Combined analysis of charm-quark fragmentation-fraction measurements

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Introduction: fragmentation

- Every new-born free quark participate in fragmentation process, producing quarks for bounding.
- The process cannot be calculated or modeled accurately; the comparison of existing models to the data is essential.
- Understanding the outcome of fragmentation process is the most important part of the picture, especially for the heavier charm and beauty quarks.

Introduction: fragmentation of c-quark

This work is about the charm-quark **fragmentation fractions,** $f(c \to H_c)$, the probabilities that charm quark c will form a charm hadron H_c.
To study the fragmentation of c quark, one has to measure the production of such hadrons with c quark in different processes.
The fragmentation process is very fast and it is possible to study only the final stages, when the relatively stable hadrons are formed.

Introduction: studied hadrons

The fragmentation fractions of charm quark into the hadrons above are studied:

- long living D^0, D^+, D_s^+, Λ_c+, Ξ_c, Ω_c;
- short living D^{*0}, D^{*+}, D_s^{*+}, charm baryons;
- very short living excited states, e.g. D_1^0, D_2^{*0}, D_1^+, D_2^{*+}, D_{s1}^+.

As well as the following hypothesis:

- the probability of charm quark to forma one of the long living hadrons is unity;
- the probability of charm quark to form a given hadron is the instrinct property of charm quark and doesn't depend on the process produced the charm quark.

Measurements: selection criteria

Available set-ups: production in $p^{\pm}p^{\pm}$, $e^{+}e^{-}$, $p^{\pm}N$, $e^{\pm}p$, $e^{\pm}N$, NN, πN, KN collisions.
The following criteria were applied:

- $\sqrt{s} \gg 2m_c \approx 3\mathrm{GeV}$;
- measurements are obtained in the collisions of particle beams as it assures an absence of possible matter effects;
- sufficient precision;
- sufficient number of measured states;
- minimal model dependence of the results;
- the results should be published.

Measurements: selected sets

Five groups, obtained in:

- e^+e^- collisions at B-factories [1, 2, 3, 4, 5, 6, 7, 8];
- Z decays [9, 10, 11, 12, 13];
- $e^{\pm}p$ collisions in photoproduction(PHP) [14, 15];
- $e^{\pm}p$ collisions in deep inelastic scattering(DIS) [16, 17, 18];
- pp collisions [19].

Each group was considered separately and the results were compared. Finally, the all measurements were combined into a global procedure without an affiliation to specific group.

Measurements: corrections

For the coherent combination and the best precision, all of them were corrected to the up-to dated supplementary inputs:

- Decay branching ratios $\mathcal{B}$ of charm hadrons from PDG [20] and Refs. [25, 26, 24];
- The theoretical up-to-dated values of $\sigma(e^+e^- \to c\bar{c})$ and $\frac{\Gamma(Z\to c\bar{c})}{\Gamma(Z\to \mathrm{hadrons})}$; charm cross-sections were considered [28, 27].
- The contribution of Ξ^+ and Ω_c baryons with respect to the contribution of Λ_c^+.

All known correlations between measurements, supplementary and derived quantities were taken into account.

Measurements: combination procedure

The combination MINUIT-based fit with respect to observables of interest. For some particular cases additional constraints, described below, were used. The total charm cross-cestions and fragmentation fractions (and, in some cases their sum) were used as the fit parameters. Some quantities, used for the fragmentation modelling are presented as well:

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

$$\gamma_s = \frac{2f(c \to D_s^+)}{f(c \to D^+) + f(c \to D^0)}, \; \gamma_{s1} = \frac{2f(c \to D_{s1}^+)}{f(c \to D_1^0) + f(c \to D_1^+)},$$

and

$$P_V^d = \frac{f(c \to D^{*+}) + f(c \to D^{*0})}{f(c \to D^+) + f(c \to D^0)},$$

$$S = \sum_{H_c = D^0, D^+, D_s^+, \Lambda_c^+, \Xi_c, \Omega_c} f(c \to H_c).$$

Results: e^+e^- at B-factories

Combined $\sigma(e^+e^- \to H_c)$, $\sigma(e^+e^- \to H_c) \cdot \mathcal{B}$, and $\frac{\sigma(e^+e^- \to H_c)}{\sigma(e^+e^- \to \text{hadrons})} \cdot \mathcal{B}$ from BELLE, BaBar, ARGUS and CLEO.

	Fixed $\sigma(e^+e^- \to c\bar{c})$	Constrained S
$f(c \to D^{*+})$	0.2470 ± 0.0137	0.2525 ± 0.0155
$f(c \to D^{*0})$	0.2241 ± 0.0304	0.2291 ± 0.0316
$f(c \to D_s^{*+})$	0.0532 ± 0.0082	0.0544 ± 0.0085
$f(c \to D^{+})$	0.2639 ± 0.0139	0.2698 ± 0.0125
$f(c \to D^{0})$	0.5772 ± 0.0241	0.5901 ± 0.0140
$f(c \to D_s^{+})$	0.0691 ± 0.0045	0.0707 ± 0.0048
$f(c \to \Lambda_c^{+})$	0.0526 ± 0.0031	0.0611 ± 0.0060
χ^2	19.2	17.0
n_{dof}	21	20
S	0.9701 ± 0.0284	1.0000 ± 0.0005
$R_{u/d}$	0.9508 ± 0.0752	0.9508 ± 0.0752
P_V^d	0.5601 ± 0.0432	0.5601 ± 0.0431
γ_s	0.1644 ± 0.0121	0.1644 ± 0.0121

Results: e^+e^- at Z-factories

Combined $\frac{\Gamma(Z\to c\bar{c})}{\Gamma(Z\to\text{hadrons})}\cdot f(c\to H_c)\cdot\mathcal{B}$, $\frac{\Gamma(Z\to c\bar{c})}{\Gamma(Z\to\text{hadrons})}\cdot f(c\to H_c)$ and $f(c\to H_c)$ from OPAL, ALEPH and DELPHI.

	Fixed $\frac{\Gamma_{cc}}{\Gamma_{\text{hadrons}}}$	Constrained S
$f(c\to D^{*+})$	0.2369 ± 0.0064	0.2454 ± 0.0071
$f(c\to D_s^{*+})$	0.0545 ± 0.0144	0.0547 ± 0.0145
$f(c\to D^{+})$	0.2267 ± 0.0100	0.2429 ± 0.0102
$f(c\to D^{0})$	0.5470 ± 0.0215	0.5894 ± 0.0132
$f(c\to D_s^{+})$	0.0925 ± 0.0082	0.0996 ± 0.0083
$f(c\to \Lambda_c^{+})$	0.0555 ± 0.0065	0.0600 ± 0.0066
χ^2	6.7	7.8
n_{dof}	13	13
S	0.9292 ± 0.0261	1.0000 ± 0.0005
$R_{u/d}$	0.9987 ± 0.0627	1.0348 ± 0.0580
P_V^d	0.6119 ± 0.0185	0.6000 ± 0.0177
γ_s	0.2390 ± 0.0224	0.2394 ± 0.0223

Results: $e^{\pm}p$ in DIS

Combined $\sigma_{\text{restricted}}(e^{\pm}p \to H_c)$ from H1 and ZEUS.

	Constrained S
$f(c \to D^{*+})$	0.2261 ± 0.0179
$f(c \to D^{+})$	0.2115 ± 0.0201
$f(c \to D^{0})$	0.5975 ± 0.0343
$f(c \to D_s^{+})$	0.0903 ± 0.0125
$f(c \to \Lambda_c^{+})$	0.0887 ± 0.0307
χ^2	1.0
n_{dof}	3
S	1.0000 ± 0.0007
$R_{u/d}$	1.2191 ± 0.1316
P_V^d	0.6201 ± 0.0438
γ_s	0.2233 ± 0.0325

Results: $e^{\pm}p$ in PHP

Combined $\sigma_{\text{restricted}}(e^{\pm}p \to H_c)$ and $f(c \to H_c)$ from ZEUS.

	Constrained S
$f(c \to D^{*+})$	0.2335 ± 0.0081
$f(c \to D^{+})$	0.2384 ± 0.0092
$f(c \to D^{0})$	0.5963 ± 0.0127
$f(c \to D_s^{+})$	0.0898 ± 0.0066
$f(c \to \Lambda_c^{+})$	0.0665 ± 0.0105
χ^2	5.2
n_{dof}	4
S	1.0000 ± 0.0005
$R_{u/d}$	1.1054 ± 0.0532
P_V^d	0.5890 ± 0.0175
γ_s	0.2152 ± 0.0172

Results: pp at hadron colliders

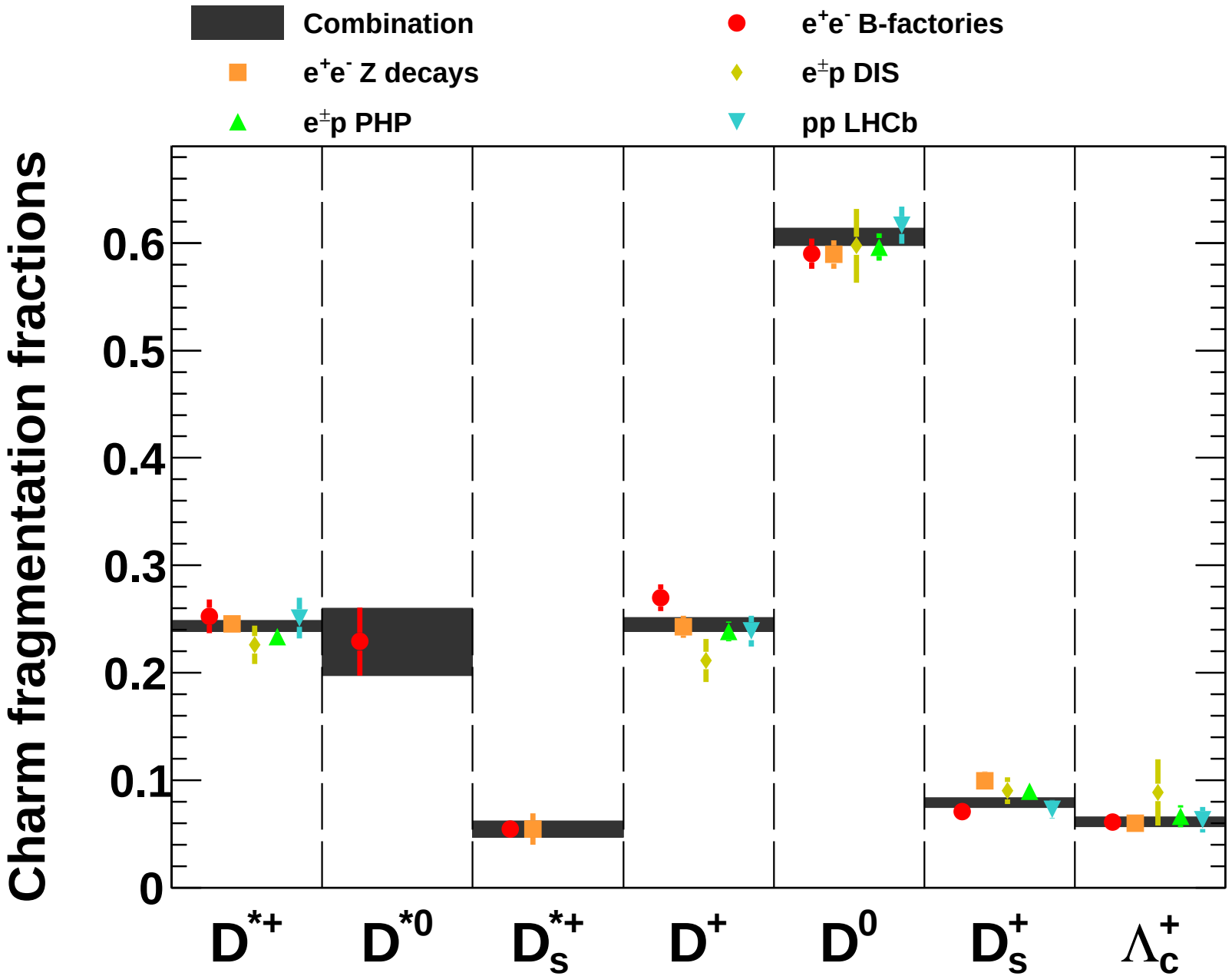
Combined $\sigma_{\text{restricted}}(pp \to H_c)$ from LHCb.

	Constrained S
$f(c \to D^{*+})$	0.2510 ± 0.0190
$f(c \to D^{+})$	0.2388 ± 0.0141
$f(c \to D^{0})$	0.6166 ± 0.0171
$f(c \to D_s^{+})$	0.0729 ± 0.0087
$f(c \to \Lambda_c^{+})$	0.0631 ± 0.0119
χ^2	0.0
n_{dof}	0
S	1.0000 ± 0.0005
$R_{u/d}$	1.0928 ± 0.0984
P_V^d	0.6140 ± 0.0324
γ_s	0.1705 ± 0.0219

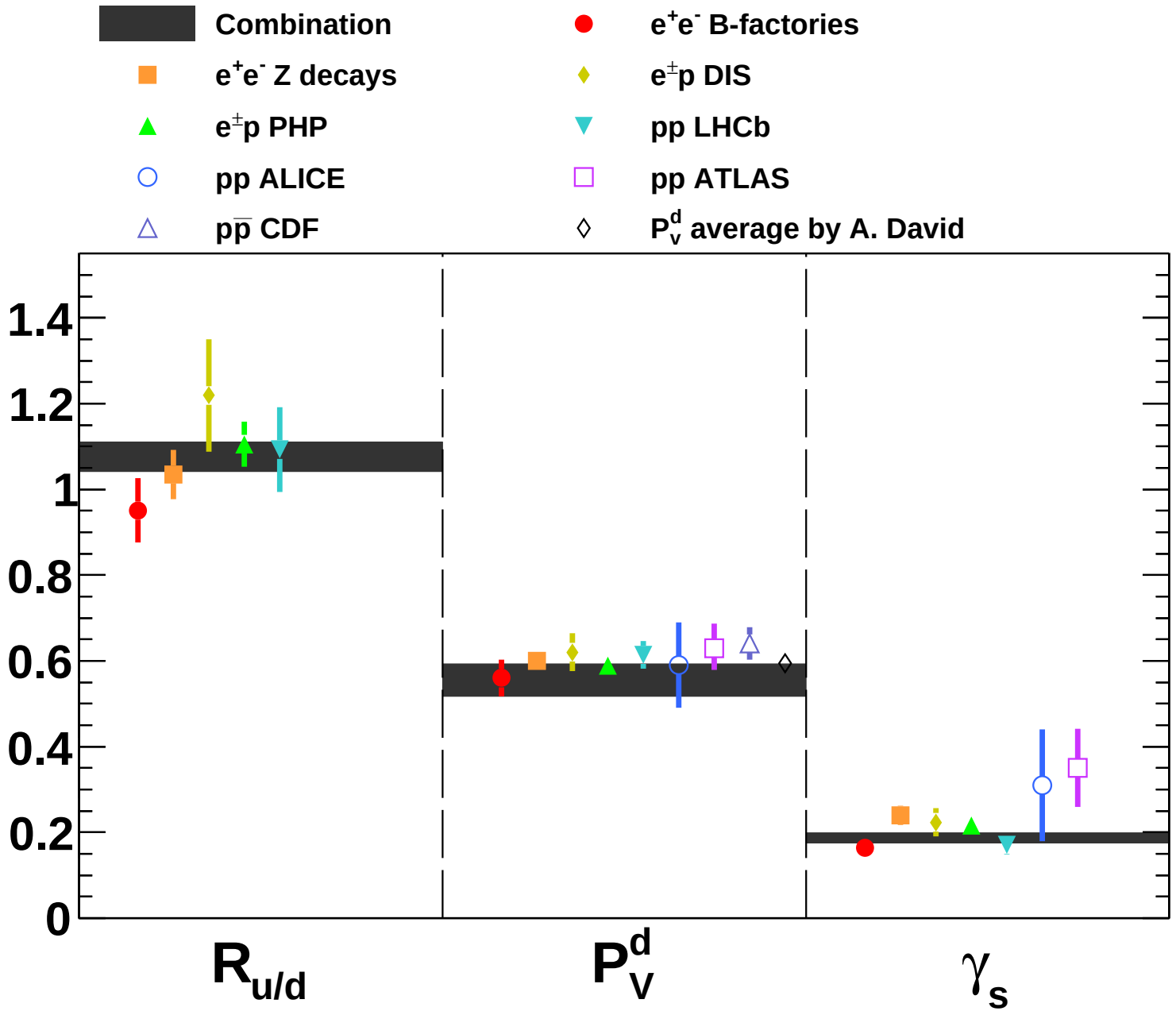
Results: global combination

	Constrained S	Constrained S, fixed $\sigma(e^+e^- \to c\bar{c})$, $\frac{\Gamma_{cc}}{\Gamma_{\text{hadrons}}}$.
$f(c \to D^{*+})$	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_V^d	0.5551 ± 0.0372	0.5455 ± 0.0357
γ_s	0.1866 ± 0.0120	0.1872 ± 0.0123

Results: global combination, $f(c)$



Results: global combination, derived



Excited states

In addition, the results for the excited states were combined in terms of simple avaraging. Those included results from ALEPH[64], OPAL [63] and ZEUS[32, 62].

	Average (10^{-2})
$f(c \to D_1^+)$	$4.60^{+2.69}_{-1.82}$
$f(c \to D_2^{*+})$	$3.20^{+0.94}_{-0.82}$
$f(c \to D_1^0)$	2.97 ± 0.38
$f(c \to D_2^{*0})$	3.94 ± 0.68
$f(c \to D_{s1}^+)$	1.09 ± 0.14
γ_{s1}	$28.7^{+7.9}_{-10.9}$

Conclusions

- A summary of measurements of the fragmentation of charm quarks into a specific charm hadron is given.
- 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.
- See also `arXiv:1509.01061`.

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