Beauty to Open Charm Final States at LHCb

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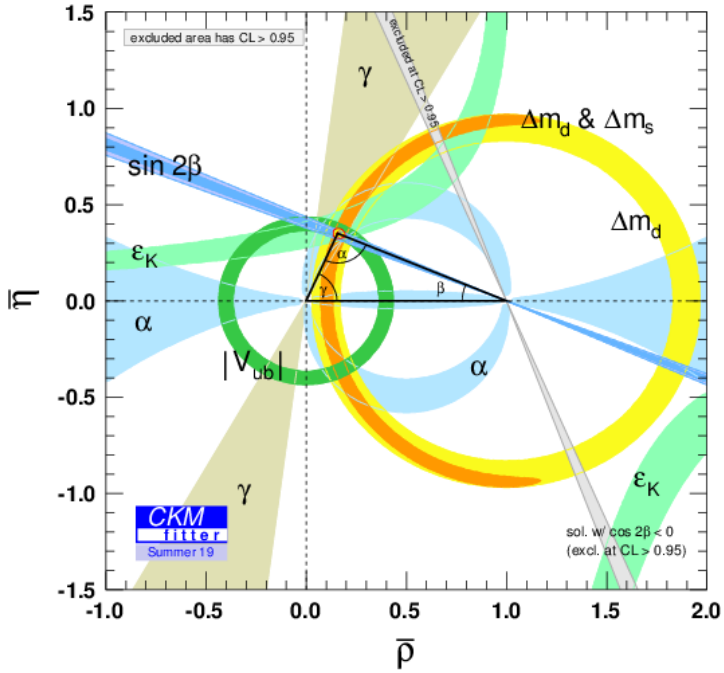
on behalf of the LHCb collaboration

EPS-HEP Conference
26/07/21

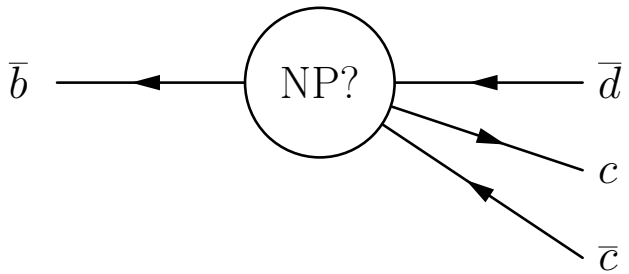
UNIVERSITY OF CAMBRIDGE

Introduction

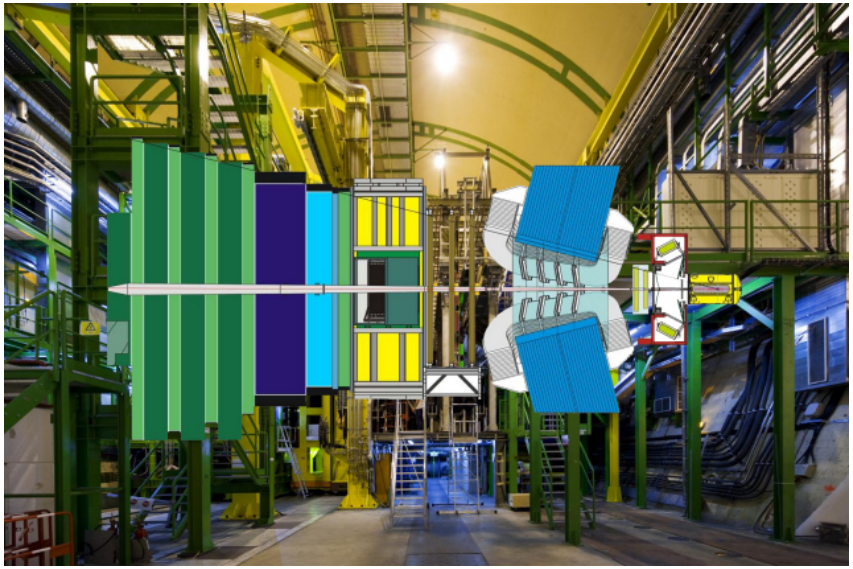
- Measurement of CKM parameters
  - Including γ from *CP*-violating decays
- Searches for rare hadronic B decays
- Precision measurements of branching fractions and CPV to probe for BSM physics

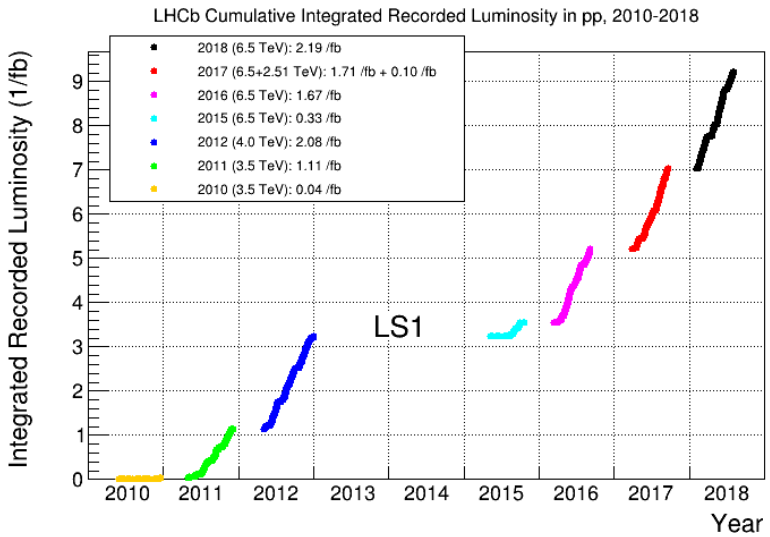


[CKMfitter]



- Optimised for beauty and charm hadrons
- Single-arm forward spectrometer: $2 < \eta < 5$
- Momentum resolution: $\Delta p/p \sim 0.5\%$ (low p)
- Impact parameter resolution: 15 µm (high p_T)
- $m(B \to hh)$ resolution: 22 MeV/c^2
- $\varepsilon(K) \sim 95\%$ at 5% $\pi \to K$ misID





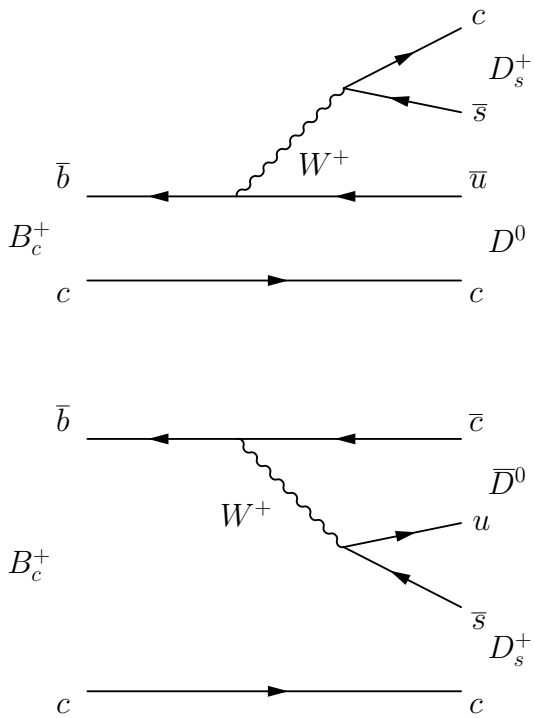
Outline

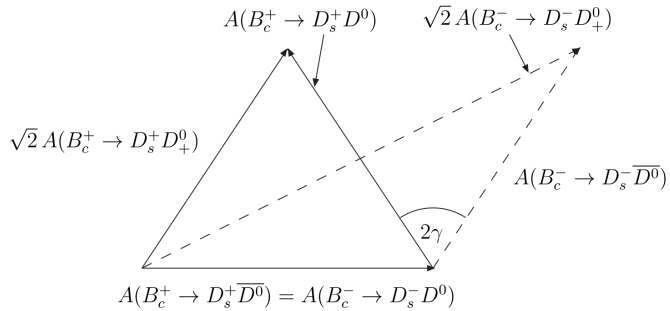
- $B_c^+ \to DD$: LHCb-PAPER-2021-023 (in preparation) NEW
- $B_s^0 \to D^{*\pm} D^{\mp}$: JHEP 03 (2021) 099
- $B^0 \to D_s^+ \pi^-$: Eur. Phys. J. C81 (2021) 314

Related talks:

- Measurements of the CKM angle γ at LHCb - Mark Whitehead

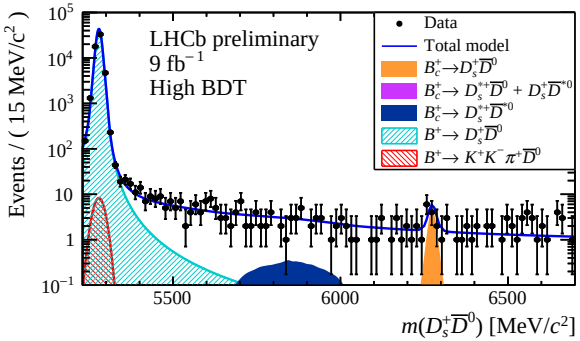
- Search for 14 $B_c^+ \to D_{(s)}^{(*)+} \overset{(-)}{D}{}^{(*)0}$ decays
- $B_c^+ \to D_s^+ \overset{(-)}{D}{}^0$ alternative for measuring γ: $\mathcal{A}^{CP} \sim \mathcal{O}(1)$
- Predictions [PRD 86 (2012) 074019]:
  - $\mathcal{B}(B_c^+ \to D_s^+ \overline{D}^0) = 2.3 \times 10^{-6}$
  - $\mathcal{B}(B_c^+ \to D^+ \overline{D}^0) = 3.2 \times 10^{-5}$
- Other predictions vary by up to order of magnitude
- $\mathcal{B}$ measurements can constrain B_c^+ theory

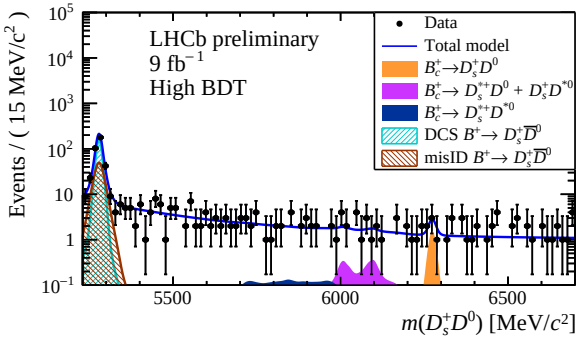


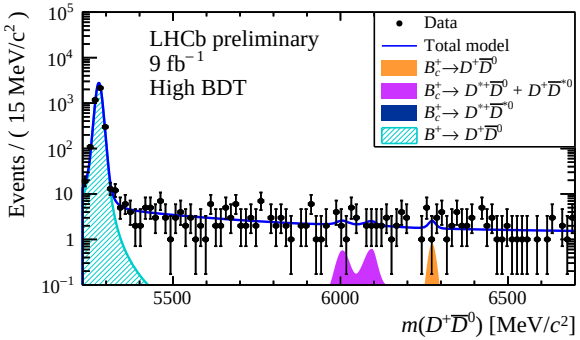


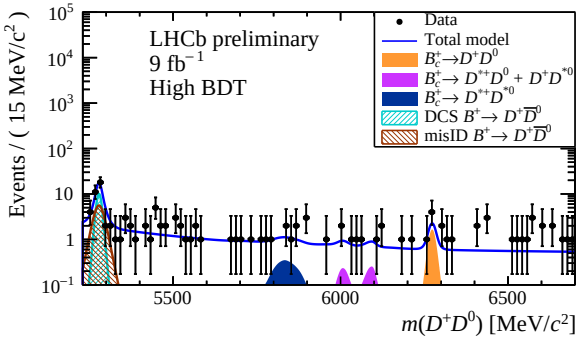
[PRD 62 (2000) 057503]

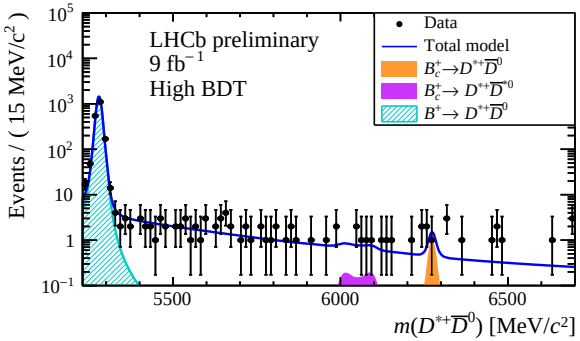
- Fourteen decays in six $D\overset{(-)}{D}{}^0$ channels ($D = D^+, D_s^+, D^{*+}$)

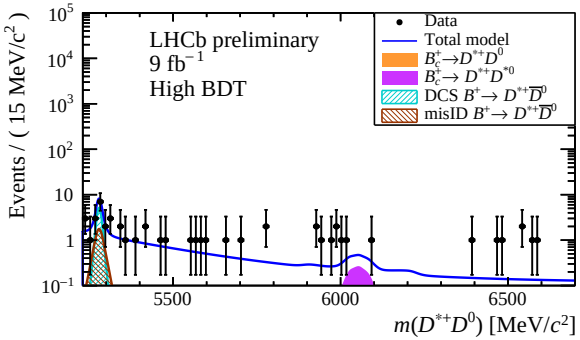








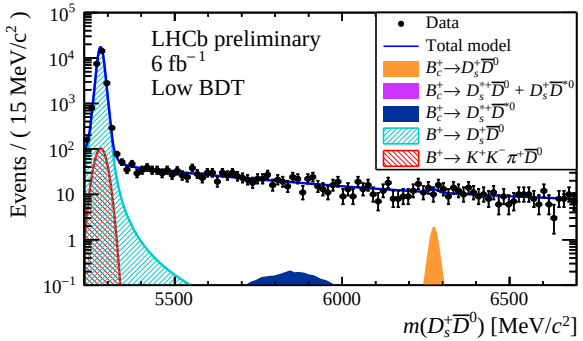


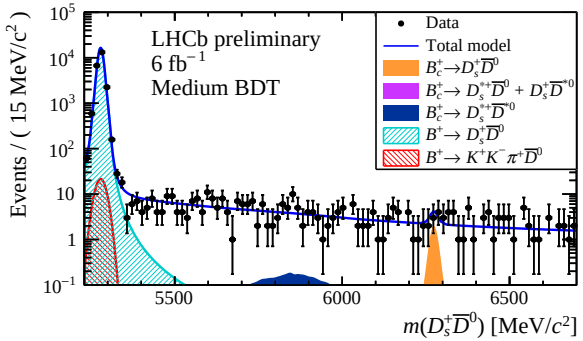


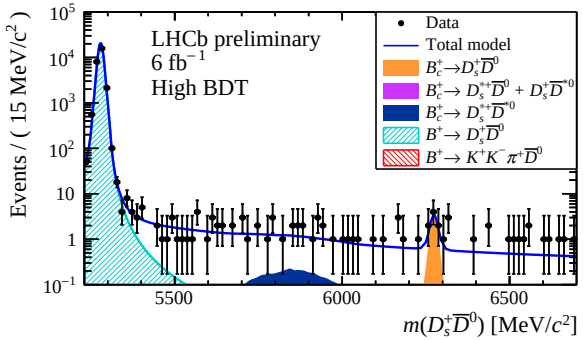
- $3\,\text{fb}^{-1}$ 2011-12; $6\,\text{fb}^{-1}$ 2015-18
- Normalise to $B^+ \to D\bar{D}^0$

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

- Fit simultaneously to bins in Boosted Decision Tree (BDT) response to improve sensitivity





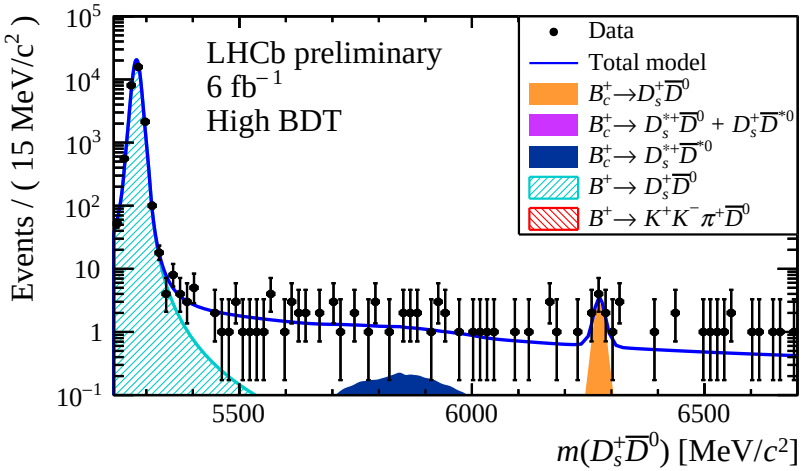


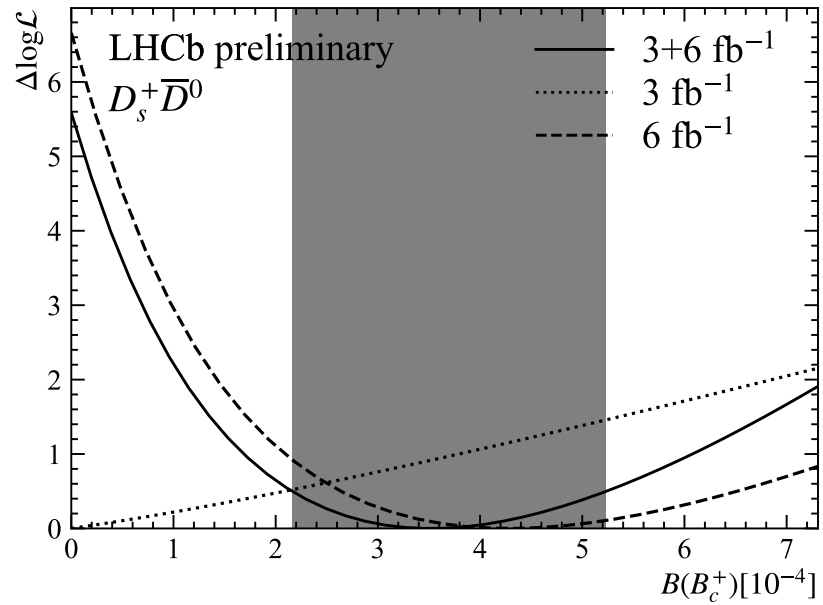
- 3.4σ evidence for $B_c^+ \to D_s^+ \overline{D}^0$

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

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

(stat, sys, ext)

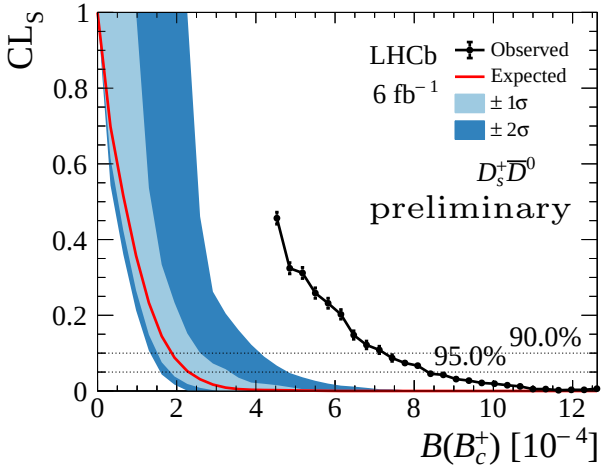


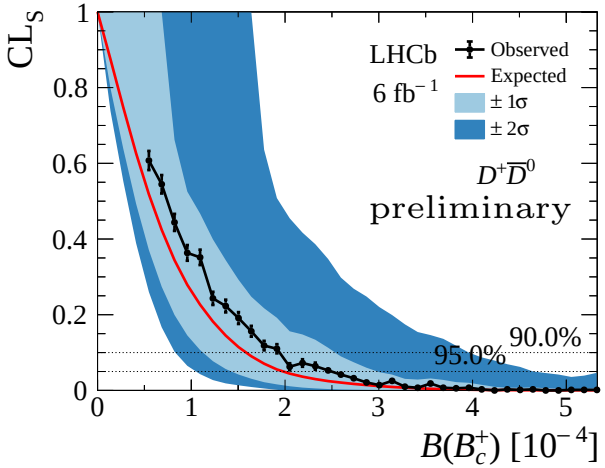


- Upper limits on $\mathcal{B}$ at 90(95)% CL:

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

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

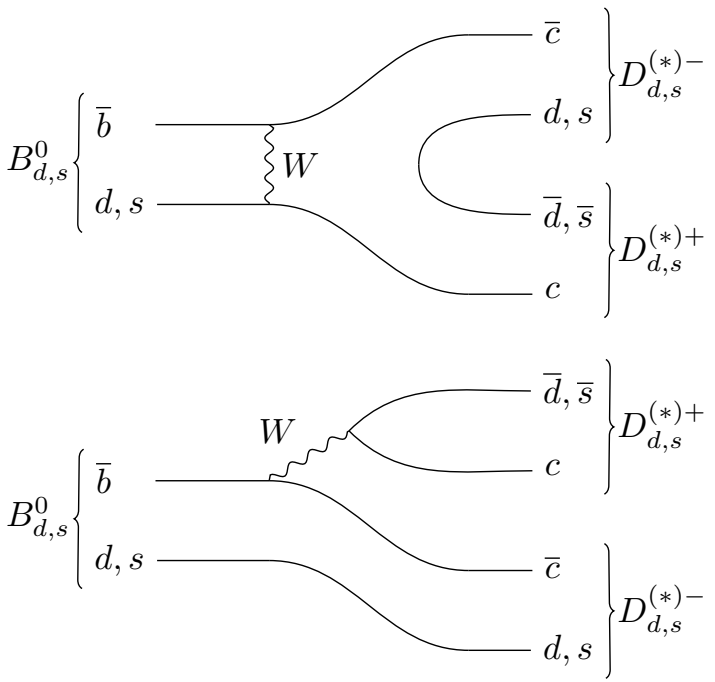




- Aim: First observation of $B_s^0 \to D^{*\pm} D^{\mp}$
- $B_s^0 \to D^{*\pm} D^{\mp}$ dominated by W-exchange, penguin annihilation and rescattering

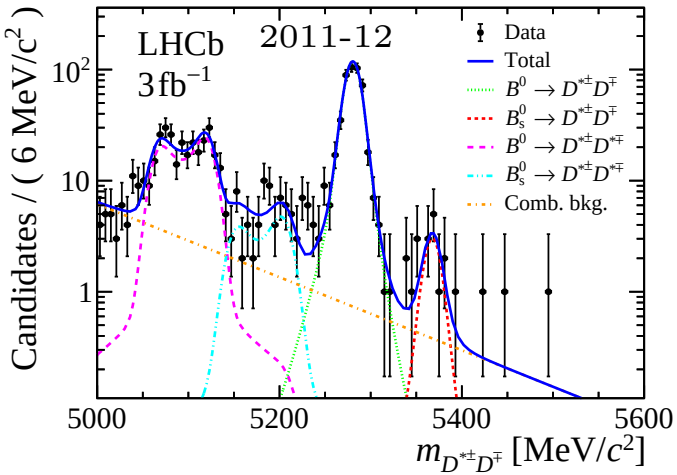
$\to$ Can estimate size of these subleading contributions to $B^0 \to D^{*\pm} D^{\mp}$

- $B^0 \to D^{(*)+} D^{(*)-}$ decays used to calculate $\sin(2\beta)$

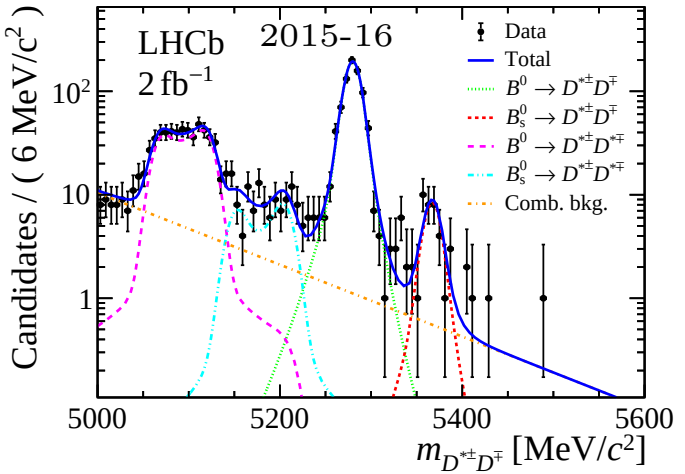


$$\frac{f_s}{f_d} \frac{\mathcal{B}(B_s^0 \to D^{*\pm} D^{\mp})}{\mathcal{B}(B^0 \to D^{*\pm} D^{\mp})} = \frac{N_{B_s^0}}{N_{B^0}} \frac{\varepsilon_{B^0}}{\varepsilon_{B_s^0}}$$

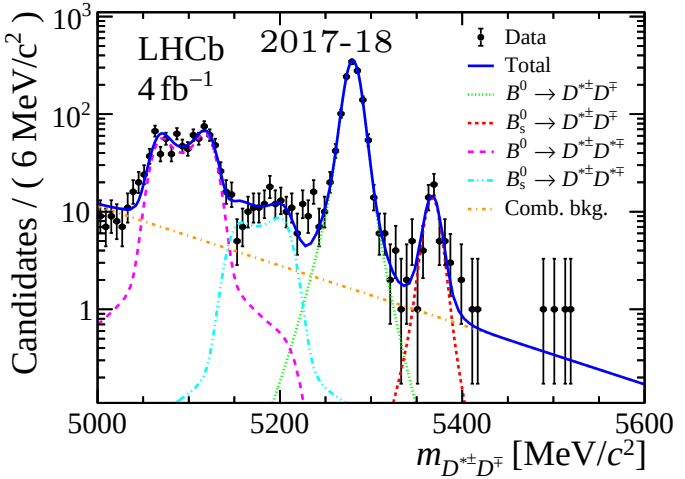
2011-12 ($3\,\text{fb}^{-1}$), 2015-16 ($2\,\text{fb}^{-1}$) and 2017-18 ($4\,\text{fb}^{-1}$) data



$N_{B_s^0} = 12 \pm 4$, $N_{B^0} = 466 \pm 22$



$N_{B_s^0} = 34 \pm 7$, $N_{B^0} = 780 \pm 29$



$N_{B_s^0} = 49 \pm 8$, $N_{B^0} = 1263 \pm 36$

- $B_s^0 \to D^{*\pm} D^{\mp}$ observed with high significance
- Combine results from all data-taking periods:

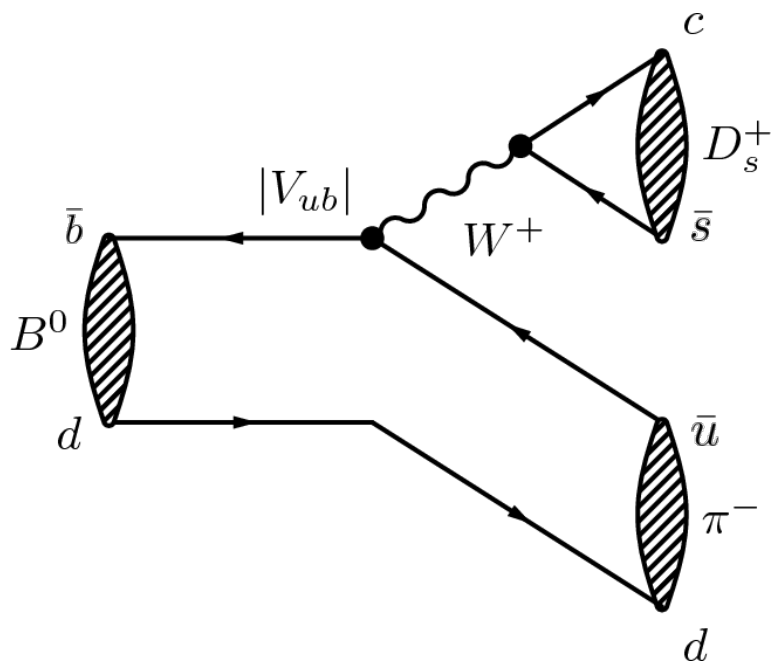
$$\frac{\mathcal{B}(B_s^0 \to D^{*\pm} D^{\mp})}{\mathcal{B}(B^0 \to D^{*\pm} D^{\mp})} = 0.137 \pm 0.017 \pm 0.002 \pm 0.006$$

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

$$(\text{stat}, \text{sys}, \frac{f_s}{f_d}, \mathcal{B}(B^0 \to D^{*\pm} D^{\mp}))$$

- Agreement with predictions which assume prominent contributions from rescattering [PRD 87 036008]

- Most precise single measurement of $\mathcal{B}(B^0 \to D_s^+\pi^-)$
- Extract:
  - $|V_{ub}||a_{NF}|$
    - $|a_{NF}|$ = relative size of non-factorisable effects
  - $r_{D\pi}$
- Measure collision energy dependence of $\frac{f_s}{f_d}$ using Cabibbo-favoured $B^0_{(s)} \to D^-_{(s)}\pi^+$ decays



$$\mathcal{R} \equiv \frac{N_{\bar{B}^0_s \to D_s^+\pi^-}}{N_{B^0 \to D^-\pi^+}} \frac{\varepsilon_{B^0 \to D^-\pi^+}}{\varepsilon_{\bar{B}^0_s \to D_s^+\pi^-}} \propto \frac{f_s}{f_d}$$

- $5\,\text{fb}^{-1}$ collected in 2011-16

$$\frac{\mathcal{B}(B^0 \to D_s^+ \pi^-)}{\mathcal{B}(B^0 \to D^- \pi^+)} =$$

$$(7.7 \pm 0.7 \pm 0.5 \pm 0.3) \times 10^{-3}$$

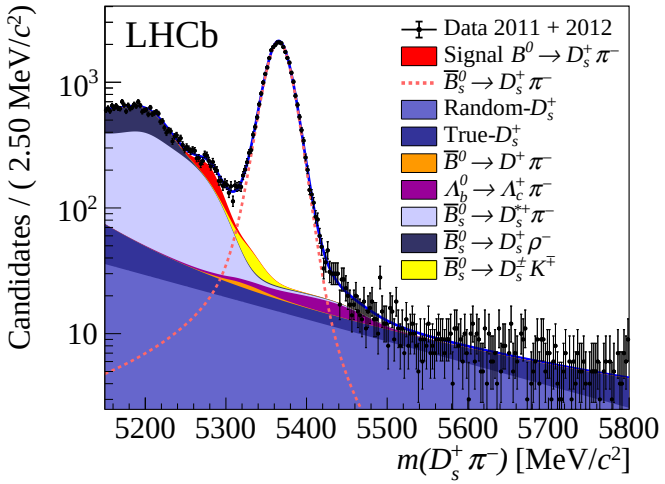
(stat, sys, ext)

- Consistent with current world average $\mathcal{B}(B^0 \to D_s^+ \pi^-) = (21.6 \pm 2.6) \times 10^{-6}$ [PDG]

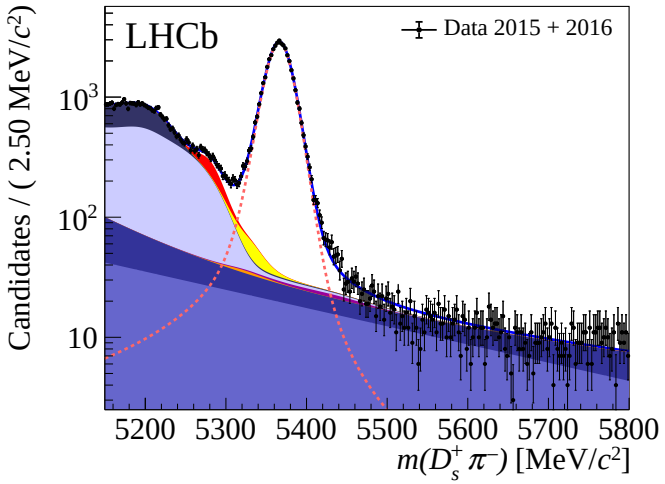
$$r_{D\pi} = \tan\theta_c \frac{f_{D^+}}{f_{D_s^+}} \sqrt{\frac{\mathcal{B}(B^0 \to D_s^+ \pi^-)}{\mathcal{B}(B^0 \to D^- \pi^+)}}$$

$$= 0.0163 \pm 0.0007 \pm 0.0007 \pm 0.0033$$

(stat, sys, SU(3)-breaking)



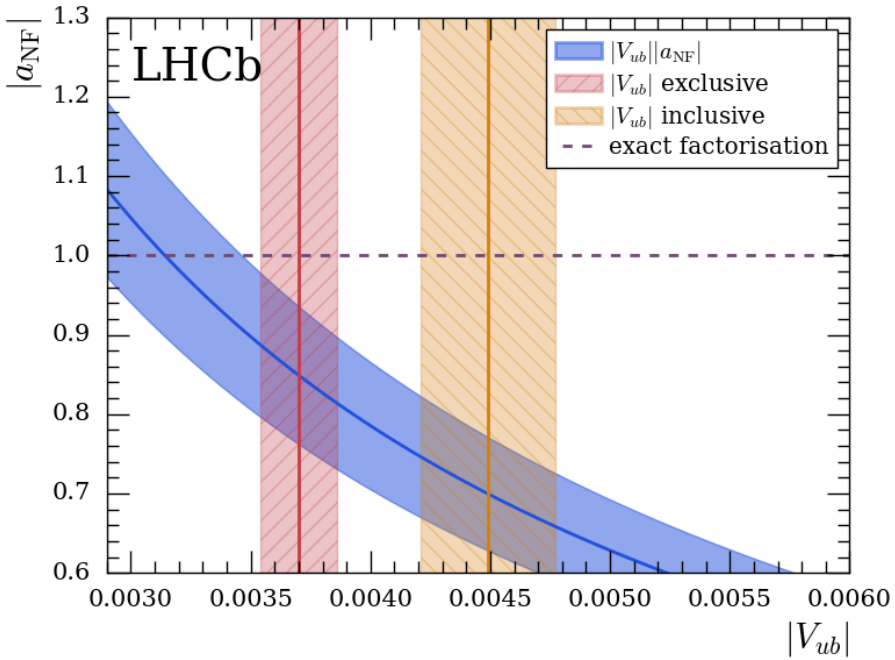
$N_{B^0 \to D_s^+ \pi^-} = (8.9 \pm 0.8) \times 10^2$



$N_{B^0 \to D_s^+ \pi^-} = (1.12 \pm 0.11) \times 10^3$

$$\mathcal{B}(B^0 \to D_s^+ \pi^-) =$$

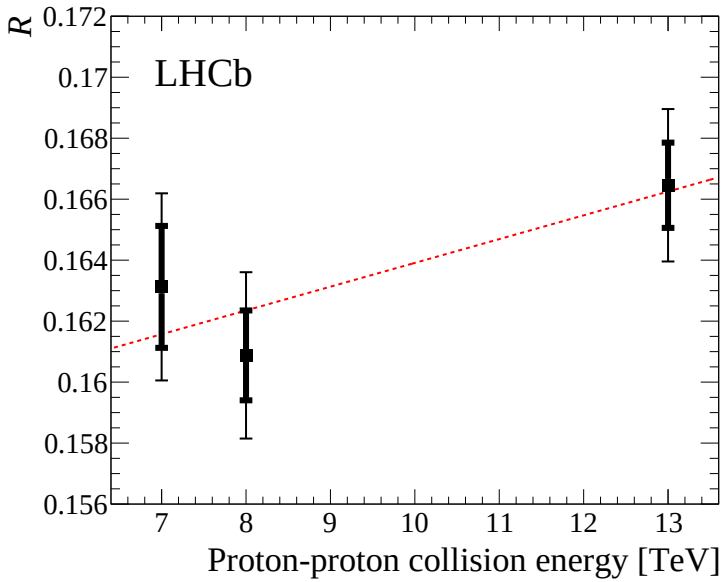
$$\Phi |V_{ub}|^2 |V_{cs}|^2 |F(B^0 \to \pi^-)|^2 f_{D_s^+}^2 |a_{NF}|^2$$



$$|V_{ub}||a_{NF}| =$$

$$(3.14 \pm 0.20 \pm 0.25) \times 10^{-3}$$

$$(\mathcal{B}(B^0 \to D_s^+ \pi^-), \text{ext})$$

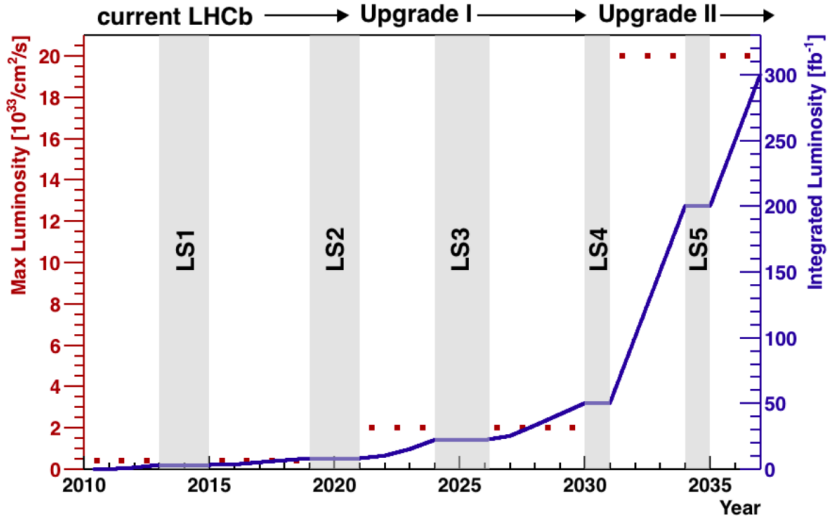


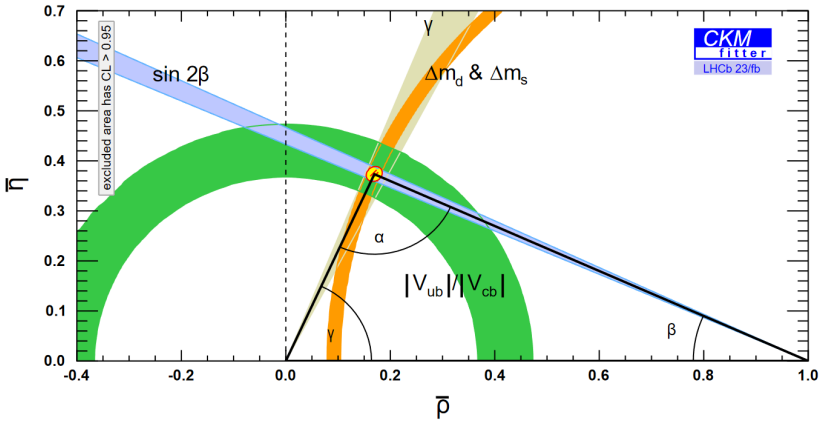
$$\frac{f_s}{f_d} \propto \mathcal{R} =$$

$$0.156(6) + 0.0008(6)(\sqrt{s}/\text{ TeV})$$

Summary

- 3.4σ evidence for $B_c^+ \to D_s^+ \overline{D}^0$
- First observation of $B_s^0 \to D^{*\pm} D^{\mp}$
- Most precise single measurement of $\mathcal{B}(B^0 \to D_s^+ \pi^-)$
- Substantial increase in data in Run 3 and beyond:
  - First observations of rare beauty to open charm decays
  - Improved constraints on CKM parameters, e.g. $\Delta\gamma \sim 1.5^\circ$ with $23\,\text{fb}^{-1}$



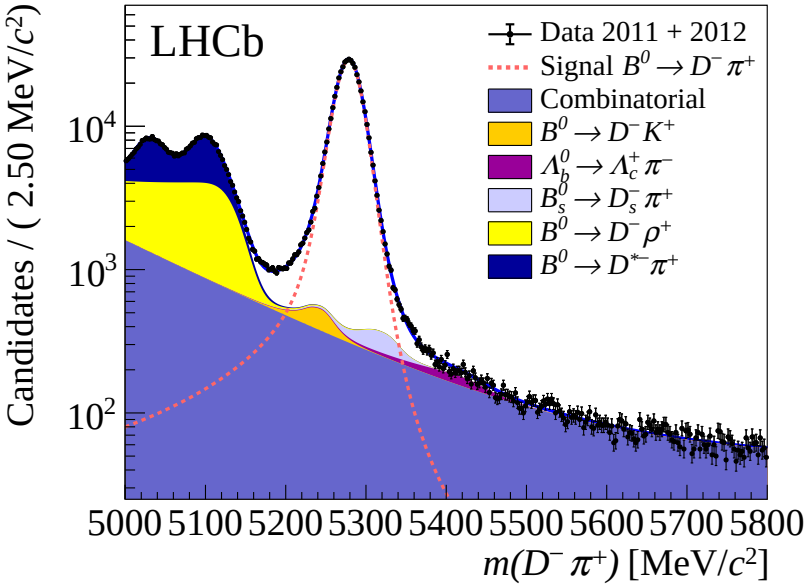


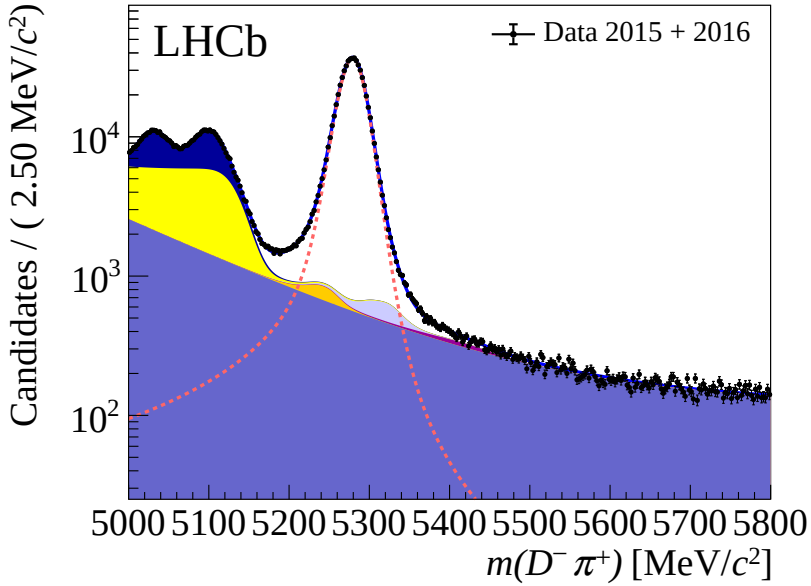
[LHCb-PUB-2018-009]

Backup

Upper limits at 90(95)% CL

$$\mathcal{B}(B_c^+ \to D_s^{*+}\overline{D}^0) + \mathcal{B}(B_c^+ \to D_s^+\overline{D}^{*0}) < 4.1\,(4.9) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D_s^{*+}D^0) + \mathcal{B}(B_c^+ \to D_s^+D^{*0}) < 7.0\,(8.5) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D^{*+}\overline{D}^0) + \mathcal{B}(B_c^+ \to D^+\overline{D}^{*0}) < 5.8\,(6.9) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D^{*+}D^0) + \mathcal{B}(B_c^+ \to D^+D^{*0}) < 3.6\,(4.5) \times 10^{-4}$$
$$\mathcal{B}(B_c^+ \to D_s^{*+}\overline{D}^{*0}) < 1.1\,(1.4) \times 10^{-3}$$
$$\mathcal{B}(B_c^+ \to D_s^{*+}D^{*0}) < 1.2\,(1.4) \times 10^{-3}$$
$$\mathcal{B}(B_c^+ \to D^{*+}\overline{D}^{*0}) < 0.9\,(1.1) \times 10^{-3}$$
$$\mathcal{B}(B_c^+ \to D^{*+}D^{*0}) < 5.2\,(6.7) \times 10^{-4}$$


LHCb
Data 2011 + 2012
Signal $B^0 \to D^- \pi^+$
Combinatorial
$B^0 \to D^- K^+$
$\Lambda_b^0 \to \Lambda_c^+ \pi^-$
$B_s^0 \to D_s^- \pi^+$
$B^0 \to D^- \rho^+$
$B^0 \to D^{*-} \pi^+$
Candidates / (2.50 MeV/c^2)
$m(D^- \pi^+)$ [MeV/c^2]


LHCb
Data 2015 + 2016
Candidates / (2.50 MeV/c^2)
$m(D^- \pi^+)$ [MeV/c^2]

$$\mathcal{B}(B^0 \to D_s^+ \pi^-) = \Phi |V_{ub}|^2 |V_{cs}|^2 |F(B^0 \to \pi^-)|^2 f_{D_s^+}^2 |a_{NF}|^2$$

$$r_{D\pi} = \tan\theta_c \frac{f_{D^+}}{f_{D_s^+}} \sqrt{\frac{\mathcal{B}(B^0 \to D_s^+ \pi^-)}{\mathcal{B}(B^0 \to D^- \pi^+)}}$$

- $\Phi = 296.2 \pm 0.8\,\text{GeV}^{-2}$ (phase space factor)
- $F(B^0 \to \pi^-) = 0.327 \pm 0.025$ from light-cone sum rules [PRD 71 (2005) 014015, PLB 644 (2007) 38]
- $f_{D_{(s)}^+} = 0.2499 \pm 0.0005\,\text{GeV}$ from lattice QCD [PRD 98 (2018) 074512, PRD 91 (2015) 054507]