processes represents an important test of the validity of the SM [3], either by confirming its prediction or by indicating the need for physics beyond the SM if observed at larger probabilities [4].

In this paper we investigate the possible presence of events originated by FCNC processes in a sample of 3.5 million hadronic events collected by DELPHI through the reaction $e^+e^- \to b\bar{q}$, $q = d, s$ at the energy scale of the Z mass (M_Z). The branching ratio of this process in the SM is expected to be of the order of 10^{-7} [5] and therefore any observation of such events in the present data sample would imply the existence of new physics. The method used to look for these events is based on the DELPHI R_b analysis [6] in which the implicit SM constraint in the fit to the data $R_b + R_c + R_\ell = 1$ ($\ell = u, d, s$) is relaxed to include FCNC processes in the form $R'_b + R'_c + R'_\ell + R_{FCNC} = 1$. The parameter R_{FCNC} is extracted in a similar way as R_b in the SM analysis.

Recent searches for processes related to the above reaction have been performed by the DELPHI, L3 and CLEO Collaborations [7, 8, 9]. The DELPHI and L3 experiment have set preliminary limits at 95% CL of 3.7×10^{-3} and 5.6×10^{-3}, respectively, by searching for the same process $e^+e^- \to b\bar{q}$, $q = d, s$ at same energy scale, M_Z. On the other hand, CLEO has produced a limit of 5.7×10^{-5} at 90% CL by looking for the inclusive decay $b \to se^+e^-$ at the M_Υ energy scale.

2 Detector description and event selection

The DELPHI detector, surrounding one of the interaction regions at the Large Electron Positron facility LEP at CERN, has been used to record the samples of events considered in this analysis. It provides both tracking and calorimetric information over almost the full solid angle. A detailed description of the detector and its performance, including the exact geometry as well as the trigger conditions and the event processing chain, appear in references [10, 11]. Especially relevant to this analysis is the double-sided microvertex detector (VD) [12], installed in spring 1994, that allowed high values of purity and efficiency in the identification of b and uds quarks.

The criteria to select charged tracks and to identify hadronic Z decays are identical to those described in [6]. Charged particles were accepted if:

- their polar angle was between 20° and 160°,
- their track length was larger than 30 cm,
- their impact parameter relative to the interaction point was less than 5 cm in the plane perpendicular to the beam direction and less than 8 cm along the beam direction,
- their momentum was larger than 200 MeV/c with relative error less than 100%.

Neutral particles detected in the HPC were required to have measured energy larger than 700 MeV and those detected in the EMF greater than 400 MeV.

Events were then selected by requiring:

- at least 6 reconstructed charged particles,
- the summed energy of the charged particles had to be larger than 15% of the centre of mass energy, with at least 3% of it in each of the forward and backward hemispheres with respect to the beam axis.

The efficiency to find hadronic Z decays with these cuts was about 95% and all backgrounds were below 0.1%. About 1.3 million hadronic Z decays were selected with two dimensional VD in 1992 and 1993, and 2.1 million hadronic Z decays from 1994 and 1995 data samples with the three dimensional VD. No selection on the centre of mass energy was made in 1993 and 1995. As the VD is essential for this analysis, the data were limited to events that have most of the tracks inside the acceptance of the VD. For this reason a cut of $|\cos\theta_{thrust}| < 0.65$ was applied. The hadronic selection efficiency was then reduced to about 61% of the events passing all previous hadronic cuts.

A sample about twice the data statistics of $Z \to q\bar{q}$ events was simulated using the Lund parton shower Monte Carlo JETSET 7.3 [13] (with parameters optimised by DELPHI) and the DELPHI detector simulation [11]. In addition dedicated samples of $Z \to b\bar{b}$ events were generated. The simulated events were passed through the same analysis chain as the real ones.

For this analysis a reasonable description of the data by the simulation for the $udsc$ quarks is required. For this reason a fine tuning of the $R\phi$ and Rz impact parameter distributions in the simulation was developed and applied [14]. This led to substantially smaller uncertainties due to the understanding of the detector resolution.

3 The experimental strategy

The method used to investigate the existence of the process $e^+e^- \to b\bar{q}$, $q = d, s$ at M_Z energy scale is mainly based on the DELPHI R_b analysis [6]. Hence only the particular aspects of the analysis are described in the following. Events are first divided into hemispheres using the plane perpendicular to the thrust axis. The quantity R_b can be extracted together with the hemisphere b-tagging efficiency from the fraction of events tagged as b in one and tagged as b in both hemispheres. In this way precise knowledge of the details of the B hadron decays is not required. This single/double tag method can be generalized to a multiple tag scheme where each hemisphere of the event is tagged between six mutually exclusive tags: three of them are designed to identify b quarks (b-tight, b-standard and b-loose tags), one c quarks (charm tag) and one uds quarks (uds tag) [1]. Finally there is a no-tag category which contains all hadronic hemispheres not classified in none of the previous tags. The b-tight tag has the best b-purity and it is used as primary b tag as in the single/double tag analysis. In this analysis scheme there are 20 independent fractions, f_{ij}, of doubly tagged events (index i, j denote each of the six tags). However, only three of them, $f_{b\ell}$, will give signal signature of the process we

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[1] In the following they are denoted generally as: i) b for the b-tight, b-standard and b-loose tags, c for the charm tag and ℓ for the uds tag.

are searching for: $f_{b-tight,\ell}$, $f_{b-standard,\ell}$ and $f_{b-loose,\ell}$. All the rest will be used to evaluate backgrounds and signal efficiencies directly from the data.

We define then the experimentally observable flavour violating ratio $R_{b\ell}$ as

$$R_{b\ell} = \frac{\Gamma(e^+e^- \to BQ)}{\Gamma(e^+e^- \to hadrons)} \tag{1}$$

where B and Q represent hadrons containig b and light quarks respectively. This differs from the flavour violating ratio R_{FCNC} defined as

$$R_{FCNC} = \frac{\sum\limits_{q=d,s} \Gamma(e^+e^- \to b\bar{q})}{\Gamma(e^+e^- \to hadrons)} \tag{2}$$

due to the fact that using the present tagging technique (see section 4) the u quark contribution cannot be distinguished from the other light quarks (d, s). Under theoretical grounds however $R_{FCNC} = R_{b\ell}$ though experimentally only the relation $R_{FCNC} \leq R_{b\ell}$ can be assured.

The fraction of hadronic FCNC events, $f_{b\ell}$, corresponding to those events with two tagged hemispheres, one with a b tag and the other with a ℓ tag, can be parameterized as

$$f_{b\ell} = \epsilon^{b\ell}_{b\ell} R_{b\ell} + \epsilon^{b}_{b\ell} R'_b + \epsilon^{c}_{b\ell} R'_c + \epsilon^{\ell}_{b\ell} R'_\ell \ , \tag{3}$$

with R_α being the probability to have an e^+e^- hadronic final state $\alpha = b\ell, b, c, \ell$ and $\epsilon^{\alpha}_{b\ell}$ the efficiency to be classified as FCNC. In this case

$$R_{b\ell} + R'_b + R'_c + R'_\ell = 1 \ . \tag{4}$$

The parameters R'_b, R'_c, R'_ℓ can be related to their equivalent SM paramaters R_b, R_c and R_ℓ verifying $R_b + R_c + R_\ell = 1$ as

$$R'_\beta = R_\beta (1 - R_{b\ell}), \quad \beta = b, c, \ell \ , \tag{5}$$

hence allowing the following relation

$$R_{b\ell} = \frac{f_{b\ell} - \epsilon^{background}_{b\ell}}{\epsilon^{b\ell}_{b\ell} - \epsilon^{background}_{b\ell}} \tag{6}$$

with

$$\epsilon^{background}_{b\ell} = \epsilon^{b}_{b\ell} R_b + \epsilon^{c}_{b\ell} R_c + \epsilon^{\ell}_{b\ell} R_\ell \ . \tag{7}$$

Each of the double hemisphere efficiencies can then be written in terms of the single hemisphere efficiencies and their correlation:

$$\epsilon^{\beta}_{b\ell} = \epsilon^{\beta}_{b} \epsilon^{\beta}_{\ell} (1 + \rho^{\beta}_{b\ell}), \quad \beta = b, c, \ell \ , \tag{8}$$

whose values are the same as those used in SM R_b analysis. The additional FCNC correlation factor $\rho^{b\ell}_{b\ell}$ is defined in terms of the FCNC double tagging efficiencies as

$$\epsilon^{b\ell}_{b\ell} = \frac{\epsilon^{b}_{b}\epsilon^{\ell}_{\ell} + \epsilon^{\ell}_{b}\epsilon^{b}_{\ell}}{2} (1 + \rho^{b\ell}_{b\ell}) \ . \tag{9}$$

Provided that all parameters except $R_{b\ell}$ and $\rho^{b\ell}_{b\ell}$ are the same as measured or estimated in the SM R_b analysis [6], one can determine easily $R_{b\ell}$ using (6) if $\rho^{b\ell}_{b\ell}$ is calculated for this study from a dedicated FCNC JETSET simulation. It should be stressed now that with this method all efficiencies for backgrounds as well as for signal are extracted directly from the data (except $\epsilon^{\ell}_{b-tight}$ and $\epsilon^{c}_{b-tight}$ which are estimated from the standard simulation) and only the hemisphere-hemisphere correlations are taken from Monte Carlo. This will result in a strong reduction of systematic errors.

4 Tagging technique

To provide the six hemisphere tags, three flavour tagging algorithms developed by DELPHI have been used.

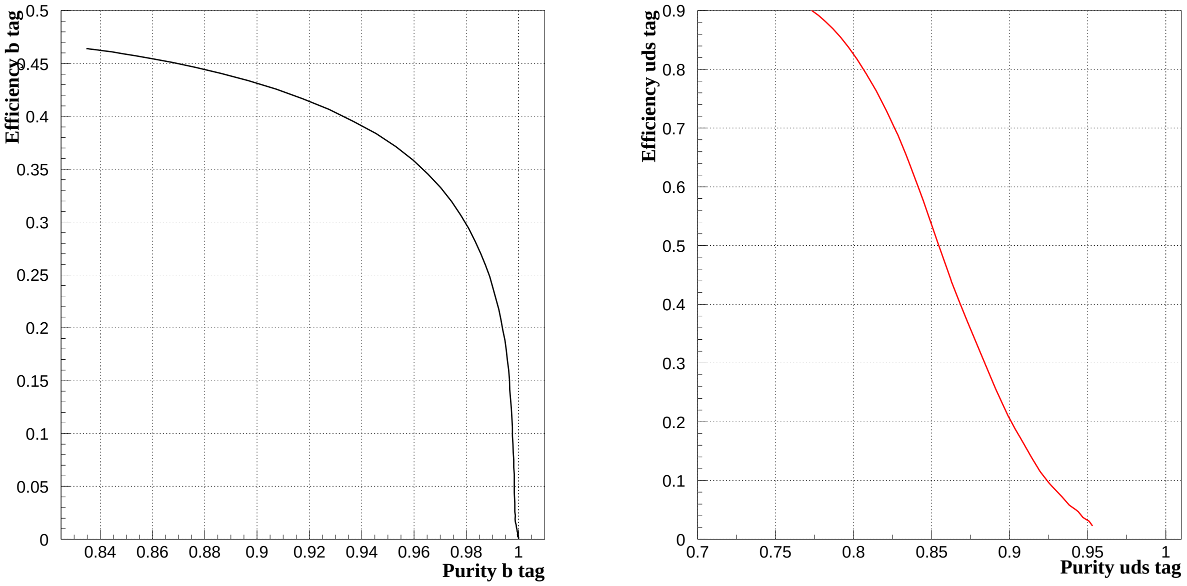
The first technique is the *enhanced impact parameter b tag* [6] which combines several properties of the B hadrons into a single variable to identify b quarks. They are the long lifetime, the large mass, the high decay multiplicity and the high B hadron energy taken from the initial quark. All discriminating variables are defined for jets (using JADE with y_{min}=0.01) with reconstructed secondary vertices. The hemisphere is then identified by the tagged jet. The lifetime information is extracted from the positively signed impact parameters of the tracks included in a jet. The large mass and high decay multiplicity of B hadrons is exploited using as tagging variables the effective invariant mass and the rapidity (computed with respect to the jet direction) of particles included in the secondary vertex. Finally, the fraction of the charged energy of the jet is added. Figure 1.a shows the hemisphere b-tagging efficiency versus purity obtained with this technique as predicted by the simulation.

The *multivariate flavour tagging* algorithm [15] is similarly based on the large mass and relatively long lifetime of the b quark and some event shape properties of its decays. All the available information is combined using multivariate techniques. As before, the lifetime information exploits the large impact parameters of tracks coming from B decays together with a search for secondary vertices and their invariant masses. Then the lifetime information is combined with event shape properties of the B decays like large transverse momentum of the tracks with respect to the jet axis, rapidity distributions and the boosted sphericity. A total of 13 variables is finally adopted.

The third technique, called *flavour confidences* [16], is based on track impact parameters and on two other kinematic variables: the track momentum and the angle with respect to the jet axis. The method uses the simulation to build a function which gives the fraction of tracks which come from uds, c and b quarks in a bin of the three particle characteristics. There are kinematic effects in the decay of B hadrons which produce correlations between the three quantities, but they are automatically taken into account by the three-dimensional binning. The individual flavour confidences are finally combined to make a hemisphere tag.

The two tags, multivariate and confidences, can be combined using a simple linear combination for each flavour [6]. There is finally a global estimator Δ_q for each flavour. Figure 1.b shows the hemisphere uds-tagging efficiency versus purity obtained with this procedure, as it is predicted by the simulation of the experiment.

The definition of the hemisphere tags in terms of the three tagging techniques is identical to the used in [6]. The b-tight and uds tags have the strongest influence on the



(a) (b)

Figure 1: Hemisphere b- and uds-tagging efficiencies versus purity for the (a) enhanced impact parameter b tag and for the (b) multivariate tag respectively.

measurement of $R_{b\ell}$, but also the b-standard and b-loose are used in the evaluation of (6) in an attempt to improve the statistical error without increasing systematics. The cuts are the same as used in R_b except $\Delta_{\ell,0}$ which is chosen softer (2.1 for 1992-1993 and 2.3 for 1994-1995 instead of 2.7 and 3.2 respectively) in order to increase the uds-efficiency and to minimize the error on $R_{b\ell}$. The Monte Carlo expectations for all efficiencies are given separately for 1993 and 1994 in table 1. This table is a measure of the performance of the tags and tagging techniques all working simultaneously. In this analysis, only the charm and light quark backgrounds of the b-tight tag are taken from simulation. All the other efficiencies are measured directly from the data.

	1993			1994		
Tag i	ϵ_i^ℓ	ϵ_i^c	ϵ_i^b	ϵ_i^ℓ	ϵ_i^c	ϵ_i^b
b-tight	0.00053	0.00396	0.23017	0.00055	0.00394	0.28257
b-standard	0.00192	0.02635	0.17049	0.00130	0.02695	0.15576
b-loose	0.01449	0.07757	0.16044	0.01223	0.07860	0.15156
charm	0.05813	0.16422	0.05708	0.04942	0.15612	0.04966
uds	0.49562	0.24982	0.05624	0.49545	0.23064	0.04881

Table 1: Simulation results for the tagging efficiencies at the nominal cuts for 1993 and 1994.

The ρ_{ij}^α hemisphere correlation corrections as estimated from simulation for the 1994 analysis together with their sensitivities to R_b are given in table 2, where the errors are due to simulation statistics. Only the relevant correlations with a sensitivity to R_b higher than 0.010 are shown. The sensitivity is defined as the relative change on R_b due to a change of a given correlation, $\frac{\Delta R_b}{R_b \Delta \rho^q_{ij}}$.

Correlation	Sensitivity to R_b	Value
	b correlations	
$\rho^b_{b-tight,b-tight}$	0.767	0.0198 ± 0.0020
$\rho^b_{b-tight,standard}$	0.219	0.0034 ± 0.0020
$\rho^b_{b-tight,loose}$	0.107	0.0031 ± 0.0020
$\rho^b_{b-tight,charm}$	-0.041	0.0047 ± 0.0039
$\rho^b_{b-standard,b-standard}$	-0.081	0.0073 ± 0.0037
$\rho^b_{b-standard,b-loose}$	-0.088	0.0034 ± 0.0031
$\rho^b_{b-standard,charm}$	0.023	0.0042 ± 0.0058
$\rho^b_{b-loose,b-loose}$	-0.047	0.0095 ± 0.0038
$\rho^b_{b-loose,charm}$	0.014	-0.0079 ± 0.0059
	c correlations	
$\rho^c_{b-standard,charm}$	0.014	0.0015 ± 0.0173
$\rho^c_{b-loose,charm}$	0.024	0.0028 ± 0.0097
$\rho^c_{charm,charm}$	-0.013	0.0434 ± 0.0080
	ℓ correlations	
$\rho^\ell_{charm,uds}$	0.020	0.0134 ± 0.0078
$\rho^\ell_{uds,uds}$	0.034	0.0758 ± 0.0057
	$b\ell$ correlations	
$\rho^{b\ell}_{b-tight,uds}$	-	-0.0206 ± 0.0039
$\rho^{b\ell}_{b-standard,uds}$	-	0.0136 ± 0.0056
$\rho^{b\ell}_{b-loose,uds}$	-	-0.0078 ± 0.0042

Table 2: Hemisphere-hemisphere correlation coefficients ρ^α_{ij} with major sensitivity ($>$ 0.010) on R_b for the 1994 data sample and the additional coefficients used for the measurement of $R_{b\ell}$. Errors are only due to the limited Monte Carlo statistics.

5 Results and systematics

From R_b and the efficiency results quoted with the SM R_b analysis [6] and using expression (6) for the b-tight, b-standard and b-loose tags, the combined $R_{b\ell}$ result is

$$R_{b\ell} = [1.3 \pm 6.1 \text{ (stat.)} \pm 5.5 \text{ (syst.)}] \times 10^{-4} \ .$$

The efficiencies obtained from the R_b fits and entering in the evaluation of $R_{b\ell}$ are shown in table 3 for 1993 and 1994. They can be compared with the simulation predictions of table 1. For a complete comparison, an estimate of the systematic errors must be included.

The systematic errors are due to the quantities estimated from simulation. In this analysis only light and charm quark backgrounds in the b-tight tag and the correlation of hemisphere tagging efficiencies are taken from Monte Carlo. Table 4 reports the breakdown of the systematic uncertainties on this measurement of $R_{b\ell}$. As stated before, the

	1993		
Tag i	ϵ_i^ℓ	ϵ_i^c	ϵ_i^b
b-tight	0.00053	0.00396	0.2387 ± 0.0022
b-standard	0.0024 ± 0.0002	0.0239 ± 0.0024	0.1751 ± 0.0014
b-loose	0.0134 ± 0.0009	0.0814 ± 0.0046	0.1602 ± 0.0016
charm	0.0730 ± 0.0011	0.1805 ± 0.0035	0.0574 ± 0.0014
uds	0.4953 ± 0.0026	0.2501 ± 0.0076	0.0531 ± 0.0016
	1994		
Tag i	ϵ_i^ℓ	ϵ_i^c	ϵ_i^b
b-tight	0.00055	0.00394	0.2961 ± 0.0015
b-standard	0.0017 ± 0.0002	0.0251 ± 0.0020	0.1576 ± 0.0009
b-loose	0.0123 ± 0.0005	0.0798 ± 0.0026	0.1493 ± 0.0010
charm	0.0617 ± 0.0007	0.1684 ± 0.0022	0.0509 ± 0.0008
uds	0.5029 ± 0.0009	0.2297 ± 0.0036	0.0492 ± 0.0009

Table 3: Tagging efficiencies with statistical errors for data as measured from the R_b fit at the nominal cuts for 1993 and 1994. For a complete comparison of the fit results with the simulation, an estimate of the systematic error must be included. Errors given in this table include data and simulation statistics.

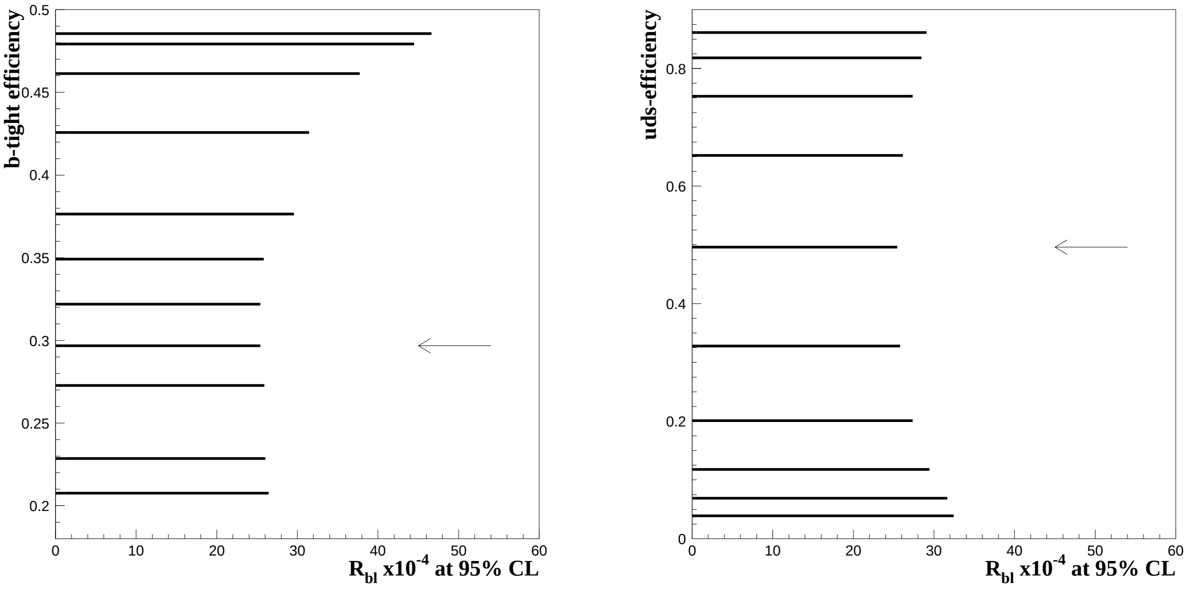
method has strongly reduced systematic errors, which are largely dominated by the limited amount of the Monte Carlo data sample. They have been estimated as in the R_b analysis and therefore here we give only the effect of them on $R_{b\ell}$. See [6] for a detailed description on how they are determined.

Source	$\Delta R_{b\ell}^{syst} \times 10^{-4}$
MC Statistics	5.40
$\ell + c$ backgrounds	0.02
$\pm 10\%$ variation of R_c	0.06
Angular correlations	0.14
QCD effects: gluon radiation	0.06
b-fragmentation+B-multiplicity	0.02
τ_B	0.02
$\rho_{b\ell}^{b\ell}$	1.12
Total error	5.52

Table 4: Breakdown of the total systematic error and the impact on $R_{b\ell}$. See [6] for a detailed description on how they are quoted.

Compared with the SM R_b analysis, the only additional source of systematics which is not estimated is due to hemisphere-hemisphere correlations in flavour violating events, $\rho_{b\ell}^{b\ell}$. To take into account this contribution properly, a modified JETSET Monte Carlo of FCNC events with full DELPHI detector simulation is required. Nevertheless, the correlations $\rho_{b\ell}^{b\ell}$ can roughly be approximated from the average of the SM correlations $\rho_{b\ell}^{b}$ and $\rho_{b\ell}^{\ell}$. This approximation is well supported by physical considerations because all sources of correlations for FCNC $b\ell$ events have similar effects to b and ℓ SM events. In fact, $\rho_{b\ell}^{b}$ and $\rho_{b\ell}^{\ell}$ are all compatible within statistical errors. The values obtained from this approximation for the 1994 data sample are given in table 2. A conservative estimation of the systematic error due to $\rho_{b\ell}^{b\ell}$ was obtained by varying its central value ($\sim 2\%$) up to $\pm 50\%$. The effect of this variation is indicated in table 2.

Finally, as a cross-check of the measurement, $R_{b\ell}$ was measured at several values of the b-tight and uds tag efficiencies. For all years the stability was remarkable. Figure 2 shows how the limit on $R_{b\ell}$ for the 1994 data sample changes as a function of the efficiency.



(a) (b)

Figure 2: Variation of the 1994 $R_{b\ell}$ limit (at 95% CL) as a function of (a) the b-tight tag efficiency and (b) the uds tag efficiency. The arrows show the cuts giving the minimal error on $R_{b\ell}$, which are chosen for the result quoted in the text.

6 Conclusions

The existence of events produced by the FCNC process $e^+e^- \to b\bar{q}$, $q = d, s$ at the M_Z scale has been investigated. The powerful tagging and self-data-calibration techniques developed by DELPHI for the R_b analysis [6] have been used to perform this study and the result obtained has been

$$R_{b\ell} = \frac{\Gamma(e^+e^- \to BQ)}{\Gamma(e^+e^- \to hadrons)} = [1.3 \pm 6.1 \text{ (stat.)} \pm 5.5 \text{ (syst.)}] \times 10^{-4} \ ,$$

which is compatible with no experimental observation of this type of events within our present data sample. The preliminary exclusion limit thus derived is

$$R_{FCNC} = \frac{\sum\limits_{q=d,s} \Gamma(e^+e^- \to b\bar{q})}{\Gamma(e^+e^- \to hadrons)} \leq R_{b\ell} \leq 1.7 \times 10^{-3} \ \text{ at } 95\% \text{ CL} \ .$$

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