Quarkonia and quarkonia-like spectroscopy at LHCb

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Introduction

- In recent years, new exotic mesons have been observed by different experiments:
  - $X(3872)$, $X(4140)$, $Z(4430)$-...
  - $X(3872)$ first assigned to $c\bar{c}$ states but they don’t fit standard charmonium model.

- Many models exists, all with limited success.
  - Tetraquark: Tightly bound four quark.
  - Molecular state: Loosely bound mesons with a quark/color exchange (short distance) or pion exchange (large distance).
  - Charmonium hybrids: States with excited gluonic degrees of freedom.
  - Threshold effects: Virtual states at thresholds.
$X(3872) \to \psi(2S)\gamma$ decay

- Predictions for $B(X(3872)\to\psi(2S)\gamma)/B(X(3872)\to J/\psi\gamma)$ vary widely in different models.
  - $c\bar{c}$ $(2^3P_1)$ interpretation: $\sim 1.2\text{--}15$. Phys.Rev.D79:094004,2009; Phys. Rev. D85 (2012) 114002
  - In molecular picture: $\sim 3\times10^{-3}$. arXiv:1401.4431

- BaBar observed the $X(3872) \to \psi(2S)\gamma$ decay in $B^+\to X(3872)K^+$ decays and measured the ratio. [Phys. Rev. Lett. 102 (2009) 132001]

- In 2011 Belle hadn't observed the $X(3872) \to \psi(2S)\gamma$ decay and set a limit. [Phys. Rev. Lett. 107 (2011) 091803]

- Can be tested by a hadron collider.
2D mass fit

- **Combinatorial bkg.**
- **Peaking bkg.** \( B^+ \rightarrow J/\psi(K^{*+} \rightarrow K^+(\pi^0 \rightarrow \gamma\gamma)) \) one \( \gamma \) missing for \( J/\psi\gamma \)
- **Signal**

\[
m_{B^+} = 5277.7 \pm 0.8 \text{ MeV}/c^2
\]

\[
m_{B^+} = 5281.9 \pm 2.4 \text{ MeV}/c^2
\]

\[
m_X = 3873.4 \pm 3.4 \text{ MeV}/c^2 \quad N = 5914 \pm 48
\]

\[
m_X = 3869.5 \pm 3.4 \text{ MeV}/c^2 \quad N = 36.4 \pm 9.0
\]

\[
4.4\sigma
\]
Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
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<tbody>
<tr>
<td>$X(3872) \rightarrow J/\psi \gamma$ yield determination</td>
<td>6</td>
</tr>
<tr>
<td>$X(3872) \rightarrow \psi(2S)\gamma$ yield determination</td>
<td>7</td>
</tr>
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<td>Photon reconstruction</td>
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<tr>
<td>$B^+ \text{ kinematics}$</td>
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<tr>
<td>Selection criteria</td>
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<tr>
<td>Trigger</td>
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<td>$\mathcal{B}(J/\psi \rightarrow e^+e^-)/\mathcal{B}(\psi(2S) \rightarrow e^+e^-)$</td>
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<tr>
<td>Simulation sample size</td>
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<tr>
<td>Sum in quadrature</td>
<td>12</td>
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</tbody>
</table>
Results and comparison

- An evidence for $X(3872) \rightarrow \psi(2S)\gamma$ in $B^+ \rightarrow X(3872)K^+$ decay with significance of $4.4\sigma$ is obtained

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

- $X(3872)$ cannot be a pure $D\bar{D}^*$ molecule
The puzzle of $Z(4430)^-$

- $Z(4430)^- \rightarrow \psi(2S)\pi^-$ observed by Belle in sample of $B^0 \rightarrow \psi(2S)K^+\pi^-$
- Not confirmed by BaBar (Not excluded, either).
- Charged state, not described by quark model, $c\bar{c}ud\bar{d}$?
- 4D amplitude fit required to disentangle the many interfering resonances in this system.
Z(4430)$^-$ at LHCb

- >25k $B^0 \rightarrow \psi(2S)K^+\pi^-$ candidates, factor 10 more than BaBar/Belle
- Perform two separate analyses
  - Model independent (BaBar) using harmonic moments of $K^*$ decay angle
  - Model dependent (Belle) using 4D amplitude fit
- Background from sidebands

arXiv:1404.1903
Model independent approach

- No constrain to any combination of known $K$ resonances, but restriction on their maximal spin. PRD88 (2013) 074026
- Check if $m_{\psi'\pi}$ distribution can be understood in terms of structures caused via angular momentum conservation.
- Moments of $K^*$ resonances ($J \leq 2$) are unable to explain observed distribution of $m_{\psi'\pi}$.
- Need 4D amplitude fit to determine the $Z(4430)^-$ parameters.
  Reflections of $\cos\theta_{K^*}$ moments

Images:
- Diagram with vector representation of angular coordinates.
- Plot showing efficiency corrected yield vs $m_{\psi'\pi}$ with data points and fitting curves.
- ArXiv:1404.1903
4D fit projections

With $Z$

Without $Z$

Everything except $Z$
$m_{\psi'\pi}$ in different $m_{K\pi}$ region
Spin determination

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

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

![Graph showing simulation experiments and data distribution](attachment:image.png)
Resonant behaviour

- Replace BW amplitude with 6 independent complex numbers in Z region.
- Observe rapid change of phase near maximum of magnitude → **Resonance!**

![Graph showing Resonance](LHCb.png)

- BW amplitude with default Z parameters
- arXiv:1404.1903
Second exotic Z?

- Fit confidence level increases to 26%.
- Significance from $\Delta(-2\ln L)$ is $6\sigma$.
- Need larger samples to characterise this state.

$J^P = 0^-$ assigned

$M_{Z_0} = 4239 \pm 18^{+45}_{-10}$ MeV

$\Gamma_{Z_0} = 220 \pm 47^{+108}_{-74}$ MeV

$f_{Z_0} = 1.6 \pm 0.5^{+1.9}_{-0.4} \%$

Evidence from model-independent approach, and measurement of phase motion inconclusive.

arXiv:1404.1903
Summary

- An evidence for \( X(3872) \rightarrow \psi(2S) \gamma \) in \( B^+ \rightarrow X(3872)K^+ \) decay with significance of 4.4\( \sigma \) is obtained.
- Branching ratio measured with respect to \( X(3872) \rightarrow J/\psi \gamma \), the measured ratio is comparable to BaBar and Belle results.
- LHCb has confirmed the existence of the \( Z(4430) \).
- \( J^P = 1^+ \)
- Possible second exotic state around 4240?