$B^0(B_s^0)$ decays into $J/\psi\ f_0(980)$, $J/\psi\ f_0(500)$ and the nature of the light scalar resonances

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CONTENTS

Introduction and motivation

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

Quantum numbers of the scalar mesons: $J^{PC} = 0^{++}$

Comparing with the Quark Model's predictions, there exist too many light scalar mesons.

Scalar mesons below 1 GeV:

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

Possible structures:

normal meson $(q\bar{q})$, tetraquark $[(q)^2(\bar{q})^2]$, molecule $[(q\bar{q})(q\bar{q})]$,
glueball (gg, ggg), hybrid $(q\bar{q}g)$, ...

- $B^0(B_s^0) \to J/\psi\ f_0(980)$[or $f_0(500)$] is a good place for studying the nature of the light scalar mesons

Experimental results:

$B_s^0 \to J/\psi\ \pi^+\pi^-$ decay : A clear peak is observed for $f_0(980)$ production ;

$f_0(500)$ production is not observed;

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

Only a very small fraction is observed for $f_0(500)$ 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.

Chiral Unitary Theory:

$f_0(500)$ and $f_0(980)$ resonance are dynamically generated from the interaction ofpseudoscalar mesons

and could be interpreted as a kind of molecular states of meson - meson.

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

$f_0(500)$ ⟹ $\pi\pi$ molecute $f_0(980)$ ⟹ $K\bar{K}$ molecute

$$\bar{B}^0(\bar{B}_s^0) \to J/\psi f_0,\ \ f_0 \to \pi^+\pi^-.$$

Considering the interactions between the meson pairs in chiral unitary theory,

$f_0(500)$ and $f_0(980)$ can be produced dynamically.

↑

$\pi^+\pi^-$ invariant mass distribution for $\bar{B}^0(\bar{B}_s^0) \to J/\psi\pi^+\pi^-$.

Formalism

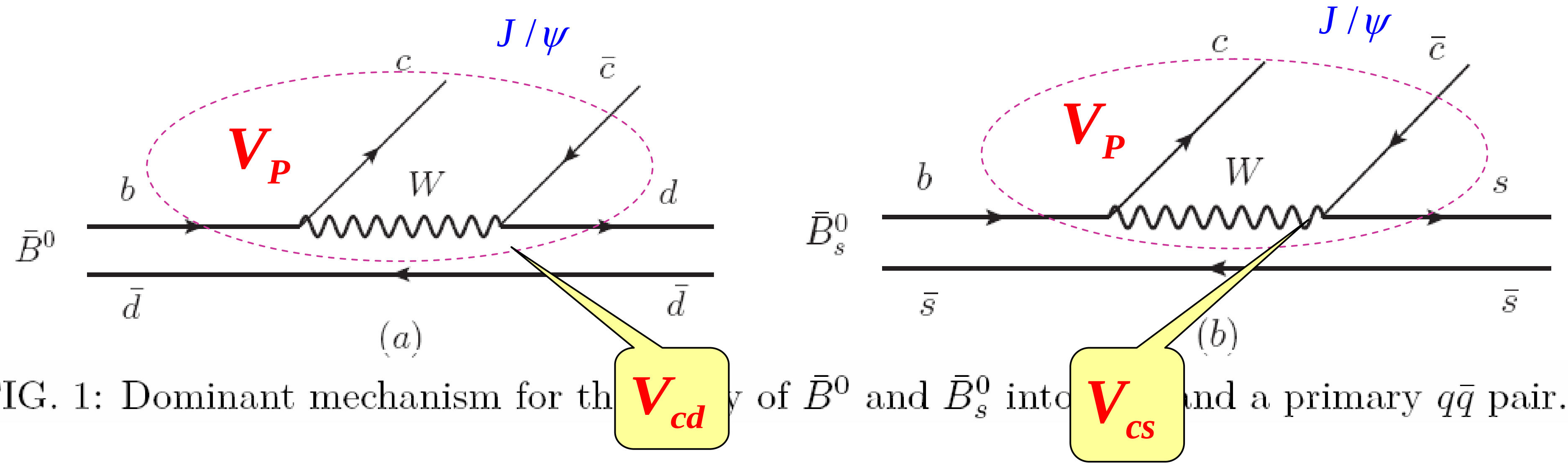
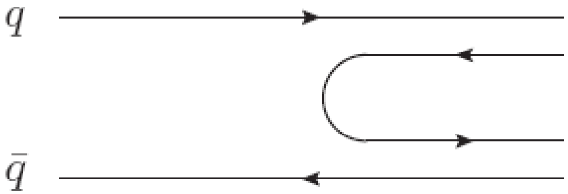


FIG. 1: Dominant mechanism for th y of $\bar{B}^0$ and $\bar{B}^0_s$ into nd a primary $q\bar{q}$ pair.

V_{cd}, V_{cs} are the matrix elements of the Cabbibo-Kobayashi-Maskawa (CKM) matrix, related to the Cabbio angle:

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

The $q\bar{q}$ pair is allowed to hadronize into a pair of pseudoscalar mesons.



$q\bar{q}(\bar{u}u + \bar{d}d + \bar{s}s)$ ⟹ $\pi^+\pi^-$ in the final state

The $q\bar{q}$ matrix :

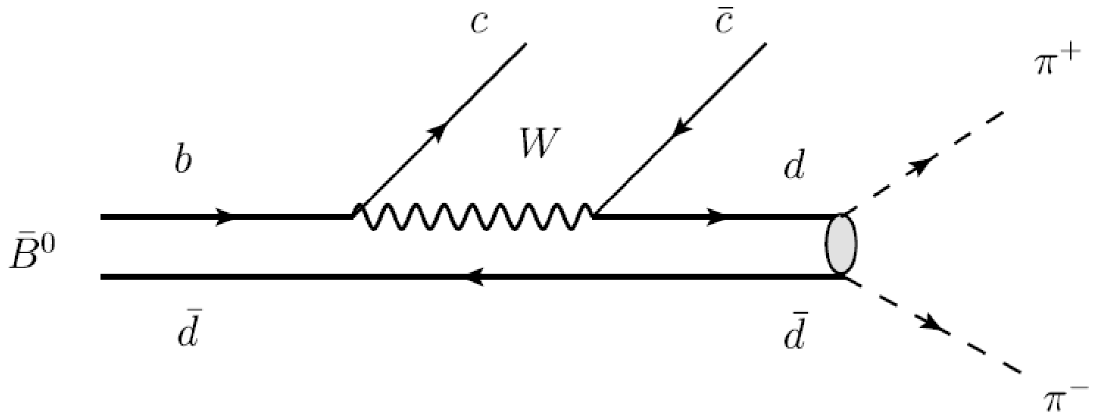
$$M = \begin{pmatrix} u\bar{u} & u\bar{d} & u\bar{s} \\ d\bar{u} & d\bar{d} & d\bar{s} \\ s\bar{u} & s\bar{d} & s\bar{s} \end{pmatrix}$$

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

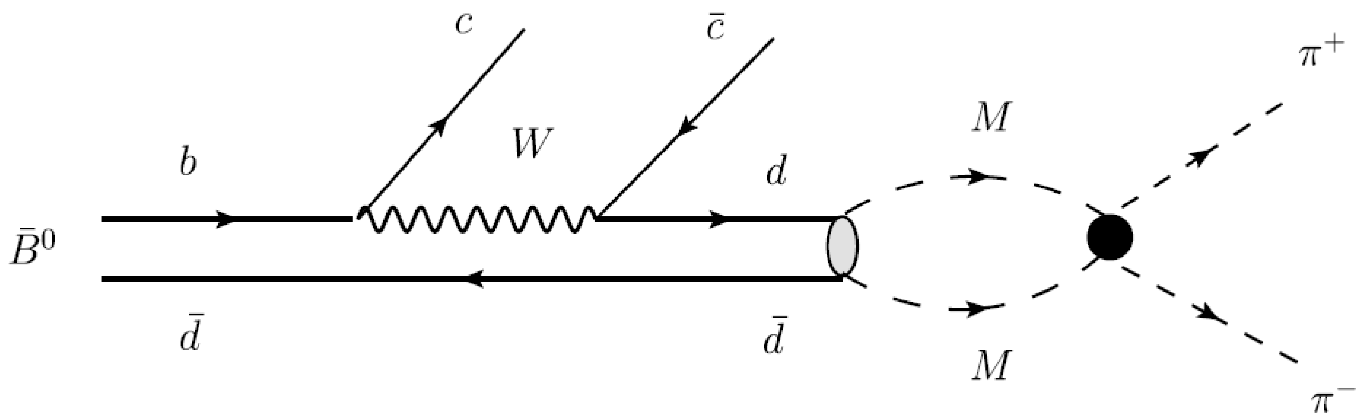
$$\phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

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

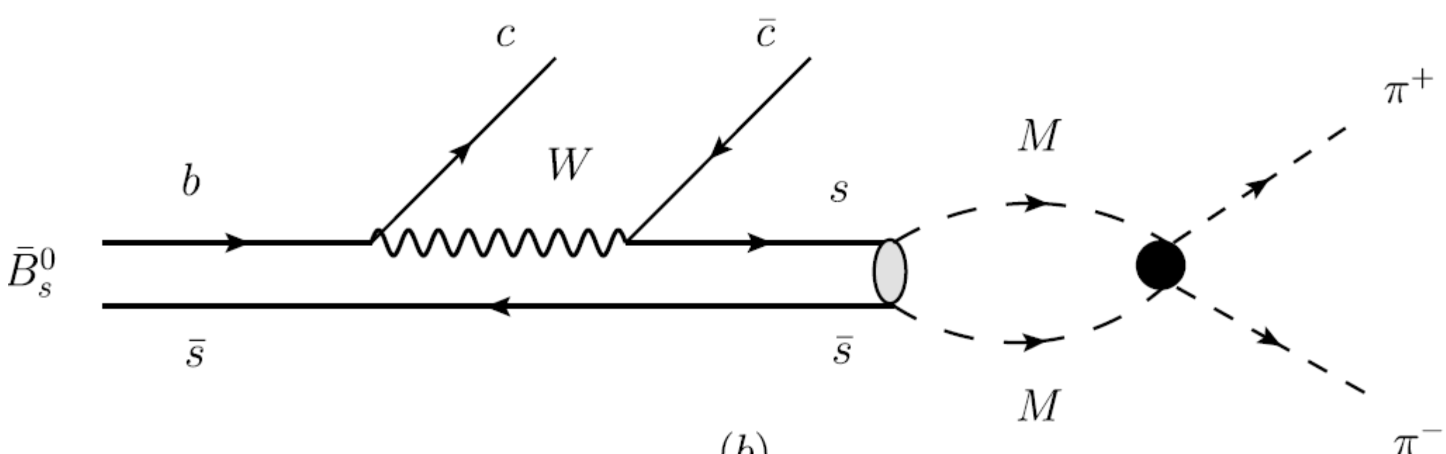
$$s\bar{s}(u\bar{u} + d\bar{d} + s\bar{s}) \equiv (\phi \cdot \phi)_{33} = K^-K^+ + K^0\bar{K}^0 + \frac{4}{6}\eta\eta.$$



c
$\bar{c}$
π^+
W
b
d
$\bar{B}^0$
$\bar{d}$
$\bar{d}$
π^-



c
$\bar{c}$
π^+
M
W
b
d
$\bar{B}^0$
$\bar{d}$
$\bar{d}$
M
π^-



c
$\bar{c}$
π^+
M
W
b
s
$\bar{B}_s^0$
$\bar{s}$
$\bar{s}$
M
π^-

(b)

The amplitudes for $\pi^+\pi^-$ production are given by

$$t(\bar{B}^0 \to J/\psi \pi^+\pi^-)$$
$$= V_P V_{cd}\left(1 + G_{\pi^+\pi^-} t_{\pi^+\pi^- \to \pi^+\pi^-} + \frac{1}{2}\frac{1}{2} G_{\pi^0\pi^0} t_{\pi^0\pi^0 \to \pi^+\pi^-}\right.$$
$$\left. + G_{K^0\bar{K}^0} t_{K^0\bar{K}^0 \to \pi^+\pi^-} + \frac{1}{6}\frac{1}{2} G_{\eta\eta} t_{\eta\eta \to \pi^+\pi^-}\right),$$

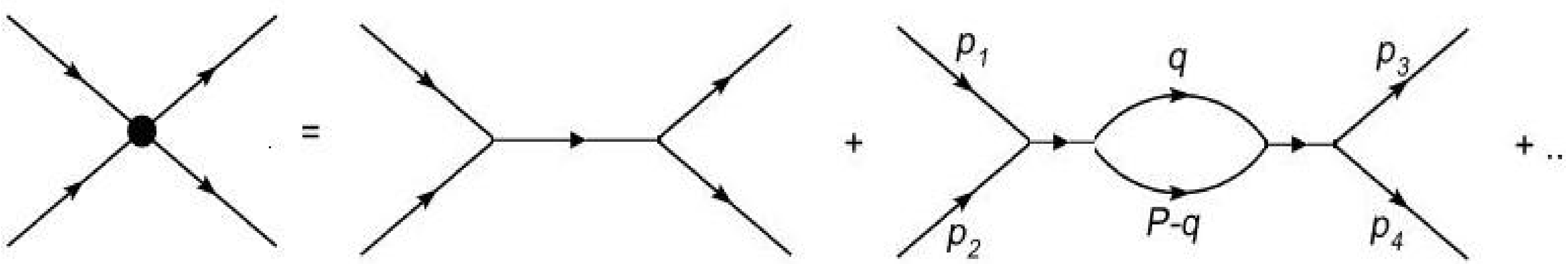
$$t(\bar{B}_s^0 \to J/\psi \pi^+\pi^-)$$
$$= V_P V_{cs}\left(G_{K^+K^-} t_{K^+K^- \to \pi^+\pi^-}\right.$$
$$\left. + G_{K^0\bar{K}^0} t_{K^0\bar{K}^0 \to \pi^+\pi^-} + \frac{4}{6}\frac{1}{2} G_{\eta\eta} t_{\eta\eta \to \pi^+\pi^-}\right),$$

G_i are the loop functions of two meson propagators

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

The elements t_{ij} are the scattering matrices for transitions of channel i to j,

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



There are 5 coupled channels:

$$\pi^+\pi^-(1),\ \pi^0\pi^0(2),\ K^+K^-(3),\ K^0\bar{K}^0(4),\ \eta\eta(5)$$

$$V_{11} = -\frac{1}{2f^2}s, \qquad V_{12} = -\frac{1}{\sqrt{2}f^2}\left(s - m_\pi^2\right), \quad V_{13} = -\frac{1}{4f^2}s,$$

$$V_{14} = -\frac{1}{4f^2}s, \qquad V_{15} = -\frac{1}{3\sqrt{2}f^2}m_\pi^2, \quad V_{22} = -\frac{1}{2f^2}m_\pi^2,$$

$$V_{23} = -\frac{1}{4\sqrt{2}f^2}s, \qquad V_{24} = -\frac{1}{4\sqrt{2}f^2}s, \quad V_{25} = -\frac{1}{6f^2}m_\pi^2,$$

$$V_{33} = -\frac{1}{2f^2}s, \qquad V_{34} = -\frac{1}{4f^2}s,$$

$\pi^+\pi^-$ invariant mass (M_{inv}) distribution :

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

$$p_{J/\psi} = \frac{\lambda^{1/2}(M_{\bar{B}}^2, M_{J/\psi}^2, M_{inv}^2)}{2M_{\bar{B}}},$$

$$\tilde{p}_\pi = \frac{\lambda^{1/2}(M_{inv}^2, m_\pi^2, m_\pi^2)}{2M_{inv}}.$$

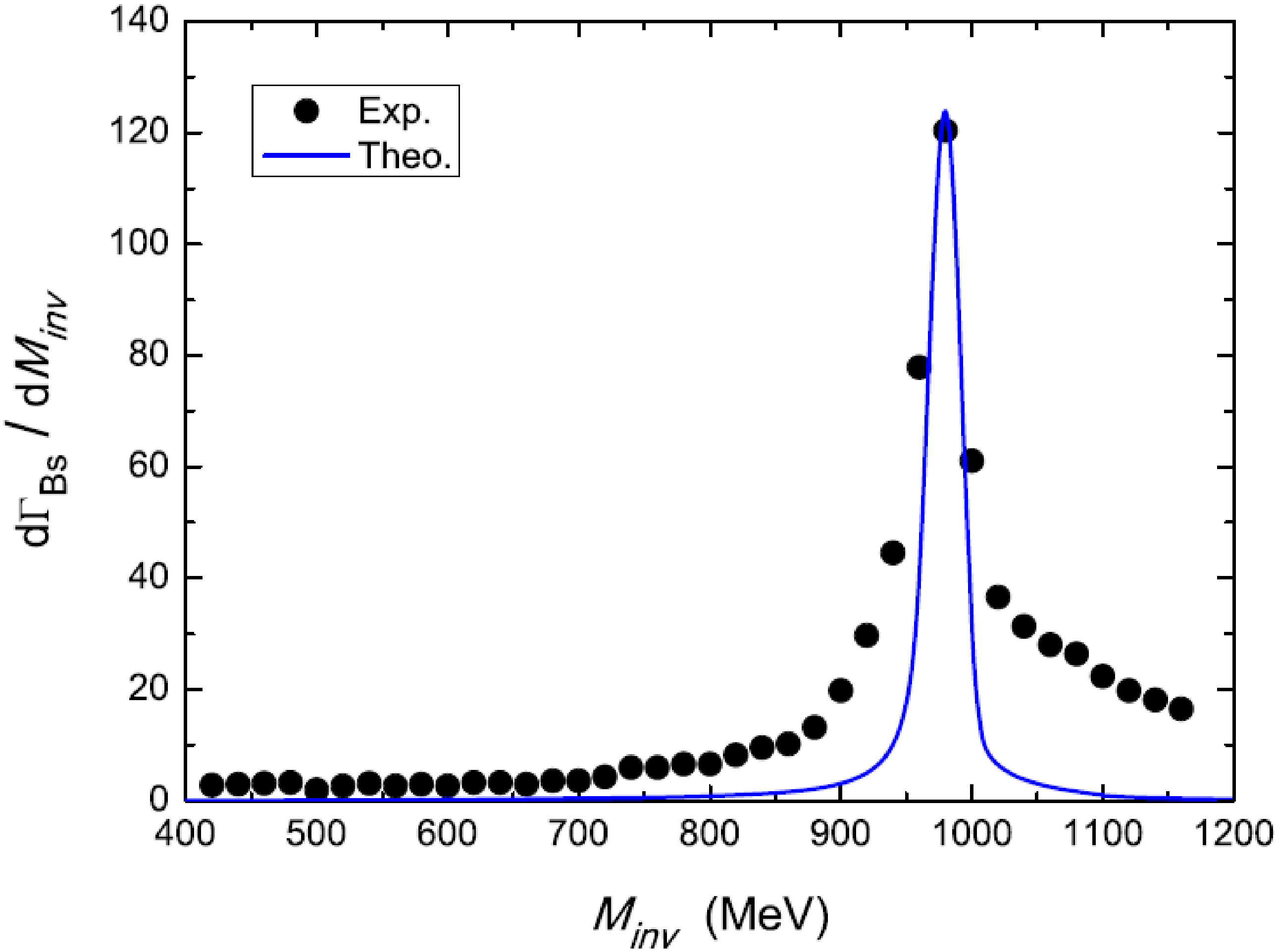


Fig. 4. $\pi^+\pi^-$ invariant mass distribution for the $\bar{B}_s^0 \to J/\psi\pi^+\pi^-$ decay, with arbitrary normalization. Data from [8]. **[LHCb, 2014]**

A clear signal for $f_0(980)$, no appreciable signal for $f_0(500)$

Clean case: $s\bar{s}$ with $I = 0$, there is no ρ^0 production.

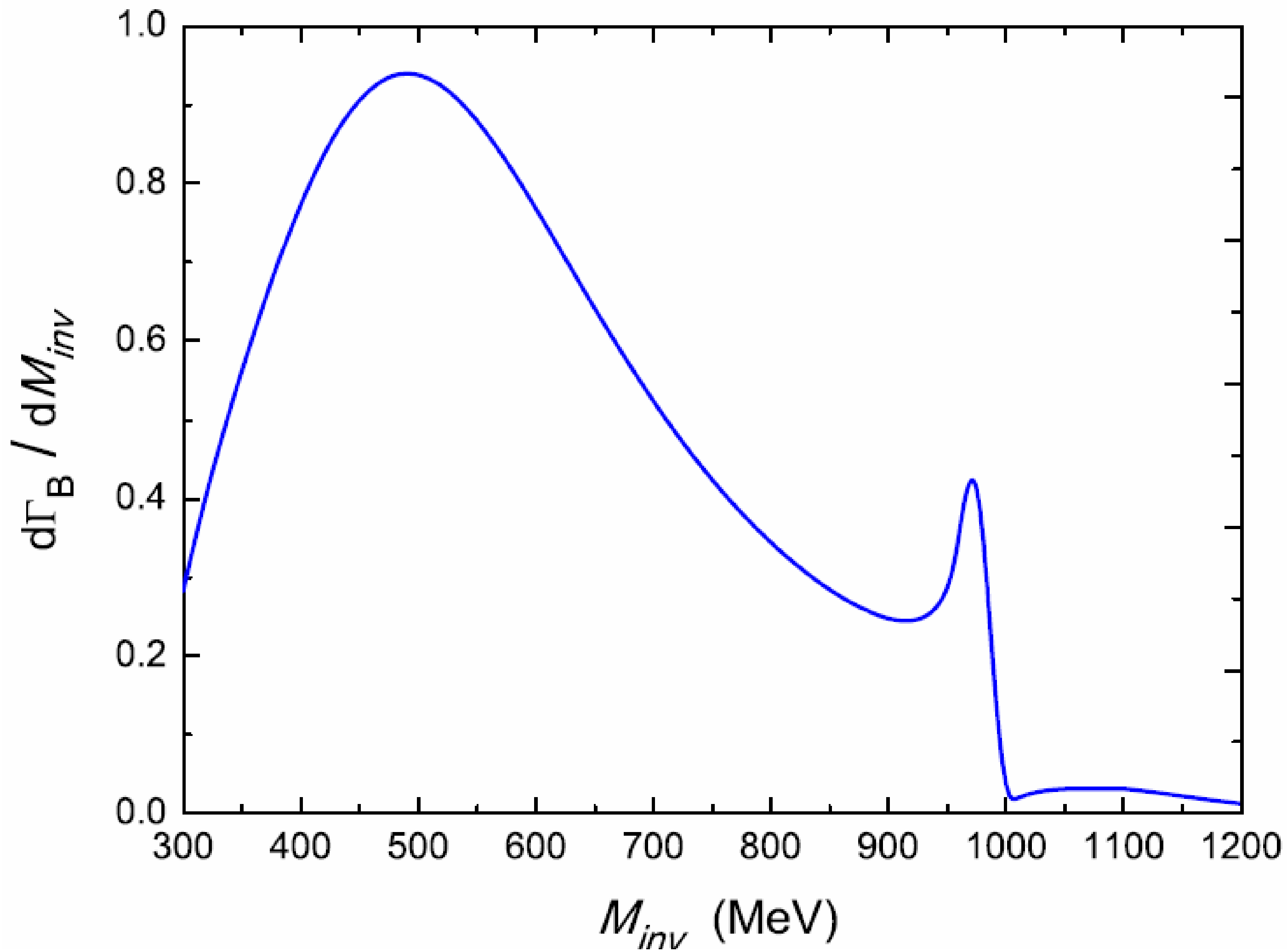


Fig. 5. $\pi^+\pi^-$ invariant mass distribution for the $\bar{B}^0 \to J/\psi\pi^+\pi^-$ decay

$f_0(500)$ production is clearly dominant.

$$\frac{\mathcal{B}[\bar{B}^0 \to J/\psi\, f_0(980),\, f_0(980) \to \pi^+\pi^-]}{\mathcal{B}[\bar{B}^0 \to J/\psi\, f_0(500),\, f_0(500) \to \pi^+\pi^-]} = 0.033 \pm 0.007,$$

with an admitted 20% uncertainty

Exp. $(0.6^{+0.7+3.3}_{-0.4-2.6}) \times 10^{-2}$

Conclusion:

$$\frac{\Gamma(B^0 \to J/\psi\, f_0(500))}{\Gamma(B_s^0 \to J/\psi\, f_0(980))} \simeq (4.5 \pm 1.0) \times 10^{-2}$$

Exp. $(2.08\text{–}4.13) \times 10^{-2}$

Our results agree with the experimental results. This gives a strong support to the idea of the low lying scalar mesons as being formed from the interaction of airs of pseudoscalar mesons.

Summary

Using the chiral unitary theory, we investigate the $\bar{B}^0$ and $\bar{B}_s^0$ decays into $J/\psi f_0(500)$, $J/\psi f_0(980)$, and find :

$B_s^0 \to J/\psi\, \pi^+\pi^-$ decay : A clear peak is observed for $f_0(980)$ production ;

$f_0(500)$ production is not observed;

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

Only a very small fraction is observed for $f_0(500)$ production .

The results agree with Exp. , surpouting f0(500) and f0(980) are melecutes.

Thank you for your attention!