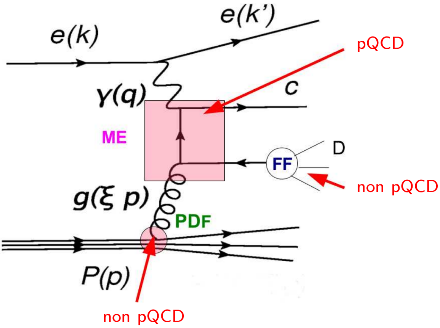
Combined analysis of charm-quark fragmentation-fraction measurements

arXiv:1509.01061, submitted to EPJ C

Mykhailo Lisovyi[a], Andrii Verbytskyi[b], Oleksandr Zenaiev[c]

[a] Physikalisches Institut der Universität Heidelberg
[b] Max-Planck-Institut für Physik
[c] DESY

DIS2016, Hamburg, 12.04.2016



$\sigma = PDF \otimes ME \otimes FF$

- Fragmentation functions and fragmentation fractions (FF) cannot be calculated perturbatively $\Rightarrow$ have to be extracted from data.
- Are FF universal?
- Do FF sum up to 1?

Input data

Criteria:

- $\sqrt{s} \gg 2m_c \approx 3$ GeV
- minimal model dependence, e.g. particle beams (absence of matter effects)
- sufficient precision

Input data sets:

- e^+e^-:
  - B-factories (CLEO, ARGUS, BABAR, BELLE)
  - LEP (OPAL, ALEPH, DELPHI)
- $e^\pm p$:
  - DIS (ZEUS, H1)
  - PHP (ZEUS)
- pp: LHCb, ALICE, ATLAS

Measurements are updated to latest branching ratios from PDG 2014 + 2015 update

Calculation of fragmentation fractions

Two considered FF calculation:

1. $f(c \to H) = \sigma(H)/\sigma(c)$
   - Need to know total charm x-section $\sigma(c)$: e^+e^- only
   - Can check $S = \sum_{w.d.} f(c \to H) = 1$
2. $f(c \to H) = \sigma(H)/\sum_{w.d.} \sigma(H)$
   - Need to measure all weakly decaying (w.d.) final states
   - More model independent (the only assumption $S = \sum_{w.d.} f(c \to H) = 1$)

Weakly decaying final states: D^0, D^+, D_s^+, Λ_c^+, Ξ_c^+, Ξ_c^0 and Ω_c^0

Final states Ξ_c^+, Ξ_c^0 and Ω_c^0 are poorly studied $\Rightarrow$ take the ratios from strange:

$$\sigma(\Xi_c^+) + \sigma(\Xi_c^0) + \sigma(\Omega_c^0) = \lambda\sigma(\Lambda_c^+)$$

$$\sum_{w.d.} \sigma(H) = \sigma(D^0) + \sigma(D^+) + \sigma(D_s^+) + \sigma(\Lambda_c^+) + \lambda\sigma(\Lambda_c^+)$$

$$\lambda = 2\frac{f(s\to\Xi^-)}{f(s\to\Lambda^0)} + \frac{f(s\to\Omega^-)}{f(s\to\Lambda^0)} = 0.136 \pm 0.006 \text{ (PDG)} \Rightarrow \Xi_c^+, \Xi_c^0, \Omega_c^0 < 1\%$$

In addition FF of some excited states have been combined

Combination procedure

- χ^2 minimisation with MINUIT
- Free parameters: FF, charm x-sections, kinematic phase space factors
- Correlation of branching fractions uncertainties are taken into account
- Experimental correlation uncertainties are taken into account if available
- Combination is performed separately for B-factories, LEP, DIS, PHP and pp, as well as one global combination
- Additionaly calculated:

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

$$\gamma_s = \frac{2f(c \to c\bar{s})}{f(c \to c\bar{u}/\bar{d})}(J=0) \approx \frac{2f(c \to D_s^+)}{f(c \to D^+) + f(c \to D^0)}$$

$$\gamma_s^* = \frac{2f(c \to c\bar{s})}{f(c \to c\bar{u}/\bar{d})}(J=1) \approx \frac{2f(c \to D_s^{*+})}{f(c \to D^{*+}) + f(c \to D^{*0})}$$

$$P_V^d = \frac{f(c \to c\bar{u}/\bar{d})(J=1)}{f(c \to c\bar{u}/\bar{d})(J=0)} \approx \frac{f(c \to D^{*+}) + f(c \to D^{*0})}{f(c \to D^+) + f(c \to D^0)}$$

Results: e^+e^-

B-factories

	Fixed $\sigma(e^+e^- \to c)$	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
$n_{\rm dof}$	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
γ_s^*	0.2257 ± 0.0385	0.2257 ± 0.0385

- Good consistency
- $S \approx 1$ checked

LEP

	Fixed $\frac{\Gamma_{c\bar{c}}}{\Gamma_{\rm had}}$	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
$n_{\rm dof}$	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

- Good consistency
- $S \approx 1$ within 3 σ

Results: $e^{\pm}p$, pp

DIS

	Constrained S
$f(c \to D^{*+})$	0.2372 ± 0.0173
$f(c \to D^{+})$	0.2170 ± 0.0203
$f(c \to D^{0})$	0.6272 ± 0.0287
$f(c \to D_s^{+})$	0.0945 ± 0.0124
$f(c \to \Lambda_c^{+})$	0.0540 ± 0.0195
χ^2	1.7
n_{dof}	3
S	1.0000 ± 0.0004
$R_{u/d}$	1.2361 ± 0.1331
P_V^d	0.6282 ± 0.0440
γ_s	0.2240 ± 0.0320

PHP

	Constrained S
$f(c \to D^{*+})$	0.2345 ± 0.0081
$f(c \to D^{+})$	0.2341 ± 0.0093
$f(c \to D^{0})$	0.5991 ± 0.0126
$f(c \to D_s^{+})$	0.0901 ± 0.0062
$f(c \to \Lambda_c^{+})$	0.0675 ± 0.0106
χ^2	5.2
n_{dof}	4
S	1.0000 ± 0.0005
$R_{u/d}$	1.1209 ± 0.0545
P_V^d	0.5970 ± 0.0181
γ_s	0.2164 ± 0.0162

pp

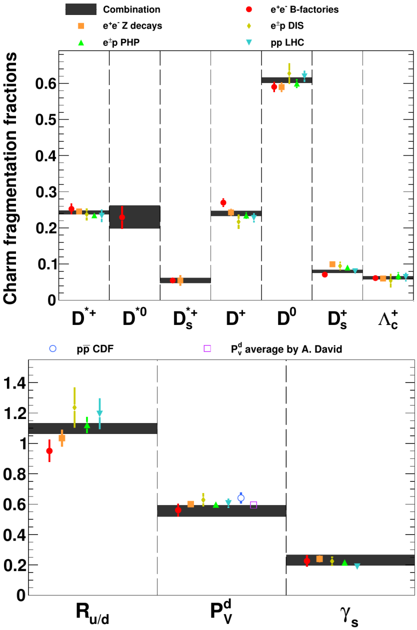
	Constrained S
$f(c \to D^{*+})$	0.2336 ± 0.0177
$f(c \to D^{+})$	0.2277 ± 0.0129
$f(c \to D^{0})$	0.6192 ± 0.0159
$f(c \to D_s^{+})$	0.0803 ± 0.0080
$f(c \to \Lambda_c^{+})$	0.0641 ± 0.0122
χ^2	7.0
n_{dof}	7
S	1.0000 ± 0.0005
$R_{u/d}$	1.1948 ± 0.1020
P_V^d	0.6055 ± 0.0307
γ_s	0.1896 ± 0.0204

- Only constrained S fit possible
- Good consistency

B-factories+LEP+DIS+PHP+pp

	Constrained S	Constrained S, fixed $\sigma(e^+e^- \to c)$, $\frac{\Gamma_{cc}}{\Gamma_{\rm had}}$.
$f(c \to D^{*+})$	0.2430 ± 0.0049	0.2386 ± 0.0046
$f(c \to D^{*0})$	0.2305 ± 0.0315	0.2251 ± 0.0299
$f(c \to D_s^{*+})$	0.0547 ± 0.0074	0.0536 ± 0.0072
$f(c \to D^+)$	0.2404 ± 0.0067	0.2439 ± 0.0067
$f(c \to D^0)$	0.6089 ± 0.0076	0.6143 ± 0.0073
$f(c \to D_s^+)$	0.0799 ± 0.0040	0.0794 ± 0.0040
$f(c \to \Lambda_c^+)$	0.0623 ± 0.0041	0.0548 ± 0.0026
χ^2	65.7	87.1
$n_{\rm dof}$	64	67
S	1.0000 ± 0.0005	1.0000 ± 0.0004
$R_{u/d}$	1.0976 ± 0.0354	1.1168 ± 0.0354
P_V^d	0.5575 ± 0.0375	0.5402 ± 0.0355
γ_s	0.1881 ± 0.0103	0.1851 ± 0.0101
γ_s^*	0.2311 ± 0.0346	0.2313 ± 0.0346

- Perfect consistency for constrained S
- Tension for fixed e^+e^- charm x-sections (consequence of $S = 0.929 \pm 0.026$ at LEP)



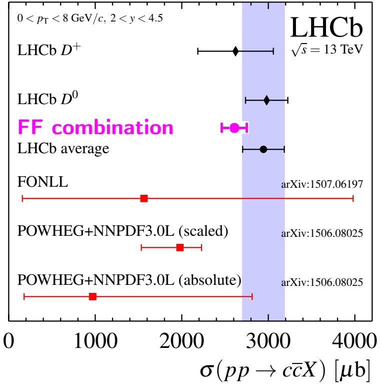
Correlation matrix for FF

	D^{*+}	D^{*0}	D_s^{*+}	D^+	D^0	D_s^+	Λ_c^+
D^{*+}	1.00	-0.02	-0.02	-0.08	0.19	-0.07	-0.12
D^{*0}	-0.02	1.00	0.02	-0.07	0.07	0.01	-0.01
D_s^{*+}	-0.02	0.02	1.00	-0.05	-0.07	0.23	-0.01
D^+	-0.08	-0.07	-0.05	1.00	-0.66	-0.19	-0.19
D^0	0.19	0.07	-0.07	-0.66	1.00	-0.32	-0.41
D_s^+	-0.07	0.01	0.23	-0.19	-0.32	1.00	-0.07
Λ_c^+	-0.12	-0.01	-0.01	-0.19	-0.41	-0.07	1.00

Fitted charm x-sections in pp

$\sqrt{s}$, TeV	p_T range, GeV	y or η range	Fit result $\sigma(pp \to c)$, μb	Original $\sigma(pp \to c)$, μb
7	$[0, 8]$	$y \in [2, 4.5]$	2675 ± 202	2838 ± 268 [19]
13	$[1, 8]$	$y \in [2, 4.5]$	4174 ± 338	4300 ± 356 [20]
13	$[0, 8]$	$y \in [2, 4.5]$	5269 ± 292	5880 ± 482 [20]
2.76	$[2, 12]$	$\|y\| < 0.5$	229 ± 67	
7	$[2, 12]$	$\|y\| < 0.5$	434 ± 84	
7	$[3.5, 20]$	$\|\eta\| < 2.1$	1399 ± 141	

[JHEP 1603 (2016) 159]



Improved charm x-sections ratios

$\boldsymbol{R_{13/7} = 1.97 \pm 0.18}$ differs by 2.7σ from theory prediction

$\boldsymbol{R_{13/7}(\text{th}) = 1.39^{+0.12}_{-0.29}}$ [arXiv:1506.08025] (based on PDF fits with 7 TeV data)

Excited states

	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}	$28.7^{+8.0}_{-10.9}$

- ZEUS, OPAL and ALEPH data have been used
- The strangeness-suppression factor for $L = 1, J = 1^+$ charm mesons is calculated neglecting $D(2430)^0$ contribution and assuming D_1^+ is 1^+ state:

$$\gamma_{s1} \approx \frac{2f(c \to D_{s1}^+)}{f(c \to D_1^0) + f(c \to D_1^+)}.$$

- First combinarion of FF for excited charm hadrons

Summary

- 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 of fragmentation universality
- Hypothesis that the sum of known weakly decaying charm hadrons FF is equal to 1 is checked to hold within 3 σ using the e^+e^- data
- Averages have significantly reduced uncertainties compared to individual measurements
- The application of the obtained values can significantly reduce uncertainties in future analyses and already published results

Acknowledgements

- Thanks to Erich Lohrmann for his major contribution to the development of the paper
- Thanks to Uri Karshon and Stefan Kluth for useful discussions and help in the work with the bibliography
- Thanks to Alexander Glazov and Ian Brock for the critical reading of the manuscript and useful suggestions on text improvement

BACKUP

BACKUP. Restricted phase space treatment (1)

The full x-section of a charm hadron, $\sigma(H)_{\in v}$ can be split into x-section of direct production $\sigma(H)_{\textbf{dir},\in v}$ and the contribution from the decays of heavier charm states H^*, $\sigma(H)_{\textbf{decays},\in v}$:

$$\sigma(H)_{\in v} = \sigma(H)_{\textbf{dir},\in v} + \sigma(H)_{\textbf{decays},\in v} = \sigma(H)_{\textbf{dir},\in v} + \sum_{all\ H^*} \sigma(H^*)\mathcal{B}(H^* \to H)k_{H^*\to H},$$

where $k_{H^*\to H} < 1$ is a fraction of $H^* \to H$ decays with H in v.
With the assumptions above, we have the equations:

$$\begin{cases} \sigma(D^+)_{\in v} & = & \sigma(D^+)_{\textbf{dir},\in v} + k\sigma(D^{*+})_{\textbf{dir}}\mathcal{B}(D^{*+} \to D^+) \\ \sigma(D^0)_{\in v} & = & \sigma(D^0)_{\textbf{dir},D^0\in v} + k\sigma(D^{*0})_{\textbf{dir}}\mathcal{B}(D^{*0} \to D^0) \\ & & +k\sigma(D^{*+})_{\textbf{dir}}\mathcal{B}(D^{*+} \to D^0) \\ \sigma(D_s^+)_{\in v} & = & \sigma(D_s^+)_{\textbf{dir},\in v} \\ \sigma(\Lambda_c^+)_{\in v} & = & \sigma(\Lambda_c^+)_{\textbf{dir},\in v} \\ \sigma(D^{*+})_{\in v} & = & \sigma(D^{*+})_{\textbf{dir},\in v} \\ \sigma(D^{*0})_{\in v} & = & \sigma(D^{*0})_{\textbf{dir},\in v} \end{cases}$$

Assuming $\sigma(H)_{\textbf{dir},\in v} = \sigma(c)_{\in v} f(c \to H)_{\textbf{dir}}$ and introducing $\kappa = k\sigma(c)/\sigma(c)_{\in v}$ we have:

$$\begin{cases} \sigma(D^+)_{\in v} & = & \sigma(c)_{\in v}(f(c \to D^+)_{\textbf{dir}} \\ & & +\kappa f(c \to D^{*+})_{\textbf{dir}}\mathcal{B}(D^{*+} \to D^+)) \\ \sigma(D^0)_{\in v} & = & \sigma(c)_{\in v}(f(c \to D^0)_{\textbf{dir}} \\ & & +\kappa f(c \to D^{*0})_{\textbf{dir}}\mathcal{B}(D^{*0} \to D^0) \\ & & +\kappa f(c \to D^{*+})_{\textbf{dir}}\mathcal{B}(D^{*+} \to D^0)) \\ \sigma(D_s^+)_{\in v} & = & \sigma(c)_{\in v} f(c \to D_s^+)_{\textbf{dir}} \\ \sigma(\Lambda_c^+)_{\in v} & = & \sigma(c)_{\in v} f(c \to \Lambda_c^+)_{\textbf{dir}} \\ \sigma(D^{*+})_{\in v} & = & \sigma(c)_{\in v} f(c \to D^{*+})_{\textbf{dir}} \\ \sigma(D^{*0})_{\in v} & = & \sigma(c)_{\in v} f(c \to D^{*0})_{\textbf{dir}}. \end{cases}$$

BACKUP. Restricted phase space treatment (2)

In the full kinematical space:

$$\begin{cases} f(c \to D^+) & = & f(c \to D^+)_{\textsf{dir}} \\ & & +f(c \to D^{*+})_{\textsf{dir}}\mathcal{B}(D^{*+} \to D^+) \\ f(c \to D^0) & = & f(c \to D^0)_{\textsf{dir}} \\ & & +f(c \to D^{*0})_{\textsf{dir}}\mathcal{B}(D^{*0} \to D^0) \\ & & +f(c \to D^{*+})_{\textsf{dir}}\mathcal{B}(D^{*+} \to D^0) \\ f(c \to D_s^+) & = & f(c \to D_s^+)_{\textsf{dir}} \\ f(c \to \Lambda_c^+) & = & f(c \to \Lambda_c^+)_{\textsf{dir}} \\ f(c \to D^{*+}) & = & f(c \to D^{*+})_{\textsf{dir}} \\ f(c \to D^{*0}) & = & f(c \to D^{*0})_{\textsf{dir}}. \end{cases}$$

In general, to solve the system the measurements of D^{*0} production are needed. However, these can be avoided with an assumption of isospin invariance:

$$\frac{f(c \to D^+)_{\textsf{dir}}}{f(c \to D^0)_{\textsf{dir}}} = \frac{f(c \to D^{*+})_{\textsf{dir}}}{f(c \to D^{*0})_{\textsf{dir}}}.$$

The last two systems are the working equations for the calculation of the charm fragmentation fractions from the cross-section measurements in the restricted phase space.

BACKUP. Predictions for charm production at B-factories (1)

The total cross-section of quark q production in e^+e^- collisions at energies $2M(q) \ll \sqrt{s} \ll M(Z)$ can be given as

$$\sigma(e^+e^- \to q) = 2\sigma(e^+e^- \to l^+l^-) \sum_{\text{colours}} v_q^2 r_q, \tag{1}$$

where v_q is the vector electromagnetic coupling of the quark q (i.e. charge), $r_q(s)$ are the correction coefficients with higher order QCD corrections and

$$\sigma(e^+e^- \to l^+l^-) = 4\alpha^2(s)\pi/3s \tag{2}$$

is the total cross-section of massless charged lepton pair production. In this work, the calculations of the $r_q(s)$ were done according to Ref. [Chetyrkin 2000] at the reference energy of $\sqrt{s} = 10.5$ GeV and assuming the c quark is the heavy one. The constants used for the calculations in Eq.1 and Eq.2 are the strong coupling $\alpha_s(\sqrt{s} = 10.5 \text{ GeV}) = 0.172$ [Chetyrkin 2000], the $\overline{\text{MS}}$ charm-quark mass $m_c(\sqrt{s} = 10.5\text{GeV}) = 0.74$ GeV [Chetyrkin 2000] and the electromagnetic coupling $\alpha(\sqrt{s} = 10.5 \text{ GeV}) = 1/132.0$ (calculated according to [Altarelli 1989, Burkhardt 1989] as implemented in [Harris 1997]). The uncertainties on the given values are negligible. The result of the calculations is $\sigma(e^+e^- \to c, \sqrt{s} = 10.5$ GeV$) = 2399.23$ nb.

BACKUP. Predictions for charm production at B-factories (2)

To verify the calculations, Eq.1 can be rewritten as

$$\sigma(e^+e^- \to c) = 2\sigma(e^+e^- \to l^+l^-)R_c R_{\textbf{had}},$$

where the quantities

$$R_{\textbf{had}} = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to l^+l^-)} = \sum_{u,d,s,c} \sum_{\textbf{colours}} v_q^2 r_q = 3.5239$$

and

$$R_c = \frac{\sigma(e^+e^- \to c\bar{c})}{\sigma(e^+e^- \to \text{hadrons})} = \frac{\sum\limits_{\text{colours}} v_c^2 r_c}{\sum\limits_{u,d,s,c} \sum\limits_{\text{colours}} v_q^2 r_q} = 0.4012$$

can be compared with the existing measurements and predictions. It was found that $R_{\textbf{had}}$ is in agreement with the direct measurement from CLEO below $\sqrt{s} = 10.56$ GeV $R_{\textbf{had,CLEO}} = 3.591 \pm 0.003 \pm 0.067 \pm 0.049$ [Besson 2007] and R_c is in agreement with the CLEO Monte-Carlo based estimation $R_{\textbf{c,CLEO}} = 0.37 \pm 0.05$ [Bortoletto 1988]. For all the theoretically calculated values, the uncertainties of calculations are negligible.

BACKUP. Predictions for charm production at LEP

The theoretically calculated value that is used,
$\frac{\Gamma(Z\to c\bar{c})}{\Gamma(Z\to \text{hadrons})} = 0.17223 \pm 0.00001$ [Freitas 2014], is in agreement with the experimental world average 0.1721 ± 0.003 [PDG].