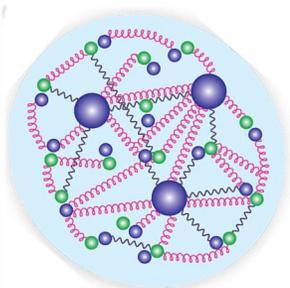


LHC实验上 重味强子激发态 的研究进展



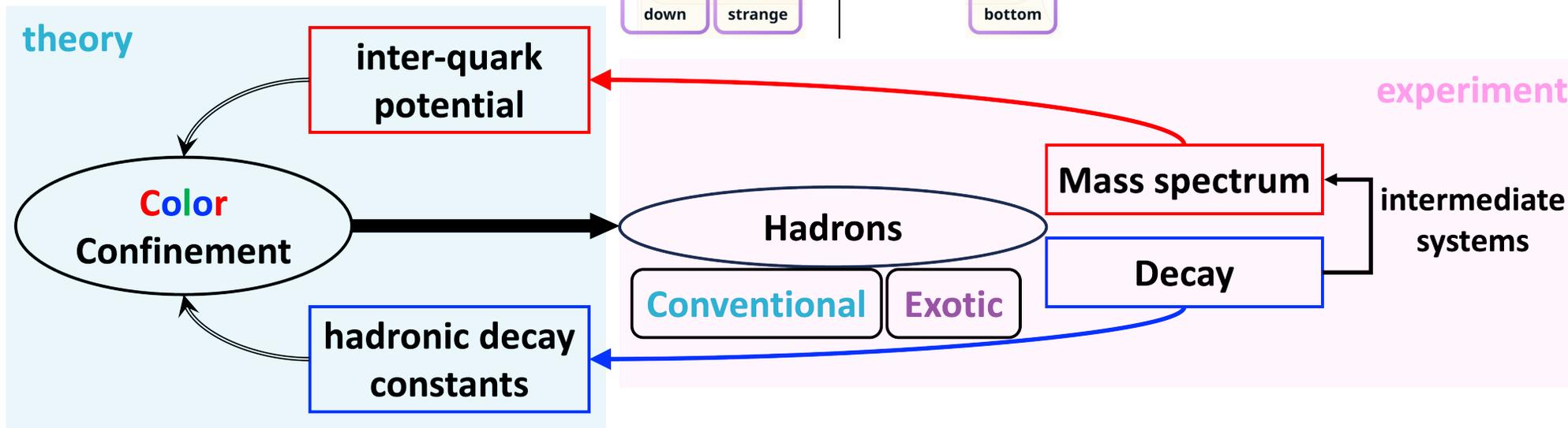
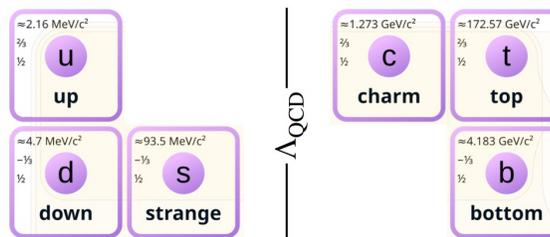
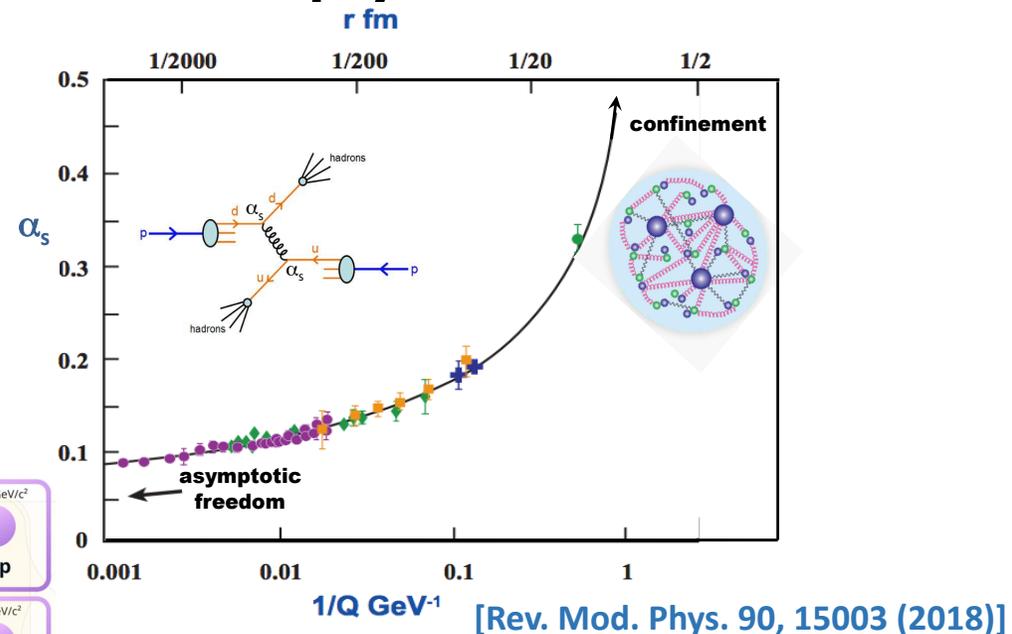
安刘攀
北京大学



味物理前沿研讨会暨味物理讲座100期特别活动 @ 三亚, 2026.01.30-02.04

QCD and hadron spectroscopy

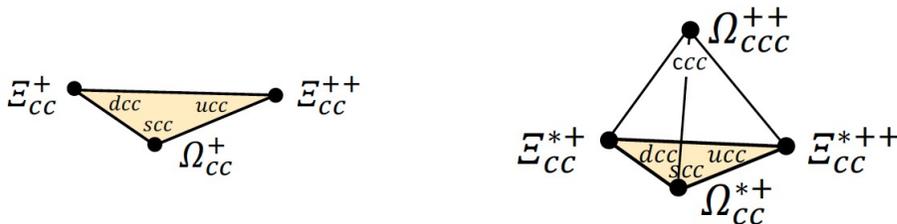
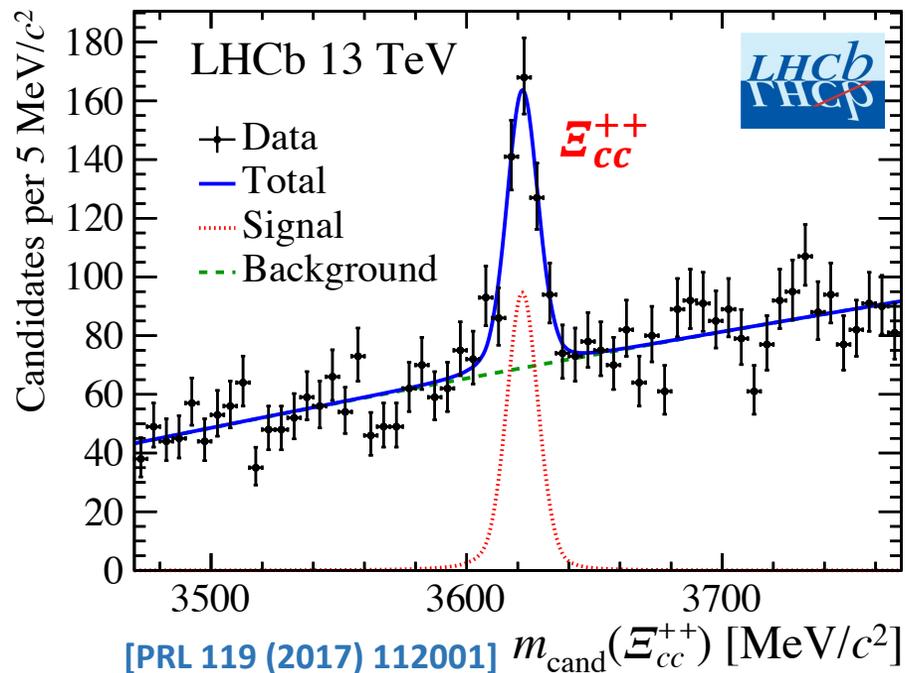
- **QCD dilemma:** understanding the non-perturbative property of QCD at low-energy scale
 - ✓ There are no rigorous, first-principle treatments except **Lattice QCD**, whose application is yet limited
- **Color confinement:** no analytic proof exists



Conventional hadron spectroscopy

➤ Hadron map far from complete

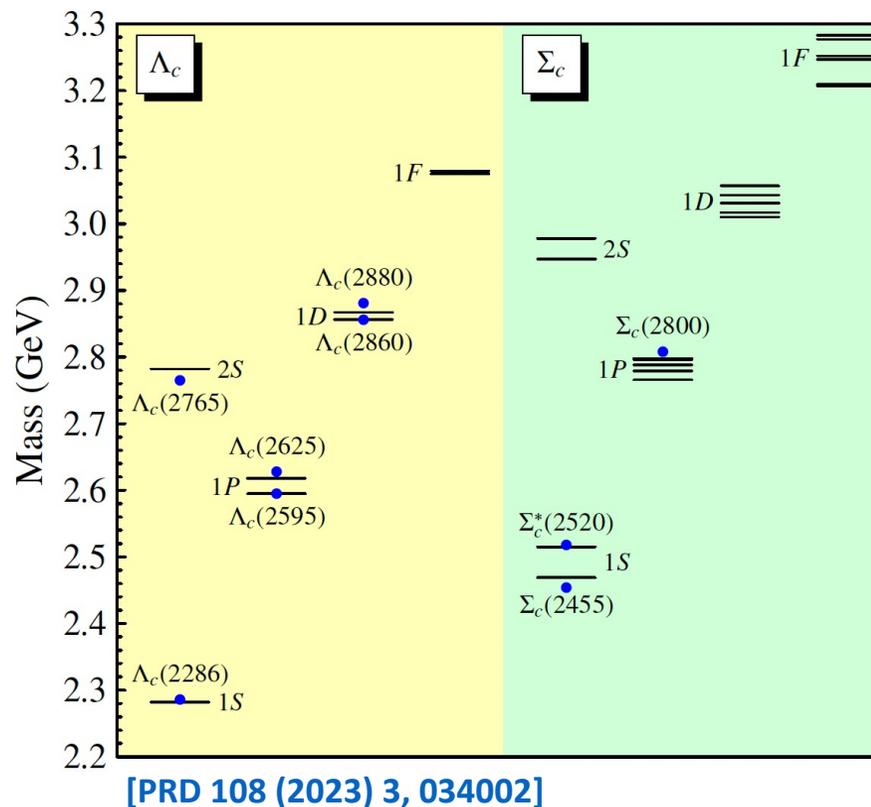
✓ Ξ_{cc}^{++} : the only doubly heavy baryon seen



➤ Excited states of existing hadrons still under exploration

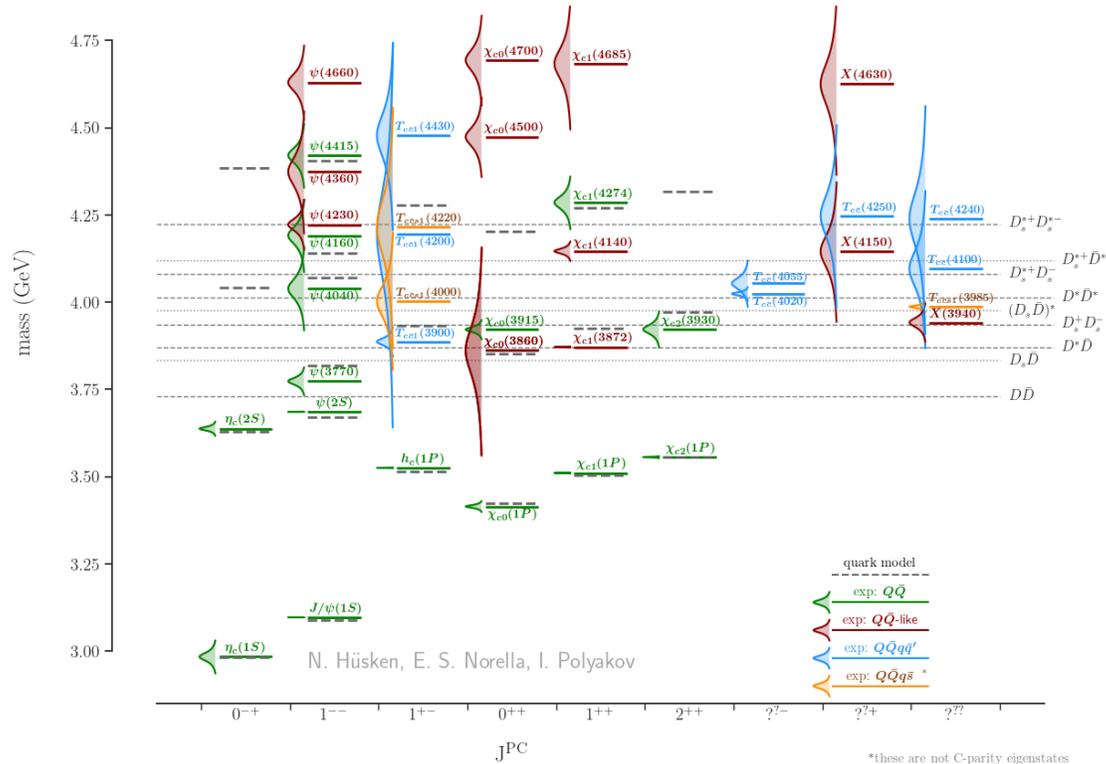
✓ Spectrum remains incomplete

✓ Many resonances lack definitive quantum number assignment



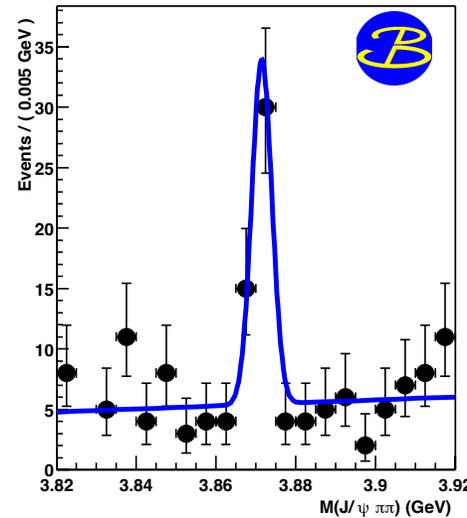
Conventional for exotic

- “Crypto”-exotic states are identified via inconsistent mass/width/production... with conventional states or the overpopulation of hadron spectrum



[Mod. Phys. Lett. A 40 (2025) 17n18, 2530002]

$\chi_{c1}(3872)$

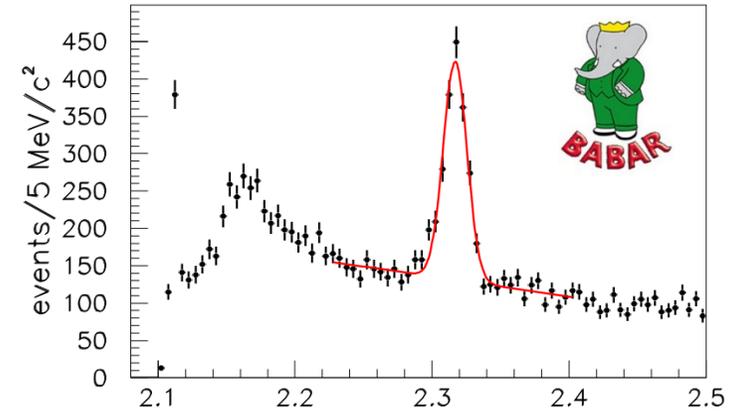


[PRL 91 (2003) 262001]

- 确认4GeV的 1^{++} $\chi_{c1} \rightarrow$ 对粲偶素谱定标

Ref: [seminar by Shi-Lin Zhu on 1st Feb.](#)

$D_{s0}^*(2317)^+$



[PRL 90 (2003) 242001]

- The hunt for conventional hadrons serves as a pioneering effort that creates fresh avenues for exotic hadron research

$I = 0$

$\Xi_{cc}\bar{K}, \Omega_{cc}\eta$??

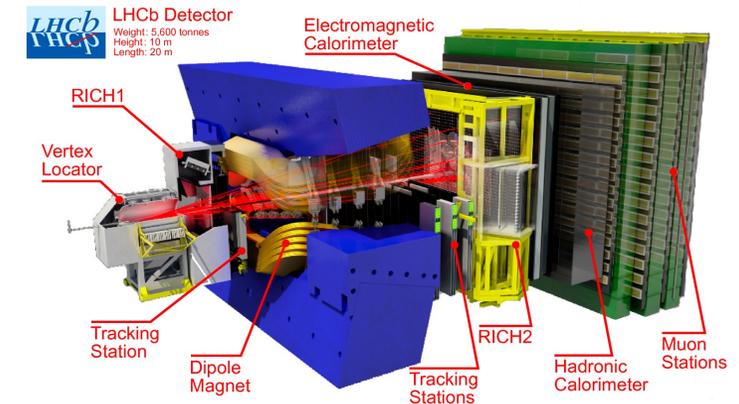
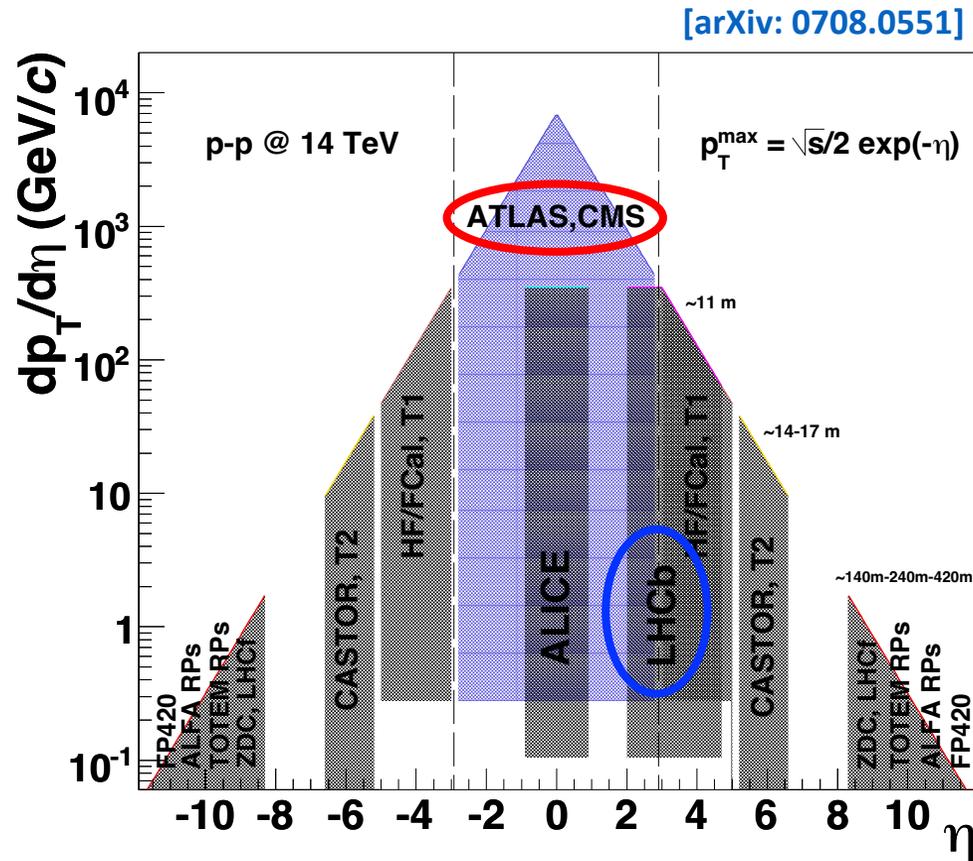
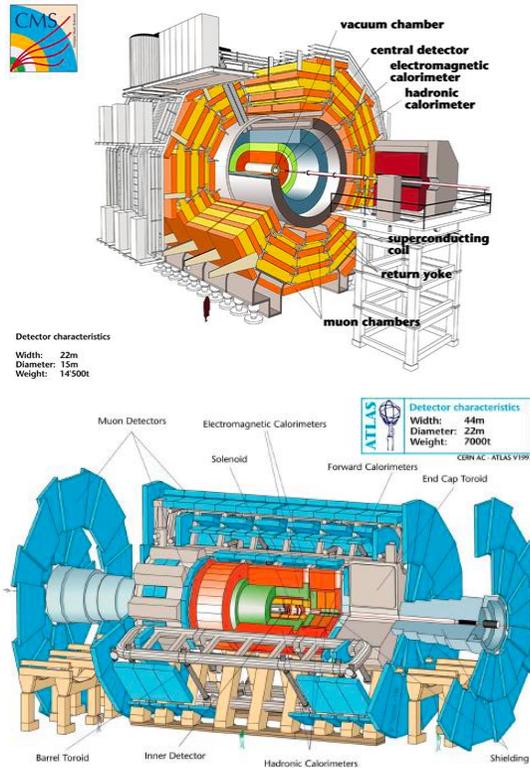
$DK, D_s\eta$

$D_{s0}^*(2317)$

Ref: [talk by Liuming Liu on 31st Jan.](#)

LHC experiments on spectroscopy

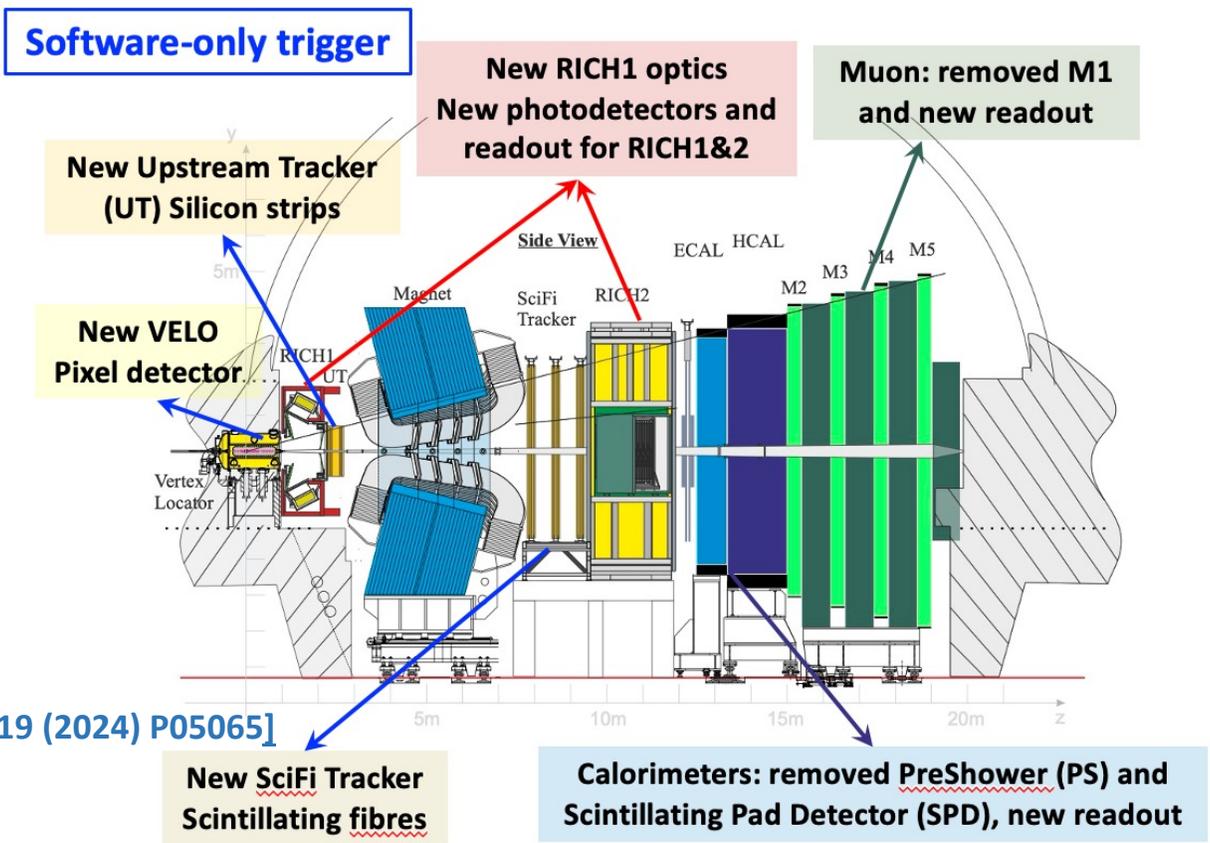
- LHC has the largest heavy-quark production rate so far
- Major LHC detectors complementary to each other in spectroscopy study



✓ CMS and ATLAS:
central region; **high luminosity**

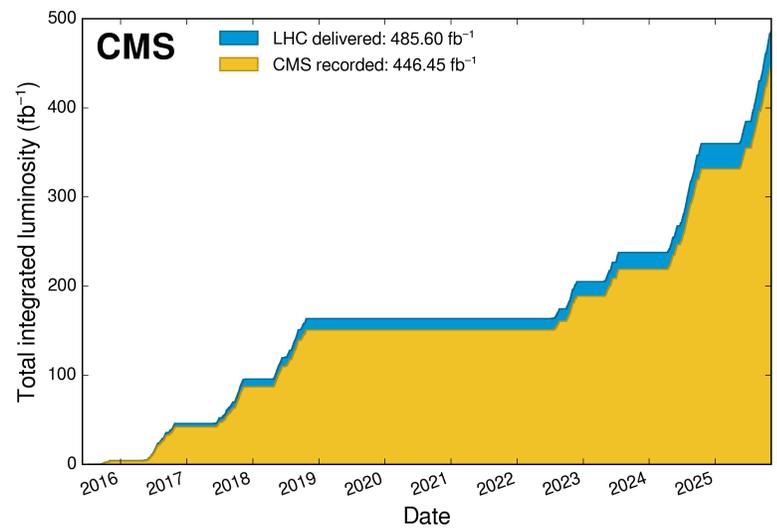
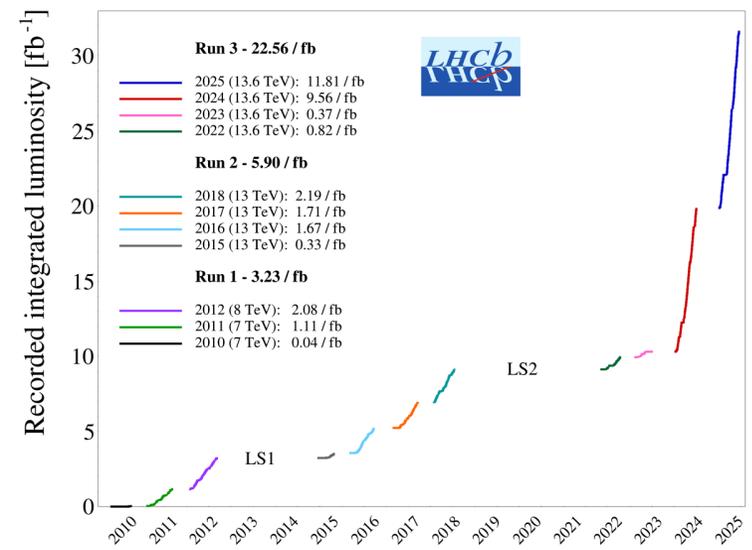
✓ LHCb:
forward region;
excellent **vertexing** and
particle identification
capabilities
⇒ optimized for
heavy flavor study

LHC experiments @ Run 3



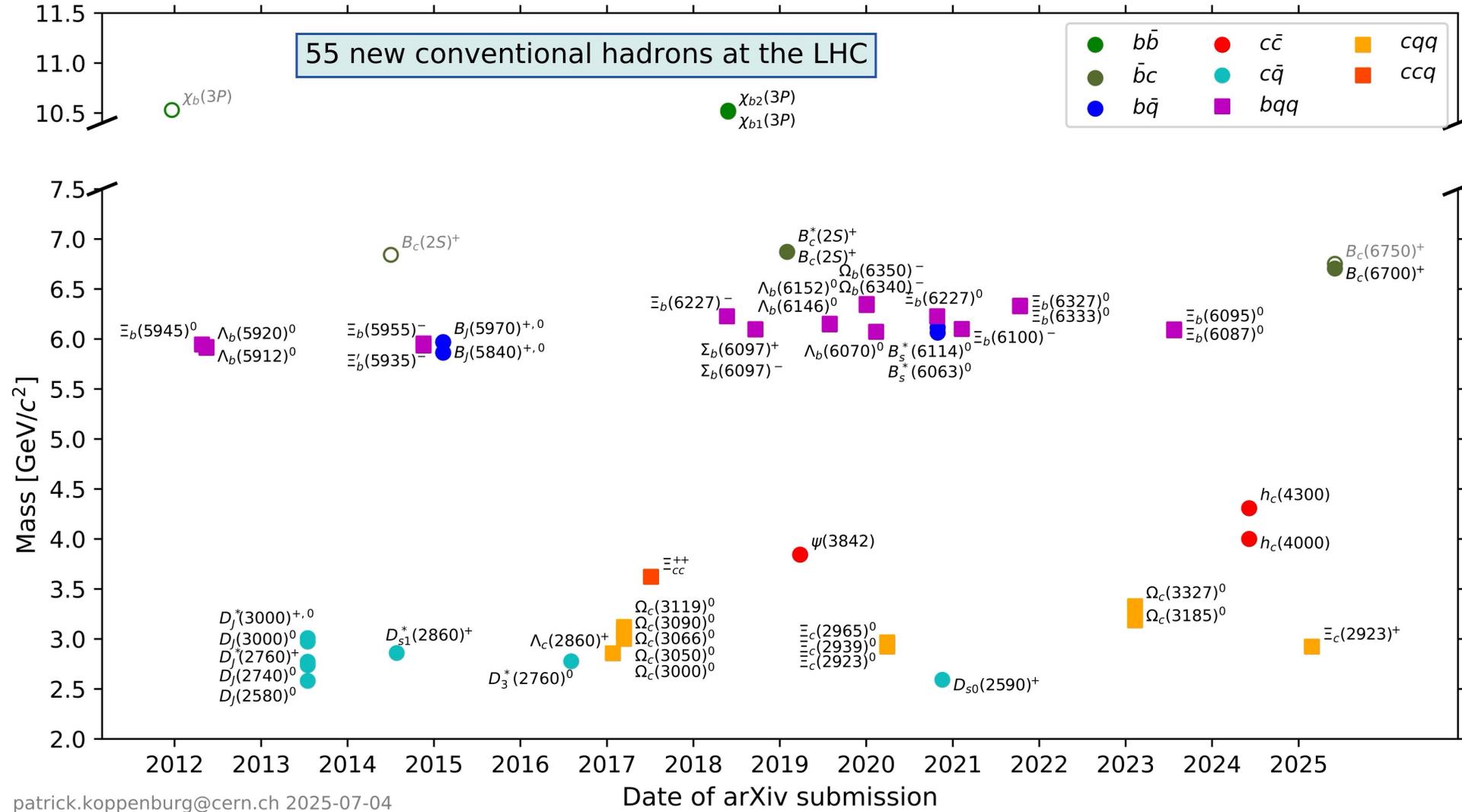
[JINST 19 (2024) P05065]

Total recorded luminosity – pp – 31.7 fb⁻¹



- LHCb: major upgrade;
9 fb⁻¹ @ 2018 → > 30 fb⁻¹ @ 2026
- CMS & ATLAS: trigger improvements;
140 fb⁻¹ @ 2018 → > 446 fb⁻¹ @ 2026

New conventional hadrons at LHC

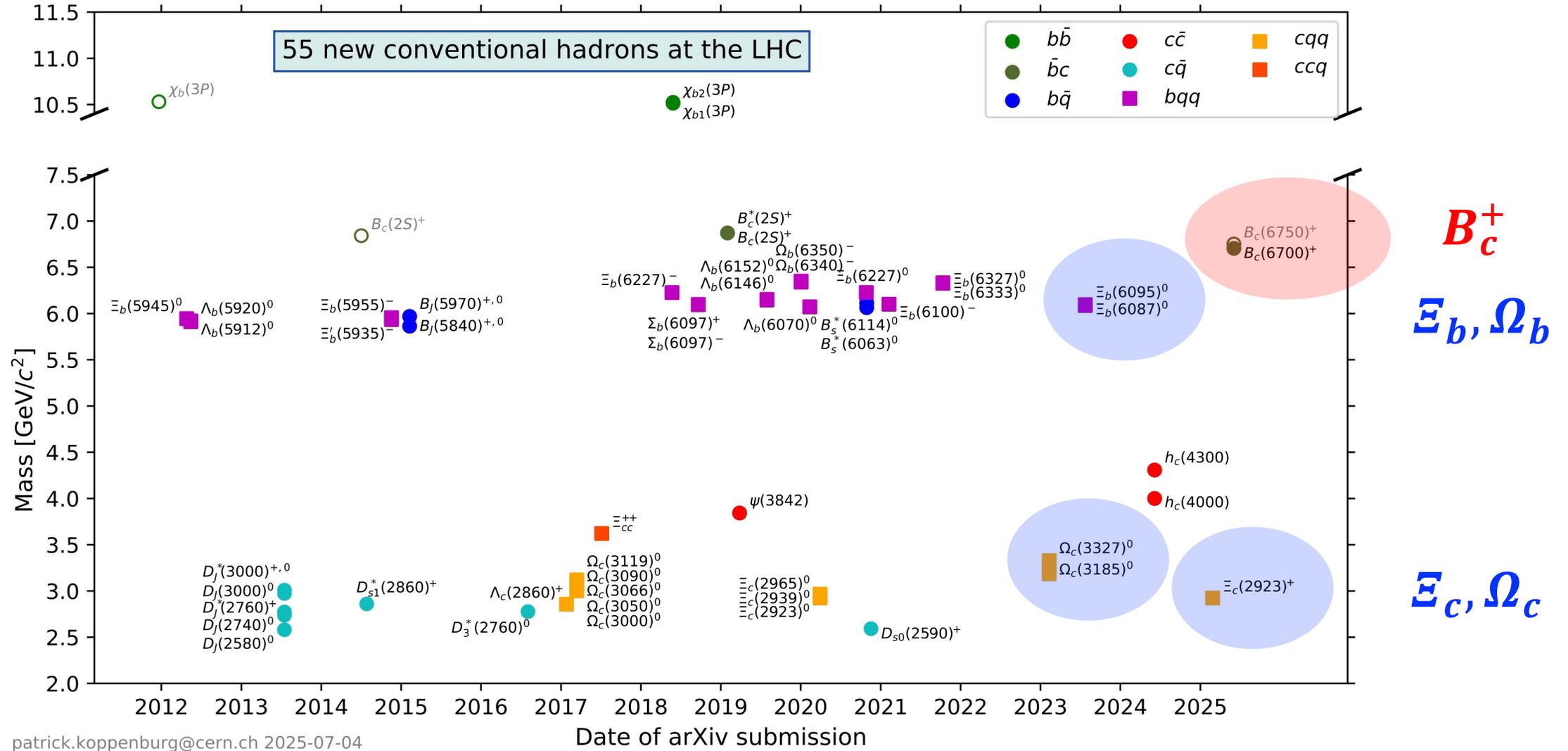


patrick.koppenburg@cern.ch 2025-07-04

<https://www.nikhef.nl/~pkoppenb/particles.html>

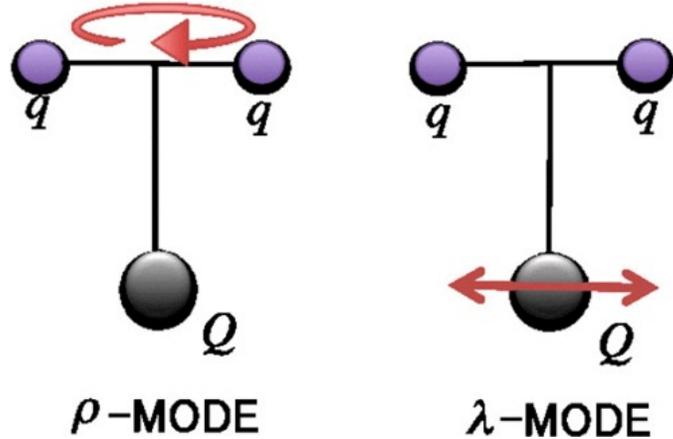
New conventional hadrons at LHC

*focus on latest results



Singly heavy baryons

- Singly heavy baryons offer
 - ✓ a crucial testbed for **Heavy Quark Effective Theory**
 - ✓ verification of **diquark model** with profound implications also for exotic hadrons
- Based on heavy quark-light diquark $Q[qq]$ model,



[\[PRD 92 \(2015\) 114029\]](#)

ρ -mode: no firm assignment yet

λ -mode: low-lying states well established

	$J_{[qq]}^P = 0^+$	$J_{[qq]}^P = 1^+$
$L = 0$	$\left(\frac{1}{2}\right)^+$	$\left(\frac{1}{2}\right)^+, \left(\frac{3}{2}\right)^+$
$L = 1$	$\left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-$	$\left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{5}{2}\right)^-$
$L = 2$	$\left(\frac{3}{2}\right)^+, \left(\frac{5}{2}\right)^+$

$\Xi_c^{0,+}$ spectroscopy

[PRL 134 (2025) 081901]

➤ $\Xi_c^{0,+}$ spectroscopy as of 2020

	$J_{[qq]}^P = 0^+$	$J_{[qq]}^P = 1^+$
$L = 0$	$\left(\frac{1}{2}\right)^+$ $\Xi_c^{0,+}$ $\Xi_c(2970)^{0,+}(2S)$	$\left(\frac{1}{2}\right)^+, \left(\frac{3}{2}\right)^+$ $\Xi_c'^{0,+}, \Xi_c(2645)^{0,+}$
$L = 1$	$\left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-$ $\Xi_c(2790)^{0,+}, \Xi_c(2815)^{0,+}$	$\left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{5}{2}\right)^-$
$L = 2$	$\left(\frac{3}{2}\right)^+, \left(\frac{5}{2}\right)^+$

$\Xi_c(2930)^{0,+}$

$\Xi_c(3055)^{0,+}$

$\Xi_c(3080)^{0,+}$

✓ First J^{PC} determination of $\Xi_c(3055)$

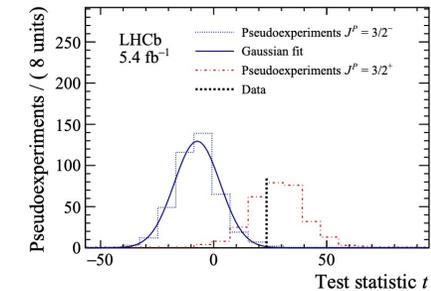
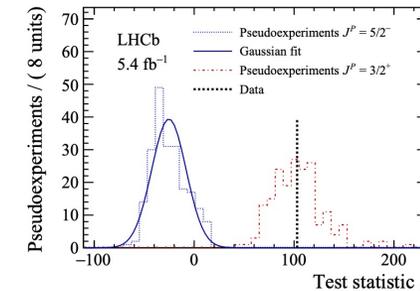
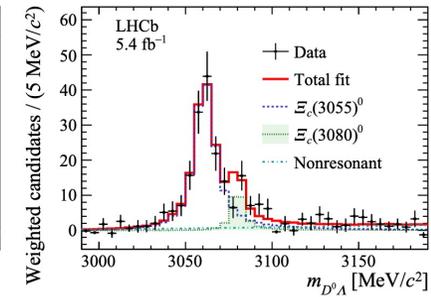
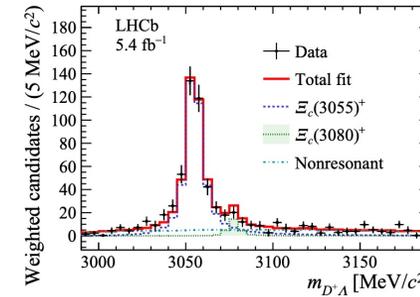
$$\Xi_b^{0(-)} \rightarrow \Xi_c(3055)^{+(0)} \pi^-$$

$$\downarrow$$

$$D^{+(0)} \Lambda$$

$\Xi_c(3055)^+$

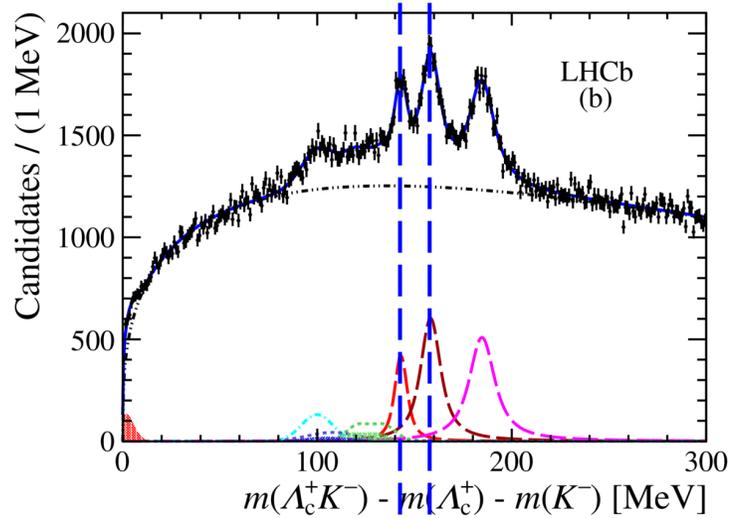
$\Xi_c(3055)^0$



$$J^P = 3/2^+$$

Observation of $\Xi_c^{**0} \rightarrow \Lambda_c^+ K^-$

[PRL 124 (2020) 222001]

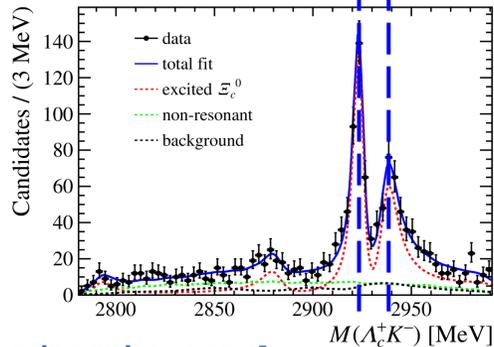


◆ $\Lambda_c^+ K^-$ mass spectrum

Resonance	Mass [MeV]	Γ [MeV]
$\Xi_c(2923)^0$	$2923.04 \pm 0.25 \pm 0.20 \pm 0.14$	$7.1 \pm 0.8 \pm 1.8$
$\Xi_c(2939)^0$	$2938.55 \pm 0.21 \pm 0.17 \pm 0.14$	$10.2 \pm 0.8 \pm 1.1$
$\Xi_c(2965)^0$	$2964.88 \pm 0.26 \pm 0.14 \pm 0.14$	$14.1 \pm 0.9 \pm 1.3$

first observation

✓ $\Xi_c(2965)^0$ inconsistent with the known $\Xi_c(2970)^0$:
 $M = 2967.8_{-0.7}^{+0.9}$ MeV, $\Gamma = 28.1_{-4.0}^{+3.4}$ MeV



evidence

◆ $\Lambda_c^+ K^-$ in $B^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^-$

State	Mass (MeV)	Width (MeV)	Significance
$\Xi_c(2880)^0$	$2881.8 \pm 3.1 \pm 8.5$	$12.4 \pm 5.2 \pm 5.8$	3.8σ
$\Xi_c(2923)^0$	$2924.5 \pm 0.4 \pm 1.1$	$4.8 \pm 0.9 \pm 1.5$	$> 10\sigma$
$\Xi_c(2939)^0$	$2938.5 \pm 0.9 \pm 2.3$	$11.0 \pm 1.9 \pm 7.5$	$> 10\sigma$

confirmation

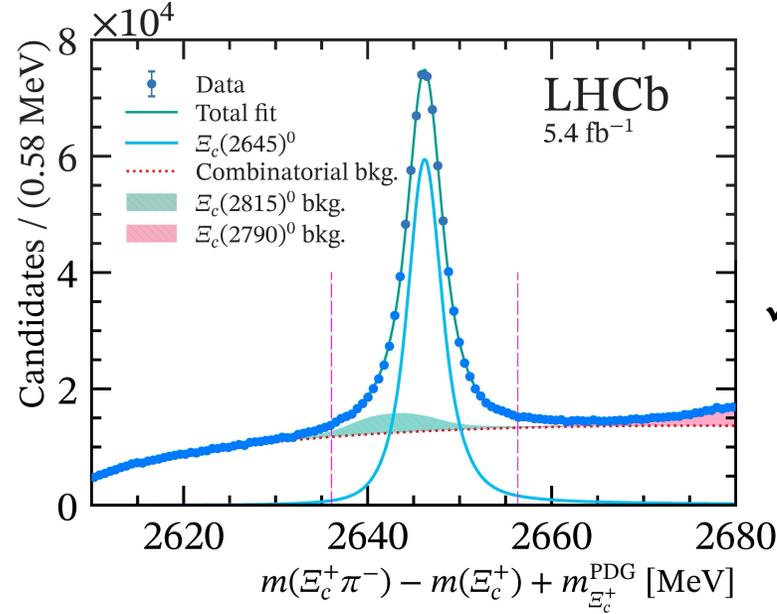
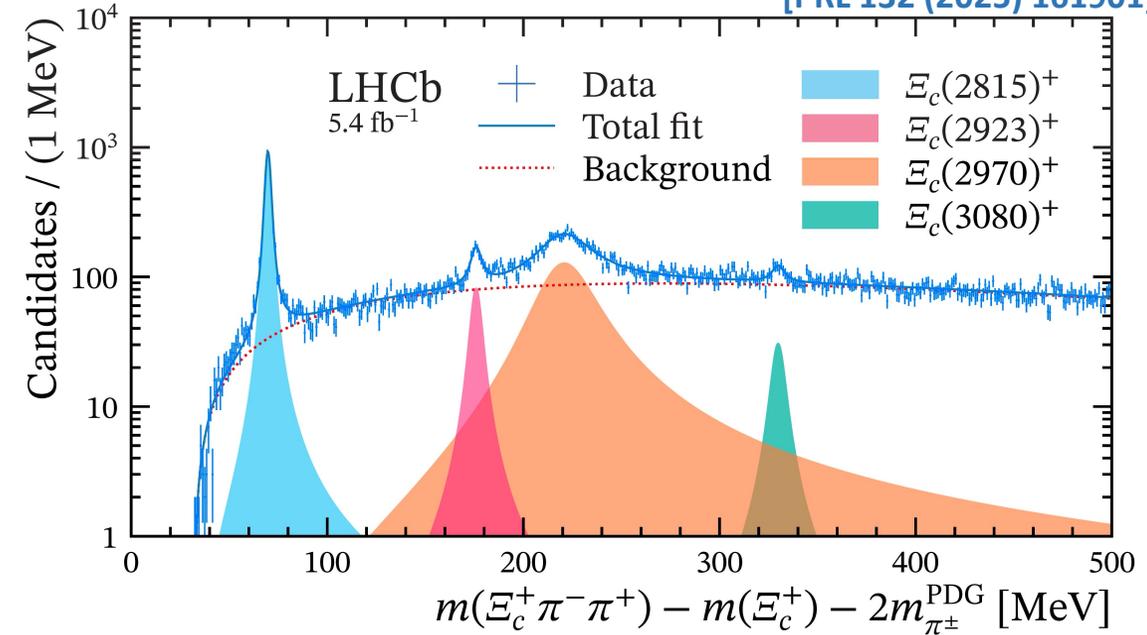
[PRD 108 (2023) 012020]

➤ Study of the isospin partners Ξ_c^{**+} can help elucidate their properties

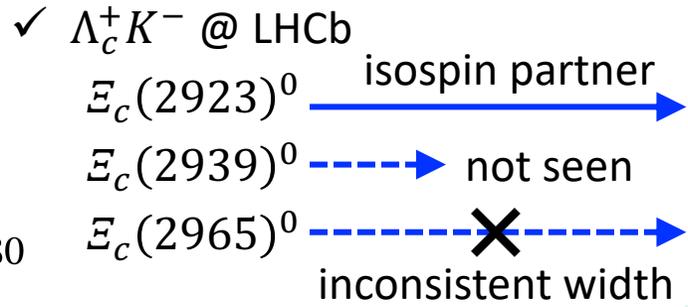
Observation of $\Xi_c^{**+} \rightarrow \Xi_c^+ \pi^+ \pi^-$

[PRL 132 (2025) 161901]

- **Dataset:** 5.4 fb⁻¹ Run2 data from LHCb
- **Decay chain:**
 $\Xi_c^{**+} \rightarrow \Xi_c(2645)^0 (\rightarrow \Xi_c^+ \pi^-) \pi^+, \Xi_c^+ \rightarrow p K^- \pi^+$
- **Selection:** three-staged MVA classifiers to optimize significance of $\Xi_c^+ \Rightarrow \Xi_c(2645)^0 \Rightarrow \Xi_c^{**+}$ successively



$N(\Xi_c(2645)^0) \sim 56.5 \times 10^4$, purity $\sim 52\%$



$m[\Xi_c(2815)^+]$	$= 2816.65 \pm 0.03 \pm 0.03 \pm 0.23$ MeV,
$\Gamma[\Xi_c(2815)^+]$	$= 2.07 \pm 0.08 \pm 0.12$ MeV,
$m[\Xi_c(2923)^+]$	$= 2922.8 \pm 0.3 \pm 0.5 \pm 0.2$ MeV,
$\Gamma[\Xi_c(2923)^+]$	$= 5.3 \pm 0.9 \pm 1.4$ MeV,
$m[\Xi_c(2970)^+]$	$= 2968.6 \pm 0.5 \pm 0.5 \pm 0.2$ MeV,
$\Gamma[\Xi_c(2970)^+]$	$= 31.7 \pm 1.7 \pm 1.9$ MeV,
$m[\Xi_c(3080)^+]$	$= 3076.8 \pm 0.7 \pm 1.3 \pm 0.2$ MeV,
$\Gamma[\Xi_c(3080)^+]$	$= 6.8 \pm 2.3 \pm 0.9$ MeV,

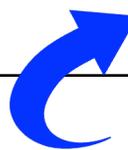
first observation

observation of new decay mode

$\Xi_b^{-,0}$ spectroscopy

➤ $\Xi_b^{-,0}$ spectroscopy as of 2020

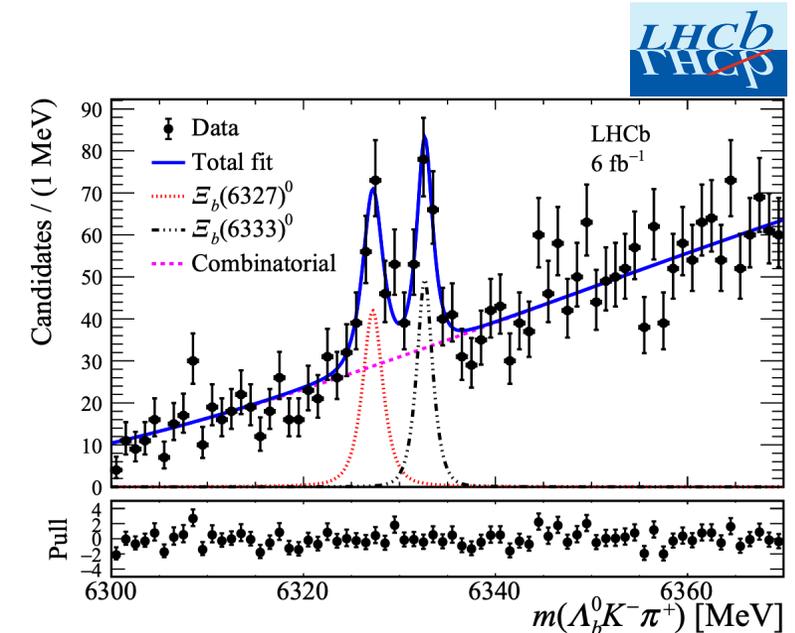
	$J_{[qq]}^P = 0^+$	$J_{[qq]}^P = 1^+$
$L = 0$	$\left(\frac{1}{2}\right)^+$ $\Xi_b^{-,0}$ $\Xi_b(6227)^{-,0} \rightarrow 2S?$ 	$\left(\frac{1}{2}\right)^+, \left(\frac{3}{2}\right)^+$ $\Xi_b'(5935)^-, \Xi_b(5955)^-$  $\Xi_b(5945)^0$ 
$L = 1$	$\left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-$	$\left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{5}{2}\right)^-$
$L = 2$	$\left(\frac{3}{2}\right)^+, \left(\frac{5}{2}\right)^+$



$$m(\Xi_b(6327)^0) = 6327.28^{+0.23}_{-0.21} \pm 0.12 \pm 0.24 \text{ MeV}$$

$$m(\Xi_b(6333)^0) = 6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22 \text{ MeV}$$

*Neutral $(1/2)^+$ not seen yet because it is highly likely below $\Xi_b^- \pi^+$ threshold thus decaying 100% to $\Xi_b^0 \pi^0$ or $\Xi_b^0 \gamma$



[PRL 128 (2022) 16, 162001]

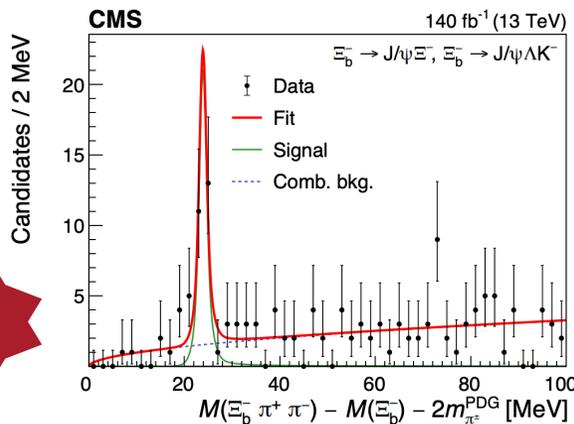
Observation of $\Xi_b^{-/0**} \rightarrow \Xi_b^{-/0} \pi^+ \pi^-$

[PRL 131 (2023) 171901]

➤ CMS: $\Xi_b^- \pi^+ \pi^-$ with $\Xi_b^- \rightarrow J/\psi \Xi^-, J/\psi \Lambda K^-$

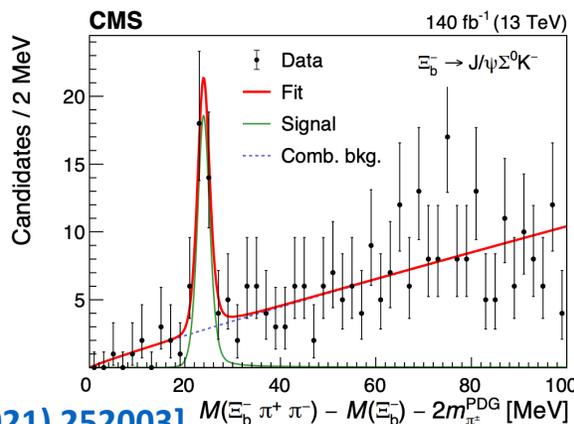
➤ LHCb: $\Xi_b^{-/0} \pi^+ \pi^-$ with $\Xi_b^{-/0} \rightarrow \Xi_c^{0/+} \pi^-$ and $\Xi_b^{-/0} \rightarrow \Xi_c^{0/+} \pi^- \pi^+ \pi^-$

$$\begin{aligned} \Xi_b^- [(1/2)^-] &\rightarrow \Xi_b^- [(1/2)^+] \pi \\ \Xi_b^- [(3/2)^-] &\rightarrow \Xi_b^- [(3/2)^+] \pi \end{aligned}$$

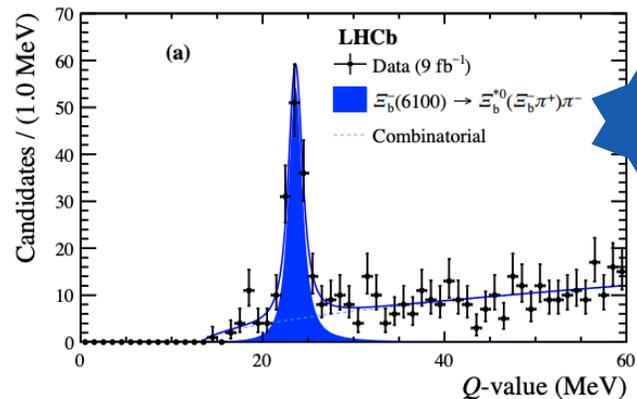
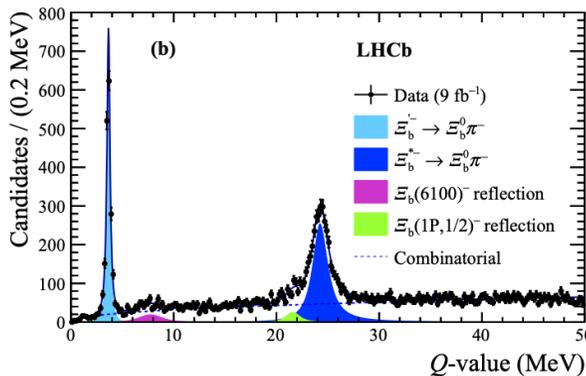
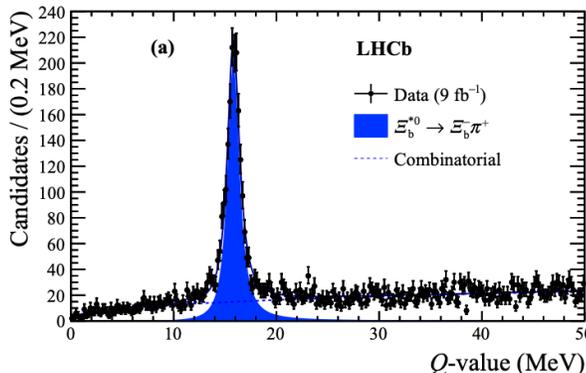


observ.

$\Xi_b(6100)^-$

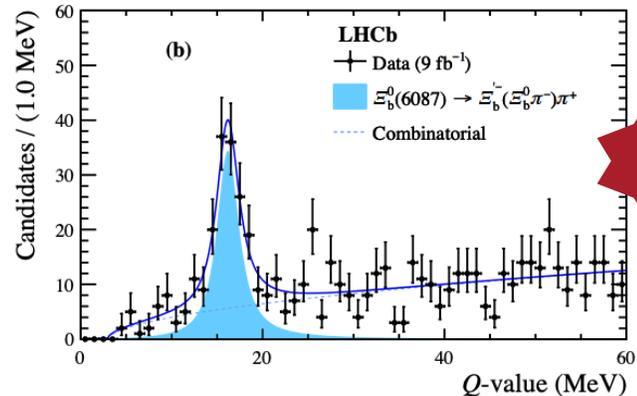


[PRL 126 (2021) 252003]



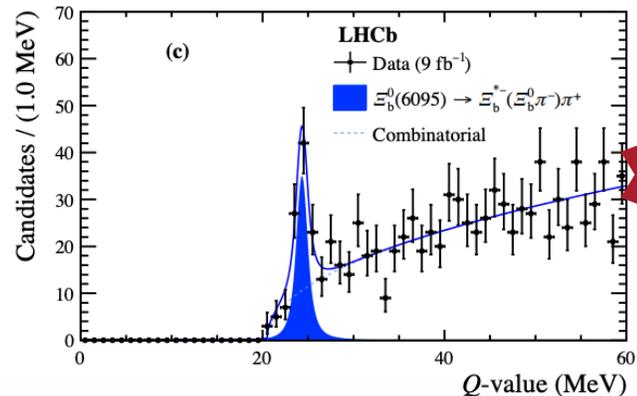
confirm.

$\Xi_b(6100)^-$



observ.

$\Xi_b(6087)^0$



observ.

$\Xi_b(6095)^0$

✓ Consistent with $1P J_{[qq]}^P = 0^+ (1/2)^-, (3/2)^-$ doublet

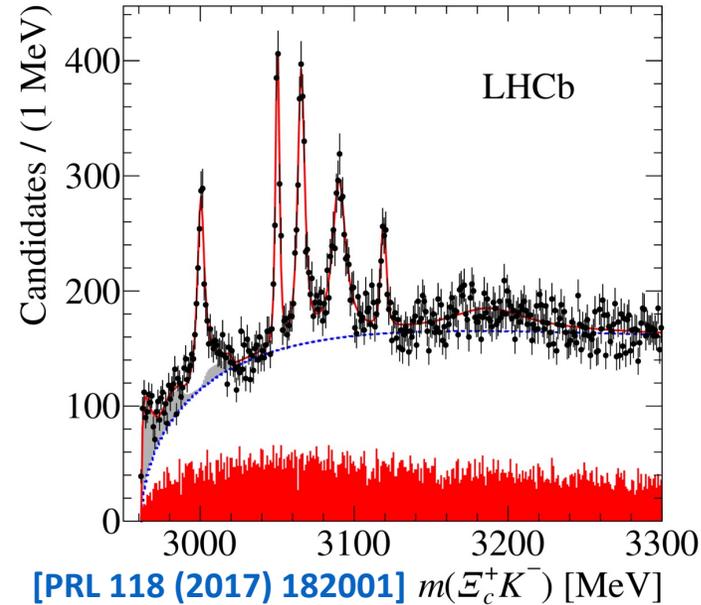
Ω_c^0 spectroscopy

➤ Ω_c^0 spectroscopy as of 2017

	$J_{[qq]}^P = 1^+$
$L = 0$	$\left(\frac{1}{2}\right)^+, \left(\frac{3}{2}\right)^+$ $\Omega_c^0, \Omega_c(2770)^0$
$L = 1$	$\left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{5}{2}\right)^-$
$L = 2$

Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1_{-0.5}^{+0.3}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1_{-0.5}^{+0.3}$	$0.8 \pm 0.2 \pm 0.1$
	confirmed	$< 1.2 \text{ MeV, 95\% CL}$
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3_{-0.5}^{+0.3}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5_{-0.5}^{+0.3}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9_{-0.5}^{+0.3}$	$1.1 \pm 0.8 \pm 0.4$
		$< 2.6 \text{ MeV, 95\% CL}$

✓ Prompt $\Xi_c^- K^+$

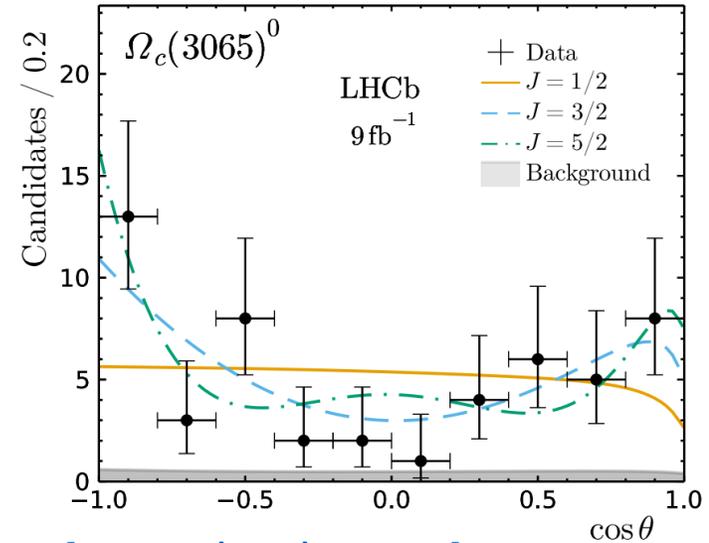
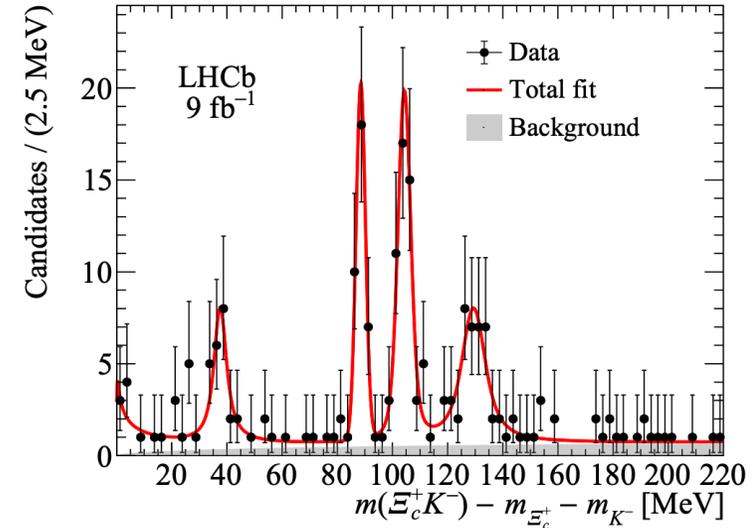


✓ ordered spin assignment

$$J = \frac{1}{2}, \frac{1}{2}, \frac{3}{2}, \frac{3}{2}$$

rejected by 3.5σ

✓ $\Omega_b^- \rightarrow [\Xi_c^+ K^-] \pi^-$

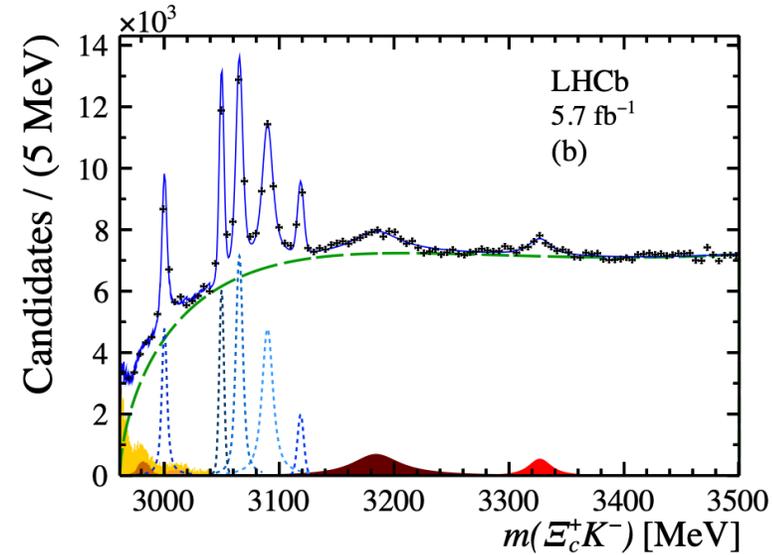
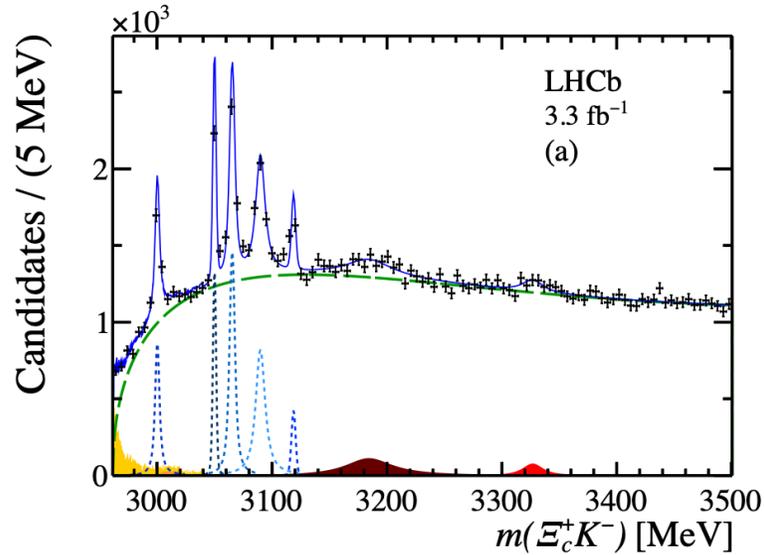
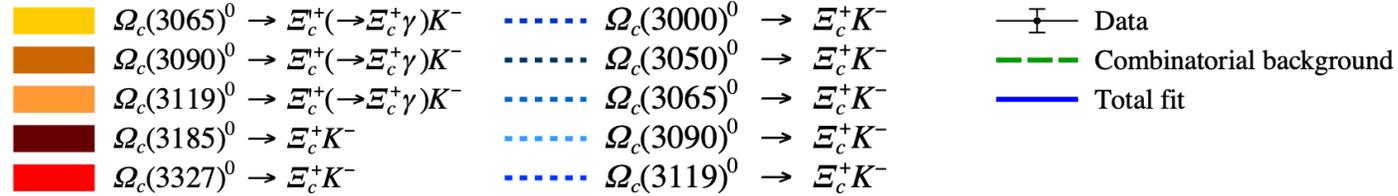


[PRD 104 (2021) L091102]

Observation of new $\Omega_c^{*0} \rightarrow \Xi_c^+ K^-$

➤ Using full 9 fb^{-1} Run1+Run2 LHCb data

[PRL 131 (2023) 131902]



✓ Two new states:

Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3185)^0$	$3185.1 \pm 1.7 \begin{smallmatrix} +7.4 \\ -0.9 \end{smallmatrix} \pm 0.2$	$50 \pm 7 \begin{smallmatrix} +10 \\ -20 \end{smallmatrix}$
$\Omega_c(3327)^0$	$3327.1 \pm 1.2 \begin{smallmatrix} +0.1 \\ -1.3 \end{smallmatrix} \pm 0.2$	$20 \pm 5 \begin{smallmatrix} +13 \\ -1 \end{smallmatrix}$

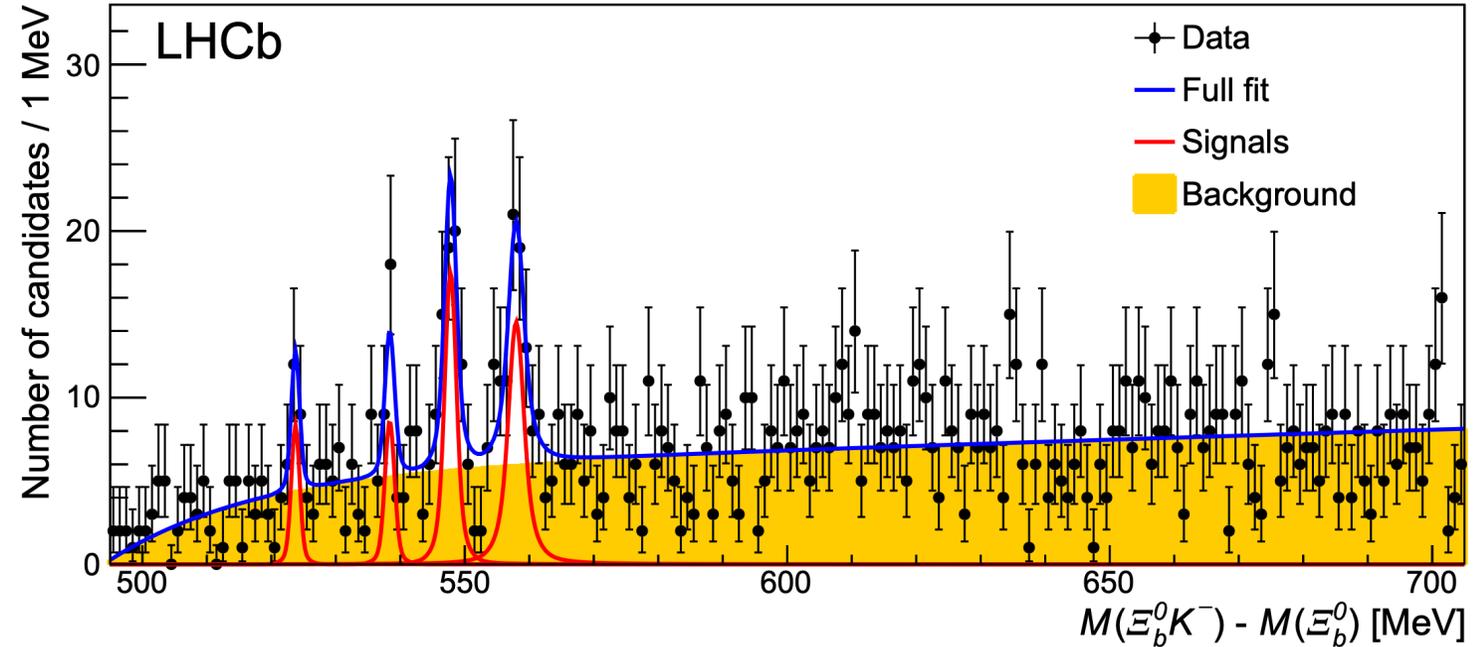
Ω_b^- spectroscopy

➤ Ω_b^- spectroscopy as of 2020

✓ Prompt $\Xi_b^0 K^-$

[PRL 124 (2020) 082002]

	$J_{[qq]}^P = 1^+$
$L = 0$	$\left(\frac{1}{2}\right)^+, \left(\frac{3}{2}\right)^+$ Ω_b^0
$L = 1$	$\left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{5}{2}\right)^-$
$L = 2$



	Width [MeV]	Signal yield	Significances [σ] Local	Global
$m(\Omega_b(6316)^-) = 6315.64 \pm 0.31 \pm 0.07 \pm 0.50$ MeV	$0.00^{+0.7}_{-0.0}$	15^{+6}_{-5}	3.6	2.1
$m(\Omega_b(6330)^-) = 6330.30 \pm 0.28 \pm 0.07 \pm 0.50$ MeV	$0.00^{+0.4}_{-0.0}$	18^{+6}_{-5}	3.7	2.6
$m(\Omega_b(6340)^-) = 6339.71 \pm 0.26 \pm 0.05 \pm 0.50$ MeV	$0.47^{+0.6}_{-0.5}$	47^{+11}_{-10}	7.2	6.7
$m(\Omega_b(6350)^-) = 6349.88 \pm 0.35 \pm 0.05 \pm 0.50$ MeV	$1.4^{+1.0}_{-0.8}$	57^{+14}_{-13}	7.0	6.2

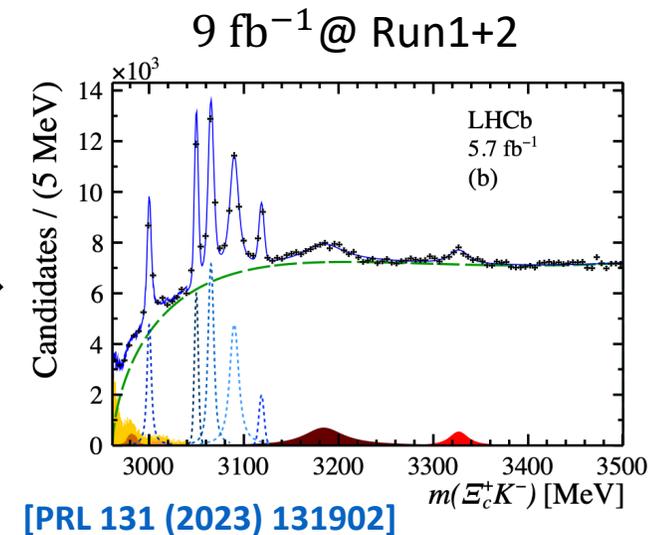
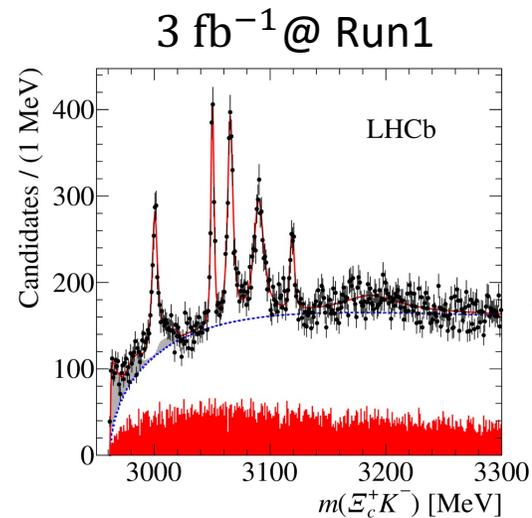
first observation

Prospects on singly heavy baryon for Run3

Λ_c^+, Σ_c	$\Lambda_c^+ + \pi, \Lambda_c^+ + \pi\pi, D + p$
Ξ_c	$\Xi_c + \pi, \Xi_c + \pi\pi, \Lambda_c^+ + K$ $D + \Lambda$
Ω_c^0	$\Xi_c + K$

Λ_b^0, Σ_b	$\Lambda_b^0 + \pi, \Lambda_b^0 + \pi\pi$
Ξ_b	$\Xi_b + \pi, \Xi_b + \pi\pi, \Lambda_b^0 + K, \Lambda_b^0 + K\pi$
Ω_b^-	$\Xi_b + K$

➤ Existing modes with larger statistics

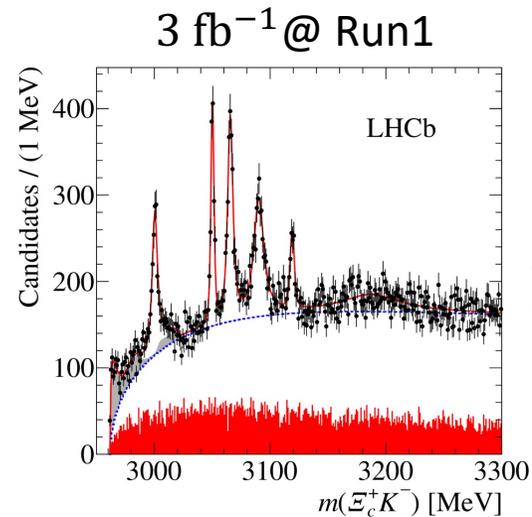


Prospects on singly heavy baryon for Run3

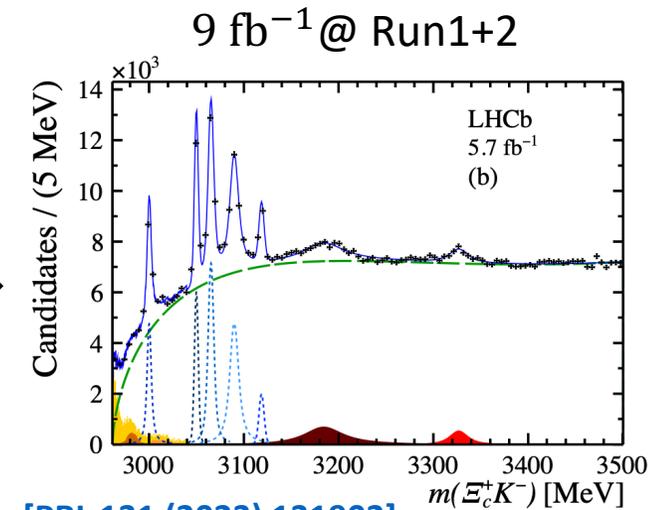
Λ_c^+, Σ_c	$\Lambda_c^+ + \pi, \Lambda_c^+ + \pi\pi, D + p$
Ξ_c	$\Xi_c + \pi, \Xi_c + \pi\pi, \Lambda_c^+ + K$ $D + \Lambda$
Ω_c^0	$\Xi_c + K, D + \Xi$

Λ_b^0, Σ_b	$\Lambda_b^0 + \pi, \Lambda_b^0 + \pi\pi, B + p$
Ξ_b	$\Xi_b + \pi, \Xi_b + \pi\pi, \Lambda_b^0 + K, \Lambda_b^0 + K\pi$ $B + \Lambda$
Ω_b^-	$\Xi_b + K, B + \Xi$

- Existing modes with larger statistics
- New modes opened up for higher states
→ **theoretical inputs are essential to define the priority**



[PRL 118 (2017) 182001]



[PRL 131 (2023) 131902]

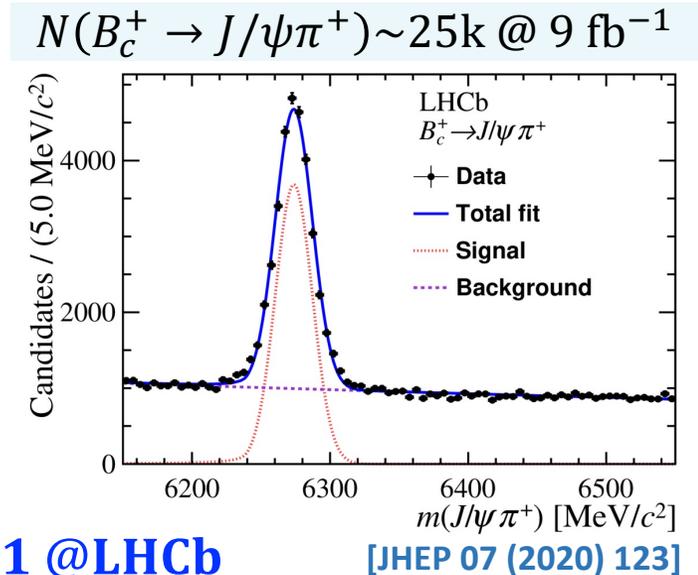
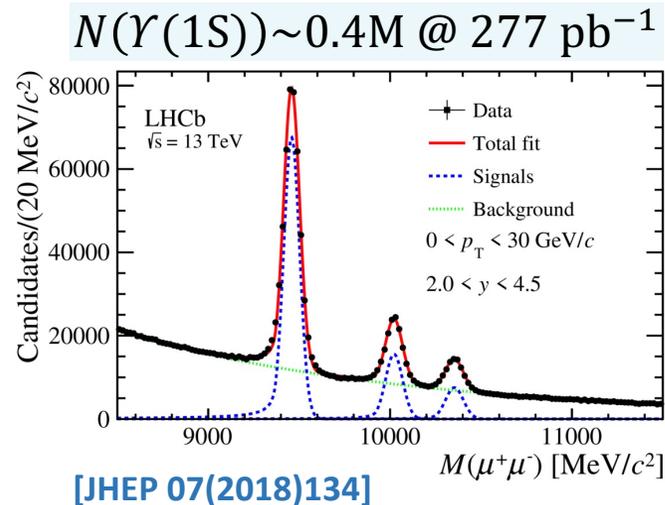
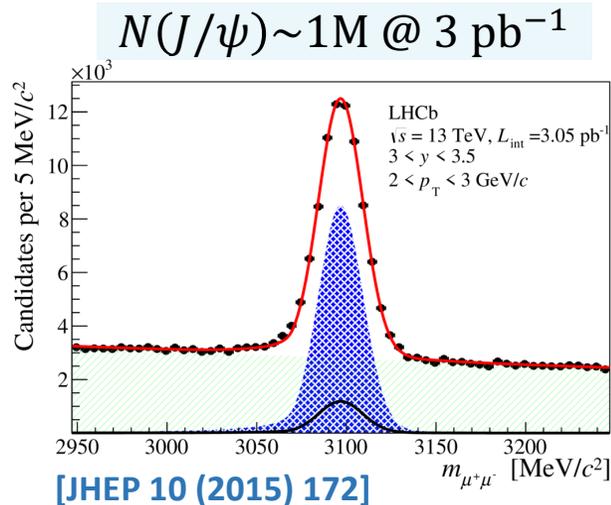
B_c meson

- B_c meson is the only meson consisting of heavy quarks of different flavors
 ⇒ can be considered intermediate of the charmonium and bottomonium systems

- The distinct flavors of constituent quarks lead to

X Challenges: limited experimental study of B_c

- production at hadron colliders suppressed as it requires production of both $b\bar{b}$ and $c\bar{c}$
- unreachable at currently running e^+e^- colliders

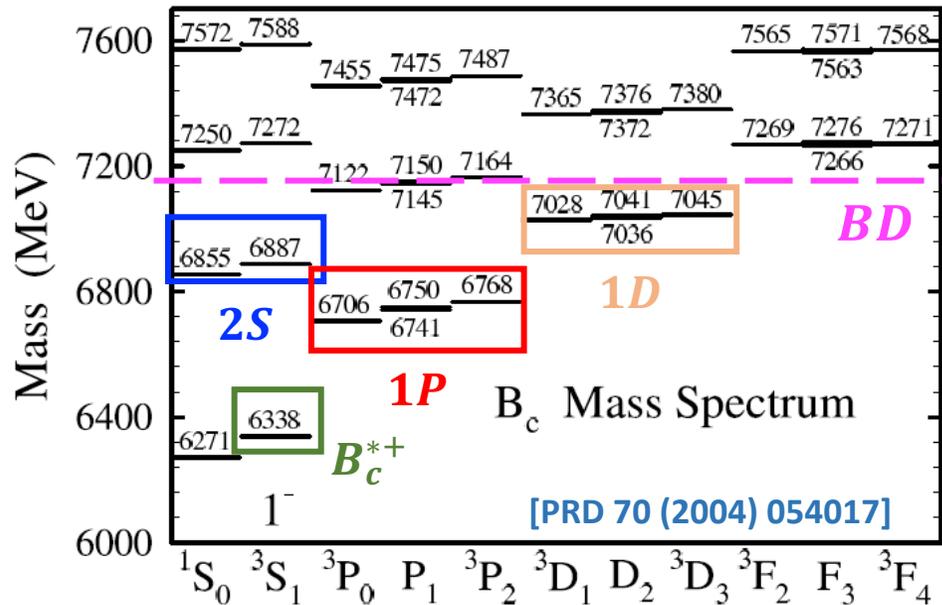


$N(J/\psi): N(\Upsilon(1S)): N(B_c^+) \sim 100\text{k}: 0.4\text{k}: 1 @ \text{LHCb}$

- ✓ **Opportunities:** unique features to extend and enforce understanding of QCD

B_c spectroscopy

- Like quarkonium systems, B_c^+ has a rich spectrum
- Unlike quarkonium systems, excited B_c^+ states below BD threshold can only undergo radiative or pionic transitions to the ground state $B_c^+ \Rightarrow \Gamma \sim \mathcal{O}(100 \text{ keV})$



■ $B_c(2S)^+ \rightarrow B_c^+ \pi^+ \pi^-$:
 most promising with
 sizable production rates &
 pionic decays



[Comput. Phys. Commun. 197 (2015) 335]

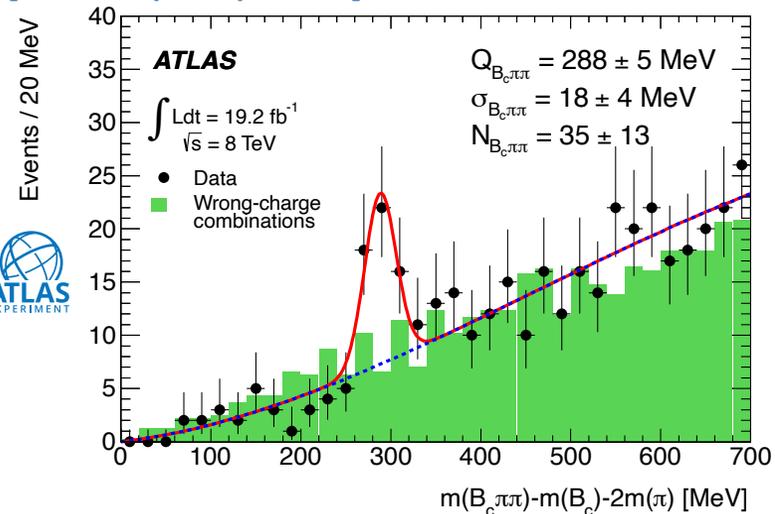
	1^1S_0	1^3S_1	1^1P_1	1^3P_0	1^3P_1	1^3P_2	1^1S_0g	3^1S_1g	2^1S_0	2^3S_1
σ_{prod} [nb]	18.8	48.7	3.5	1.1	2.7	7.2	0.4	1.55	4.5	11.1

[PRD 70 (2004) 054017]

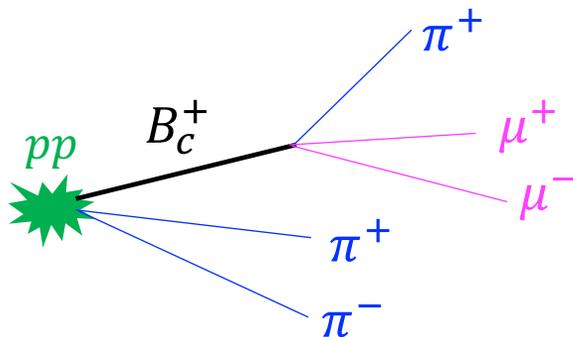
Initial state	Final state	Width (keV)	B.F. (%)
1^3S_1	1^1S_0	0.08	100
1^3P_2	1^3S_1	83	100
$1P_1'$	1^3S_1	11	12.1
	1^1S_0	80	87.9
	Total	91	100
$1P_1$	1^3S_1	60	82.2
	1^1S_0	13	17.8
	Total	73	100
1^3P_0	1^3S_1	55	100
2^1S_0	$1^1S_0 + \pi\pi$	57 ± 7	88.1
	$1P_1' + \gamma$	6.1	9.4
	$1P_1 + \gamma$	1.3	2.0
	$1^3S_1 + \gamma$	0.3	0.5
	Total	64.7	100
2^3S_1	$1^3S_1 + \pi\pi$	57 ± 7	79.6
	$1^3P_2 + \gamma$	5.7	8.0
	$1P_1' + \gamma$	0.7	1.0
	$1P_1 + \gamma$	4.7	6.6
	$1^3P_0 + \gamma$	2.9	4.0
	$2^1S_0 + \gamma$	0.01	1×10^{-2}
Total	$1^1S_0 + \gamma$	0.6	0.8
	Total	71.6	100

Observation of $B_c(2S)^+$ states

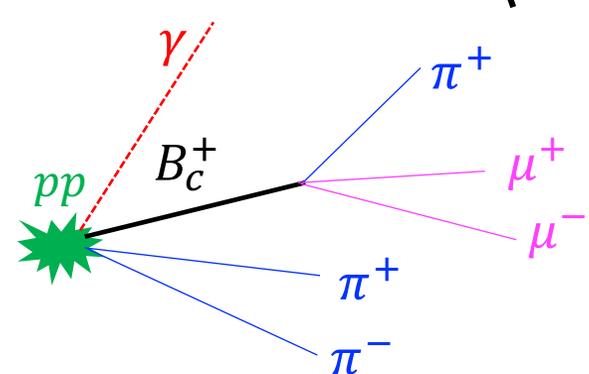
[PRL 113 (2014) 12004]



$$B_c(2^1S_0)^+ \rightarrow B_c^+ \pi^+ \pi^-$$

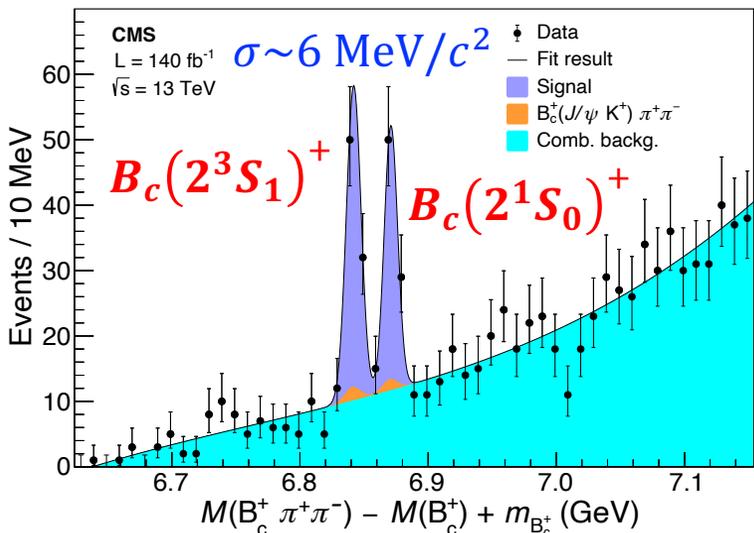


$$B_c(2^3S_1)^+ \rightarrow B_c^{*+} (\rightarrow B_c^+ \gamma) \pi^+ \pi^-$$



and/or?

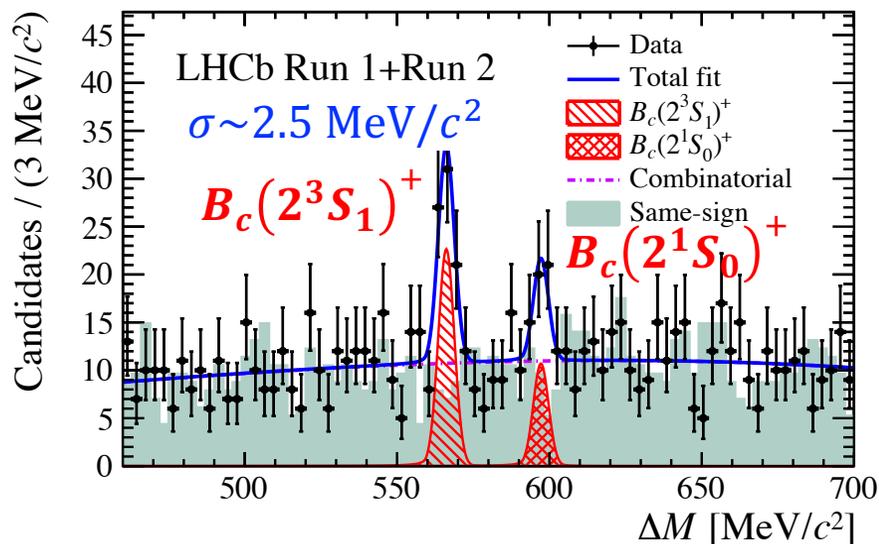
[PRL 122 (2019) 132001]



$$2^3S_1: 66 \pm 10; 2^1S_0: 51 \pm 10$$

2026/3/3

[PRL 122 (2019) 232001]



$$2^3S_1: 51 \pm 10; 2^1S_0: 24 \pm 9$$

Liupan An

$$M(2^1S_0)$$

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

$$M(2^1S_0) - M(2^3S_1)_{\text{rec}}$$

$$= 29.0 \pm 1.5(\text{stat}) \pm 0.7(\text{syst}) \text{ MeV}/c^2$$

$$M(2^1S_0)$$

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

$$M(2^1S_0) - M(2^3S_1)_{\text{rec}}$$

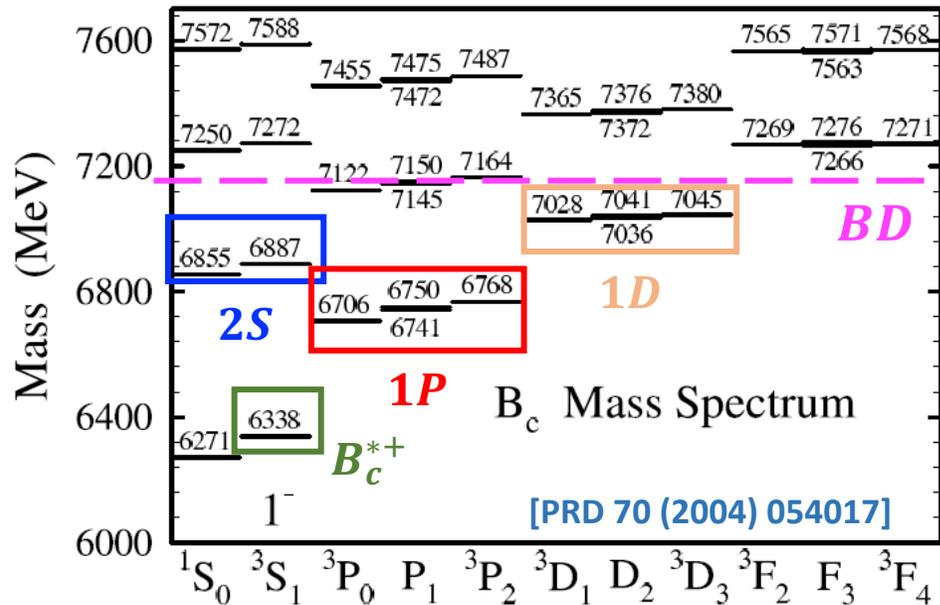
$$= 31.0 \pm 1.4(\text{stat}) \text{ MeV}/c^2$$



B_c spectroscopy

[PRD 70 (2004) 054017]

- Like quarkonium systems, B_c^+ has a rich spectrum
- Unlike quarkonium systems, excited B_c^+ states below BD threshold can only undergo radiative or pionic transitions to the ground state $B_c^+ \Rightarrow \Gamma \sim \mathcal{O}(100 \text{ keV})$



□ $B_c^{*+} \rightarrow B_c^+ \gamma$: photon energy too small

■ $B_c(1P)^+ \rightarrow B_c^+ \gamma$:  challenging but promising given sizable production rates & larger photon energy vs. B_c^{*+}

□ $B_c(1D)$: small prod. rate & complex decays

[Comput. Phys. Commun. 197 (2015) 335]

	1^1S_0	1^3S_1	1^1P_1	1^3P_0	1^3P_1	1^3P_2	1^1S_0g	3^1S_1g	2^1S_0	2^3S_1
σ_{prod} [nb]	18.8	48.7	3.5	1.1	2.7	7.2	0.4	1.55	4.5	11.1

Initial state	Final state	Width (keV)	B.F. (%)
1^3S_1	1^1S_0	0.08	100
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	Total	73	100
1^3P_0	1^3S_1	55	100
2^1S_0	$1^1S_0 + \pi\pi$	57 ± 7	88.1
	$1P_1' + \gamma$	6.1	9.4
	$1P_1 + \gamma$	1.3	2.0
	$1^3S_1 + \gamma$	0.3	0.5
	Total	64.7	100
2^3S_1	$1^3S_1 + \pi\pi$	57 ± 7	79.6
	$1^3P_2 + \gamma$	5.7	8.0
	$1P_1' + \gamma$	0.7	1.0
	$1P_1 + \gamma$	4.7	6.6
	$1^3P_0 + \gamma$	2.9	4.0
$2^1S_0 + \gamma$	0.01	1×10^{-2}	
$1^1S_0 + \gamma$	0.6	0.8	
Total	71.6	100	

$B_c(1P)^+$ states

$B_c(1P)^+$ states	Decay mode	B. F. prediction (%)
1^3P_0	$B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$	100
$1P_1$	$B_c^+\gamma$	17.8
	$B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$	82.2
$1P_1'$	$B_c^+\gamma$	87.9
	$B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$	12.1
1^3P_2	$B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$	100

[PRD 70 (2004) 054017]

→ $B_c^+\gamma$: peak in $B_c^+\gamma$ mass spectrum

→ $B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$: peak in $B_c^+\gamma$ mass spectrum but shifted downwards by $\delta M = M(B_c^{*+}) - M(B_c^+)$

four $B_c(1P)^+$ states → six peaks in $B_c^+\gamma$

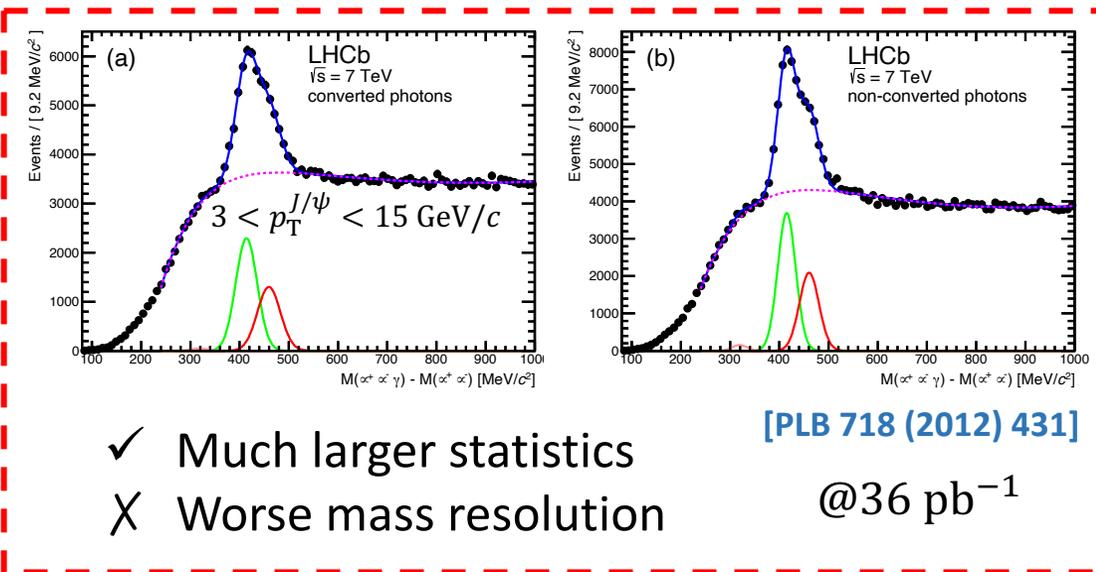
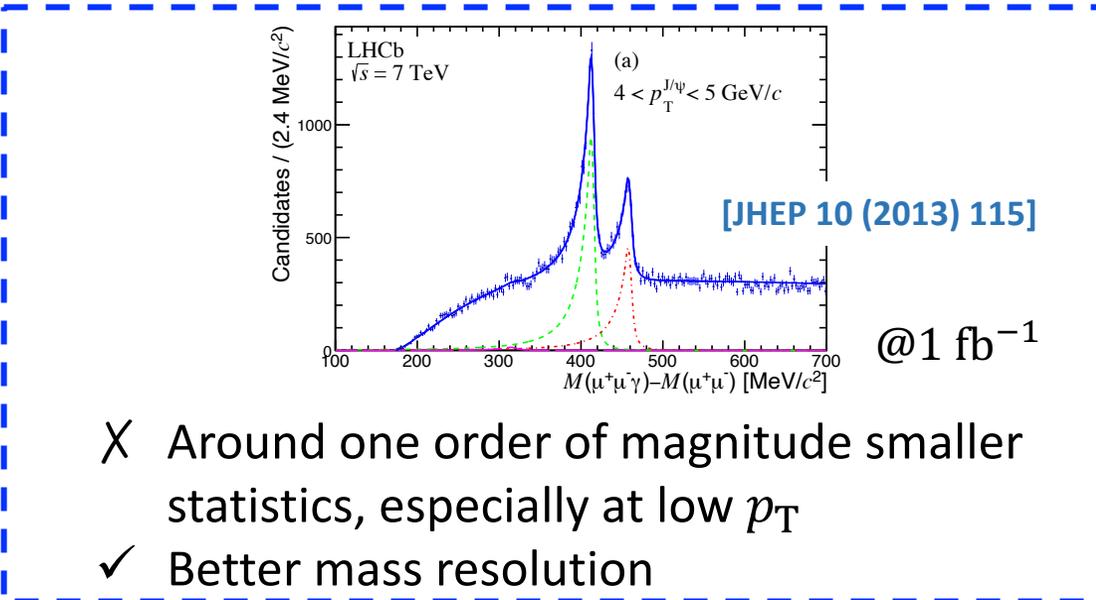
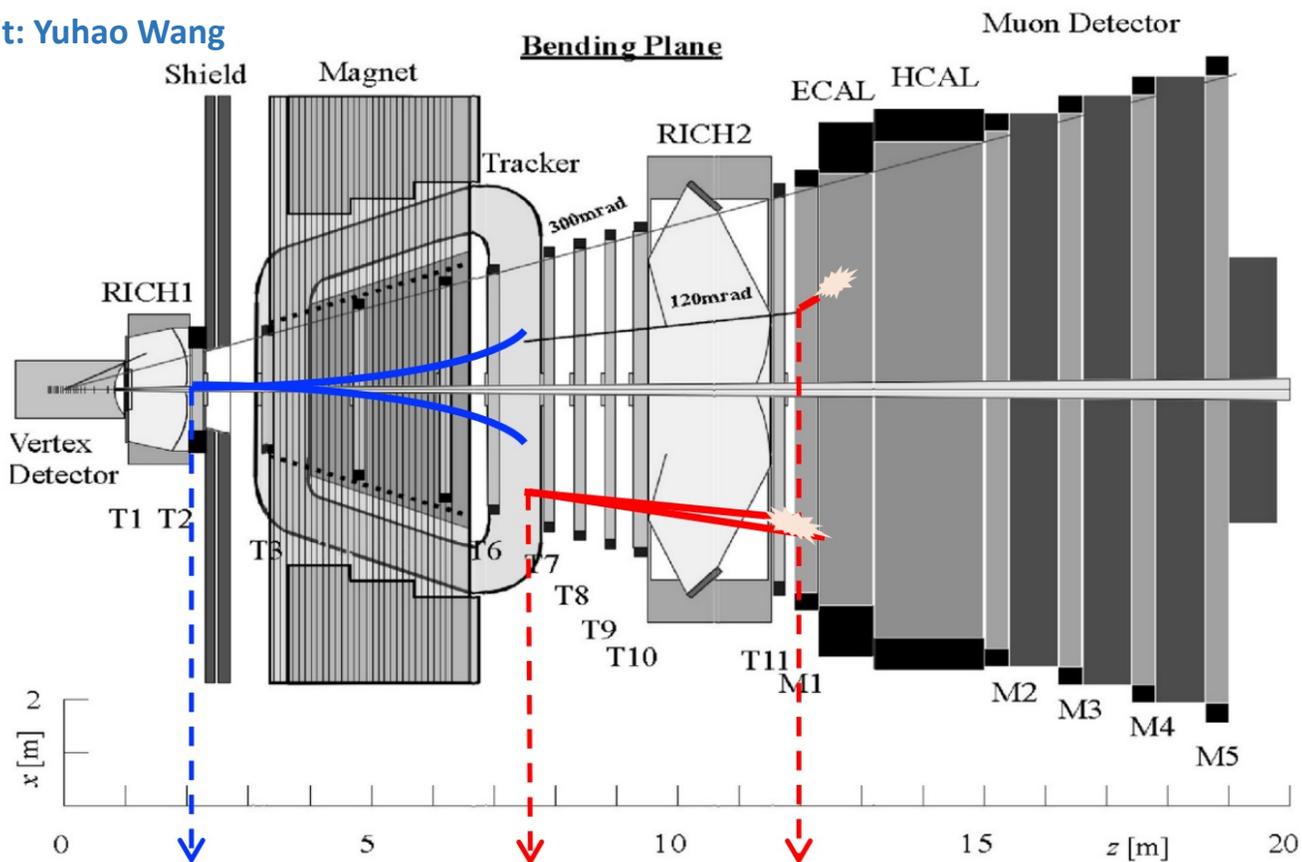
➤ $B_c(1P)^+$ states are searched for in $B_c^+\gamma$ mass spectrum in $340 < M(B_c^+\gamma)_{\text{rec}} - M(B_c^+) < 520$ MeV

	δM	$M(1^3P_0)$	$M(1P_1)$	$M(1P_1')$	$M(1^3P_2)$	θ [°]
Lattice QCD	41	6727	6743	6765	6783	33.4
GKLT	64	6683	6717	6729	6743	17.1
GJ	61	6689	6738	6757	6773	25.6
FUII	55	6701	6737	6760	6772	28.5
EFG	62	6699	6734	6749	6762	20.4
GI	67	6706	6741	6750	6768	22.4
EQ	54	6693	6731	6739	6759	18.7
LLLLGZ	55	6714	6757	6776	6787	35.5
WWLC	55	6705	6739	6748	6762	32.2
LTFWP	53	6712	6770	6761	6783	-24.3
LLWL	67	6701	6745	6754	6773	35.2
HZ	63	6707	6751	6786	6802	55.0

Photon reconstruction at LHCb

$$\chi_c \rightarrow J/\psi \gamma$$

Credit: Yuhao Wang



photons convert before magnet
 reconstructed from e^+e^-

photons convert after magnet
 non-converted photons
 reconstructed as calorimeter clusters



Liupan An

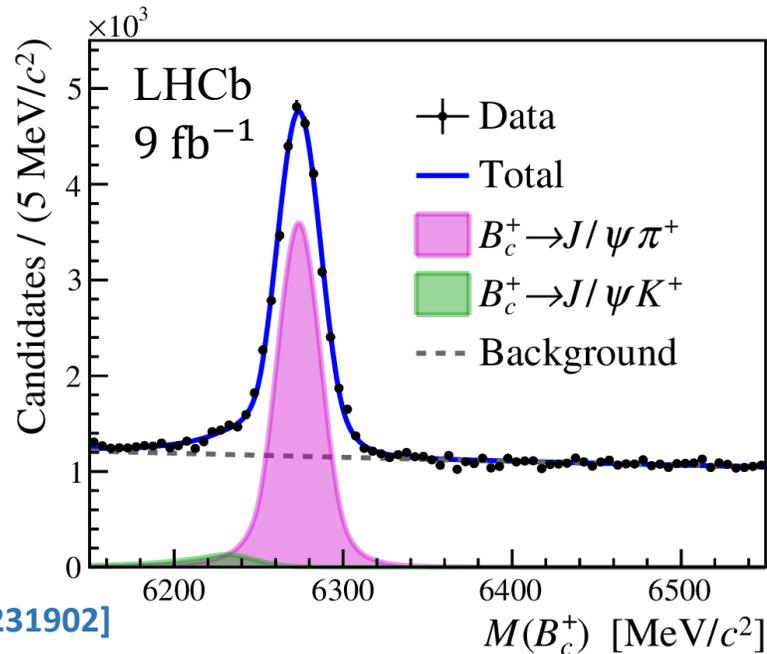


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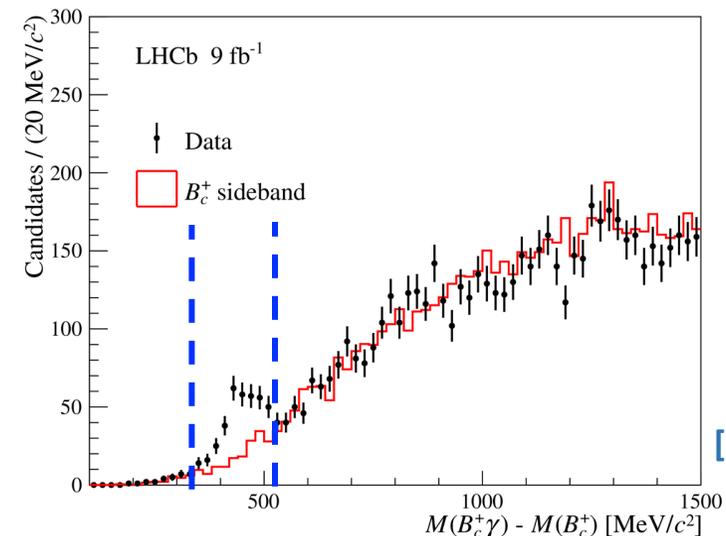
Study of $B_c^+ \gamma$ mass spectrum

- **Dataset:** Run1 & 2 data at LHCb corresponding to 9 fb^{-1}
- **Decay chain:** $B_c(1P)^+ \rightarrow B_c^+ \gamma, B_c^+ \rightarrow J/\psi \pi^+, J/\psi \rightarrow \mu^+ \mu^-$ (charge conjugation implied)
- **Candidate reconstruction and selection – photons reconstructed from calo clusters are used**
 - ✓ BDT classifier on B_c^+ to maximize the B_c^+ signal significance
 - ✓ Cut-based selections on $B_c(1P)^+$ to maximize Punzi figure-of-merit $\rightarrow \begin{matrix} E_T(\gamma) > 1 \text{ GeV} \\ E(\gamma) > 4 \text{ GeV} \end{matrix}$



[PRL 135 (2025) 231902]

$$N = (24.86 \pm 0.24) \times 10^3$$



[PRD 112 (2025) 112003]

- ✓ A **pronounced wide peaking structure** is evident within the predicted mass range for $B_c(1P)^+$

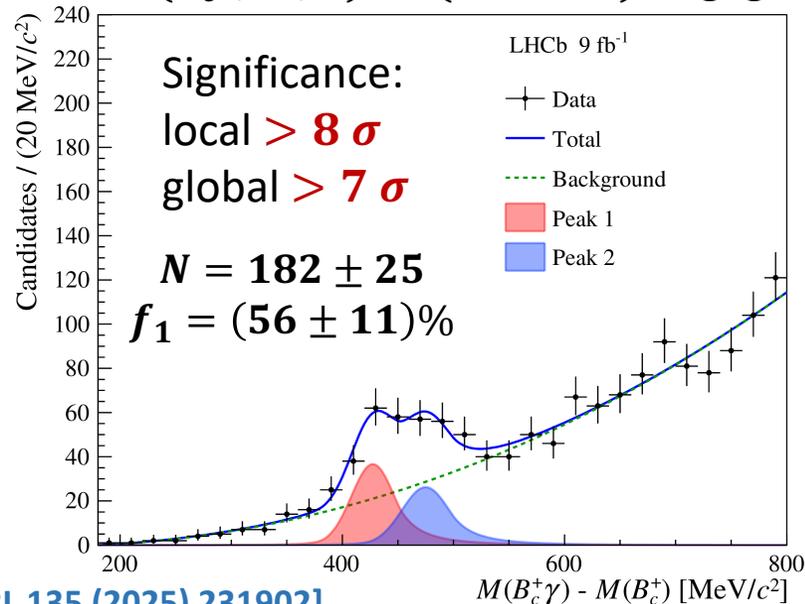
Observation of $B_c(1P)^+$ states

➤ **Photon energy correction** is applied to the simulation to eliminate the mismatch to data

◆ Theory-independent fit

- ✓ The visible width is $\sim 37 \text{ MeV}/c^2$
- ✓ Width of a single peak is $\sim 20 \text{ MeV}/c^2$
- ⇒ a **minimal effective two-peak model**

* $\Gamma(B_c(1P)^+) \sim \mathcal{O}(100 \text{ keV})$ negligible



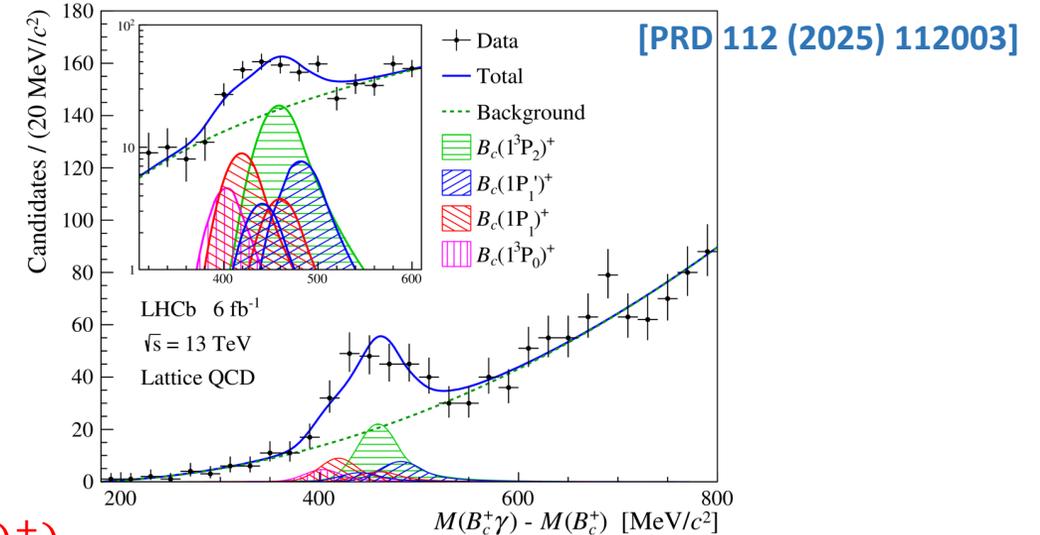
[PRL 135 (2025) 231902]

$$M_1 = 6704.8 \pm 5.5(\text{stat.}) \pm 2.8(\text{syst.}) \pm 0.3(B_c^+) \text{ MeV}/c^2$$

$$M_2 = 6752.4 \pm 9.5(\text{stat.}) \pm 3.1(\text{syst.}) \pm 0.3(B_c^+) \text{ MeV}/c^2$$

◆ Theory-constrained fit

- ✓ masses and relative yields of six peaks fixed according to predictions
- ⇒ verification of various QCD models



$$\frac{\sigma(B_c(1P)^+)}{\sigma(B_c^+)} = 0.20 \pm 0.03(\text{stat.}) \pm 0.02(\text{syst.}) \pm 0.03(\text{theo.})$$

for $p_T(B_c^+) < 20 \text{ GeV}/c$, $2.0 < y(B_c^+) < 4.5$ at $\sqrt{s} = 13 \text{ TeV}$

[Comput. Phys. Commun. 197 (2015) 335]

- ✓ consistent with BcVegPy calculations

Prospects on B_c^+ for Run3

◆ $B_c(1P)^+$: distinction of contributions from each $B_c(1P)^+$ state

- ✓ much larger statistics
- ✓ significant improvement in mass resolution:
 $\gamma \rightarrow e^+e^-$ conversion before magnet

◆ B_c spectroscopy

[PRD 70 (2004) 054017]

- ✓ B_c^{*+} : easier to measure from resolved $B_c(1P)^+$ states?
- ✓ $B_c(1D)$: dominant decay modes with multiple photons
- ✓ states above BD threshold may hold a better chance?

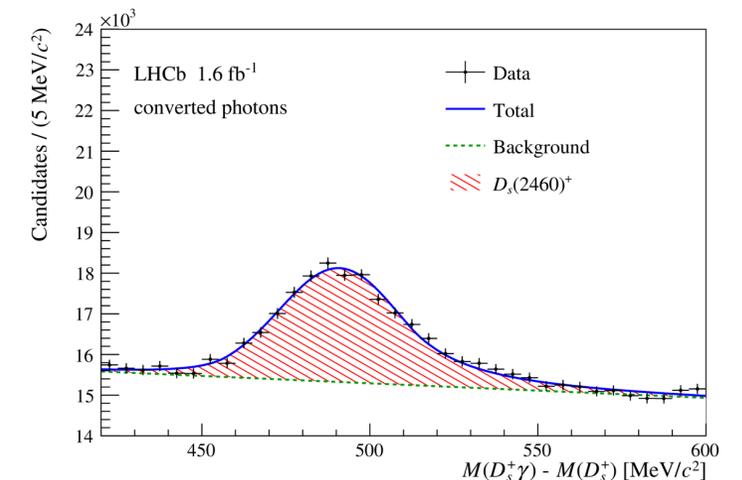
◆ B_c^+ -like exotics?

- ✓ naively, a rich set of $\bar{b}c + q\bar{q}/qqq$ states also expected
- ✓ decay modes for some of them are experimentally more friendly than higher excited states, e.g. $B_c^+ + p/K^\pm/\pi^\pm$

■ Spectroscopy studies using radiative decay

- ✓ potential well established by $B_c(1P)^+$ observation

Initial state	Final state	Width (keV)	B.F. (%)
1^3D_3	$1^3S_1 + \pi\pi$	4.3	5.2
	$1^3P_2 + \gamma$	78	94.8
	Total	82.3	100
$1D_2'$	$1^3S_1 + \pi\pi$	2.1	2.5
	$1^1S_0 + \pi\pi$	2.2	2.6
	$1^3P_2 + \gamma$	8.8	10.6
	$1P_1' + \gamma$	63	75.8
	$1P_1 + \gamma$	7	8.4
	Total	83.1	100
$1D_2$	$1^3S_1 + \pi\pi$	2.2	2.4
	$1^1S_0 + \pi\pi$	2.1	2.3
	$1^3P_2 + \gamma$	9.6	10.3
	$1P_1' + \gamma$	15	16.1
	$1P_1 + \gamma$	64	68.9
	Total	92.9	100
1^3D_1	$1^3S_1 + \pi\pi$	4.3	4.6
	$1^3P_2 + \gamma$	1.8	1.9
	$1P_1' + \gamma$	4.4	4.7
	$1P_1 + \gamma$	28	29.9
	$1^3P_0 + \gamma$	55	58.8
Total	93.5	100	



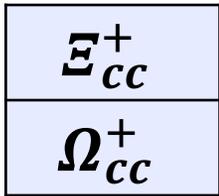
Prospects on doubly-heavy baryon for Run3



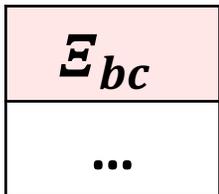
➤ Possibility for excited Ξ_{cc}^{++} ?

A small ray of hope comes from the observation of the doubly-heavy $B_c = (\bar{b}c)$ mesons [14], suggesting that simultaneous production of $\bar{b}b$ and $\bar{c}c$ pairs which are close to each other in space and in rapidity and can coalesce to form doubly-heavy hadrons is not too rare. For example, in the last paper

[JHEP 07 (2013) 153]



➤ Highly promising in Run3

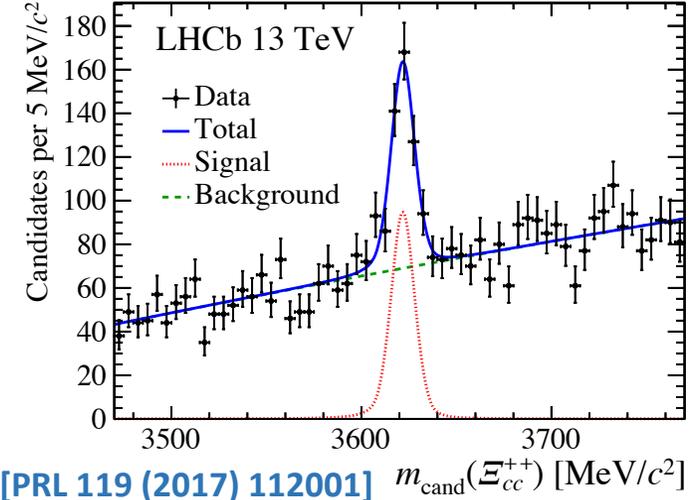


✓ Reference: $\sim 100 B_c^+ \rightarrow J/\psi D_s^+$ with 3 fb^{-1} @ 7/8 TeV

✓ Assuming (with sizable uncertainties):

- $f_{\Xi_{bc}^+} / f_{B_c^+} \sim 0.2$
- $\mathcal{B}(\Xi_{bc}^+ \rightarrow J/\psi \Xi_c^+) / \mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+) \sim 1$
- $\mathcal{B}(\Xi_c^+ \rightarrow p K^- \pi^+) / \mathcal{B}(D_s^+ \rightarrow K^+ K^- \pi^+) \sim 0.1$
- $\varepsilon_{\Xi_{bc}^+} / \varepsilon_{B_c^+} \sim 0.5$

$$N = \mathcal{L} \times \sigma \times \mathcal{B} \times \varepsilon$$



[PRL 119 (2017) 112001] $m_{\text{cand}}(\Xi_{cc}^{++})$ [MeV/c²]

$$\tau(\Xi_{cc}^{++}(ccu)) \gg \tau(\Xi_{cc}^+(ccd))$$

[arXiv:1808.08865]

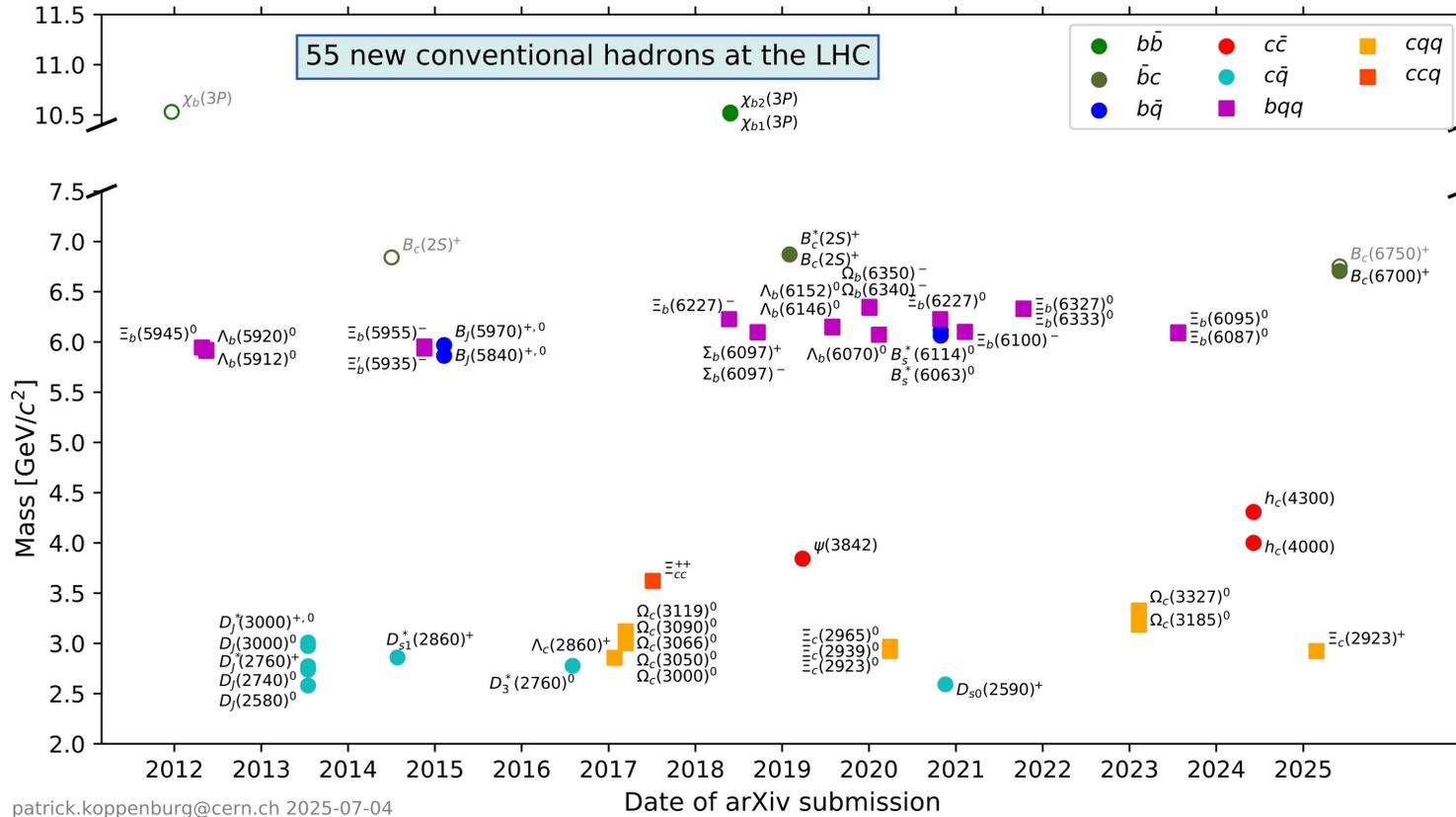
⇒ $\mathcal{O}(10)$ with 30 fb^{-1} @ 14 TeV

& combination of different modes

◆ **Potential for discovery in Run3**

Conclusion

➤ The LHC experiments maintain a strong momentum in conventional hadron spectroscopy



<https://www.nikhef.nl/~pkoppenb/particles.html>

➤ More exciting results expected from Run3

Stay tuned!

Thank you!

Photon energy correction in simulation

mass measurement

resolution of multiple peaks

- Knowledge on *photon energy scale* and *resolution* is required to interpret the structure
- They can be obtained from simulation, but **photon energy correction** needs to be applied to the simulation to eliminate mismatch between simulation and data

● Reference mode: $\chi_{c1} \rightarrow J/\psi\gamma$

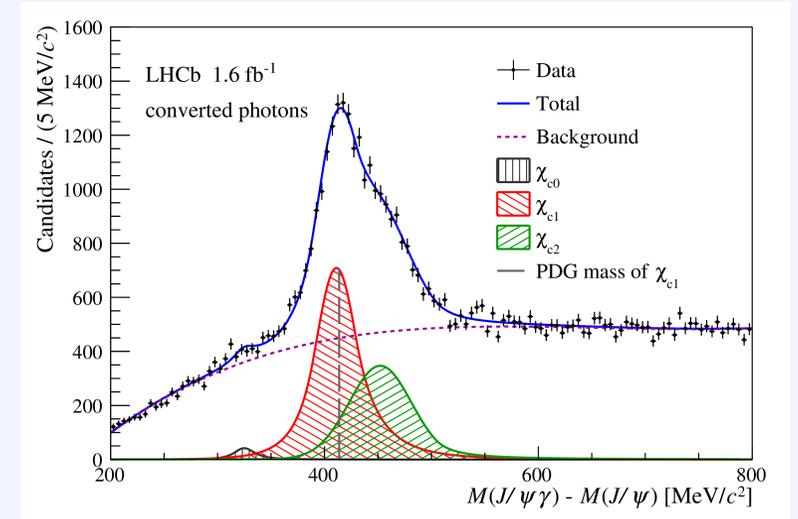
- ✓ similar photon energy spectrum to signal decay
- ✓ identical photon selections are applied

● Extraction of correction parameters:

- ✓ separately for converted and non-converted photons
- ✓ independently for each data-taking period
- ✓ in bins of E_γ and n_{tracks}
(prominent variables that corrections are dependent on)
- ✓ **key linear relation** (well established by simulation):

$$\text{photon energy bias} \sim M(\chi_{c1}) - M_{\text{PDG}}(\chi_{c1})$$

$$\text{photon energy resolution} \sim \sigma(M(\chi_{c1}))$$



- ✓ **Resonances:** non-relativistic Breit Wigner (width fixed) ⊗ double-sided Crystal Ball (DSCB, Gaussian kernel with tails)
- ✓ **Background:** third-order polynomial

Check of photon energy correction

- The corrections are applied to simulated samples on a **per-event** basis, taking the photon energy bias and resolution extracted for the corresponding E_γ and n_{tracks} bin
- The correction parameters and the method are **validated** before application to $B_c^+ \gamma$

- **Self-consistency check: good agreement** (e.g. converted photons @2016)

- ✓ $\chi_{c1} \rightarrow J/\psi\gamma$: ΔM : 2.0 \rightarrow 0.3 MeV/ c^2 ; $\Delta\sigma$: 0.3 \rightarrow 0.1 MeV/ c^2

- ✓ $\chi_{c2} \rightarrow J/\psi\gamma$: ΔM : 2.0 \rightarrow 0.4 MeV/ c^2 ; $\Delta\sigma$: 0.7 \rightarrow 0.4 MeV/ c^2

- **Independent validation: $D_{s1}(2460)^+ \rightarrow D_s^+ \gamma$**

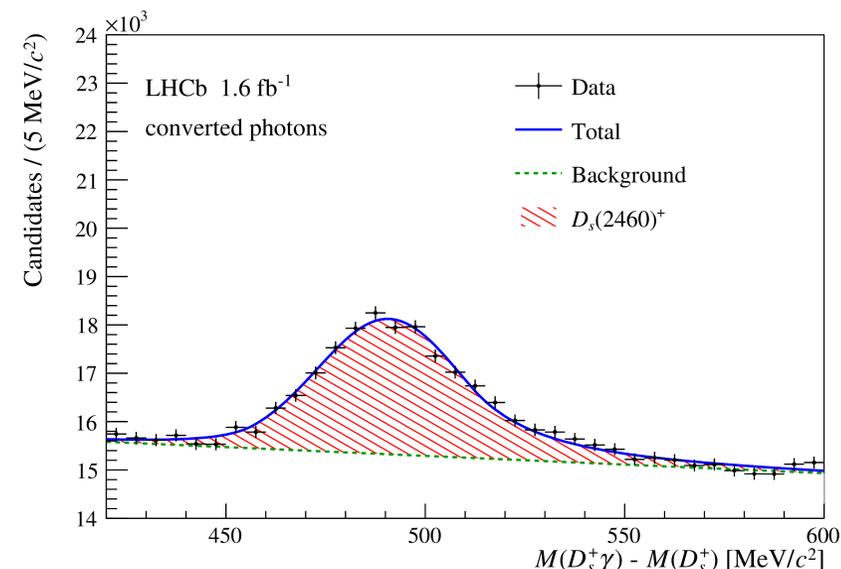
- ✓ similar photon energy spectrum and decay topology

- ✓ the largest remaining difference among all categories is

- ΔM : 3.6 \rightarrow 2.9 MeV/ c^2

- $\Delta\sigma$: 4.6 \rightarrow 2.6 MeV/ c^2

- \Rightarrow scaled to $B_c(1P)^+ \rightarrow B_c^+ \gamma$ according to energy release as **systematic uncertainty** on peak location measurement



Measurement on $D_{s1}(2460)^+ \rightarrow D_s^+ \gamma$ is by itself an interesting topic given $D_{s1}(2460)^+$ is a $D^ K$ molecule candidate

Theory-constrained mass fits (I)

For a given theoretical model,

➤ masses fixed to prediction

➤ relative yields of six peaks fixed as $N_i = \sigma_{\text{prod},i} \cdot \mathcal{B}_i \cdot \varepsilon_i$

	1^1S_0	1^3S_1	1^1P_1	1^3P_0	1^3P_1	1^3P_2	$1S_0g$	$3S_1g$	2^1S_0	2^3S_1
σ_{prod} [nb]	18.8	48.7	3.5	1.1	2.7	7.2	0.4	1.55	4.5	11.1

✓ calculated using BcVegPy [Comput. Phys. Commun. 197 (2015) 335]

✓ $B_c(2S)^+ \rightarrow B_c(1P)^+$ feeddown is considered

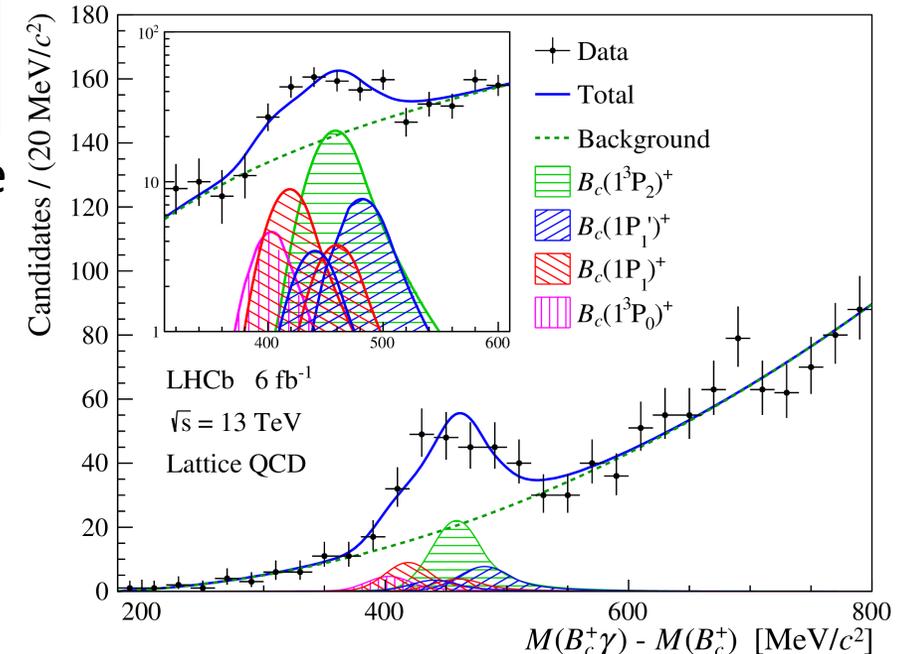
✓ \mathcal{B}_i : obtained from GI model with masses and mixing angle modified for each specific model [PRD 70 (2004) 054017]

✓ ε_i : estimated with simulation

◆ All considered models provide a generally good description, with p -values ranging from 15% to 90%

◆ **Lattice QCD calculation** by *Davies et al.* is taken as baseline, as it is first-principle & provides highest p -value

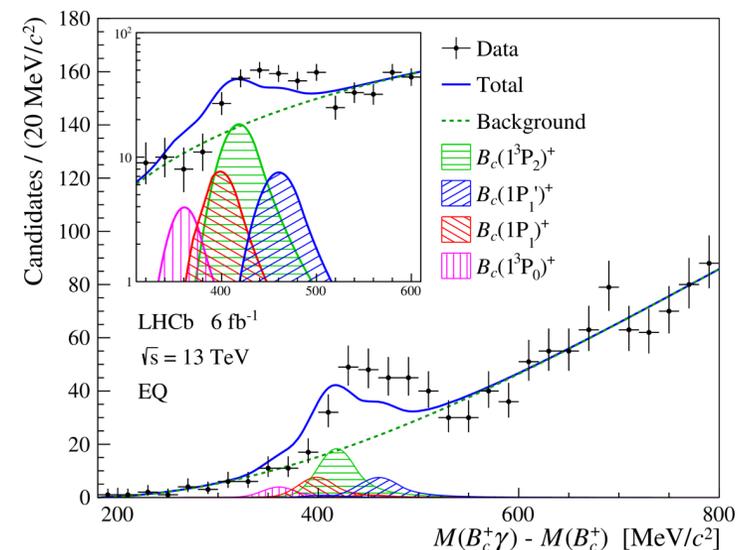
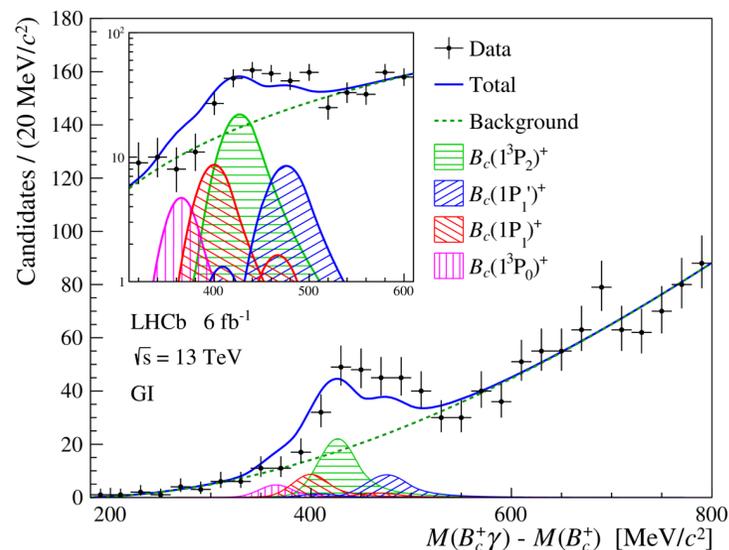
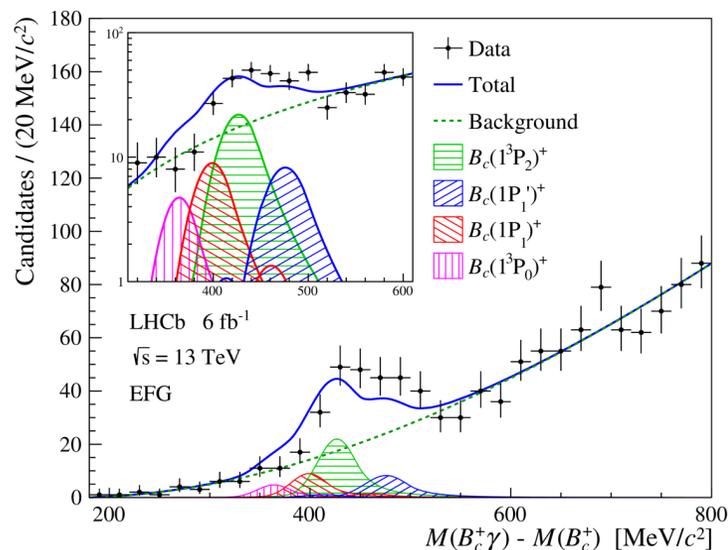
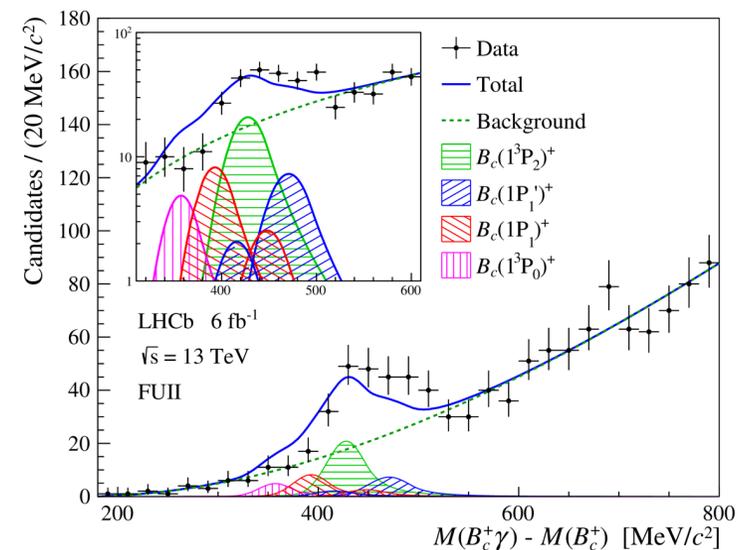
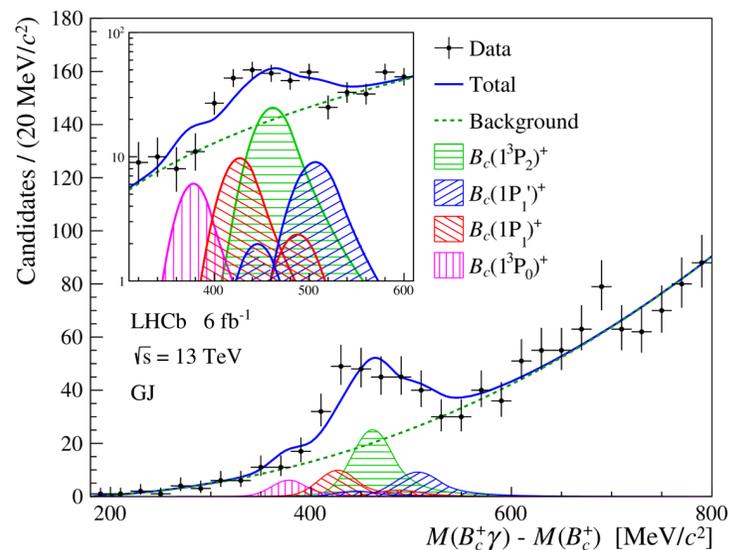
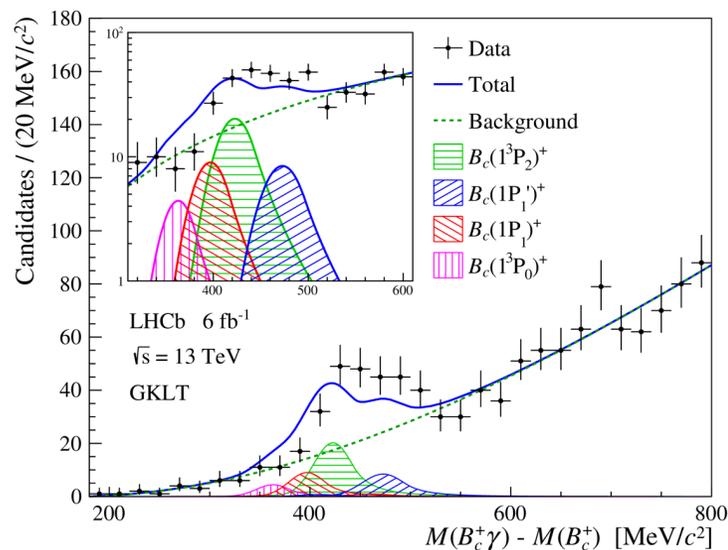
	δM	$M(1^3P_0)$	$M(1P_1)$	$M(1P_1')$	$M(1^3P_2)$	θ [°]
Lattice QCD	41	6727	6743	6765	6783	33.4
GKLT	64	6683	6717	6729	6743	17.1
GJ	61	6689	6738	6757	6773	25.6
FUII	55	6701	6737	6760	6772	28.5
EFG	62	6699	6734	6749	6762	20.4
GI	67	6706	6741	6750	6768	22.4
EQ	54	6693	6731	6739	6759	18.7
LLLLGZ	55	6714	6757	6776	6787	35.5
WWLC	55	6705	6739	6748	6762	32.2
LTFWP	53	6712	6770	6761	6783	-24.3
LLWL	67	6701	6745	6754	6773	35.2
HZ	63	6707	6751	6786	6802	55.0



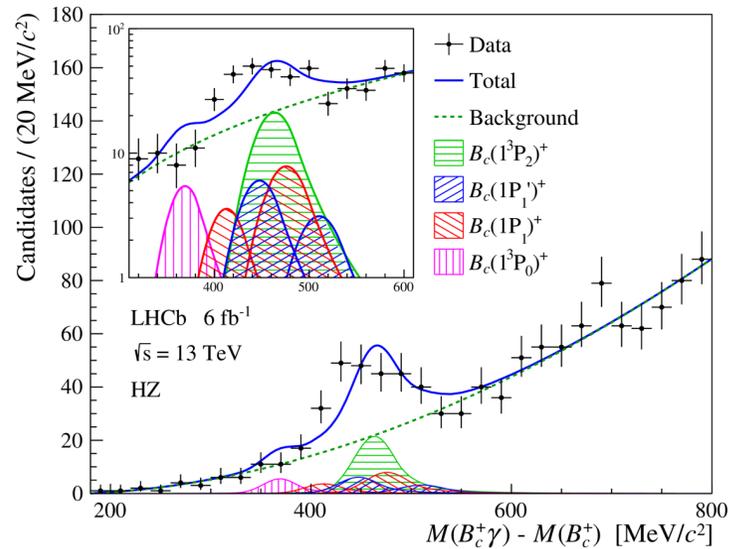
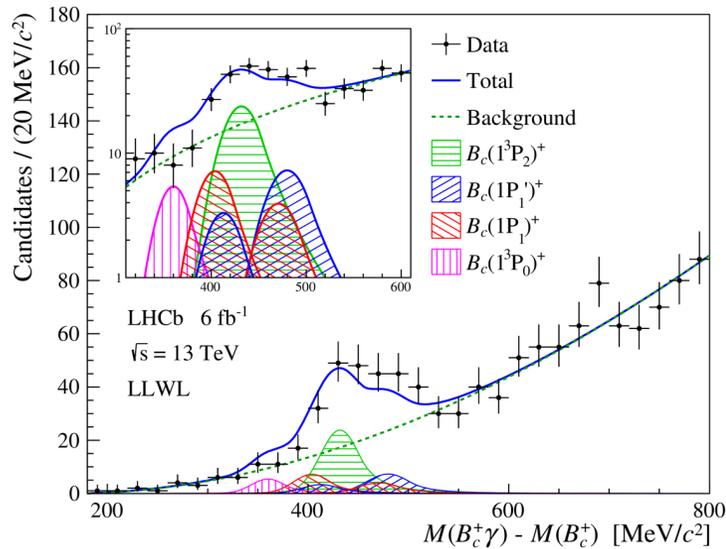
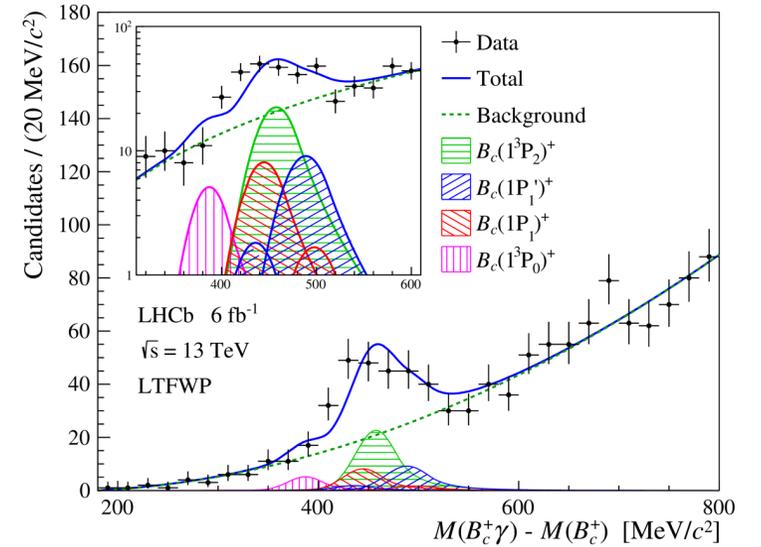
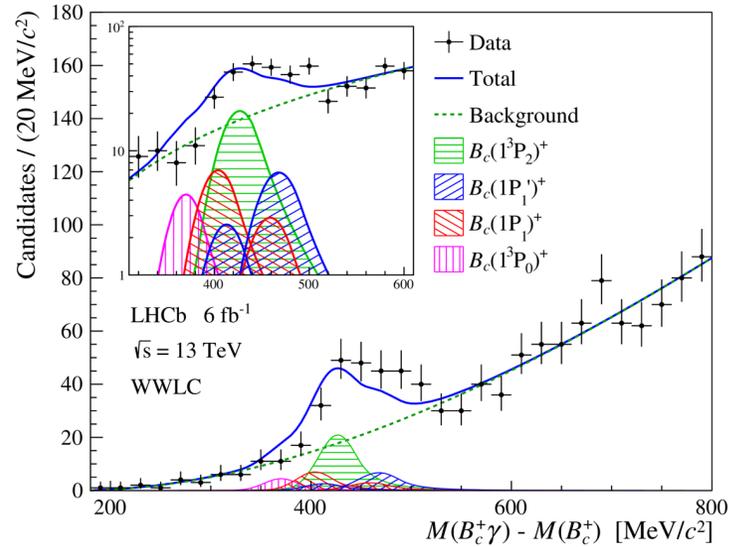
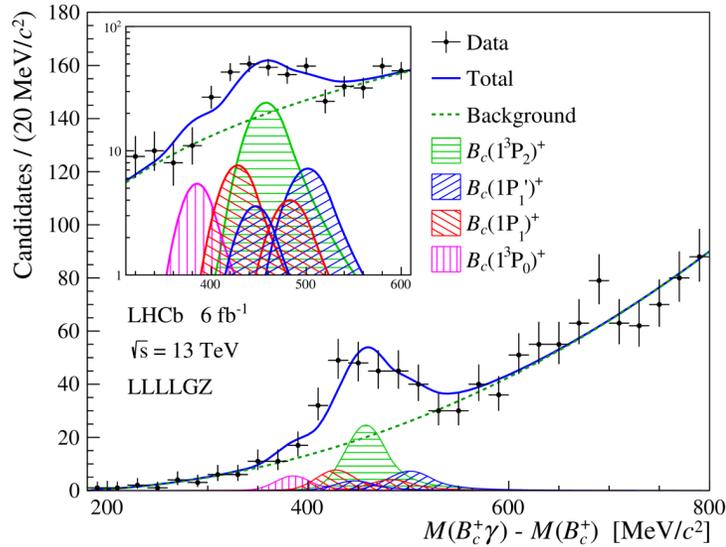
$N = 153 \pm 22$

34/30

Theory-constrained mass fits (II)



Theory-constrained mass fits (III)



*The fit quality is not solely due to **mass predictions**, but also affected by the **relative yields of six peaks**, according to predictions on **production, branching fractions** and **mixing angle**