Charm and bottom spectroscopy at the LHC

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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

Introduction

- Recent results on conventional spectroscopy from LHC experiments:

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

  - **CMS:**
    - Observation of $B^0 \rightarrow \psi(2S)K_s^0 \pi^+ \pi^-$ and $B^0 \rightarrow \psi(2S)K_s^0$ 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 $B^+_c \rightarrow J/\psi D_s^+$ and $B^+_c \rightarrow J/\psi D_s^{*+}$ 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 $SU(4)$ multiplets)
- $\lambda$-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

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

New excited $\Xi_c^0$ resonances in $B^- \rightarrow \Lambda_c^+\Lambda_c^-K^-$ decays

- Signal extracted using 3D fit to invariant mass of $B^-$, $\Lambda_c^+$ and $\Lambda_c^-$ candidates
- No significant structures in $m(\Lambda_c^-K^-)$ and $m(\Lambda_c^+\Lambda_c^-)$
- 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

$\Xi_c(2790)^0$: 3.7$\sigma$ — evidence of a new decay mode
$\Xi_c(2880)^0$: 3.8$\sigma$ — evidence of a new state

$m(\Xi_c(2923)^0) = 2924.5 \pm 0.4 \pm 1.1$ MeV, \hspace{1cm} \Gamma(\Xi_c(2923)^0) = 4.8 \pm 0.9 \pm 1.5$ MeV

$m(\Xi_c(2939)^0) = 2938.5 \pm 0.9 \pm 2.3$ MeV, \hspace{1cm} \Gamma(\Xi_c(2939)^0) = 11.0 \pm 1.9 \pm 7.5$ MeV
Observation of a new excited $\Xi_{b}^{-}$ state

- Search simultaneously in several topologies
  - Including partially reconstructed $\Xi_{b}^{-} \rightarrow J/\psi \Sigma^{0} (\rightarrow \Lambda \gamma) K^{-}$ with soft photon

- Observed peak in $\Xi_{b}^{-} \pi^{+} \pi^{-}$ spectrum

\[ m(\Xi_{b}(6100)^{-}) = 6100.3 \pm 0.2 \text{(stat)} \pm 0.1 \text{(syst)} \pm 0.6(\Xi_{b}^{-}) \text{ MeV} \]

\[ \Gamma(\Xi_{b}(6100)^{-}) < 1.9 \text{ MeV} \]

- In analogy with $\Xi_{c}$ states: $J^{P} = 3/2^{-}$

Fit to mass spectra with $\Xi_{b}^{-}$ signal

\[ \Xi_{b} \rightarrow J/\psi \Sigma^{0} (\rightarrow \Lambda \gamma) K^{-} \]
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

• $\Xi_{bc}^{+}(bcu) \rightarrow J/\psi \Xi_{c}^{+}$ 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 $J/\psi \rightarrow \mu^{+}\mu^{-}$ selection
  - No other Cabibbo-suppression than $V_{cb}$

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

Search for doubly heavy $\Xi_{bc}^+$

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

Expected value:

\[
\mathcal{R} = \frac{\sigma(\Xi_{bc}^+) \times \mathcal{B}(\Xi_{bc}^+ \rightarrow J/\psi \Xi_c^+) \times \mathcal{B}(\Xi_c^+ \rightarrow pK^-\pi^+)}{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+) \times \mathcal{B}(D_s^+ \rightarrow K^+K^-\pi^+)} \approx 0.015
\]

cross-section fraction $\sim 0.4$

From PDG: BF ratio $\sim 0.12$

Upper limit is greater than a prediction at almost all the range -> more data is needed
$B_c^+$ 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 $J/\psi$ and light hadrons can be described using QCD factorisation:
  - Transition $B_c^+ \rightarrow J/\psi W^+$
  - $W^+$ fragmentation into light hadrons (e.g. multihadron $\tau$ decays)
$B^+_c$ decay to charmonia and multihadron

- Charmonia ($J/\psi$, $\psi(2S)$) with five ($5\pi$, $2K3\pi$) or seven ($7\pi$) 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

\[ \Re_{J/\psi K^+\pi^+\pi^-} = (33.7 \pm 5.7) \times 10^{-2} \]
\[ \Re_{J/\psi \pi^+\pi^-} = (28.5 \pm 8.7) \times 10^{-2} \]
\[ \Re_{\psi(2S)\pi^+\pi^-} = (17.6 \pm 3.6) \times 10^{-2} \]
Measurement of $B_c^+ \rightarrow J/\psi D_{s}^{(*)+}$ 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:

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

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

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

• Fraction of transverse polarisation:

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

Leading order Feynman diagrams: a) colour-favoured spectator, b) colour-suppressed spectator, c) annihilation topology
Measurement of $B_{c}^{+} \rightarrow J/\psi D_{s}^{(*)+}$ branching fractions

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

**Results show increased precision compared to previous measurements**

**Good agreement with theoretical predictions and previous measurements**
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**.