Study of B_c^+ physics at LHCb

俞洁晟（湖南大学）

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Outline

- **Introduction**
- **Recent results of B_c^+ study**
  - b quark decays
  - c quark decays
  - mass
- **Conclusion and outlook**

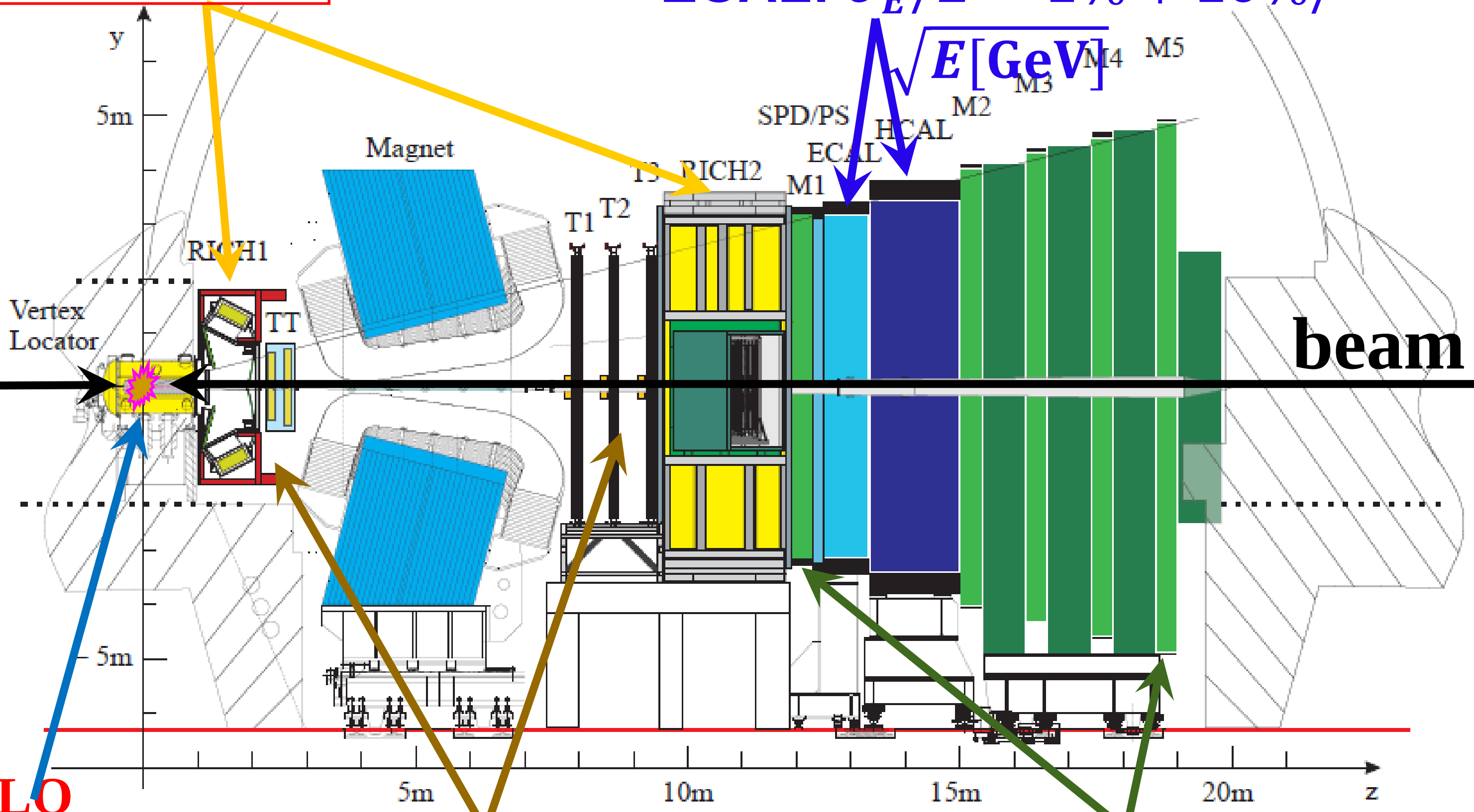
LHCb detector

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

Pseudorapidity acceptance
$2 < \eta < 5$

RICH1 & RICH2
$\epsilon(K \to K) \sim 95\%$
$\pi \to K$ mis-id: $\sim 5\%$

Calorimeters
ECAL: $\sigma_E/E \sim 1\% + 10\%/\sqrt{E[\mathrm{GeV}]}$



VELO
$\sigma_{\mathrm{IP}} \sim 20\ \mu\mathrm{m}$
Decay time resolution: 45 fs (τ)~1.5 p

Tracking System
$\Delta p/p = 0.5\%@5\ \mathrm{GeV}/c$
to $1\%@200\ \mathrm{GeV}/c$

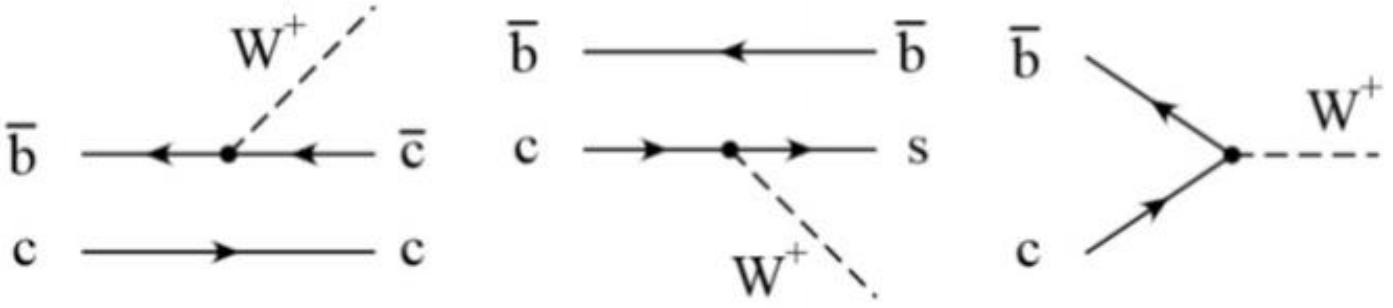
Muon System
$\epsilon(\mu \to \mu) \sim 97\%$
$\pi \to \mu$ mis-id: $1 \sim 3\%$

3

B_c^+ physics

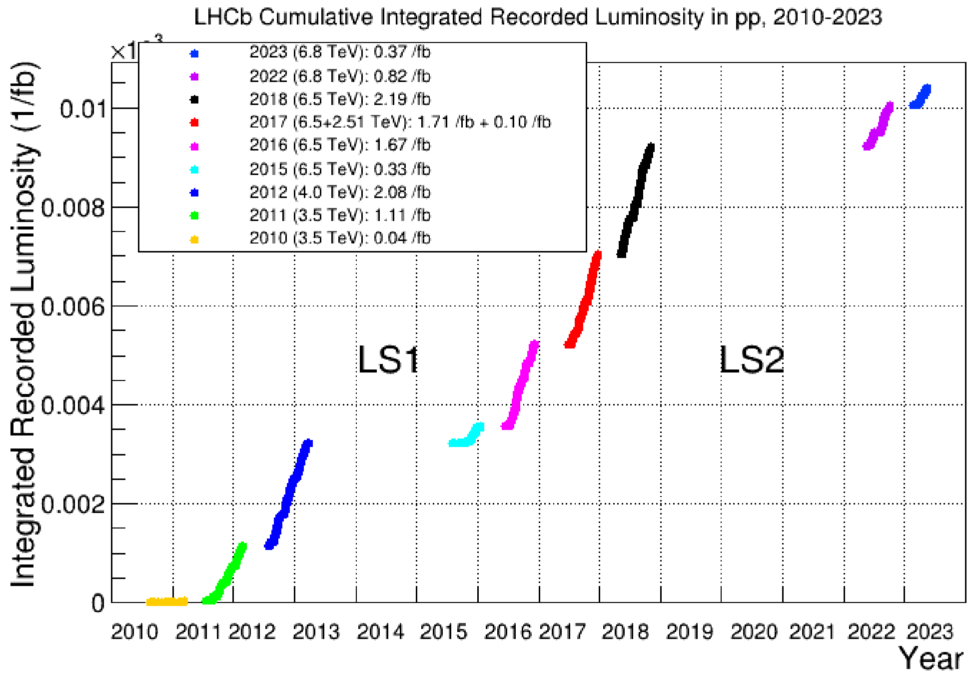
- **Unique state that contains two heavy quarks of different flavors**

- **Rich decay modes**
  - b quark decay ~20%
  - c quark decay ~70%
  - annihilation decay ~10%



- **Precise measurements of mass, lifetime, branching fractions can provide information to test theoretical models**

LHCb data samples



- **Luminosity levelling $L \sim 3 \times 10^{32}\ \mathrm{cm^{-2}s^{-1}}$**
- **Run-I: 3 fb^{-1}, Run-II: 6 fb^{-1}, Run-III: 14 fb^{-1}**
- **All b hadrons: $B^0, B^{\pm}, B_s^0, B_c^{\pm}$ ...**

LHCb: $\sigma(pp \to B_c^+)_{\mathrm{incl}} \approx 0.3\ \mu\mathrm{b}$

	B^0	B^+	B_s^0	b baryons (Λ_b ...)	B_c^+
Fraction(%)	40	40	10	10	0.1
Component	$\bar{b}d$	$\bar{b}u$	$\bar{b}s$	bqq	$\bar{b}c$

PRD 85.032008

B_c^+ studies at LHCb

Mass	$M(B_c^+ \to J/\psi\pi^+)$	$M(B_c^+ \to J/\psi\pi^+\pi^-\pi^+)$
	$M(B_c^+ \to J/\psi D_s^+)$	$M(B_c^+ \to J/\psi D^{(*)}K^{(*)})$
	$M(B_c^+ \to J/\psi p\bar{p}\pi^+)$	$M(B_c^+ \to B_s^0\pi^+)$
Production	$\frac{\sigma(B_c^+)}{\sigma(B^+)}\frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)}$	$\frac{\sigma(B_c^+)}{\sigma(B_s^0)}\mathcal{B}(B_c^+ \to B_s^0\pi^+)$
Lifetime	$\tau(B_c^+ \to J/\psi\mu^+\nu_\mu X)$	$\tau(B_c^+ \to J/\psi\pi^+)$
Decays	$B_c^+ \to J/\psi\pi^+\pi^-\pi^+$	$B_c^+ \to \psi(2S)\pi^+\pi^-\pi^+$
	$\mathcal{B}(B_c^+ \to J/\psi K^+)$	$B_c^+ \to (\psi(2S) \to J/\psi\pi^+\pi^-)\pi^+$
	$\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)$	$B_c^+ \to (\psi(2S) \to J/\psi\pi^+\pi^-)\pi^+\pi^-\pi^+$
	$B_c^+ \to J/\psi K^+K^-\pi^+$	$B_c^+ \to \psi(2S)K^+K^-\pi^+$(evidence)
	$B_c^+ \to J/\psi 3\pi^+2\pi^-$	$B_c^+ \to J/\psi K^+K^-\pi^+\pi^-\pi^+$
	$\mathcal{B}(B_c^+ \to J/\psi\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$	$B_c^+ \to J/\psi 4\pi^+3\pi^-$(evidence)
	$B_c^+ \to p\bar{p}\pi^+$(upper limit)	$B_c^+ \to B_s^0\pi^+$
	$B_c^+ \to K^+K^-\pi^+$	$B_c^+ \to \chi_{cj}\pi^+$
	$B_c^\pm \to D^0\pi^\pm$	$B_c^{(*)+}(2S) \to B_c^+\pi^+\pi^-$

b quark decays

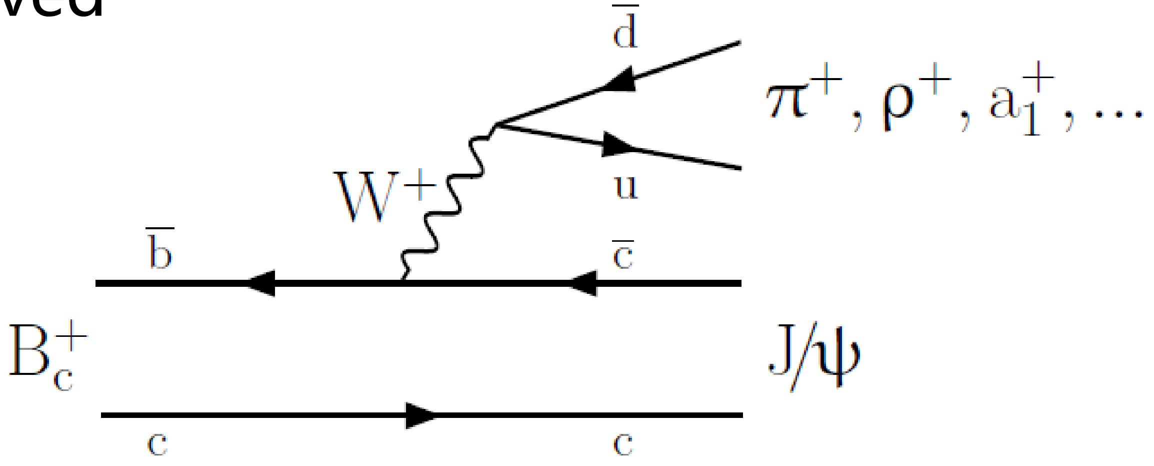
$$B_c^+ \to [c\bar{c}]X$$

$B_c^+ \to J/\psi\pi^+\pi^0$ with Run-I and Run-II data

- $B_c^+ \to J/\psi\pi^+\pi^0$ has not yet been observed

- $B_c^+ \to J/\psi\pi^+$ as a normalization mode

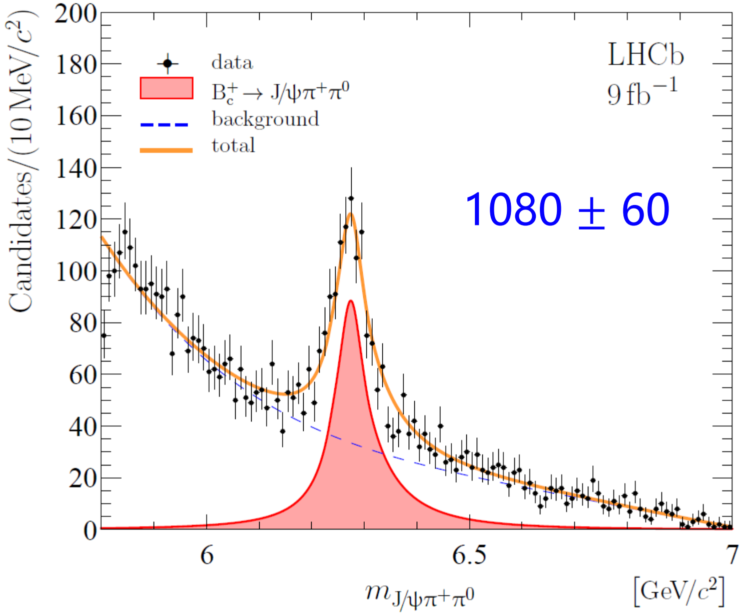
$$\mathcal{R} \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+\pi^0)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$$

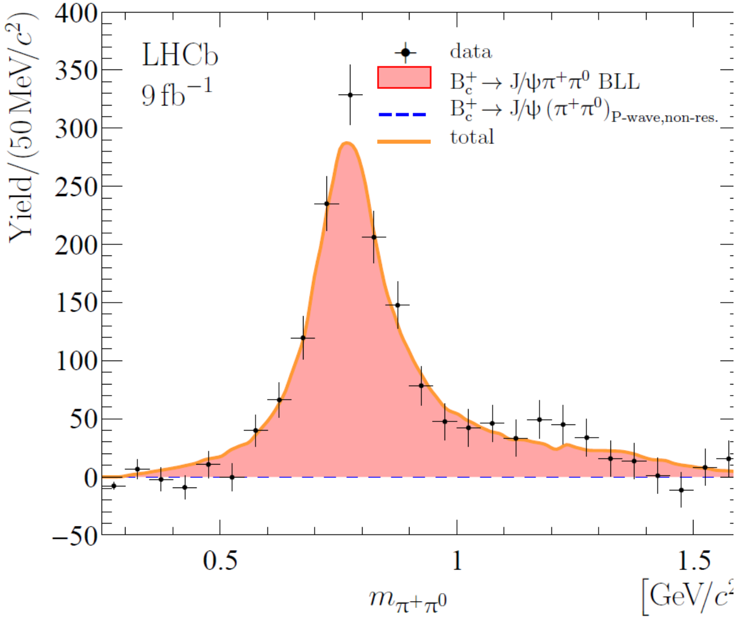


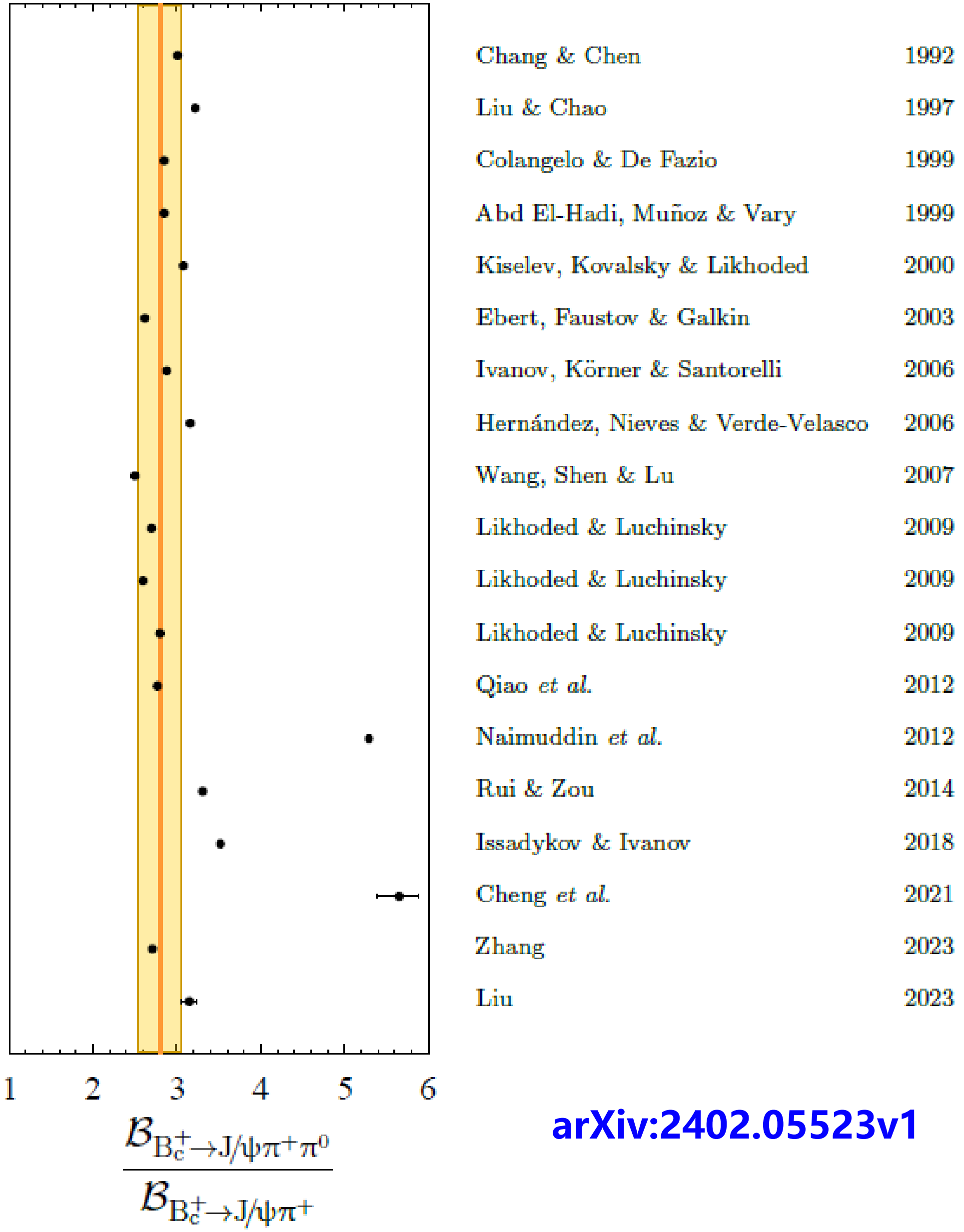
- In the SM, theoretical prediction $\mathcal{R}$:(2.5~5.7)

- $B^+ \to J/\psi K^{*+}(\to K^+\pi^0)$ as a control mode
  - detector resolution
  - mass bias

Results of $B_c^+ \to J/\psi\pi^+\pi^0$







- First observation
- Dominance ρ^+ and small $\rho^+(1450)$

$$\mathcal{R} \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+\pi^0)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = 2.80 \pm 0.15 \pm 0.11 \pm 0.16$$

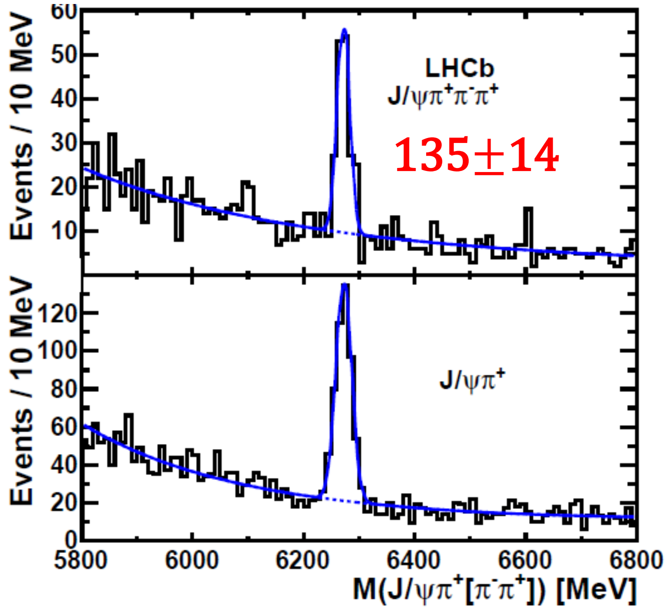
arXiv:2402.05523v1

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

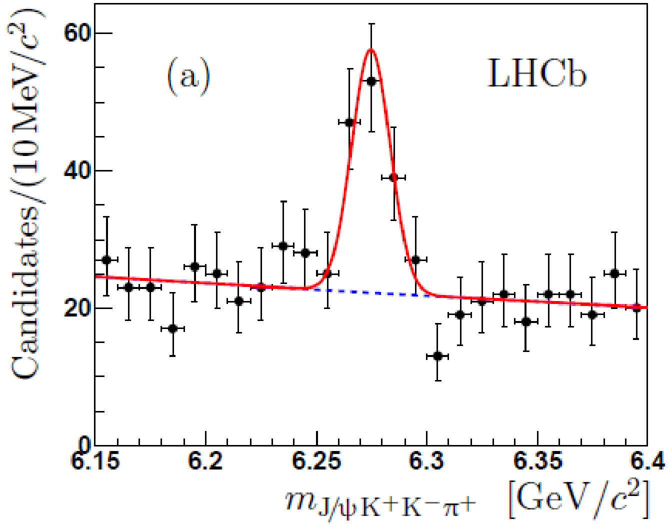
- Only two $B_c^+ \to \psi 3h$ decay mode were observed
- $B_c^+ \to J/\psi\pi^+$as a normalization mode

$$\mathcal{R} \equiv \frac{\mathcal{B}(B_c^+ \to \psi 3h)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$$

- Theoretical prediction $\mathcal{R}(J/\psi\pi^+\pi^-\pi^+)$: (1.5~2.3)
- $\mathcal{R}(J/\psi\pi^+\pi^-\pi^+) = 2.41 \pm 0.30 \pm 0.33$
- Prefers the latter predictions
- Theoretical prediction $\mathcal{R}(J/\psi K^+K^-\pi^+)$: (0.49 and 0.47)
- $\mathcal{R}(J/\psi K^+K^-\pi^+) = 0.53 \pm 0.10 \pm 0.05$

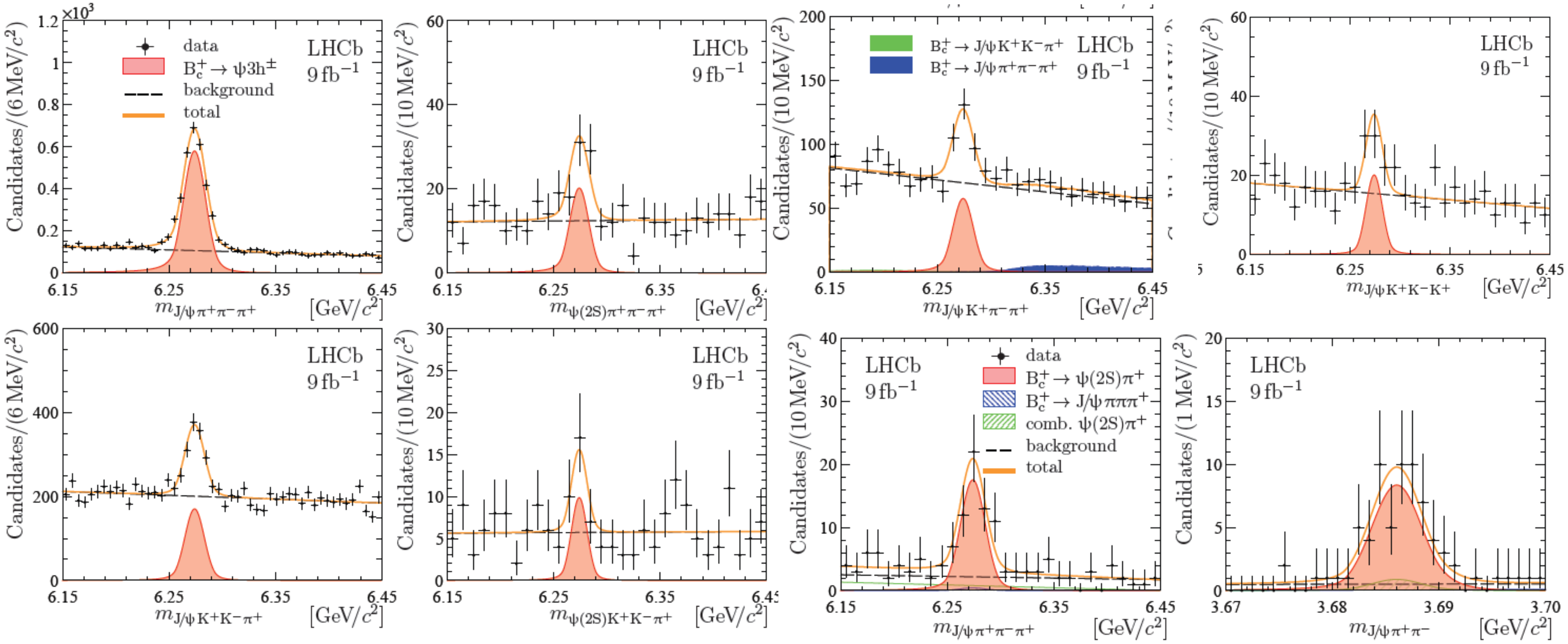


Phys. Rev. Lett. 108 (2012) 251802



JHEP 11 (2013) 094

$B_c^+ \to J/\psi(\psi(2S))h^+h^-h^+$ with Run-I and Run-II data



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

JHEP01(2022)065

$B_c^+ \to J/\psi(\psi(2S))h^+h^-h^+$ with Run-I and Run-II data

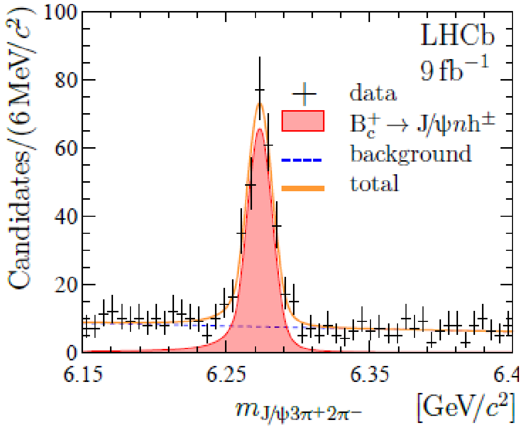
$\mathcal{R}^{\psi(2S)K^+K^-\pi^+}_{\psi(2S)\pi^+\pi^-\pi^+}$	$0.37 \pm 0.15 \pm 0.01$	0.16	BLL [27, 28]
$\mathcal{R}^{J/\psi K^+\pi^-\pi^+}_{J/\psi K^+K^-\pi^+}$	$0.35 \pm 0.06 \pm 0.01$	0.37	BLL [27]
$\mathcal{R}^{J/\psi K^+\pi^-\pi^+}_{J/\psi \pi^+\pi^-\pi^+}$	$(6.4 \pm 1.0 \pm 0.2) \times 10^{-2}$	7.7×10^{-2}	BLL [27]
$\mathcal{R}^{J/\psi K^+K^-\pi^+}_{J/\psi \pi^+\pi^-\pi^+}$	$0.185 \pm 0.013 \pm 0.006$	0.21	BLL [27, 28]
$\mathcal{R}^{\psi(2S)\pi^+}_{J/\psi K^+K^-\pi^+}$	$0.19 \pm 0.03 \pm 0.01$	0.18 ± 0.04	LHCb [6, 11]
$\mathcal{R}^{\psi(2S)\pi^+}_{J/\psi \pi^+\pi^-\pi^+}$	$(3.5 \pm 0.6 \pm 0.2) \times 10^{-2}$	$(3.9 \pm 0.9) \times 10^{-2}$	LHCb [1, 11]
$\mathcal{R}^{J/\psi K^+K^-\pi^+}_{J/\psi \pi^+\pi^-\pi^+}$	$0.185 \pm 0.013 \pm 0.006$	0.22 ± 0.06	LHCb [1, 6]

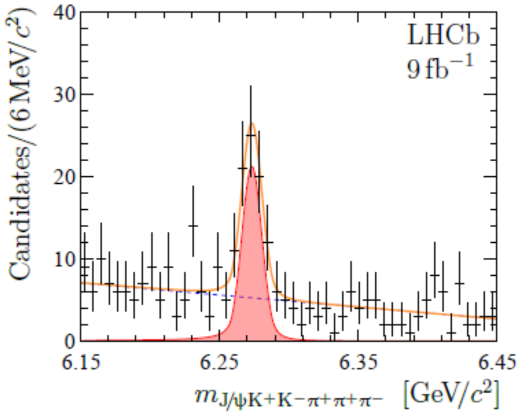
JHEP01(2022)065

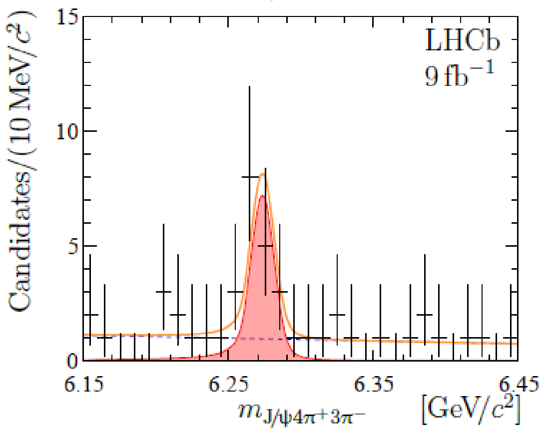
	Value $[10^{-2}]$	Reference
$\mathcal{R}^{J/\psi K^+K^-K^+}_{J/\psi K^+K^-\pi^+}$	$7.0 \pm 1.8 \pm 0.2$	This paper
$\mathcal{R}^{J/\psi K^+\pi^-\pi^+}_{J/\psi \pi^+\pi^-\pi^+}$	$6.4 \pm 1.0 \pm 0.2$	This paper
$\frac{\mathcal{B}(B_c^+ \to J/\psi K^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)}$	7.9 ± 0.8	[14]
$\frac{\mathcal{B}(B^+ \to \overline{D}^0 K^+\pi^-\pi^+)}{\mathcal{B}(B^+ \to \overline{D}^0 \pi^+\pi^-\pi^+)}$	9.3 ± 5.1	[51, 69]
$\frac{\mathcal{B}(B^0 \to D^- K^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^- \pi^+\pi^-\pi^+)}$	5.8 ± 1.5	[51, 69]
$\frac{\mathcal{B}(B^0 \to D^{*-} K^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-} \pi^+\pi^-\pi^+)}$	6.5 ± 0.6	[51, 70]
$\frac{\mathcal{B}(B_s^0 \to D_s^- K^+\pi^-\pi^+)}{\mathcal{B}(B_s^0 \to D_s^- \pi^+\pi^-\pi^+)}$	5.2 ± 1.3	[51, 71]

- Agree with BLL model based on QCD factorisation
- Consistent with Run I result
- Agree with the ratios of branching fraction for the multibody decays of B^+, B^0 and B_s^0

$B_c^+ \to J/\psi(\psi(2S))nh$ with Run-I and Run-II data







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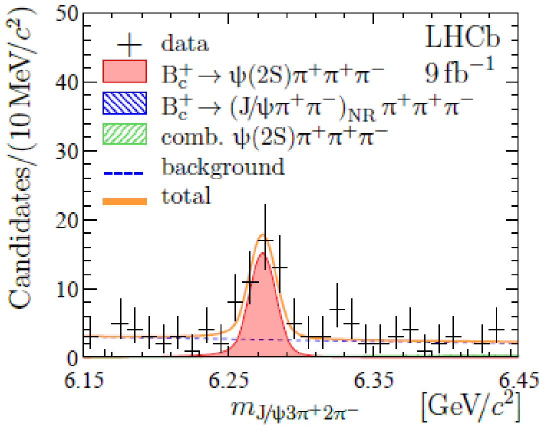
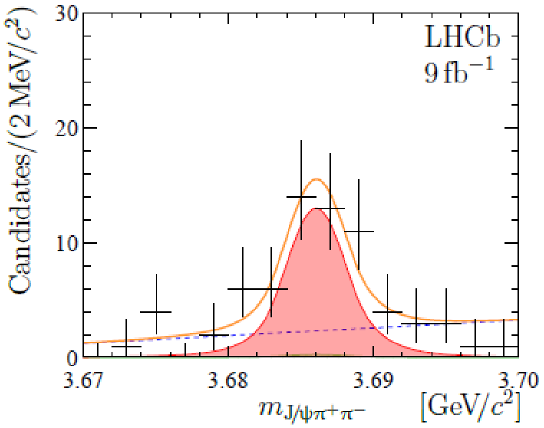
Decay	Yield	$\mathcal{S}$ [σ]
$B_c^+ \to J/\psi 3\pi^+ 2\pi^-$	268 ± 20	21.0
$B_c^+ \to J/\psi K^+K^-\pi^+\pi^+\pi^-$	69 ± 11	9.1
$B_c^+ \to J/\psi 4\pi^+ 3\pi^-$	16 ± 5	4.9
$B_c^+ \to (\psi(2S) \to J/\psi\pi^+\pi^-)\pi^+\pi^+\pi^-$	40 ± 8	6.4





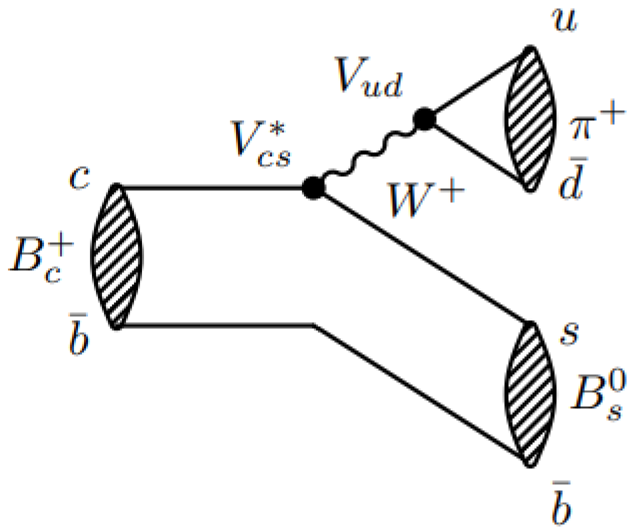
$$\mathcal{R}^{J/\psi K^+K^-\pi^+\pi^+\pi^-}_{J/\psi 3\pi^+2\pi^-} = (33.7 \pm 5.7 \pm 1.6) \times 10^{-2},$$

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

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

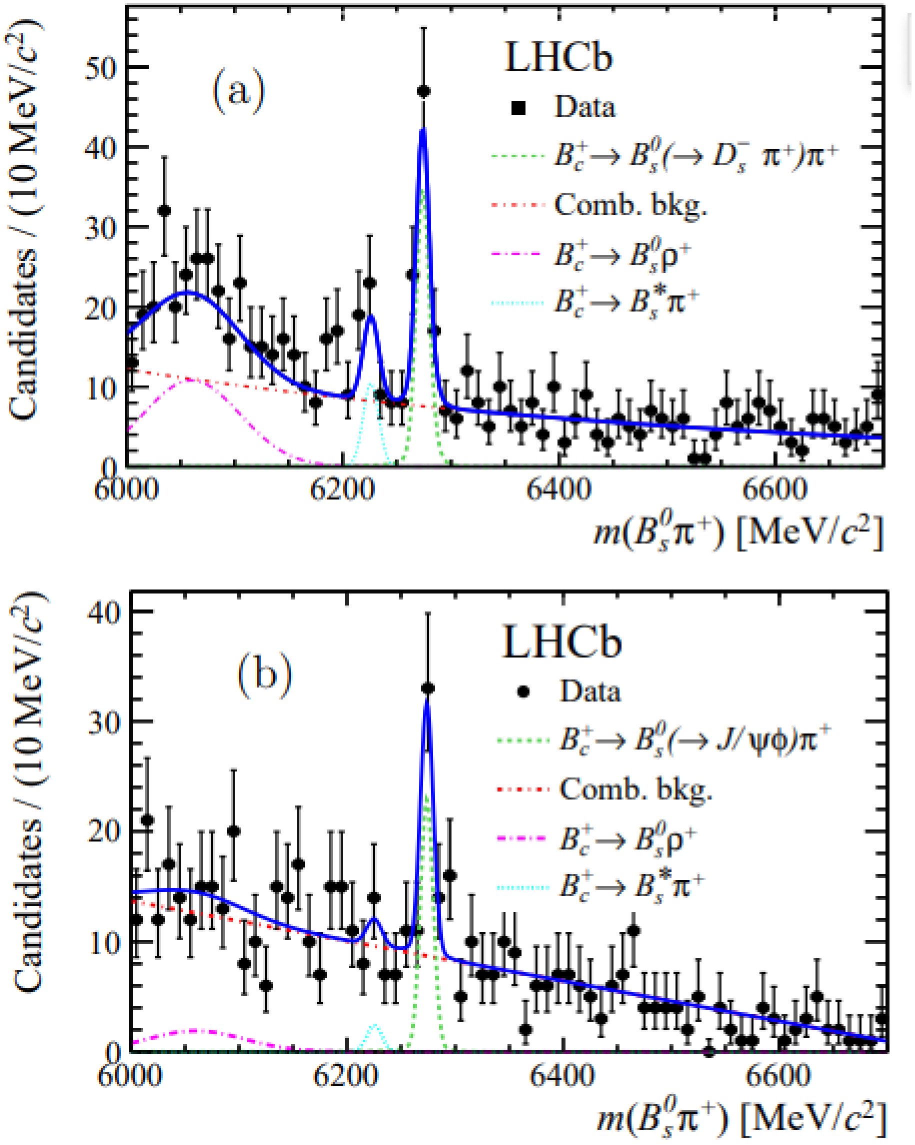
- Agree with BLL model based on QCD factorization (backup)
- $\mathcal{R}^{J/\psi K^+K^-\pi^+}_{J/\psi\pi^+\pi^-\pi^+} = (18.5 \pm 1.3 \pm 0.6) \times 10^{-2} < \mathcal{R}^{J/\psi K^+K^-\pi^+\pi^-\pi^+}_{J/\psi 3\pi^+2\pi^-}$

c quark decays



$B_c^+ \to B_s^0\pi^+$

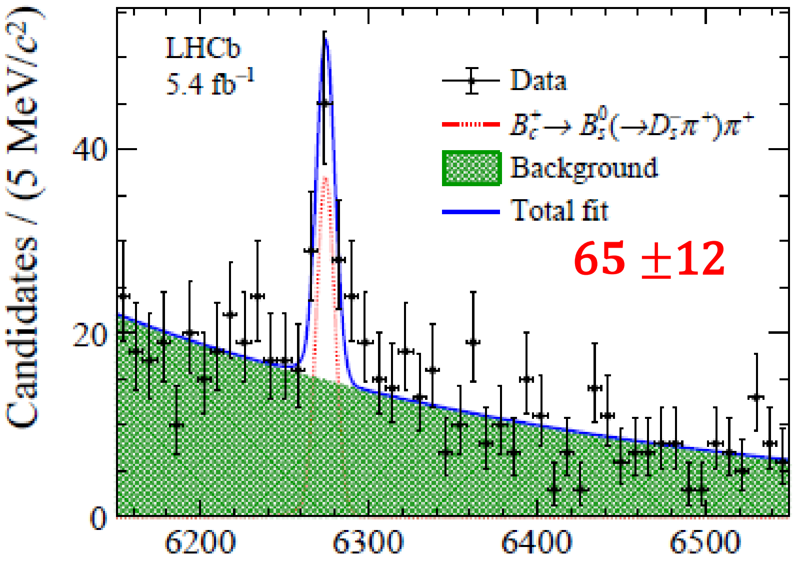
- $B_c^+ \to B_s^0\pi^+$ was first observed by LHCb with Run I data
- A wide range of predictions $\mathcal{B}(B_c^+ \to B_s^0\pi^+)$: (16.4% ~2.5%)
- $B_s^0 \to D_s^+\pi^+$ and $B_s^0 \to J/\psi\phi$ as normalization mode
- $R \equiv \frac{\sigma(B_c^+)}{\sigma(B_s^0)} \times \mathcal{B}(B_c^+ \to B_s^0\pi^+) = (2.37 \pm 0.31 \pm 0.11^{+0.17}_{-0.13}) \times 10^{-3}$
- $\mathcal{B}(B_c^+ \to B_s^0\pi^+) \approx 10\%$



Phys. Rev. Lett. 111 (2013) 181801

Study of $B_c^+ \to B_s^0\pi^+$ with Run II data

- $B_c^+ \to J/\psi\pi^+$ as a normalization mode
- $\mathcal{R} \equiv \frac{\mathcal{B}(B_c^+\to B_s^0\pi^+)}{\mathcal{B}(B_c^+\to J/\psi\pi^+)} = 91 \pm 10(\text{stat}) \pm 8(\text{syst}) \pm 3(\mathcal{B})$
- $\mathcal{B}(B_c^+ \to B_s^0\pi^+) = (8.3 \pm 0.7(\text{stat}) \pm 0.3(\text{syst}) \pm 2.2(\mathcal{B}))\%$
- Consistent with Run I result
- The largest branching fraction of B_c^+



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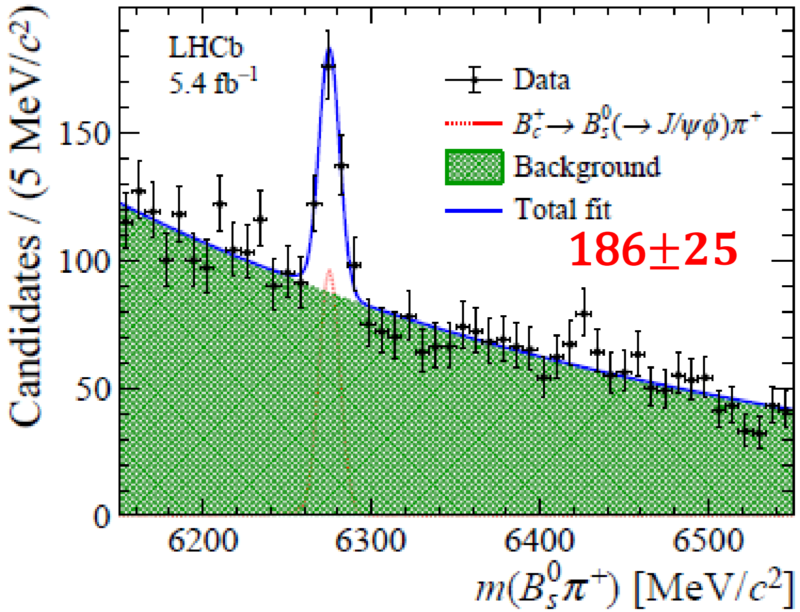

Mass

B_c^+ mass

- Theoretical predictions range: 6.2 ~ 6.4 GeV/c^2
- First measured at Tevatron with $B_c^+ \to J/\psi\pi^+$: **PRL 100(2008)182002, PRL 101(2008)012001**

$$m(B_c^+) = 6275.6 \pm 2.9(\mathrm{stat}) \pm 2.5(\mathrm{syst})\ \mathrm{MeV}/c^2$$

- LHCb measured B_c^+ mass with many decay channels

PRD 95.032005 **PRL 109,232001(2012)** **PRD 87.112012** **PRL 113(2014)152003**

Mode	Lum (fb^{-1})	Result (MeV/c^2)	Lum (fb^{-1})	Result (MeV/c^2)
$B_c^+ \to J/\psi\pi^+$	1.0	$6273.7 \pm 1.3 \pm 1.6$	9.0	$6273.78 \pm 0.12 \pm 0.92$
$B_c^+ \to J/\psi D_s^+$	3.0	$6276.3 \pm 1.4 \pm 0.3$	9.0	$6274.11 \pm 0.27 \pm 0.38$
$B_c^+ \to J/\psi p\bar{p}\pi^+$	3.0	$6274.0 \pm 1.8 \pm 0.4$	9.0	$6274.61 \pm 0.73 \pm 0.37$
$B_c^+ \to J/\psi D^0 K^+$	3.0	$6274.3 \pm 1.4 \pm 0.3$	9.0	$6274.08 \pm 0.53 \pm 0.28$
$B_c^+ \to J/\psi\pi^+\pi^-\pi^+$	x	x	9.0	$6274.38 \pm 0.18 \pm 0.84$
$B_c^+ \to B_s^0(D_s^+\pi^-)\pi^+$	x	x	9.0	$6274.08 \pm 0.44 \pm 0.43$
$B_c^+ \to B_s^0(J/\psi\phi)\pi^+$	x	x	9.0	$6275.46 \pm 0.66 \pm 0.41$

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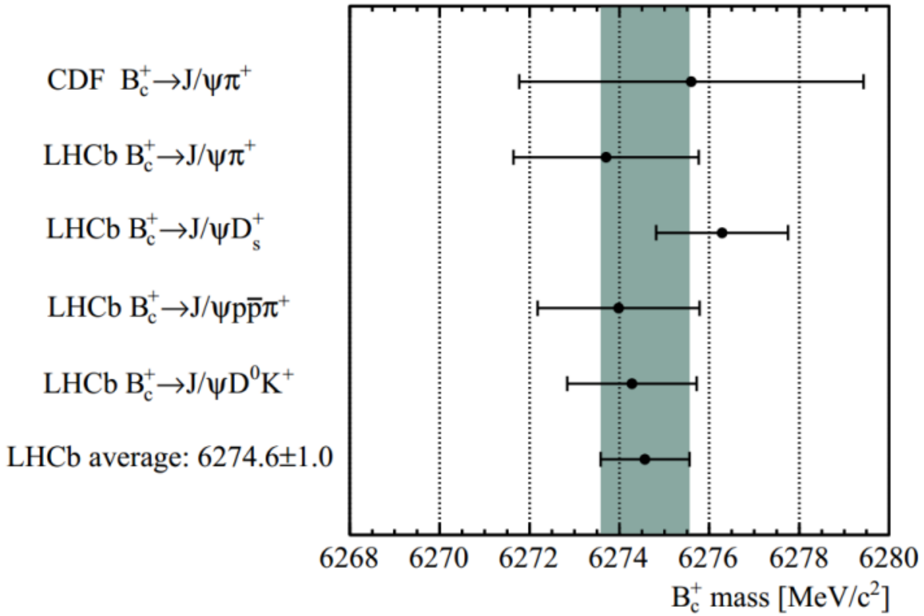
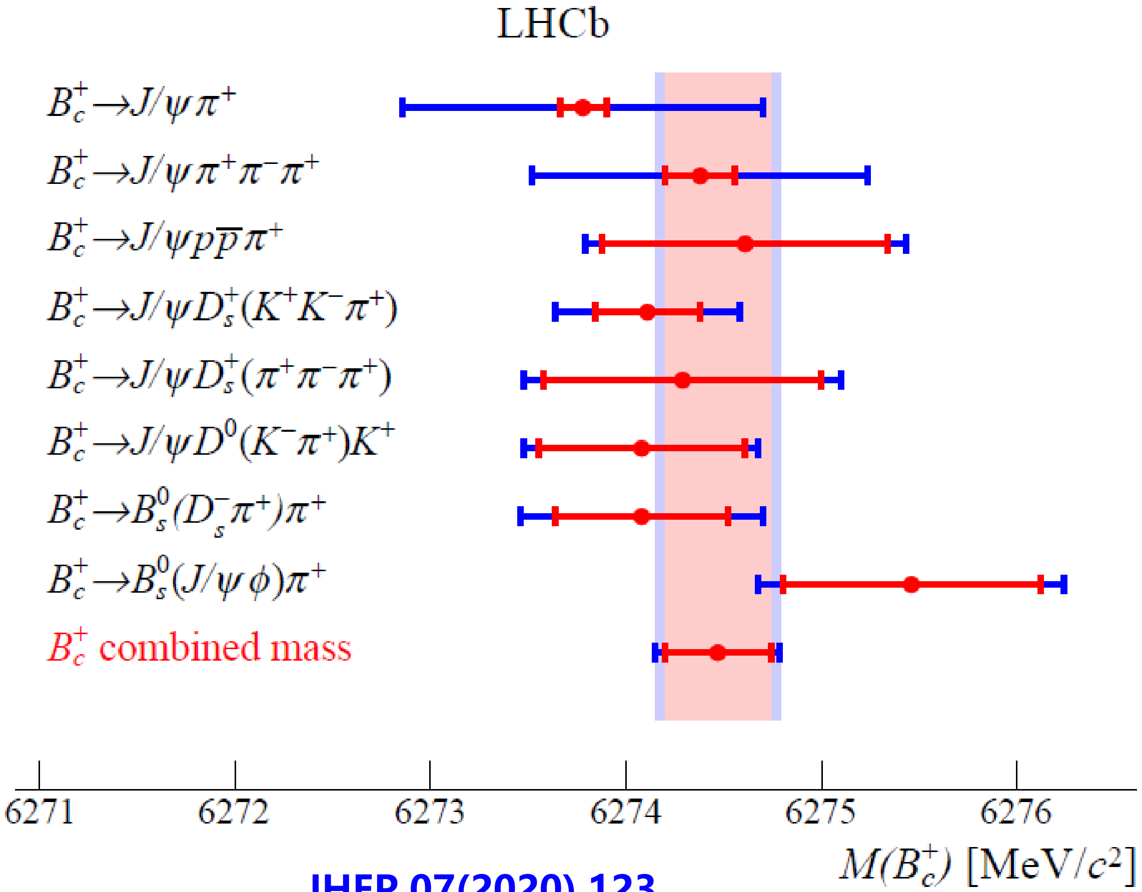
B_c^+ mass



$$\text{LHCb}_{\text{average}} = 6274.6 \pm 1.0\ \text{MeV}/c^2$$



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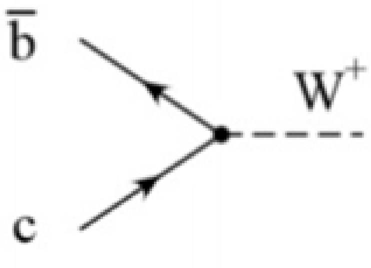
$$\text{LHCb}_{comb} = 6274.47 \pm 0.27 \pm 0.17\ \text{MeV}/c^2$$

Summary and Outlook

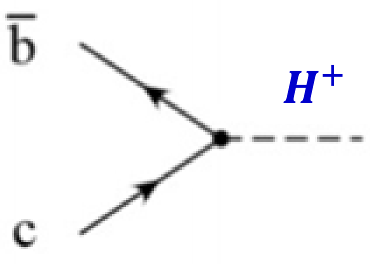
- **Many results on B_c^+ mesons physics by LHCb**
  - b quark decays: $B_c^+ \to [c\bar{c}]X$
  - c quark decays: $\mathcal{B}(B_c^+ \to B_s^0\pi^+)\sim 10\%$
  - Mass: $6274.47 \pm 0.27 \pm 0.17\ MeV/c^2$
- **Opportunities with Run-III (14 $\mathbf{fb^{-1}}$)**
  - Search for annihilation decay: $B_c^+ \to 3h$
  - CPV?
  - Search for more c quark decays: $B_c^+ \to B^+X, B^0X$?
  - Form factor never be measured
  - Lepton universality

Outlook of $B_c^+ \to h^+h^-h^+$

- In the SM, theoretical prediction B_c^+ annihilation decays :10^{-8}~10^{-6})

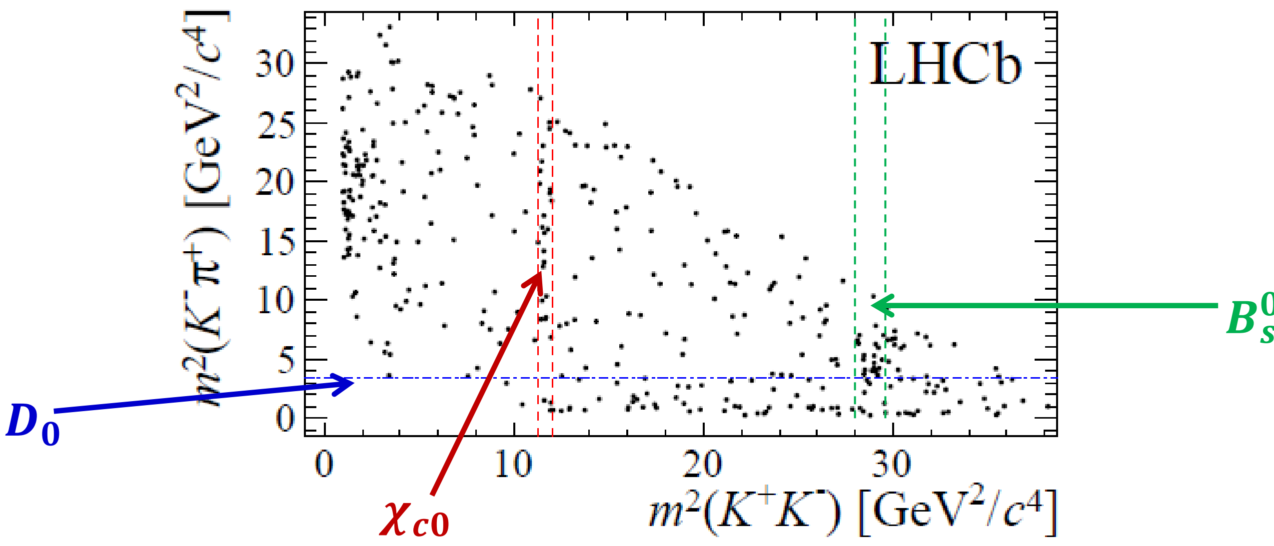


- Any significant enhancement could indicate the particles beyond the SM (like H^+)



- Decay modes for $B_c^+ \to K^+K^-\pi^+$
  1. $\bar{b} \to \bar{q}$: $B_c^+ \to K^+D^0(\to K^-\pi^+)$
  2. $\bar{c} \to \bar{q}$: $B_c^+ \to \pi^+B_q^0(\to K^-K^+)$
  3. $\bar{b} \to \bar{c}$: $B_c^+ \to \pi^+[c\bar{c}](\to K^-K^+)$
  4. **$\bar{b}c$ annihilation: NR**

PRD 94(2016) 091102



Outlook of CPV

No.	Final state	$\Gamma(B_c^+ \to f)$ (GeV)	$\overline{\Gamma(B_c^- \to \bar{f})}$ (GeV)	$\mathcal{A}_{CP}$
1	ψD^{*+}	6.65×10^{-16}	6.53×10^{-16}	0.00954
2	$\eta_c D^{*+}$	9.42×10^{-17}	9.09×10^{-17}	0.0179
3	ψD^+	2.91×10^{-17}	2.89×10^{-17}	0.00383
4	$\eta_c D^+$	4.07×10^{-16}	3.89×10^{-16}	0.0226
5	ψD_s^{*+}	1.76×10^{-14}	1.76×10^{-14}	−0.000480
6	$\eta_c D_s^{*+}$	2.20×10^{-15}	2.21×10^{-15}	−0.000902
7	ψD_s^+	8.54×10^{-16}	8.55×10^{-16}	−0.000186
8	$\eta_c D_s^+$	9.58×10^{-15}	9.60×10^{-15}	−0.00118
9	$D^{*0}\rho^+$	8.34×10^{-18}	8.99×10^{-18}	−0.0379
10	$D^0\rho^+$	8.38×10^{-18}	9.04×10^{-18}	−0.0379
11	$D^{*0}\pi^+$	2.80×10^{-18}	2.88×10^{-18}	−0.0154
12	$D^0\pi^+$	3.11×10^{-18}	3.54×10^{-18}	−0.0645
13	$D^{*0}K^{*+}$	5.81×10^{-18}	5.13×10^{-18}	0.0622
14	D^0K^{*+}	5.35×10^{-18}	4.72×10^{-18}	0.0622
15	$D^{*0}K^+$	7.71×10^{-19}	6.46×10^{-19}	0.0879
16	D^0K^+	6.76×10^{-18}	6.16×10^{-18}	0.0463
17	$D^{*+}\rho^0$	1.94×10^{-18}	1.83×10^{-18}	0.0302
18	$D^{*+}\pi^0$	9.83×10^{-20}	9.46×10^{-20}	0.0210
19	$D^+\rho^0$	5.90×10^{-19}	5.56×10^{-19}	0.0302
20	$D^+\pi^0$	3.12×10^{-19}	3.01×10^{-19}	0.0185
21	$D^{*+}K^{*0}$	4.48×10^{-18}	4.41×10^{-18}	0.00822
22	D^+K^{*0}	4.22×10^{-18}	4.15×10^{-18}	0.00822
23	$D^{*+}K^0$	4.10×10^{-19}	4.03×10^{-19}	0.00822
24	DK^0	7.22×10^{-18}	7.11×10^{-18}	0.00822
25	$D_s^{*+}\phi$	5.68×10^{-18}	5.58×10^{-18}	0.00822
26	$D_s^+\phi$	2.30×10^{-18}	2.26×10^{-18}	0.00822
27	$D_s^{*+}\overline{K}^{*0}$	2.88×10^{-19}	3.76×10^{-19}	−0.133
28	$D_s^{*+}\overline{K}^0$	2.69×10^{-20}	3.52×10^{-20}	−0.133
29	$D_s^+\overline{K}^{*0}$	1.32×10^{-19}	1.72×10^{-19}	−0.133
30	$D_s^+\overline{K}^0$	2.40×10^{-19}	3.14×10^{-19}	−0.133

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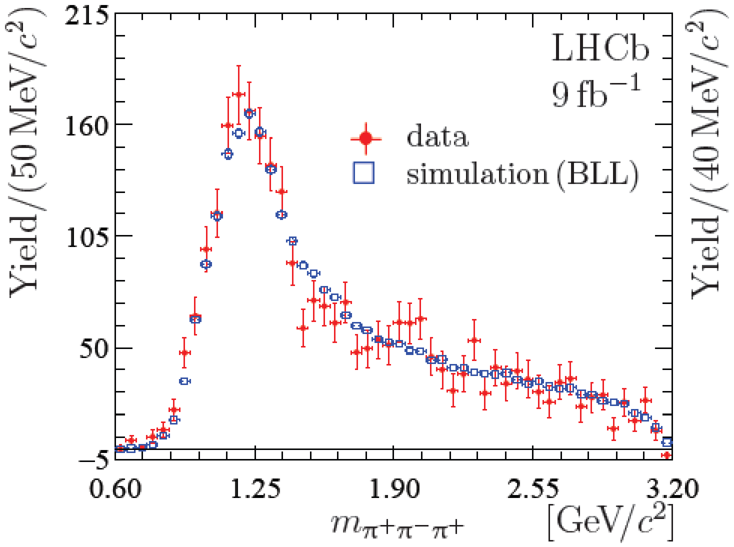
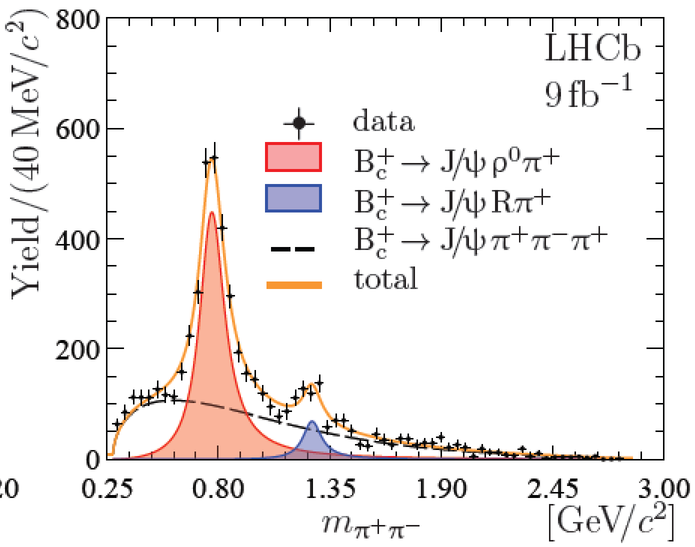
Mode Prediction: A_{cp}	Lum (fb^{-1})	N Precision of A_{cp}	Lum (fb^{-1})	N Precision of A_{cp}
$B_c^+ \to J/\psi D^+$ $A_{cp} = 0.4\%$	9.0	x	14.0	x
$B_c^+ \to J/\psi D_s^+$ $A_{cp} = 0.02\%$	9.0	1135 ± 49 ~5%	14.0	~2000 ~3%
$B_c^+ \to D^0K^+$ $A_{cp} = 4.6\%$	3.0	20 ± 5 x	9.0 14.0	~100 15~20% 200~300 10%
$B_c^+ \to D_s^+K^{*0}$ $A_{cp} = 13.3\%$	9.0	x	14.0	x

Backup

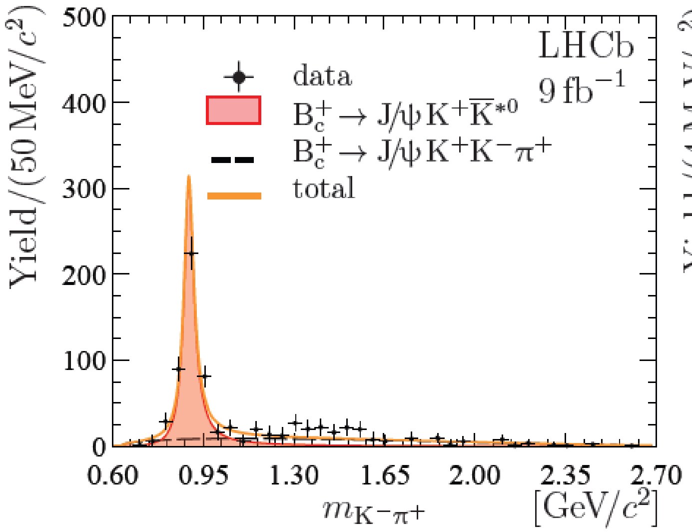
Resonance structure of $B_c^+ \to J/\psi(\psi(2S))h^+h^-h^+$

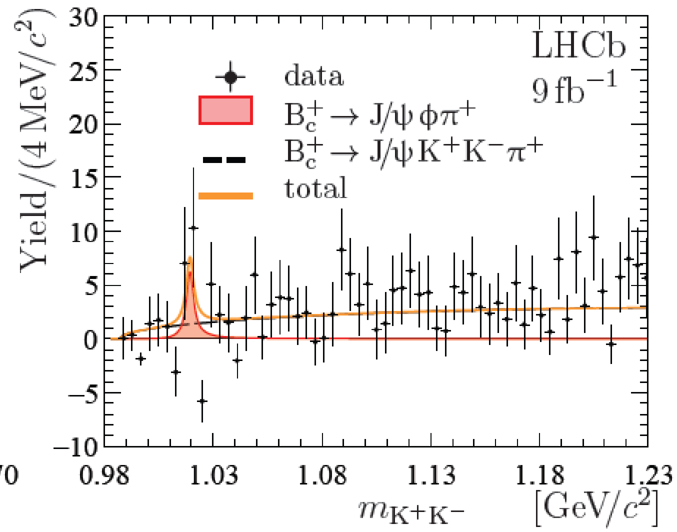




Parameter		Value
$f_{\rho^0}^{B_c^+\to J/\psi\pi^+\pi^-\pi^+}$	[%]	88.1 ± 3.0
$f_{R}^{B_c^+\to J/\psi\pi^+\pi^-\pi^+}$	[%]	10.4 ± 1.4
m_R	[MeV/c^2]	1265 ± 10
Γ_R	[MeV]	110 ± 21
$\mathcal{S}_R$	[σ]	8

- BLL model: $B_c^+ \to J/\psi a_1(1260)(\to 3\pi)$





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

$$f_{\phi}^{B_c^+\to J/\psi K^+K^-\pi^+} = \left(1.6\,^{+0.7}_{-0.6}\right)\,\%\,,$$

Resonance structure of $B_c^+ \to J/\psi(\psi(2S))nh$