

# **Study on the radiative decays of $hc$ via intermediate meson loops model**

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Ref: Q. Wu, G. Li, Y. W. Zhang, EPJC77,336 (2017)

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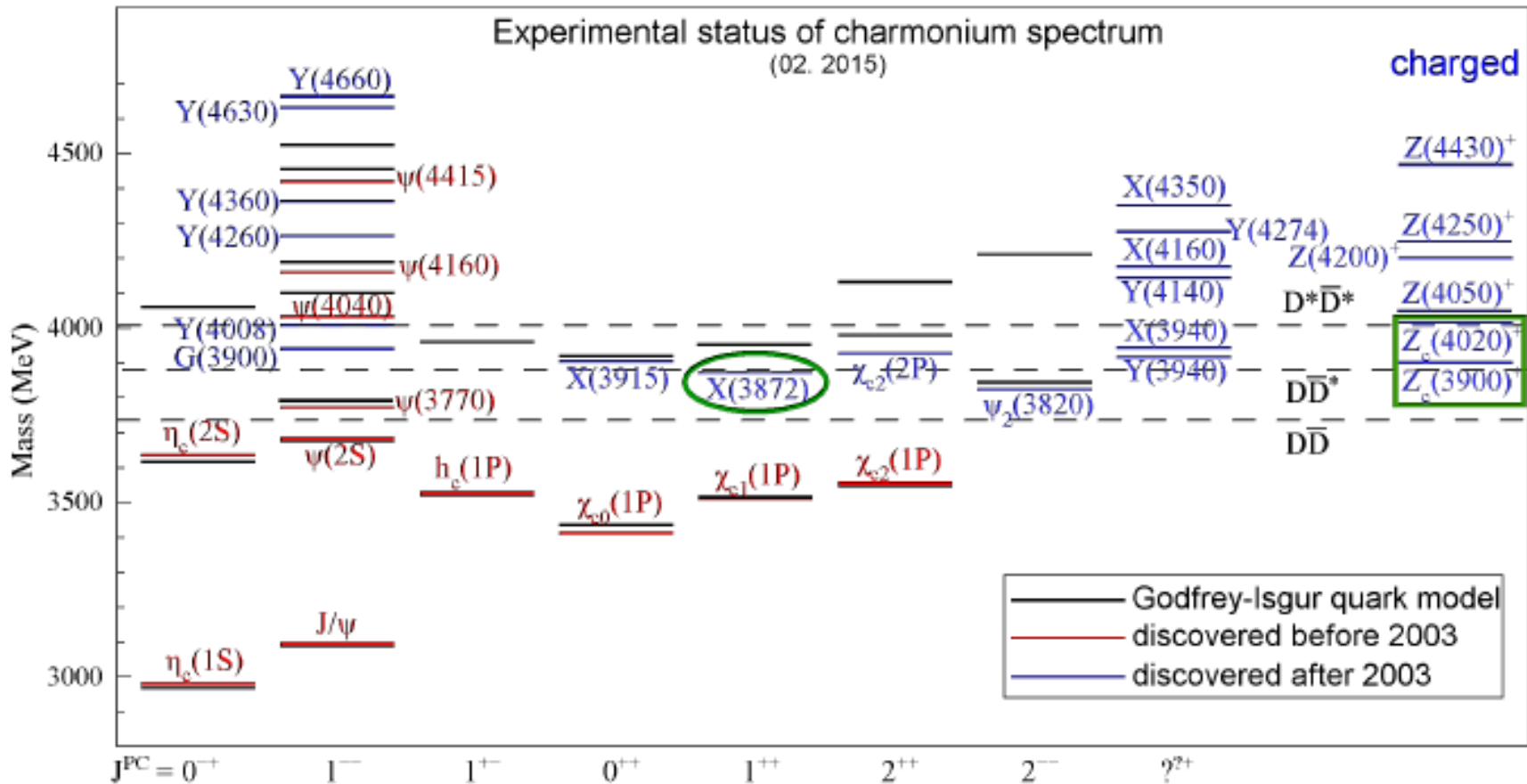


# Outline

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- **Motivation**
- **Model and Numerical results**
- **Summary**

# A summary of charmonia spectrum

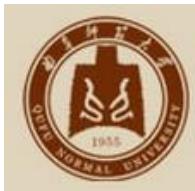




# hc decay modes

## $h_c(1P)$ DECAY MODES

Mode	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level
$\Gamma_1 J/\psi(1S)\pi^0$		
$\Gamma_2 J/\psi(1S)\pi\pi$	not seen	
$\Gamma_3 p\bar{p}$	$< 1.5 \times 10^{-4}$	90%
$\Gamma_4 \eta_c(1S)\gamma$	$(51 \pm 6) \%$	
$\Gamma_5 \pi^+ \pi^- \pi^0$	$< 2.2 \times 10^{-3}$	
$\Gamma_6 2\pi^+ 2\pi^- \pi^0$	$(2.2^{+0.8}_{-0.7}) \%$	
$\Gamma_7 3\pi^+ 3\pi^- \pi^0$	$< 2.9 \%$	



# Theoretical studies of hc

## hc Production at hadron collider

J.X. Wang, H.F. Zhang, J. Phys. G **42**, 025004 (2015).

## hc Production at ee annihilation

J.X. Wang, H.F. Zhang, Phys. Rev. D **86**, 074012 (2012).

## hc Production by the B factory

M. Beneke, F. Maltoni, I.Z. Rothstein, Phys. Rev. D **59**, 054003 (1999).  
Y. Jia, W.L. Sang, J. Xu, Phys. Rev. D **86**, 074023 (2012).

## hc decays

J.Z. Li, Y.Q. Ma, K.T. Chao, Phys. Rev. D **88**(3), 034002 (2013).

## hc production in $\psi' \rightarrow hc\pi$

F.K. Guo, C. Hanhart, G. Li, U.G. Meissner, Q. Zhao, Phys. Rev. D**82**, 034025 (2010).

## HSR evading mechanism of $hc \rightarrow B \bar{B}$

X.H. Liu, Q. Zhao, J. Phys. G **38**, 035007 (2011).

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# Experiments observation of $h_c \rightarrow \gamma\eta(\gamma\eta')$

Since  $h_c$  has negative C parity, it very likely decays into a photon plus a pseudoscalar meson, such as  $\eta_c$ ,  $\eta$  and  $\eta'$ .

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## Observation of $h_c$ Radiative Decay $h_c \rightarrow \gamma\eta'$ and Evidence for $h_c \rightarrow \gamma\eta$

A search for radiative decays of the  $P$ -wave spin singlet charmonium resonance  $h_c$  is performed based on  $4.48 \times 10^8 \psi'$  events collected with the BESIII detector operating at the BEPCII storage ring. Events of the reaction channels  $h_c \rightarrow \gamma\eta'$  and  $\gamma\eta$  are observed with a statistical significance of  $8.4\sigma$  and  $4.0\sigma$ , respectively, for the first time. The branching fractions of  $h_c \rightarrow \gamma\eta'$  and  $h_c \rightarrow \gamma\eta$  are measured to be  $\mathcal{B}(h_c \rightarrow \gamma\eta') = (1.52 \pm 0.27 \pm 0.29) \times 10^{-3}$  and  $\mathcal{B}(h_c \rightarrow \gamma\eta) = (4.7 \pm 1.5 \pm 1.4) \times 10^{-4}$ , respectively, where the first errors are statistical and the second are systematic uncertainties.



# Some puzzles in charmonium decays

- ◆ “ $\rho\pi$  puzzle” in  $J/\psi, \psi' \rightarrow VP$  decay
- ◆  $\psi(3770)$  non-D  $\bar{D}$  decay
- ◆ Large  $\eta_c \rightarrow VV$  branching ratios
- ◆ M1 transition problem in  $J/\psi, \psi' \rightarrow \gamma \eta_c, (\gamma \eta_c')$
- ◆ Isospin-violating decay of  $\psi' \rightarrow J/\psi \pi^0$ , and  $\psi' \rightarrow h_c \pi^0$
- ◆ Helicity selection rule violations
- ◆ Some issues on the recent discovered  $Z_b, Z_c$
- ◆ Could be more ... ...

**These puzzles could be related to non-pQCD mechanisms in charmonium decays due to intermediate D meson loops.**

# Heavy-meson loops effects in the production and decays of ordinary states and exotic state candidates

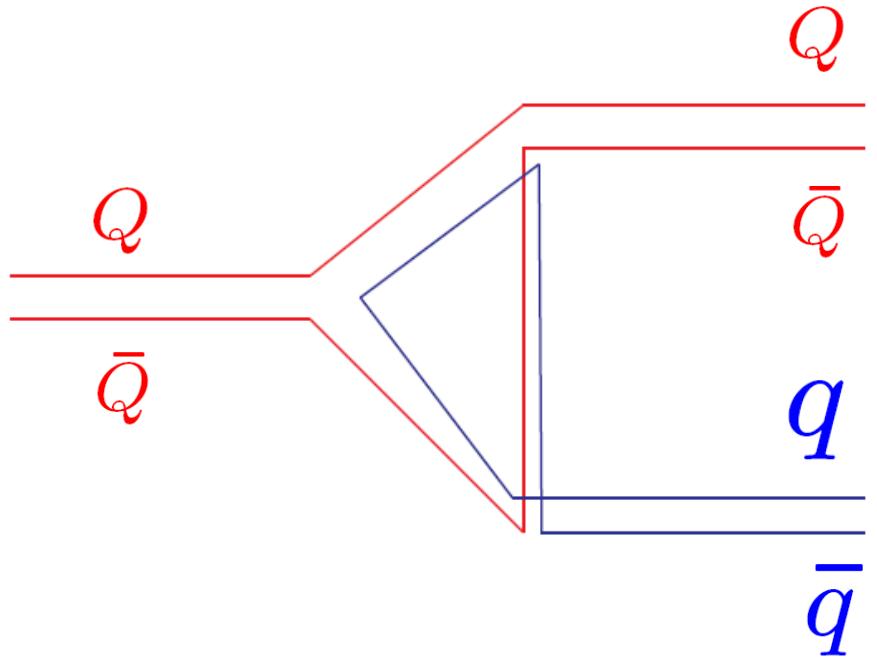


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- ◆ D. -Y. Chen, X. Liu and T. Matsuki, Phys. Rev. D 84, 074032 (2011); D. -Y. Chen, X. Liu and T. Matsuki, arXiv:1208.2411 [hep-ph]; D. -Y. Chen, X. Liu and T. Matsuki, Phys. Rev. D 88, 036008 (2013); D. -Y. Chen, X. Liu and T. Matsuki, Phys. Rev. D 88, 014034 (2013); D. -Y. Chen and X. Liu, Phys. Rev. D 84, 094003 (2011).
- ◆ M. B. Voloshin, Phys. Rev. D 87, no. 7, 074011 (2013); M. B. Voloshin, Phys. Rev. D 84, 031502 (2011).
- ◆ A. E. Bondar, A. Garmash, A. I. Milstein, R. Mizuk and M. B. Voloshin, Phys. Rev. D 84, 054010 (2011).
- ◆ G. Li, F. -I. Shao, C. -W. Zhao and Q. Zhao, Phys. Rev. D 87, no. 3, 034020 (2013); X. -H. Liu and G. Li, Phys. Rev. D 88, 014013 (2013); G. Li and X. -H. Liu, Phys. Rev. D 88, 094008 (2013).

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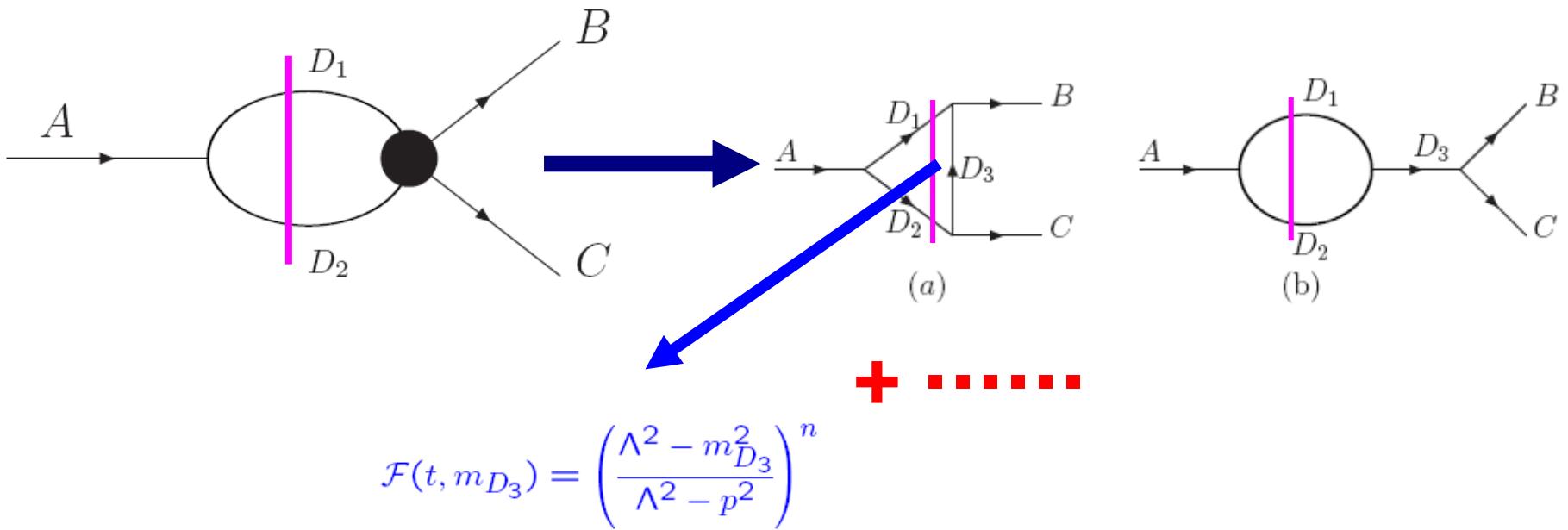


# Quark-level descriptions of hadronic loop mechanism





# Decomposition of intermediate meson loop transitions



$$h_c \rightarrow \gamma\eta(\gamma\eta')$$

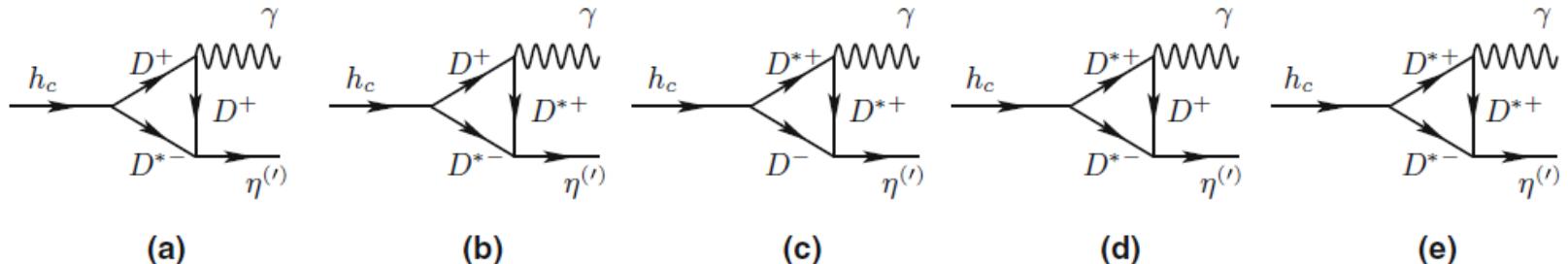


Fig. 1 The hadron-level diagrams for  $h_c \rightarrow \gamma\eta$  and  $\gamma\eta'$  via charged intermediate charmed meson loops. Similar diagrams for neutral and strange intermediate charmed meson loops

Introduce form factors to kill the divergence and also compensate the off-shell effects of intermediate mesons

Monopole  $\mathcal{F}(m_2, q_2^2) \equiv \frac{\Lambda^2 - m_2^2}{\Lambda^2 - q_2^2}$

$$M_{fi} = \int \frac{d^4 q_2}{(2\pi)^4} \sum_{B^* \text{ pol.}} \frac{V_1 V_2 V_3}{a_1 a_2 a_3} \mathcal{F}(m_2, q_2^2)$$

$$\Lambda \equiv m_2 + \alpha \Lambda_{\text{QCD}}$$

$$\Lambda_{\text{QCD}} = 220 \text{ MeV}$$

$$|\eta\rangle = \cos \alpha_P |n\bar{n}\rangle - \sin \alpha_P |s\bar{s}\rangle$$

$$\alpha_P \simeq \theta_P + \arctan \sqrt{2}.$$

$$|\eta'\rangle = \sin \alpha_P |n\bar{n}\rangle + \cos \alpha_P |s\bar{s}\rangle,$$

# Adopt the effective Lagrangian approach to do the calculation



$$\mathcal{L}_{h_c D^{(*)} \bar{D}^{(*)}} = g_{h_c D^* \bar{D}} h_c^\mu (\bar{D} \bar{D}_\mu^* + \bar{D}_\mu^* \bar{D}) + i g_{h_c D^* D^*} \varepsilon_{\mu\nu\alpha\beta} \partial^\mu h_c^\nu D^{*\alpha} \bar{D}^{*\beta}$$

$$\mathcal{L}_{D^{(*)} \bar{D}^{(*)} P} = -i g_{D^* D P} \left( D^i \partial^\mu \mathcal{P}_{ij} D_\mu^{*j\dagger} - D_\mu^{*i} \partial^\mu \mathcal{P}_{ij} D^{j\dagger} \right) + \frac{1}{2} g_{D^* D^* P} \varepsilon_{\mu\nu\alpha\beta} D_i^{*\mu} \partial^\nu P \overset{\leftrightarrow}{\partial}{}^\alpha D_j^{*\beta\dagger}$$

$$\mathcal{L}_{DD\gamma} = ie A_\mu D^- \overset{\leftrightarrow}{\partial}{}^\mu D^+ + ie A_\mu D_s^- \overset{\leftrightarrow}{\partial}{}^\mu D_s^+,$$

$$\begin{aligned} \mathcal{L}_{D^* D^* \gamma} &= ie A_\mu \left[ g^{\alpha\beta} D_\alpha^{*-} \overset{\leftrightarrow}{\partial}{}^\mu D_\beta^{*+} + g^{\mu\beta} D_\alpha^{*-} \partial^\alpha D_\beta^{*+} - g^{\mu\alpha} \partial^\beta D_\alpha^{*-} D_\beta^{*+} \right] \\ &\quad + ie A_\mu \left[ g^{\alpha\beta} D_{s\alpha}^{*-} \overset{\leftrightarrow}{\partial}{}^\mu D_{s\beta}^{*+} + g^{\mu\beta} D_{s\alpha}^{*-} \partial^\alpha D_{s\beta}^{*+} - g^{\mu\alpha} \partial^\beta D_{s\alpha}^{*-} D_{s\beta}^{*+} \right] \end{aligned}$$

$$\mathcal{L}_{D^* D \gamma} = \frac{e}{4} \varepsilon^{\mu\nu\alpha\beta} F_{\mu\nu} [g_{D^{*+} D^+ \gamma} D_{\alpha\beta}^{*+} D^+ + g_{D^{*0} D^0 \gamma} D_{\alpha\beta}^{*0} D^0 + g_{D_s^{*+} D_s^+ \gamma} D_{s\alpha\beta}^{*+} D_s^+] + H.c.$$

P. Colangelo, F. De Fazio, T.N. Pham, Phys. Rev. D 69 (2004) 054023, arXiv:hep-ph/0310084.

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# Coupling constants determination

$$g_{h_c D^* D} = -2g_1 \sqrt{m_{h_c} m_D m_{D^*}}, \quad g_{h_c D^* D^*} = 2g_1 \frac{m_{D^*}}{\sqrt{m_h}} \quad g_{D^* D \mathcal{P}} = \frac{2g}{f_\pi} \sqrt{m_D m_{D^*}}, \quad g_{D^* D^* \mathcal{P}} = \frac{g_{D^* D \mathcal{P}}}{\sqrt{m_D m_{D^*}}}$$

$$g_{D^{*+} D^+ \gamma} = 0.5 \text{ GeV}^{-1} \quad g_{D^{*0} D^0 \gamma} \simeq 2.0 \text{ GeV}^{-1} \quad g_{D_s^* D_s \gamma} = -0.3 \pm 0.1 \text{ GeV}^{-1}$$

$$g = 0.59, \quad f_\pi = 132 \text{ MeV} \quad g_1 = -\sqrt{m_{\chi_{c0}}/3}/f_{\chi_{c0}} \quad f_{\chi_{c0}} = 510 \pm 40 \text{ MeV}$$

P. Colangelo, F. De Fazio, T.N. Pham, Phys. Rev. D 69 (2004) 054023, arXiv:hep-ph/0310084.

R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio, G. Nardulli, Phys. Rep. 281 (1997) 145, arXiv:hep-ph/9605342.

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# Numerical results

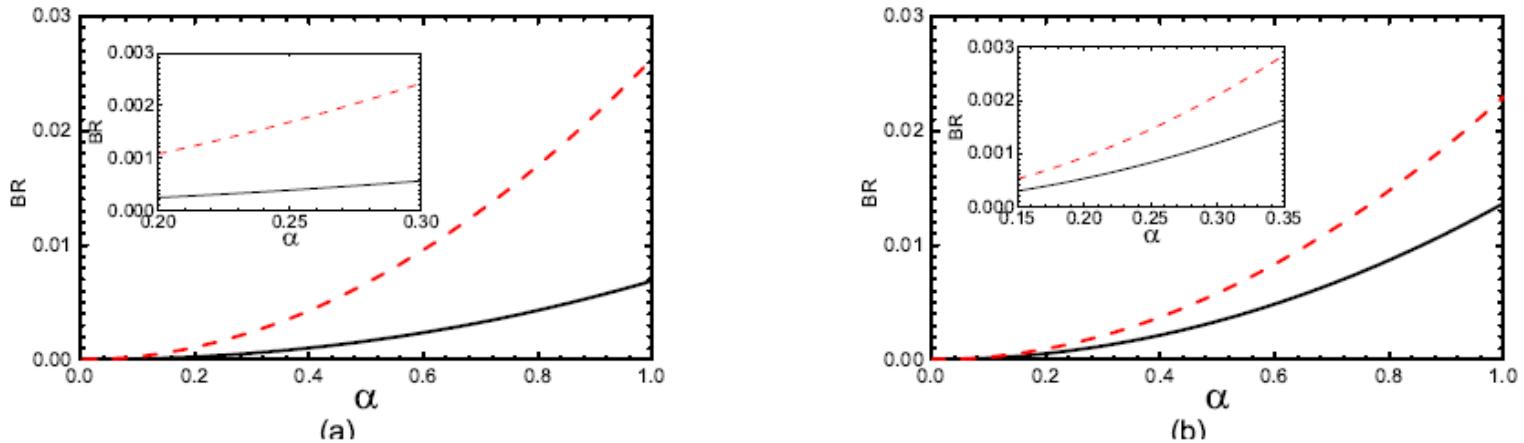


FIG. 2: (color online). (a) The  $\alpha$ -dependence of the branching ratios of  $h_c \rightarrow \gamma\eta$  (solid line) and  $\gamma\eta'$  (dashed line), respectively. The  $\eta$ - $\eta'$  mixing angle  $\theta_P = -19.3^\circ$  from Ref. [58]. (b) The  $\alpha$ -dependence of the branching ratios of  $h_c \rightarrow \gamma\eta$  (solid line) and  $\gamma\eta'$  (dashed line), respectively. The  $\eta$ - $\eta'$  mixing angle  $\theta_P = -14.4^\circ$  from Ref. [59].

With  $\theta_P = -19.3^\circ$ , the branching ratios of  $h_c \rightarrow \gamma\eta$  and  $\gamma\eta'$  can reproduce the experimental data with  $\alpha = 0.27 \pm 0.06$  and  $0.24 \pm 0.03$

With  $\theta_P = -14.4^\circ$ , the branching ratios of  $h_c \rightarrow \gamma\eta$  and  $\gamma\eta'$  can reproduce the experimental data with  $\alpha = 0.188^{+0.038}_{-0.048}$  and  $0.26^{+0.02}_{-0.03}$ .

# Numerical results

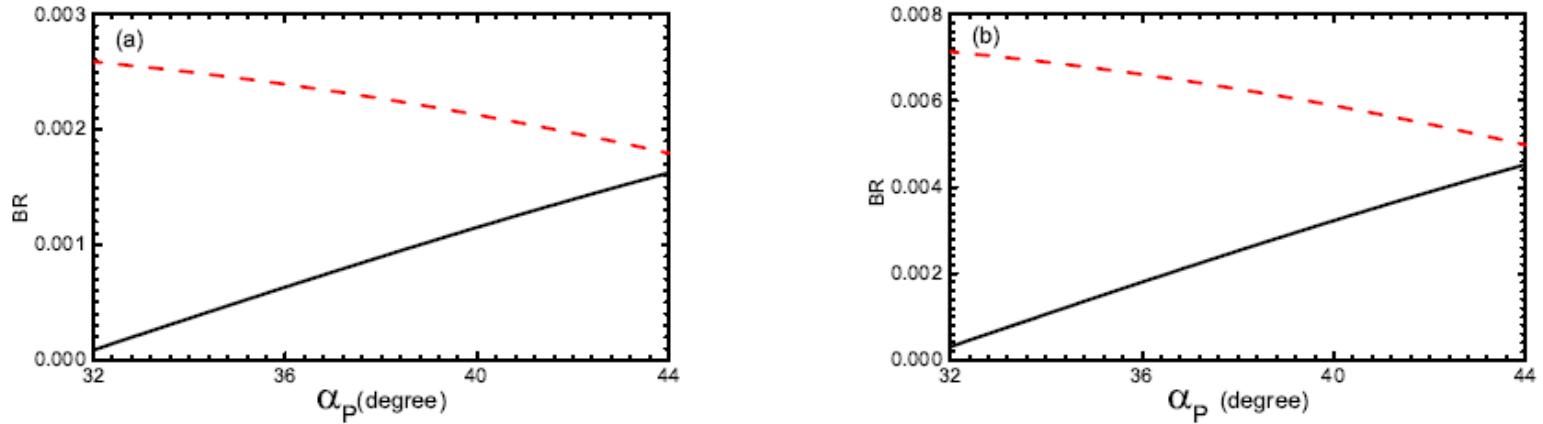


FIG. 3: (color online). (a). The branching ratios of  $h_c \rightarrow \gamma\eta$  (solid line) and  $h_c \rightarrow \gamma\eta'$  (dashed line) in terms of the  $\eta\text{-}\eta'$  mixing angle with  $\alpha = 0.3$ . (b). The branching ratios of  $h_c \rightarrow \gamma\eta$  (solid line) and  $h_c \rightarrow \gamma\eta'$  (dashed line) in terms of the  $\eta\text{-}\eta'$  mixing angle with  $\alpha = 0.5$ .

This behavior suggests how the mixing angle influences our calculated results to some extent.

# Numerical results

$$R_{hc} = \frac{Br(h_c \rightarrow \gamma\eta)}{Br(h_c \rightarrow \gamma\eta')}$$

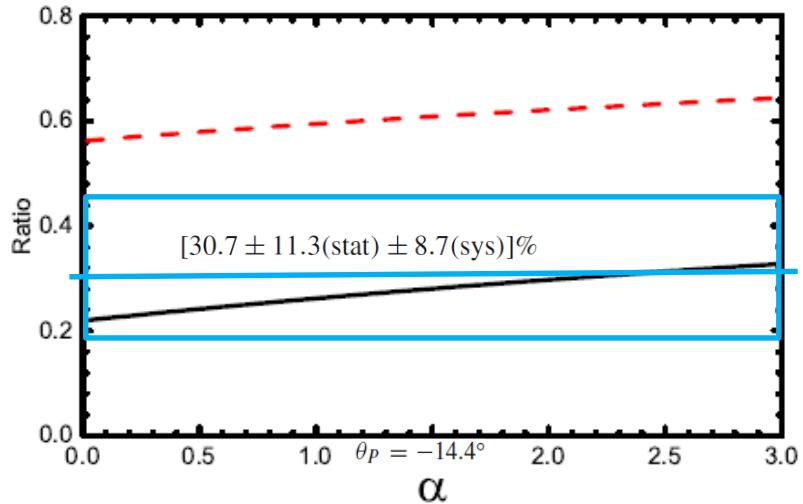


FIG. 4: (color online). The  $\alpha$ -dependence of the ratios  $R_{hc}$  with  $\eta$ - $\eta'$  mixing angle  $\theta_P = -19.3^\circ$  (solid line) and  $\theta_P = -14.4^\circ$  (dashed line), respectively.

The calculated ratio can reproduce the experimental measurements at the commonly acceptable cutoff range for  $\theta_P = -19.3^\circ$ . With  $\theta_P = -14.4^\circ$ , the calculated ratio is slightly larger than the experimental value.



# Numerical results

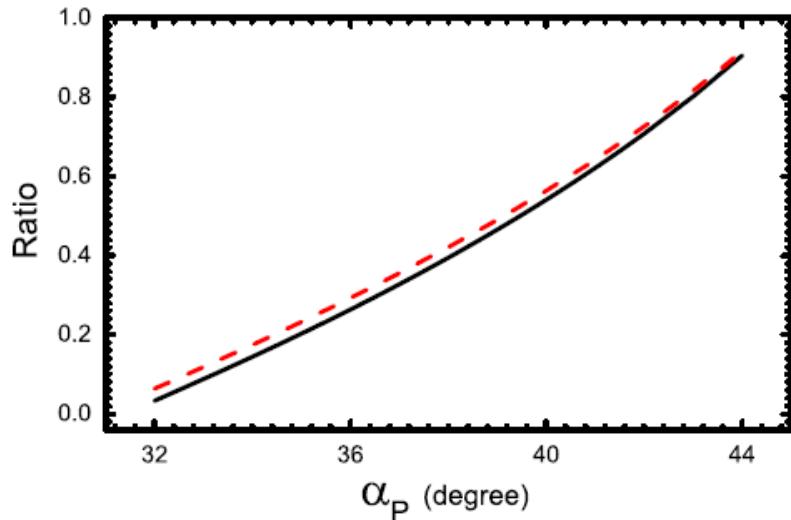


Fig. 5 The ratios  $R_{h_c}$  in terms of the  $\eta-\eta'$  mixing angle with  $\alpha = 0.3$  (solid line) and  $\alpha = 1.0$  (dashed line)

For  $\alpha = 0.3$ , our results are consistent with the experimental measurements in the range  $\alpha_p = (36.7^{+2.1}_{-2.3})^\circ$ , which corresponds to  $\theta_p = (-18.3^{+2.3}_{-2.1})^\circ$ .

For  $\alpha = 1.0$ , our results are consistent with the experimental measurements in the range  $\alpha_p = (36.2^{+2.2}_{-2.4})^\circ$ , which corresponds to  $\theta_p = (-18.5^{+2.4}_{-2.2})^\circ$ .

The calculations can give a strong constraint on the mixing angle and we expect more precise measurements on this ratio, which may help us constrain this mixing angle.



## Summary

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We investigate the radiative decay processes  $hc \rightarrow \gamma\eta$  and  $\gamma\eta'$  via an intermediate meson loop model in an effective Lagrangian approach.

The study of these two decay channels, especially their ratio, can provide us some information on the  $\eta-\eta'$  mixing, which may be helpful for us to test SU(3)-flavor symmetries in QCD.

Heavy meson loops effects play an important role in many processes, especially when the initial state mass are close to the intermediate meson pair thresholds.

Thanks for your attention !