Classical and Exotic Spectroscopy at LHCb

Daniele Marangotto

on behalf of the LHCb Collaboration

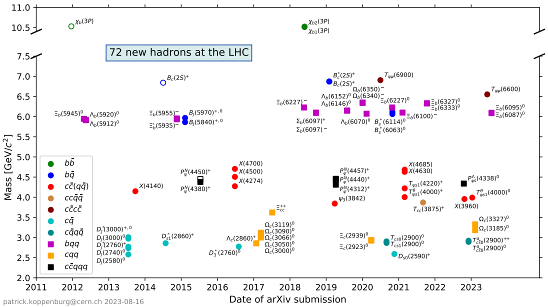
INFN & Università degli Studi, Milano, Italy

La Thuile 2024 - Les Rencontres de Physique de la Vallée d'Aoste

Mar 6th 2024

Why Hadron Spectroscopy?

- Systematic study of hadron production gives info on
  - quark production mechanisms
  - hadron formation from quarks (hadronisation)
  - hadron internal structure
- Important measurements for quantum chromodynamics (QCD), especially at low-energy
  - Discrimination among predictions obtained in different effective low energy QCD approaches



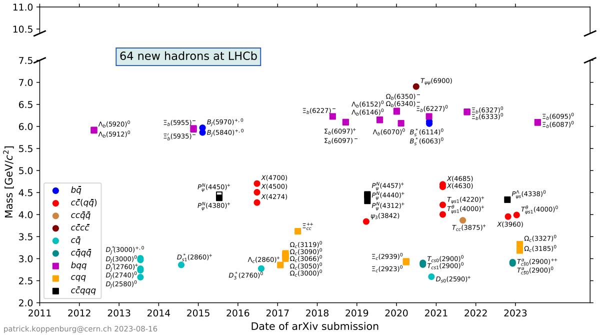
`https://www.nikhef.nl/~pkoppenb/particles.html`

- Discovery and characterisation of a huge number of new hadronic states at the LHC
  - mostly driven by the LHCb experiment

Spectroscopy at LHCb

- LHCb primarily designed to study heavy hadron decays
  - Turned out to be an impressive hadron discovery machine!
  - Hadron spectroscopy has become a major part of LHCb physics program

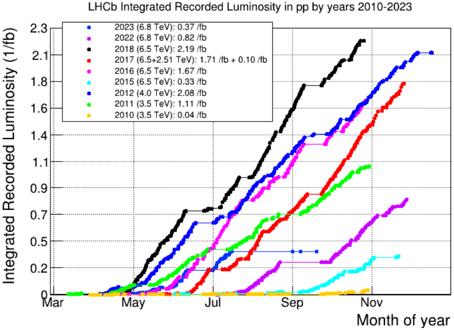
- Major contribution to the hadron taxonomy for both
  - Conventional states (baryons and mesons)
  - Exotic states (like tetra/pentaquarks)
- Detailed study of hadron properties and decays possible at LHCb
  - *e.g.* spin-parity assignments, polarisation, amplitude analyses



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

LHCb current/future datasets

- Current physics results based on LHCb [JINST3 (2008) S08005] datasets from
  - Run 1 (2011-2012): $\approx 3\,\text{fb}^{-1}$, $\sqrt{s} = 7, 8$ TeV
  - Run 2 (2015-2018): $\approx 6\,\text{fb}^{-1}$, $\sqrt{s} = 13$ TeV
- Run 3 data-taking started, expected larger and cleaner datasets thanks to
  - Higher integrated luminosity
  - LHCb upgraded with fully software-based trigger [IJMPA 30 (2015) 1530022]
- A program of high-precision hadron spectroscopy is envisaged!



Menu (it's nearly dinner time!)

Selection of recent LHCb results on classical and exotic spectroscopy

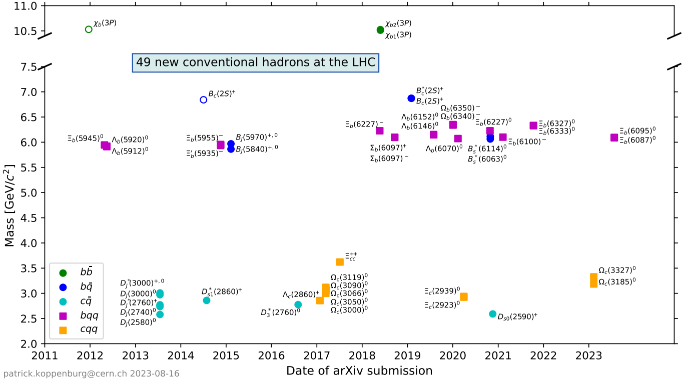
Conventional Courses

- *Fresh results on charmonium states*
- *Refined studies on the strange charm Ω_c^0 baryon*
- *New strange beauty baryons*

Exotic Courses

- *Fresh new channels for pentaquark searches in beauty decays*
- *Prompt pentaquark searches*
- *A decay for new tetraquark searches*

Conventional hadrons



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

Study of $B_c^+ \to \chi_c \pi^+$ decays

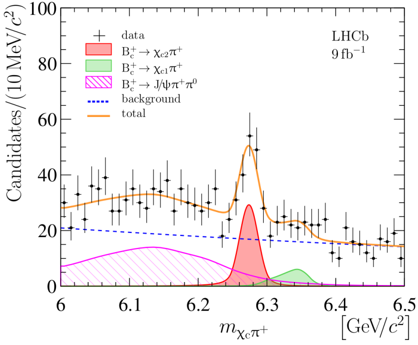
JHEP 02 (2024) 173. **NEW!**

- Studied $B_c^+ \to \chi_{c1,2}\pi^+$ decays with $\chi_{c1,2}$ reconstructed in $J/\psi(\to \mu^+\mu^-)\gamma$
- Benchmark test for QCD factorisation in $B_c^+ \to [c\bar{c}]\, W^+$ transitions
  - Described by associated form factors + $W^+ \to$ *hadrons* universal spectral functions
- First observation of $B_c^+ \to \chi_{c2}\pi^+$ decay with 7σ significance
  - measured branching fraction w.r.t. $B_c^+ \to J/\psi\pi^+$

$$\frac{\mathcal{B}(B_c^+ \to \chi_{c2}\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = 0.37 \pm 0.06 \pm 0.02 \pm 0.01(\chi_{c2} BF)$$

- No evidence for $B_c^+ \to \chi_{c1}\pi^+$, set upper limit at

$$\frac{\mathcal{B}(B_c^+ \to \chi_{c1}\pi^+)}{\mathcal{B}(B_c^+ \to \chi_{c2}\pi^+)} < 0.49 \qquad 90\%\mathrm{C.L.}$$



Study of charmonium decays to $K_S^0 K\pi$ in the $B \to (K_S^0 K\pi)K$ channels

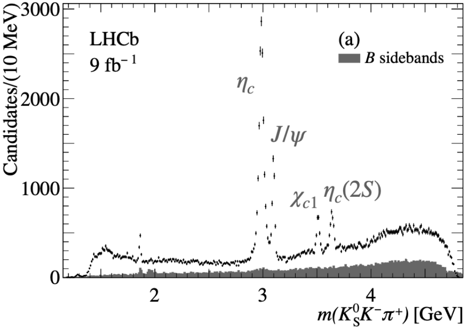
Phys. Rev. D108 (2023) 032010

- Charmonia states studied in mass distributions of $B^+ \to K_S^0 K^\mp \pi^\pm K^+$ decays
  - along with decay structure, probe for (non-)factorisation in QCD physics
- Branching fractions of $B^+ \to c\bar{c}K^+$ measured for η_c, J/ψ, $\eta_c(2S)$, χ_{c1} states

- Best single measurements of η_c, $\eta_c(2S)$ parameters achieved

$$m(\eta_c) = 2985.01 \pm 0.17 \pm 0.89\,\text{MeV}$$
$$\Gamma(\eta_c) = 29.7 \pm 0.5 \pm 0.2\,\text{MeV}$$
$$m(\eta_c(2S)) = 3637.90 \pm 0.54 \pm 1.40\,\text{MeV}$$
$$\Gamma(\eta_c(2S)) = 10.77 \pm 1.62 \pm 1.08\,\text{MeV}$$

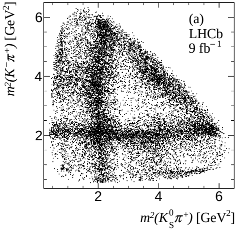
- 1^{st} observation of $B^+ \to \chi_{c0} K_S^0 \pi^+$
- Evidence for $B^+ \to \chi_{c2} K_S^0 \pi^+$, 4.6σ



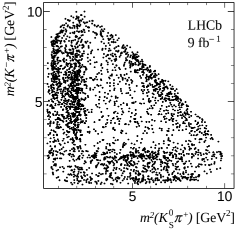
Study of charmonium decays to $K^0_S K\pi$ in the $B \to (K^0_S K\pi)K$ channels

Phys. Rev. D108 (2023) 032010

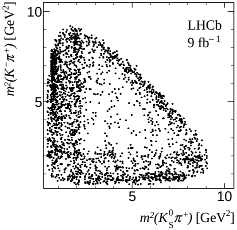
η_c

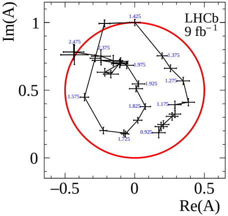


η_c (2S)



χ_{c1}





$K\pi$ S-wave

- Performed Dalitz plot analyses of $\eta_c, \eta_c(2S) \to K^0_S K\pi$
- Detailed study of $K\pi$ S-wave with QMI lineshape and isobar model
- Measurement of $K^*_0(1430)$, $K^*_0(1950)$ and $a_0(1700)$ parameters
- Determined BFs of four $\chi_{c1} \to K^*K$ modes, 1$^{\text{st}}$ observation of $K^*_2(1430)$ channels

Hadronic two-body decays of Ω_c^0 baryon

Phys. Rev. Lett. 132 (2024) 081802

- Better understanding of Ω_c^0 [css] baryon properties desirable
  - uncertainty in mass and lifetime measurements
- Studied new hadronic two-body decays
  - additional ways to study Ω_c^0 properties
- First observation of singly Cabibbo-suppressed modes $\Omega_c^0 \to \Omega^- K^+$, $\Omega_c^0 \to \Xi^- \pi^+$
  - measured BF ratios w.r.t. $\Omega_c^0 \to \Omega^- \pi^+$

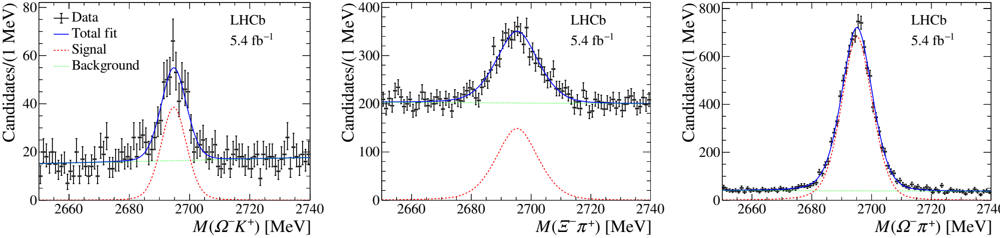
$$R(\Omega_c^0 \to \Omega^- K^+) = 0.0608 \pm 0.0051(stat) \pm 0.0040(syst)$$

$$R(\Omega_c^0 \to \Xi^- \pi^+) = 0.1581 \pm 0.0087(stat) \pm 0.0043(syst) \pm 0.0016(BFs)$$

Hadronic two-body decays of Ω_c^0 baryon

Phys. Rev. Lett. 132 (2024) 081802

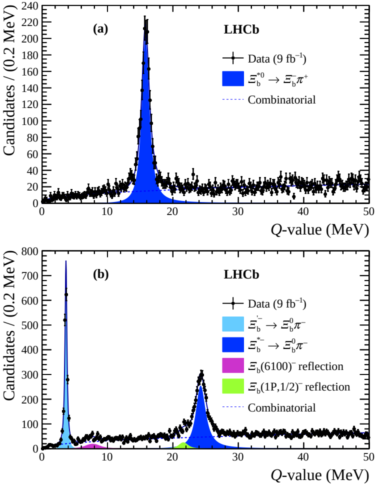
- Precision mass measurement of Ω_c^0 baryon using $\Omega_c^0 \to \Omega^-\pi^+$ decay
  $m(\Omega_c^0) = 2695.28 \pm 0.07(stat) \pm 0.27(syst) \pm 0.30(masses)$ MeV
  - world average precision improved by a factor of four



Observation of new baryons in the $\Xi_b^- \pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$ systems

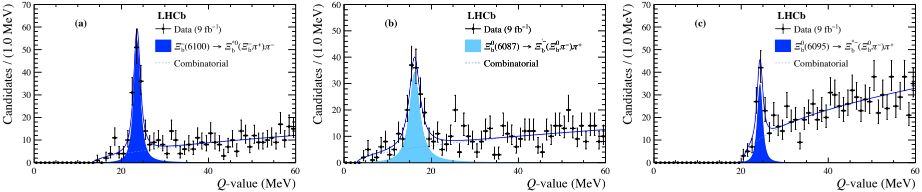
Phys. Rev. Lett. 131 (2023) 171901

- Study of baryonic structures in Ξ_b^- (Ξ_b^0) $\pi^+\pi^-$ states
- Candidates selected requiring $m(\Xi_b{}^{0/-}\pi^+)$ around intermediate Ξ_b^{*0} or Ξ_b^{*-}, $\Xi_b^{\prime -}$ states
  - Ξ_b^- (Ξ_b^0) reconstructed combining Ξ_c^0 (Ξ_c^+) with π^- or $\pi^-\pi^+\pi^-$ states
- Up to nine reconstructed tracks per event: nice benchmark for LHCb performances!



Observation of new baryons in the $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$ systems

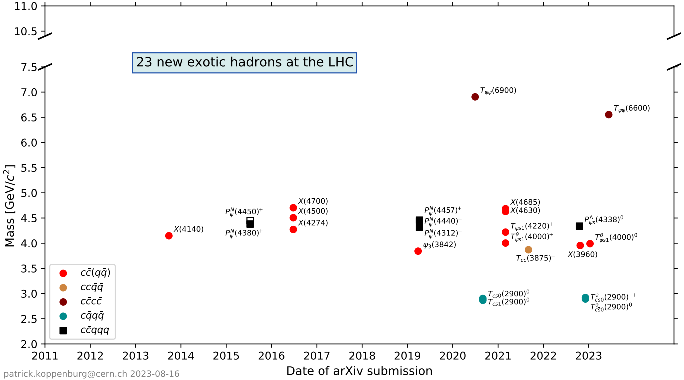
Phys. Rev. Lett. 131 (2023) 171901



- Confirmed $\Xi_b(6100)^-$ reported by CMS [PRL 126 (2021) 252003]
- First observation of two strange-beauty baryons with quark content *bsu*: $\Xi_b(6087)^0$, $\Xi_b(6095)^0$
- Properties of Ξ_b^{*0}, Ξ_b^{*-}, $\Xi_b^{\prime -}$ states measured with high precision

State	Observ.	Value (MeV)
$\Xi_b(6100)^-$	Q_0	$23.6 \pm 0.11 \pm 0.02$
	Γ	$0.94 \pm 0.30 \pm 0.08$
	m_0	$6099.74 \pm 0.11 \pm 0.02 \pm 0.6\ (\Xi_b^-)$
$\Xi_b(6087)^0$	Q_0	$16.20 \pm 0.20 \pm 0.06$
	Γ	$2.43 \pm 0.51 \pm 0.10$
	m_0	$6087.24 \pm 0.20 \pm 0.06 \pm 0.5\ (\Xi_b^0)$
$\Xi_b(6095)^0$	Q_0	$24.32 \pm 0.15 \pm 0.03$
	Γ	$0.50 \pm 0.33 \pm 0.11$
	m_0	$6095.36 \pm 0.15 \pm 0.03 \pm 0.5\ (\Xi_b^0)$
Ξ_b^{*0}	Q_0	$15.80 \pm 0.02 \pm 0.01$
	Γ	$0.87 \pm 0.06 \pm 0.05$
	m_0	$5952.37 \pm 0.02 \pm 0.01 \pm 0.6\ (\Xi_b^-)$
$\Xi_b^{\prime -}$	Q_0	$3.66 \pm 0.01 \pm 0.00$
	Γ	$0.03 \pm 0.01 \pm 0.03$
	m_0	$5935.13 \pm 0.01 \pm 0.00 \pm 0.5\ (\Xi_b^0)$
Ξ_b^{*-}	Q_0	$24.27 \pm 0.03 \pm 0.01$
	Γ	$1.43 \pm 0.08 \pm 0.08$
	m_0	$5955.74 \pm 0.03 \pm 0.01 \pm 0.5\ (\Xi_b^0)$

Exotic hadrons



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

Observation of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$ decays

arXiv:2311.14088, submitted to EPJC. **NEW!**

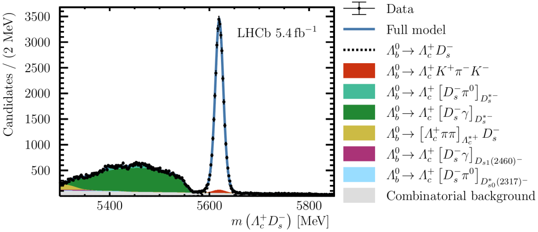
- First observation of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$ decays
- BF ratios measured w.r.t. $\Lambda_b^0 \to \Lambda_c^+ D_s^-$

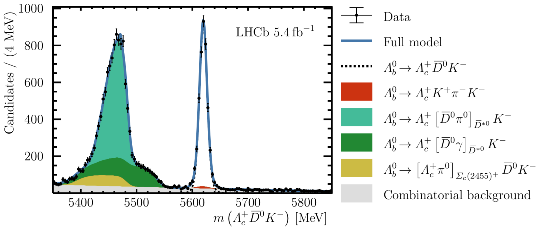
$$R(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-) = 0.1908^{+0.0036}_{-0.0034}{}^{+0.0016}_{-0.0018} \pm 0.0038(BFs)$$

$$R(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-) = 0.589^{+0.018}_{-0.017}{}^{+0.017}_{-0.018} \pm 0.012(BFs)$$

$$R(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}) = 1.668 \pm 0.022^{+0.061}_{-0.055}$$

- Provide normalisation for future pentaquark searches in $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ channels
  - test model predictions for P_c^+ BF ratio between $\Lambda_c^+ \overline{D}^{(*)0}$ and $J/\psi p$ states





Prompt production of pentaquarks in open charm hadron final states

LHCb-PAPER-2023-018, in preparation

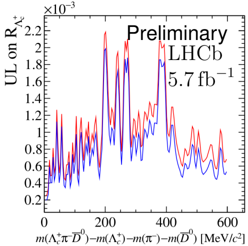
- Observed pentaquarks are close to mass thresholds of charm baryon-meson combinations
- Structure still debated: molecule-like states or compact ones?
- Search for pentaquarks in prompt *pp* production, considering Λ_c^+, D, Σ_c pairs
- Studied 32 out of 42 modes, others discarded due to low statistics

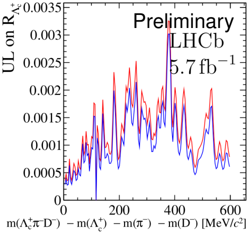
$\Sigma_c^{++}\bar{D}^0$	~~$\Sigma_c^{++}D^0$~~	$\Sigma_c^{++}D^-$	~~$\Sigma_c^{++}D^+$~~	~~$\Sigma_c^{++}D^{*-}$~~	~~$\Sigma_c^{++}D^{*+}$~~
$\Sigma_c^{0}\bar{D}^0$	~~$\Sigma_c^{0}D^0$~~	$\Sigma_c^{0}D^-$	~~$\Sigma_c^{0}D^+$~~	~~$\Sigma_c^{0}D^{*-}$~~	~~$\Sigma_c^{0}D^{*+}$~~
$\Sigma_c^{*++}\bar{D}^0$	$\Sigma_c^{*++}D^0$	$\Sigma_c^{*++}D^-$	$\Sigma_c^{*++}D^+$	$\Sigma_c^{*++}D^{*-}$	~~$\Sigma_c^{*++}D^{*+}$~~
$\Sigma_c^{*0}\bar{D}^0$	$\Sigma_c^{*0}D^0$	$\Sigma_c^{*0}D^-$	$\Sigma_c^{*0}D^+$	$\Sigma_c^{*0}D^{*-}$	~~$\Sigma_c^{*0}D^{*+}$~~
$\Lambda_c^+\bar{D}^0$	$\Lambda_c^+D^0$	$\Lambda_c^+D^-$	$\Lambda_c^+D^+$	$\Lambda_c^+D^{*-}$	$\Lambda_c^+D^{*+}$
$\Lambda_c^+\bar{D}^0\pi^+$	$\Lambda_c^+D^0\pi^+$	$\Lambda_c^+D^-\pi^+$	$\Lambda_c^+D^+\pi^+$	$\Lambda_c^+D^{*-}\pi^+$	$\Lambda_c^+D^{*+}\pi^+$
$\Lambda_c^+\bar{D}^0\pi^-$	$\Lambda_c^+D^0\pi^-$	$\Lambda_c^+D^-\pi^-$	$\Lambda_c^+D^+\pi^-$	$\Lambda_c^+D^{*-}\pi^-$	$\Lambda_c^+D^{*+}\pi^-$

Prompt production of pentaquarks in open charm hadron final states

LHCb-PAPER-2023-018, in preparation

- Simultaneous fit to signal and sideband regions for each mode, shared background shape
- Peak search in steps of 4 MeV mass intervals
- No evidence for known or new pentaquarks obtained
  - mass-dependent upper limits set w.r.t. $\Lambda_c^+ \to pK^-\pi^+$ channel
- Improved search envisaged with Run 3 data

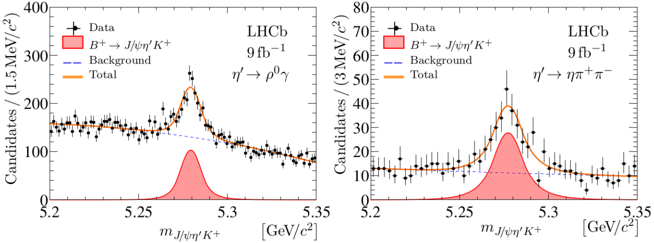




Observation of $B^+ \to J/\psi\eta' K^+$ decay

JHEP 08 (2023) 174

- First observation ($> 10\sigma$) of $B^+ \to J/\psi\eta' K^+$ decays in both $\eta' \to \rho^0\gamma$ and $\eta' \to \eta\pi^+\pi^-$ modes
  - Previously unobserved emission of η' meson from charmonium(-like) systems



- Measured BF ratio w.r.t. $B^+ \to \psi(2S)K^+$ decay

$$R(B^+ \to J/\psi\eta' K^+) = (4.91 \pm 0.47(stat) \pm 0.29(syst) \pm 0.07(BFs)) \times 10^{-2}$$

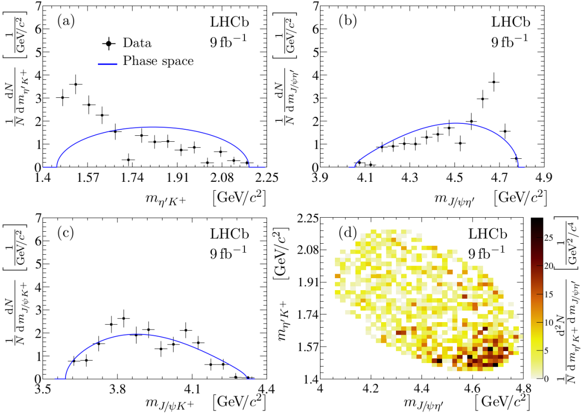
  - BF value obtained from known $\mathcal{B}(B^+ \to \psi(2S)K^+)$

$$\mathcal{B}(B^+ \to J/\psi\eta' K^+) = (3.06 \pm 0.29(stat) \pm 0.18(syst) \pm 0.04(BFs)) \times 10^{-5}$$

Observation of $B^+ \to J/\psi\eta' K^+$ decay

JHEP 08 (2023) 174

- First search of tetraquark states in $J/\psi\eta'$ system
  - analysis of background-subtracted phase-space distributions
- Indication of excited K^* contributions in $\eta' K^+$ mass and potential exotic states in $J/\psi\eta'$
  - not statistically significant
- Full amplitude analysis should be feasible with Run 3 data



Conclusions

- Presented a selection of the latest LHCb results on classical and exotic spectroscopy
- Confirm capabilities and flexibility of LHCb experiment in this field
- Interesting results still coming from Run 2 samples

- Looking forward for Run 3 data, promising a further leap in hadron spectroscopy
- Dishes to suit all tastes!