EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Measurement of the Z Branching Fraction into Bottom Quarks Using Double Tag Methods

The L3 Collaboration

Abstract

We present an updated L3 measurement of $R_b = \Gamma(\mathrm{Z} \to \mathrm{b\bar{b}})/\Gamma(\mathrm{Z} \to \mathrm{hadrons})$ using double-tag methods. Two analyses have been performed on one million hadronic Z events collected in 1994 and 1995. The first analysis exploits the capabilities of the silicon microvertex detector. The tagging of b-events is based on the large impact parameter of tracks from weak b-decays with respect to the $\mathrm{e}^+\mathrm{e}^-$ collision point. In the second analysis a high-p_t lepton tag is used to enrich the b-content of the sample. The analyses are combined in order to provide a more precise determination of R_b:

$$R_b = 0.2176 \ \pm\ 0.0015\ (\mathrm{stat})\ \pm\ 0.0026\ (\mathrm{syst})\ -\ 0.212\ (R_c - 0.172)\ ,$$

where the first error comes from data statistics, the second is the total systematic uncertainty and the third term gives the result's dependence on assumptions about the fraction of charm in hadronic Z decays. The result is preliminary.

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1 Introduction

The Z partial width into $\mathrm{b\bar{b}}$ quark pairs is of special interest since this decay process receives sizeable contributions from vertex corrections involving top quarks and Higgs bosons. The partial width $\Gamma(\mathrm{Z} \to \mathrm{b\bar{b}})$ is usually measured as its relative contribution to the total hadronic width, $R_b = \Gamma(\mathrm{Z} \to \mathrm{b\bar{b}})/\Gamma(\mathrm{Z} \to \mathrm{hadrons})$, since many experimental and theoretical uncertainties cancel when forming this ratio. A departure from the SM value 0.2158 ± 0.0003 could be a signal for new physics. The average of present measurements [1] is 0.2177 ± 0.0011 [2].

In this note we present an updated R_b measurement obtained with the L3 detector at LEP [3]. Features that distinguish the production of $\mathrm{b\bar{b}}$ pairs from lighter quark production are: the long lifetime of b-flavored hadrons, the semileptonic decays of heavy b-flavored hadrons and the broad event shape caused by the large quark mass. The b-tagging method using lifetime information relies on data from the L3 Silicon Microvertex Detector (SMD) [4, 5] which was fully operational from 1994 onwards. The study presented here is thus limited to 1994-1995 data. The method using the characteristic semileptonic decays of B-hadrons relies on L3's excellent lepton identification and energy resolution for leptons. It requires lepton candidates with high momentum along and transverse to the direction of the associated jet, caused by the hard fragmentation and high mass of the decaying hadron.

2 Hadronic event selection

Hadronic events are selected with criteria similar to the ones used for the measurement of the total hadronic cross section [6]. The basic requirements used there select 99.15% of all hadronic Z decays with a background of 0.15% from other processes. A few additional requirements ensure that the events are amenable to an analysis of lifetime information. These are:

- The number of reconstructed tracks must be larger than four.
- The polar angle of the thrust axis, θ_T, reconstructed from calorimetric information, must point into a fiducial region delimited by the barrel part of the detector, $|\cos\theta_T| < 0.7$.

With these additional criteria, 970k hadronic events are selected from the data taken in 1994-1995, corresponding to an integrated luminosity of 71 pb^{-1}.

Hadronic Z decays are simulated using JETSET [7] and passed through a simulation of the L3 detector response [8]. The simulation takes carefully into account the inefficiencies and resolutions of the different subdetectors as a function of time, weighted according to the collected luminosity in data.

3 Double Tag Methods

An event is first split into two hemispheres defined by a plane normal to the thrust axis. Separately for each hemisphere, a set of criteria is applied in order to significantly enhance the purity of b-events. A hemisphere satisfying those criteria is declared to be "tagged". The number N_t of tagged hemispheres is related to the total number N_{had} of hadronic events by the following equation:

$$\frac{N_t}{2\ N_{had}} = R_b\epsilon_b + R_c\epsilon_c + (1 - R_c - R_b)\,\epsilon_{uds} \tag{1}$$

where ϵ_b, ϵ_c and ϵ_{uds} are the efficiencies of obtaining a tag from b, c and light quark hemispheres. The number of events with both hemispheres tagged, N_{tt}, is given by:

$$\frac{N_{tt}}{N_{had}} = c_b R_b\epsilon_b^2 + c_c R_c\epsilon_c^2 + c_{uds}\,(1 - R_c - R_b)\,\epsilon_{uds}^2 \tag{2}$$

where the additional factors c_b, c_c and c_{uds}, called hemisphere correlation factors, quantify residual correlations between the two hemispheres, which lead to a deviation from the simple power law reduction of the efficiencies.

Two parameters can be determined from the two experimental ratios $N_t/(2\ N_{had})$ and N_{tt}/N_{had}; we choose R_b and ϵ_b as determined from data alone. The relative rate of c production, R_c is fixed to its Standard Model value of 0.172. The efficiencies for quarks lighter than b, as well as the hemisphere correlation factors, are taken from the Monte Carlo simulation. However, only the factor c_b is relevant to the analysis for samples of good b purity ($c_c = c_{uds} = 1$). Typical values of the Monte Carlo parameters are $\epsilon_c \approx 2\%$, $\epsilon_{uds} \approx 0.5\%$ and $c_b \approx 1$.

A second tag, t', provides three additonal equations:

$$\frac{N_{t'}}{2\ N_{had}} = R_b\epsilon'_b + R_c\epsilon'_c + (1 - R_c - R_b)\,\epsilon'_{uds} \tag{3}$$

$$\frac{N_{t't'}}{N_{had}} = c'_b R_b{\epsilon'_b}^2 + R_c{\epsilon'_c}^2 + (1 - R_c - R_b)\,{\epsilon'}^2_{uds} \tag{4}$$

$$\frac{N_{tt'}}{2\ N_{had}} = c''_b R_b\epsilon_b\epsilon'_b + R_c\epsilon_c\epsilon'_c + (1 - R_c - R_b)\,\epsilon_{uds}\epsilon'_{uds} \tag{5}$$

The measurement can be performed by a global fit in which the values of the five ratios: $N_t/(2\ N_{had})$, N_{tt}/N_{had}, $N_{t'}/(2\ N_{had})$, $N_{tt'}/(2\ N_{had})$, $N_{t't'}/N_{had}$ are used to determine the values of R_b, ϵ_b and ϵ'_b, while c_b, ϵ_c, ϵ_{uds}, c'_b, ϵ'_c, ϵ'_{uds}, c''_b are constrained to the values obtained from the Monte Carlo simulation with their statistical and systematic errors.

4 Impact parameter analysis

4.1 Track and vertex reconstruction

The inner tracker of L3 reconstructs particle trajectories from hits in the two layers of double sided silicon of the SMD, up to 62 measurements in the central tracker chamber and two measurements in the Z chamber. All these measurements are used in conjunction to measure the five parameters characterising the trajectory, i.e. its curvature in the $r-\phi$ plane, its transverse distance of closest approach (DCA) to the vertex, its azimuthal angle at the DCA, its polar angle θ and the Z coordinate at the DCA. Their covariance matrix is determined from the estimated single point resolution function. The most important parameters for this analysis are the DCA and its error, σ_{DCA}. Small biases in the DCA itself are removed recalibrating the mean DCA value as a function of the azimuthal angle of the track and as a function of the track position inside a sector of the chamber [9]. The DCA error is recalibrated using tracks with a high probability to come from the primary vertex. For these, the width of the DCA distribution for tracks with high momentum, where multiple scattering is negligible, is used to determine a factor that multiplies the calculated DCA error from the track fit. The factor is found to be close to 1, in agreement with an analysis performed using high momentum tracks from $e^+e^- \to e^+e^-$, $\mu^+\mu^-$, and $\tau^+\tau^-$. Typical values for σ_{DCA} are 30 μm and 100 μm for tracks with and without SMD information, respectively. In addition, the contribution from multiple scattering, not included in the error calculated in the track fit, is estimated from the dependence of the distribution's width on transverse momentum. It is found that the additional multiple scattering error is $110/(p_\perp\sqrt{\sin\theta})$ μm for tracks with a hit in the inner SMD layer, $200/(p_\perp\sqrt{\sin\theta})$ μm for tracks without such hits, with $p_\perp$ measured in GeV.

The average position of the LEP luminous region inside L3 is reconstructed using tracks collected in hadronic events. The position and its error are averaged over 200 events, in order to closely follow drifts in the beam position. The result, called the 200-event-vertex, is used as a constraint in the reconstruction of the primary vertex in each event, weighted by the r.m.s. width of the luminous region in the horizontal (110 μm) and vertical (20 μm) directions.

For the reconstruction of primary vertices, tracks are selected using loose criteria on the track quality. These are:

- The track fit should be performed with at least 20 hits.
- The distance of closest approach (DCA) to the primary vertex (initially taken to be the 200-event-vertex) has to be less than 1 mm.
- The significance of the DCA, defined by the ratio of the DCA and its total error, σ_{DCA}, has to be less than five.
- At least one hit in the inner layer of the SMD has to be included in the track fit.
- The transverse momentum of the track with respect to the beam direction has to be greater than 150 MeV.

The procedure uses an iterative method which starts from the 200-event-vertex as an initial estimate of the primary vertex position. At each step of the iteration, the vertex is calculated with all the tracks selected for that step. If the χ^2 probability of the vertex is less than 0.05, the track with the largest contribution to χ^2 is removed and the vertex is recalculated with the remaining tracks. This procedure is repeated until the χ^2 probability of the vertex is at least 0.05 or only three tracks are left. In every step, the 200-event-vertex is used as a constraint. With this procedure, a primary vertex is reconstructed in 99.5% of all selected events. This efficiency is found to be independent of the quark flavor within one per mill, using Monte Carlo simulation. The value of the uncertainty depends on the azimuthal angle of the event thrust and on the number and quality of the tracks retained for its determination. The average uncertainty on the primary vertex position in the horizontal direction is 42 μm for light-quark events and 77 μm for b-events. The worse resolution for b-events is due to the unavoidable inclusion of b-decay tracks in the vertex determination. The uncertainty in the vertical direction is dominated by the small vertical width of the beam spot (20 μm).

4.2 Heavy quark tagging using impact parameters

The information from all tracks in a hemisphere is combined to form a discriminating variable, D, which describes the likelihood that all tracks come from the primary vertex. The sensitive single track quantity used for constructing D is the impact parameter, defined as the absolute value of the track's DCA with a sign that is positive if the track intersects the direction of the associated jet in the direction of the jet's total momentum, negative if it intersects opposite to that direction. The angular resolution for the jet direction is 40 mrad.

The ratio of the impact parameter and its error is taken to define the significance s. The total impact parameter error is composed of the error from the track fit, the multiple scattering contribution and the contribution of the primary vertex error, all determined according to the procedure described in section 4.1.

The discriminant variable is constructed on the basis of a resolution function, $R(x)$, which describes the probability that a track which comes from the primary vertex is measured to have an apparent impact parameter significance x. The probability P of finding a significance greater than the measured one, s, is given by:

$$P(s) = \frac{\int_s^\infty R(x)dx}{\int_{-\infty}^\infty R(x)dx} \tag{6}$$

The combined probability for the n tracks in the hemisphere is $\prod_{i=1}^n P(s_i)$. The probability of measuring a value greater than $\prod_{i=1}^n P(s_i)$ is:

$$\mathcal{P}(n) = \prod_{i=1}^n P(s_i) \sum_{j=0}^{n-1} \frac{(-\ln \prod_{i=1}^n P(s_i))^j}{j!} \tag{7}$$

We define the discriminant variable as $D = -\log_{10} \mathcal{P}(n)$. A tagged hemisphere must have a value of D above some cut. This definition of the discriminant cut ensures that the amount of background from hemispheres which have tracks consistent with the primary vertex is 10^{-D}, independently of n.

Tracks retained for the determination of D have to fulfill the following quality criteria:

- The angle, θ_j, between the track and its associated jet axis must satisfy $\cos\theta_j > 0.7$.
- The track should have at least 30 hits spanned over a distance of at least 40 wires.
- The distance of closest approach (DCA) to the primary vertex has to be less than 1.5 mm and 3 mm for tracks with and without SMD infomation, respectively.
- The angular separation of the track from the anode and cathode planes of the tracking chanber, where the resolution is worse, should be more than 11 mrad.
- If a track comprises no hits from the SMD, at least 2 hits from the inner ring of the tracking chamber should be used in the track fit.

The retained tracks are then classified into classes according to the pattern of the associated SMD clusters. Each class corresponds to a different resolution function for the impact parameter measurement. The repartition among classes agrees with the Monte Carlo simulation to within a percent.

The resolution function $R(s)$ is determined for each class by a fit to all tracks with negative significance in data. The r.m.s. width of the significance in each class is compatible with one, but the distributions have substantial tails. Therefore, a model of the resolution function $R(s)$ is constructed as a sum of two gaussian functions and an exponential tail. The same resolution functions are used for data and Monte Carlo. Special care has been taken to ensure that the simulation takes into account correctly the time dependence of multiple scattering, tracking chamber wire inefficiencies, wire resolutions as a function of the drift distance, SMD noise and SMD strip inefficiencies. Only small final adjustments are needed in order to reflect the data's behaviour. The uncertainty on the adjustment will be used later for the determination of the systematic error due to resolution effects. Figure 1a) shows the negative part of the significance distribution for all tracks. The good agreement between data and MC shows that the resolution effects are well understood over the whole range of the significance. Figure 1b) shows the positive part of the significance distribution, compared to the Monte Carlo expectation for $R_b = 0.217$. Good agreement is also observed.

The resolution function determined from data is used to calculate the track probability $P(s)$. The distribution of the hemisphere discriminant $D(n)$ is shown in Figure 2, together with the Monte Carlo expectation and its components in terms of primary quark flavors. The agreement is satisfactory for the bulk as well as the tail of the distribution and the tagging power of the discriminant is clearly exhibited.

The efficiency for b-tagging and the purity of the obtained sample can be varied by changing the cut in the discriminant variable. We obtain a b-tagging efficiency as a function of the sample purity as shown in Figure 3 for the data and the Monte Carlo simulation. There is a residual difference between the efficiency observed in data with respect to the one predicted by Monte Carlo, which never exceeds 2.5%. It is independent of the discriminant cut value over a wide range and it is consistent with the estimated statistical and systematic errors. For the discriminant cut used in the double-tag analysis we obtain $\epsilon_b^{\text{data}} = (23.70 \pm 0.19\ (\text{stat}) \pm 0.22\ (\text{syst}))\%$, whereas the Monte Carlo estimate is $\epsilon_b^{\text{MC}} = (24.21 \pm 0.03\ (\text{stat}) \pm 1.58\ (\text{syst}))\%$. The large b-physics modelling uncertainties on ϵ_b^{MC} do not propagate to an error in R_b since the Monte Carlo efficiency is not used.

4.3 Systematic errors

4.3.1 Tracking Resolution

The tracking resolution function is determined from data alone. Its statistical accuracy is such that it causes a negligible uncertainty, but a wrong description in the Monte Carlo simulation influences the values of auxiliary parameters like the efficiencies for lighter quarks and hemisphere correlations. In order to estimate the systematic error from the tracking resolution, two Monte Carlo samples are used, one with the final adjustment, MC_{final}, and the other one corresponding to the 1-sigma resolution uncertainty, $\text{MC}_{1\sigma}$. The sample MC_{final} is found to produce a stable value of R_b as a function of the discriminant cut within statistical and systematic fluctuations. $\text{MC}_{1\sigma}$ is defined by the change in the final adjustment that leads to a behaviour of R_b which is inconsistent with a constant value by one standard deviation of the observed fluctuations. The differences in ϵ_c, ϵ_{uds} and c_b predicted by the two Monte Carlo samples are propagated as an estimate of the tracking resolution error.

4.3.2 Systematic Error from Background Modelling

The background efficiencies ϵ_{uds}, ϵ_c, and the hemisphere correlation factor c_b, which enter equations (1) and (2) have to be determined externally from Monte Carlo simulation. For the charm efficiencies the production and decay properties of the charmed hadrons have to be controlled, since the different species, D^0, D^+, D_s and Λ_c have lifetimes varying in the range of 0.2 to 1.1 ps. Modelling uncertainties in ϵ_{uds} arise from the residual contamination by light hadrons with long lifetime, K_s^0 and Λ, as well as the probabilities for gluon splitting into $\text{b}\bar{\text{b}}$ and $\text{c}\bar{\text{c}}$ pairs. Modelling uncertainties of the B-hadron properties only influence the correlation factor c_b. They are estimated by varying the mean value of the B energy fraction $< x_E(\text{b}) >$, the charged decay multiplicity and the average lifetime of B-hadrons.

The variation of the parameters is performed following the suggestions of reference [10]. The parameter ranges are listed in Table 1.

4.3.3 Systematics from Hemisphere Correlations

Systematic errors on c_b are due to uncertainties in the Monte Carlo simulation. In addition to resolution and modelling effects, taken into account as described in 4.3.1 and 4.3.2, reconstruction algorithms and detector inhomogeneities may create correlations between the tagging efficiencies on both hemispheres.

Error source	Variation
Beauty fragmentation parameter:	
$< x_E(\mathrm{b}) >$	0.702 ± 0.008 [10]
Beauty decay parameters:	
B lifetimes	1.55 ± 0.05 ps [10]
B decay multiplicity	5.73 ± 0.35 [10]
Fractions in $\mathrm{c\overline{c}}$ events:	
D^+	0.233 ± 0.028 [10]
D_s	0.102 ± 0.037 [10]
Λ_c	0.065 ± 0.029 [10]
$g \to c\overline{c}$	$(2.38 \pm 0.48)\%$ [10]
$g \to b\overline{b}$	$(0.13 \pm 0.04) \times g \to c\overline{c}$ [10]
Charm decay parameters:	
D^0 lifetime	0.415 ± 0.004 ps [11]
D^+ lifetime	1.057 ± 0.015 ps [11]
D_s lifetime	0.467 ± 0.017 ps [11]
Λ_c lifetime	0.206 ± 0.012 ps [11]
D decay multiplicity	[10]
$\mathrm{D}^0 \to 0$ prong	0.054 ± 0.011
$\mathrm{D}^0 \to 4$ prong	0.293 ± 0.023
$\mathrm{D}^0 \to 6$ prong	0.019 ± 0.009
$\mathrm{D}^+ \to 1$ prong	0.384 ± 0.023
$\mathrm{D}^+ \to 5$ prong	0.075 ± 0.015
$\mathrm{D}_s \to 1$ prong	0.37 ± 0.10
$\mathrm{D}_s \to 5$ prong	0.21 ± 0.11
$\mathrm{D} \to \mathrm{K}^0$ multiplicity	0.46 ± 0.06 [12]
Charm fragmentation parameter:	
$< x_E(\mathrm{c}) >$	0.484 ± 0.008 [10]
Fractions in uds events:	
K^0 and Λ	JETSET $\pm$ 10%
$g \to c\overline{c}$	$(2.38 \pm 0.48)\%$ [10]
$g \to b\overline{b}$	$(0.13 \pm 0.04) \times g \to c\overline{c}$ [10]

Table 1: Variation of modelling parameters used for the determination of the systematic error in the impact parameter double-tag measurement.

A possible source of correlation can be quantified by choosing a variable q for each hemisphere which could be influenced by tagging the opposite hemisphere. For a particular cut on the hemisphere discriminant we then define three distributions:

- The normalised distribution of q for all hemispheres, $N(q)$.
- The single hemisphere tagging efficiency as a function of q, $\epsilon(q)$
- The normalised distribution of q in a co-tagged hemisphere, $C(q)$. A co-tagged hemisphere is the opposite to a tagged hemisphere, regardless of whether it is itself tagged.

We then form a coefficient, c_b^q, reflecting the correlation characterised by q for a particular discriminant cut:

$$c_b^q = \frac{\int \epsilon(q)\ C(q)\ dq}{\int \epsilon(q)\ N(q)\ dq} \tag{8}$$

The value $c_b^q = 1$ implies that there is no correlation between hemispheres from effects characterized by q. A value $c_b^q > 1$ indicates a positive correlation, $c_b^q < 1$ an anti-correlation.

The analysis is performed on several candidate variables q. For a $b\bar{b}$ Monte Carlo sample, the sum of the separate components is then compared to the total correlation factor c_b. A reasonable agreement between them means that the relevant sources of correlation have been identified. The following sources have been determined to be relevant:

- Angular effects: Inefficient regions of the detector can lead to correlations due to the back-to-back nature of hadronic events. This is estimated using $q = \cos\theta$ and $q = \phi$ where θ and ϕ are the polar and azimuthal angles of the most energetic jet in each hemisphere.
- Vertex effects: Both hemispheres use the same primary vertex, which is determined as explained in section 4.1. The main effect arises because the primary vertex fit may also include tracks coming from B-hadron decays (negative correlation). To quantify the effect, a primary vertex is constructed separately in each hemisphere using only the tracks assigned to it. The variable q is taken to be the distance in the xy plane between the vertex in each hemisphere and the overall event vertex. Its sign is given according to how far each hemisphere vertex moves when the 200-event vertex constraint is removed: the positive sign is assigned to the hemisphere with the larger movement.
- QCD effects: The presence of hard gluons in the event can influence the tagging efficiency of both hemispheres by taking energy away from the primary quarks (positive correlation) or, in an extreme case, by pushing both quarks into the same hemisphere (negative correlation). This effect is modified by reconstruction and detector resolution effects. The signed event thrust, $q = \pm T$, is used as a probe. The positive sign is assigned to the hemisphere with the highest energy jet.

The dominant components are those due to gluon radiation and vertex bias. There is a remaining discrepancy between the linear sum of the correlation components due to the above three sources and the total observed correlation factor. That is expected, due to the interference between the sources considered and to additional sources of less relevance. For instance, ϕ and vertex effects are intrinsically correlated, since the primary vertex uncertainty is affected by the ϕ dependent beam spot size.

To test the quality of the MC correlation simulation, a 70% b-purity sample is selected by requiring the event discriminant to be greater than 1.5. The same cut is applied to the MC sample. The correlation coefficients are calculated for each of the three previous sources in data and Monte Carlo. The differences are taken as the systematic uncertainties on the correlation term (Table 4) and propagated through to a systematic error on R_b.

The complete list of systematic uncertainties on c_b is shown in Table 4.

Error source	$\Delta\epsilon_c$
MC Statistics	0.02%
Track Resolution	0.02%
D^+ fraction	+0.10%
D_s fraction	+0.02%
Λ_c fraction	-0.04%
D^0 lifetime	+0.02%
D^+ lifetime	+0.01%
D_s lifetime	+0.01%
Λ_c lifetime	+0.01%
D^+ 1-prong decay multiplicity	-0.03%
D^+ 5-prong decay multiplicity	0.00%
D^0 0-prong decay multiplicity	0.00%
D^0 4-prong decay multiplicity	+0.02%
D^0 6-prong decay multiplicity	0.00%
D_s 1-prong decay multiplicity	-0.02%
D_s 5-prong decay multiplicity	-0.04%
$D \rightarrow K^0_s$ multiplicity	+0.02%
$< x_E(c) >$	+0.06%
$g \rightarrow c\overline{c}$	+0.00%
$\frac{g\rightarrow b\overline{b}}{g\rightarrow c\overline{c}}$	+0.00%
Total	0.15%

Table 2: Error contributions to ϵ_c for a cut at $D > 2.3$.

4.4 Results

Systematic errors on ϵ_c, ϵ_{uds}, c_b, are propagated into the double-tag R_b measurement. Figure 4a) shows the measured value of R_b as a function of the discriminant cut, in the region around the minimum of the total uncertainty. The value is stable. Figure 4b) shows the statistical and systematic errors on R_b in the same range. The minimum of the total error occurs at $D > 2.3$,

Error source	$\Delta\epsilon_{uds}$
MC Statistics	0.004%
Track Resolution	0.010%
K^0 and Hyperons	+0.033%
$g \to c\overline{c}$	+0.003%
$\frac{g\to b\overline{b}}{g\to c\overline{c}}$	+0.003%
Total	0.035%

Table 3: Error contributions to ϵ_{uds} for a cut at $D > 2.3$.

Error source	Δc_b
MC Statistics	0.0036
Track Resolution	0.0002
Vertex bias	0.0053
θ correlations	0.0002
ϕ correlations	0.0009
Hard gluon emission	0.0004
B fragmentation	+0.0014
B lifetimes	+0.0008
B decay multiplicity	+0.0015
Total	0.0068

Table 4: Error contributions to c_b for a cut at $D > 2.3$.

which defines the central value of our measurement. For this cut 118817 tagged hemispheres and 11705 double-tagged events are selected on a sample of 968964 hadrons.

The value of ϵ_c is estimated by Monte Carlo to be $\epsilon_c = (3.05 \pm 0.02(\text{stat}) \pm 0.15(\text{syst}))\%$ A breakdown of the error is shown in Table 2. Since the individual charm lifetimes are measured very accurately, the fractions of the different species become one of the major error contributions. Among all the charmed hadrons the D^+ properties lead to the dominant errors because it has the longest lifetime.

The value of ϵ_{uds} is estimated to be $\epsilon_{uds} = (0.738 \pm 0.004(\text{stat}) \pm 0.035(\text{syst}))\%$. The different error contributions are shown in Table 3. The systematic error is dominated by the uncertainty in the rate of light flavoured hadrons with long lifetime.

The value of the correlation coefficient is $c_b = 0.9729 \pm 0.0048(\text{stat}) \pm 0.0058(\text{syst})$.The different error contributions are listed in Table 4. Primary vertex effects are the dominant source of uncertainty.

The measured value of R_b is:

$$R_b = 0.2176 \pm 0.0018(\text{stat}) \pm 0.0031(\text{syst}) - 0.196\ (R_c - 0.172) \quad (9)$$

for a b efficiency of $\epsilon_b = (23.70 \pm 0.19\ (\text{stat}) \pm 0.22\ (\text{syst}))\%$. These results are preliminary.

The detailed list of contributions to the error on R_b is given in Table 5. The sources internal to L3 are separated from the ones in common with other experiments.

5 Lepton analysis

5.1 Lepton identification

Electrons are identified as clusters in the electromagnetic calorimeter matched to a track in the tracking chamber:

- The cluster energy must be greater than 3 GeV.
- The cluster in the electromagnetic calorimeter must have more than 5 crystals with signal, more than 90% of the energy contained in a 3x3 matrix and a shower shape consistent with the deposit of an electromagnetic particle ($\chi^2_{\text{em shape}} < 6$).
- Such electromagnetic cluster must be matched in angle (5 mrad) and in energy (within 4 standard deviations) to a good track in the central tracking chamber.
- The energy deposited in the hadron calorimeter in a cone of half angle 7° should be less than 3 GeV.

Error source	ΔR_b internal	ΔR_b external
MC statistics	0.00092	-
Resolution	0.00056	-
Vertex effects on c_b	0.00125	-
θ effects on c_b	0.00006	-
ϕ effects on c_b	0.00021	-
D^+ fraction	-	-0.00133
D_s fraction	-	-0.00022
Λ_c fraction	-	+0.00047
D^+ lifetime	-	-0.00020
D^0 lifetime	-	-0.00013
D_s lifetime	-	-0.00012
Λ_c lifetime	-	-0.00008
D^+ 1-prong decay multiplicity	-	+0.00045
D^+ 5-prong decay multiplicity	-	-0.00006
D^0 0-prong decay multiplicity	-	-0.00004
D^0 4-prong decay multiplicity	-	-0.00024
D^0 6-prong decay multiplicity	-	0.00000
D_s 1-prong decay multiplicity	-	+0.00028
D_s 5-prong decay multiplicity	-	+0.00055
$D \to K_s^0$ multiplicity	-	-0.00025
$< x_E(c) >$	-	-0.00086
$g \to c\bar{c}$ in $c\bar{c}$ events	-	-0.00001
$\frac{g\to b\bar{b}}{g\to c\bar{c}}$ in $c\bar{c}$ events	-	-0.00003
K_s^0 and Λ	-	-0.00176
$g \to c\bar{c}$ in uds events	-	-0.00018
$\frac{g\to b\bar{b}}{g\to c\bar{c}}$ in uds events	-	-0.00015
B fragmentation $< x_E(b) >$	-	0.00032
B lifetimes	-	0.00018
B decay multiplicity	-	0.00037
Hard gluon fragmentation	-	0.00010
Total	0.0017	0.0026

Table 5: Internal and external error contributions to R_b for a cut at $D > 2.3$. The errors from the D fractions are propagated according to the correlation matrix defined in [2].

Muons are identified as tracks in the muon chambers:

- A muon track is required to have track segments in at least two of the three layers of the P chambers which measure the trajectory in the plane transverse to the beam. In addition, it must have at least one of the two segments of Z layers which measure longitudinal cooordinates.
- The measured muon momentum must be greater than 3 GeV.
- The track should point to the interaction vertex region within 3 standard deviations from the uncertainty in the extrapolation. This uncertainty takes into account multiple scattering and energy losses in the calorimeters.
- The muon track should be matched to a track in the central tracking chamber.

5.2 Heavy quark tagging using high-p_t leptons

Hemispheres containing high-energy leptons are selected as b-candidates. Due to the hard b fragmentation and mass, a higher b-purity sample is obtained as the measured transverse momentum of the lepton with respect to the b-jet, p_t, increases. The distribution of this variable is shown in Figure 5. Very good agreement between data and simulation is observed. A p_t cut of 1 GeV is used for the double-tag measurement.

5.3 Systematic errors

5.3.1 Lepton selection uncertainties

Uncertainties in the lepton selection are expected if electromagnetic clusters, punch-through and tracking resolutions are not well reproduced in the simulation. Since the Monte Carlo simulation takes into account the behaviour of the detector as a function of time, a small uncertainty is expected. It has been estimated by studying the statistical consistency of the measured R_b values as a function of the p_t cut.

5.3.2 Systematics from background modelling

The charm efficiencies depend on the assumptions for the overall rate and properties of semileptonic c-decays. The uncertainty on these assumptions is taken into account by varying the semileptonic branching fraction, $\mathrm{Br}(c \to \ell\nu X)$, the charm fragmentation, $< x_E(c) >$, and the semileptonic decay model within the ranges suggested in [10]. The physics uncertainty in ϵ_{uds} has been estimated by a 10% change in the average energy carried by hadrons in the light-quark fragmentation. The parameter ranges are summarized in Table 6.

Error source	Variation
Charm fragmentation parameter: $< x_E(\mathrm{c}) >$	0.484 ± 0.008 [10]
$\mathrm{Br}(\mathrm{c} \to \ell \nu \mathrm{X})$	$(9.8 \pm 0.5)\%$ [10]
Semileptonic Decay Model $c \to \ell$	$^{+\mathrm{ACCMM\ model\ 1}}_{-\mathrm{ACCMM\ model\ 2}}$ [10]
Light quark fragmentation	$\pm 10\%$ [10]

Table 6: Variation of modelling parameters used for the determination of the systematic error in the lepton double-tag measurement.

5.3.3 Systematics from hemisphere correlations

The correlation between the semileptonic decay properties of the two hemispheres is expected to be very small. The value obtained for c_b from the Monte Carlo simulation is $c_b = 0.993 \pm 0.009$, consistent with no correlation.

Evidences of non-negligible correlation effects have been looked for. The following quantity is defined:

$$\mathrm{C} = \frac{< x_1 x_2 >}{< x_1 > \quad < x_2 >} \tag{10}$$

where x_1 and x_2 are values of a physical variable in the two hemispheres of the event. We have used the lepton momentum and transverse momentum, since they are the relevant variables of the analysis. The values obtained for C are consistent with 1 within the statistical errors, independently of the p_t cut applied and of restrictions in the detector acceptance. Since no evidence of correlation is found, only the size of the MC statistical uncertainty will be assigned as a systematic error.

5.4 Results

For a p_t cut of 1 GeV 49308 hemispheres are tagged and 1927 events are double-tagged on a sample of 968964 hadrons.

The value of ϵ_c is found to be $\epsilon_c = (1.70 \pm 0.01(\mathrm{stat}) \pm 0.11(\mathrm{syst}))\%$. The error is dominated by the background modelling of semileptonic charm decays. The value of ϵ_{uds} is determined to be $\epsilon_{uds} = (0.362 \pm 0.003(\mathrm{stat}) \pm 0.003(\mathrm{syst}))\%$, and the value of the correlation coefficient is $c_b = 0.993 \pm 0.009(\mathrm{stat})$.

Taking into account statistical and systematic errors we get:

$$R_b = 0.2116 \ \pm \ 0.0050 \ (\mathrm{stat}) \ \pm \ 0.0042 \ (\mathrm{syst}) \ - \ 0.270 \ (R_c - 0.172) \ , \tag{11}$$

for a b efficiency of $\epsilon_b = (9.59 \pm 0.22 \ (\mathrm{stat}) \pm 0.11 \ (\mathrm{syst}))\%$. These results are preliminary.

The different contributions to the systematic error are shown in Table 7.

Sources of systematics	Error on R_b
MC statistics	0.0022
Br(c $\rightarrow \ell\nu$X)	-0.0028
Semileptonic Decay Model	-0.0022
$< x_E(\mathrm{c}) >$	-0.0006
Light quark fragmentation	-0.0002
Lepton Identification	0.0005
Total	0.0042

Table 7: Systematic error contributions to R_b from the lepton double-tag measurement.

6 Combined result

For an impact parameter discriminant cut of D> 2.3 and a lepton p_t cut of 1 GeV, 9368 events are selected with a lepton tag and an impact parameter tag on opposite hemispheres on a sample of 968964 hadronic events. The correlation factor between both tags is $c_b'' = 1.004 \pm 0.005$ (stat) $\pm\, 0.015$ (syst), where the error conservatively takes into account detector and reconstruction effects.

A combined fit using equations 1-5 for impact parameter and lepton tags is performed. The Monte Carlo input efficiencies and correlation factors with their uncertainties are included as constraints in the fit. The final value of R_b is:

$$R_b = 0.2176 \ \pm \ 0.0015 \text{ (stat)} \ \pm \ 0.0026 \text{ (syst)} \ - \ 0.212 \ (R_c - 0.172) \tag{12}$$

The statistical error of the measurement is determined by fixing the Monte Carlo efficiencies and correlations to their fitted values. The systematic uncertainties are propagated according to the covariance matrix of the fit. Charm, light-quark and b-quark systematics are uncorrelated, except for the case of the charm fragmentation, which correlates impact parameter and lepton tags. All systematic error contributions to the measurement are shown in Table 8.

The measurement is in agreement with the expectation from the Standard Model, $R_b^{SM} = 0.2158 \pm 0.0003$ [2], and compatible with previous determinations of R_b [1]. This result is preliminary.

Error source	ΔR_b internal	ΔR_b external
MC statistics	0.00081	-
Tracking Resolution	0.00042	-
Vertex effects on c_b	0.00079	-
θ effects on c_b	0.00003	-
ϕ effects on c_b	0.00013	-
Lepton identification	0.00010	-
Correlation between tags	0.00079	-
D^+ fraction	-	-0.00104
D_s fraction	-	-0.00017
Λ_c fraction	-	+0.00036
D^+ lifetime	-	-0.00016
D^0 lifetime	-	-0.00010
D_s lifetime	-	-0.00010
Λ_c lifetime	-	-0.00006
D^+ 1-prong decay multiplicity	-	+0.00035
D^+ 5-prong decay multiplicity	-	-0.00005
D^0 0-prong decay multiplicity	-	-0.00003
D^0 4-prong decay multiplicity	-	-0.00018
D^0 6-prong decay multiplicity	-	0.00000
D_s 1-prong decay multiplicity	-	+0.00022
D_s 5-prong decay multiplicity	-	+0.00043
$D \to K^0_s$ multiplicity	-	-0.00019
$< x_E(\mathrm{c}) >$	-	-0.00082
$\mathrm{Br}(\mathrm{c} \to \ell\nu\mathrm{X})$	-	-0.00068
Semileptonic Decay Model	-	-0.00054
$g \to c\bar{c}$ in $c\bar{c}$ events	-	-0.00001
$\frac{g\to b\bar{b}}{g\to c\bar{c}}$ in $c\bar{c}$ events	-	-0.00002
K^0_s and Λ in uds events	-	-0.00131
Light quark fragmentation	-	-0.00002
$g \to c\bar{c}$ in uds events	-	-0.00013
$\frac{g\to b\bar{b}}{g\to c\bar{c}}$ in uds events	-	-0.00011
B fragmentation $< x_E(\mathrm{b}) >$	-	+0.00020
B lifetimes	-	+0.00011
B decay multiplicity	-	+0.00023
Hard gluon fragmentation	-	+0.00007
Total	0.0014	0.0022

Table 8: Internal and external error contributions to the L3 R_b measurement. The errors from the D fractions are propagated according to the correlation matrix defined in [2]. Other errors in the table can be considered as uncorrelated.

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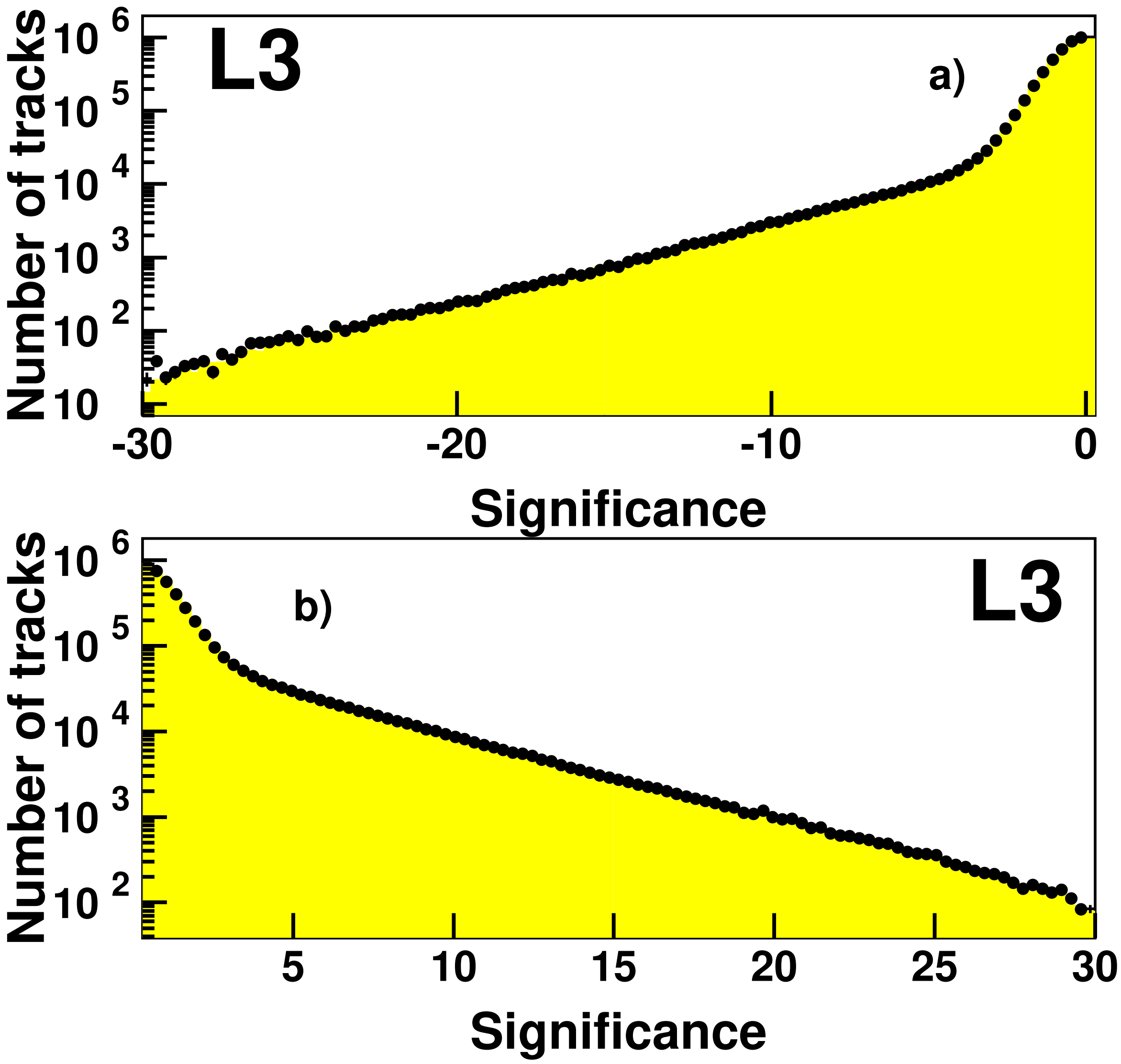

Figure 1: Significance distribution for tracks with a) negative and b) positive impact parameter. The points are the data and the shaded histogram is the Monte Carlo prediction for a value of $R_b = 0.217$.

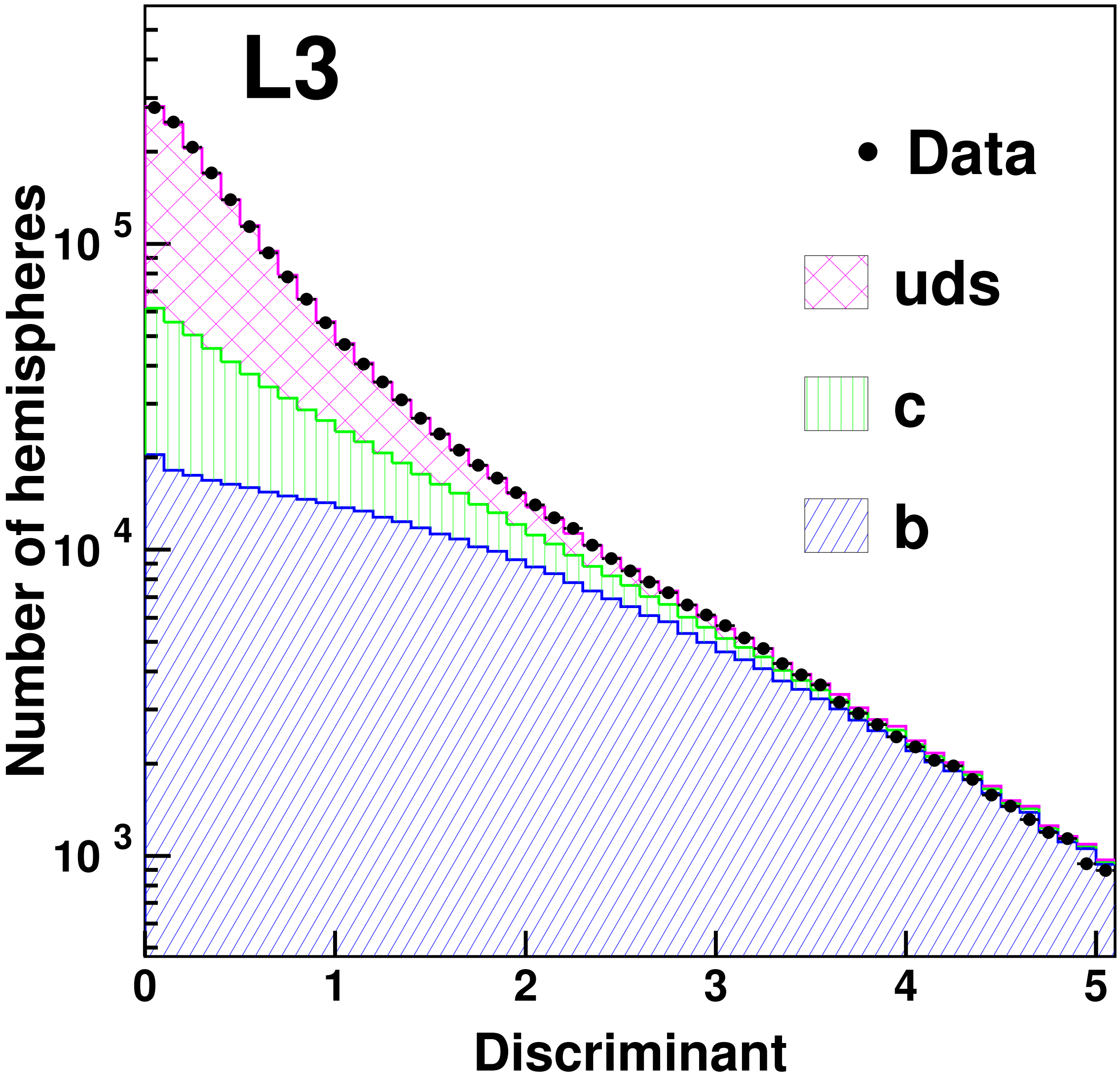

Figure 2: Discriminant distribution in data compared with the Monte Carlo prediction. The flavor composition of the hadronic sample is also shown. Good agreement is observed. The high b-tagging power for high values of the discriminant is exhibited.

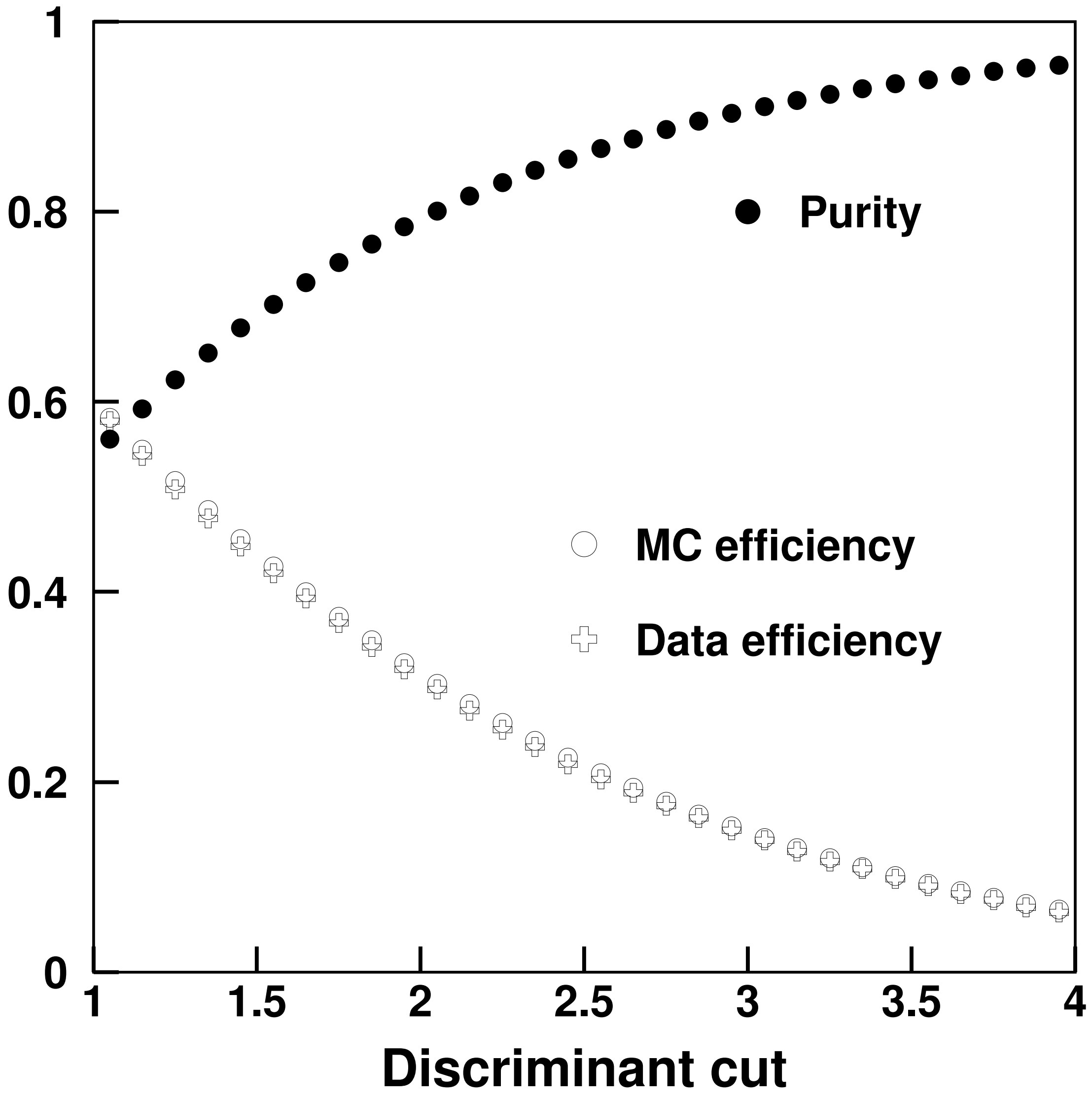

Figure 3: Efficiency and purity of the sample obtained as a function of the discriminant cut. For a discriminant cut at $D > 2.3$, the purity is 0.843. The efficiency determined from data is $\epsilon_b^{\rm data} = (23.70 \pm 0.19\ ({\rm stat}) \pm 0.22\ ({\rm syst}))\%$, the Monte Carlo predicts $\epsilon_b^{\rm MC} = (24.21 \pm 0.03\ ({\rm stat}) \pm 1.58\ ({\rm syst}))\%$. Over the range $1 < D < 4$, the relative difference between data and Monte Carlo efficiency never exceeds 2.5%.

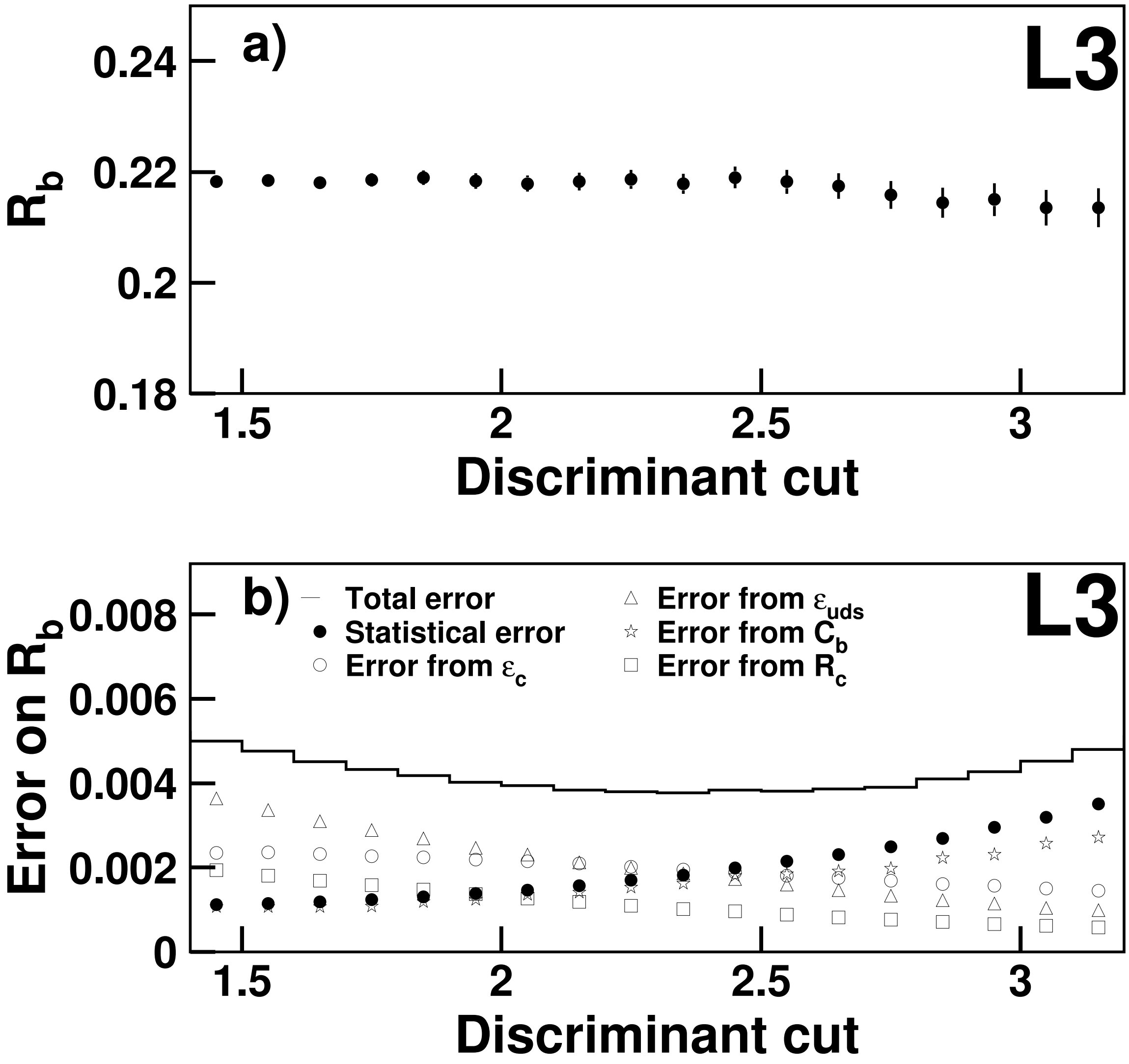

Figure 4: a) Value of R_b obtained as a function of the impact parameter discriminant cut. b) Statistical, systematic and total errors for R_b as a function of the discriminant cut. The uncertainty on R_c, $\Delta R_c = 0.0052$, has been taken from [2].

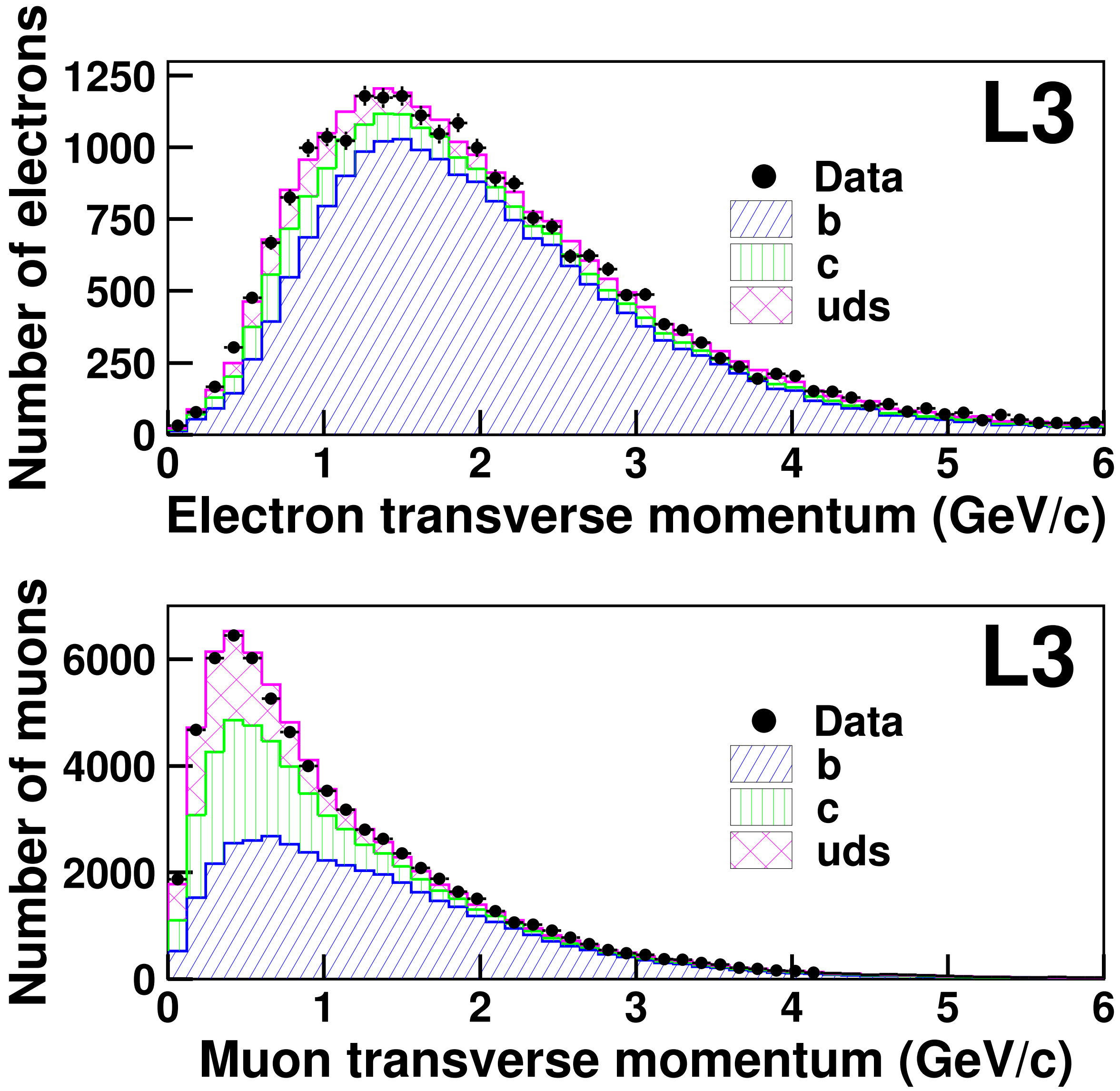

Figure 5: Transverse momentum distributions with respect to the closest jet for electrons and muons in hadronic Z decays.