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Combined analysis of charm-quark fragmentation-fraction measurements

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Abstract. A summary of measurements of the fragmentation of charm quarks into a specific hadron is given. Measurements performed in photoproduction and deep inelastic scattering in $e^{\pm}p$, pp and $e^{+}e^{-}$ collisions are compared, using up-to-date branching ratios. Within uncertainties, all measurements agree, supporting the hypothesis that fragmentation is independent of the specific production process. Averages of the fragmentation fractions over all measurements are presented. The average has significantly reduced uncertainties compared to individual measurements.

1 Introduction

The fragmentation process is one of the most important phenomena in the high-energy physics. Every new-born quark participates in this process producing more quarks and consequently forms a hadron.

The fragmentations is difficult for modelling, so it is important to improve the knowledge about the process and study the most basic properties of the fragmentation. One of these is the probability of the fragmented quark q to create a given hadron H_q. This is called the fragmentation fraction and is denoted below as $f(q \to H_q)$.

An important question is whether the fragmentation fractions are universal, i.e. independent of the hard production mechanism. If true, once precisely measured in one environment, these can be applied in any other. This is especially important for the studies of heavier c and b quarks, as the precise knowledge of $f(c \to H_c)$ and $f(b \to H_b)$ can help for many measurement in the modern high-energy physics experiments.

The goal of this analysis [1] is to provide the most precise and model-independent values for fragmentation fractions of the charm quark. In this context it is also important to check that the sum of fragmentation fractions to all known ground states of charm hadrons is equal to unity, thus, all these states are known.

To achieve these goals, we extract the fragmentation fractions from all measurements simultaneously and separately for different environments and compare the results. To perform the desired checks we utilise the Standard Model predictions.

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2 Selection of measurements for the extraction of fragmentation fractions

The selection of the measurements for the extraction of fragmentation fractions was done according to a set of criteria explained below. First, the selection is limited to the measurements obtained in the collisions of particle beams as these environments have well know production mechanisms of charm quarks and assure an absence of possible matter effects. Thus, only the measurements from high-energy ep, pp and e^+e^- collisions satisfy the requirements. The second criterion of the selection is the precision of the measured quantities. Basically, only the experiments on LEP, TEVATRON, HERA, LHC and B-factories. The third criterion of the selection is the sufficient number of measurements in the given physical environment. Several analyses of charm production (e.g. Ref. [2]) do not contain enough simultaneous measurements of hadron production and, therefore, cannot be treated independently and/or constrain the fragmentation fractions. The fourth criterion of the selection is a minimal model dependence of the results. Finally, only results that were published, or, at least submitted to peer-reviewed journals were considered.

The measurements selected according to the criteria described above form five groups. The first group is provided by B-factories. The results of the CLEO [3, 4] and ARGUS [5–7] experiments are represented as a product of the charm-hadron cross-sections times decay branching ratios, $\sigma(e^+e^- \to H_c) \cdot \mathcal{B}(H_c \to X)$. The BELLE experiment [8] provided measurements of the charm-hadrons cross-sections $\sigma(e^+e^- \to H_c)$. The BABAR experiment [9] provided a measurement of an average number of $\Lambda_c^+ \to pK\pi$ decays per hadronic event. The full list of the measured quantities used in the analysis is given in Ref. [1]. The second group of measurements is provided by the OPAL [10, 11], ALEPH [12] and DELPHI [13] experiments. Of those, the most valuable for the studies of fragmentation are results obtained from the studies of hadronic Z decays. These are represented in the form of fraction of charm events multiplied by branching ratios $\frac{\Gamma(Z\to c\bar{c})}{\Gamma(Z\to \text{hadrons})} \cdot f(c \to H_c) \cdot \mathcal{B}(H_c \to X)$ [10–13], or $\frac{\Gamma(Z\to c\bar{c})}{\Gamma(Z\to \text{hadrons})} \cdot f(c \to H_c)$ [12, 14]. In addition, ALEPH [12], DELPHI [14] and OPAL [11] provided measurements of $f(c \to H_c)$ and $f(c \to H_c) \cdot \mathcal{B}(H_c \to X)$ from the fits of fragmentation functions. The full list of the measured quantities used in the analysis is given in Ref. [1]. The third group of measurements are the charm-hadron production measurements in DIS in $e^\pm p$ collisions done by ZEUS [15, 16] and H1 [17] collaboration. Those experiments provide the cross-sections of the charm-hadron production in the restricted kinematic space. To extract the fragmenation fractions a procedure described in Ref. [1] is used. The fourth group of measurements are the charm-quark production measurements in PHP in $e^\pm p$ collisions done by ZEUS [18, 19]. The experiment provides the cross-sections of the charm hadron production in the restricted kinematic space and the fragmentation fractions. To extract the fragmenation fractions a procedure described in Ref. [1] is used. The last group of measurements comes from the studies of pp collisions at LHCb. The experiment provided measurements of charm-hadron cross-sections at $\sqrt{s} = 7$TeV [20] and at $\sqrt{s} = 13$TeV [21][1].

To make separate inputs consistent, the original measurements are corrected to the same up-to-date world averages of branching ratios of the charm-hadron decays. Most of the values were taken from Ref. [22]. Exceptions are made for the branching ratios of Λ_c^+ and D^{*0} decays, calculated from Refs. [23–25] as described in Ref. [1].

2.1 Calculation of the fragmentation fractions

In this analysis the charm-quark fragmentation fraction to a specific hadron assumed to be equal to the ratio of the production cross-section of the hadron via charm quark over the production cross-section of the charm quark

$$f(c \to H_c) = \sigma(H_c)/\sigma(c), \tag{1}$$

[1]The latter was presented on this conference.

i.e. the charm hadrons produced from beauty decays are excluded. With the available precise predictions for the total charm cross-section in e^+e^- collisions it is possible to calculate $f(c \to H_c)$ according to Eq. (1). However, sufficiently precise predictions for the charm-quark production in pp and $e^\pm p$ collisions are not available and other approaches are needed. Hereby,we make an assumption that the sum of charm-quark fragmentation fractions to all known ground states of charm hadrons is unity, the charm-quark fragmentation fraction to a specific hadron can be calculated as the ratio of the hadron-production cross-section over the sum of cross-sections of all known known ground states of charm hadrons

$$f(c \to H_c) = \sigma(H_c)/\Sigma_i \sigma(H_{c,i}). \quad (2)$$

The fragmentation fractions calculated according to Eq. (1) for the e^+e^- collisions and Z decays allow an independent check that

$$S = f(c \to D^0) + f(c \to D^+) + f(c \to D_s^+) + f(c \to \Lambda_c^+) + \sum f(c \to \Xi_c^{+,0}, \Omega_c^0) \quad (3)$$

is close to unity with sufficient accuracy. To perform the check we combine the available measurements of D^0, D^+, D_s^+, Λ_c^+ and assume $\sum f(c \to \Xi_c^{+,0}, \Omega_c^0) = \lambda f(c \to \Lambda_c^+)$, where $\lambda \ll 1$ is estimated from the production rates of strange hadrons.

2.2 Extraction procedure

The extraction of $f(c \to H_c)$ from the measurements in the present analysis is done separately for each group of measurements and then from all of them together regardless of the affiliation.

The procedure is based on numerical fit with respect to observables of interest. The details on the implementation are in Ref. [1] and only a brief description is given below. Basically, for the set of measurements the corresponding expectation values calculated from fit parameters together with the residuals R, the differences between the measurements and the corresponding expectation. The covariance matrix, V is calculated from the uncertainties of the residuals and takes into account all of the known correlations, including these for branching ratios, theoretical predictions etc. The full description of the correlations taken into account is given in Ref. [1]. The fit is performed with a minimisation of the $\chi^2 = R^T V^{-1} R$ quantity. The uncertainties on the fit parameters (e.g. fragmentation fractions) are determined using the Hessian method.

The obtained fragmentation fractions and the corresponding correlation matrix are used to calculate, the quantities commonly used as Monte Carlo generator parameters:

$$R_{u/d} = \frac{f(c \to D^0) - f(c \to D^{*+})\mathcal{B}_{D^{*+}\to D^0}}{f(c \to D^+) + f(c \to D^{*+})\mathcal{B}_{D^{*+}\to D^0}},$$

$$\gamma_{s(1)}^{(*)} = \frac{2f(c \to D_{s(1)}^{(*)+})}{f(c \to D^{(*)+}) + f(c \to D^{(*)0})} \text{ and } P_V^d = \frac{f(c \to D^{*+}) + f(c \to D^{*0})}{f(c \to D^+) + f(c \to D^0)}.$$

3 Results

The results of the fragmentation fraction extraction procedure for each of the groups introduced above is shown in Fig. 1. The numerical values are given in Ref. [1].

To check the consistency of the data from different production environments and also to extract the charm-quark fragmentation fractions with high precision, all input measurements are used together to produce a global combination. The constraint on the sum of the cross-sections of the weakly decaying

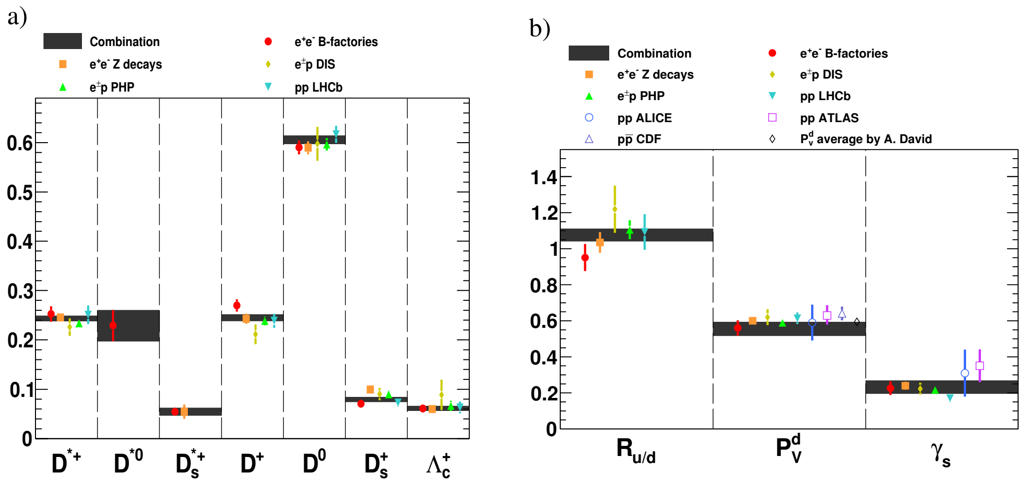

Figure 1. The values of a)charm-quark fragmentation fractions, $f(c \to H_c)$, and b) $R_{u/d}$, P^d_V, γ_s in different experiments with the S constraint. The global combination with the S constraint is shown with the shaded band. Averages of included data in different production environments are shown with various full symbols. Data that were not included in the combination [26–31] are shown with open symbols. Note, that the latter are quoted from the original papers, i.e. without correction to the up-to-date branching ratios and with no branching ratio uncertainty, if not given in the source.

Table 1. Results of the global combination.

	Constrained S	Constrained S, fix $\sigma(e^+e^- \to c\bar{c})$, $\frac{\Gamma_{c\bar{c}}}{\Gamma_{\text{hadrons}}}$.
$f(c \to D^{*+})$	0.2436 ± 0.0050	0.2411 ± 0.0048
$f(c \to D^{*0})$	0.2286 ± 0.0313	0.2270 ± 0.0304
$f(c \to D_s^{*+})$	0.0548 ± 0.0076	0.0549 ± 0.0076
$f(c \to D^{+})$	0.2449 ± 0.0065	0.2451 ± 0.0064
$f(c \to D^{0})$	0.6058 ± 0.0079	0.6130 ± 0.0075
$f(c \to D_s^{+})$	0.0794 ± 0.0047	0.0803 ± 0.0048
$f(c \to \Lambda_c^{+})$	0.0615 ± 0.0046	0.0542 ± 0.0030
χ^2	60.0	74.6
n_{dof}	57	60
S	1.0000 ± 0.0005	1.0000 ± 0.0004
$R_{u/d}$	1.0757 ± 0.0341	1.1017 ± 0.0335
P^d_V	0.5551 ± 0.0372	0.5455 ± 0.0357
γ_s	0.1866 ± 0.0120	0.1872 ± 0.0123
γ_s^*	0.2321 ± 0.0356	0.2344 ± 0.0361

charm states, S, is imposed in the combination, i.e. the prediction for the total charm cross-sections in e^+e^- collisions is not used, in order to minimise model dependence of the averaging procedure. The result of averaging e^+e^-, $e^\pm p$ and pp data, with the constraint $S = 1$ is presented in the middle column of Tab. 1 and is shown in Fig. 1. The input data are in very good agreement with $\chi^2/n_{\rm dof} = 64/61$. The result of the combination has significantly reduced uncertainties compared to individual measurements. The combined results are also compared to recent measurements [26–31] (see Fig. 1) that were not included in the combination. In particular, $R_{u/d} = 1.078 \pm 0.033$ is in fair agreement with the isospin invariance hypothesis $R_{u/d} = 1$ within 2.4 standard deviations.

4 Results for the excited states

In addition to the average fragmentation fractions for the ground, $L = 0$, states, some fragmentation fractions for the excited, $L = 1$ charm hadrons are calculated.

The measurements used for the averaging are obtained by ZEUS [32, 33], OPAL [34] and ALEPH [35] experiments. For the detailed list of those see Ref. [1]. The unpublished measurement of $f(c \to D_{s1}^+)$ from Ref. [36] was rejected. As the measurements have limited precision, the correction to the most recent branching ratios cannot improve the results and was not done. The averages, as well as the γ_{s1}, are calculated with an assumption of fully uncorrelated statistical and systematical uncertainties. The results are given in Tab. 2.

Table 2. Results of the global combination for $L = 1$ states.

	Average
$f(c \to D_1^+)$	$0.0460^{+0.0269}_{-0.0182}$
$f(c \to D_2^{*+})$	$0.0320^{+0.0094}_{-0.0082}$
$f(c \to D_1^0)$	0.0297 ± 0.0038
$f(c \to D_2^{*0})$	0.0394 ± 0.0068
$f(c \to D_{s1}^+)$	0.0109 ± 0.0014
γ_{s1}	$0.287^{+0.079}_{-0.109}$

5 Summary

A summary of measurements of the fragmentation of charm quarks into a specific charm hadron is given. The analysis includes data collected in photoproduction and deep inelastic scattering in $e^\pm p$ collisions and well as e^+e^- and pp data. Measurements in different production regimes agree within uncertainties, supporting the hypothesis that fragmentation proceeds independent of the specific production process. Averages of the fragmentation fractions are presented. The global average has significantly reduced uncertainties compared to individual measurements. In addition, the hypothesis that the sum of fragmentation fractions of all known weakly decaying charm hadrons is equal to unity is checked to hold within 3 standard deviations using the e^+e^- data. The relation $\gamma_{s1} > \gamma_s^* > \gamma_s$ indicates smaller charm-strange hadron production suppression for the heavier charm states in comparison to the ground ones.

The obtained results should be applied for the best precision of relevant measurements and theoretical predictions.

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