Update of the Double Tag Measurement of Γ_c/Γ_h and $P_{c\to D^{*+}}$ using inclusive $D^{*\pm}$

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Abstract

An updated analysis of the combined measurements of the Z^0 partial decay width into $c\bar{c}$ pair, $R_c = \Gamma_c/\Gamma_h$, and of the fragmentation probability of charm quark into D^{*+}, $P_{c\to D^{*+}}$, is reported. The method relies on the comparison between single and double tags of charm quark(s), using the low p_T pion produced in the inclusive $D^{*+} \to D^0\pi^+$ decay. The updated results benefit from a more detailed study of systematic effects. A new measurement, combined with other DELPHI analyses, leads to

$$\frac{R_b P_{b\to D^{*\pm}}}{R_c P_{c\to D^{*+}}} = 1.25 \pm 0.06\,(\text{stat}) \pm 0.07\,(\text{syst})\ ,$$

from which the following results are obtained :

$$R_c = \frac{\Gamma_c}{\Gamma_h} = 0.171^{+0.014}_{-0.012}\,(\text{stat}) \pm 0.015\,(\text{syst})$$

$$P_{c\to D^{*+}} Br(D^{*+} \to D^0\pi^+) = 0.170 \pm 0.009\,(\text{stat}) \pm 0.013\,(\text{syst}).$$

1 Introduction

This note is an update of a previous analysis of inclusive $D^{*+} \rightarrow D^0\pi^+$ production [1] in Z^0 hadronic decays [1]. The method relies on the comparison between single and double tags of charm quark(s), using the low p_T pion, called π_* in the following, produced in the inclusive $D^{*+} \rightarrow D^0\pi^+$ decay.

A similar method was already used in DELPHI to measure $R_c = \Gamma_c/\Gamma_h$ only [2], but with a large error due to statistical and systematic uncertainties. The 3.1 million Z^0 hadronic decays collected from 1991 to 1994 allows to drastically reduce the statistical error. It also allows to reduce the systematics by comparing the fraction of events with one or two π_* candidates (the latter corresponds to $c\overline{c}$ events where each charm quark fragments to a $D^{*\pm}$, both decaying into $D^0\pi^+$ or $\overline{D}^0\pi^-$). Both R_c and the fragmentation probability of charm quark into D^{*+}, $P_{c\rightarrow D^{*+}}$, are measured.

Compared to reference [1], only the part relevant to the low p_T charged pion analysis will be detailed in the following.

2 The event sample and the simulation

Charged particles were selected as follows : the momentum had to be between 0.1 GeV/c and 50 GeV/c, the relative error on momentum measurement less than 100%, the track length in the TPC had to be larger than 30 cm, the projection of their impact parameter relative to the interaction point had to be less than 4 cm in the plane transverse to the beam direction and the distance to the interaction point along the beam direction less than 10 cm.

Hadronic events were selected by requiring five or more charged particles (of momentum larger than 0.4 GeV/c) and a total energy in charged particles larger than 12% of the collision energy, assuming all charged particles to be pions. A total of 1.7 (1.4) million hadronic events was obtained from the 1991-1993 (1994) data at centre-of-mass energies between 88.2 GeV and 94.2 GeV in 1991 and 1993, and at the Z^0 peak energy in 1992 and 1994.

Neutral particles observed in the electromagnetic and hadronic calorimeters were selected if their energy was between 1 and 30 GeV and their polar angle between 20° and 160°.

Simulated hadronic events have been generated with the JETSET 7.3 Parton Shower program [3]. The fragmentation parameters of the simulation were tuned from various event-shape distributions observed in DELPHI hadronic final states [4]. Different tuning parameters were used for each year of simulation.

The fraction of D^{**} and B^{**} mesons produced in $c\overline{c}$ and $b\overline{b}$ events, respectively, was set to 30%. The fragmentation of c and b quarks was described in the Lund string fragmentation model by the Peterson function [5] :

$$D_q(z) \quad \propto \quad \frac{1}{z\,[1-(1/z)-\varepsilon_q/(1-z)]^2} \tag{1}$$

where $z = (E+p_l)_{\mathrm{hadron}}/(E+p)_{\mathrm{q=c,b}}$, p_l being the longitudinal momentum relative to the quark axis. For b quark fragmentation, the Peterson coefficient $\varepsilon_b = 0.00225 \pm 0.00075$

[1] Throughout the paper charge-conjugate states are implicitly included

was used which corresponds to the average energy fraction taken by B hadrons at LEP energy : $\langle X_E(\mathrm{B})\rangle = \langle E(\mathrm{B})/E_{\mathrm{beam}}\rangle = 0.70 \pm 0.02$ (stat + syst) [6]. The measurement of the Peterson coefficient, ε_{c}, for c quark fragmentation, was performed in a previous analysis [1] and the average energy fraction of final state $\mathrm{D}^{*\pm}$ was obtained :

$$\langle X_E(\mathrm{D}^*)\rangle_{\mathrm{c}} = 0.492 \pm 0.006\ (\mathrm{stat}) \pm 0.003\ (\mathrm{syst}) \pm 0.008\ (\mathrm{model}) \qquad (2)$$

where the last systematic uncertainty was evaluated in OPAL by using different fragmentation models for the charm quark [7].

The multiplicity of charm quark pairs from gluons in Z^0 hadronic decays was estimated to be $(1.6 \pm 0.8) \times 10^{-2}$ [6].

The generated events were used through the detailed detector simulation DELSIM [8] which included simulation of secondary interactions and digitization of all electronic signals. The simulated data were then processed through the same analysis chain as the real data. The hadronic event selection efficiency was thus estimated to be $\epsilon_{\mathrm{Z_h}} = (95.1 \pm 0.2)\%$ [9]. A total of 1.9 (4.7) million simulated Z^0 hadronic decays was used for the 1991-1993 (1994) analysis from which the acceptance and reconstruction efficiency were obtained.

The primary interaction vertex was computed in space for each event using an iterative procedure based on the χ^2 of the fit. The average transverse position of the interaction point, known for each fill, was included as a constraint during the primary vertex fit. The average widths of the beam overlap region, transverse to the beam axis, were taken to be 140 μm in the horizontal and 60 μm in the vertical directions (the latter is larger than the real beam dispersion in order to apply a looser constraint on the primary vertex fit). The overall χ^2 divided by the number of charged particles used in the fit had to be less than 5. To achieve this, the charged particle with the largest χ^2 contribution was discarded and a new primary vertex was computed.

3 Selection of the pion from $\mathrm{D}^{*+} \to (\mathrm{D}^0)\pi^+$ decay

The method followed to measure R_{c} and $P_{\mathrm{c}\to\mathrm{D}^{*+}}$ relies on the slow momentum pion, π_*, from the decay $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$. Due to the small mass difference between the D^{*+} and the D^0 mesons, only an energy of 40 MeV remains for this pion in the D^{*+} rest frame. This leads to an average transverse momentum, p_T, of this pion relative to the D^{*+} direction of about 40 MeV/c, much smaller than the average p_T of particles in ordinary jets which is about 300 MeV/c. Furthermore there is a correlation between the energy of the slow pion and the energy of the D^{*+}. Selecting π_* candidates with a momentum between 1.6 and 4 GeV/c allows to select $\mathrm{D}^{*\pm}$ with an energy fraction $X_E(\mathrm{D}^*)$ between 0.5 and 1 and thus to enrich the sample in $\mathrm{c\bar{c}}$ events and reduce the $\mathrm{b\bar{b}}$ contamination.

In order to reduce some backgrounds to the pion candidate from $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$ decays in $\mathrm{c\bar{c}}$ events, the impact parameter of this pion relative to the primary interaction vertex was required to be less than 3 mm.

Using the selected charged and neutral particles (see section 2) the thrust axis was computed, allowing two hemispheres to be defined in each event.

In each event, charged and neutral particles were clustered into jets using the LUCLUS algorithm with default parameters [3]. For each π_* candidate, its jet axis was computed as the vectorial sum of the momenta of all particles belonging to the same jet, not using the

π_*. Then an iterative procedure was followed in order to reject the particle with the lowest rapidity y relative to the jet axis. If the y value was found less than 2.5, a new jet axis was computed, not using this particle and the π_*, and the same y selection was required for the remaining particles. This procedure was repeated in order to have a y value larger than 2.5 for all particles in the jet. At least two remaining charged or neutral particles in the jet were required, not taking into account the π_* candidate. This jet axis computation allowed to have the smallest p_T value for genuine π_* candidates from $D^{*+} \to D^0\pi^+$ decays in the simulation : an average value $\langle p_T(\pi_*)\rangle = 62$ MeV/c was obtained for generated $c\bar{c}$ events.

The reconstruction times selection efficiency of π_* candidates was $\epsilon_*^c = 0.281$ in $c\bar{c}$ events and $\epsilon_*^b = 0.063$ in $b\bar{b}$ events. The efficiency to reconstruct and select two π_* candidates in events with two opposite $D^{*+}D^{*-}$, both decaying into $D^0\pi^+$ or $\overline{D}^0\pi^-$, was $\epsilon_{**}^c = 0.087$ in $c\bar{c}$ events and $\epsilon_{**}^b = 0.005$ in $b\bar{b}$ events according to the simulation. These $\epsilon_*^{c(b)}$ and $\epsilon_{**}^{c(b)}$ efficiencies include the correction factors mentioned in section 7.

4 Estimate of the low p_T pion yield

Figure 1a) presents the p_T^2 distribution of all slow pion candidates. A clear excess is observed at low p_T^2 which is interpreted as a signal of $D^{*\pm}$ production. Figure 1c) (or d) is the same distribution when another candidate of opposite (or same) charge was reconstructed in the opposite thrust hemisphere with a p_T^2 value lower than 0.01 (GeV/c)^2 . In order to count only once each charged particle contributing to the distributions 1c-d), each entry in these figures were appropriately weighted. The excess of events at low p_T^2 in figure 1c) is interpreted as a signal of $D^{*+}D^{*-}$ production.

However, selecting events with a low p_T^2 on one side to plot the p_T^2 distribution on the opposite side may simply show random coincidences between a low p_T^2 particle and a real D^{*+} on the opposite side. These random coincidences are evaluated as follows : figure 1b) presents the p_T^2 distribution, weighted as in 1c-d), of all charged particles when another one is reconstructed with a p_T^2 value between 0.02 (GeV/c)^2 and 0.10 (GeV/c)^2 in the opposite hemisphere; this distribution is then appropriately normalized by a factor α in order to correspond to the fraction of events with a p_T^2 lower than 0.01 (GeV/c)^2 in the background distribution function (dashed curve in figures 1a-d)); this normalized distribution can then be subtracted from figures 1c) and d) to evaluate the number of events with two $D^{*\pm}$ mesons.

In practice, an overall fit can be applied on the four distributions shown in figures 1a-d) using a common exponential shape for the $D^{*\pm}$ signal, a function with common parameters for the combinatorial background, a background normalization for each distribution and the number of $D^{*\pm}$ signal events for each distribution. The function used to describe the combinatorial background was :

$$F(p_{\mathrm{T}}^2) = \frac{1}{1 + a p_{\mathrm{T}}^2 + b p_{\mathrm{T}}^6} \qquad (3)$$

where the coefficients a and b are free parameters, common to all four distributions. Compared to the Gaussian shape used in the previous analysis, this parameterization allows a better convergence of the overall fit and a good confidence in the statistical errors.

The overall number of signal events in figure 1a) can be expressed as :

$$N_{tot} = 2\frac{N_{\mathrm{Z_h}}}{\epsilon_{\mathrm{Z_h}}} R_{\mathrm{c}} P_{\mathrm{c}\to\mathrm{D^{*+}}} B_* \epsilon_*^c \left[1 + r\frac{\epsilon_*^b}{\epsilon_*^c}\right](1+\delta) \tag{4}$$

where $N_{\mathrm{Z_h}}$ is the number of collected $\mathrm{Z^0}$ hadronic final states and $\epsilon_{\mathrm{Z_h}}$ their selection efficiency (see section 2); R_{c} (R_{b}) stands for the $\mathrm{Z^0}$ partial width into c (b) quark pair; $P_{\mathrm{c}\to\mathrm{D^{*+}}}$ is the probability for a charm quark to fragment into a $\mathrm{D^{*+}}$ meson; $B_* = Br(\mathrm{D^{*+}} \to \mathrm{D^0}\pi^+) = 0.681 \pm 0.016$ [10]; a new measurement of $r = \frac{R_{\mathrm{b}} P_{\mathrm{b}\to\mathrm{D^{*\pm}}}}{R_{\mathrm{c}} P_{\mathrm{c}\to\mathrm{D^{*+}}}}$ is presented in the next section; the $(1+\delta)$ term takes into account any additional contribution to the excess at low p_T^2 which is not due to $\mathrm{D^{*\pm}}$ production (assuming this eventual contribution to be similar in $\mathrm{c\bar{c}}$ and $\mathrm{b\bar{b}}$ events and negligible in light quark events).

The number of fitted signal events in figures 1b), c) and d) are noted N_{bkg}, N_{opp} and N_{same}, respectively. The overall number of tagged signal events can be expressed as :

$$N_{opp} + N_{same} - \alpha N_{bkg} = 2\frac{N_{\mathrm{Z_h}}}{\epsilon_{\mathrm{Z_h}}} R_{\mathrm{c}} \left(P_{\mathrm{c}\to\mathrm{D^{*+}}} B_*\right)^2 \epsilon_{**}^c \left[1 + r^2 \frac{R_{\mathrm{c}}}{R_{\mathrm{b}}} \frac{\epsilon_{**}^b}{\epsilon_{**}^c}\right](1+\delta)^2 \tag{5}$$

where α, the factor introduced above for the background sample, is computed in the overall fit of the four distributions 1a-d).

From these equations (4-5), the $\mathrm{Z^0}$ partial width R_{c} can be obtained from the ratio $N_{tot}^2/(N_{opp} + N_{same} - \alpha N_{bkg})$ where the unknown $P_{\mathrm{c}\to\mathrm{D^{*+}}}$ and $(1+\delta)$ terms cancel.

The $(1+\delta)$ term can also be evaluated dividing the previous equation (5) by the following one :

$$N_{opp} - N_{same} = 2\frac{N_{\mathrm{Z_h}}}{\epsilon_{\mathrm{Z_h}}} R_{\mathrm{c}} \left(P_{\mathrm{c}\to\mathrm{D^{*+}}} B_*\right)^2 \epsilon_{**}^c \left[1 + r^2 \frac{R_{\mathrm{c}}}{R_{\mathrm{b}}} \frac{\epsilon_{**}^b}{\epsilon_{**}^c} (1 - 2\chi_{\mathrm{D^*}})^2\right] \tag{6}$$

where the eventual excess of events at low p_T^2 which is not due to $\mathrm{D^{*\pm}}$ production is assumed to have no charge correlation with the opposite hemisphere. The term $\chi_{\mathrm{D^*}} = \frac{P_{\mathrm{b}\to\mathrm{D^{*-}}}}{P_{\mathrm{b}\to\mathrm{D^{*+}}} + P_{\mathrm{b}\to\mathrm{D^{*-}}}}$ describes the probability to find a $\mathrm{D^{*-}}$ in the fragmentation of a b quark into $\mathrm{D^{*\pm}}$. This can be due to $\mathrm{B_d^0} - \overline{\mathrm{B_d^0}}$ mixing, the production of orbitally excited $\mathrm{D^{**0}}$ in $\mathrm{B^-}$ decays or $\mathrm{W^-} \to \bar{\mathrm{c}}\mathrm{d}$ transitions in B decays. An effective $\chi_{eff} = 2\chi_{\mathrm{D^*}}(1-\chi_{\mathrm{D^*}})$ was estimated in reference [11] :

$$\chi_{eff} = 0.241^{+0.033}_{-0.045} \, , \tag{7}$$

in agreement with the DELPHI simulation. This estimation was used in the following.

Finally in the overall fit of the four distributions of figure 1a-d), the last four free parameters were chosen to be R_{c}, $P_{\mathrm{c}\to\mathrm{D^{*+}}} B_*$, $(1+\delta)$ and $(N_{opp} + N_{same})$ according to the relations :

$$R_{\mathrm{c}} = \frac{1}{2}\frac{\epsilon_{\mathrm{Z_h}}}{N_{\mathrm{Z_h}}} \frac{N_{tot}^2}{N_{opp} + N_{same} - \alpha N_{bkg}} \frac{\epsilon_{**}^c}{(\epsilon_*^c)^2} \frac{\left[1 + r^2 \frac{R_{\mathrm{c}}}{R_{\mathrm{b}}} \frac{\epsilon_{**}^b}{\epsilon_{**}^c}\right]}{\left[1 + r\frac{\epsilon_*^b}{\epsilon_*^c}\right]^2}$$

$$P_{\mathrm{c}\to\mathrm{D^{*+}}} B_* = \frac{\sqrt{(N_{opp} + N_{same} - \alpha N_{bkg})(N_{opp} - N_{same})}}{N_{tot}} \frac{\epsilon_*^c}{\epsilon_{**}^c} \times$$

$$\times \frac{\left[1 + r\,\frac{\epsilon_*^b}{\epsilon_*^c}\right]}{\sqrt{\left[1 + r^2\,\frac{R_{\rm c}}{R_{\rm b}}\,\frac{\epsilon_{**}^b}{\epsilon_{**}^c}\right]\left[1 + r^2\,\frac{R_{\rm c}}{R_{\rm b}}\,\frac{\epsilon_{**}^b}{\epsilon_{**}^c}\,(1-2\chi_{\rm D^*})^2\right]}} \tag{8}$$

$$(1+\delta) = \sqrt{\frac{N_{opp} + N_{same} - \alpha N_{bkg}}{N_{opp} - N_{same}}}\;\frac{\left[1 + r^2\,\frac{R_{\rm c}}{R_{\rm b}}\,\frac{\epsilon_{**}^b}{\epsilon_{**}^c}\,(1-2\chi_{\rm D^*})^2\right]}{\left[1 + r^2\,\frac{R_{\rm c}}{R_{\rm b}}\,\frac{\epsilon_{**}^b}{\epsilon_{**}^c}\right]}\,.$$

5 Determination of $(R_{\rm b}P_{\rm b\to D^{*\pm}})/(R_{\rm c}P_{\rm c\to D^{*+}})$

In this section the determination of the ratio of $\rm D^{*\pm}$ produced in b and c events is described. This quantity is obtained from a fit to the p_T^2 spectra of slow pions in different bins of b purity. For this analysis, only 1994 data were used and π_* candidates were selected and their p_T^2 defined as in section 4, apart for their momentum which was required between 1.5 and 3.5 GeV/c.

The resulting p_T^2 spectrum shows a clear enhancement at low p_T^2 over a smooth falling background. In order to extract the number of $\rm D^{*\pm}$, several signal and background functions were tested in the simulation. The sum of two exponentials for the signal and a third order polynomial for the background were used. The fitted function can be written as :

$$f(x) = f_s(x) + f_b(x) = N_{\rm D^{*\pm}}(e^{-a_1 x} + a_3 e^{-a_2 x}) + b_0 + b_1 x + b_2 x^2 + b_3 x^3 \tag{9}$$

The signal term is internally normalized to extract directly the number of $\rm D^{*\pm}$ out of the fit. In the first step f_s is fitted to the Monte Carlo sample which contains only real π_* . From this, one gets the shape parameters a_1, a_2 and a_3. In the second step the total spectrum is fitted with these parameters fixed, so that the signal normalization (number $N_{\rm D^{*\pm}}$ of $\rm D^{*\pm}$) and the background function are the remaining free quantities . This leads to a χ^2 per degree of freedom of the order of one.

Having found the method to extract the number of $\rm D^{*\pm}$ out of the π_* spectra, one has to care about a proper separation between the c and b contribution to these numbers. In order to have good separation power, a combined binning in momentum of the π_* candidates and a transformed b-tag variable $prob_p$

$$b_{trans} = \frac{4}{4 - \log(prob_p)}$$

was chosen, where $prob_p$ denotes the probability for charged particle tracks with positive impact parameter relative to the interaction point [12]. The next step is to build up the efficiency corrected momentum spectra of the π_*

$$\frac{d\sigma}{dp} = \frac{dN_{dat}^{\pi_*}}{dp}\frac{1}{\epsilon(p)}$$

in six chosen bins of b_{trans} with

$$\epsilon(p) = \frac{dN_{acc}^{\pi_*}/dp}{dN_{gen}^{\pi_*}/dp}\,\Delta\epsilon$$

as the efficiency to reconstruct a π_* in a certain bin. Due to a large amount of background in the signal region the accepted part in the efficiency is extracted in the same way for data and Monte Carlo with the fit function described above. However, the fit on the Monte Carlo spectra overestimates the signal rate resulting in an artificially increased efficiency. As a consequence the efficiency is calculated with the counted real π_* and a global correction factor $\Delta\epsilon$, which is determined as the average difference between counting and fitting. This leads to six corrected momentum spectra in b_{trans} which supply together with their generated b and c-contributions the input for the final fit.
In general the number of single tags in b and c-events can be written as :

$$
\begin{aligned}
N_S^c &= 2R_{\rm c}P_{{\rm c}\to{\rm D}^{*+}}B_* \\
N_S^b &= 2R_{\rm b}P_{{\rm b}\to{\rm D}^{*\pm}}B_*
\end{aligned}
$$

The measured number of single tags in a certain bin of b_{trans} and momentum (p) is represented in this analysis by

$$
N_S(b_{trans},p) = \frac{t}{(1+r)N^c_{S,gen}} N^c_{S,gen}(b_{trans},p) + \frac{t}{\left(1+\dfrac{1}{r}\right)N^b_{S,gen}} N^b_{S,gen}(b_{trans},p) \;,
$$

with

$$
\begin{aligned}
r &= (R_{\rm b}P_{{\rm b}\to{\rm D}^{*\pm}})/(R_{\rm c}P_{{\rm c}\to{\rm D}^{*+}}) \;\text{ and} \\
t &= (R_{\rm b}P_{{\rm b}\to{\rm D}^{*\pm}} + R_{\rm c}P_{{\rm c}\to{\rm D}^{*+}})B_* \;.
\end{aligned}
$$

These quantities can be directly extracted from a simultaneous fit of the 6×2 generated b and c momentum spectra to the according corrected ones. The fit leads to :

$$
\begin{aligned}
(R_{\rm b}P_{{\rm b}\to{\rm D}^{*\pm}})/(R_{\rm c}P_{{\rm c}\to{\rm D}^{*+}}) &= 1.16 \quad \pm 0.06 \quad ({\rm stat}) \pm 0.13 \quad ({\rm syst}) \\
(R_{\rm b}P_{{\rm b}\to{\rm D}^{*\pm}} + R_{\rm c}P_{{\rm c}\to{\rm D}^{*+}})B_* &= 0.0612 \pm 0.0011({\rm stat}) \pm 0.0051({\rm syst})
\end{aligned}
$$

with a statistical correlation of 0.620.

Table 1 contains a breakdown of the contributions to the systematic errors and figure 2 shows the fit results in bins of b_{trans} with the corresponding b and c contributions scaled.

In the previous analysis of exclusive $\mathrm{D}^{*\pm}$ mesons [1], the value $r = 1.47 \pm 0.15$ (stat) $\pm$ 0.13 (syst) was obtained. Combining both results and taking into account the constraint from recent DELPHI analyses [13], the following value is inferred :

$$
r = \frac{R_{\rm b}P_{{\rm b}\to{\rm D}^{*\pm}}}{R_{\rm c}P_{{\rm c}\to{\rm D}^{*+}}} = 1.25 \pm 0.06\ ({\rm stat}) \pm 0.07\ ({\rm syst})\;. \tag{10}
$$

6 Fit results

The simultaneous fit of $R_{\rm c}$, $P_{{\rm c}\to{\rm D}^{*+}}B_*$ and $1+\delta$ (see section 4) is presented in this section. For real data, the value of $r = \frac{R_{\rm b}P_{{\rm b}\to{\rm D}^{*\pm}}}{R_{\rm c}P_{{\rm c}\to{\rm D}^{*+}}}$ obtained in the previous section was used.

The results for the simulated p_T^2 distributions are shown in Table 2 where generated data with the 1993 and 1994 tunings are separated. The $(1+\delta)$ contribution in the 1993

		$(R_b P_{b\to D^{*\pm}})/(R_c P_{c\to D^{*+}})$	$(R_b P_{b\to D^{*\pm}} + R_c P_{c\to D^{*+}})B_*$
MC statistics		$\pm$ 0.057	$\pm$ 0.005
Fit procedure	shape	$\pm$ 0.025	$\pm$ 0.003
	background	$\pm$ 0.001	$\mp$ 0.053
	efficiency	—	$\pm$ 0.007
Acceptance	$\cos\Theta$	$\pm$ 0.006	$\pm$ 0.006
	momentum	$\mp$ 0.001	$\pm$ 0.050
	Hemisphere	—	—
b_{tag}		$\pm$ 0.005	—
$g \to c\bar{c}$		$\pm$ 0.003	$\pm$ 0.007
Fragmentation	c quarks	$\pm$ 0.055	$\mp$ 0.007
	b quarks	$\mp$ 0.069	$\mp$ 0.040
Total		$\pm$ 0.108	$\pm$ 0.084

Table 1: Relative systematic uncertainty of $(R_b P_{b\to D^{*\pm}})/(R_c P_{c\to D^{*+}})$ and $(R_b P_{b\to D^{*\pm}} + R_c P_{c\to D^{*+}})B_*$.

	R_c		$P_{c\to D^{*+}} B_*$		$1+\delta$	χ^2/dof
	measured	gen.	measured	gen.	measured	
1993 simulation	0.173±0.016	0.171	0.183±0.013	0.179	1.13±0.07	191/189
1994 simulation	0.185±0.013	0.171	0.153±0.008	0.163	1.05±0.04	174/189

Table 2: Results of the low p_T^2 analysis in simulated data.

simulation is closest to 1 than in the previous analysis [1]. It is compatible with 1 in the 1994 simulation. For both simulated samples, the obtained values for R_c and $P_{c\to D^{*+}} B_*$ are compatible with the generated ones.

The overall fit in the real data has a χ^2 per degree of freedom of 206/189. The total fitted function is shown as a solid curve in figure 1. The fitted function describing the background is the dashed curve. The fitted exponential slope for the slow pion signal corresponds to an average p_T of 59.1 ± 0.6 (stat) MeV/c. Figure 1e) presents the distribution of low p_T^2 tagged events after combinatorial background subtraction, according to equation (5). Figure 1f) presents this distribution when the fitted background function is subtracted : about 69000 $D^{*\pm}$ and 1500 $D^{*+}D^{*-}$ are obtained from the 1991-1994 real data sample.

The fitted results in the data are :

$$
\begin{aligned}
R_c = \frac{\Gamma_c}{\Gamma_h} &= 0.171^{+0.014}_{-0.012}\ (\text{stat}) \\
P_{c\to D^{*+}} Br(D^{*+} \to D^0\pi^+) &= 0.170 \pm 0.009\ (\text{stat}) \\
1+\delta &= 1.03 \pm 0.05\ (\text{stat})
\end{aligned}
\qquad (11)
$$

where the statistical correlation between $R_{\rm c}$ and $P_{\rm c\to D^{*+}}B_*$ is -0.744 (see Table 3).

	$R_{\rm c}$	$P_{\rm c\to D^{*+}}$	$1+\delta$
$R_{\rm c}$	1.000	-0.744	-0.596
$P_{\rm c\to D^{*+}}$	-0.744	1.000	-0.028
$1+\delta$	-0.596	-0.028	1.000

Table 3: Statistical correlation matrix.

7 Systematic uncertainties

The systematic uncertainties are detailed in Table 4. The one relying on the Monte Carlo statistics describes the agreement observed between the measured and generated quantities (see Table 2).

The uncertainty on the fraction of π_* candidates with a momentum greater than 1.6 GeV/c in c$\bar{\rm c}$ events is evaluated in the simulation by varying the average energy fraction $X_E({\rm D}^{*+})$ taken by the ${\rm D}^{*\pm}$ around the value measured in the previous note [1]. In Table 4 it is split in two parts : the one relying on the DELPHI measurement alone (first two errors in equation (2)) and the uncertainty describing the charm quark fragmentation model (last error in equation (2)).

A relative uncertainty of ± 0.09 on the π_* selection efficiency in b$\bar{\rm b}$ events is included in order to describe the uncertainty in the energy spectrum of B mesons in b quark fragmentation (see section 2).

The uncertainty due to $r = \frac{R_{\rm b}P_{\rm b\to D^{*\pm}}}{R_{\rm c}P_{\rm c\to D^{*+}}}$ is computed from its measured value 1.25 ± 0.10 in DELPHI (see section 5).

A correction factor of 1.016 ± 0.021 was applied to the α value used in equation (5). This correction was obtained by counting true π_* particles in the simulation when any other charged particles were selected at low p_T^2 in the opposite hemisphere. The theoretical α obtained in this counting was slightly larger, in average, than its value obtained in the fit of the background shape. The correction factor was 1.037 (0.995) in the 1993 (1994) simulation. The uncertainty on the averaged correction factor leads to a systematic error on $R_{\rm c}$ and $P_{\rm c\to D^{*+}}$.

A correction to the efficiency of π_* candidates when they are tagged in the opposite hemisphere is also taken into account. This includes a first correction factor of 1.01 ± 0.01 which arises from the small difference observed in the average p_T of the fitted signal in the simulation ($\langle p_T(\pi_*)\rangle = 62$ MeV/c) and in the data ($\langle p_T(\pi_*)\rangle = 59.1 \pm 0.6$ (stat) MeV/c). A second correction factor of 1.04 ± 0.02 was applied to ϵ^c_{**} and ϵ^b_{**} and obtained as follows : in the simulation, the true number of reconstructed $\pi^+_*\pi^-_*$ pairs was compared to the difference between the number of π_* candidates tagged in the opposite hemisphere by any particles of same charge or opposite charge. This correction factor has to be applied to $R_{\rm c}$ and for $P_{\rm c\to D^{*+}}$ its error almost cancels with the error on the association efficiency mentioned below.

The relative uncertainty on the π_* reconstruction efficiency is estimated to be ± 0.035. This includes a ± 0.02 due to the tracking efficiency, a ± 0.02 due to the impact parameter requirement of less than 3 mm and a ± 0.02 due to the uncertainty in the association between simulated and reconstructed π_* candidates. Only the first two components of this uncertainty affect the measurement of $P_{\mathrm{c}\to\mathrm{D}^{*+}}$ (see above), whereas they all cancel for R_c (see equation (8)).

The uncertainties on the Z^0 hadronic selection efficiency and on the χ_{eff} factor due to the $\mathrm{b}\to\mathrm{D}^{*-}$ fraction (see equation (7)) are small and only affect R_c and $P_{\mathrm{c}\to\mathrm{D}^{*+}}$, respectively. The residual uncertainty due to the R_b factor in equation (8) is negligible.

The overall relative systematic uncertainty is $\pm 9\%$ on R_c and $\mp 8\%$ on $P_{\mathrm{c}\to\mathrm{D}^{*+}} B_*$.

	R_c	$P_{\mathrm{c}\to\mathrm{D}^{*+}} B_*$
Monte Carlo statistics	± 0.055	∓ 0.040
c fragmentation (DELPHI)	± 0.017	∓ 0.034
(model)	± 0.019	∓ 0.039
b fragmentation	∓ 0.027	± 0.010
$\frac{R_\mathrm{b} P_{\mathrm{b}\to\mathrm{D}^{*\pm}}}{R_\mathrm{c} P_{\mathrm{c}\to\mathrm{D}^{*+}}} = 1.25 \pm 0.10$	∓ 0.027	± 0.011
background subtraction (α)	± 0.039	∓ 0.020
correction to ϵ^c_{**} and ϵ^b_{**}	± 0.024	∓ 0.012
π_* reconstruction efficiency	—	∓ 0.028
Z^0 selection	± 0.002	—
χ_{eff}	—	± 0.004
Total	± 0.085	∓ 0.076

Table 4: Relative systematic uncertainty on R_c and $P_{\mathrm{c}\to\mathrm{D}^{*+}} B_*$.

8 Conclusion

An update has been presented for the measurement of R_c and $P_{\mathrm{c}\to\mathrm{D}^{*+}}$ using the single and double tags of low p_T pions from $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$ decays.

Using 1994 data and the b-tagging procedure, the ratio

$$\frac{R_\mathrm{b} P_{\mathrm{b}\to\mathrm{D}^{*\pm}}}{R_\mathrm{c} P_{\mathrm{c}\to\mathrm{D}^{*+}}} = 1.25 \pm 0.06\ (\mathrm{stat})) \pm 0.07\ (\mathrm{syst})$$

is measured (where the new value is combined with a previous DELPHI analysis [1] of exclusive $\mathrm{D}^{*\pm}$ and recent DELPHI results [13]).

Using 3.1 million Z^0 hadronic decays collected from 1991 to 1994, the following results are obtained :

$$R_\mathrm{c} = \frac{\Gamma_\mathrm{c}}{\Gamma_\mathrm{h}} \quad = \quad 0.171^{+0.014}_{-0.012}\ (\mathrm{stat}) \pm 0.015\ (\mathrm{syst})$$

$$P_{\mathrm{c}\rightarrow\mathrm{D}^{*+}} Br(\mathrm{D}^{*+} \rightarrow \mathrm{D}^0\pi^+) \quad = \quad 0.170 \pm 0.009\ (\mathrm{stat}) \pm 0.013\ (\mathrm{syst}).$$

The measurement of $P_{\mathrm{c}\rightarrow\mathrm{D}^{*+}}$ allows a more precise estimate of R_{c} using exclusive $\mathrm{D}^{*\pm}$. The result for R_{c} using only inclusive $\mathrm{D}^{*\pm}$ is compatible with the Standard Model expectation of 0.172.

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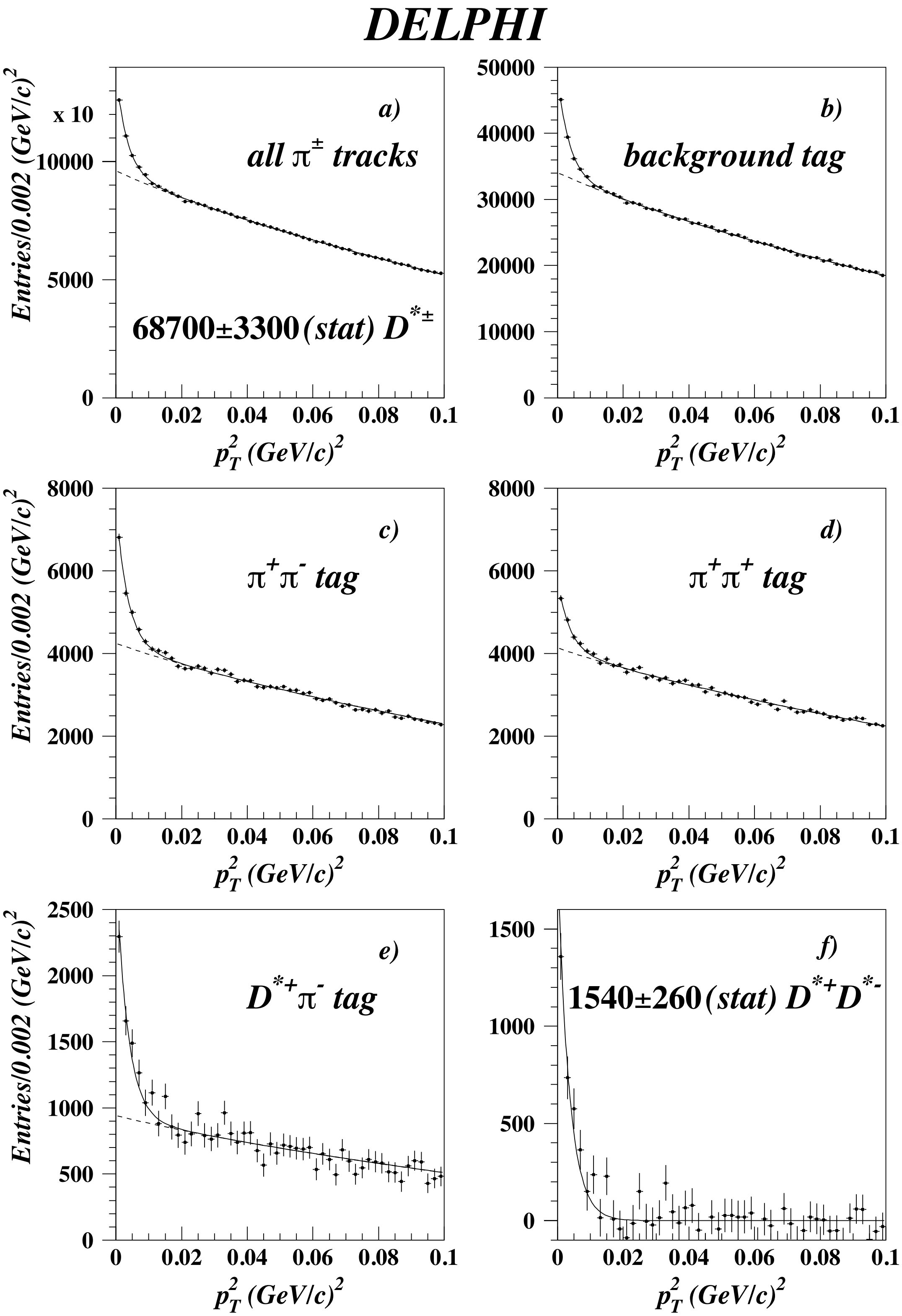

Figure 1: p_T^2 distributions of selected charged particles : a) all candidates; b) when another particle has p_T^2 between 0.02 (GeV/c)^2 and 0.10 (GeV/c)^2 in the opposite hemisphere; c) (d) when another one of opposite (same) charge has p_T^2 lower than 0.01 (GeV/c)^2 in the opposite hemisphere; e) sum of c) and d) minus the normalized combinatorial background b) distribution; f) same as e) after fitted background subtraction. The curves are explained in the text.

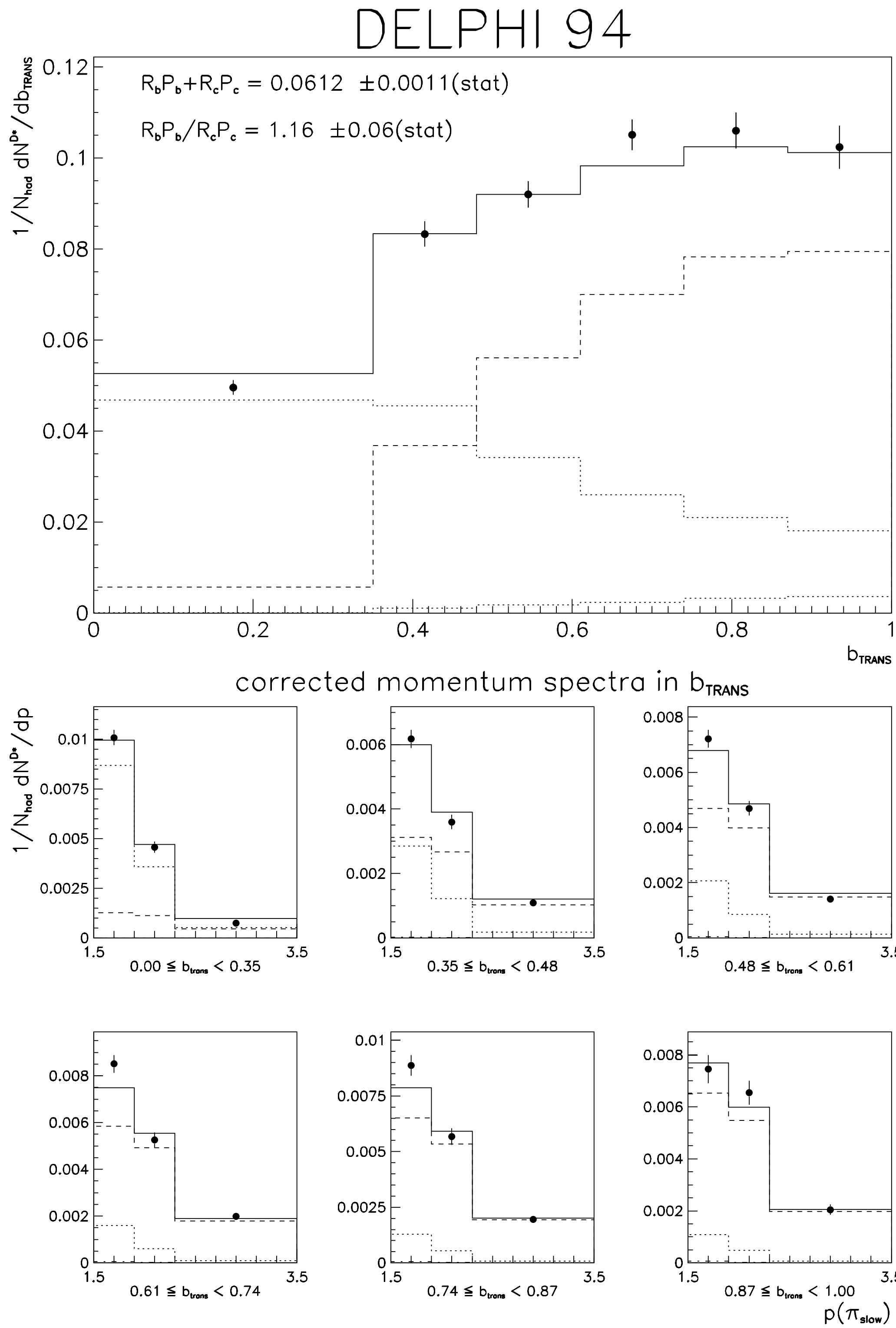

Figure 2: Fit result in function of the slow pion momentum (lower part) for different bins of b_{trans} (solid histogram) with normalized b quark (dashed curve) and c quark (dotted curve) contributions. The sum off the 6 spectra is shown in the upper part in funcion of the b_{trans} variable.