



中国科学院大学
University of Chinese Academy of Sciences



Doubly heavy mesons & baryons at LHCb

Jibo HE (UCAS), for the LHCb collaboration,
presented at QWG 2021

Outline

- Doubly heavy mesons

- B_c^+ production
- Excited B_c^+ states
- B_c^+ mass

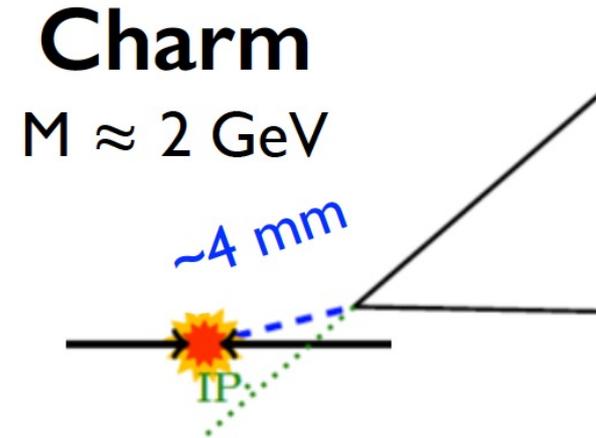
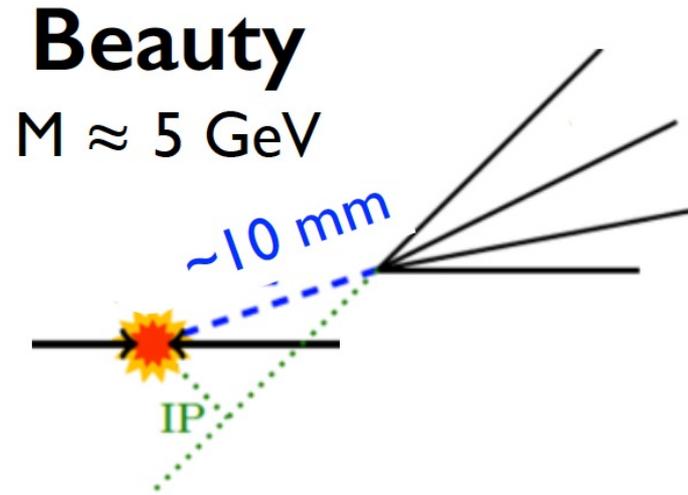
Please see V. Zhovkovska's, J. Crkovska's talks for quarkonium productions

- Doubly heavy baryons

- Ξ_{cc}^{++} production

Please see S. Li's talk for DHB results

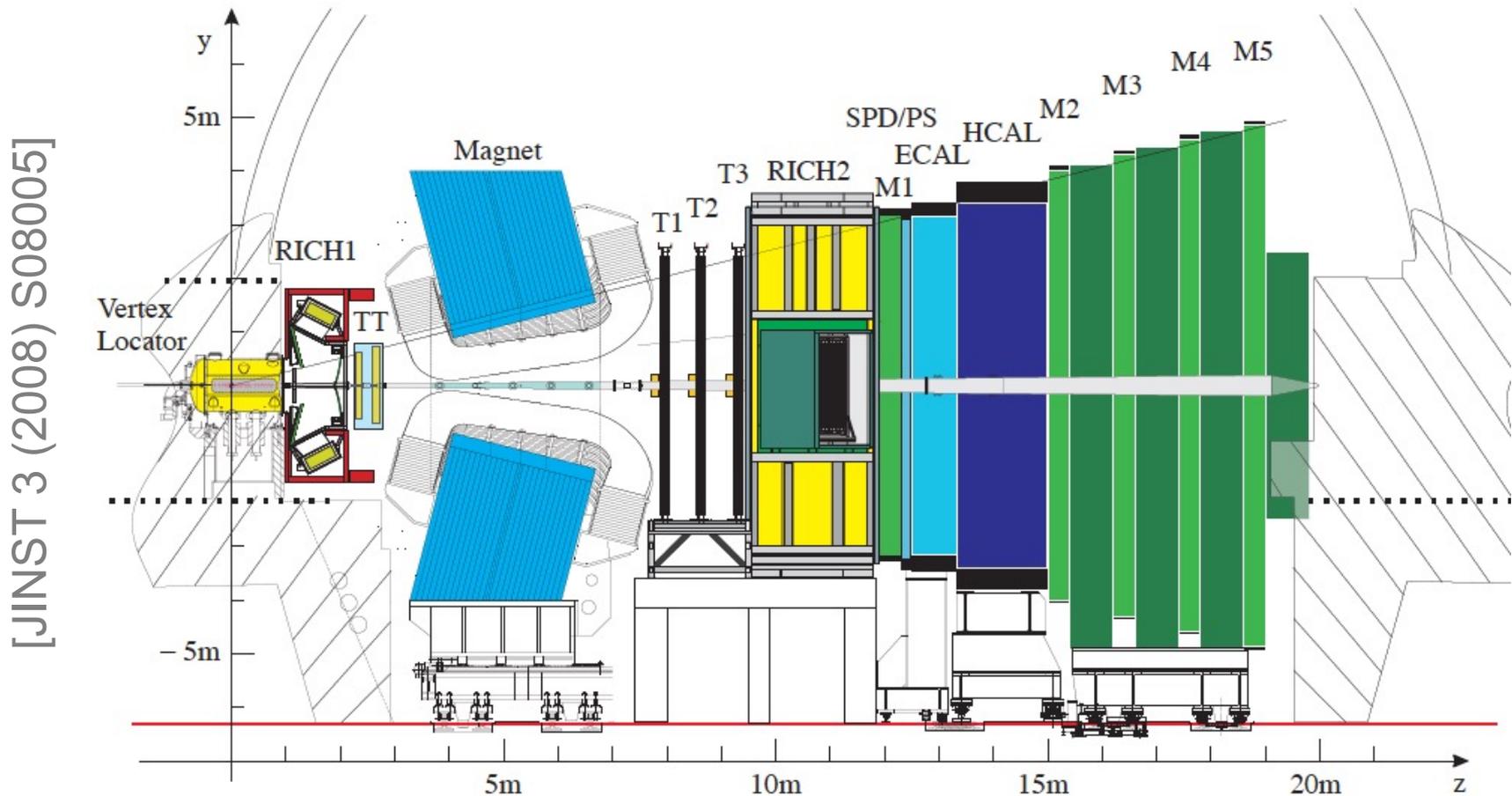
Beauty/charm signature



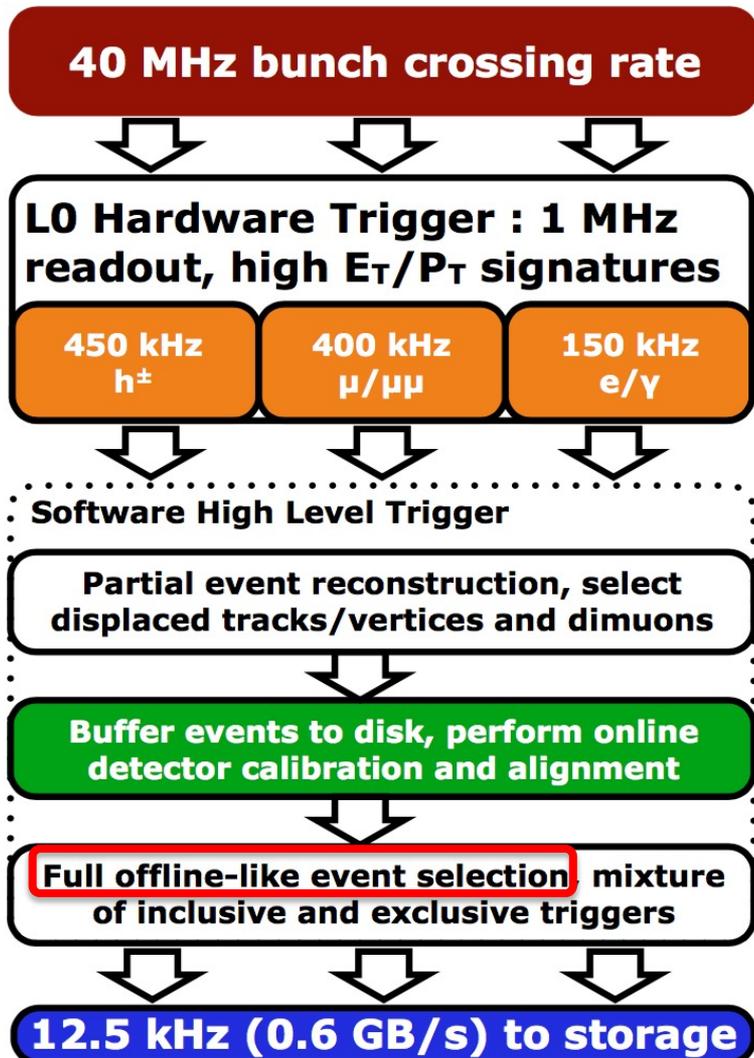
- Compared to minimum bias (background)
 - Relatively high mass \rightarrow high *transverse momentum*
 - Relatively long lifetime \rightarrow large *impact parameter (IP)*
- Requires excellent vertexing, tracking, particle-identification

The LHCb experiment

- Dedicated to **precision study** of b/c -hadrons



The LHCb trigger (Run-II)



- **Level-0, Hardware**

- ▶ Fully synchronous at 40 MHz
- ▶ Selection of high p_T particles
 - ★ $p_T(\mu) > \sim 1.5 \text{ GeV}/c$,
 - $p_T(\mu_1) \times p_T(\mu_2) > \sim (1.5 \text{ GeV}/c)^2$
 - ★ $E_T(h, e, \gamma) > 2.5 - 4 \text{ GeV}$

- **High Level Trigger (HLT), Software**

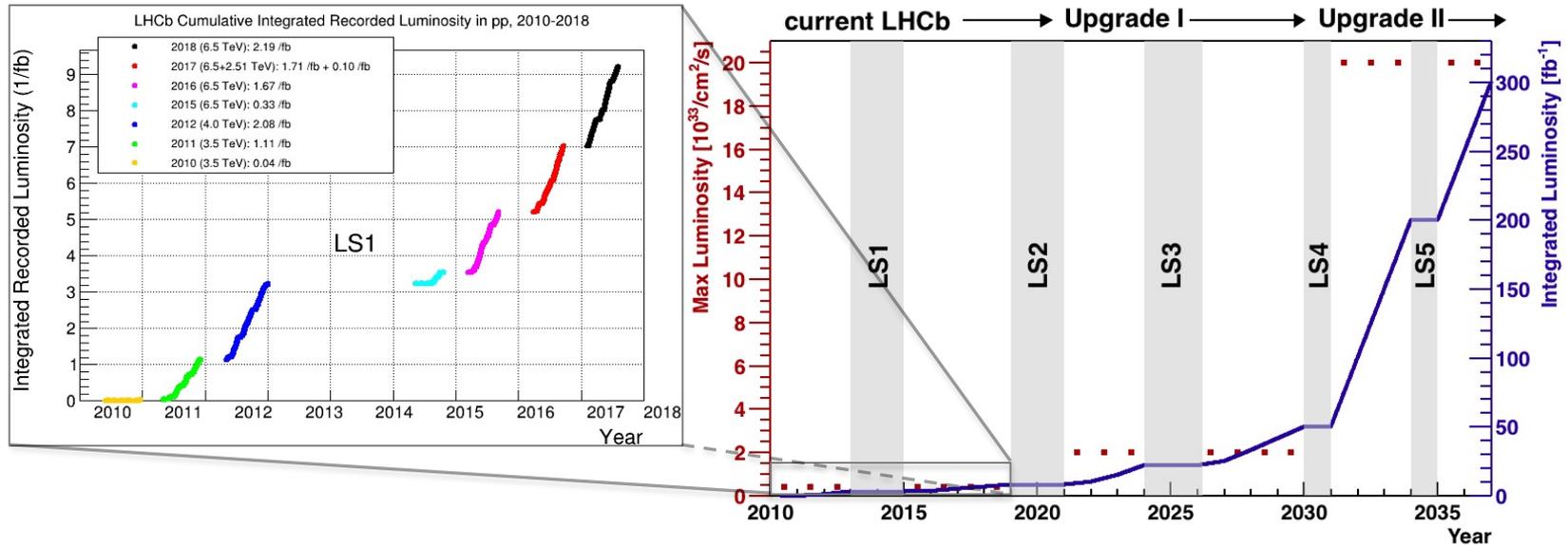
- ▶ Stage 1, tracking info, IP cuts
 - ▶ Stage 2, full reconstruction + selections
- $\sim 50 \text{ kB/event} \Rightarrow 0.25 \text{ GB/s}, \sim 2 \text{ PB/year}$

- **Offline data flow**

Raw data $\xrightarrow{\text{Rec}}$ **Stripping** $\xrightarrow{10\%}$ $(\mu)\text{DST}$

Stripping, also as HLT3, **Pre-selections** of all decay channels under study

LHCb luminosity prospects



LHC era		HL-LHC era		
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2022-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb ⁻¹	6 fb ⁻¹	23 fb ⁻¹	46 fb ⁻¹	>300 fb ⁻¹ ??
		Phase-1 Upgrade!!	Phase-1b Upgrade!?	Phase-2 Upgrade??

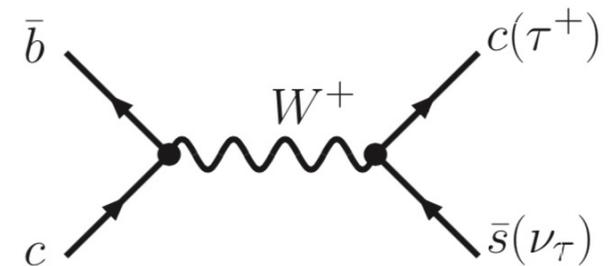
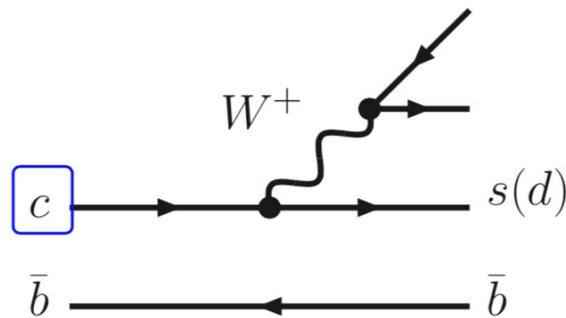
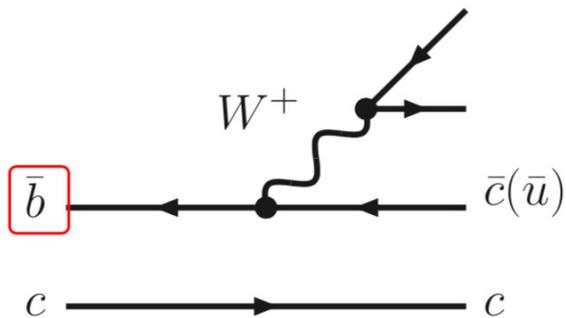
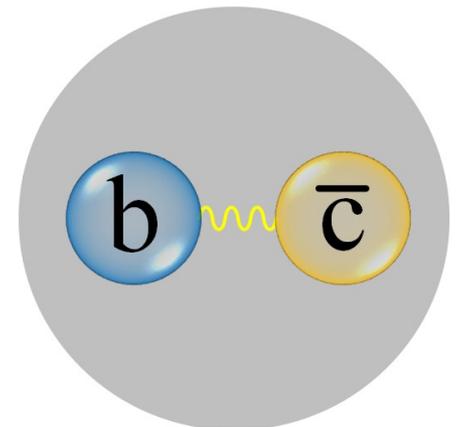
B_c meson

- Formed by two different heavy quarks, unique in the Standard Model. Both b - & c -quark can decay, or annihilate

– $\bar{b} \rightarrow \bar{c}W^+$, e.g., $J/\psi \ell^+ \nu_\ell$

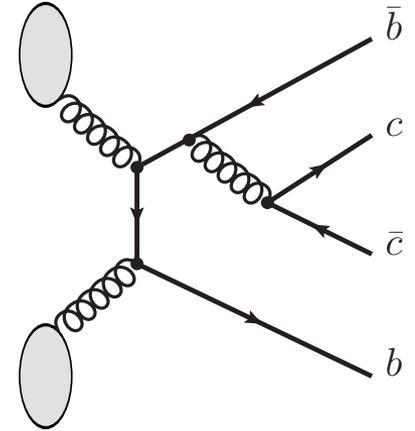
– $c \rightarrow sW^+$, e.g., $B_S^0 \pi^+$

– $c\bar{b} \rightarrow W^+$, e.g., $\tau^+ \nu_\tau$



B_c production

- Difficult to produce at e^+e^- machine. Mainly through $gg \rightarrow B_c + b + \bar{c}$ at LHC
- Production rate
 - Theoretical prediction (in nb)



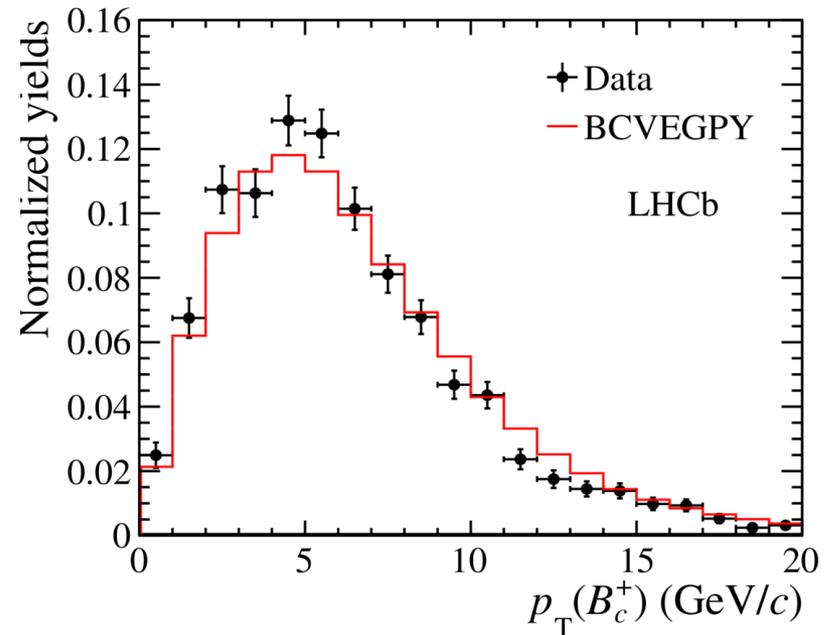
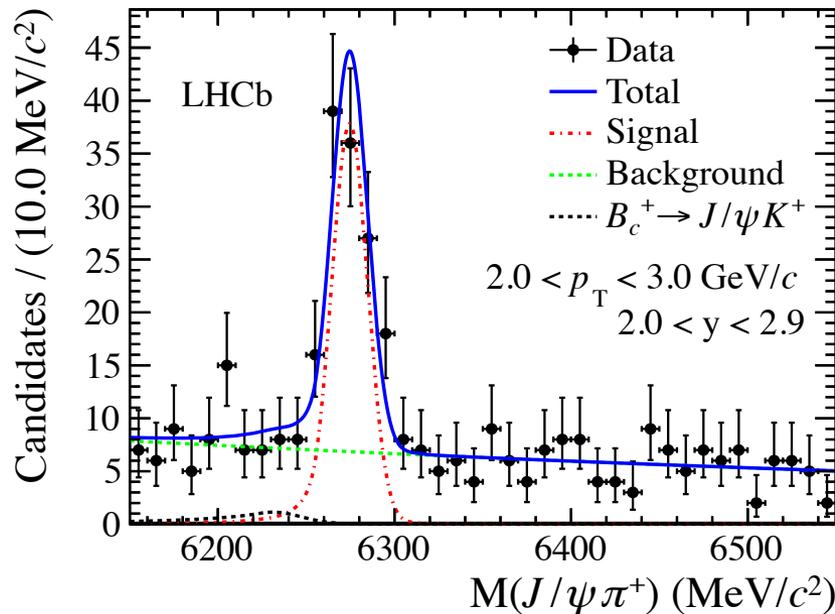
[C.-H. Chang, *et al.*, PRD 71 (2005) 074012]

-	$ (^1S_0)_1\rangle$	$ (^3S_1)_1\rangle$	$ (^1S_0)_{8g}\rangle$	$ (^3S_1)_{8g}\rangle$	$ (^1P_1)_1\rangle$	$ (^3P_0)_1\rangle$	$ (^3P_1)_1\rangle$	$ (^3P_2)_1\rangle$
LHC [†]	71.1	177.	(0.357, 3.21)	(1.58, 14.2)	9.12	3.29	7.38	20.4
TEVATRON	5.50	13.4	(0.0284, 0.256)	(0.129, 1.16)	0.655	0.256	0.560	1.35

- Color octet contribution is small
 - $\sigma(2S)/\sigma(1S)$ would be $|R_{2S}(0)/R_{1S}(0)| \approx 0.6$
 - $\sigma(B_c^+) \sim 0.9 \mu\text{b}$ for $\sqrt{s} = 14 \text{ TeV}$

B_c^+ production w/ $J/\psi\pi^+$

- Normalized to $B^+ \rightarrow J/\psi K^+$, as (p_T, y)
- With 8 TeV data (2012)
- p_T distribution well described by BcVegPy

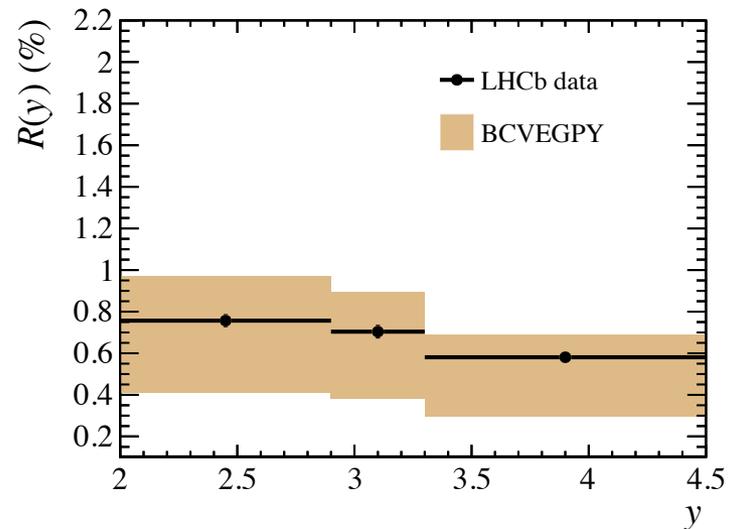
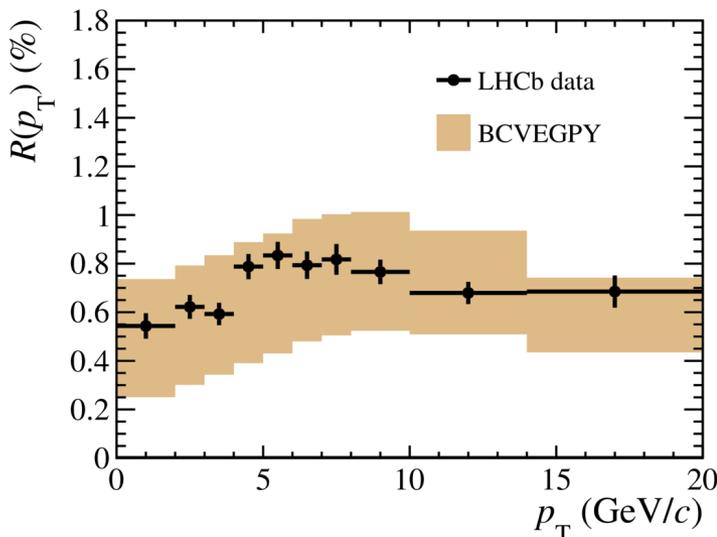


B_c^+ production w/ $J/\psi\pi^+$

- $$\mathcal{R} = \frac{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)}{\sigma(B^+) \times \mathcal{B}(B^+ \rightarrow J/\psi K^+)} = (0.683 \pm 0.018 \pm 0.009)\%$$

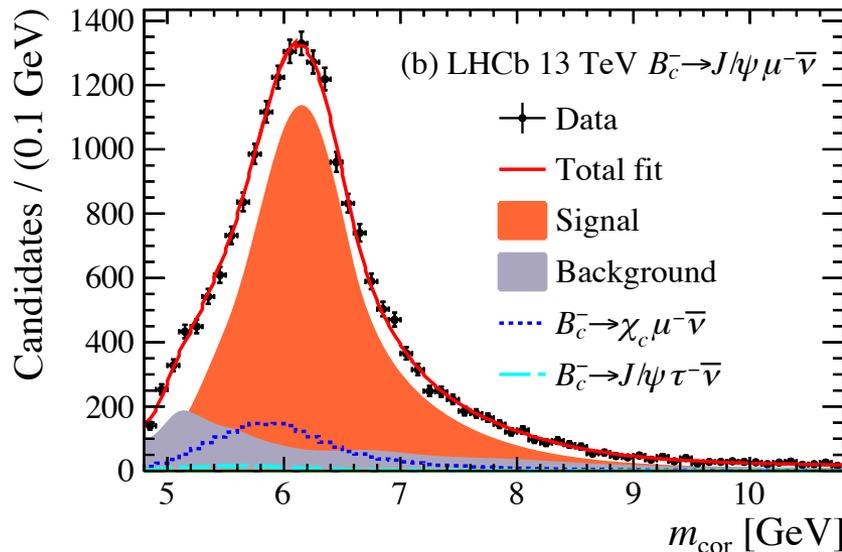
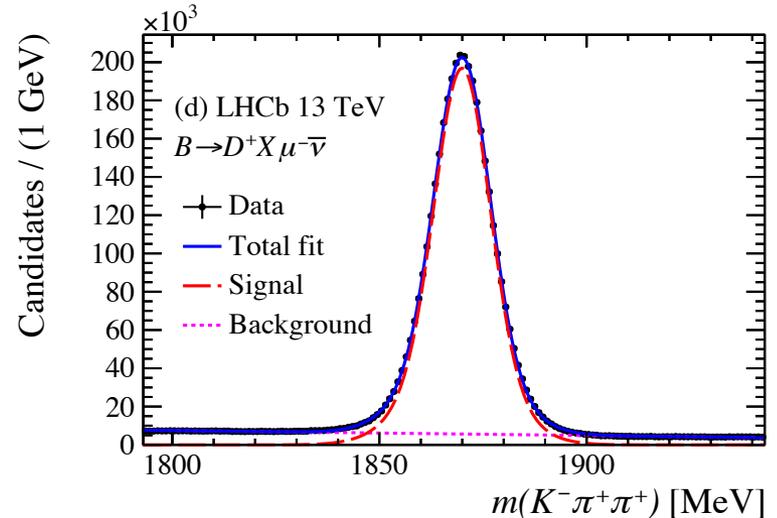
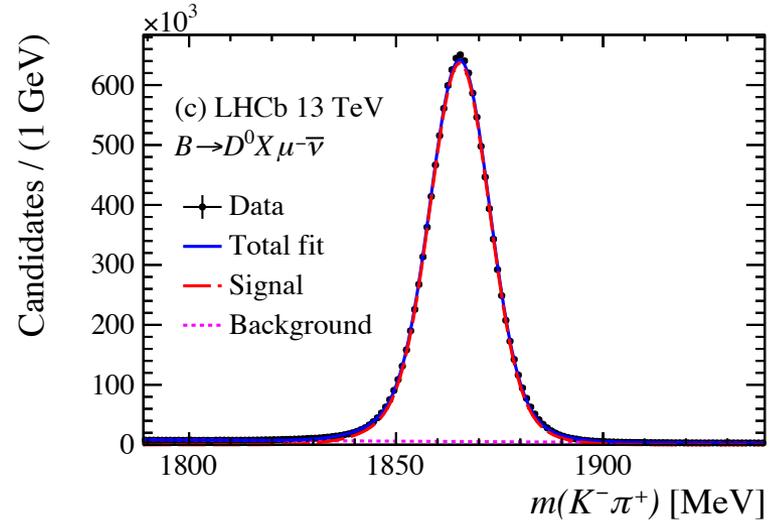
for $p_T < 20$ GeV, $y \in [2, 4.5]$

- Using $\sigma(B_c^+) = 0.47 \mu\text{b}$, theoretical prediction by BcVegPy
 $\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+) = 0.33\%$ [C.-F. Qiao *et al.*, PRD 89 (2014) 034008]
 $\sigma(B^+, p_T(B) < 40 \text{ GeV}/c, 2.0 < y < 4.5) = 38.9 \mu\text{b}$ at $\sqrt{s} = 7$ TeV,
 measured by LHCb [JHEP 08 (2013) 117], scaled up by 1.2 for 8 TeV
 $\mathcal{B}(B^+ \rightarrow J/\psi K^+) = (0.1016 \pm 0.0033)\%$, PDG'12



B_c^+ production w/ $J/\psi\mu^+X$

- Normalized to $B \rightarrow D^{0/+}\mu^-X$
- With 7 and 13 TeV
- 15170 ± 710 signal



[PRD 100 (2019) 112006]

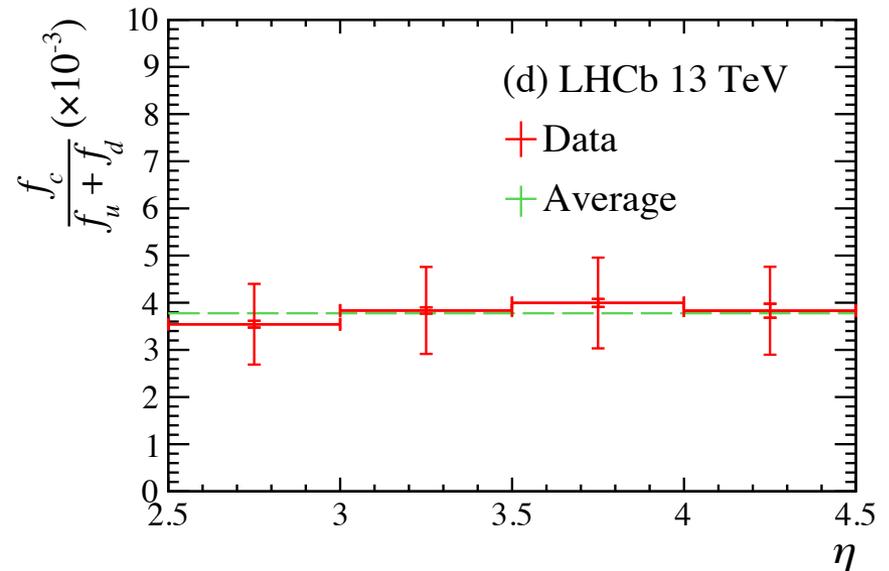
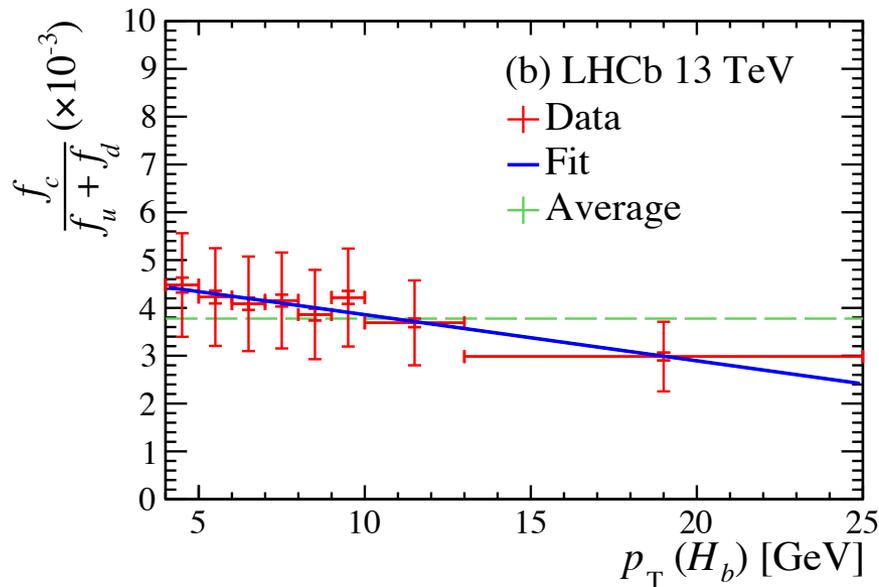
B_c^+ production w/ $J/\psi\mu^+ X$

- Similar trend seen in $p_T > 5$ GeV region

Use $\langle B_{sl} \rangle = (10.70 \pm 0.19)\%$, $B(B_c^+ \rightarrow J/\psi\mu^+\nu) = (1.95 \pm 0.46)\%$

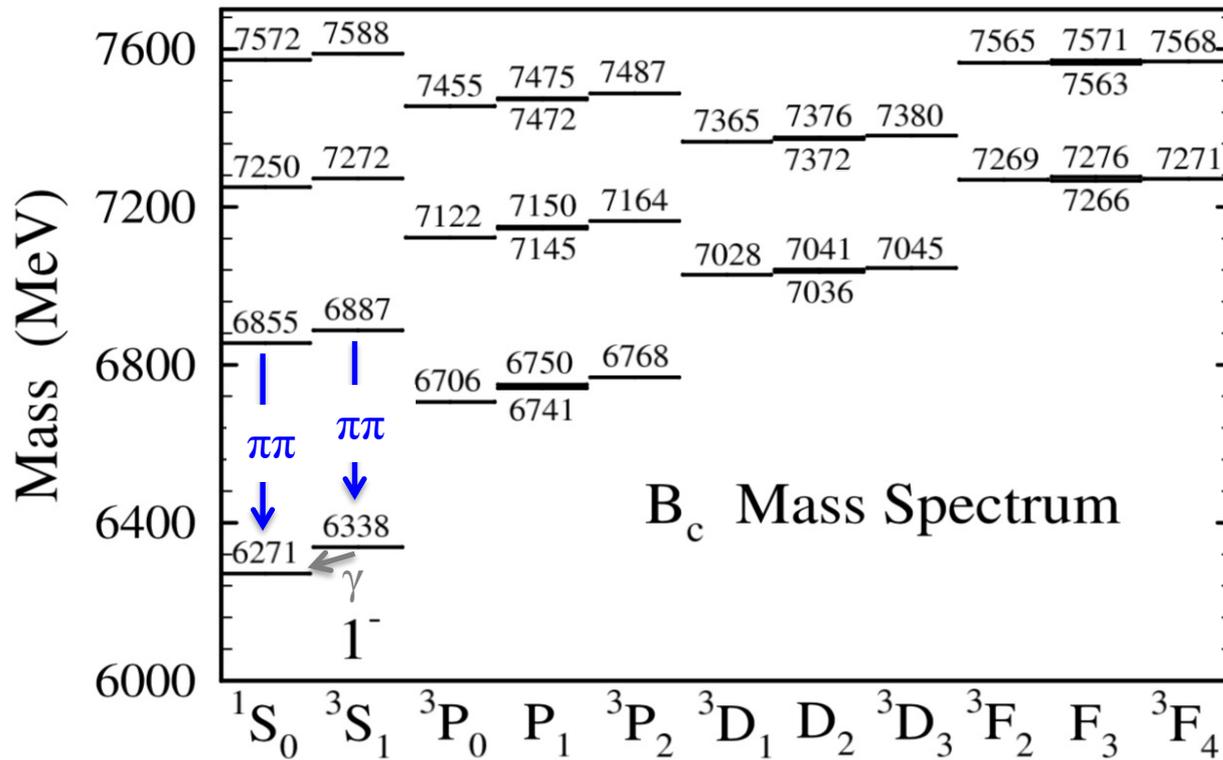
$$\frac{f_c}{f_u+f_d} = (3.78 \pm 0.04 \pm 0.15 \pm 0.89) \times 10^{-3} \text{ at 13 TeV}$$

[PRD 100 (2019) 112006]



Excited B_c^+ states

- B_c has a rich spectrum



[S.Godfrey, PRD 70 (2004) 054017]

State	Decay	GKLRY *	Godfrey †
1^3S_1	$1^1S_0 + \gamma$	100	100
1^3P_2	$1^3S_1 + \gamma$	100	100
$1P'_1$	$1^3S_1 + \gamma$	6	12.1
	$1^1S_0 + \gamma$	94	87.9
$1P_1$	$1^3S_1 + \gamma$	87	82.2
	$1^1S_0 + \gamma$	13	17.8
1^3P_0	$1^3S_1 + \gamma$	100	100
2^1S_0	$1^1S_0 + \pi\pi$	74	88.1
	$1P'_1 + \gamma$		9.4
	$1P_1 + \gamma$		2.0
	$1^3S_1 + \gamma$		0.5
2^3S_1	$1^3S_1 + \pi\pi$	58	79.6
	$1^3P_2 + \gamma$		8.0
	$1P'_1 + \gamma$		1.0
	$1P_1 + \gamma$		6.6
	$1^3P_0 + \gamma$		4.0
	$2^1S_0 + \gamma$		0.01
	$1^1S_0 + \gamma$		0.8

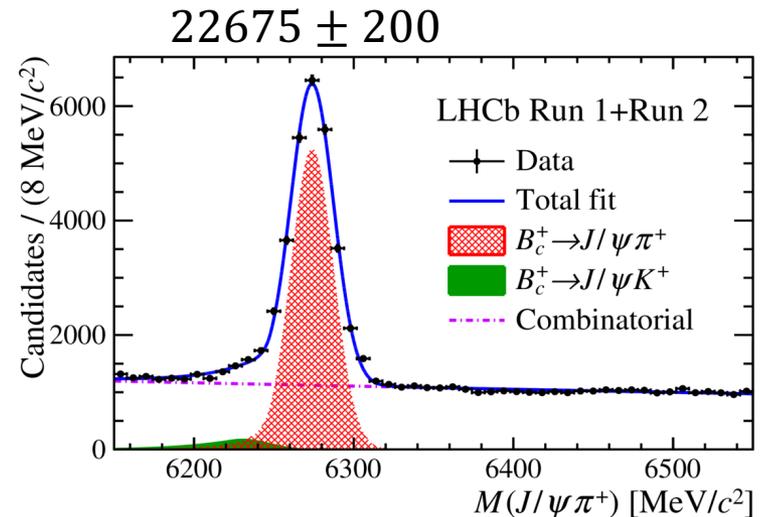
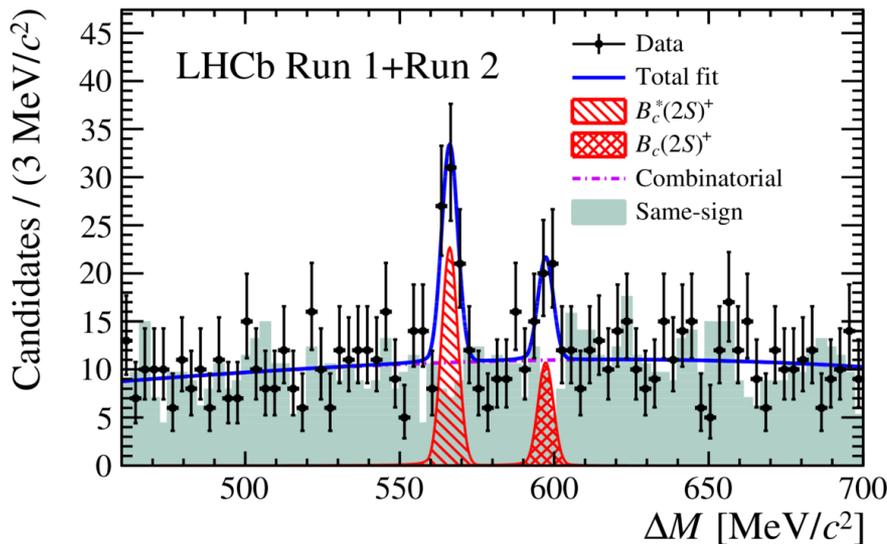
* [I. P. Gouz, et al., Phys. Atom. Nucl. 67 (2004) 1559]

† [S.Godfrey, PRD 70 (2004) 054017]

Observation of $B_c^{(*)}(2S)^+$

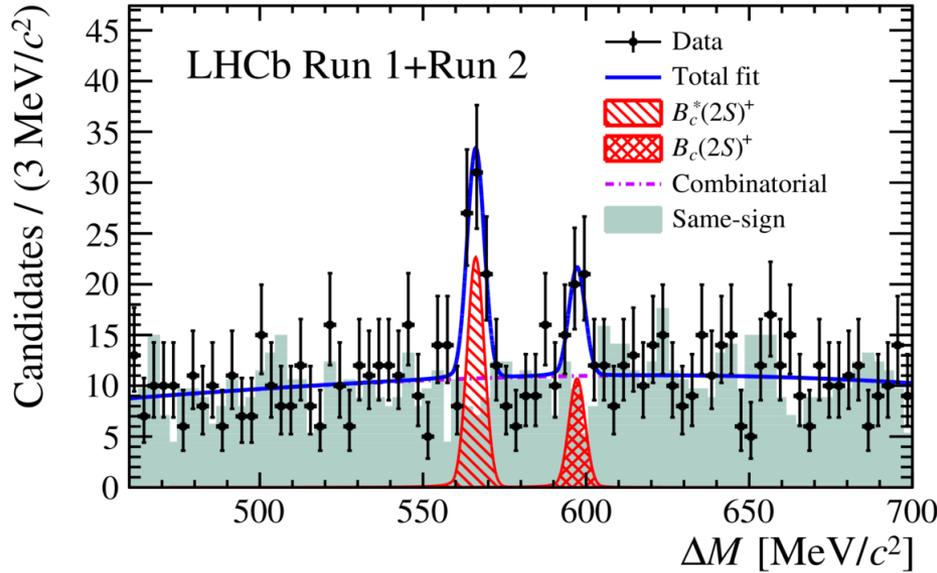
- $B_c(2S)$ observed with all Run1+2 data
- Largest B_c^+ sample

[PRL 122 (2019) 232001]

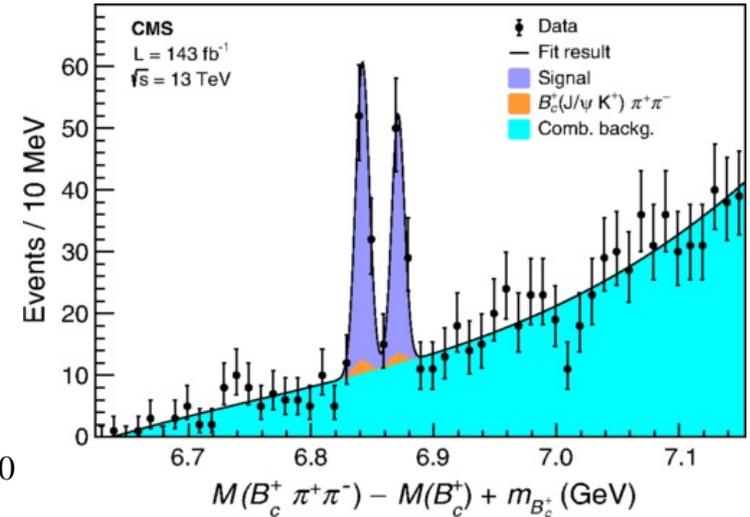


	$B_c^*(2S)^+$	$B_c(2S)^+$
Signal yield	51 ± 10	24 ± 9
Peak ΔM value (MeV/c^2)	566.2 ± 0.6	597.2 ± 1.3
Resolution (MeV/c^2)	2.6 ± 0.5	2.5 ± 1.0
Local significance	6.8σ	3.2σ
Global significance	6.3σ	2.2σ

Comparison with CMS



[PRL 122 (2019) 132001]



LHCb {

$$M(B_c(2^3S_1)^+)_{\text{rec}} = 6841.2 \pm 0.6(\text{stat}) \pm 0.1(\text{syst}) \pm 0.8(B_c^+) \text{ MeV}/c^2$$

$$M(B_c(2S)^+) = 6872.1 \pm 1.3(\text{stat}) \pm 0.1(\text{syst}) \pm 0.8(B_c^+) \text{ MeV}/c^2$$

$$M(B_c(2S)^+) - M(B_c^*(2S)^+)_{\text{rec}} = 31.0 \pm 1.4(\text{stat}) \pm 0.0(\text{syst}) \text{ MeV}/c^2$$

CMS {

$$M(B_c(2^3S_1)^+)_{\text{rec}} = 6842.0 \pm 1.0(\text{stat}) \pm 0.0(\text{syst}) \pm 0.8(B_c^+) \text{ MeV}/c^2$$

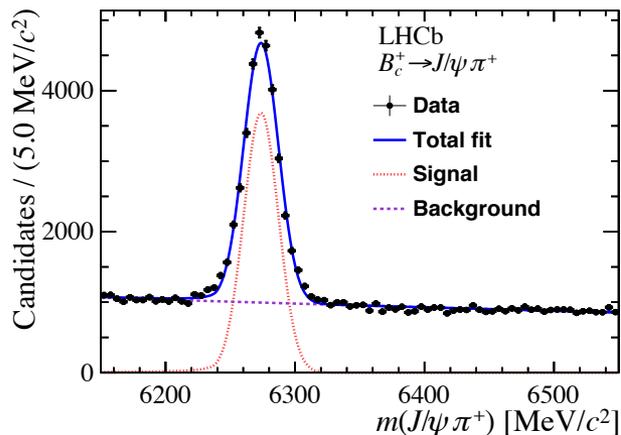
$$M(B_c(2S)^+) = 6871.0 \pm 1.2(\text{stat}) \pm 0.8(\text{syst}) \pm 0.8(B_c^+) \text{ MeV}/c^2$$

$$M(B_c(2S)^+) - M(B_c^*(2S)^+)_{\text{rec}} = 29.0 \pm 1.5(\text{stat}) \pm 0.7(\text{syst}) \text{ MeV}/c^2$$

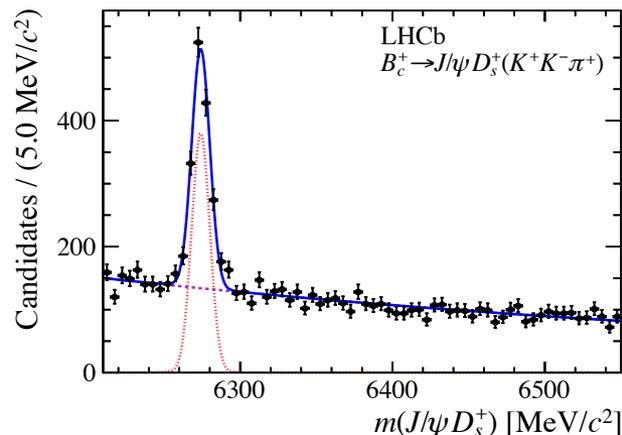
B_c^+ mass measurement

- Six decay modes, with all Run1+2 data

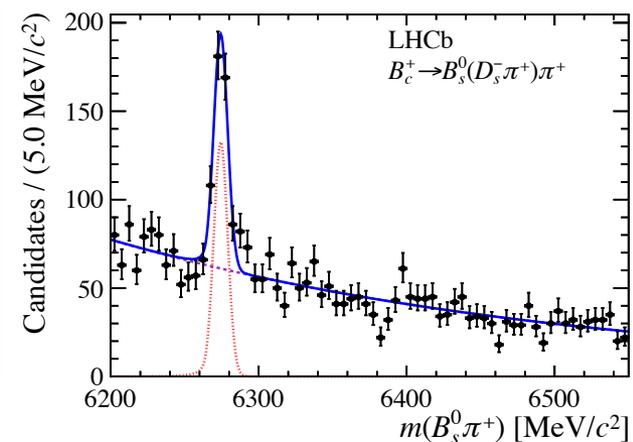
Decay mode	Yield	Fitted mass [MeV/ c^2]	Corrected mass [MeV/ c^2]	Resolution [MeV/ c^2]
$J/\psi \pi^+$	25181 ± 217	6273.71 ± 0.12	6273.78 ± 0.12	13.49 ± 0.11
$J/\psi \pi^+ \pi^- \pi^+$	9497 ± 142	6274.26 ± 0.18	6274.38 ± 0.18	11.13 ± 0.18
$J/\psi p \bar{p} \pi^+$	273 ± 29	6274.66 ± 0.73	6274.61 ± 0.73	6.34 ± 0.76
$J/\psi D_s^+(K^+ K^- \pi^+)$	1135 ± 49	6274.09 ± 0.27	6274.11 ± 0.27	5.93 ± 0.30
$J/\psi D_s^+(\pi^+ \pi^- \pi^+)$	202 ± 20	6274.57 ± 0.71	6274.29 ± 0.71	6.63 ± 0.67
$J/\psi D^0(K^- \pi^+) K^+$	175 ± 21	6273.97 ± 0.53	6274.08 ± 0.53	3.87 ± 0.57
$B_s^0(D_s^- \pi^+) \pi^+$	316 ± 27	6274.36 ± 0.44	6274.08 ± 0.44	4.67 ± 0.48
$B_s^0(J/\psi \phi) \pi^+$	299 ± 37	6275.87 ± 0.66	6275.46 ± 0.66	5.32 ± 0.74



Jibo HE (UCAS)



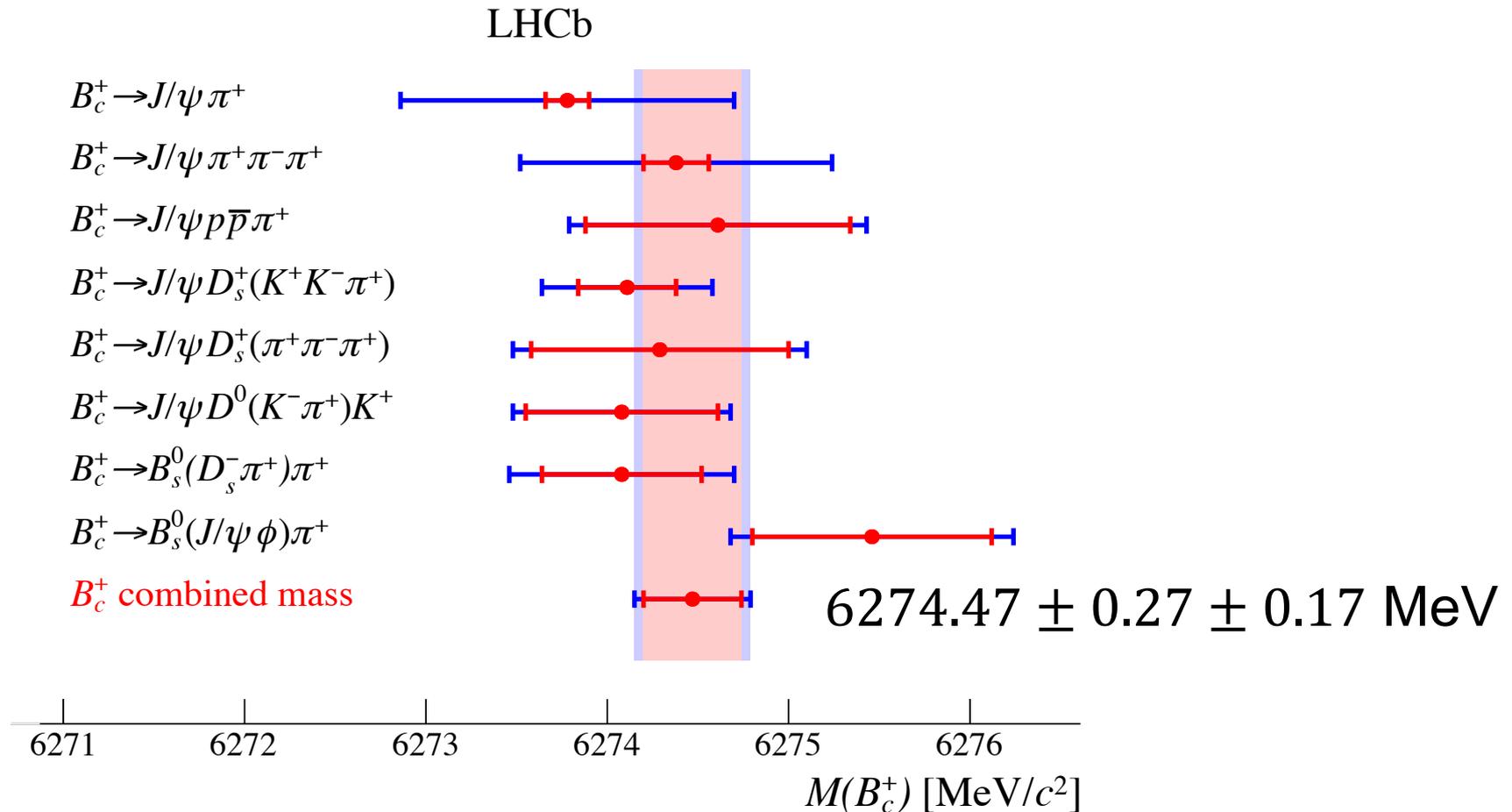
Doubly heavy mesons & baryons



B_c^+ mass measurement

- Precision improved by a factor of 2

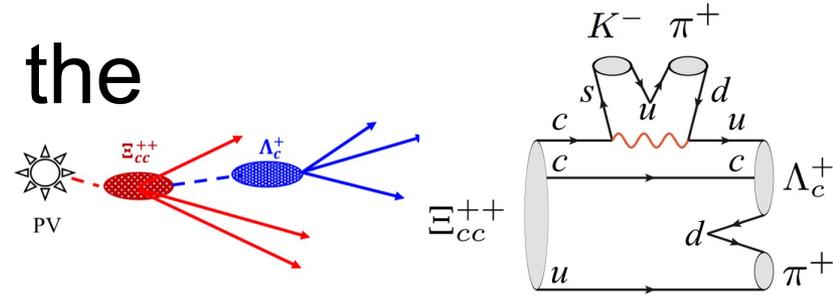
[JHEP 07 (2020) 123]



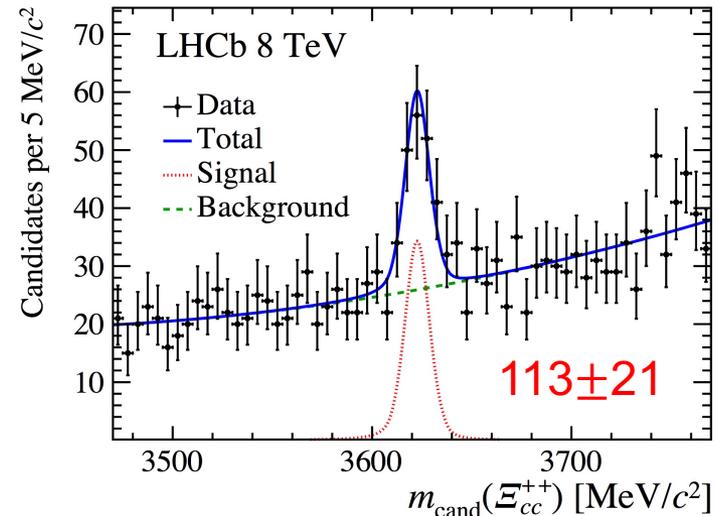
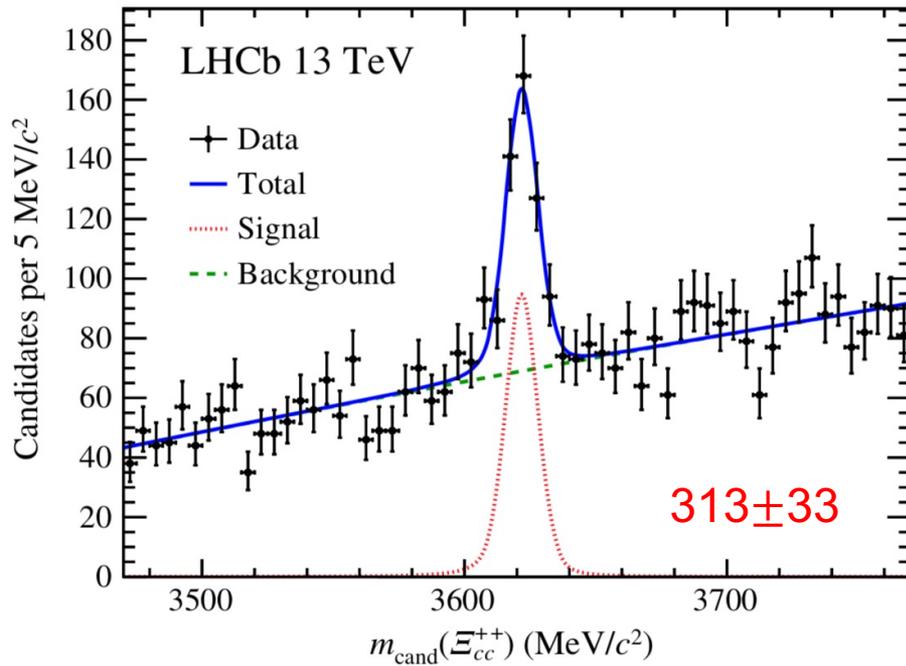
Observation of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$

- $\Lambda_c^+ K^- \pi^+ \pi^+$ identified as the most promising channel

[F.-S. Yu *et al.*, CPC 42 (2018) 051001]

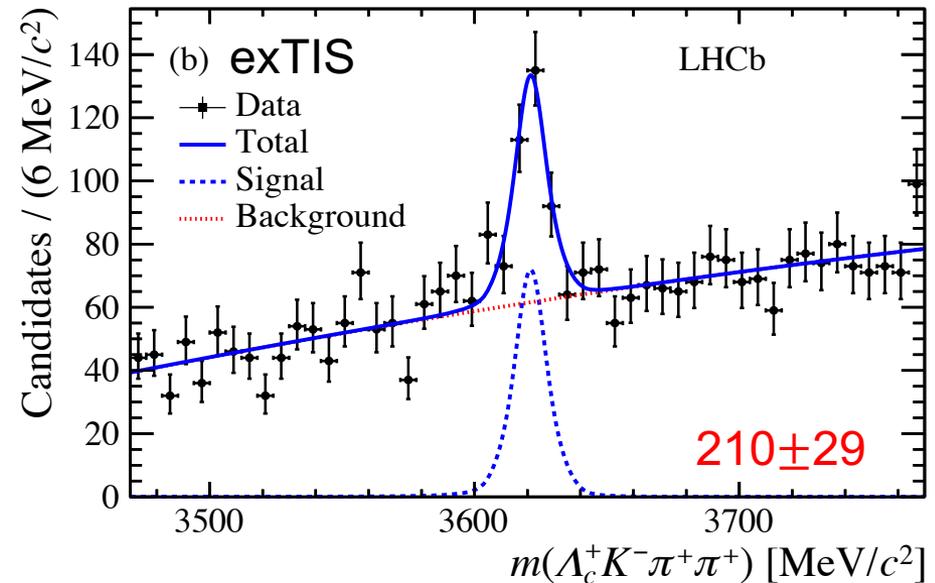
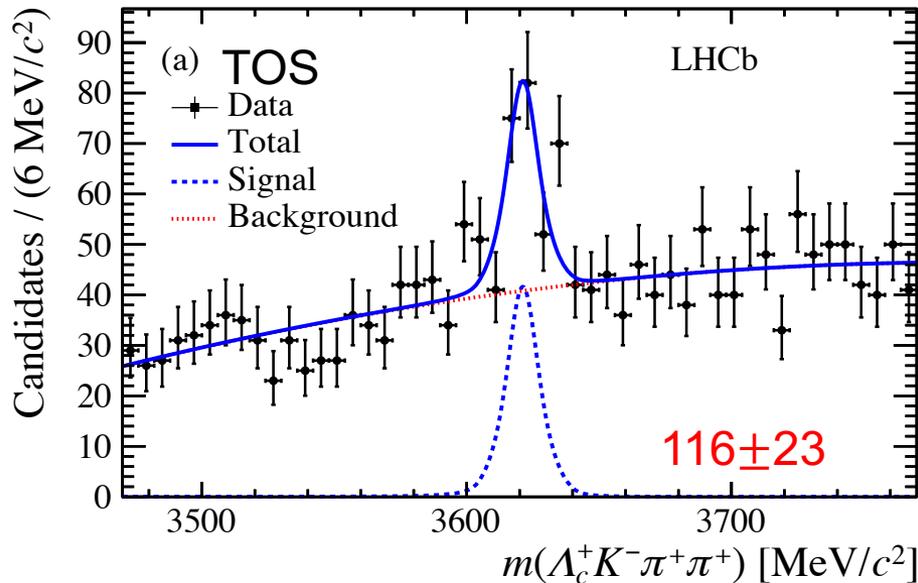
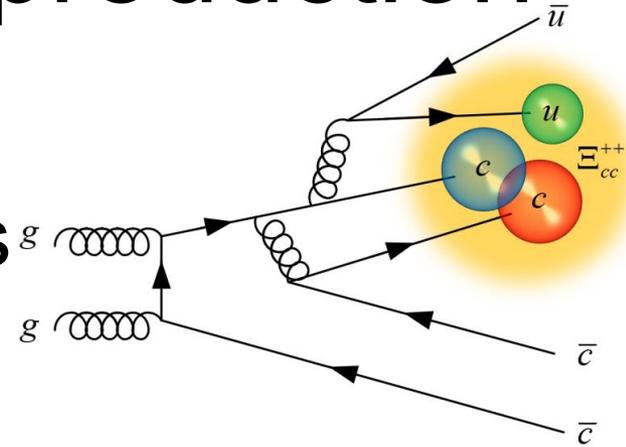


- First observation, in 2016 ($>12\sigma$) & Run-I ($>7\sigma$)



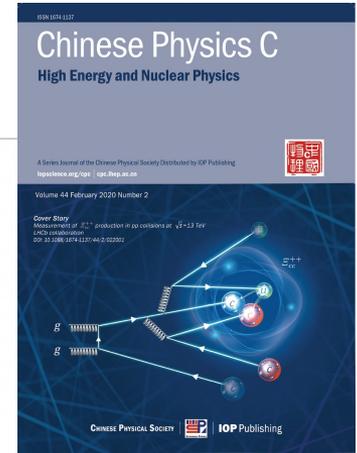
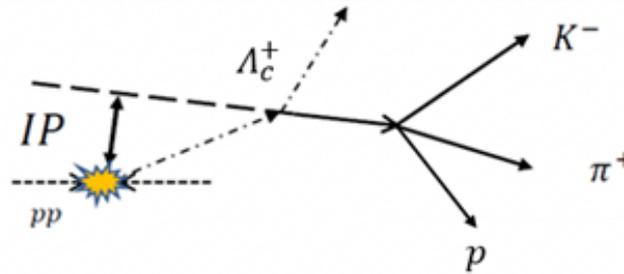
Measurement of Ξ_{cc}^{++} production

- Measured w/ 2016 data
- Accompanying $\bar{c}\bar{c}$ dominates in trigger, lots of work on validating efficiency



Measurement of Ξ_{cc}^{++} production

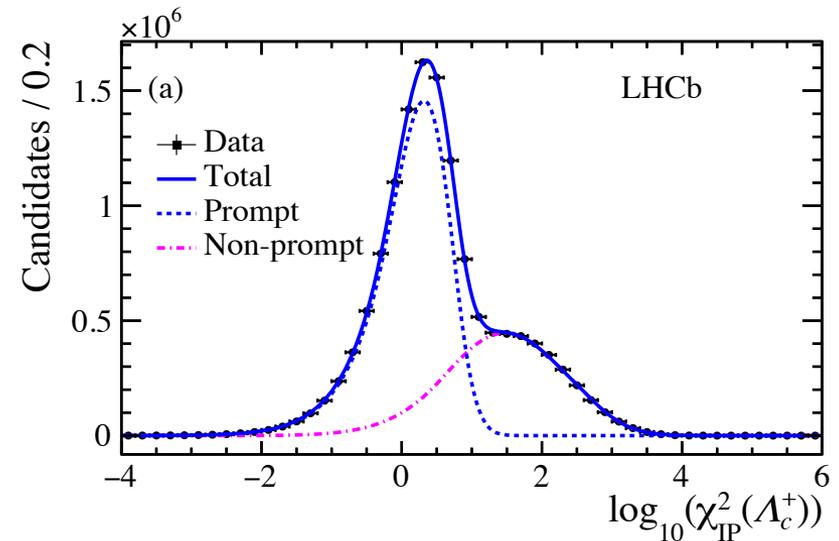
- Relative to Λ_c^+ , in
 $4 < p_T < 15$ GeV,
 $2 < y < 4.5$



$$\frac{\sigma(\Xi_{cc}^{++})}{\sigma(\Lambda_c^+)} \mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)$$

$$= (2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$$

SELEX, 20% Λ_c^+ from Ξ_{cc}^+



Summary

- LHCb has made great progress on studies of the doubly heavy mesons & baryons
 - B_c^+ production with both $J/\psi\pi^+$, $J/\psi\mu^+X$, world-best measurement of B_c^+ mass, observation of $B_c(2S)^{(*)+}$
 - Ξ_{cc}^{++} production
- With LHCb upgrade (50 fb^{-1}) & upgrade-II (300 fb^{-1}), much more will be done
- Your suggestions are always welcome!