Tetra- and pentaquark 'spectroscopy'

LHCP, 7-12 June '21

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on behalf of the LHCb collaboration

June 10th, 2021
Introduction to exotic spectroscopy

Recent results by LHCb

➢ Evidence for a new structure in $J/\psi p$ and $J/\psi \bar{p}$ systems in $B_s \rightarrow J/\psi p\bar{p}$ decays

➢ Observation of new resonances decaying to $J/\psi K$ and $J/\psi \phi$ in $B^+ \rightarrow J/\psi \phi K^+$
Multiquark hadrons are called **exotics**:

- ‘tetraquarks’ with 4 quarks
- ‘pentaquarks’ with 5 quarks
Exotics in the quark model

Multiquark hadrons are called **exotics**:
- ‘tetraquarks’ with 4 quarks
- ‘pentaquarks’ with 5 quarks

X, Y: neutral, Z charged

~30 exotics states seen in heavy-quark sector

First exotic candidates

**Tetraquark**
by Belle in 2003 in $B^\pm \rightarrow K^\pm \pi^+\pi^- J/\psi$ decays

$X(3870)$

[Phys. Rev. Lett. 91, 262001]

**Pentaquark**
by LHCb in 2015 in $\Lambda_b \rightarrow J/\psi pK$

Run 1 [PRL 115, 072001 (2015)]

Run 1 + Run 2 [PRL 122, 222001 (2019)]

Amplitude model fit to $m_{J/\psi}$ [GeV]

$P_c(4380)$ and $P_c(4450)$

new state: $P_c(4312)^+ + 2$ peaks at 4450 MeV
The unresolved nature

Theoretical interpretations

- Molecules
- Compact states
- Kinematic effects

Loosely-bound pentaquark

Molecules

Compact states

Kinematic effects

Tightly-bound pentaquark

Low binding energy, narrow states, S-wave only

Tightly-bound states, Large widths, isospin multiplets

$M_{P^+} = M_{D^*} + M_{\Sigma^+} \approx \text{few MeV}$

$M_{P_c^+} = M_{J/\psi} + M_p + \sim 400\text{MeV}$

Favor molecular hypothesis:

- Close to threshold of molecules and narrow widths

⇒ We need independent evidence
Evidence of new structure in $J/\psi p$ and $J/\psi \bar{p}$ systems in $B^0_{(s)} \to J/\psi p\bar{p}$ decays
Searching for pentaquarks in $B^0_{(s)} \rightarrow J/\psi p\bar{p}$

Candidate for pentaquark searches in $J/\psi p$ and $J/\psi \bar{p}$ and for glueball\cite{2} in $p\bar{p}$ system

→ Same final state as $\Lambda_b \rightarrow J/\psi pK$ \cite{1} but mesonic decay

Clean channel: not known resonances w.r.t. $\Lambda_b \rightarrow J/\psi pK$, where several $\Lambda^*$ resonances are present

Resonant state $f_J(2230) \rightarrow p\bar{p}$, peak at 2.2 GeV and $J^P = 2^{++}$ or $4^{++}$ \cite{2}

\begin{itemize}
\item \cite{1} PRL 122, 222001 (2019)
\item \cite{2} Eur. Phys. J. C75 (2015), no. 3 101
\end{itemize}
Selection

Dataset: 9 fb^{-1}

~800 B_s events in 3\sigma window with 15% of background

N_{\text{sig}}(B_s) = 776 +/- 30

f_{bkg} = 14.9 +/- 0.6 %

Purity: 85.1%

Structure in J/\psi p, but to rule out possible pp reflections

Amplitude analysis in 4D

[LHCb-PAPER-2021-018]
The amplitude analysis

4D phsp
\( \Phi=(m_{pp'}, \cos\theta_p, \cos\theta_{\psi}, \varphi) \)

DATA → MODEL

Helicity formalism
- flavour untagged \( B_s \) decays
- assuming CP symmetry

\[ -2 \ln L(\bar{\omega}) = -2 \sum_i \ln P(m_{pp'}, \Omega_i | \bar{\omega}) \]

Fit models:
- **Baseline model**: only non resonant (NR) in pp chain
- Baseline + old \( P_c \) states: \( P_c(4312) \)
- Baseline + new \( P_c \) state \( \Rightarrow \) **Nominal model**
Building a first model

Non resonant contribution ($J^{PC}=1^{--}$) + bkg

→ $J^{PC}=1^{--}$ is the only term in S-wave

→ Different $J^P$ can be excluded (2ΔlogL worse by 140 units)

→ $m(J/\psi p(\bar{p}))$ still not well described

Goodness-of-fit test:

$\chi^2/ndf = 1.7 \rightarrow p = 4 \cdot 10^{-3}$

Can we improve upon this model?
Improve with $P_c$ states

Add $P_c^+$ and $P_c^-$ with same $M$, $\Gamma$ and coupling

$\rightarrow$ Improvement in $\cos\theta_p$ (helicity angle of $p$)

Goodness of fit test:

$\chi^2/ndf = 0.998 \pm 0.008$

Other models tested:

- **Old $P_c$ states** observed by LHCb in 2019
- **Glueball** at $M \sim 2.2\text{GeV}$ and $\Gamma = 20 \text{ MeV}$

$\Rightarrow$ No evidence
Testing different $J^P$

Models with different $J^P$ of $P_c^+$ have been tested.

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>$M_0$</th>
<th>$\Gamma_0$</th>
<th>$f(P_c)$ (%)</th>
<th>$A(P_c)$</th>
<th>$\phi(P_c)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1/2^-$</td>
<td>4335$^{+3}_{-3}$</td>
<td>23$^{+11}_{-8}$</td>
<td>17.4$^{+7.0}_{-3.8}$</td>
<td>0.15$^{+0.07}_{-0.05}$</td>
<td>2.8$^{+1.3}_{-1.4}$</td>
</tr>
<tr>
<td>$1/2^+$</td>
<td>4337$^{+7}_{-4}$</td>
<td>29$^{+26}_{-12}$</td>
<td>22.0$^{+8.5}_{-4.4}$</td>
<td>0.19$^{+0.19}_{-0.08}$</td>
<td>-0.6$^{+2.4}_{-3.0}$</td>
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<td>$3/2^-$</td>
<td>4337$^{+5}_{-3}$</td>
<td>23$^{+16}_{-9}$</td>
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<td>0.10$^{+0.05}_{-0.03}$</td>
<td>-3.1$^{+0.6}_{-0.6}$</td>
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</table>

**Significance**

Likelihood-ratio based frequentistic tests with ‘look-elsewhere’ effect considered.

Values in the range: 3.1-3.7 $\sigma$

None of the $J^P$ can be discarded with CL$_s$ method @95% of CL

$\rightarrow$ dominant systematic uncertainty

$J^P = 1/2^+$  \( \sigma = 3.73 \pm 0.05 \)

$J^P = 3/2^+$  \( \sigma = 3.09 \pm 0.04 \)
Evidence of a new exotic state

New pentaquark-like state (uud cc-bar) with significance between $3.1 - 3.7\sigma$

$$M_{P_c} = 4337^{+7}_{-4} \text{ (stat)} \pm 2 \text{ (sys) MeV},$$

$$\Gamma_{P_c} = 29^{+26}_{-12} \text{ (stat)} \pm 14 \text{ (sys) MeV}$$

Fit fraction of the sum of $P_c^+ + P_c^-$

$$f(P_c) = 22.0^{+8.5}_{-4.0} \text{ (stat)} \pm 8.6 \text{ (sys) \%}$$

We can exclude:

- Old $P_c$ states, in particular $P_c(4312)$
- Glueball $f_J(2230)$

Theoretical interpretation:

- no near threshold except for $\chi_{c0}(1P)p$
- Tight pentaquark?

$\Rightarrow$ need predictions from theorists

$P_c(4337)$ not consistent with previously observed $P_c$ states
Observation of new resonances decaying to $J/\psi K$ and $J/\psi \phi$ in $B^+ \rightarrow J/\psi \phi K^+$
The $B^+ \rightarrow J/\psi \phi K^+$ decay

LHCb analysis Run1 data:

- $J/\psi \phi$ structures:
  - observation of $X(4274)$, $X(4500)$ and $X(4700)$
- $J/\psi K^+$ structure: evidence

$\Rightarrow$ search for $Z_{cs}^+$ after evidence of $P_{cs}$ and observation of $X(2900)$

[arXiv:2012.10380]

LHCb Run 1: Phys. Rev. Lett. 118, 022003
A zoo exotic channel

Optimised selection: 9 fb$^{-1}$
- $N_{\text{sig}} \sim 24k$, 6 times Run 1 data,
- background fraction of 4% in +/-15MeV
  $\rightarrow$ 15% higher signal efficiency

Clear structures in the Dalitz plot:
- four X states in $J/\psi \phi$
- clear band at 16 MeV$^2$ in $J/\psi K$

[arXiv:2103.01803]
New $X$ and $Z_{cs}$ states

Amplitude fit based on Run 1 model

but extended with:
New X and $Z_{cs}$ states

Amplitude fit based on Run 1 model but extended with:

- $2\ X$ states:
  - $X(4630)$ and $X(4685)$

- $2\ Z_{cs}^+ \rightarrow J/\psi K^+$
  - tetraquark with strangeness

Observation of all $>5\sigma$

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Significance [$\times\sigma$]</th>
<th>$M_0$ [MeV]</th>
<th>$\Gamma_0$ [MeV]</th>
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<td>$X(4630)$</td>
<td>5.5 (5.7)</td>
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<td>174 $\pm$ 27 $^{+134}_{+73}$</td>
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<td>$X(4685)$</td>
<td>15 (15)</td>
<td>4684 $\pm$ 7 $^{+13}_{-16}$</td>
<td>126 $\pm$ 15 $^{+37}_{-41}$</td>
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<td>25 $\pm$ 5 $^{+11}_{-12}$</td>
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<tr>
<td>$Z_{cs}(4000)$</td>
<td>15 (16)</td>
<td>4003 $\pm$ 6 $^{+4}_{-14}$</td>
<td>131 $\pm$ 15 $\pm$ 26</td>
<td>9.4 $\pm$ 2.1 $\pm$ 3.4</td>
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<td>$Z_{cs}(4220)$</td>
<td>5.9 (8.4)</td>
<td>4216 $\pm$ 24 $^{+43}_{-30}$</td>
<td>233 $\pm$ 52 $^{+97}_{-73}$</td>
<td>10 $\pm$ 4 $^{+10}_{-7}$</td>
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Fit projection for $Z_{cs}(4000)$ onto $J/\psi K^+$ in two slices of $J/\psi \phi$
New X and $Z_{cs}$ states

Amplitude fit based on Run 1 model but extended with:

- 2 X states:
  - $X(4630)$ and $X(4685)$

- 2 $Z_{cs}^+$ → $J/\psi K^+$
  → tetraquark with strangeness

Observation of all >5σ

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New state observed by BESIII $Z(3985)$ in $D_s^- D^{*0} + D^0 D_s^*$ [PRL 126 (2021) 102201]

No evidence that is the same as $Z_{cs}(4000)$ state:
- Fixing $Z_{cs}(4000)$ to BESIII’s result
  ⇒ -2 $\Delta$logL worse by 160 units
Conclusion and prospects

A lot of interesting results from LHCb

- New evidence of pentaquark $P_c(4337)$ in $B_s \rightarrow J/\psi p\bar{p}$
- Observation of 4 new exotics in $B^+ \rightarrow J/\psi \phi K^+$:
  - 2 $Z_{cs}$ with strangeness
- First $P_{cs}$ evidence in $E_b^{-} \rightarrow J/\psi K K$ [arXiv:2012.10380]
- Observation of $X(2900)$ in $B^+ \rightarrow D^+ D^* K^+$ [PRD 102 (2020) 112003]

Need larger dataset:

- to confirm the evidences
- to help understand the nature of these states

LHCb is boosting data to a new level:

- $\sim 7x$ more data by 2029, half by 2024
- expected $6x$ increase with Upgrade II

Thank you for listening!
Tetraquark multiplets

For SU(3)_f symmetry, Z_{cs}(4003) and Z_{cs}(3985) belong to 1^{++} and 1^{+-} nonets \[\text{arXiv:2103.08331v2}\]

Prediction for a new state X_{ss} with mass equal to 4076 MeV,
- Decaying to: η_c φ, η_J/Ψ, D_s^- D_s
Evidence of $P_{cs} \rightarrow J/\psi \Lambda$
Evidence of $P_{cs} \to J/\psi \Lambda$

$\sim 1750 \Xi_b^{-} \text{ signals in } \Xi_b^{-} \to J/\psi \Lambda K \text{ decays, with purity } \sim 80\%$

Potential $P_{cs} \to J/\psi \Lambda$ need an amplitude analysis to answer
Evidence of $P_{cs} \rightarrow J/\psi \Lambda$

$\Rightarrow P_{cs}(4459)$ at $3.1\sigma$ including systematics

$M = 4458.8 \pm 2.9$ (stat) MeV
$\Gamma = 17.3 \pm 6.5$ (stat) MeV

- More prominent when $\Xi^{*-}$ resonances are suppressed
- Improvement in $\cos\theta_{Pcs}$

[arXiv:2012.10380]
Evidence of $P_{cs} \rightarrow J/\psi\Lambda$

No other $P_{cs}$ states observed

<table>
<thead>
<tr>
<th>State</th>
<th>$M_0$ (MeV)</th>
<th>$\Gamma_0$ (MeV)</th>
<th>FF (%)</th>
</tr>
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<tr>
<td>$P_{cs}(4459)^0$</td>
<td>$4458.8 \pm 2.9^{+4.7}_{-1.1}$</td>
<td>$17.3 \pm 6.5^{+8.0}_{-5.7}$</td>
<td>$2.7^{+1.9+0.7}_{-0.6-1.3}$</td>
</tr>
<tr>
<td>$\Xi(1690)^-$</td>
<td>$1692.0 \pm 1.3^{+1.2}_{-0.4}$</td>
<td>$25.9 \pm 9.5^{+14.0}_{-13.5}$</td>
<td>$22.1^{+6.2+6.7}_{-2.6-8.9}$</td>
</tr>
<tr>
<td>$\Xi(1820)^-$</td>
<td>$1822.7 \pm 1.5^{+1.0}_{-0.6}$</td>
<td>$36.0 \pm 4.4^{+7.8}_{-8.2}$</td>
<td>$32.9^{+3.2+6.7}_{-6.2-4.1}$</td>
</tr>
<tr>
<td>$\Xi(1950)^-$</td>
<td>$1910.6 \pm 18.4$</td>
<td>$105.7 \pm 23.2$</td>
<td>$11.5^{+5.8+49.9}_{-3.5-9.4}$</td>
</tr>
<tr>
<td>$\Xi(2030)^-$</td>
<td>$2022.8 \pm 4.7$</td>
<td>$68.2 \pm 8.5$</td>
<td>$7.3^{+1.8+3.8}_{-1.8-4.1}$</td>
</tr>
<tr>
<td>NR</td>
<td>—</td>
<td>—</td>
<td>$35.8^{+4.6+10.3}_{-6.4-11.2}$</td>
</tr>
</tbody>
</table>

- New pentaquark with strangeness:
  - test of SU(3) flavour symmetry
  - 19 MeV below the $\Xi_c^0D^*0$ threshold
    $\Rightarrow$ molecular interpretation?
- 2 new $\Xi^{*-}$ states
Observation of $X(2900)$
$B^+ \rightarrow D^+ D^- K^+$ decays

~ 1260 signal events in +/-20 MeV
Purity > 99.5%

Both amplitude analysis & model-independent analysis to investigate $D K^+$ structure
Amplitude analysis

Resonances in $D^+D^-$ do not describe the data well

\[ m(D^+D^-) > 4 \text{ GeV}^2 \]

+ two $X(2900)$ with overwhelming significances

[PRD 102 (2020) 112003]
Model-independent analysis

Expansion in Legendre polynomials in $m(D^+D^-)$ up to order $k_{\text{max}} = 2J_{\text{max}}$

Coefficients:

$$\langle Y^j_k \rangle = \sum_{l=1}^{N_{\text{Data}}} w_l P_k[h_l(D^+D^-)],$$

Deviations in $m(D'K^+)$ can be observed at 3.9σ

⇒ compatible with new exotic structures

⇒ Support results of amplitude analysis

Up to order 4: $J_{\text{max}} = 2$ for resonances in $D^+D^-$

PRL 125 (2020) 242001