Combined analysis of charm-quark fragmentation-fraction measurements

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

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

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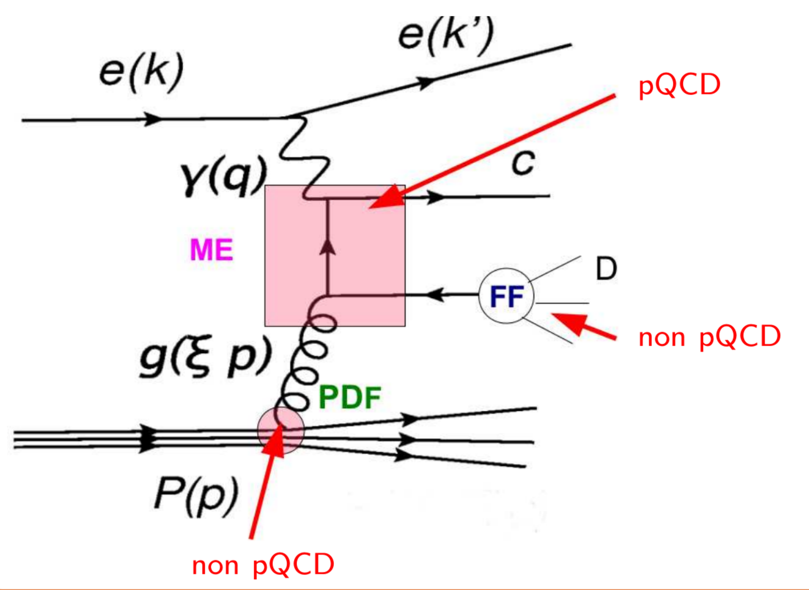


$$\sigma = PDF \otimes ME \otimes FF$$

- **Fragmentation** process cannot be described perturbatively $\Rightarrow$ comparison to experimental data is essential.
- An important parameter of the fragmentation is a probability to form a given hadron in the end of the process, **fragmentation fraction (FF)**:

$$f(c \to H) = \sigma(H)/\sigma(c)$$

- *Are FF universal, i.e. independent of the hard production mechanism?*
- *Do FF of all known weakly decaying (w.d.) charm hadrons sum up to 1?*
- *Provide combined FF with best precision*

Input data

Input data criteria:

- $\sqrt{s} \gg 2m_c \approx 3$GeV
- minimal model dependence (partice beams)
- sufficient data precision
- sufficient number of measured w.d. states

Selected data form following groups of measurements:

★ e^+e^-, B-factories [BELLE, BaBar, ARGUS, CLEO]

★ e^+e^-, Z decays [OPAL, ALEPH, DELPHI]

★ $e^{\pm}p$, DIS [H1, ZEUS]

★ $e^{\pm}p$, PHP [ZEUS]

★ pp [LHCb, ALICE, ATLAS] $\Leftarrow$ **LHC Run I & and Run II data included!**

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
- Additionaly calculated:

$$R_{u/d} = \frac{f(c\to c\bar{u})}{f(c\to c\bar{d})} \approx \frac{f(c\to D^0) - f(c\to D^{*+})\mathcal{B}_{D^{*+}\to D^0}}{f(c\to D^+) + f(c\to D^{*+})\mathcal{B}_{D^{*+}\to D^0}} \qquad \gamma_s = \frac{2f(c\to c\bar{s})}{f(c\to c\bar{u}/\bar{d})}(J=0) \approx \frac{2f(c\to D_s^+)}{f(c\to D^+) + f(c\to D^0)}$$

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

FF extraction

1. $f(c \to H) = \sigma(H)/\sigma(c)$
   - Need to know $\sigma(c)$ (e^+e^- only), can check $S = \sum_{w.d.} f(c \to H) = 1$
2. $f(c \to H) = \sigma(H)/\sum_{w.d.}\sigma(H)$
   - More model independent, but needs all weakly decaying states measured

e^+e^-, B-factories

	Fix $\sigma(e^+e^-\to c\bar{c})$	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
$\chi^2/n_{\rm dof}$	19.2/21	17.0/20
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

e^+e^-, Z decays

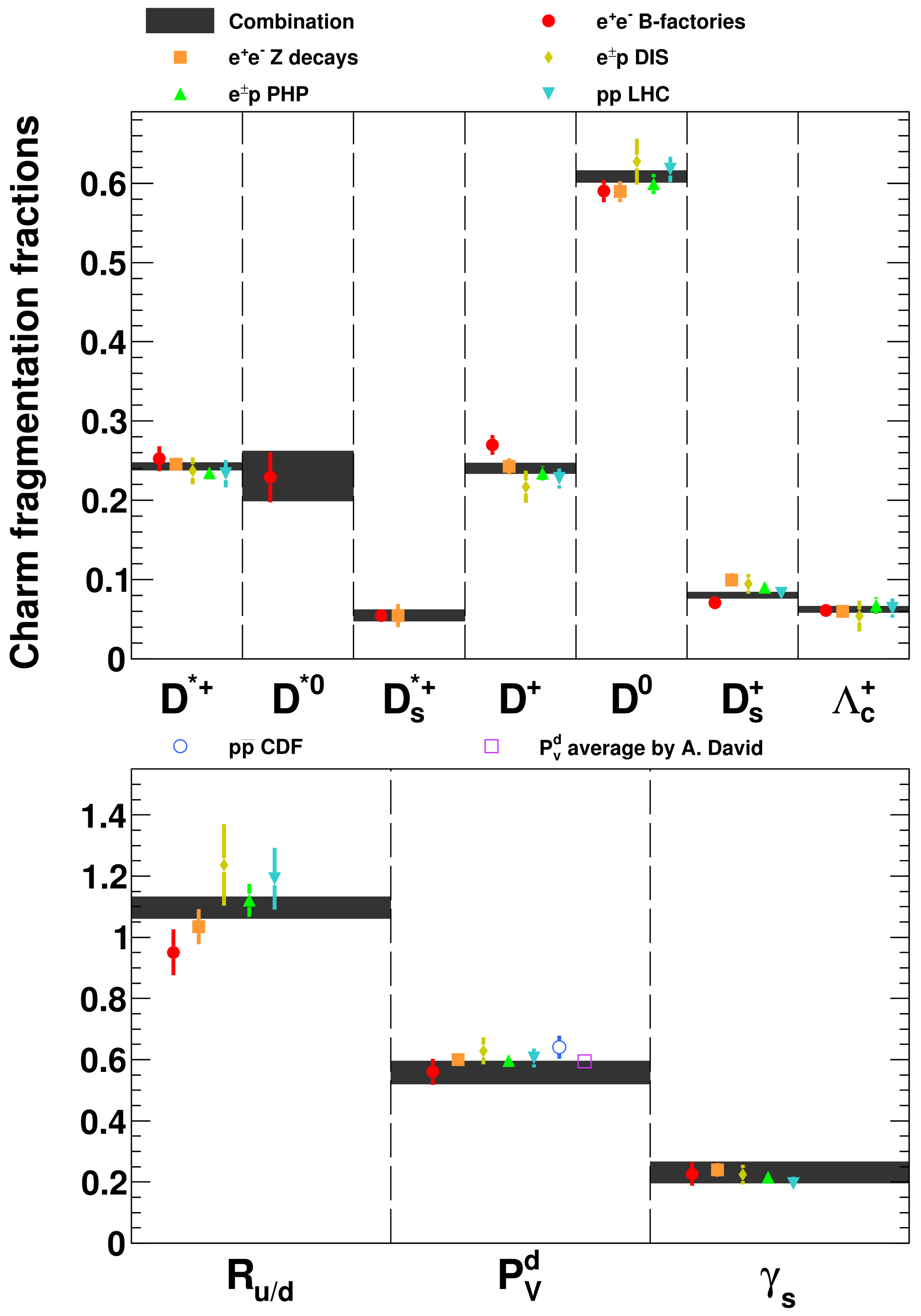
	Fix $\frac{\Gamma_{c\bar{c}}}{\Gamma_{\rm hadrons}}$	Constrained S
$f(c\to D^{*+})$	0.2369±0.0064	0.2454±0.0071
$f(c\to D_s^{*+})$	0.0545±0.0144	0.0547±0.0145
$f(c\to D^+)$	0.2267±0.0100	0.2429±0.0102
$f(c\to D^0)$	0.5470±0.0215	0.5894±0.0132
$f(c\to D_s^+)$	0.0925±0.0082	0.0996±0.0083
$f(c\to \Lambda_c^+)$	0.0555±0.0065	0.0600±0.0066
$\chi^2/n_{\rm dof}$	6.7/13	7.8/13
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

$$S = \sum_{w.d.} f(c \to H) \approx 1 \text{ within } 3\ \sigma$$

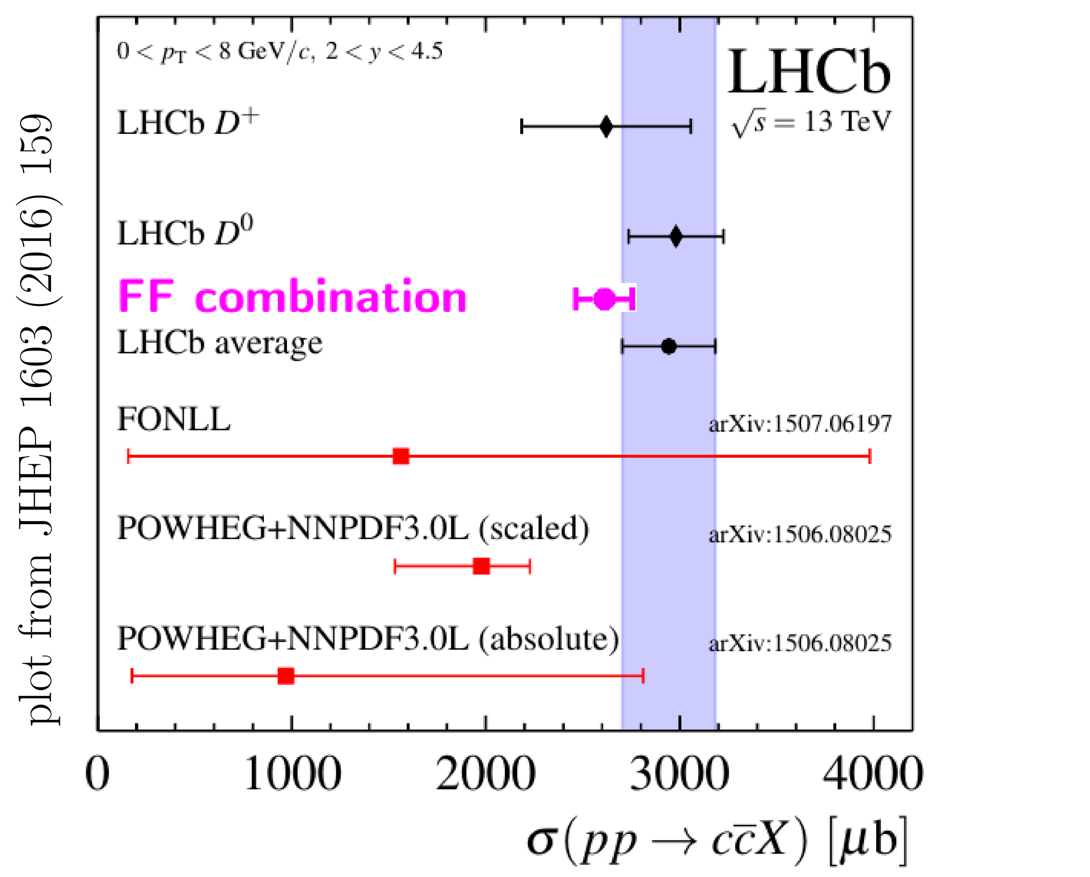
Global combination

	Constrained S	+ fix $\sigma(ee\to c\bar{c})$, $\frac{\Gamma_{c\bar{c}}}{\Gamma_{\rm hadrons}}$
$f(c\to D^{*+})$	**0.2429±0.0049**	0.2386±0.0046
$f(c\to D^{*0})$	**0.2306±0.0315**	0.2250±0.0299
$f(c\to D_s^{*+})$	**0.0548±0.0074**	0.0537±0.0072
$f(c\to D^+)$	**0.2404±0.0067**	0.2439±0.0067
$f(c\to D^0)$	**0.6086±0.0076**	0.6141±0.0073
$f(c\to D_s^+)$	**0.0802±0.0040**	0.0797±0.0040
$f(c\to \Lambda_c^+)$	**0.0623±0.0041**	0.0549±0.0026
$\chi^2/n_{\rm dof}$	65.6/64	87.1/67
$R_{u/d}$	1.0971±0.0354	1.1164±0.0354
P_V^d	0.5578±0.0375	0.5403±0.0355
γ_s	0.1890±0.0103	0.1859±0.0101
γ_s^*	0.2314±0.0347	0.2316±0.0346
$f(c\to D_1^+)$	$0.0460^{+0.0269}_{-0.0182}$	
$f(c\to D_2^{*+})$	$0.0320^{+0.0094}_{-0.0082}$	
$f(c\to D_1^0)$	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}	$0.287^{+0.079}_{-0.109}$	

- **Best precise reliable up-to-date charm FF: use them in your analysis!**
- Precision driven mainly by e^+e^- data
- LHC data are not dominating at the moment
- Consistent with recent LHCb data at 5 TeV, including these data is straightforward and improves precision of the combined results [work in progress]



$\sqrt{s}$ TeV,	p_T, GeV	y or η	Fit $\sigma(pp\to c)$, μb	Original σ
7	[0, 8]	$y \in [2, 4.5]$	2689±203	2838±268
13	[1, 8]	$y \in [2, 4.5]$	4174±339	4300±356
13	[0, 8]	$y \in [2, 4.5]$	5269±293	5880±482
2.76	[2, 12]	$\lvert y\rvert < 0.5$	229±67	
7	[2, 12]	$\lvert y\rvert < 0.5$	434±84	
7	[3.5, 20]	$\lvert\eta\rvert < 2.1$	1400±141	



- Physical implications of reduced uncertainties are in improved charm cross sections, their ratios etc.
- E.g. charm cross-section ratio extracted from LHCb data $R_{13/7} = 1.97 \pm 0.18$ vs theoretical prediction $R_{13/7}(\text{th}) = 1.39^{+0.12}_{-0.29}$ [arXiv:1506.08025] (based on PDF fits with 7 TeV data)

Conclusions

- 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 new analyses and published results**

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