Charmonium-like exotic states at LHC
Results and prospects

A. Augusto Alves Jr, on behalf of the LHCb collaboration.
(Including results from CMS collaboration.)

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CHARM-2016, VIII International Workshop on Charm Physics
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1. The LHC accelerator and its detectors.
2. The LHCb detector.
3. Exotic states.
4. Results on pentaquark states on $\Lambda_b^0 \rightarrow J/\psi pK^-$ and $\Lambda_b^0 \rightarrow J/\psi p\pi^-$. 
5. Search for structures in the $J/\psi \phi$ spectrum.
The LHC accelerator and its detectors

The LHC is designed to collide two high luminosity and high energy beams of protons or heavy ions.

- Two general proposal high luminosity experiments: CMS and ATLAS.
- One experiment dedicated to flavour physics: LHCb.
- Heavy-ion experiment: ALICE.

![Diagram of LHC accelerator and detectors]
The LHC environment

During most of 2012 run, LHC collided protons at 8 TeV with an average instantaneous luminosity of $4 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ (LHCb) and 20 MHz of bunch crossing.

- Inelastic cross section $\sim 60 \text{mb}$
- $\sigma(pp \to b\bar{b}X) = (284 \pm 20(\text{stat}) \pm 49(\text{syst})) \mu\text{b}$ [PLB 694, 209]
- $\Rightarrow \sim 10^6 B\bar{B}$ produced per second
- $\sigma(pp \to c\bar{c}X)$ is about 20 times higher. [Nucl.Phys. B871 (2013) 1-20]

At the LHC energy, the $b\bar{b}$ pairs are produced preferentially at forward (backward) directions.

- Optimal design is a forward detector: LHCb
LHCb experiment was designed to perform high precision flavour physics measurements at the LHC.

- **Single-arm design.** Covering the range $2 < \eta < 5$, LHCb can exploit the dominant heavy flavour production mechanism at the LHC and detects $\sim 40\%$ of the $b\bar{b}$ produced in forward region.

- **Good particle identification.** Excellent muon identification and good separation of $\pi$, $K$ and $p$ over $(2 - 100)$ GeV.

- **Good vertexing and tracking.** Precise primary and secondary vertex reconstruction. Excellent momentum, IP and proper time resolution.

- These same features make LHCb very suitable for precision spectroscopy studies in the forward region.
The calibration and alignment process takes place now automatically online.

The stored data are immediately available offline for physics analysis (turbo stream).

The “turbo” data sample keeps only information necessary to perform physics analysis with the offline quality.

Already 1 fb$^{-1}$ recorded in RUNII/2015 and increasing.
Many new states have been observed at Charm, b-factories and Tevatron:

- Masses lying on the limits of the quarkonia spectrum.
- Observed many different production mechanisms: ISR, $e^+e^−$, $\gamma\gamma$ and B decays.
- The measured masses do not correspond to the predicted values for conventional quarkonia.
- The properties do not fit very well to the quarkonia picture.

Many theoretical interpretations in discussion:

- conventional quarkonia;
- multiquark states;
- meson-molecules;
- hybrid mesons;
- threshold effects;

The table should be updated to include some new states: $P(4380)_c^+$, $P(4450)_c^+$...
Sample with $>26,000$ $\Lambda_b^0 \to J/\psi pK^-$ signal candidates,
Analysis: six-dimensional amplitude fit (invariant masses, helicity and decay planes angles).
Background from sidebands. Estimated 5.4% of combinatorial background in the signal region.
Six-dimensional efficiency calculated using complete simulation of the detector.
Pentaquark states in $\Lambda_{b}^{0} \to J/\psi pK^{-}$

Some analysis details

- Two parametizations: $\Lambda_{b}^{0} \to K^{-}(P_{c}^{+} \to pJ/\psi)$ and $\Lambda_{b}^{0} \to J/\psi (\Lambda^{*} \to pK^{-})$, with $J/\psi \to \mu^{+}\mu^{-}$

- Six-dimensional amplitude fit. Resonance invariant mass, three helicities angles, and two differences between decay planes.

- Lorentz transformations relates the two helicity representantions.

- Resonances described by Breit-Wigner.

- Angular distribution calculated using helicity formalism.
Fit results with pentaquark states

- Fit including just well motivated $\Lambda^*$ resonances (Reduced model).
- Two $P_c^+$ states necessary to achieve acceptable fit quality.
- $P(4380)^+_{c}$ with $M = 4380 \pm 8 \pm 29$ MeV/$c^2$ and $\Gamma = 205 \pm 18 \pm 86$ MeV/$c^2$ $J^P = 3/2^-$, fit fraction of $(8.4 \pm 0.7 \pm 4.2)\%$ and significance of 9$\sigma$
- $P(4450)^+_{c}$ with $M = 4449.8 \pm 1.7 \pm 2.5$ MeV/$c^2$ and $\Gamma = 39 \pm 5 \pm 19$ MeV/$c^2$ $J^P = 5/2^+$, fit fraction $(4.1 \pm 0.5 \pm 1.1)\%$ and significance of 12$\sigma$
- The mass resolution is approximately 2.5 MeV/$c^2$ and combined significance 15$\sigma$
Pentaquark states in $\Lambda_b^0 \rightarrow J/\psi pK^-$

Resonant character of the pentaquark states

- $P(4450)_c^+$ amplitude is now described by 6 independent complex numbers instead of a Breit-Wigner.
- Six equidistant points in the range $\pm \Gamma_0 = 39 \text{ MeV}/c^2$ around $M_0 = 4449.8 \text{ MeV}/c^2$ (from the default fit).
- Observe a fast change of phase crossing maximum of magnitude. Expected behavior for a resonance.
- Same test on $P(4380)_c^+$ leads to inconclusive results.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{plot.png}
\caption{Re $A$ vs. Im $A$ for $P_c(4450)$ (a) and $P_c(4380)$ (b).}
\end{figure}
The goal of this analysis approach is to explain the structures observed in the $pJ/\psi$ invariant mass as reflections of the activity of the conventional resonances on the $K^-p$ system.

No model dependent assumptions are made. Instead, the $m_{K^-p}$ distribution is taken from data as it is.

The angular structure of the $K^-p$ system is acquired via Legendre polynomials calculated from the $\Lambda^*$ helicity angle.

This method was introduced by the BaBar collaboration and later improved upon by the LHCb collaboration, both in the context of the search for $Z(4430)^+$ on $B^0 \rightarrow \psi(2S)K^+\pi^-$ decays.
The maximum order of the Legendre polynomials considered in each $m_{K^-p}$ slice is limited by the maximum spin of the $\Lambda^*$ expected to give local contributions.

A normalized weight is calculated and used to reweight simulated events to obtain a prediction for $m_{J/\psi p}$ distribution consistent with the conventional resonances contributions.

The predicted distribution does not provide a satisfactory description of LHCb data.
Evidence for exotic hadron contributions to $\Lambda_0^b \rightarrow J/\psi p\pi^-$

Sample with $1885 \pm 50$ $\Lambda_0^b \rightarrow J/\psi p\pi^-$ signal candidates,

Analysis: six-dimensional amplitude fit (invariant masses, helicity and decay planes angles).

Combinatorial background modeled by an exponential function and events from $\Lambda_0^b \rightarrow J/\psi pK^-$ modeled using simulated samples.

Six-dimensional efficiency calculated using complete simulation of the detector.
Evidence for exotic hadron contributions to $\Lambda_0^b \to J/\psi p\pi^-$

Some analysis details

- Three parametrizations: $\Lambda_0^b \to (P_c^+ \to J/\psi p)\pi^-$, $\Lambda_0^b \to (Z_c(4200)^+ \to J/\psi \pi^-) p$ and $\Lambda_0^b \to J/\psi (N^* \to p\pi^-)$, with $J/\psi \to \mu^+\mu^-$.
- Six-dimensional amplitude fit: resonance invariant mass, three helicities angles, and two differences between decay planes.
- Lorentz transformations relates the two helicity representations.

Resonances described by Breit-Wigner.
- Angular distribution calculated using helicity formalism.
Evidence for exotic hadron contributions to $\Lambda^0_b \rightarrow J/\psi p\pi^-$

**Amplitude analysis**

- **Reduced Model.** Including only well established $N^*$ resonances.
- **Extended Model.** Used to calculate systematic uncertainties and the significances.
- Exotic states contributions are necessary to achieve acceptable fit quality, mainly in the $m_{p\pi^-} > 1.8 \text{ GeV}/c^2$ region.

![Graph showing yields in different mass regions](image)

- LHCb data
- Reduced Model (RM) $N^*$ resonances
- Extended Model (EM) $N^*$ resonances

<table>
<thead>
<tr>
<th>Mass Region</th>
<th>Data</th>
<th>RM $N^*$ + Zc + 2Pc</th>
<th>EM $N^*$</th>
</tr>
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<tbody>
<tr>
<td>1.5 - 2 GeV</td>
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<tr>
<td>2 - 2.5 GeV</td>
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<tr>
<td>3.5 - 4 GeV</td>
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<tr>
<td>4 - 4.5 GeV</td>
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</table>

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Evidence for exotic hadron contributions to $\Lambda^0_b \rightarrow J/\psi p\pi^-$

**Results**

- Fit fractions from the RM + exotic states.
  - $P(4380)_c^+$: $(5.1 \pm 1.5^{+2.6}_{-1.6})\%$
  - $P(4450)_c^+$: $(1.6^{+0.8+0.6}_{-0.6-0.5})\%$
  - $Z_c(4200)^+$: $(7.7 \pm 2.8^{+3.4}_{-4.0})\%$

- When the two $P_c^+$ states are not considered, the fraction for the $Z_c(4200)^+$ state is $(17.2 \pm 3.5)\%$.

- Conversely, the fit fractions of the two $P_c^+$ states remain stable regardless of the inclusion of the $Z_c(4200)^+$ state.

- If both types of exotic resonances are included, the total significance for them is $3.1\sigma$.

- Assuming that the $Z_c(4200)^+$ contribution is negligible, there is a $3.3\sigma$ significance for the two $P_c^+$ states taken together.
The $X(4140)$ and $X(4274)$

- Two exotic resonance candidates observed by CDF in $B^\pm \rightarrow J/\psi \phi K^\pm$ decays and decaying into $J/\psi \phi$. [Ref. Phys.Rev.Lett. 102.242002].
- D0 experiment also reported the observation of structures on $J/\psi \phi$ invariant mass on $B$ decays and prompt candidates. [Ref. Phys. Rev. D 89, 012004, arXiv:1508.07846].
- Belle experiment also have searched for $X(4140)$ and $X(4274)$. Belle accumulated more events on $B^\pm \rightarrow J/\psi \phi K^\pm$ than CDF but could not confirm or exclude the $X(4140)$. due loss of efficiency near the threshold, which resulted in a lower sensitivity to $X(4140)$. [see J. Brodzicka, Heavy flavour spectroscopy (LP09)]

In summary:

- Charmonium states at this mass are expected to have much larger widths because of open flavour decay channels.
- Their decay rate into the $J/\psi \phi$ mode (so near the kinematic threshold) should be small and unobservable.
- This make $X(4140)$ and $X(4274)$ strongly exotic chamornium-like candidates.
Search for structures in the $J/\psi \phi$ spectrum at CMS


- Analysis performed on a sample of $2480 \pm 160$ $B^\pm \to J/\psi \phi K^\pm$ signal candidates.

- $J/\psi \phi$-spectrum is modeled by two S-wave relativistic Breit-Wigner over a three-body phase-space non-resonant component.

- $m_1 = 4148.2 \pm 2.4$(stat) $\pm 6.3$(syst) MeV/$c^2$, $\Gamma_1 = 28^{+15}_{-11}$(stat) $\pm 19$(syst) MeV/$c^2$, and significance exceeding 5 $\sigma$.

- $m_2 = 4313.8 \pm 5.3$(stat) $\pm 7.3$(syst) MeV/$c^2$ and $\Gamma_2 = 38^{+30}_{-15}$(stat) $\pm 16$(syst) MeV/$c^2$. 

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**Diagrams:**

1. CMS, $\sqrt{s} = 7$ TeV, $L=5.2$ fb$^{-1}$

   - Data
   - Global fit
   - Three-body PS (global fit) ±1$\sigma$ uncertainty band
   - Event-mixing ($J/\psi$, $\phi$, $K^*$)
   - Event-mixing ($J/\psi$, $\phi$ $K^+$)
   - 1D fit

2. CMS, $\sqrt{s} = 7$ TeV, $L=5.2$ fb$^{-1}$

   - 1.008 $< m(K^*K^-) < 1.035$ GeV
   - $\Delta m < 1.568$ GeV
   - Candidates / 5 MeV

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Sample with $4289 \pm 151$ $B^\pm \rightarrow J/\psi \phi K^\pm$ with $J/\psi \rightarrow \mu^+ \mu^-$ and and $\phi \rightarrow K^+K^-$ signal candidates.

Analysis: six-dimensional amplitude fit (invariant masses, helicity and decay planes angles).

Background from sidebands. Estimated $(23 \pm 6)\%$ of combinatorial background in the signal region.

Six-dimensional efficiency calculated using complete simulation of the detector.
Search for structures in the $J/\psi \phi$ spectrum at LHCb

Some analysis details

- Three parametizations: $B^+ \to J/\psi K^{*+}$ with $K^{*+} \to \phi K$, $B^+ \to X K^+$ with $X \to J/\psi \phi$ and $B^+ \to Z^+ \phi$ with $Z^+ \to J/\psi K^+$ all followed $J/\psi \to \mu^+ \mu^-$ and $\phi \to K^+ K^-$.  
- Six variables: resonance invariant mass, three helicities angles, and two differences between decay planes.  
- Lorentz transformations relates the different helicity representantions.

- Resonances described by Breit-Wigner.  
- Angular distribution calculated using helicity formalism.
Search for structures in the $J/\psi \phi$ spectrum at LHCb

Fit only with conventional contributions

- The masses and widths of all states are left free.
- The $m_{\phi K}$ and $m_{J/\psi K}$ distributions well with $K^{*+}$ contributions alone.
- The fit projections onto $m_{J/\psi \phi}$ do not provide an acceptable description of the data.
Search for structures in the $J/\psi\phi$ spectrum at LHCb

Fit with conventional plus exotic contributions

- Only X contributions lead to significant improvements in the description of the data.
- The model contains seven $K^{*+}$ states, four X states and $\phi K$ and $J/\psi\phi$ nonresonant components.

![Graphs showing the $m_{J/\psi K}$ and $m_{J/\psi\phi}$ distributions with various contributions and fit results.]
Search for structures in the $J/\psi \phi$ spectrum at LHCb

Modeling near threshold X contributions as $D_s^{\pm} D_s^{*\mp}$ cusps

- Modeling $X(4140)$ and $X(4274)$ using the threshold cusp parameterization proposed by Swanson [Int. J. Mod. Phys. E, 25, 1642010 (2016)].

- On the left: only $X(4140)$ is represented as a $J^{PC} = 1^{++} D_s^{+} D_{s}^{*-}$ cusp.

- On the right: $X(4140)$ and $X(4274)$ are represented as a $J^{PC} = 1^{++} D_s^{+} D_s^{*-}$ and $J^{PC} = 0^{--} D_s^{\pm} D_{s}^{*+}(2317)^{\mp}$ cusps, respectively.
Search for structures in the $J/\psi \phi$ spectrum at LHCb

Results

- The LHCb data cannot be well described without several $J/\psi \phi$ contributions.

(Table[1] and references [28,25] on arXiv:1606.07895)

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Sign. or Ref.</th>
<th>$M_0$ [MeV]</th>
<th>$\Gamma_0$ [MeV]</th>
<th>FF %</th>
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<tbody>
<tr>
<td>All $X(1^+)$</td>
<td></td>
<td>16$\pm$3 $^{+6}_{-2}$</td>
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<td></td>
</tr>
<tr>
<td>$X(4140)$</td>
<td>8.4$\sigma$</td>
<td>4146.5$\pm$4.5 $^{+4.6}_{-2.8}$</td>
<td>83$\pm$21 $^{+21}_{-14}$</td>
<td>13$\pm$3.2 $^{+4.8}_{-2.0}$</td>
</tr>
<tr>
<td>ave. Table 1</td>
<td></td>
<td>4143.4$\pm$1.9</td>
<td>15.7$\pm$6.3</td>
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</tr>
<tr>
<td>$X(4274)$</td>
<td>6.0$\sigma$</td>
<td>4273.3$\pm$8.3 $^{+17.2}_{-3.6}$</td>
<td>56$\pm$11 $^{+8}_{-11}$</td>
<td>7.1$\pm$2.5 $^{+3.5}_{-2.4}$</td>
</tr>
<tr>
<td>CDF</td>
<td>Ref.28</td>
<td>4274.4 $^{+8.4}_{-6.7}$ $\pm$ 1.9</td>
<td>32 $^{+22}_{-15}$ $\pm$ 8</td>
<td></td>
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<tr>
<td>CMS</td>
<td>Ref.25</td>
<td>4313.8$\pm$5.3 $^{+7.3}_{-15}$</td>
<td>38 $^{+30}_{-15}$ $\pm$ 16</td>
<td></td>
</tr>
<tr>
<td>All $X(0^+)$</td>
<td></td>
<td>28$\pm$ 5 $^{+7}_{-5}$</td>
<td>46$\pm$11 $^{+11}_{-21}$</td>
<td></td>
</tr>
<tr>
<td>NR.$J/\psi \phi$</td>
<td>6.4$\sigma$</td>
<td></td>
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<tr>
<td>$X(4500)$</td>
<td>6.1$\sigma$</td>
<td>4506$\pm$11 $^{+12}_{-15}$</td>
<td>92$\pm$21 $^{+21}_{-20}$</td>
<td>6.6$\pm$2.4 $^{+3.5}_{-2.3}$</td>
</tr>
<tr>
<td>$X(4700)$</td>
<td>5.6$\sigma$</td>
<td>4704$\pm$10 $^{+14}_{-24}$</td>
<td>120$\pm$31 $^{+42}_{-33}$</td>
<td>12$\pm$ 5 $^{+9}_{-5}$</td>
</tr>
</tbody>
</table>

- $X$ contributions near threshold are consistent with $D_s^\pm$ $D_s^*\mp$ cusps.
- First full amplitude analysis performed on $B^\pm \rightarrow J/\psi \phi K^\pm$ decays.
Charmonium-like exotic states spectroscopy at LHC

Recent results not included in this talk

LHCb:

- Evidence of $X(3872) \rightarrow \psi(2S)\gamma$ [Nuclear Physics B 886 (2014) 665-680].
- Quantum numbers of the $X(3872)$ state and orbital angular momentum in its $\rho^0 J/\psi$ decays [Phys. Rev. D 92 (2015) 011102].

ATLAS:

- Production measurements of $\psi(2S)$ and $X(3872)$ in pp collisions at 8 TeV [ATLAS-CONF-2016-028].
Many other results in $b$ and $c$ spectroscopy


The LHCb Public results

List of papers (Total of 284 papers)

<table>
<thead>
<tr>
<th>TITLE</th>
<th>DOCUMENT NUMBER</th>
<th>JOURNAL</th>
<th>SUBMITTED ON</th>
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<tr>
<td>Search for the rare decays $B^0 \to J/\psi\gamma$ and $B^0_s \to J/\psi\gamma$</td>
<td>PAPER-2015-044</td>
<td>PRD</td>
<td>16 Oct 2015</td>
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<tr>
<td>Evidence for the strangeness-changing weak decay $\Xi_b^- \to \Lambda_b^0\pi^-$</td>
<td>PAPER-2015-047</td>
<td>PRL</td>
<td>13 Oct 2015</td>
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<td>A model-independent confirmation of the $Z(4430)^-$ state</td>
<td>PAPER-2015-038</td>
<td>PRD</td>
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<td>Model-independent measurement of mixing parameters in $D_s^0 \to K_S^0\pi^+$ decays</td>
<td>PAPER-2015-042</td>
<td>JHEP</td>
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<td>Measurement of the forward-backward asymmetry in $B^0/\psi^+ \to \mu^+\mu^-$ decays and determination of the effective weak mixing angle</td>
<td>PAPER-2015-039</td>
<td>JHEP</td>
<td>25 Sep 2015</td>
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<td>Studies of the resonance structure in $D^0 \to K_S^0 K^+\pi^-$ decays</td>
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<td>PRD</td>
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<td>Forward production of $T$ mesons in $pp$ collisions at $\sqrt{s} = 7$ and 8 TeV</td>
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<td>08 Sep 2015</td>
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<td>First measurement of the differential branching fraction and $CP$ asymmetry of the $B^- \to \pi^+\mu^+\mu^-$ decay</td>
<td>PAPER-2015-035</td>
<td>JHEP</td>
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<td>Measurement of $CP$ violation parameters and polarisation fractions in $B^0_s \to J/\psi K_{S0}^{*0}$ decays</td>
<td>PAPER-2015-034</td>
<td>JHEP</td>
<td>01 Sep 2015</td>
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<td>Study of the production of $\Lambda_{cJ}$ and $B^0_s$ hadrons in $pp$ collisions and first measurement of the $\Lambda_{cJ} \to J/\psi K^-$ branching fraction</td>
<td>PAPER-2015-032</td>
<td>Chin Phys C</td>
<td>01 Sep 2015</td>
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<td>Measurement of the time-integrated $CP$ asymmetry in $D_s^0 \to K^{*0}_S K^0_S$ decays</td>
<td>PAPER-2015-030</td>
<td>JHEP</td>
<td>25 Aug 2015</td>
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<td>Search for hidden-sector bosons in $B^0 \to K^{(*)0}\mu^+\mu^-$ decays</td>
<td>PAPER-2015-036</td>
<td>PRL</td>
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<td>Measurement of the $B_{s1} \to \phi\phi$ branching fraction and search for the decay $B^0 \to \phi\phi$</td>
<td>PAPER-2015-028</td>
<td>JHEP</td>
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<td>$B$ flavour tagging using charm decays at the LHCb experiment</td>
<td>PAPER-2015-027</td>
<td>JINST</td>
<td>28 Jul 2015</td>
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<td>Measurement of the branching fraction ratio $B(B^+_s \to \psi(2S)\pi^+)/B(B_s^0 \to J/\psi\pi^+)$</td>
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<td>Search for long-lived heavy charged particles using a ring imaging Cherenkov technique at LHCb</td>
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<td>Angular analysis and differential branching fraction of the decay $B^0_s \to \phi\phi\mu^-\overline{\nu}$</td>
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</table>
Summary

Pentaquark states in $\Lambda_b^0 \to J/\psi pK^-$ at LHCb

- $P(4380)_c^+$ observed with $9.0\sigma$ in multidimensional amplitude fit. Quantum numbers $J^P = 3/2^-$.  
- $P(4450)_c^+$ observed with $12.0\sigma$ in multidimensional amplitude fit. Quantum numbers $J^P = 5/2^+$.  
- Resonance behavior observed for $P(4450)_c^+$. $P(4380)_c^+$ needs further studies.  
- Model independent analysis rules out conventional only explanation with $9\sigma$.

Evidence for exotic hadron contributions to $\Lambda_b^0 \to J/\psi p\pi^-$ at LHCb

- Evidence of exotic contributions observed with $3.1\sigma$.  
  - $P(4380)_c^+$: $(5.1 \pm 1.5^{+2.6}_{-1.6})\%$  
  - $P(4450)_c^+$: $(1.6^{+0.8}_{-0.6}^{+0.6}_{-0.5})\%$  
  - $Z_c(4200)^+$: $(7.7 \pm 2.8^{+3.4}_{-4.0})\%$
Search for structures in the \( \J / \psi \phi \) spectrum at LHCb and CMS

- First full amplitude analysis performed on \( B^\pm \rightarrow \J / \psi \phi K^\pm \) with \( \J / \psi \rightarrow \mu^+ \mu^- \) and \( \phi \rightarrow K^+ K^- \).
- \( X(4140) \) and \( X(4274) \) resonances confirmed with consistent masses and larger widths than previous measurements.
- Two new higher mass resonances observed with high significance.
- \( X(4140) \) and \( X(4274) \) contributions also consistent with \( D_s^\pm \ D_s^{*\mp} \) cusps.

Thanks!
Backup
$\Lambda_b^0 \to K^- p J/\psi$

Fit results without pentaquark states

- Fit including only $\Lambda^*$ resonances, allowing all possible known states (Extended model)
- The masses and widths of the $\Lambda^*$ states are fixed to their PDG values
- The $m_{KP}$ distribution is reasonably well fitted
- The peaking structure in $m_{J/\psi P}$ is not described

<table>
<thead>
<tr>
<th>State</th>
<th>$J^P$</th>
<th>$M_0$ (MeV)</th>
<th>$\Gamma_0$ (MeV)</th>
<th># Reduced</th>
<th># Extended</th>
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<td>$\Lambda(1405)$</td>
<td>$1/2^-$</td>
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<td>50.5$^{+2.0}_{-2.0}$</td>
<td>3</td>
<td>4</td>
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<tr>
<td>$\Lambda(1520)$</td>
<td>$3/2^-$</td>
<td>1519.5$^{+1.0}_{-1.0}$</td>
<td>15.6$^{+1.0}_{-1.0}$</td>
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<td>$\Lambda(1600)$</td>
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<td>$\Lambda(1670)$</td>
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<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>0</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(2585)$</td>
<td>$?$</td>
<td>$\approx 2585$</td>
<td>200</td>
<td>0</td>
<td>6</td>
</tr>
</tbody>
</table>
**Λ^0_b → K^-pJ/ψ**: Systematic uncertainties

Table 2: Summary of systematic uncertainties on \( P_c^+ \) masses, widths and fit fractions, and \( Λ^* \) fit fractions. A fit fraction is the ratio of the phase space integrals of the matrix element squared for a single resonance and for the total amplitude. The terms “low” and “high” correspond to the lower and higher mass \( P_c^+ \) states. The sFit/cFit difference is listed as a cross-check and not included as an uncertainty.

<table>
<thead>
<tr>
<th>Source</th>
<th>( M_0 ) (MeV)</th>
<th>( Γ_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>Λ* 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_T ) &lt; 100 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>
</tr>
<tr>
<td>( L_{P_{c}^+}^{\Lambda^0_b} \Lambda^0_b \rightarrow P_{c}^+ \text{ (low/high)}K^- )</td>
<td>6</td>
<td>0.7</td>
<td>4</td>
</tr>
<tr>
<td>( L_{P_{c}^+}^\Lambda^0_b \text{ (low/high)} \rightarrow J/\psi p )</td>
<td>4</td>
<td>0.4</td>
<td>31</td>
</tr>
<tr>
<td>( L_{P_{c}^+}^\Lambda^0_b \Lambda^0_b \rightarrow J/\psi Λ^* )</td>
<td>11</td>
<td>0.3</td>
<td>20</td>
</tr>
<tr>
<td>Efficiencies</td>
<td>1</td>
<td>0.4</td>
<td>4</td>
</tr>
<tr>
<td>Change ( Λ(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>
</tr>
<tr>
<td>sFit/cFit cross check</td>
<td>5</td>
<td>1.0</td>
<td>11</td>
</tr>
</tbody>
</table>
Figure 8: $m_{J/\psi p}$ in various intervals of $m_{Kp}$ for the fit with two $P_c^+$ states: (a) $m_{Kp} < 1.55$ GeV, (b) $1.55 < m_{Kp} < 1.70$ GeV, (c) $1.70 < m_{Kp} < 2.00$ GeV, and (d) $m_{Kp} > 2.00$ GeV. The data are shown as (black) squares with error bars, while the (red) circles show the results of the fit. The blue and purple histograms show the two $P_c^+$ states. See Fig. 7 for the legend.
Figure 11: Projections onto $m_{J/\psi K}$ in various intervals of $m_{Kp}$ for the reduced model fit (cFit) with two $P^+_c$ states of $J^P$ equal to $3/2^-$ and $5/2^+$: (a) $m_{Kp} < 1.55$ GeV, (b) $1.55 < m_{Kp} < 1.70$ GeV, (c) $1.70 < m_{Kp} < 2.00$ GeV, (d) $m_{Kp} > 2.00$ GeV, and (e) all $m_{Kp}$. The data are shown as (black) squares with error bars, while the (red) circles show the results of the fit. The individual resonances are given in the legend.
Charged charmonium like state reported by Belle in $B^0 \rightarrow \psi(2S)K^+\pi^-$ decays [Phys.Rev.D88:074026]

Searched and not confirmed or excluded by BaBar [Phys.Rev.D79:112001]

Can not be explained as conventional meson.

Minimum quark content: $c\bar{c}u\bar{d}$

No corresponding structure observed in $B^0 \rightarrow J/\psi K^+\pi^-$

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

With $Z(4430)^+$ and No $Z(4430)^+$

$Z(4430)^+$ at BaBar. Legendre polynomials approach.

\[ Z(4430)^+ \] at Belle.  $K^{*0}$ and $K_2^*(1432)$ vetoed.

With $Z(4430)^+$ and No $Z(4430)^+$

\[ Z(4430)^+ \] at BaBar.  Legendre polynomials 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 shape and coupling of the $K^*$ resonances.
- Only its maximum $J$ is restricted.
$Z(4430)^+$: model independent analysis

Slices of $m_{K\pi}$

Toy Monte Carlo prediction in slices of $m_{K\pi}$.

- Data points (black dots)
- MC prediction (blue solid line)
- Phase space MC weighted to reproduce $m_{K\pi}$ (red line)
- Clear disagreement between data and MC on the slice $1.0 < m_{K\pi} < 1.39$ GeV/$c^2$
\( Z(4430)^+ \): model independent analysis

Additional studies: \( l_{\text{max}} \leq 4 \)

- Setting the maximum Legendre polynomial order to four, independent of \( m_{K\pi} \)
- This corresponds to suppose the \( K\pi \) system has S, P and D waves contributing in all regions.
- Data can not be reproduced
Setting the maximum Legendre polynomial order to six, independent of $m_{K\pi}$

This corresponds to suppose the $K\pi$ system has S, P, D and F waves contributing in all regions.

Data still can not be reproduced
Confirmation of $Z(4430)^+$ at LHCb


- Sample with $>25,000$ $B^0 \rightarrow K^+\pi^-\psi(2S)$ signal candidates,

- Analysis performed using two different approaches:
  - Model dependent. Four-dimensional amplitude fit (invariant masses, helicity and decay planes angles).
  - Model independent. An analysis based on the Legendre polynomial moments extracted from the $K\pi$ system

- Background from sidebands. Estimated 4% of combinatorial background in the signal region.

- Four-dimensional efficiency calculated using complete simulation of the detector
**Fitted parameters:**

\[
M_{Z(4430)^+} = 4475 \pm 7^{+15}_{-25} \text{ MeV}/c^2, \quad \Gamma_{Z(4430)^+} = 172 \pm 13^{+37}_{-34} \text{ MeV}/c^2
\]

\[
f_{Z(4430)^+} = (5.9 \pm 0.9^{+1.5}_{-3.3})\%
\]

**Significance:** \(\Delta(-2\ln L) > 13.9\sigma\)
**Z(4430)**

Resonance character and spin determination

- $J^P = 1^+$ assignment favored.
- Other $J^P$ assignments are ruled out with large significance: $> 9\sigma$

- $Z(4430)^+$ amplitude is described by 6 independent complex numbers instead of a Breit-Wigner.
- Observe a fast change of phase crossing maximum of magnitude.
- Expected behaviour for a resonance.
Very active $K\pi$ system.

$m_{K\pi}$ taken directly from data, as it is.

Angular structure of the $K\pi$ system acquired via Legendre polynomials.

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

$$\langle P_j^U \rangle = \sum_{i=1}^{N_{\text{reco}}} \frac{W_{\text{signal}}^i}{c^i} P_j(\cos\theta_{K^*0})$$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV/c$^2$)</th>
<th>Width (MeV/c$^2$)</th>
<th>$J^P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(800)^0$</td>
<td>682±29</td>
<td>547±24</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$K^*(892)^0$</td>
<td>895.81±0.19</td>
<td>47.4±0.6</td>
<td>1$^-$</td>
</tr>
<tr>
<td>$K^*(1410)^0$</td>
<td>1414±15</td>
<td>232±21</td>
<td>1$^-$</td>
</tr>
<tr>
<td>$K^*_0(1430)^0$</td>
<td>1425±50</td>
<td>270±80</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$K^*_2(1430)^0$</td>
<td>1432.4±1.3</td>
<td>109±5</td>
<td>2$^+$</td>
</tr>
<tr>
<td>$K^*(1680)^0$</td>
<td>1717±27</td>
<td>322±110</td>
<td>1$^-$</td>
</tr>
<tr>
<td>$K^*_3(1780)^0$</td>
<td>1776±7</td>
<td>159±21</td>
<td>3$^-$</td>
</tr>
</tbody>
</table>
The rich angular structure of the $K\pi$ system is shown by the very featured Legendre polynomial moments.
The moments are normalized and used to predict, through a MC simulation, the expected $m_{\psi(2S)\pi}$ spectrum.

The order of the Legendre polynomial expansion depends on the locally dominant $K\pi$ resonances:

$$l_{\text{max}}(m_{K\pi}) = \begin{cases} 
2 & m_{K\pi} < 836 \text{ MeV/}c^2 \\
3 & 836 \text{ MeV/}c^2 < m_{K\pi} < 1000 \text{ MeV/}c^2 \\
4 & m_{K\pi} > 1000 \text{ MeV/}c^2 .
\end{cases}$$
**Z(4430)⁺**: model independent analysis

Hypothesis test

- Performed using a series of pseudo-experiments produced according with $l_{\text{max}}$ ($m_{K\pi}$).
- Hypothesis test based on likelihood ratio between $l_{\text{max}}$ ($m_{K\pi}$) and $l_{\text{max}} = 30$.
- Efficiency effects and background subtraction taken into account in the pseudo-experiment generation.

The hypothesis that the structure of the $m_{\psi(2S)\pi}$ spectrum can be described as a reflection of the activity of the resonances in the $K\pi$ system is ruled out with high significance.

The yield from the LHCb experiment is shown for different regions of $m_{K\pi}$, with the data compared to the expected background. The significance of the observed yield is indicated for two mass windows: $0.0 < m_{K\pi} < 1.39$ GeV/$c^2$.
Quantum numbers of the X(3872) state and orbital angular momentum in its $\rho^0 J/\psi$ decays


- Previous quantum number determinations assumed that the lowest orbital angular momentum between the X(3872) decay products dominated the matrix element.

- Significant contributions from higher orbital angular amplitudes could invalidate the $1^{++}$ assignment. **It is necessary to perform again the analysis allowing more general angular configurations.**

- Using the 3.0 fb$^{-1}$ dataset recorded by LHCb in 2011 and 2012

- $1011 \pm 38$ $B^+ \rightarrow K^+ X(3872)$ with $X(3872) \rightarrow J/\psi \pi^+ \pi^-$.

- 5D analysis: all angular correlations used to measure X(3872) $J^{PC}$
Quantum numbers of the $X(3872)$ state and orbital angular momentum in its $\rho^0 J/\psi$ decays

Hypothesis test

- A large set of $X(3872)$ $J^{PC}$ configurations is considered.
- Likelihood-ratio test to discriminate between the assignments against the $1^{++}$;
- Results on data compared to simulated experiments.
- Data favour the $1^{++}$ over the alternative hypothesis with $> 16.0\sigma$;
- No significant D-wave fraction is found, with an upper limit of 0.4% at 95% C.L.
At LHCb, the $X(3872)$ can be studied using:

- Prompt candidates: higher statistics but large combinatorial background.
- Candidates from $B$ decays: lower statistics but more clear samples
- Both kinds of candidates (inclusive selection)

$X(3872)$ production studies at LHCb were performed:

- Measuring the product of production cross-section multiplied by branching ratio to $X(3872) \rightarrow J/\psi \pi^+\pi^-$
- Assuming $X(3872)$ as a $1^{++}$ state
- Performing an inclusive selection of $X(3872) \rightarrow J/\psi \pi^+\pi^-$ final state
- Fiducial range: $5 < p_T < 20$ GeV and $2.5 < y < 4.5$
- Efficiency estimated from Monte Carlo
**X(3872) production studies at LHCb**

Analysis performed on data sample with integrated luminosity of $34.7 \text{ pb}^{-1}$ collected by the LHCb experiment in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ in 2010. [Eur. Phys. J. C. 72 (2012) 1972]

$$\sigma(pp \rightarrow X(3872) + \cdots) \times B(X(3872) \rightarrow J/\psi \pi^+ \pi^-) = 5.4 \pm 1.3(\text{stat}) \pm 0.8(\text{syst}) \text{ nb}$$

$$M(X(3872)) = 3871.95 \pm 0.48(\text{stat}) \pm 0.12(\text{syst}) \text{ MeV/c}^2$$

- $585 \pm 74$ $X(3872)$ signal candidates
- Momentum scale calibration using $J/\psi \rightarrow \mu^+ \mu^-$.
- $X(3872)$ peak fitted using a Voigt function with fixed width.
- Background studied from wrong-sign pions combinations and modeled by exponential function.
- Uncertainty dominated by statistics. It will improve with 2011 dataset.
Status of $X(3872)$ mass

- World average and $D^0 \bar{D}^{0*}$-threshold are indistinguishable.
- Mass is a critical parameter for the $D^0 \bar{D}^{0*}$-bound state hypothesis.
- Very low binding energy: $E_{\text{bind}} = 0.16 \pm 0.26 \text{ MeV}/c^2$

\[
\begin{align*}
\text{D}^0 & \\
\text{Babar (J/ψ, ω, K)} & \\
\text{BaBar B}^0 & \\
\text{BaBar B}^+ & \\
\text{LHCb} & \\
\text{Belle} & \\
\text{CDF} & \\
\text{PDG 2012: } 3871.68 \pm 0.17 & \\
M(D^0) + M(D^*) & \\
\end{align*}
\]
CMS collaboration performed detailed X(3872) production studies using the decay mode \( X(3872) \rightarrow J/\psi \pi^+\pi^- \), with \( J/\psi \rightarrow \mu^+\mu^- \) and 4.1 fb\(^{-1}\) 7 TeV.

- Measurements are performed in the range \( 10 < p_T X(3872) < 50 \) GeV and rapidity \( |y| < 1.2 \).
- Detailed study of the dipion mass showing the decay proceeds dominantly through a intermediate \( \rho \)

\[ \text{[arXiv:1302.3968]} \]
X(3872) production studies at CMS

- Ratio of the X(3872) and ψ(2S) cross sections times their branching fractions into J/ψ π⁺π⁻ measured in function of $p_T$.
- Fraction of X(3872) originating from B decays.
- Prompt X(3872) differential cross section times branching fraction into J/ψ π⁺π⁻ and comparison with theory prediction.

[arXiv:1302.3968]