Exotic Hadrons at LHCb

M. Kreps on behalf of LHCb

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Introduction

- In original Gell-Mann’s paper, hadrons can be formed from more than quark-antiquark or three quarks
- Long standing puzzle where such combinations are
- Back in 2003 discovery of $X(3872)$ renewed interest in this question
- Since then many states are seen in charmonium region
  - Too many to fit to charmonium spectrum
  - Some charged, so cannot be simple $c\bar{c}$
- Usual difficulty is to prove exotic nature and understand what it is

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**Original Gell-Mann’s paper**

> We then refer to the members $u^2$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) $q$ and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\bar{q}q)$, $(q\bar{q}q\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(q\bar{q}\bar{q})$, etc. It is assuming that the lowest
Pentaquark states

- In summer 2015 LHCb observed two pentaquark states in $\Lambda_b \to J/\psi pK$ decays
- Original analysis used amplitude fit
  - Sensitive, but depends on assumptions on resonances shapes
- Can do model independent test in the same decay

![Invariant mass squared of $m_{J/\psi p}$ for candidates within 200 MeV of the resonance](image1)

![Invariant mass of (a) spectrum shown in Fig. 2(b).](image2)
Pentaquark states

- Expand angular distribution in $m(pK)$ bins in Legendre polynomials
- $pK$ resonances will contribute to limited number of terms (up to $2 \times \text{spin}$)
- On contrary pentaquark will be peaking in angular distribution and thus will contribute to much higher moments
- Remove terms above selected $J_{\text{max}}$
  - Dump pentaquark contribution
- Build model with pentaquark contribution suppressed
Pentaquark states

- Model independent analysis confirms pentaquark contributions
- Can quantify significance using pseudo-likelihood (>9σ)
Pentaquark states

- Study Cabibbo suppressed \( \Lambda_b \to J/\psi p \pi \) decays
- Statistics about factor 10 lower
- Possible \( J/\psi \pi \) states in addition to \( p \pi \) and \( J/\psi p \)
- Fit with two pentaquark and \( Z_c(4200) \) about 3.1\( \sigma \) better than fit without exotic contributions
  - Without \( Z_c(4200) \) in the fit, 3.3\( \sigma \) evidence for pentaquark states
- Consistent with \( \Lambda_b \to J/\psi pK \) decays
X(4140) → J/ψφ state

- X(4140) → J/ψφ claimed first by CDF in B⁺ → J/ψφK
- Seen by some experiments, but not others
- Confusing situation
X(4140)→J/ψφ state

- LHCb performs amplitude analysis of B⁺→J/ψφK decays
- Selection removes events when two KK combinations are consistent with φ
- Modelling becomes tricky as there is little information on K⁺→φK resonances

![Graph](attachment:image.png)

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Fit with $\phi K$ resonances only could not describe data
Adding more $\phi K$ resonances does not improve description
X(4140)→J/ψφ state

- Need 4 exotic contributions to describe data
- X(4140) possibly D_sD_s^* cusp
- Some disagreement in parameters compared to previous experiments
  - Possibly due to missing interference effects in 1D fits

<table>
<thead>
<tr>
<th>Contribution</th>
<th>sign. or Ref.</th>
<th>M_0 [MeV]</th>
<th>Γ_0 [MeV]</th>
<th>FF %</th>
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<tbody>
<tr>
<td>All X(1^+)</td>
<td></td>
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<tr>
<td>X(4140)</td>
<td>8.4σ</td>
<td>4146.5±4.5</td>
<td>83±21</td>
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<td>ave. Table 1</td>
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<td>4147.1±2.4</td>
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<tr>
<td>X(4274)</td>
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<td>X(4500)</td>
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<td>X(4700)</td>
<td>5.6σ</td>
<td>4704±10</td>
<td>120±31</td>
<td>12±5</td>
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</table>

X(4140)→J/ψφ state

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Observation of $\Xi_b \rightarrow J/\psi \Lambda K$

- With observation of pentaquark, quest for other such states
- It was suggested that $J/\psi \Lambda$ system could be place to observe strange pentaquark
- Search for large exclusive decay
  - Ultimately want amplitude analysis
- Decay $\Xi_b \rightarrow J/\psi \Lambda K$ observed
  - About 300 events in Run1
  - Significance of 21σ
- Can measure mass difference to $\Lambda_b$
  - and combine with result from $\Xi_c \pi$
  - $\delta M = 177.73 \pm 0.33 \pm 0.14$ MeV/$c^2$
Observation of $\Lambda_b \rightarrow \chi_{c(1,2)}pK$

- In meson system charged states were seen in $\chi_{c\pi}$
- $P_c(4450)^+$ is close to $\chi_{c1p}$ threshold
- Information from $\chi_{c1p}$ can help to understand observed pentaquarks
- Search for decay $\Lambda_b \rightarrow \chi_{c(1,2)}pK$ decays

- Measured BF $\mathcal{B} (\Lambda_b^0 \rightarrow \chi_{c1}pK^-) = (7.3 \pm 0.4 \pm 0.4 \pm 0.6^{+1.0}_{-0.7}) \times 10^{-5}$

- $\mathcal{B} (\Lambda_b^0 \rightarrow \chi_{c2}pK^-) = (7.4 \pm 0.6 \pm 0.4 \pm 0.6^{+1.1}_{-0.7}) \times 10^{-5}$

- Improve $\Lambda_b$ mass (combined with other LHCb measurements)

$$M(\Lambda_b) = 5619.62 \pm 0.16 \pm 0.13 \text{ MeV}/c^2$$
Structure in $B_s \pi$ spectrum?

- D0 collaboration claimed state decaying to $B_s \pi^+$
- LHCb has large data sample to check it
  - 112600 $B_s$ events (LHCb) vs. 5582 (D0)
- No state seen in place of D0 state
Conclusions

- LHCb has now large samples of b-hadron decays
- Several possible exotic hadrons could be studied in amplitude analysis
- Amplitude analysis allows to determine quantum numbers
- In past year we followed on pentaquarks observation
  - Clear evidence for states in model independent way
  - Decay $\Lambda_b \rightarrow J/\psi p\pi$ consistent with $\Lambda_b \rightarrow J/\psi pK$
  - Observed few other decays we can use for further searches of pentaquarks
- Cleared up some confusion with $X(4140)$ state
  - Amplitude analysis prefers up to 4 exotic states
- We have Run2 data waiting to be exploited
  - Adds about factor of 2 in statistics right now