Hadron Spectroscopy at LHCb

R. Cardinale on behalf of the LHCb Collaboration

University of Genova and INFN Genova

“Spectroscopy of resonances and QCD”
ECT* workshop
8-12 February 2016
The LHCb detector
Exotic spectroscopy
  \(X(3872)\)
  \(Z(4430)^-\)
  Pentaquarks
\(B^{**}\) mesons
\(b\)-baryon
The LHCb detector

LHCb experiment is designed to perform high precision flavor physics measurements at the LHC

- Single-arm forward spectrometer
- Pseudorapidity range: $2 < \eta < 5$
- Excellent muon identification and good separation of $\pi$, $K$, and $p$
- Good vertexing: proper time resolution $30-50 \text{ fs}^{-1}$
- Good tracking system: $\Delta p/p \sim 0.5\%$
- Selective and flexible trigger system
LHCb Physics Programme

CKM and CP violation with $b$ and $c$ hadrons

Electroweak and QCD measurements in the forward acceptance

Rare decays of $b$ and $c$ hadrons

Heavy quark production

Spectroscopy in pp interactions and B decays

Exotica searches
\[ X(3872) \]
Since its discovery more than a decade ago (2003) by Belle [PRL91 (2003) 262001] in $B \rightarrow K X(3872)$, $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ decays, the $X(3872)$ has been studied at a number of experiments.

The existence of the $X(3872)$ is now beyond doubt, but structure is still unclear.

Isospin violating decays.

Mass is roughly equal to $m(D^0) + M(D^{*0})$ and the width is surprisingly narrow $< 1.2$ MeV.

Large production rate in $p\bar{p}$ collisions.

LHCb is largely contributing to shed light on the nature of the $X(3872)$ state,

- The $D^0$ mass measurement performed at LHCb [JHEP 1306 (2013) 065] reinforces that if the $X(3872)$ is a $D^0 \bar{D}^{*0}$ bound-state, it is loosely bound: $E_B = m(D^0 \bar{D}^{*0}) - m(X(3872)) = 3 \pm 192$ keV/c$^2$.
- Production cross-section in pp collisions at $\sqrt{s} = 7$ TeV [EPJC 72 (2012) 1972] $\sigma_X(3872) \times B(X(3872) \rightarrow J/\psi \pi^+ \pi^-)[^{2.5<y<4.5, p_T>5 \text{ GeV}}] = 5.4 \pm 1.3 \pm 0.8$ nb.
- Search for $X(3872) \rightarrow p\bar{p}$ [EPJC 73 (2013) 2462] $\frac{B(X(3872) \rightarrow p\bar{p})}{B(X(3872) \rightarrow J/\psi \pi^+ \pi^-)} < 2.0 \times 10^{-3}$.
Quantum numbers were narrowed down by CDF to be $1^{++}$ or $2^{-+}$.

LHCb has measured its quantum numbers using $\sim 300 \, B^+ \rightarrow X(3872)K^+$, with $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ and $J/\psi \rightarrow \mu^+ \mu^-$ using full angular correlations in 5D.

An amplitude analysis on $1 \text{ fb}^{-1}$ [PRL 110 (2013) 222001] established $J^{PC} = 1^{++}$.

- Assumed the lowest possible angular momentum in the $X(3872) \rightarrow J/\psi \pi^+ \pi^-$.
- But several values of $L$ can return the same $J^P$.

Reanalysis using full $3 \text{ fb}^{-1}$ of Run1 data [Phys Rev D 92, 011102 (2015)] with no assumptions on orbital angular momentum.

A significant $L > L_{\text{min}}$ could invalidate the previous $J^{PC} = 1^{++}$ assignment and give hint molecular structure of $X(3872)$. 

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R. Cardinale
ECT* workshop
Amplitude analysis $X(3872) \rightarrow J/\psi \rho$

[Phys Rev D 92, 011102 (2015)]

- Tripled size of dataset wrt the first analysis: $1011 \pm 38$ candidates of $B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow \rho^0 J/\psi$ decays
- Allows a full amplitude model, including D-wave contributions
- $J^{PC} = 1^{++}$ confirmed
- D-wave amplitudes consistent with zero: $< 4\%$ @ 95% CL
- Compatible with tetraquark, molecule or $\chi_{c1}(2^3P_1)$ hypotheses (possibly mixed). It excludes any other charmonium state.
Radiative decays of $X(3872)$

- The nature of the $X(3872)$ state is not clear
- Valuable opportunity to understand its nature and in particular to test molecular models

$$R_{\psi\gamma} = \frac{B(X(3872) \rightarrow \psi(2S)\gamma)}{B(X(3872) \rightarrow J/\psi\gamma)}$$ can give information about the $X(3872)$ structure

- Predictions for $R_{\psi\gamma}$ vary widely in different models
  - $c\bar{c}(2^3P_1)$ interpretation: $\sim 1.2-15$ \cite{PhysRevD79(2009)094004;PhysRevD85(2012)114002} \\
  - $D\bar{D}^*$ molecule: $\sim 3 \cdot 10^{-3}$ \cite{arXiv:1401.4431} \\
  - Mixture of $c\bar{c}$ and $D\bar{D}^*$: 0.5-5 \cite{PhysRevD85(2012)114002;PhysRevD73(2006)014014}

- Controversial experimental status
  - BaBar observed the $X(3872) \rightarrow \psi(2S)\gamma$ decay in $B^+ \rightarrow X(3872)K^+$ decays and measured the ratio: $3.4 \pm 1.4$
  - Belle(2011): no evidence for $X(3872) \rightarrow \psi(2S)\gamma$: $R_{\psi\gamma} < 1.2@90$ CL
Evidence of $X(3872) \rightarrow \psi(2S)\gamma$ at LHCb

- Analysis performed using $3 \text{ fb}^{-1}$
- $N(X(3872) \rightarrow J/\psi\gamma) = 591 \pm 48$ and $N(X(3872) \rightarrow \psi(2S)\gamma) = 36.4 \pm 9.0$
- $B^+ \rightarrow J/\psi\rightarrow \mu\mu\gamma K^+$
- 2D fit: $(M_{\psi\gamma K}, M_{\psi\gamma})$
- Peaking backgrounds
  - $J/\psi$ mode: $B^+ \rightarrow J/\psi K^*(K^+\pi^0(\rightarrow \gamma\gamma))$ with one missing $\gamma$
  - $\psi(2S)$ mode: $B^+ \rightarrow \psi(2S)K^+ h$ with a random $\gamma$

Evidence at $4.4\sigma$ of $X(3872) \rightarrow \psi(2S)\gamma$ in $B^+ \rightarrow X(3872)K^+$ decays
Evidence of $X(3872) \rightarrow \psi(2S)\gamma$ at LHCb

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

The measured value of $R_{\psi\gamma}$ does not support a pure $D\bar{D}^*$ molecular interpretation of the $X(3872)$ state! Standard charmonium and other scenarios still compatible [arXiv:1404.0275]
\[ X(4140) \text{ and } X(4270) \]
CDF: observation of a narrow state $[5\sigma]$

$M = 4143.4^{+2.9}_{-3.0} \pm 0.6$ MeV and

$\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5$ MeV and evidence of a state $[3.1\sigma]$ with mass $4274.4^{+8.4}_{-6.7} \pm 1.9$ MeV [PRL 102, 242002 (2009)]

Belle: no evidence of $X(4140)$ in $\gamma\gamma \rightarrow J/\psi \phi$.

Observation of a new state $X(4350)$ [PRL 104(2010)112004]

$D0$ observed the narrow $X(4140)$ with a marginal significance and large errors [PRD 89, 012004 (2014)]

CMS confirmed the $X(4140)$ state in 2011 data with $5\sigma$ significance, but with a larger $28^{+15}_{-11} \pm 19$ MeV width. Peak also at $M = 4313.8 \pm 5.3 \pm 7.3$ MeV with $\Gamma = 38^{+30}_{-15} \pm 16$ MeV. [PLB734, 261 (2014)]

BaBar: no evidence of $X(4140)/X(4274)$ [PRD91 (2015) 012003]
Search for $X(4140)/X(4270)$ at LHCb

- Analysis performed with 0.37 fb$^{-1}$
- No narrow structure is observed near the threshold
- The LHCb result disagree at 2.4σ level with the CDF measurement
- Set an UL @ 90% CL

\[
\frac{\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)} < 0.07 \\
\frac{\mathcal{B}(B^+ \to X(4274)K^+) \times \mathcal{B}(X(4274) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)} < 0.08
\]

An amplitude analysis needed to investigate the resonance nature of these peaks
$Z(4430)^+$
**Z^-(4430)**

- Charged charmonium-like state $Z^-(4430)$ observed by Belle in $B^0 \rightarrow \psi(2S)K^+\pi^-$ [PRL100 (2008) 142001]

- Clear signature of exotic state: charged state with $c\bar{c}$ pair content, cannot be described as conventional meson: minimum quark content: $c\bar{c}ud$

- Later 2D Dalitz technique [PRD80 (2009) 031104]

- Not confirmed nor excluded by BaBar [PRD79 (2009) 112001]

- Full 4D amplitude analysis by Belle confirms new state, $J^P = 1^+$ favoured but $J^P = 0^-$ not excluded [PRD88 (2013) 074026]

$Z(4430)^+$ at Belle. $K^*(892)^0$ and $K_2^*(1432)$ vetoed.

$Z(4430)^+$ at BaBar. Legendre polynomials approach.
Sample with $> 25000$ $B^0 \rightarrow K^+\pi^- \psi(2S)$, factor 10 more than BaBar/Belle, in $3 \text{ fb}^{-1}$

Analysis performed using two separate approaches:

- Model independent: based on the Legendre polynomial moments extracted from the $K\pi$ system (BaBar)
- Model dependent: 4D amplitude fit (Belle)

Very clean signal: 3% residual background

Four-dimensional efficiency calculated using complete simulation of the detector
**Z(4430): amplitude analysis**

- 4D amplitude analysis using the isobar approach
- cFit technique used to account for the background
- The amplitude analysis includes all the resonances with nominal mass within or slightly above the kinematical limit
- Also included a non-resonant s-wave contribution
- Masses and widths of the resonances fixed to the world average values, except for the widths of the two dominant contributions, $K^*(892)$ and $K_2^*(1430)$, and the poorly known $K_0(800)$ mass and width
- As $K_3^*(1780)$ is spin 3 and well above threshold, it is unlikely to be present in the data and is excluded from the default model (systematic)
- Alternative s-wave model uses LASS parametrization

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$J^P$</th>
<th>Likely $n^{2S+1}L_J$</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>$\mathcal{B}(K^{*0} \rightarrow K^+\pi^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*_0(800)^0$ (κ)</td>
<td>0$^+$</td>
<td>—</td>
<td>682 ± 29</td>
<td>547 ± 24</td>
<td>~ 100%</td>
</tr>
<tr>
<td>$K^*(892)^0$</td>
<td>1$^-$</td>
<td>$1^3S_1$</td>
<td>895.94 ± 0.262</td>
<td>48.7 ± 0.7</td>
<td>~ 100%</td>
</tr>
<tr>
<td>$K_0^*(1430)^0$</td>
<td>0$^+$</td>
<td>$1^3P_0$</td>
<td>1425 ± 50</td>
<td>270 ± 80</td>
<td>(93 ± 10)%</td>
</tr>
<tr>
<td>$K_1^*(1410)^0$</td>
<td>1$^-$</td>
<td>$2^3S_1$</td>
<td>1414 ± 15</td>
<td>232 ± 21</td>
<td>(6.6 ± 1.3)%</td>
</tr>
<tr>
<td>$K_2^*(1430)^0$</td>
<td>2$^+$</td>
<td>$1^3P_2$</td>
<td>1432.4 ± 1.3</td>
<td>109 ± 5</td>
<td>(49.9 ± 1.2)%</td>
</tr>
</tbody>
</table>

$B^0 \rightarrow \psi(2S)K^+\pi^-$ phase space limit: 1593

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$J^P$</th>
<th>Likely $n^{2S+1}L_J$</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>$\mathcal{B}(K^{*0} \rightarrow K^+\pi^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_1^*(1680)^0$</td>
<td>1$^-$</td>
<td>$1^3D_1$</td>
<td>1717 ± 27</td>
<td>322 ± 110</td>
<td>(38.7 ± 2.5)%</td>
</tr>
<tr>
<td>$K_3^*(1780)^0$</td>
<td>3$^-$</td>
<td>$1^3D_3$</td>
<td>1776 ± 7</td>
<td>159 ± 21</td>
<td>(18.8 ± 1.0)%</td>
</tr>
</tbody>
</table>
**Z(4430): Amplitude analysis results**

- Data well described in all dimensions only when a $J^P = 1^+$ $Z(4430)$ is included.
- The (binned) $\chi^2$ probability is $2 \times 10^{-6}$ without the $Z$, 14% with it.
- Main source of systematic uncertainty comes from varying model to include higher $K\pi$ spin-states.
- Good agreement between Belle and LHCb parameters:
  
  $$M_{Z(4430)^-} = 4475 \pm 7^{+15}_{-25} \text{ MeV}/c^2$$
  
  $$\Gamma_{Z(4430)^-} = 172 \pm 13^{+37}_{-34} \text{ MeV}/c^2$$
  
  $$\Delta(-2\ln L) > 13.9\sigma$$
Spin determination and resonant behaviour

- Argand plot: amplitude in complex plane
- Replace BW amplitude with 6 independent complex numbers in $Z$ peak region $(18.0 - 21.5) \text{ GeV}^2/c^2$
- Observed rapid change of phase near maximum of magnitude $\rightarrow$ Resonance!
- Demonstrated the resonant character of the four-quark candidate!

\[ \Delta(-2\ln L) = [-2\ln L(0^-)] - [-2\ln L(1^+)] \]

- $J^P = 1^+$ assignment favoured (confirms Belle)
- Other $J^P$ assignments ruled out with large significance ($> 9.7\sigma$)

[PRD92(2015)112009]
**Z(4430): model independent approach**

The main goal is to check if the structures in the $m_{\psi(2S)\pi}$ spectrum can be explained as reflections of the resonance activity in the $K\pi$ system.

- No assumptions on the $K^*$ resonances, but restriction on their maximal spin
- Angular structure of the $K\pi$ system is extracted using Legendre polynomial moments
- The moments are used in toy MonteCarlo simulation to predict the expected $m_{\psi(2S)\pi}$ spectrum considering different $L_{\text{max}}$ contributions

[PRL 112, 222002 (2015)]

- Implementation of the $K\pi$ mass dependence in $L_{\text{max}}$

\[
L_{\text{max}}(m_{K\pi}) = \begin{cases} 
2 & \text{if } m_{K\pi} < 0.863 \text{ GeV/}c^2 \\
3 & \text{if } 0.836 < m_{K\pi} < 1.0 \text{ GeV/}c^2 \\
4 & \text{if } 1.0 < m_{K\pi} < 1.39 \text{ GeV/}c^2 \\
8 & \text{if } m_{K\pi} > 1.39 \text{ GeV/}c^2 
\end{cases}
\]

- $L_{\text{max}}$ and $m_{K\pi}$ intervals are defined according to the local dominant resonance and the most probable interference term
- The spread of the yellow bands correlated to the data errors
**Z(4430): model independent approach**

- Other possible configurations have been investigated
  - Allows for S, P, D waves
  - Allows implausible contributions setting $l_{\text{max}} = 30$ (unphysical value)
  - High moments wouldn’t contribute except in presence of an exotic state
  - Qualitatively the $m_{\psi(2S)\pi}$ spectrum cannot be explained as a reflection of the angular structure of the $K\pi$ system
\( Z(4430)^+ \): model independent approach

- Hypothesis test based on likelihood ratio used to quantify the results
- Efficiency and background subtraction taken into account in the toy MC generation
- Physical configurations compared with \( l_{\text{max}} = 30 \) prediction
- Test significance of implausible \( l_{\text{max}} < l < 30 \) moments using the log-likelihood ratio

\[
\Delta(-2NLL) = -2 \log \frac{\mathcal{L}_{l_{\text{max}}}}{\mathcal{L}_{30}} = -2 \log \frac{\prod_i \mathcal{F}_{l_{\text{max}}}(m_{i\psi\pi})}{\prod_i \mathcal{F}_{l_{30}}(m_{i\psi\pi})}
\]

Explanation of the data with plausible \( K^* \) contributions is ruled at high significance without assuming anything about \( K^* \) resonance shapes or their interference patterns!
Pentaquark
Sample with $> 26000 \Lambda_b^0$ signal candidates in $3 \text{ fb}^{-1}$

Background from sidebands: only $5.4\%$ of combinatorial bkg in the signal region

Sideband distributions are flat: no major reflections from the other $b$-hadrons

6D efficiency calculated using complete simulation of the detector

The decay was used to measure $\Lambda_b^0$ lifetime [PRL111 (2013) 102003]

But looking closer at the $J/\psi pK$ Dalitz plot with $3 \text{ fb}^{-1}$ of data
Large activity due to $\Lambda^*$ excited states

Unexpected narrow peak in the $m_{J/\psi p}$ at 19.5 GeV$^2$

Cross-checks to exclude possible artifacts:
- Efficiencies vary smoothly
- Veto of the $B_s \rightarrow J/\psi KK$ and $B^0 \rightarrow J/\psi K\pi$ after swapping the mass hypothesis of the $\Lambda_b$ daughters
- Removed clone and ghost tracks

None of them explained the narrow peak
Could the interference between $\Lambda^*$ resonances generate a peak in the $J/\psi p$ mass spectrum?

A full amplitude analysis that incorporate both decay sequences is necessary!

Analyze all dimensions of the $\Lambda_b^0 \rightarrow J/\psi pK^-$, $J/\psi \rightarrow \mu^+\mu^-$ decay kinematics:
- to maximise sensitivity to the decay dynamics
- to avoid biases due to averaging over some dimensions in presence of the non-uniform detector efficiency

6D amplitude fit based on the helicity formalism: the matrix element $\mathcal{M}$ is parametrized as a function of the invariant mass $m_{pK}^2$ and 5 angles (helicity and decay planes angles)

Two different background subtraction methods have been investigated
Amplitude analysis with $\Lambda^*$

- All known $\Lambda^*$ resonances included (14 states)

<table>
<thead>
<tr>
<th>State</th>
<th>$J^P$</th>
<th>$M_0$ (MeV)</th>
<th>$\Gamma_0$ (MeV)</th>
<th>Red.</th>
<th>Ext.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda(1405)$</td>
<td>$1/2^-$</td>
<td>$1405.1^{+1.3}_{-1.0}$</td>
<td>$50.5 \pm 2.0$</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda(1520)$</td>
<td>$3/2^-$</td>
<td>$1519.5 \pm 1.0$</td>
<td>$15.6 \pm 1.0$</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(1600)$</td>
<td>$1/2^+$</td>
<td>1600</td>
<td>150</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda(1670)$</td>
<td>$1/2^-$</td>
<td>1670</td>
<td>35</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda(1690)$</td>
<td>$3/2^-$</td>
<td>1690</td>
<td>60</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(1800)$</td>
<td>$1/2^-$</td>
<td>1800</td>
<td>300</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda(1810)$</td>
<td>$1/2^+$</td>
<td>1810</td>
<td>150</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda(1820)$</td>
<td>$5/2^+$</td>
<td>1820</td>
<td>80</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(1830)$</td>
<td>$5/2^-$</td>
<td>1830</td>
<td>95</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(1890)$</td>
<td>$3/2^+$</td>
<td>1890</td>
<td>100</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(2100)$</td>
<td>$7/2^-$</td>
<td>2100</td>
<td>200</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(2110)$</td>
<td>$5/2^+$</td>
<td>2110</td>
<td>200</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(2350)$</td>
<td>$9/2^+$</td>
<td>2350</td>
<td>150</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>$\Lambda(2585)$</td>
<td>?</td>
<td>$\approx 2585$</td>
<td>200</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Last columns show number of parameters are left free. Masses and Width are fixed. Red.: Reduced model (fast). Ext.: Allows for more helicity (LS) couplings.
Fit results without pentaquark states

- \( m_{Kp} \) looks fine, but not \( m_{J/\psi p} \)

Extended model used in this fit: adding more \( \Lambda \) resonances does not help
Letting the width and masses float does not help
Additions of non-resonant term and suppressed \( \Sigma^* \) states does not help
$P_c^+ \colon$ Fit results with pentaquark states

[Chin.Phys.C 40 (2016) 1,011001]

Extended $\Lambda^*$ model + 1 $P_c^+$

- Extended $\Lambda^*$ model + 1 pentaquark
  - Explored all $J^P$ up to $7/2^\pm$
  - Best fit has $J^P = 5/2^+$ but still not a good fit
  - Improvement wrt to fit without $P_c$: $\sqrt{\Delta 2\mathcal{L}} = 14.7\sigma$
$P_c^+$: Fit results with pentaquark states

Reduced $\Lambda^*$ model + 2 $P_c^+$

- Good fit even with the reduced $\Lambda^*$ model
- Best fit has $J^P = (3/2^-, 5/2^+)$ also $(3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$ preferred
- Improvement wrt to fit without $P_c$: $\sqrt{\Delta 2\mathcal{L}} = 18.7\sigma$
- Adding further states (also in $J/\psi K$) did not improve the fit significance
The peaking structure in $m_{J/\psi p}$ is asymmetric as a function of $m_{KP}$ (or $\cos \theta_{Pc}$)

This can be explained by interference of two states with opposing parity

The need for a second broad $P_{c}^{+}$ state becomes visually apparent in the region where the $\Lambda^{*} \rightarrow pK^{-}$ background is the smallest
Angular distributions

All data

$P_c$ enriched region

Good description of the data in all 6 dimensions!
Simulations of pseudo-experiments are used to quote the significances

- $P_c(4450)^+: 12\sigma$
- $P_c(4380)^+: 9\sigma$

Main systematic uncertainty: difference between extended and reduced fit models

Systematic uncertainty included when computing significances

Spin-parity assignment not conclusive

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4380)^+$</td>
<td>$4380 \pm 8 \pm 29$</td>
<td>$205 \pm 18 \pm 86$</td>
<td>$3/2^-$</td>
<td>$(8.4 \pm 0.7 \pm 4.2)%$</td>
</tr>
<tr>
<td>$P_c(4450)^+$</td>
<td>$4449.8 \pm 1.7 \pm 2.5$</td>
<td>$39 \pm 5 \pm 19$</td>
<td>$5/2^+$</td>
<td>$(4.1 \pm 0.5 \pm 1.1)%$</td>
</tr>
</tbody>
</table>
Replace the BW amplitude in the model with complex valued cubic spline $A$ in 6 bins of $m^2(J/\psi p)$, centered around the $P_c$ peaks from nominal fit.

$P_c(4450)$ shows resonance behaviour: a rapid counter-clockwise change of phase across the pole mass.

The errors for $P_c(4380)$ are too large to be conclusive.
New $b$-hadrons

- Excited $b$-mesons
- Excited $b$-baryons
Heavy quark effective theories predict $B$ mass spectrum by perturbative expansion of $\Lambda_{QCD}/m_b$, yet many states remain unconfirmed.

- Two narrow states $B_1(5721)$, $B_2^*(5747)$ observed by CDF and D0 [PRL102(2009)102003, PRL99 (2007) 172001]
- Evidence for higher mass states from CDF [PRD90 (2014) 012013]

Analysis based on $3 \text{ fb}^{-1}$ of data

Selection of a high purity $B^+$ and $B^0$ samples in

- $B^- \rightarrow J/\psi K^-$
- $B_{-}^-, 0 \rightarrow D^0, -\pi^+ (\pi^+ \pi^-)$ with $D^0 \rightarrow K^- \pi^+ (\pi^- \pi^+)$
- $B^0 \rightarrow J/\psi K^*(892)^0$

for a total of $1.2 \times 10^6 \ B^0$ and $2.5 \times 10^6 \ B^+$

Form $B^{**}$ candidates adding pions from the same primary vertex of the $B$ candidate

Combinatorial background modeled by wrong-sign (WS) combinations
The analysis carried out by fitting the $Q = m(B\pi) - m(B) - m(\pi)$ distributions

The Q-value distributions of $B^+\pi^-$ and $B^0\pi^+$ samples are fitted independently

Two clear peaks followed by broad structures at high mass

The narrow states are identified with the $B_1(5721)^0$ and $B_2(5747)^0$ states, and their $B_1(5721)^+$ and $B_2(5747)^+$ isospin counterparts
Results: $B_1(5721)^{0,+}$ and $B_2^*(5747)^{0,+}$

- Most precise measurement of $B_1(5721)$ and $B_2^*(5747)$ mass and width

\[
\begin{align*}
m_{B_1(5721)^0} &= 5727.7 \pm 0.7 \pm 1.4 \pm 0.17 \pm 0.4 \text{ MeV} \\
m_{B_2^*(5747)^0} &= 5739.44 \pm 0.37 \pm 0.33 \pm 0.17 \text{ MeV} \\
m_{B_1(5721)^+} &= 5725.1 \pm 1.8 \pm 3.1 \pm 0.17 \pm 0.4 \text{ MeV} \\
m_{B_2^*(5747)^+} &= 5737.20 \pm 0.72 \pm 0.40 \pm 0.17 \text{ MeV} \\
\Gamma_{B_1(5721)^0} &= 30.1 \pm 1.5 \pm 3.5 \text{ MeV} \\
\Gamma_{B_2^*(5747)^0} &= 24.5 \pm 1.0 \pm 1.5 \text{ MeV} \\
\Gamma_{B_1(5721)^+} &= 29.1 \pm 3.6 \pm 4.3 \text{ MeV} \\
\Gamma_{B_2^*(5747)^+} &= 23.6 \pm 2.0 \pm 2.1 \text{ MeV}
\end{align*}
\]

- First evidence $(3.7\sigma)$ of $B_2^* \to B^*\pi^+$

\[
\begin{align*}
\frac{\mathcal{B}(B_2^*(5747)^0 \to B^{*0}\pi^-)}{\mathcal{B}(B_2^*(5747)^0 \to B^{+}\pi^-)} &= 0.71 \pm 0.14 \pm 0.30 \\
\frac{\mathcal{B}(B_2^*(5747)^+ \to B^{*0}\pi^+)}{\mathcal{B}(B_2^*(5747)^+ \to B^{0}\pi^+)} &= 1.0 \pm 0.5 \pm 0.8
\end{align*}
\]

- Enhancements over background are observed in the mass range 5850-6000 MeV

- Observation of 2 pairs of states assuming isospin invariance: $B_J(5840)$ and $B_J(5960)$

- $B_J(5960)^{0,+}$ consistent and more precise than CDF result

- Mass and width consistent with $B(2S)$ and $B^*(2S)$ under quark model
Study of the $\Xi_b^0\pi^-$ combinations in $\Xi_b^0 \rightarrow \Xi_c^+\pi^-$ and $\Xi_c^+ \rightarrow \Lambda_c^+pK^-$ using 3 fb$^{-1}$ of data

Taking wrong-sign combination as background proxy

Observation of two narrow peaks, labeled as $\Xi_b^\prime [1/2^+]$ and $\Xi_b^* [3/2^+]$

Angular analysis does not exclude quark model interpretation

Very precise mass measurement

\[
\begin{align*}
m(\Xi_b^\prime \pi^-) - m(\Xi_b^0) - m(\pi^-) &= 3.653 \pm 0.018 \pm 0.006 \text{ MeV}/c^2 \\
m(\Xi_b^* \pi^-) - m(\Xi_b^0) - m(\pi^-) &= 23.96 \pm 0.12 \pm 0.06 \text{ MeV}/c^2 \\
\Gamma(\Xi_b^* \pi^-) &= 1.65 \pm 0.31 \pm 0.10 \text{ MeV}
\end{align*}
\]
Conclusions

- Spectroscopy studies are very active at LHCb!

- $X(3872)$
  - Spin-parity of $X(3872)$ determined: $J^{PC} = 1^{++}$ but nature still unclear
  - Radiative decays of $X(3872)$ disfavour pure molecular state

- $Z(4430)^+$
  - Model independent approach: consistent with the existence of an exotic state
  - Amplitude analysis confirms $Z(4430)^+$
  - Resonant behaviour shown
  - $J^P = 1^+$ established: disfavor the interpretation as a $D^*D_1$ molecule or cusp. Tetraquark scenario still standing

- Pentaquark
  - Two pentaquark candidates observed with high significance by an amplitude analysis of $\Lambda_b$ decays at LHCb
  - More data required to determine $J^{PC}$

- Observation of new beauty baryons and excited $b$-mesons

- We will triple data sample in Run II of the LHC: stay tuned!
Spare slides
Z(4430): model independent approach

The main goal is to check if the structures in the $m_{\psi(2S)\pi}$ spectrum can be explained as reflections of the resonance activity in the $K\pi$ system.

- Angular structure of the $K\pi$ system is extracted using Legendre polynomial moments

$$\frac{dN}{d \cos \theta_{K^*}} = \sum_{k=0}^{l_{\text{max}}} \langle P_K^U \rangle P_K(\cos \theta_{K^*})$$

- Moments are determined in bins of $m_{K\pi}$

$$\langle P_l^U \rangle = \sum_{i=1}^{N_{\text{data}}} \frac{1}{\epsilon} P_l(\cos \theta_{K^*_i})$$

- No assumptions on the $K^*$ resonances, but restriction on their maximal spin

- Select moments with

$$l < l_{\text{max}} = 2 \times J_{\text{max}}$$

- The moments are used in toy MonteCarlo simulation to predict the expected $m_{\psi(2S)\pi}$ spectrum
Additional cross-checks

- Many additional cross-check have been performed
  - Same $P_c^+$ structure found using very different selections by different LHCb teams
  - Two independently coded fitters using different background subtractions (cFit-sFit)
  - Split data show consistency: 2011/2012, magnet up/down, ...
  - Extended model fits tried without $P_c$ states, but with two additional high mass $\Lambda^*$ resonances allowing masses and widths to vary, or 4 non-resonant terms of $J$ up to $3/2$
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>( M_0 ) (MeV)</th>
<th>( \Gamma_0 ) (MeV)</th>
<th>Fit fractions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>low</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Extended vs. reduced</td>
<td>21</td>
<td>0.2</td>
<td>54</td>
</tr>
<tr>
<td>( \Lambda^* ) masses &amp; widths</td>
<td>7</td>
<td>0.7</td>
<td>20</td>
</tr>
<tr>
<td>Proton ID</td>
<td>2</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>( 10 &lt; p_\rho &lt; 100 , \text{GeV} )</td>
<td>0</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Nonresonant</td>
<td>3</td>
<td>0.3</td>
<td>34</td>
</tr>
<tr>
<td>Separate sidebands</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>( J^P ) (3/2^+, 5/2^-) or (5/2^+, 3/2^-)</td>
<td>10</td>
<td>1.2</td>
<td>34</td>
</tr>
<tr>
<td>( d = 1.5 - 4.5 , \text{GeV}^{-1} )</td>
<td>9</td>
<td>0.6</td>
<td>19</td>
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<tr>
<td>( L_{A^0_b} \rightarrow P^+_c ) (low/high)( K^- )</td>
<td>6</td>
<td>0.7</td>
<td>4</td>
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<tr>
<td>( L_{P^+_c} ) (low/high) ( \rightarrow J/\psi p )</td>
<td>4</td>
<td>0.4</td>
<td>31</td>
</tr>
<tr>
<td>( L_{A^0_b} \rightarrow J/\psi \Lambda^* )</td>
<td>11</td>
<td>0.3</td>
<td>20</td>
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<tr>
<td>Efficiencies</td>
<td>1</td>
<td>0.4</td>
<td>4</td>
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<tr>
<td>Change ( \Lambda(1405) ) coupling</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Overall</td>
<td>29</td>
<td>2.5</td>
<td>86</td>
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<tr>
<td>sFit/cFit cross check</td>
<td>5</td>
<td>1.0</td>
<td>11</td>
</tr>
</tbody>
</table>
Isobar Model helicity amplitudes for $\Lambda_b \rightarrow J/\psi \Lambda^*$

- Angular structure of $J/\psi$ decay (no free parameters)
- Helicity coupling for $\Lambda^*$ decay (complex fit parameters)
- $\Lambda^*$ resonant amplitudes (masses/widths)

\[ M^\Lambda_{\Lambda_b, \Lambda^*, \Delta \lambda} = \sum_n R_n(m_{KP}) \mathcal{H}_{\lambda^*_n \rightarrow KP}^\Lambda \sum_{\lambda} e^{i \lambda \phi_{\mu}} d^1_{\lambda \psi, \Delta \lambda_{\psi}}(\theta_{\psi}) \times \]

- Helicity coupling for $\Lambda_b$ decay (complex fit parameters)
- Angular structure of $\Lambda_b$ decay (no free parameters)
- Angular structure of $\Lambda^*$ decay (no free parameters)

Wigner D-functions for $A \rightarrow BC$:
\[ D^A_{\lambda_A, \Delta \lambda_{BC}}(\phi, \theta, 0) = \langle J \Delta \lambda | R(\phi, \theta, 0) | J \lambda \rangle = e^{i \lambda_A \phi} d_{\lambda_A, \Delta \lambda_{BC}}(\theta) \]
\[ D^\xi_{\gamma m0}(\alpha, \beta, 0) = \sqrt{\frac{4\pi}{2\ell + 1}} Y^{m*}_{\xi}(\alpha, \beta) \]
Dynamical Terms $R_n(m_{Kp})$ given by

- Relativistic, single-channel Breit-Wigner amplitudes $BW(M_{Kp}|M_0^{\Lambda^*}, \Gamma_0^{\Lambda^*})$
- Special case $\Lambda(1405)$ is subthreshold: Flatté ($Kp$ and $\Sigma\pi$ channels)
- Blatt-Weiskopf barrier factors $B_{\ell}^\prime(p, p_0, d)$

$$R_n(M_{Kp}) = B_{\ell_\Lambda}^\prime(p, p_0, d) \left( \frac{p}{M_{\Lambda^*}} \right)^{\ell_\Lambda} \times BW(M_{Kp}|M_0^{\Lambda^*}, \Gamma_0^{\Lambda^*}) \times B_{\ell_\Lambda}^\prime(q, q_0, d) \left( \frac{q}{M_0^{\Lambda^*}} \right)^{\ell_\Lambda}.$$  

$$BW(M|M_0, \Gamma_0) = \frac{1}{M_0^2 - M^2 - iM_0\Gamma(M)}.$$  

Where

$$\Gamma(M) = \Gamma_0 \left( \frac{q}{q_0} \right)^{2\ell_\Lambda + 1} \frac{M_0}{M} B_{\ell_\Lambda}^\prime(q, q_0, d)^2.$$  

$q(p)$ are momenta of the daughter particles in the rest-frame of the decaying particle.

$p_0(q_0)$ calculated on the nominal resonance mass.
The angular momentum barrier should suppress decays with high orbital angular momentum.

Express helicity couplings through $\ell S$-couplings $B_{\ell S}$ using Clebsch-Gordan coefficients

$$\mathcal{H}_{\lambda_B,\lambda_c}^{A\rightarrow BC} = \sum_{\ell} \sum_{S} \sqrt{\frac{2\ell+1}{2J_A+1}} \times B_{\ell S} \times \left( \begin{array}{c} J_B \hline \lambda_B \end{array} \right) \times \left( \begin{array}{c} J_C \hline -\lambda_C \end{array} \right) \times \left( \begin{array}{c} S \hline \lambda_B - \lambda_C \end{array} \right) \times \left( \begin{array}{c} J_A \hline \lambda_B - \lambda_C \end{array} \right)$$

Spin–Spin coupling

Spin–Orbit coupling

Limit the allowed range of $\ell$ in the fit model

Automatically implements parity conservation in strong decays by choice of $\ell$
<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>Any $L$ value</th>
<th>Minimal $L$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0$^{-+}$</td>
<td>$B_{11}$</td>
<td>$B_{11}$</td>
</tr>
<tr>
<td>0$^{++}$</td>
<td>$B_{00}, B_{22}$</td>
<td>$B_{00}$</td>
</tr>
<tr>
<td>1$^{-+}$</td>
<td>$B_{10}, B_{11}, B_{12}, B_{32}$</td>
<td>$B_{10}, B_{11}, B_{12}$</td>
</tr>
<tr>
<td>1$^{++}$</td>
<td>$B_{01}, B_{21}, B_{22}$</td>
<td>$B_{01}$</td>
</tr>
<tr>
<td>2$^{-+}$</td>
<td>$B_{11}, B_{12}, B_{31}, B_{32}$</td>
<td>$B_{11}, B_{12}$</td>
</tr>
<tr>
<td>2$^{++}$</td>
<td>$B_{02}, B_{20}, B_{21}, B_{22}, B_{42}$</td>
<td>$B_{02}$</td>
</tr>
<tr>
<td>3$^{-+}$</td>
<td>$B_{12}, B_{30}, B_{31}, B_{32}, B_{52}$</td>
<td>$B_{12}$</td>
</tr>
<tr>
<td>3$^{++}$</td>
<td>$B_{21}, B_{22}, B_{41}, B_{42}$</td>
<td>$B_{21}, B_{22}$</td>
</tr>
<tr>
<td>4$^{-+}$</td>
<td>$B_{31}, B_{32}, B_{51}, B_{52}$</td>
<td>$B_{31}, B_{32}$</td>
</tr>
<tr>
<td>4$^{++}$</td>
<td>$B_{22}, B_{40}, B_{41}, B_{42}, B_{62}$</td>
<td>$B_{22}$</td>
</tr>
</tbody>
</table>

Parity-allowed $LS$ couplings in

$X \to \rho^0 J/\psi$
4-6 independent complex helicity couplings per $\Lambda_{n^*}$ resonance

\[
M_{\Lambda_{n^*}^0, \lambda_p, \Delta \lambda} \equiv \sum_{n} \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} H_{\Lambda_b^0 \to \Lambda_{n^*}^0 \psi} D_{\frac{1}{2}} \frac{1}{2} \lambda_{\Lambda_b^0}, \lambda_{\Lambda^*} = \lambda_\psi \psi (0, \theta_{\Lambda_b^0}, 0)^* \]

6 independent data variables:
1 mass, 5 angles

Breit-Wigner

\[
R_X(m) = B'_{LX} (p, p_0, d) \left( \frac{p}{M_{\Lambda_b^0}^L} \right) BW(m | M_{0X}, \Gamma_{0X}) B'_{LX} (q, q_0, d) \left( \frac{q}{M_{0X}} \right) \frac{1}{MW^2 - m^2 - iMW \Gamma(m)}
\]

Blatt-Weisskopf functions
1 mass ($m_{J/\psi}$), 6 angles
all derivable from the $\Lambda^*$ decay variables

One more angle than in $\Lambda^*$ decay: $P_c^+$ production angles must be defined relative to the $\Lambda_b$ reference frame established for $\Lambda_b \to J/\psi \Lambda^*$ decay

3-4 independent complex helicity couplings per $P_{c_j}^+$ resonance depending on its $J^P$

$M_{P_c}^{\Lambda_0, \lambda_{P_c}, \Delta \lambda_{P_c}} = \sum_j \sum_{\lambda_{P_c}} \sum_{\Delta \lambda_{P_c}} \mathcal{H}_{\Lambda_0 \to P_{c_j}, 0}^{\Lambda_0} \mathcal{D}_{\lambda_{P_c}, 0}^{P_c} \left( \phi_{P_c}, \theta_{P_c}, 0 \right) \left( \phi_{P_c}, \theta_{P_c}, 0 \right)^*$

$R_X(m) = B'_{LX, \Lambda_0} (p, p_0, d) \left( \frac{p}{M_{\Lambda_0}} \right)^{(p)} \text{BW}(m | M_{0X}, \Gamma_{0X}) B'_{LX} (q, q_0, d) \left( \frac{q}{M_{0X}} \right)^{(q)}$

Blatt-Weisskopf functions

Breit-Wigner

BW($m | M_{0X}, \Gamma_{0X}$) = \frac{1}{M_{0X}^2 - m^2 - iM_{0X} \Gamma(m)}