$\overline{B}^0, B^-$ and $\overline{B}_s^0$ Decays into J/ψ and $K\overline{K}$ or $\pi\eta$

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Based on: WHL, J.J. Xie, E. Oset, Eur. Phys. J. C 75(2015)609.

Outline

- Introduction and motivation
- Formalism
- Results and discussions
- Summary

◆ Introduction and motivation

- **The nature of the light scalar mesons is a topic of long-standing debate.**

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

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

Scalar mesons below 1 GeV:

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

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 κ are dynamically generated from the interaction of pseudoscalar mesons, and could be interpreted as a kind of molecular sates of meson-meson.

$f_0(500)$ couples mostly to $\pi\pi$; $f_0(980)$ couples mostly to $K\bar{K}$; and $a_0(980)$ mostly to $\pi\eta$ and $K\bar{K}$.

$f_0(500)$ ⟹ $\pi\pi$ resonance **$f_0(980)$ ⟹ $K\bar{K}$ molecule**

$a_0(980)$ ⟹ $\pi\eta + K\bar{K}$ molecule

[Oller and Oset, NPA620(1997)438]

◆ Introduction and motivation

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

Experimental results:

$\bar{B}_s^0 \to J/\psi\,\pi^+\pi^-$ **decay : A clear peak is observed for** $f_0(980)$ **production ;**

$f_0(500)$ **production is not seen;**

$\bar{B}^0 \to J/\psi\,\pi^+\pi^-$ **decay : A signal is seen for** $f_0(500)$ **production ;**

Only a very small fraction is observed for $f_0(980)$ **production .**

LHCb: PLB698(2011)115; PRD86(2012)052006; PRD87(2013)052001; PRD89(2014)092006; PRD90(2014)012003;

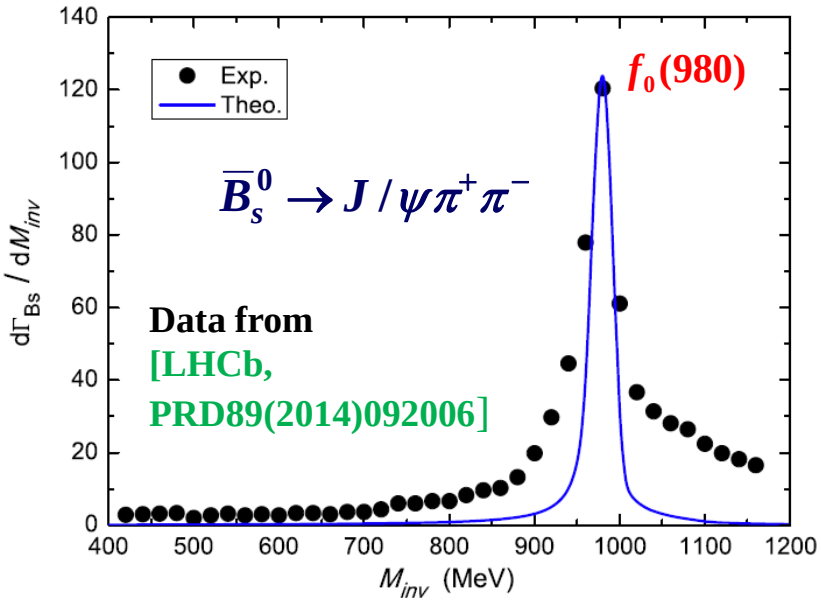
Belle, PRL106(2011)121802; **CDF,** PRD84(2011)052012;

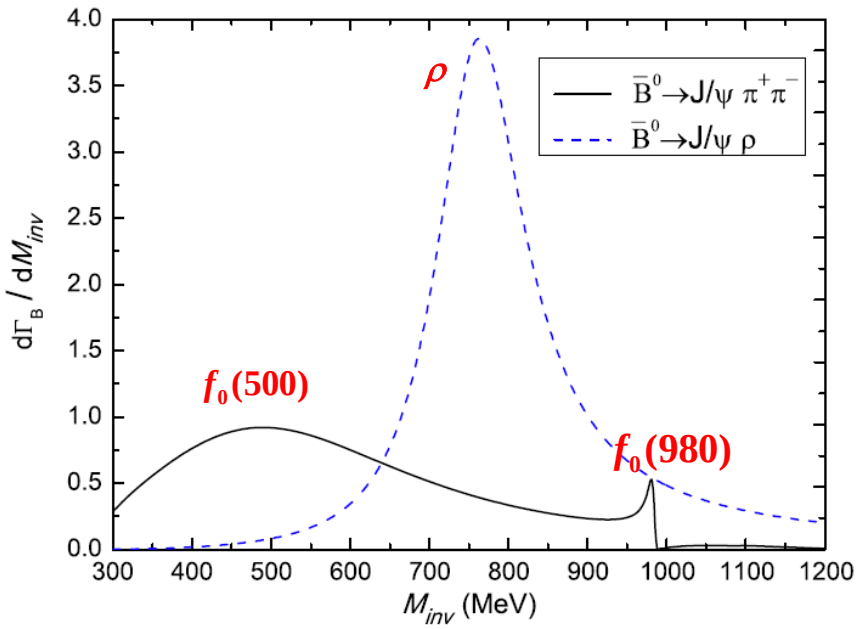
D0, PRD85(2012)011103.

◆ Introduction and motivation

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

WHL, E. Oset, Phys. Lett. B 737 (2014) 70;
M. Bayar, WHL, E. Oset, Phys. Rev. D 90 (2014) 114004;





$\pi^+\pi^-$ 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

$$\bar{B}^0(\bar{B}_s^0) \to J/\psi\, K^+K^-, \quad B^- \to J/\psi\, K^0K^-,$$

$$\bar{B}^0 \to J/\psi\, \pi^0\eta, \quad B^- \to J/\psi\, \pi^-\eta.$$

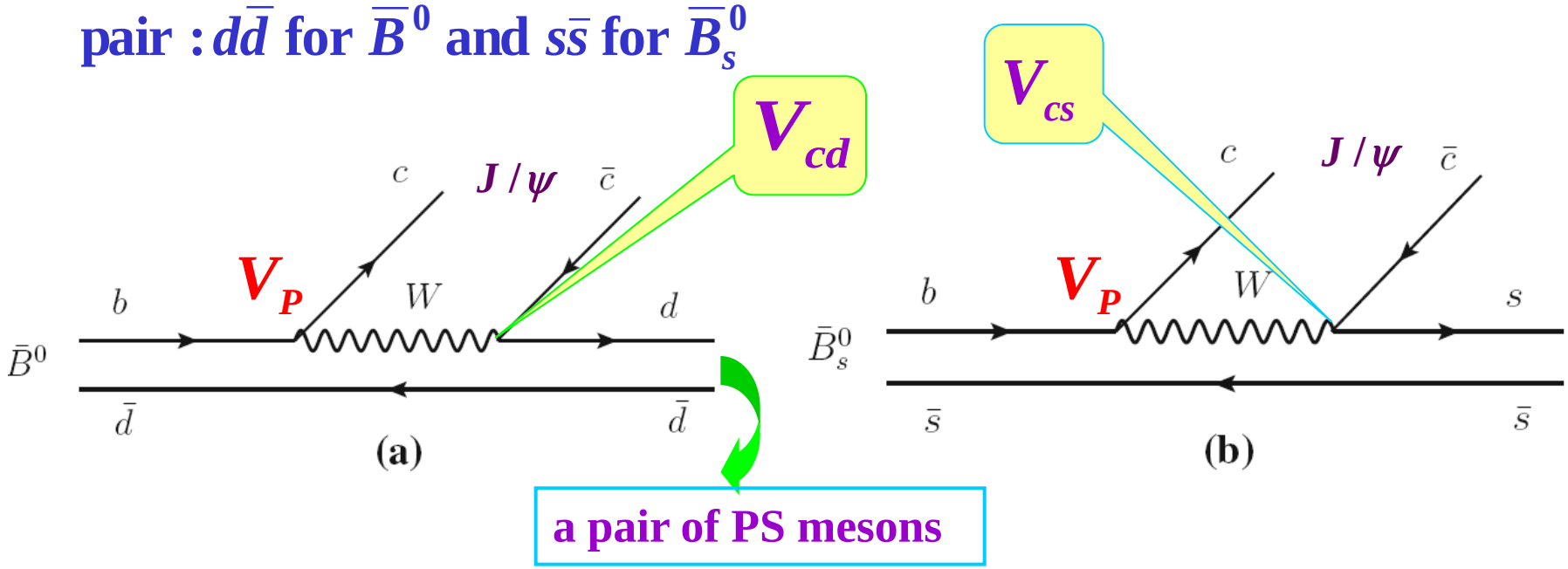
Considering the final state interactions between the light pseudoscalar meson pairs in chiral unitary approach, $f_0(500)$, $f_0(980)$ and $a_0(980)$ can be produced dynamically.

K^+K^-, K^0K^-, $\pi^0\eta$, $\pi^-\eta$ 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/ψ and a primary $q\bar{q}$ pair : $d\bar{d}$ for $\bar{B}^0$ and $s\bar{s}$ for $\bar{B}_s^0$**



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

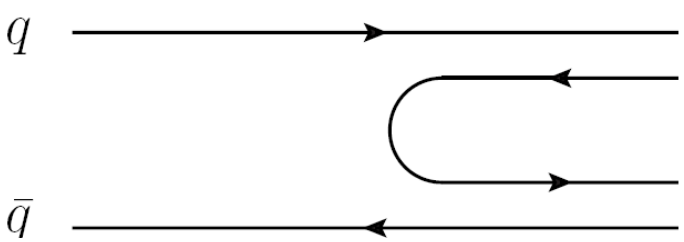
V_{cd}, V_{cs} are the matrix elements of the CKM matrix, related to the Cabbibo angle:

$$V_{cd} = -\sin\theta_c = -0.22534, \quad V_{cs} = \cos\theta_c = 0.97427.$$

◆ Formalism $[\bar{B}^0(\bar{B}_s^0) \to J/\psi\, K^+K^-,\ \bar{B}^0 \to J/\psi\, \pi^0\eta.]$

- $\bar{B}^0(\bar{B}_s^0) \to J/\psi\, M_1 M_2$ a pair of PS mesons

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



$q\bar{q}(\bar{u}u + \bar{d}d + \bar{s}s)$ ⇒ final state $\begin{cases} K^+K^- \\ \pi^0\eta \end{cases}$

an extra $\bar{q}q$ 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 :

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

◆ Formalism $[\bar{B}^0(\bar{B}_s^0) \to J/\psi K^+K^-,\ \bar{B}^0 \to J/\psi \pi^0\eta.]$

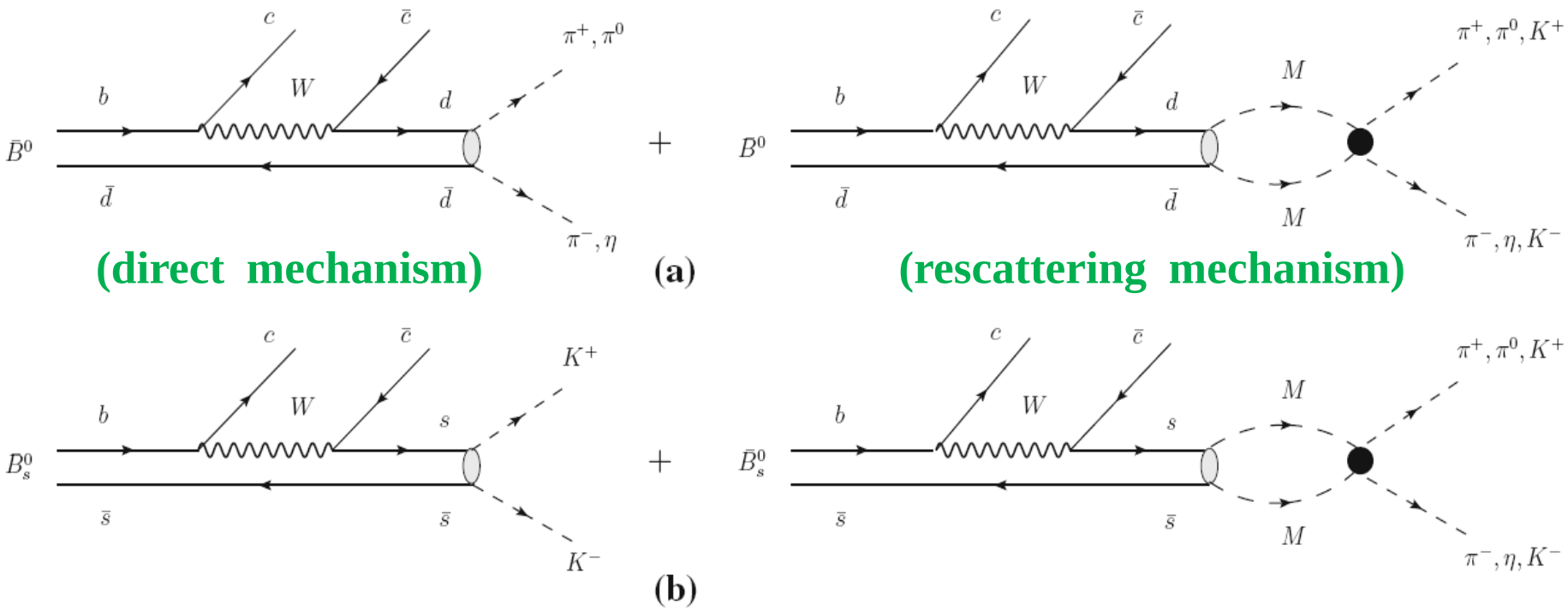
The hadronization leads us to

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

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

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

Let these PS mesons interact:



◆ Formalism $[\bar{B}^0(\bar{B}_s^0) \to J/\psi K^+K^-,\ \bar{B}^0 \to J/\psi \pi^0\eta.]$

The amplitudes for a final production of the different meson pairs are given by

$$t(\bar{B}^0 \to J/\psi\pi^+\pi^-) = V_P V_{cd}\Big(1G_{\pi^+\pi^-}t_{\pi^+\pi^-\to\pi^+\pi^-} + 2\frac{1}{2}\frac{1}{2}G_{\pi^0\pi^0}t_{\pi^0\pi^0\to\pi^+\pi^-} + G_{K^0\bar{K}^0}t_{K^0\bar{K}^0\to\pi^+\pi^-} + 2\frac{1}{3}\frac{1}{2}G_{\eta\eta}t_{\eta\eta\to\pi^+\pi^-}\Big)$$

$$t(\bar{B}^0 \to J/\psi\pi^0\eta) = V_P V_{cd}\Big(-\frac{2}{\sqrt{6}} - \frac{2}{\sqrt{6}}G_{\pi^0\eta}t_{\pi^0\eta\to\pi^0\eta} + G_{K^0\bar{K}^0}t_{K^0\bar{K}^0\to\pi^0\eta}\Big),$$

⋮

$$t(\bar{B}_s^0 \to J/\psi K^+K^-) = V_P V_{cs}\Big(1 + G_{K^+K^-}t_{K^+K^-\to K^+K^-} + G_{K^0\bar{K}^0}t_{K^0\bar{K}^0\to K^+K^-} + 2\frac{1}{3}\frac{1}{2}G_{\eta\eta}t_{\eta\eta\to K^+K^-}\Big),$$

V_P : a common factor to all $\bar{B}^0(\bar{B}_s^0) \to J/\psi K\bar{K}(\pi\eta)$ decays;

◆ Formalism

G_i : the loop function of two PS meson propagators.

$$G_i(s) = i\int \frac{d^4q}{(2\pi)^4}\frac{1}{(P-q)^2-m_1^2+i\varepsilon}\frac{1}{q^2-m_2^2+i\varepsilon}, \qquad s = P^2$$

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

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

[Oller and Oset, NPA620(1997)438] [F.K. Guo et al., NPA773(2006)78]

Invariant mass distribution:

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

Similar formulas for $B^- \to J/\psi K^0 K^-$, $B^- \to J/\psi \pi^- \eta$ decays.

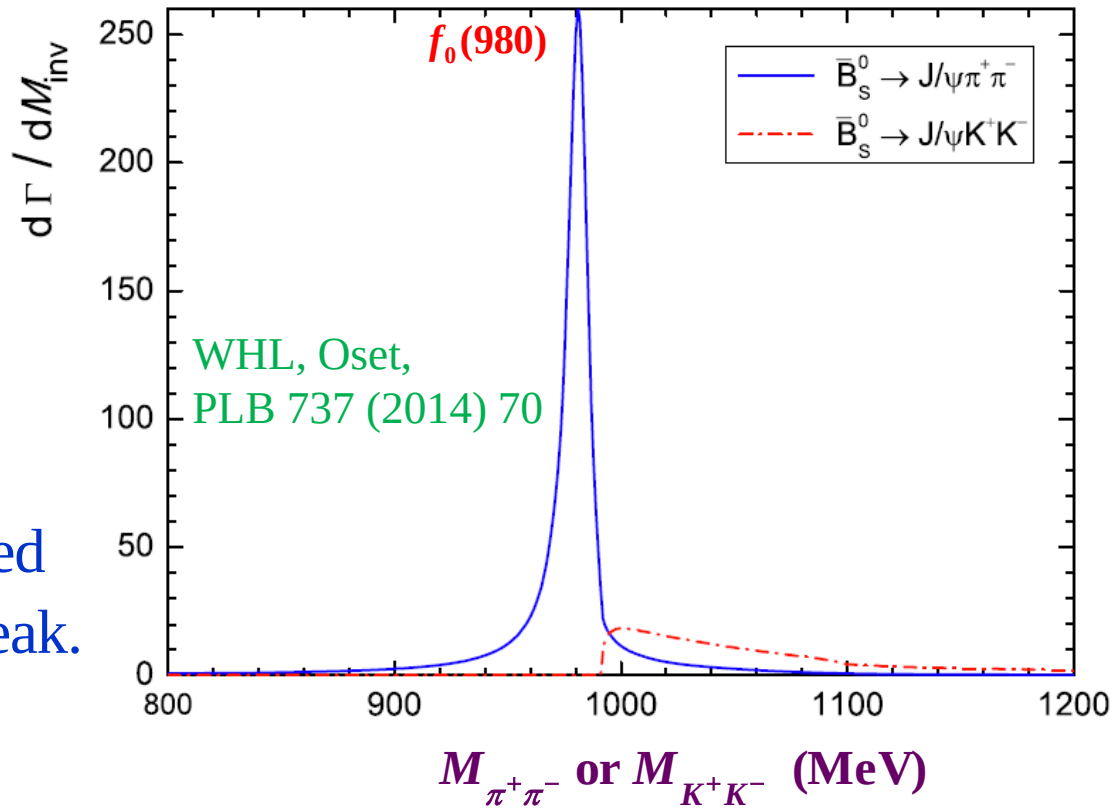
◆ Results and discussions

$\bar{B}_s^0 \to J/\psi\,\pi^+\pi^-,\ J/\psi\,K^+K^-$

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.



◆ Results and discussions

The ratios:

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

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

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

[LHCb, PRD88(2013)072005;]

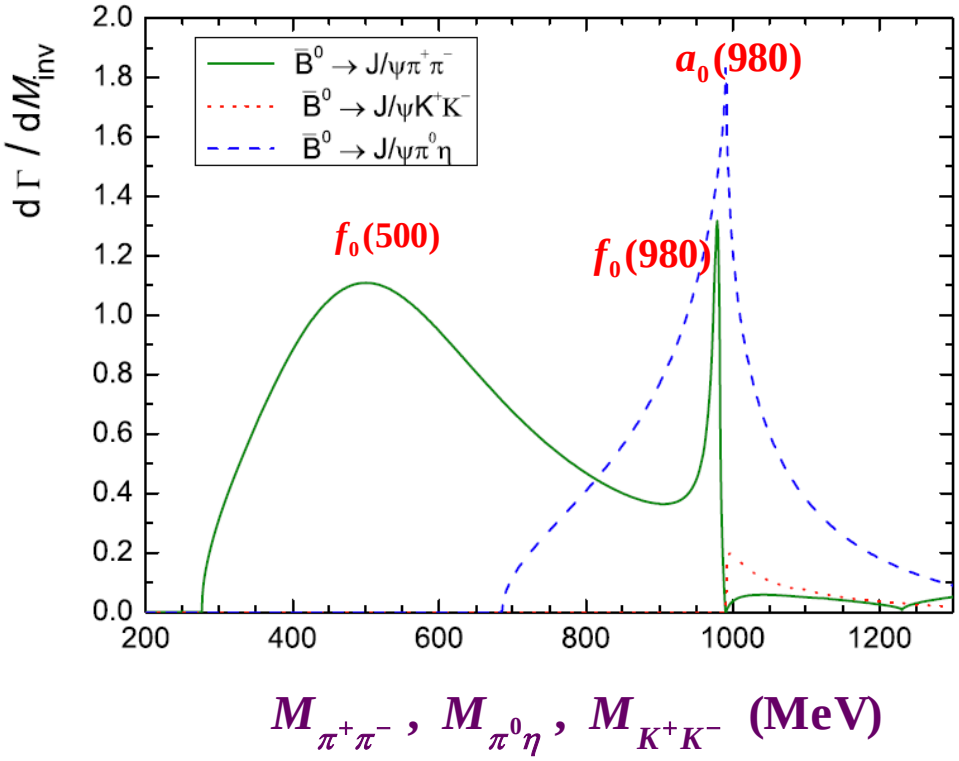
◆ Results and discussions

$\bar{B}^0 \to J/\psi\,\pi^+\pi^-,\ J/\psi\,K^+K^-,\ J/\psi\,\pi^0\eta$

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

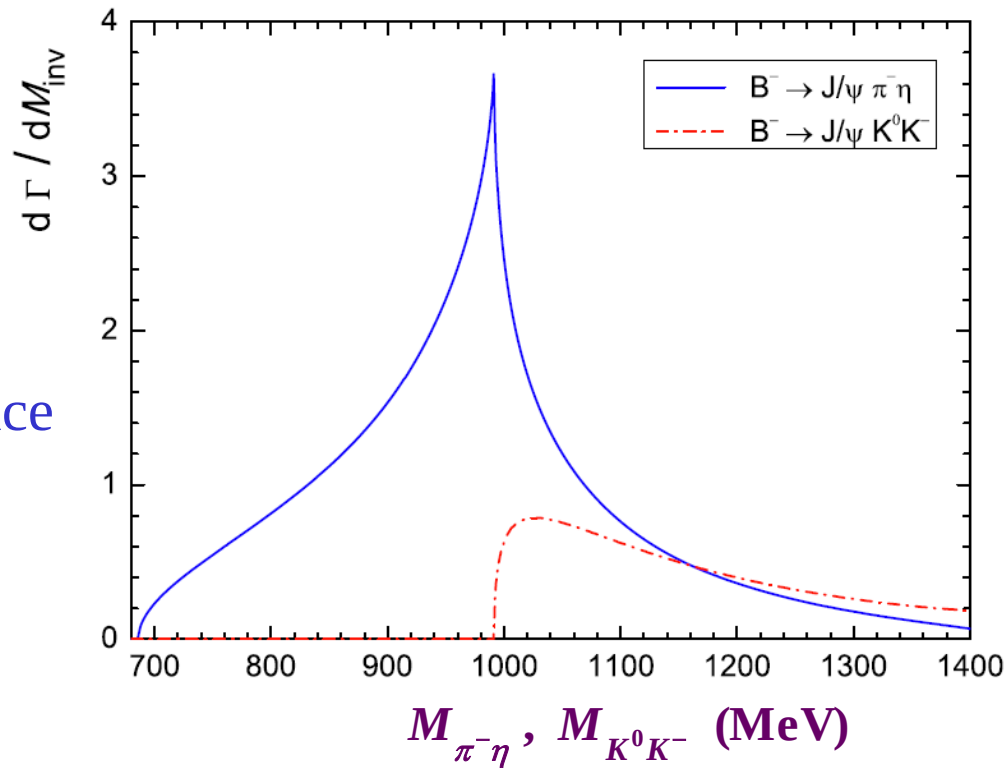
- The strength of $a_0(980)$ excitation is bigger than that for $f_0(980)$.

- 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

$B^- \to J/\psi\, \pi^- \eta,\ \ J/\psi\, K^0 K^-$



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

- 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 $\bar{B}^0(\bar{B}_s^0) \to J/\psi\, K^+K^-$, $\bar{B}^0 \to J/\psi\, \pi^0\eta$, $B^- \to J/\psi\, \pi^-\eta$, $B^- \to J/\psi K^0 K^-$, and compared them to the rates obtained for the $\bar{B}_s^0 \to J/\psi\, \pi^+\pi^-$ and $\bar{B}^0 \to J/\psi\, \pi^+\pi^-$.

- 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!