Study B^0 and B_s^0 decays into ϕ and a scalar or vector meson

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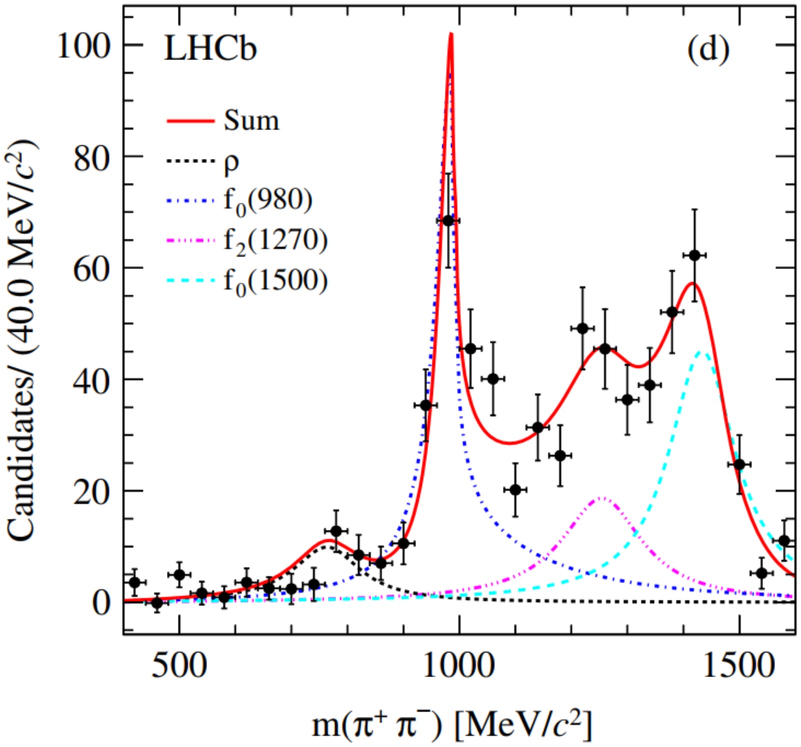
4. Summary

1. Introduction

- 2017, LHCb collaboration observed the decay $B_s^0 \to \phi\pi^+\pi^-$ and evidence for $B^0 \to \phi\pi^+\pi^-$.



$$\mathcal{B}(B_s^0 \to \phi f_0(980), f_0(980) \to \pi^+\pi^-) = [1.12 \pm 0.16^{+0.09}_{-0.08} \pm 0.11] \times 10^{-6}.$$

$$\mathcal{B}(B_s^0 \to \phi f_2(1270), f_2(1270) \to \pi^+\pi^-) = [0.61 \pm 0.13^{+0.12}_{-0.05} \pm 0.06] \times 10^{-6}.$$

$$\mathcal{B}(B_s^0 \to \phi \rho^0) = [2.7 \pm 0.7 \pm 0.2 \pm 0.2] \times 10^{-7}.$$

*R. Aaij et al. (LHCb Collaboration), **Phys. Rev. D** 95, 012006 (2017).*

1. Introduction

- Theoretical research on the above experiments.

- 2017, $B_s^0 \to \phi\rho^0$ decay.

  Qin Chang, Xiaonan Li, Xin-Qiang Li, and Junfeng Sun. ***Eur. Phys. J. C*** *77, no.6, 415 (2017).*

- 2019, Direct CP violation for $B_s^0 \to \phi\pi^+\pi^-$.

  Sheng-Tao Li and Gang Lü. ***Phys. Rev. D*** *99, 116009 (2019).*

- 2019, $B_s^0 \to \phi f_0\ (980) \to \phi\pi^+\pi^-$ decay.

  Na Wang, Qin Chang, Yueling Yang, and Junfeng Sun. ***J. Phys. G*** *46, no.9, 095001 (2019).*

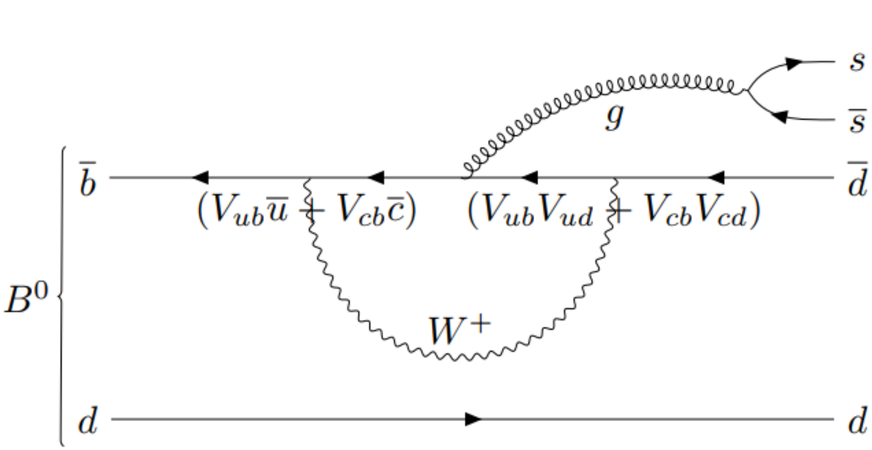
- 2020, $B_s^0 \to \phi(f_0\ (980)/f_2(1270))\ \pi^+\pi^-$ decay.

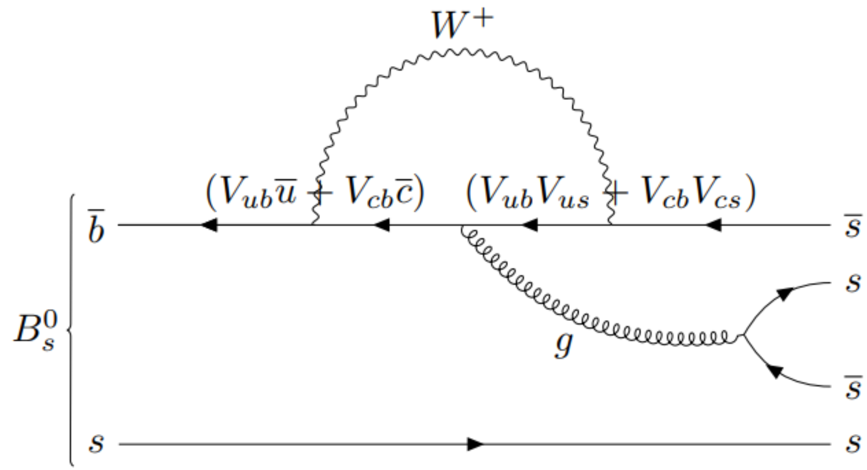
  Zhi-Tian Zou, Lei Yang, Ying Li, and Xin Liu. ***arXiv:2011.07676*** *[hep-ph].*

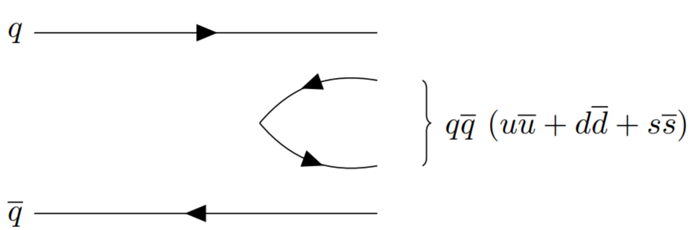
➢ B^0 and B_s^0 decays into $\phi f_0(980)$ and $\phi f_0(500)$ are studied by using the chiral unitary approach (<1200MeV). (arXiv:2011.08758)

2. Formalism

- The decays of $B^0_{(s)}$ and the primary $q\bar{q}$ pair undergoes hadronaization.







$$B^0(\bar{b}d) \Rightarrow (V_{ub}\bar{u} + V_{cb}\bar{c})\,W^+d \Rightarrow (V_{ub}\bar{u}g + V_{cb}\bar{c}g)\,W^+d$$
$$\Rightarrow (V_{ub}V_{ud} + V_{cb}V_{cd})(s\bar{s})(d\bar{d})\,,$$
$$B_s^0(\bar{b}s) \Rightarrow (V_{ub}\bar{u} + V_{cb}\bar{c})\,W^+s \Rightarrow (V_{ub}\bar{u}g + V_{cb}\bar{c}g)\,W^+s$$
$$\Rightarrow (V_{ub}V_{us} + V_{cb}V_{cs})(s\bar{s})(s\bar{s})\,,$$

2. Formalism

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

$$B^0 \quad d\bar{d}(u\bar{u}+d\bar{d}+s\bar{s}) \equiv (\Phi\cdot\Phi)_{22}$$

$$= \pi^+\pi^- + \frac{1}{2}\pi^0\pi^0 - \frac{1}{\sqrt{3}}\pi^0\eta + K^0\bar{K}^0 + \frac{1}{6}\eta\eta,$$

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

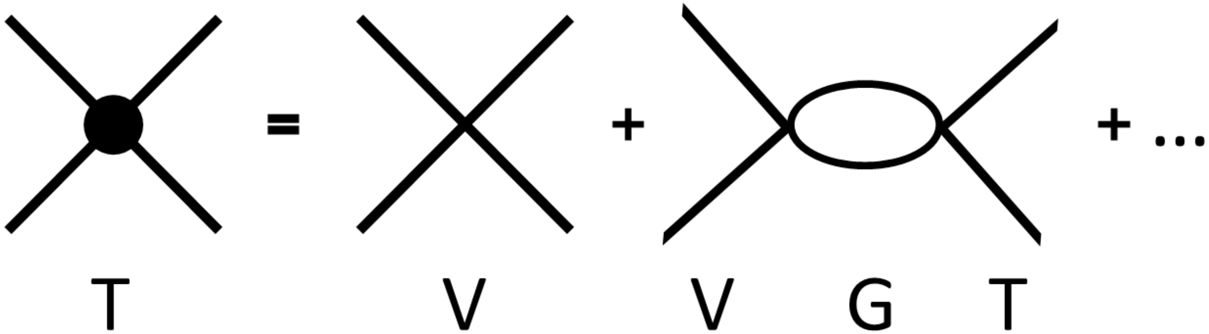
$$t\left(B^0 \to \phi\pi^+\pi^-\right) = V_P(V_{ub}V_{ud} + V_{cb}V_{cd})\Big(1 + G_{\pi^+\pi^-}T_{\pi^+\pi^-\to\pi^+\pi^-} + \frac{1}{2}G_{\pi^0\pi^0}T_{\pi^0\pi^0\to\pi^+\pi^-}$$
$$+ G_{K^0\bar{K}^0}T_{K^0\bar{K}^0\to\pi^+\pi^-} + \frac{1}{6}G_{\eta\eta}T_{\eta\eta\to\pi^+\pi^-}\Big),$$

$$t\left(B_s^0 \to \phi\pi^+\pi^-\right) = V_P(V_{ub}V_{us} + V_{cb}V_{cs})\Big(G_{K^+K^-}T_{K^+K^-\to\pi^+\pi^-} + G_{K^0\bar{K}^0}T_{K^0\bar{K}^0\to\pi^+\pi^-} +$$
$$\frac{4}{6}G_{\eta\eta}T_{\eta\eta\to\pi^+\pi^-}\Big),$$

2. Formalism

- Use the Bethe-Salpeter (BS) equation in coupled channels to evaluate the scattering amplitudes.

$$T = V + VGT, T = [1 - VG]^{-1} V$$



- where V matrix can be evaluated from chiral effective Lagrangians.
- where G function, we take

$$G_i(s) = i\int \frac{d^4q}{(2\pi)^4}\frac{1}{q^2 - m_1^2 + i\varepsilon}\frac{1}{(p_1 + p_2 - q)^2 - m_2^2 + i\varepsilon}$$
$$= \int_0^{q_{\max}} \frac{q^2 dq}{(2\pi)^2}\frac{\omega_1 + \omega_2}{\omega_1\omega_2[P^{02} - (\omega_1 + \omega_2)^2 + i\varepsilon]}$$

$$\begin{cases} \omega_i = \left(\vec{q}^{\,2} + m_i^2\right)^{1/2} \\ P^{02} = s \end{cases}$$

2. Formalism

- The Lagrangian will provide the potentials which will be used in the coupled channel scattering equations. Denoting the channels $\pi^+\pi^-, \pi^0\pi^0, K^+K^-, K^0\bar{K}^0, \eta\eta$, with the indices 1 to 5, respectively.

I = 0:

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

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

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

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

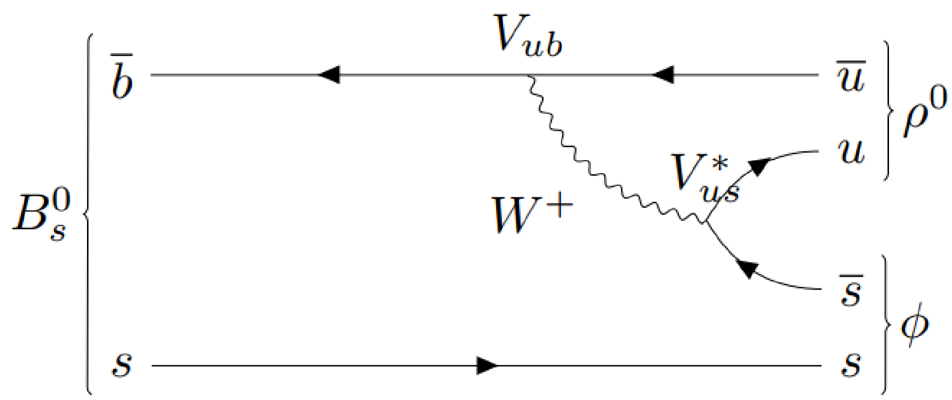
$$V_{35} = -\frac{1}{12\sqrt{2}f^2}\left(9s - 6m_\eta^2 - 2m_\pi^2\right), \quad V_{44} = -\frac{1}{2f^2}s,$$

$$V_{45} = -\frac{1}{12\sqrt{2}f^2}\left(9s - 6m_\eta^2 - 2m_\pi^2\right),$$

$$V_{55} = -\frac{1}{18f^2}\left(16m_K^2 - 7m_\pi^2\right),$$

2. Formalism

- B_s^0 decays into ϕ and ρ^0.



$$t_{B_s^0\to\phi\rho^0} = \frac{1}{\sqrt{2}}\tilde{V}_P V_{ub} V_{us}^*$$

$$\Gamma_{B_{(s)}^0\to\phi V} = \frac{1}{8\pi}\frac{1}{m_{B_{(s)}^0}^2}\left|t_{B_{(s)}^0\to\phi V}\right|^2 p_\phi$$

$$\frac{d\Gamma_{B_s^0\to\phi\rho^0}}{dM_{\mathrm{inv}}\left(\pi^+\pi^-\right)} = -\frac{1}{\pi}2m_\rho \,\mathrm{Im}\,\frac{1}{M_{\mathrm{inv}}^2 - m_\rho^2 + i m_\rho \tilde{\Gamma}_\rho\left(M_{\mathrm{inv}}\right)}\Gamma_{B_s^0\to\phi\rho^0}$$

$$\tilde{\Gamma}_\rho\left(M_{\mathrm{inv}}\right) = \Gamma_\rho\left(\frac{p_\pi^{\mathrm{off}}}{p_\pi^{\mathrm{on}}}\right)^3,$$

$$p_\pi^{\mathrm{off}} = \frac{\lambda^{1/2}\left(M_{\mathrm{inv}}^2, m_\pi^2, m_\pi^2\right)}{2M_{\mathrm{inv}}}\theta\left(M_{\mathrm{inv}} - 2m_\pi\right),$$

$$p_\pi^{\mathrm{on}} = \frac{\lambda^{1/2}\left(m_\rho^2, m_\pi^2, m_\pi^2\right)}{2m_\rho},$$

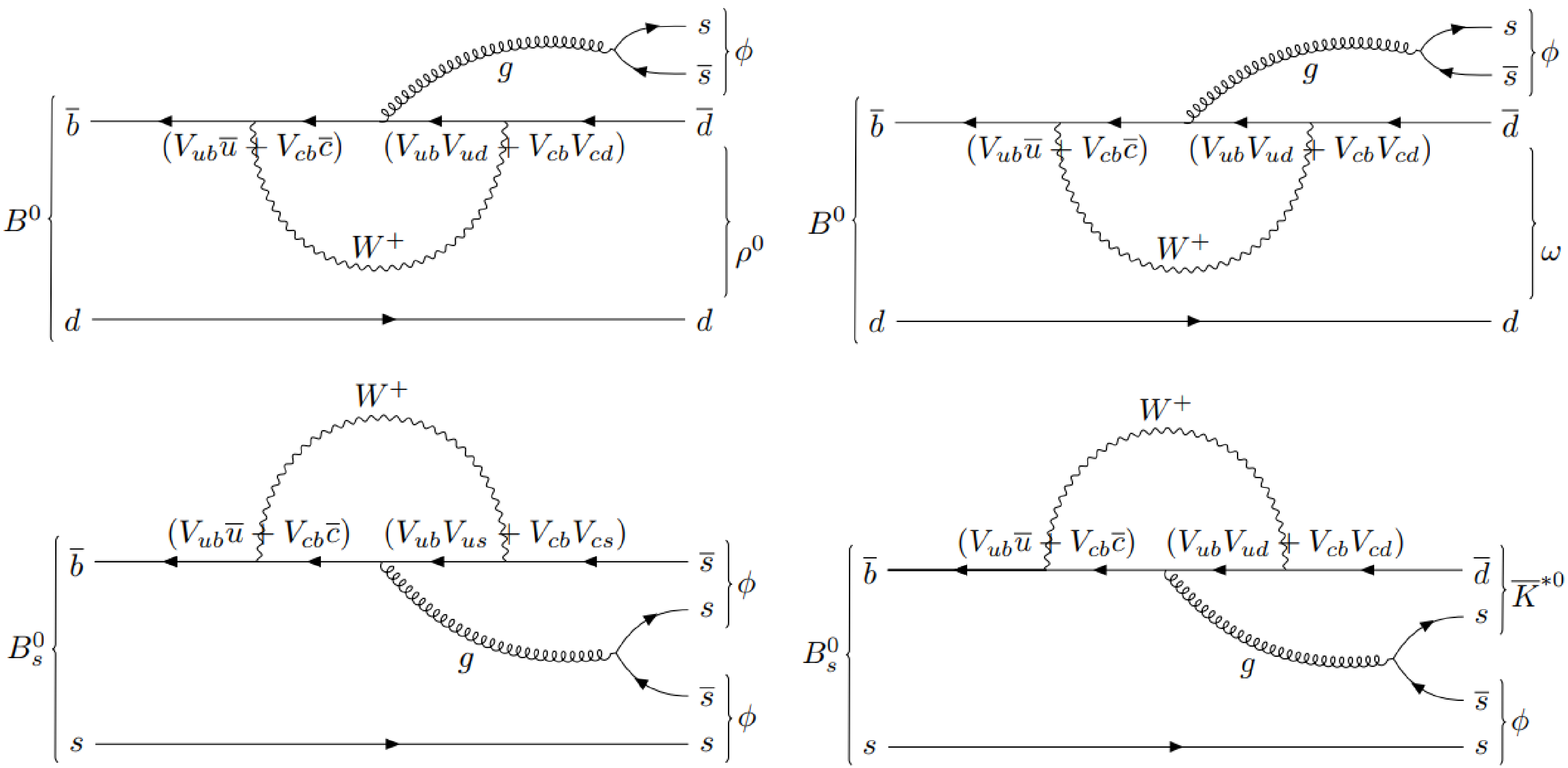
M. Bayar, W. H. Liang, and E. Oset. ***Phys. Rev. D*** *90, 114004 (2014).*

W. H. Liang, J. J. Xie, and E. Oset, ***Phys. Rev. D*** *92, no.3, 034008 (2015).*

Z. Wang, Y. Y. Wang, E. Wang, D. M. Li, and J. J. Xie, ***Eur. Phys. J. C*** *80 no.9, 842 (2020).*

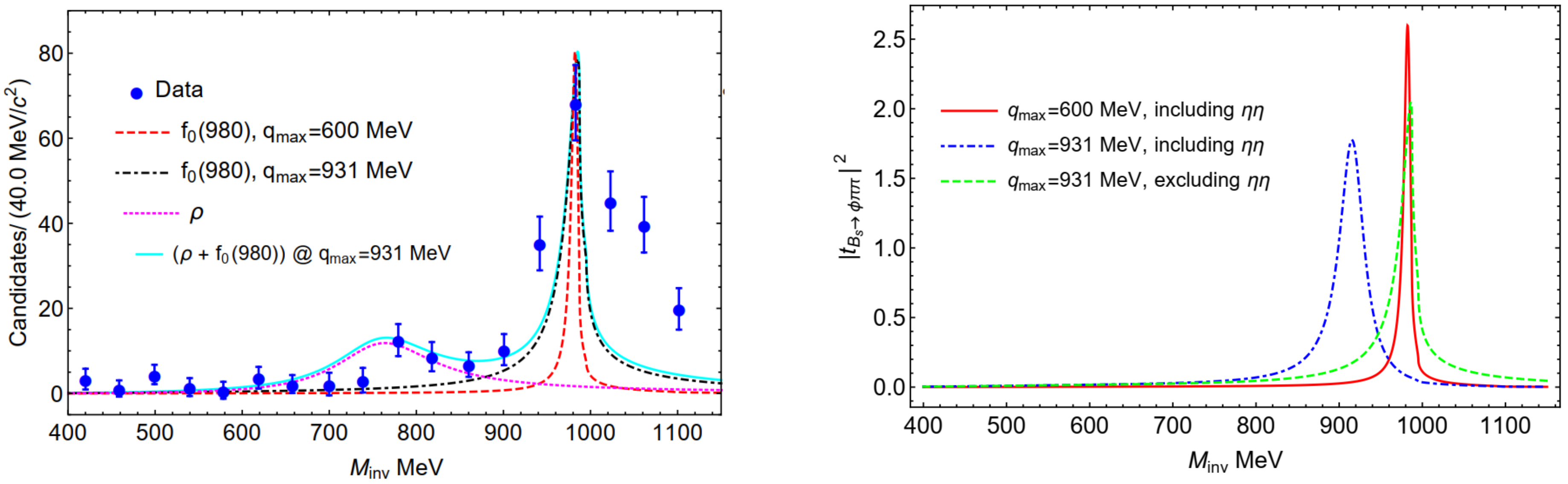
2. Formalism

- B^0 and B_s^0 decays into ϕ and a vector meson.



3. Results

- $\pi^+\pi^-$ invariant mass distribution of the $B_s^0 \to \phi\pi^+\pi^-$ decay.



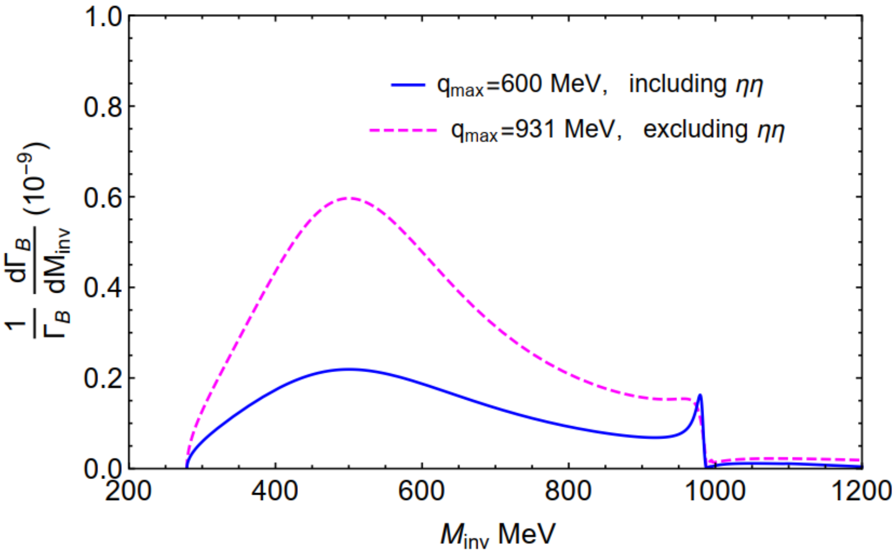
For the bound state of the $K\bar{K}$ channel, should decrease the cutoff to move the pole of the $f_0(980)$ state to higher energy when the $\eta\eta$ channel is included, which will lead to the width of the pole decrease.

Hiwa A. Ahmed and C.W. Xiao. ***Phys. Rev. D*** *101, 094034 (2020).*

3. Results

- $\pi^+\pi^-$ invariant mass distribution of the $B^0 \to \phi\pi^+\pi^-$ decay and the prediction of the branching ratios.

$$BR(B_s^0 \to \phi f_0(980)) = (1.12 \pm 0.21) \times 10^{-6}$$



$$\mathrm{Br}(B_s^0 \to \phi f_0(980)) = \frac{\int_{2m_\pi}^{1200} \frac{d\Gamma_{B_s^0 \to \phi f_0(980)}}{dM_{inv}} dM_{inv}}{\Gamma_{B_s}} = \frac{V_p^2}{\Gamma_{B_s}} \times 32.95$$

excluding $\eta\eta$

$$= \frac{\int_{2m_\pi}^{1200} \frac{d\Gamma_{B_s^0 \to \phi f_0(980)}}{dM_{inv}} dM_{inv}}{\Gamma_{B_s}} = \frac{V_p^2}{\Gamma_{B_s}} \times 51.18$$

$$\mathrm{Br}(B^0 \to \phi f_0(980)) = \frac{\Gamma_{B^0 \to \phi f_0(980)}}{\Gamma_B} = \frac{\int_{900}^{1200} \frac{d\Gamma_{B^0 \to \phi f_0(980)}}{dM_{inv}} dM_{inv}}{\Gamma_B}$$

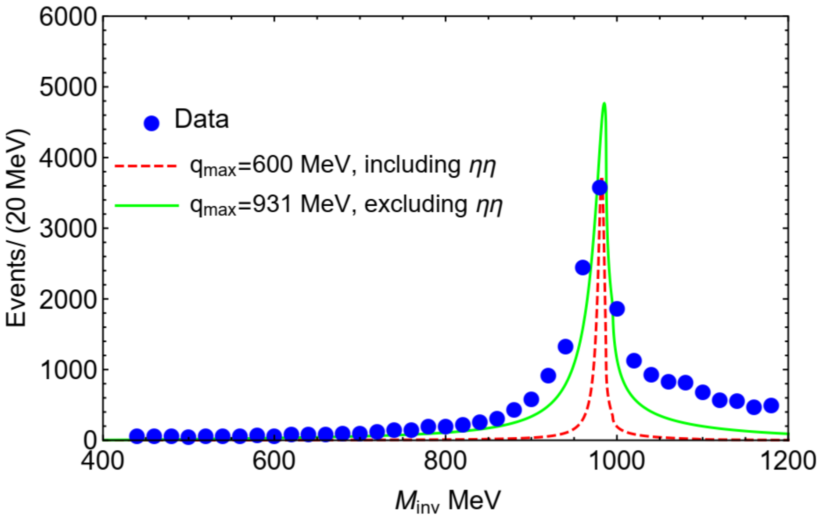
$$\mathrm{Br}(B^0 \to \phi f_0(500)) = \frac{\Gamma_{B^0 \to \phi f_0(500)}}{\Gamma_B} = \frac{\int_{2m_\pi}^{900} \frac{d\Gamma_{B^0 \to \phi f_0(500)}}{dM_{inv}} dM_{inv}}{\Gamma_B}$$

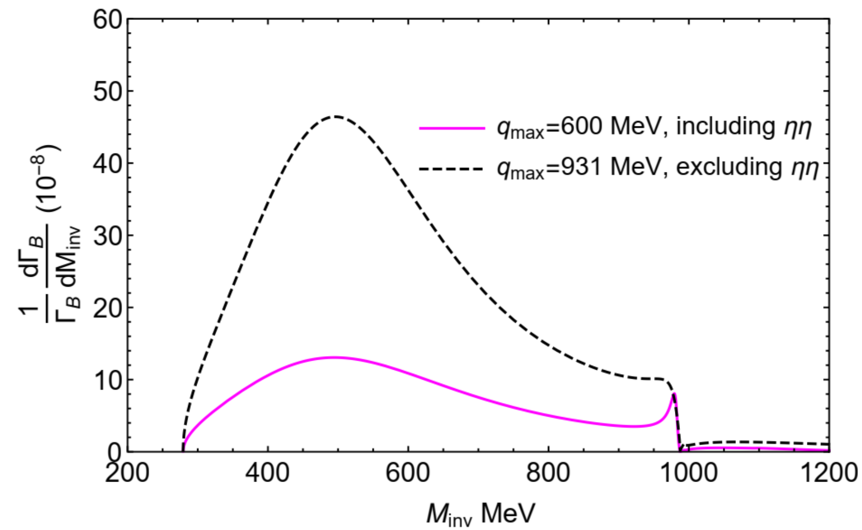
Branching ratios	Without $\eta\eta$ channel	With $\eta\eta$ channel	Exp.
$\mathrm{Br}(B^0 \to \phi f_0(980))$	$(4.69 \pm 0.88 \pm^{+3.96}_{-1.55}) \times 10^{-9}$	$(7.37 \pm 1.38^{+4.61}_{-2.11}) \times 10^{-9}$	$< 3.8 \times 10^{-7}$
$\mathrm{Br}(B^0 \to \phi f_0(500))$	$(6.20 \pm 1.16^{+0.24}_{-0.21}) \times 10^{-8}$	$(7.17 \pm 1.35^{+0.31}_{-0.27}) \times 10^{-8}$	-

3. Results

- The prediction of the branching ratios of the decays $B^0 \to \phi f_0(500) \to \phi\pi^+\pi^-$ by compare with $B^0 \to J/\psi f_0(500) \to J/\psi\pi^+\pi^-$.

W. H. Liang and E.Oset. ***Phys. Lett. B*** *737, 70–74 (2014) .*





$$\frac{\mathrm{Br}(B_s^0 \to \phi f_0(980))}{\mathrm{Br}(B_s^0 \to J/\psi f_0(980))} = (\frac{V_p}{V_p'})^2 \times 3.78$$

$$BR(B^0 \to J/\psi f_0(500)) = 8^{+1.1}_{-0.9} \times 10^{-6}$$

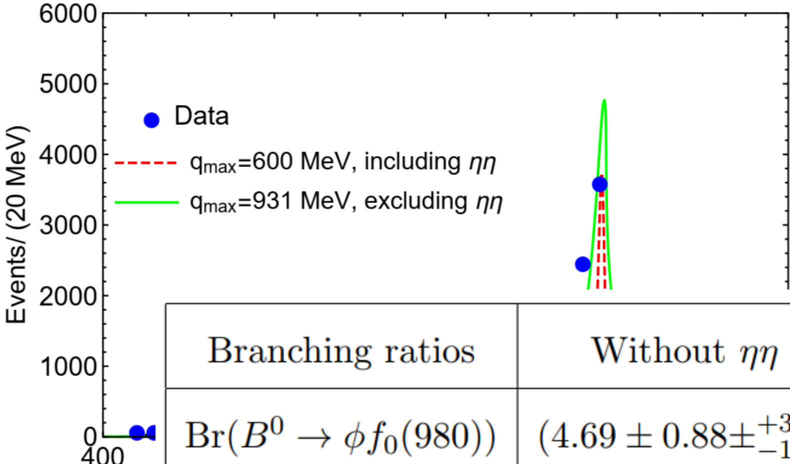
$$\frac{\mathrm{Br}(B_s^0 \to \phi f_0(980))}{\mathrm{Br}(B_s^0 \to J/\psi f_0(980))} = (8.75 \pm 2.87) \times 10^{-3}$$

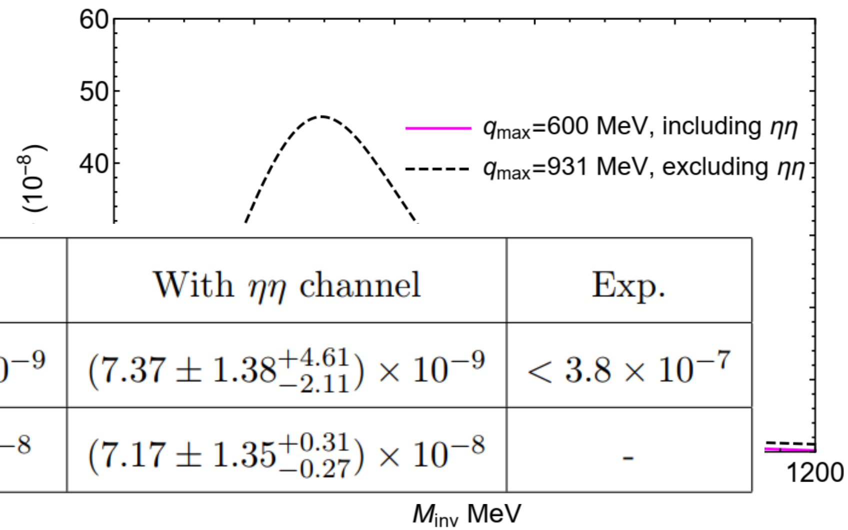
$$\mathrm{Br}(B^0 \to \phi f_0(500)) = (5.67^{+2.64}_{-2.50}{}^{+0.02}_{-0.02}) \times 10^{-8}$$

3. Results

- The prediction of the branching ratios of the decays $B^0 \to \phi f_0(500) \to \phi\pi^+\pi^-$ by compare with $B^0 \to J/\psi f_0(500) \to J/\psi\pi^+\pi^-$.

*W. H. Liang and E.Oset. **Phys. Lett. B** 737, 70–74 (2014) .*





Branching ratios	Without $\eta\eta$ channel	With $\eta\eta$ channel	Exp.
$\mathrm{Br}(B^0 \to \phi f_0(980))$	$(4.69 \pm 0.88 \pm^{+3.96}_{-1.55}) \times 10^{-9}$	$(7.37 \pm 1.38^{+4.61}_{-2.11}) \times 10^{-9}$	$< 3.8 \times 10^{-7}$
$\mathrm{Br}(B^0 \to \phi f_0(500))$	$(6.20 \pm 1.16^{+0.24}_{-0.21}) \times 10^{-8}$	$(7.17 \pm 1.35^{+0.31}_{-0.27}) \times 10^{-8}$	-

$$\frac{\mathrm{Br}(B_s^0 \to \phi f_0(980))}{\mathrm{Br}(B_s^0 \to J/\psi f_0(980))} = (\frac{V_p}{V'_p})^2 \times 3.78$$

$$BR(B^0 \to J/\psi f_0(500)) = 8^{+1.1}_{-0.9} \times 10^{-6}$$

$$\frac{\mathrm{Br}(B_s^0 \to \phi f_0(980))}{\mathrm{Br}(B_s^0 \to J/\psi f_0(980))} = (8.75 \pm 2.87) \times 10^{-3}$$

$$\mathrm{Br}(B^0 \to \phi f_0(500)) = (5.67^{+2.64}_{-2.50}{}^{+0.02}_{-0.02}) \times 10^{-8}$$

3. Results

- B^0 and B_s^0 decays into ϕ and a vector meson.

$$t_{B^0\to\phi\rho^0} = -\frac{1}{\sqrt{2}}\tilde{V}_P'(V_{ub}V_{ud}+V_{cb}V_{cd}), \quad t_{B^0\to\phi\omega} = \frac{1}{\sqrt{2}}\tilde{V}_P'(V_{ub}V_{ud}+V_{cb}V_{cd}),$$
$$t_{B_s^0\to\phi\phi} = 2\tilde{V}_P'(V_{ub}V_{us}+V_{cb}V_{cs}), \quad t_{B_s^0\to\phi\bar{K}^{*0}} = 2\tilde{V}_P'(V_{ub}V_{ud}+V_{cb}V_{cd}),$$

$$\mathrm{Br}(B_s^0\to\phi\phi) = (1.87\pm0.15)\times10^{-5}$$

$$\mathrm{Br}(B^0\to\phi\rho^0) = \frac{\Gamma_{B^0\to\phi\rho^0}}{\Gamma_B} = (1.13\pm0.09)\times10^{-7},$$
$$\mathrm{Br}(B^0\to\phi\omega) = \frac{\Gamma_{B^0\to\phi\omega}}{\Gamma_B} = (1.13\pm0.09)\times10^{-7},$$
$$\mathrm{Br}(B_s^0\to\phi\bar{K}^{*0}) = \frac{\Gamma_{B_s^0\to\phi\bar{K}^{*0}}}{\Gamma_{B_s}} = (8.83\pm0.71)\times10^{-7},$$

Experimental results

$$\mathrm{Br}(B^0\to\phi\rho^0) < 3.3\times10^{-7},$$
$$\mathrm{Br}(B^0\to\phi\omega) < 7\times10^{-7},$$
$$\mathrm{Br}(B_s^0\to\phi\bar{K}^{*0}) = (1.14\pm0.30)\times10^{-6}.$$

4. Summary

- We studied the rare non-leptonic three body decays $B_s^0 \to \phi f_0(980) \to \phi\pi^+\pi^-$ with the final state interaction approach. Our result is in good agreement with the experimental distribution.

- We have predicted the mass spectrum of the B^0 decay, the branching ratios of the $B^0 \to \phi f_0(500) \to \phi\pi^+\pi^-$ and $B^0 \to \phi f_0(980) \to \phi\pi^+\pi^-$.

- The mass spectrum of the $B_s^0 \to \phi\rho^0$ and the predicted branching ratios for the three vector mesons production are in agreement with the experiment considering the errors.

Thank you!