Latest Results on Tetra- and Penta-quark Candidates from LHCb: Amplitude Analysis of $B \to J/\psi \phi K$

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Exotic hadrons at LHCb

• Over the last few years there has been exciting research in exotic spectroscopy, more specifically charmonium and bottomonium like states

• LHCb has contributed important results based on amplitude fits to the data:
  – Quantum number determination of \(X(3872)\) using \(B^+ \rightarrow X(3872)K^+\), \(X(3872) \rightarrow \rho^0J/\psi\) decays
  – Study of the resonant nature of \(Z(4430)^- \rightarrow \pi^-\psi'\) in \(B^0 \rightarrow \psi'\pi^-K^+\) decays
  – Discovery of pentaquark candidates \(P_c(4380)^+\) and \(P_c(4450)^+ \rightarrow pJ/\psi\) in \(\Lambda_b \rightarrow J/\psi pK^-\) decays

• This talk will focus on possible exotic \(J/\psi\phi\) tetraquark contributions to \(B \rightarrow J/\psi\phi K\) decays

\(X(3872)\)

\(Z(4430)\)

\(P_c\)

\(X(4140)\)?
• Narrow near-threshold $X(4140)$ state. Possibly also a second peak at 4274 MeV.
• They did not investigate the high $J/\psi\phi$ mass region due to high backgrounds.
• In 2012 LHCb looked at 0.37 fb\(^{-1}\) of data with about double the number \(B \rightarrow J/\psi \phi K\) events compared to CDF
• Saw no evidence for a narrow \(X(4140)\) (2.4\(\sigma\) tension with CDF)
In 2013 CMS analyzed 5.2 fb$^{-1}$ of data and obtained, at the time, the largest B$\rightarrow$J/$\psi$φK sample analyzed but with high backgrounds.

- They confirmed X(4140) with somewhat larger width.
- They did not quote significance for the second state and saw it at higher mass.
- Once again the high J/$\psi$φ mass region was not analyzed.
Also in 2013 D0 looked at 10.4 fb\(^{-1}\) of data and saw 3.1\(\sigma\) evidence for \(X(4140)\) as well.

The 2\(^{nd}\) peak is not significant.
• Both Belle and Babar also looked at $B \rightarrow J/\psi \phi K$ in 2010 and 2014, respectively.
• Low backgrounds for $B$ mesons produced at $Y(4S)$ at the $e^+e^-$ colliders
• They studied entire $J/\psi \phi$ mass region but suffered from low statistics, especially at low masses due to poor threshold efficiency.
• Belle analyzed $325 \pm 21$ $B \rightarrow J/\psi \phi K$ events and found no evidence for $X(4140)$
• Babar, only having $215$ $B \rightarrow J/\psi \phi K$ events, found little evidence for either state ($<2\sigma$ significance)
• Neither in contradiction with the results from the hadron colliders
Limitations of the previous analyses

• Previous studies often lacked statistics, had high backgrounds, or lacked efficiency at low mass

• Disagreement between experiments.
  – 3.2σ disagreement between CMS/CDF on the location of the second state
  – LHCb in 2.4σ tension with CDF on the existence of a narrow X(4140)

• Utilized naïve one dimensional fits to J/ψφ mass
  – Did not take any information from angular distributions
  – Used ad-hoc functions to parameterize the background

• Need a proper amplitude analysis!
LHCb: this analysis

- Analysis performed on ~3 fb⁻¹ of data collected by LHCb in 2011 and 2012.
- φ candidates were selected in a ±15 MeV window around φ peak
  - non-φ KK backgrounds (red dashed line) is small in the φ window
- J/ψφK combinations were taken with only one φ candidate in K⁺K⁻K⁺
  - 4289±151 B→J/ψφK events and a background fraction of β=22.8±0.8%

- This amounts to the largest B→J/ψφK sample of any previously published analysis
- Has good efficiency in the entire J/ψφ mass region which allows for proper analysis of the entirety of phase-space
Amplitude Analysis

- **Difficult:**
  - Two spin-1 particles involved, both decaying:
    - \( J/\psi \rightarrow \mu^+\mu^−, \phi \rightarrow K^+K^− \)
  - Three different decay chains which can interfere:
    - \( B \rightarrow X K \text{ with } X \rightarrow J/\psi \phi \)
    - \( B \rightarrow J/\psi \ K^*, K^* \rightarrow \phi K \)
    - \( B \rightarrow Z \phi \text{ with } Z \rightarrow J/\psi K \)
  - Decay phase-space is 6-dimensional:
    - E.g. for \( K^* \) decay chain in helicity formulation:
      \[ M(\phi K), \cos(\theta_{K^*}), \cos(\theta_{J/\psi}), \cos(\theta_{\phi}), \Delta \phi_{K^*, J/\psi}, \Delta \phi_{K^*, \phi} \]
  - High \( K^* \) mass region; not very well understood experimentally:
    - Experimental evidence primarily from old scattering experiments. They lacked statistics especially at high masses. Some inconsistencies.
    - Only a few confirmed states, not necessarily established to decay to \( \phi K \).
    - Some unconfirmed states.
    - Many more states expected in the quark model.
Status of the analysis

• Fitter code was developed with efficient use of multi-core computers to deal with a large number of free parameters and complicated matrix element structure.

• Fits performed on the full six dimensions of the decay kinematics with explicit parameterization of the background

• Extensive exploration of matrix element for K* and exotic contributions was performed with no a priori assumptions about presence of any specific resonances
  – Mass and width of every state always a free parameter
  – All helicity couplings for each state are allowed
  – Total of 98 free parameters in the default model
  – Explored number of states for each JP

• Good quality fits to the data in all dimensions have been achieved (see next few slides)

• The results are under internal review of the LHCb collaboration and details cannot be disclosed yet.
Mass Distributions

• K* contributions are broad and the lack of apparent structures can be misleading. Many K* contribution are present as revealed by the angular distributions which can separate components with different quantum numbers.

• Bumpy structure at all J/ψφ masses. First meaningful exploration of the high mass region. Cannot discuss yet whether these structures are reflections or exotic contributions.
Very good agreement between the total fit and the data in every decay angle.
Again, very good agreement between the total fit and the data in every decay angle.
Last but not least, the angles in the Z decay chain show very good agreement between the total fit and the data in every decay angle.
Conclusion

• With the full 3 fb$^{-1}$ of data collected in 2011 and 2012 at LHCb we have the largest sample of $B \rightarrow J/\psi \phi K$ events analyzed so far. Good efficiency and manageable backgrounds at all $J/\psi \phi$ masses.

• Given the width of expected $K^*$ contributions, a lack of strong features in $\phi K$ does not mean that such resonances don’t dominate the decays.

• Full angular analysis must accompany mass fits to identify contributing $K^*$ resonances and properly estimate reflections of such structures onto $J/\psi \phi$ mass distribution, which has a lot of visible structures.

• A successful amplitude model which describes the data in all dimensions has been found. Cannot discuss its details yet since still under the collaboration review.