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

L = 780 pb$^{-1}$

*Data points*

acc. corrected prediction for:
- $0^{++}$
- $1_s^-$
- $1^{++}$
- $2_p^+$

Number of experiments / bin

LHCb

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

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

$t_{data}$

$-200$ $-100$ $0$ $100$ $200$

$10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^0$ $10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$ $10^7$

PRL 98, 132002

PRL 91, 262001

PRL 110, 222001

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Today radiative decays

$X(3872)$ yield / unit volume

$0.40$ $0.80$ $1.20$

$M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-)$ (GeV)

Events / 0.010 GeV

Number of experiments / bin

$10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^0$ $10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$ $10^7$
$X(3872) \rightarrow \psi\gamma$

$M(J/\psi\gamma K^+)[\text{GeV}/c^2]$ for $M(\psi(2S)\gamma K^+)[\text{GeV}/c^2]$ = 591 ± 48

$M(\psi(2S)\gamma K^+)[\text{GeV}/c^2]$ for $M(\psi(2S)\gamma)[\text{GeV}/c^2]$ = 36.4 ± 9.0

4.4σ

arXiv:1404.0275
We measure

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

Compare to theory for different interpretations

- Clear inconsistency with pure molecule
- Pure $c\bar{c}$ or mixture of molecule with $c\bar{c}$ possible
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

- Seen by Belle, but not Babar
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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
  $$\sum_i \frac{1}{\epsilon_i} P_l(\cos \theta_{Ki})$$
- 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

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

- Mass described by relativistic Breit-Wigner
- Angular part using helicity formalism
- Imposes model how invariant mass distribution should look like

Rotation between helicity frames
Only $K^*$ resonances

$|m_{\psi\pi}^2| < 1.8$ GeV$^2$

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

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

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

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Only $K^*$ resonances

Data cannot be described by $K^*$ only

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$B^0 \rightarrow \psi(2S)K^+\pi^-$ phase space limit: 1,593

| $K^*_1(1680)^0$  | $1^-$ | $1^3 D_1$           | 1717 ± 27  | 322 ± 110   | (38.7 ± 2.5)%                     |
| $K^*_2(1780)^0$  | $3^-$ | $1^3 D_3$           | 1776 ± 7   | 159 ± 21    | (18.8 ± 1.0)%                     |
| $K^*_0(1950)^0$  | $0^+$ | $2^3 P_0$           | 1945 ± 22  | 201 ± 78    | (52 ± 14)%                        |
| $K^*_1(2045)^0$  | $4^+$ | $1^3 F_4$           | 2045 ± 9   | 198 ± 30    | (9.9 ± 1.2)%                      |

$B^0 \rightarrow J/\psi K^+\pi^-$ phase space limit: 2,183

| $K^*_5(2380)^0$  | $5^-$ | $1^3 G_5$           | 2382 ± 9   | 178 ± 32    | (6.1 ± 1.2)%                      |
Adding $Z^+$
Dalitz plot slices

\[ m_{K^+\pi^-}^2 < 0.7 \text{ GeV}^2 \]

\[ 0.7 < m_{K^+\pi^-}^2 < 1.0 \text{ GeV}^2 \]

\[ m_{K^+\pi^-}^2 > 1.8 \text{ GeV}^2 \]

\[< 0.7 \text{ GeV}^2 \]

\[< 1.0 \text{ GeV}^2 \]

\[> 1.8 \text{ GeV}^2 \]

arXiv:1404.1903

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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

$LHCb$

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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>$M(Z)$</td>
<td>$4475 \pm 7^{+15}_{-25}$ MeV</td>
</tr>
<tr>
<td>$\Gamma(Z)$</td>
<td>$172 \pm 13^{+37}_{-34}$ MeV</td>
</tr>
<tr>
<td>$f_Z$</td>
<td>$5.9 \pm 0.9^{+1.5}_{-3.3}$ %</td>
</tr>
<tr>
<td>$f_I^Z$</td>
<td>$16.7 \pm 1.6^{+2.6}_{-5.2}$ %</td>
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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
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

⇒ It shows resonance behaviour without imposing it
Second $Z^+$ state

Data can be described even better by adding second $\psi(2S)\pi$ state

- On its own, it is significant
- Preferred $0^-$ (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
Conclusions

- Decay $X(3872) \rightarrow \psi(2S)\gamma$ seen with significance 4.4σ
- 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
Backup
- Good mass resolution
- Good time resolution
- High trigger rate on $c$ and $b$
- Uniform running conditions