Pentaquark and tetraquark states at LHCb

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(Tsinghua University)

On behalf of the LHCb Collaboration

DPF
July 31 – Aug. 4, 2017, Fermilab
• Introduction

• All results are based on Run-I 3fb\(^{-1}\) data
  – Tetraquark states in \(B^+ \rightarrow J/\psi \phi K^+\)
  – \(X(5568)^\pm\)
  – Pentaquark states in \(\Lambda_b^0 \rightarrow J/\psi pK^-\)
  – Search for pentaquark states in \(\Lambda_b^0 \rightarrow J/\psi p\pi^-\)
  – Observation of \(E_b^- \rightarrow J/\psi \Lambda K^-\)
  – Observation of \(\Lambda_b^0 \rightarrow \chi_{c(1,2)} p K^-\)

• Interpretation of pentaquarks

• Summary
Introduction

- Exotic states are important for understanding strong force in QCD
  - Predicted in quark model
  - Recent experimental results show strong evidence for their existence

- Mesonic molecule?
- Tetraquark?
- Pentaquark?
- Hybrid?
Tetraquark candidates
4 \( X \to J/\psi\phi \) states in \( B^+ \to J/\psi\phi K^+ \)

- \( X(4140) \) first observed by CDF; evidence for \( X(4274) \)
- 1st full amplitude w/ world largest sample of 4300 signals at LHCb
- Good fit with 4 \( X \) states + 7 \( K^{*+} \to \phi K^+ \) + NR’s

PRL 118, 022003 (2017)
### Results

- $J^{PC}$ are useful for interpretations of the states
- $X(4140)$ & $X(4274)$: identified as $J^{PC} = 1^{++}$ at $> 5\sigma$
- $X(4500)$ & $X(4700)$: $J^{PC} = 0^{++}$ at $> 4\sigma$

<table>
<thead>
<tr>
<th>Contribution</th>
<th>sign. or Ref.</th>
<th>$M_0$ [MeV]</th>
<th>$\Gamma_0$ [MeV]</th>
<th>FF %</th>
</tr>
</thead>
<tbody>
<tr>
<td>All $X(1^+)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X(4140)$</td>
<td>8.4σ</td>
<td>$4146.5 \pm 4.5^{+4.6}_{-2.8}$</td>
<td>$83 \pm 21^{+21}_{-14}$</td>
<td>$16 \pm 3^{+6}_{-2}$</td>
</tr>
<tr>
<td>Average other experiments</td>
<td></td>
<td>$4143.4 \pm 1.9$</td>
<td>$15.7 \pm 6.3$</td>
<td></td>
</tr>
<tr>
<td>$X(4274)$</td>
<td>6.0σ</td>
<td>$4273.3 \pm 8.3^{+17.2}_{-3.6}$</td>
<td>$56 \pm 11^{+8}_{-11}$</td>
<td>$7.1 \pm 2.5^{+3.5}_{-2.4}$</td>
</tr>
<tr>
<td>CDF</td>
<td>[28]</td>
<td>$4274.4^{+8.4}_{-6.7} \pm 1.9$</td>
<td>$32^{+22}_{-15} \pm 8$</td>
<td></td>
</tr>
<tr>
<td>CMS</td>
<td>[25]</td>
<td>$4313.8 \pm 5.3 \pm 7.3$</td>
<td>$38^{+30}_{-15} \pm 16$</td>
<td></td>
</tr>
<tr>
<td>All $X(0^+)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NR$_{J/\psi\phi}$</td>
<td>6.4σ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X(4500)$</td>
<td>6.1σ</td>
<td>$4506 \pm 11^{+12}_{-15}$</td>
<td>$92 \pm 21^{+21}_{-20}$</td>
<td>$6.6 \pm 2.4^{+3.5}_{-2.3}$</td>
</tr>
<tr>
<td>$X(4700)$</td>
<td>5.6σ</td>
<td>$4704 \pm 10^{+14}_{-24}$</td>
<td>$120 \pm 31^{+42}_{-33}$</td>
<td>$12 \pm 5^{+9}_{-5}$</td>
</tr>
</tbody>
</table>

Substantially larger
A new $B_s^0 \pi^\pm$ state claimed by DØ

Claimed evidence of an exotic state

- $X(5568)^\pm \to B_s^0 \pi^\pm$, $B_s^0 \to J/\psi \phi$, $J/\psi \to \mu^+ \mu^-$, $\phi \to K^+ K^-$
  
  $M = 5567.8 \pm 2.9^{+0.9}_{-1.9}$ MeV
  
  $\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}$ MeV

- Fraction of $B_s^0$ from $X^\pm$ decay: $\rho^{DØ}_{X} = (8.6 \pm 1.9 \pm 1.4)\%$

- If confirmed, would be unique with 4 different flavours

$$N(X) = 106 \pm 23$$

$B_s^0 \to J/\psi \phi$

$B_s^0 \to D_s^- \mu^+ \nu$

D0 Preliminary 10.4 fb$^{-1}$

Data

MC Background Simulation

Signal significance

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Samples from LHCb

\[ B_s^0 \rightarrow D_s^- \pi^+ \]
\[ N(B_s) = 62k \]
\[ \sigma_{\text{Res}} = 15 \text{ MeV} \]
\[ S/B = 10 \]

\[ B_s^0 \rightarrow J/\psi \phi \]
\[ N(B_s) = 44k \]
\[ \sigma_{\text{Res}} = 6 \text{ MeV} \]
\[ S/B = 50 \]

\( B_s^0 \) sample 20x larger and much cleaner than DØ

No evident \( X(5568) \) in \( B_s^0 \pi^\pm \) sample for 3 different \( p_T(B_s^0) \) cuts
Upper limits

\[ \rho_{X}^{\text{LHCb}} = \frac{\sigma(pp\to X + \text{anything}; X\to B_{S}^{0}\pi^{\pm})}{\sigma(pp\to B_{S}^{0} + \text{anything})} \] in LHCb acceptance

\[ \rho_{X} < 2.1\% \text{ (LHCb) } @ 90\% \text{ C. L. for } p_{T}(B_{S}^{0}) > 10 \text{ GeV} \]

- No significant \( B_{S}^{0}\pi^{\pm} \) states for any mass and width below 6 GeV
Pentaquark candidates
Observation of pentaquark states

- Observed two exotic states in $\Lambda_b^0 \rightarrow J/\psi pK^-$, consistent with charmonium pentaquarks ($uudc\bar{c}$)
- Good fit in all dimensions

PRL 115, 072001 (2015)
Observation of pentaquark states

<table>
<thead>
<tr>
<th></th>
<th>$P_c(4380)^\pm$</th>
<th>$P_c(4450)^\pm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance</td>
<td>$9\sigma$</td>
<td>$12\sigma$</td>
</tr>
<tr>
<td>Mass (MeV)</td>
<td>$4380 \pm 8 \pm 29$</td>
<td>$4449.8 \pm 1.7 \pm 2.5$</td>
</tr>
<tr>
<td>Width (MeV)</td>
<td>$205 \pm 18 \pm 86$</td>
<td>$39 \pm 5 \pm 19$</td>
</tr>
<tr>
<td>Fit fraction(%)</td>
<td>$8.4 \pm 0.7 \pm 4.2$</td>
<td>$4.1 \pm 0.5 \pm 1.1$</td>
</tr>
<tr>
<td>$\Sigma(\Lambda_b^0 \rightarrow P_c^+K^-; P_c^+ \rightarrow J/\psi p)$</td>
<td>$(2.56 \pm 0.22 \pm 1.28^{+0.46}_{-0.36}) \times 10^{-5}$</td>
<td>$(1.25 \pm 0.15 \pm 0.33^{+0.22}_{-0.18}) \times 10^{-5}$</td>
</tr>
</tbody>
</table>

PRL 115, 072001 (2015)

$\Sigma$ measurements reported in Chinese Physics C, 40, 011001 (2016)
**JP determination**

- **JP** are important for their interpretations
  - $(3/2^-, 5/2^+)$ is the best fit
  - $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are also possible

- Information from the angular distribution of $P_c^+$

- Ongoing Run-II analysis, aim to identify $JP$ with improved $Λ^*$ modellings [PRD 93, 034029 (2016)]

The discovery opened a gate to study pentaquarks
Cabibbo-suppressed decays

- Find the same $P_c^+$ in other channels is helpful to understand the production mechanism and internal structure
- $\Lambda_b^0 \to J/\psi p\pi^-$ is Cabibbo-suppressed w.r.t. $J/\psi pK^-$
- Two production mechanisms predicted:
  
  $b \to c$
  
  $b \to u$ & $c\bar{c}$ from sea quarks

$$R_{\pi/K} \equiv \frac{B(\Lambda_b^0 \to \pi^- P_c^+)}{B(\Lambda_b^0 \to K^- P_c^+)} = 0.07 \sim 0.08$$

$[\text{Cheng, Phys. Rev. D 92, 096009 (2015)}]$  

$R_{\pi/K} = 0.58 \pm 0.05$

$\Lambda_b^0 \rightarrow J/\psi p\pi^-$ decays

- >10 lower signal in $\Lambda_b^0 \rightarrow J/\psi p\pi^-$ than in $\Lambda_b^0 \rightarrow J/\psi pK^-$
- But more complex because of possible $Z_c^- \rightarrow J/\psi \pi^-$
Full amplitude fits to $\Lambda_b^0 \rightarrow J/\psi p\pi^-$

- Significance of $P_c(4380)^+, P_c(4450)^+, Z_c(4200)^-$ take together is $3.1 \sigma$ including syst.

- First evidence!

PRL 117, 082003 (2016)
Further results for $\Lambda_b^0 \to J/\psi p\pi^-$

- Significance of two $P_c$ is $3.3\sigma$, if assuming production of $Z_c(4200)^-$ is negligible. More data statistics are needed!

- Overall, $P_c^+$ productions are consistent between the two $\Lambda_b^0$ decays

PRL 117, 082003 (2016)

<table>
<thead>
<tr>
<th>State</th>
<th>Fit fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_c(4200)^-$</td>
<td>$7.7 \pm 2.8^{+3.4}_{-4.0}$</td>
</tr>
<tr>
<td>$P_c(4380)^+$</td>
<td>$5.1 \pm 1.5^{+2.6}_{-1.6}$</td>
</tr>
<tr>
<td>$P_c(4450)^+$</td>
<td>$1.6 \pm 0.8^{+0.6}_{-0.6}$</td>
</tr>
</tbody>
</table>

$\times$ Another prediction $R_{\pi/K} = 0.58 \pm 0.05$ is ruled out

$(b \to u \& c\bar{c}$ from sea quarks)
Observation of $\Xi_b^- \rightarrow J/\psi \Lambda K^-$

- Strange pentaquark ($udsc\bar{c}$) predicted in [PRL 105, 232001 (2010)]
- Can be searched for in the $\Xi_b^- \rightarrow \Upsilon J/\psi$ decay [PRC 93, 065203 (2016)]

$N_{\text{sig}} = 308 \pm 21 \ (21\sigma)$  \quad PLB 772 (2017) 265-273

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \cdot \frac{B(\Xi_b^- \rightarrow J/\psi \Lambda K^-)}{B(\Lambda_b^0 \rightarrow J/\psi \Lambda)} = (4.19 \pm 0.29 \pm 0.15) \times 10^{-2}$$

$M(\Xi_b^-) - M(\Lambda_b^0) = 177.08 \pm 0.47 \pm 0.16 \text{ MeV}/c^2$

One of two world best measurements!

Expect $\sim$1500 signals after 2018 for amplitude analysis

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Observation of $\Lambda_{b}^{0} \rightarrow \chi_{c(1,2)} pK^{-}$

- Search for $P_{c}(4450)^{+}$ in $\Lambda_{b}^{0} \rightarrow \chi_{c(1,2)} pK^{-}$ decays
  $\Rightarrow$ Test hypothesis of kinematic rescattering effect
- First step: observe the decays, measure $\mathcal{B}$
- Use $\chi_{c(1,2)} \rightarrow J/\psi\gamma$, constrain $J/\psi\gamma$ mass to known $\chi_{c1}$ mass

$$\frac{\mathcal{B}(\Lambda_{b}^{0} \rightarrow \chi_{c1} pK^{-})}{\mathcal{B}(\Lambda_{b}^{0} \rightarrow J/\psi pK^{-})} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$$

$$\frac{\mathcal{B}(\Lambda_{b}^{0} \rightarrow \chi_{c2} pK^{-})}{\mathcal{B}(\Lambda_{b}^{0} \rightarrow J/\psi pK^{-})} = \mathcal{B}(\chi_{c1})$$

$$= 0.248 \pm 0.020 \pm 0.014 \pm 0.009$$

Next step: full amplitude analysis with more data
**Interpretations and how to distinguish**

<table>
<thead>
<tr>
<th>Hadronic molecules</th>
<th>Tightly-bounded states</th>
<th>Abnormal kinematic effects</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Close to two heavy hadron thresholds</td>
<td>Predicted more than 10 $J^P$ states</td>
<td>Predicted no decay of $P_c(4450)^+ \rightarrow \chi_{c1}p$</td>
</tr>
</tbody>
</table>

Summary

• LHCb is an active laboratory to study many exotic states

• Other than updating these results with Run-II data, many ongoing analyses:
  – Tetraquark search in $B^0 \rightarrow J/\psi K^+ \pi^-$, aka $Z_c(4200)^-$ …
  – Search for $P_c^+$ in $\Lambda_b^0 \rightarrow \Lambda_c^+ D^0 K^-$
  – Search for $J=1/2$ $P_c^+$ in $\Lambda_b^0 \rightarrow \eta_c p K^-$
  – Search for pentaquarks with a single $b$ quark and pentaquarks with a single $c$ quark
Summary

stay tuned!
future epic content
coming soon

Thanks for your attention!
BACKUP
$4 \ X \rightarrow J/\psi\phi$ states in $B^+ \rightarrow J/\psi\phi K^+$

- $X(4140)$ first observed by CDF; evidence for $X(4274)$
- 1st full amplitude w/ world largest sample of 4300 signals at LHCb
- No obvious $J/\psi K^+$ structure
Log-likelihood ratio method

- Likelihood ratio for \( \text{PDF}(m_{\psi'\pi}/\psi\rho | H_0) \) and \( \text{PDF}(m_{\psi'\pi}/\psi\rho | H_1) \)
- \( H_1 \) can well present \( m_{\psi'\pi}/\psi\rho \) spectrum in data using \( l_{\text{max}} = 30/31 \)

\[
B^0 \rightarrow \psi'\pi^-K^+ \quad \Delta_b \rightarrow J/\psi \rho K^-
\]

However, this approach cannot characterize exotics – amplitude analysis is still necessary
Fitted angles in $J/\psi\phi K$

- Fit quality is good in all fitted variables
Model of N* and exotic states

- Reduced model for central values
- Extended for significance and systematics
- Almost as many free parameters as in $\Lambda_b^0 \to J/\psi \, p \, K^-$
- Fixed $m_0$ and $\Gamma_0$ for the N* and exotic states
- $Z_c(4200)$: 10 free parameters
- Each $P_c$: 4 free parameters + 8 fixed to that from $\Lambda_b^0 \to J/\psi \, p \, K^-$

<table>
<thead>
<tr>
<th>State</th>
<th>$J^P$</th>
<th>$M_0$ (MeV)</th>
<th>$\Gamma_0$ (MeV)</th>
<th># of complex couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR $\rho\pi$</td>
<td>$1/2^-$</td>
<td>-</td>
<td>-</td>
<td>4 Red. 4 Ext.</td>
</tr>
<tr>
<td>N(1440)</td>
<td>$1/2^+$</td>
<td>1430</td>
<td>350</td>
<td>3 Red. 4 Ext.</td>
</tr>
<tr>
<td>N(1520)</td>
<td>$3/2^-$</td>
<td>1515</td>
<td>115</td>
<td>3 Red. 3 Ext.</td>
</tr>
<tr>
<td>N(1535)</td>
<td>$1/2^-$</td>
<td>1535</td>
<td>150</td>
<td>4 Red. 4 Ext.</td>
</tr>
<tr>
<td>N(1650)</td>
<td>$1/2^-$</td>
<td>1655</td>
<td>140</td>
<td>1 Red. 4 Ext.</td>
</tr>
<tr>
<td>N(1675)</td>
<td>$5/2^-$</td>
<td>1675</td>
<td>150</td>
<td>3 Red. 5 Ext.</td>
</tr>
<tr>
<td>N(1680)</td>
<td>$5/2^+$</td>
<td>1685</td>
<td>130</td>
<td>0 Red. 3 Ext.</td>
</tr>
<tr>
<td>N(1700)</td>
<td>$3/2^-$</td>
<td>1700</td>
<td>150</td>
<td>0 Red. 3 Ext.</td>
</tr>
<tr>
<td>N(1710)</td>
<td>$1/2^+$</td>
<td>1710</td>
<td>100</td>
<td>0 Red. 4 Ext.</td>
</tr>
<tr>
<td>N(1720)</td>
<td>$3/2^+$</td>
<td>1720</td>
<td>250</td>
<td>3 Red. 5 Ext.</td>
</tr>
<tr>
<td>N(1875)</td>
<td>$3/2^-$</td>
<td>1875</td>
<td>250</td>
<td>0 Red. 3 Ext.</td>
</tr>
<tr>
<td>N(1900)</td>
<td>$3/2^+$</td>
<td>1900</td>
<td>200</td>
<td>0 Red. 3 Ext.</td>
</tr>
<tr>
<td>N(2190)</td>
<td>$7/2^-$</td>
<td>2190</td>
<td>500</td>
<td>0 Red. 3 Ext.</td>
</tr>
<tr>
<td>N(2300)</td>
<td>$1/2^+$</td>
<td>2300</td>
<td>340</td>
<td>0 Red. 3 Ext.</td>
</tr>
<tr>
<td>N(2570)</td>
<td>$5/2^-$</td>
<td>2570</td>
<td>250</td>
<td>0 Red. 3 Ext.</td>
</tr>
</tbody>
</table>

Total # of free parameters: 40 Red. 106 Ext.
Full amplitude fits to $\Lambda_b^0 \rightarrow J/\psi p\pi^-$

- 14 $N^* \rightarrow p\pi^-$ states included to get significances of exotic states
- High mass $N^*$ are important for exotic study
  - since exotic contribution is more visible in large $m(p\pi^-)$

Included $N(2300), N(2700)$ reported by BESIII in $\psi' \rightarrow p\bar{p}\pi^0$
[PRL 110, 022001 (2013)]

If without them, exotic significance is > 5$\sigma$

PRL 117, 082003 (2016)
Model-independent confirmation

- $m_J/\psi_p$ can not be explained by the reflections of $K^-p$ alone
- Angular distribution of $K^-p$ can be decomposed by $P_l(\cos \theta)$

$$\frac{dN}{d \cos \theta} = \sum_{l=0}^{l_{\max}} \langle P_l^U \rangle P_l(\cos \theta)$$

$L_{\max} = 2J_{\max}$ for $\Lambda^*$-only

Legendre moments

$\Lambda^*$-only rejected by $9.0\sigma$
Exotic contribution confirmed

LHCb

PRL 117, 082002 (2016)

Non-zero-moments in the yellow region mean exotic contribution

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X(4140) and X(4274)

- CDF observed a narrow \( (J/\psi \phi) \) structure in \( B^+ \to J/\psi \phi K^+ \) decays
  [Initial publication on 2.7 fb\(^{-1}\) PRL102, 242002 (2009)]
  - \( M=4143.4 \pm 3.0 \pm 0.6 \) MeV
  - \( \Gamma=15.3^{+10.4}_{-6.1} \pm 2.5 \) MeV
  - Necessarily exotic since it is narrow and above the DsDs threshold
  - [csc\(\bar{s}\)] tetraquark ?
  - Hint of a second structure: X(4274)
- Not confirmed by B-factories and LHCb with 0.37fb\(^{-1}\) data
X(4140) and X(4274) from CMS

• Crucial to check by different experiments with larger statistics.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Significance</td>
<td>&gt;5σ</td>
<td>&gt;5σ</td>
<td>3.1σ</td>
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<td>$M_0$ (MeV)</td>
<td>$4143.4 \pm 3.0 \pm 0.6$</td>
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<td>$4159.0 \pm 4.3 \pm 6.6$</td>
</tr>
<tr>
<td>$\Gamma_0$ (MeV)</td>
<td>$15.3^{+10.4}_{-6.1} \pm 2.5$</td>
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<td>$19.9\pm 12.6^{+1}_{-8}$</td>
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X(4140) and X(4274) from CMS

- Crucial to check by different experiments with larger statistics.

![Graph showing CMS data](image)

2480±160 events

<table>
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<tr>
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<tbody>
<tr>
<td>Significance</td>
<td>3.1σ</td>
<td>&gt;3σ</td>
<td></td>
</tr>
<tr>
<td>( M_0 ) (MeV)</td>
<td>4274.4^{+8.4}_{-6.7} ± 1.9</td>
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<td>( \Gamma_0 ) (MeV)</td>
<td>32.3^{+21.9}_{-15.3} ± 7.6</td>
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Statistically, the most powerful $B \to J/\psi \phi K$ sample analyzed so far

Use sidebands to subtract background