Hadronic B decay rate measurements at LHCb

Andrea Villa, on behalf of the LHCb Collaboration

Large Hadron Collider Physics - Belgrade, 22-26 May 2023

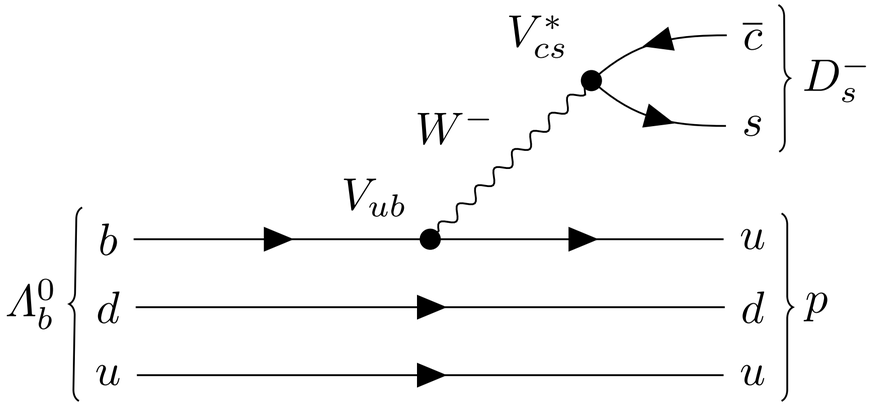
Outline

- Observation of the $\Lambda_b^0 \to D_s^- p$ decay
  [arXiv:2212.12574], submitted to JHEP
- First observation of the $B^+ \to D_s^+ D_s^- K^+$ decay
  [arXiv:2211.05034], submitted to Phys. Rev. D
- Observation of the $B_s^0 \to D^{*+} D^{*-}$ decay
  [arXiv:2210.14945], submitted to JHEP
- Study of B_c^+ meson decays to charmonia plus multihadron final states
  [arXiv:2208.08660], submitted to JHEP
- Measurement of the ratio of branching fractions $\mathcal{B}(B_c^+ \to B_s^0 \pi^+)/\mathcal{B}(B_c^+ \to J/\psi \pi^+)$
  [arXiv:2210.12000], submitted to JHEP
- Searches for the rare hadronic decays $B^0 \to p\bar{p}p\bar{p}$ and $B_s^0 \to p\bar{p}p\bar{p}$
  [arXiv:2211.08847], submitted to Phys. Rev. Lett.
- Search for the rare hadronic decay $B_s^0 \to p\bar{p}$
  [arXiv:2206.06673], submitted to Phys. Rev. D

Observation of the $\Lambda_b^0 \to D_s^- p$ decay

- $|V_{ub}|$ is the least precisely known element of the CKM matrix
- Critical input to test SM consistency [JHEP 10 (2006) 081] [Phys. Rev. D91 (2015) 073007]
- The decay $\Lambda_b^0 \to D_s^- p$ proceeds via a LO tree diagram, therefore

$$\mathcal{B}(\Lambda_b^0 \to D_s^- p) \propto |V_{ub}|^2 |V_{cs}|^2 f_{D_s}^2 |a_{NF}|^2 |F_{\Lambda_b^0 \to p}(m_{D_s}^2)|^2$$

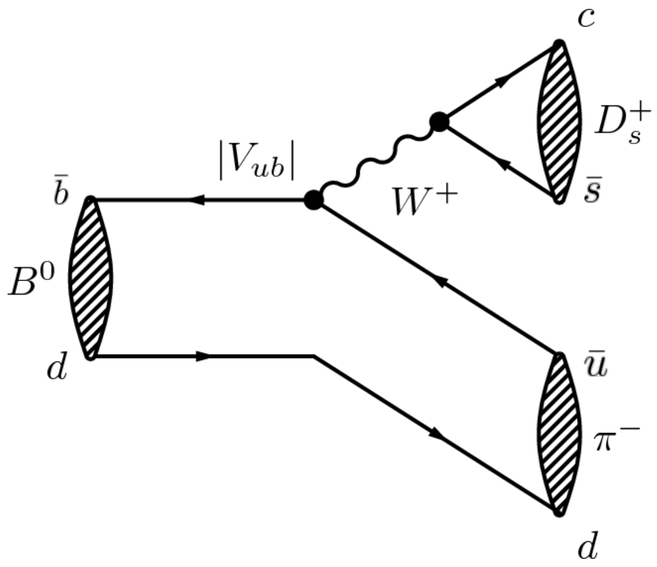


a_{NF} : effects of final-state contributions breaking factorisation assumption

$F_{\Lambda_b^0 \to p}(m_{D_s}^2)$: form factor for $\Lambda_b^0 - p$ transition (not well known)

- $B^0 \to D_s^+ \pi^-$ decay has the same formula with different a_{NF} and F
  → Complementary measurements

[Eur. Phys. J. C81 (2021) 314]

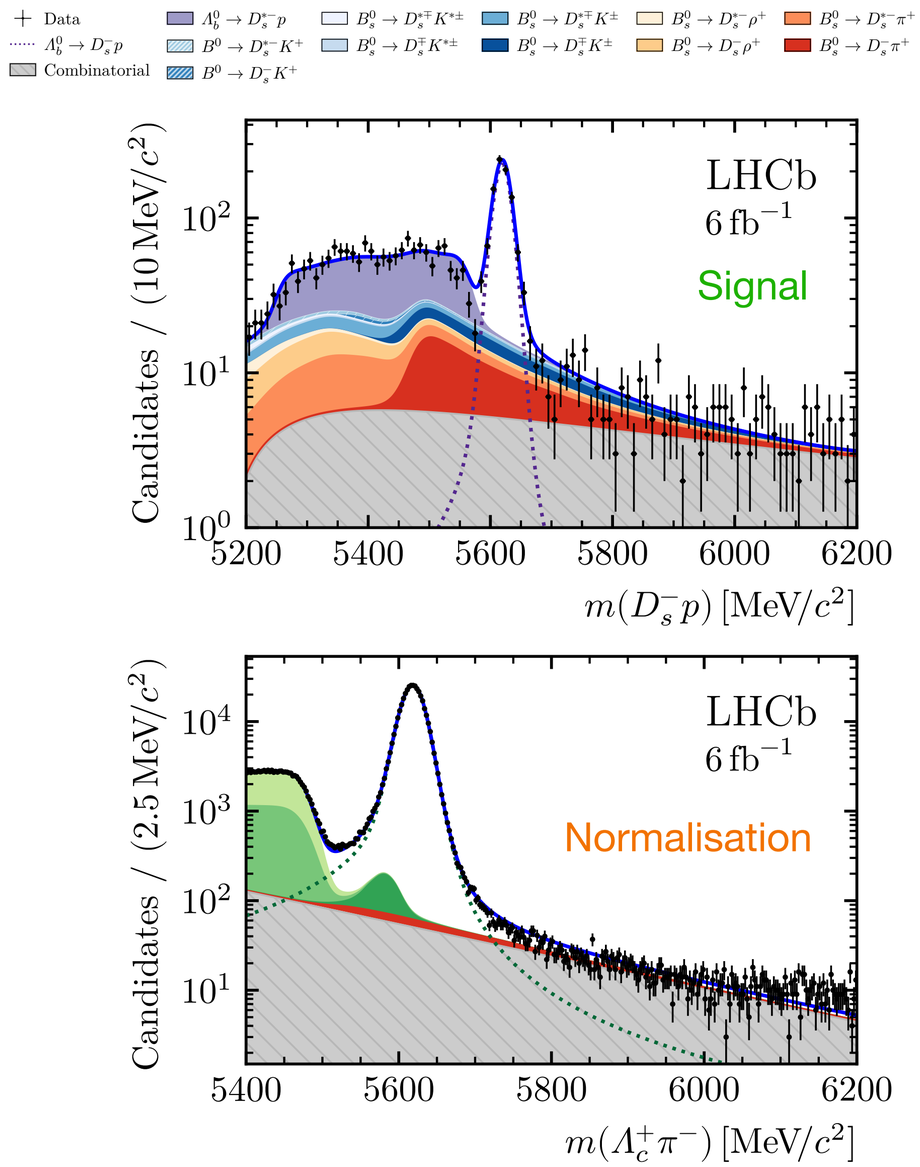


Observation of the $\Lambda_b^0 \to D_s^- p$ decay

- Full Run 2 dataset, $\sqrt{s} = 13$ TeV, $\mathscr{L} = 6$ fb^{-1} [arXiv:2212.12574]
- $\Lambda_b^0 \to (D_s^- \to K^-K^+\pi^-)p$: signal channel (831 ± 32 events)
- $\Lambda_b^0 \to (\Lambda_c^+ \to pK^+\pi^-)\pi^-$: normalisation channel
  - $$\mathscr{B}(\Lambda_b^0 \to D_s^- p) = \mathscr{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)\frac{N(D_s^- p)}{N(\Lambda_c^+\pi^-)}\frac{\varepsilon(\Lambda_c^+\pi^-)}{\varepsilon(D_s^- p)}\frac{\mathscr{B}(\Lambda_c^+ \to pK^+\pi^-)}{\mathscr{B}(D_s^- \to K^-K^+\pi^-)}$$
  - $\mathscr{B}(\Lambda_b^0 \to D_s^- p) = (12.6 \pm 0.5 \pm 0.3 \pm 1.2) \times 10^{-6}$

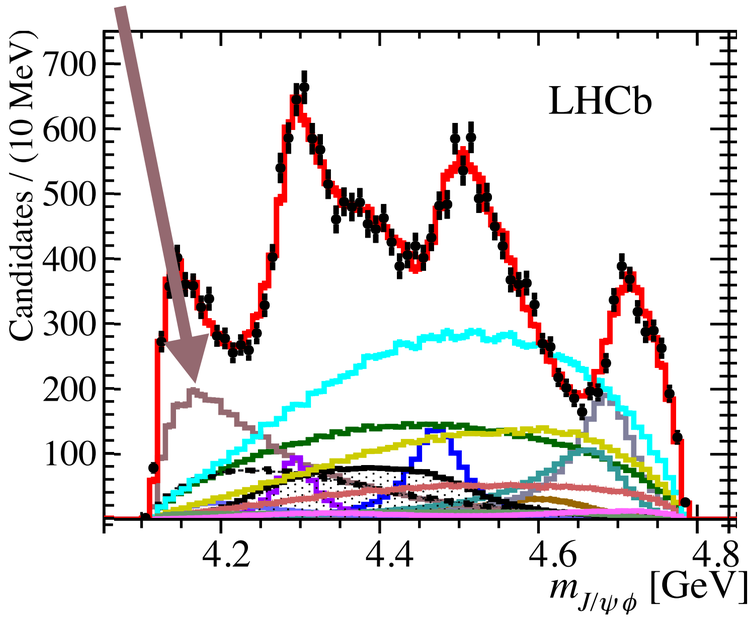
From external $\mathscr{B}$ inputs

- First observation of the $\Lambda_b^0 \to D_s^- p$ decay
- Will serve as input for future studies of factorisation in Λ_b^0 decays

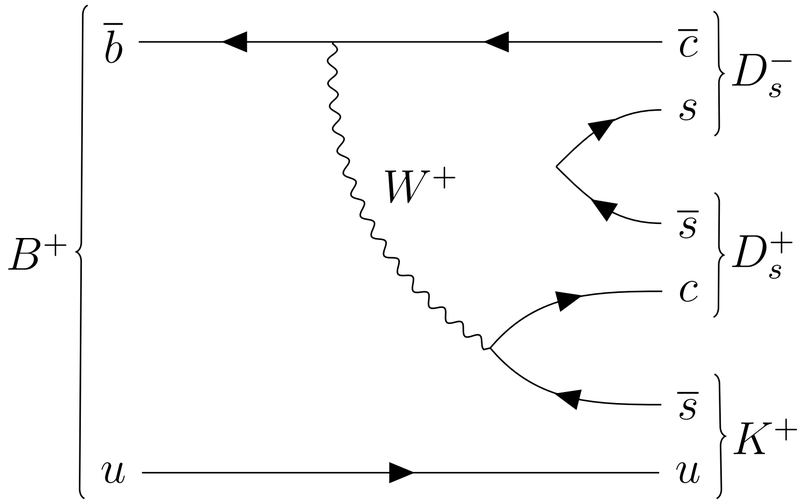


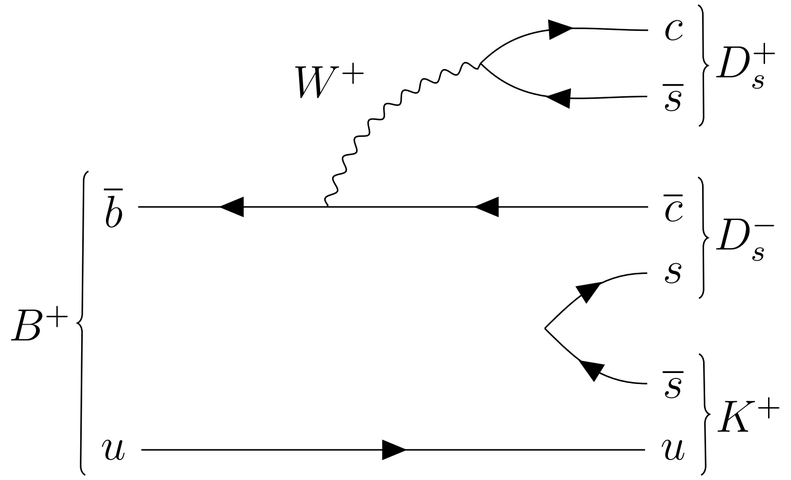
First observation of the $B^+ \to D_s^+ D_s^- K^+$ decay

- Cabibbo-favoured $b \to c\bar{c}s$ transitions allow to investigate charm meson spectroscopy (conventional and exotic)
- Many new decays and resonances have been observed in $B \to D^{(*)}\bar{D}^{(*)}K^{(*)}$ decays
- The previously unobserved $B^+ \to D_s^+ D_s^- K^+$ decay could give insights into charmonium-like $c\bar{c}s\bar{s}$ hadrons
- $\chi_{c1}(4140)$ candidates seen in $J/\psi\phi$ final state from $B^+ \to J/\psi\phi K^+$ decays, could also decay to $D_s^+ D_s^-$



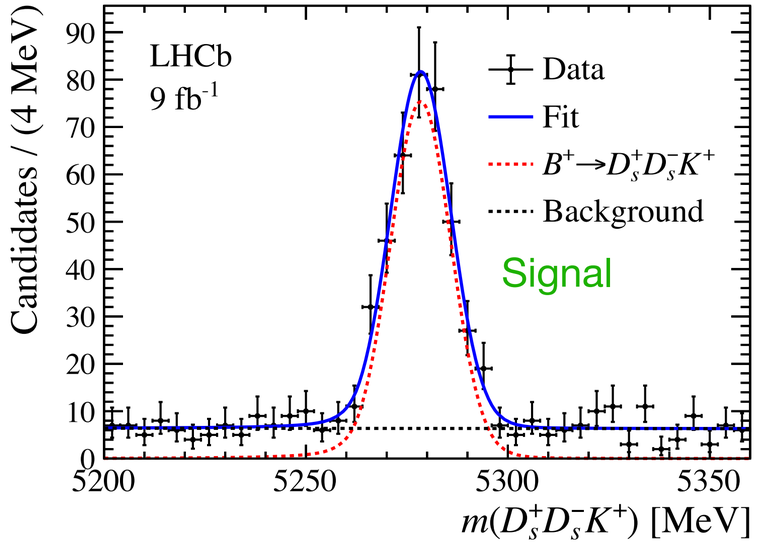
[Phys. Rev. Lett. 127, 082001 (2021)]

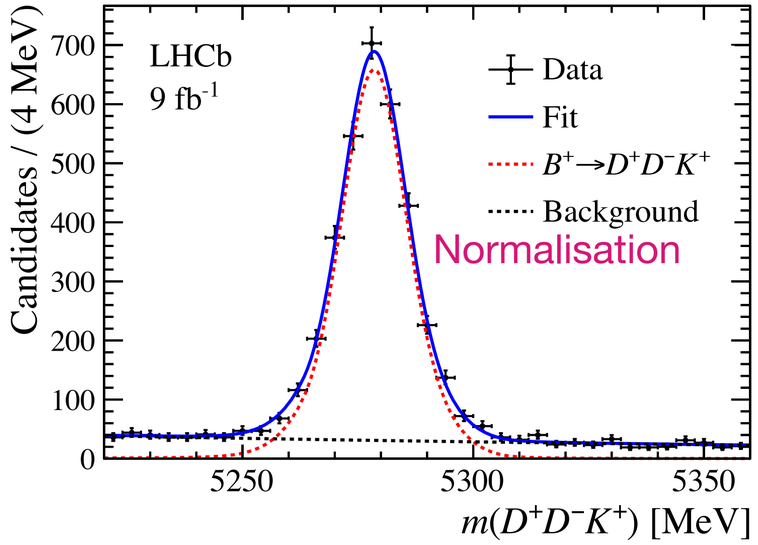




First observation of the $B^+ \to D_s^+ D_s^- K^+$ decay

- Signal $B^+ \to D_s^+ D_s^- K^+$ selected by $D_s^+ \to K^+ K^- \pi^+$
- Using $B^+ \to D^+ D^- K^+$ as normalisation channel with $D^+ \to K^- \pi^+ \pi^+$
- Non double-charm bkgs. suppressed by vertex constraints
- Mass window chosen to exclude partially reco. bkgs ($D^{*\pm}_{(s)} \to D^{\pm}_{(s)} \gamma$ or $D^{*\pm}_{(s)} \to D^{\pm}_{(s)} \pi^0$)
- Full Run 1+2 dataset
- Signal yields: 360 ± 22 (84 % purity)





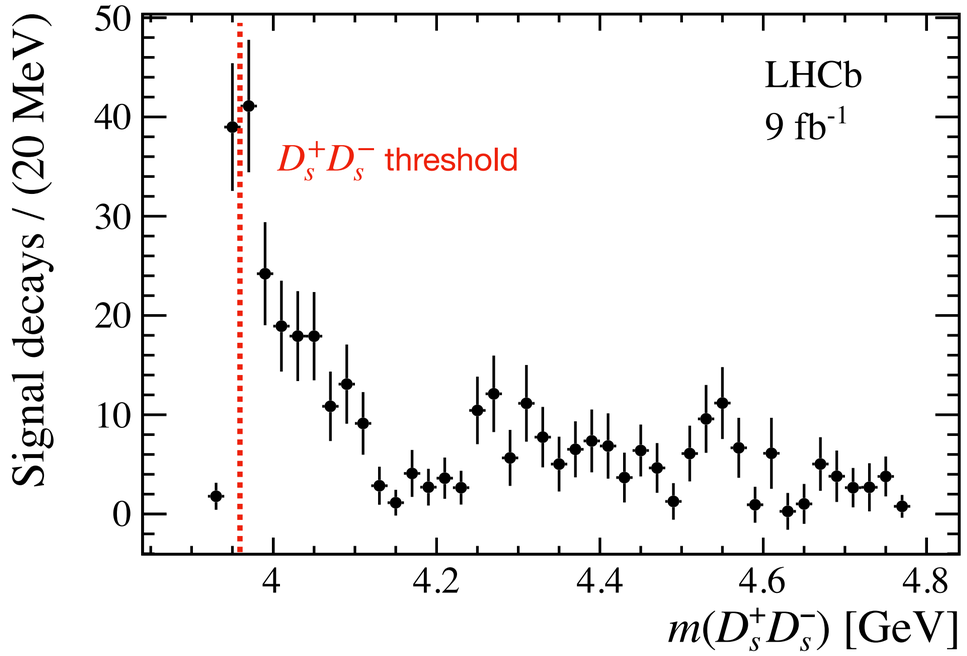
First observation of the $B^+ \to D_s^+ D_s^- K^+$ decay

- Branching fraction result [arXiv:2211.05034]

$$\mathcal{B}(B^+ \to D_s^+ D_s^- K^+) = (1.15 \pm 0.07 \pm 0.06 \pm 0.38) \times 10^{-4}$$

From external $\mathcal{B}$ inputs

- Significance $> 10\sigma$
- First observation of $B^+ \to D_s^+ D_s^- K^+$ decay
- Fills an experimental gap in knowledge of Cabibbo-favoured $b \to c\bar{c}s$ transitions
- Clear resonant structure in $D_s^+ D_S^-$ invariant mass



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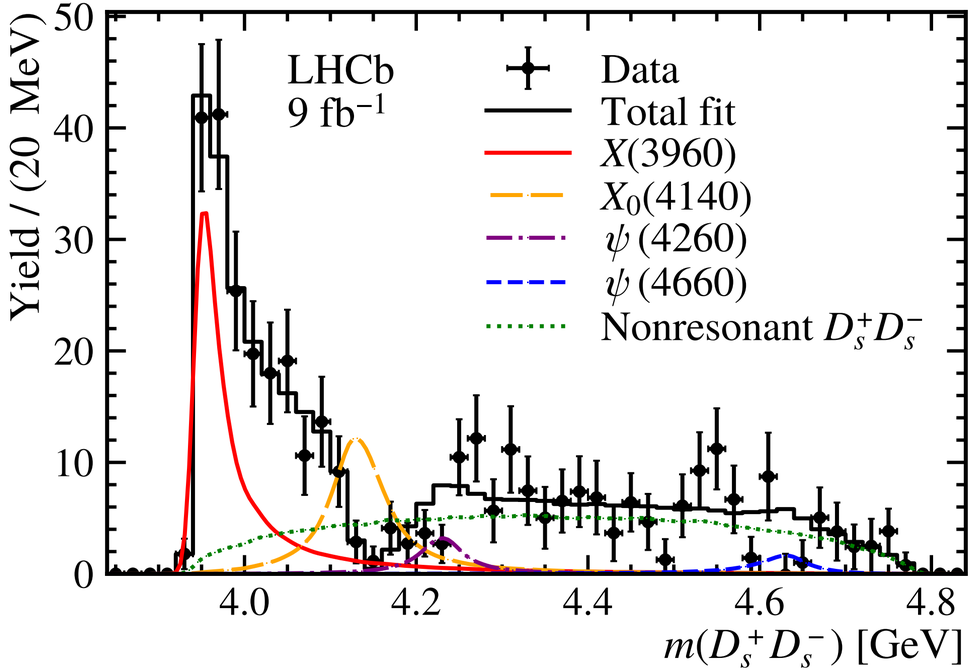
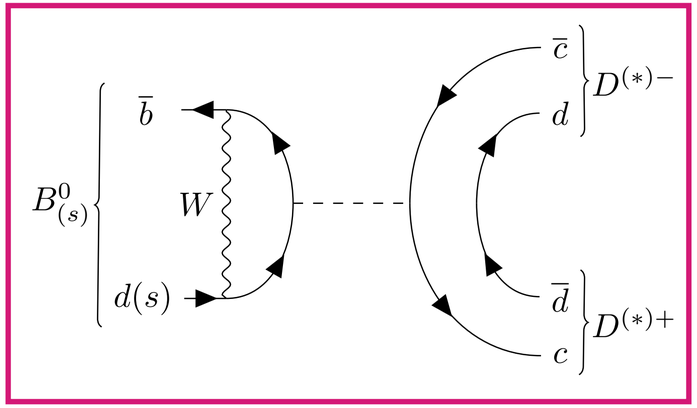
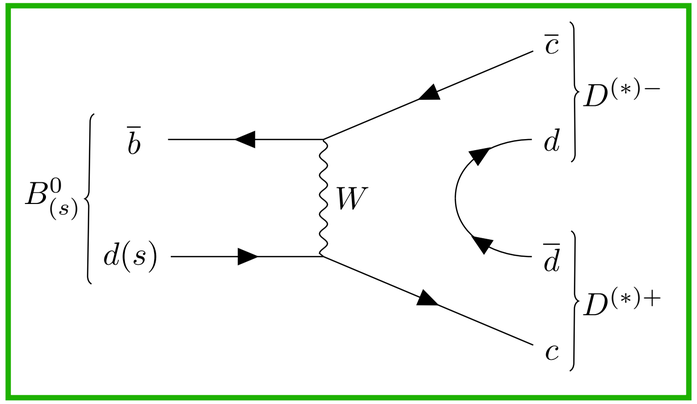
- Clear resonant structure in $D_s^+ D_S^-$ invariant mass
- Investigated by amplitude analysis in accompanying paper [arXiv:2210.15153]
  talk by L. Capriotti



Observation of the $B_s^0 \to D^{*+}D^{*-}$ decay

- $B^0 \to D^{(*)+}D^{(*)-}$ and $B_s^0 \to D_s^{(*)+}D_s^{(*)-}$ decays are used to measure the angles β and β_s
- Their determination can be constrained by other decays, e.g. $B_s^0 \to D^{*+}D^{*-}$ [arXiv:hep-ph/9907455] [arXiv:hep-ph/9904360]
- Tree-level and penguin transitions not allowed
- Sensitive to penguin-annihilation and W-exchange
- Full Run 1+2 dataset
- Normalisation channel: $B^0 \to D^{*+}D^{*-}$
- D^* mesons reconstructed by $D^0\pi^+$ decay
  D^0 meson selected with $K^-\pi^+$, K^+K^-, $\pi^+\pi^-$ final states





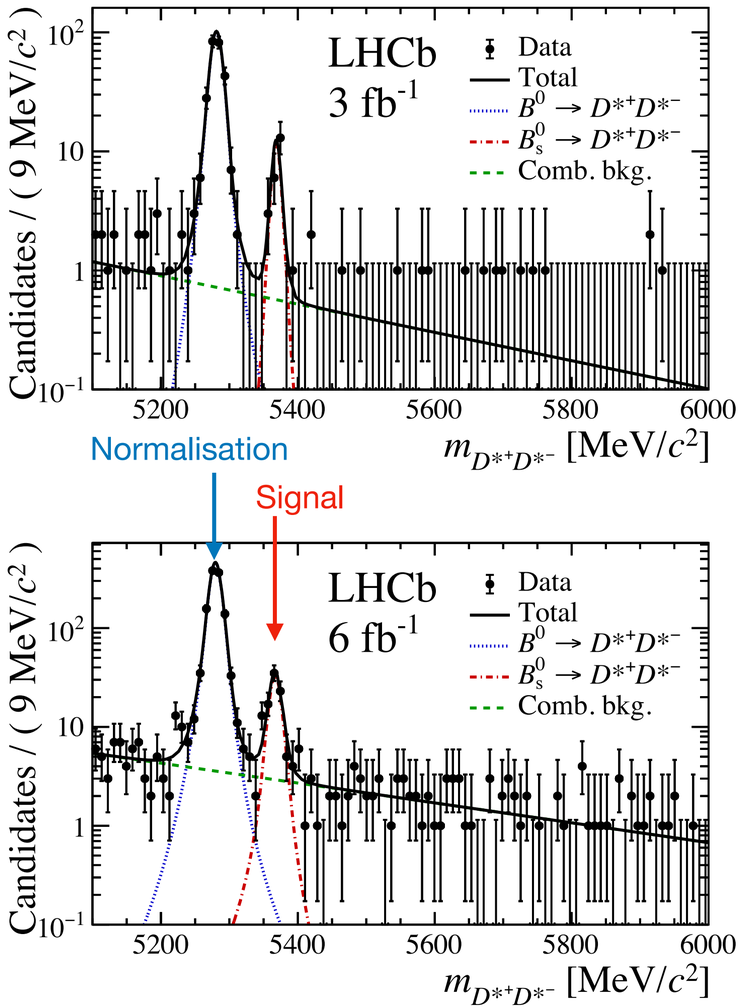
Observation of the $B_s^0 \to D^{*+}D^{*-}$ decay

- Partially reconstructed bkgs. excluded by mass window selection
- Total signal yield: 20 ± 5 (Run 1) and 79 ± 10 (Run 2)
- Branching fraction: [arXiv:2210.14945]

$$\mathcal{B}(B_s^0 \to D_s^{*+}D_s^{*-}) = \mathcal{B}(B^0 \to D_s^{*+}D_s^{*-})\frac{N_{B_s^0}}{N_{B^0}}\frac{\varepsilon_{B_s^0}}{\varepsilon_{B^0}}\frac{f_s}{f_d}$$

$$= (2.15 \pm 0.26 \pm 0.09 \pm 0.06 \pm 0.16) \times 10^{-4}$$

- Precision limited by statistics and knowledge of $\mathcal{B}(B^0 \to D_s^{*+}D_s^{*-})$
- First observation of $B_s^0 \to D^{*+}D^{*-}$ decay



B_c^+ decays to charmonia + multihadron

- The B_c^+ is the only meson containing two heavy-flavour quarks
- Its decay to J/ψ + light hadrons is well predicted by the BLL model, based on QCD factorisation [arXiv:0910.3089]
- Direct measurement can test the factorisation hypothesis
- New study of B_c^+ mesons decaying to:

$J/\psi 3\pi^+ 2\pi^-$ ← First evidence in [JHEP 1405 (2014)]

$J/\psi K^+ K^- \pi^+ \pi^+ \pi^-$

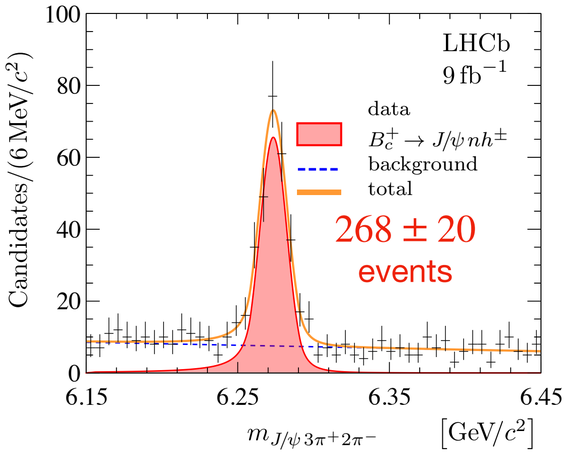
$(\psi(2S) \to J/\psi \pi^+ \pi^-)\pi^+ \pi^+ \pi^-$ ← First observed in [JHEP 01 (2022) 065]

$J/\psi 4\pi^+ 3\pi^-$

with $J/\psi \to \mu^+ \mu^-$

- Full Run 1+2 dataset, $\sqrt{s} = 7,8,13$ TeV, $\mathscr{L} = 9\text{fb}^{-1}$

B_c^+ decays to charmonia + multihadron

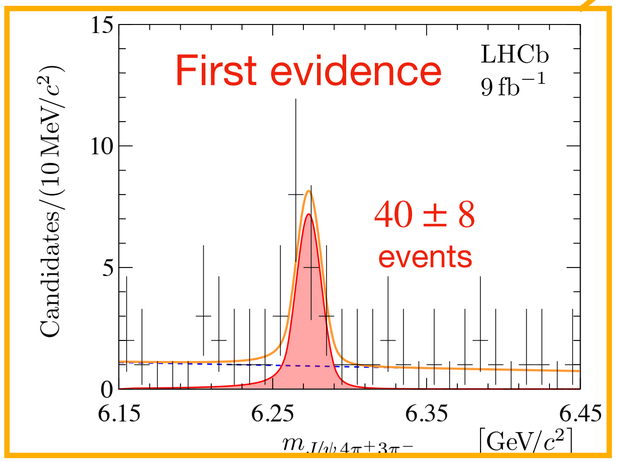


- Ratios of branching fractions w.r.t. $J/\psi 3\pi^+2\pi^-$

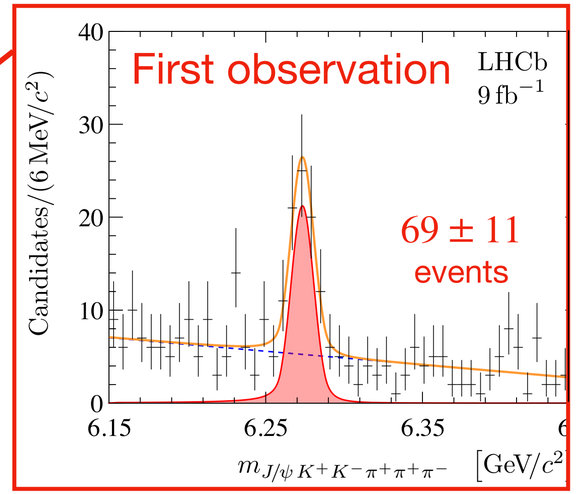
$$\frac{\mathcal{B}(J/\psi K^+K^-\pi^+\pi^+\pi^-)}{\mathcal{B}(J/\psi 3\pi^+2\pi^-)} = (33.7 \pm 5.7 \pm 1.6) \times 10^{-2}$$

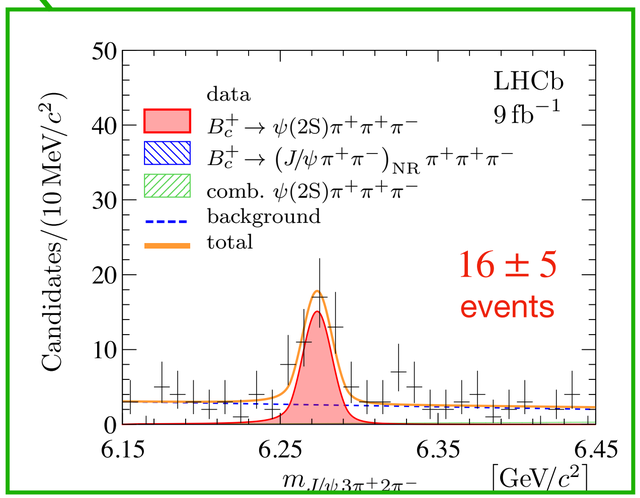
$$\frac{\mathcal{B}(\psi(2S)\pi^+\pi^+\pi^-)}{\mathcal{B}(J/\psi 3\pi^+2\pi^-)} = (17.6 \pm 3.6 \pm 0.8) \times 10^{-2}$$

$$\frac{\mathcal{B}(J/\psi 4\pi^+3\pi^-)}{\mathcal{B}(J/\psi 3\pi^+2\pi^-)} = (28.5 \pm 8.7 \pm 2.0) \times 10^{-2}$$



- Currently limited by statistics [arXiv:2208.08660]
- Predictions of BLL model well describe the distributions of $m(nh)$





Measurement of $\mathscr{B}(B_c^+ \to B_s^0\pi^+)/\mathscr{B}(B_c^+ \to J/\psi\pi^+)$

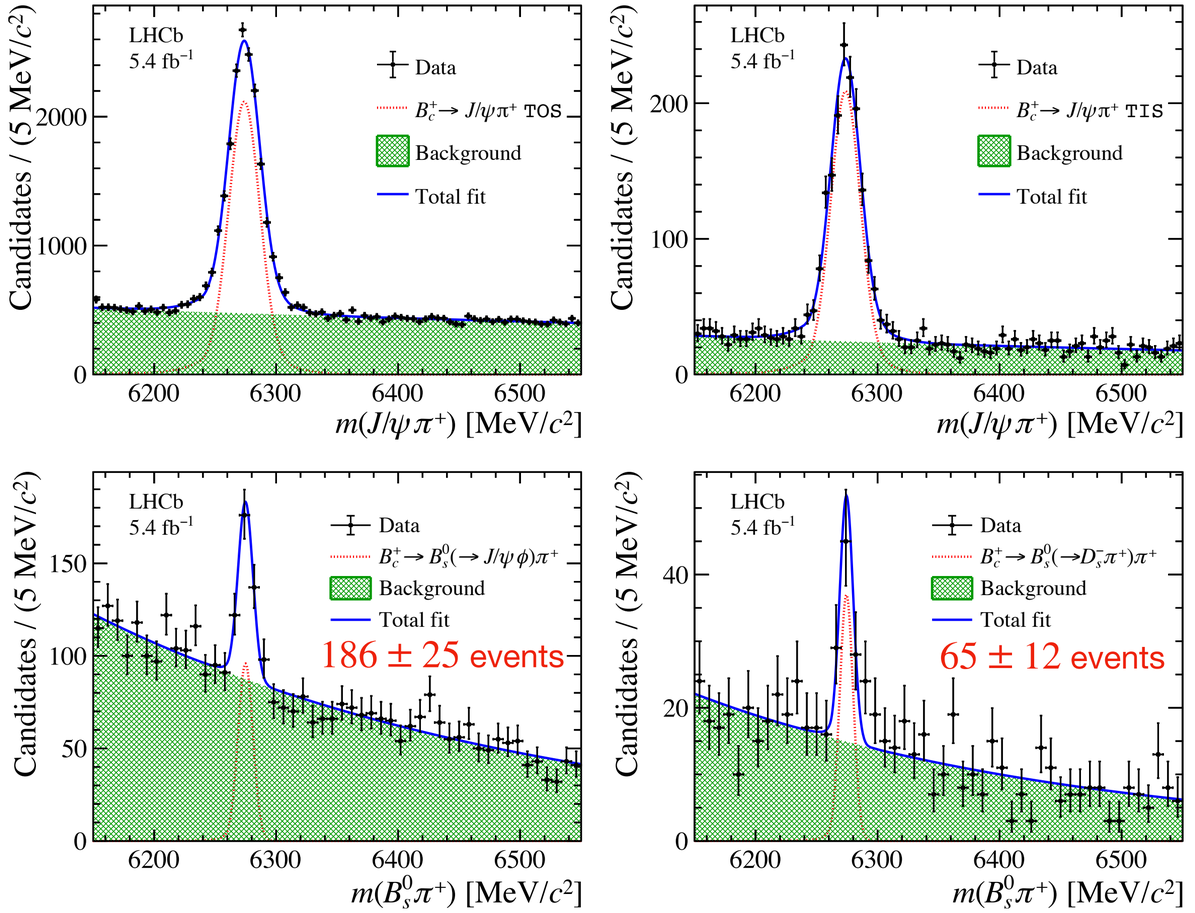
- The $B_c^+ \to B_s^0\pi^+$ is an ideal channel to test theoretical models on B mesons
- Predictions range between $2.6\,\%$ and $16.4\,\%$ [JHEP 09 (2019) 103] [Phys. Atom. Nucl. 67 (2004)] [Nucl. Phys. B585 (2000)]
- Precise measurement can also improve constraints on $\mathscr{B}(B_c^+ \to \tau^+\nu_\tau)$
- Run 2 dataset used for this analysis, $\sqrt{s} = 13\ \text{TeV}$, $\mathscr{L} = 6\text{fb}^{-1}$
- B_s^0 mesons reconstructed from two decays:
  $D_s^-\pi^+$, with $D_s^- \to K^+K^-\pi^-$
  $J/\psi\phi$, with $\phi \to K^+K^-$
- Different trigger categories different final states: tradeoff between higher signal yield and better control of efficiencies

Measurement of $\mathcal{B}(B_c^+ \to B_s^0\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$

- Results from $D_s^-\pi^+$ and $J/\psi\phi$ channels combined using the BLUE method [Nucl. Instrum. Meth. A500 (2003)]
- $$\frac{\mathcal{B}(B_c^+ \to B_s^0\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = (91 \pm 10 \pm 8 \pm 3)$$

  From external $\mathcal{B}$ inputs
- Extraction of $\mathcal{B}(B_c^+ \to B_s^0\pi^+)$ unfeasible because of uncertainties in determination of $\mathcal{B}(B_c^+ \to J/\psi\pi^+)$ [Phys. Rev. D89 (2014)] [Phys. Rev. D90 (2014)]
- The result indicates that the $B_s^0\pi^+$ is the B_c^+ decay with the highest branching fraction measured to date

  [arXiv:2210.12000]



Rare baryonic decays of B^0 and B_s^0 mesons

- Baryonic decays of B mesons with $p\bar{p}$ pairs are not well understood
- Two-body $B \to p\bar{p}$ decays are suppressed while multi-body $B \to p\bar{p}hh'$ decays are enhanced
- Observation of missing baryonic decays can give insights on the underlying dynamics
- Two new searches from LHCb:

$B^0_{(s)} \to p\bar{p}p\bar{p}$ full Run 1+2 dataset

Tighter selection criteria for B_s^0 mode

Measured relatively to
$B^0 \to J/\psi(\to p\bar{p})K^{*0}(\to K^+\pi^-)$

and $B_s^0 \to J/\psi(\to p\bar{p})\phi(\to K^+K^-)$

[arXiv:2211.08847]

$B_s^0 \to p\bar{p}$ with Run 2 dataset

B^0 analog observed in [Phys. Rev. Lett. 119 (2017)]

Measured relatively to $B^0 \to K^+\pi^-$

[arXiv:2206.06673]

Rare baryonic decays of B^0 and B_s^0 mesons

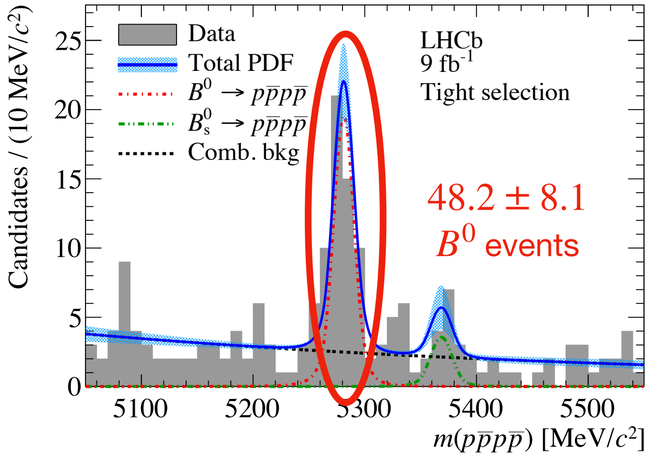
$$\mathcal{B}(B^0 \to p\bar{p}p\bar{p}) = (2.2 \pm 0.4 \pm 0.1 \pm 0.1) \times 10^{-8}$$

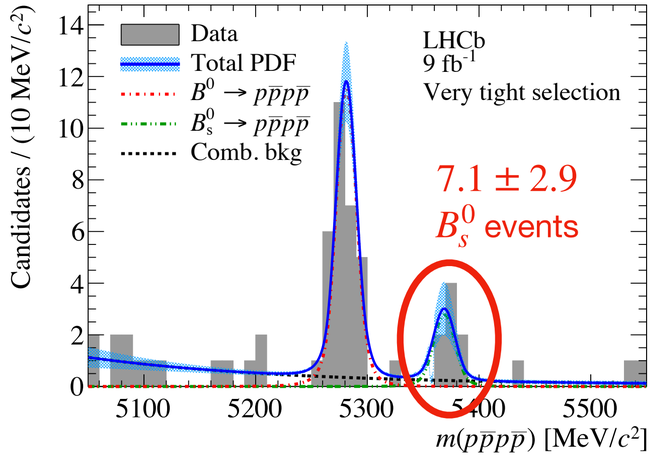
First observation (9.3σ significance)

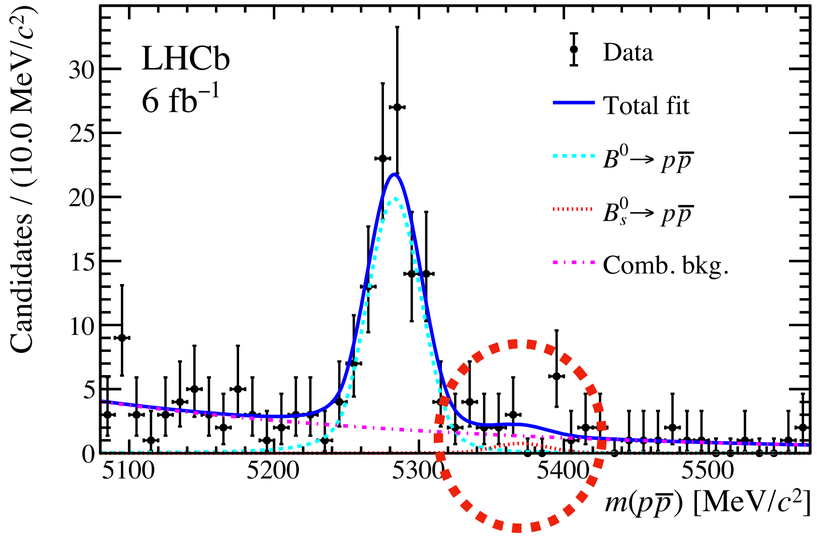
$$\mathcal{B}(B_s^0 \to p\bar{p}p\bar{p}) = (2.3 \pm 1.0 \pm 0.2 \pm 0.1) \times 10^{-8}$$

first evidence (4.0σ significance)

[arXiv:2211.08847]







$B^0 \to p\bar{p}$ decay confirmed with high significance

$$\mathcal{B}(B^0 \to p\bar{p}) = (1.27 \pm 0.13 \pm 0.05 \pm 0.03)) \times 10^{-8}$$

No evidence of $B_s^0 \to p\bar{p}$

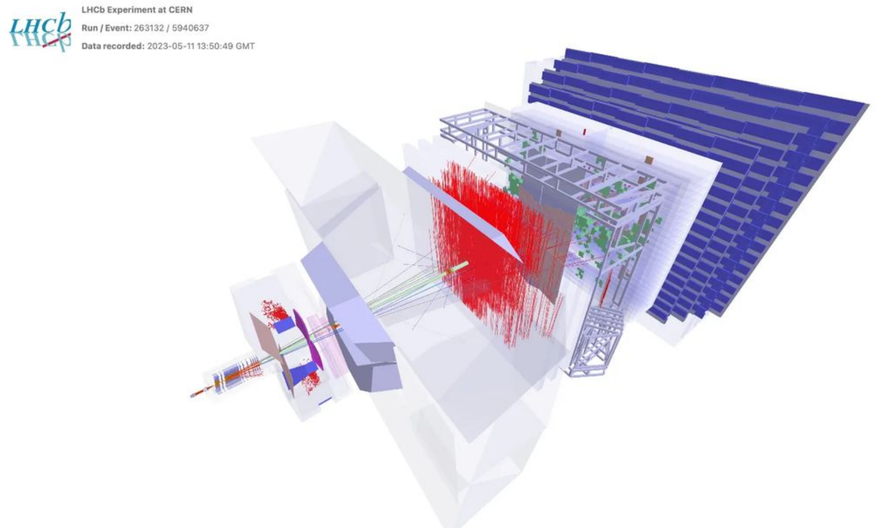
$\mathcal{B}(B_s^0 \to p\bar{p}) < 4.4\ (5.1) \times 10^{-9}$ at 90 % (95%) CL

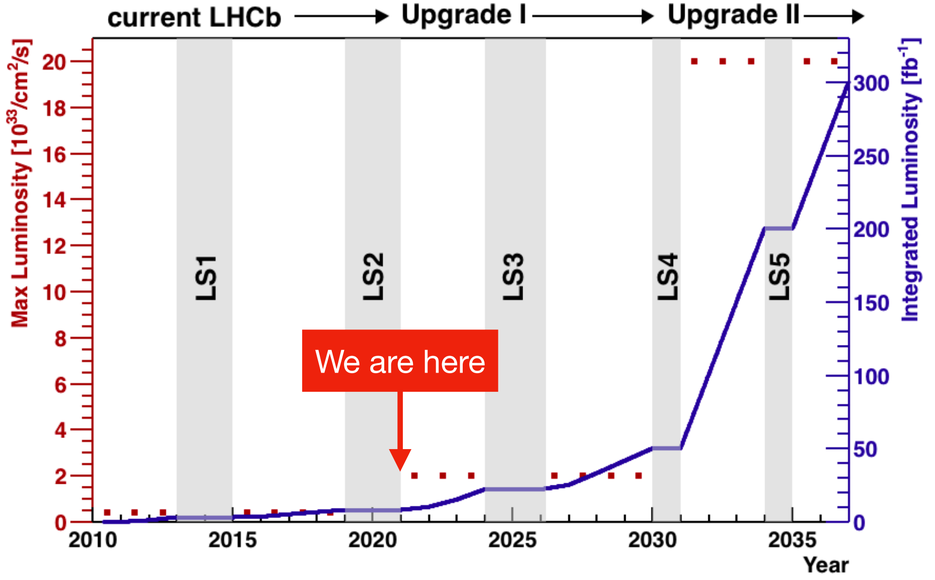
improvement of a factor 4 over previous limits

[arXiv:2206.06673]

Conclusions

- The LHCb experiment has the capabilities to discover many new decays of heavy-flavour hadrons
- The measurements provide:
  - Tests of the SM
  - Insights into hadronization and exotic spectroscopy
  - Constraints of theory models
  - And much more
- Run 3 just started, expect to collect $2\times$ the statistics of Run 1+2
- $300\ \mathrm{fb}^{-1}$ by the end of LHC ⟶ the best is yet to come!





BACKUP

Observation of the $\Lambda_b^0 \to D_s^- p$ decay

- Systematic uncertainties and efficiencies

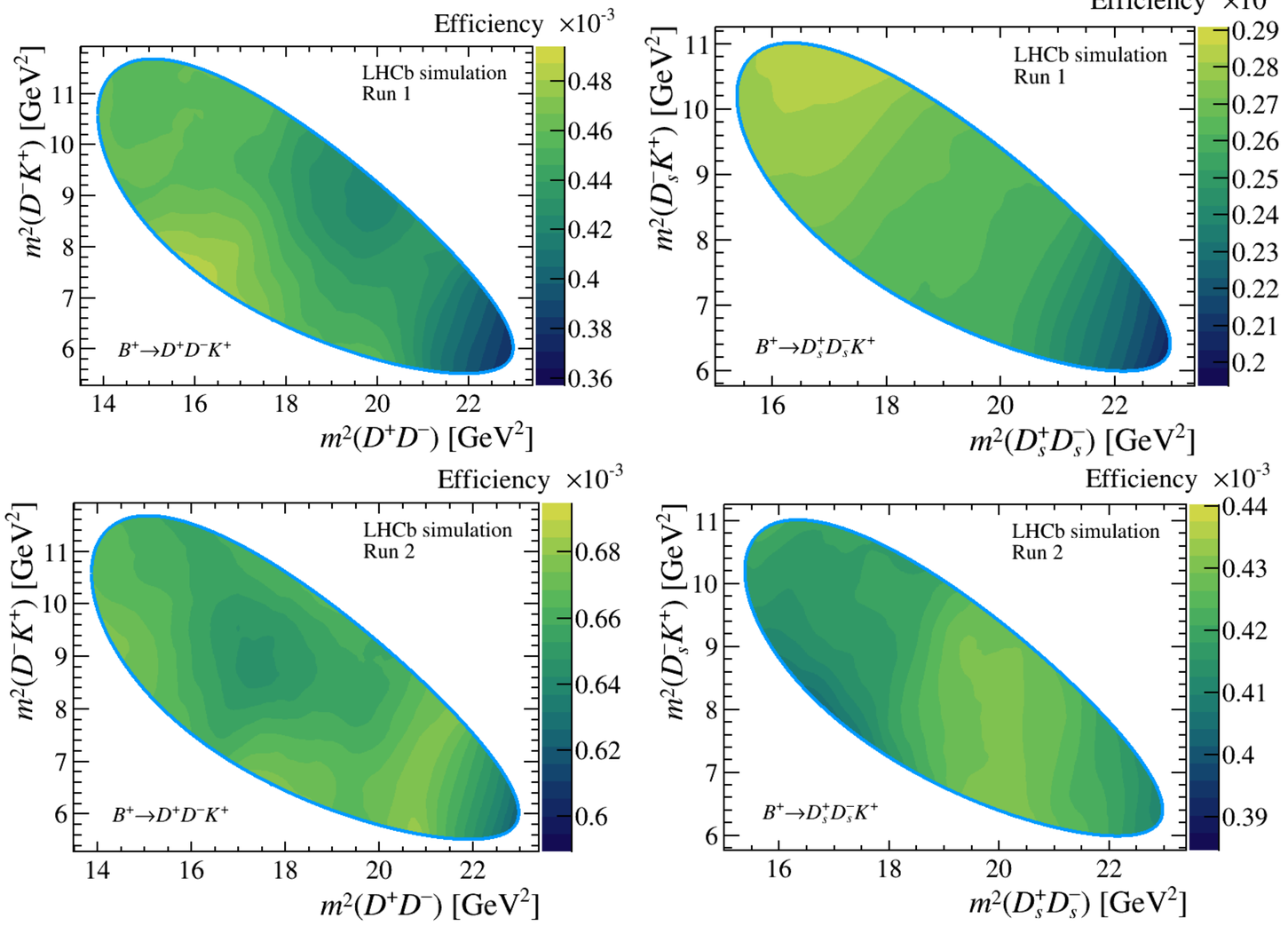
Source	Relative uncertainty (%)
Invariant-mass fits:	
$m(D_s^- p)$ fit:	
Signal parametrisation	0.54
Combinatorial background parametrisation	0.73
Constrained/fixed yields	0.71
Specific background parametrisation	0.89
$m(\Lambda_c^+ \pi^-)$ fit:	
Signal parametrisation	0.27
Combinatorial background parametrisation	0.04
Constrained/fixed yields	0.03
Specific background parametrisation	0.01
Efficiencies:	
PID efficiency	0.49
hardware trigger efficiency	1.15
Reconstruction efficiency	0.50
Total	2.01

	$\Lambda_b^0 \to D_s^- p$	$\Lambda_b^0 \to \Lambda_c^+ \pi^-$
Yield	831 ± 32	$(4.047 \pm 0.007) \times 10^5$
Efficiency	$(0.1819 \pm 0.0013)\%$	$(0.1947 \pm 0.0012)\%$
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)$	$(4.9 \pm 0.4) \times 10^{-3}$ [7]	
$\mathcal{B}(D_s^- \to K^- K^+ \pi^-)$	$(5.38 \pm 0.10) \times 10^{-2}$ [7]	
$\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)$	$(6.28 \pm 0.32) \times 10^{-2}$ [7]	

First observation of the $B^+ \to D_s^+ D_s^- K^+$ decay

- Systematic uncertainties and efficiencies

Systematic source	Relative uncertainty (%)
Signal model	0.3
Background model	0.1
NDC background	2.9
Mass fit bias	0.1
Multiple-candidate removal	0.7
Hardware trigger correction	2.3
PID correction	2.8
Classifier modelling	1.6
Tracking	1.0
Truth matching	0.6
Limited size of simulated samples	0.5
KDE parameters	0.4
Total syst. (stat.)	5.1 (6.3)



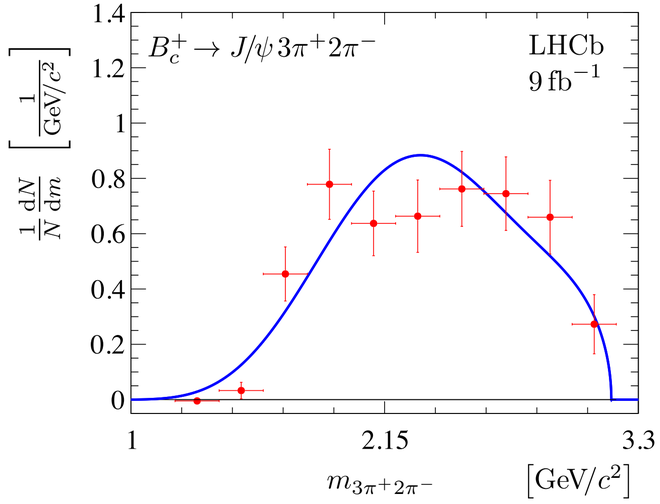
Observation of the $B_s^0 \to D^{*+}D^{*-}$ decay

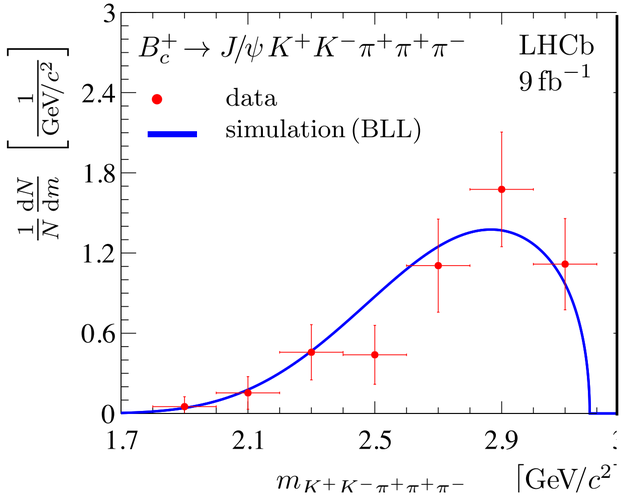
- Systematic uncertainties

Source	Run 1 [%]	Run 2 [%]	Combined [%]
Size of simulated sample	1.50	1.09	0.93
Polarisation	4.47	3.66	3.82
Multiple candidates	0.12	1.05	0.85
Mass model	0.08	0.09	0.09
Mass fit range	1.49	0.51	0.70
Total without f_s/f_d	4.94	3.99	5.13
f_s/f_d	3.18	3.11	3.11
Total	5.88	5.06	5.13

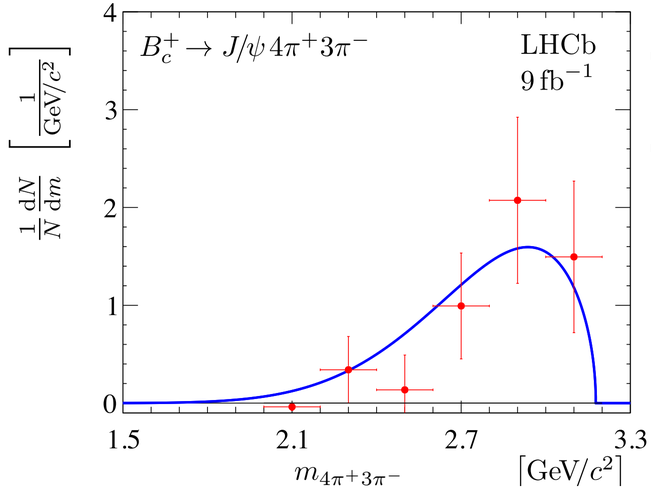
B_c^+ decays to charmonia + multihadron

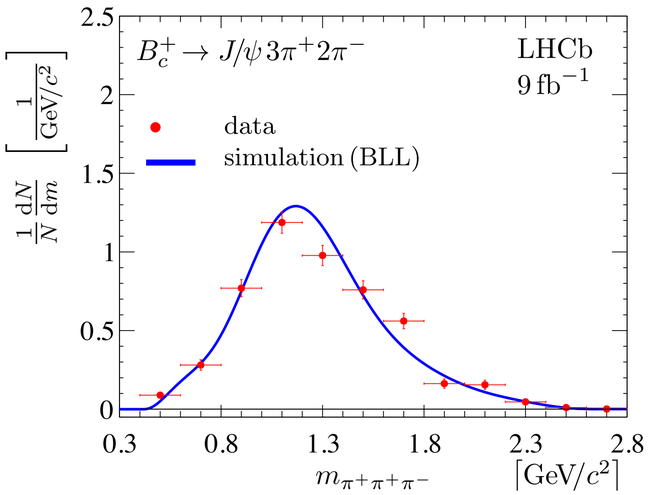
- BLL model predictions

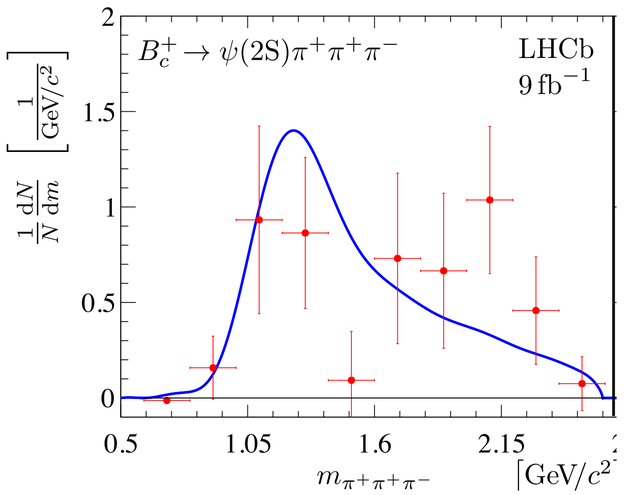




Source	Uncertainty [%]
Fit model	
Signal shape	0.1 – 2.5
Background shape	0.4 – 1.0
Multiple candidates exclusion	1.3
B_c^+ decay model	2.2 – 5.1
Efficiency corrections	0.1 – 1.1
Hadron interactions	0.0 – 2.8
Trigger efficiency	1.1
Data-simulation difference	2.3
Size of simulated sample	1.5 – 2.4
Total	4.4 – 7.1







Measurement of $\mathcal{B}(B_c^+ \to B_s^0\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$

- Signal yields, efficiencies and systematic uncertainties

Decay channel	Efficiency [%]
$B_c^+ \to J/\psi\pi^+$ (TOS)	1.6141 ± 0.0028
$B_c^+ \to J/\psi\pi^+$ (TIS)	0.15846 ± 0.00063
$B_c^+ \to B_s^0(\to J/\psi\phi)\pi^+$	0.4526 ± 0.0013
$B_c^+ \to B_s^0(\to D_s^-\pi^+)\pi^+$	0.02801 ± 0.00028

Decay channel	Signal yields
$B_c^+ \to J/\psi\pi^+$ (TOS)	14641 ± 195
$B_c^+ \to J/\psi\pi^+$ (TIS)	1376 ± 45
$B_c^+ \to B_s^0(\to J/\psi\phi)\pi^+$	186 ± 25
$B_c^+ \to B_s^0(\to D_s^-\pi^+)\pi^+$	65 ± 12

	$\mathcal{R}_{J/\psi\phi}$ [%]	$\mathcal{R}_{D_s^-\pi^+}$ [%]
Signal model	3.0	4.4
Background model	5.5	4.5
$B_c^+ \to B_s^{*0}\pi^+$ component	3.2	3.1
Data-simulation agreement	2.3	4.8
Tracking efficiency	3.2	6.0
Simulation sample size	0.3	1.1
Trigger	1.0	1.0
Total	8.1	10.5

Rare baryonic decays of B^0 and B_s^0 mesons

- Systematic uncertainties

Systematic source	$\mathcal{B}(B^0 \to p\bar{p}p\bar{p})$	$\mathcal{B}(B_s^0 \to p\bar{p}p\bar{p})$
Efficiencies (sample size)	5	3
Efficiencies (weights)	16	9
PID	8	3
Tracking	5	2
Fixed PDF parameters	5	2
Signal model	1	4
Background model	8	18
Total systematic	22	21
Normalisation $\mathcal{B}$	24	13

Source of systematic uncertainties	$B^0 \to p\bar{p}$	$B_s^0 \to p\bar{p}$
f_s/f_d	-	3.1
L0 trigger efficiency	1.0	1.0
Selection efficiency relative to $B^0 \to K^+\pi^-$	2.0	2.0
Tracking efficiency	1.9	1.9
PID efficiency	2.4	2.4
Fit model	1.0	22.0
Total	3.9	22.5