Charm and bottom spectroscopy at the LHC

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on behalf of ATLAS, CMS and LHCb collaborations

QCD@LHC 2022
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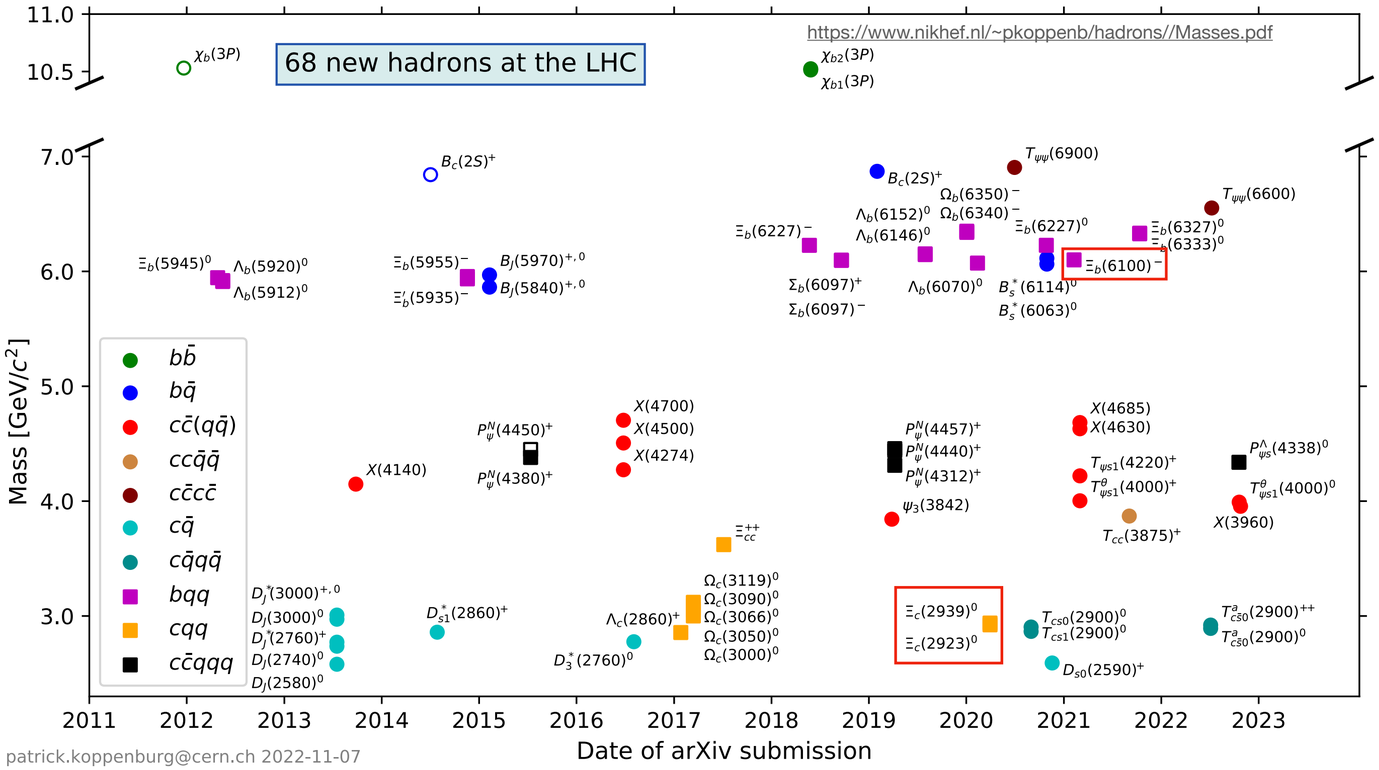
Introduction

- QCD at non-perturbative regime:
  - **Lattice QCD** — first principle approach but yet limited application
  - **Effective theory** and **phenomenological models** proposed
- Hadron spectroscopy provides important inputs



New “Exotic hadron naming convention” proposed by LHCb: arXiv:2206.15233

Introduction

- Recent results on conventional spectroscopy from LHC experiments:

  LHCb:

  - **Study of the $B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-$ decay** [arXiv:2211.00812]
  - Measurement of the ratio of branching fractions $\mathscr{B}(B_c^+ \to B_s^0 \pi^+)/\mathscr{B}(B_c^+ \to J/\psi \pi^+)$ [arXiv:2210.12000]
  - **Study of B_c^+ meson decays to charmonia plus multihadron final states** [arXiv:2208.08660]
  - **Search for doubly heavy baryon Ξ_{bc}^+ decaying to $J/\psi \Xi_c^+$** [arXiv:2204.09541]
  - Observation of two new excited Ξ_b^0 states decaying to $\Lambda_b K^- \pi^+$ [Phys. Rev. Lett. 128, 162001]
  - Observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c'^+ \pi^+$ [J. High Energ. Phys. 2022, 38]
  - Observation of the $B_s^0 \to D^{*-} D^{*+}$ decay [arXiv:2210.14945]

  CMS:

  - Observation of $B^0 \to \psi(2S) K_s^0 \pi^+ \pi^-$ and $B^0 \to \psi(2S) K_s^0$ decays [Eur. Phys. J. C 82, 499]
  - **Observation of a new excited beauty strange baryon decaying to $\Xi_b^- \pi^+ \pi^-$** [Phys. Rev. Lett. 126, 252003]

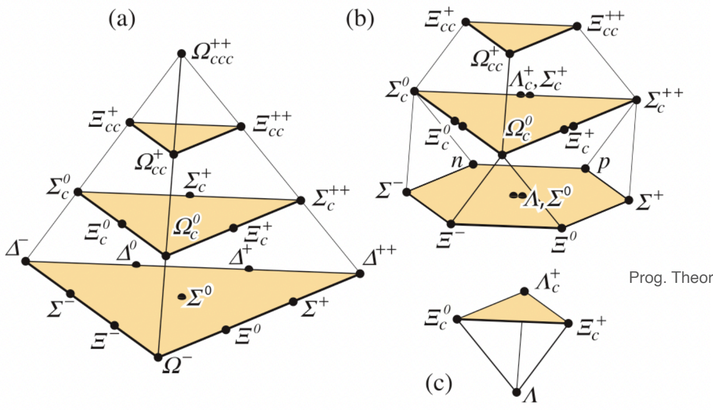
  ATLAS:

  - **Study of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays** [J. High Energ. Phys. 2022, 87]

- Results on exotic spectroscopy are covered in the talk by Mindaugas Sarpis later this afternoon

Study of singly heavy baryons

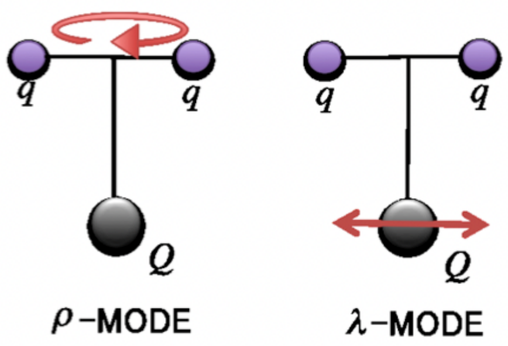
- Quark model predicts a **rich spectrum** of singly heavy baryons
- Spectra similar for c-baryons and b-baryons ($c \leftrightarrow b$ in $SU(4)_f$ multiplets)
- λ-type excitations dominate low-lying singly heavy states
- ~ 26 c-baryons and ~19 b-baryons in PDG, with many new to come
- Increasing precision allows **separating previously unresolvable states**
  - $\Xi_c(2930)^0$ measured by BaBar, later Belle
  - Resolved into $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ by LHCb



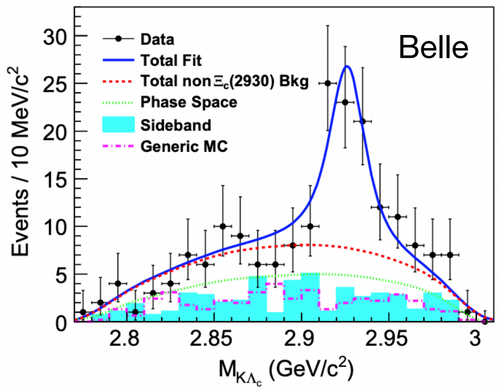
Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

$SU(4)_f$ multiplets: a) 20-plet of spin 3/2, b) 20-plet of spin 1/2, c) the $\bar{4}$-plet

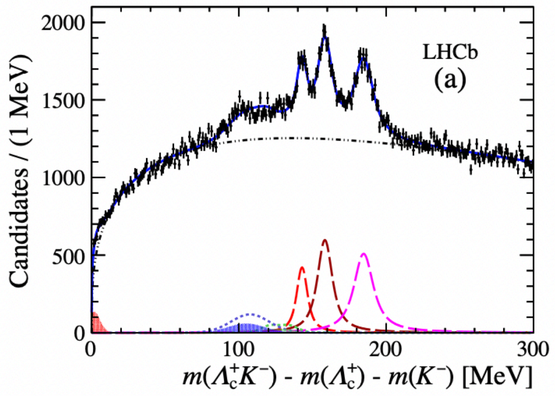
Phys. Rev. D **92**, 114029 (2015)



Eur. Phys. J. C (2018) 78:252



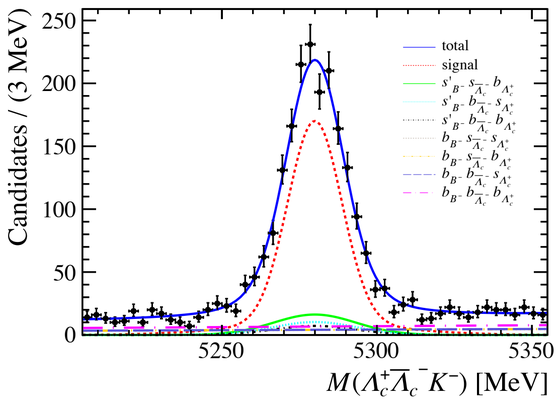
Phys. Rev. Lett. **124**, 222001 (2020)

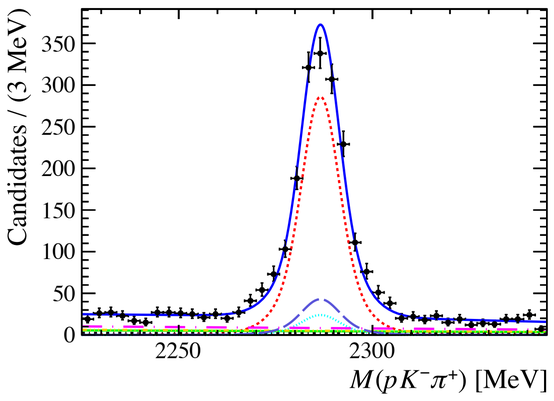


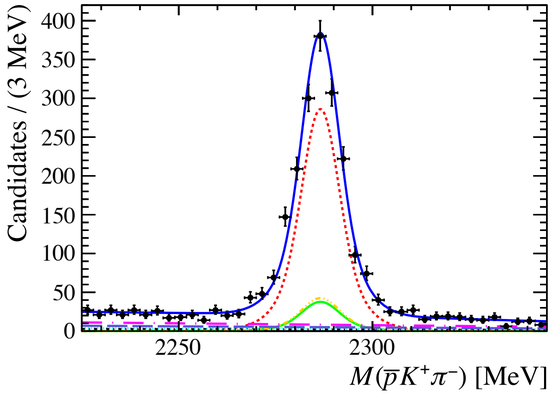
[arXiv:2211.00812]

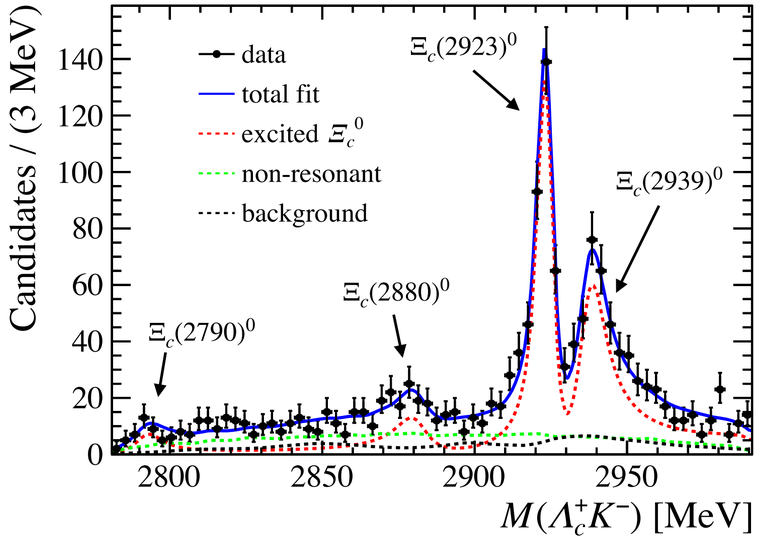
New excited Ξ_c^0 resonances in $B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-$ decays

- Signal extracted using 3D fit to invariant mass of B^-, Λ_c^+ and $\bar{\Lambda}_c^-$ candidates
- No significant structures in $m(\bar{\Lambda}_c^- K^-)$ and $m(\Lambda_c^+ \bar{\Lambda}_c^-)$
- Observed states can be interpreted as a part of **1P multiplet** with $J^P = (1/2)^-, (1/2)^-, (3/2)^-, (3/2)^-$ (alternative model for systematics)
  - Precise **measurement of the quantum numbers** is needed









$\Xi_c(2790)^0$: 3.7σ — evidence of a new decay mode

$\Xi_c(2880)^0$: 3.8σ — evidence of a new state

$$m(\Xi_c(2923)^0) = 2924.5 \pm 0.4 \pm 1.1 \text{ MeV}, \qquad \Gamma(\Xi_c(2923)^0) = 4.8 \pm 0.9 \pm 1.5 \text{ MeV}$$

$$m(\Xi_c(2939)^0) = 2938.5 \pm 0.9 \pm 2.3 \text{ MeV}, \qquad \Gamma(\Xi_c(2939)^0) = 11.0 \pm 1.9 \pm 7.5 \text{ MeV}$$

[Phys. Rev. Lett. 126, 252003]

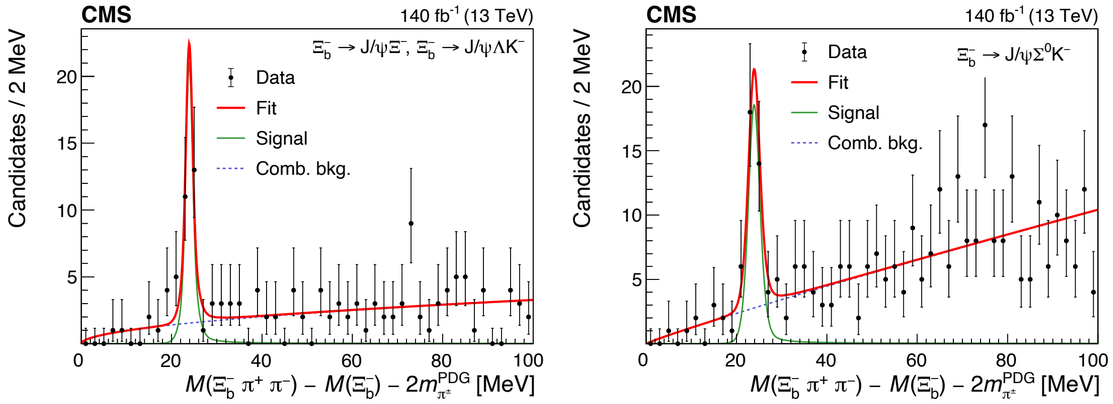
Observation of a new excited Ξ_b^- state

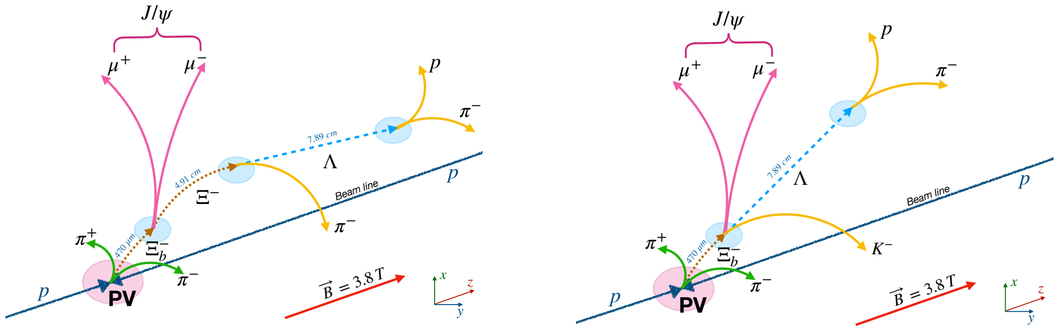
- Search simultaneously in several topologies
  - Including partially reconstructed $\Xi_b^- \to J/\psi\Sigma^0(\to \Lambda\gamma)K^-$ with soft photon
- Observed peak in $\Xi_b^-\pi^+\pi^-$ spectrum

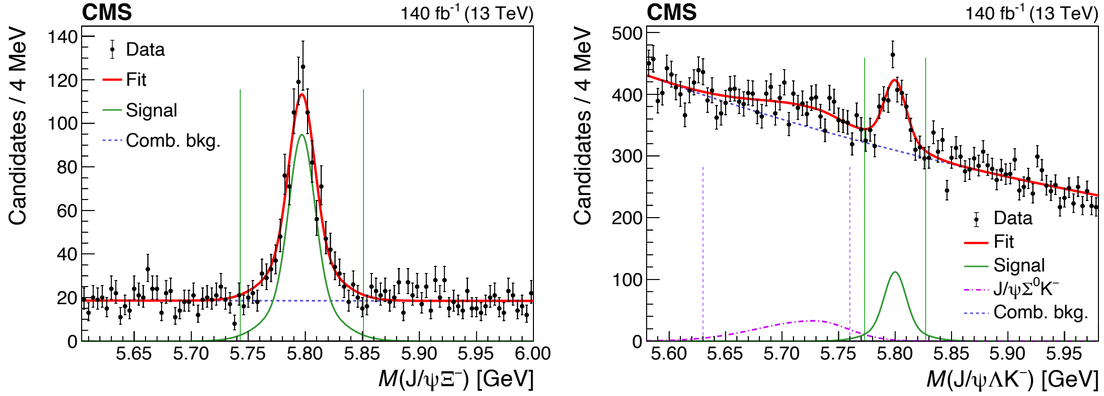
$$m(\Xi_b(6100)^-) = 6100.3 \pm 0.2(stat) \pm 0.1(syst) \pm 0.6(\Xi_b^-)\ \text{MeV}$$

$$\Gamma(\Xi_b(6100)^-) < 1.9\ \text{MeV}$$

- In analogy with Ξ_c states: $J^P = 3/2^-$



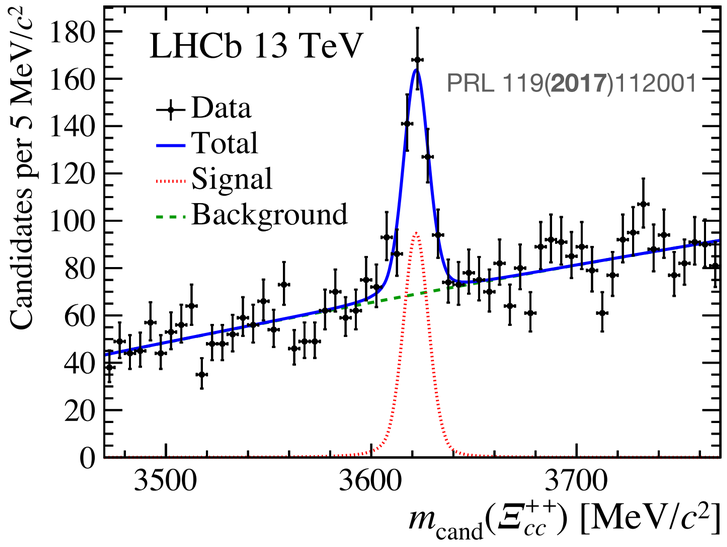


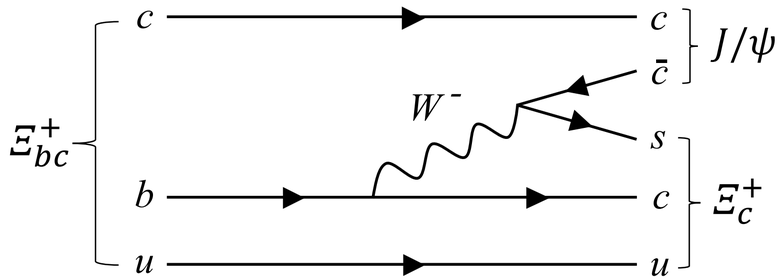


Fit to mass spectra with Ξ_b^0 signal

Doubly heavy baryons

- Doubly heavy baryons consist of **two heavy** and one light quark (ccq, bcq, bbq)
- **First doubly heavy baryon** $\Xi_{cc}^{++}(ccu)$ established by LHCb
- Further searches for $\Xi_{cc}^{+}(ccd)$[1,2] and $\Omega_{cc}^{+}(ccs)$[3] were performed — only hints of a signal
- Also searches for $\Xi_{bc}^{0}(bcd)$[4] and $\Omega_{bc}^{0}(bcs)$[5], yet no signal
- $\Xi_{bc}^{+}(bcu) \to J/\psi \Xi_{c}^{+}$ is a **promising channel** for new doubly heavy baryon searches
  - Predicted $\tau(\Xi_{bc}^{+}) > \tau(\Xi_{bc}^{0}, \Omega_{bc}^{0})$ — separates from prompt background
  - High-efficiency $J/\psi \to \mu^+\mu^-$ selection
  - No other Cabibbo-suppression than V_{cb}





Leading order diagram for the $\Xi_{bc}^{+}(bcu) \to J/\psi \Xi_{c}^{+}$ decay

[1] *Sci. China Phys. Mech. Astron.* **63**, 221062 (2020)
[2] *J. High Energ. Phys.* **2021**, 107 (2021)
[3] *Sci. China Phys. Mech. Astron.* **64**, 101062 (2021)
[4] *J. High Energ. Phys.* **2020**, 95 (2020)
[5] *Chinese Phys. C* **45** 093002 (2021)

Search for doubly heavy Ξ_{bc}^{+}

- Search performed in full LHCb pp dataset ($9\ fb^{-1}$)
- Estimated yield using $B_c^+ \to J/\psi D_s^+$ for normalization:
  - $N(B_c^+ \to J/\psi D_s^+) \approx 1100$ after reconstruction and selection in the full dataset
  - $\mathscr{R} \approx 0.015$
  - Assuming efficiency ratio ≈ 1 expect $N(\Xi_{bc}^+) \approx 15$
- Some local excesses are seen -> test for look-elsewhere effect
- No excess larger than 3σ (global) observed — upper limit set

Expected value:

$$\mathscr{R} = \frac{\sigma(\Xi_{bc}^+) \times \mathscr{B}(\Xi_{bc}^+ \to J/\psi \Xi_c^+) \times \mathscr{B}(\Xi_c^+ \to pK^-\pi^+)}{\sigma(B_c^+) \times \mathscr{B}(B_c^+ \to J/\psi D_s^+) \times \mathscr{B}(D_s^+ \to K^+K^-\pi^+)} \approx 0.015$$

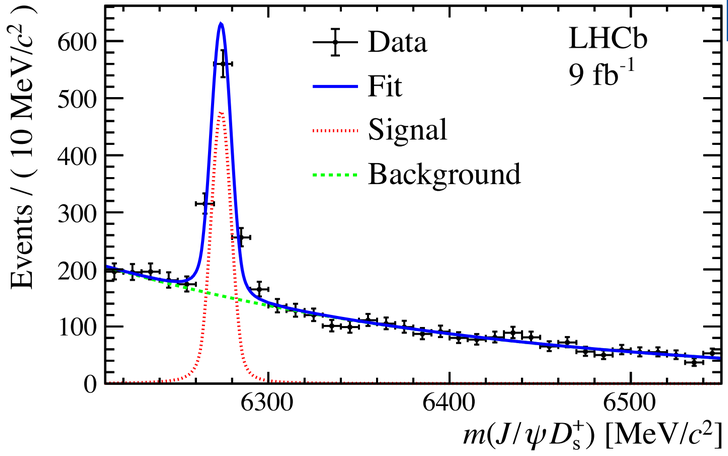
cross-section fraction ~0.4

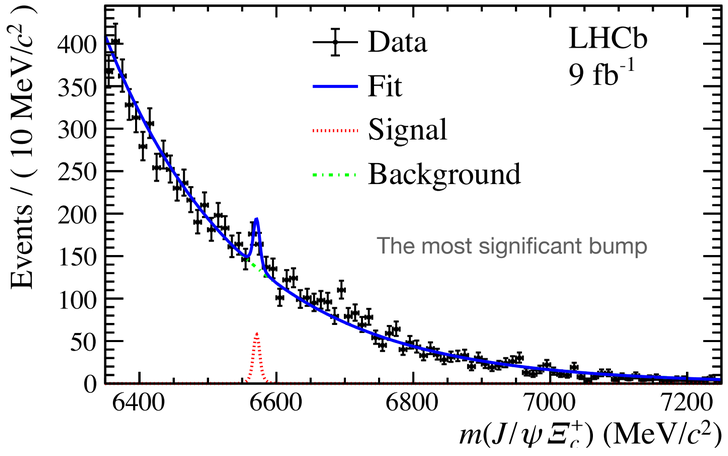
Same diagrams but color suppression (1/3)

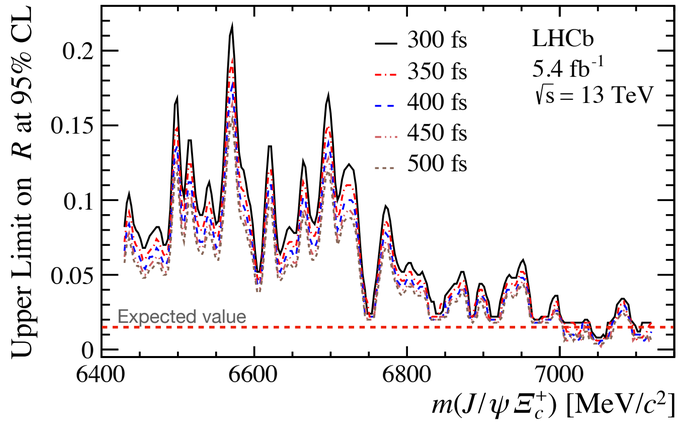
From PDG: BF ratio ~ 0.12

Upper limit is greater than a prediction at almost all the range -> **more data is needed**

[arXiv:2204.09541]



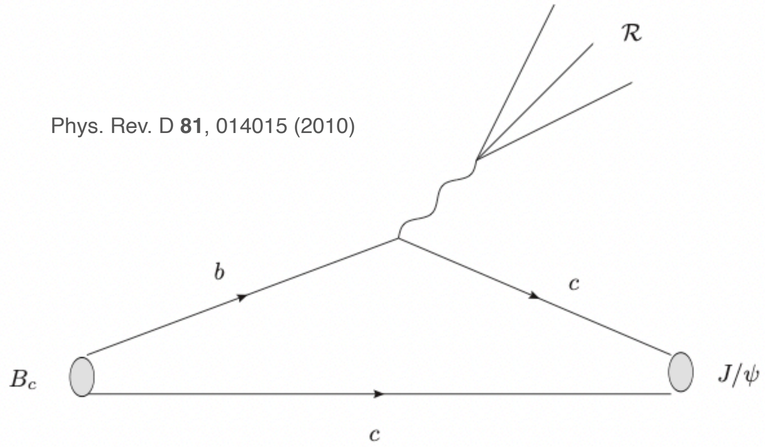


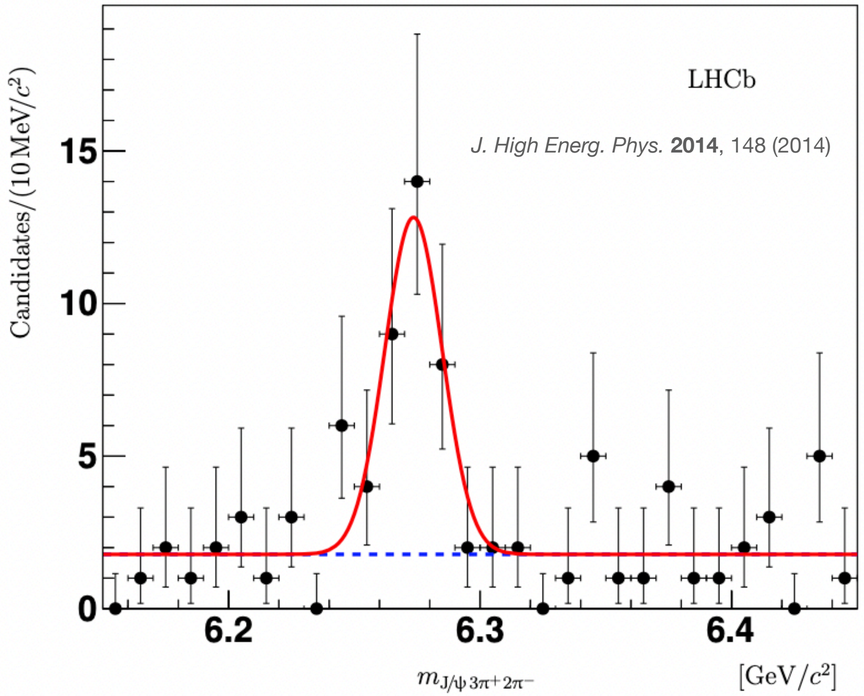


[arXiv:2208.08660]

B_c^+ decay to charmonia and multihadron

- B_c^+ meson is a system of **two heavy quarks**: b and c
- Rich set of decay modes: either of **quarks decay** or **annihilation** into W^+
- Decay to J/ψ and light hadrons can be described using **QCD factorisation**:
  - Transition $B_c^+ \to J/\psi W^+$
  - W^+ **fragmentation** into light hadrons (e.g. multihadron τ decays)

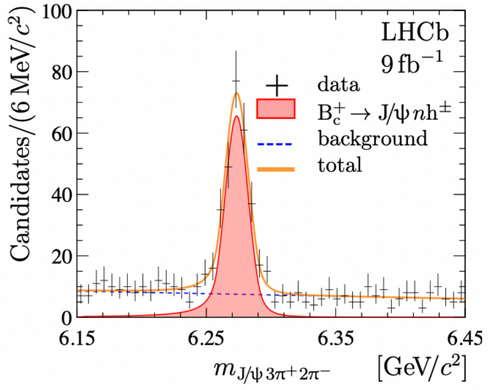


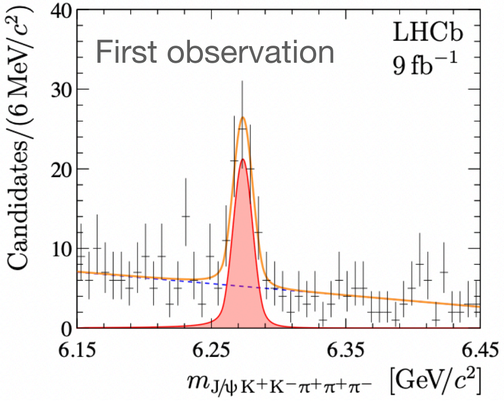


[arXiv:2208.08660]

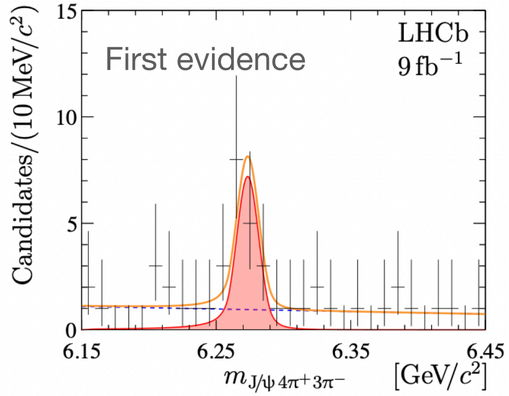
B_c^+ decay to charmonia and multihadron

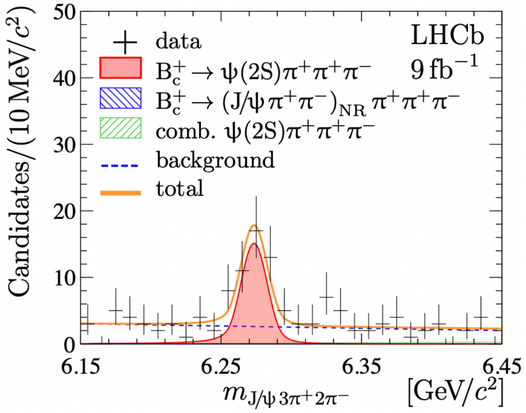
- Charmonia (J/ψ, $\psi(2S)$) with five (5π, $2K3\pi$) or seven (7π) light hadrons in final state
- New decay modes, BF ratios to $3\pi^+2\pi^-$ measured
- Data compared to spectral functions predicted by BLL[1] model — shows **good agreement**

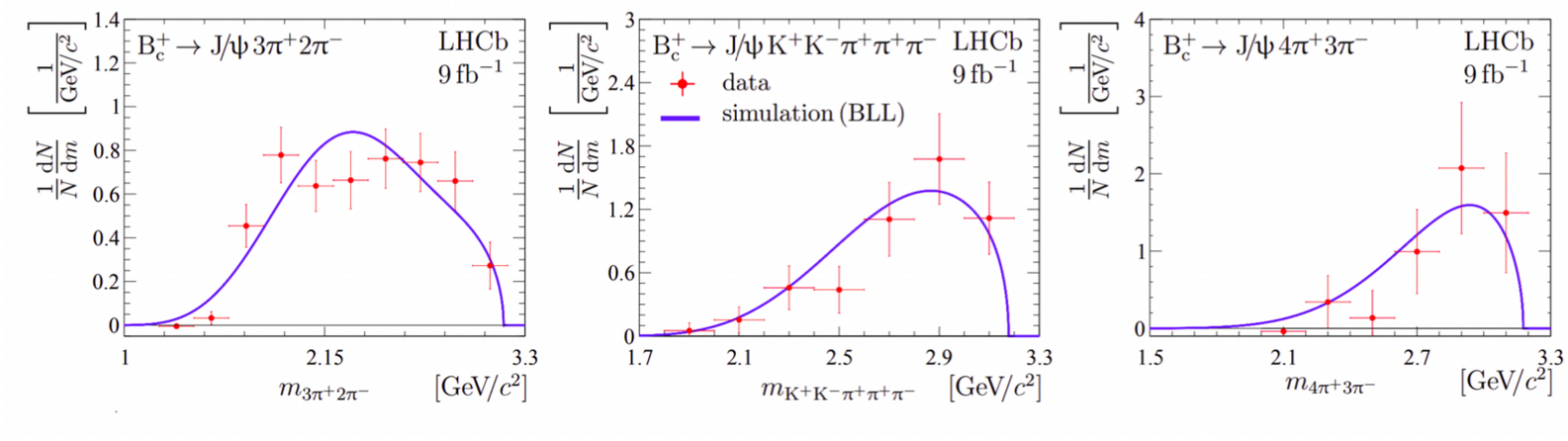




$$\mathcal{R}^{J/\psi K^+K^-\pi^+\pi^+\pi^-}_{J/\psi 3\pi^+2\pi^-} = (33.7 \pm 5.7) \times 10^{-2}$$
$$\mathcal{R}^{J/\psi 4\pi^+3\pi^-}_{J/\psi 3\pi^+2\pi^-} = (28.5 \pm 8.7) \times 10^{-2}$$
$$\mathcal{R}^{\psi(2S)\pi^+\pi^+\pi^-}_{J/\psi 3\pi^+2\pi^-} = (17.6 \pm 3.6) \times 10^{-2}$$







[1]Phys. Rev. D **81**, 014015 (2010)

[J. High Energ. Phys. 2022, 87]

Measurement of $B_c^+ \to J/\psi D_s^{(*)+}$ branching fractions

- First observed in LHCb, later in ATLAS with Run 1 pp data
- Branching fraction ratios are measured in ATLAS with Run 2 data:

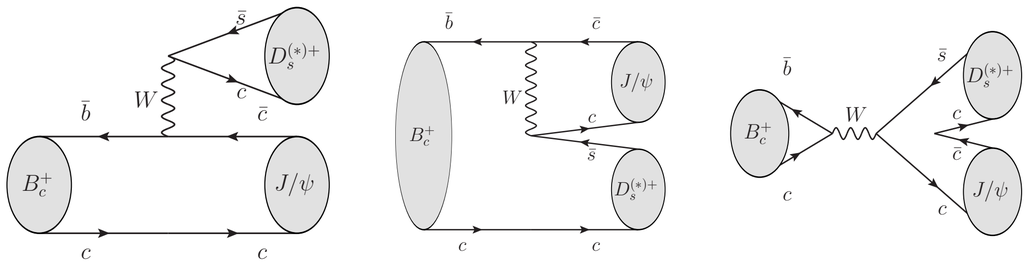
$$\frac{\mathscr{B}(B_c^+ \to J/\psi D_s^+)}{\mathscr{B}(B_c^+ \to J/\psi \pi^+)} = 2.76 \pm 0.33 \pm 0.29 \pm 0.16$$

$$\frac{\mathscr{B}(B_c^+ \to J/\psi D_s^{*+})}{\mathscr{B}(B_c^+ \to J/\psi \pi^+)} = 5.33 \pm 0.61 \pm 0.67 \pm 0.32$$

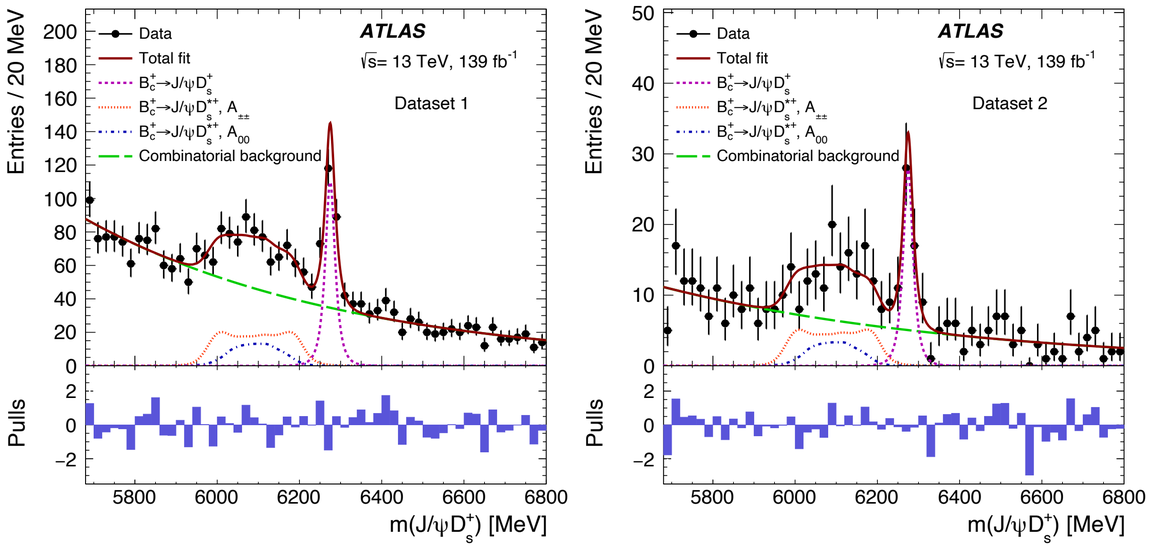
$$\frac{\mathscr{B}(B_c^+ \to J/\psi D_s^{*+})}{\mathscr{B}(B_c^+ \to J/\psi D_s^+)} = 1.93 \pm 0.24 \pm 0.09$$

- Fraction of transverse polarisation:

$$\Gamma_{\pm\pm}/\Gamma = 0.70 \pm 0.10 \pm 0.04$$



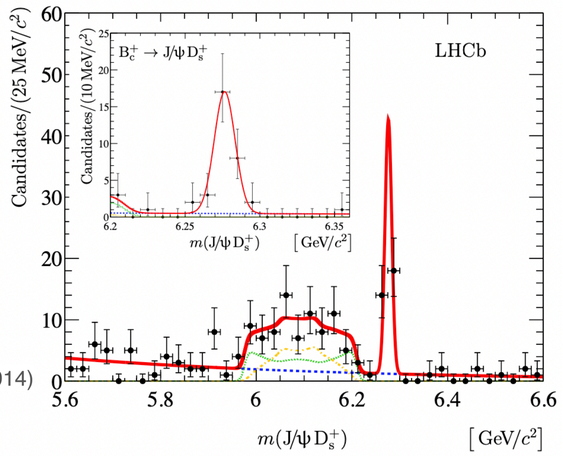
Leading order Feynman diagrams: a) colour-favoured spectator, b) colour-suppressed spectator, c) annihilation topology



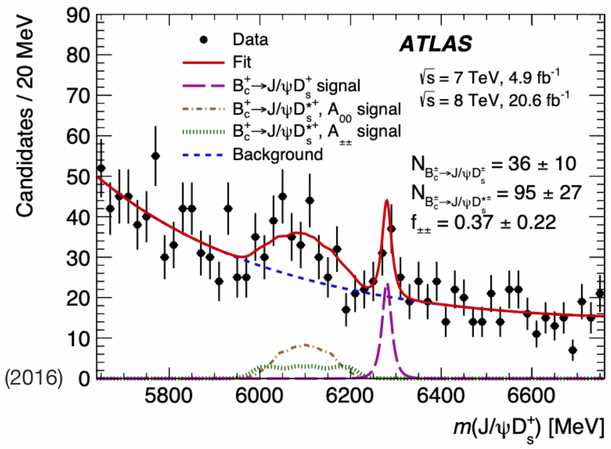
[J. High Energ. Phys. 2022, 87]

Measurement of $B_c^+ \to J/\psi D_s^{(*)+}$ branching fractions

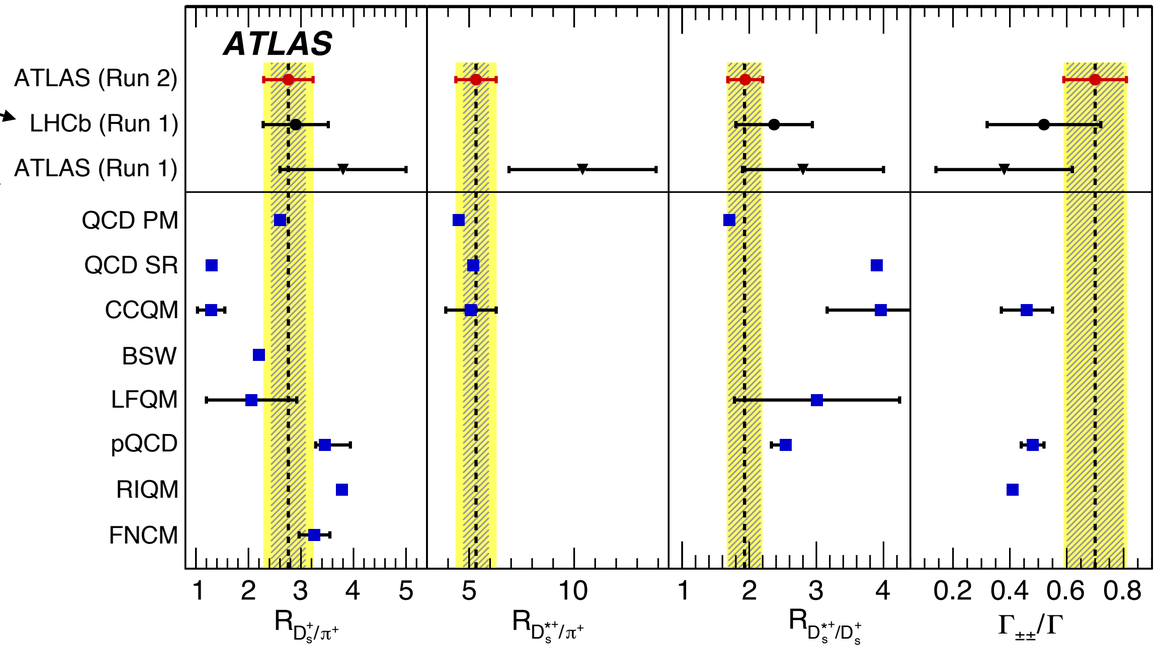
- Results show **increased precision** compared to previous measurements
- **Good agreement** with theoretical predictions and previous measurements



Phys. Rev. D **89**, 019901 (2014)



Eur. Phys. J. C **76**, 4 (2016)



Summary

- Hadron spectroscopy provides an **important input** for non-perturbative QCD models
- Many **new results at LHC**:
  - Heavy hadron spectroscopy — new excited states
  - Doubly heavy hadrons — some ground states are missing
  - New decay modes of B_c^+
- LHC Run 3 starts promising **higher luminosity** and **improved resolution** after an extensive upgrade
- Next level of precision expected with future **LHC Upgrade 2**