Doubly charming B meson decays at LHCb

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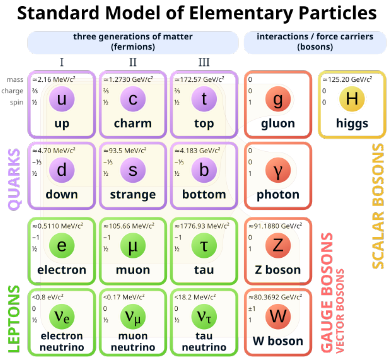
LAPP Seminar
17/01/25

- Standard Model (SM) describes majority of fundamental particle phenomena

- Many outstanding problems, e.g.
  - Where is all the antimatter?
  - What is dark matter and dark energy?
  - Why are there three generations of fermions with a weird mass hierarchy?



[Wikimedia Commons]

Where is all the antimatter?

- Expect matter $\approx$ antimatter immediately after big bang
- Therefore observed abundance of baryonic matter $>$ antimatter requires violation of charge-parity symmetry (CPV)
- Allowed and measured in decays of hadrons in SM
  - Imaginary parts of CKM quark mixing matrix (phase γ)

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\gamma} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\gamma} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\gamma} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\gamma} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\gamma} & c_{23}c_{13} \end{pmatrix}$$

- But many orders of magnitude too small to explain observed baryon asymmetry in universe!

$\rightarrow$ Motivates sources of large CPV beyond the SM

$\rightarrow$ Measuring CPV is an excellent place to look for beyond Standard Model (BSM) physics

Where is all the BSM physics?

- b-hadron decays generally promising area to search for BSM physics
  - Sensitive to perturbations from BSM particles too heavy to be produced directly by LHC
- Deviations from SM measured in charmless and single-charm (= c quark + lighter antiquark) B meson (= b quark + lighter antiquark) decays
  - e.g. $B \to \{\pi\pi/KK/K\pi\}$ [arXiv:2401.15734, JHEP 06 (2023) 108]
  - e.g. $B^0_{(s)} \to D\{\pi/K\}$ [EPJC 80 951, PRD 102 071701]
- What about double charm?
  - Sensitive to contributions from BSM, including with large CPV
  - Improve understanding of quantum chromodynamics (QCD) in weak decays of hadrons → Permits more precise SM predictions → Further BSM sensitivity

Overview

1. Search for the rare $B_c^+ \to DD$ decays
2. Measurements of CP-violating B^-, $B^0_{(s)} \to DD$ decays
   - Time-integrated CPV and branching fractions in B^- decays
   - Decay time-dependent CPV and branching fractions in $B^0_{(s)}$ decays

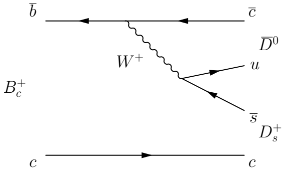
NB D meson $= c + (\overline{u}/\overline{d}/\overline{s})$ "charm"

B meson $= b + (\overline{u}/\overline{d}/\overline{s}/\overline{c})$

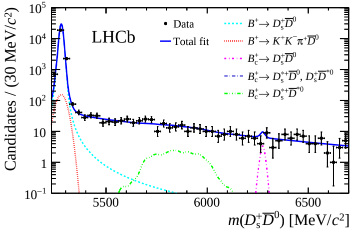
Introduction - $B_c^+ \to DD$

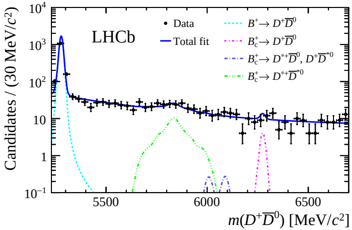
- Combination of heavy $\overline{b}$ and c $\to$ Predictions for B_c^+ meson decays extremely challenging
- History of surprises: Measured $\mathcal{B}(B_c^+ \to D^0 K^+) > \mathcal{B}(B_c^+ \to D^0 \pi^+)$ indicated annihilation and QCD penguin dominant over tree amplitudes [PRL 118 111803 (LHCb 3 fb^{-1})]
- $B_c^+ \to DD$: Dominant contributions expected from tree and annihilation amplitudes

$B_c^+ \to$	$\mathcal{B}/10^{-6}$ [PRD86 074019]	$\mathcal{B}/10^{-6}$ [PRD86 094028]
$D_s^+ \overline{D}^0$	2.3	0.3
$D_s^+ D^0$	3.0	0.2
$D^+ \overline{D}^0$	32	1.3
$D^+ D^0$	0.10	0.008



- LHCb provides unique environment to study these decays
    - $m(B_c^+)$ beyond SuperKEKB
    - Excellent particle ID and momentum resolution required
- Experimentally challenging:
    - Small production cross section: $\sigma(B_c^+)/\sigma(B^+) \sim 0.8\%$
    - Short lifetime
    - Large number of final state particles

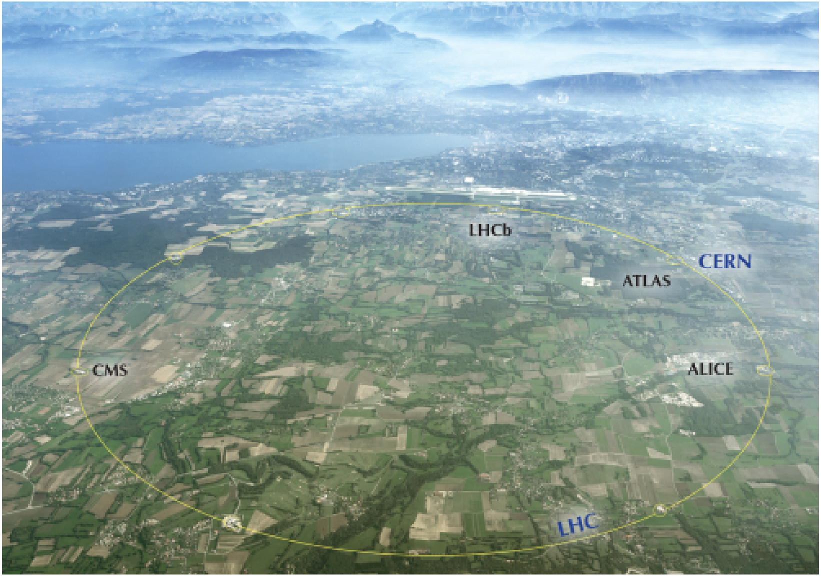




- No evidence found with $3\,\text{fb}^{-1}$ pp collisions collected from 2011-12

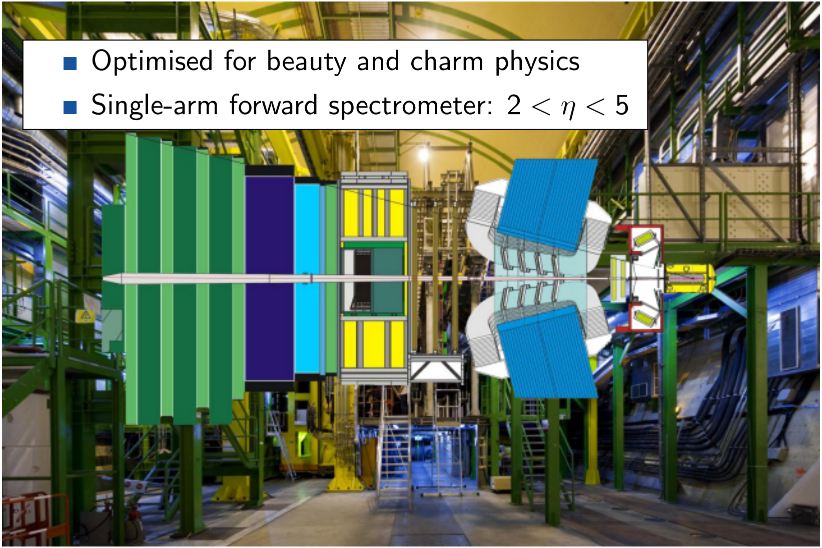
[NPB 930 (2018) 563]

The LHCb detector at the LHC

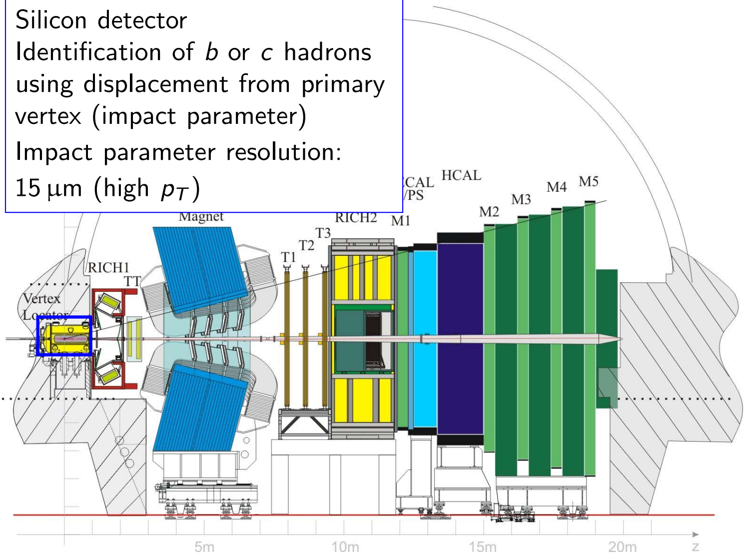


https://visits.web.cern.ch/node/616

- Optimised for beauty and charm physics
- Single-arm forward spectrometer: $2 < \eta < 5$



VErtex LOcator
Silicon detector
Identification of b or c hadrons using displacement from primary vertex (impact parameter)
Impact parameter resolution: 15 µm (high p_T)

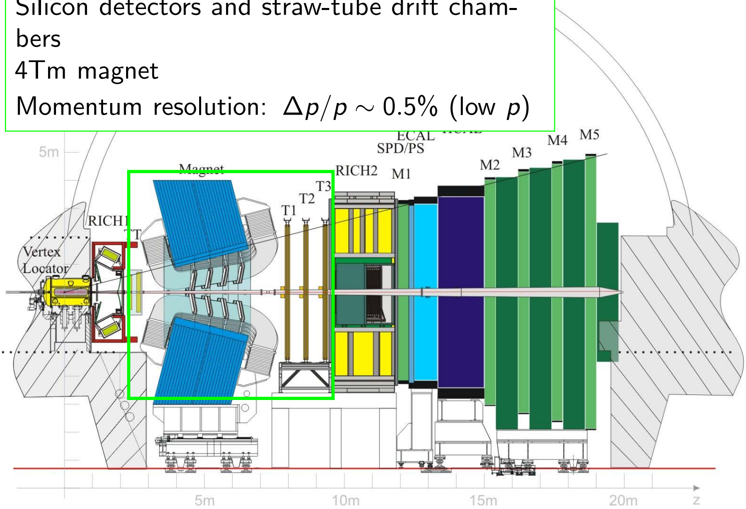


Tracking system

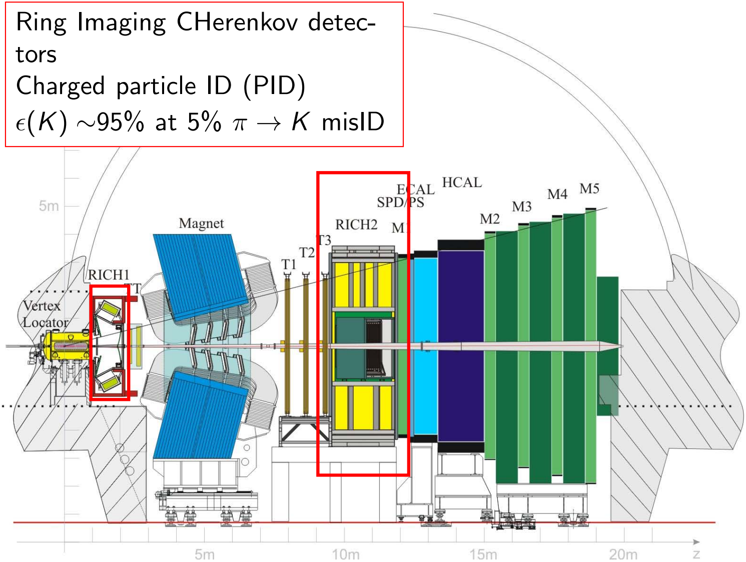
Silicon detectors and straw-tube drift chambers

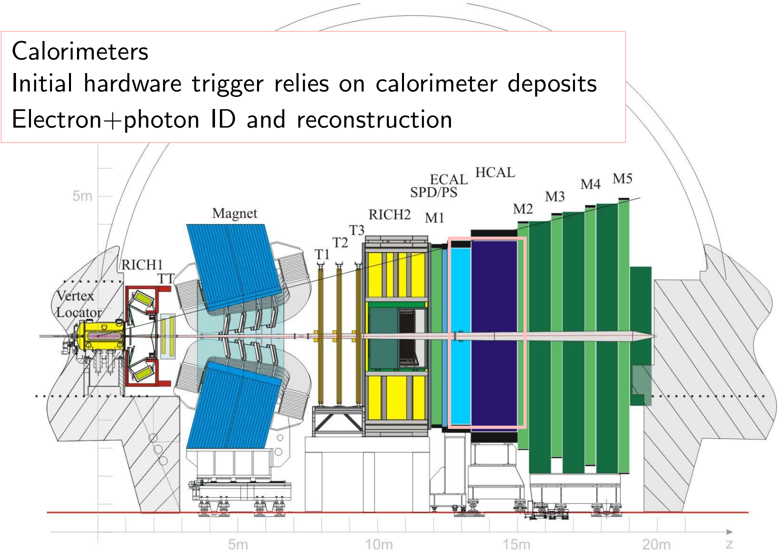
4Tm magnet

Momentum resolution: $\Delta p/p \sim 0.5\%$ (low p)



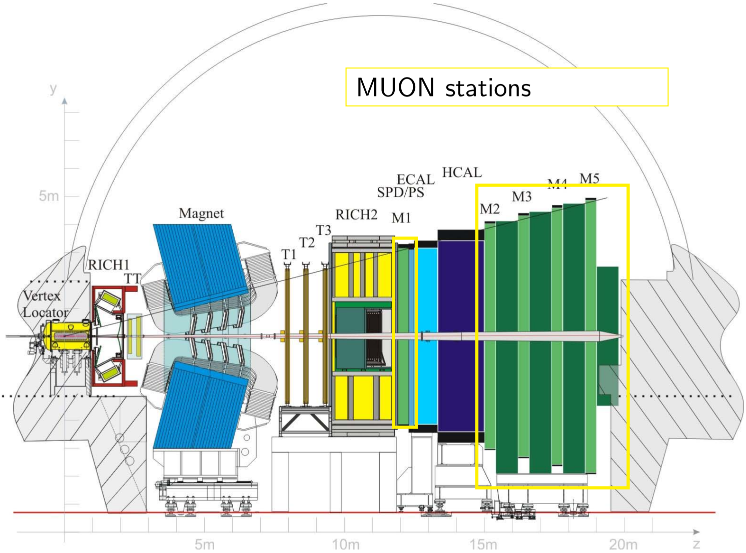
Ring Imaging CHerenkov detectors
Charged particle ID (PID)
$\epsilon(K)$ ~95% at 5% $\pi \to K$ misID





Calorimeters
Initial hardware trigger relies on calorimeter deposits
Electron+photon ID and reconstruction
5m
Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
M1
ECAL
SPD/PS
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z

MUON stations

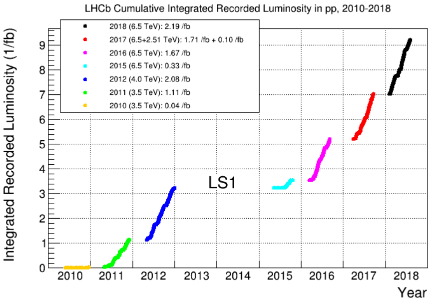


The Run 1+2 LHCb dataset

- 2011: $1\,\text{fb}^{-1}$ @ $\sqrt{s} = 7\,\text{TeV}$ } Run 1
- 2012: $2\,\text{fb}^{-1}$ @ $\sqrt{s} = 8\,\text{TeV}$
- 2015-18: $6\,\text{fb}^{-1}$ @ $\sqrt{s} = 13\,\text{TeV}$ } Run 2

$$\frac{\sigma(pp \to B, 13\,\text{TeV})}{\sigma(pp \to B, 8\,\text{TeV})} \sim 2$$

$\to$ Run 2 signal yields 4x larger

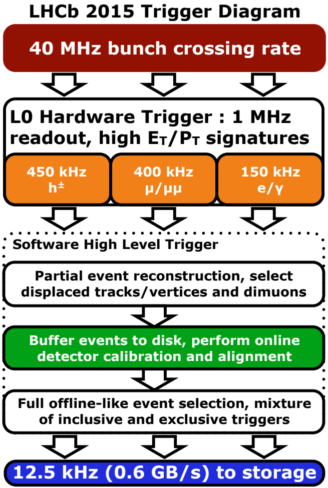


- $9\,\text{fb}^{-1}$ pp collisions collected from 2011-2018
- Search for 16 $B_c^+ \to D_{(s)}^{(*)+} \overset{(-)}{D}{}^{(*)0}$ decays
  - 6 final states: $(D^+/D_s^+/D^{*+})\overset{(-)}{D}{}^0$
  - $D^{*+} \to D^0\pi^+$
  - $D^0 \to K\pi(\pi\pi)$, $D^+ \to K\pi\pi$, $D_s^+ \to KK\pi$
  - Both fully and partially reconstructed (miss one or more neutral particles from D^{*0} or D_s^{*+}) decays
- Measure $\mathcal{B}$: Reduce uncertainties from luminosity, cross sections etc by measuring relative to $B^+ \to D\bar{D}^0$ decays

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

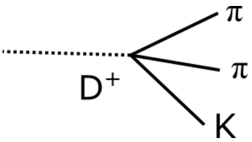
- Selection efficiency (ε) ratio from simulation

- L0 Hardware Trigger
  - High transverse energy (E_T) deposit from signal decay or underlying event
- HLT1
  - High quality, high transverse momentum (p_T) track displaced from primary vertex in signal decay
- HLT2
  - Topological triggers: Candidates consistent with multibody B decay
  - Geometric and kinematic properties



D meson candidates:

- Combine good-quality, high p_T tracks
- Incompatible with originating from primary vertex
- PID requirements



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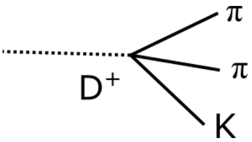
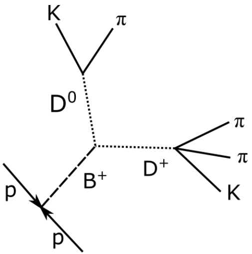


B meson candidates:

- Combine two D meson candidates
- Good vertex quality

Single-charm and charmless backgrounds:

- *D* meson mass and lifetime requirements



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- Combine good-quality, high p_T tracks
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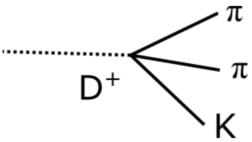

B meson candidates:

- Combine two D meson candidates
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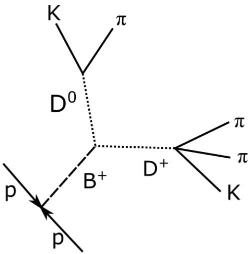


Single-charm and charmless backgrounds:

- D meson mass and lifetime requirements

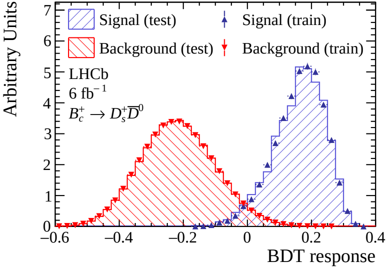
Vetoes:

- $B^0_{(s)} \to D\pi^+(\pi^-\pi^+)$ decays
- D^+/D_s^+ cross-feed

- Boosted Decision Tree (BDT) further reduces combinatorial background
  - Signal: Simulated signal
  - Background: High-$m(B)$ sideband data
  - Kinematic, geometric, vertex quality, and PID variables

- Discard lowest purity data

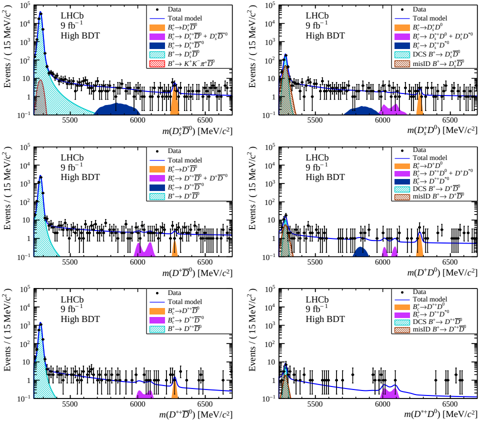
- Split remainder into low/medium/high purity samples to enhance signal sensitivity



$\mathcal{B}(B_c^+ \to DD)$ - Fit to data

JHEP 12 (2021) 117

- $B_c^+ \to DD$ signal with zero, one or two missing soft particles
- $B^+ \to D\overline{D}^0$
- $B^+ \to D\overline{D}^0$ cross-feed to DD^0
- $B^+ \to \overline{D}^0 K^+ K^- \pi^+$
- Combinatorial background

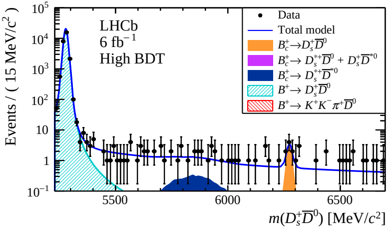


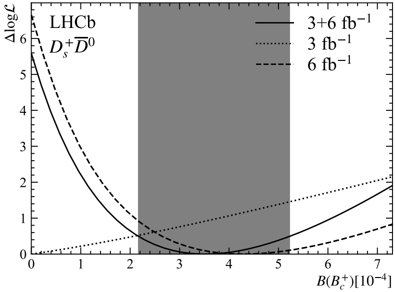
- 3.4σ evidence for $B_c^+ \to D_s^+ \overline{D}^0$

$$\mathcal{B}(B_c^+ \to D_s^+ \overline{D}^0) = (3.5^{+1.5+0.3}_{-1.2-0.2} \pm 1.0) \times 10^{-4}$$

(stat, sys, ext)

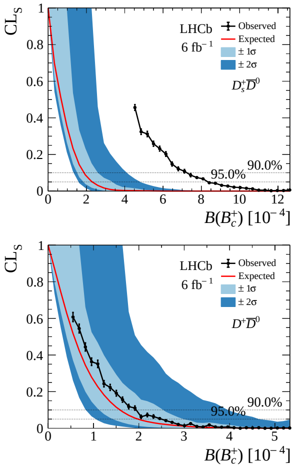
- Dominant systematic uncertainties: Signal and background mass distributions
- Two orders of magnitude larger than predicted
  - No obvious SM or BSM explanation





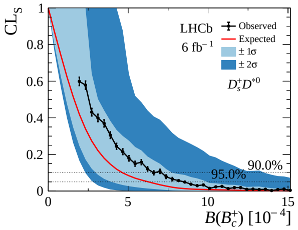
- Upper limits on $\mathcal{B}$ at 90(95)% CL with frequentist CLs method

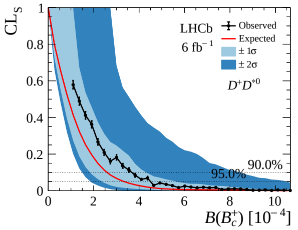
$$\mathcal{B}(B_c^+ \to D_s^+ \overline{D}^0) < 7.2\,(8.4) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D_s^+ D^0) < 3.0\,(3.7) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D^+ \overline{D}^0) < 1.9\,(2.5) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D^+ D^0) < 1.4\,(1.8) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to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



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

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





- **Direct CPV:**

$$\mathcal{A}^{CP} = \frac{\Gamma(B \to f) - \Gamma(\overline{B} \to \overline{f})}{\Gamma(B \to f) + \Gamma(\overline{B} \to \overline{f})}$$

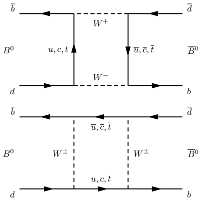
Non-zero when at least two diagrams with weak and strong phase differences interfere.

- **Neutral meson oscillations:**

Mass eigenstates (M_H, M_L) linear combinations of flavour eigenstates with mass and width differences

$$\Delta m \equiv m_H - m_L$$

$$\Delta\Gamma \equiv \Gamma_H - \Gamma_L$$



Box diagrams contributing to B^0 meson oscillations [FDL]

- **CPV in interference between neutral meson mixing and decay**

$$\Gamma(t; \overset{(-)}{M}{}^0 \to f^{\pm}) \propto e^{-\Gamma t}(1 \pm \mathcal{A}^{CP})(\cosh(\Delta\Gamma t/2) + A^{\Delta\Gamma\pm}\sinh(\Delta\Gamma t/2) + q[(S \pm \Delta S)\sin(\Delta m t) - (C \pm \Delta C)\cos(\Delta m t)])$$

* Approximated as 1 in B^0 system where $\Delta\Gamma/\Gamma \ll 1$

$q = \pm 1$: Production flavour
S: CPV in mixing
C, $\mathcal{A}^{CP}$: CPV in decay
$(A^{\Delta\Gamma\pm})^2 = 1 - (S^{\pm})^2 - (C^{\pm})^2$

t: Decay time
ΔS: Function of strong phase difference
ΔC: Flavour specificity of decay

SM CPV in $B^- \to DD$ decays

- $\mathcal{A}^{CP}$ from interference between tree and suppressed QCD penguin+annihilation diagrams

$\to$ Expect small $\mathcal{A}^{CP}(B^- \to D^-_{(s)} D^0) \sim \mathcal{O}(10^{-2(3)})$

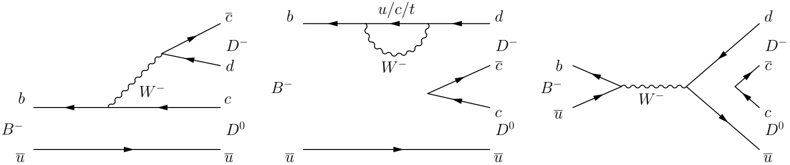


Figure 1: (Left) tree, (centre) penguin, and (right) annihilation diagrams contributing to the $B^- \to D^- D^0$ decay [JHEP 09 (2023) 202].

SM CPV in $B^0_{(s)} \to DD$ decays

- $B^0 \to D^{(*)+} D^{(*)-}$

$+$ $B^0_s \to D_s^{(*)+} D_s^{(*)-}$
  - $S \approx +(-)\sin(2\beta_{(s)})$
  - $C \sim \mathcal{O}(10^{-2})$

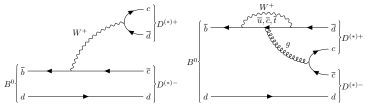


Figure 2: (Left) tree and (right) QCD penguin diagrams contributing to $B^0 \to D^{(*)+} D^{(*)-}$ decays [JHEP 07 (2023) 119].

- $B^0 \to D_s^{(*)+} D_s^{(*)-}$

$+$ $B^0_s \to D^{(*)+} D^{(*)-}$
  - Annihilation-dominated $\to$ Small BF, larger C

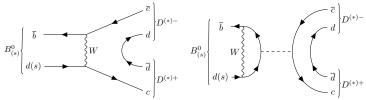
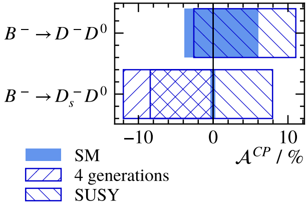


Figure 3: (Left) W-exchange and (right) penguin-annihilation diagrams contributing to $B^0_{(s)} \to D^{(*)+} D^{(*)-}$ decays [JHEP 07 (2023) 119].

CPV in $B \to DD$ decays

- BSM models can substantially modify CP observables
  - e.g. 4th generation quarks [IJTP 55 5290]
  - Supersymmetry [PRD 79 055004]
- Large theoretical uncertainty on e.g. penguin amplitudes → limits sensitivity



- SU(3) flavour symmetry (with small symmetry-breaking corrections) relates amplitudes of different decays in SM

→ Excellent sensitivity to flavour symmetry-violating NP by comparing measurements from multiple decays [arXiv:2311.16952, PRD 91 034027]

- $\mathcal{A}^{CP}$ of seven $B^- \to D_{(s)}^{(*)-} D^{(*)0}$ decays
  - Both fully and partially reconstructed decays (miss neutral particle from D^{*0} or D_s^{*-})
- $9\,\text{fb}^{-1}$ pp collisions, collected from 2011-2018

Channel	Quantity	PDG average	Previous Measurements
$B^- \to D_s^- D^0$	$\mathcal{A}^{CP}(B^- \to D_s^- D^0)$	$(-0.4 \pm 0.7)\%$	[LHCb $3\,\text{fb}^{-1}$]
	$\mathcal{A}^{CP}(B^- \to D_s^{*-} D^0)$	-	-
	$\mathcal{A}^{CP}(B^- \to D_s^- D^{*0})$	-	-
$B^- \to D^- D^0$	$\mathcal{A}^{CP}(B^- \to D^- D^0)$	$(1.6 \pm 2.5)\%$	[LHCb $3\,\text{fb}^{-1}$][Belle I][BaBar]
	$\mathcal{A}^{CP}(B^- \to D^- D^{*0})$	$(13 \pm 18)\%$	[BaBar]
$B^- \to D^{*-} D^0$	$\mathcal{A}^{CP}(B^- \to D^{*-} D^0)$	$(-6 \pm 13)\%$	[BaBar]
	$\mathcal{A}^{CP}(B^- \to D^{*-} D^{*0})$	$(-15 \pm 11)\%$	[BaBar]

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

$$\mathcal{A}^{CP} = \mathcal{A}_{\text{raw}} - \mathcal{A}_{\text{P}} - \mathcal{A}_{\text{D}}$$

- Raw asymmetry: Fit to selected data

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

- Production and detection asymmetries measured in calibration samples

$$\mathcal{A}_{\text{P}} = \frac{\sigma(B^-) - \sigma(B^+)}{\sigma(B^-) + \sigma(B^+)}$$

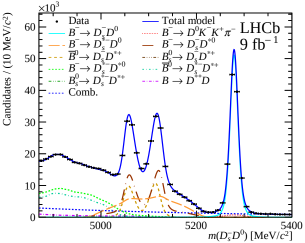
$$\mathcal{A}_{\text{D}} = \frac{\varepsilon(B^-) - \varepsilon(B^+)}{\varepsilon(B^-) + \varepsilon(B^+)}$$

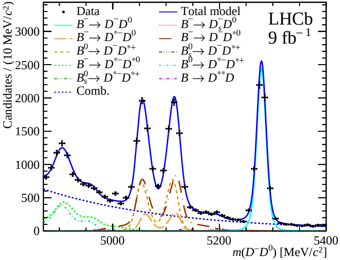
- Selection: Similar to selection of $B_c^+ \to DD$ decays but single cut on BDT response to optimise significance $S = \frac{N_{sig}}{\sqrt{N_{sig}+N_{bkg}}}$

$$R(D^- D^0 / D_s^- D^0) \equiv \frac{\mathcal{B}(B^- \to D^- D^0)}{\mathcal{B}(B^- \to D_s^- D^0)} \frac{\mathcal{B}(D^- \to K\pi\pi)}{\mathcal{B}(D_s^- \to KK\pi)}$$
$$= \frac{N(B^- \to D^- D^0)}{N(B^- \to D_s^- D^0)} \times \frac{\varepsilon(B^- \to D_s^- D^0)}{\varepsilon(B^- \to D^- D^0)}$$

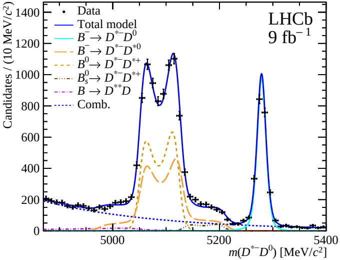
$$R(D^{*-} D^0 / D^- D^0) \equiv \frac{\mathcal{B}(B^- \to D^{*-} D^0)}{\mathcal{B}(B^- \to D^- D^0)} \frac{\mathcal{B}(D^{*-} \to \overline{D}^0 \pi^-)\mathcal{B}(\overline{D}^0 \to K\pi)}{\mathcal{B}(D^- \to K\pi\pi)}$$
$$= \frac{N(B^- \to D^{*-} D^0)}{N(B^- \to D^- D^0)} \times \frac{\varepsilon(B^- \to D^- D^0)}{\varepsilon(B^- \to D^{*-} D^0)}$$

- Raw yields N from fit to data
- Efficiencies ε from simulation corrected for mismodelling





- Background asymmetries and yields constrained where possible
- Pseudoexperiments to confirm no undercoverage or bias



- pp collisions favour production of $B^+ = \overline{b}u$ over B^-
  - $\rightarrow$ Production asymmetry
- Expected to be larger at higher rapidity, lower p_T [arXiv:hep-ph/0003056]
- Measured in $B^+ \rightarrow J/\psi K^+$ decays in bins of p_T and rapidity using known $\mathcal{A}^{CP}$
- Asymmetry in signal decays from weighting binned measurement by signal kinematics

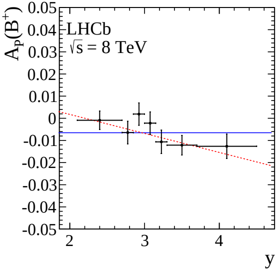


Figure 4: Measured $\mathcal{A}_{\mathrm{P}}(B^-)$ in pp collisions at $\sqrt{s} = 8$ TeV within LHCb acceptance as a function of $y(B^-)$ [PLB774 139].

K and π detection asymmetries JHEP 09 (2023) 202

- $\mathcal{A}_{\mathrm{D}}(K^-) \sim 1\%$ largest detection asymmetry
- Best precision from measuring $\mathcal{A}_{K\pi} \equiv \mathcal{A}_{\mathrm{D}}(K^-\pi^+) = \mathcal{A}_{\mathrm{raw}}(D^+ \to K^-\pi^+\pi^+) - \mathcal{A}_{\mathrm{raw}}(D^+ \to \overline{K}^0\pi^+) + \mathcal{A}_{\mathrm{raw}}(\overline{K}^0)$
- $\mathcal{A}_{\pi} \equiv \mathcal{A}_{\mathrm{D}}(\pi^+)$ measured in $D^{*+} \to D^0\pi^+$ decays
- Strong momentum dependence
- Weaker pseudorapidity dependence due to amount of material

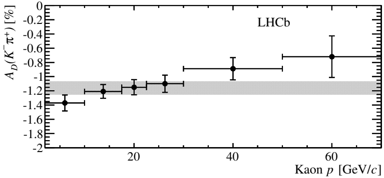


Figure 5: $\mathcal{A}_{K\pi}$ as a function of kaon momentum [JHEP 07 (2014) 041].

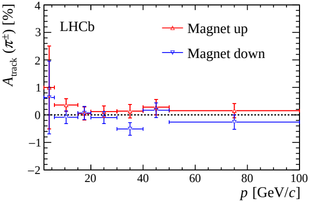
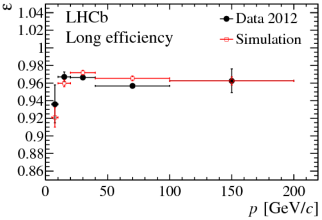


Figure 6: $\mathcal{A}_{\pi}$ as a function of pion momentum [PRL 117 061803].

- Hardware hadron trigger fired by signal:
  - Per-hadron charge-dependent trigger efficiency measured as a function of E_T with $D^{*+} \to D^0\pi^+$ decays [LHCb-PUB-2011-026]
  - Corrections for overlap of signal track deposits, occupancy from underlying event, and HCAL cell miscalibration
- Any hardware trigger fired by underlying event:
  - Charge asymmetry measured as function of B kinematics in $B \to \overline{D}^0\mu^+\nu_\mu X$ decays [PRD 95 052005]
- PID requirements:
  - Evaluated as a function of kinematics and event multiplicity with calibration data e.g. $D^{*+} \to D^0\pi^+$ [LHCb-PUB-2016-021]

- Hardware trigger efficiency → Up to 3% correction
- PID requirement efficiency → Up to 3% correction
- Track reconstruction efficiency:
  - Measured with $J/\psi \to \mu^+\mu^-$ decays as a function of kinematics [JINST 10 (2015) P02007]

→ Up to 6% ε correction



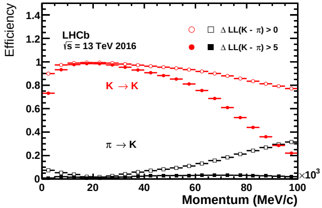


Table 2: Measured $\mathcal{A}^{CP}$ and comparison to existing world averages. Uncertainties are statistical, systematic, and on $\mathcal{A}^{CP}(B^+ \to J/\psi K^+)$.

Decay	$\mathcal{A}^{CP}$	World average [PDG]
$B^- \to D_s^- D^0$	$(+0.5 \pm 0.2 \pm 0.5 \pm 0.3)\%$	$(-0.4 \pm 0.7)\%$
$B^- \to D_s^{*-} D^0$	$(-0.5 \pm 1.1 \pm 1.0 \pm 0.3)\%$	-
$B^- \to D_s^- D^{*0}$	$(+1.1 \pm 0.8 \pm 0.6 \pm 0.3)\%$	-
$B^- \to D^- D^0$	$(+2.5 \pm 1.0 \pm 0.5 \pm 0.3)\%$	$(+1.6 \pm 2.5)\%$
$B^- \to D^{*-} D^0$	$(+3.3 \pm 1.6 \pm 0.6 \pm 0.3)\%$	$(-6 \pm 13)\%$
$B^- \to D^- D^{*0}$	$(-0.2 \pm 2.0 \pm 1.4 \pm 0.3)\%$	$(+13 \pm 18)\%$
$B^- \to D^{*-} D^{*0}$	$(+2.3 \pm 2.1 \pm 1.7 \pm 0.3)\%$	$(-15 \pm 11)\%$

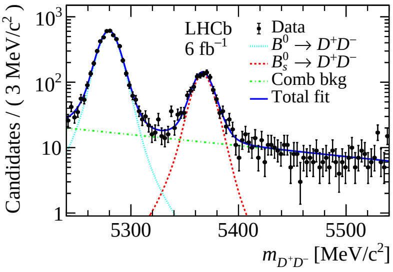
- Compatible with CP symmetry
- Dominant systematic uncertainties:
  - $\mathcal{A}_{\mathrm{P}}$ including $\mathcal{A}^{CP}(B^+ \to J/\psi K^+)$ (full. rec.)
  - Modelling of $B \to D^{**} D$ and combinatorial backgrounds (part. rec.)

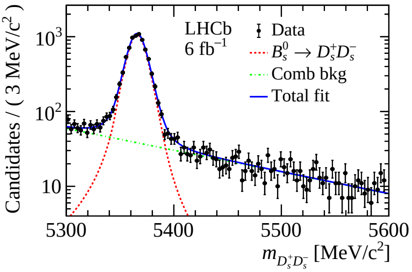
$$R(D^- D^0 / D_s^- D^0) = (7.25 \pm 0.09(stat.) \pm 0.09(syst.)) \times 10^{-2}$$

$$R(D^{*-} D^0 / D^- D^0) = 0.271 \pm 0.007(stat.) \pm 0.005(syst.)$$

- Dominant systematic uncertainties: Simulation sample size, tracking efficiency, PID efficiency
- Good agreement with current world average

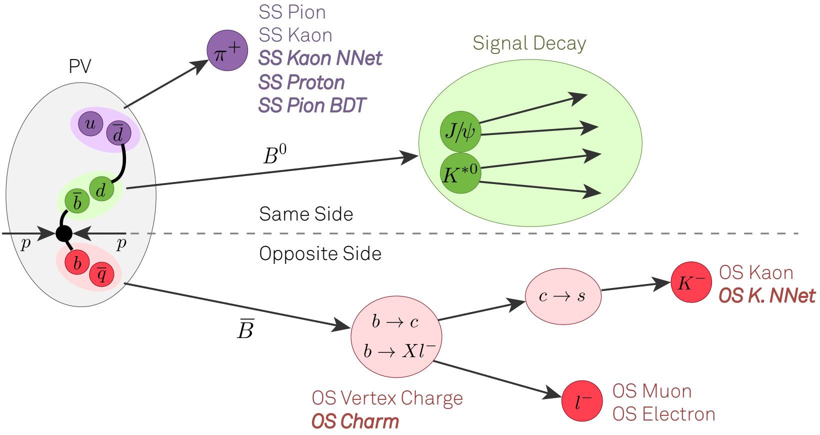
- Data corresponding to $6\,\text{fb}^{-1}$ pp collisions
- $D^+ \to K\pi\pi/KK\pi$, $D_s^+ \to KK\pi/K\pi\pi/\pi\pi\pi$
- Selection similarly to in previous measurements
- Background-subtraction weights obtained with fit to $m(D^+_{(s)} D^-_{(s)})$ and sPlot method [NIMA 555 356]





Flavour tagging

Predict initial b flavour using other particles from same primary vertex [EPJC 72 2022, EPJC 77 238, JINST 11 (2016) P05010, JINST 10 (2015) P10005]

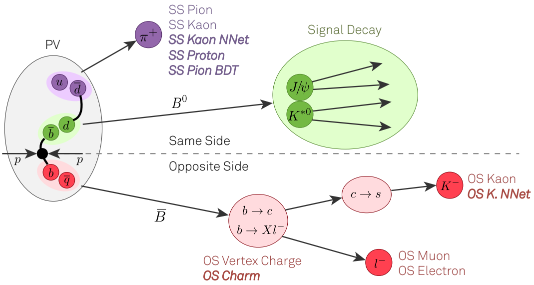


Flavour tagging

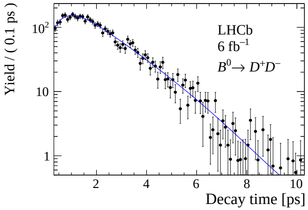
Mistag rate $\omega \sim 35 - 45\%$:

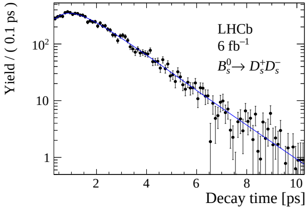
- From background and oscillations of opposite-side tagging meson
- Mistag probability calibrated with $B^0 \to D_s^- D^+$ and $B_s^0 \to D_s^- \pi^+$ decays in data

- Relative statistical power $\ll$Tagging power$\gg$ $\varepsilon(1-2\omega)^2 = (6.28 \pm 0.11)\%$ $(B^0 \to D^+ D^-$, Run 2)
- ($\varepsilon \equiv$ tagging efficiency)



- Fit to background-subtracted data as function of decay time and flavour tagging decision
- Model includes:
  - Decay rate as function of CP observables and mistag rate
  - B meson production asymmetry measured in $\overline{B}^0 \to D_s^+ D^{(*)-}$ and $B_s^0 \to D_s^- \pi^+$ decays [JHEP 03 (2020) 147,Nature Physics 18 (2022) 1]
  - Decay-time resolution
  - Acceptance as a function of decay time



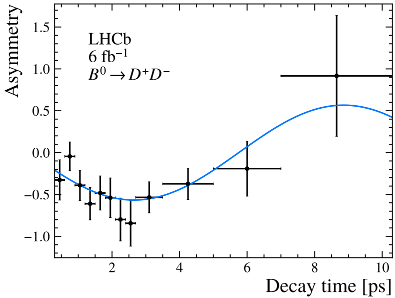


Combine with LHCb $3\,\text{fb}^{-1}$ measurement [PRL 117 261081]:

$$S = -0.549 \pm 0.085 \pm 0.015 \qquad C = \quad 0.162 \pm 0.088 \pm 0.009$$

i.e. CP symmetry rejected by $> 6\sigma$

- Most precise single measurement
- Compatible with existing LHCb and BaBar measurements [PRD 79 032002 (BaBar)]; increased tension with Belle I [PRD 85 091106]

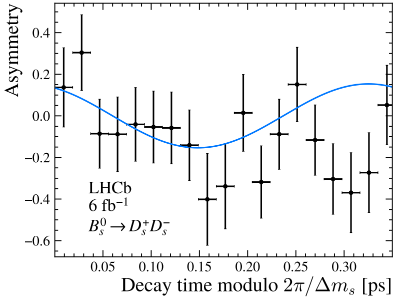


Combine with LHCb $3\,\text{fb}^{-1}$ measurement [PRL 113 211801]:

$$\phi_s = -0.086 \pm 0.106 \pm 0.028 \quad |\lambda| = \quad 1.145 \pm 0.126 \pm 0.031$$

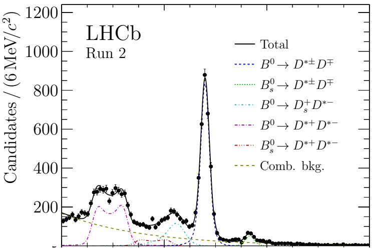
where $C = \frac{1-|\lambda|^2}{1+|\lambda|^2}$ and $S = -2\frac{|\lambda| \sin\phi_s}{1+|\lambda|^2}$

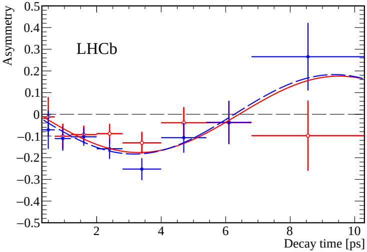
- Compatible with CP symmetry
- Most important systematic uncertainties from decay time resolution and bias



- $9\,\text{fb}^{-1}$ pp collisions/ $D^{*+} \to D^0\pi^+$, $D^0 \to K\pi(\pi\pi)$, $D^+ \to K\pi\pi$
- Most precise single measurement; Compatible with existing measurements [PRD 85 091106 (Belle I), PRD 79 032002 (BaBar)]
- CP symmetry rejected at $> 10\sigma$

$$S = -0.861 \pm 0.077 \pm 0.019, \quad \Delta S = 0.019 \pm 0.075 \pm 0.012$$
$$C = -0.059 \pm 0.092 \pm 0.020, \quad \Delta C = -0.031 \pm 0.092 \pm 0.016$$
$$A = 0.008 \pm 0.014 \pm 0.006$$





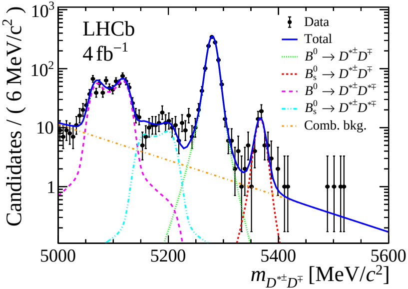
BF in $B_s^0 \to DD$ decays

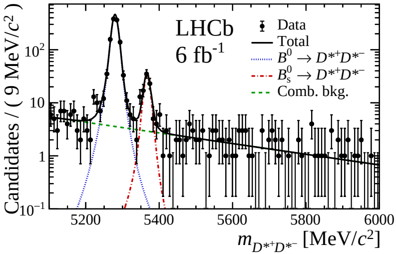
- First observations of suppressed $B_s^0 \to D^{*\pm} D^{(*)\pm}$ decays with data corresponding to $9\,\text{fb}^{-1}$ pp collisions [JHEP 03 (2021) 099, JHEP 07 (2023) 119]

$$\mathcal{B}(B_s^0 \to D^{*+} D^{*-}) = (2.15 \pm 0.26 \pm 0.09 \pm 0.06 \pm 0.16) \times 10^{-4}$$

$$\mathcal{B}(B_s^0 \to D^{*\pm} D^{\mp}) = (8.41 \pm 1.02 \pm 0.12 \pm 0.39 \pm 0.79) \times 10^{-5}$$

$$(stat., sys., f_s/f_d, norm\,\mathcal{B})$$





And many more!

$$\mathcal{B}(B^0_s \to D_s^{(*)+} D_s^{(*)-}) = (3.05 \pm 0.10 \pm 0.20 \pm 0.34)\%,$$
$$\mathcal{B}(B^0_s \to D_s^{*\pm} D_s^{\mp}) = (1.35 \pm 0.06 \pm 0.09 \pm 0.15)\%,$$
$$\mathcal{B}(B^0_s \to D_s^{*+} D_s^{*-}) = (1.27 \pm 0.08 \pm 0.10 \pm 0.14)\%.$$

$1\,\text{fb}^{-1}$ [PRD93 092008] (stat., sys., norm.)

$$\frac{\mathcal{B}(\overline{B}^0_s \to D^+ D^-)}{\mathcal{B}(\overline{B}^0 \to D^+ D^-)} = 1.08 \pm 0.20 \pm 0.10, \qquad \frac{\mathcal{B}(\overline{B}^0 \to D^0 \overline{D}^0)}{\mathcal{B}(B^- \to D^0 D_s^-)} = 0.0014 \pm 0.0006 \pm 0.0002,$$
$$\frac{\mathcal{B}(\overline{B}^0_s \to D_s^+ D^-)}{\mathcal{B}(B^0 \to D_s^+ D^-)} = 0.050 \pm 0.008 \pm 0.004, \qquad \frac{\mathcal{B}(\overline{B}^0_s \to D_s^+ D_s^-)}{\mathcal{B}(B^0 \to D_s^+ D^-)} = 0.56 \pm 0.03 \pm 0.04,$$
$$\frac{\mathcal{B}(\overline{B}^0_s \to D^0 \overline{D}^0)}{\mathcal{B}(B^- \to D^0 D_s^-)} = 0.019 \pm 0.003 \pm 0.003, \qquad \frac{\mathcal{B}(B^- \to D^0 D_s^-)}{\mathcal{B}(B^0 \to D_s^+ D^-)} = 1.22 \pm 0.02 \pm 0.07,$$

$1\,\text{fb}^{-1}$ [PRD87 092007] (stat., sys.)

Current status

Table 3: Summary of existing measurements of CP observables and branching fractions. References are not included where they contribute negligibly to the world average. * denotes an annihilation-dominated decay.

Decay	CP observables	Branching fraction
$B^- \to D_s^- D^0$	LHCb 9 fb^{-1}	Belle II 362 fb^{-1}, BaBar, CLEO
$B^- \to D_s^{*-} D^0$	LHCb 9 fb^{-1}	BaBar, CLEO
$B^- \to D_s^- D^{*0}$	LHCb 9 fb^{-1}	Belle II 362 fb^{-1}, BaBar, CLEO
$B^- \to D_s^{*-} D^{*0}$	-	BaBar, CLEO
$B^- \to D^- D^0$	LHCb 9 fb^{-1}, Belle I, BaBar	LHCb 9 fb^{-1}, Belle I, BaBar
$B^- \to D^{*-} D^0$	LHCb 9 fb^{-1}, BaBar	LHCb 9 fb^{-1}, BaBar, Belle I
$B^- \to D^- D^{*0}$	LHCb 9 fb^{-1}, BaBar	BaBar
$B^- \to D^{*-} D^{*0}$	LHCb 9 fb^{-1}, BaBar	BaBar
$B^0 \to D^+ D^-$	LHCb 9 fb^{-1}, Belle I, BaBar	Belle I
$B^0 \to D^{*\pm} D^\mp$	LHCb 9 fb^{-1}, Belle I, BaBar	Belle I
$B^0 \to D^{*+} D^{*-}$	Belle I, BaBar	Belle I
$*B^0 \to D^0 \bar{D}^0$	-	LHCb 1 fb^{-1}
$\bar{B}^0 \to D_s^- D^+$	-	Belle II 362 fb^{-1}, BaBar
$\bar{B}^0 \to D_s^{*-} D^+$	-	BaBar
$\bar{B}^0 \to D_s^- D^{*+}$	-	Belle II 362 fb^{-1}, BaBar
$\bar{B}^0 \to D_s^{*-} D^{*+}$	-	BaBar
$*\bar{B}^0 \to D_s^- D_s^+$	-	-
$\bar{B}_s^0 \to D^- D_s^+$	-	LHCb 3 fb^{-1}
$B_s^0 \to D_s^- D_s^+$	LHCb 9 fb^{-1}	LHCb 1 fb^{-1}
$*B_s^0 \to D^+ D^-$	-	LHCb 1 fb^{-1}
$*B_s^0 \to D^{*\pm} D^\mp$	-	LHCb 9 fb^{-1}
$*B_s^0 \to D^{*+} D^{*-}$	-	LHCb 9 fb^{-1}
$*B_s^0 \to D^0 \bar{D}^0$	-	LHCb 1 fb^{-1}

Phenomenological implications

- Measurements analysed within $SU(3)_F$ symmetry framework in [arXiv:2311.16952 (Davies, Jung, Schacht)]
- Good SM fit of CP observables
- Some isospin-symmetry violation: Best fit $f_d/f_u = 0.86 \pm 0.05$ @ 7 TeV
- $\mathcal{A}^{CP}(B^- \to D^- D^0) = (2.4 \pm 1.1)\%$ indicates penguin contributions relatively small

→ Very tight constraint on $\mathcal{A}^{CP}(B^- \to D_s^- D^0)$: $> 0.5\%$ would already indicate NP

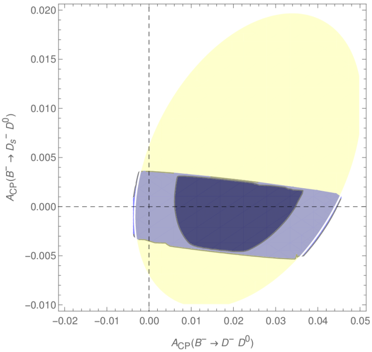


Figure 7: Constraints from (yellow) experiment at 95% CL and from global fit at (dark blue) 68% and (light blue) 95% CL [arXiv:2311.16952].

The allowed phase space for non-SM measurements is enormous

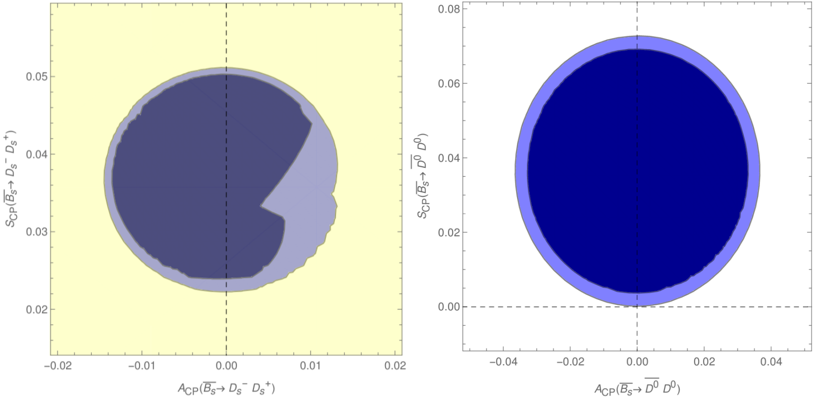
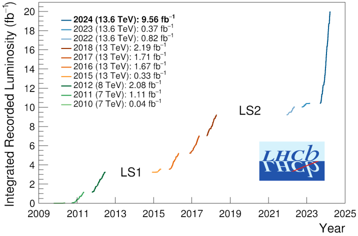
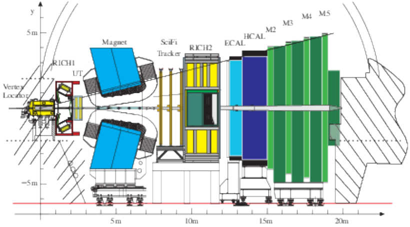


Figure 8: Constraints from (yellow) experiment at 95% CL and from global fit at (dark blue) 68% and (light blue) 95% CL [arXiv:2311.16952].

Future prospects

- 2023-2032 (Run 3+4): 5× higher instantaneous luminosity
- Detector upgrade + redesign [JINST 19 (2024) P05065] to accommodate higher pileup
  - Including entirely new higher-granularity tracking detectors





Future prospects

- Hardware trigger removed
- First trigger (30MHz) now software trigger on GPUs
  - $\rightarrow$ Substantial improvement in low-p_T trigger efficiency: Particularly important for hadronic B decays
- Real-time analysis and calibration in trigger enable exclusive selections $\rightarrow$ Yet higher efficiency

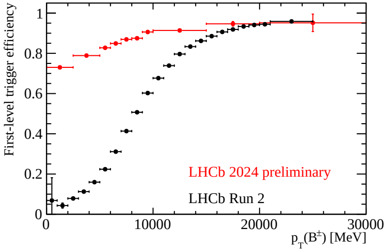


Figure 9: Efficiency of first-level hadron track software triggers in 2024 data and hardware hadron trigger in Run 2 data as a function of p_T for $B^+ \rightarrow D^0\pi^+$ decays [LHCb-FIGURE-2024-014].

$\rightarrow \sim 3\times$ trigger efficiency increase in Run 3 for $B \rightarrow DD$

Future prospects

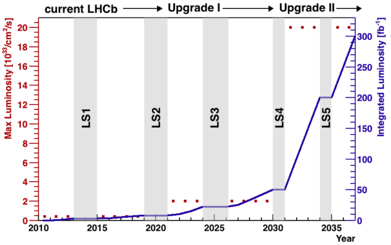
- 2024 data may already permit to confirm or refute $B_c^+ \to D_s^+ \overline{D}^0$ evidence (work in progress!)

$+$ $2-3\times$ precision on $\mathcal{A}^{CP}$ by end of Run 3

$+$ Measure CPV in rarer decays

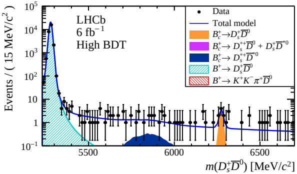
- Run 5+6:
  - Further $10\times \uparrow$ instantaneous luminosity
  - Further substantial upgrades [Upgrade II FTDR]

$\to$ $10\times$ precision by end of HL-LHC



Summary

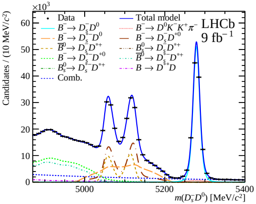
- Double charm B meson decays provide insight into SM and BSM physics
- Search for 16 $B_c^+ \to DD$ decays with $9\,\text{fb}^{-1}$ [JHEP 12 (2021) 117]
- 3.4σ evidence for $B_c^+ \to D_s^+ \overline{D}^0$ corresponding to $\mathcal{B} = (3.5^{+1.5+0.3}_{-1.2-0.2} \pm 1.0) \times 10^{-4}$

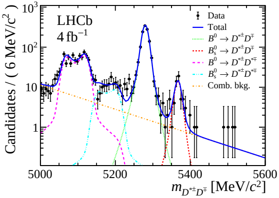


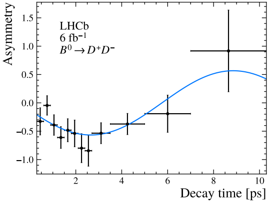
$\rightarrow$ Two orders of magnitude larger than SM prediction

- Improved upper limits on 15 further $B_c^+ \to DD$ decays
- If evidence confirmed with future LHCb data, would challenge understanding of B_c^+ meson phenomenology or potentially SM itself

- Measurements of CP asymmetries and branching fractions in $B^- / B^0 / B_s^0 \to DD$ decays with up to $9\,\text{fb}^{-1}$ LHCb data presented
- Results constrain QCD penguin amplitudes and CP-violating BSM physics
- Excellent BSM sensitivity prospects with future LHCb data

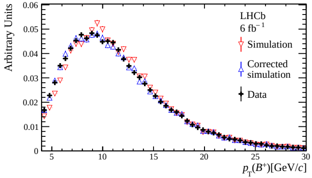


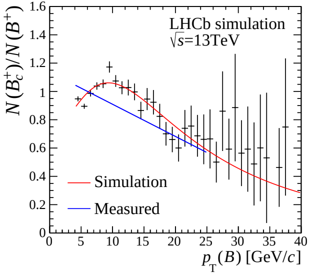




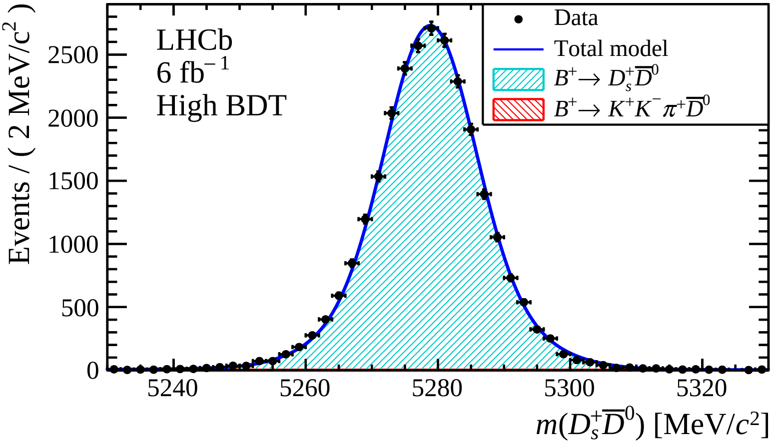
Backup

- Correct $p_T(B^+)$, $y(B^+)$, event multiplicity to match background-subtracted data
  - Gradient boosted reweighting (GBR) [JPCS 762 012036]
- Linear dependence of $\frac{f_c}{f_u}$ on $(p_T(B), y(B))$ has been measured [PRD100 112006]
  - Correct so that $N(B_c^+)/N(B^+)$ matches
- $D^0 \to K3\pi$ angular distribution generated according to phase space
  - Correct all 2- and 3-body mass combinations with GBR to background-subtracted data





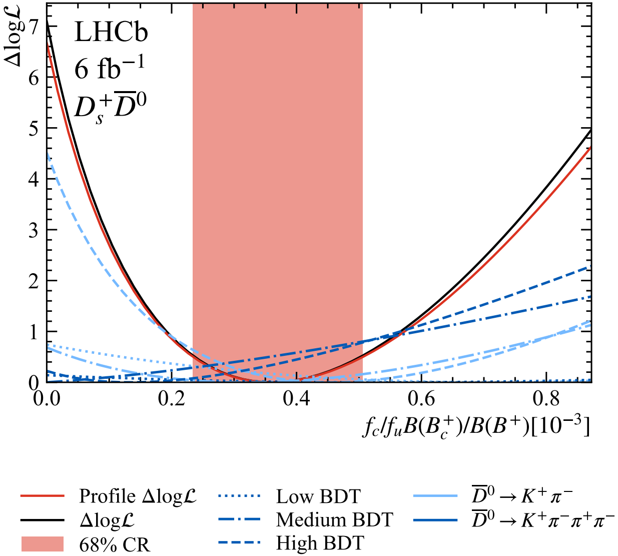
Fit to $B^+ \to DD$ in data



$B_c^+ \to DD$ systematics

Final state	$D_s^+ D^0$		$D^+ D^0$		$D^{*+} D^0$	
	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
B_c^+ signal shape	9.4	3.8	4.8	5.3	2.8	3.9
B_c^+ production spectrum	3.7	2.4	3.9	2.4	4.2	2.9
B^+ production spectrum	0.5	0.9	0.6	1.0	0.6	1.1
Hit resolution parameterisation	–	1.5	–	1.2	–	2.2
R simulation sample size	1.2	1.0	1.4	1.1	1.5	1.5
$R'_{(+,0)}$ simulation sample size	1.4	0.9	2.1	1.2	1.1	1.1
R'' simulation sample size	1.5	0.8	1.7	0.9	–	–
B_c^+ lifetime	1.3	1.4	1.3	1.3	2.1	2.6
PID efficiencies	1.6	1.2	2.8	0.8	2.2	1.4
Multiple $B_{(c)}^+$ candidates	0.4	0.4	0.6	0.5	1.4	1.2
Data-simulation differences	0.1	0.1	0.1	0.1	0.1	0.2
$B^+ \to \overline{D}^0 K^+ K^- \pi^+$	0.7	0.5	–	–	–	–
$\mathcal{B}(D^{*+} \to D^+ X^0)$	–	–	1.5	1.5	–	–
R total	10.4	5.3	7.2	6.6	6.3	6.5
$R'_{(+,0)}$ total	4.6	3.7	5.7	3.8	5.5	5.0
R'' total	4.6	3.7	5.5	3.7	–	–

$B_c^+ \to D_s^+ \overline{D}^0$



$\mathcal{A}^{CP}$ systematic uncertainties

Largest systematics:

- Full. rec.: $\mathcal{A}_{\mathrm{P}}$ incl. $\mathcal{A}^{CP}(B^+ \to J/\psi K^+)$
- Part. rec.: Combinatorial model, $B \to D^{**} D$ model, $\mathcal{A}^{CP}/f_L(B_s^0 \to D_{(s)}^{(*)-} D^{*+})$

Table 2: Systematic uncertainties on $\mathcal{A}^{CP}$ in percent, averaged over all D^0 decay modes.

Source	$D_s^- D^0$		$D^- D^0$		$D^{*-} D^0$	
	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
$\mathcal{A}_{\text{raw}}(B^- \to D_{(s)}^{(*)-} D^0)$						
Double charm model	0.01	0.02	0.11	0.08	0.21	0.18
Single charm model	0.05	0.05	-	-	-	-
Cross-feed model	-	-	0.00	0.00	-	-
Combinatorial model	0.01	0.00	0.14	0.13	0.52	0.15
External inputs	0.05	0.06	0.01	0.00	0.04	0.01
Total	0.07	0.08	0.18	0.15	0.56	0.23
$\mathcal{A}_{\text{raw}}(B^- \to D_{(s)}^{(*)-} D^{*0})$						
Double charm model	0.14	0.23	1.10	1.04	1.51	1.19
Cross-feed model	-	-	0.00	0.00	-	-
Combinatorial model	0.08	0.04	1.14	0.92	4.49	1.02
External inputs	0.55	0.38	0.14	0.12	0.11	0.11
Total	0.57	0.45	1.59	1.40	4.74	1.57
$\mathcal{A}_{\text{raw}}(B^- \to D_s^{*-} D^0)$						
Double charm model	0.78	0.51				
Combinatorial model	0.55	0.22				
External inputs	0.89	0.73				
Total	1.31	0.91				
$\mathcal{A}_{\mathrm{P}}$	0.42	0.43	0.41	0.43	0.48	0.48
$\mathcal{A}^{CP}(B^+ \to J/\psi K^+)$	0.30	0.30	0.30	0.30	0.30	0.30
$\mathcal{A}_{\mathrm{K}\pi}$	0.28	0.11	0.04	0.04	0.10	0.00
$\mathcal{A}_{\pi}$	0.09	0.09	0.06	0.06	0.18	0.17
$\mathcal{A}_{\mathrm{PID}}$	0.29	0.03	0.25	0.11	0.55	0.10
$\mathcal{A}_{\mathrm{L0\,TIS}}$	0.08	0.10	0.08	0.10	0.09	0.11
$\mathcal{A}_{\mathrm{L0\,TOS}}$	0.01	0.03	0.01	0.02	0.01	0.01
Weighting	0.01	0.00	0.04	0.00	0.01	0.00
Part. rec. weighting	0.03	0.02	0.02	0.01	0.03	0.01
Total	0.67	0.55	0.58	0.55	0.82	0.61

R systematic uncertainties

Table 3: Fractional systematic uncertainties on branching fraction ratios in percent, combined over all D^0 decay modes.

Source	$R(B^- \to D^- D^0)$		$R(B^- \to D^{*-} D^0)$	
	Run 1	Run 2	Run 1	Run 2
Double charm model	0.8	0.1	1.2	0.4
Single charm model	0.3	0.3	-	-
Cross-feed model	0.0	0.0	0.0	0.0
Combinatorial model	0.1	0.0	0.5	0.2
Hardware trigger efficiency	0.6	0.1	1.4	0.2
Tracking efficiency	0.4	0.3	1.4	1.1
PID efficiency	0.8	0.6	1.6	0.7
Simulation sample size	0.8	0.9	1.1	1.1
Multiple candidate removal	0.1	0.1	0.2	0.4
MVA variable mismodelling	0.8	0.1	1.0	0.4
Track χ^2 mismodelling	0.5	0.1	0.5	0.1
Weighting	0.1	0.0	0.1	0.0
Total	1.8	1.2	3.3	1.9

Prospects for Run 3

- Removal of hardware trigger
- Real-time analysis and calibration in software triggers

$\rightarrow \sim 3\times$ increase in trigger efficiency in Run 3