Xth Rencontres du Vietnam

Flavour Physics Conference

Heavy flavor spectroscopy and production at LHCb

Victor Egorychev

On behalf of the LHCb collaboration
Outline

Heavy flavor spectroscopy

✓ X(3872) state in $B^+ \rightarrow \psi(2S)\gamma$ $K^+$ decays
✓ Z(4430)$^-$ state in $B^0 \rightarrow \psi(2S) K^+\pi^-\pi^-$ decays
✓ Search for $f_0(980)$ in $B^0 \rightarrow J/\psi\pi^+\pi^-$ decays

Heavy flavor production

✓ Kinematic dependences of the relative production rates $f_{\Lambda_b} / f_d$
✓ Production of $\chi_b(1P,2P,3P)$ states
X(3872) state

X(3872) discovered by Belle in 2003, also observed by CDF, D0, BaBar, LHCb and CMS

- Exotic particle X(3872)
  - discovered in
    X(3872)→J/ψπ⁺π⁻ decay mode
  - M = 3871.68 ± 0.17 MeV/c²
  - M ≈ M(D⁰) + M(D*⁰)
  - Γ < 1.2 MeV/c²
  - J^{PC} = 1^{++} by LHCb using
    B⁺→X(3872)K⁺, X(3872)→J/ψπ⁺π⁻

- Nature is still unclear, possible interpretations:
  - D⁰D*⁰ molecule
  - conventional χ_{c1}(2P)
  - tetraquark
  - ...
  - and their mixtures

η_{c2}(1^{1}D_2) is now ruled out
χ_{c1}(2^{3}P_1) possible but disfavored by mass

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Radiative decay of $X(3872)$

$X(3872) \rightarrow \psi(2S)\gamma$ decay allows to better understand the nature of $X(3872)$

Predictions for the ratio $R_{\psi\gamma} \equiv \frac{\mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma)}{\mathcal{B}(X(3872) \rightarrow J/\psi\gamma)}$

<table>
<thead>
<tr>
<th>Model</th>
<th>Prediction</th>
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<tbody>
<tr>
<td>charmonium, $\chi_{c1}(2P)$</td>
<td>1.2 – 15</td>
</tr>
<tr>
<td>molecule, DD*</td>
<td>$(3 – 4) \times 10^{-3}$</td>
</tr>
<tr>
<td>mixture $\chi_{c1}(2P) + DD^*$</td>
<td>0.5 – 5</td>
</tr>
</tbody>
</table>

BaBar vs Belle discrepancy

<table>
<thead>
<tr>
<th>events</th>
<th>significance</th>
</tr>
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<tbody>
<tr>
<td>$\psi(2S)\gamma$</td>
<td>25.4$^{+7.3}_{-11.9}$</td>
</tr>
<tr>
<td>$J/\psi\gamma$</td>
<td>23.0$^{+6.4}_{-7.4}$</td>
</tr>
<tr>
<td>$\psi(2S)\gamma$</td>
<td>5.0$^{+11.9}_{-11.0}$</td>
</tr>
</tbody>
</table>

not seen

PRL 107 (2011) 091803
Radiative decay of X(3872) in LHCb

\[ B^+ \rightarrow X(3872)K^+, X(3872) \rightarrow \psi(2S)\gamma \]

\[ B^+ \rightarrow X(3872)K^+, X(3872) \rightarrow J/\psi \gamma \]

The significance was estimated with simplified simulation
Radiative decay of \( X(3872) \) in LHCb

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

The LHCb results are consistent with, but more precise than, the BaBar and Belle results.

The results are not consistent with the expectations for pure molecular \( X(3872) \).

\( X(3872) \) is likely a mixture of a \( \chi_{c1}(2^3P_1) \) charmonium state and of \( D^0D^{*0} \) molecule.

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Observation of a resonance-like structure in the $\pi^\pm \psi'$ mass distribution in exclusive $B \to K \pi^\pm \psi'$ decays

The observation could be interpreted as the first evidence for the existence of mesons beyond the traditional quark-anti-quark model

$\text{Z}(4430)^-$

$\text{Phys. Rev. Lett. 100 (2008) 142001}$

M(Z) = 4433 ± 4 ± 2 MeV

$\Gamma(Z) = 45 ^{+30}_{-13} ^{+13}_{-13}$ MeV

significance 6.5σ
Almost model independent approach to \( K^* \to K\pi \) backgrounds 

**BaBar** did not confirm \( Z(4430)^- \) in B sample comparable to Belle 

Did not numerically contradict the Belle results 

\[
\text{BR}(B^0 \to Z^- K^+) \times \text{BR}(Z^- \to \pi^- \psi(2S)) < 3.1 \times 10^{-5}
\]

Model dependent approach to \( K^* \to K\pi \) backgrounds 

\( J^P = 1^+ \) preferred by > 3.4 \( \sigma \) 

\[
M(Z) = 4485 \pm 22 \pm 28 \text{ MeV}
\]

\[
\Gamma(Z) = 200 \pm 41 \pm 26 \text{ MeV}
\]

significance 6.4\( \sigma \) (5.6 \( \sigma \) with sys.)
\( Z(4430)^- \) state in LHCb

An order of magnitude larger signal statistics than in Belle or BaBar thanks to hadronic production of \( b \)-quarks at LHC

Even smaller non-B background than at the \( e^+e^- \) experiments thanks to excellent performance of the LHCb detector (vertexing, particle identification)
**Z(4430)** state in **LHCb**

LHCb uses both approaches

**Moments analysis**

No assumptions about K* contributions except for the maximal J

K* reflection do not describe the Z(4430)** state** region

This approach does not allow to define Z(4430)** state** parameters

**4D fit method**

The χ² p-value < 2 x 10⁻⁶ (Z excluded)

The χ² p-value = 12% (with Z(4430)** state**)

**LHCb-PAPER-2014-014**

arXiv: 1404.1903
**Z(4430)^- parameters in LHCb**

Spin parity

Likelihood-ratio test to discriminate between 0^- and 1^+ hypotheses

Including systematic variations

<table>
<thead>
<tr>
<th>JP</th>
<th>LHCb</th>
<th>Belle</th>
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</thead>
<tbody>
<tr>
<td>0^-</td>
<td>9.7σ</td>
<td>3.4σ</td>
</tr>
<tr>
<td>1^-</td>
<td>15.8σ</td>
<td>3.7σ</td>
</tr>
<tr>
<td>2^+</td>
<td>16.1σ</td>
<td>5.1σ</td>
</tr>
<tr>
<td>2^-</td>
<td>14.6σ</td>
<td>4.7σ</td>
</tr>
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</table>

JP = 1^+ now established beyond any doubt
Replace the Breit-Wigner amplitude for \( Z(4430)^- \) by 6 independent amplitudes in \( M^2(\psi(2S)\pi^-) \) bins in its peak region.

Observe a fast change of phase crossing maximum of magnitude.

Expected behaviour for a resonance.

First time ever the resonant character of the four-quark candidate has been demonstrated this way!
More than one $Z(4430)^- \rightarrow \psi(2S)\pi^-$

K*(872) and K*$_2$(1430) veto region

Inclusion increases the fit probability 12% $\rightarrow$ 26%

0$^-$ state is preferred over 1$^-$, 2$^-$, 2$^+$ by 8$\sigma$ over 1$^+$ by 1$\sigma$

One more Z resonance may be included

Argand diagram studies are inconclusive

Need more data to clarify!

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

$\Gamma(Z) = 200 \pm 47^{+108}_{-74}$ MeV
Excitement

LHCb confirms existence of exotic hadrons

How CERN’s Discovery of Exotic Particles May Affect Astrophysics

Large Hadron Collider Discovers ‘Very Exotic Matter’ That Challenges Traditional Physics! (Must-See Videos)

Tetra Quark: Not a New Star Trek Character, a New State of Matter.

Time To Open the Gates of Hell? CERN: Large Hadron Collider DisCOVERS ‘Very Exotic Matter’ That Challenges Traditional Physics! (Must-See Videos)

Exotisches Teilchen: Physikern gelingt Nachweis eines Partikels aus vier Quarks

De LHCb heeft 't bevestigd: er bestaan exotische hadronen

LHCb confirma la existencia de la partícula Z(4430) formada por cuatro quarks

LHCb confirma la existencia de la partícula Z(4430) formada por cuatro quarks

Tetraquark: to hop to thành từ 4 quark

Mystisk partikel udfordrer fysikernes kvarkmodel

PISTOLA FUMANTE DI UNA PARTICELLA A QUATTRO QUARK

LHCb kinnitas tetrakvargi olemusalu

LHC Beauty Tangkap Z (4430) Munegun Tetraquark

Nowa forma materii: potwierdzono istnienie egzotycznych hadronów

Confirmada l’existència d’une nova partícula subatòmica

Objavili čudnú časticu, urýchľovač ju potvrdil

Exotischer Teilchen: Physikern gelingt Nachweis eines Partikels aus vier Quarks

How CERN’s Discovery of Exotic Particles May Affect Astrophysics

14/04/2014

EXPERIMENT LHCb окончательно доказал реальность экзотического мезона Z(4430)

Confirmation of the Existence of Exotic Hadrons

CERN-fysici bevestigen bestaan nieuw exotisch deeltje
Spectroscopy in light quark sector

Scalar mesons in general (particular \( f_0(980) \)) are not well understood. Recently, LHCb observed two channels \( B_s \rightarrow J/\psi \ f_0(980) \) and \( B_d \rightarrow J/\psi \ f_0(500) \).

Many possibilities: \( q \bar{q} \), \( q \bar{q} q \bar{q} \), mixtures…

When \( f_0(500) \) and \( f_0(980) \) are considered as \( q \bar{q} \) states there is the possibility of their being mixtures of light and strange quarks:

\[
\begin{align*}
|f_0(980)\rangle &= \cos \varphi_m |s\bar{s}\rangle + \sin \varphi_m |n\bar{n}\rangle \\
|f_0(500)\rangle &= -\sin \varphi_m |s\bar{s}\rangle + \cos \varphi_m |n\bar{n}\rangle,
\end{align*}
\]

where \( |n\bar{n}\rangle \equiv \frac{1}{\sqrt{2}} (|u\bar{u}\rangle + |d\bar{d}\rangle) \).

When these states are viewed as \( q \bar{q} q \bar{q} \) states the wave functions becomes:

\[
\begin{align*}
|f_0(980)\rangle &= \frac{1}{\sqrt{2}} ([su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]) \\
|f_0(500)\rangle &= |ud|[u\bar{d}]\).
\end{align*}
\]

Observable:

\[
\tan^2 \varphi_m \equiv r^f = \frac{\mathcal{B}(\overline{B}^0 \rightarrow J/\psi f_0(980)) \Phi(500)}{\mathcal{B}(\overline{B}^0 \rightarrow J/\psi f_0(500)) \Phi(980)},
\]

for pure tetraquark states \( \sim 1/2 \).
Amplitude analysis $B_d \rightarrow J/\psi \pi^+ \pi^-$

Similar to the $Z(4430)^-$: 4D analysis
No evidence for $J/\psi \pi^+$
Best fit model does not require $f_0(980)$ component

$$\tan^2 \varphi_m \equiv r^f_\sigma = (1.1^{+1.2+6.0}_{-0.7-0.7}) \times 10^{-2} < 0.098 \text{ at 90\% C.L}$$

The measured upper limit on $r^f_\sigma$ deviates from the tetraquark prediction $(1/2)$ by $8\sigma$

<table>
<thead>
<tr>
<th>$R$</th>
<th>$\mathcal{B}(\bar{B}^0 \rightarrow J/\psi R, R \rightarrow \pi^+ \pi^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho(770)$</td>
<td>$(2.50 \pm 0.10^{+0.18}_{-0.15}) \times 10^{-5}$</td>
</tr>
<tr>
<td>$f_0(500)$</td>
<td>$(8.8 \pm 0.5^{+1.1}_{-1.5}) \times 10^{-6}$</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>$(3.0 \pm 0.3^{+0.2}_{-0.3}) \times 10^{-6}$</td>
</tr>
<tr>
<td>$\omega(782)$</td>
<td>$(2.7^{+0.8+0.7}_{-0.6-0.5}) \times 10^{-7}$</td>
</tr>
<tr>
<td>$\rho(1450)$</td>
<td>$(4.6 \pm 1.1 \pm 1.9) \times 10^{-6}$</td>
</tr>
<tr>
<td>$\rho(1700)$</td>
<td>$(2.0 \pm 0.5 \pm 1.2) \times 10^{-6}$</td>
</tr>
</tbody>
</table>
The relative production rates of beauty hadrons are described by the fragmentation fractions $f_u$, $f_d$, $f_s$, $f_c$, and $f_{\Lambda_b}$ which describe the probability that a $b$ quark fragments into a $B_q$ or a $\Lambda_b$.

The kinematic dependences of the relative production rates $f_{\Lambda_b}/f_d$ of $\Lambda_b$ baryons and $B_d$ mesons are measured using $\Lambda_b \rightarrow \Lambda_c \pi^+$ and $B_d \rightarrow D^+ \pi^-$ decays.

$$f_{\Lambda_b}(x) = \frac{BR(B_d^0 \rightarrow D^+ \pi^-)}{BR(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} \times \frac{BR(D^+ \rightarrow K^- \pi^+ \pi^+)}{BR(\Lambda_c^+ \rightarrow pK^- \pi^+)} \times R(x)$$

$$R(x) = \frac{N_{\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-}(x)}{N_{B_d^0 \rightarrow D^+ \pi^-}(x)} \times \frac{\varepsilon_{\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-}(x)}{\varepsilon_{B_d^0 \rightarrow D^+ \pi^-}(x)}$$

$N(\Lambda_b) = 44,859 \pm 229$

$N(B_d) = 106,197 \pm 344$

LHCb-PAPER-2014-004, arXiv 1405.6842
Dependences of $f_{\Lambda_b}/f_d$ on the $p_T$ and $\eta$ of the beauty hadrons

- The $p_T$ dependence is accurately described by an exponential function.

- The ratio of fragmentation fractions $f_{\Lambda_b}/f_d$ decreases by a factor of three in the range $1.5 < p_T < 40$ GeV/c.

- The ratio of fragmentation fractions $f_{\Lambda_b}/f_d$ versus $\eta$ is described by a linear dependence in the range $2 < \eta < 5$. 
Production of $\chi_b(1P,2P,3P)$ state

LHCb preliminary

$\gamma(1S)$  LHCb preliminary
$\sqrt{s} = 8$ TeV

$\gamma(2S)$  LHCb preliminary
$\sqrt{s} = 8$ TeV

$\gamma(3S)$  LHCb preliminary
$\sqrt{s} = 8$ TeV

| $N_{\gamma(1S)}$ | $283252 \pm 592$ | $659599 \pm 906$ |
| $N_{\gamma(2S)}$ | $87541 \pm 263$  | $203277 \pm 558$ |
| $N_{\gamma(3S)}$ | $50419 \pm 289$  | $115271 \pm 435$ |

| $N_{\chi_b(1P_1)\rightarrow\gamma(1S)}$ | $1908 \pm 71$ | $4608 \pm 115$ |
| $N_{\chi_b(2P_1)\rightarrow\gamma(1S)}$ | $390 \pm 41$  | $904 \pm 68$  |
| $N_{\chi_b(3P_1)\rightarrow\gamma(1S)}$ | $133 \pm 31$  | $196 \pm 50$  |
| $N_{\chi_b(1P_2)\rightarrow\gamma(1S)}$ | $265 \pm 30$  | $660 \pm 46$  |
| $N_{\chi_b(2P_2)\rightarrow\gamma(1S)}$ | $48 \pm 17$   | $73 \pm 26$   |
| $N_{\chi_b(3P_2)\rightarrow\gamma(1S)}$ | $56 \pm 12$   | $126 \pm 20$  |

$M_{\chi_b(3P_1)} = 10511.3 \pm 1.7 \pm 2.4$ MeV/c$^2$

Most precise measurement
χ_b(nP) to Υ(n’S) feeddown fractions

Fraction of Υ mesons originating from χ_b radiative decays

χ_b(3P) to Υ(3S) feed-down has been often neglected when comparing data and theory on Υ(3S). This measurement demonstrates its importance.

The measurement of the Υ(3S) production fraction due to radiative χ_b(3P) decays is performed for the first time.
Conclusions

✓ $X(3872)\to\psi(2S)\gamma$ decay now established at 4.4 $\sigma$

  • $\text{BR}(X(3872)\to\psi(2S)\gamma)/\text{BR}(X(3872)\to J/\psi\gamma)$ inconsistent with pure molecular interpretation of $X(3872)$

✓ Existence confirmation of $Z(4430)^-$ with $>13.9\sigma$

  • Quantum numbers determination $J^P = 1^+$
  • Resonant behaviour observed
  • The charge and spin-party make $Z(4430)^-$ unambiguous four-quark candidate

✓ No evidence for $f_0(980)$ in $B_d \to J/\psi\pi^+\pi^-$ decays

  • Resonance production $f_0(980)$ as a tetraquark state ruled out at 8$\sigma$

✓ New interesting results on $\chi_b(3P)$ production rate:

  • $\chi_b(3P)$ to $\Upsilon(3S)$ feed-down is large

✓ The kinematic dependences of the relative production rates $f_{\Lambda_b}/f_{d}$ of $\Lambda_b$ baryons and $B_d$ mesons are measured

✓ Looking forward for new exciting results!