Heavy quark production at the Z

Fernando Martínez-Vidal
IFIC, Centro Mixto Universitat de València-CSIC, Spain
Actually at IN2P3-CNRS et Université de Paris 6 et 7, France

The most recent results on decays of Z into final states including b- and c-quarks reported by the four LEP experiments and SLD at SLC are summarized. The average values of the decay rates of $\mathrm{Z} \to \mathrm{b\bar{b}}$ and $\mathrm{Z} \to \mathrm{c\bar{c}}$, $R_{\mathrm{b}} = 0.21661 \pm 0.00073$ and $R_{\mathrm{c}} = 0.1735 \pm 0.0044$ respectively, agree within one standard deviation with the Standard Model prediction. The rare decay $\mathrm{Z} \to \mathrm{b\bar{b}b\bar{b}}$ is observed and its rate is found to be $R_{4\mathrm{b}} = (5.4 \pm 2.3) \times 10^{-4}$. The upper limit on the flavor changing neutral current decay $\mathrm{Z} \to \mathrm{b\bar{q}}$, $\mathrm{q} \neq \mathrm{b}$ is set to be $R_{\mathrm{b\bar{q}}} < 2.4 \times 10^{-3}$ (90% CL).

I. INTRODUCTION

The measurements of the decay rates[1] of $\mathrm{Z} \to \mathrm{b\bar{b}}$ (R_{b}) and $\mathrm{Z} \to \mathrm{c\bar{c}}$ (R_{c}) provide fundamental tests of the Standard Model (SM). The uncertainty of the theoretical calculations of these values is small and the experimental techniques allow to measure them with high accuracy. Additionally the R_{b} branching ratio is sensitive to extensions of the SM whereas R_{c} is quite stable in a wide variety of models. Thus their simultaneous and precise determination can give a hint for new physics.

All experiments at LEP and SLD at SLC participate in the measurements of R_{b} and R_{c}. In this report we summarize all results presented by the experiments. In addition, the measurement of the rate of $\mathrm{Z} \to \mathrm{b\bar{b}b\bar{b}}$ ($R_{4\mathrm{b}}$) and the search for the decay $\mathrm{Z} \to \mathrm{b\bar{q}}$, $\mathrm{q} \neq \mathrm{b}$ ($R_{\mathrm{b\bar{q}}}$) mediated by flavor changing neutral currents are presented.

II. MEASUREMENT OF R_{b}

A. Double-tag method

The high experimental accuracy of the measurement of R_{b} is achieved by using the so-called double-tag method. It is based on the fact that in Z decays quarks are produced in pairs and that each quark can be selected almost independently and with small background contamination. The b-quarks are tagged separately in 2 hemispheres defined e.g. by the plane perpendicular to the thrust axis of the event. The fraction of tagged hemispheres, f_H, and the fraction of events with both hemispheres tagged, f_E, can be expressed as:

$$\begin{aligned} f_H &= R_{\mathrm{b}}\epsilon_{\mathrm{b}} + R_{\mathrm{c}}\epsilon_{\mathrm{c}} + R_{\mathrm{uds}}\epsilon_{\mathrm{uds}} \ ; \\ f_E &= R_{\mathrm{b}}{\epsilon_{\mathrm{b}}}^2(1+\rho_{\mathrm{b}}) + R_{\mathrm{c}}{\epsilon_{\mathrm{c}}}^2 + R_{\mathrm{uds}}{\epsilon_{\mathrm{uds}}}^2 \ . \end{aligned} \tag{1}$$

Here ϵ_{q} is the selection efficiency of the quark of flavor q ($\mathrm{q} = \mathrm{b}, \mathrm{c}, \mathrm{uds}$) and R_{q} is its production rate ($R_{\mathrm{b}} + R_{\mathrm{c}} + R_{\mathrm{uds}} = 1$). The small correlation of the tagging efficiencies between hemispheres is accounted for by the coefficient ρ_{b}. Provided that the background efficiencies ϵ_{c}, ϵ_{uds} and the coefficient ρ_{b} are taken from simulation, R_{b} and ϵ_{b} can be determined simultaneously from equations (1).

The advantage of the double-tag method is that the quantity ϵ_{b}, which would give the largest systematic uncertainty to the determination of R_{b}, is derived directly from the data. Another source of systematics, coming from the remaining background, is vanishing in the limit of pure b-tag (ϵ_{c}, $\epsilon_{\mathrm{uds}} \to 0$). Therefore the quality of the b-quark selection is crucial for this analysis.

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[1] All decay rates in this paper are given relatively to the Z hadronic width. Thus $R_{\mathrm{b}} = \Gamma(\mathrm{Z} \to \mathrm{b\bar{b}})/\Gamma(\mathrm{Z} \to \mathrm{hadrons})$ and $R_{\mathrm{c}} = \Gamma(\mathrm{Z} \to \mathrm{c\bar{c}})/\Gamma(\mathrm{Z} \to \mathrm{hadrons})$.

B. Multi-tag method

An improved method to measure R_{b} was developed by ALEPH [1] and DELPHI [2]. It is in fact the extension of the double-tag technique described above. In both methods a quark in each hemisphere is classified into $\mathrm{N_T}$ samples with different flavor content. For the double-tag method $\mathrm{N_T} = 2$ (quark is tagged or not tagged) while for the multi-tag measurement larger number ($\mathrm{N_T} = 6$) is used.

The fraction of events f_E^{IJ} classified into the sample I in the first hemisphere and into the sample J in the second hemisphere can be expressed as:

$$f_E^{\mathrm{IJ}} = \sum_{\mathrm{q}} \epsilon_{\mathrm{q}}^{\mathrm{I}} \epsilon_{\mathrm{q}}^{\mathrm{J}} (1 + \rho_{\mathrm{q}}^{\mathrm{IJ}}) R_{\mathrm{q}} \; ; \tag{2}$$

$$\sum_{\mathrm{q}} R_{\mathrm{q}} = 1; \;\; \sum_{\mathrm{I}} \epsilon_{\mathrm{q}}^{\mathrm{I}} = 1 \; ; \;\; \sum_{\mathrm{I}} \epsilon_{\mathrm{q}}^{\mathrm{I}} \rho_{\mathrm{q}}^{\mathrm{IJ}} = 0;$$

$$\mathrm{q} = \mathrm{b}, \mathrm{c}, \mathrm{uds}; \;\; \mathrm{I}, \mathrm{J} = 1, ..., \mathrm{N_T}.$$

The background efficiencies ϵ_1^{c}, $\epsilon_1^{\mathrm{uds}}$ for the purest sample are taken from the simulation together with all correlation coefficients $\rho_{\mathrm{q}}^{\mathrm{IJ}}$. The remaining 13 efficiencies, $\epsilon_{\mathrm{q}}^{\mathrm{I}}$, and R_{b} are obtained from (2).

The b-tagging used in the double-tag method is taken as the first tag here so that all hemispheres selected for the double-tag measurement are put into the first sample. Therefore the systematics due to the background description for these two methods is essentially the same. However, the multi-tag method has two main advantages. On one hand, events with a b-quark classified in the additional samples are also used for analysis, thus increasing the statistical precision of the measurement. On the other hand, the impact of the uncertainty due to the correlation coefficients on the value of R_{b} is reduced.

In table I the precision of the two methods is compared [1,2]. It can be seen that the multi-tag method decreases the statistical error and the uncertainty from efficiency correlations by more than 20% while the central value of R_{b} is compatible for the two methods. The physics uncertainty, coming mainly from the background subtraction, remains the same at a given cut value.

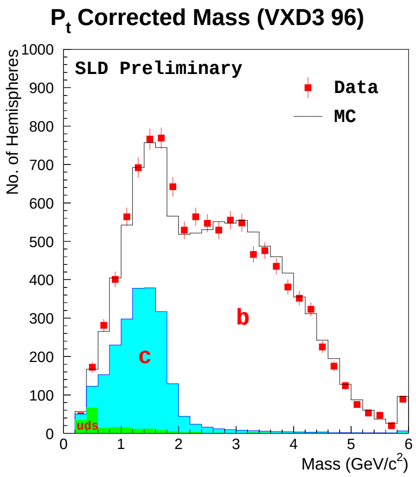
C. Selection of b-quarks

All experiments achieved both high efficiency and high purity of b-quark selection thanks to the excellent operation of the detectors and to sophisticated b-tagging algorithms [1–5]. In the early measurements of R_{b} [6], only the long lifetime of B hadrons was used as signature for the b-quark selection. Currently, many experiments include in the tagging other properties like a large mass of B hadrons and event shape variables which reflect the difference of the production and decay between b-quarks and other flavors.

Figure 1 (left) shows the distribution of the mass of secondary vertices in the SLD experiment [5]. A clear separation of b- and c-quarks can be seen for this variable. For c-quarks, the mass is limited by the mass of D mesons which is around 1.8 GeV/c^2, while for b-quarks it takes much higher values.

TABLE I. Comparison of double-tag and multi-tag R_{b} measurements of ALEPH and DELPHI.

Source of uncertainty	ALEPH ΔR_{b}		DELPHI ΔR_{b}	
	Double-tag	Multi-tag	Double-tag	Multi-tag
Data statistics	0.0011	0.00087	0.00088	0.00067
Simulation statistics	0.0005	0.00047	0.00034	0.00033
Event selection	0.0001	0.00017	0.00009	0.00009
Tracking uncertainty	0.0006	0.00046	0.00013	0.00013
Physics uncertainty	0.0007	0.00066	0.00041	0.00041
Correlation uncertainty	0.0006	0.00028	0.00041	0.00024
Total systematics	0.0012	0.00103	0.00070	0.00060
R_{b} value	0.2167	0.2160	0.21686	0.21634



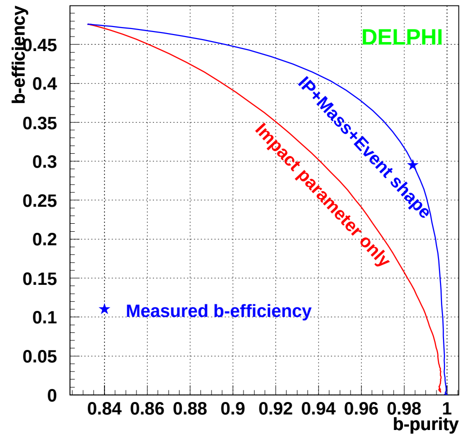


FIG. 1. Left: Distribution of the mass of secondary vertices (SLD). Right: Efficiency and purity of b-quark selection (DELPHI).

Table II compares the performance of the b-tagging techniques in the measurements of R_b presented in this conference and at the EPS-HEP'95 Conference [6]. It shows a significant progress in the b-quark tagging obtained in all experiments. For DELPHI, OPAL and SLD a big part of this amelioration is due to the upgraded vertex detectors. Using the complementary properties of b-quarks give an additional enhancement of the performance, as it can be seen from figure 1 (right) taken from [2]. In the case of DELPHI, the tagging with the combination of variables is more than twice efficient for the same purity of about 98% than the simple lifetime tagging [2].

D. Systematic uncertainties and results

The systematics on this measurement comes from the estimation of background efficiencies and correlation coefficients. Table III shows the breakdown of uncertainties in the different experiments.

The background is due to light quark (u, d, s, c) events which are tagged as b-quarks. There are 4 different sources of such events: detector resolution, production of K^0, Λ and other long lived baryons, production of charm particles and gluon splitting g$\rightarrow$ c$\bar{\mathrm{c}}$, g$\rightarrow$ b$\bar{\mathrm{b}}$. The contribution of the detector resolution and of K^0, Λ is almost negligible. In older measurements, the charm systematics was the largest source of background [6], which limited the final precision due to its full correlation between the experiments. Currently the charm systematics is significantly reduced (2-6 times) because of the purer b-quark selection and the better knowledge of the charm properties, especially the lifetime and production rate of D mesons which were measured at LEP [9].

Actually the splitting of gluons to c$\bar{\mathrm{c}}$ and b$\bar{\mathrm{b}}$ gives the largest single contribution to the systematic error of R_b. This background is rather dangerous because it is not reduced by improving the b-tagging purity and the theoretical prediction of its rate has large uncertainties [7].

TABLE II. Performance of b-tagging for the LEP and SLD experiments presented in this conference and at the EPS-HEP'95 Conference. Also shown is the readout of the micro-vertex detectors for each experiment.

	EPS-HEP'95			DPF'99		
	μ-vertex readout	ϵ_b	background	μ-vertex readout	ϵ_b	background
ALEPH	$R\phi$,Rz	26%	4%	$R\phi$,Rz	19.2%	1.5%
DELPHI	$R\phi$	21%	8%	$R\phi$,Rz	29.6%	1.5%
OPAL	$R\phi$	23%	6%	$R\phi$,Rz	25.5%	3.3%
L3	-	-	-	$R\phi$	23.7%	16.%
SLD	$R\phi$,Rz	31%	6%	$R\phi$,Rz	50.3%	2.2%

The direct measurements of the gluon splitting [8] allow to reduce substantially the systematics from this source. The most recent average values proposed by the Electroweak Heavy Flavor Group for the systematics estimate [9] are $R(\mathrm{g} \to \mathrm{c\bar{c}}) = (2.33 \pm 0.50)\%$ and $R(\mathrm{g} \to \mathrm{b\bar{b}}) = (0.269 \pm 0.067)\%$ per multihadronic Z event. The precision of these numbers can be compared with the relative uncertainty of 50% which was assigned to this source of systematics in older measurements.

The hemisphere-hemisphere tagging efficiency correlation is an unavoidable consequence of deriving the b-efficiency from the data. However the corresponding systematics is under control and is much less than the systematics which would be generated by ϵ_b borrowed from simulation. The origin of the correlation is well understood to be induced by the geometrical acceptance of the detector and the hard gluon emission. One more cause of correlation - a vertex of primary interaction common for both hemispheres of the event - is almost completely removed in the recent measurements where the primary vertex is measured independently in each hemisphere.

The flight directions of the two b-quarks are correlated. Thus any detector response inhomogeneity generates an efficiency correlation. The hard gluon emission produces two different effects. First, it takes a part of the event energy so that the momentum of both b-quarks is reduced. Such reduction induces a positive correlation since the tagging efficiency strongly depends on the energy of B hadrons. In some cases the energy of the emitted gluon is so high that both b-quarks are boosted into the same hemisphere of the event. Such effect produces a negative correlation because only the hemisphere containing the two b-quarks can be selected by the b-tagging.

The contribution of each source of correlation can be disentangled both in the data and in simulation using the distribution of the relevant variables. For the detector acceptance, it can be the direction of the thrust axis. For the hard gluon emission the momentum of the jet can be used. The obtained agreement between data and simulation is such that the corresponding systematics is less than the contribution of the correlation uncertainty due to the limited simulation statistics, as shown in table III.

The combination of the R_b values reported by the experiments (table III) was done by the EWHF group using the method described in [10]. The world average value of R_b is [11]:

$$R_b = 0.21661 \pm 0.00073\ , \tag{3}$$

which is in good agreement with the Standard Model expectation [12] $R_b = 0.21584 \mp 0.00018$, assuming a the top quark mass $m_t = 173.8 \pm 5.2$ GeV/c^2 [13].

III. MEASUREMENT OF R_c

Contrary to R_b, the measurement of R_c is performed by many different methods where both single-tag and double-tag techniques are used [14–22]. In the single-tag measurements, there is no condition on the second quark, thus the statistical precision is better. However, the efficiency of the c-quark selection is estimated from the simulation and gives the main contribution to the systematics. Double-tag methods are less systematics dependent but have higher statistical error. In practice the total precision of all methods is comparable but the composition of the error is different so that a significant reduction of the error on R_c can be obtained by combining all results.

TABLE III. Breakdown of uncertainties and value of the R_b measurements for all experiments.

Source of uncertainty	ALEPH	DELPHI	L3 (prel.)	OPAL	SLD (prel.)
Data statistics	0.00087	0.00067	0.00150	0.00112	0.00139
Simulation statistics	0.00047	0.00033	0.00081	0.00047	0.00026
Internal	0.00049	0.00018	0.00121	0.00088	0.00122
uds background	0.00004	0.00004	0.00131	0.00001	0.00002
Charm background	0.00038	0.00025	0.00169	0.00064	0.00037
$\mathrm{g} \to \mathrm{b\bar{b}}, \mathrm{c\bar{c}}$	0.00047	0.00028	0.00017	0.00032	0.00043
b-physics	0.00025	0.00015	0.00032	0.00015	0.00020
Correlations	0.00028	0.00024	0.00007	0.00050	0.00016
Total systematics	0.00103	0.00060	0.00258	0.00130	0.00139
R_b value	0.2160	0.21634	0.2179	0.2176	0.21594

A. Single-tag measurements

R_c can be obtained from the fit of the inclusive lepton spectra in hadronic jets. The leptons come from the decays ($c \to l$), ($b \to l$), ($b \to c \to l$) and from decays of light hadrons. The lepton misidentification also gives some contribution. The momentum spectra of the leptons from these sources are significantly different, so the fraction $R_c \times Br(c \to l)$ can be determined from the fit of the momentum and transverse momentum distributions. Figure 2, taken from [14], shows these distributions together with their composition and the result of the fit. The distributions of leptons from b-decays were obtained by using a pure b-tagging in the opposite hemisphere where the lepton was contained and were already subtracted in this figure. With this technique the value of $Br(c \to l)$ is taken from other measurements, so that the obtained R_b result includes the uncertainty in $Br(c \to l)$. The uncertainty from this branching rate dominates in the systematics. It is a specific feature of the single-tag method.

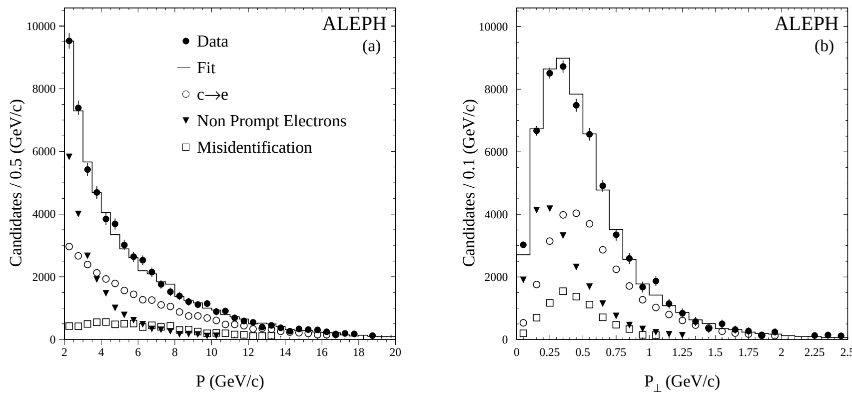


FIG. 2. Momentum and transverse momentum distribution of leptons in hadronic jets (ALEPH). ($b \to l$) and ($b \to c \to l$) components are subtracted.

Another possibility to measure R_c consists in the counting of the production rate of all ground state charmed hadrons in $Z \to c\bar{c}$ decays. The production rate of charmed hadron D_i is $R_c \times Br(c \to D_i)$. If all ground states are counted then $\sum_i Br(c \to D_i) = 1$ and $\sum_i R_c Br(c \to D_i) = R_c$.

The production of D^0, D^+, D_s^+, Λ_c^+ is measured directly using their exclusive decay modes. The rate of Ξ_c^0, Ξ_c^+, Ω_c relative to Λ_c^+ is estimated to be similar to the rate of non-charmed baryons Ξ^0, Ξ^-, Ω^- relative to Λ [19]. As charmed hadrons are produced in both $Z \to c\bar{c}$ and $Z \to b\bar{b}$ decays, to extract $R_c \times Br(c \to D_i)$ the separation of these processes must be done. It is quoted using b-tagging and differences in the energy spectra. Figure 3 from [17] shows the distribution of the b-tagging variable $tr(P_{ev})$ and the energy fraction X_E in the reconstructed decays $D^0 \to K^-\pi^+$. Also shown are the contributions of different flavors and the result of the fit. It can be seen that these distributions are significantly different for c- and b-quarks and they can therefore be separated. Again in this technique the systematic error due to the uncertainty in the decay rate of the different D hadrons is significant.

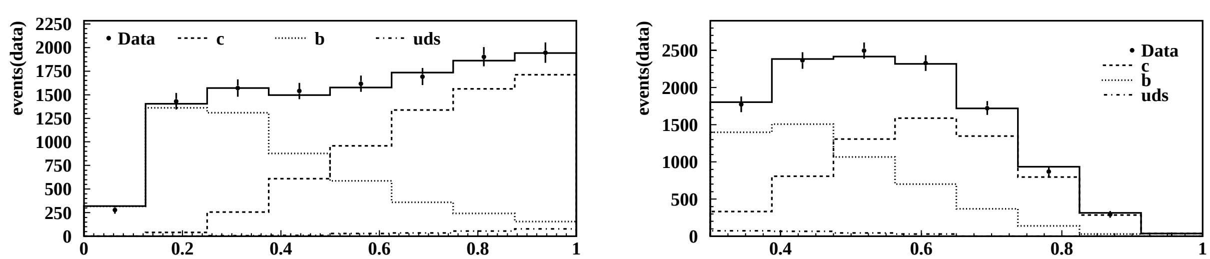


FIG. 3. Distribution of b-tagging variable $tr(P_{ev})$ and energy fraction X_E for the reconstructed decays $D^0 \to K^-\pi^+$ (DELPHI).

B. Double-tag measurements

The double-tag measurement of R_c is complicated by the difficulty of construction of an efficient c-tagging. One possibility is to select exclusive decays of charmed mesons (D^{*+}, D^+, D^0). The purity of such tagging can be as high as 80% but the c-efficiency is only about 2%. To increase the tagging efficiency, a c-quark in the opposite hemisphere can be tagged by a slow pion from the decay $D^{*+} \to D^0\pi^+$. Such pions have small transverse momentum with respect to the D^{*+} direction and selecting them allows to increase the fraction of c-quarks in the sample. In addition, the charge of the slow pion is correlated with the charge of the exclusively reconstructed D^* meson in the opposite hemisphere and the combinations ($\pi^\mp$ $D^{*\pm}$) with the wrong sign allow to determine the background. In addition, ALEPH has recently reported one more double-tag measurement [14] where c-quarks are selected in both hemispheres using exclusive decay modes of D mesons.

Another inclusive technique of charm tagging was developed by the SLD collaboration [21]. In this method events with reconstructed secondary vertices are used. Such events contain mainly c- and b-quarks. They are separated using the correlation of the mass of particles attached to a secondary vertex and their total momentum. The small reconstructed mass of the secondary vertex in the jets with b-quark means that some particles are not included in the secondary vertex. The secondary vertex from charm should include more particles for the same mass so that it has a higher momentum than that from b-quarks. Such effect is clearly seen in figure 4 taken from [21]. The solid line in figure 4 shows the condition of c-tagging. With this method the SLD collaboration obtained a 67% purity and an efficiency of c-quark selection of about 15%. Due to the high efficiency of c-tagging and the use of the double-tag technique this approach provides the best precision determination among all other measurements of R_c although the statistics used by SLD is about 20 times smaller than in the LEP experiments (see figure 5).

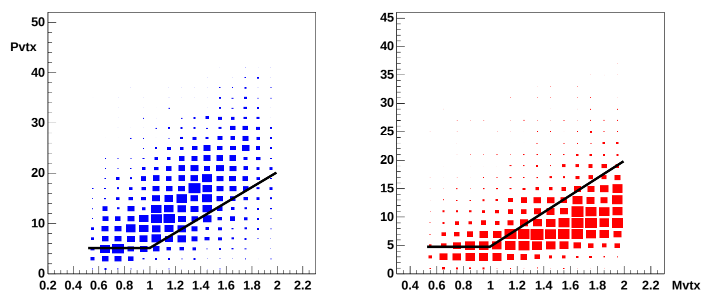


FIG. 4. Vertex momentum as a function of vertex mass for c (left) and b (right) events (SLD).

C. Combined result

Figure 5 presents all results discussed here and reported by the experiments [14–22]. It can be seen that consistent results are obtained by different techniques and by different experiments. The EWHF combination of all measurements [11] gives:

$$R_c = 0.1735 \pm 0.0044 \;, \tag{4}$$

which is in good agreement with the Standard model expectation [12] $R_c = 0.1723$.

IV. RARE DECAY $Z \to b\bar{b}b\bar{b}$

The rate of the rare decay $Z \to b\bar{b}b\bar{b}$ is measured by DELPHI [23]. In the Standard Model the final state with four b-quarks is produced by the splitting $g \to b\bar{b}$ of a hard gluon emitted in the $Z \to b\bar{b}$ decay. The signal is obtained by selecting events with 3 jets and requiring a strong b-tag for all of them. The excess of events with high values of the b-tagging variable for the less likely b-jet, attributed to the process $Z \to b\bar{b}b\bar{b}$, is used to obtain the decay rate:

$$R_{4b} = (5.4 \pm 1.8(\text{stat}) \pm 1.5(\text{syst.})) \times 10^{-4} \ (\text{DELPHI}) \tag{5}$$

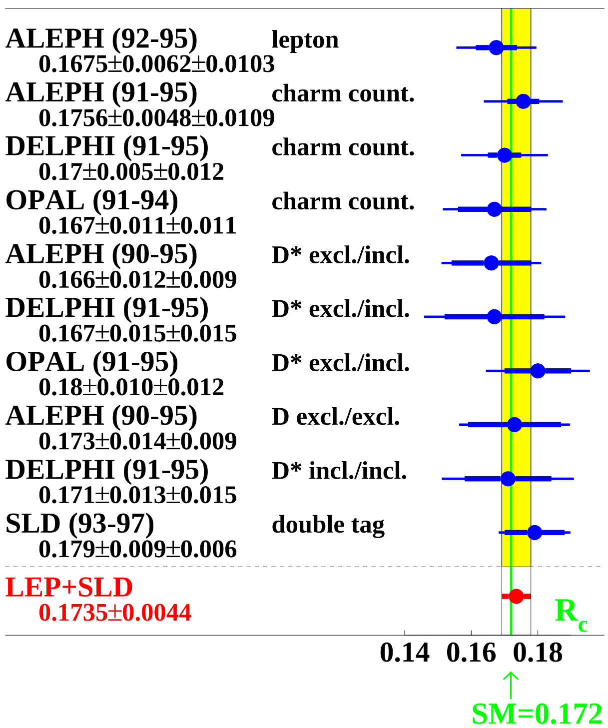


FIG. 5. Combination of all R_c measurements.

V. SEARCH FOR $\mathrm{Z} \to \mathrm{b\bar{q}}$, $\mathrm{q} \neq \mathrm{b}$ DECAYS

A. Flavor changing neutral currents

The decay $\mathrm{Z} \to \mathrm{b\bar{q}}$, $\mathrm{q} \neq \mathrm{b}$ is mediated by a flavor changing neutral current (FCNC) and is suppressed in the Standard Model. In the general form, FCNCs can be written as [24]:

$$J_\mu = \bar{\mathrm{q}}_1 \left(\gamma_\mu A + i\sigma_{\mu\nu} \frac{k_\nu}{M_\mathrm{Z}} B \right) \mathrm{q}_2 \ . \tag{6}$$

Here k_ν is the momentum of the Z. The part proportional to A is called the electric-type term and the part proportional to B is called the magnetic-type term.

FCNCs with a b-quark was searched for in the decays of B hadrons. The most recent limits are [25]:

$$\begin{aligned} \mathrm{Br}(\mathrm{b} \to \mathrm{s}\mu\mu) &< 5.7 \times 10^{-5} \ (90\%\mathrm{CL})(\mathrm{CLEO}) \\ \mathrm{Br}(\mathrm{b} \to \mathrm{see}) &< 5.8 \times 10^{-5} \ (90\%\mathrm{CL})(\mathrm{CLEO}) \ . \end{aligned} \tag{7}$$

These limits constrain only the electric-type term of FCNCs. Due to the small momentum of the virtual Z boson compared with its mass, in the decay of b-quarks the contribution of the magnetic-type term is vanishing. But in the decay $\mathrm{Z} \to \mathrm{b\bar{q}}$, $\mathrm{q} \neq \mathrm{b}$ this term can become important. Therefore, the search of $\mathrm{Z} \to \mathrm{b\bar{q}}$, $\mathrm{q} \neq \mathrm{b}$ decays is complementary to the search for FCNCs in B decays and puts additional constraints on them.

B. Search technique and results

Two experiments at LEP - DELPHI [26] and L3 [27] - performed a search of the decay $\mathrm{Z} \to \mathrm{b\bar{q}}$, $\mathrm{q} \neq \mathrm{b}$. To select it, both b-tagging and light quark tagging are required. The light quark tagging is constructed as the combination of the lifetime and event shape variables.

Due to the clear signature of B hadrons, the b-tagging is much purer than the light quark tagging. E.g. in the analysis of DELPHI, the purity of b-tagging is 98.5% and the purity of light quark tagging is only 92.5%. Thus, the background consists mainly of events $\mathrm{Z} \to \mathrm{b\bar{b}}$ in which one b-quark is tagged as a light quark. Nevertheless, a good ratio of background to signal efficiencies is obtained: 0.019 for DELPHI and 0.069 for L3. Both experiments don't observe the signal of $\mathrm{Z} \to \mathrm{b\bar{q}}$:

$$
\begin{aligned}
R_{\mathrm{b\bar{q}}} &= (1.3 \pm 6.1(\mathrm{stat}) \pm 5.5(\mathrm{syst})) \times 10^{-4} \ (\mathrm{DELPHI}) \\
R_{\mathrm{b\bar{q}}} &= (-0.8 \pm 1.5(\mathrm{stat}) \pm 3.2(\mathrm{syst})) \times 10^{-3} \ (\mathrm{L3})
\end{aligned} \tag{8}
$$

The combined upper limit on this decay rate is established to be:

$$
R_{\mathrm{b\bar{q}}} < 2.4 \times 10^{-3} \ (90\%\mathrm{CL}) \tag{9}
$$

VI. SUMMARY

This report has summarized the current status of the study of decays of Z to b- and c-quarks. In total 5 precise measurements of R_{b} and 10 measurements of R_{c} by different methods are performed. The consistency of all results is good. The average values of R_{b}, R_{c} are:

$$
\begin{aligned}
R_{\mathrm{b}} &= 0.21661 \pm 0.00073 \\
R_{\mathrm{c}} &= 0.1735 \pm 0.0044 \ .
\end{aligned}
$$

They agree within one standard deviation with the expectation of the Standard Model. The measurement of the rare decay rate $\mathrm{Z} \to \mathrm{b\bar{b}b\bar{b}}$ is reported to be:

$$
R_{4\mathrm{b}} = (5.4 \pm 2.3) \times 10^{-4} \ .
$$

The FCNC decay $\mathrm{Z} \to \mathrm{b\bar{q}}$, $\mathrm{q} \neq \mathrm{b}$ is not observed and the upper limit on its rate is set to be:

$$
R_{\mathrm{b\bar{q}}} < 2.4 \times 10^{-3} \ (90\% \ \mathrm{CL}) \ .
$$

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I wish to thank all collaborations at LEP and SLD at SLC for providing me their results. I am indebted to the LEP Heavy Flavor Working Group for providing me the combined average values of R_{b} and R_{c}.

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