中国科学院高能物理研究所
Institute of High Energy Physics, CAS

Towards a Dynamical Understanding of the Non-D Dbar Decay of psi(3770)

Yuan-Jiang Zhang

In collaboration with Gang Li and Qiang Zhao

Motivations

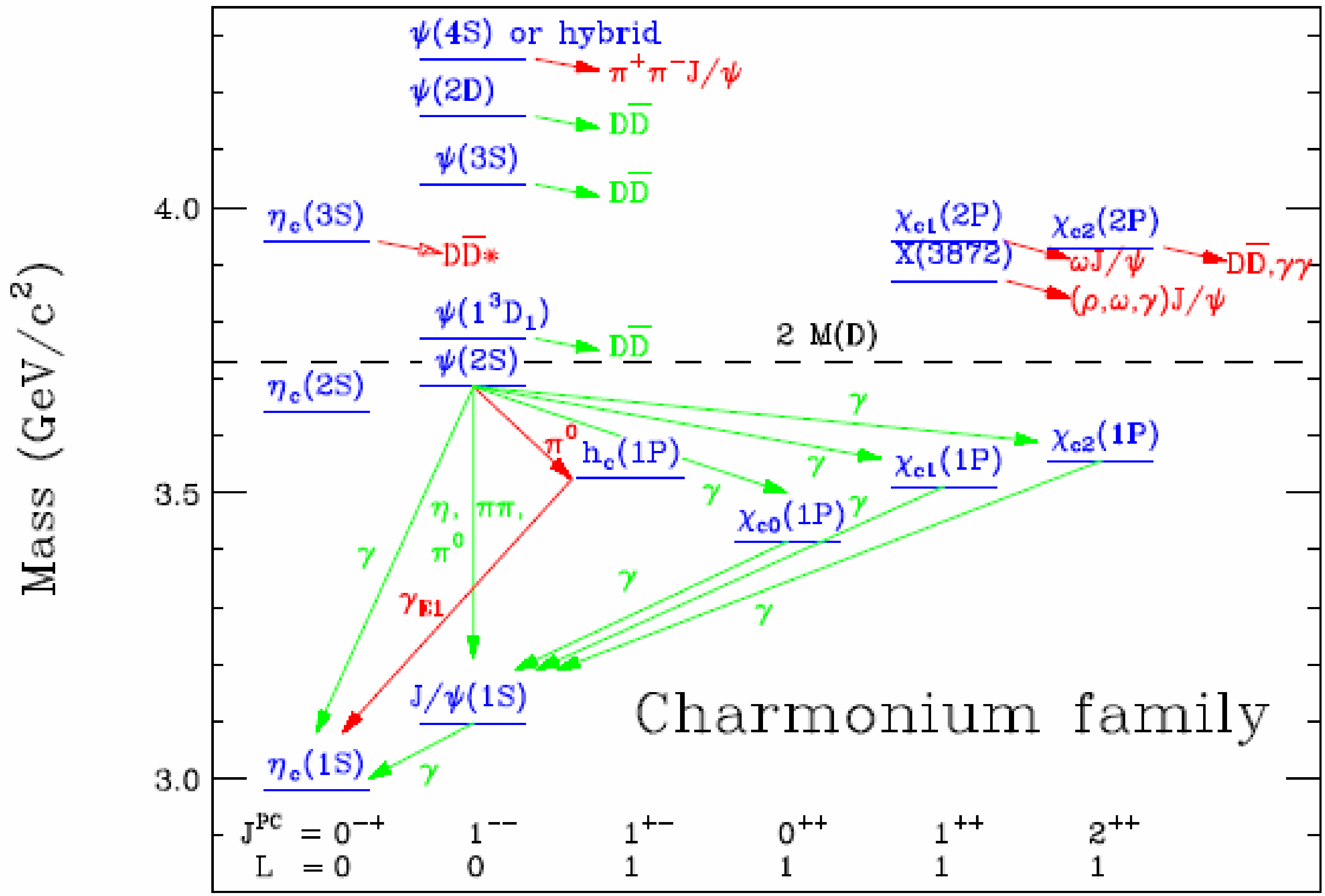
- Charmonium decays as a probe for non-perturbative QCD mechanisms
- Several challenges in low-energy charmonium decays

Several well-known puzzles in charmonium decays

- $\psi(3770)$ non-$D\bar{D}$ decay
- "$\rho\pi$ puzzle" in J/ψ, $\psi' \to$ VP decay
- M1 transition problem in J/ψ, $\psi' \to \gamma\, \eta_c$, $(\gamma\, \eta_c')$
- … …

Conjecture: These puzzles could be related to non-pQCD mechanisms in charmonium decays, see the talk by Qiang Zhao at quarks and nuclear physics, Beijing.

❑ Charmonium spectrum



❑ Experimental results

$\psi(3770)$ 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}	$\phi\eta$	$(3.1 \pm 0.7) \times 10^{-4}$	

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CLEO-c :

$$\sigma_{\text{non-}D\bar{D}} = -0.21 \pm 0.09^{+0.41}_{-0.30}$$

$$\mathcal{B}(\psi(3770) \to \text{non-}D\bar{D}) < 9\%$$

at 90% confidence level

PRL **104,** 159901 (2010)

Erratum to Phys.Rev.Lett.96:092002 (2006)

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

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

M. Ablikim *et al*. Phys.Lett.B659:74 (2008)

Particle Data Group 2008

$\psi(2S)$

Mass m = 3686.09 ± 0.04 MeV , (S = 1.6)

Full width Γ = 309 ± 9 keV

Γ_{ee} = 2.36 ± 0.04 keV

$\psi(3770)$

Mass m = 3772.92 ± 0.35 MeV

Full width Γ = 27.3 ± 1.0 MeV

Γ_{ee} = 0.265 ± 0.018 keV , (S = 1.3)

Yanong Zhu, PhD Thesis, (unpublished).

$$R = \frac{\Gamma(^3S_1) \to 3g)}{\Gamma(^3S_1) \to e^+e^-)} \simeq \frac{\alpha_s^3}{\alpha^2} \frac{5}{18\pi}(\pi^2 - 9) \approx 25$$

$$\alpha_s = 0.26$$

$$R = \frac{\Gamma(^3D_1) \to 3g)}{\Gamma(^3D_1) \to e^+e^-)} \simeq \frac{\alpha_s^3}{\alpha^2} \frac{304}{45\pi} ln(\frac{M}{\Delta}) \approx 780$$

$$\Delta = \frac{1}{< r >} \sim 1 \quad \text{GeV}$$

⇒ Less than branch ratio 1% in $\psi(3770)$ 3g decay.

❑ Theoretical interpretation

- S-D wave mixing scheme.
  J. L. Rosner, Phys. Rev. D 64, 094002 (2001).

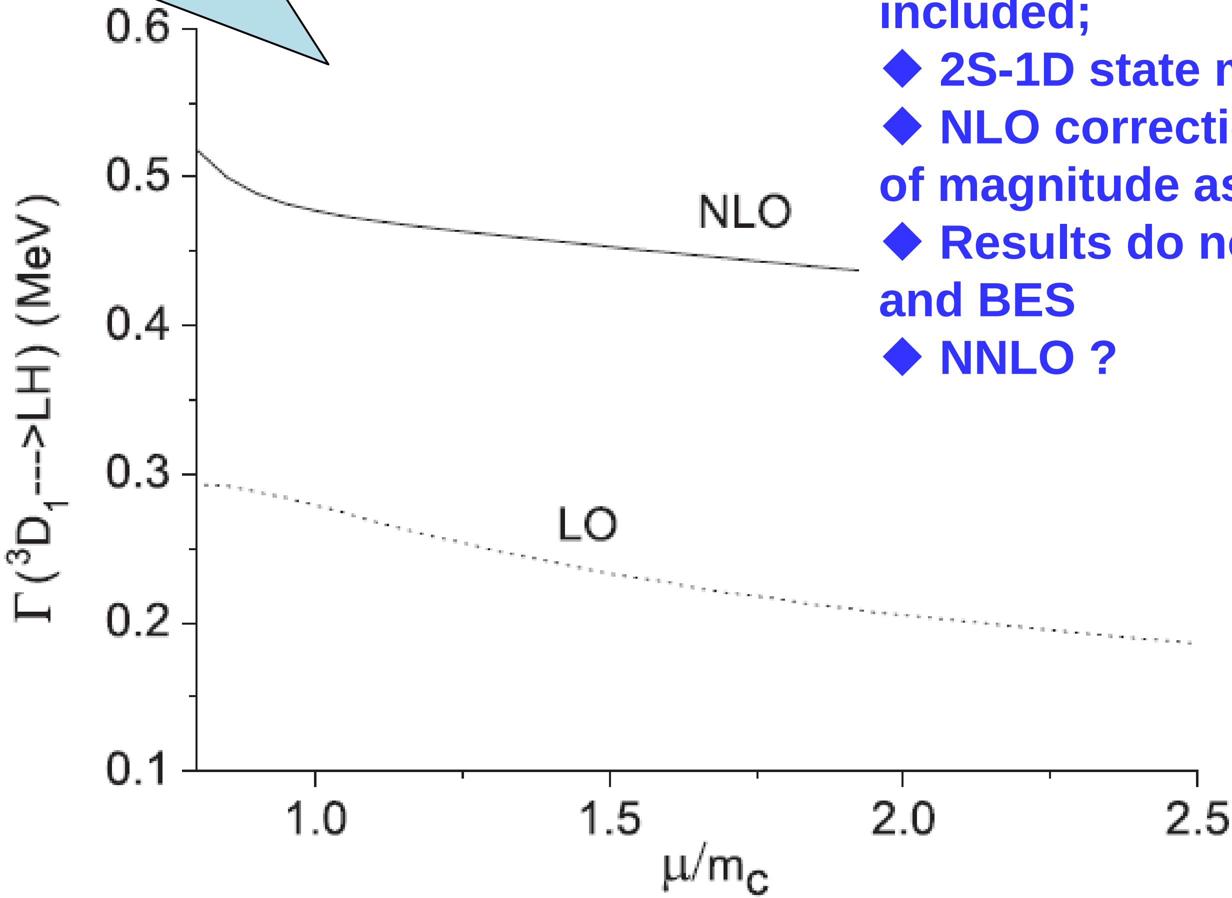
- Four quark component in $\psi(3770)$.
  M. B. Voloshin, Phys. Rev. D 71, 114003 (2005).

- FSI effects from intermediate state.
  N. N. Achasov and A. A. Kozhevnikov, Phys. At. Nucl. 69, 988 (2006).

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

- …….

pQCD calculation:
BR(non-D $\bar{D}$) < 5%



- **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 ?**

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

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

infrared divergences. We find that for the $\psi(3770)$ the D-wave contribution is dominant, and the effect of S-D mixing is very small. Numerically, our results do not favor either of the two experimental results measured by the BES and CLEO Collaborations. We hope that our theoretical result can serve as a clue to clarify the long-standing puzzle of the $\psi(3770)$ non-$D\bar{D}$ decay. We urge doing more precise measurements on both inclusive and exclusive non-$D\bar{D}$ decays of $\psi(3770)$ in the future. If their total branching ratio can be as large as 10%, it will be a real challenge to our current understanding of QCD, and new decay mechanisms have to be considered.

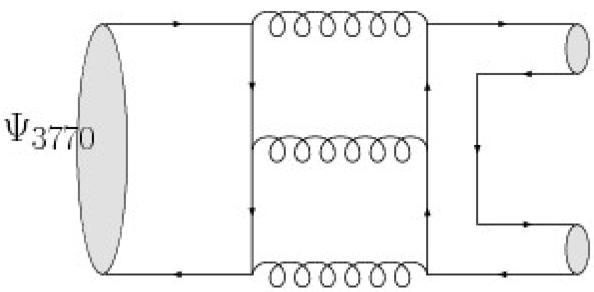
long-range interaction such as intermediate meson loop (or FSI) mechanism ? If it does, how to quantify it?

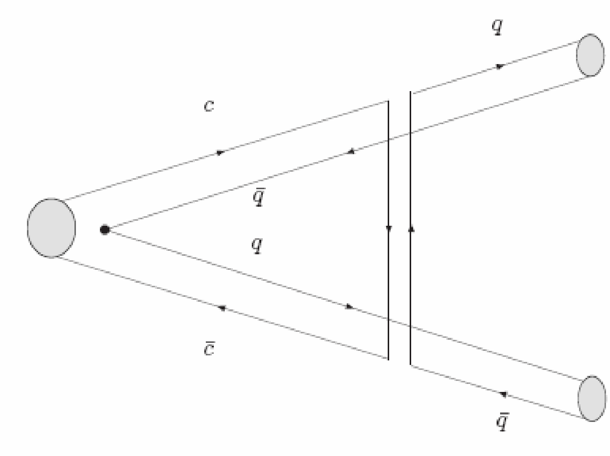
Non-D Dbar Decay of psi(3770)

long-range transition mechanisms in ψ(3770) non-D $\bar{D}$ decays

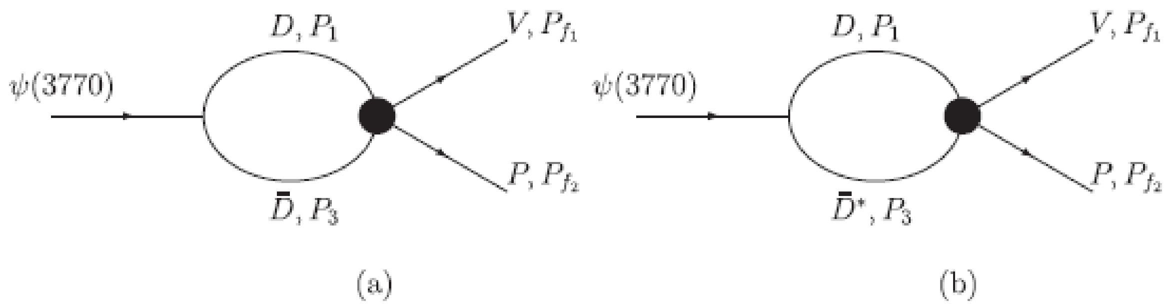
Short-range pQCD transition via single OZI (SOZI) process

Long-range OZI evading transition





Intermediate meson loop scheme in ψ(3770) non-D $\bar{D}$ decay



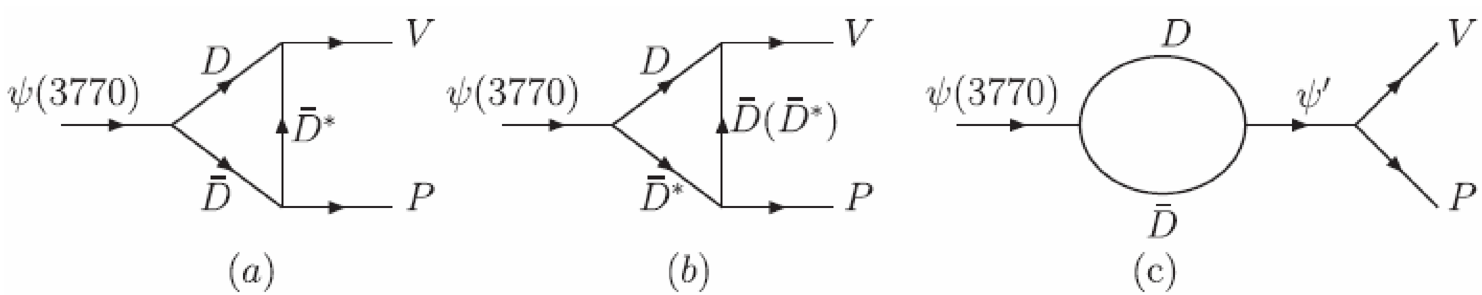


FIG. 2. The t- [(a) and (b)] and s-channel (c) meson loops in $\psi(3770) \to VP$.

s-channel meson loops can be a source of ψ(2S)-ψ(1D) mixing.

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

Talk by Q. Zhao at QNP

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.

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

■ The Effective Lagrangians and couplings

$$\mathcal{L}_{\psi D\bar{D}} = g_{\psi D\bar{D}}\{D\partial_\mu \bar{D} - \partial_\mu D\bar{D}\}\psi^\mu,$$

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

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

$$\mathcal{L}_{\mathcal{P}\bar{D}D^*} = g_{D^*\mathcal{P}\bar{D}}\{\bar{D}\partial_\mu \mathcal{P} - \partial_\mu \bar{D}\mathcal{P}\}D^{*\mu} + \text{H.c.},$$

→

$$\Gamma_{\psi(3770)\to D\bar{D}} = \frac{g^2_{\psi(3770)D\bar{D}}|\vec{p}|^3}{6\pi M^2_{\psi(3770)}}$$

Coupling constants:

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

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

$$g_{D^*D\rho} = \sqrt{2}\lambda g_\rho, \qquad g_{DD\rho} = g_{D^*D\rho}\tilde{M}_D,$$

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].

For other coupling, we can obtain by SU(3) flavor symmetry.

For J/ψ couple to charm mesons pair, we adopt:

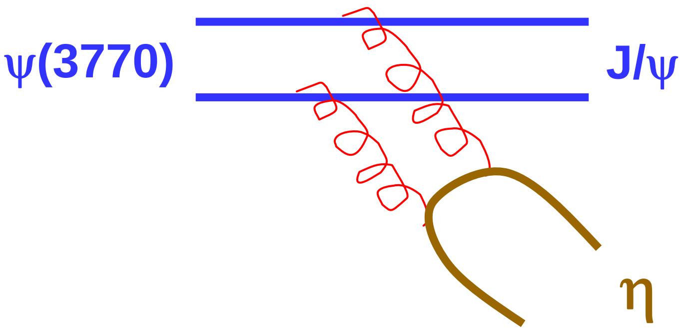
$$g_{J/\psi DD^*} = 3.84\ \mathrm{GeV}^{-1}$$

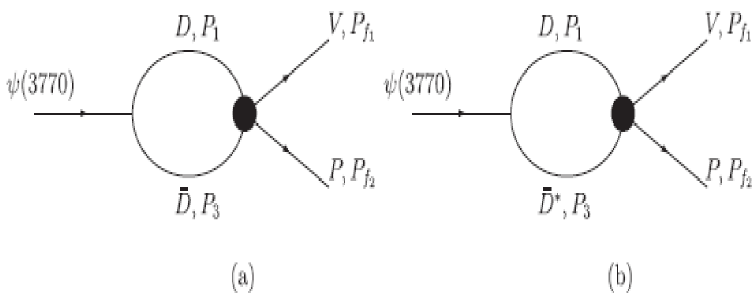
$$g_{J/\psi DD} = 7.44$$

$$g_{\psi(3770)D\bar{D}^*} = g_{\psi(3770)D\bar{D}}/\tilde{M}_D \qquad \tilde{M}_D \equiv \sqrt{m_D m_{D^*}}$$

Y. Oh, W. Liu, and C. M. Ko, Phys. Rev. C **75**, 064903 (2007).
A. Deandrea, G. Nardulli, and A. D. Polosa, Phys. Rev. D **68** (2003).

Constrain the long-distance parameter





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

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

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

$$\alpha = 1.73$$

- **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.

Constrain the short-distance parameter and the relative phase.

Relative strengths among pQCD transition amplitudes (SOZI):

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

← Flavor –bind assumption

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

$\theta_P = -19.1^\circ$

Particle Data Group 2008

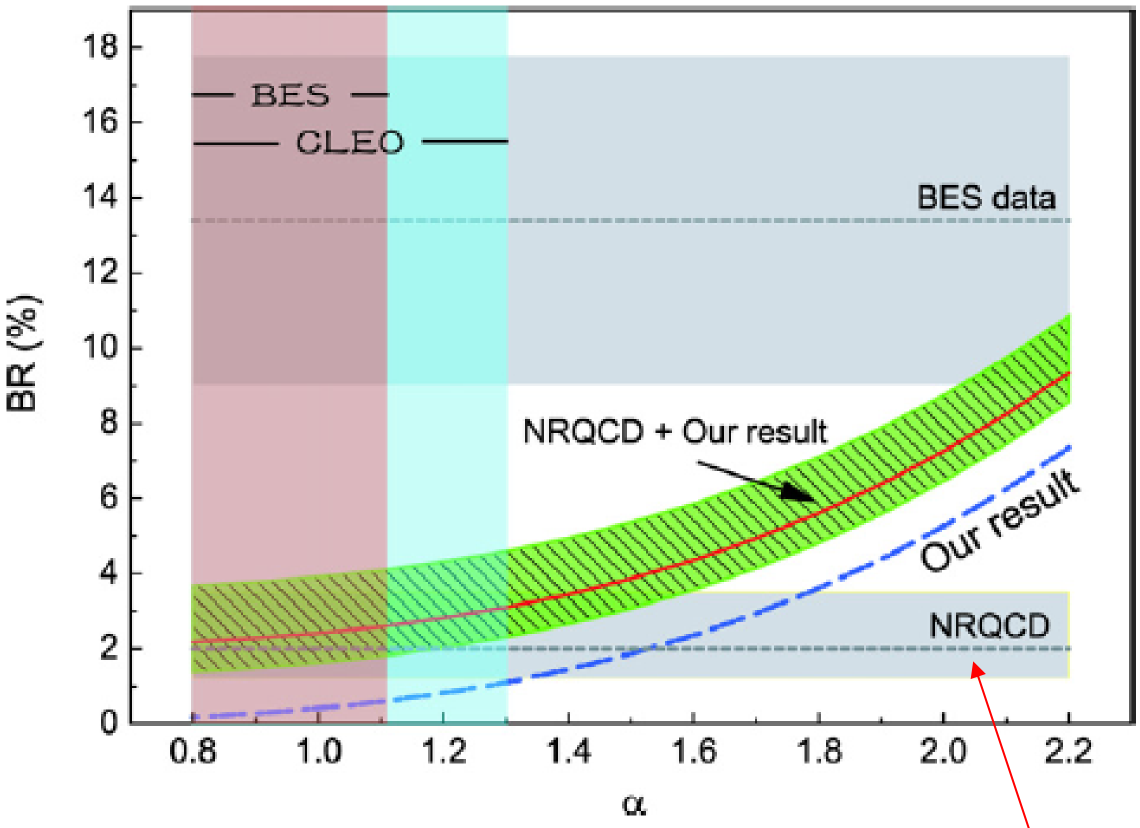
With $\alpha = 1.73$ fixed, we can then determine the other two parameters $g_S \equiv g_S^{\rho^0\pi^0} = 0.085$ and $\delta = -66^\circ$ by experimental data, i.e., $\mathrm{BR}_{\phi\eta} = (3.1 \pm 0.7) \times 10^{-4}$ [8] and $\mathrm{BR}_{\rho\pi} < 0.24\%$ with C.L. of 90% [28]. In Table I

Results for ψ(3770) → VP mode.

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 $\bar{\delta}$, 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).

Summary

- **Intermediate meson loop effects seem to play a role in ψ(3770) non-D $\bar{D}$ decays.**
- **However, the quantitative calculations are sensitive to cut-off energy and exhibit model-dependent aspects.**
- **More experimental data from BES-III will be able to clarify that non-perturbative mechanisms are also important in the psi(3770) mass regime.**

Thank you!