Study of doubly heavy hadrons at LHCb

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Outline

- Introduction to LHCb
- B_c^+ physics
- Doubly heavy baryons

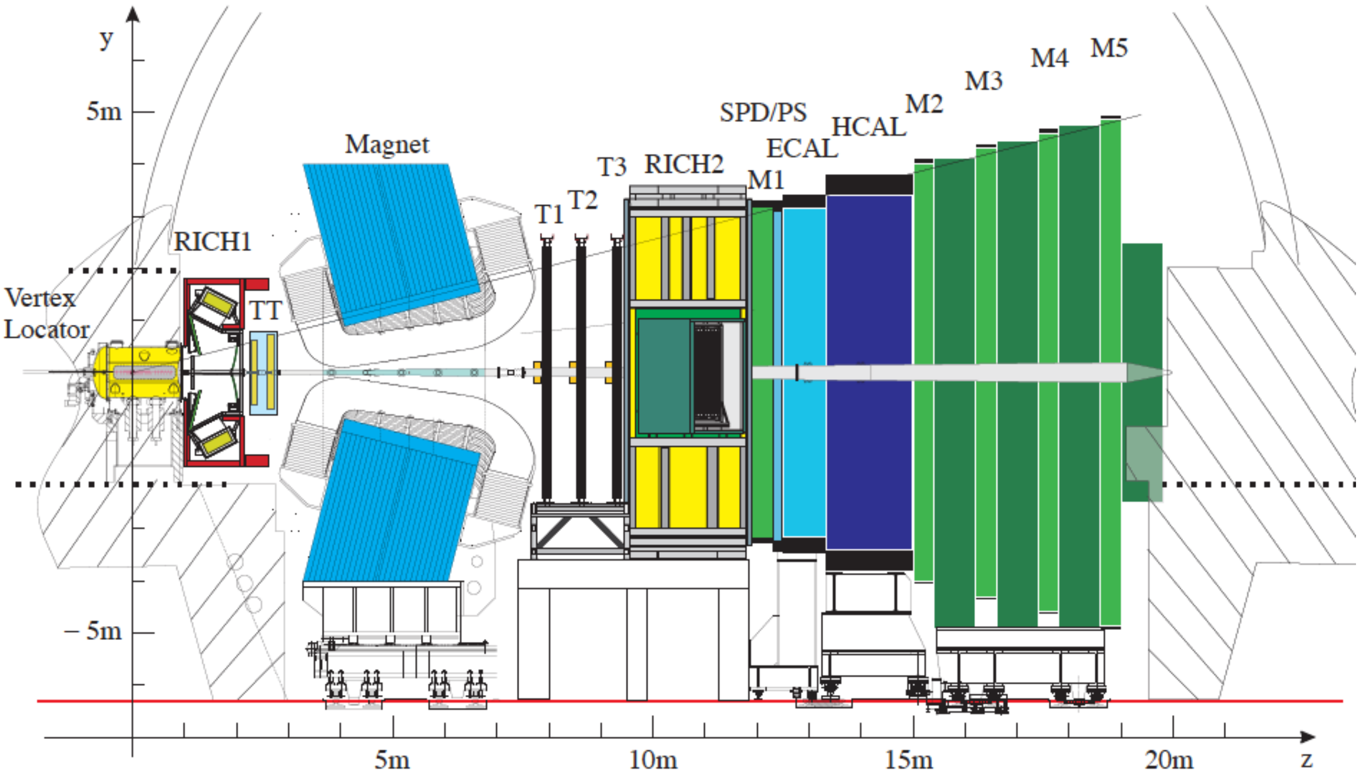
XYZ production (41届）

Large Hadron Collider

Proton energy: up to 7 TeV (10^{12} eV)
speed: 0.999999991 c

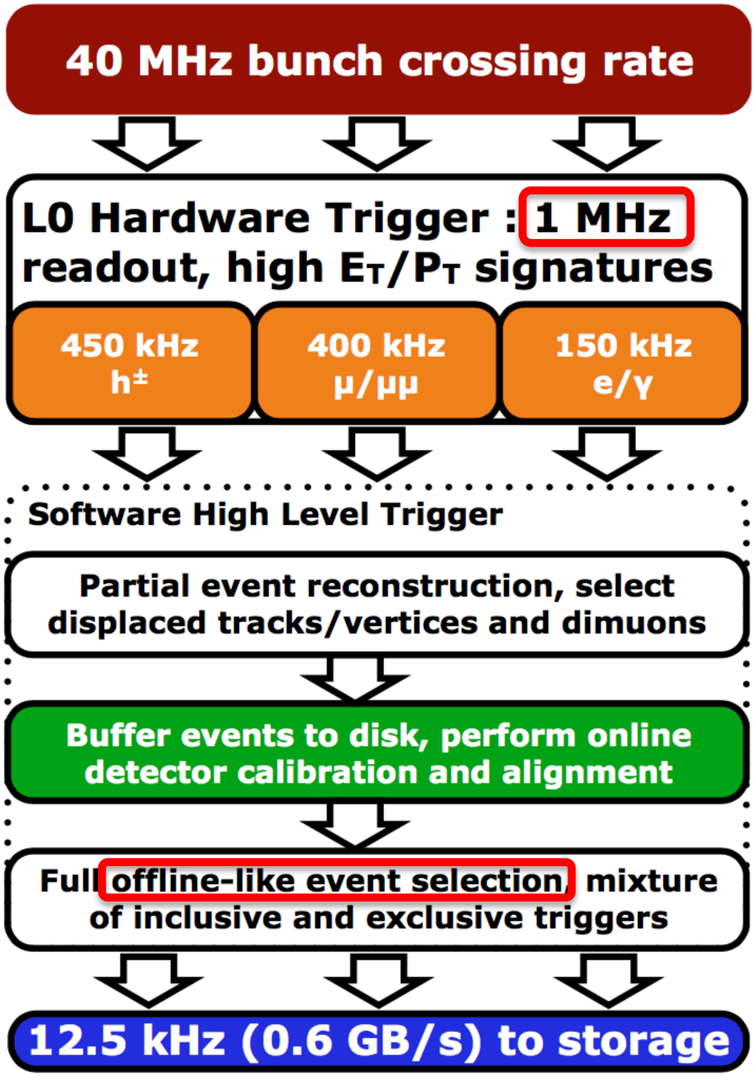
The LHCb experiment

[JINST 3 (2008) S08005]



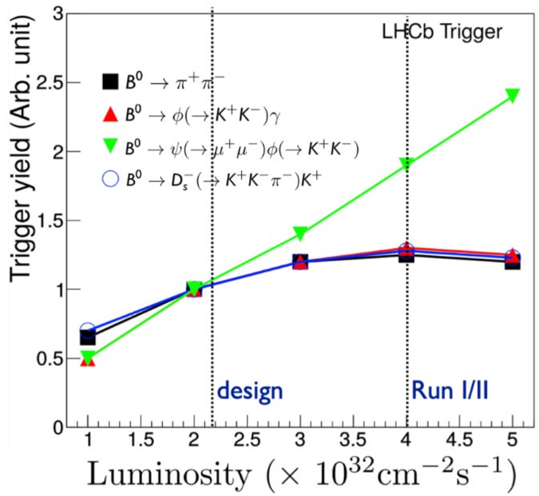
Vertex Locator	$\sigma_{\mathrm{PV,x/y}} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV,z}} \sim 60\ \mu\mathrm{m}$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) = 1 - 3\%$
ECAL	$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)
HCAL	$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$ (E in GeV)

The LHCb trigger (2018)



- L0, Hardware
  - $p_{\mathrm{T}}(\mu_1)\times p_{\mathrm{T}}(\mu_2) >$ (1.5 GeV)^2
  - $p_{\mathrm{T}}(\mu) >$ 1.8 GeV
  - $E_{\mathrm{T}}(e) >$ 2.4 GeV
  - $E_{\mathrm{T}}(\gamma) >$ 3.0 GeV
  - $E_{\mathrm{T}}(h) >$ 3.7 GeV
- High Level Trigger
  - Stage1, p_{T}, IP
  - Stage2, full selection

The LHCb trigger (Run3)



Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

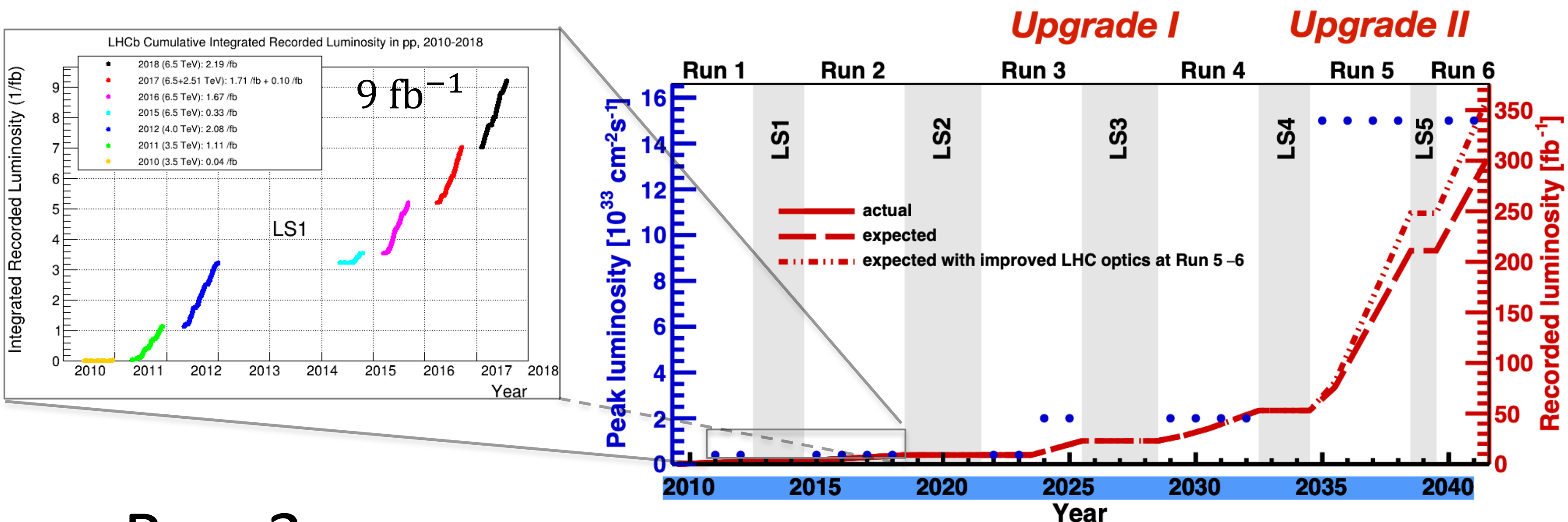
Buffer events to disk, perform online detector calibration and alignment

Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

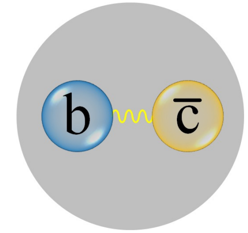
2-5 GB/s to storage

LHCb luminosity prospects



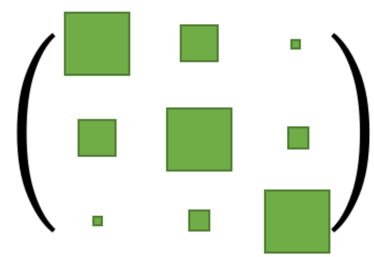
- Run-3
  - Luminosity: 7 fb^{-1} (2024) + 7 fb^{-1} (2025)
  - Yields, compared to Run 1+2
    - Muon modes ~2
    - Hadronic modes ~4 (2 x 2 due to higher trigger eff.)

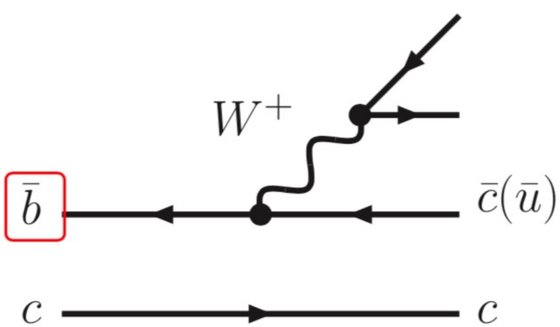
B_c meson

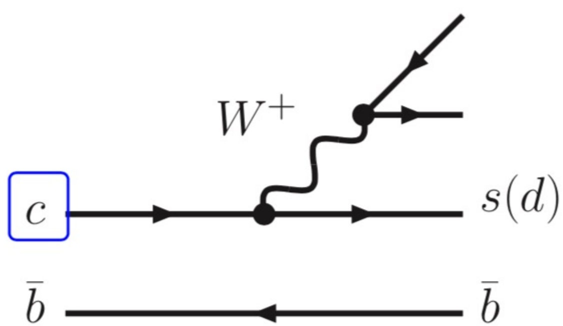


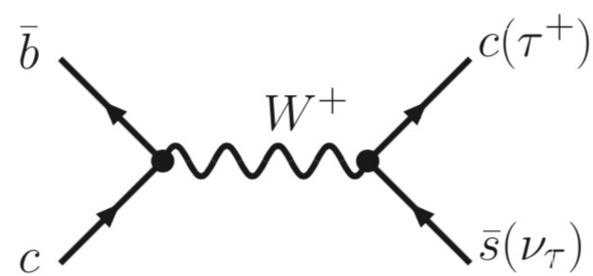
- Formed by two different heavy quarks, unique in the Standard Model. Both *b*- & *c*-quark can decay, or annihilate
  - $\bar{b} \to \bar{c}W^+$, 20%, e.g., $J/\psi\ell^+\nu_\ell$
  - $c \to sW^+$, 70%, e.g., $B_s^0\pi^+$
  - $c\bar{b} \to W^+$, 10%, e.g., $\tau^+\nu_\tau$

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

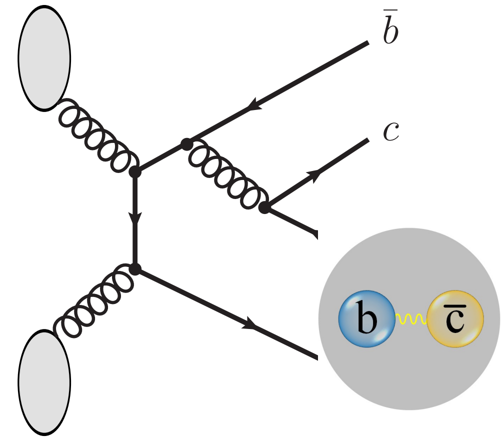








B_c production



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

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

-	$\lvert({}^1S_0)_{\mathbf{1}}\rangle$	$\lvert({}^3S_1)_{\mathbf{1}}\rangle$	$\lvert({}^1S_0)_{\mathbf{8}}g\rangle$	$\lvert({}^3S_1)_{\mathbf{8}}g\rangle$	$\lvert({}^1P_1)_{\mathbf{1}}\rangle$	$\lvert({}^3P_0)_{\mathbf{1}}\rangle$	$\lvert({}^3P_1)_{\mathbf{1}}\rangle$	$\lvert({}^3P_2)_{\mathbf{1}}\rangle$
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 $|R_{2S}(0)/R_{1S}(0)| \approx 0.6$
  - $\sigma(B_c^+) \sim 0.9$ μb for $\sqrt{s} = 14$ TeV

Before LHC started

CHIN. PHYS. LETT. Vol. 27, No. 6 (2010) 061302

Experimental Prospects of the B_c Studies of the LHCb Experiment *

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The experimental prospects of the B_c studies of the LHCb experiment are discussed. Production rates of B_c mesons at different center-of-mass energies are estimated with the dedicated generator BCVEGPY. Theoretical estimates and experimental measurements of the $B_c^\pm$ inclusive production cross section at $\sqrt{s} = 1.96$ TeV are compared. The possibilities of studying B_c production, B_c spectroscopy, B_c decays and CP violation in B_c decays in the LHCb experiment are evaluated.

identify, as discussed above. A fast simulation shows that the mass of the $B_c(2^3S_1)$ state would be shifted down by the mass difference of $M(B_c^{*+}) - M(B_c^+)$ and the mass resolution is not affected much when the $B_c(2^3S_1)$ state is reconstructed only with $B_c^+\pi^+\pi^-$ and the photon is missing. Thus the $2S$ states will probably be observed at the LHCb experiment, and it will also be possible to distinguish the 2^3S_1 state from the 2^1S_0 state if the mass difference between the B_c^{*+} and B_c^+ mesons is sufficiently larger than that between the 2^3S_1 and 2^1S_0 states.

LHCb experiment. Taking the inclusive cross section of the B_c^+ meson as 0.9 μb and the branching ratio $\mathcal{B}(B_c^+ \to B_s^0\pi^+)$ as 16.4%[1] and assuming the efficiency of reconstructing B_c^+ from $B_s^0\pi^+$ as 30%, we will be able to observe about 100 $B_c^+ \to B_s^0\pi^+$ events with $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ and about 120 $B_c^+ \to B_s^0\pi^+$ events with $B_s^0 \to D_s^-(K^+K^-\pi^-)\pi^+$ from 1 fb^{-1} of data, which may be not very interesting for the CP violation studies of the B_s^0 meson, but we can at least measure the branching ratios of such decays and test the theoretical predictions of their branching ratios.

Progress in the past 16 years

2008

$B_c^{\pm}$ $I(J^P) = 0(0^-)$
I, J, P need confirmation.

Quantum numbers shown are quark-model predictions.

$B_c^{\pm}$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
6.276 ±0.004 OUR AVERAGE				
$6.2756 \pm 0.0029 \pm 0.0025$	[1] AALTONEN	08M	CDF	$p\bar{p}$ at 1.96 TeV
$6.4 \quad \pm 0.39 \quad \pm 0.13$	[2] ABE	98M	CDF	$p\bar{p}$ at 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$6.2857 \pm 0.0053 \pm 0.0012$	[1] ABULENCIA	06C	CDF	Repl. by AALTONEN 08M
$6.32 \quad \pm 0.06$	[3] ACKERSTAFF	98O	OPAL	$e^+e^- \rightarrow Z$

[1] Measured using a fully reconstructed decay mode of $B_c \rightarrow J/\psi\pi$.

[2] ABE 98M observed $20.4^{+6.2}_{-5.5}$ events in the $B_c^+ \rightarrow J/\psi(1s)\ell\nu_\ell$ with a significance of > 4.8 standard deviations. The mass value is estimated from $m(J/\psi(1S)\ell)$.

[3] ACKERSTAFF 98O observed 2 candidate events in the $B_c \rightarrow J/\psi(1S)\pi^+$ channel with an estimated background of 0.63 ± 0.20 events.

$B_c^{\pm}$ MEAN LIFE

VALUE (10^{-12} s)	DOCUMENT ID		TECN	COMMENT
0.46 ±0.07 OUR AVERAGE				
$0.463^{+0.073}_{-0.065} \pm 0.036$	[4] ABULENCIA	06O	CDF	$p\bar{p}$ at 1.96 TeV
$0.46 \;^{+0.18}_{-0.16} \pm 0.03$	[4] ABE	98M	CDF	$p\bar{p}$ 1.8 TeV

[4] The lifetime is measured from the $J/\psi(1S)e$ decay vertices.

B_c^+ DECAY MODES × B($\bar{b} \rightarrow B_c$)

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

	Mode	Fraction (Γ_i/Γ)	Confidence level
	The following quantities are not pure branching ratios; rather the fraction $\Gamma_i/\Gamma \times B(\bar{b} \rightarrow B_c)$.		
Γ_1	$J/\psi(1S)\ell^+\nu_\ell$anything	$(5.2^{+2.4}_{-2.1}) \times 10^{-5}$	
Γ_2	$J/\psi(1S)\pi^+$	$< 8.2 \times 10^{-5}$	90%
Γ_3	$J/\psi(1S)\pi^+\pi^+\pi^-$	$< 5.7 \times 10^{-4}$	90%
Γ_4	$J/\psi(1S)a_1(1260)$	$< 1.2 \times 10^{-3}$	90%
Γ_5	$D^*(2010)^+\bar{D}^0$	$< 6.2 \times 10^{-3}$	90%

2024

B_c^+ $I(J^P) = 0(0^-)$ I, J, P need confirmation.

Quantum numbers shown are quark-model predictions.

B_c^+ MASS	6274.47 ± 0.32 MeV
$mB_c^+ - mB_s^0$	907.8 ± 0.5 MeV
B_c^+ MEAN LIFE	$(0.510 \pm 0.009) \times 10^{-12}$ s
POLARIZATION IN B_c^+ DECAY	
$\Gamma L/\Gamma$ in $B_c^+ \rightarrow J/\psi D_s^{*+}$	0.34 ± 0.09
$AP(B_c^+)$	-0.010 ± 0.010

Expand all decays

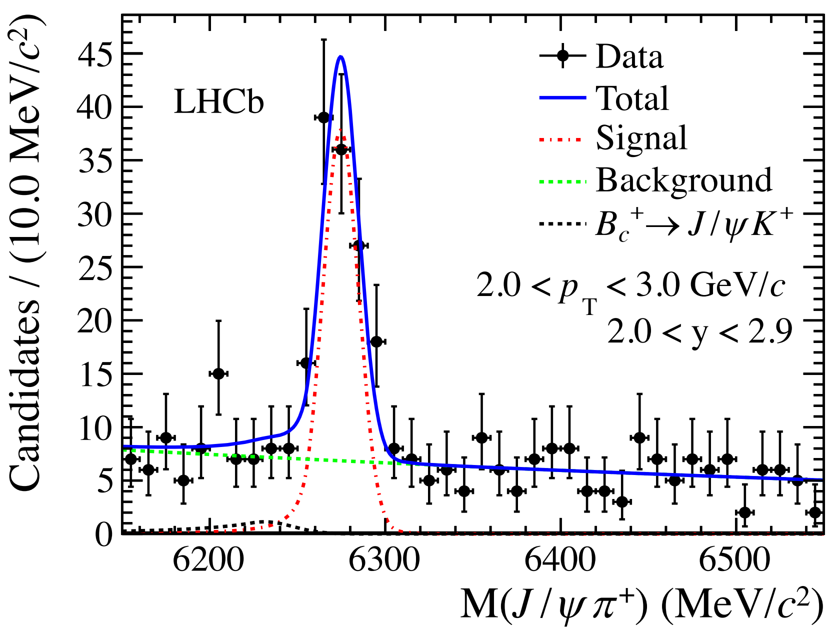
conjugates of the modes below.

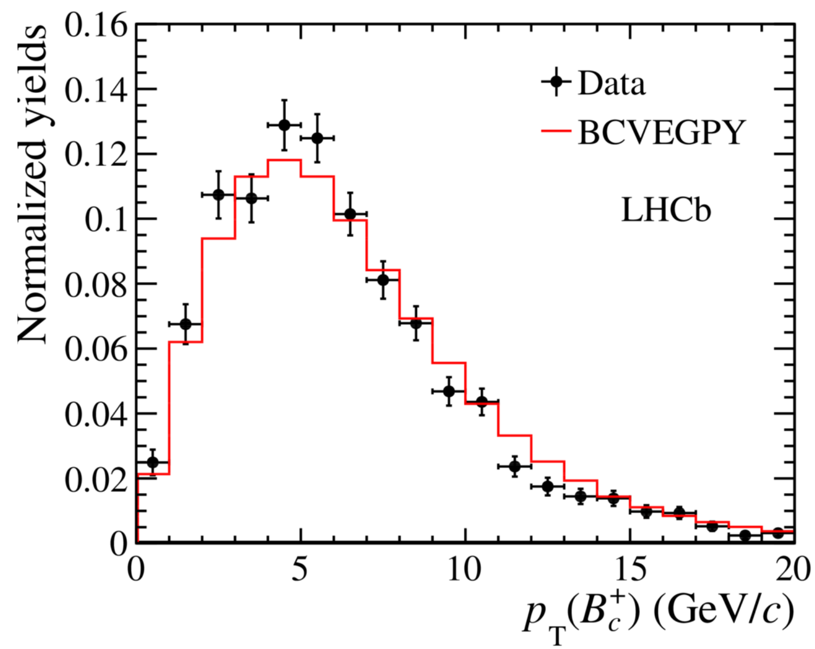
		Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$J/\psi(1S)\ell^+\nu_\ell$ anything	seen		
Γ_2	$J/\psi(1S)\mu^+\nu_\mu$	seen		2372
Γ_3	$J/\psi(1S)\tau^+\nu_\tau$	seen		1932
Γ_4	$J/\psi(1S)\pi^+$	seen		2370
Γ_5	$J/\psi(1S)K^+$	seen		2341
Γ_6	$J/\psi(1S)\pi^+\pi^+\pi^-$	seen		2350
Γ_7	$J/\psi(1S)K^+\pi^-\pi^+$			2294
Γ_8	$J/\psi(1S)K^+K^-K^+$			2073
Γ_9	$J/\psi(1S)a_1(1260)$	not seen		2169
Γ_{10}	$J/\psi(1S)K^+K^-\pi^+$	seen		2203
Γ_{11}	$J/\psi(1S)\pi^+\pi^+\pi^+\pi^-\pi^-$	seen		2309
Γ_{12}	$\psi(2S)\pi^+$	seen		2051
Γ_{13}	$\psi(2S)\pi^+\pi^-\pi^+$			2026
Γ_{14}	$\psi(2S)K^+K^-\pi^+$			1838
Γ_{15}	$J/\psi(1S)D^0K^+$	seen		1539
Γ_{16}	$J/\psi(1S)D^*(2007)^0K^+$	seen		1411
Γ_{17}	$J/\psi(1S)D^*(2010)^+K^{*0}$	seen		919
Γ_{18}	$J/\psi(1S)D^+K^{*0}$	seen		1122
Γ_{19}	$J/\psi(1S)D_s^+$	seen		1821
Γ_{20}	$J/\psi(1S)D_s^{*+}$	seen		1727
Γ_{21}	$J/\psi(1S)p\bar{p}\pi^+$	seen		1791
Γ_{22}	$\chi c0\pi^+$	$(2.4^{+0.9}_{-0.8}) \times 10^{-5}$		2205
Γ_{23}	$p\bar{p}\pi^+$	not seen		2970
Γ_{24}	D^0K^+	seen		2837
Γ_{25}	$D^0\pi^+$	not seen		2858
Γ_{26}	$D^{*0}\pi^+$	not seen		2814
Γ_{27}	$D^{*0}K^+$	not seen		2792
Γ_{28}	$D_s^+\bar{D}^0$	$< 7.2 \times 10^{-4}$	CL=90%	2483
Γ_{29}	$D_s^+D^0$	$< 3.0 \times 10^{-4}$	CL=90%	2483
Γ_{30}	$D^+\bar{D}^0$	$< 1.9 \times 10^{-4}$	CL=90%	2521
Γ_{31}	D^+D^0	$< 1.4 \times 10^{-4}$	CL=90%	2521
Γ_{32}	$D_s^{*+}\bar{D}^0$	$< 5.3 \times 10^{-4}$	CL=90%	2425
Γ_{33}	$D_s^+\bar{D}^*(2007)^0$	$< 4.6 \times 10^{-4}$	CL=90%	2427
Γ_{34}	$D_s^{*+}D^0$	$< 9 \times 10^{-4}$	CL=90%	2425
Γ_{35}	$D_s^+D^*(2007)^0$	$< 6.6 \times 10^{-4}$	CL=90%	2427
Γ_{36}	$D^*(2010)^+\bar{D}^0$	$< 3.8 \times 10^{-4}$	CL=90%	2467
Γ_{37}	$D^*(2010)^+\bar{D}^0$, $D^{*+} \rightarrow D^+\pi^0 / \gamma$	not seen		
Γ_{38}	$D^+\bar{D}^*(2007)^0$	$< 6.5 \times 10^{-4}$	CL=90%	2466
Γ_{39}	$D^*(2007)^+D^0$	$< 2.0 \times 10^{-4}$	CL=90%	
Γ_{40}	$D^*(2010)^+D^0$, $D^{*+} \rightarrow D^+\pi^0 / \gamma$	not seen		2467

B_c^+ production

- Double-differential production as (p_T, y), w/ 2 fb^{-1} data at 8 TeV
- p_T distribution well described by BcVegPy

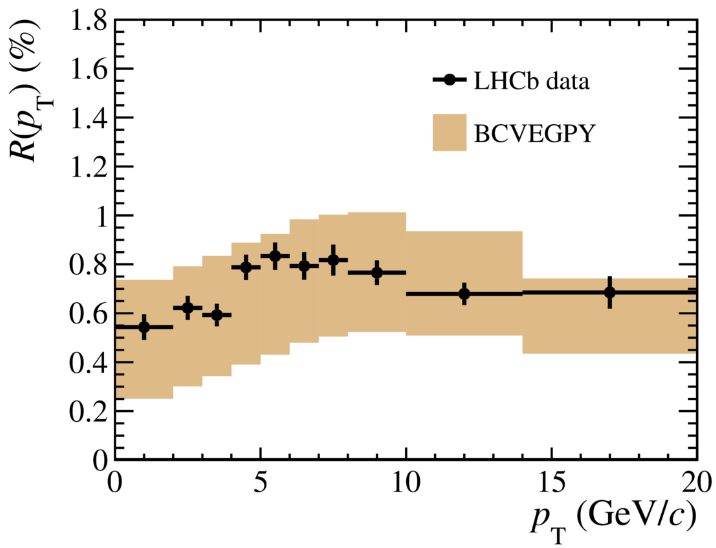
[PRL 114 (2015) 132001]

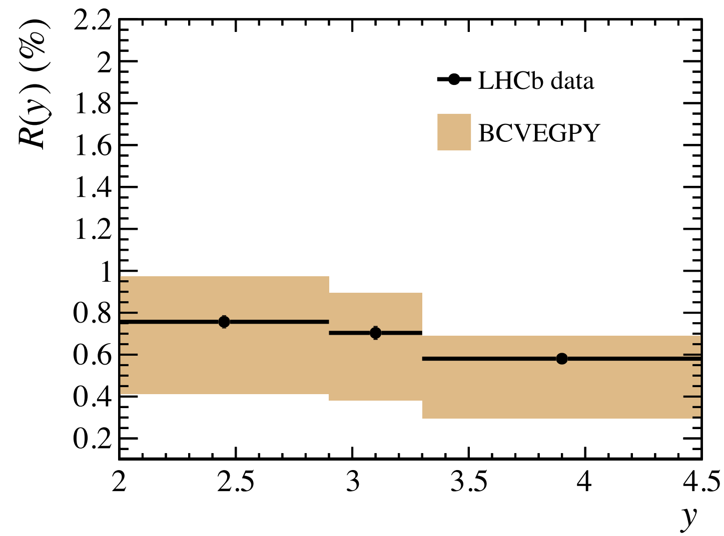




B_c^+ production

- $\mathcal{R} = \frac{\sigma(B_c^+)\cdot\mathcal{B}(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\cdot\mathcal{B}(B^+\to J/\psi K^+)} = (0.683 \pm 0.018 \pm 0.009)\%$
  for $p_\mathrm{T} < 20$ GeV, $y \in [2, 4.5]$
- Using
  $\sigma(B_c^+) = 0.47$ μb, theoretical prediction by BcVegPy
  $\mathcal{B}(B_c^+ \to J/\psi\pi^+) = 0.33\%$ [C.-F. Qiao *et al.*, PRD 89 (2014) 034008]
  $\sigma(B^+, p_\mathrm{T}(B) < 40\,\mathrm{GeV}/c, 2.0 < y < 4.5) = 38.9\,\mu\mathrm{b}$ at $\sqrt{s} = 7$ TeV, measured by LHCb [JHEP 08 (2013) 117], scaled up by 1.2 for 8 TeV
  $\mathcal{B}(B^+ \to J/\psi K^+) = (0.1016 \pm 0.0033)\%$, PDG'12

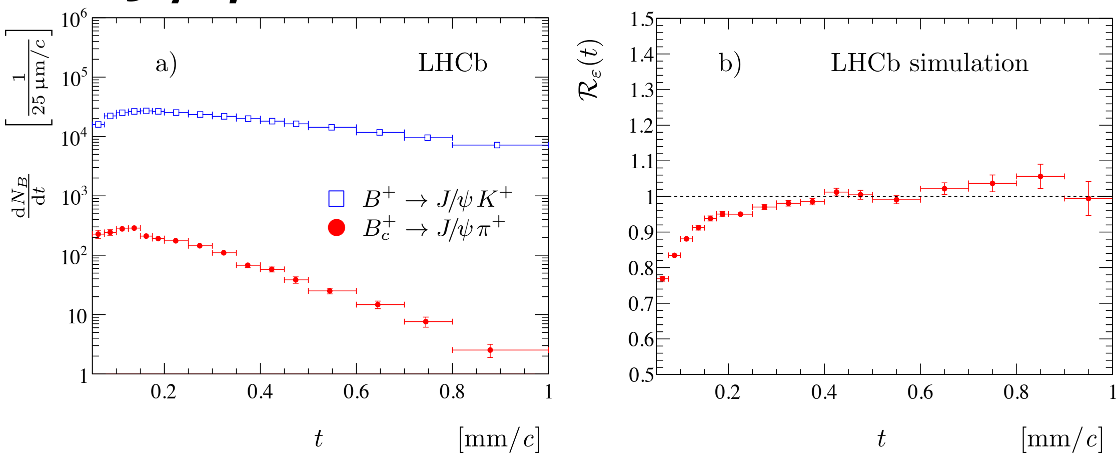




[PRL 114 (2015) 132001]

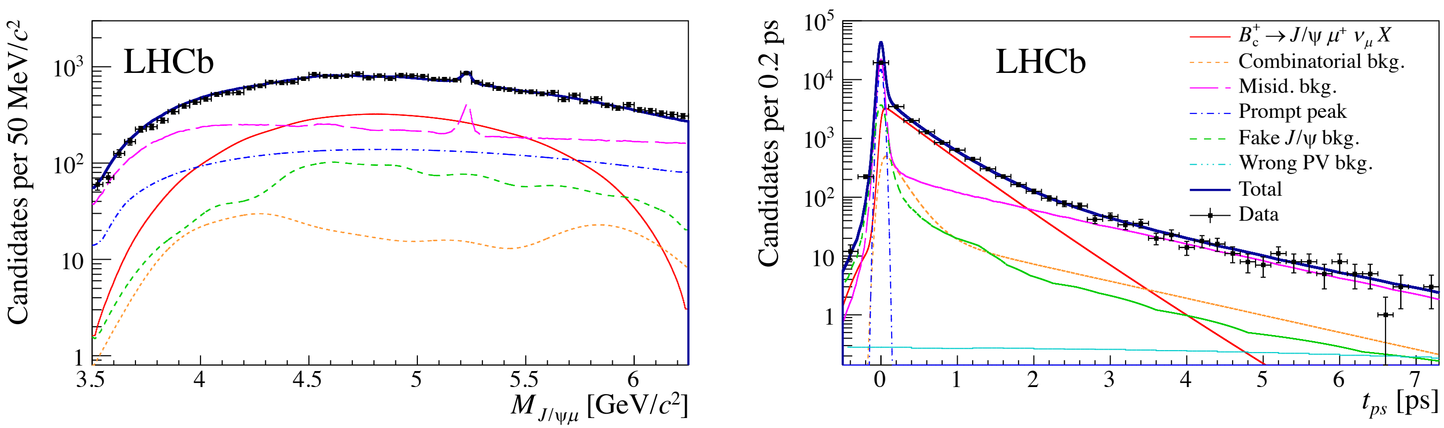
B_c^+ lifetime

- $B_c^+ \to J/\psi\pi^+, \quad \tau = 513 \pm 11 \pm 6$ fs



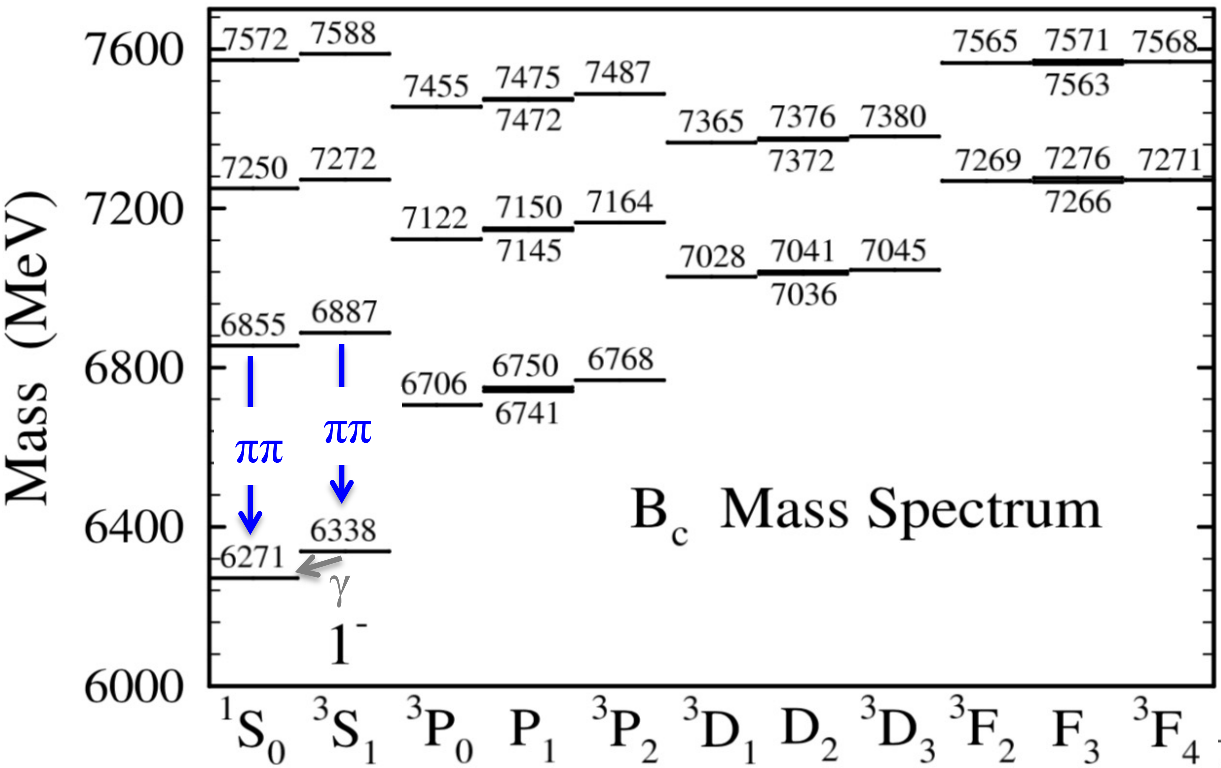
[PLB 742 (2015) 39]

- $B_c^+ \to J/\psi\mu^+X, \ \tau = 509 \pm 8 \pm 12$ fs



Excited B_c^+ states

- B_c has a rich spectrum



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

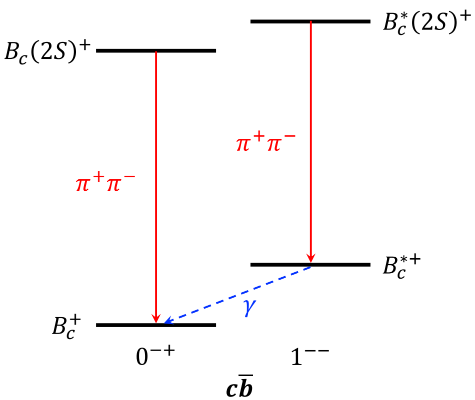
State	Decay	GKLRY *	Godfrey †
1^3S_1	$1^1S_0+\gamma$	100	100
1^3P_2	$1^3S_1+\gamma$	100	100
$1P_1'$	$1^3S_1+\gamma$	6	12.1
	$1^1S_0+\gamma$	94	87.9
$1P_1$	$1^3S_1+\gamma$	87	82.2
	$1^1S_0+\gamma$	13	17.8
1^3P_0	$1^3S_1+\gamma$	100	100
2^1S_0	$1^1S_0+\pi\pi$	74	88.1
	$1P_1'+\gamma$		9.4
	$1P_1+\gamma$		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]

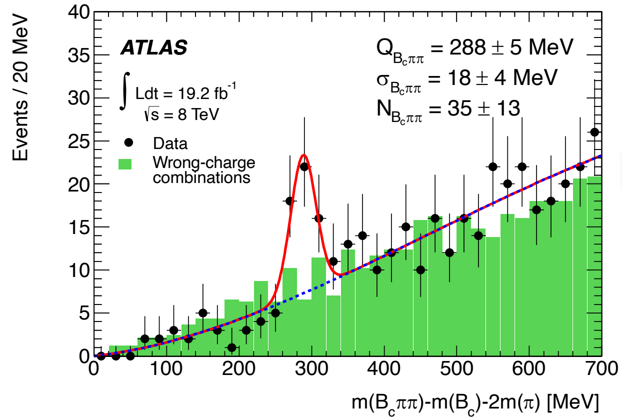
† [S.Godfrey, PRD 70 (2004) 054017]

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

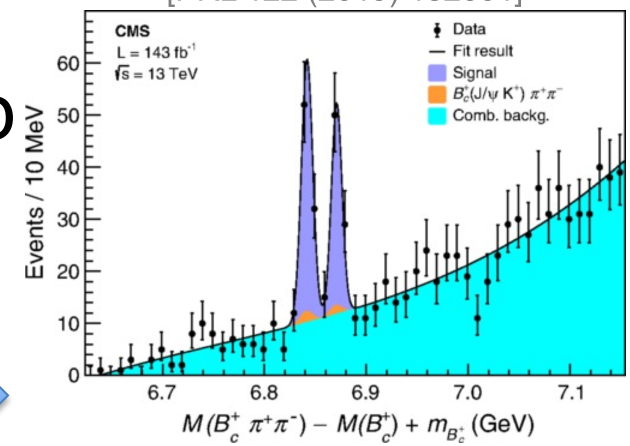
- Mixture (?) by ATLAS, then both states by CMS and LHCb

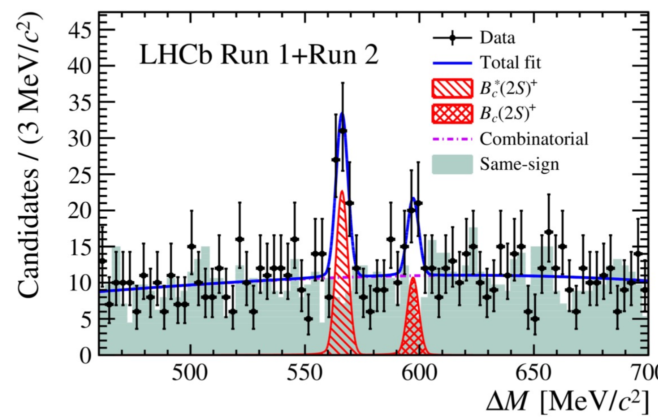


[PRL 113 (2014) 212004]



[PRL 122 (2019) 132001]





[PRL 122 (2019) 232001]

LHCb

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

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

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

CMS

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

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

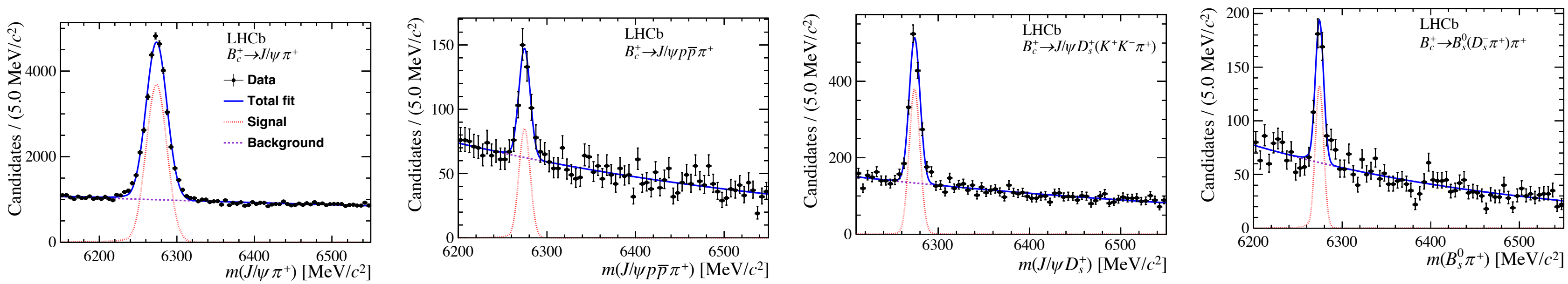
$$M(B_c(2S)^+) - M(B_c^*(2S)^+)_{\rm rec} = 29.0 \pm 1.5({\rm stat}) \pm 0.7({\rm syst})\ {\rm MeV}/c^2$$

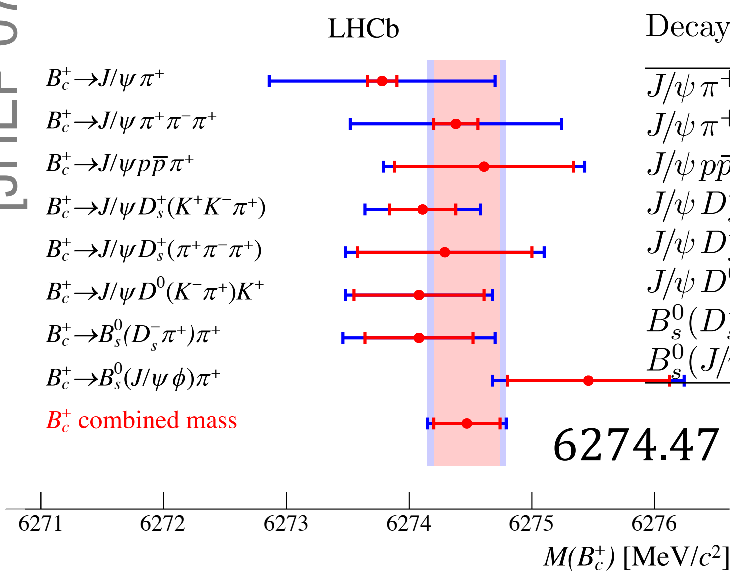
UROP

B_c^+ mass measurement

- Six decay modes, with all Run1+2 data, precision improved by a factor of 2

[JHEP 07 (2020) 123]





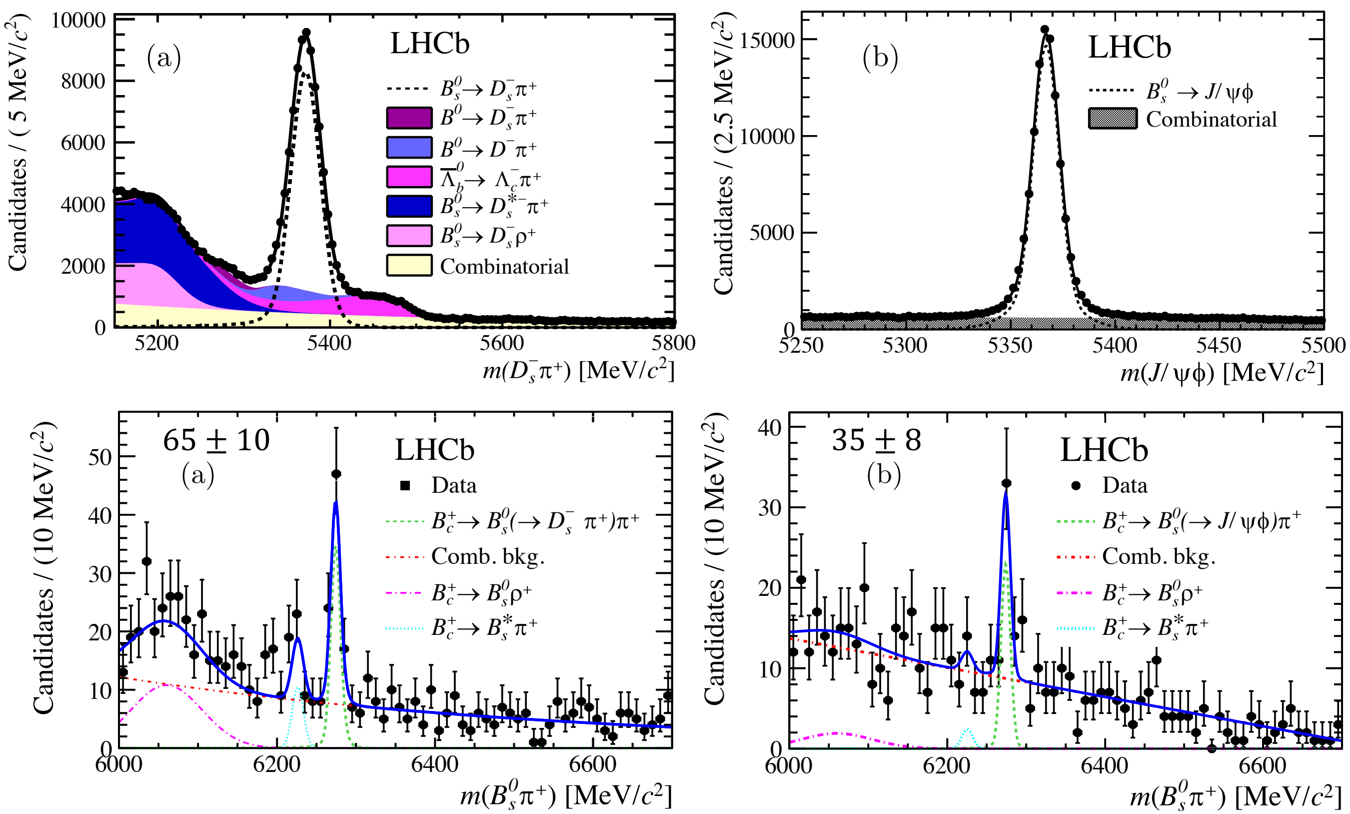
Decay mode	Yield	Fitted mass [MeV/c^2]	Corrected mass [MeV/c^2]	Resolution [MeV/c^2]
$J/\psi\,\pi^+$	25181 ± 217	6273.71 ± 0.12	6273.78 ± 0.12	13.49 ± 0.11
$J/\psi\,\pi^+\pi^-\pi^+$	9497 ± 142	6274.26 ± 0.18	6274.38 ± 0.18	11.13 ± 0.18
$J/\psi\, p\bar{p}\pi^+$	273 ± 29	6274.66 ± 0.73	6274.61 ± 0.73	6.34 ± 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

$6274.47 \pm 0.27 \pm 0.17$ MeV, taken as WA by PDG

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

- Observed w/ Run1 data, production ratio for $\eta \in [2, 5]$

$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \cdot \mathcal{B}(B_c^+ \to B_s^0 \pi^+) = \left(2.37 \pm 0.31 \pm 0.11^{+0.17}_{-0.13}\,(\tau_{B_c})\right) \times 10^{-3}$$



[PRL 111 (2013) 181801]

UROP

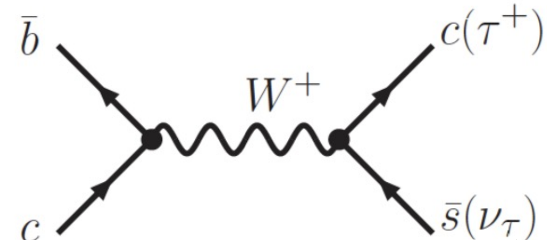
$\mathcal{B}(B_c^+ \to B_s^0 \pi^+)$

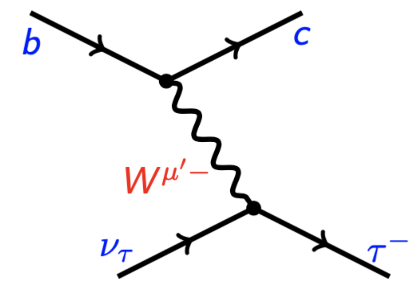
[JHEP 07 (2023) 066]

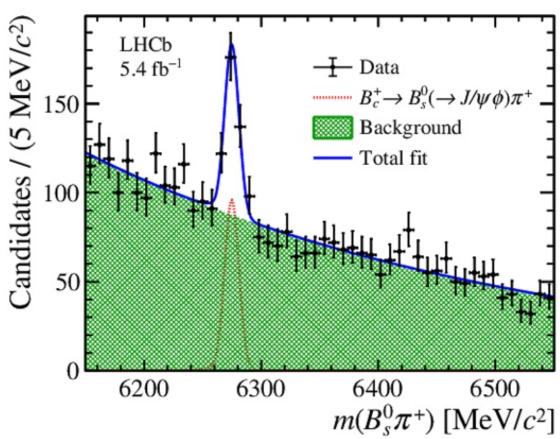
- Measured w/ Run2 data, helps constrain $\Gamma(b \to c\tau\nu)$

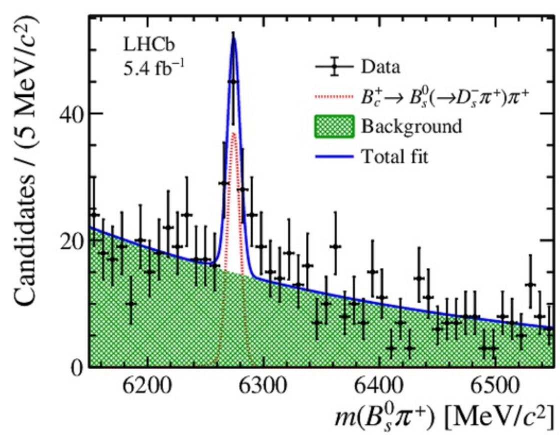
$$\frac{\mathcal{B}(B_c^+ \to B_s^0 \pi^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = 91 \pm 13$$

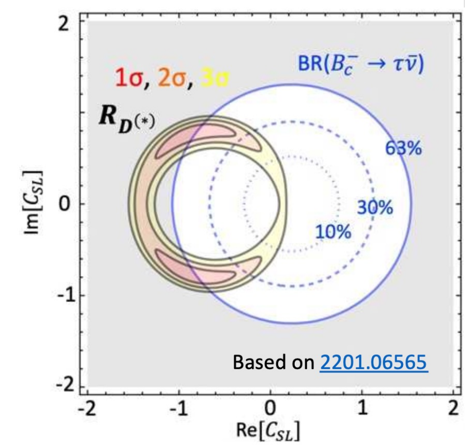
$\Longrightarrow \mathcal{B}(B_c^+ \to B_s^0 \pi^+)$ is 8% - 30% depending on $\mathcal{B}(B_c^+ \to J/\psi \pi^+)$







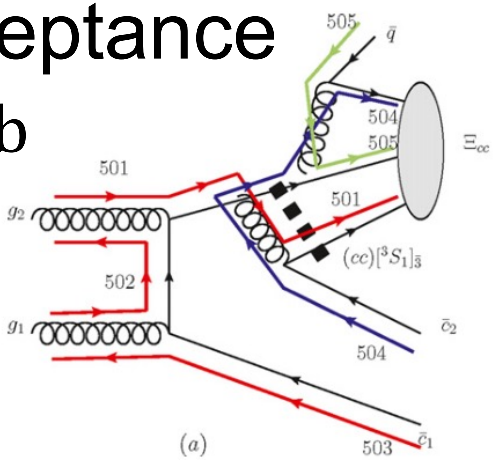




Credit: R. Watanabe

Doubly heavy baryons

- Production @ 13 TeV, in LHCb acceptance
  - $\sigma(\Xi_{cc}^{++}) = \sigma(\Xi_{cc}^{+})$~40 nb, $\sigma(\Omega_{cc}^{+})$~13 nb
  - $\sigma(\Xi_{bc}^{+}) = \sigma(\Xi_{bc}^{0})$~17 nb, $\sigma(\Omega_{bc}^{0})$~5 nb

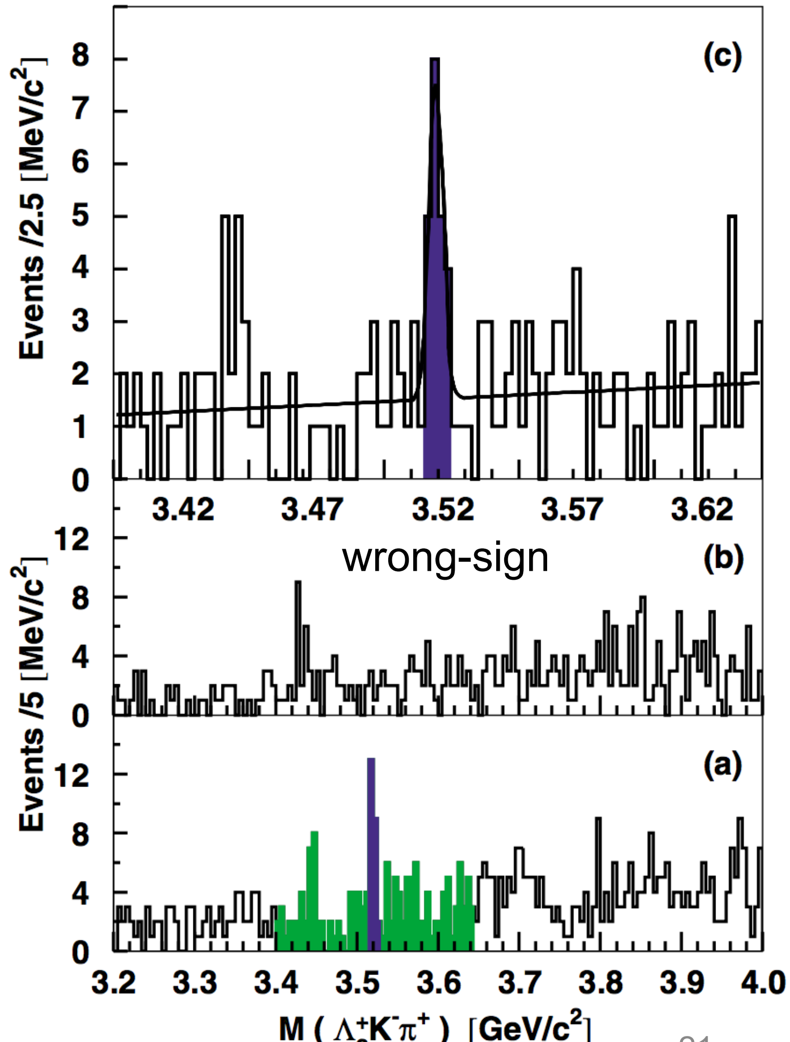


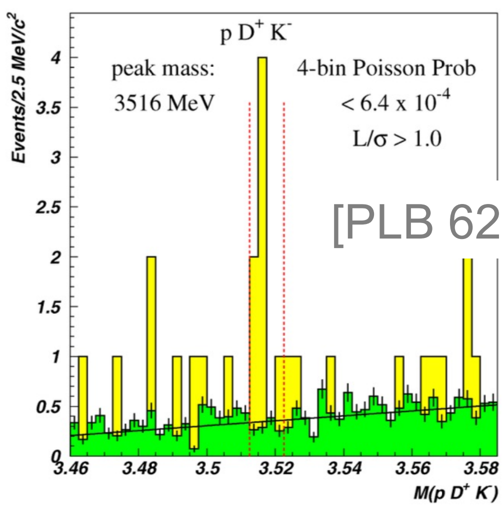
- Mass
  - $M(\Xi_{cc}^{+}) \approx M(\Xi_{cc}^{++})$: 3.5-3.7 GeV, $M(\Omega_{cc}^{+})$, +0.1-0.2 GeV
  - $M(\Xi_{bc}^{+}) \approx M(\Xi_{bc}^{0})$: 6.8-7.1 GeV, $M(\Omega_{bc}^{0})$, +0.05-0.1 GeV
- Lifetime
  - $\tau(\Xi_{cc}^{+}) \approx \tau(\Omega_{cc}^{+}) \approx \frac{1}{3}\tau(\Xi_{cc}^{++})$, $\tau(\Xi_{cc}^{++})$: 0.2-1.05 ps
  - Ξ_{bc}^{+}, Ξ_{bc}^{0}, Ω_{bc}^{0}: 0.1-0.5 ps

Ξ_{cc}^{+} @ SELEX

- SELEX claimed $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ (6.3σ)
  - M, 3519±1 MeV
  - τ, <33 fs @90%CL
  - σ_{prod}, 20% Λ_c^{+} from Ξ_{cc}^{+}
- Also $\Xi_{cc}^{+} \to p D^{+} K^{-}$

[PRL 89 (2002) 112001]

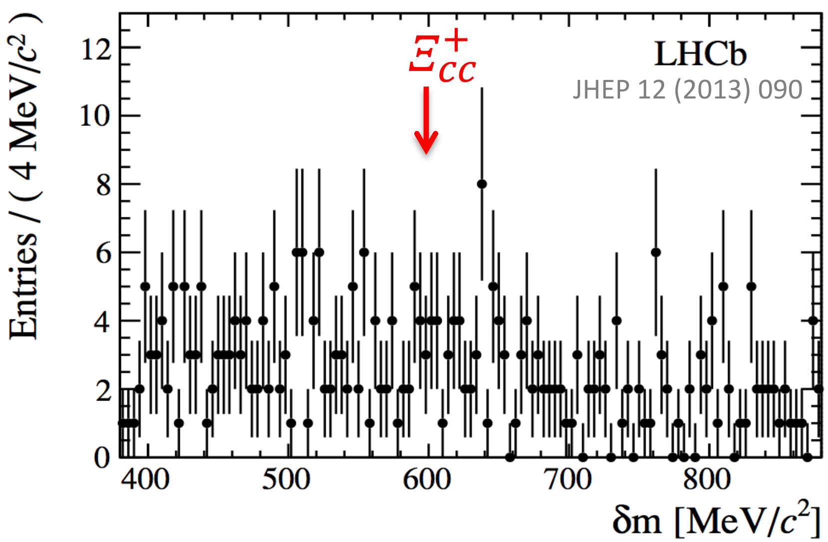


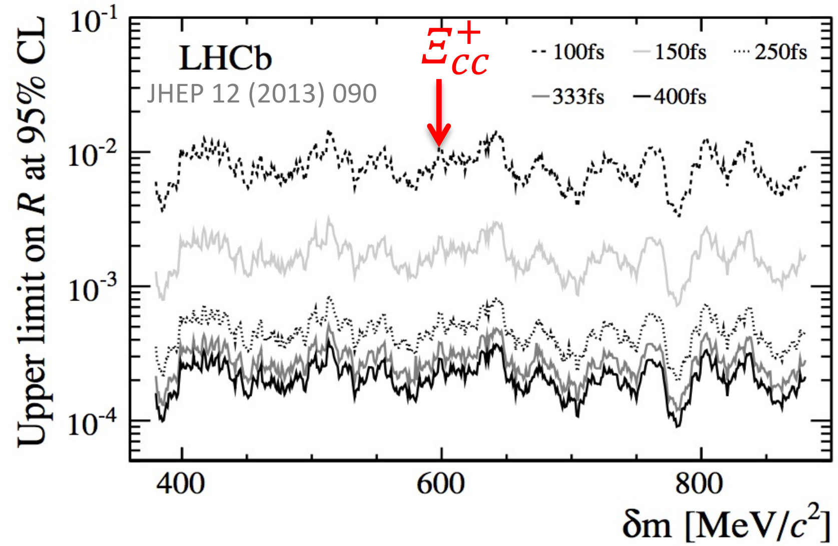


[PLB 628 (2005)18]

Ξ_{cc} @ LHCb & others

- SELEX results not confirmed by FOCUS, Babar, Belle & LHCb
- $\Xi_{cc}^{+} \rightarrow \Lambda_{c}^{+} K^{-} \pi^{+}$ searched by LHCb w/ 2011 data

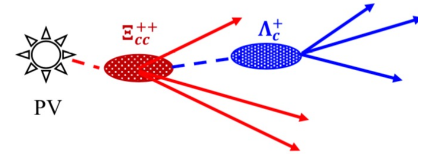


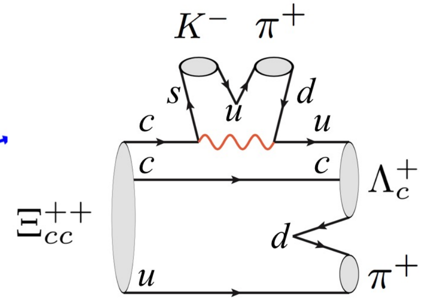


- However, LHCb already had lots of B_{c}^{+} events, and double-charm events…

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

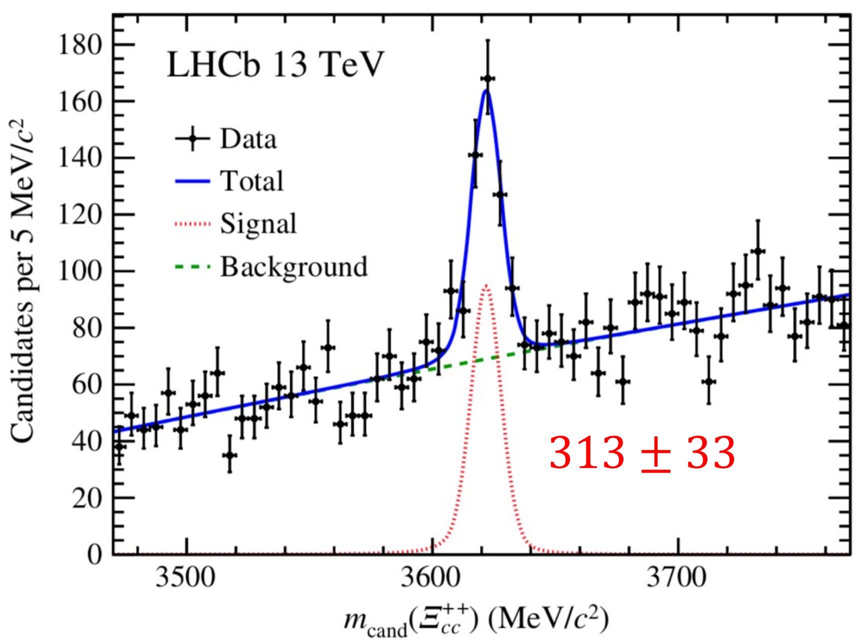
- $\Lambda_c^+ K^- \pi^+ \pi^+$ identified as the most promising channel

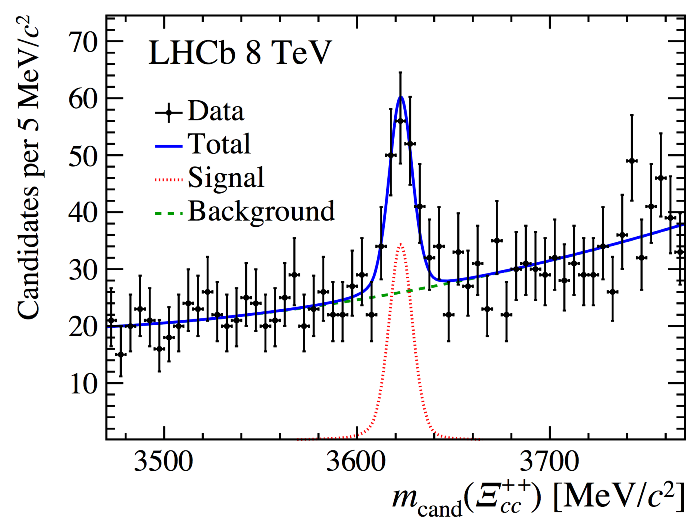




[F.-S. Yu *et al.*, CPC 42 (2018) 051001]

- First observation, in 2016 (>12σ) & Run-I (>7σ)





[PRL 119 (2017) 112001]

Ξ_{cc}^{++} properties

- Ξ_{cc}^{++} mass measured:

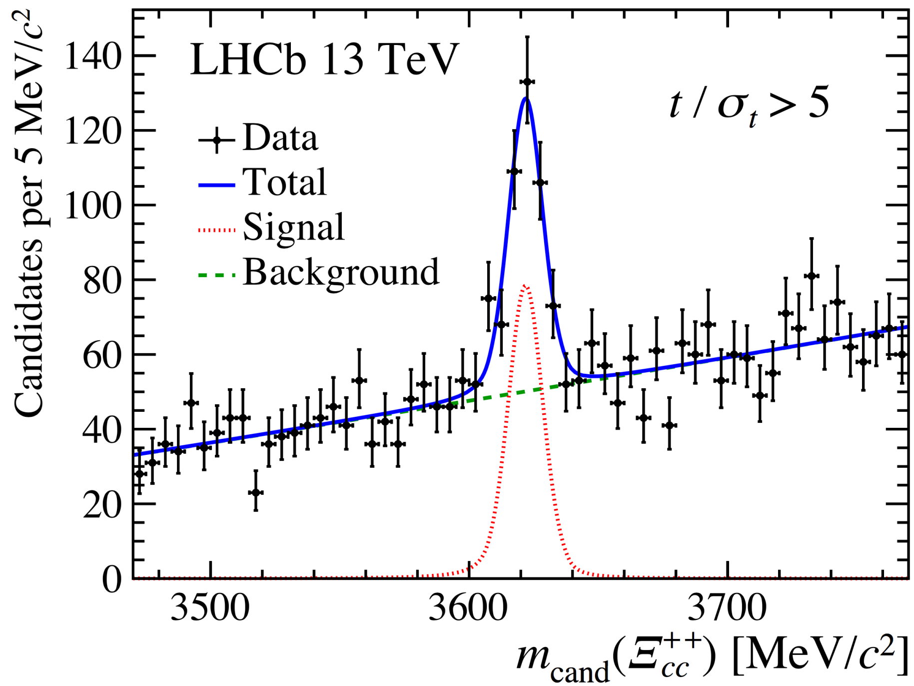
$3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$

SELEX: $M(\Xi_{cc}^{+})$=3519±1 MeV

Isospin partner?

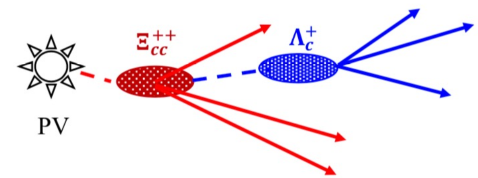
- Decay weakly, mass peak remains after lifetime cut

$\Longrightarrow$Measurement of $\tau(\Xi_{cc}^{++})$ needed

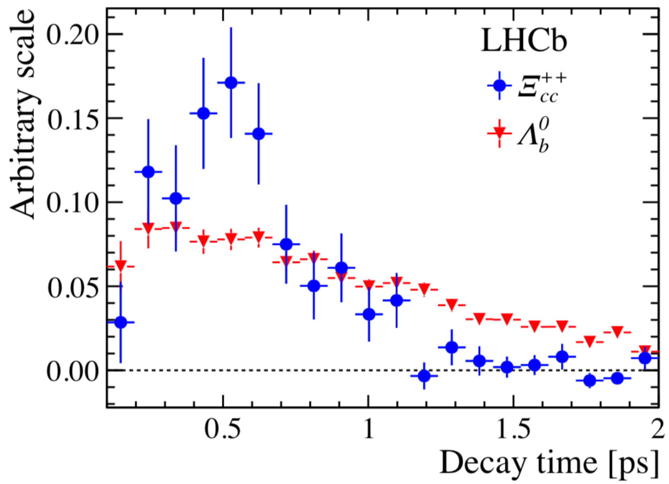


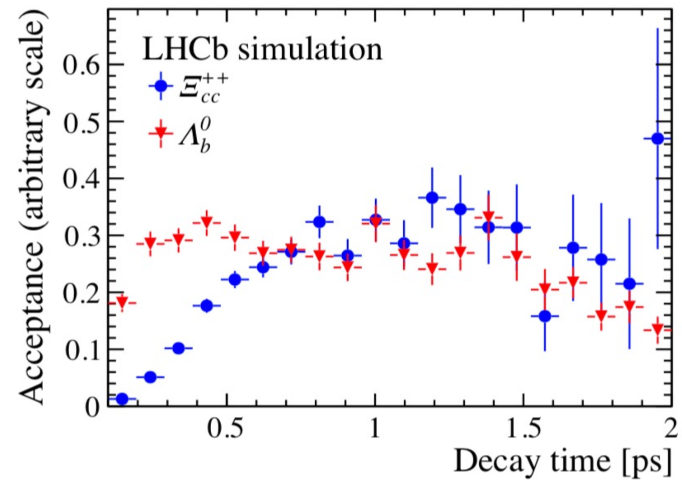
[PRL 119 (2017) 112001]

Ξ_{cc}^{++} lifetime



- Control mode, $\Lambda_b^0 \to \Lambda_c^+ 3\pi$

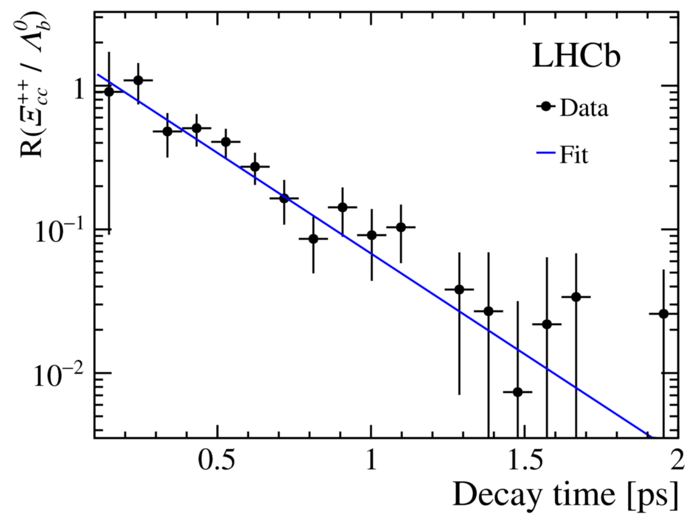




- $\tau(\Xi_{cc}^{++})$
  $= 0.256^{+0.024}_{-0.022} \pm 0.014$ ps

  at lower side prediction: 0.2-1.05ps

- Weakly decay nature established!



[PRL 121 (2018) 052002]

Observation of $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

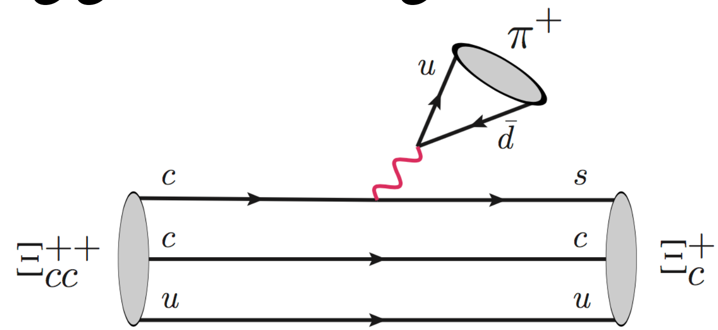
[PRL 121 (2018) 162002]

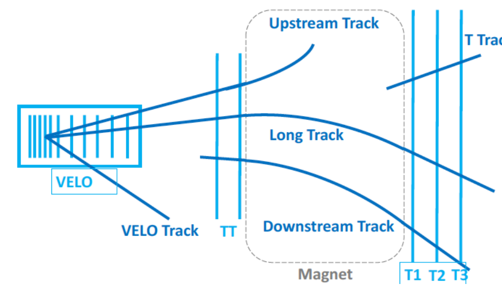
- $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ expected to have large BR

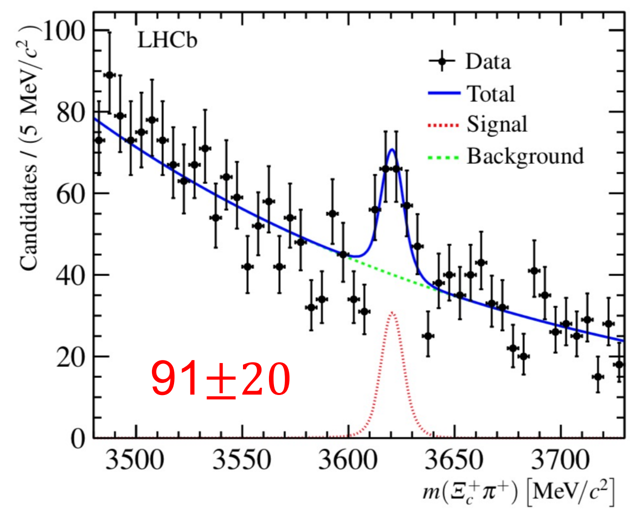
  [F.-S. Yu *et al.*, CPC 42 (2018) 051001]

- Re-discovery with 2016 data, 5.9σ
- BR ratio measured

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \cdot \mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+) \cdot \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}$$
$$= 0.035 \pm 0.009 \pm 0.003$$





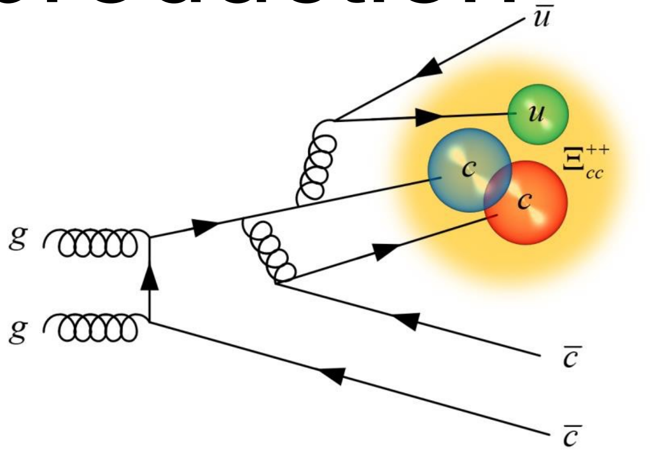


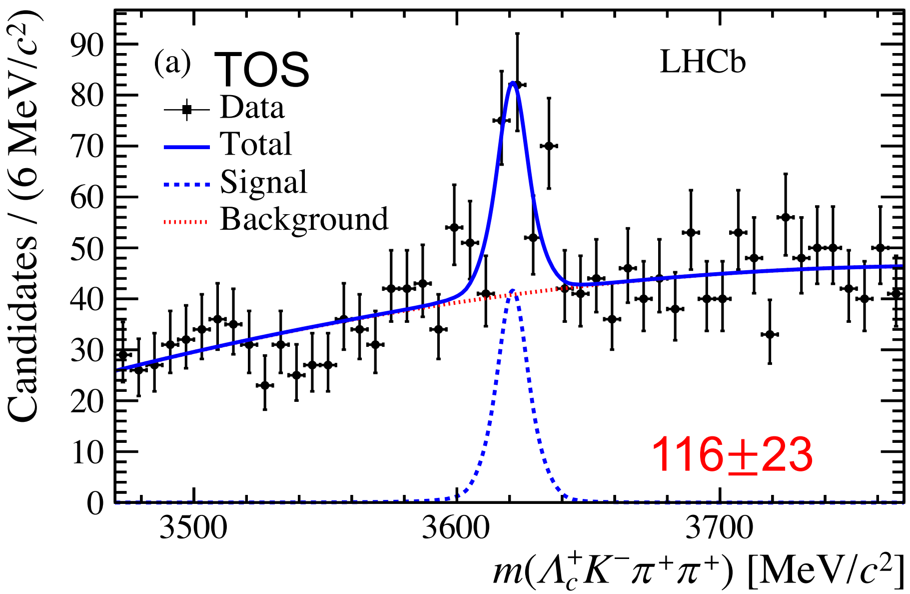
Measurement of Ξ_{cc}^{++} production

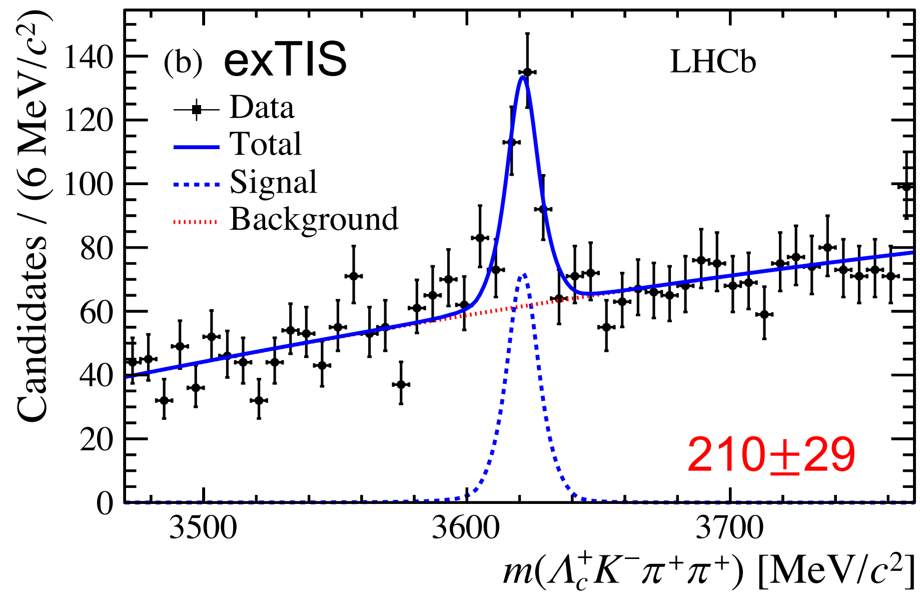
- Measured w/ 2016 data

$$N = \sigma_{\text{prod}} \cdot \mathcal{L} \cdot \mathcal{B} \cdot \varepsilon, \qquad \sigma_{\text{prod}} \cdot \mathcal{B} = \frac{N}{\varepsilon \mathcal{L}}$$

- Accompanying $\bar{c}\bar{c}$ dominates in trigger



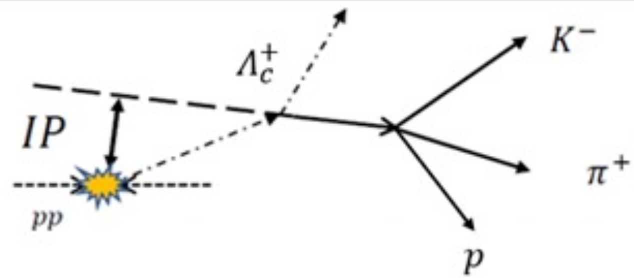


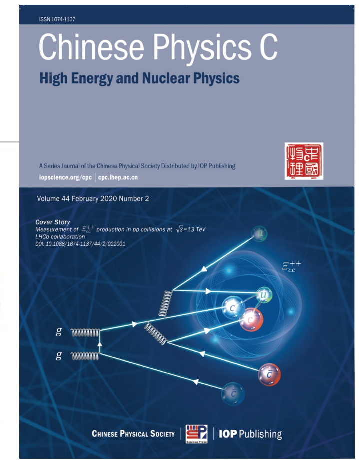


Measurement of Ξ_{cc}^{++} production

[CPC 44 (2020) 022001]

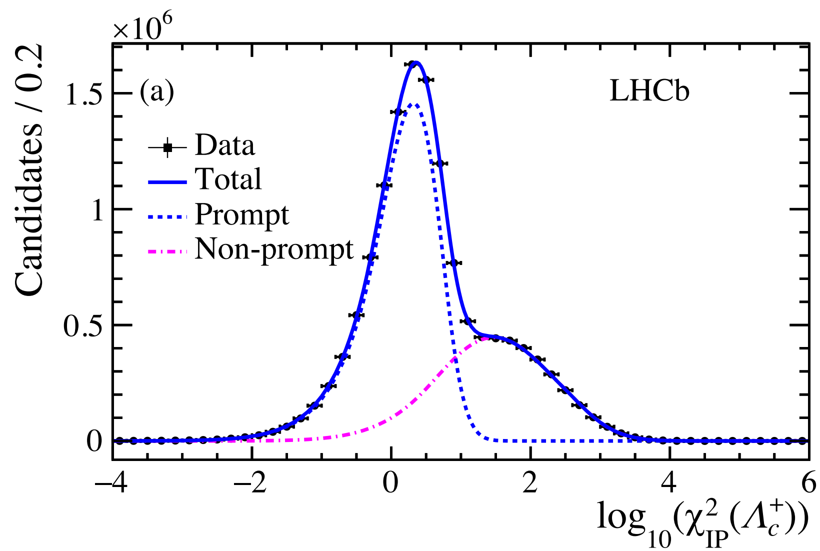
- Relative to Λ_c^+, in
  $4 < p_{\mathrm{T}} < 15$ GeV,
  2<y<4.5





$$\frac{\sigma(\Xi_{cc}^{++})}{\sigma(\Lambda_c^+)}\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)$$
$$= (2.22 \pm 0.27 \pm 0.29)\times 10^{-4}$$

SELEX, 20% Λ_c^+ from Ξ_{cc}^+?

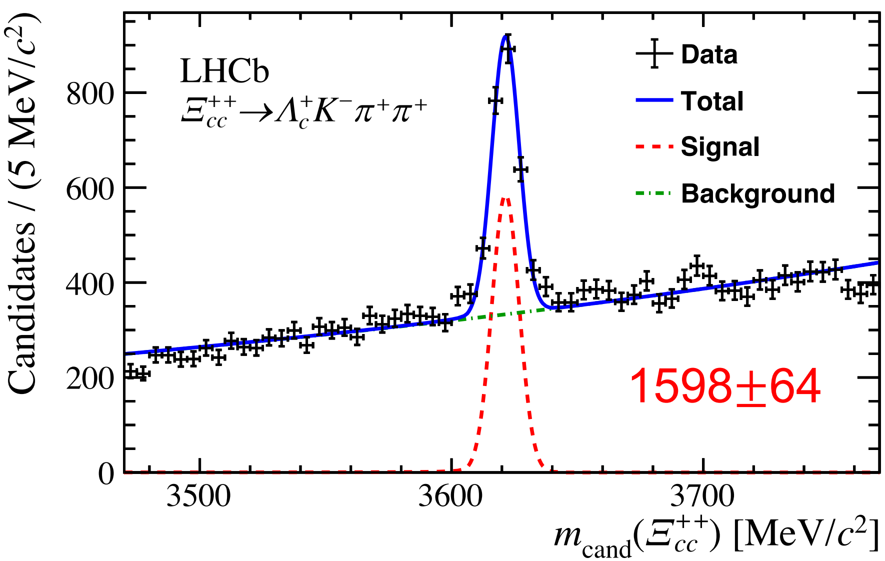


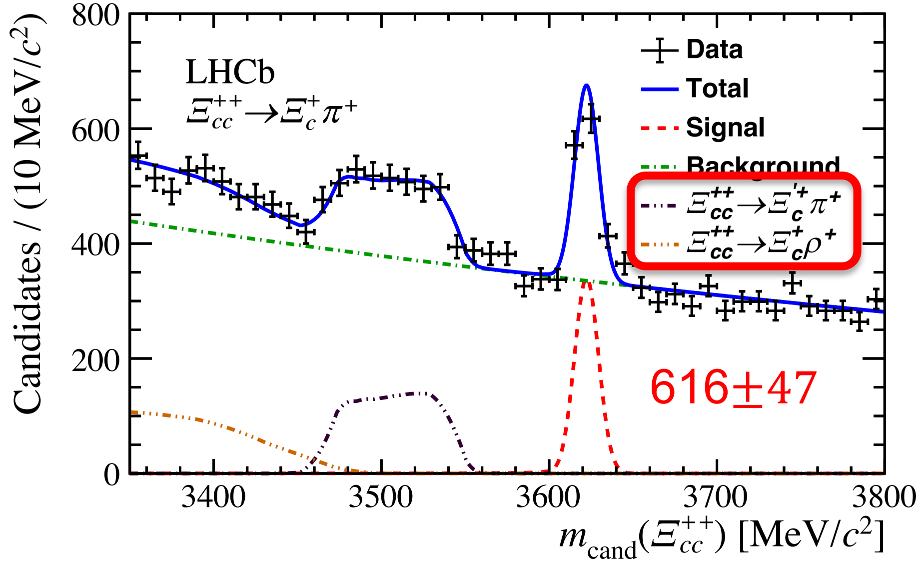
UROP

Precision measurement of $m(\Xi_{cc}^{++})$

- Preparing to search for excited states, event-selection re-optimised

[JHEP 02 (2020) 049]



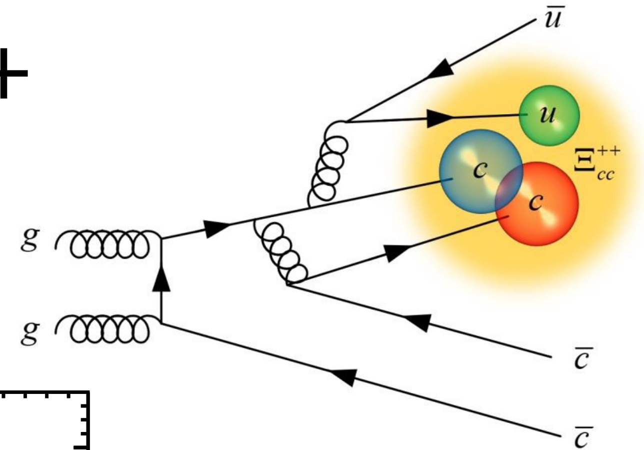


$$m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23 \pm 0.30 \text{ MeV}/c^2$$

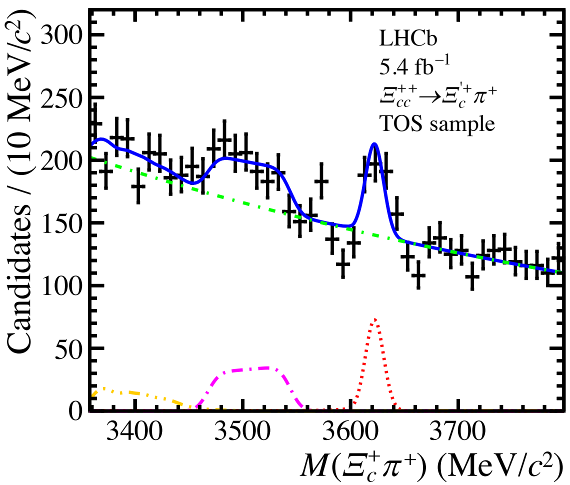
c.f., $3620.6 \pm 0.65 \pm 0.31 \text{ MeV}/c^2$

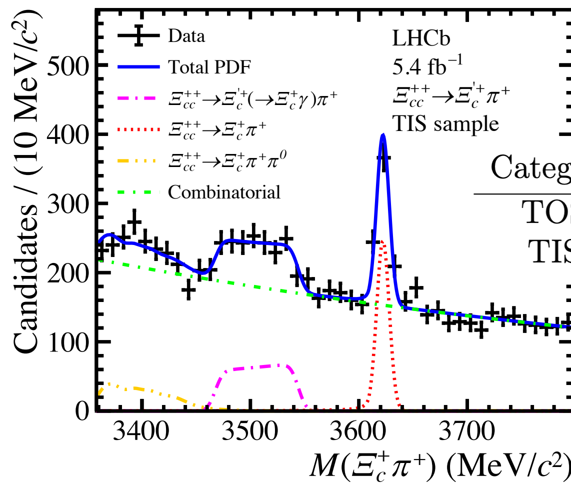
$\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+$

[JHEP 05 (2022) 038]



- 2016-2018 data, $\Xi_{cc}^{++} \to \Xi_c'^{+}(\to \Xi_c^{+}\gamma)\pi^+$





Category	$\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+$	$\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+$
TOS	262 ± 53	159 ± 32
TIS	494 ± 63	379 ± 32

- Branching fraction ratio

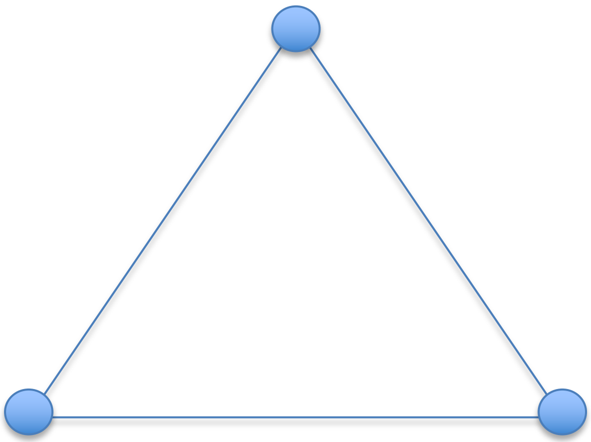
$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+)} = 1.41 \pm 0.17 \pm 0.10$$

  – some tension with existing predictions

Summary of DHB studies

First search, Hint[SCPMA 64 (2021) 101062]

$\Omega_{cc}^{+}\ (ccs)$



$\Xi_{cc}^{++}\ (ccu)$

Observation[PRL 119 (2017) 112001]

Mass[JHEP 02 (2020) 049]

Lifetime[PRL 121 (2018) 052002]

Production[CPC 44 (2020) 022001]

Decay $\Xi_c^{+}\pi^{+}$ [PRL 121 (2018) 162002]

$\Xi_c'^{+}\pi^{+}$ [JHEP 05 (2022) 038]

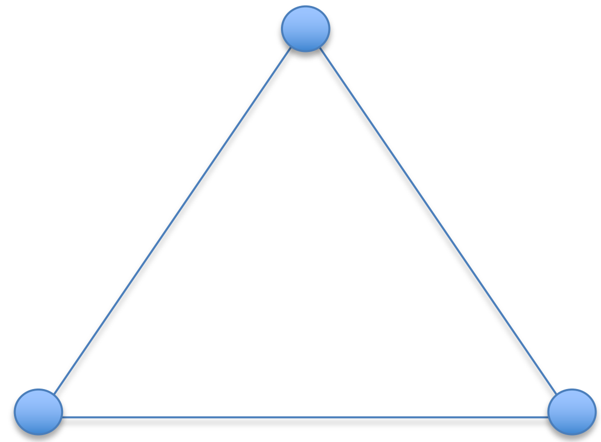
$\Xi_{cc}^{+}\ (ccd)$

Hint/Evidence

[SCPMA 63 (2020) 221062, JHEP 12 (2021) 107]

First search[CPC 45 (2021) 093002]

$\Omega_{bc}^{0}\ (bcs)$



$\Xi_{bc}^{+}\ (bcu)$

First search

Hint

[CPC 47 (2023) 093001]

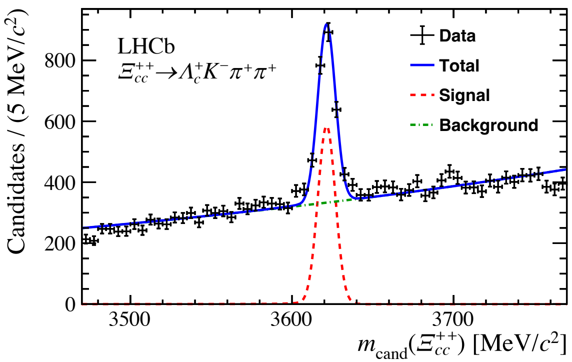
$\Xi_{bc}^{0}\ (bcd)$

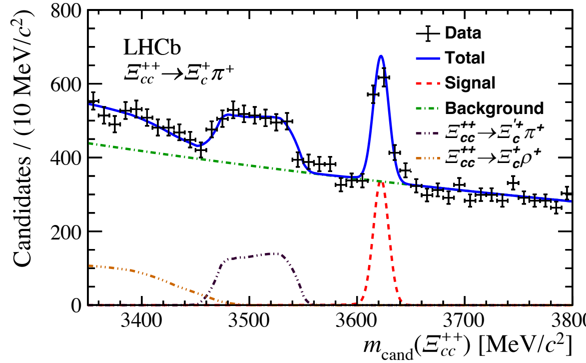
First search

[JHEP 11 (2020) 095]

Summary of DHB studies

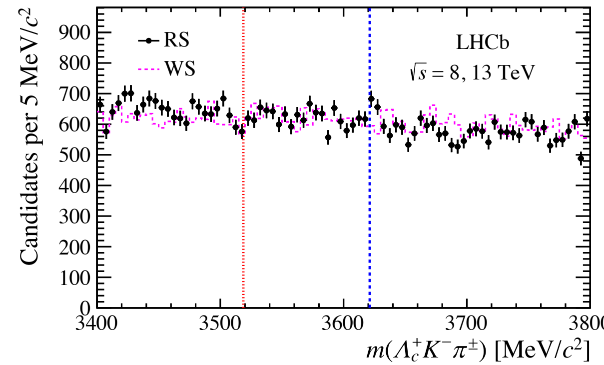
$\Xi_{cc}^{++}(ccu)$





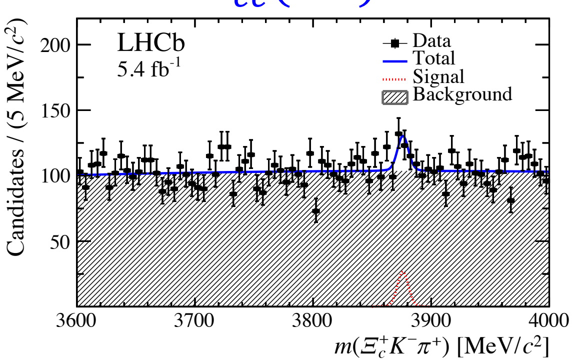
PRL 119 (2017) 112001, PRL 121 (2018) 052002, PRL 121 (2018) 162002, CPC 44 (2020) 022001, JHEP 02 (2020) 049, JHEP 05 (2022) 038

$\Xi_{cc}^{+}(ccd)$



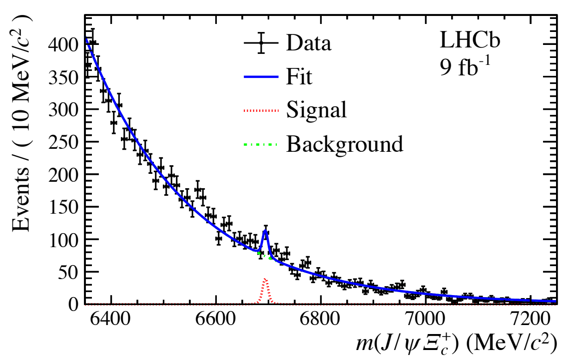
SCPMA 63 (2020) 221062

$\Omega_{cc}^{+}(ccs)$



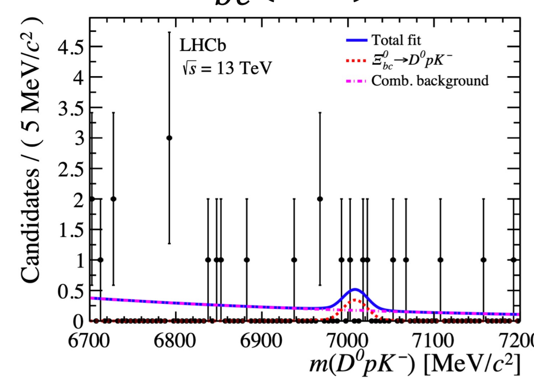
SCPMA 64 (2021) 101062

$\Xi_{bc}^{+}(bcu)$



CPC 47 (2023) 093001

$\Xi_{bc}^{0}(bcd)$



JHEP 11 (2020) 095

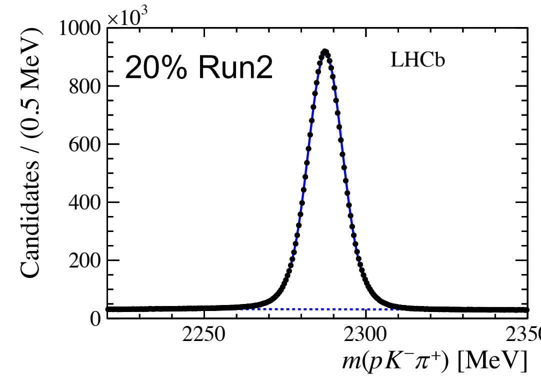
UROP

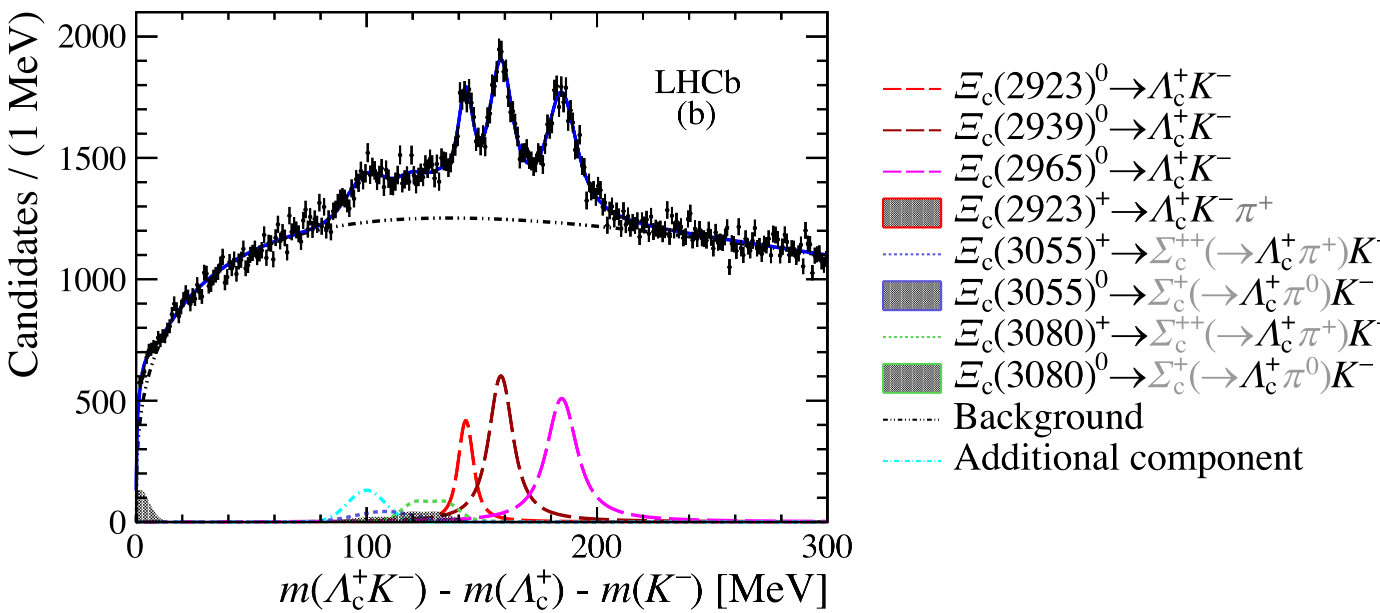
Excited Ξ_c^0 states

(csd)

[PRL 124 (2020) 222001]

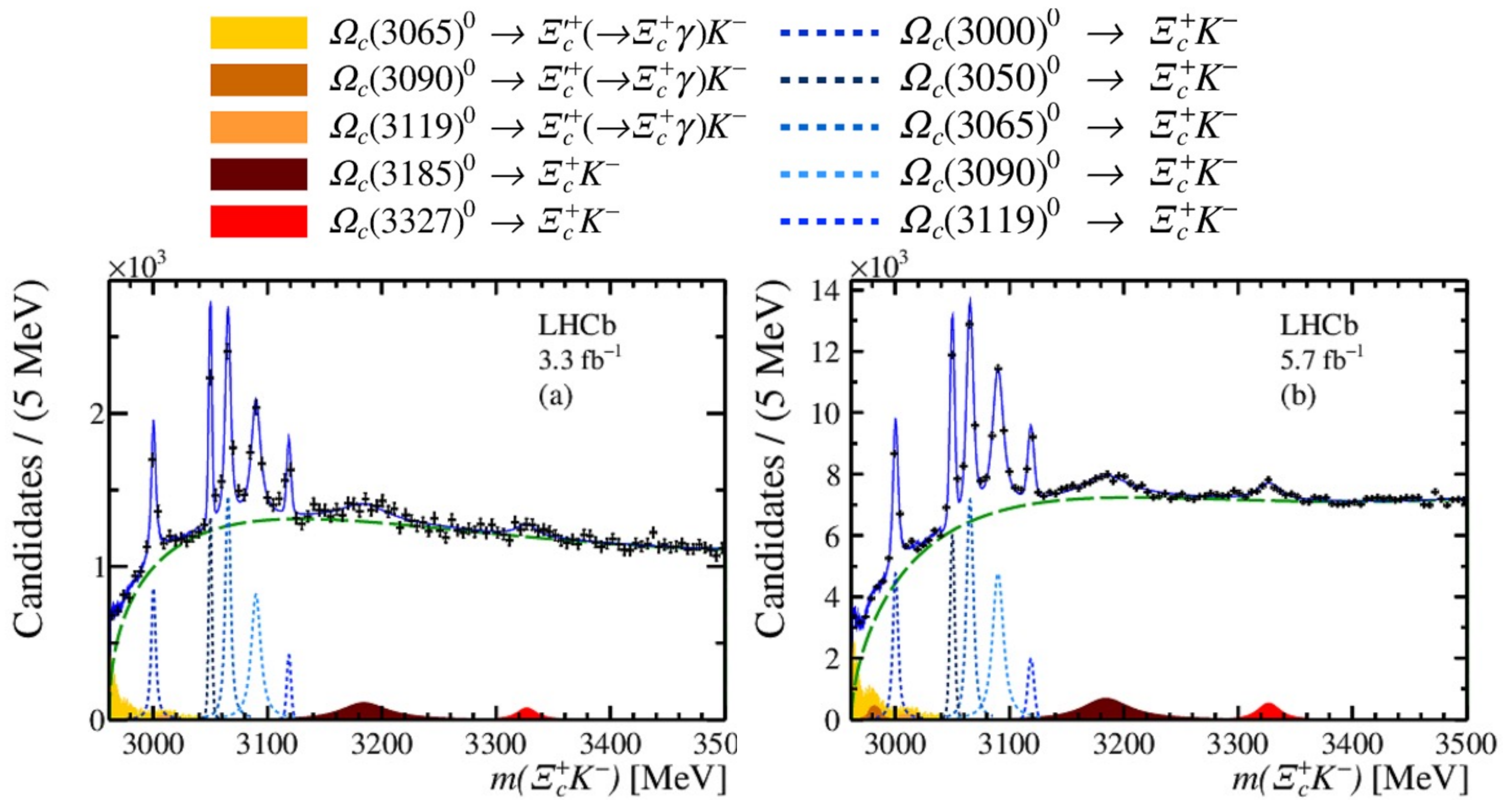
- Lots of singly charmed baryons
- New excited Ξ_c^0 states in $m(\Lambda_c^+ K^-)$





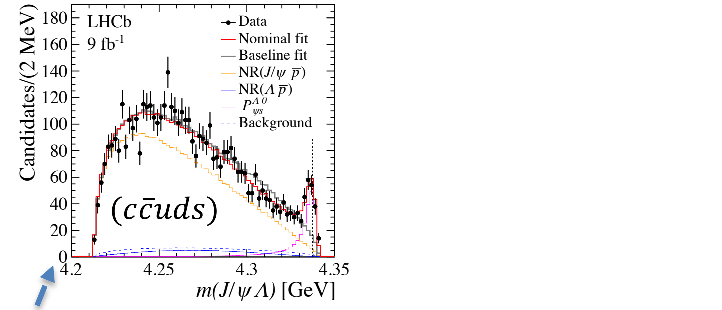
Two new charmed hadrons

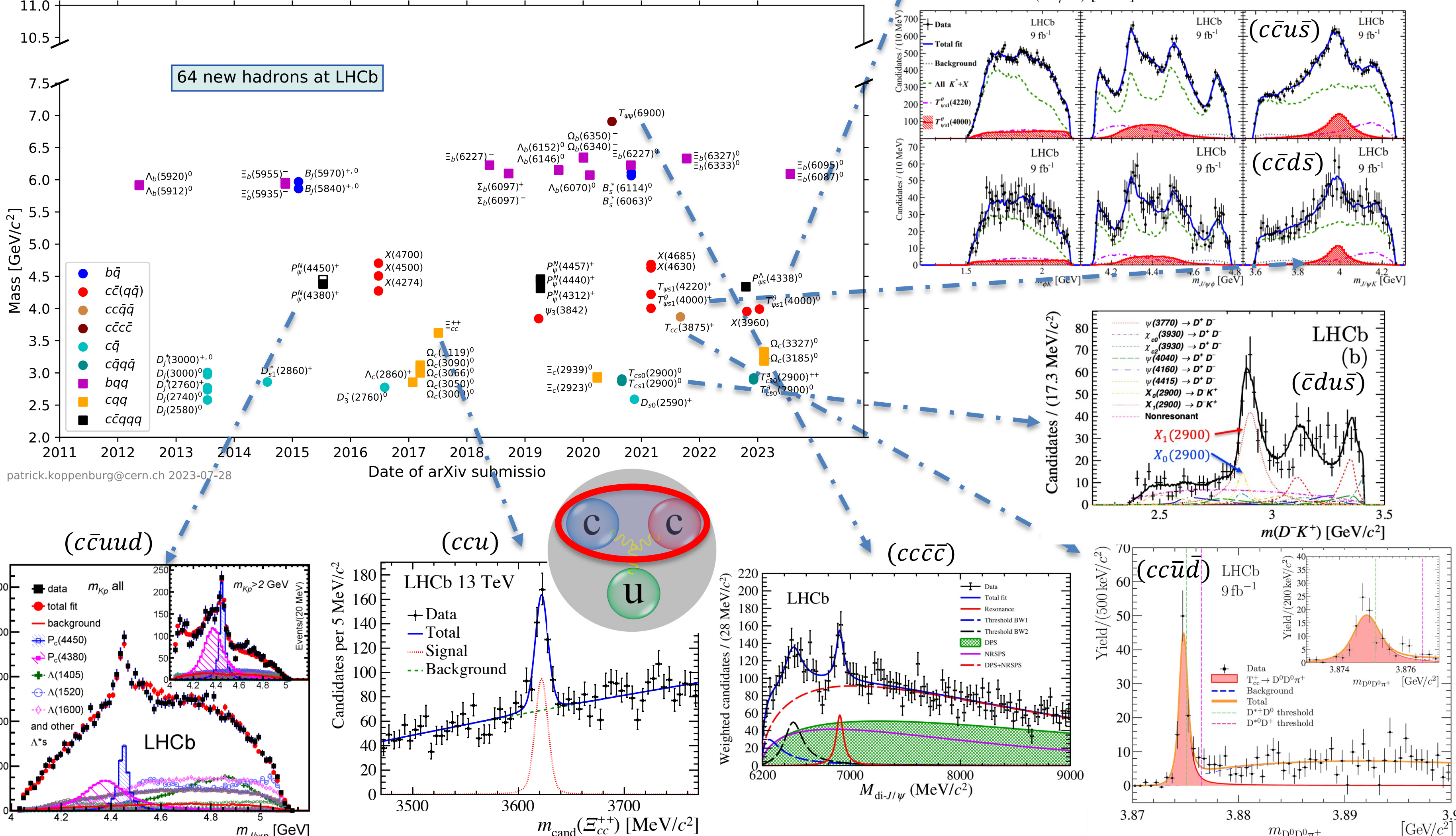
- Five states observed in $m(\Xi_c^+ K^-)$ in 2017, two new $\Omega_c(3185)^0, \Omega_c(3327)^0$ in 2023, nature unclear
  - Excited Ω_c^0 (css), molecular, pentaquark $(cssq\bar{q})$?



[PRL 131 (2023) 131902]

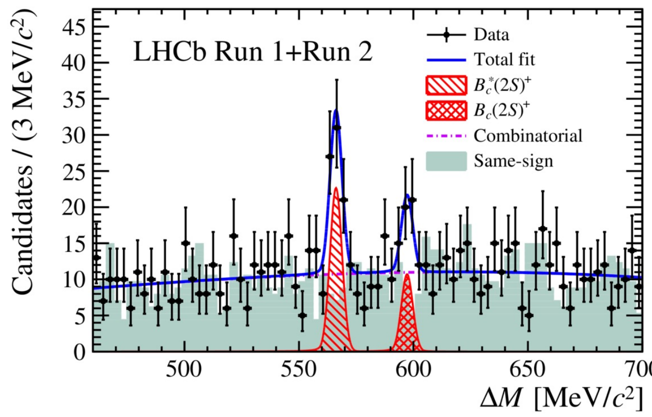
Spectroscopy at LHCb

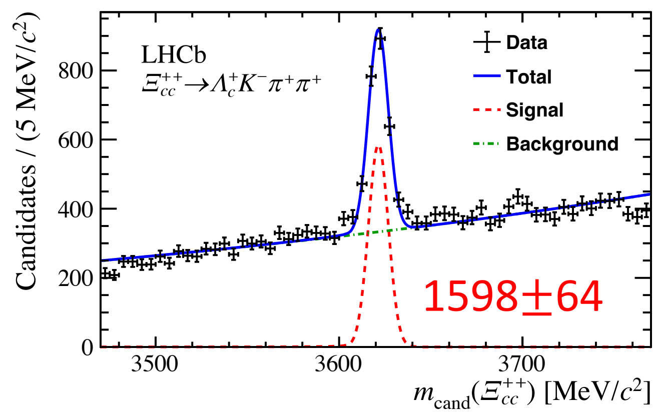




Summary

- Great progress on the study of doubly heavy hadrons
- B_c^+ physics
  - Production, mass, lifetime
  - $B_c^+ \to B_s^0 \pi^+$, …
- Doubly heavy baryons
  - Ξ_{cc}^{++}, first observation
  - $\Xi_{cc}^{+}, \Omega_{cc}^{+}$ on horizon





Your strong & continued supports always appreciated!