# Testing the Structure of Light Scalar Mesons in the Decays of $\bar{B}^0 \to D^0 \pi^+ \pi^-$, $D^0 K^+ K^-$, $D^0 \pi^0 \eta$ and $\bar{B}_s^0 \to D^0 \pi^- K^+$


**Wei-Hong Liang**

**(Guangxi Normal University)**

**In collaboration with:**

**J.J. Xie, and E. Oset**


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# ◆ Introduction and motivation

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

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

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 $\kappa$ are dynamically generated from the interaction of pseudoscalar mesons,
and could be interpreted as a kind of molecular states of meson-meson.

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

$f_0(500) \Longrightarrow \pi\pi$ resonance

$f_0(980) \Longrightarrow K\bar{K}$ molecule

$a_0(980) \Longrightarrow \pi\eta + K\bar{K}$ 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:**

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

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

$\overline{B}^0 \to J/\psi\, \pi^+\pi^-$ **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;**

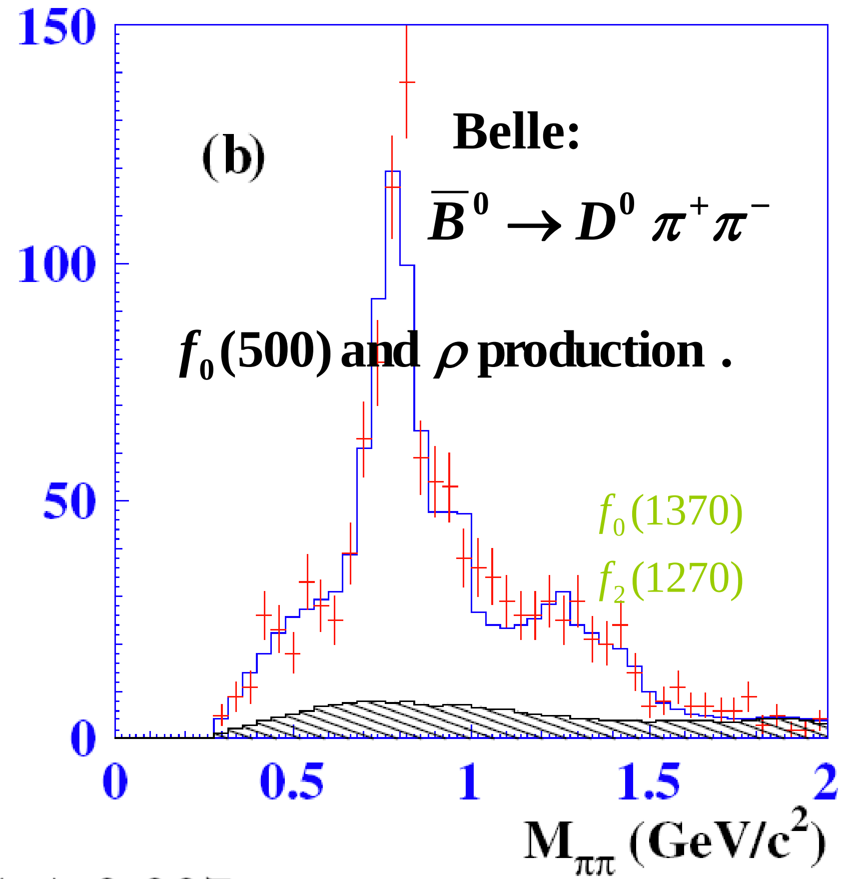
**D0, PRD85(2012)011103.**

# Introduction and motivation

$$Br[\bar{B}^0 \to D^0 f_0(500)] \cdot Br[f_0(500) \to \pi^+\pi^-]$$
$$= (0.68 \pm 0.08) \times 10^{-4},$$

[ Belle, PRD76(2007)012006 ]

$$Br(B^0 \to \bar{D}^0 \rho^0) = (3.2 \pm 0.5) \times 10^{-4},$$




$$\frac{\Gamma(B^0 \to \bar{D}^0 K^+ K^-)}{\Gamma(B^0 \to \bar{D}^0 \pi^+ \pi^-)} = 0.056 \pm 0.011 \pm 0.007$$

[ LHCb, PRL109(2012)131801 ]

# Introduction and motivation

**In this work:** Using these experimental information, we can investigate the production of the light scalar mesons in

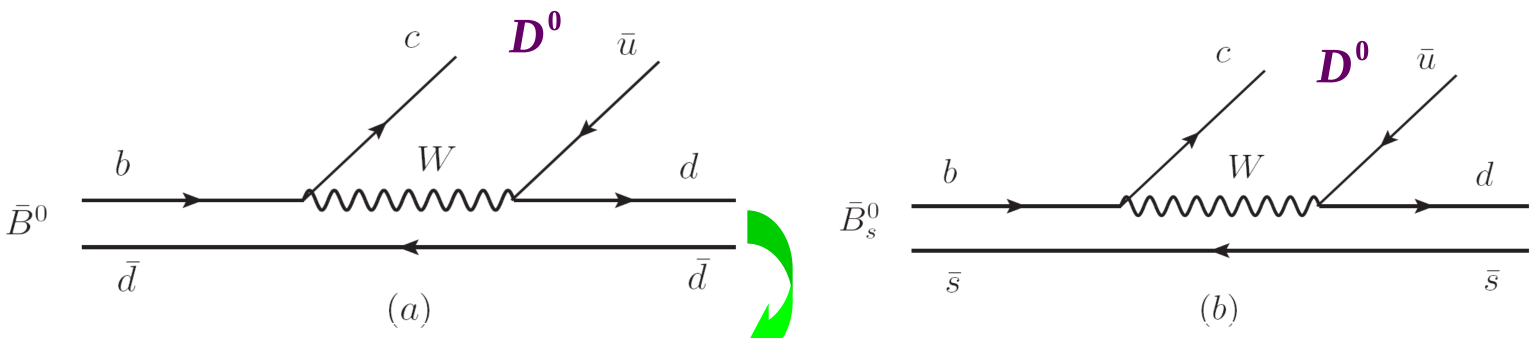
$$\bar{B}^0 \to D^0\,\pi^+\pi^-,\ D^0\,K^+K^-,\ D^0\,\pi^0\eta$$
$$\bar{B}_s^0 \to D^0\,\pi^-K^+.$$

Considering the final state interactions between the light pseudoscalar meson pairs in chiral unitary approach, $f_0(500)$, $f_0(980)$, $a_0(980)$ and $\kappa(800)$ can be produced dynamically.

↑ $\pi^+\pi^-,\ K^+K^-,\ \pi^0\eta,\ \pi^-K^+$ **invariant mass distribution**

# Formalism

- **The Cabibbo favored dominant mechanism:**




**a pair of PS mesons or a vector meson**

$\bar{d}$ and $\bar{s}$ act as spectators. ⇨ Amplitudes for these processes are identical.

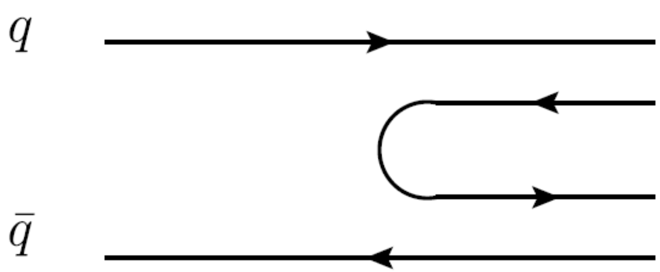
**Assume:** A $q\bar{q}$ nature for vector mesons;

$f_0(500)$, $f_0(980)$, $a_0(980)$ and $\kappa$ generated dynamically from PS-PS interaction.

# Formalism

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

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




$$q\bar{q}(u\bar{u} + d\bar{d} + s\bar{s})$$

$$\text{final state} \begin{cases} \pi^+\pi^- \\ K^+K^- \\ \pi^0\eta \\ \pi^- K \end{cases}$$

**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 :**

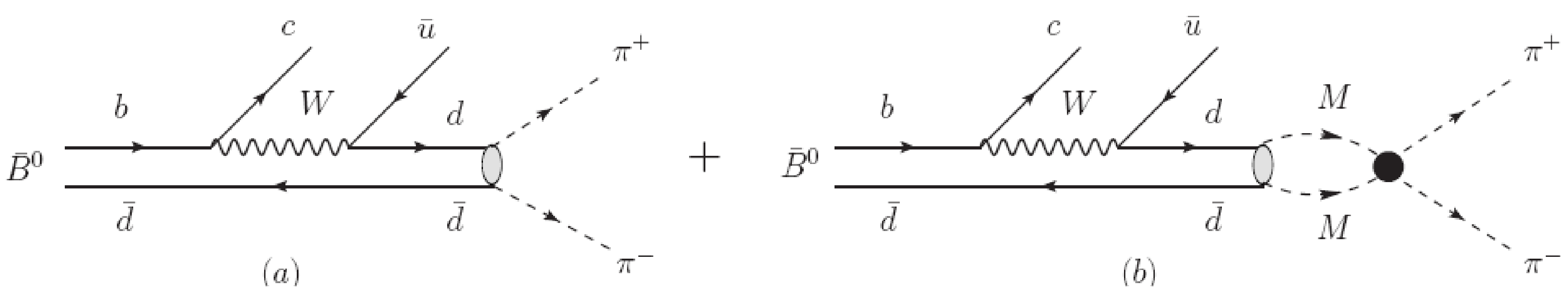
$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & K^0 \\ K^- & \bar{K}^0 & -\frac{1}{\sqrt{3}}\eta + \sqrt{\frac{2}{3}}\eta' \end{pmatrix}$$

# Formalism

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

$$s\bar{d}(\bar{u}u+\bar{d}d+\bar{s}s) \to (\Phi\cdot\Phi)_{23} = \pi^-K^+ - \frac{1}{\sqrt{2}}\pi^0K^0,$$

**Let these PS mesons interact:**




**(direct mechanism)** **(rescattering mechanism)**

## The amplitude for $\pi^+\pi^-$ production :

$$t(\bar{B}^0 \to D^0\pi^-\pi^+) = V_P(1 + G_{\pi^-\pi^+}t_{\pi^-\pi^+\to\pi^-\pi^+} + \frac{1}{2}G_{\pi^0\pi^0}t_{\pi^0\pi^0\to\pi^-\pi^+} + \frac{1}{3}G_{\eta\eta}t_{\eta\eta\to\pi^-\pi^+} + G_{K^0\bar{K}^0}t_{K^0\bar{K}^0\to\pi^-\pi^+}),$$

$V_P$ **:** $a$ common factor to all $\bar{B}^0(\bar{B}_s^0) \to D^0 MM$ decays;

$G_i$ **:** 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]

# Formalism

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

$$\frac{d\Gamma}{dM_{\text{inv}}} = \frac{1}{(2\pi)^3}\frac{p_D \tilde{p}_\pi}{4M_{\bar{B}^0}^2}|t(\bar{B}^0 \to D^0\pi^-\pi^+)|^2,$$

**Similar fomulas for** $\bar{B}^0 \to D^0 K^- K^+$, $\bar{B}^0 \to D^0\pi^0\eta$, $\bar{B}^0 \to D^0\pi^- K^+$.

# Formalism

- $\bar{B}^0(\bar{B}_s^0) \to D^0 V_i$

$$|\rho^0> = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}); \quad |\omega> = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}); \quad |K^{*0}> = d\bar{s}.$$

$J^P$ : $\mathbf{0^- \to 0^- \; 1^-}$, ( $L$=1, $P$-wave )

**The amplitudes:**

$$t_{\bar{B}^0 \to D^0 \rho^0} = -\frac{1}{\sqrt{2}} V'_P p_D, \qquad t_{\bar{B}^0 \to D^0 \phi} = 0,$$

$$t_{\bar{B}^0 \to D^0 \omega} = \frac{1}{\sqrt{2}} V'_P p_D, \qquad t_{\bar{B}_s^0 \to D^0 K^{*0}} = V'_P p_D,$$

$V'_P$ : *a* common factor to all $\bar{B}^0(\bar{B}_s^0) \to D^0 V_i$ decays;

$P_D$ : the momentum of $D^0$ in the rest frame of $\bar{B}^0$ or $\bar{B}_s^0$.

# ◆ Formalism

**The decay width:**

$$\Gamma_{\bar{B}_i^0 \to D^0 V_i} = \frac{1}{8\pi M_{\bar{B}_i^0}^2} |t_{\bar{B}_i^0 \to D^0 V_i}|^2 p_D .$$

**Convert the total date for vector production into a mass distibution:**

$$\frac{d\Gamma_{\bar{B}^0 \to D^0 \rho^0 \to D^0 \pi^+ \pi^-}}{dM_{\rm inv}} = -\frac{2m_\rho}{\pi} \times$$

$$\mathrm{Im}\left[\frac{1}{M_{\rm inv}^2 - m_\rho^2 + i m_\rho \Gamma_\rho(M_{\rm inv})}\right] \tilde{\Gamma}_{\bar{B}^0 \to D^0 \rho^0},$$

$M_{\rm inv}$ is the $\pi^+\pi^-$ invariant mass.

**Similar fomula for $\overline{B}_s^0 \to D^0 \pi^- K^+$ decay.**

# Results, discussions and conclusion

## Determine the common factors $V_P$ and $V'_P$.

Exp. information from Belle: [ Belle, PRD76(2007)012006 ]

$$Br[\bar{B}^0 \to D^0 f_0(500)] \cdot Br[f_0(500) \to \pi^+\pi^-] = (0.68 \pm 0.08) \times 10^{-4},$$

$$Br(B^0 \to \bar{D}^0 \rho^0) = (3.2 \pm 0.5) \times 10^{-4},$$

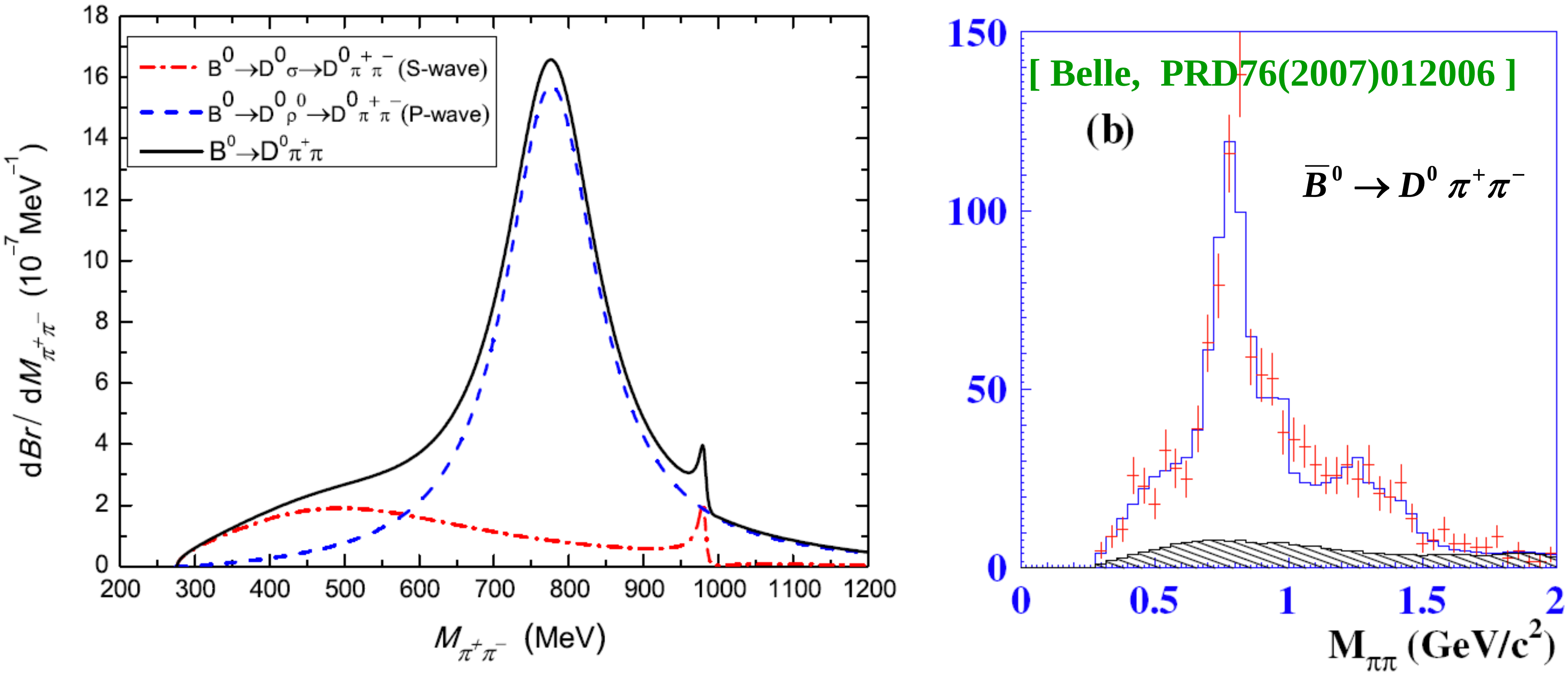
$$\tilde{V}_P = (8.8 \pm 0.5) \times 10^{-2}\ \mathrm{MeV}^{-1/2},$$

$$\tilde{V}'_P = (6.8 \pm 0.5) \times 10^{-3}\ \mathrm{MeV}^{-1/2}.$$

**Make some predictions with no free parameters.**

# Results, discussions and conclusion

- $f_0(500)$ and $\rho^0$ productions in $\bar{B}^0 \to D^0\pi^+\pi^-$ decay




Invariant mass distribution for $\pi^+\pi^-$ in $\bar{B}^0 \to D^0\pi^+\pi^-$ decay.

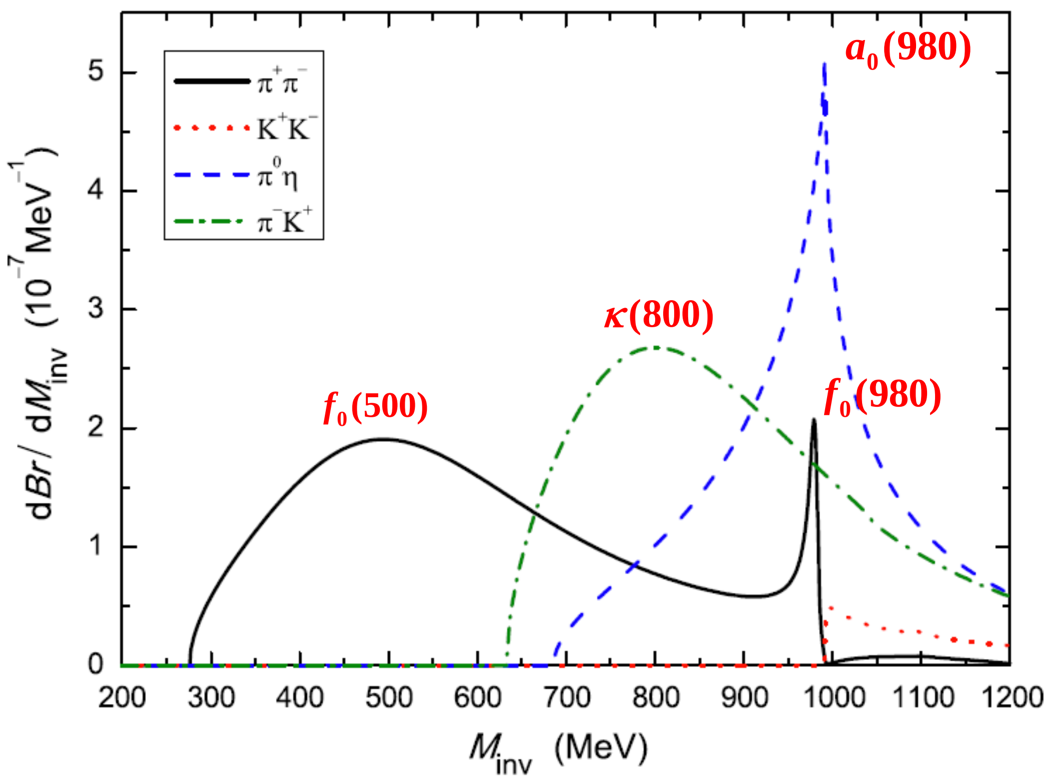
$f_0(500)$ is clearly visible in the region of 400-600 MeV.

A larger contribution from $\rho^0$.

The shape of $M_{\pi\pi}$ distribution is similar to that of Belle.

# Results, discussions and conclusion

- **Production of the scalar resonances (in *S*-wave)**




**Invariant mass distribution for the $\pi^+\pi^-$, $K^+K^-$, $\pi^0\eta$, $\pi^-K^+$ in $\bar{B}^0 \to D^0\pi^+\pi^-$, $D^0K^+K^-$, $D^0\pi^0\eta$ and $\bar{B}_s^0 \to D^0\pi^-K^+$ decays.**

**The relative weight of the distributions are predicted.**

# Results, discussions and conclusion

## Test some of our predictions:

$$\left.\frac{Br[\bar{B}^0 \to D^0 f_0(980)] \cdot Br[f_0(980) \to \pi^+\pi^-]}{Br[\bar{B}^0 \to D^0 f_0(500)] \cdot Br[f_0(500) \to \pi^+\pi^-]}\right|_{\mathrm{Exp.}} = 0.12 \pm 0.06.$$

[ Belle, PRD76(2007)012006 ]

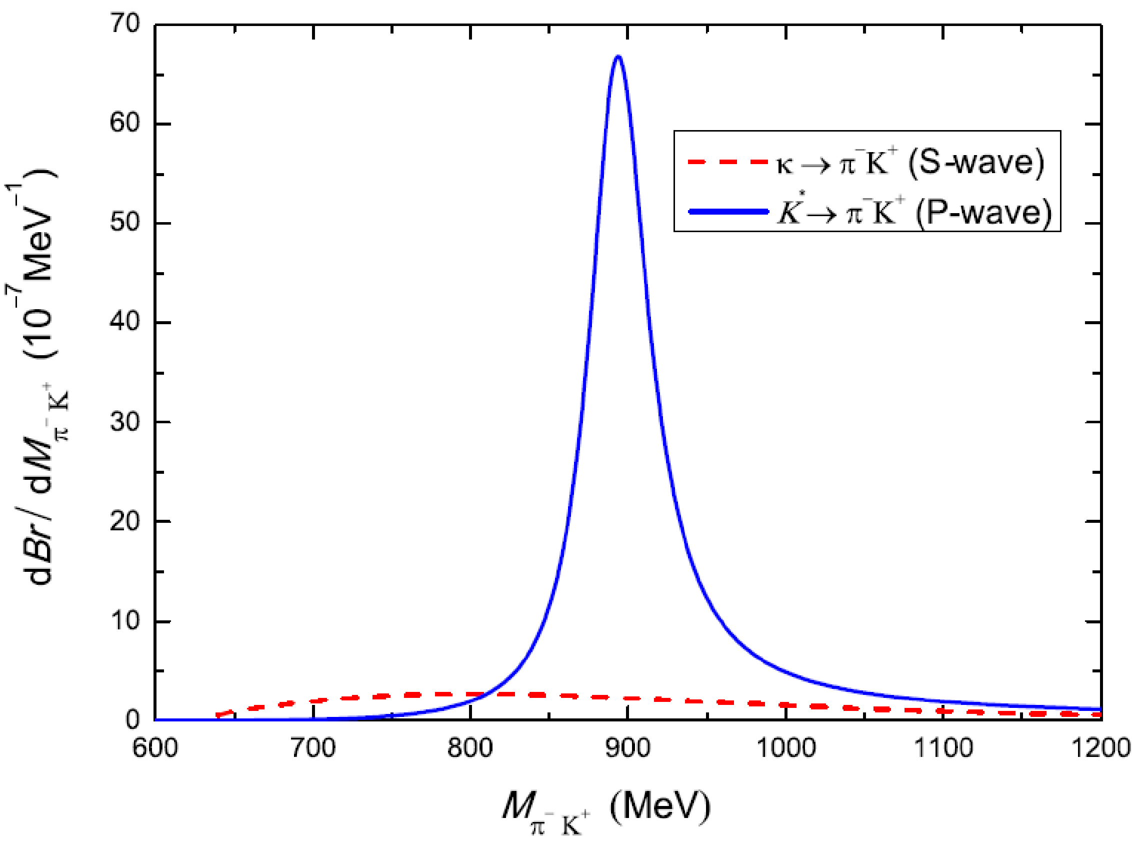
$$\left.\frac{Br[\bar{B}^0 \to D^0 f_0(980)] \cdot Br[f_0(980) \to \pi^+\pi^-]}{Br[\bar{B}^0 \to D^0 f_0(500)] \cdot Br[f_0(500) \to \pi^+\pi^-]}\right|_{\mathrm{Theo}} = 0.08,$$

with an estimated error of about 10%.

**A good agreement within errors.**

# Results, discussions and conclusion

- The strength of $K^{*0}$ production versus $\kappa(800)$ production in $\overline{B}_s^0 \to D^0 \pi^- K^+$ decay.




$\kappa$ is visible in the lower part of the spectrum.

The strength of $K^{*0}$ is much bigger than for $\kappa$.

Invariant mass distribution for $\pi^- K^+$ in $\overline{B}_s^0 \to D^0 \pi^- K^+$ decay.

# Results, discussions and conclusion

$$\left.\frac{\Gamma(B^0\to\bar{D}^0K^+K^-)}{\Gamma(B^0\to\bar{D}^0\pi^+\pi^-)}\right|_{\mathrm{Exp.}} = 0.056\pm0.011\pm0.007$$

[ LHCb, PRL 109(2012)131801 ]

$$\left.\frac{\Gamma(B^0\to\bar{D}^0K^+K^-)}{\Gamma(B^0\to\bar{D}^0\pi^+\pi^-)}\right|_{\mathrm{Theo.}} = 0.03\sim0.06.$$

**A qualitative agreement.**

**Conclusion:**

**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 pairs of pseudoscalar mesons.**

# Summary

- Using the chiral unitary theory, we investigate the Decays of $\bar{B}^0 \to D^0 \pi^+\pi^-$, $D^0 K^+K^-$, $D^0 \pi^0\eta$ and $\bar{B}_s^0 \to D^0 \pi^- K^+$, and find :

The results agree with Exp., surporting $f_0(500)$, $f_0(980)$, $a_0(980)$, $\kappa$ are dynamically generated from the PS-PS interaction.

$f_0(500)$ is a $\pi\pi$ resonance, $f_0(980)$ is a $K\bar{K}$ molecule,

$a_0(980)$ is a $\pi\eta$ molecule, $\kappa$ is a $\pi$K molecule.

- **The production rates of some light scalar mesons in the weak decays of *B* mesons are predicted with no free parameters.**

- **More Exp. data from LHCb or other facilities are expected to test the structure of the light scalar mesons.**



**Thanks for your attention!**