The B_c^+ meson decays at LHCb into charmonium and light hadron final states

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Topical B&Q meeting on B_c^+ meson spectroscopy

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Introduction

The B_c^+ meson is unique state consistent of two heavy quarks of different flavors ($\bar{b}c$ quarks)

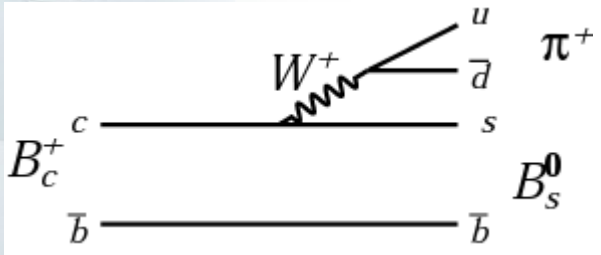
- non-relativistic system ⇒ expected a wide spectrum of excited states;
- not available for the study on e^+e^- machines;
- the mean lifetime is 3 times lower, w. r. t. B^+ meson ⇒ important role of c quark in decay mechanism;

$$\tau_{B_c^+} = 513.4 \pm 11.0 \pm 5.7 \text{ fs} \qquad \tau_{B^+} = 1.637 \pm 0.004 \pm 0.003 \text{ ps}$$

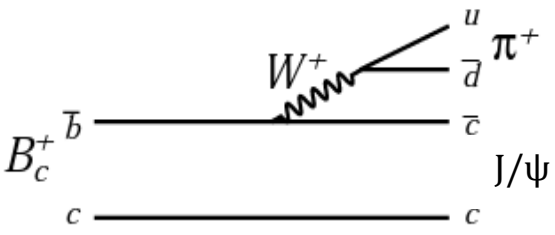
[Phys. Lett. B 742 (2015) 29] [JHEP 04 (2014) 114]

- the heaviest meson, that decays via weak interactions;
- expected a large number of possible decay modes.

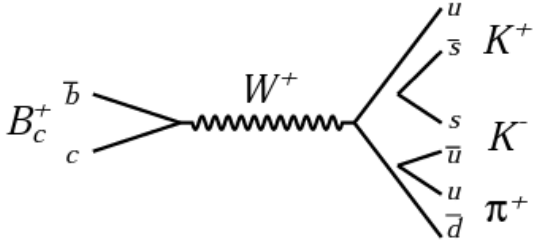
$\bar{b}$ quark-spectator



c quark-spectator



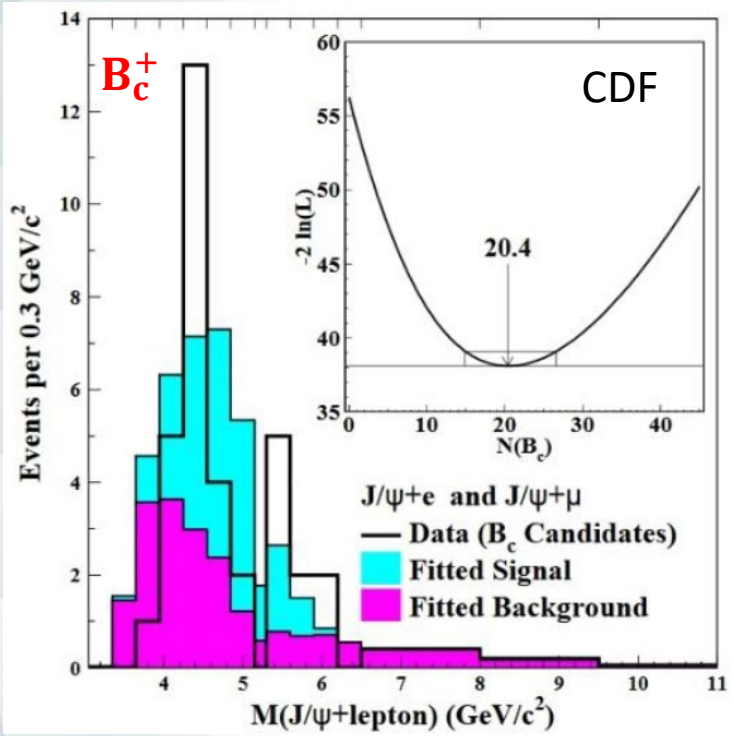
annihilation of $\bar{b}$ and c quarks



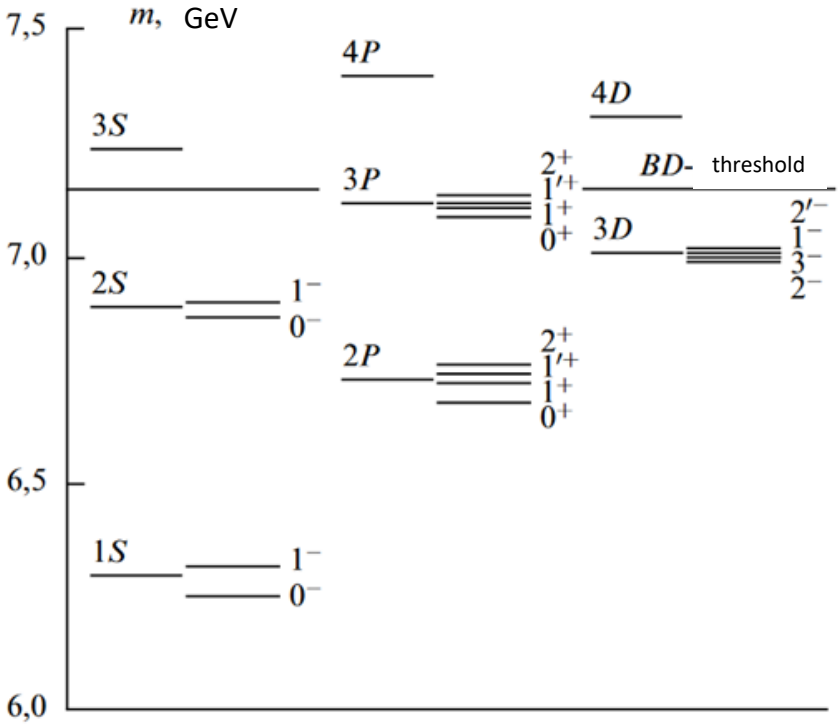
Introduction

The B_c^+ meson was discovered in 1998 by the CDF experiment in semileptonic decay mode $B_c^+ \to J/\psi l \nu_l$.

[Phys. Rev. Lett. 81 (1998) 2432]



Mass spectra of B_c^+ states



Studies of B_c^+ meson spectroscopy provides significant information about the dynamics of heavy quarks and contributes to the development of theories for description of the strong interactions.

Introduction

Despite the fact that the particle is known for 25 years, the B_c^+ meson is still poorly studied and **only a few decay channels have been discovered**.

The B_c^+ meson spectroscopy is aimed on:

- study of production mechanism;
- measurement of the main properties:
  - lifetime;
  - mass;
- searches for the new decay modes.

[Prog. Theor. Exp. Phys. (2020) 083C01]

B_c^+ $I(J^P) = 0(0^-)$

I, J, P need confirmation.

Quantum numbers shown are quark-model predictions.

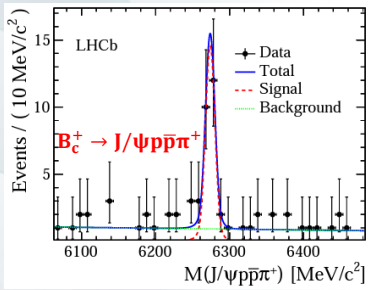
Mass $m = 6274.47 \pm 0.32$ MeV

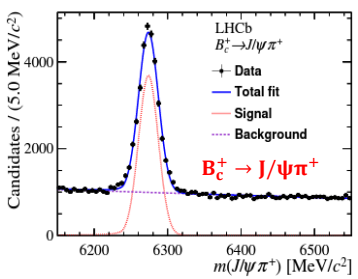
$m_{B_c^+} - m_{B_s^0} = 907.8 \pm 0.5$ MeV

Mean life $\tau = (0.510 \pm 0.009) \times 10^{-12}$ s

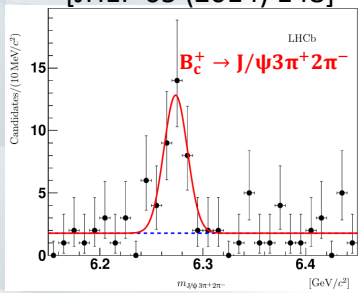
B_c^- modes are charge conjugates of the modes below.

[Phys. Rev. Lett. 113 (2014) 152003] [JHEP 07 (2020) 123]

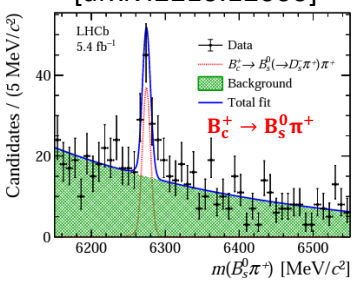




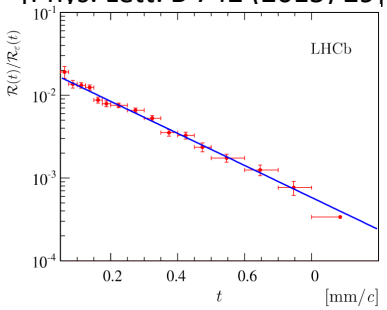
[JHEP 05 (2014) 148]



[arxiv:2210.12000]



[Phys. Lett. B 742 (2015) 29]



B_c^+ DECAY MODES × B($\bar{b} \to B_c$)		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$J/\psi(1S)\ell^+\nu_\ell$ anything		seen		–
$J/\psi(1S)\mu^+\nu_\mu$	✓	seen		2372
$J/\psi(1S)\tau^+\nu_\tau$	✓	seen		1932
$J/\psi(1S)\pi^+$		seen		2370
$J/\psi(1S)K^+$	✓	seen		2341
$J/\psi(1S)\pi^+\pi^+\pi^-$	✓	seen		2350
$J/\psi(1S)a_1(1260)$		not seen		2169
$J/\psi(1S)K^+K^-\pi^+$	✓	seen		2203
$J/\psi(1S)\pi^+\pi^+\pi^+\pi^-\pi^-$	✓	seen		2309
$\psi(2S)\pi^+$	✓	seen		2051
$J/\psi(1S)D^0K^+$	✓	seen		1539
$J/\psi(1S)D^*(2007)^0K^+$	✓	seen		1411
$J/\psi(1S)D^*(2010)^+K^{*0}$	✓	seen		919
$J/\psi(1S)D^+K^{*0}$	✓	seen		1122
$J/\psi(1S)D_s^+$	✓	seen		1821
$J/\psi(1S)D_s^{*+}$		seen		1727
$J/\psi(1S)p\bar{p}\pi^+$	✓	seen		1791
$\chi_c^0\pi^+$	✓	$(2.4^{+0.9}_{-0.8}) \times 10^{-5}$		2205
$p\bar{p}\pi^+$	✓	not seen		2970
D^0K^+	✓	seen		2837

~90% of the B_c^+ meson decays are discovered by the LHCb. Moreover, the experiment provides record-breaking accuracy in measuring the masses and lifetimes of all kinds of heavy hadrons. The analyses presented in the following are **based on full LHCb datasample** collected between 2011-2018.

Study of the B_c^+ meson decays into charmonium and three light hadrons

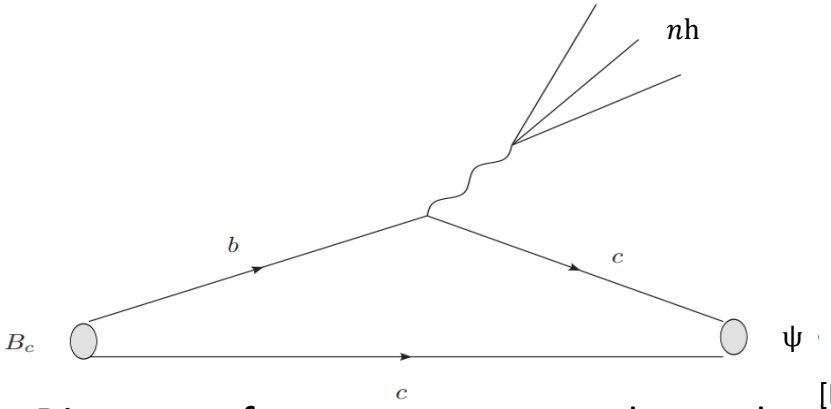
Channels under study:

- $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$;
- $B_c^+ \to J/\psi K^+\pi^-\pi^+$;
- $B_c^+ \to J/\psi K^+K^-\pi^+$;
- $B_c^+ \to \psi(2S)\pi^+\pi^-\pi^+$;
- $B_c^+ \to \psi(2S)(\to J/\psi\pi^+\pi^-)\pi^+$;
- $B_c^+ \to \psi(2S)K^+K^-\pi^+$;
- $B_c^+ \to J/\psi K^+K^-K^+$.

[JHEP 01 (2022) 065]

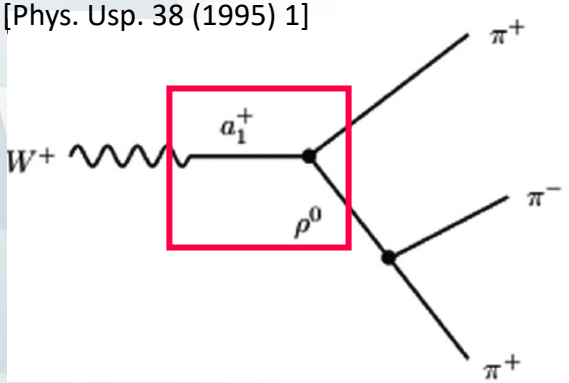
Study of the $B_c^{\pm} \to \psi 3h^{\pm}$ decays

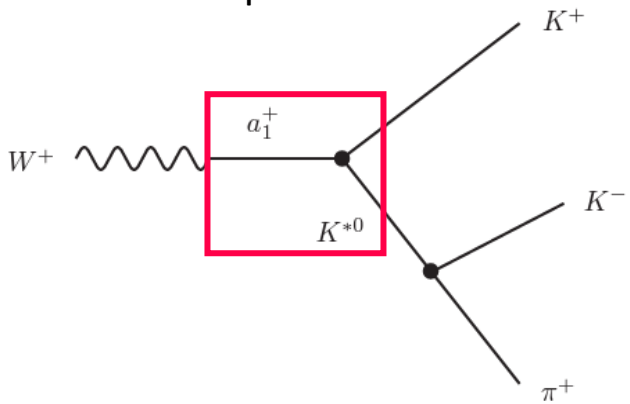
The B_c^+ decays into charmonium (ψ) and light hadrons ($h^{\pm} = \pi^{\pm}, K^{\pm}$), can be described using the QCD factorisation approach. Such decays are caused by weak b-quark decay $b \to cW^* \to c\bar{u}d$ and clean analogy with similar τ-lepton decays ($\tau \to \nu_\tau + nh$) can be easily seen. Such analogy allows to use existing experimental data on τ -lepton decays and give reliable predictions on $B_c^{\pm} \to \psi n h^{\pm}$ **branching fractions** and **expected contributions from intermediate resonances**.



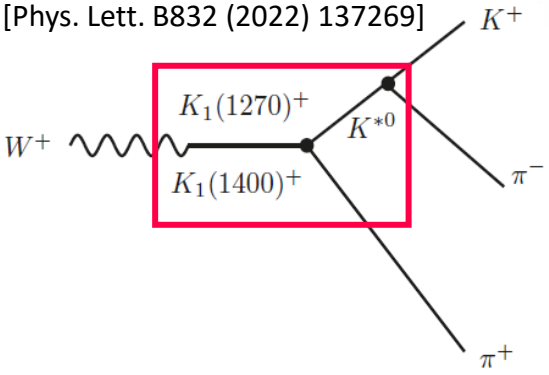
Diagrams of some processes under study

[Z. Phys. C34 (1987) 103]
[Prog. Part. Nucl. Phys. 21 (1988) 33]
[Phys. Usp. 38 (1995) 1]





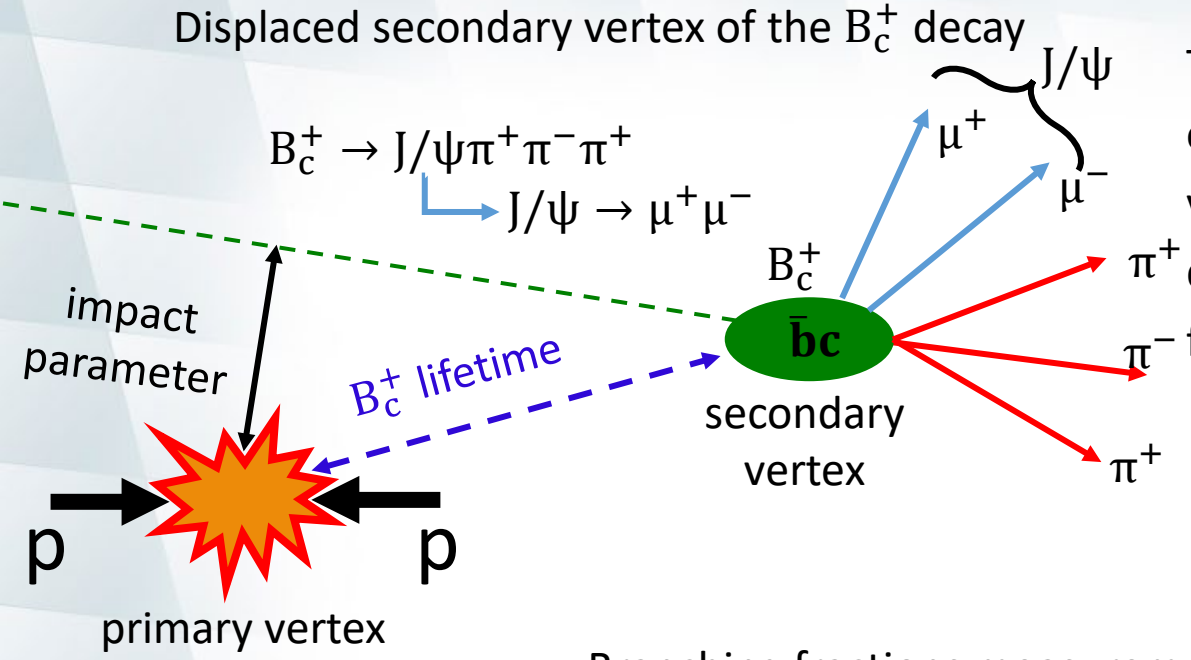
[Phys. Atom. Nucl. 76 (2013) 787]
[arXiv:1307.0953v2]
[Phys. Lett. B832 (2022) 137269]



The theoretical model based on this approach and used to describe the studied decays was proposed by A. V. Berezhny, A. V. Luchinskii and A. K. Likhoded (the BLL model).

(**more details in Alexey's talk**)

Branching fraction measurement



The B_c^+ candidate selection is based on requirements to the different variables: kinematics, reconstruction quality, geometry, identification of final-state particles.

Branching fractions measurement:

$$\mathcal{R}_Y^X = \frac{N_X}{N_Y} \times \frac{\epsilon_Y}{\epsilon_X}$$

From data fit

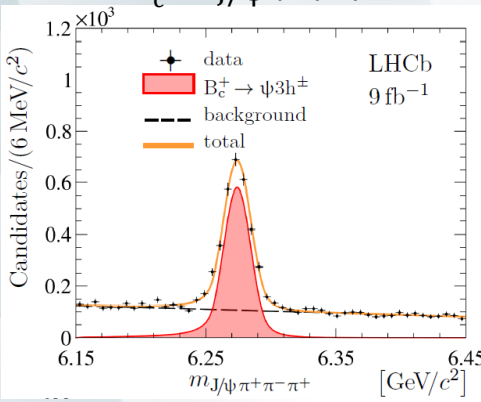
From simulation produced with BLL model

- X – signal channel
- Y – normalization channel
- N – signal yield
- ϵ - total efficiency

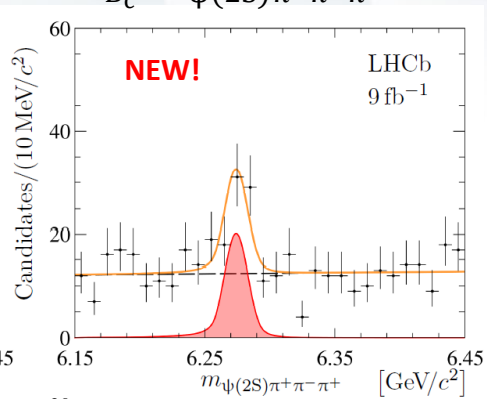
Study of the $B_c^{\pm} \to \psi 3h^{\pm}$ decays

[JHEP 01 (2022) 065]

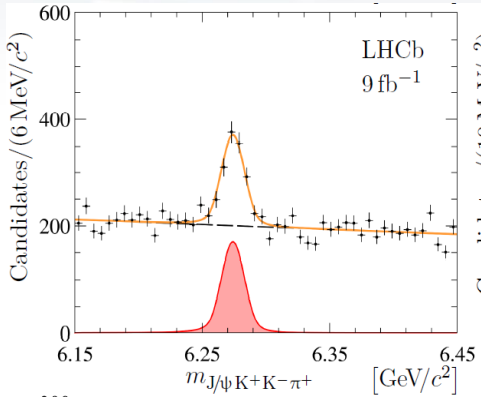
$B_c^+ \to J/\psi\pi^+\pi^-\pi^+$



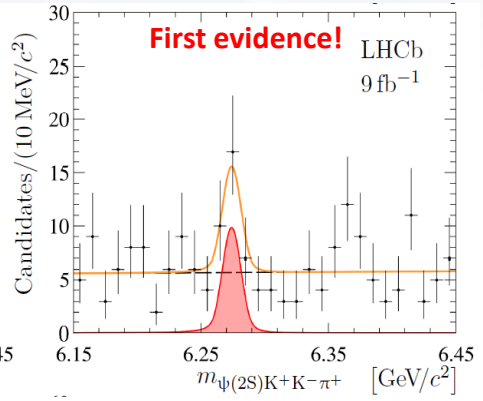
$B_c^+ \to \psi(2S)\pi^+\pi^-\pi^+$



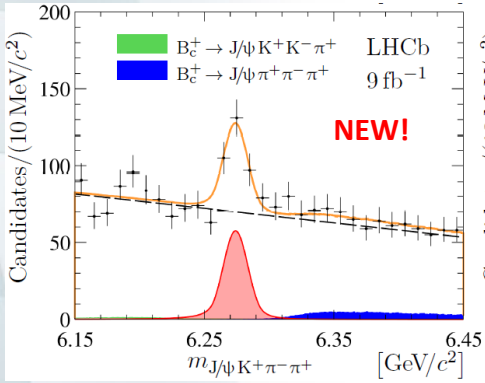
$B_c^+ \to J/\psi K^+K^-\pi^+$



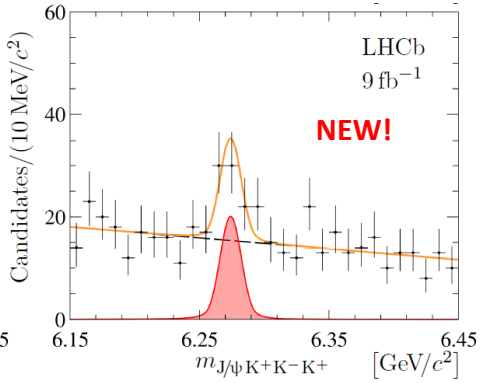
$B_c^+ \to \psi(2S)K^+K^-\pi^+$



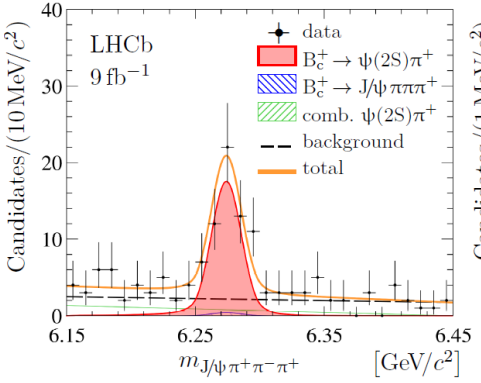
$B_c^+ \to J/\psi K^+\pi^-\pi^+$

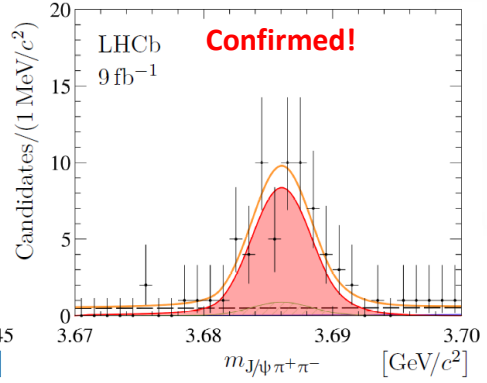


$B_c^+ \to J/\psi K^+K^-K^+$



$B_c^+ \to \psi(2S)(\to J/\psi\pi^+\pi^-)\pi^+$





Decay	Yield	$\mathcal{S}$ [σ]
$B_c^+ \to J/\psi\pi^+\pi^-\pi^+$	2750 ± 69	
$B_c^+ \to J/\psi K^+K^-\pi^+$	686 ± 48	
$B_c^+ \to J/\psi K^+K^-K^+$	43 ± 10	5.2
$B_c^+ \to J/\psi K^+\pi^-\pi^+$	148 ± 22	7.8
$B_c^+ \to \psi(2S)\pi^+\pi^-\pi^+$	49 ± 11	5.8
$B_c^+ \to \psi(2S)K^+K^-\pi^+$	19 ± 6	3.7
$B_c^+ \to (\psi(2S) \to J/\psi\pi^+\pi^-)\pi^+$	54 ± 9	11.8

- three new B_c^+ decay modes **are observed**;
- **first evidence** of the $B_c^+ \to \psi(2S)K^+K^-\pi^+$ decay;
- the decay of $B_c^+ \to \psi(2S)\pi^+$ **confirmed** using $\psi(2S) \to J/\psi\pi^+\pi^-$ mode.

Study of the $B_c^{\pm} \to \psi 3h^{\pm}$ decays

Measured branching fractions are **in agreement** with **theoretical predictions, previous LHCb measurements** and **similar studies** in charged and neutral B-meson systems.

Ratio	Value	Prediction, measurement
$\mathcal{R}^{\psi(2S)K^+K^-\pi^+}_{\psi(2S)\pi^+\pi^-\pi^+}$	$0.37 \pm 0.15 \pm 0.01$	0.16
$\mathcal{R}^{J/\psi K^+\pi^-\pi^+}_{J/\psi K^+K^-\pi^+}$	$0.35 \pm 0.06 \pm 0.01$	0.37
$\mathcal{R}^{J/\psi K^+\pi^-\pi^+}_{J/\psi \pi^+\pi^-\pi^+}$	$(6.4 \pm 1.0 \pm 0.2) \times 10^{-2}$	7.7×10^{-2}
$\mathcal{R}^{J/\psi K^+K^-\pi^+}_{J/\psi \pi^+\pi^-\pi^+}$	$0.185 \pm 0.013 \pm 0.006$	0.21
$\mathcal{R}^{\psi(2S)\pi^+}_{J/\psi K^+K^-\pi^+}$	$0.19 \pm 0.03 \pm 0.01$	0.18 ± 0.04
$\mathcal{R}^{\psi(2S)\pi^+}_{J/\psi \pi^+\pi^-\pi^+}$	$(3.5 \pm 0.6 \pm 0.2) \times 10^{-2}$	$(3.9 \pm 0.9) \times 10^{-2}$
$\mathcal{R}^{J/\psi K^+K^-\pi^+}_{J/\psi \pi^+\pi^-\pi^+}$	$0.185 \pm 0.013 \pm 0.006$	0.22 ± 0.06

[arXiv:1307.0953, Phys. Atom. Nucl. 76 (2013) 787]

	Value $[10^{-2}]$
$\mathcal{R}^{J/\psi K^+K^-K^+}_{J/\psi K^+K^-\pi^+}$	$7.0 \pm 1.8 \pm 0.2$
$\mathcal{R}^{J/\psi K^+\pi^-\pi^+}_{J/\psi \pi^+\pi^-\pi^+}$	$6.4 \pm 1.0 \pm 0.2$
$\frac{\mathcal{B}(B_c^+ \to J/\psi K^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)}$	7.9 ± 0.8
$\frac{\mathcal{B}(B^+ \to \overline{D}^0 K^+\pi^-\pi^+)}{\mathcal{B}(B^+ \to \overline{D}^0 \pi^+\pi^-\pi^+)}$	9.3 ± 5.1
$\frac{\mathcal{B}(B^0 \to D^- K^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^- \pi^+\pi^-\pi^+)}$	5.8 ± 1.5
$\frac{\mathcal{B}(B^0 \to D^{*-} K^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-} \pi^+\pi^-\pi^+)}$	6.5 ± 0.6
$\frac{\mathcal{B}(B_s^0 \to D_s^- K^+\pi^-\pi^+)}{\mathcal{B}(B_s^0 \to D_s^- \pi^+\pi^-\pi^+)}$	5.2 ± 1.3

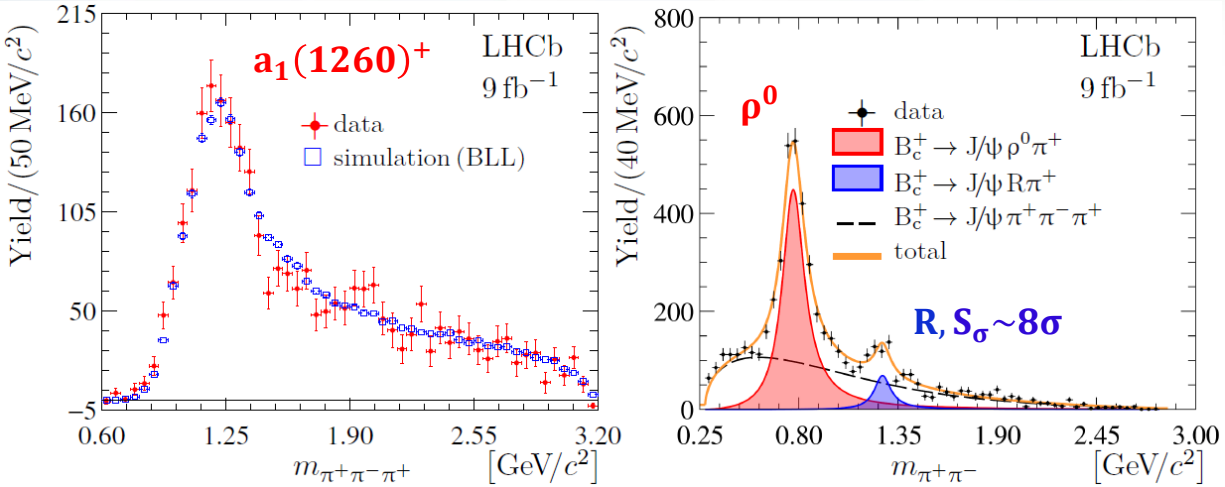
[Prog. Theor. Exp. Phys. (2020) 083C01]

The results **largely support** the factorisation approach used for a theoretical description of the studied decays.

Decay of $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$

For the cross-check of BLL model predictions the light hadron systems were considered.

$B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ [JHEP 01 (2022) 065]



- the dominating contribution from $a_1(1260)^+ \to \rho^0\pi^+$, $\rho^0 \to \pi^+\pi^-$ states is seen (**confirms BLL model**);
- in $\pi^+\pi^-$ mass spectrum the new resonant structure is observed (**R-state**), the measured mass and width are:

$$m_R = 1265 \pm 10 \ [\mathrm{MeV}/c^2]$$
$$\Gamma_R = 110 \pm 21 \ [\mathrm{MeV}]$$

1275.4 ± 0.8 MeV (S = 1.1) $f_2(1270)$ (PDG)

186.6 ± 2.3 MeV (S = 1.5)

- The fractions of decays proceed via ρ^0 and **R** states are measured to be:

$$f_{\rho^0}^{B_c^+ \to J/\psi\pi^+\pi^-\pi^+} = \left(88.1 \pm 3.0^{+12.0}_{-0.3}\right)\%$$
$$f_R^{B_c^+ \to J/\psi\pi^+\pi^-\pi^+} = \left(10.4 \pm 1.4^{+8.0}_{-1.2}\right)\%$$

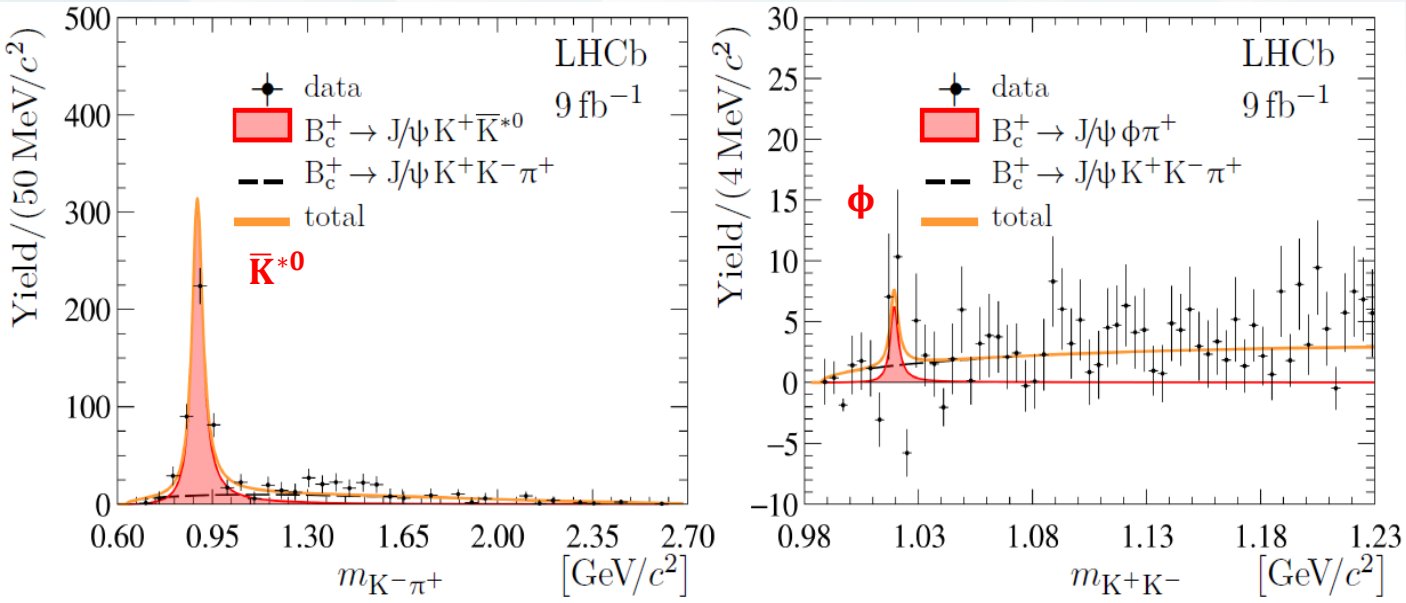
- the relative fraction of decays via **R** and ρ^0 resonances are:

$$f_R/f_{\rho^0} = (11.8 \pm 1.6)\% \quad \text{[Phys. Rev. D 61 (2000) 012002]}$$

in agreement with CLEO measurement for the fractions of $f_{f_0(1370)}/f_{\rho^0}$ **states**. It allows interpretation of the R-structure as the $f_0(1370)$ resonance, however alternative interpretations such as $f_2(1270)$ or $\rho(1450)$ state are also possible.

Decay of $B_c^+ \to J/\psi K^+K^-\pi^+$

$B_c^+ \to J/\psi K^+K^-\pi^+$ [JHEP 01 (2022) 065]



- the dominating contribution from $\overline{K}^{*0} \to K^-\pi^+$ decays. The contributions from $\phi \to K^+K^-$ process is significantly suppressed (**confirms BLL model**);
- the fraction of the decays proceeding via intermediate $\overline{K}^{*0}$ state is measured to be:

$$f_{\overline{K}^{*0}}^{B_c^+ \to J/\psi K^+K^-\pi^+} = \left(64.5 \pm 4.7^{+3.9}_{-4.8}\right)\%$$

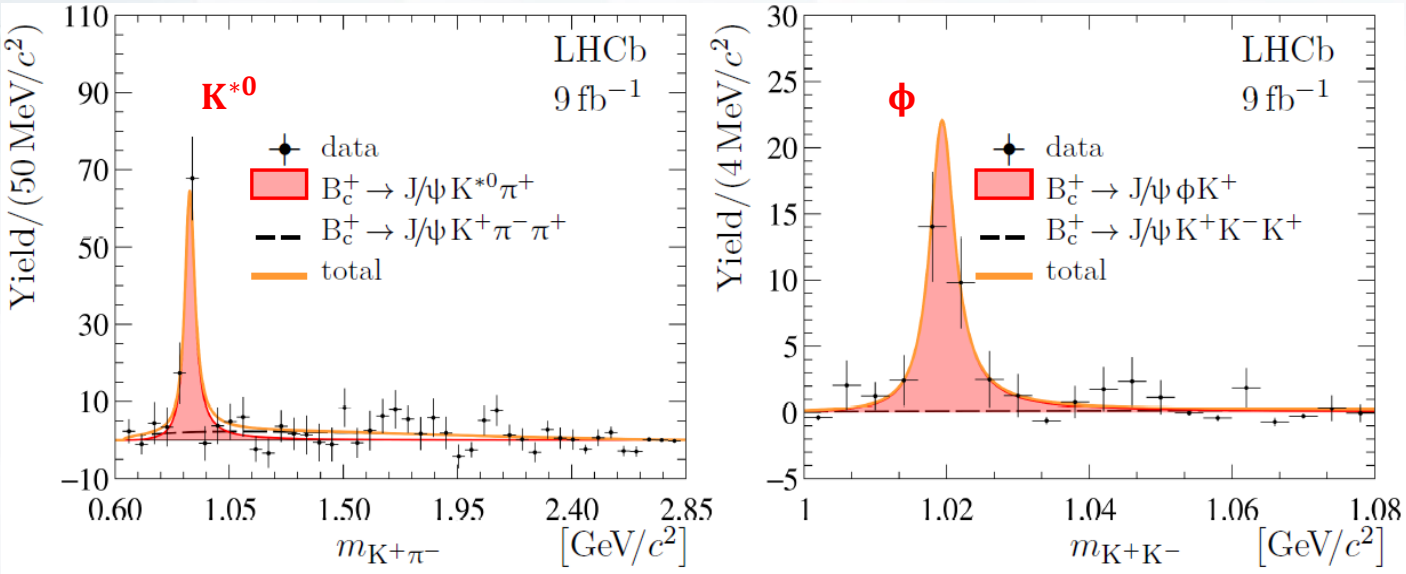
- the upper limit at 90(95%) CL's for the fraction decays proceeding via intermediate ϕ is set to be:

$$f_{\phi}^{B_c^+ \to J/\psi K^+K^-\pi^+} < 4.2\,(4.8)\%$$

Both results are **in agreement** with the previous LHCb study [JHEP 11 (2013) 094].

Decays of $B_c^+ \to J/\psi K^+\pi^-\pi^+$ and $B_c^+ \to J/\psi K^+K^-K^+$

$B_c^+ \to J/\psi K^+\pi^-\pi^+$ [JHEP 01 (2022) 065 $B_c^+ \to J/\psi K^+K^-K^+$



- $B_c^+ \to J/\psi K^+\pi^-\pi^+$ channel:
  - large fraction of decays via intermediate $K^{*0} \to K^+\pi^-$ state (**confirms BLL model**):

$$f_{K^{*0}}^{B_c^+ \to J/\psi K^+\pi^-\pi^+} = \left(61.3 \pm 5.0^{+7.7}_{-0.3}\right)\%$$

- $B_c^+ \to J/\psi K^+K^-K^+$ channel:
  - large fraction of decays via intermediate $\phi \to K^+K^-$ state:

$$f_{\phi}^{B_c^+ \to J/\psi K^+K^-K^+} = \left(90 \pm 19^{+5}_{-7}\right)\%$$

Study of B_c^+ meson decays into charmonium and multihadron final states

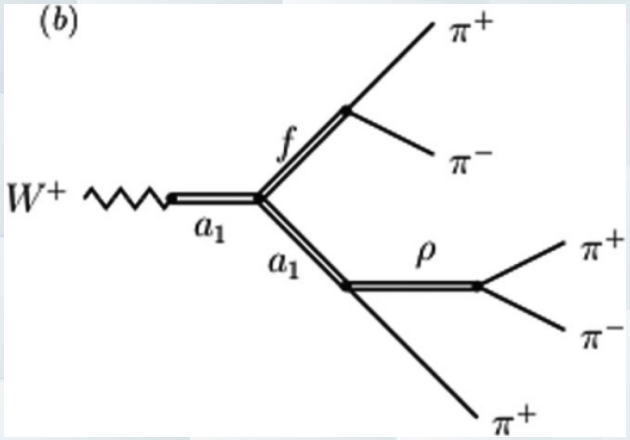
Channels under study:

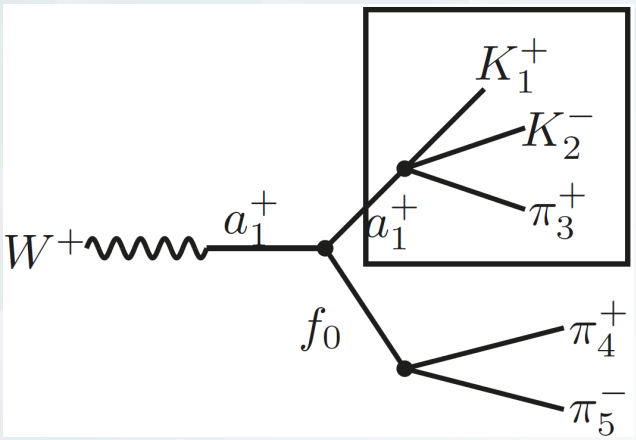
- $B_c^+ \to J/\psi 3\pi^+ 2\pi^-$;
- $B_c^+ \to (\psi(2S) \to J/\psi\pi^+\pi^-)\pi^+\pi^-\pi^+$;
- $B_c^+ \to J/\psi K^+ K^- \pi^+\pi^-\pi^+$;
- $B_c^+ \to J/\psi 4\pi^+ 3\pi^-$.

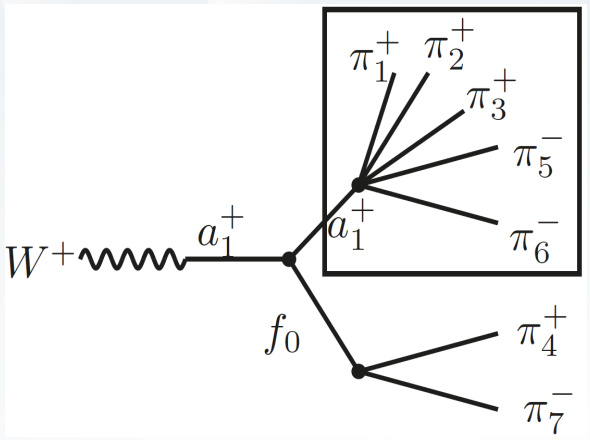
[arXiv:2208.08660]

Study of the $B_c^{\pm} \to J/\psi n h^{\pm}$ decays

An experimental test of the factorization approach was also investigated in the study of new B_c^+ decays into J/ψ meson and multihadron final states (n = 5 or 7 light hadrons).





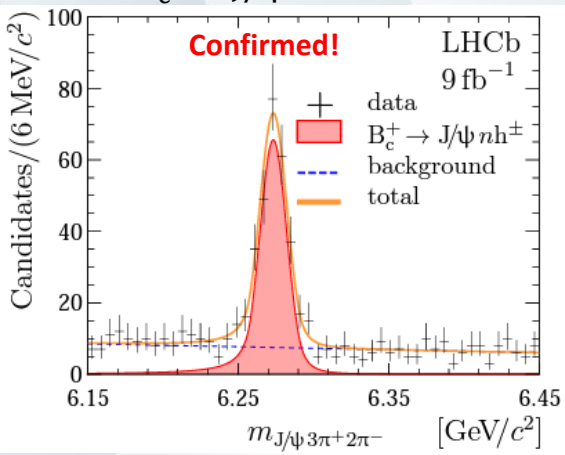


[Phys. Rev. D81 (2010) 014015; Phys. Atom. Nucl. 76 (2013) 787; arXiv:1307.0953v2; Phys. Rev. D86 (2012) 074024; Phys. Lett. B832 (2022) 137269; Phys. Rev. D99 (2019) 036019]

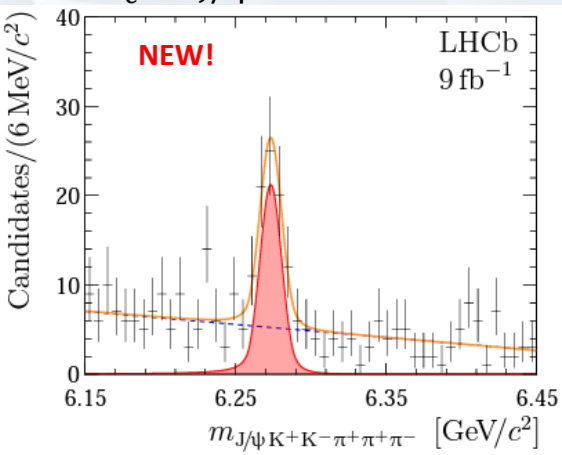
The theoretical description of these processes is performed using the advanced BLL model, which predicts the shapes of invariant mass distributions for systems of light hadrons and the contributions from intermediate resonances.

Study of the $B_c^{\pm} \to J/\psi n h^{\pm}$ decays

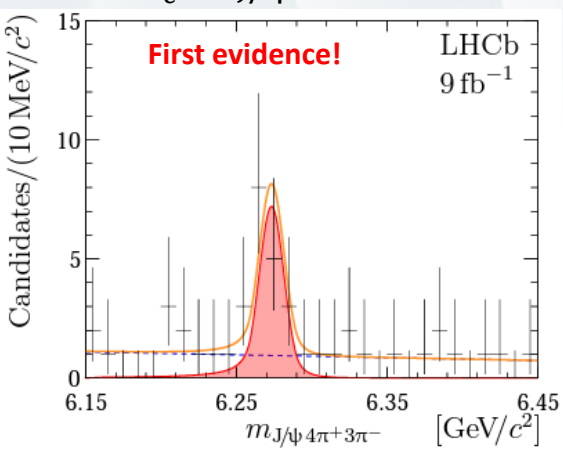
$B_c^+ \to J/\psi 3\pi^+ 2\pi^-$



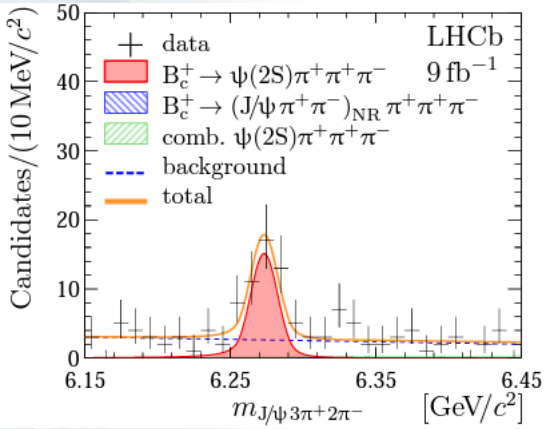
$B_c^+ \to J/\psi K^+ K^- \pi^+ \pi^- \pi^+$

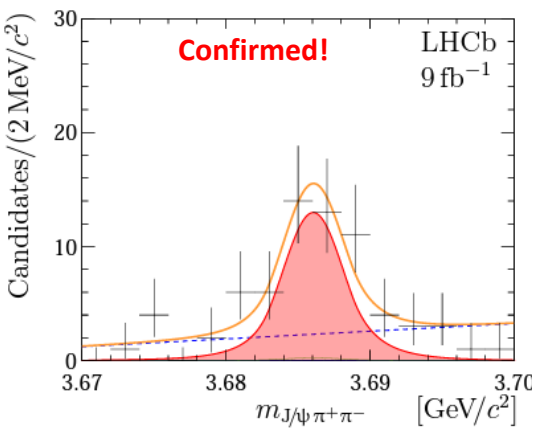


$B_c^+ \to J/\psi 4\pi^+ 3\pi^-$



$B_c^+ \to (\psi(2S) \to J/\psi \pi^+ \pi^-)\pi^+ \pi^- \pi^+$





Decay	[arXiv:2208.08660] Yield	$\mathcal{S}$ [σ]
$B_c^+ \to J/\psi 3\pi^+ 2\pi^-$	268 ± 20	21.0
$B_c^+ \to J/\psi K^+ K^- \pi^+ \pi^+ \pi^-$	69 ± 11	9.1
$B_c^+ \to J/\psi 4\pi^+ 3\pi^-$	16 ± 5	4.9
$B_c^+ \to (\psi(2S) \to J/\psi \pi^+ \pi^-)\pi^+ \pi^+ \pi$	40 ± 8	6.4

Measured branching ratios

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

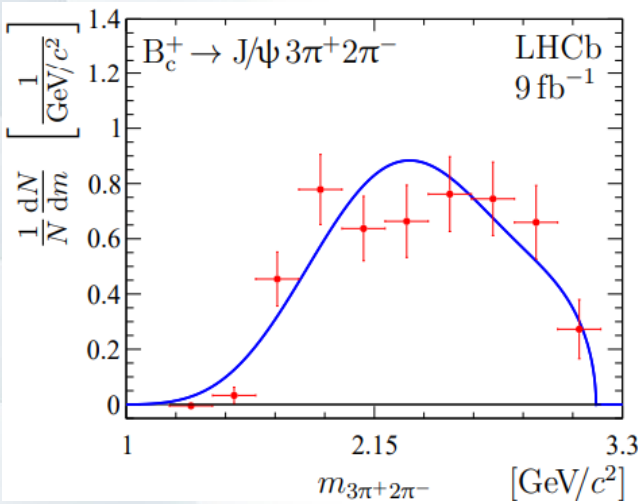
$$\mathcal{R}^{J/\psi 4\pi^+ 3\pi^-}_{J/\psi 3\pi^+ 2\pi^-} = (28.5 \pm 8.7 \pm 2.0) \times 10^{-2},$$

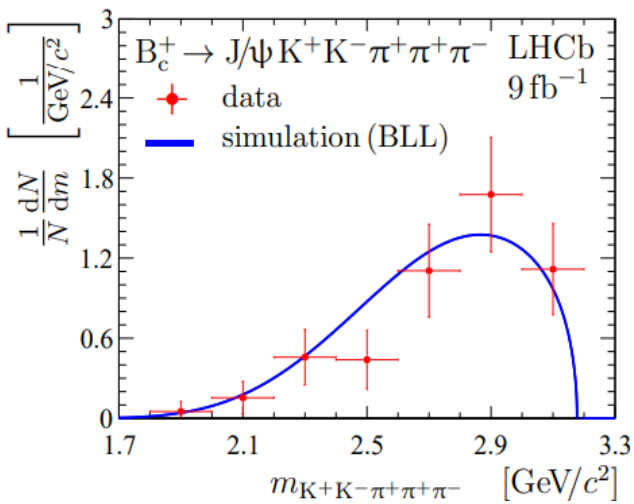
$$\mathcal{R}^{\psi(2S)\pi^+\pi^+\pi^-}_{J/\psi 3\pi^+ 2\pi^-} = (17.6 \pm 3.6 \pm 0.8) \times 10^{-2},$$

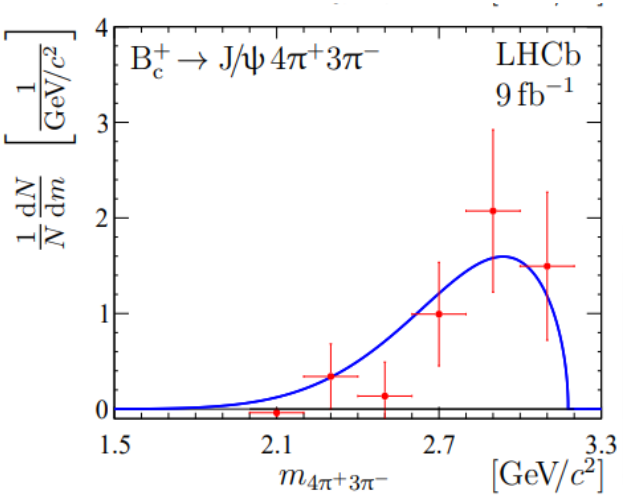
- the $B_c^+ \to J/\psi K^+ K^- \pi^+ \pi^- \pi^+$ decay is **observed** for the first time;
- **first evidence** of the $B_c^+ \to J/\psi 4\pi^+ 3\pi^-$ decay (**9 track secondary vertex!**);
- the $B_c^+ \to \psi(2S)\pi^+\pi^-\pi^+$ channel **is confirmed** using $\psi(2S) \to J/\psi\pi^+\pi^-$ decay mode;
- the decay of $B_c^+ \to J/\psi 3\pi^+ 2\pi^-$ **is confirmed**.

Multihadron systems

Similarly, as in the previous analysis, the systems of light hadrons were studied to test the predictions of the BLL model.





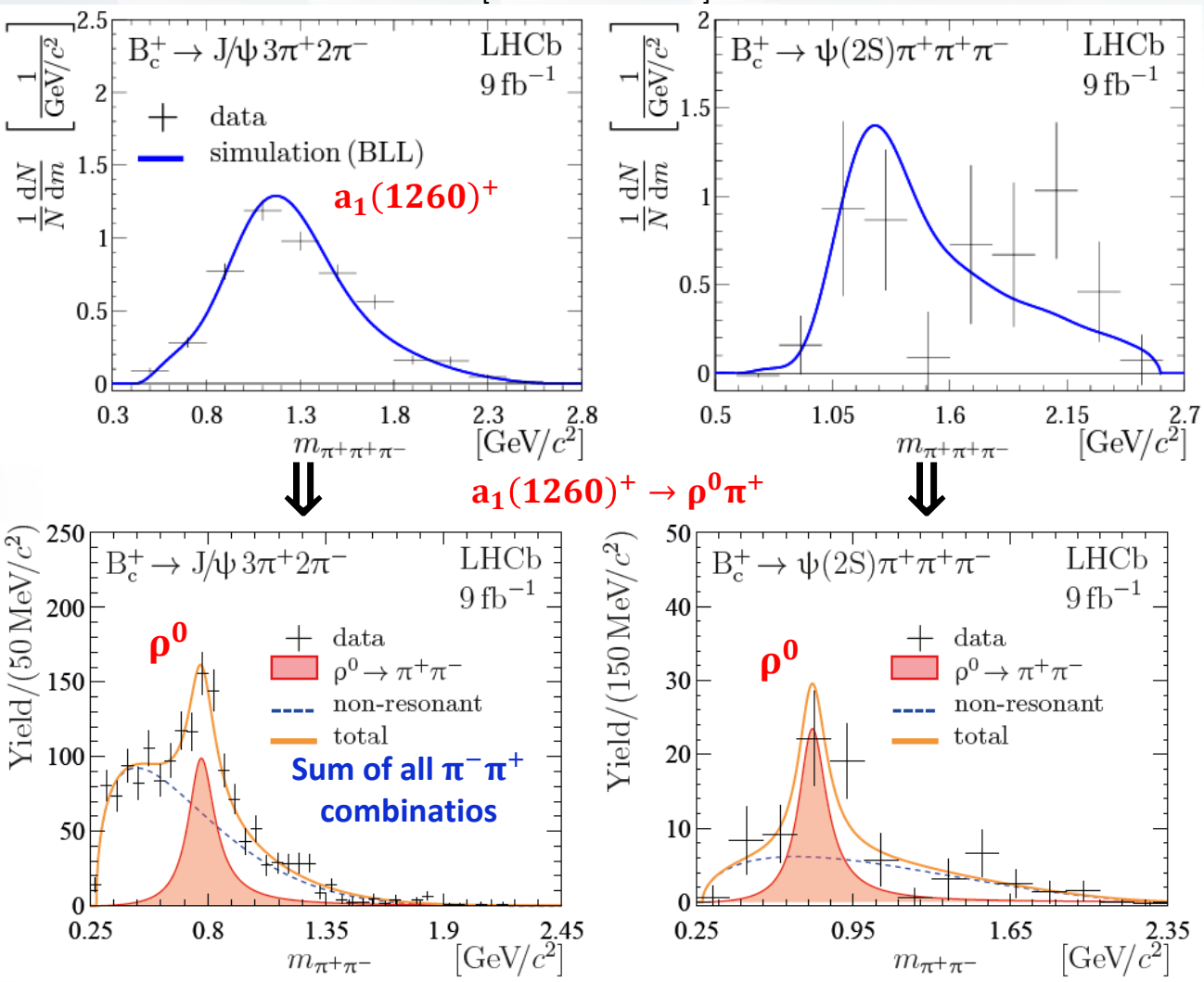


For the shapes of multihadron systems the BLL model predictions are **in good agreement** with experimental data.

$B_c^+ \to J/\psi 3\pi^+ 2\pi^-$ and $B_c^+ \to (\psi(2S) \to J/\psi\pi^+\pi^-)\pi^+\pi^-\pi^+$ decays

Study of pion systems

[arXiv:2208.08660]

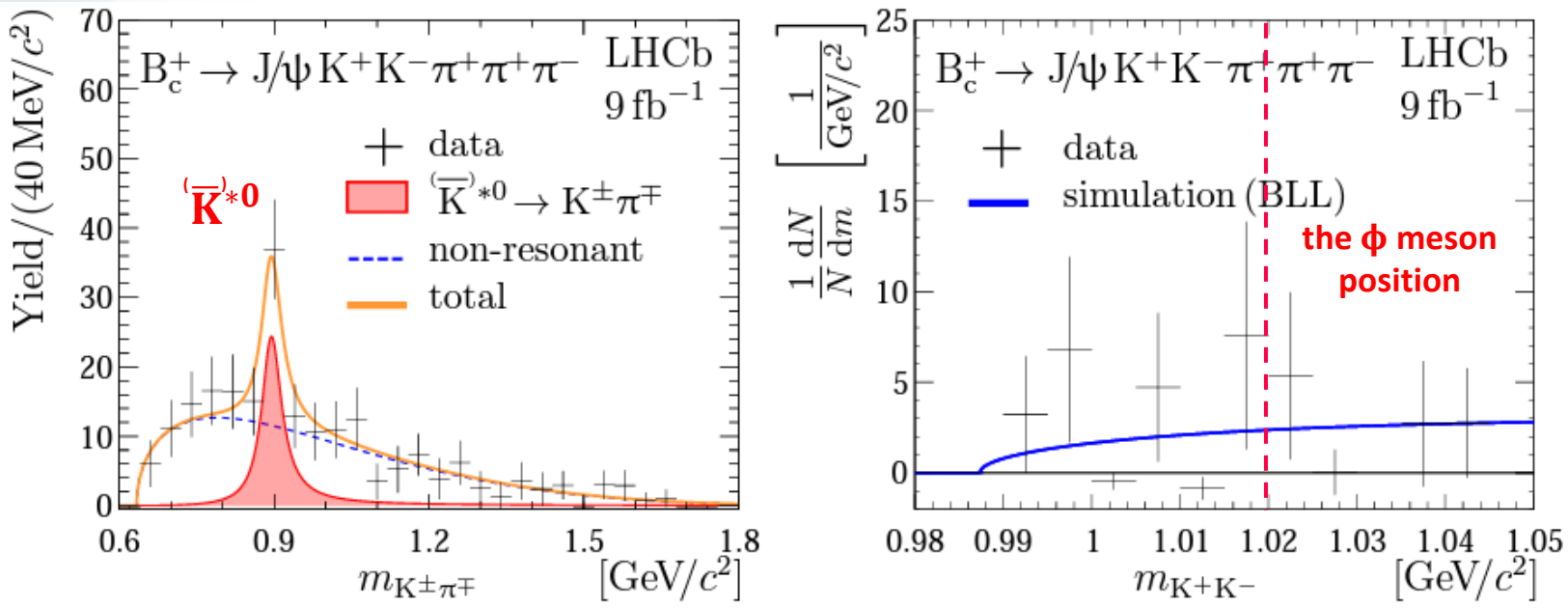


The fit results show that most of the decays proceed via intermediate ρ^0 resonance (**confirms the BLL model**). The mass and width of ρ^0 state in the fit model are constrained to the PDG value

Decay of $B_c^+ \to J/\psi K^+K^-\pi^+\pi^-\pi^+$

In the $B_c^+ \to J/\psi K^+K^-\pi^+\pi^-\pi^+$ decay, the invariant mass distributions of $K^\pm\pi^\mp$ and K^+K^- combinations were studied.

[arXiv:2208.08660]



- the fit results shows that the most of decays passing through intermediate $\overline{K}^{*0}$ and K^{*0} states;
- in invariant mass distribution of the K^+K^- system the contributions from ϕ meson are not seen, **which agrees with BLL model predictions**;
- same effects were observed in the $B_c^+ \to J/\psi K^+K^-\pi^+$ mode from previous study.

Conclusion

- For the recent years, there has been significant progress in B_c^+ meson spectroscopy:
  - the decays of $B_c^+ \to \psi(2S)\pi^+\pi^-\pi^+$, $B_c^+ \to J/\psi K^+\pi^-\pi^+$, $B_c^+ \to J/\psi K^+K^-K^+$, and $B_c^+ \to J/\psi K^+K^-\pi^+\pi^-\pi^+$ **are observed for the first time**;
  - the **first evidence** of the $B_c^+ \to \psi(2S)K^+K^-\pi^+$ and $B_c^+ \to J/\psi 4\pi^+3\pi^-$ decays is performed;
  - the decays of $B_c^+ \to \psi(2S)\pi^+$ and $B_c^+ \to \psi(2S)\pi^+\pi^-\pi^+$ **are confirmed** using $\psi(2S) \to J/\psi\pi^+\pi^-$ channel;
  - the resonant structures in the light hadron systems **are studied**;
  - experimental observables **supports the factorisation hypothesis** and **agrees** with theoretical predictions of the BLL model;
- more new and significant results are expected with Run 3 data.

Thank you!