\( \bar{B}^0, B^- \) and \( \bar{B}_s^0 \) Decays into \( J/\psi \) and \( K\bar{K} \) or \( \pi \eta \)

Wei-Hong Liang

Guangxi Normal University, Guilin, China

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Outline

• Introduction and motivation
• Formalism
• Results and discussions
• Summary
• The nature of the light scalar mesons is a topic of long-standing debate.

In the Quark Model: meson $\rightarrow q\bar{q}$

Comparing with the Quark Model’s predictions, there exist much more light scalar mesons.

Scalar mesons below 1 GeV:

$f_0(500)$ (or $\sigma$), $f_0(980)$, $a_0(980)$, $\kappa(800)$

Possible structure:

normal meson $(q\bar{q})$, tetraquark $[(q)^2(\bar{q})^2]$, molecular state$[(q\bar{q})(q\bar{q})]$, glueball $(gg, ggg)$, hybrid $(q\bar{q}g)$, ......
Introduction and motivation

• In the Chiral Unitary Approach:

\( f_0(500), f_0(980), a_0(980) \) and \( \kappa \) are dynamically generated from the interaction of pseudoscalar mesons, and could be interpreted as a kind of molecular states of meson-meson.

\[ f_0(500) \text{ couples mostly to } \pi\pi; \quad f_0(980) \text{ couples mostly to } K\bar{K}; \]
\[ \text{and } a_0(980) \text{ mostly to } \pi\eta \text{ and } K\bar{K}. \]

\[
\begin{align*}
 f_0(500) & \quad \rightarrow \quad \pi\pi \text{ resonance} & f_0(980) & \quad \rightarrow \quad K\bar{K} \text{ molecule} \\
a_0(980) & \quad \rightarrow \quad \pi\eta + K\bar{K} \text{ molecule}
\end{align*}
\]

Introduction and motivation

- The weak decay of $B$ mesons is a good place for testing the structure of the light scalar mesons.

Experimental results:

$\bar{B}_s^0 \rightarrow J/\psi \pi^+\pi^- \text{decay}:$ A clear peak is observed for $f_0(980)$ production; $f_0(500)$ production is not seen;

$\bar{B}^0 \rightarrow J/\psi \pi^+\pi^- \text{decay}:$ A signal is seen for $f_0(500)$ production; Only a very small fraction is observed for $f_0(980)$ production.


Belle, PRL106(2011)121802; CDF, PRD84(2011)052012;

D0, PRD85(2012)011103.
Introduction and motivation

Theoretical results (in the frame of Chiral Unitary Approach):


\[ \bar{B}_s^0 \rightarrow J/\psi \pi^+ \pi^- \]

Data from [LHCb, PRD89(2014)092006]

\[ \pi^+ \pi^- \] invariant mass distribution, with arbitrary normalization.

Good agreement with Exp., supporting that the low lying scalar mesons are generated dynamically from the PS-PS interaction.
Introduction and motivation

To make further test of the molecular nature of the light scalar mesons, in this work: we investigate the production of the light scalar mesons in

\[
\begin{align*}
\bar{B}^0(\bar{B}_s^0) & \rightarrow J/\psi K^+ K^-, \\
B^- & \rightarrow J/\psi K^0 K^-, \\
\bar{B}^0 & \rightarrow J/\psi \pi^0\eta, \\
B^- & \rightarrow J/\psi \pi^-\eta.
\end{align*}
\]

Considering the final state interactions between the light pseudoscalar meson pairs in chiral unitary approach, \( f_0(500), f_0(980) \) and \( a_0(980) \) can be produced dynamically.

\( K^+ K^-, K^0 K^-, \pi^0\eta, \pi^-\eta \) invariant mass distributions are predicted with no free parameters.

The comparison of the results with experimental measurements will be valuable to make progress in our understanding of the meson-meson interaction and the nature of \( f_0(500), f_0(980) \) and \( a_0(980) \).
Formalism

- Diagrams for the decay of $\bar{B}^0$ and $\bar{B}_s^0$ into $J/\psi$ and a primary $q\bar{q}$ pair: $d\bar{d}$ for $\bar{B}^0$ and $s\bar{s}$ for $\bar{B}_s^0$

$d\bar{d}$ and $s\bar{s}$ act as spectators.

$V_{cd}, V_{cs}$ are the matrix elements of the CKM matrix, related to the Cabbibo angle:

$$V_{cd} = -\sin \theta_c = -0.22534, \quad V_{cs} = \cos \theta_c = 0.97427.$$
**Formalism** \[ \overline{B}^0 (\overline{B}_s^0) \rightarrow J / \psi K^+ K^-, \ \overline{B}^0 \rightarrow J / \psi \pi^0 \eta. \]

- \( \overline{B}^0 (\overline{B}_s^0) \rightarrow J / \psi M_1 M_2 \) a pair of PS mesons

The \( q\bar{q} \) pair is allowed to hadronize into two PS mesons.

\[ q\bar{q}(\bar{u}u + \bar{d}d + \bar{s}s) \rightarrow \text{final state} \begin{cases} K^+ K^- \\ \pi^0 \eta \end{cases} \]

**an extra \( q\bar{q} \) pair with the quantum numbers of the vacuum**
Formalism

The $q\bar{q}$ matrix:

$$M = \begin{pmatrix}
    u\bar{u} & u\bar{d} & u\bar{s} \\
    d\bar{u} & d\bar{d} & d\bar{s} \\
    s\bar{u} & s\bar{d} & s\bar{s}
\end{pmatrix}$$

with the property $M \cdot M = M \times (\bar{u}u + \bar{d}d + \bar{s}s)$.

Write the matrix $M$ in terms of PS mesons:

$$\Phi = \begin{pmatrix}
    \frac{1}{\sqrt{2}} \pi^0 + \frac{1}{\sqrt{3}} \eta + \frac{1}{\sqrt{6}} \eta' \\
    \pi^- \\
    K^-
\end{pmatrix} \begin{pmatrix}
    \pi^+ \\
    -\frac{1}{\sqrt{2}} \pi^0 + \frac{1}{\sqrt{3}} \eta + \frac{1}{\sqrt{6}} \eta' \\
    \bar{K}^0
\end{pmatrix}
\begin{pmatrix}
    K^+ \\
    K^0 \\
    -\frac{1}{\sqrt{3}} \eta + \sqrt{\frac{2}{3}} \eta'
\end{pmatrix}$$
Formalism

The hadronization leads us to

\[ d\bar{d}(\bar{u}u + \bar{d}d + \bar{s}s) \equiv (\phi \cdot \phi)_{22} = \pi^-\pi^+ + \frac{1}{2}\pi^0\pi^0 + \frac{1}{3}\eta\eta - \frac{2}{\sqrt{6}}\pi^0\eta + \bar{K}^0K^0, \]

\[ s\bar{s}(\bar{u}u + \bar{d}d + \bar{s}s) \equiv (\phi \cdot \phi)_{33} = K^-K^+ + \bar{K}^0K^0 + \frac{1}{3}\eta\eta , \]

with the weight by which a pair of PS mesons is produced in the first step.

Let these PS mesons interact:

\( 
\begin{align*}
B^0 \rightarrow \pi^+, \pi^0, K^+K^- \\
B_s^0 \rightarrow K^+, K^- \\
\end{align*}
\)

\( 
\begin{align*}
B^0 \rightarrow \pi^+, \pi^0, K^+K^- \\
B_s^0 \rightarrow K^+, K^- \\
\end{align*}
\)

\( 
\begin{align*}
B^0 \rightarrow \pi^+, \pi^0, K^+K^- \\
B_s^0 \rightarrow K^+, K^- \\
\end{align*}
\)
The amplitudes for a final production of the different meson pairs are given by

\[ t(\bar{B}^0 \rightarrow J/\psi \pi^+ \pi^-) = V_P V_{cd} \left( \frac{1}{2} G_{\pi^+ \pi^-} t_{\pi^+ \pi^-} + \frac{1}{2} G_{\pi^0 \pi^0} t_{\pi^0 \pi^0} \right) \]

\[ t(\bar{B}^0 \rightarrow J/\psi \pi^0 \eta) = V_P V_{cd} \left( \frac{2}{\sqrt{6}} G_{\pi^0 \eta} t_{\pi^0 \eta} + G_{K^0 \bar{K}^0} t_{K^0 \bar{K}^0} \right) \]

\[ t(\bar{B}^0_s \rightarrow J/\psi K^+ K^-) = V_P V_{cs} \left( 1 + G_{K^+ K^-} t_{K^+ K^-} + G_{K^0 \bar{K}^0} t_{K^0 \bar{K}^0} \right) \]

\[ V_P : \text{ a common factor to all } \bar{B}^0 (\bar{B}^0_s) \rightarrow J/\psi K\bar{K} (\pi \eta) \text{ decays;} \]
**Formalism**

$G_i :$  the loop function of two PS meson propagators.

$$G_i(s) = i \int \frac{d^4q}{(2\pi)^4} \frac{1}{(P - q)^2 - m_i^2 + i\varepsilon} \frac{1}{q^2 - m_2^2 + i\varepsilon}, \quad s = P^2$$

$t_{i \to j} :$  scattering matrix for $i \to j$, calculated in the chiral unitary approach, following the Bethe-Salpeter Equation in coupled channels:

$$t = V + V G t, \quad \text{or} \quad t = [1 - V G]^{-1} V,$$


**Invariant mass distribution:**

$$\frac{d\Gamma}{dM_{\text{inv}}} = \frac{1}{(2\pi)^3} \frac{1}{4M_j^2} \frac{1}{3} p_{J/\psi}^2 p_{J/\psi} \tilde{p}_\pi \sum \sum |\tilde{t}(\bar{B}_j^0 \to J/\psi \pi^+ \pi^-)|^2$$

**Similar formulas for** $B^- \to J/\psi K^0 K^-$, $B^- \to J/\psi \pi^- \eta$ **decays.**
\[ \bar{B}_s^0 \rightarrow J/\psi \pi^+\pi^-, J/\psi K^+K^- \]

In this case, we started from an \( s\bar{s} \) quark state, with \( I = 0 \).

- \( K^+K^- \) distribution gets maximum strength close to the \( K^+K^- \)-threshold, due to the effect of \( f_0(980) \) below threshold.

- The strength is small compared to the one of \( f_0(980) \) at its peak.

\[ f_0(980) \]
Results and discussions

The ratios:

\[
\frac{\mathcal{B}[\bar{B}_s^0 \rightarrow J/\psi K^+ K^-]}{\mathcal{B}[\bar{B}_s^0 \rightarrow J/\psi f_0(980); f_0(980) \rightarrow \pi^+ \pi^-]} = 0.34 \pm 0.03,
\]

\[
\frac{\mathcal{B}[\bar{B}_s^0 \rightarrow J/\psi K^+ K^-](S\text{-wave})}{\mathcal{B}[\bar{B}_s^0 \rightarrow J/\psi \phi; \phi \rightarrow K^+ K^-]} = 0.017 \pm 0.003,
\]

[in agreement with experiment: \((1.1 \pm 0.1^{+0.2}_{-0.1}) \times 10^{-2}\)]

[ LHCb, PRD88(2013)072005;]
Results and discussions

\[ \bar{B}^0 \rightarrow J/\psi \pi^+ \pi^-, J/\psi K^+ K^-, J/\psi \pi^0 \eta \]

- The relative strengths of \( f_0(500) \), \( f_0(980) \) and \( a_0(980) \) productions are predicted with no free parameters.

- The strength of \( a_0(980) \) excitation is bigger than that for \( f_0(980) \).

- The \( K^+ K^- \) distribution is now both in \( I=0 \) and \( I=1 \), reflecting the effects of both \( f_0(980) \) and \( a_0(980) \).
Results and discussions

\[ B^- \rightarrow J/\psi \pi^- \eta, \ J/\psi K^0K^- \]

- The strength for the \( M_{\pi^-\eta} \) mass distribution in \( B^- \rightarrow J/\psi \pi^- \eta \) is twice as big as the one of \( B^0 \rightarrow J/\psi \pi^0 \eta \).

- The strength for the \( M_{K^0K^-} \) mass distribution at the peak is about 4 times bigger than the one for \( M_{K^+K^-} \) in the \( \overline{B}^0 \) decay.
Summary

- Using the chiral unitary approach, we studied the decay rates for $\bar{B}^0 (\bar{B}^0_s) \rightarrow J/\psi K^+ K^-$, $\bar{B}^0 \rightarrow J/\psi \pi^0 \eta$, $B^- \rightarrow J/\psi \pi^- \eta$, $B^- \rightarrow J/\psi K^0 K^-$, and compared them to the rates obtained for the $\bar{B}^0_s \rightarrow J/\psi \pi^+ \pi^-$ and $\bar{B}^0 \rightarrow J/\psi \pi^+ \pi^-$. 

- We could predict all these mass distributions with no free parameters. The predictions compare reasonably well with present experimental information.

- More precise data are coming from LHCb and other facilities. Comparison with these data will be useful to make progress in our understanding of the meson-meson interaction and the nature of the low-lying scalar mesons.
Thank you for your attention!