Hadron spectroscopy at LHCb

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on behalf of the LHCb collaboration

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Spectroscopy at LHCb

High luminosity, high $b/c$ production cross-section, a unique dedicated design

LHCb: major player in the field of heavy hadron spectroscopy

70 new hadrons at the LHC

From [P. Koppenburg]
Spectroscopy at LHCb

High luminosity, high $b/c$ production cross-section, a unique dedicated design

LHCb: major player in the field of heavy hadron spectroscopy

62 new hadrons at LHCb


From [P. Koppenburg]
The spectroscopy programme

Conventional heavy-hadron spectroscopy

- Excited open-flavour mesons: $B^{+}, B^{0}, B_{c}^{+}, D^{+}, D_{s}^{+}$...
- Excited conventional charmonia
- Excited baryons: $\Xi_{b}^{0}, \Lambda_{b}^{0}, \Sigma_{b}^{+}, \Omega_{c}^{0}, \Omega_{b}^{-}$...
- Discovery and searches of new particles and decay modes
- Precise mass, width, BR measurements and more

Exotic spectroscopy

- $\chi_{c1}(3872)$: production and decay, lineshape, mass
- Many other $c\bar{c}$ tetraquark candidates in various final states from $b$ decays and primary vertex
- Exotic non-charmonia: charged states, $cc, c\bar{c}c\bar{c}$, open charm
- Pentaquark candidates
- Searches for unexpected contributions

Today: focus on most recent results
The LHCb experiment at CERN
Single-arm spectrometer designed for high precision flavour physics measurements

Total recorded luminosity:

- Run 1: 1 fb$^{-1}$ at $\sqrt{s} = 7$ TeV + 2 fb$^{-1}$ at $\sqrt{s} = 8$ TeV
- Run 2: 6 fb$^{-1}$ at $\sqrt{s} = 13$ TeV

CONVENTIONAL HEAVY HADRON SPECTROSCOPY
Search for $\Xi_c^{0**} \rightarrow \Lambda_c^+ K^-$

Prompt $\Lambda_c^+ K^-$ already studied by LHCb, new states observed:
- $\Xi_c(2923)^0$, $\Xi_c(2939)^0$

Study of the decay $B^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^-$ also looking for exotics

- $\Xi_c(2790)^0$: evidence of new decay mode
- $\Xi_c(2880)^0$: evidence of new state
- $\Xi_c(2923)^0$, $\Xi_c(2939)^0$ confirmed
- No structures found in $\bar{\Lambda}_c^- K^-$ and $\Lambda_c^+ \bar{\Lambda}_c^-$ spectra

New excited $\Xi_b$ baryons

New excited $\Xi_b$ baryons are observed in the $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$ final states decaying mainly through the intermediate $\Xi_b^*0$, $\Xi_b'$ and $\Xi_b^{*-}$ states

- $\Xi_b(6100)^-$: confirmed previous CMS observation \cite{PRL 126 (2021) 252003}
- New states: $\Xi_b(6087)^0$ and $\Xi_b(6095)^0$
- Similarity of decay pattern with $c$-baryon system suggests P-wave states
- Additional studies required to measure quantum numbers

\cite{LHCb-PAPER-2023-008} in preparation
Search for $\Xi_{bc}^+ \rightarrow J/\psi \Xi_c^+$

First search of the $\Xi_{bc}$ baryon, mass expected in range $[6700, 7029]$ MeV/$c^2$

No excess larger than $3\sigma$ is observed, upper limits are set on the production ratio with respect to $B_{c}^{+} \rightarrow J/\psi D_{s}^{+}$

[arXiv:2204.09541], submitted to Chin. Phys. C
EXOTIC SPECTROSCOPY
Observation of $B^0_s \rightarrow \chi_{c1}(3872)\pi^+\pi^-$

First observation of the decay $B^0_s \rightarrow \chi_{c1}(3872)\pi^+\pi^-$

Significance $>7\sigma$

BR ratio with respect to $B^0_s \rightarrow \psi(2S)\pi^+\pi^-$ measured

Using the known $B^0_s$ and $\psi(2S)$ BRs:

$$\mathcal{B}(B^0_s \rightarrow \chi_{c1}(3872)\pi^+\pi^-) \times \mathcal{B}(\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-) = (1.6 \pm 0.3 \pm 0.1 \pm 0.3) \times 10^{-6}$$

Dipion system found to proceed through a coherent sum of the $f_0(980)$ and $f_0(1500)$ states

[arXiv:2302.10629], submitted to JHEP
Observation of $X(3960)$
Amplitude analysis of the $B^+ \to D_s^+ D_s^- K^+$ decay

- Threshold enhancement in the $D_s^+ D_s^-$ mass spectrum
- $X(3960)$ (14σ) and $X_0(4140)$ (3.9σ) both with preferred $J^{PC} = 0^{++}$
- Alternatively, the dip can be explained by $J/\psi\phi \to D_s^+ D_s^-$ rescattering
- $X(3960)$ state could be the same as $\chi_{c0}(3930)$ observed in $D^+ D^-$?
- $\frac{\Gamma(X \to D_s^+ D_s^-)}{\Gamma(X \to D_s^+ D_s^-)} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$
- Incompatible with the suppression of $s\bar{s}$ pair from vacuum (wrt $u\bar{u}$ or $d\bar{d}$) and the smaller phase-space volume of $D_s^+ D_s^-$
- Exotic candidate with minimal quark content $[c\bar{c}s\bar{s}]$

Evidence for a $J/\psi K^0_s$ structure

Amplitude analysis of $B^0 \to J/\psi \phi K^0_s \to J/\psi \phi K_s$ search for the isospin partners of the $T^{\theta+}_{\psi s}$ states observed in the $B^+ \to J/\psi \phi K^+$ channel

- Amplitude model includes 9 excited $K$ states, excited charmonia and the known $J/\psi \phi$ exotics
- Evidence for a new state $T^{\theta+}_{\psi s1}(4000)^0$ at $4\sigma$
- Mass difference between $T^{\theta0}_{\psi s1}$ and $T^{\theta+}_{\psi s1}$ is $\Delta M = 12^{+11+6}_{-10-4}$ MeV which is consistent with the two states being isospin partners

New open-charm tetraquarks

Two $T_{cs}$ states ($X_0(2900)$ and $X_1(2900)$) observed in $B^+ \rightarrow D^+D^-K^+$ amplitude analysis: first discovery of open-charm tetraquarks $[cs\bar{u}\bar{d}]$ → study of the $B^0 \rightarrow \bar{D}^0D_s^+\pi^-$ and $B^+ \rightarrow D^-D_s^+\pi^+$ channels

- Joint amplitude analysis linked through isospin symmetry
- Two new states necessary (9σ) to describe the peaking structure
- $T^a_{cs0}(2900)^0$ and $T^a_{cs0}(2900)^{++}$, $J^P = 0^+$ favoured by >7.5σ

New pentaquarks: $P^\Lambda_{\psi s}$

Amplitude analysis of $B^- \rightarrow J/\psi \Lambda \bar{p}$

- Observation of a narrow pentaquark state with high significance
- $J = \frac{1}{2}$, odd parity preferred: $J^P = \frac{1}{2}^+$ excluded at 90% CL
- First observation of a pentaquark with strange quark content: $[c\bar{c}uds]$  
- Very close to the $\Xi^+_cD^-$ mass threshold
- Furthermore, most precise single measurement of $B^-$ mass  
  \[ m_{B^-} = 5279.44 \pm 0.05 \pm 0.07 \text{ MeV} \]

CONCLUSIONS AND PROSPECTS
Conclusions

- Heavy meson spectroscopy is an extremely rich and productive field, both for conventional and exotic states
- New conventional and exotic hadrons are discovered every year
- LHCb has established itself to be a major player due to high luminosity, high $b/c$ production cross-section and a unique, dedicated design
- Spectroscopy of heavy hadrons is crucial to understand QCD dynamics and binding rules
- Many excitation spectra are still mostly unexplored territory
- New "non-conventional" exotic states have been discovered recently
Prospects for Run 3

- Run 3 started with an upgraded detector and a software-only trigger, with improvements on hadronic triggers
- LHC experiments will be the only explorers of the $B_c^+$ spectrum in the near future and LHCb will play a major role in it
- Heavy baryon spectroscopy already started in Run 2
- Run 3: access to $bc$ tetraquarks and pentaquarks and $b\bar{b}$ spectroscopy
- Confirm new pentaquarks and measure their properties
- For Runs 1-2 exotic hadron searches rely on $J/\psi$ for reconstruction
- In Run 3, with the removal of the L0 trigger, fully-hadronic final states will be accessible allowing studies on open-flavour exotic states
Study of the $B^+ \rightarrow J/\psi \eta^{(')} K^+$ decay

Search for charmonia and charmonia-like exotics decaying into $J/\psi \eta$

Only contribution found: $\psi_2(3823)$ and $\psi(4040)$
Limits at 90% CL set on $\mathcal{B}(X \rightarrow J/\psi \eta)$ scanning $m_X \in [3750, 4700]$ GeV/$c^2$

Searches also in the $B^+ \rightarrow J/\psi \eta' K^+$
no obvious unknown structure observed
amplitude analysis necessary

[JHEP 2022 (2022) 46], [arXiv:2303.09443], submitted to JHEP
ω contribution in \( \chi_{c1}(3872) \rightarrow \pi^+ \pi^- J/\psi \)

Study of the resonant \( \pi^+ \pi^- \) structure in the \( \chi_{c1}(3872) \) "golden channel"

Using a single Breit-Wigner with a Blatt-Weisskopf radius of 1.45 GeV\(^{-1}\)

Adding an \( \omega \) contribution with a 2-channel \( K \)-matrix model

Ratio of couplings

\[
\frac{g_{\chi_{c1}(3872) \rightarrow \rho J/\psi}}{g_{\chi_{c1}(3872) \rightarrow \omega J/\psi}} = 0.29 \pm 0.04
\]

is one order of magnitude larger than expected for pure \( c\bar{c} \) states

[arXiv:2204:12597], submitted to PRL
$B_c^+ - B_s^0$ mass difference

\[ \Delta m = 907.75 \pm 0.37 \pm 0.27 \text{ MeV/c}^2 \]
Observation of new excited $B_s^0$ states

The $B_s^0$ excitation spectrum is mostly inexplored as well

- Only ground state + three excited states observed
- First radial excitation ($B_{s1}^*$) and first orbital excitations ($B_{s1}^0$, $B_{s2}^0$)
- This analysis: observation of two new states

Adapted from [PRD 94 (2016) 054025]
$B^+ \to J/\psi \phi K^+$ fit results

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>Contribution</th>
<th>Significance [$\times \sigma$]</th>
<th>$M_0$ [MeV]</th>
<th>$\Gamma_0$ [MeV]</th>
<th>FF [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^+$</td>
<td>$2^1P_1$ $K(1^+)$</td>
<td>4.5 (4.5)</td>
<td>$1861 \pm 10^{+16}_{-46}$</td>
<td>$149 \pm 41^{+21}_{-23}$</td>
<td>15 $\pm 3^{+3}_{-11}$</td>
</tr>
<tr>
<td></td>
<td>$2^3P_1$ $K'(1^+)$</td>
<td>4.5 (4.5)</td>
<td>$1911 \pm 37^{+124}_{-48}$</td>
<td>$276 \pm 50^{+319}_{-159}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$1^3P_1$ $K_1(1400)$</td>
<td>9.2 (11)</td>
<td>1403</td>
<td>174</td>
<td></td>
</tr>
<tr>
<td>$2^-$</td>
<td>$1^1D_2$ $K_2(1770)$</td>
<td>7.9 (8.0)</td>
<td>1773</td>
<td>186</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$1^3D_2$ $K_2(1820)$</td>
<td>5.8 (5.8)</td>
<td>1816</td>
<td>276</td>
<td></td>
</tr>
<tr>
<td>$1^-$</td>
<td>$1^3D_1$ $K^*(1680)$</td>
<td>4.7 (13)</td>
<td>1717</td>
<td>322</td>
<td>14 $\pm 2^{+35}_{-8}$</td>
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<tr>
<td></td>
<td>$2^3S_1$ $K^*(1410)$</td>
<td>7.7 (15)</td>
<td>1414</td>
<td>232</td>
<td>38 $\pm 5^{+11}_{-17}$</td>
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<tr>
<td>$2^-$</td>
<td>$2^3P_2$ $K^*_2(1980)$</td>
<td>1.6 (7.4)</td>
<td>$1988 \pm 22^{+194}_{-31}$</td>
<td>$318 \pm 82^{+481}_{-101}$</td>
<td>2.3 $\pm 0.5 \pm 0.7$</td>
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<tr>
<td>$0^-$</td>
<td>$2^1S_0$ $K(1460)$</td>
<td>12 (13)</td>
<td>1483</td>
<td>336</td>
<td>10.2 $\pm 1.2^{+1.0}_{-3.8}$</td>
</tr>
<tr>
<td>$2^-$</td>
<td>$X(4150)$</td>
<td>4.8 (8.7)</td>
<td>$4146 \pm 18 \pm 33$</td>
<td>$135 \pm 28^{+59}_{-30}$</td>
<td>2.0 $\pm 0.5^{+0.8}_{-1.0}$</td>
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<tr>
<td>$1^-$</td>
<td>$X(4630)$</td>
<td>5.5 (5.7)</td>
<td>$4626 \pm 16^{+18}_{-110}$</td>
<td>$174 \pm 27^{+134}_{-73}$</td>
<td>2.6 $\pm 0.5^{+2.9}_{-1.5}$</td>
</tr>
<tr>
<td>$0^+$</td>
<td>$X(4500)$</td>
<td>20 (20)</td>
<td>$4474 \pm 3 \pm 3$</td>
<td>$77 \pm 6^{+10}_{-8}$</td>
<td>5.6 $\pm 0.7^{+2.4}_{-0.6}$</td>
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<tr>
<td></td>
<td>$X(4700)$</td>
<td>17 (18)</td>
<td>$4694 \pm 4^{+16}_{-3}$</td>
<td>$87 \pm 8^{+16}_{-6}$</td>
<td>8.9 $\pm 1.2^{+4.9}_{-1.4}$</td>
</tr>
<tr>
<td></td>
<td>NR $J/\psi \phi$</td>
<td>4.8 (5.7)</td>
<td></td>
<td></td>
<td>$28 \pm 8^{+19}_{-11}$</td>
</tr>
<tr>
<td>$1^+$</td>
<td>$X(4140)$</td>
<td>13 (16)</td>
<td>$4118 \pm 11^{+19}_{-36}$</td>
<td>$162 \pm 21^{+24}_{-49}$</td>
<td>17 $\pm 3^{+19}_{-6}$</td>
</tr>
<tr>
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<td>$X(4274)$</td>
<td>18 (18)</td>
<td>$4294 \pm 4^{+3}_{-6}$</td>
<td>$53 \pm 5 \pm 5$</td>
<td>2.8 $\pm 0.5^{+0.8}_{-0.4}$</td>
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<tr>
<td></td>
<td>$X(4685)$</td>
<td>15 (15)</td>
<td>$4684 \pm 7^{+13}_{-16}$</td>
<td>$126 \pm 15^{+37}_{-41}$</td>
<td>7.2 $\pm 1.0^{+4.0}_{-2.0}$</td>
</tr>
<tr>
<td>$1^+$</td>
<td>$Z_{cs}(4000)$</td>
<td>15 (16)</td>
<td>$4003 \pm 6^{+4}_{-14}$</td>
<td>$131 \pm 15 \pm 26$</td>
<td>9.4 $\pm 2.1 \pm 3.4$</td>
</tr>
<tr>
<td></td>
<td>$Z_{cs}(4220)$</td>
<td>5.9 (8.4)</td>
<td>$4216 \pm 24^{+43}_{-30}$</td>
<td>$233 \pm 52^{+97}_{-73}$</td>
<td>10 $\pm 4^{+10}_{-7}$</td>
</tr>
</tbody>
</table>