ICHEP'96 Ref. pa01-060
Submitted to Pa 1, Pa 5, Pa 7
Pl 7, Pl 9

DELPHI 96-110 CONF 37
25 June, 1996

Summary of R_c Measurements in DELPHI

Preliminary

DELPHI Collaboration

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Abstract

A summary of all DELPHI measurements on R_c using charmed hadrons, $P_{c\to D^{*+}}$ and $\frac{R_b P_{b\to D^{*+}}}{R_c P_{c\to D^{*+}}}$ is presented. This allows to provide the relevant tables for the LEP average including the fractions of charmed hadron production rates used to constraint the R_b measurements at LEP. Results are updated to match the requirements of the LEP heavy flavour group input tables.

Including also a value $P_{c\to D^{*+}} BR(D^{*+} \to D^0\pi^+) = 0.178 \pm 0.013$ from low energy experiments, the combined values obtained in DELPHI are

$$\begin{aligned} R_c &= 0.1657 \pm 0.0074\ (\text{stat}) \pm 0.0071\ (\text{syst}) \\ P_{c\to D^{*+}} BR(D^{*+} \to D^0\pi^+) &= 0.1717 \pm 0.0061\ (\text{stat}) \pm 0.0048\ (\text{syst}) \\ \frac{R_b P_{b\to D^{*+}}}{R_c P_{c\to D^{*+}}} &= 1.056 \pm 0.047\ (\text{stat}) \pm 0.048\ (\text{syst})\ . \end{aligned}$$

The fractions of charmed hadrons are determined to be

$$\begin{aligned} f(D^+) &= 0.208 \pm 0.020\ (\text{stat}) \pm 0.017\ (\text{syst}) \\ f(D_s) &= 0.118 \pm 0.019\ (\text{stat}) \pm 0.030\ (\text{syst}) \\ f(c_{baryon}) &= 0.117 \pm 0.022\ (\text{stat}) \pm 0.025\ (\text{syst}) \end{aligned}$$

(assuming $f(D^0) + f(D^+) + f(D_s) + f(c_{baryon}) = 1$).

1 Introduction

The precise determination of the partial width $R_c^0 = \Gamma_{c\bar{c}}/\Gamma_{had}$ is an important test of the standard model. In contrast to R_b measurements based on b lifetime tagging most of the R_c measurements are statistically limited due to low charm tagging efficiencies in hadronic Z decays. To overcome this limitation DELPHI uses many exclusive charm hadron decay modes and inclusive $D^{*+} \to D^0\pi^+$ reconstruction in combination with different approaches to extract R_c. The sensitivity on low energy results is drastically reduced due to double tagging measurements where R_c and $P_{c\to D^{*+}}$ are obtained simultaneously from the DELPHI data. From the analysis of the production of all weak decaying charm hadron states, their fractions in c events is measured providing valuable constraints for the R_b measurements at LEP.

The aim of this note is to summarize the DELPHI results and to give consistent averages taking correlations between the different measurements into account. Technically the averages are computed using the program of the LEP heavy flavour working group [1].

2 Common inputs

All results given in the following are evaluated using a common set of input parameters. For a more detailed description see ref. [2]. DELPHI results are modified to match the requirements of the LEP heavy flavour group as described in the following.

1. b fragmentation [2]: $\langle X_E(B)\rangle = \langle E(B)/E_{beam}\rangle = 0.702 \pm 0.008$
2. $b \to D$ model [2]: from $\epsilon = 0.42 \pm 0.07$ one would assign another 40% of the b fragmentation error to this source.
3. c fragmentation [3]: $\langle X_E(D^*)\rangle_c = 0.492 \pm 0.007$ (stat + syst.) ± 0.008 (model) or measured.
4. gluon splitting [2]: $\langle n(g \to c\bar{c})\rangle = (2.38 \pm 0.48)\%$
5. average B lifetime [2]: $\tau(B) = 1.55 \pm 0.05$ ps
6. Effective mixing $\chi_{eff} = 2\chi_{D^*}(1-\chi_{D^*})$ [4]: $\chi_{eff} = 0.241^{+0.033}_{-0.045}$
7. Error on tracking efficiency [7]: $\pm 1.2\%$ per track
8. Charm hadrons branching fraction and lifetime see table 1.

3 DELPHI measurements

In the following a list of all DELPHI measurements is given.

	$D^0 \to K^-\pi^+$	$D^+ \to K^-\pi^+\pi^+$	$D_s \to \Phi\pi^+$	$\Lambda_c \to pK^-\pi^+$
branching ratio	0.0383 ± 0.0012	0.091 ± 0.006	0.035 ± 0.009	0.044 ± 0.006
lifetime (ps)	0.415 ± 0.004	1.057 ± 0.015	0.467 ± 0.017	0.206 ± 0.012

Table 1: The ratio $\frac{BR(D_s \to K^{*0}K^+)}{BR(D_s \to \Phi\pi^+)} = 0.95 \pm 0.10$ was also used in the D_s analysis. All values in the table are from ref. [2] based on the new PDG [5] world averages. The value for $D_s \to \Phi\pi^+$ was obtained using [6] $\frac{BR(D_s \to \Phi\pi)}{BR(D^0 \to K\pi)} = 0.91 \pm 0.23$.

3.1 Exclusive channels

The product of R_c times the production probability $P_{c\to x}$ times the branching ratio is measured using the $D^{*+} \to D^0\pi^+$ and the weak decaying states D^0, D^+, D_s and Λ_c. Simultaneously with $R_c P_{c\to D^{*+}} BR(D^{*+} \to (K^-\pi^+)\pi^+)$ the ratio $r_{bc} = \frac{R_b P_{b\to D^{*+}}}{R_c P_{c\to D^{*+}}}$ is measured. This parameter describes the relative rate of charm events in the total sample and therefore has a large correlation of -91% to $R_c P_{c\to D^{*+}} BR(D^{*+} \to (K^-\pi^+)\pi^+)$. The results are

$$R_c P_{c\to D^{*+}} BR(D^{*+} \to (K^-\pi^-)\pi^+) = (1.119 \pm 0.071\ (\text{stat}) \pm 0.075\ (\text{syst}))\ 10^{-3}\ \ [8] \quad (1)$$

$$r_{bc} = \frac{R_b P_{b\to D^{*+}}}{R_c P_{c\to D^{*+}}} = 0.972^{+0.102}_{-0.093}\ (\text{stat}) \pm 0.078\ (\text{syst})\ \ [8] \quad (2)$$

and

$$R_c P_{c\to D^0} BR(D^0 \to K^-\pi^+) = (3.57 \pm 0.34\ (\text{stat}) \pm 0.22\ (\text{syst}))\ 10^{-3}\ \ [3] \quad (3)$$

$$R_c P_{c\to D^+} BR(D^+ \to K^-\pi^+\pi^+) = (3.16 \pm 0.31\ (\text{stat}) \pm 0.22\ (\text{syst}))\ 10^{-3}\ \ [3] \quad (4)$$

$$R_c P_{c\to D_s} BR(D_s^+ \to \Phi\pi) = (0.71 \pm 0.11\ (\text{stat}) \pm 0.11\ (\text{syst}))\ 10^{-3}\ \ [9] \quad (5)$$

$$R_c P_{c\to \Lambda_c} BR(\Lambda_c \to pK\pi) = (0.76 \pm 0.15\ (\text{stat}) \pm 0.15\ (\text{syst}))\ 10^{-3}\ \ [10] \quad (6)$$

The systematic errors are detailed in table 2. In the D^{*+} analysis the fragmentation function is measured directly. Its uncertainty is therefore a part of the statistical error. 15% of the D^0 are also included in the D^{*+} sample.

3.2 Double tags

DELPHI uses two different double tagging methods to measure charm production properties. The first analysis measures $P_{c\to D^{*+}}$ using inclusive D^{*+} rate in the opposite hemisphere to an exclusive reconstructed D meson:

$$P_{c\to D^{*+}} BR(D^{*+} \to D^0\pi^+) = 0.169 \pm 0.014\ (\text{stat}) \pm 0.012\ (\text{syst})\ \ [11]\ . \quad (7)$$

The other analysis uses inclusive D^{*+} reconstruction in both hemispheres to measure both R_c and $P_{c\to D^{*+}}$:

$$R_c = 0.171^{+0.014}_{-0.012}\ (\text{stat}) \pm 0.015\ (\text{syst})\ \ [12] \quad (8)$$

$$P_{c\to D^{*+}} BR(D^{*+} \to D^0\pi^+) = 0.170 \pm 0.009\ (\text{stat}) \pm 0.013\ (\text{syst})\ \ [12]\ . \quad (9)$$

	r_{bc}	D^{*+} $[10^{-3}]$	D^0 $[10^{-3}]$	D^+ $[10^{-3}]$	D_s $[10^{-3}]$	Λ_c $[10^{-3}]$
statistics	∓ 0.098	± 0.071	± 0.34	± 0.31	± 0.113	± 0.150
internal	∓ 0.072	± 0.061	± 0.175	± 0.171	± 0.085	± 0.133
tracking	-	∓ 0.040	∓ 0.086	∓ 0.114	∓ 0.026	∓ 0.027
$\langle X_E(B)\rangle$	∓ 0.016	± 0.014	± 0.043	± 0.035	± 0.014	± 0.011
$B \to D$ model	∓ 0.006	± 0.005	± 0.016	± 0.013	± 0.006	± 0.004
$\langle X_E(D)\rangle$	meas.	meas.	∓ 0.071	∓ 0.063	∓ 0.057	∓ 0.043
$g \to c\bar{c}$	-	∓ 0.002	∓ 0.012	∓ 0.010	∓ 0.004	∓ 0.003
b hadron lifetime	∓ 0.024	± 0.010	± 0.039	± 0.033	± 0.004	± 0.010
$\tau(D, \Lambda)$	∓ 0.007	± 0.002	± 0.007	± 0.019	± 0.006	± 0.041
all systematics	± 0.078	± 0.075	± 0.217	± 0.222	± 0.108	± 0.149

Table 2: Systematic uncertainties for the exclusive channels. For r_{bc} and D^{*+} -83% and for D^0 and D^+ 31% of the internal errors are correlated.

Only 8% of the double tagged $\pi_*^+\pi_*^-$ events are common with the $D^{*+}\pi_*^-$ candidates. Note that all results have a slight dependence on R_c itself and on r_{bc}, which is given by

$$P_{c\to D^{*+}} BR(D^{*+} \to D^0\pi^+) = 0.169 - 0.028 \cdot (\frac{r_{bc}}{1.225} - 1) \quad (10)$$

$$R_c = 0.171 - 0.058 \cdot (\frac{r_{bc}}{1.25} - 1) \quad (11)$$

$$P_{c\to D^{*+}} BR(D^{*+} \to D^0\pi^+) = 0.170 + 0.023 \cdot (\frac{r_{bc}}{1.25} - 1) \quad (12)$$

and

$$P_{c\to D^{*+}} BR(D^{*+} \to D^0\pi^+) = 0.169 - 0.0020 \cdot (\frac{R_c}{0.172} - 1) \quad (13)$$

$$R_c = 0.171 + 0.0013 \cdot (\frac{R_c}{0.172} - 1) \quad (14)$$

$$P_{c\to D^{*+}} BR(D^{*+} \to D^0\pi^+) = 0.170 - 0.0009 \cdot (\frac{R_c}{0.172} - 1)\ . \quad (15)$$

In ref. [12] a measurement of the ratio r_{bc} is presented:

$$r_{bc} = \frac{R_b P_{b\to D^{*+}}}{R_c P_{c\to D^{*+}}} = 1.16 \pm 0.06\ (\text{stat}) \pm 0.10\ (\text{syst})\ \ [12]\ . \quad (16)$$

The following table 3 summarizes the systematics. For the $\pi_*^+\pi_*^-$ analysis the correlation of the internal error and the statistical errors is found to be -74.4% between R_c and $P_{c\to D^{*+}}$.

	$P_{c\to D^{*+}}$	R_c	$P_{c\to D^{*+}}$	r_{bc}
statistics	∓ 0.014	± 0.013	∓ 0.009	∓ 0.06
internal	∓ 0.0108	± 0.0123	∓ 0.0085	∓ 0.073
tracking	∓ 0.0020	-	∓ 0.0020	-
$\langle X_E(B)\rangle$	± 0.0012	∓ 0.0018	± 0.0007	± 0.033
$B \to D$ model	± 0.0005	∓ 0.0007	± 0.0003	± 0.013
$\langle X_E(D)\rangle$	∓ 0.0027	± 0.0044	∓ 0.0088	∓ 0.064
$g \to c\bar{c}$	-	-	-	∓ 0.003
χ_{eff}	± 0.0016	-	± 0.0007	-
r_{bc}	∓ 0.0023	∓ 0.0046	± 0.0019	-
all systematics	± 0.0117	± 0.0140	± 0.0126	± 0.103

Table 3: Systematic uncertainties for the inclusive channels.

4 Combination of measurements

4.1 R_c from the overall charm rate and the fractions of charm hadrons

In a first step R_c and the fractions of charm hadrons were deduced from the the production rates of D^0, D^+, D_s and Λ_c, assuming the branching ratios given in table 1. In addition the Λ_c was scaled by $\mathcal{R}_{baryon} = 1.15 \pm 0.05$ to account for Ξ_c and Ω_c production:

$$R_c = R_c \cdot (P_{c\to D^0} + P_{c\to D^+} + P_{c\to D_s} + \mathcal{R}_{baryon} \cdot P_{c\to D^0}) \ . \tag{17}$$

The result is

$$\begin{aligned} R_c &= 0.168 \pm 0.011\ (\text{stat}) \pm 0.013\ (\text{syst}) && (18)\\ f(D^+) &= 0.206 \pm 0.020\ (\text{stat}) \pm 0.017\ (\text{syst}) && (19)\\ f(D_s) &= 0.121 \pm 0.018\ (\text{stat}) \pm 0.032\ (\text{syst}) && (20)\\ f(c_{baryon}) &= 0.118 \pm 0.021\ (\text{stat}) \pm 0.025\ (\text{syst}) && (21)\\ & && (22) \end{aligned}$$

which yields $f(D^0) = 0.555$. The correlation matrix is given in table 4.

	R_c	$f(D^+)$	$f(D_s)$	$f(c_{baryon})$
R_c	1.00	-0.30	0.23	0.16
$f(D^+)$	-0.30	1.00	-0.25	-0.21
$f(D_s)$	0.23	-0.25	1.00	-0.18
$f(c_{baryon})$	0.16	-0.21	-0.18	1.00

Table 4: Correlation matrix for the fit to the overall charm rate.

4.2 R_c from the exclusive D^{*+} rate

In a second step the exclusive D^{*+} and the $D^{*+}\pi_*$ double tag measurement of $P_{c\to D^{*+}}$ are combined. Here the exclusive measurement of r_{bc} is used to constrain the result of $P_{c\to D^{*+}}$:

$$\begin{aligned} R_c &= 0.167 \pm 0.015\ (\text{stat}) \pm 0.015\ (\text{syst}) \\ P_{c\to D^{*+}} BR(D^{*+} \to D^0\pi^+) &= 0.175 \pm 0.014\ (\text{stat}) \pm 0.012\ (\text{syst}) \\ r_{bc} &= 0.972 \pm 0.098\ (\text{stat}) \pm 0.078\ (\text{syst})\ . \end{aligned}$$

The correlation matrix is given in table 5.

	R_c	$P_{c\to D^{*+}}$	r_{bc}
R_c	1.00	-0.63	-0.37
$P_{c\to D^{*+}}$	-0.63	1.00	-0.18
r_{bc}	-0.37	-0.18	1.00

Table 5: Correlation matrix for fit to the exclusive D^{*+} rate.

4.3 Combination of all measurements

Combining all DELPHI measurements the following set of parameters is obtained:

$$\begin{aligned} R_c &= 0.1692 \pm 0.0080\ (\text{stat}) \pm 0.0084\ (\text{syst}) && (23) \\ P_{c\to D^{*+}} BR(D^{*+} \to D^0\pi^+) &= 0.1678 \pm 0.0069\ (\text{stat}) \pm 0.0066\ (\text{syst}) && (24) \\ r_{bc} &= 1.061 \pm 0.046\ (\text{stat}) \pm 0.049\ (\text{syst})\ . && (25) \end{aligned}$$

The fractions of charmed hadrons are determined to be (assuming $\sum f(x) = 1$)

$$\begin{aligned} f(D^+) &= 0.206 \pm 0.019\ (\text{stat}) \pm 0.017\ (\text{syst}) && (26) \\ f(D_s) &= 0.119 \pm 0.019\ (\text{stat}) \pm 0.030\ (\text{syst}) && (27) \\ f(c_{baryon}) &= 0.118 \pm 0.021\ (\text{stat}) \pm 0.024\ (\text{syst})\ . && (28) \end{aligned}$$

The full error breakdown is given in table 6. The statistical and systematic correlation matrices are given in table 7 and 8. The differences in the fractions $f(x)$ to the values given before are due to the correlation to the overall R_c. The χ^2/ndf is found to be 1.85/4.In figures 1 (a)-(c) the comparison of the DELPHI results of R_c, $P_{c\to D^{*+}}$ and r_{bc} are shown.

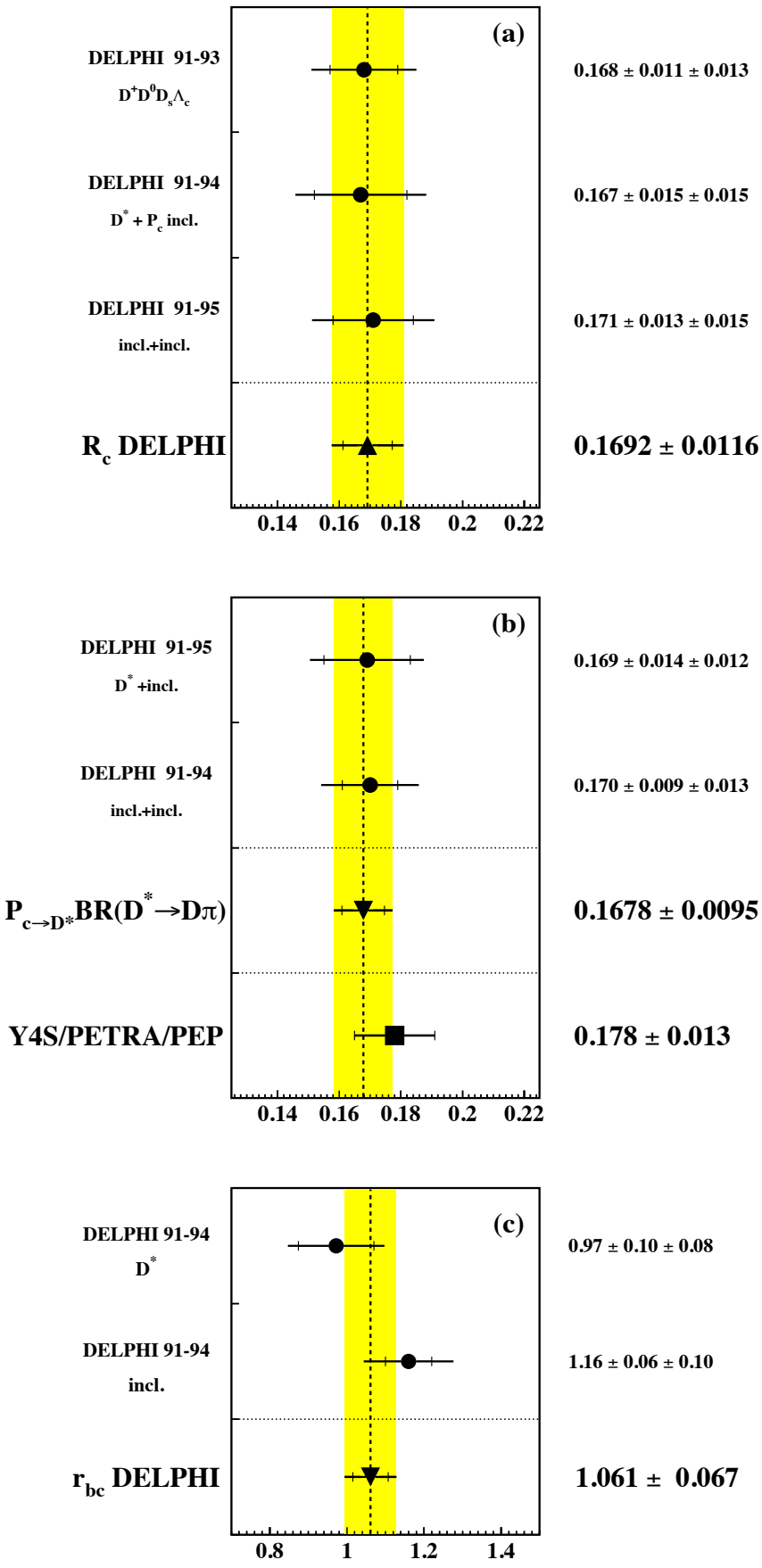

Figure 1: A comparison of the DELPHI results on R_c, $P_{c\to D^{*+}} BR(D^{*+} \to D^0\pi^+)$ and $r_{bc} = \frac{R_b P_{b\to D^{*+}}}{R_c P_{c\to D^{*+}}}$ to the combined results from a fit to the data.

	R_c	$P_{c\to D^{*+}}$	r_{bc}	$f(D^+)$	$f(D_s)$	$f(c_{baryon})$
statistics	0.0080	0.0069	0.046	0.019	0.019	0.021
internal	0.0063	0.0056	0.044	0.010	0.014	0.018
tracking	-0.0033	-0.0011	-0.004	-0.002	-0.001	-0.001
$\langle X_E(B)\rangle$	-	-0.0007	0.009	0.001	-0.001	-0.001
$\langle X_E(D)\rangle$	0.0005	-0.0019	-0.004	-	-0.001	-
BR($D^0 \to K^-\pi^+$)	-0.0026	-	-0.010	0.003	0.002	0.002
BR($D^+ \to K^-\pi^+\pi^+$)	-0.0002	0.0009	0.003	-0.011	0.002	0.002
BR($D_s \to \Phi\pi^+$)	-0.0027	0.0019	0.007	0.005	-0.026	0.005
BR($\Lambda_c \to pK^-\pi^+$)	-0.0014	0.0010	0.004	0.003	0.003	-0.014
$B \to D$ model.	-	-0.0003	0.003	-	-	-
D^0 lifetime	0.0002	-0.0001	-0.003	-	-	-
D^+ lifetime	-	-0.0001	-	0.001	-	-
D_s lifetime	-	-	-	-	0.001	-
Λ_c lifetime	0.0005	-0.0004	-0.001	-0.001	-0.001	0.005
b hadron lifetime	0.0010	-0.0007	-0.012	-	-0.001	-
$g \to c\bar{c}$	-0.0003	0.0002	-0.001	-	-	-
χ_{eff}	-0.0004	0.0008	-0.002	-	-	-
Λ_c to baryon	0.0004	-0.0003	-0.001	-0.001	-0.001	0.004
total syst	0.0084	0.0066	0.049	0.017	0.030	0.024

Table 6: Error breakdown for the fit to all DELPHI measurements.

	R_c	$P_{c\to D^{*+}}$	r_{bc}	$f(D^+)$	$f(D_s)$	$f(c_{baryon})$
R_c	1.00	-0.75	-0.33	-0.25	-0.07	0.03
$P_{c\to D^{*+}}$	-0.75	1.00	-0.09	0.19	0.07	-0.02
r_{bc}	-0.33	-0.09	1.00	0.09	0.04	-0.01
$f(D^+)$	-0.25	0.19	0.09	1.00	-0.07	-0.13
$f(D_s)$	-0.07	0.07	0.04	-0.07	1.00	-0.09
$f(c_{baryon})$	0.03	-0.02	-0.01	-0.13	-0.09	1.00

Table 7: Statistical correlation matrix.

	R_c	$P_{c\to D^{*+}}$	r_{bc}	$f(D^+)$	$f(D_s)$	$f(c_{baryon})$
R_c	1.00	-0.61	-0.27	-0.28	0.09	0.21
$P_{c\to D^{*+}}$	-0.61	1.00	-0.25	0.17	-0.02	-0.15
r_{bc}	-0.27	-0.25	1.00	0.07	-0.02	-0.07
$f(D^+)$	-0.28	0.17	0.07	1.00	-0.22	-0.35
$f(D_s)$	0.09	-0.02	-0.02	-0.22	1.00	-0.21
$f(c_{baryon})$	0.21	-0.15	-0.07	-0.35	-0.21	1.00

Table 8: Internal correlation matrix.

5 Summary

Including also the value $P_{c\to D^{*+}} BR(D^{*+} \to D^0\pi^+) = 0.178 \pm 0.013$ [2] from low energy experiments, the combined values obtained in DELPHI are

$$R_c = 0.1657 \pm 0.0074\ (\text{stat}) \pm 0.0071\ (\text{syst}) \quad (29)$$

$$P_{c\to D^{*+}} BR(D^{*+} \to D^0\pi^+) = 0.1717 \pm 0.0061\ (\text{stat}) \pm 0.0048\ (\text{syst}) \quad (30)$$

$$\frac{R_b P_{b\to D^{*+}}}{R_c P_{c\to D^{*+}}} = 1.056 \pm 0.047\ (\text{stat}) \pm 0.048\ (\text{syst})\ . \quad (31)$$

The fractions of charmed hadrons are determined to be (assuming $\sum f(x) = 1$)

$$f(D^+) = 0.208 \pm 0.020\ (\text{stat}) \pm 0.017\ (\text{syst}) \quad (32)$$

$$f(D_s) = 0.118 \pm 0.019\ (\text{stat}) \pm 0.030\ (\text{syst}) \quad (33)$$

$$f(c_{baryon}) = 0.117 \pm 0.022\ (\text{stat}) \pm 0.025\ (\text{syst})\ . \quad (34)$$

The result on R_c is compatible with the Standard Model expectation of 0.172.

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