Beauty meson to doubly open charm decays

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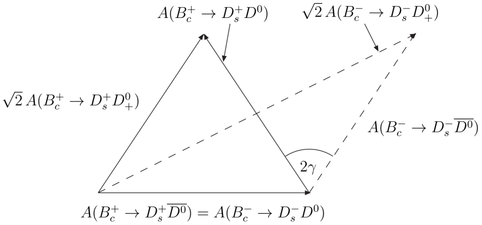
Introduction - $B_c^+ \to DD$

- Interference between $b \to c$ and $b \to u$ tree diagrams $\to$ CP violation
- Similar amplitudes

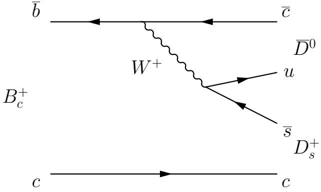
$\to$ $\mathcal{A}^{CP}(B_c^+ \to D_s^+ D_+^0) \sim \mathcal{O}(1)$

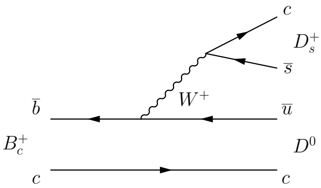
$\to$ Sensitivity to $\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$

[PRD 65 034016, PRD 62 057503, PLB 286 160-164]



[PRD 62 057503]



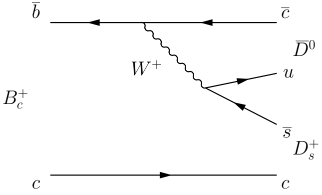


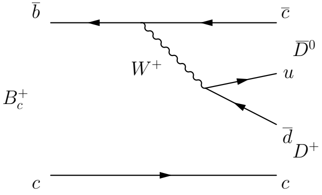
Introduction - $B_c^+ \to DD$

- In general:
  - $\mathcal{B}(B_c^+ \to D_s^+ \overline{D}^0) \sim 10^{-6}$
  - $\mathcal{B}(B_c^+ \to D^+ \overline{D}^0) \sim 10^{-5}$

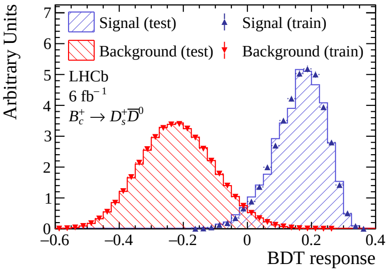
  [PRD 86 074019]
- But BF predictions vary by up to an order of magnitude
- Hadronic B decays could be affected by NP [EPJC 80:951, PRD 102 071701, JHEP 10 (2021) 235]
- Small production cross section ($\frac{f_c}{f_u} \sim 0.8\%$) $\to$ Rare

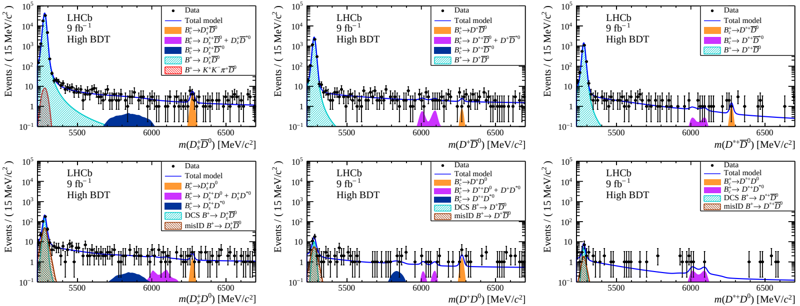
$\to$ No evidence in Run 1 [NPB 930 563-582]





- Search for 16 $B_c^+ \to DD$ decays in 6 channels: $D_{(s)}^{(*)+} \overset{(-)}{D}{}^0$
  - Fully and partially reconstructed decays
  - $D^{*+} \to D^0\pi^+$, $D^0 \to K\pi(\pi\pi)$, $D_s^+ \to KK\pi$, $D^+ \to K\pi\pi$
- Full Run 1+2 dataset: $3\,\text{fb}^{-1}$ 2011-12; $6\,\text{fb}^{-1}$ 2015-18
  - Selections to reduce combinatorial and peaking backgrounds
- Boosted Decision Tree (BDT) reduces combinatorial background
  - Discard lowest purity data
  - Split remainder into low/medium/high purity samples





- Fit simultaneously to BDT samples and D^0 final states
- Measure relative to abundant $B^+ \to D\overline{D}^0$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to DD)}{\mathcal{B}(B^+ \to D\overline{D}^0)} = \frac{N_{B_c^+ \to DD}}{N_{B^+ \to D\overline{D}^0}}\frac{\varepsilon_{B^+ \to D\overline{D}^0}}{\varepsilon_{B_c^+ \to DD}}$$

- Efficiency (ε) ratio from simulation

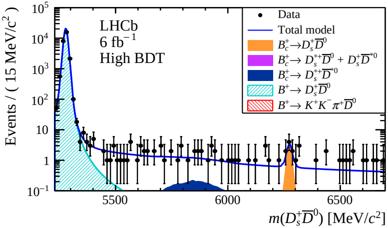
- 3.4σ evidence for $B_c^+ \to D_s^+ \overline{D}^0$
- External inputs for $\mathcal{B}(B^+ \to D_s^+ \overline{D}^0)$ and $\frac{f_c}{f_u}$

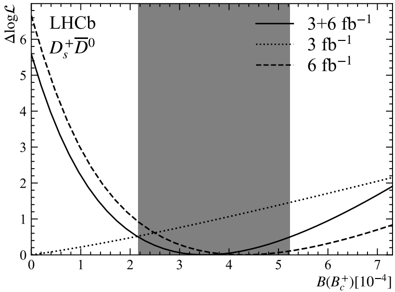
$$\mathcal{B}(B_c^+ \to D_s^+ \overline{D}^0) =$$

$$(3.5^{+1.5+0.3}_{-1.2-0.2} \pm 1.0) \times 10^{-4}$$

$$(\text{stat}, \text{sys}, \text{ext})$$

- Dominant systematics: Signal and background shapes, B_c^+ kinematic correction
- Two orders of magnitude larger than SM prediction

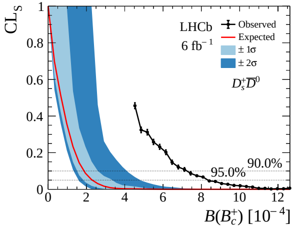


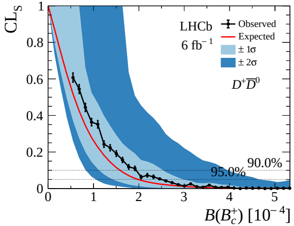


- Upper limits on $\mathcal{B}$ at 90(95)% CL
- Use frequentist CLs method implemented in GammaCombo

$$\mathcal{B}(B_c^+ \to D_s^+ \overline{D}^0) < 7.2\,(8.4) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D_s^+ D^0) < 3.0\,(3.7) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D^+ \overline{D}^0) < 1.9\,(2.5) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D^+ D^0) < 1.4\,(1.8) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D^{*+} \overline{D}^0) < 3.8\,(4.8) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D^{*+} D^0) < 2.0\,(2.4) \times 10^{-4}$$

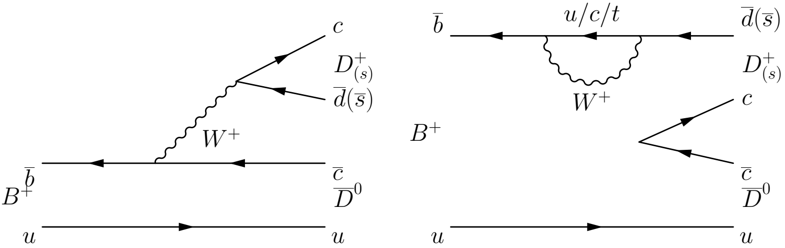
plus ten limits on $B_c^+ \to D^{(*)} D^{(*)}$ using partially reconstructed decays





Introduction - $\mathcal{A}^{CP}(B^- \to DD)$

- Tree and penguin interference produces small $\mathcal{A}^{CP}(B^{-/0} \to DD)$
  - $\mathcal{A}^{CP}(B^- \to D^- D^0) \sim \mathcal{O}(1\%)$
  - $\mathcal{A}^{CP}(B^- \to D_s^- D^0) \sim \mathcal{O}(0.1\%)$
- $\mathcal{A}^{CP}$ could be enhanced by NP [PRD 79 055004, CTP 56 125, IJTP 55 5290]
- Deviation from isospin symmetry expectations between $B^- \to D^-_{(s)} D^0$ and $\overline{B}^0 \to D^-_{(s)} D^+$ could also indicate NP [PRD 91 034027, PRD 78 033011]



$\mathcal{A}^{CP}(B^- \to DD)$

- Measure $\mathcal{A}^{CP}$ of seven fully or partially reconstructed $B^- \to D_{(s)}^{(*)-} D^{(*)0}$ decays
- Full Run 1+2 dataset: $3\,\mathrm{fb}^{-1}$ 2011-12; $6\,\mathrm{fb}^{-1}$ 2015-18

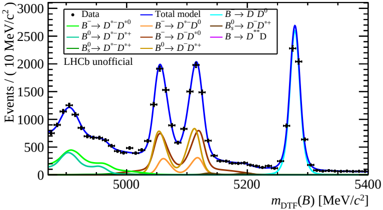
Table 1: CP asymmetries to be measured in each channel, their PDG average and experiments which have previously measured this quantity. All previous measurements are consistent with zero and with SM predictions.

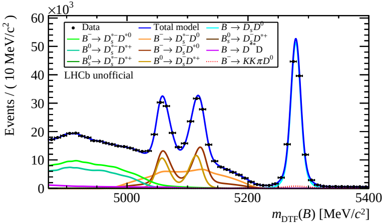
Channel	Quantity	PDG average	Previous Measurements
$B^- \to D_s^- D^0$	$\mathcal{A}^{CP}(B^- \to D_s^- D^0)$	$(-0.4 \pm 0.7)\%$	[JHEP 05 (2018) 160 [LHCb]]
	$\mathcal{A}^{CP}(B^- \to D_s^{*-} D^0)$	-	-
	$\mathcal{A}^{CP}(B^- \to D_s^- D^{*0})$	-	-
$B^- \to D^- D^0$	$\mathcal{A}^{CP}(B^- \to D^- D^0)$	$(1.6 \pm 2.5)\%$	[JHEP 05 (2018) 160 [LHCb], PRD 77 091101 [Belle I], PRD 73 112004 [BaBar]]
	$\mathcal{A}^{CP}(B^- \to D^- D^{*0})$	$(13 \pm 18)\%$	[PRD 73 112004 [BaBar]]
$B^- \to D^{*-} D^0$	$\mathcal{A}^{CP}(B^- \to D^{*-} D^0)$	$(-6 \pm 13)\%$	[PRD 73 112004 [BaBar]]
	$\mathcal{A}^{CP}(B^- \to D^{*-} D^{*0})$	$(-15 \pm 11)\%$	[PRD 73 112004 [BaBar]]

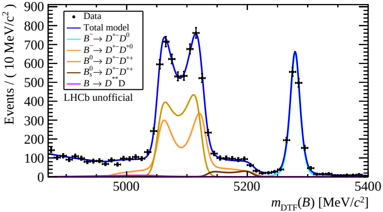
Raw Asymmetry

$$\mathcal{A}^{CP} = \mathcal{A}_{raw} - \mathcal{A}_P - \mathcal{A}_D$$

$$\mathcal{A}_{raw} = \frac{N(B^-) - N(B^+)}{N(B^-) + N(B^+)}$$







Corrections

$$\mathcal{A}^{CP} = \mathcal{A}_{raw} - \mathcal{A}_P - \mathcal{A}_D$$

- Production asymmetry $\mathcal{A}_P \equiv \frac{\sigma(B^-)-\sigma(B^+)}{\sigma(B^-)+\sigma(B^+)}$
  - $B^+ \to \overline{D}^0\pi^+$ and $B^+ \to J/\psi K^+$
- Detection asymmetry $\mathcal{A}_D \equiv \frac{\varepsilon(B^-)-\varepsilon(B^+)}{\varepsilon(B^-)+\varepsilon(B^+)}$
  - Calibration samples corrected for kinematics
  - Largest: $\mathcal{A}_D(K^-\pi^+) \sim -1\%$. $\Delta\mathcal{A}_{raw}$ in $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K^0_S\pi^+$ samples.
  - Pion tracking
  - Particle ID requirements
  - L0 hardware triggers

$\mathcal{A}^{CP}$ prospects (unofficial)

Table 2: Statistical and systematic uncertainties on $\mathcal{A}^{CP}$ and comparison to existing world averages. Statistical uncertainty is entirely from $\mathcal{A}_{raw}$.

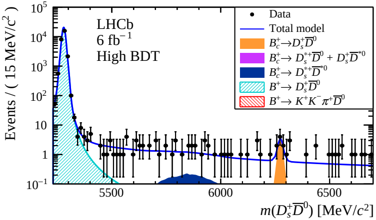
Decay	Run1+2	PDG
$B^- \to D_s^- D^0$	$(X \pm 0.2 \pm 0.4)\%$	$(-0.4 \pm 0.7)\%$
$B^- \to D_s^{*-} D^0$	$(X \pm 1.3 \pm 0.7)\%$	-
$B^- \to D_s^- D^{*0}$	$(X \pm 1.7 \pm 0.9)\%$	-
$B^- \to D^- D^0$	$(X \pm 1.0 \pm 0.4)\%$	$(1.6 \pm 2.5)\%$
$B^- \to D^{*-} D^0$	$(X \pm 1.6 \pm 0.6)\%$	$(-6 \pm 13)\%$
$B^- \to D^- D^{*0}$	$(X \pm 2.2 \pm 1.3)\%$	$(13 \pm 18)\%$
$B^- \to D^{*-} D^{*0}$	$(X \pm 2.4 \pm 2.4)\%$	$(-15 \pm 11)\%$

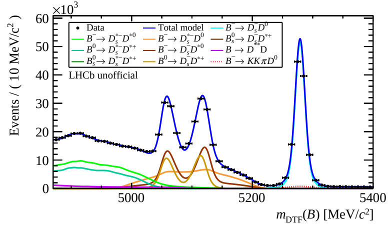
- Dominant systematics:
  - Contribution of $\mathcal{A}^{CP}(B^+ \to J/\psi K^+)$ to $\mathcal{A}_P$
  - Calibration sample size for $K^-\pi^+$ detection asymmetry
  - Combinatorial, $B_s^0 \to DD$, and $B \to D^{**}D$ modelling
- Anticipate publication this year

Conclusion

- Recent and in-progress results on $B^+_{(c)} \to DD$ decays from Run 1+2 LHCb data

- Search for sixteen $B^+_c \to DD$ decays
  - 3.4σ evidence for $B^+_c \to D^+_s \overline{D}^0$
  - Upper limits on $\mathcal{B}$
- $\mathcal{A}^{CP}$ of seven $B^- \to DD$ decays in progress
  - Substantial improvements in precision
  - BSM sensitivity





Backup

Upper limits at 90(95)% CL

$$\mathcal{B}(B_c^+ \to D_s^{*+} \overline{D}^0) < 5.3(5.7) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D_s^{*+} D^0) < 0.9\,(1.0) \times 10^{-3}$$
$$\mathcal{B}(B_c^+ \to D_s^+ \overline{D}^{*0}) < 5.3\,(5.7) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D_s^+ D^{*0}) < 6.6\,(8.4) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D^+ \overline{D}^{*0}) < 6.5\,(8.2) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D^+ D^{*0}) < 3.7\,(4.6) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D_s^{*+} \overline{D}^{*0}) < 1.3\,(1.5) \times 10^{-3}$$
$$\mathcal{B}(B_c^+ \to D_s^{*+} D^{*0}) < 1.3\,(1.6) \times 10^{-3}$$
$$\mathcal{B}(B_c^+ \to D^{*+} \overline{D}^{*0}) < 1.0\,(1.3) \times 10^{-3}$$
$$\mathcal{B}(B_c^+ \to D^{*+} D^{*0}) < 7.7\,(8.9) \times 10^{-4}$$