中国科学院高能物理研究所

Institute of High Energy Physics, CAS

Evasion of the helicity selection rule and its implications in heavy quarkonium decays

Qiang Zhao

Institute of High Energy Physics, CAS

and Theoretical Physics Center for Science Facilities (TPCSF), CAS

zhaoq@ihep.ac.cn

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Motivations

- Charmonium decays as a probe for non-perturbative QCD mechanisms
- pQCD helicity selection rule is badly violated in exclusive processes
- Several exisiting puzzles in low-lying vector charmonium decays

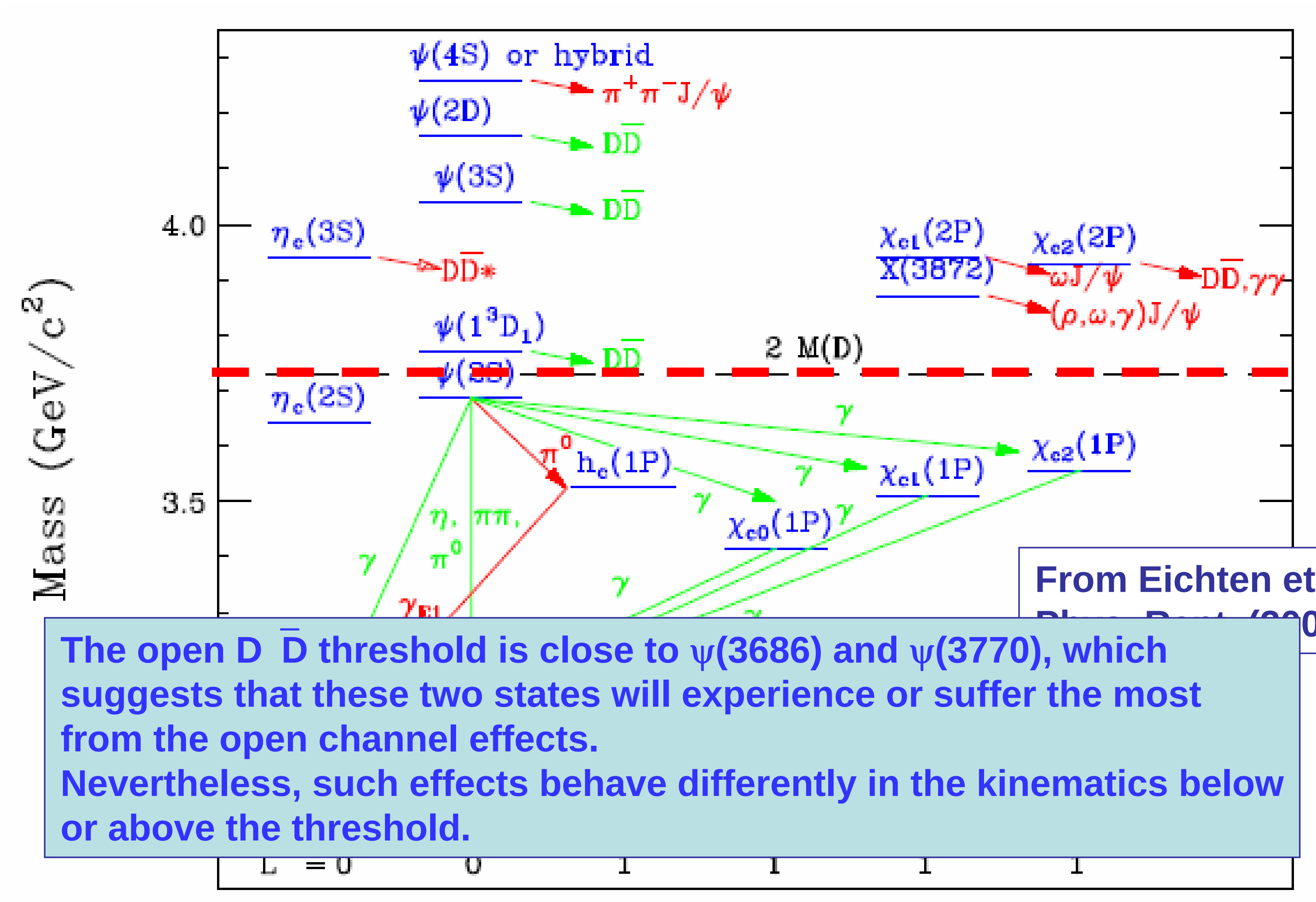
Several well-known puzzles in charmonium decays

- $\psi(3770)$ non-$D\bar{D}$ decay
- "$\rho\pi$ puzzle" in J/ψ, $\psi' \to VP$ decay
- Large $\eta_c \to VV$ branching ratios
- M1 transition problem in J/ψ, $\psi' \to \gamma\,\eta_c$, ($\gamma\,\eta_c'$)
- Isospin-violating decay of $\psi' \to J/\psi\,\pi^0$, and $\psi' \to h_c\pi^0$
- Could be more … …

Conjecture:

1) These puzzles could be related to non-pQCD mechanisms in charmonium decays due to intermediate D meson loops.
2) The intermediate meson loop transition could be a mechanism for the evasion of the helicity selection rule.

❑ Charmonium spectrum



From Eichten et al,

The open D $\bar{\text{D}}$ threshold is close to ψ(3686) and ψ(3770), which suggests that these two states will experience or suffer the most from the open channel effects.
Nevertheless, such effects behave differently in the kinematics below or above the threshold.

Outline

- Introduction to the helicity selection rule
- Long-distance contribution from intermediate hadron loop transitions
  - $\psi(3770)$ non-$D\bar{D}$ decays
  - "$\rho\pi$ puzzle"
  - $\chi_{c1} \to VV$ **and** $\chi_{c2} \to VP$
  - η_c, χ_{c0}, $h_c \to$ Baryon + Antibaryon
- Summary

Helicity selection rule

According to the perturbative method of QCD, Chernyark and Zitnitsky showed that the asymptotic behavior for some exclusive processes has a power-counting as follows:

$$BR_{J_{c\bar{c}}(\lambda)\to h_1(\lambda_1)h_2(\lambda_2)} \sim \left(\frac{\Lambda^2_{QCD}}{m_c^2}\right)^{|\lambda_1+\lambda_2|+2}$$

Chernyark and Zitnitsky, Phys. Rept. 112, 173 (1984); Brodsky and Lepage, PRD24, 2848 (1981).

The QCD leading term will contribute when $\lambda_1+\lambda_2=0$, while the next to leading order contribution will be suppressed by a factor of Λ^2_{QCD}/m_c^2

Helicity selection rule

An alternative description of this selection rule with the quantum number named “naturalness”

$$\sigma \equiv P(-1)^J$$

The selection rule requires that

$$\sigma^{initial} = \sigma_1 \sigma_2$$

Take the process J/ψ→ VP as an example $(\sigma^{initial} \neq \sigma_1 \sigma_2)$

$$\mathcal{M}_{J/\psi(\lambda_\psi) \to V(\lambda_V) P(\lambda_P)} \propto \epsilon_{\mu\nu\alpha\beta} p_\psi^\mu \epsilon_\psi^\nu (p_\psi, \lambda_\psi) p_V^\alpha \epsilon_V^{*\beta} (p_V, \lambda_V)$$

In the rest frame of initial state, it requires $\lambda_V=0$ at leading twist accuracy. ε_V can be approximately expressed as a linear combination of the final state momenta, which then results in a vanishing amplitude.

S- and P-wave charmonium exclusive decays

	PP	PV	VV
η_c	-	$(\surd)$	ϵ
$\psi(3770)$	$(\surd)$	ϵ	$(\surd)$
χ_{c0}	$\surd$	-	$\surd$
χ_{c1}	-	$(\surd)$	ϵ
χ_{c2}	$\surd$	(ϵ)	$\surd$

Feldmann and Kroll, PRD62, 074006 (2000)

"-" : forbidden by angular-momentum and parity conserv.

" ϵ " : to leading twist order forbidden in pQCD

"$\surd$" : to leading twist order allowed in pQCD

"()" : either G-parity or isospin are violated

$\psi(3770)$ non-D $\bar{D}$ decays into VP

$$BR(\chi_{c1} \to K^{*0}\bar{K}^{*0}) = (1.6 \pm 0.4) \times 10^{-3}$$ PDG2008

The helicity selection rule seems to be violated badly in charmonium decays!

$\psi(3770)$ non-$D\bar{D}$ decay

-- IML as a mechanism for evading the helicity selection rule

$\psi(3770)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\psi(3770)$ MASS

OUR FIT includes measurements of $m_{\psi(2S)}$, $m_{\psi(3770)}$, and $m_{\psi(3770)} - m_{\psi(2S)}$.

VALUE (MeV)			*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3772.92±0.35			**OUR FIT**	Error includes scale factor of 1.1.			
3775.2	**±1.7**		**OUR AVERAGE**	Error includes scale factor of 1.4. See the ideogram below.			
3772.0	±1.9			[1] ABLIKIM	08D	BES2	$e^+e^- \rightarrow$ hadrons
3775.5	±2.4	±0.5	57	AUBERT	08B	BABR	$B \rightarrow D\overline{D}K$
3776	±5	±4	68	BRODZICKA	08	BELL	$B^+ \rightarrow D^0\overline{D}^0K^+$
3778.8	±1.9	±0.9		AUBERT	07BE	BABR	$e^+e^- \rightarrow D\overline{D}\gamma$

Particle Data Group 2008

$\psi(3770)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
27.3±1.0 OUR FIT					
27.6±1.0 OUR AVERAGE					
30.4± 8.5		[4] ABLIKIM	08D	BES2	$e^+e^- \to$ hadrons
27 ±10 ±5	68	BRODZICKA	08	BELL	$B^+ \to D^0\overline{D}^0K^+$
28.5± 1.2±0.2		ABLIKIM	07E	BES2	$e^+e^- \to$ hadrons
23.5± 3.7±0.9		AUBERT	07BE	BABR	$e^+e^- \to D\overline{D}\gamma$
26.9± 2.4±0.3		ABLIKIM	06L	BES2	$e^+e^- \to$ hadrons
24 ± 5		SCHINDLER	80	MRK2	e^+e^-
24 ± 5		BACINO	78	DLCO	e^+e^-
28 ± 5		RAPIDIS	77	LGW	e^+e^-

[4] Reanalysis of data presented in BAI 02C. From a global fit over the center-of-mass energy region 3.7–5.0 GeV covering the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$ resonances. Phase angle fixed in the fit to $\delta = 0°$.

Particle Data Group 2008

$\psi(3770)$ DECAY MODES

In addition to the dominant decay mode to $D\overline{D}$, $\psi(3770)$ was found to decay into the final states containing the J/ψ (BAI 05, ADAM 06). ADAMS 06 and HUANG 06A searched for various decay modes with light hadrons and found a statistically significant signal for the decay to $\phi\eta$ only (ADAMS 06).

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$D\overline{D}$	(85.3 ± 3.2) %	
Γ_2	$D^0\overline{D}^0$	(48.7 ± 3.2) %	
Γ_3	D^+D^-	(36.1 ± 2.8) %	
Γ_4	$J/\psi\pi^+\pi^-$	$(1.93 \pm 0.28) \times 10^{-3}$	
Γ_5	$J/\psi\pi^0\pi^0$	$(8.0 \pm 3.0) \times 10^{-4}$	
Γ_6	$J/\psi\eta$	$(9 \pm 4) \times 10^{-4}$	
Γ_7	$J/\psi\pi^0$	$< 2.8 \times 10^{-4}$	CL=90%
Γ_8	$\gamma\chi_{c0}$	$(7.3 \pm 0.9) \times 10^{-3}$	
Γ_9	$\gamma\chi_{c1}$	$(2.9 \pm 0.6) \times 10^{-3}$	
Γ_{10}	$\gamma\chi_{c2}$	$< 9 \times 10^{-4}$	CL=90%
Γ_{11}	e^+e^-	$(9.7 \pm 0.7) \times 10^{-6}$	S=1.2
Γ_{26}	$\phi\eta$	$(3.1 \pm 0.7) \times 10^{-4}$	

Particle Data Group 2008

❑ ψ(3770) non-D $\bar{D}$ decay

■ Experimental discrepancies:

Exclusive D $\bar{D}$ cross sections are measured at BES and CLEO-c:

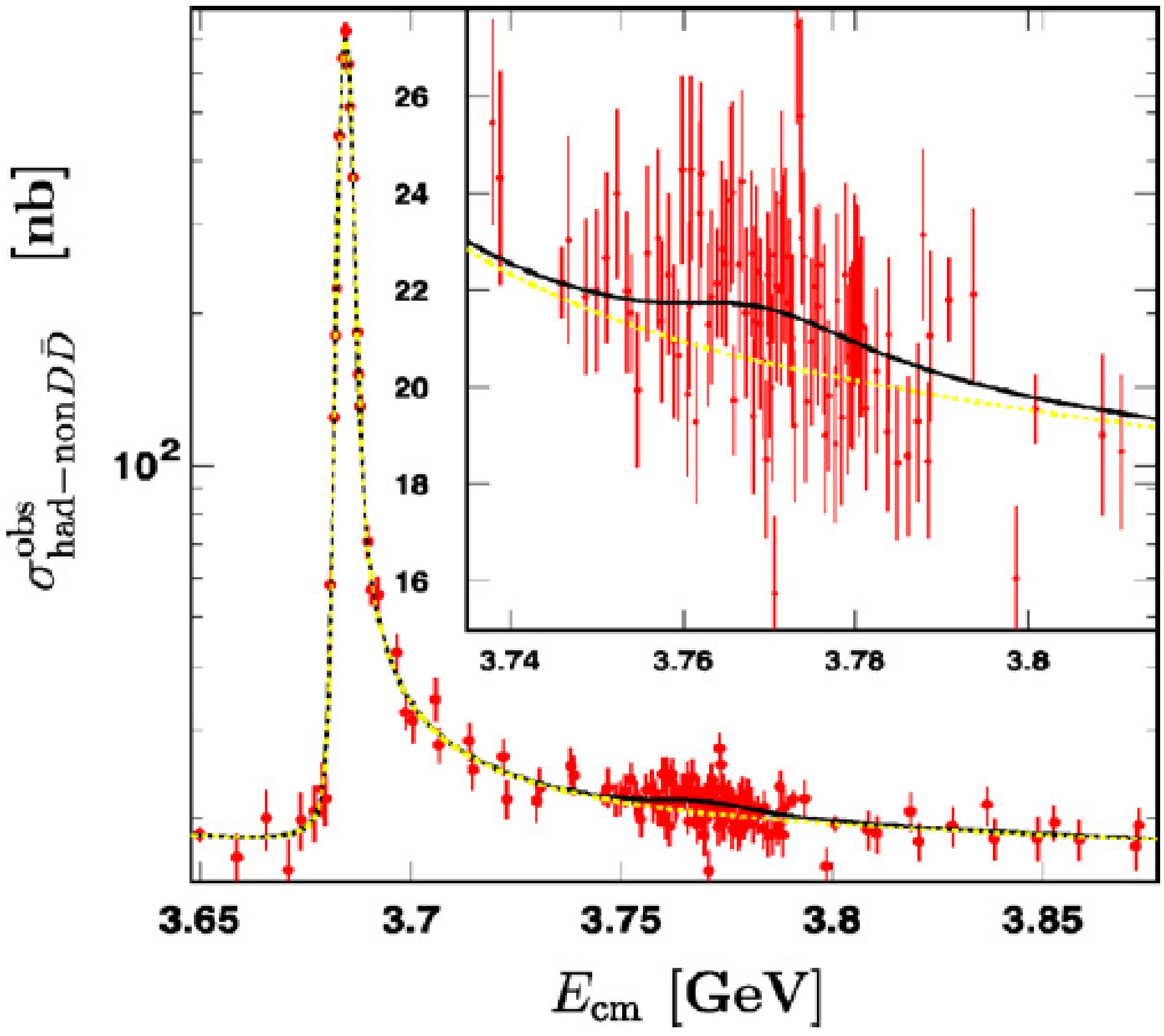
M. Ablikim *et al.*, Phys. Rev. Lett. **97**, 121801 (2006); M. Ablikim *et al.*, Phys. Lett. B **641**, 145 (2006); M. Ablikim *et al.*, Phys. Rev. D **76**, 122002 (2007); M. Ablikim *et al.*, Phys. Lett. B **659**, 74 (2008).

$$\boxed{\sigma_{D\bar{D}}^{\text{obs}} = (6.07 \pm 0.40 \pm 0.35)\ \text{nb}}$$

S. Dobbs *et al.*, Phys. Rev. D **76**, 112001 (2007).

Quantity	Value
$\sigma(e^+e^- \to D^0\bar{D}^0)$	$(3.66 \pm 0.03 \pm 0.06)$ nb
$\sigma(e^+e^- \to D^+D^-)$	$(2.91 \pm 0.03 \pm 0.05)$ nb
$\sigma(e^+e^- \to D\bar{D})$	$(6.57 \pm 0.04 \pm 0.10)$ nb
$\sigma(e^+e^- \to D^+D^-)/\sigma(e^+e^- \to D^0\bar{D}^0)$	$0.79 \pm 0.01 \pm 0.01$

Inclusive non-D $\bar{D}$ hadronic cross sections from BES



BES Collaboration / Physics Letters B 659 (2008) 74–79

- **BES-II: non-D $\bar{\mathrm{D}}$ branching ratio can be up to 15%**

$$\boxed{\sigma^{\mathrm{obs}}_{\mathrm{non}\text{-}D\bar{D}} = (1.08 \pm 0.40 \pm 0.15)\ \mathrm{nb}}$$

- **CLEO-c:** $\mathrm{BR}_{\psi(3770)\to D\bar{D}} = (103.0 \pm 1.4^{+5.1}_{-6.8})\%$

The lower bound suggests the maximum of non-D $\bar{\mathrm{D}}$ b.r. is about 6.8%.

Updated results from CLEO-c : 1004.1358[hep-ex]

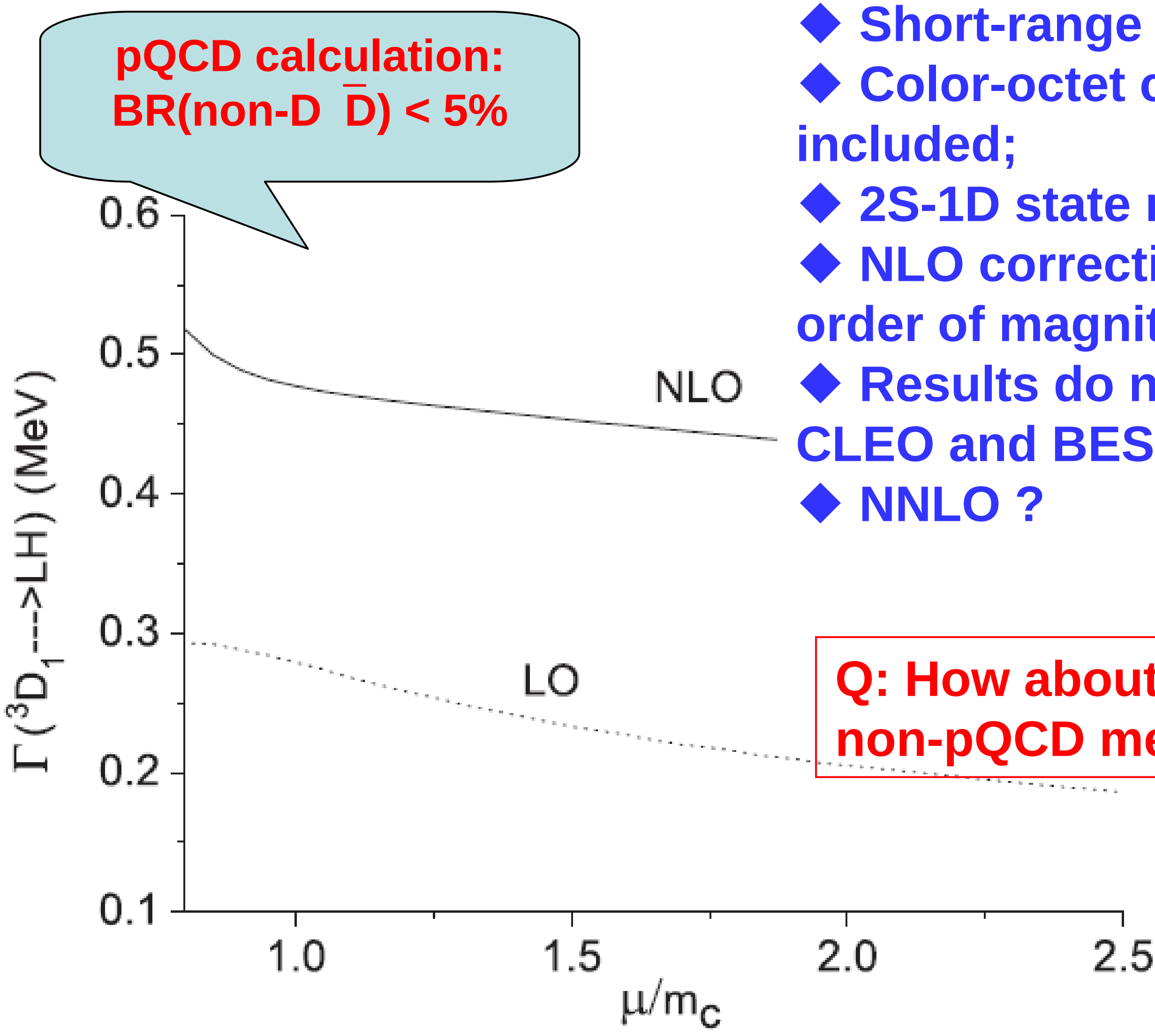
$$\mathcal{B}(\psi(3770) \to \text{non-}D\bar{D}) = (-3.3 \pm 1.4^{+6.6}_{-4.8})\ \%$$

$$< 9\% \text{ at } 90\% \text{ confidence level}$$

■ Theoretical discrepancies:

In theory

Y. P. Kuang and T. M. Yan, Phys. Rev. D **41**, 155 (1990).
Y. B. Ding, D. H. Qin, and K. T. Chao, Phys. Rev. D **44**, 3562 (1991).
J. L. Rosner, Phys. Rev. D **64**, 094002 (2001).
J. L. Rosner, Ann. Phys. (N.Y.) **319**, 1 (2005).
E. Eichten, S. Godfrey, H. Mahlke, and J. L. Rosner, Rev. Mod. Phys. **80**, 1161 (2008).
M. B. Voloshin, Phys. Rev. D **71**, 114003 (2005).
N. N. Achasov and A. A. Kozhevnikov, Phys. At. Nucl. **69**, 988 (2006).
Z. G. He, Y. Fan, and K. T. Chao, Phys. Rev. Lett. **101**, 112001 (2008).



- Short-range pQCD transition;
- Color-octet contributions are included;
- 2S-1D state mixings are small;
- NLO correction is the same order of magnitude as LO.
- Results do not favor both CLEO and BES
- NNLO ?

Q: How about the long-range non-pQCD mechanisms?

Z. G. He, Y. Fan, and K. T. Chao, Phys. Rev. Lett. **101**, 112001 (2008).

❑ Recognition of possible long-range transition mechanisms

pQCD (non-relativistic QCD):

◆If the heavy $c\bar{c}$ are good constituent degrees of freedom, c and $\bar{c}$ annihilate at the origin of the ($c\bar{c}$) wavefunction. Thus, NRQCD should be valid.

◆pQCD is dominant in $\psi(3770) \to$ light hadrons via 3g exchange, hence the OZI rule will be respected.

$\Rightarrow$ ψ(3770) non-$D\bar{D}$ decay will be suppressed.

Non-pQCD:

◆Are the constituent $c\bar{c}$ good degrees of freedom for $\psi(3770) \to$ light hadrons? Or is pQCD dominant at all?

◆If not, how the OZI rule is violated?

$\Rightarrow$ Could the OZI-rule violation led to sizeable ψ(3770) non-$D\bar{D}$ decay?

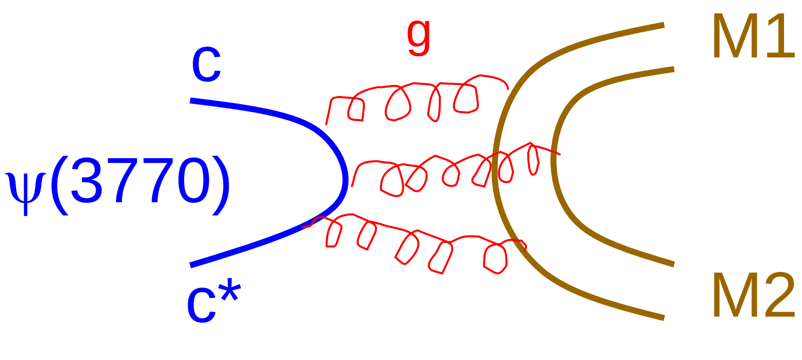
$\Rightarrow$ How to quantify it?

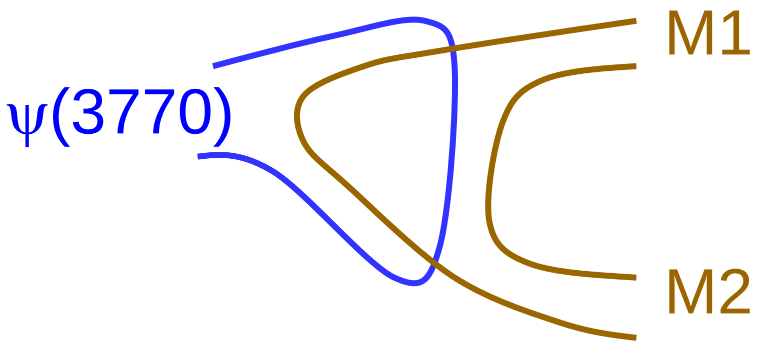
❑ Recognition of long-range transition mechanisms

<u>in ψ(3770) non-D $\bar{D}$ decays</u>

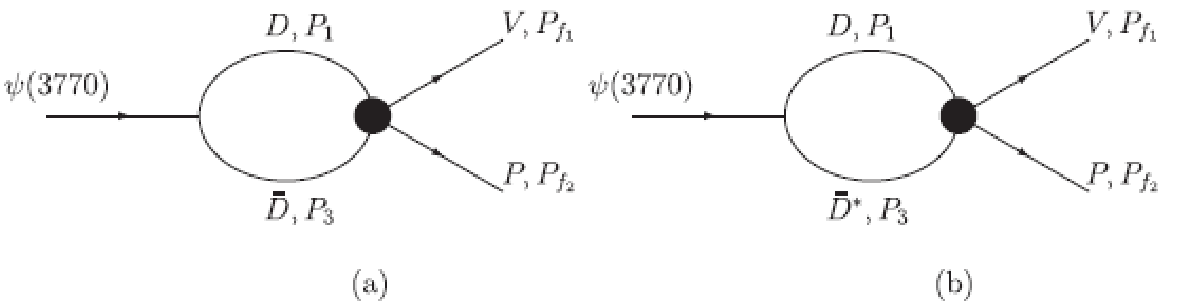
Short-range pQCD transition via single OZI (SOZI) process

Long-range OZI evading transition





ψ(3770) decays to vector and pseudoscalar via $D\bar{D}$ and $D\bar{D}^*$ + c.c. rescatterings



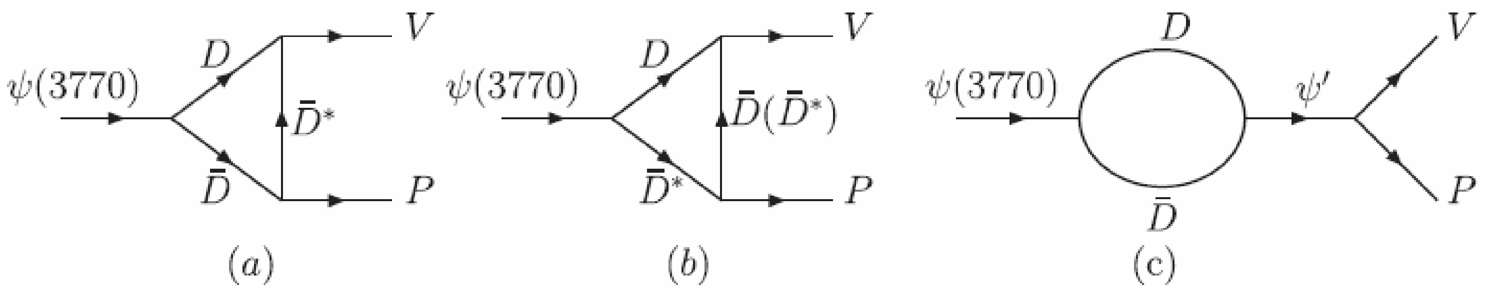


FIG. 2. The t- [(a) and (b)] and s-channel (c) meson loops in $\psi(3770) \to VP$.

Y.-J. Zhang, G. Li and Q. Zhao, Phys. Rev. Lett. 102, 172001 (2009)

The V → VP transition has only one single coupling of anti-symmetric tensor form

Transition amplitude can thus be decomposed as:

Long-range non-pQCD amp.

Short-range pQCD amp.

$$\mathcal{M}_{fi} = \mathcal{M}^L + e^{i\delta}\mathcal{M}^{\text{SOZI}} \equiv i[g_L + e^{i\delta} g_S \mathcal{F}_S(\vec{p}_V)] \times \boxed{\varepsilon_{\alpha\beta\mu\nu} P_\psi^\alpha \epsilon_\psi^\beta P_V^\mu \epsilon_V^{*\nu}} / M_{\psi(3770)},$$

■ Effective Lagrangians for meson couplings

$$\mathcal{L}_{\psi D\bar{D}} = g_{\psi D\bar{D}}\{D\partial_\mu \bar{D} - \partial_\mu D\bar{D}\}\psi^\mu,$$
$$\mathcal{L}_{\mathcal{V}D\bar{D}^*} = -ig_{\mathcal{V}D\bar{D}^*}\epsilon_{\alpha\beta\mu\nu}\partial^\alpha \mathcal{V}^\beta \partial^\mu \bar{D}^{*\nu} D + \text{H.c.},$$
$$\mathcal{L}_{\mathcal{P}D^*\bar{D}^*} = -ig_{\mathcal{P}D^*\bar{D}^*}\epsilon_{\alpha\beta\mu\nu}\partial^\alpha D^{*\beta}\partial^\mu \bar{D}^{*\nu}\mathcal{P} + \text{H.c.},$$
$$\mathcal{L}_{\mathcal{P}\bar{D}D^*} = g_{D^*\mathcal{P}\bar{D}}\{\bar{D}\partial_\mu \mathcal{P} - \partial_\mu \bar{D}\mathcal{P}\}D^{*\mu} + \text{H.c.},$$

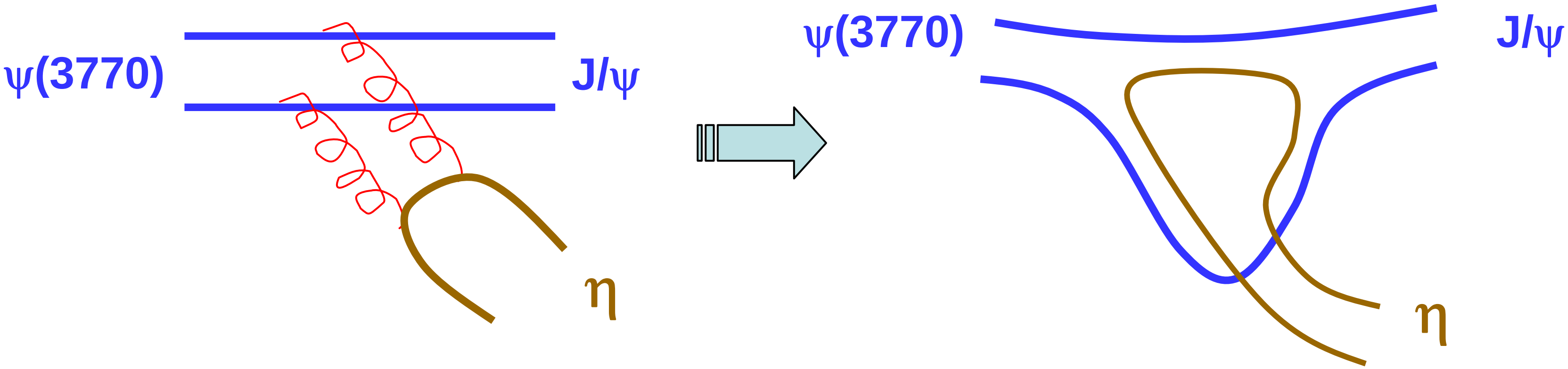
Coupling constants: $\boxed{g_{\psi(3770)D^+D^-} = 12.71 \quad g_{\psi(3770)D^0\bar{D}^0} = 12.43}$

$$g_{D^*D\pi} = \frac{2}{f_\pi} g\sqrt{m_D m_{D^*}}, \qquad g_{D^*D^*\pi} = \frac{g_{D^*D\pi}}{\tilde{M}_D},$$
$$g_{D^*D\rho} = \sqrt{2}\lambda g_\rho, \qquad g_{DD\rho} = g_{D^*D\rho}\tilde{M}_D,$$

where $f_\pi = 132$ MeV is the pion decay constant, and $\tilde{M}_D \equiv \sqrt{m_D m_{D^*}}$ sets a mass scale. The parameters g_ρ respect the relation $g_\rho = m_\rho / f_\pi$ [20]. We take $\lambda = 0.56\ \text{GeV}^{-1}$ and $g = 0.59$ [21,22].

Cacalbuoni et al, Phys. Rept. (1997).

i) Determine long-range parameter in ψ(3770) → J/ψ η.



$$\mathrm{BR}^{\mathrm{exp}}_{J/\psi\,\eta} = (9.0 \pm 4) \times 10^{-4}$$

$$\mathcal{F}(q^2) = \left(\frac{\Lambda^2 - m_{\mathrm{ex}}^2}{\Lambda^2 - q^2}\right)^2,$$

where $\Lambda \equiv m_{\mathrm{ex}} + \alpha\Lambda_{\mathrm{QCD}}$, with $\Lambda_{\mathrm{QCD}} = 0.22$ GeV.

$$\boxed{\alpha = 1.73}$$

- Soft η production
- η-η′ mixing is considered
- a form factor is needed to kill the loop integral divergence

The cut-off energy for the divergent meson loop integral can be determined by data, and then extended to other processes.

ii) Determine short-range parameter combing $\psi(3770) \to \phi\eta$ and $\psi(3770) \to \rho\pi$.

Relative strengths among pQCD transition amplitudes:

$$g_S^{\rho^0\pi^0} : g_S^{K^{*+}K^-} : g_S^{\omega\eta} : g_S^{\omega\eta'} : g_S^{\phi\eta} : g_S^{\phi\eta'}$$
$$= 1:1:\cos\alpha_P : \sin\alpha_P : (-\sin\alpha_P) : \cos\alpha_P$$

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

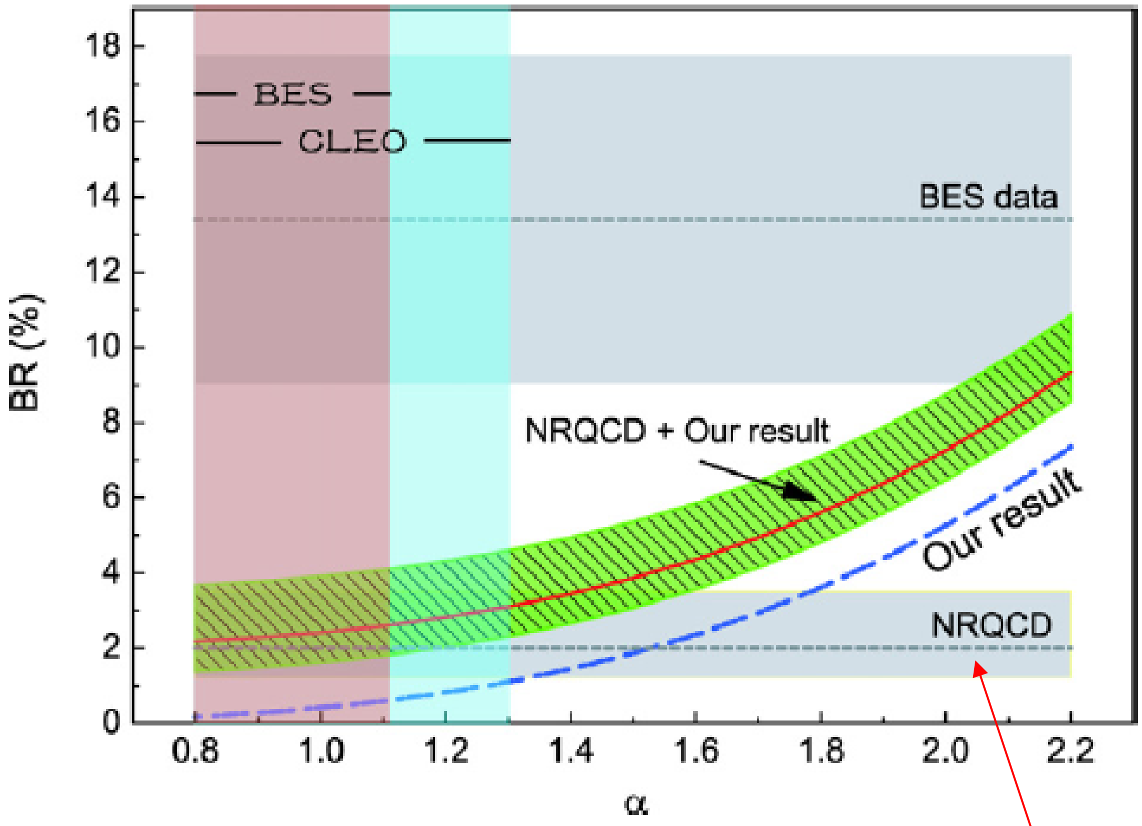
With $\alpha = 1.73$ fixed, we can then determine the other two parameters $g_S \equiv g_S^{\rho^0\pi^0} = 0.085$ and $\delta = -66°$ by experimental data, i.e., $\underline{\mathrm{BR}_{\phi\eta} = (3.1 \pm 0.7) \times 10^{-4}}$ [8] and $\underline{\mathrm{BR}_{\rho\pi} < 0.24\%}$ with C.L. of 90% [28].

iii) Predictions for $\psi(3770) \to$ VP.

BR ($\times 10^{-4}$)	t channel	s channel	SOZI	Total
$J/\psi\,\eta$	8.44	0.13	$\cdots$	9.0
$J/\psi\,\pi^0$	0.1	2.58×10^{-2}	$\cdots$	4.4×10^{-2}
$\rho\pi$	34.45	7.69×10^{-5}	8.53	24.0
$K^{*+}K^{-}$ + c.c	10.97	6.83×10^{-6}	5.72	8.91
$K^{*0}\bar{K}^0$ + c.c	11.80	4.38×10^{-5}	5.72	9.90
$\phi\eta$	1.25	1.13×10^{-5}	1.16	3.1
$\phi\eta'$	0.87	2.53×10^{-5}	1.86	3.78
$\omega\eta$	6.83	9.64×10^{-6}	1.88	4.69
$\omega\eta'$	0.58	2.87×10^{-5}	0.97	0.39
$\rho\eta$	1.88×10^{-2}	1.77×10^{-5}	$\cdots$	1.8×10^{-2}
$\rho\eta'$	1.08×10^{-2}	1.54×10^{-5}	$\cdots$	1.0×10^{-2}
$\omega\pi^0$	2.57×10^{-2}	1.82×10^{-5}	$\cdots$	2.5×10^{-2}
Sum	75.34	0.16	25.84	63.87

By varying δ, but keeping the $\phi\eta$ rate unchanged (i.e. g_S will be changed), we obtain a lower bound for the sum of branching ratios $\sim 0.41\%$.

X. Liu, B. Zhang and X.Q. Li, PLB675, 441(2009)



Z. G. He, Y. Fan, and K. T. Chao, Phys. Rev. Lett. **101**, 112001 (2008).

■ Further evidence for the role played by IHL

◆ "$\rho\pi$ puzzle" in J/ψ, $\psi(3686) \to VP$.

[Zhao, Li and Chang, PLB645, 173(2007); Li, Zhao, and Chang, JPG (2008); Zhao, Li and Chang, arXiv:0812.4092[hep-ph], and work in progress]

◆ Isospin-violating decays as a probe for IML, e.g. $\psi' \to J/\psi\ \pi^0$, $h_c\pi^0$, etc.

[Guo, Hanhart, and Meissner, PRL103, 082003(2009); Guo et al, 1002.2712[hep-ph], and also talk by Hanhart at this conference]

◆ An analogue to the $\psi(3770)$ non-$D\bar{D}$ decay: the $\phi(1020)$ non-$K\bar{K}$ decay

[Li, Zhao and Zou, PRD77, 014010(2008); Li, Zhang and Zhao, JPG36, 085008(2009)].

- **Helicity selection rule evading in $\chi_{c1} \rightarrow VV$, $\chi_{c2} \rightarrow VP$, and η_c, χ_{c0}, $h_c \rightarrow B \bar{B}$,**

[Liu and Zhao, PRD81, 014017(2010); arXiv: 1004.0496]

- **More to be studied in order to gain systematic insights into the underlying mechanisms …**

Thanks !

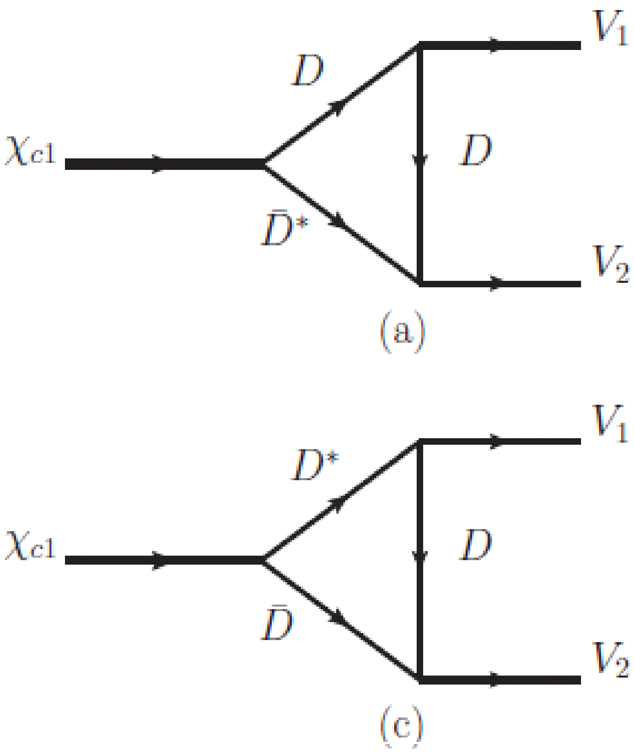
Backup slides

$\chi_{c1} \rightarrow$ VV and $\chi_{c2} \rightarrow$ VP

-- further evidence for the IML

Long-distance contribution

Intermediate charmed meson loop transitions in $\chi_{c1} \rightarrow VV$



Wavefunctions and effective Lagrangian based on heavy quark symmetry and SU(3) flavor symmetry

The spin multiplet for these four P-wave charmonium states are expressed as

$$P_{c\bar{c}}^{\mu} = \left(\frac{1+\not{v}}{2}\right)\left(\chi_{c2}^{\mu\alpha}\gamma_\alpha + \frac{1}{\sqrt{2}}\epsilon_{\mu\nu\alpha\beta}v^\alpha\gamma^\beta\chi_{c1}^{\nu} + \frac{1}{\sqrt{3}}(\gamma^\mu - v^\mu)\chi_{c0} + h_c^\mu\gamma_5\right)\left(\frac{1-\not{v}}{2}\right).$$

The charmed and anti-charmed meson triplet read

$$\begin{aligned} H_{1i} &= \left(\frac{1+\not{v}}{2}\right)[\mathcal{D}_i^{*\mu}\gamma_\mu - \mathcal{D}_i\gamma_5], \\ H_{2i} &= [\bar{\mathcal{D}}_i^{*\mu}\gamma_\mu - \bar{\mathcal{D}}_i\gamma_5]\left(\frac{1-\not{v}}{2}\right), \end{aligned}$$

where $\mathcal{D}^{(*)} = (D^{0(*)}, D^{+(*)}, D_s^{+(*)})$.

Effective Lagrangian for the P-wave charmonium couplings to charmed mesons:

$$\mathcal{L}_1 = ig_1 Tr[P_{c\bar{c}}^{\mu}\bar{H}_{2i}\gamma_\mu\bar{H}_{1i}] + H.c.$$

The effective Lagrangians describe the couplings of charmed mesons to light hadrons read

$$
\begin{aligned}
\mathcal{L}_{\mathcal{D}\mathcal{D}\mathcal{V}} &= -ig_{DDV}\bar{\mathcal{D}}_i\overleftrightarrow{\partial}_\mu\mathcal{D}_j(\mathcal{V}^\mu)_{ij},\\
\mathcal{L}_{\mathcal{D}^*\mathcal{D}\mathcal{V}} &= -2f_{D^*DV}\epsilon_{\mu\nu\alpha\beta}(\partial^\mu\mathcal{V}^\nu)_{ij}(\bar{\mathcal{D}}_i\overleftrightarrow{\partial}^\alpha\mathcal{D}_j^{*\beta}-\bar{\mathcal{D}}_i^{*\beta}\overleftrightarrow{\partial}^\alpha\mathcal{D}_j),\\
\mathcal{L}_{\mathcal{D}^*\mathcal{D}^*\mathcal{V}} &= ig_{D^*D^*V}\bar{\mathcal{D}}_i^{*\nu}\overleftrightarrow{\partial}_\mu\mathcal{D}_{j\nu}^*(\mathcal{V}^\mu)_{ij}+4if_{D^*D^*V}\bar{\mathcal{D}}_i^{*\mu}(\partial_\mu\mathcal{V}_\nu-\partial_\nu\mathcal{V}_\mu)_{ij}\mathcal{D}_j^{*\nu},\\
\mathcal{L}_{\mathcal{D}^*\mathcal{D}\mathcal{P}} &= -ig_{D^*DP}(\bar{\mathcal{D}}_i\partial_\mu\mathcal{P}_{ij}\mathcal{D}_j^{*\mu}-\bar{\mathcal{D}}_i^{*\mu}\partial_\mu\mathcal{P}_{ij}\mathcal{D}_j),\\
\mathcal{L}_{\mathcal{D}^*\mathcal{D}^*\mathcal{P}} &= \frac{1}{2}g_{D^*D^*P}\epsilon_{\mu\nu\alpha\beta}\bar{\mathcal{D}}_i^{*\mu}\partial^\nu\mathcal{P}_{ij}\overleftrightarrow{\partial}^\alpha\mathcal{D}_j^{*\beta},
\end{aligned}
$$

$$
\mathcal{V}=\begin{pmatrix}
\frac{1}{\sqrt{2}}(\rho^0+\omega) & \rho^+ & K^{*+}\\
\rho^- & \frac{1}{\sqrt{2}}(-\rho^0+\omega) & K^{*0}\\
K^{*-} & \bar{K}^{*0} & \phi
\end{pmatrix}
$$

$$
\mathcal{P}=\begin{pmatrix}
\frac{1}{\sqrt{2}}(\pi^0+\eta) & \pi^+ & K^+\\
\pi^- & \frac{1}{\sqrt{2}}(-\pi^0+\eta) & K^0\\
K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta
\end{pmatrix}
$$

Transition amplitudes for $\chi_{c1} \to$ VV

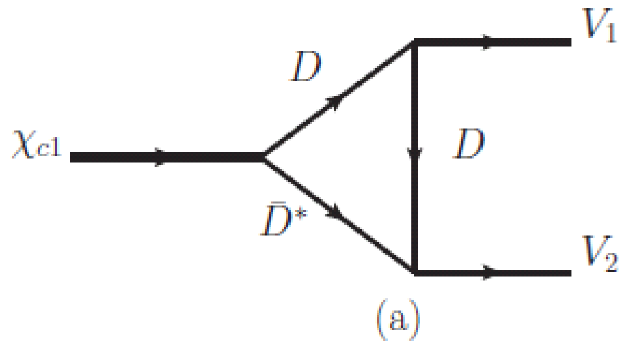
With an effective Lagrangian method considering heavy quark symmetry and SU(3) symmetry, the IML amplitudes are expressed as

$$
\begin{aligned}
\mathcal{M}_{1a} &= 2ig_{DD^*\chi_{c1}} g_{DDV} f_{D^*DV} \epsilon_\lambda^{\chi_{c1}} \epsilon_1^{*\sigma} \epsilon_2^{*\tau} \int \frac{d^4q}{(2\pi)^4} \\
&\times (q_{1\sigma} + q_\sigma) \epsilon_{\mu\tau\alpha\beta} p_2^\mu (q^\alpha - q_2^\alpha) \frac{g^{\lambda\beta} - q_2^\lambda q_2^\beta / m_{D^*}^2}{D_a D_1 D_2} \mathcal{F}(q^2) \\
\mathcal{M}_{1b} &= 2ig_{DD^*\chi_{c1}} g_{DDV} f_{D^*DV} \epsilon_\lambda^{\chi_{c1}} \epsilon_1^{*\sigma} \epsilon_2^{*\tau} \int \frac{d^4q}{(2\pi)^4} \\
&\times \epsilon_{\mu\sigma\alpha\beta} p_1^\mu (q_1^\alpha + q^\alpha) \left[g_{D^*D^*V} (q_{2\tau} - q_\tau) g_{\gamma\delta} + 4 f_{D^*D^*V} (p_{2\delta} g_{\tau\gamma} - p_{2\gamma} g_{\delta\tau}) \right] \\
&\times (g^{\beta\gamma} - q^\beta q^\gamma / m_{D^*}^2)(g^{\lambda\delta} - q_2^\lambda q_2^\delta / m_{D^*}^2) \times \frac{1}{D_b D_1 D_2} \mathcal{F}(q^2)
\end{aligned}
$$

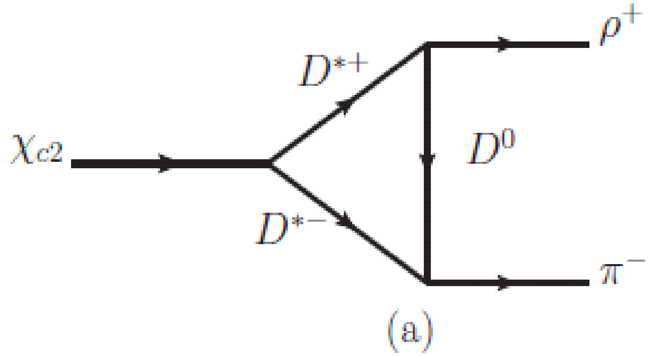
The phenomenologically introduced form factor:

$$
\mathcal{F}(q^2) = \prod_i \left(\frac{m_i^2 - \Lambda_i^2}{q_i^2 - \Lambda_i^2} \right)
$$

where $\Lambda_i = m_i + \alpha \Lambda_{QCD}$



Couplings for χ_{c1} and χ_{c2} to charmed mesons



$$
\begin{aligned}
g_{DD^*\chi_{c1}} &= 2\sqrt{2}g_1\sqrt{m_D m_{D^*} m_{\chi_{c1}}}, \\
g_{D^*D^*\chi_{c2}} &= 4g_1 m_{D^*}\sqrt{m_{\chi_{c2}}}, \\
g_1 &= -\sqrt{\frac{m_{\chi_{c0}}}{3}}\frac{1}{f_{\chi_{c0}}},
\end{aligned}
$$

with $f_{\chi_{c0}} \simeq 0.51\ \mathrm{GeV}$

Casalbuoni et al, Phys. Rept. 281, 145(1997); Cheng, Chua, and Soni, PRD71, 014030 (2005)

Numerical Result for $\chi_{c1} \rightarrow VV$

BR ($\times 10^{-4}$)	$K^{*0}\bar{K}^{*0}$	$\rho\rho$	$\omega\omega$	$\phi\phi$
Exp. data	16 ± 4	—	—	—
Meson loop	$12 \sim 20$	$26 \sim 54$	$8.7 \sim 18$	$2.7 \sim 4.6$
SU(3)($R = 1$)	16.0	26.8	8.8	6.8
SU(3)($R = 0.838$)	16.0	32.0	10.6	4.0

α=0.3 ~ 0.33

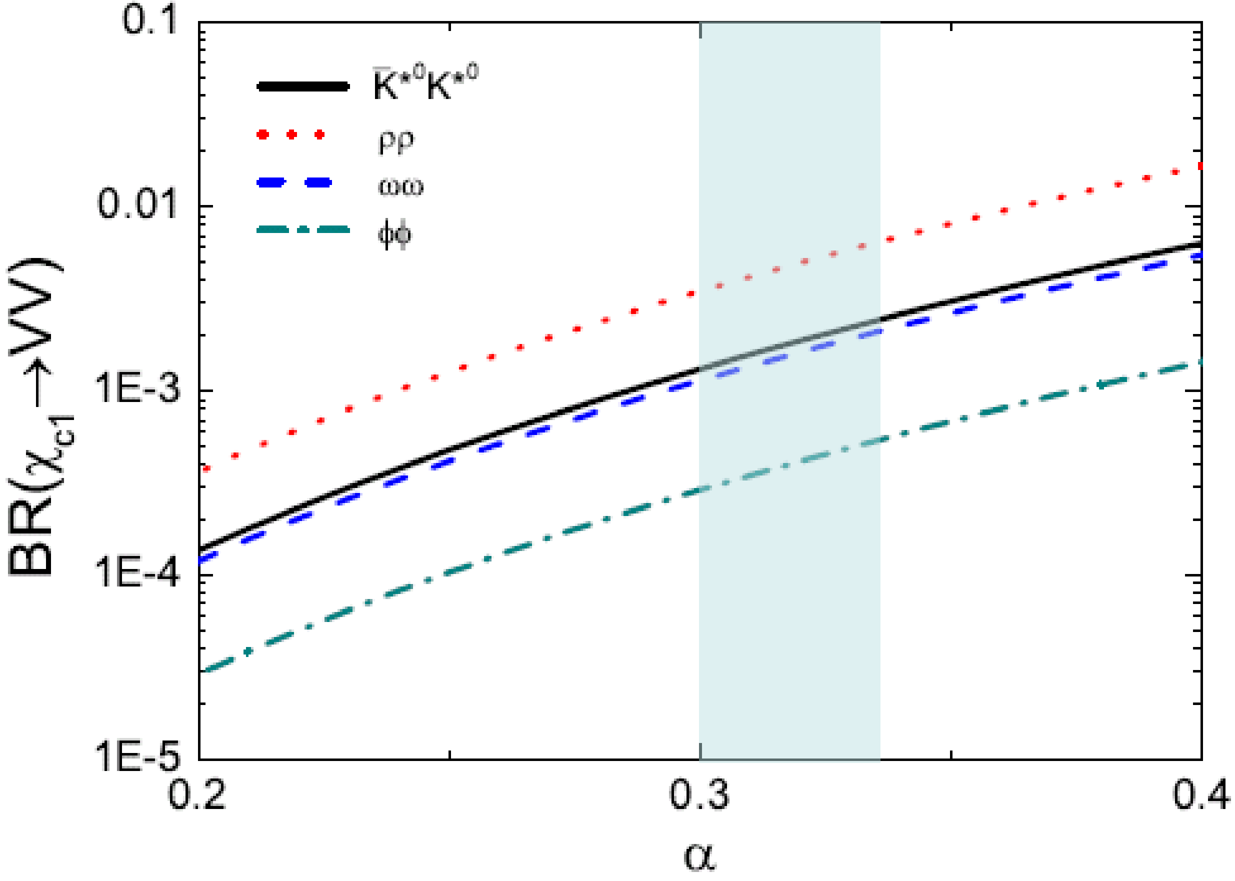
The results of a simple parameterization method based on SU(3) flavour symmetry are also presented in the table, where

$$R \equiv \langle (q\bar{s})_{V_1}(s\bar{q})_{V_2}|\hat{H}|\chi_{c1}\rangle / \langle (q\bar{q})_{V_1}(q\bar{q})_{V_2}|\hat{H}|\chi_{c1}\rangle$$

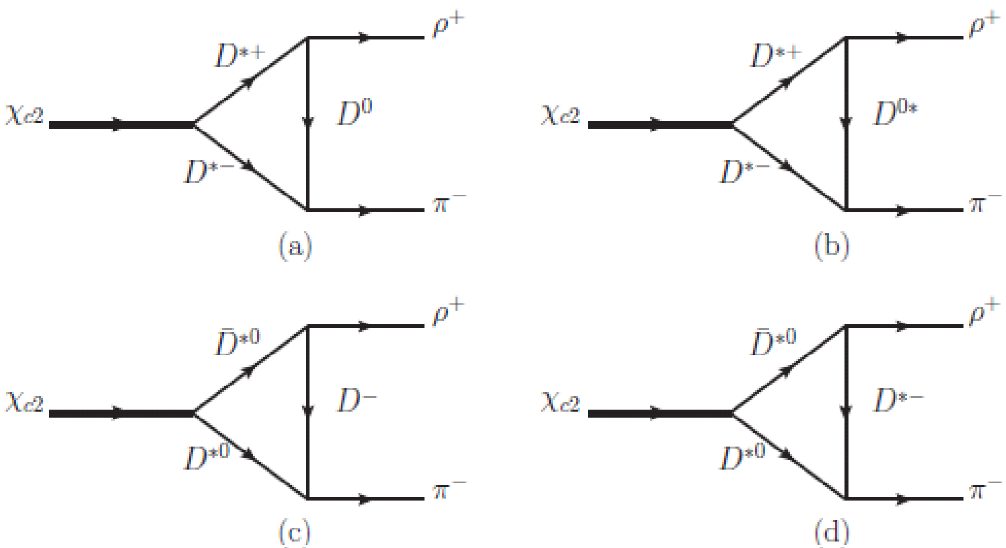
and $R \simeq f_\pi / f_K$

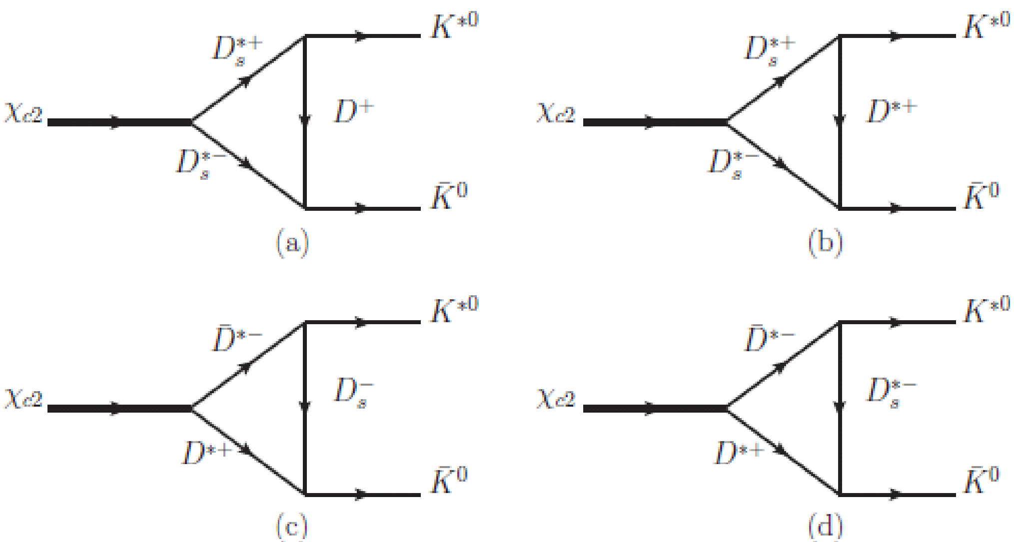
Liu and Zhao, PRD2010

Model-dependence on α



χ_{c2}→VP





◆ **Further suppressed by approximate G-parity or isospin/U-spin conservation.**

◆ **Decay to neutral VP is forbidden by C-parity conservation.**

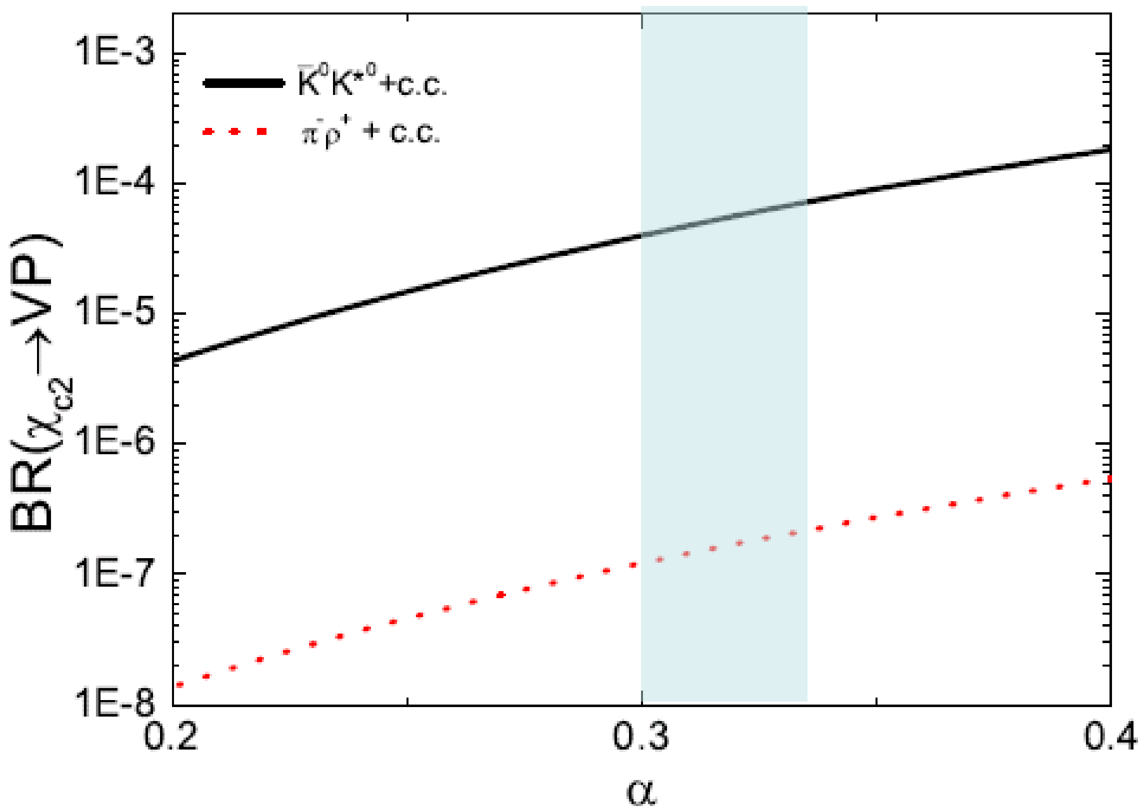
Transition amplitudes for $\chi_{c2} \to$ VP

$$
\begin{aligned}
\mathcal{M}_{2a} &= 2ig_{D^*D^*\chi_{c2}} f_{D^*DV} g_{D^*DP} \epsilon^{\chi_{c2}}_{\xi\eta} \epsilon^{\nu}_{\rho^+} \int \frac{d^4q}{(2\pi)^4} \epsilon_{\mu\nu\alpha\beta} p_1^\mu (q_1^\alpha + q^\alpha) p_2^\lambda \\
&\times (g^{\xi\beta} - q_1^\xi q_1^\beta / m^2_{D^*})(g^{\eta\lambda} - q_2^\eta q_2^\lambda / m^2_{D^*}) \frac{1}{D_a D_1 D_2} \mathcal{F}(q^2), \\
\mathcal{M}_{2b} &= -\frac{1}{2} i g_{D^*D^*\chi_{c2}} g_{D^*D^*P} \epsilon^{\chi_{c2}}_{\xi\eta} \epsilon^{\tau}_{\rho^+} \int \frac{d^4q}{(2\pi)^4} \epsilon_{\rho\sigma\alpha\beta} p_2^\sigma (q^\alpha - q_2^\alpha) \\
&\times \left[-g_{D^*D^*V}(q_{1\tau} + q_\tau) g^{\gamma\delta} - 4 f_{D^*D^*V} (p_1^\gamma g_\tau^\delta - p_1^\delta g_\tau^\gamma) \right] \\
&\times (g^{\xi\gamma} - q_1^\xi q_1^\gamma / m^2_{D^*})(g^{\eta\beta} - q_2^\eta q_2^\beta / m^2_{D^*})(g^{\delta\rho} - q^\delta q^\rho / m^2_{D^*}) \frac{1}{D_b D_1 D_2} \mathcal{F}(q^2)
\end{aligned}
$$

$\chi_{c2} \rightarrow VP$

BR($\times 10^{-5}$)	$K^{*0}\bar{K}^0 + c.c.$	$K^{*+}K^- + c.c.$	$\rho^+\pi^- + c.c.$
Meson loop	$4.0 \sim 6.7$	$4.0 \sim 6.7$	$(1.2 \sim 2.0) \times 10^{-2}$
Exp. data	—	—	—

α=0.3 ~ 0.33



Summary

- The long-distance rescattering effects can give sizeable contributions to the processes $\chi_{c1} \rightarrow VV$ and $\chi_{c2} \rightarrow VP$, which are supposed to be suppressed according to the helicity selection rule.
- With the parameter α constrained by the measured BR($\chi_{c1} \rightarrow \bar{K}^{*0} K^{*0}$) , BR($\chi_{c1} \rightarrow VV$) are predicted to be at least at the order of 10^{-4}, and BR($\chi_{c2} \rightarrow \bar{K}^{*0} K + c.c.$) is at the order of 10^{-5} that may be detectable.
- The P-wave charmonium decay should be ideal for examining the evading mechanisms of the helicity selection rule. The huge data sample accumulated by BESIII provide a good opportunity to check this.
- Similar mechanisms via intermediate hadron loops are also studied in η_c, χ_{c0}, $h_c \rightarrow B \bar{B}$.