Summary of R_c measurements in DELPHI

D. Bloch, J.-P. Engel (CRN Strasbourg)
T. Brenke, M. Elsing, P. Sponholz (Univ. Wuppertal)
D. Bertini, , L. Chaussard, I. Laktineh, F. Zach (IPN Univ. Lyon I)
U. Gasparini (Univ. and INFN Padova)
K. Mönig (CERN)

Abstract

A summary of all DELPHI measurements on R_c using charmed hadrons, $P_{c\to D^{*+}}$ and $\frac{R_b P_{b\to D^{*\pm}}}{R_c P_{c\to D^{*+}}}$ is presented. This allows to provide the relevant tables for the LEP average. Including also a value $P_{c\to D^{*+}} B_* = 0.178 \pm 0.013$ from low energy experiments, the combined values obtained in DELPHI are :

$$\begin{aligned} R_c &= 0.1605 \pm 0.0055\,(\text{stat}) \pm 0.0075\,(\text{syst}) \\ P_{c\to D^{*+}} Br(D^{*+} \to D^0\pi^+) &= 0.1698 \pm 0.0044\,(\text{stat}) \pm 0.0073\,(\text{syst}) \\ \frac{R_b P_{b\to D^{*\pm}}}{R_c P_{c\to D^{*+}}} &= 1.225 \pm 0.061\,(\text{stat}) \pm 0.072\,(\text{syst})\ . \end{aligned}$$

1 Common inputs

1. b fragmentation [1] : $\langle X_E(\mathrm{B})\rangle = \langle E(\mathrm{B})/E_{\mathrm{beam}}\rangle = 0.70 \pm 0.02$

2. c fragmentation [2] :
   $\langle X_E(\mathrm{D}^*)\rangle_{\mathrm{c}} = 0.492 \pm 0.007$ (stat + syst.DELPHI) $\pm\, 0.008$ (model)

3. gluon splitting [1] : $\langle n(\mathrm{g} \to \mathrm{c\bar{c}})\rangle = (1.6 \pm 0.8)\%$

4. B lifetime [3] (with increased error) : $\tau(\mathrm{B}) = 1.54 \pm 0.10$ ps

5. Effective mixing $\chi_{eff} = 2\chi_{\mathrm{D}^*}(1 - \chi_{\mathrm{D}^*})$ [4] : $\chi_{eff} = 0.241^{+0.033}_{-0.045}$

6. Charm hadrons branching fraction and lifetime :
   The ratio $\frac{Br(\mathrm{D_s} \to \mathrm{K}^{*0}\mathrm{K}^+)}{Br(\mathrm{D_s} \to \Phi\pi^+)} = 0.95 \pm 0.10$ was used.

	$\mathrm{D}^0 \to \mathrm{K}^-\pi^+$	$\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+$	$\mathrm{D_s} \to \Phi\pi^+$	$\Lambda_\mathrm{c} \to \mathrm{pK}^-\pi^+$
Branching ratio	0.0384 ± 0.0013	0.091 ± 0.006	0.035 ± 0.004	0.044 ± 0.006
Lifetime (ps)	0.415 ± 0.004	1.057 ± 0.015	0.467 ± 0.017	0.206 ± 0.012

Table 1:

   All values are from ref. [5] and are identical to those from ref. [3], except for the D^0 branching fraction.

7. Tracking efficiency [6] : $\pm 2\%$ per track

2 Exclusive channels

2.1 D^{*+}, D^0, D^+

$$
\begin{aligned}
[R_\mathrm{c} P_{\mathrm{c}\to\mathrm{D}^{*+}} B_*]_0 &= (2.36 \pm 0.16\ (\mathrm{stat}) \pm 0.18\ (\mathrm{syst}) \pm 0.08\ (\mathrm{syst.}Br))\%\ [2] \\
R_\mathrm{c} P_{\mathrm{c}\to\mathrm{D}^0} &= (9.30 \pm 0.89\ (\mathrm{stat}) \pm 0.66\ (\mathrm{syst}) \pm 0.32\ (\mathrm{syst.}Br))\%\ [2] \\
R_\mathrm{c} P_{\mathrm{c}\to\mathrm{D}^+} &= (3.47 \pm 0.34\ (\mathrm{stat}) \pm 0.27\ (\mathrm{syst}) \pm 0.23\ (\mathrm{syst.}Br))\%\ [2]
\end{aligned}
$$

with $B_* = Br(\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+)$. The ratio

$$
r_0 = \frac{R_\mathrm{b} P_{\mathrm{b}\to\mathrm{D}^{*\pm}}}{R_\mathrm{c} P_{\mathrm{c}\to\mathrm{D}^{*+}}} = 1.47 \pm 0.15\ (\mathrm{stat}) \pm 0.13\ (\mathrm{syst})
$$

was also measured in ref.[2] with the statistical correlation coefficient of -0.905 relative to the previous $[R_\mathrm{c} P_{\mathrm{c}\to\mathrm{D}^{*+}} B_*]_0$ value.

2.2 $\mathrm{D_s}$

$$R_c P_{c\to \mathrm{D_s}} = (2.02 \pm 0.32\ (\mathrm{stat}) \pm 0.40\ (\mathrm{syst}) \pm 0.24\ (\mathrm{syst}.Br))\%\ [7]\ .$$

2.3 Λ_c

$$R_c P_{c\to \Lambda_c} = (1.39 \pm 0.31\ (\mathrm{stat}) \pm 0.43\ (\mathrm{syst}) \pm 0.19\ (\mathrm{syst}.Br))\%\ [8]\ .$$

2.4 Systematics

The following Table 2 summarizes the systematics. For r_0 and $[R_c P_{c\to \mathrm{D}^{*+}} B_*]_0$, 61% of the internal errors are correlated. For D^0 and D^+, 31% of the internal errors are correlated.

	r_0	D^{*+}	D^0	D^+	$\mathrm{D_s}$	Λ_c
Statistical	∓ 0.102	± 0.068	± 0.096	± 0.098	± 0.158	± 0.223
Internal	∓ 0.050	± 0.048	± 0.049	± 0.054	± 0.145	± 0.295
Tracking	—	∓ 0.035	∓ 0.028	∓ 0.035	∓ 0.035	∓ 0.035
c fragmentation	∓ 0.020	± 0.020	± 0.020	± 0.020	± 0.053	± 0.060
b fragmentation	± 0.043	∓ 0.033	∓ 0.030	∓ 0.028	∓ 0.118	∓ 0.030
$\tau(\mathrm{B})$	∓ 0.048	± 0.023	± 0.022	± 0.021	± 0.015	± 0.027
$\mathrm{g} \to \mathrm{c\bar{c}}$	∓ 0.018	± 0.008	± 0.008	± 0.008	± 0.008	± 0.008
Branching ratio	—	∓ 0.034	∓ 0.034	∓ 0.066	∓ 0.119	∓ 0.136
$\tau(\mathrm{D},\Lambda)$	∓ 0.004	± 0.002	± 0.002	± 0.006	∓ 0.008	∓ 0.048
All systematics	∓ 0.086	± 0.082	± 0.079	± 0.101	± 0.231	± 0.338

Table 2: Relative statistical and systematic uncertainties for the exclusive channels.

3 Double tags

The fragmentation probability $P_{c\to \mathrm{D}^{*+}} B_*$ is measured both in the $\pi_*\pi_*$ analysis [10] (labeled $_1$) and in the $\mathrm{D}^*\pi_*$ analysis [9] (labeled $_2$). Only 10% of the double tagged $\pi_*^+\pi_*^-$ events are common with the $\mathrm{D}^{*+}\pi_*^-$ candidates. The results are :

$$\begin{aligned} [P_{c\to \mathrm{D}^{*+}} B_*]_1 &= 0.170 \pm 0.009\ (\mathrm{stat}) \pm 0.013\ (\mathrm{syst}) \\ [P_{c\to \mathrm{D}^{*+}} B_*]_2 &= 0.163 \pm 0.016\ (\mathrm{stat}) \pm 0.009\ (\mathrm{syst})\ . \end{aligned}$$

Note also that in the $D^*\pi_*$ method, $[P_{c\to D^{*+}}B_*]_2$ slightly depends on R_c :

$$[P_{c\to D^{*+}}B_*]_2 = 0.163\cdot\left[1-0.12\left(\frac{R_c}{0.172}-1\right)\right] .$$

The ratio r and the value of R_c are also measured in the $\pi_*\pi_*$ analysis :

$$\begin{aligned} r_1 = \frac{R_b P_{b\to D^{*\pm}}}{R_c P_{c\to D^{*+}}} &= 1.16\pm 0.06\,(\mathrm{stat})\pm 0.13\,(\mathrm{syst}) \\ [R_c]_1 = \frac{\Gamma_c}{\Gamma_h} &= 0.171^{+0.014}_{-0.012}\,(\mathrm{stat})\pm 0.015\,(\mathrm{syst}) \end{aligned}$$

and the statistical correlation between $[R_c]_1$ and $[P_{c\to D^{*+}}B_*]_1$ is -0.744. The same averaged ratio $r = 1.25\pm 10$ was used in these results on R_c and $P_{c\to D^{*+}}B_*$. In the $\pi_*\pi_*$ method, there is also a remaining dependence of the results on R_c :

$$\begin{aligned} [P_{c\to D^{*+}}B_*]_1 &= 0.170\cdot\left[1-0.055\left(\frac{R_c}{0.172}-1\right)\right] \\ [R_c]_1 &= 0.171\cdot\left[1+0.074\left(\frac{R_c}{0.172}-1\right)\right] . \end{aligned}$$

The following Table 3 summarizes the systematics. In the internal error, the correlation between $[R_c]_1$ and $[P_{c\to D^{*+}}B_*]_1$ is also -0.744.

	r_1	$[R_c]_1$	$[P_{c\to D^{*+}}B_*]_1$	$[P_{c\to D^{*+}}B_*]_2$
Statistical	∓ 0.052	± 0.076	∓ 0.053	∓ 0.099
Internal	∓ 0.063	± 0.072	∓ 0.050	∓ 0.052
Tracking	—	—	∓ 0.020	∓ 0.020
c fragmentation	∓ 0.055	± 0.025	∓ 0.052	∓ 0.017
b fragmentation	± 0.069	∓ 0.027	± 0.010	± 0.004
$g\to c\bar{c}$	∓ 0.003	—	—	—
χ_{eff}	—	—	± 0.004	± 0.006
$r = 1.25\pm 0.10$	—	∓ 0.027	± 0.011	∓ 0.010
All systematics	∓ 0.108	± 0.085	∓ 0.076	∓ 0.060

Table 3: Relative systematic uncertainties for the double tag analyses.

4 R_c from the overall charm rate

$$\begin{aligned} [R_c]_3 &= R_c\,[P_{c\to D^0} + P_{c\to D^+} + P_{c\to D_s} + (1+\delta_{\Sigma_c+\Xi_c})P_{c\to\Lambda_c}] \\ &= 0.164\pm 0.011\,(\mathrm{stat})\pm 0.013\,(\mathrm{syst}) \end{aligned}$$

where $\delta_{\Sigma_c+\Xi_c} = 0.15\pm 0.05$ describes the $P_{c\to\Sigma_c} + P_{c\to\Xi_c}$ fraction. Due to the D^0 and D^+ measurements, there is still a statistical correlation between R_c from the overall charm rate and the results of the exclusive D^{*+} analysis (see Table 4). The systematics are detailed in the following Table 5.

	$[R_c]_3$	$[R_c P_{c\to D^{*+}} B_*]_0$	r_0
$[R_c]_3$	1.000	0.202	-0.196
$[R_c P_{c\to D^{*+}} B_*]_0$	0.202	1.000	-0.905
r_0	-0.196	-0.905	1.000

Table 4: Statistical correlation matrix between the overall charm rate method and the exclusive D^{*+} analysis.

Statistical	$\pm$ 0.067
Internal	$\pm$ 0.042
Tracking	$\mp$ 0.031
c fragmentation	$\pm$0.028
b fragmentation	$\mp$0.040
$\tau(B)$	$\pm$0.023
$g \to c\bar{c}$	$\pm$0.008
$Br(D^0 \to K^-\pi^+)$	$\mp$0.019
$Br(D^+ \to K^-\pi^+\pi^+)$	$\mp$0.014
$Br(D_s \to \Phi\pi^+)$	$\mp$0.014
$\frac{Br(D_s \to K^{*0}K^+)}{Br(D_s \to \Phi\pi^+)}$	$\pm$0.004
$Br(\Lambda_c) \to pK^-\pi^+$	$\mp$0.013
$\Sigma_c + \Xi_c$ fraction	$\pm$0.004
$\tau(D^0)$	$\pm$0.001
$\tau(D^+)$	$\pm$0.001
$\tau(D_s)$	$\mp$0.001
$\tau(\Lambda_c)$	$\mp$0.005
All systematics	$\pm$0.082

Table 5: Relative statistical and systematic uncertainties on R_c from the overall charm rate method.

5 Combination of measurements

The measurements presented here are combined together using the procedure defined by the LEP heavy flavour working group [1]. In a first step the exclusive D^{*+} and the double tag measurements are combined. For this average R_c, $P_{c\to D^{*+}} B_*$ and r are treated as free parameters. The results of this fit is :

$$\begin{aligned} R_c &= 0.1622 \pm 0.0090 \text{ (stat)} \pm 0.0093 \text{ (syst)} \\ P_{c\to D^{*+}} B_* &= 0.1653 \pm 0.0086 \text{ (stat)} \pm 0.0095 \text{ (syst)} \\ r &= 1.259 \pm 0.066 \text{ (stat)} \pm 0.077 \text{ (syst)} \end{aligned}$$

with statistical and systematic correlation matrices (Table 6). The detailed breakdown of the error is given in Table 7.

	Statistical			Systematic		
	R_c	$P_{c\to D^{*+}}B_*$	r	R_c	$P_{c\to D^{*+}}B_*$	r
R_c	1.00	-0.83	-0.33	1.00	-0.61	-0.11
$P_{c\to D^{*+}}B_*$	-0.83	1.00	-0.02	-0.61	1.00	-0.24
r	-0.33	-0.02	1.00	-0.11	-0.24	1.00

Table 6: Statistical and systematic correlation matrices of the D^{*+} and double tag analyses.

	R_c	$P_{c\to D^{*+}}B_*$	r
Statistical	± 0.056	∓ 0.052	∓ 0.052
Internal	± 0.051	∓ 0.039	∓ 0.045
Tracking	∓ 0.009	∓ 0.019	∓ 0.002
c fragmentation	± 0.016	∓ 0.035	± 0.027
b fragmentation	± 0.001	∓ 0.002	± 0.020
$Br(D^0 \to K^-\pi^+)$	∓ 0.020	± 0.002	∓ 0.003
$\tau(B)$	± 0.001	± 0.004	∓ 0.021
$g \to c\bar{c}$	—	± 0.002	∓ 0.008
χ_{eff}	∓ 0.003	± 0.005	∓ 0.001
All Systematics	± 0.057	∓ 0.058	∓ 0.061

Table 7: Relative statistical and systematic errors on R_c using the D^{*+} and double tag analyses.

In a second step also the R_c measurement from the overall charm rate has been included in the average. The following results have been obtained :

$$
\begin{aligned}
R_c &= 0.1661 \pm 0.0072\ \text{(stat)} \pm 0.0081\ \text{(syst)} \\
P_{c\to D^{*+}}B_* &= 0.1622 \pm 0.0076\ \text{(stat)} \pm 0.0088\ \text{(syst)} \\
r &= 1.245 \pm 0.062\ \text{(stat)} \pm 0.074\ \text{(syst)}\ .
\end{aligned}
$$

6 Conclusion

The DELPHI measurement of $P_{c\to D^{*+}}B_*$ agrees well with $P_{c\to D^{*+}}B_*$ obtained from low energy data of 0.178 ± 0.013. If this number is used as an additional constraint in the fit, the results change to :

$$\begin{aligned}
R_c &= 0.1605 \pm 0.0055\ (\text{stat}) \pm 0.0075\ (\text{syst}) \\
P_{c\to D^{*+}}Br(D^{*+}\to D^0\pi^+) &= 0.1698 \pm 0.0044\ (\text{stat}) \pm 0.0073\ (\text{syst}) \\
\frac{R_b P_{b\to D^{*\pm}}}{R_c P_{c\to D^{*+}}} &= 1.225 \pm 0.061\ (\text{stat}) \pm 0.072\ (\text{syst})\ .
\end{aligned}$$

The statistical and systematic correlation matrices are presented in Table 8 and the error breakdown in Table 9. The result for R_c is compatible with the Standard Model expectation of 0.172.

	Statistical			Systematic		
	R_c	$P_{c\to D^{*+}}B_*$	r	R_c	$P_{c\to D^{*+}}B_*$	r
R_c	1.00	-0.57	-0.40	1.00	-0.40	-0.12
$P_{c\to D^{*+}}B_*$	-0.57	1.00	-0.76	-0.40	1.00	-0.28
r	-0.40	-0.76	1.00	-0.12	-0.28	1.00

Table 8: Statistical and systematic correlation matrices of the final DELPHI + low energy data result.

	R_c	$P_{c\to D^{*+}}B_*$	r
Statistical	± 0.034	∓ 0.026	∓ 0.050
Internal	± 0.037	∓ 0.024	∓ 0.047
Tracking	∓ 0.022	∓ 0.007	—
c fragmentation	± 0.005	∓ 0.020	± 0.024
b fragmentation	∓ 0.005	± 0.001	∓ 0.016
$P_{c\to D^{*+}}B_*$ (low energy)	∓ 0.023	± 0.029	∓ 0.011
$Br(D^0\to K^-\pi^+)$	∓ 0.008	∓ 0.013	∓ 0.002
other charm Br	∓ 0.007	± 0.004	± 0.004
charm lifetime	∓ 0.001	± 0.001	± 0.002
B lifetime	± 0.005	—	∓ 0.002
$g\to c\bar{c}$	± 0.001	—	∓ 0.009
χ_{eff}	∓ 0.001	± 0.002	—
All Systematics	± 0.047	∓ 0.043	∓ 0.059

Table 9: Relative stat. and syst. errors of the final DELPHI + low energy data result.

The three (almost) independent DELPHI measurements of R_c are summarized in Table 10. The exclusive D^{*+} result is obtained by combining $[R_c P_{c\to D^{*+}} B_*]_0$ and r_0 with the double tag measurements $[P_{c\to D^{*+}} B_*]_2$ and r_1 and with the value $P_{c\to D^{*+}} B_* = 0.178 \pm 0.013$ from low energy data.

	R_c
Exclusive $D^{*\pm}$	0.148 ± 0.007 (stat) ± 0.011 (syst)
Double tag of inclusive $D^{*\pm}$	$0.171^{+0.014}_{-0.012}$ (stat) ± 0.015 (syst)
Overall charm rate	0.164 ± 0.011 (stat) ± 0.013 (syst)
Total	0.1605 ± 0.0055 (stat) ± 0.0075 (syst)

Table 10: DELPHI R_c results.

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