Exotic charm hadrons at LHCb

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On behalf of LHCb collaboration
Exotic states and interpretations

Exotic hadrons: hadrons with quark content other than well-established $q\bar{q}$ (mesons) and $qqq$ (baryon) states.

- Tightly-bound **multiquark states**:
  - $qq\bar{q}:$ tetraquarks
  - $qqq\bar{q}:$ pentaquarks

- Loosely-bound **molecules** (meson-meson, meson-baryon, baryon-baryon)

Strong evidence from many analyses for the existence of such states. However, kinematical effects in rescattering can lead to structures that can resemble resonances.

- **Cusps**: rescattering without binding.
LHCb analyses related to exotic charm hadron spectroscopy:

- Measurements of $X(3872)$
- $Z(4430)$ in $B^0 \rightarrow \psi(2S)K^+\pi^-$
- Exotic states in $B^+ \rightarrow J/\psi \phi K^+$
- Pentaquark states in $\Lambda_b^0 \rightarrow J/\psi pK^-$
- Exotic states in $\Lambda_b^0 \rightarrow J/\psi p\pi^-$
- $D^0 p$ states in $\Lambda_b^0 \rightarrow D^0 p\pi^-$
- Excited $\Omega_c$ states
- Searches for other exotic contributions

Other related talks at this conference:

- Prospects with upgraded LHCb [Tomasz Skwarnicki]
- Conventional spectroscopy [Patrick Spradlin]
- Doubly-charmed hadrons [Daniel Vieira]
- Amplitude analysis techniques [Tim Evans]
One-arm spectrometer optimised for studies of beauty and charm decays at LHC

- Covers forward region (maximum of $c$ and $b$ production)
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**Calorimetry**

$B_s^0 \rightarrow \chi_{c1}\phi$, $\chi_{c1} \rightarrow J/\psi\gamma$

[Covers forward region (maximum of $c$ and $b$ production)]

[Good vertexing: measure $B^0$ and $B_s^0$ oscillations, reject prompt background]

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One-arm spectrometer optimised for studies of beauty and charm decays at LHC

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- Calorimetry: reconstruct neutrals ($\pi^0$, $\gamma$) in the final state
- Efficient trigger, including fully hadronic modes
LHCb in Run 1 and Run 2

LHCb Integrated Recorded Luminosity in pp, 2010-2018

- 2018 (6.5 TeV): 0.35 /fb
- 2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
- 2016 (6.5 TeV): 1.67 /fb
- 2015 (6.5 TeV): 0.33 /fb
- 2012 (4.0 TeV): 2.08 /fb
- 2011 (3.5 TeV): 1.11 /fb
- 2010 (3.5 TeV): 0.04 /fb

3 fb\(^{-1}\) in 2011 and 2012 (Run 1, \(\sqrt{s} = 7, 8\) TeV): All results in this talk
4 fb\(^{-1}\) in 2015–2018 so far (Run 2, \(\sqrt{s} = 13\) TeV, higher \(b\) cross section)
Production mechanisms and properties

Conventional and exotic charm states are studied at LHCb in two production regimes:

- **Prompt production** in $pp$ collisions
  - High statistics
  - High combinatorial background

- **Weak decays** of beauty hadrons (fully or partially reconstructed)
  - Low background
  - Well-defined initial state, determination of quantum numbers
  - Kinematic constraints

Properties of exotic states which can be determined and tested against theory models:

- Mass and width
- Production and decay channels, branching ratios
- Quantum numbers: spin, parity
- Line shape
Amplitude analyses

Many of LHCb exotic measurements use amplitude analysis technique.

Perform fits of the amplitude as a function of phase space variables

- Three-body decays $D \rightarrow ABC$: two kinematic variables $M_{AB}^2, M_{BC}^2$ (Dalitz plot)
- Add angular variables if initial/final state not scalar

![Graph showing Dalitz plot with color gradient indicating phase space dynamics and helicity structure.](image)

- Both lineshape parameters and spin can be extracted.
- Complex phases of components can be accessed though interference with other structures.
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- Complex phases of components can be accessed through interference with other structures.
First manifestly exotic candidate: $X(3872)$
Discovered by Belle in 2003

- $B^+ \to X(3972)K^+$, $X(3872) \to J/\psi \pi^+ \pi^-$
- Mass close to $D^0 D^*_0^-$
  \[ m(D^0 D^*_0) - m(X(3872)) = 3 \pm 192 \text{ keV (sic!)} \]
- Small width ($\Gamma < 1.2 \text{ MeV}$)

Hadron machines are also active in studies of $X(3872)$ production

**D0**, [PRL 93:162002,2004]

**CMS, 7 TeV** [JHEP 04 (2013) 154]
X(3872) results from LHCb

Observation of prompt X(3872) in pp collisions and mass measurement:

\[ M(X(3872)) = 3871.95 \pm 0.48 \pm 0.12 \text{ MeV} \text{ with } 35 \text{ pb}^{-1} \]

[EPJC 72 (2012) 1972]

Quantum numbers: \( J^{PC} = 1^{++} \) (> 8σ over 2−+)

[PRL 110, 222001 (2013)]

\[ D \text{-wave decay could invalidate } 1^{++}, \text{ constrained < 4%} \]

[PRD 92 (2015) 011102]

Branching ratio to \( c\bar{c}\gamma \):

\[ R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi \gamma)} = 2.46 \pm 0.64 \pm 0.29 \]


Rules out purely molecular interpretation \( (R_{\psi\gamma} \ll 1) \)
Charged exotic state: \( Z(4430) \)
Decay $B^0 \rightarrow \psi(2S)K^+\pi^-$

- Signal yield: 25k events
- Combinatorial background: $\sim 4\%$
- 4D amplitude analysis:
  $(m^2(K\pi), m^2(\psi(2S)\pi), \theta_{\psi'}, \phi_{\psi'})$
Model-dependent fit prefers resonance-like state with $J^P = 1^+$

$$\mathcal{F}(Z(4430)^+) = (5.9 \pm 0.9^{+1.5}_{-3.3}(\text{syst}))\%$$

Quantum numbers (wrt. favoured $J^P = 1^+$)

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>LHCb</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^-$</td>
<td>9.7</td>
<td>3.4</td>
</tr>
<tr>
<td>$1^-$</td>
<td>15.8</td>
<td>3.7</td>
</tr>
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<td>16.1</td>
<td>5.1</td>
</tr>
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<td>$4485 \pm 22^{+28}_{-11}$</td>
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<td>Width, MeV</td>
<td>$172 \pm 13^{+27}_{-34}$</td>
<td>$200^{+41}<em>{-46}^{+26}</em>{-35}$</td>
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Model-independent test of phase rotation

[PRD 92 (2015) 112009]

Check that $K^- \pi^+$ amplitude only fails to describe the decay.

$K^- \pi^+$ should contribute to reasonably low moments, while exotic $\psi' \pi^-$ contributes to all moments.

$K^*$ states provide reference amplitude for phase motion measurement.

Clockwise rotation: characteristic of a resonant behaviour.

Resonances with spin up to 3 cannot reproduce the features seen in data.
$X(4140)$ and $J/\psi \phi$ family
Exotic states in $B^+ \rightarrow J/\psi \phi K^+$

Peaks in $J/\psi \phi$ around 4140 and 4274 MeV are found by CDF and confirmed by D0 and CMS

[CDF, PRL 102, 242002 (2009)]

[D0, PRD 89, 012004 (2014)]

[CMS, PLB 734 (2014) 261]

Belle [PRL 104:112004 (2010)]:
no $X(4140)$, but $X(4350)$ in $\gamma \gamma \rightarrow J/\psi \phi$

no evidence from:
BaBar [PRD 91, 012003 (2015)],
LHCb (0.37 fb$^{-1}$) [PRD 85, 091103(R) (2012)]
Exotic states in $B^+ \to J/\psi \phi K^+$

Signal yield: $4289 \pm 151$ events
Background: $\sim 20\%$

Full 6D amplitude analysis
Exotic states in $B^+ \rightarrow J/\psi \phi K^+$

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Full 6D amplitude analysis

\[ \text{Candidates/(1 MeV)} \]

\[ \begin{array}{cccccc}
50 & 100 & 150 & 200 & 250 & 300 \\
5250 & 5300 & 5350 & \end{array} \]

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LHCb & \text{Signal yield: 4289 ± 151 events} & \text{Background: } \sim 20\% \\
\end{array} \]

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\end{array} \]
Exotic states in $B^+ \rightarrow J/\psi \phi K^+$

$K^*$ states only

$K^*$ plus 4(!) exotic states in $J/\psi \phi$

<table>
<thead>
<tr>
<th>Contribution</th>
<th>$J^{PC}$</th>
<th>Significance</th>
<th>$M_0$ [MeV]</th>
<th>$\Gamma_0$ [MeV]</th>
<th>FF %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(4140)$</td>
<td>$1^{++}$</td>
<td>$8.4\sigma$</td>
<td>$4146.5 \pm 4.5$</td>
<td>$83 \pm 21$</td>
<td>$13 \pm 3.2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{+4.6}_{-2.8}$</td>
<td>$^{+21}_{-14}$</td>
<td></td>
</tr>
<tr>
<td>$X(4274)$</td>
<td>$1^{++}$</td>
<td>$6.0\sigma$</td>
<td>$4273.3 \pm 8.3$</td>
<td>$56 \pm 11$</td>
<td>$7.1 \pm 2.5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{+17.2}_{-3.6}$</td>
<td>$^{+8}_{-11}$</td>
<td></td>
</tr>
<tr>
<td>$X(4500)$</td>
<td>$0^{++}$</td>
<td>$6.1\sigma$</td>
<td>$4506 \pm 11$</td>
<td>$92 \pm 21$</td>
<td>$6.6 \pm 2.4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{+12}_{-15}$</td>
<td>$^{+21}_{-20}$</td>
<td></td>
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<tr>
<td>$X(4700)$</td>
<td>$0^{++}$</td>
<td>$5.6\sigma$</td>
<td>$4704 \pm 10$</td>
<td>$120 \pm 31$</td>
<td>$12 \pm 5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{+14}_{-24}$</td>
<td>$^{+42}_{-33}$</td>
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Masses for $X(4140)$ and $X(4274)$ are consistent with previous measurements, but widths significantly larger.
**Exotic states in** \( B^+ \rightarrow J/\psi \phi K^+ \)

**[PRL 118 (2017) 022003], [PRD 95 (2017) 012002]**

\[
J^P = 1^+ \text{ assignment rules out interpretation of } X(4140) \text{ as a } D_s^{*+} D_s^{*-} \text{ molecule.}
\]

\( X(4140) \) could be a \( D_s^{*+} D_s^{*-} \) state, below threshold \( \Rightarrow \) line shape differs from a Breit-Wigner ("cusp").

Check one particular "cusp" model by [E.S.Swanson, Phys. Rev. D91 034009, 2015]
Preferred by 3\( \sigma \) over Breit-Wigner fit. Should be able to distinguish BW and "cusp" with larger statistics.
Pentaquarks: $P_c(4380)$ and $P_c(4450)$
Pentaquark states in $\Lambda_b^0 \rightarrow J/\psi pK^-$

$\Lambda_b^0 \rightarrow J/\psi pK^-$ decay

Conventional contributions only in $pK^-$ spectrum ($\Lambda^*$ states).

Event yield: 26007 ± 166 events
Low background (5.4%)

Not an experimental effect (veto $B \rightarrow J/\psi Kh$, check part-rec $\Xi_b$ decays, clones and ghosts...)

Dalitz distribution shows an unexpected narrow feature in $J/\psi p$ mass.

[Anton Poluektov]
Exotic charm hadrons at LHCb
Charm 2018, BINP Novosibirsk, 21–25 May 2018

21/36
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Dalitz distribution shows an unexpected narrow feature in $J/\psi p$ mass.
Pentaquark states in $\Lambda_b^0 \rightarrow J/\psi pK^-$

Full amplitude analysis of the $\Lambda_b^0 \rightarrow J/\psi pK^-$ decay to understand its dynamics.

Fit in 6D phase space: $(M_{KP}, \theta_{\Lambda_b^0}, \theta_\mu, \phi_\mu, \theta_K, \phi_K)$

Two models for $\Lambda^*$ system (both isobar based on Breit-Wigners):

- "Extended": 14 $\Lambda^*$ states ("**" and higher).
- "Reduced": 12 states, exclude two higher mass (2350, 2585), fewer $LS$-couplings.

Admixture of all known $\Lambda^*$ states does not reproduce the peak observed at $m_{J/\psi_p} = 4450$ MeV.
Pentaquark states in $\Lambda^0_b \rightarrow J/\psi p K^-$

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Inclusion of the exotic $J/\psi p$ state improves the fit, best $J^P = 5/2^\pm$
Pentaquark states in $\Lambda_b^0 \to J/\psi pK^-$

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Two $J/\psi p$ states give the best fit, $J = 3/2$ and $5/2$ with opposite parities.
Pentaquark states in $\Lambda_b^0 \to J/\psi pK^-$

**Parameters of the pentaquark states**

$P_c(4380)$:
- $M = 4380 \pm 8 \pm 29$ MeV,
- $\Gamma = 205 \pm 18 \pm 86$ MeV
- $\mathcal{F} = (8.4 \pm 0.7 \pm 4.2\text{(syst)})\%$

$P_c(4450)$:
- $M = 4449.8 \pm 1.7 \pm 2.5$ MeV
- $\Gamma = 39 \pm 5 \pm 19$ MeV
- $\mathcal{F} = (4.1 \pm 0.5 \pm 1.1\text{(syst)})\%$

Significance (stat+syst) is overwhelming: 9σ and 12σ
Pentaquark states in $\Lambda_b^0 \rightarrow J/\psi pK^-$

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Pentaquark states in $\Lambda_b^0 \rightarrow J/\psi pK^-$: model-independent confirmation

Argand plots: model-independent confirmation of the resonant character of the exotic states.
Interference with $\Lambda^*$ states allows to extract the phase in bins of $m_{J/\psi p}$.

![Argand plots](image)

Clear phase rotation for $P_c(4450)$, direction consistent with Breit-Wigner amplitude
Not conclusive for $P_c(4380)$, need more statistics.

Model-independent PWA analysis (similar to $Z(4430)$): $\Lambda^*$ resonances only cannot describe the data; 10σ significance of exotic contribution.
Exotic contributions in $\Lambda_b^0 \rightarrow J/\psi p\pi^-$

Signal yield: $1885 \pm 50$ events
Background: $\sim 20\%$

$N^*$ states in $p\pi^-$

Possible exotic contributions:

- $P_c(4380, 4450)$ in $J/\psi p$
- $Z_c$ in $J/\psi \pi^- \ [Belle, PRD 90, 112009 (2014)]$
  
  $M = 4196^{+31+17}_{-29-13}$ MeV
  
  $\Gamma = 370 \pm 70^{+70}_{-132}$ MeV

  Total significance of exotic contributions: $3.1\sigma$. 
Observation of $\Lambda_0^b \to \chi_{c(1,2)} pK^-$

Test exotic nature of $P(4450)$

- Mass close to $\chi_{c1} p$ threshold, could be a rescattering effect
- If a kinematic effect, should be absent in $\Lambda_0^b \to \chi_{c(1)} pK^-$

First step: observation of $\Lambda_0^b \to \chi_{c(1)} pK^-$

$m(J/\psi \gamma)$ constrained to equal $m(\chi_{c1}) \Rightarrow \Lambda_0^b \to \chi_{c2} pK^-$ peak is displaced

$$\frac{B(\Lambda_0^b \to \chi_{c1} pK^-)}{B(\Lambda_0^b \to J/\psi pK^-)} = 0.242 \pm 0.014 \pm 0.013(syst) \pm 0.009(Br), \quad 453 \pm 25 \text{ events}$$

$$\frac{B(\Lambda_0^b \to \chi_{c2} pK^-)}{B(\Lambda_0^b \to J/\psi pK^-)} = 0.248 \pm 0.020 \pm 0.014(syst) \pm 0.009(Br), \quad 285 \pm 23 \text{ events}$$

Next step: amplitude analysis adding Run 2 data
Observation of $\Xi_b^- \rightarrow J/\psi \Lambda K^-$: search for strange pentaquark

[PLB 772 (2017) 265]

Search for strange hidden-charm pentaquark $udsc\bar{c}$

[PRL 105:232001 (2010)]

First observation of this decay:

$\Lambda$ inside VELO: $99 \pm 12$ events;
$\Lambda$ outside VELO: $209 \pm 17$ events

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\mathcal{B}(\Xi_b^- \rightarrow J/\psi \Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda)} = (4.19 \pm 0.29(stat) \pm 0.15(syst)) \times 10^{-2},$$
Possible open-charm exotics in $\Lambda_c$ excitations
Excited $\Lambda_c^+$ states

$J^P = 3/2^+$ state (2nd member of $D$-wave doublet) is missing in data

Two experimentally observed states without clear assignment: $\Lambda_c(2765)^+$ and $\Lambda_c(2940)^+$.

$\Lambda_c(2940)^+$ has mass close to $D^*N$ threshold: possible molecular interpretation.
Amplitude analysis of $\Lambda_b^0 \rightarrow D^0 p\pi^-$ decay

$\Lambda_b^0 \rightarrow D^0 p\pi^-$, $D^0 \rightarrow K^-\pi^+$

Looking at excited $\Lambda_c^+$ states in the exclusive $b$ decay for the first time.
Well-defined initial state, low background, access to quantum numbers.

Signal yield: $11212 \pm 126$ events
Background: $\sim 16\%$

$\Lambda_b^0$ unpolarised $\Rightarrow$ two DoF, 2D Dalitz plot phase space.
Amplitude analysis of $\Lambda_b^0 \rightarrow D^0 p\pi^-$ decay

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Amplitude analysis of $\Lambda_b^0 \to D^0 p\pi^-$ decay

- New resonance: $\Lambda_c(2860)^+$, $J^P = 3/2^+$
  
  \[
  M(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7} \pm 0.5(\text{syst})^{+1.1}_{-5.6}(\text{model}) \text{ MeV} \\
  \Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1} \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model}) \text{ MeV}
  \]
  Fits well into $\Lambda_c^+$ spectrum as $1D$ state.

- $\Lambda_c(2940)^+$: preferred $J^P = 3/2^-$
  
  \[
  M(\Lambda_c(2940)^+) = 2944.8^{+3.5}_{-2.5} \pm 0.4(\text{syst})^{+0.1}_{-4.6}(\text{model}) \text{ MeV} \\
  \Gamma(\Lambda_c(2940)^+) = 27.7^{+8.2}_{-6.0} \pm 0.9(\text{syst})^{+5.2}_{-10.4}(\text{model}) \text{ MeV}
  \]


2$P$ radial excitation (B. Chen, K.-W. Wei, A. Zhang, [arXiv:1406.6561]), or their admixture.

<table>
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<th>$\Lambda_c(2940)^+$</th>
<th>Significance wrt 3/2$^-$</th>
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<tbody>
<tr>
<td>$J^P$</td>
<td>(stat + syst)</td>
</tr>
<tr>
<td></td>
<td>Exp NR</td>
</tr>
<tr>
<td>None</td>
<td>8.2</td>
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<tr>
<td>1/2$^+$</td>
<td>7.9</td>
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Possible open-charm exotics in $\Omega_c$ excitations
Observation of five new $\Omega_c^0$ states

Search for $\Omega_c^{*0} \rightarrow \Xi_c^+ K^-$

Large sample of $\Xi_c^+ \rightarrow pK^-\pi^+$ decays, combine with a $K^-$

<table>
<thead>
<tr>
<th>State</th>
<th>Mass, MeV</th>
<th>Width, MeV</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_c^0(3000)$</td>
<td>3000.4 ± 0.2 ± 0.1±0.3±0.5</td>
<td>4.5 ± 0.6 ± 0.3</td>
<td>1300 ± 100 ± 80</td>
</tr>
<tr>
<td>$\Omega_c^0(3050)$</td>
<td>3050.2 ± 0.1 ± 0.1±0.3±0.5</td>
<td>0.8 ± 0.2 ± 0.1</td>
<td>970 ± 60 ± 20</td>
</tr>
<tr>
<td>$\Omega_c^0(3066)$</td>
<td>3065.6 ± 0.1 ± 0.3±0.3±0.5</td>
<td>3.5 ± 0.4 ± 0.2</td>
<td>1740 ± 100 ± 50</td>
</tr>
<tr>
<td>$\Omega_c^0(3090)$</td>
<td>3090.2 ± 0.3 ± 0.5±0.3±0.5</td>
<td>8.7 ± 1.0 ± 0.8</td>
<td>2000 ± 140 ± 130</td>
</tr>
<tr>
<td>$\Omega_c^0(3119)$</td>
<td>3119.1 ± 0.3 ± 0.9±0.3±0.5</td>
<td>1.1 ± 0.8 ± 0.4</td>
<td>480 ± 70 ± 30</td>
</tr>
</tbody>
</table>

Two of the states are surprisingly narrow (3050, 3119); possible exotic interpretation (meson-baryon molecules, e.g. $K\Xi_c', D\Xi$: [arXiv:1709.08737], [arXiv:1710.04231])
Searches for dibaryons  New!
Observation of $\Lambda_b^0 \rightarrow \Lambda_c^+ p\bar{p}\pi^-$: search for dibaryons [arXiv:1804.09617]

First observation of $\Lambda_b^0 \rightarrow \Lambda_c^+ p\bar{p}\pi^-$:

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ p\bar{p}\pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} = 0.0540 \pm 0.0023 \pm 0.0032.$$  

Search for charmed dibaryon $cdudud$ [PLB 750 (2015) 37]

No evidence of exotic contributions:
Summary

- Exotic spectroscopy is an essential part of LHCb physics programme
- Many important results with 3 fb\(^{-1}\):
  - \(X(3872)\) measurements
  - Confirmation and quantum numbers of \(Z(4430)\)
  - Discovery of hidden-charm pentaquarks
  - Exotic states in \(J/\psi\phi\)
  - Studies of open-charm baryons
- Many more expected after adding Run 2:
  - Updates of present analyses with higher stats, precision measurements
  - Pentaquark searches with open-charm states
  - Prompt production of exotic states
  - Final states with neutrals (\(\chi_c\), \(\Lambda^0\), \(K^0_S\), \(\omega\))
  - New initial states (\(B^0_s\), \(B^+_c\), \(b\)-baryons)
  - More amplitude analyses; more sophisticated models based on unitarity and analyticity
Backup
Model-independent confirmation of a structure in $\psi'\pi^-$. Check that $K^-\pi^+$ amplitude only fails to describe the decay. $K^-\pi^+$ should contribute to reasonably low moments, while exotic $\psi'\pi^-$ contributes to all moments.

$$J_{\text{max}} = 2$$
$$l_{\text{max}} = 4$$
$(K^*, K_2^* \text{ etc.})$

$$J_{\text{max}} = 3$$
$$l_{\text{max}} = 6$$
$(+K_3^*(1780) \text{ etc.})$

$$J_{\text{max}} = 15$$
$$l_{\text{max}} = 30$$
...

Resonances with spin up to 3 cannot reproduce the features seen in data. $m(\psi(2S)\pi)$ distribution can only be described by an unreasonable number of Legendre moments.
Z(4430): model-independent confirmation

Test statistic:

\[-2\Delta NLL = -2 \sum_i W_i \frac{F_i(m^i_{\psi\pi})}{F_{30}(m^i_{\psi\pi})} \log \frac{\epsilon_i}{F_{30}(m^i_{\psi\pi})}\]

Run toys with $K^+\pi^-$-only model to determine distribution, compare with $-2\Delta NLL$ in data.

Resonances with spin up to 3 cannot reproduce the features seen in data.
Search for $X(3872) \rightarrow p\bar{p}$

- Decay $B^+ \rightarrow p\bar{p}K^+$
- First observation of $\eta_c(2S) \rightarrow p\bar{p}$
- Mass and width of $\eta_c(1S)$

No evidence of $X(3872) \rightarrow p\bar{p}$ in $B^+ \rightarrow p\bar{p}K^+$:

\[
\frac{\mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X(3872) \rightarrow p\bar{p})}{\mathcal{B}(B^+ \rightarrow J/\psi K^+) \times \mathcal{B}(J/\psi \rightarrow p\bar{p})} < 0.25 \times 10^{-2} \quad \text{@ 95\% CL}
\]
Model-independent approach: $\Lambda^0_b \rightarrow J/\psi pK^-$

Checking that $\Lambda^*$ resonances only cannot describe the data. Use Legendre moments in $\cos \theta_{\text{hel}}$ as a function of $m_{pK}$. Allow $l_{\text{max}}$ depending on $m_{pK}$

Moments from model

Moments from data

$10\sigma$ significance

[PR 117 (2016) 082002]
Exotic contributions in $\Lambda_b^0 \rightarrow J/\psi p\pi^-$

Signal yield: $1885 \pm 50$ events

Background: $\sim 20\%$

$N^*$ states in $p\pi^-$

Possible exotic contributions:

- $P_c$ in $J/\psi p$
- $Z_c$ in $J/\psi \pi^-$ [Belle, PRD 90, 112009 (2014)]
  
  $M = 4196^{+31+17}_{-29-13}$ MeV
  
  $\Gamma = 370 \pm 70^{+70}_{-132}$ MeV
Exotic contributions in $\Lambda_b^0 \rightarrow J/\psi p\pi^-$

$N^* \rightarrow p\pi^-$ contributions:
- Baseline: isobar $p\pi^-$ with 7-14 states.
- Tried BW and Flatté for $N(1535)$ (opening of $n\eta$ threshold)
- Cross-check: $K$-matrix for $1/2^-$ wave using Bonn-Gatchina parametrisation [A. Anisovich et al., arXiv:0911.5277]

Exotic contributions:
- Considered $P_c(4380)$, $P_c(4450)$ (in $J/\psi p$) and $Z_c(4200)$ (in $J/\psi\pi^-$).
- Total significance of exotic contributions: 3.1σ.
- Individual contributions are not significant
- Fit fractions:
  - $F(P_c(4380)) = (5.1 \pm 1.5^{+2.6}_{-1.6})\%$
  - $F(P_c(4450)) = (1.6^{+0.8+0.6}_{-0.6-0.5})\%$
  - $F(Z_c(4200)) = (7.7 \pm 2.8^{+3.4}_{-4.0})\%$
Fit model: $\Lambda_0(2880)^+ (J^P = \frac{5}{2}^+)$, $\Lambda_0(2940)^+$, $\Lambda_0(2860)^+ (J^P$ varied) and non-resonant (exponential or 2nd-order polynomial, $J^P = \frac{1}{2}^\pm, \frac{3}{2}^-$).

Rotation of phase for $J^P = \frac{3}{2}^+$ component ($\Lambda_0(2860)^+$) wrt. non-resonant amplitudes.
Amplitude analysis of $\Lambda_b^0 \rightarrow D^0 p\pi^-$ decay

Basically, a PWA in the low-$M(D^0 p)$ region (admixture of $p\pi^-$ amplitude is small).

Since no known “reference” amplitude and a large number of unknown parameters, make analysis in steps:

Consider a range of model variations, including:

- Non-resonant amplitude model (exponential, 2nd-order polynomial).
- Helicity formalism vs. covariant tensors [M. Williams, QFT++], e.g.:
  
  $$A(5/2^+) = \bar{u}(p_{\Lambda_b^0}, m_{\Lambda_b^0}) (C_2 + C_1 \gamma^5) P_{\Lambda_b^0}^\alpha P_{\Lambda_b^0}^\beta P^{(5/2)}_{\alpha\beta\mu\nu}(q^2) p^\mu p^\nu \gamma^5 u(p_p, m_p)$$