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Search for $B_c \to DD$ decays and measurement of $A_{CP}(B^+ \to D^+_{(s)}\overline{D}^0)$ with the LHCb detector

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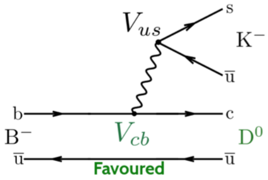
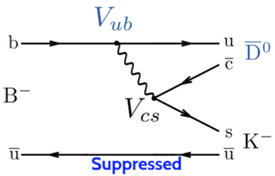
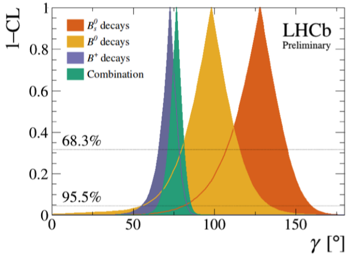
CKM angle γ

- $\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ is the least well known angle of the Unitarity triangle
- The only CP violating parameter that can be measured through tree decays
  - Important Standard Model **benchmark**
  - Compare tree and loop level determinations to test for **new physics** - currently consistent but with large uncertainties
- Theoretically pristine $|\delta_\gamma \leq \mathcal{O}(10^{-7})|$ [JHEP 01 (2014) 051]
- Access through the interference of $b \to c$ and $b \to u$ decays to the same final state
- World average of $(73.4^{+4.3}_{-5.0})^\circ$ [HFLAV] dominated by the combination of LHCb measurements $(76.8^{+5.1}_{-5.7})^\circ$ made with B^+, B^0 and B^0_s [LHCb-CONF-2017-004]



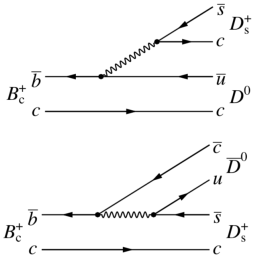


interference $\sim$ 10%

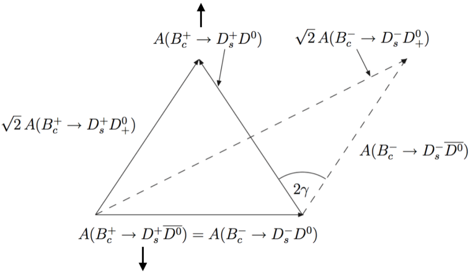


Motivation

- **CP violation not yet observed in $\mathbf{B_c^+}$ mesons**
- $B_c^+ \to D_{(s)}^{(*)+} D^{(*)}$ decays, where D is an admixture of D^0 or $\overline{D}^0$, have been proposed to measure γ [Phys. Rev. D 62, 057503, Phys. Rev. D 65, 034016]
- Advantage over traditional $B \to DK$ since the sides of the amplitude triangles are of comparable length, interference $\sim 100\%$
- Disadvantage is small B_c^+ production cross section, lifetime, branching fractions, final state



V_{ub}, not colour suppressed



V_{cb}, colour suppressed

$$\frac{f_c}{f_u} \times \mathcal{B}(B_c^+ \to D_{(s)}^+ D) = \mathcal{B}(B^+ \to D_{(s)}^+ \overline{D}^0) \times \frac{N(B_c^+)}{N(B^+)} \times \frac{\varepsilon(B^+)}{\varepsilon(B_c^+)}$$

- From 2011/12 data
- From MC

$D_s^+ \to K^+ K^- \pi^+$, $D^+ \to K^- \pi^+ \pi^+$
$D^0 \to K^- \pi^+, K^- \pi^+ \pi^- \pi^+$

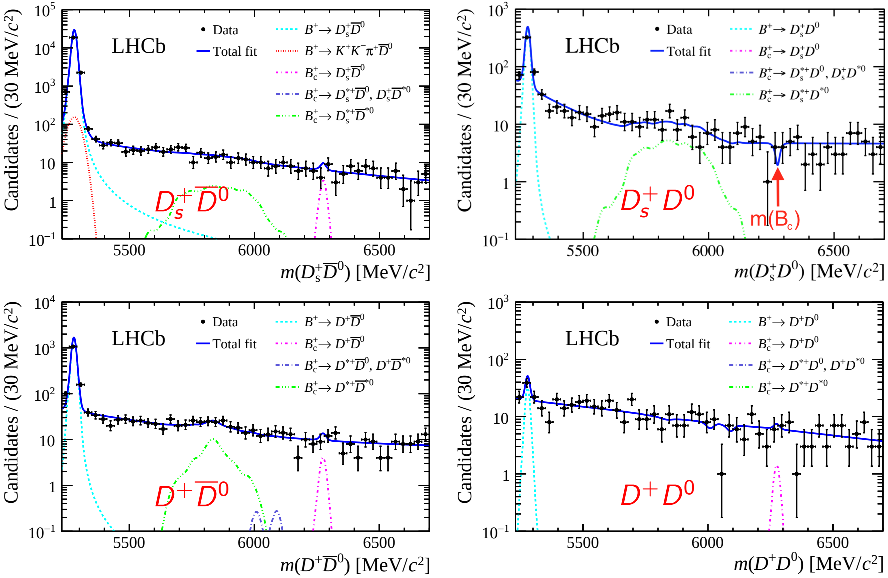
- Combining an LHCb measurement with theory predictions, predict f_c/f_u in the range $0.24\% - 1.2\%$ [PRL 114, 132001 (2015), PRD 68, 094020 (2003), PRD 89, 034008 (2014)]
- $\mathcal{B}(B_c^+)$ theory predictions

Channel	Prediction for the branching fraction $[10^{-6}]$			
$B_c^+ \to D_s^+ \overline{D}^0$	2.3 ± 0.5	4.8	1.7	2.1
$B_c^+ \to D_s^+ D^0$	3.0 ± 0.5	6.6	2.5	7.4
$B_c^+ \to D^+ \overline{D}^0$	32 ± 7	53	32	33
$B_c^+ \to D^+ D^0$	0.10 ± 0.02	0.32	0.11	0.32

[Phys. Rev. D 86, 074019, arXiv:hep-ph/0211021, Phys.Lett.B555:189-196,2003, Phys. Rev. D 73, 054024]

- An MVA is used to reject combinatorial background: 85% signal efficiency, 99% background rejection
- The fit model is comprised of six components
  - $B^+ \to D^+_{(s)} D$ model
  - $B_c^+ \to D^+_{(s)} D$ model
  - $B_c^+ \to D^{*+}_{(s)} D, D^+_{(s)} D^*$ model
  - $B_c^+ \to D^{*+}_{(s)} D^*$ model
  - For $B^+ \to D_s^+ \overline{D}^0$ modes, the single charm background $B^+ \to K^+ K^- \pi^+ \overline{D}^0$
  - Combinatorial background, described by an exponential plus a constant
- An unbinned extended maximum likelihood is performed simultaneously to both D^0 decay modes with only the total B_c^+ yield floating
- Systematics are included in the fit as Gaussian constraints

Mass fits: $D^0 \to K^- \pi^+$



- Measured branching fractions [upper limit set at 90%(95%) C.L.]:

$$\frac{f_c}{f_u} \times \frac{\mathcal{B}(B_c^+ \to D_{(s)}^+ D)}{\mathcal{B}(B^+ \to D_{(s)}^+ D)} = \frac{N(B_c^+)}{N(B^+)} \times \frac{\varepsilon(B^+)}{\varepsilon(B_c^+)}$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^+ \overline{D}^0)}{\mathcal{B}(B^+ \to D_s^+ \overline{D}^0)} = (\ \ 3.0 \pm 3.7) \times 10^{-4}\ [< 0.9\,(1.1) \times 10^{-3}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^+ D^0)}{\mathcal{B}(B^+ \to D_s^+ \overline{D}^0)} = (-3.8 \pm 2.6) \times 10^{-4}\ [< 3.7\,(4.7) \times 10^{-4}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D^+ \overline{D}^0)}{\mathcal{B}(B^+ \to D^+ \overline{D}^0)} = (\ \ 8.0 \pm 7.5) \times 10^{-3}\ [< 1.9\,(2.2) \times 10^{-2}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D^+ D^0)}{\mathcal{B}(B^+ \to D^+ \overline{D}^0)} = (\ \ 2.9 \pm 5.3) \times 10^{-3}\ [< 1.2\,(1.4) \times 10^{-2}].$$

- Measured branching fractions [upper limit set at 90%(95%) C.L.]:

$$\frac{f_c}{f_u} \times \frac{\left(\mathcal{B}(B_c^+ \to D_{(s)}^{+*} D)\mathcal{B}(D_{(s)}^{+*}) + \mathcal{B}(B_c^+ \to D_{(s)}^{+} D^*)\right)}{\mathcal{B}(B^+ \to D_{(s)}^{+} D)} = \frac{N(B_c^+)}{N(B^+)} \times \frac{\varepsilon(B^+)}{\varepsilon(B_c^+)}$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^{*+}\overline{D}^0) + \mathcal{B}(B_c^+ \to D_s^+\overline{D}^{*0})}{\mathcal{B}(B^+ \to D_s^+\overline{D}^0)} = (-0.1 \pm 1.5) \times 10^{-3}\ [< 2.8\,(3.4) \times 10^{-3}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^{*+}D^0) + \mathcal{B}(B_c^+ \to D_s^+D^{*0})}{\mathcal{B}(B^+ \to D_s^+\overline{D}^0)} = (-0.3 \pm 1.9) \times 10^{-3}\ [< 3.0\,(3.6) \times 10^{-3}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to (D^{*+} \to D^+\pi^0,\gamma)\overline{D}^0) + \mathcal{B}(B_c^+ \to D^+\overline{D}^{*0})}{\mathcal{B}(B^+ \to D^+\overline{D}^0)} = (\ \ 0.2 \pm 3.2) \times 10^{-2}\ [< 5.5\,(6.6) \times 10^{-2}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to (D^{*+} \to D^+\pi^0,\gamma)D^0) + \mathcal{B}(B_c^+ \to D^+D^{*0})}{\mathcal{B}(B^+ \to D^+\overline{D}^0)} = (-1.5 \pm 1.7) \times 10^{-2}\ [< 2.2\,(2.8) \times 10^{-2}].$$

- Measured branching fractions [upper limit set at 90%(95%) C.L.]:

$$\frac{f_c}{f_u} \times \frac{\mathcal{B}(B_c^+ \to D_{(s)}^{+*} D^*)}{\mathcal{B}(B^+ \to D_{(s)}^+ D)} = \frac{1}{\mathcal{B}(D_{(s)}^{+*})} \times \frac{N(B_c^+)}{N(B^+)} \times \frac{\varepsilon(B^+)}{\varepsilon(B_c^+)}$$

$$\frac{f_c}{f_u} \frac{\mathcal{B}(B_c^+ \to D_s^{*+} \overline{D}^{*0})}{\mathcal{B}(B^+ \to D_s^+ \overline{D}^0)} = (\;\;3.2 \pm 4.3) \times 10^{-3} \; [< 1.1\,(1.3) \times 10^{-2}],$$

$$\frac{f_c}{f_u} \frac{\mathcal{B}(B_c^+ \to D_s^{*+} D^{*0})}{\mathcal{B}(B^+ \to D_s^+ \overline{D}^0)} = (\;\;7.0 \pm 9.2) \times 10^{-3} \; [< 2.0\,(2.4) \times 10^{-2}],$$

$$\frac{f_c}{f_u} \frac{\mathcal{B}(B_c^+ \to D^{*+} \overline{D}^{*0})}{\mathcal{B}(B^+ \to D^+ \overline{D}^0)} = (\;\;3.4 \pm 2.3) \times 10^{-1} \; [< 6.5\,(7.3) \times 10^{-1}],$$

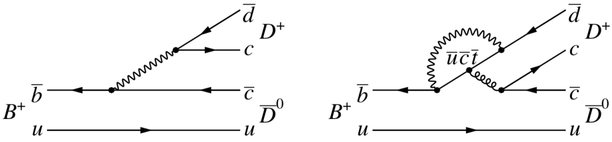
$$\frac{f_c}{f_u} \frac{\mathcal{B}(B_c^+ \to D^{*+} D^{*0})}{\mathcal{B}(B^+ \to D^+ \overline{D}^0)} = (-4.1 \pm 9.1) \times 10^{-2} \; [< 1.3\,(1.6) \times 10^{-1}].$$

Bonus measurement

- Measure the CP asymmetry of the B^+ normalisation modes

$$A_{CP} = \frac{\Gamma(B^- \to D^-_{(s)} D^0) - \Gamma(B^+ \to D^+_{(s)} \overline{D}^0)}{\Gamma(B^- \to D^-_{(s)} D^0) + \Gamma(B^+ \to D^+_{(s)} \overline{D}^0)}$$

- A large CP asymmetry requires two diagrams to contribute to the decay of a similar size and with differing weak (CKM elements) and strong phases (final state interactions)
- $B^+ \to D^+_{(s)} \overline{D}^0$ has both tree and penguin contributions
- SM predicts $A_{CP}(B^+ \to D^+ \overline{D}^0) = \mathcal{O}(1)\%$ [PRD 81, 034006 (2010)]
- PDG value is $A_{CP}(B^+ \to D^+ \overline{D}^0) = (3 \pm 7)\%$
- **$\mathbf{A_{CP}}$ can be enhanced by new physics contributions**



- The raw asymmetry can be measured directly from the fitted yields

$$A_{raw} = \frac{N(D^-_{(s)}D^0) - N(D^+_{(s)}\overline{D}^0)}{N(D^-_{(s)}D^0) + N(D^+_{(s)}\overline{D}^0)}$$

- Corrections to A_{raw} need to be made to account for the B production asymmetry and K, π detection asymmetries

$$A_{CP} = A_{raw} - A_P - A_D$$

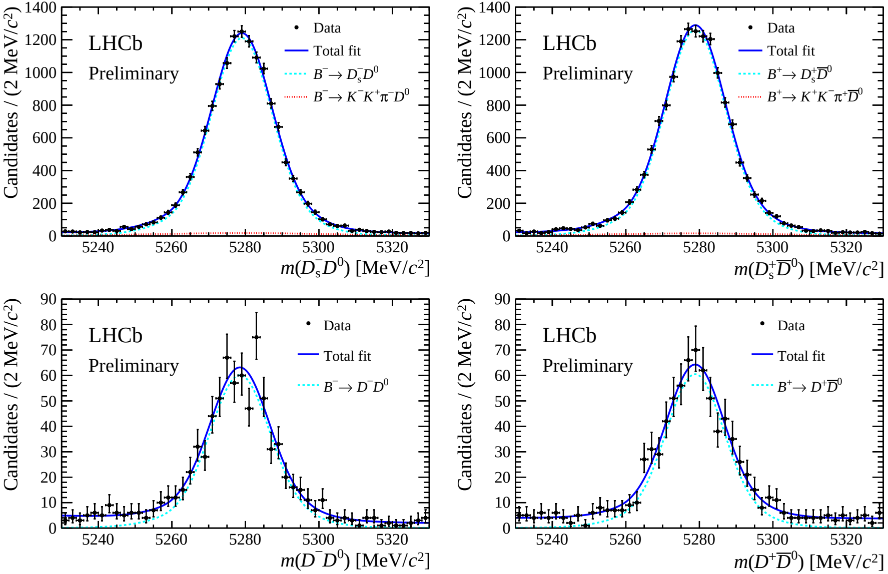
- Where A_P and A_D are defined as

$$A_P = \frac{\sigma(B^-) - \sigma(B^+)}{\sigma(B^-) + \sigma(B^+)}$$

$$A_D = \frac{\varepsilon(B^- \to D^-_{(s)}D^0) - \varepsilon(B^+ \to D^+_{(s)}\overline{D}^0)}{\varepsilon(B^- \to D^-_{(s)}D^0) + \varepsilon(B^+ \to D^+_{(s)}\overline{D}^0)}$$

Mass fits: $D^0 \to K^-\pi^+$

- A_{raw} is $(-1.8 \pm 0.5)\%$ for $B^+ \to D_s^+ \overline{D}^0$ and $(2.0 \pm 2.7)\%$ for $B^+ \to D^+ \overline{D}^0$



A_{CP} measurement

- The raw asymmetry is then corrected for the production and detection asymmetries to give the CP asymmetry

$$A_{CP} = A_{raw} - A_P - A_D$$

- $A_P + A_D$ is $(-1.4 \pm 0.5)\%$ for $B^+ \to D_s^+ \overline{D}^0$ and $(-0.3 \pm 0.4)\%$ for $B^+ \to D^+ \overline{D}^0$
- Putting everything together

$$A_{CP}(B^+ \to D_s^+ \overline{D}^0) = (-0.4 \pm 0.5 \pm 0.5)\%$$

$$A_{CP}(B^+ \to D^+ \overline{D}^0) = (2.3 \pm 2.7 \pm 0.4)\%$$

- Results consistent with zero so **no evidence of CP violation**
- First measurement of $A_{CP}(B^+ \to D_s^+ \overline{D}^0)$ and most precise measurement of $A_{CP}(B^+ \to D^+ \overline{D}^0)$ to date (2.5$\times$ better precision than PDG value)

Conclusion and prospects

- The CP asymmetry in $B^+ \to D^+_{(s)}\overline{D}^0$ decays was measured and a search was performed for $B_c^+ \to DD$ decays
- The B_c^+ channel with the largest theory prediction is

$$\mathcal{B}(B_c^+ \to D^+\overline{D}^0) = 5.3 \times 10^{-5}$$

- Combining the 90%(95%) limit with the most optimistic value for $f_c/f_u = 1.2\%$

$$\mathcal{B}(B_c^+ \to D^+\overline{D}^0) < 6.0(7.0) \times 10^{-4}$$

- Limits are consistent with the theoretical expectations
- LHCb to collect 6 fb^{-1} during run II, 50 fb^{-1} over less than 10 years during upgrade phase and 300 fb^{-1} by the end of the second upgrade
  - Likely to observe $B_c^+ \to D^+\overline{D}^0$, however, measurement of γ with these modes probably still out of reach
  - Expect statistical uncertainties in A_{CP} measurements to halve with a run II update
- More information in the paper: https://arxiv.org/abs/1712.04702

Backup

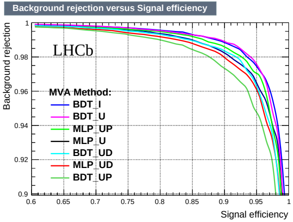
MVA

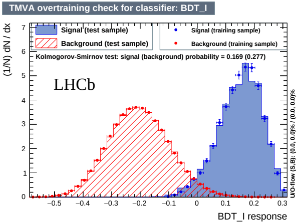
- $B_c^+ \to D_{(s)}^+ \overline{D}^0$ MC was used as the signal sample
- Background training sample ($\sim 10^5$ events):
  - Data from B^+ upper mass sideband ($5350 < m(D_{(s)}^+ D) < 6200\,\text{MeV}$)
  - Combined background from $\overline{D}^0$ and D^0 and wide charm mass windows

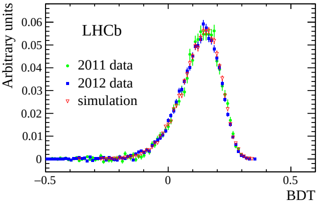
Rank	Variable	Variable Importance ($\times 10^{-2}$)
1	$m(D_s^+)$	6.391
2	$m_{23}^2(\pi^+K^-)$	6.115
3	$m_{13}^2(K^+K^-)$	5.925
4	$\log(p_T(z1))$	5.832
5	$\log(\text{DLL}_{K\pi}(p1)+5)$	5.692
6	$\log(\tau(D_s^+)/\Delta\tau)$	5.435
7	$\log(\tau(B_c^+)/\Delta\tau)$	5.403
8	$\log(\tau(D^0)/\Delta\tau)$	5.310
9	$\log(p_T(p3))$	5.258
10	$\log(p_T(p1))$	5.157
11	$\log(\text{DLL}_{K\pi}(p3)+5)$	5.040
12	$m(D^0)$	4.903
13	$\log(\text{DLL}_{K\pi}(z1)+5)$	4.762
14	$\log(p_T(z2))$	4.754
15	$IP\chi^2(B_c^+)$	4.388
16	$\log(p_T(p2))$	4.071
17	$\log(\text{vertex } \chi^2(\text{D}_\text{s}^+))$	3.666
18	$\log(10-\text{DLL}_{K\pi}(p2))$	3.213
19	$\log(\text{vertex } \chi^2(\text{D}^0))$	3.047
20	$\log(\text{vertex } \chi^2(\text{B}_\text{c}^+))$	2.895
21	$\log(10-\text{DLL}_{K\pi}(z2))$	2.743

MVA response

- Tried out BDT and MLP (default neural network of TMVA) with various transformations
- Used k-folding technique
  - Train 5 MVAs, each time witholding a different 20% for testing
  - Evaluate the response using the MVA that withheld the event from training
- Best performance from BDT with identity transformation
- Good separation of signal and background
- Agreement between sWeighted B^+ data and MC







Simultaneous fit

- An unbinned extended maximum likelihood is performed simultaneously to both D^0 decay modes
- Only the total B_c^+ yield is floating

$$N_{B_c^+}^{K\pi} = \frac{N_{B^+}^{K\pi}\varepsilon_{B_c^+}^{K\pi}/\varepsilon_{B^+}^{K\pi}}{N_{B^+}^{K\pi}\varepsilon_{B_c^+}^{K\pi}/\varepsilon_{B^+}^{K\pi} + N_{B^+}^{K\pi\pi\pi}\varepsilon_{B_c^+}^{K\pi\pi\pi}/\varepsilon_{B^+}^{K\pi\pi\pi}} N_{B_c^+}^{\mathrm{tot}}$$

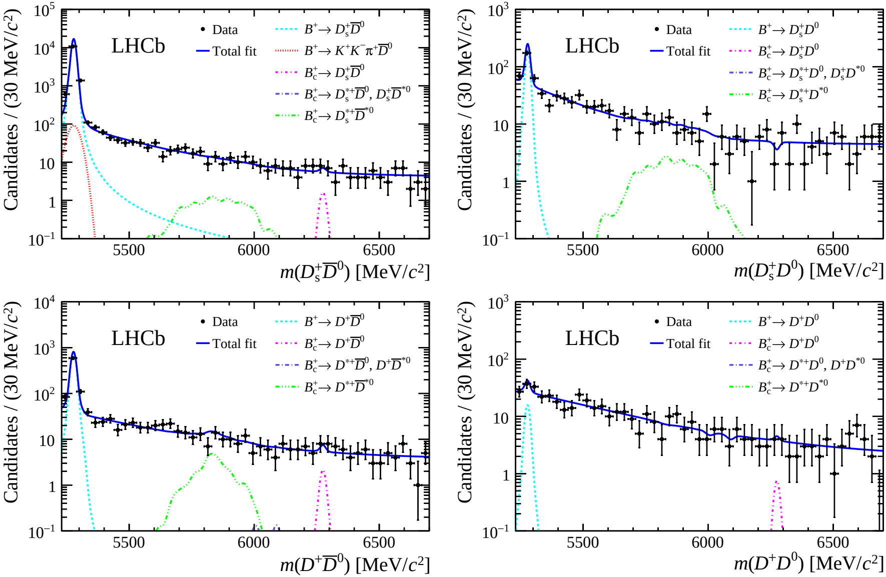
$$N_{B_c^+}^{K\pi\pi\pi} = \frac{N_{B^+}^{K\pi\pi\pi}\varepsilon_{B_c^+}^{K\pi\pi\pi}/\varepsilon_{B^+}^{K\pi\pi\pi}}{N_{B^+}^{K\pi}\varepsilon_{B_c^+}^{K\pi}/\varepsilon_{B^+}^{K\pi} + N_{B^+}^{K\pi\pi\pi}\varepsilon_{B_c^+}^{K\pi\pi\pi}/\varepsilon_{B^+}^{K\pi\pi\pi}} N_{B_c^+}^{\mathrm{tot}}$$

- The efficiencies are measured using MC

Table 2: Ratio $\varepsilon_{B_c^+}/\varepsilon_{B^+}$ of total efficiencies of B_c^+ decays relative to the corresponding fully reconstructed B^+ decays. The quoted uncertainties are statistical only.

	Reconstructed state			
	$D_s^+ \overset{(-)}{D}{}^0$ with $D^0 \to$		$D^+ \overset{(-)}{D}{}^0$ with $D^0 \to$	
Decay channel	$K^-\pi^+$	$K^-\pi^+\pi^-\pi^+$	$K^-\pi^+$	$K^-\pi^+\pi^-\pi^+$
$B_c^+ \to D_{(s)}^+ \overset{(-)}{D}{}^0$	0.420 ± 0.005	0.373 ± 0.009	0.441 ± 0.007	0.398 ± 0.010
$B_c^+ \to D_{(s)}^{*+} \overset{(-)}{D}{}^0, D_{(s)}^+ \overset{(-)}{D}{}^{*0}$	0.372 ± 0.006	0.317 ± 0.010	0.381 ± 0.008	0.337 ± 0.011
$B_c^+ \to D_{(s)}^{*+} \overset{(-)}{D}{}^{*0}$	0.339 ± 0.006	0.278 ± 0.009	0.342 ± 0.007	0.297 ± 0.010

Mass fits: $D^0 \to K^-\pi^+\pi^-\pi^+$



Systematics on the yields

Table 4: Systematic uncertainties on the B_c^+ yields, for the combined fit to both the $D^0 \to K^-\pi^+$ and the $D^0 \to K^-\pi^+\pi^-\pi^+$ decay channels. The total systematic uncertainty is calculated as the quadratic sum of the individual components.

Source	Reconstructed state $D_s^+\overline{D}^0$	$D_s^+D^0$	$D^+\overline{D}^0$	D^+D^0
$B_c^+ \to D_{(s)}^+ \overset{(-)}{D}{}^0$				
Signal shape	0.25	0.28	0.31	0.13
Signal model	0.40	0.34	0.61	0.44
B_c^+ mass	0.64	0.62	0.79	0.51
Background model	1.12	1.75	1.88	0.56
Fit bias	0.70	1.28	0.27	0.19
Total	1.54	2.30	2.17	0.91
$B_c^+ \to D_{(s)}^{*+} \overset{(-)}{D}{}^0, D_{(s)}^+ \overset{(-)}{D}{}^{*0}$				
Signal composition	7.6	5.5	7.1	5.7
Background model	11.9	17.5	16.4	4.5
Fit bias	5.5	9.4	3.9	1.3
Total	15.2	20.6	18.3	7.4
$B_c^+ \to D_{(s)}^{*+} \overset{(-)}{D}{}^{*0}$				
Polarisation	23	14	9	5
Background model	43	98	37	9
Fit bias	10	7	8	1
Total	49	99	39	10

Systematics on the normalisation

Table 5: Systematic uncertainties, in %, on the normalisation of the B_c^+ branching fraction determination. The total systematic uncertainty is calculated as the quadratic sum of the individual components.

		Reconstructed state			
		$D_s^+ \overset{(-)}{D}{}^0$, with $D^0 \to$		$D^+ \overset{(-)}{D}{}^0$, with $D^0 \to$	
Channel	Source	$K^-\pi^+$	$K^-\pi^+\pi^-\pi^+$	$K^-\pi^+$	$K^-\pi^+\pi^-\pi^+$
Common	B^+ stat.	0.7	0.9	3.1	4.3
	B^+ signal shape	0.0	0.0	0.0	0.3
	B^+ signal model	0.1	0.2	0.1	0.3
	Background model	0.0	0.6	1.6	1.3
	$B^+ \to \overline{D}{}^0 K^+ K^- \pi^+$	1.4	1.4	—	—
	B_c^+ lifetime	1.5	1.5	1.5	1.5
	PID	2.4	0.9	1.2	3.2
	D^0 model	—	1.1	—	0.7
$B_c^+ \to D_{(s)}^+ \overset{(-)}{D}{}^0$	Simulation stat.	1.2	2.4	1.6	2.5
	Total	3.5	3.6	4.3	6.3
$B_c^+ \to D_{(s)}^{*+} \overset{(-)}{D}{}^0, D_{(s)}^+ \overset{(-)}{D}{}^{*0}$	Simulation stat.	1.7	3.3	2.0	3.3
	Signal composition	1.0	0.8	0.7	2.6
	Total	3.8	4.3	4.5	7.1
$B_c^+ \to D_{(s)}^{*+} \overset{(-)}{D}{}^{*0}$	Simulation stat.	1.7	3.4	2.0	3.3
	Polarisation	1.5	0.4	1.4	1.3
	$\mathcal{B}(D^{*+} \to D^+\pi^0, \gamma)$	—	—	1.5	1.5
	Total	3.9	4.4	4.9	6.9

Mass fits: $D^0 \to K^-\pi^+\pi^-\pi^+$

- The raw asymmetry is measured from the fitted yields