Exotic meson studies at LHCb

M. Kreps on behalf of the LHCb Collaboration
We think of hadrons as $q\bar{q}$ or $qqq$

But there is nothing preventing other combinations

Can we find

- molecule
- tetraquark
- your other favourite choice
**X(3872) enigma**

- Discovered in 2003 by Belle
- Huge number of results available
- Quantum numbers $J^{PC} = 1^{++}$
- Nature of $X(3872)$ still unclear
- Today radiative decays

**CDF Run II Preliminary**

$$0.40 \quad 0.80 \quad 1.20$$

**M($\pi^{+}\pi^{-}\ell^{+}\ell^{-}$) - M($\ell^{+}\ell^{-}$) (GeV)**

<table>
<thead>
<tr>
<th>Events/0.010 GeV</th>
<th>0</th>
<th>100</th>
<th>200</th>
<th>300</th>
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**LHCb**

- Simulated $J^{PC}=2^{+}$
- Simulated $J^{PC}=1^{++}$

**PRL 91, 262001**

PRL 98, 132002

**PRL 110, 222001**

**Number of experiments / bin**

- $t_{data}$
- $t = -2\ln[ L(2^{+})/L(1^{++}) ]$
$X(3872) \rightarrow \psi \gamma$

\[ M(J/\psi \gamma K^+)[\text{GeV}/c^2] \]

\[ M(\psi(2S)\gamma K^+)[\text{GeV}/c^2] \]

591 ± 48

36.4 ± 9.0

4.4σ

arXiv:1404.0275
\[ X(3872) \rightarrow \psi(2S)\gamma \]

- We measure

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

- Compare to theory for different interpretations
  - Clear inconsistency with pure molecule
  - Pure $c\bar{c}$ or mixture of molecule with $c\bar{c}$ possible

![Diagram showing comparison of the $R$ values from various experiments and predictions.](image-url)
Z(4430)$^+$ history

- Seen by Belle, but not Babar
- Data consistent
- Charged state
- → Cannot be $c\bar{c}$
- Latest Belle result uses 4D analysis
- Is it real and if yes, is it resonance?
Z(4430)$^+$ history

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Data sample

- Use $B^0 \rightarrow \psi(2S)K\pi$ decays
- Large statistics (> 25k), about 10 times what B-factories had
- Very clean signal, background 4% of events (about 8% at B-factories)
- Perform both model-independent analysis (BABAR) and amplitude fit (Belle)
Model independent method

- Look to $\cos(\theta_K)$ in bins of $K\pi$ mass
- Allows to find out which spins contribute
  $$\sum_i \frac{1}{\epsilon_i} P_i(\cos \theta_{Ki})$$
- Take only moments corresponding to $J \leq 2$
- Construct Dalitz plot and project on $\psi(2S)\pi$ axis

- Test whether contributions in $K\pi$ system can describe data
- Do not impose specific model for resonances
  → Model independent test
Clearly, pure kaon resonances cannot explain $M(\psi(2S)\pi)$ spectrum.

Understanding details difficult.

- Resonances in $\psi(2S)\pi$ will contribute to $K\pi$ and its moments.
- Any fit to $\psi(2S)\pi$ on top of reflections neglects interference between two axes.
Amplitude analysis

- Full 4D amplitude analysis
- Amplitude

\[ |M|^2 = \sum_{\Delta \lambda_{\mu}} \left| \sum_{\lambda_{\psi}} \sum_{k} A_{k,\lambda_{\psi}} (\Omega | m_{0k}, \Gamma_{0k}) + \sum_{\lambda_{\psi}^Z} A_{Z,\lambda_{\psi}^Z} (\Omega_{0Z}^Z | m_{0Z}, \Gamma_{0Z}) e^{i \Delta_{\mu} \alpha} \right|^2 \]

- Mass described by relativistic Breit-Wigner
- Angular part using helicity formalism
- Imposes model how invariant mass distribution should look like
Only $K^*$ resonances

**LHCb**

Candidates / (0.2 GeV$^2$)

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<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>$B(K^{*0} \rightarrow K^+ \pi^-)$</th>
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<td>$K_0^*(800)^0$</td>
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<td>682 ± 29</td>
<td>547 ± 24</td>
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$B^0 \rightarrow \psi(2S)K^+ \pi^-$ phase space limit 1593

| $K_1^*(1680)^0$    | 1$^-$ | $1^3 D_1$           | 1717 ± 27  | 322 ± 110   | (38.7 ± 2.5)$\%$                |
| $K_3^*(1780)^0$    | 3$^-$ | $1^3 D_3$           | 1776 ± 7   | 159 ± 21    | (18.8 ± 1.0)$\%$                |
| $K_0^*(1950)^0$    | 0$^+$ | $2^3 P_0$           | 1945 ± 22  | 201 ± 78    | (52 ± 14)$\%$                   |
| $K_4^*(2045)^0$    | 4$^+$ | $1^3 F_4$           | 2045 ± 9   | 198 ± 30    | (9.9 ± 1.2)$\%$                 |

$B^0 \rightarrow J/\psi K^+ \pi^-$ phase space limit 2183

| $K_5^*(2380)^0$    | 5$^-$ | $1^3 G_5$           | 2382 ± 9   | 178 ± 32    | (6.1 ± 1.2)$\%$                 |

**LHCb**

$1.0 < m_{K^+\pi^-}^2 < 1.8$ GeV$^2$

Candidates / (0.2 GeV$^2$)

- **data**
- **total fit**
- **$K^*$ S-wave**
- **$K_2(1430)$**
- **background**
- **$K^*(1680)$**
- **$K^*(1410)$**

arXiv:1404.1903

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Only $K^*$ resonances

\[ m_{\psi^*}^2 \text{ [GeV}^2] \]

- Data cannot be described by $K^*$ only

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### Additional Data

- $B^0 \rightarrow J/\psi K^+ \pi^-$ phase space limit: 2183

- $K_5^*(2380)^0$ | $5^-$ | $1^2 S_5$ | 2382 ± 9  | 178 ± 32  | (6.1 ± 1.2)%

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Adding $Z^+$
Dalitz plot slices

LHCb
\(m_{K\pi}^2 < 0.7 \text{ GeV}^2\)

Candidates / (0.2 GeV^2)

LHCb
\(1.0 < m_{K\pi}^2 < 1.8 \text{ GeV}^2\)

Candidates / (0.2 GeV^2)

LHCb
\(0.7 < m_{K\pi}^2 < 1.0 \text{ GeV}^2\)

Candidates / (0.2 GeV^2)

LHCb
\(m_{K\pi}^2 > 1.8 \text{ GeV}^2\)

Candidates / (0.2 GeV^2)

LHCb
\(m_{\psi'\pi}^2 < 0.7 \text{ GeV}^2\)

Candidates / (0.2 GeV^2)

LHCb
\(1.0 < m_{\psi'\pi}^2 < 1.8 \text{ GeV}^2\)

Candidates / (0.2 GeV^2)

LHCb
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Candidates / (0.2 GeV^2)

LHCb
\(m_{\psi'\pi}^2 > 1.8 \text{ GeV}^2\)

Candidates / (0.2 GeV^2)

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Results

Data are described well with $1^+ \ Z(4430)^+$ contribution ($\chi^2$ p-value 12%)

- Parameters extracted consistent with Belle
- Large interference effects seen
- Adding additional $K^*$ resonances to model does not alter conclusion

\[ M(Z) \quad 4475 \pm 7^{+15}_{-25} \text{ MeV} \]
\[ \Gamma(Z) \quad 172 \pm 13^{+37}_{-34} \text{ MeV} \]
\[ f_Z \quad 5.9 \pm 0.9^{+1.5}_{-3.3} \% \]
\[ f_I^Z \quad 16.7 \pm 1.6^{+2.6}_{-5.2} \% \]

Significance \( > 13.9\sigma \)
As we use full kinematic information, we have sensitivity to quantum numbers.
Test spins 0, 1, and 2 with both parities.
Based on likelihood ratio.
Quote exclusion based on asymptotic formula (lower bound).
Verified by simulation.
All rejections relative to $1^+$.
$Z(4430)^+$ is $1^+$ state without any doubts.
Is $Z(4430)^+$ resonance?

- Data are consistent with BW for $Z(4430)^+$
- But will they follow if BW is not imposed?
- Change BW in $Z(4430)^+$ amplitude to 6 complex numbers in 6 $M(\psi(2S)\pi)$ bins
- Plot resulting amplitude on Argand plot
Data are consistent with BW for $Z(4430)^+$

But will they follow if BW is not imposed?

Change BW in $Z(4430)^+$ amplitude to 6 complex numbers in 6 $M(\psi(2S)\pi)$ bins

Plot resulting amplitude on Argand plot

⇒ It shows resonance behaviour without imposing it
Data can be described even better by adding second $\psi(2S)\pi$ state

On its own, it is significant

Prefered $0^-$ (but $660 \pm 150$ MeV wide $1^+$ option cannot be ruled out)

Argand diagram is inconclusive

No evidence in model-independent approach

Will need more data to clarify situation

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

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

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

$f_{I_{Z_0}} = 2.4 \pm 1.1^{+1.7}_{-0.2}$ %

Significance: $6\sigma$
Conclusions

- Decay $X(3872) \rightarrow \psi(2S)\gamma$ seen with significance $4.4\sigma$
- Radiative $X(3872)$ decays inconsistent with pure molecule
- $Z(4430)^+$ from Belle confirmed and $J^P = 1^+$ without any doubts
- From Argand plot, resonance character of $Z(4430)^+$ is demonstrated
- Charge and quantum numbers rule out conventional explanations
- $Z(4430)^+$ most likely tetraquark state
- Really interesting era is ahead of us
LHCb detector

- Good mass resolution
- Good time resolution
- High trigger rate on $c$ and $b$
- Uniform running conditions