



Beauty to open charm final states at LHCb

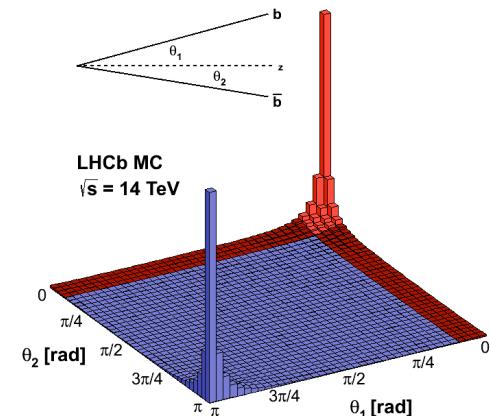
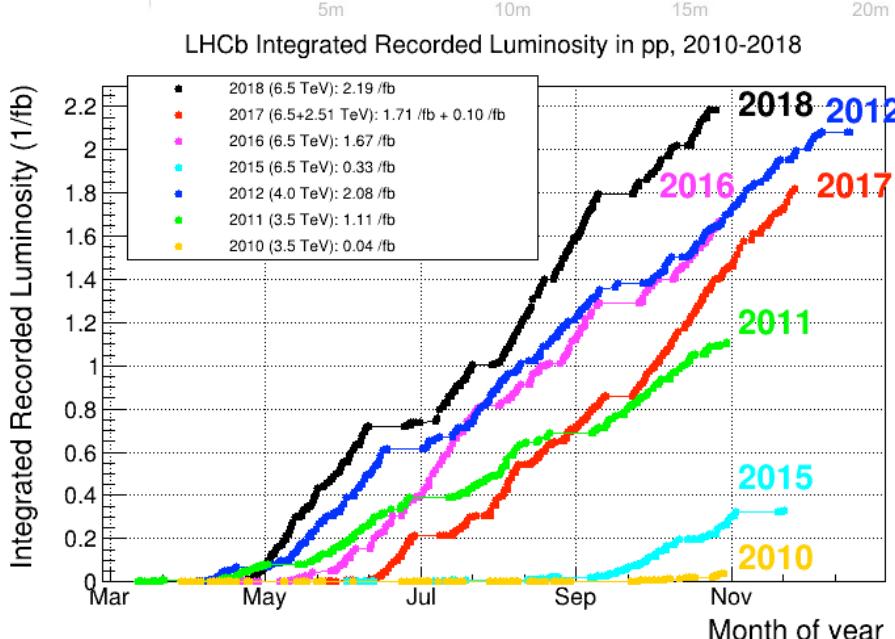
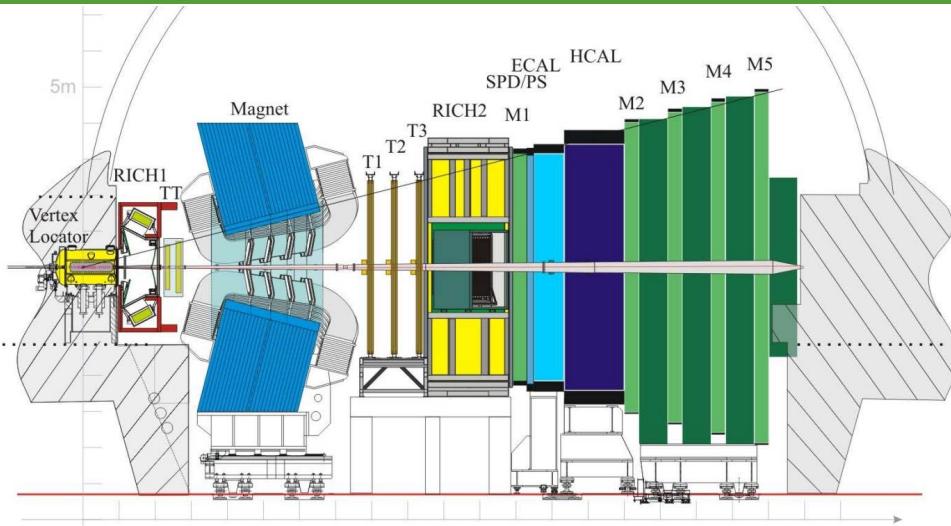
tu technische universität
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Sophie Hollitt, on behalf of the LHCb Collaboration

41st International Conference of High Energy Physics (ICHEP),
Bologna, Italy, 06-13 July 2022

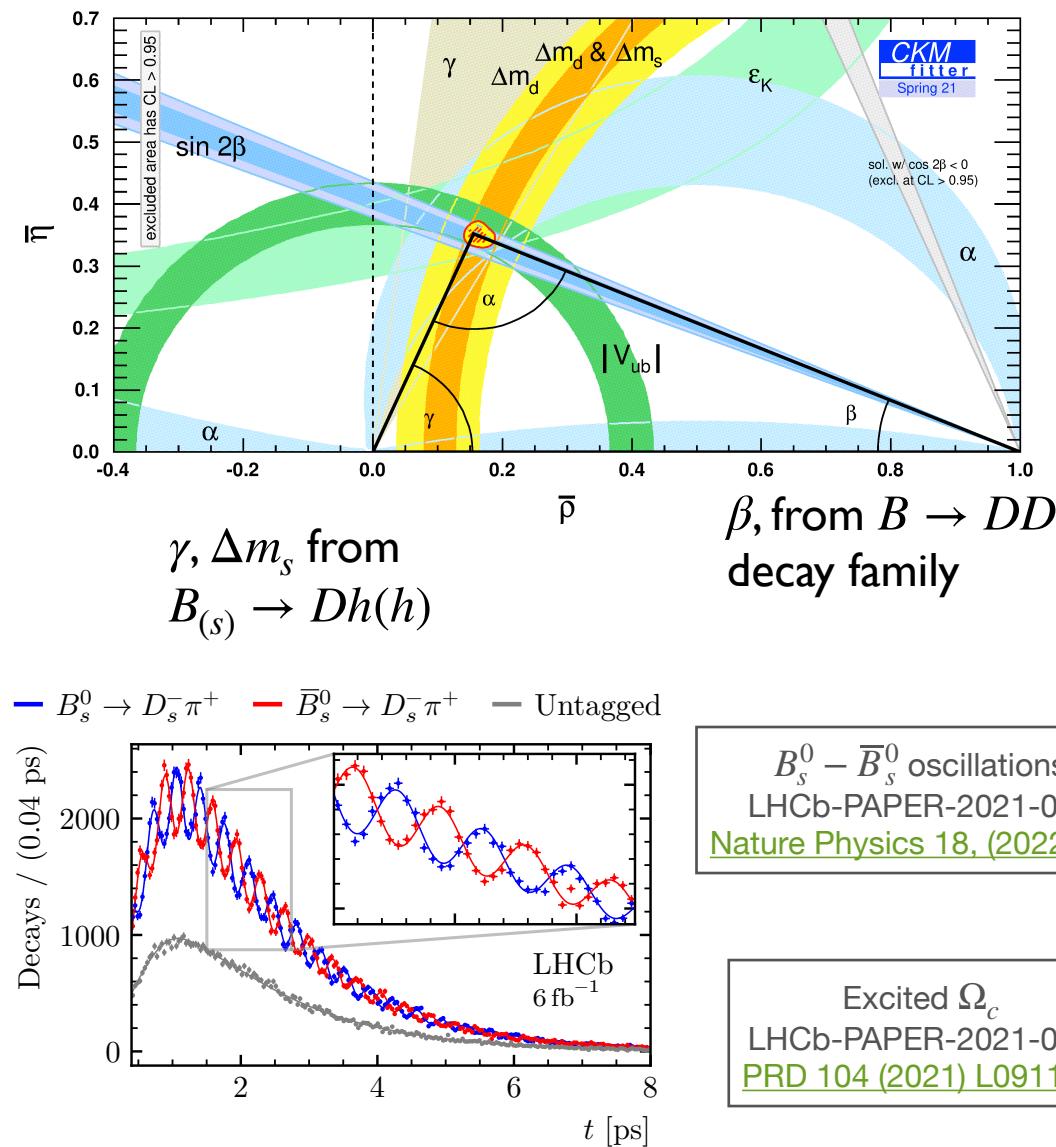
The LHCb detector



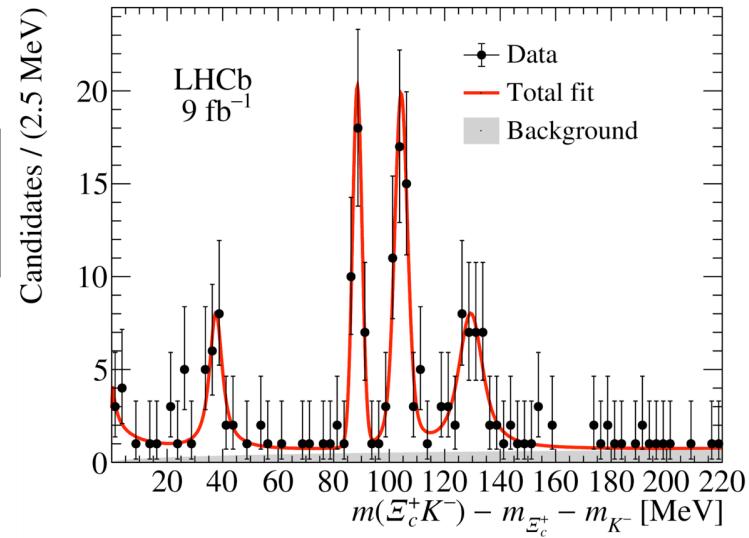
- Forward spectrometer:
 - Collect beauty (and charm) from pp collisions
 - Pseudorapidity $2 < \eta < 5$
 - 9 fb^{-1} collected 2011-2018

About LHCb detector upgrade:
Multiple talks in Operations, Performance,
and Upgrade, Friday & Saturday

Overview of beauty to open charm



- Final states including charm quarks (no charmonia)
- Why open charm?
 - General B meson properties (lifetimes, Δm_s , Δm_d)
 - Measure CKM angles (γ, β, β_s) and CPV
 - Observe new decays (including charm resonances!)



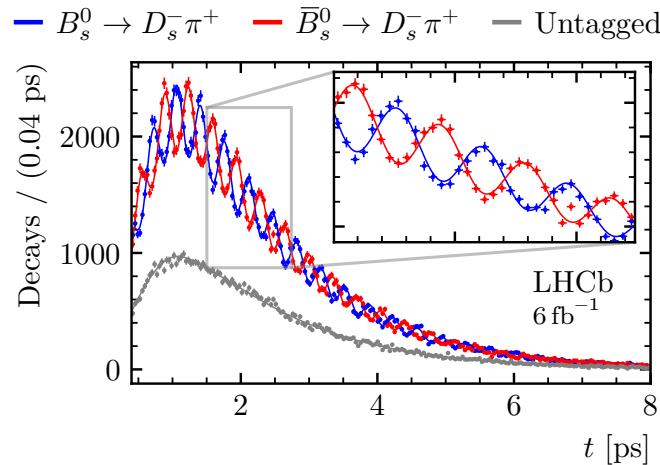
Overview of beauty to open charm



Many studies also require good knowledge of BR for multiple open charm modes

- To constrain contributions from extra Feynman diagrams
- To make checks of U-spin symmetry rules
- To provide control modes for rarer b-hadron decays in future

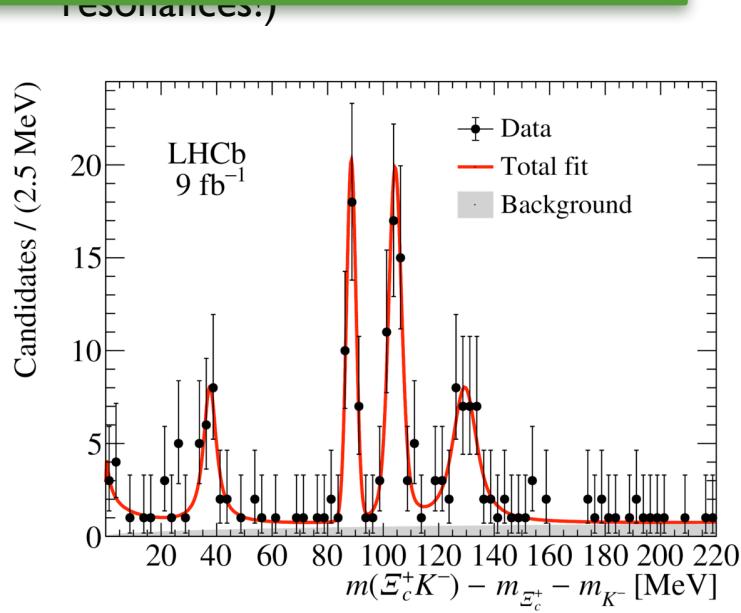
$\gamma, \Delta m_s$ from
 $B_{(s)} \rightarrow Dh(h)$



decay family

$B_s^0 - \bar{B}_s^0$ oscillations
LHCb-PAPER-2021-005
Nature Physics 18, (2022) 1-5

Excited Ω_c
LHCb-PAPER-2021-012
PRD 104 (2021) L091102



Overview of beauty to open charm

- Autumn/Winter new beauty observations and branching ratios:
 - Observation of the suppressed $\Lambda_b^0 \rightarrow D p K^-$ decay with $D \rightarrow K^+ \pi^-$ and measurement of its CP asymmetry
 - Updated search for B_c^+ decays to two charm mesons
 - Observation of $\Lambda_b^0 \rightarrow D^+ p \pi^- \pi^-$ and $\Lambda_b^0 \rightarrow D^{*+} p \pi^- \pi^-$ decays
 - Constraints on the CKM angle γ from $B^\pm \rightarrow D h^\pm$ decays using $D \rightarrow h^\pm h^\mp \pi^0$ final states
 - Observation of the $B^0 \rightarrow \bar{D}^{*0} K^+ \pi^-$ and $B_s^0 \rightarrow \bar{D}^{*0} K^+ \pi^-$ decays
- New summer branching ratios:
 - Observation of the $B_s^0 \rightarrow D^{*+} D^{*-}$ decay
 - First observation of the $B^+ \rightarrow D_s^+ D_s^- K^+$ decay

More about CPV and CKM:
Next talk: Tim Evans

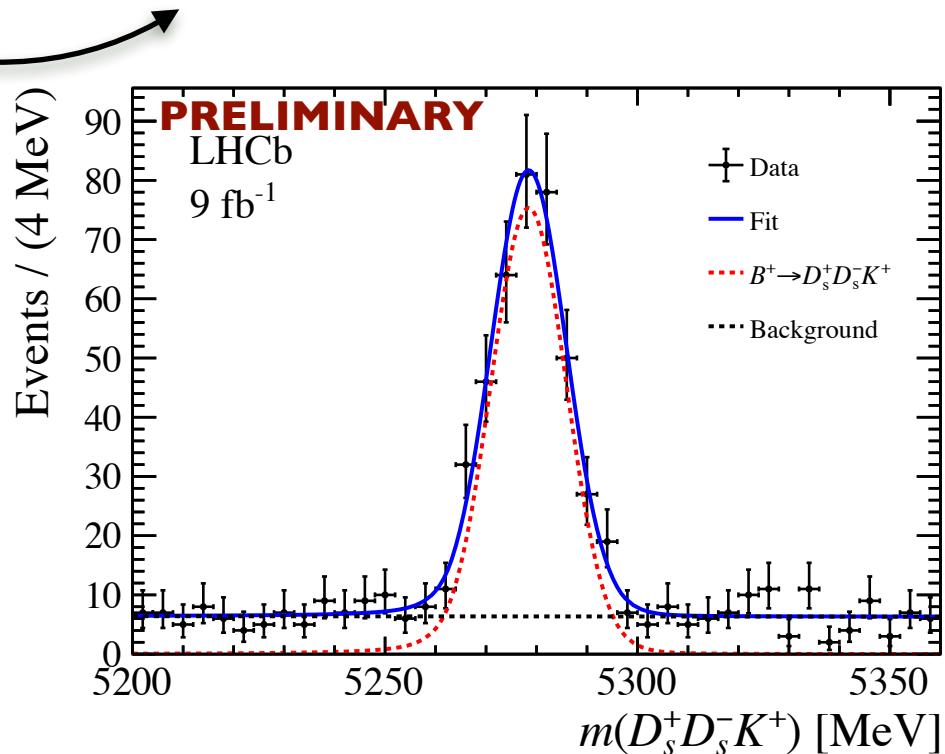
More about charm resonances from beauty:
“Excited charm hadron spectroscopy at LHCb”, Chen Chen QCD stream, 11.15am Sat 9th July
“Studies of mesonic exotic states at LHCb”, Ruiting Ma, Strong interactions & Hadrons stream, 3:00pm Sat 9th July

Observation of $B^+ \rightarrow D_s^+ D_s^- K^+$

- Very interesting mode for spectroscopy
 - (see talks on Saturday!)
- Measured relative to $B^+ \rightarrow D^+ D^- K^+$
- 84% purity for signal mode in B mass region
- Non-double-charm background reduced with B vs D flight distance requirements

“Studies of mesonic exotic states at LHCb”, Ruiting Ma, Strong interactions & Hadrons stream, 3:00pm Sat 9th July

LHCb-PAPER-2022-018
LHCb-PAPER-2022-019
coming soon
Data: 2011-2018 (9 fb^{-1})



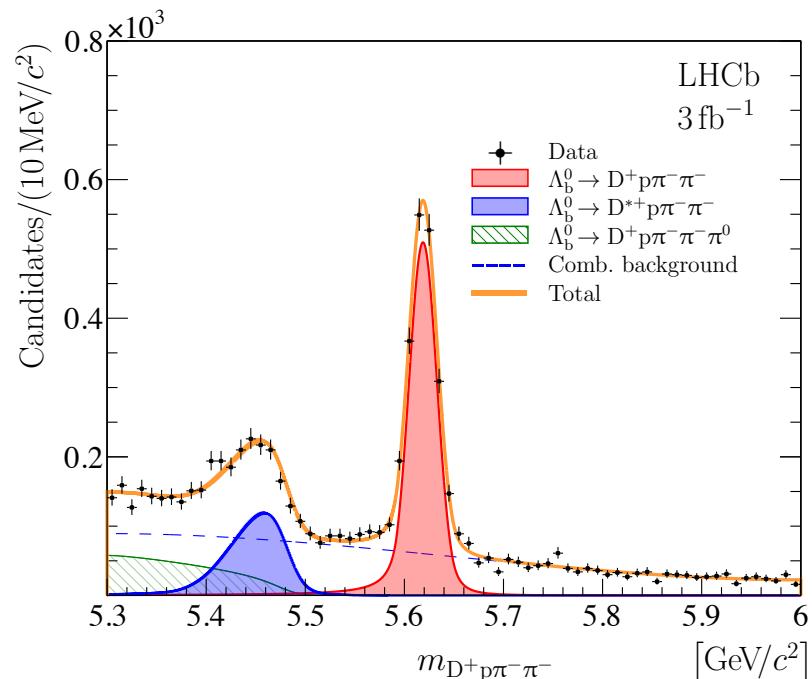
$$\mathcal{B}(B^+ \rightarrow D_s^+ D_s^- K^+) = (1.15 \pm 0.07(\text{stat}) \pm 0.06(\text{syst}) \pm 0.38(\mathcal{B}_{D,D_s})) \times 10^{-4}$$

First observation for this decay channel!

Observation of $\Lambda_b^0 \rightarrow D^{(*)+} p \pi^- \pi^-$

- b-baryon decays without a charm baryon
 - Tests of non-perturbative QCD
 - Charm spectroscopy potential
 - Normalisation for other similar b-baryon decays
- Measured relative to $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^+ \pi^- \pi^-$
(simulated in a mixture of resonances)
- Yields are corrected with a second fit to the $D^{(*)}$ or Λ_c^+ resonance after background-subtraction
 - Remove cross feeds

LHCb-PAPER-2021-040
[JHEP 03 \(2022\) 153](#)
 Data: 2011-2012 (3 fb^{-1})

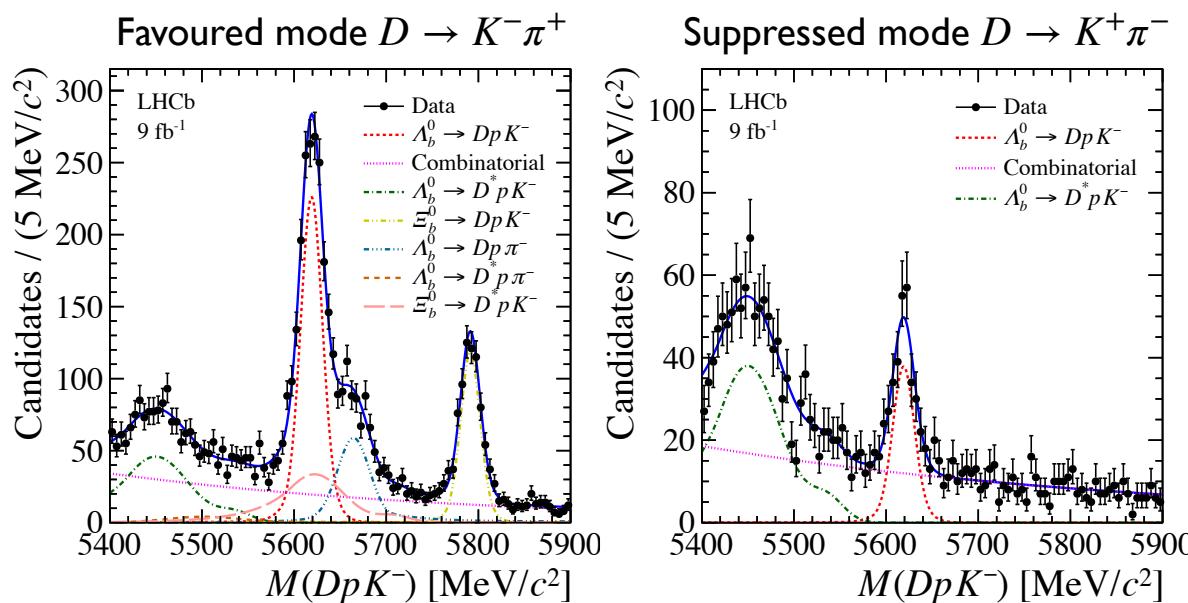


$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow D^+ p \pi^- \pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^+ \pi^- \pi^-)} = (3.58 \pm 0.14(\text{stat}) \pm 0.11(\text{syst}) \pm 0.19(\mathcal{B}_{D, \Lambda_c})) \%$$

First observation for both D and D* modes !

Observation of $\Lambda_b^0 \rightarrow \bar{D}^0 p K$

- Interference between decays with D^0 and \bar{D}^0 , consider suppressed final state $D \rightarrow K^+ \pi^-$
- Also many CP measurements in this paper!
 - Related to CKM γ , some complications from resonances



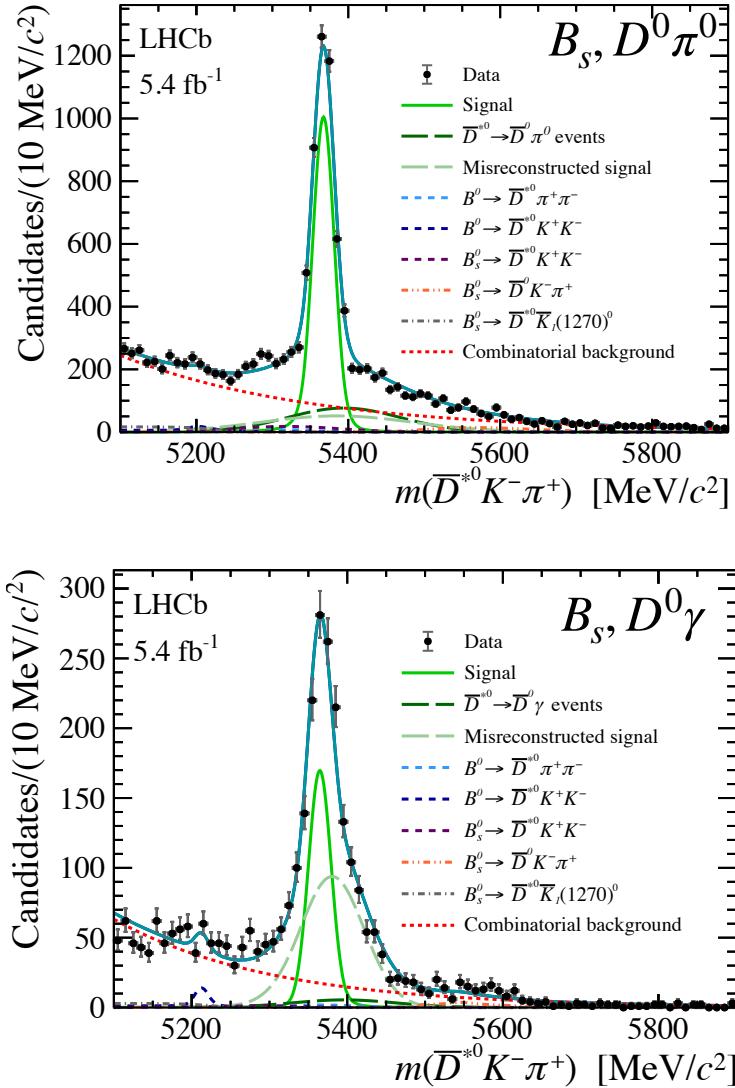
$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow [K^- \pi^+]_D p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow [K^+ \pi^-]_D p K^-)} = 7.1 \pm 0.8(\text{stat})^{+0.4}_{-0.3}(\text{syst})$$

LHCb-PAPER-2021-027
[PRD 104 \(2021\) 112008](#)
 Data: 2011-2018 (9 fb⁻¹)

- D mass constrained in mass fit
- Decay time significance of D used to suppress background
- Efficiency corrections across phase space

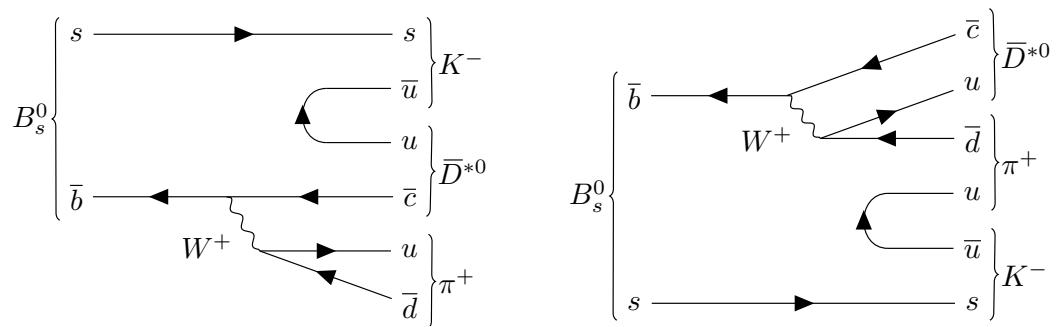
First observation of suppressed mode!

Observing $B_{(s)}^0 \rightarrow \bar{D}^{*0} K\pi$ decays



LHCb-PAPER-2021-043
[PRD 105, 072005 \(2022\)](#)
Data: 2016-2018 (5.4 fb^{-1})

- Important background in CKM γ measurements of $B^0 \rightarrow DK^+\pi^-$
 - This background not previously measured



- Simultaneous measurements with $D^* \rightarrow D^0\gamma$ and $D^* \rightarrow D^0\pi^0$
 - Cross-check using $D^* \rightarrow D^0\pi^0$ vs $D^* \rightarrow D^0\gamma$ rates

Observing $B_{(s)}^0 \rightarrow \bar{D}^{*0} K\pi$ decays

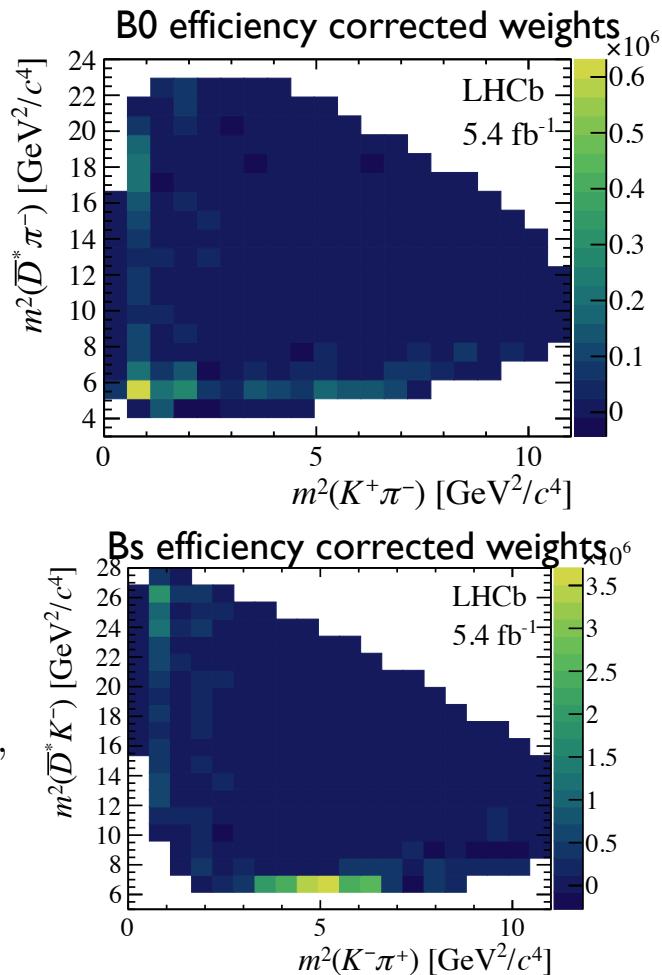
- Charmless background was reduced with “D from B” classifier
 - Data-driven training with $B^+ \rightarrow \bar{D}^0 \pi^+$
- Simulation is weighted to match data using constrained mass fit
- Branching ratio relative to $B^0 \rightarrow \bar{D}^{*0} \pi\pi$
- Future work: amplitude analysis for charm resonances!

$$\begin{aligned}\mathcal{B}(B^0 \rightarrow \bar{D}^{*0} K^+ \pi^-) &= (5.18 \pm 0.27 \pm 0.38 \pm 1.84) \times 10^{-5}, \\ \mathcal{B}(B_s^0 \rightarrow \bar{D}^{*0} K^- \pi^+) &= (7.30 \pm 0.18 \pm 0.56 \pm 2.59 \pm 0.23) \times 10^{-4},\end{aligned}$$

stat syst $\bar{D}^0 \pi\pi$ fs/fd

First observation for both modes !

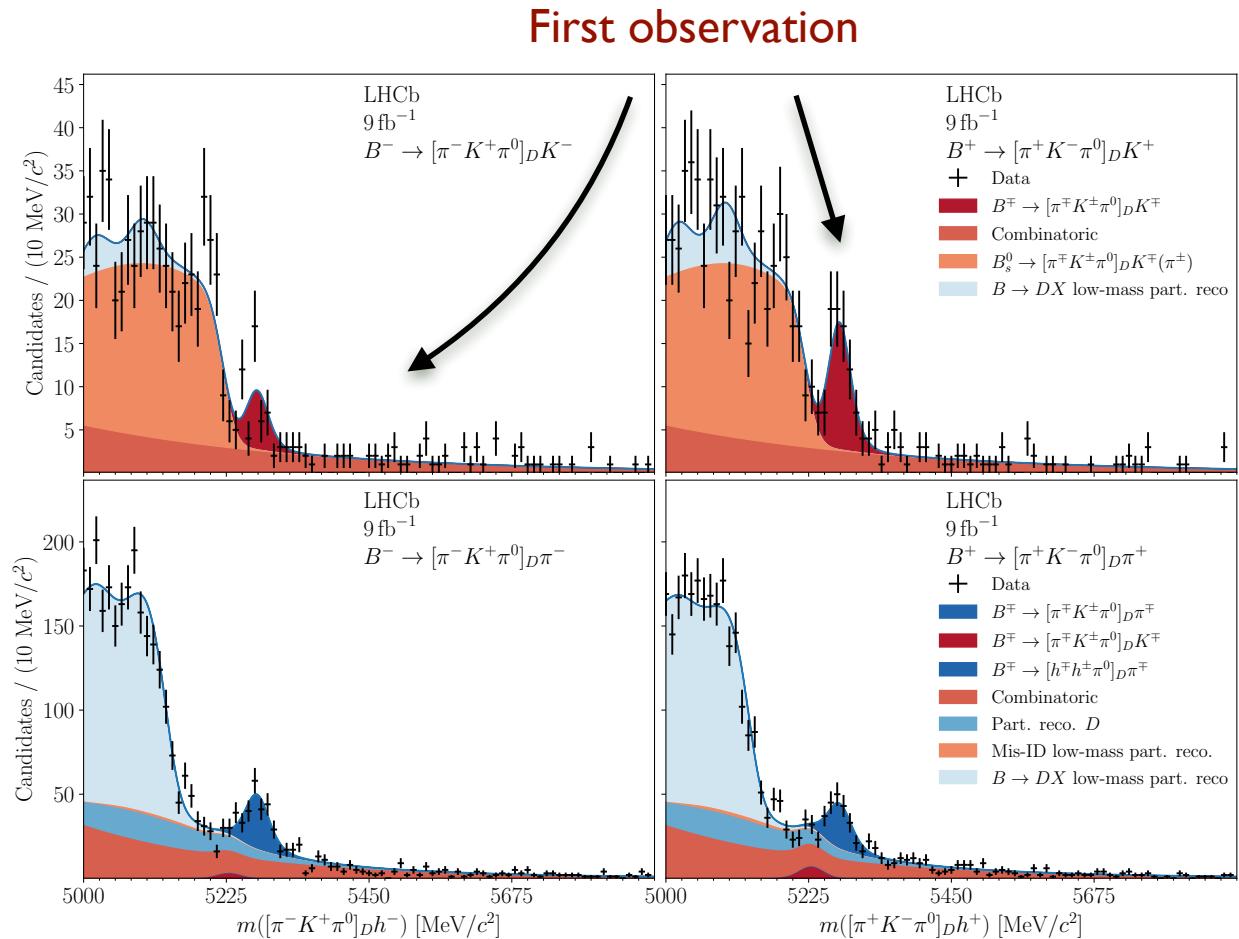
LHCb-PAPER-2021-043
[PRD 105, 072005 \(2022\)](#)
Data: 2016-2018 (5.4 fb⁻¹)



$B^\pm \rightarrow Dh^\pm$ with $D \rightarrow hh'\pi^0$

- More in next talk about this mode for measurements of CKM γ
- Four final states for D:
 $\pi^+\pi^-\pi^0$ $K^+K^-\pi^0$
 $K^+\pi^-\pi^0$ $\pi^+K^-\pi^0$ (circled)
- Suppressed $B^+ \rightarrow [\pi^+K^-\pi^0]_D K^-$ is observed for the first time!

LHCb-PAPER-2021-036
arxiv.org/abs/2112.10617
Data: 2011-2018 (9 fb^{-1})



Updated search for B_c^+ to two charm

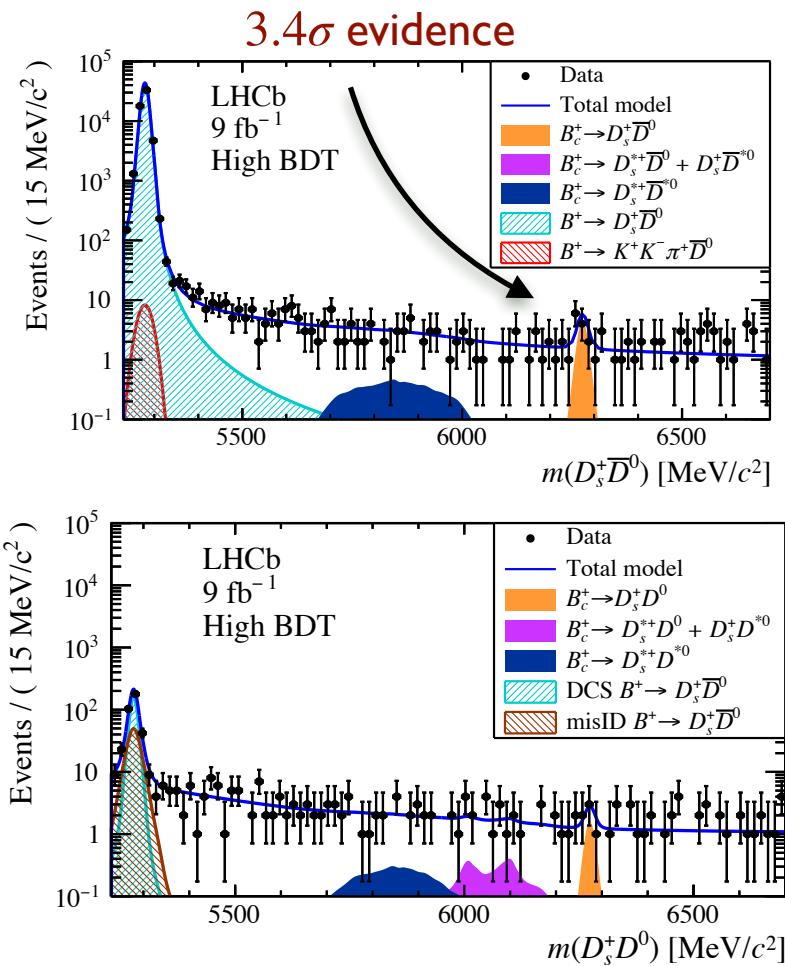
- Big picture: can CKM γ be measured with $B_c^+ \rightarrow D_s^+ D^0$ and $B_c^+ \rightarrow D_s^+ \bar{D}^0$?
 - Colour-suppressed decay is CKM-favoured
- BDT to reduce combinatorial background
 - Final mass fit simultaneous in low, medium, high BDT bins
- Many modes included in search

$D_s^+ \bar{D}^0$	$D_s^+ D^0$	$D^+ \bar{D}^0$	$D^+ D^0$
$D_s^+ \bar{D}^{*0}$	$D_s^+ D^{*0}$	$D^+ \bar{D}^{*0}$	$D^+ D^{*0}$
$D_s^+ \bar{D}^{*0}$	$D_s^+ D^{*0}$	$D^+ \bar{D}^{*0}$	$D^+ D^{*0}$
$D_s^{*+} \bar{D}^{*0}$	$D_s^{*+} D^{*0}$	$D^{*+} \bar{D}^{*0}$	$D^{*+} D^{*0}$

- Evidence for $B_c^+ \rightarrow D_s^+ \bar{D}^0$ found!

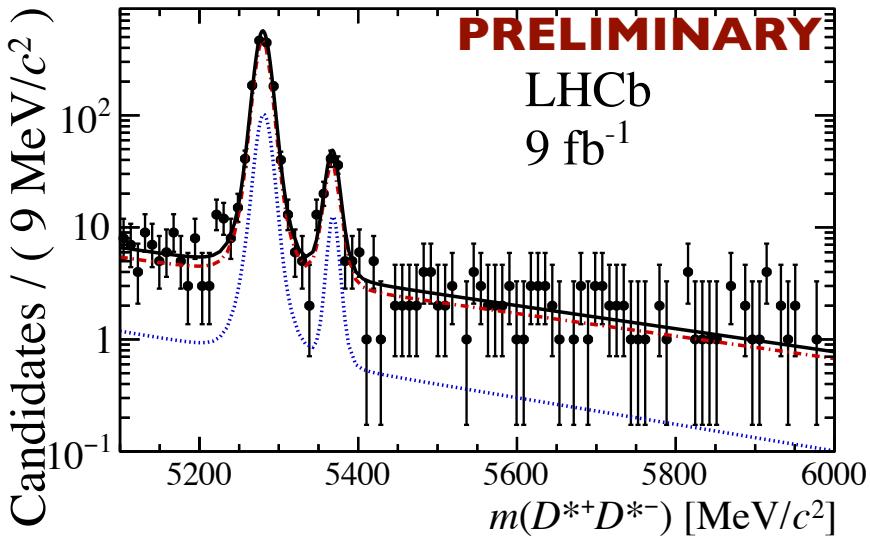
$$\frac{f_c}{f_u} \frac{\mathcal{B}(B_c^+ \rightarrow D_s^+ \bar{D}^0)}{\mathcal{B}(B^+ \rightarrow D_s^+ \bar{D}^0)} = (3.6^{+1.5+0.3}_{-1.2-0.2}) \times 10^{-4}$$

LHCb-PAPER-2021-023
[JHEP 12 \(2021\) 117](#)
 Data: 2011-2018 (9 fb^{-1})

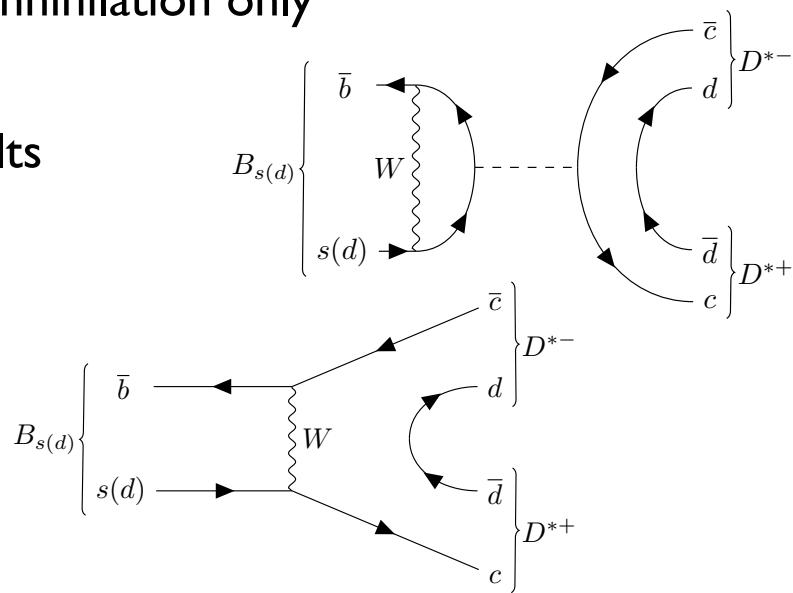


Observation of $B_s^0 \rightarrow D^{*+}D^{*-}$

- CKM angles β and β_s can be measured with $B \rightarrow D^{(*)}D^{(*)}$ type decays
 - $B_s \rightarrow D^{*+}D^{*-}$ has W-exchange and penguin annihilation only
- BR measured relative to $B^0 \rightarrow D^{*+}D^{*-}$
- Selections on $m(D^*) - m(D)$ give very clean results
- Dominant uncertainty: polarisation state
- Matches with perturbative QCD prediction



LHCb-PAPER-2022-023
coming soon
Data: 2011-2018 (9 fb^{-1})



$$\begin{aligned} \mathcal{B}(B_s^0 \rightarrow D^{*+}D^{*-}) = & (2.15 \pm 0.26(\text{stat}) \\ & \pm 0.09(\text{syst}) \pm 0.06(f_s/f_d) \\ & \pm 0.16(\mathcal{B}(B^0)) \times 10^{-4} \end{aligned}$$

First observation of this mode!

Summary and prospects

- Many new branching ratios and first observations
 - Λ_b^0 decays with D and p
 - B_c^+ decays
 - Rarer modes in $B \rightarrow Dh, B \rightarrow Dhh$ families
 - Preview of results for $B_s^0 \rightarrow D^{*+}D^{*-}$ and $B^+ \rightarrow D_s^+D_s^-K^+$
- Inputs for future observation studies, CKM analyses, and charm spectroscopy
- Commissioning is in progress for upgraded LHCb, more data at increased luminosity coming in the next few years
- Updates to these results with increased precision are possible in future! (and still more 2011-2018 results on the way)