Hidden-Charm Decays: An Elegant Probe for Internal Structure

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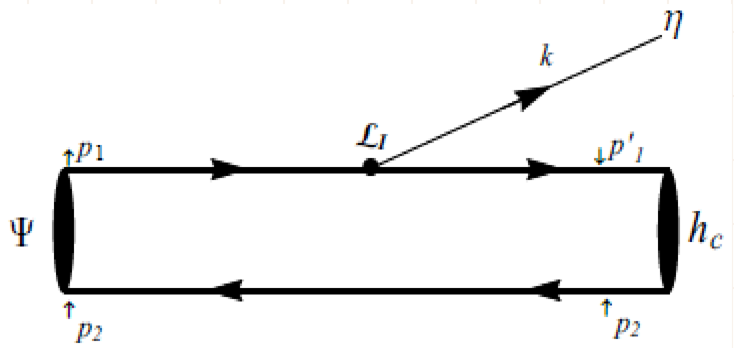
Outline

- HQSS Violation in Heavy Quarkonium Transitions
- Motivation
- Effective Model & Results
- Assignments for Charmonium-like States
- Summary

HQSS in Decays

- Consider the process

$$\psi(3686) \to J/\psi\eta \ \ \& \ \psi(4160) \to h_c\eta$$



- Requires the rotation (flip) of the spin of the heavy quark

M. B. Voloshin, PRD 85, 034024 (2012)

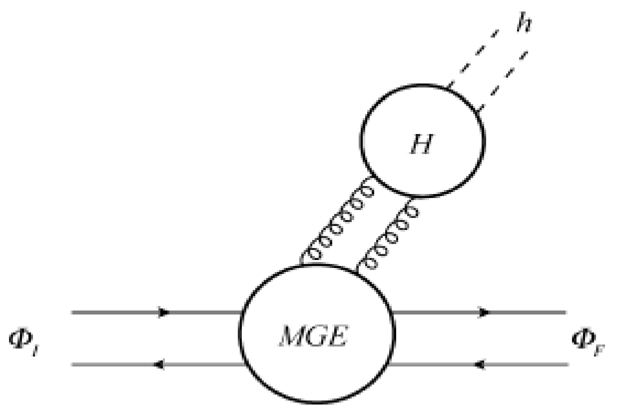
- HQSS violation expected to be small
- Experimental info

$\mathcal{B}[\psi(3686) \to J/\psi\eta]$	$\mathcal{B}[\psi(4160) \to h_c(1P)\eta]$
$(3.36 \pm 0.05)\%$	$< 2 \times 10^{-3}$
$\Gamma_{\psi(3686)} = 296 \pm 8$ keV	$\Gamma_{\psi(4160)} = 70 \pm 10$ MeV

PDG, CPC 40, 100001 (2016)

What is QCD of $\psi(2S, 1D) \rightarrow J/\psi\eta(\pi^0)$?

- Well-known formalism for hadronic transitions → QCD multipole expansion



K. Gottfried, PRL 40, 598 (1977)
T.-M Yan, PRD 22, 1652 (1980)

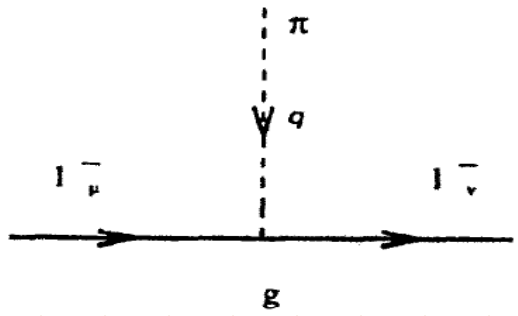
Y.-P Kuang, Front. Phys. China 1, 19 (2006)

- Multi gluon exchange → hadronize to light hadron(s)
- Gluons are supposed to be soft → wavelength much larger than $Q\bar{Q}$
- Emitted light hadron are predominantly of lower momenta

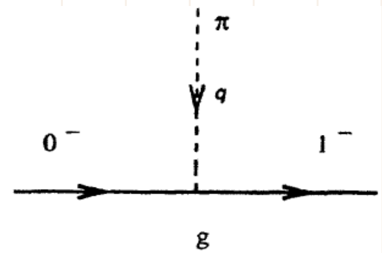
Chiral Effective Lagrangians

- First simplification to QCDME → EFT of QCD with soft gluons

R. Casalbuoni et. al. Phys. Rep. 281, 145 (1997) & PLB 309, 193 (1993)



$$\Longrightarrow \; -(2M_P/f_\pi)\, g\, \varepsilon_{\mu\nu\alpha\beta}\,\varepsilon^{\mu}(1^-)\,\varepsilon^{*\nu}(1^-)\,q^{\alpha}v^{\beta}$$



$$\Longrightarrow \; (2M_P/f_\pi)\, g(\varepsilon(1^-)\cdot q)$$

- Soft exchange approximation (SLA), limited momenta of gluon
- Assumptions
  - → $Q\bar{Q}$ is well separated to consider string-like
  - → light meson momentum not very large

- Successfully describe the transitions among lower quarkonia

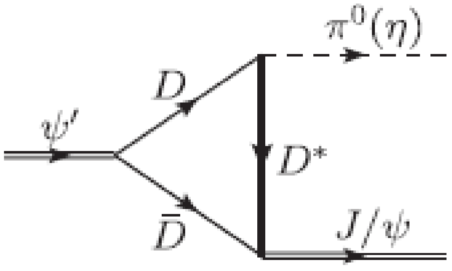
NREFT Formalism

- To incorporate the intermediate meson loops effects

  F.-K. Guo et. al. PRL 103 082003 (2009) & PRD 83, 034013 (2011)

- Find sizeable contribution from loops in

  $$\psi' \to J/\psi\eta(\pi^0)$$



- Non-perturbative effects, in principle, can also play role in the decays of higher $J^{PC} = 1^{--}$ states

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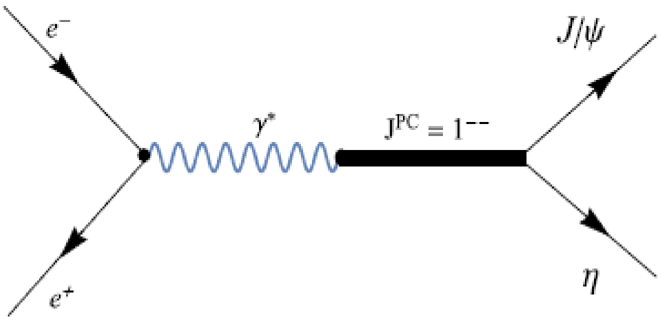
- For $\psi(4S, 3D, 5S, 4D, 6S, 5D) \to J/\psi\eta(\pi^0)$

  → decay momentum lies in relativistic regime

- Potential need for a suitable theory which can incorporates the hadronic transition with large decay momenta

Why $J^{PC} = 1^{--}$ Charmonia ?

- $J^{PC} = 1^{--}$ have direct access @ e^+e^- colliders



- Physics of production of $J^{PC} = 1^{--}$ is well-established
- Rich & Precise Spectrum
- Several non-conventional states

$$Y(4260),\ Y(4360),\ Y(4390),\ Y(4660),\ \ldots$$

- $Y(4260)$ → We argued that it has sizeable component of $D_1\bar{D}$ molecule through D wave coupling

Y. Lu, MNA, B.-S. Zou, arXiv:1705.00449 [hep-ph]

Effective Model

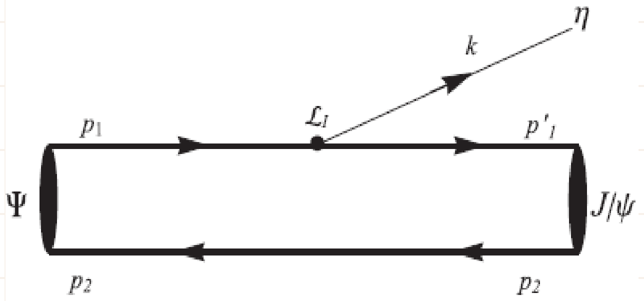
- Motivated by NJL model

$$\mathcal{L}_{\mathrm{NJL}} = \frac{1}{2} g_s \sum_{a=0}^{N_c} [(\bar{\psi}\lambda^a\psi)^2 + (\bar{\psi}\lambda^a i\gamma^5\psi)^2]$$

- Coupling of heavy quark with light scalar and pseudoscalar d-o-f
- Modify four-quark vertex → two quark + light d-o-f

$$\mathcal{L}_I = g(\bar{\psi}\psi\langle\sigma\rangle + \bar{\psi}i\gamma^5\psi\langle\eta\rangle)$$

Overall Coupling



- $<\sigma>$ and $<\eta>$ are SU(3) singlets
- Data is available for η transitions of higher $J^{PC} = 1^{--}$
- Test the model for $\psi \to J/\psi\eta$ $\quad\quad \psi = \psi(2S, 1D, 3S, 2D, 4S)$

$$\Gamma_{A\to BC} = 2\pi k \frac{E_B E_C}{m_A} \sum_{m_{J_B}, m_{J_C}} \int d\Omega_B |\mathcal{M}^{m_{J_A} m_{J_B} m_{J_C}}|^2,$$

$$\mathcal{M}^{m_{J_A} m_{J_B} m_{J_C}} = g \frac{i}{2m_c} \int d^3 p_1 \phi_A(\vec{p}_1)\phi_B^*(\vec{p}_1 - x_B \vec{P}_B) \times \langle 1'|\vec{\sigma}|1\rangle \cdot (\vec{p}_1 - \vec{p'}_1) \cdot \langle 2|\delta_{ss'}|2'\rangle.$$

Vanish at HQ limit $m_Q \to \infty$

$S - D$ Mixing & Wavefunctions

- Standard mixing → used in literature to reproduce Γ_{ee}

Y.-B. Ding et. al. PRD 44, 3562 (1993) & J. L Rosner, PRD 64, 094002 (2001)

$$\psi_{\text{phys}} = \cos\theta|n^3S_1\rangle + \sin\theta|(n-1)^3D_1\rangle$$

$$\psi'_{\text{phys}} = -\sin\theta|n^3S_1\rangle + \cos\theta|(n-1)^3D_1\rangle$$

→ $\theta \approx -10 \sim -13$ & $\theta \approx +26 \sim +30$

- Large mixing such as $\theta \approx 34$ [Badalian, PAN (2009)] & $\theta \approx 40$ [Liu, PRD (2004)] is not favored by this study

- To compute overlap, wavefunctions is key ingredient → prefer SHO wf

$$\psi_{n_r lm}(\vec{p}) = R_{n_r l}(p)\mathcal{Y}_l^m(p,\theta,\varphi)$$

$$R_{n_r l}(p) = \sqrt{\frac{2n_r!}{\Gamma(n_r+l+\frac{3}{2})}}\beta^{-(l+\frac{3}{2})}e^{-p^2/2\beta^2}L_{n_r}^{l+\frac{1}{2}}(p^2/\beta^2)$$

- Qualitatively, SHO wf are same as true wf
- Useful in producing analytic results

Results (i)

$m_c = 1.50$ GeV	$\beta = 0.40$ GeV	$g = 0.80$	$\|\theta\| = 13°$

MNA, Y. Lu & B.-S. Zou Phys. Rev. D 95, 114031 (2017)

- $\psi(nS) \to J/\psi\eta$ & $\psi((n-1)D) \to J/\psi\eta$

State	$n^{2S+1}L_J$	Γ_{total} [18]	$\mathcal{B}(\psi \to J/\psi\eta)$ [18]	$\Gamma^{\text{th}}_{\psi\to J/\psi\eta}$	$\Gamma^{\text{exp}}_{\psi\to J/\psi\eta}$ [18]
$\psi(3686)$	2^3S_1	0.296 ± 0.008	$(3.36 \pm 0.05)\%$	0.010	0.010 ± 0.001
$\psi(3770)$	1^3D_1	27.2 ± 1.0	$9 \pm 4 \times 10^{-4}$	0.025	0.025 ± 0.011
$\psi(4040)$	3^3S_1	80 ± 10	$5.2 \pm 0.7 \times 10^{-3}$	0.347	0.416 ± 0.076
$\psi(4160)$	2^3D_1	70 ± 10	$< 8 \times 10^{-3}$	0.204	$< 0.560 \pm 0.080$
$\psi(4415)$	4^3S_1	62 ± 20	$< 6 \times 10^{-3}$	0.425	$< 0.372 \pm 0.120$

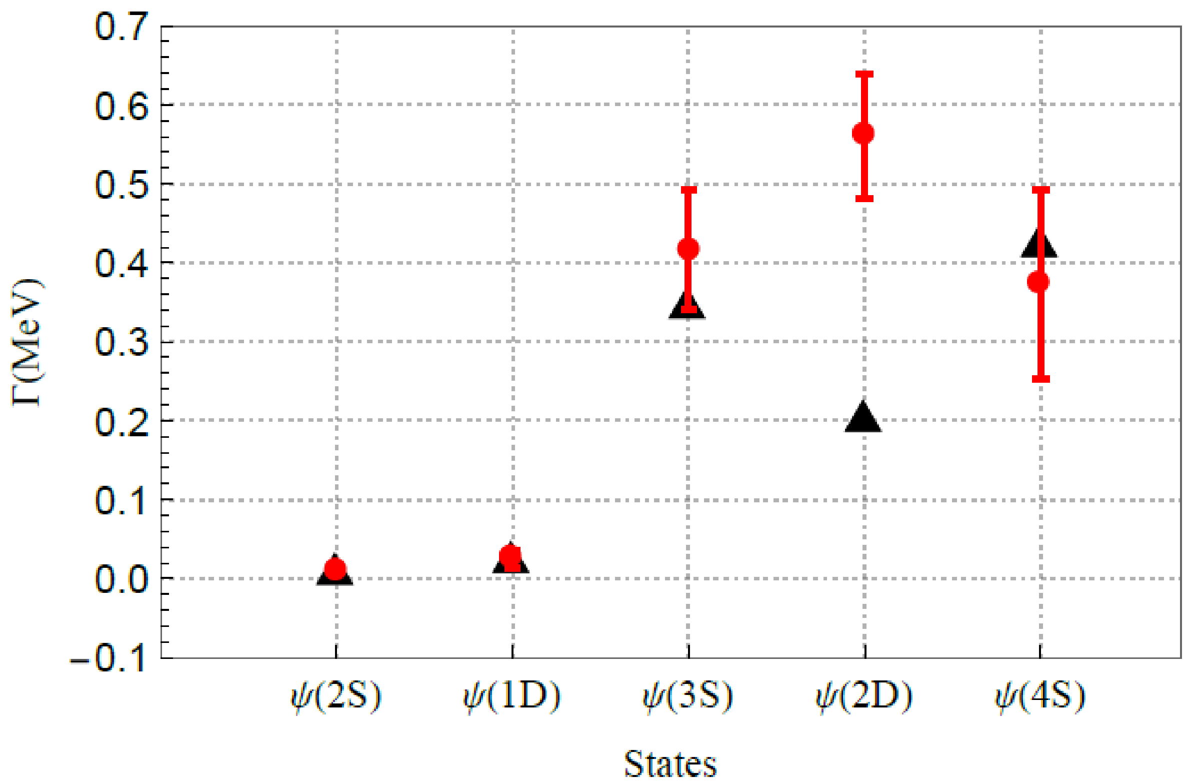
- For $\psi(4160)$ & $\psi(4415)$ only upper limits available

Results (ii)

$m_c = 1.50$ GeV	$\beta = 0.40$ GeV	$g = 0.80$	$\lvert\theta\rvert = 13^\circ$

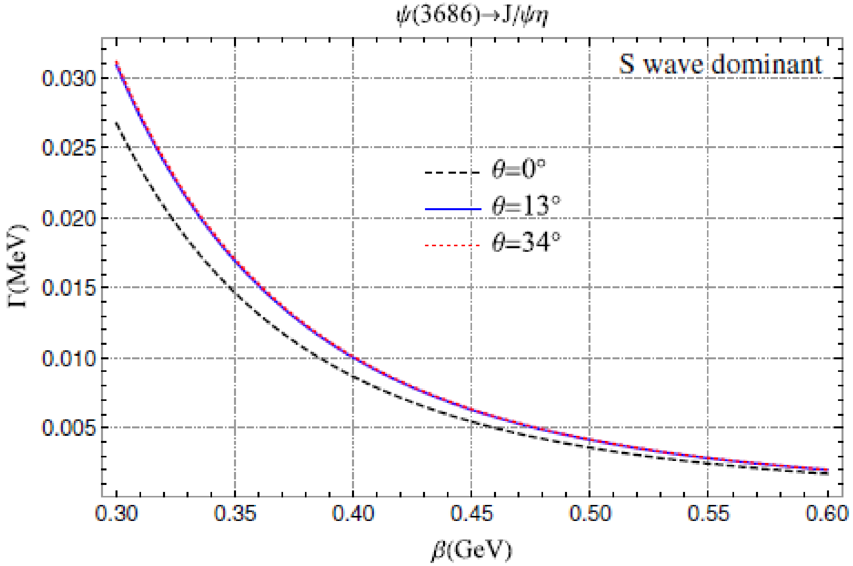
MNA, Y. Lu & B.-S. Zou Phys. Rev. D 95, 114031 (2017)

- $\psi(nS) \to J/\psi\eta$ & $\psi((n-1)D) \to J/\psi\eta$

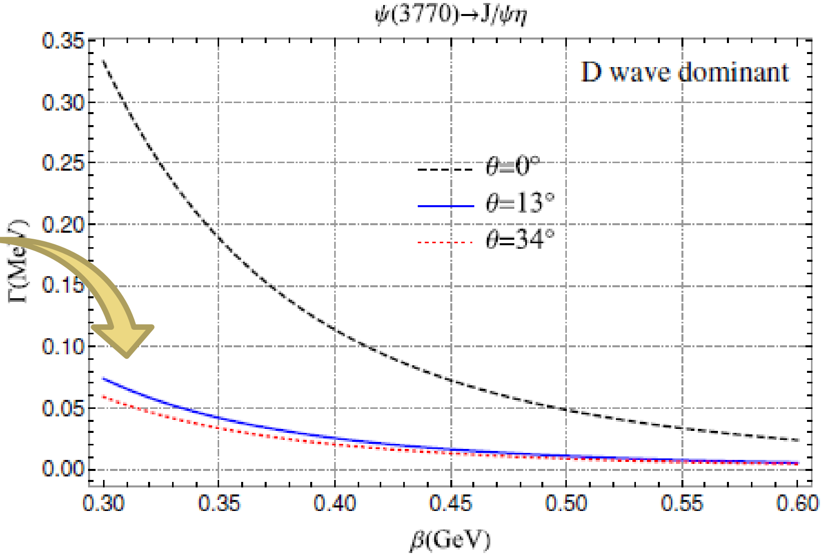


- For $\psi(4160)$ & $\psi(4415)$ only upper limits available

Results (iii); β dependence

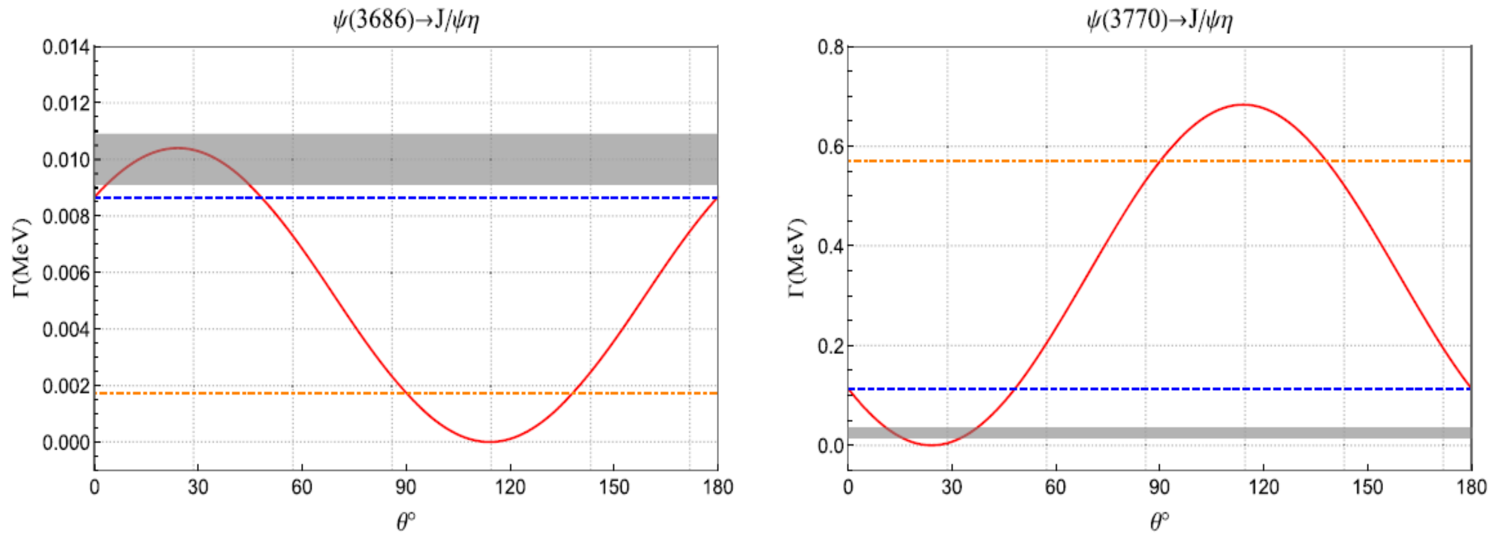


Overlap of the red and blue curve is a coincidence



- For D wave, destructive interference causes sizeable decrease in the width

Results (iv); θ dependence



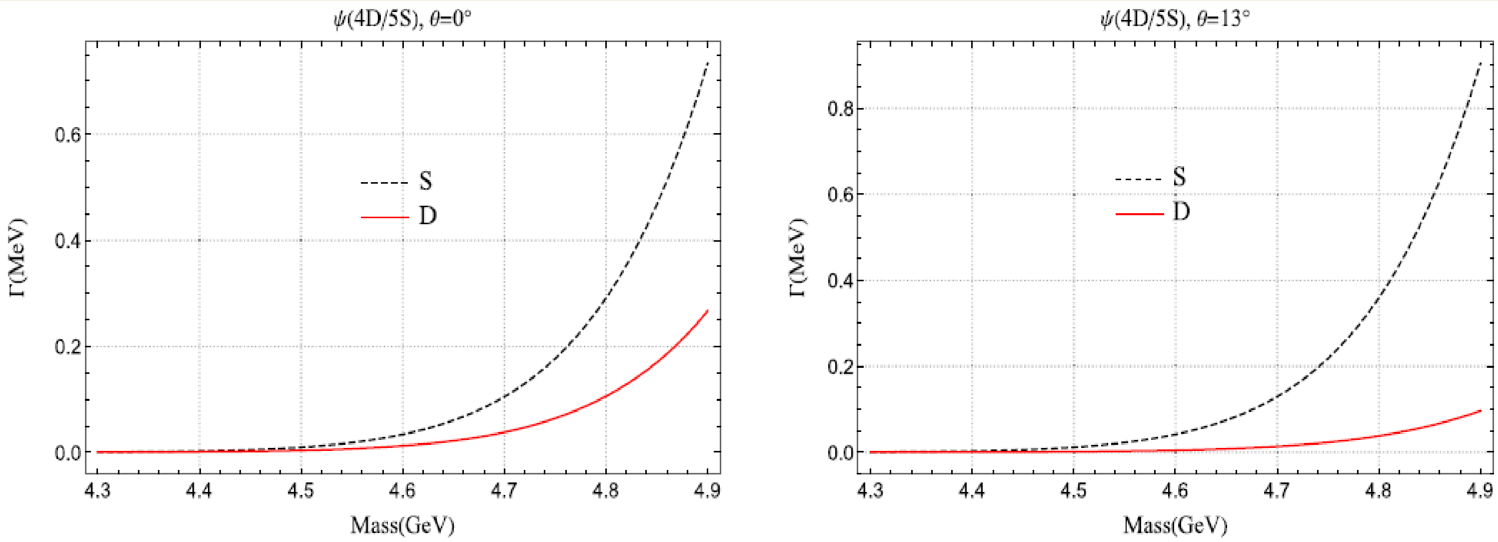
- Due to sinusoidal behavior, Γ could be the same for two different values of mixing angle

Predictions (i)

MNA, Y. Lu & B.-S. Zou Phys. Rev. D 95, 114031 (2017)

- $J^{PC} = 1^{--}$ states $\psi(3D), \psi(5S), \psi(4D), \psi(6S), \psi(5D)$ are unknown experimentally
- made initial mass depending predictions for

$$\psi(3D, 4D, 5S, 6S, 5D) \to J/\psi\eta$$



- Provide constraints on the mass of unknown higher vector charmonia

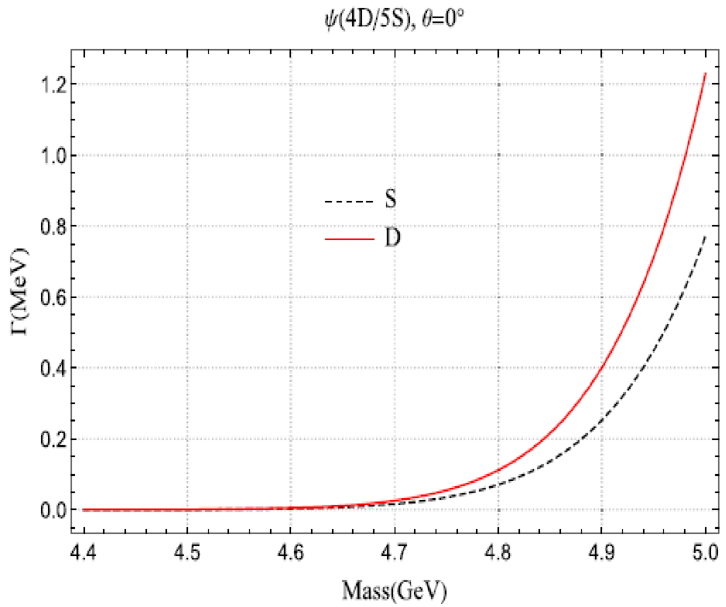
→ upper bound

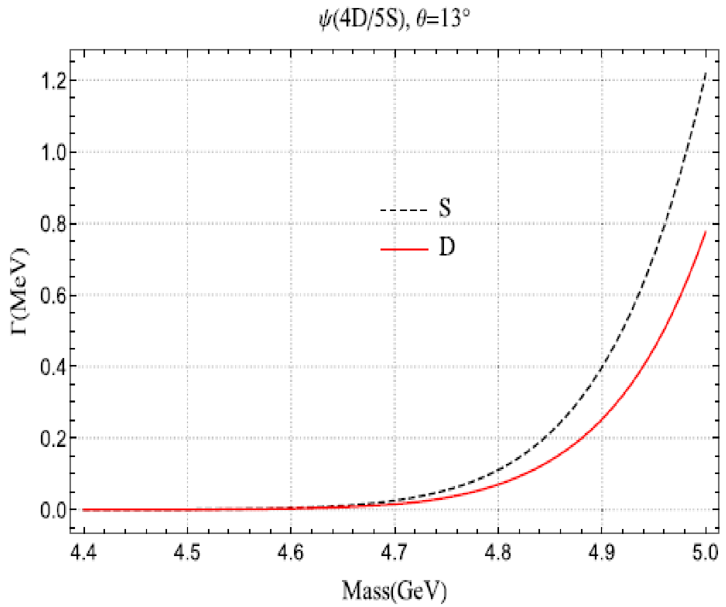
Predictions (ii); $\psi(4160) \to h_c\eta$ & $\psi(4415) \to h_c\eta$

- Coupling of spin-singlet P wave lowest $c\bar{c}$ with initial S and D wave $c\bar{c}$ found to be much smaller than J/ψ

$$\frac{\Gamma(\psi(4160) \to h_c(1P)\eta)}{\Gamma(\psi(4160) \to J/\psi\eta)} = 7.887 \times 10^{-2} \qquad \frac{\Gamma(\psi(4415) \to h_c(1P)\eta)}{\Gamma(\psi(4415) \to J/\psi\eta)} = 6.736 \times 10^{-2}$$

- Also made predictions for initial mass dependence width for $\psi(3D, 4D, 5S) \to h_c\eta$





Assignment for Y States

- $Y(4360)$ & $Y(4660)$ are observed at Belle in ISR $e^+e^- \to \pi^+\pi^-\psi(2S)$

- Theoretical interpretations

  $Y(4360) \rightarrow 3D\ c\bar{c}$ state — G.-J Ding et. al. PRD 77, 014033 (2008); D. Molina et. al. PRD 95, 094021 (2017)

  $Y(4660) \rightarrow 5S\ c\bar{c}$ state — J. Segovia et. al. PRD 78, 114033 (2008); G.-J Ding et. al. PRD 77, 014033 (2008)

- Assign $3D$ to $Y(4360)$ and compute $Y(4360) \to J/\psi\eta$
- Mixing is considered b/w $3D$ & $4S$

- Experimental measurement requires Γ_{ee} to get abs. $\Gamma[Y(4360) \to J/\psi\eta]$

$$\mathcal{B}(Y \to J/\psi\eta) \cdot \Gamma^{Y}_{e^+e^-}$$

Puzzle for me???

- Pick up quark model estimates for $\Gamma_{ee}[Y(4360)]$ for pure $3D$ & with admixture of $4S$

Y Assignments: Results (i)

- $Y(4360) \to J/\psi\eta$

State	$n^{2S+1}L_J$	Γ_{total}	$\mathcal{B}(Y \to J/\psi\eta)$	$\Gamma^{\text{th}}_{Y\to J/\psi\eta}$ $\theta = 0^\circ$	$\theta = 13^\circ$	$\theta = 34^\circ$	$\Gamma^{\text{exp}}_{Y\to J/\psi\eta}$ $\theta = 0^\circ$	$\theta = 34^\circ$
$Y(4360)$	3^3D_1	74 ± 18 [18]	$\frac{6.8}{\Gamma_{e^+e^-}}$ [64]	0.047	0.016	1.0×10^{-3}	< 0.963	< 0.799
$Y(4390)$	3^3D_1	139.5 ± 16.1 [60]	–	0.083	0.028	1.6×10^{-3}	–	–
$Y(4660)$	5^3S_1	48 ± 15 [18]	$\frac{0.94}{\Gamma_{e^+e^-}}$ [64]	0.057	0.070	0.077	< 0.046	< 0.116

- $\psi(3D)$ assignment of $Y(4360)$ describes data well in all three cases

- $Y(4390)$, a new state from BESIII in $\pi^+\pi^-h_c$, looking forward to have measurements on its hadronic transitions

- $Y(4660)$, for pure $\psi(5S)$, $\theta = 0$ → larger width than corresponding exp. upper limit

Summary

- Motivated by NJL model, we developed an effective model to create light meson(s) in heavy quarkonium transitions
- With small $S-D$ mixing among $J^{PC}=1^{--}$ successfully describe the corresponding available data
- Made several predictions for $\psi(3D,4S,4D,5S,5D,6S)\to J/\psi\eta$ & $h_c(1P)\eta$
- Studied spectroscopic quantum numbers for $Y(4360)$, $Y(4390)$ and $Y(4660)$
- Based on the current exp. data, $Y(4360)$ is a potential candidate for $\psi(3D)$ in presented effective model
- Update is available from BESIII for $Y(4360)\to h_c(1P)\eta$ ← study ongoing
- $\psi\to J/\psi\pi^+\pi^-$ and $\psi\to h_c\pi^+\pi^-$ study also ongoing, stay tune!

Thanks for Your Attention