“International Workshop on QCD Exotics”

Open charm decays of higher charmonia

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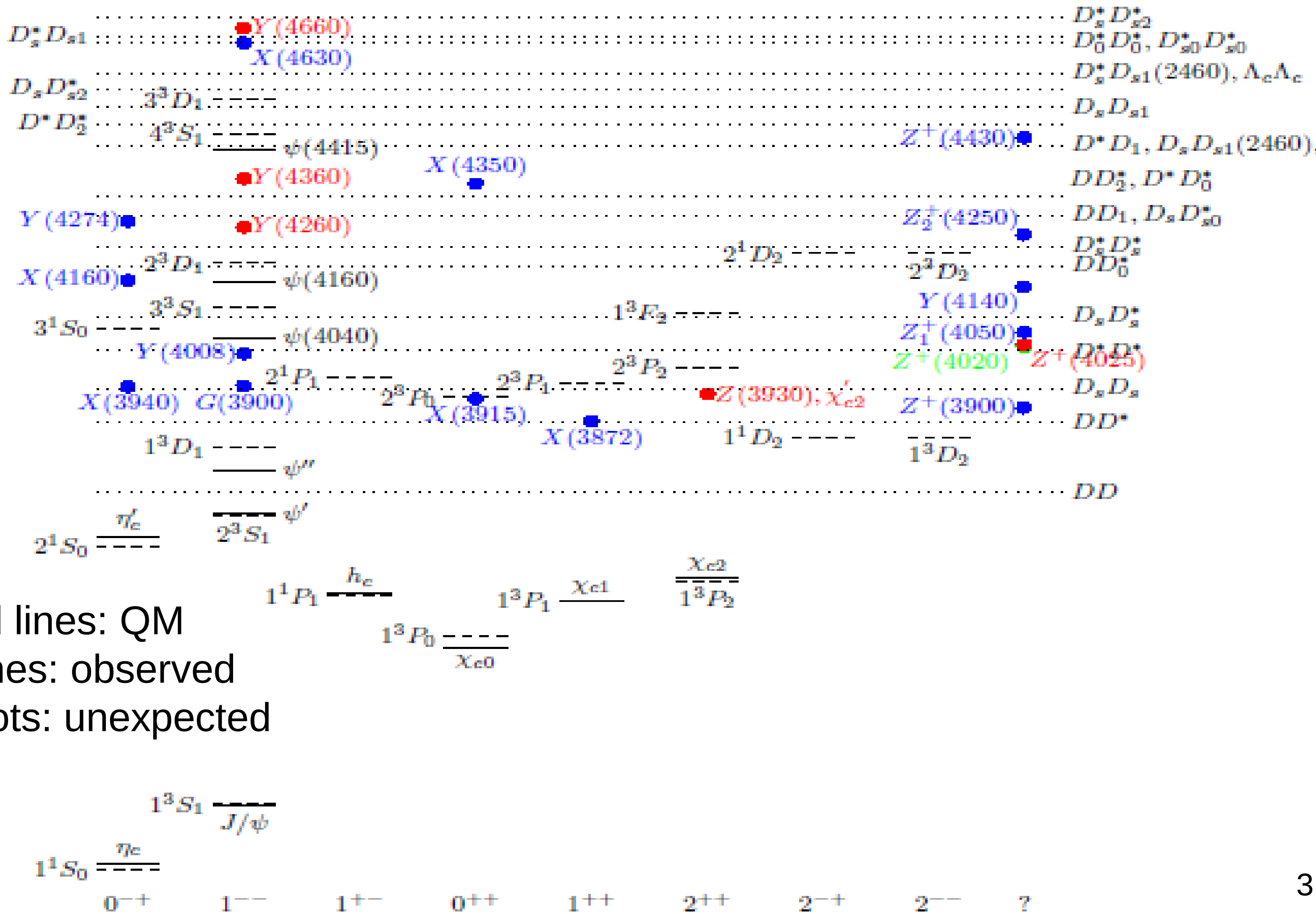
Higher charmonium-like states



Dashed lines: QM
Solid lines: observed
Solid dots: unexpected

Meson properties

- Properties:

  Above $D\underline{D}$ threshold

  Near-threshold resonances

  Charged and explicitly exotic

- Hadronic molecules? Coupled channel effects? Threshold effects? ...

  difficult to understand

Quark structure?

- Information from experiments: mass, cross section, decay and branching ratios
- Open charm decays: Y(4260) above $D^*\underline{D}^*$ but NO $D\underline{D}$, $D\underline{D}^*$, $D^*\underline{D}^*$ channels observed
- Strange structure: hybrid? Four-quark state?

  production and decay mechanism
- Is 3P0 model enough for higher charmonia?
- Here: this decay mechanism in heavy quark limit!

Heavy quark limit

For $Q\bar{q}$ mesons, degenerate spin doublets

$$H^{L=0}_{j_\ell=\frac{1}{2}} = \begin{pmatrix} (\bar{q}Q)_{J^P=0^-} \\ (\bar{q}Q)_{J^P=1^-} \end{pmatrix}, \qquad m_D = m_{D^*},$$
$$H^{L=1}_{j_\ell=\frac{1}{2}} = \begin{pmatrix} (\bar{q}Q)_{J^P=0^+} \\ (\bar{q}Q)_{J^P=1^+} \end{pmatrix}, \qquad m_{D_0} = m_{D_1'},$$
$$H^{L=1}_{j_\ell=\frac{3}{2}} = \begin{pmatrix} (\bar{q}Q)_{J^P=1^+} \\ (\bar{q}Q)_{J^P=2^+} \end{pmatrix}, \qquad m_{D_1} = m_{D_2},$$
$$\cdots$$

For $Q\bar{Q}$ mesons, $m^{2S+1}L_J$. Only heavy quark spin symmetry

$$H^{L=0}_m = \begin{pmatrix} (Q\bar{Q})_{S=0,J^{PC}=0^{-+}} \\ (Q\bar{Q})_{S=1,J^{PC}=1^{--}} \end{pmatrix}, \qquad m_{\eta_c} = m_{J/\psi},$$
$$H^{L=1}_m = \begin{pmatrix} (Q\bar{Q})_{S=0,J^{PC}=1^{+-}} \\ (Q\bar{Q})_{S=1,J^{PC}=0^{++}} \\ (Q\bar{Q})_{S=1,J^{PC}=1^{++}} \\ (Q\bar{Q})_{S=1,J^{PC}=2^{++}} \end{pmatrix}, \qquad m_{h_c} = m_{\chi_{c0}} = m_{\chi_{c1}} = m_{\chi_{c2}},$$
$$\cdots$$

$S_{Q\bar{Q}}$ conserved

Casalbuoni et al, PLB302,95 (1993)

HQSS constraints

- For interactions: EFT

$$\mathcal{L}_{PP^*} = D_\mu P D^\mu P^\dagger - M_P^2 PP^\dagger + f_Q(PA^\mu P_\mu^{*\dagger} + P_\mu^* A^\mu P^\dagger)$$
$$-\frac{1}{2}P^{*\mu\nu}P_{\mu\nu}^{*\dagger} + M_{P^*}^2 P^{*\mu}P_\mu^{*\dagger}$$
$$+\frac{1}{2}g_Q \varepsilon_{\mu\nu\lambda\kappa}(P^{*\mu\nu}A^\lambda P^{*\kappa\dagger} + P^{*\kappa}A^\lambda P^{*\mu\nu\dagger}), \quad (2.20)$$

T.M. Yan et a l., PRD46,1148 (1992)

HQSS $\Rightarrow$ $g = \frac{1}{2}f$

- With doublets

$$\mathcal{L} = gTr[H\not{A}\gamma_5\bar{H}] + g'Tr[S\not{A}\gamma_5\bar{S}] + g''Tr[T_\mu\not{A}\gamma_5\bar{T}^\mu] + [hTr[S\not{A}\gamma_5\bar{H}] + h.c.]$$
$$+[h'Tr[T^\mu A_\mu\gamma_5\bar{S}] + h.c.] + \frac{h_1}{\Lambda_\chi}Tr[T^\mu(D_\mu\not{A})\gamma_5\bar{H}] + h.c.$$
$$+\frac{h_2}{\Lambda_\chi}Tr[T^\mu(\not{D}A_\mu)\gamma_5\bar{H}] + h.c.$$

$$H = \frac{1+\not{v}}{2}[P^{*\mu}\gamma_\mu + \delta_H P\gamma_5], \quad S = \frac{1+\not{v}}{2}[P_1'^{\mu}\gamma_\mu + \delta_S P_0^*],$$
$$T^\mu = \frac{1+\not{v}}{2}P_2^{*\mu\nu}\gamma_\nu + \delta_T\sqrt{\frac{3}{2}}P_1^\nu\gamma_5[g_\nu^\mu - \frac{1}{3}\gamma_\nu(\gamma^\mu - v^\mu)]$$

Casalbuoni et al, Phys.Rep.281,145(1997)

Open charm decay at hadron level

- Only higher charmonia can decay into open-charm mesons
- HQS → Special ratios for decay widths
- $\psi(nS) \to D\underline{D} : D\underline{D}^* : D^*\underline{D}^* \quad = \quad 1:4:7$

  [Rujula,Georgi,Glashow, PRL 37,398 (1976)]

- The ratio has been confirmed by following studies. e.g.

$$g_1 tr[J\bar{H}_{(\bar{Q})}\gamma^\mu i \overleftrightarrow{D}_\mu \bar{H}_{(Q)}] + h.c.$$

Ratios for open charm decay

- Here consider more decays of charmonium states in HQ limit.

  (hadron level and quark level)

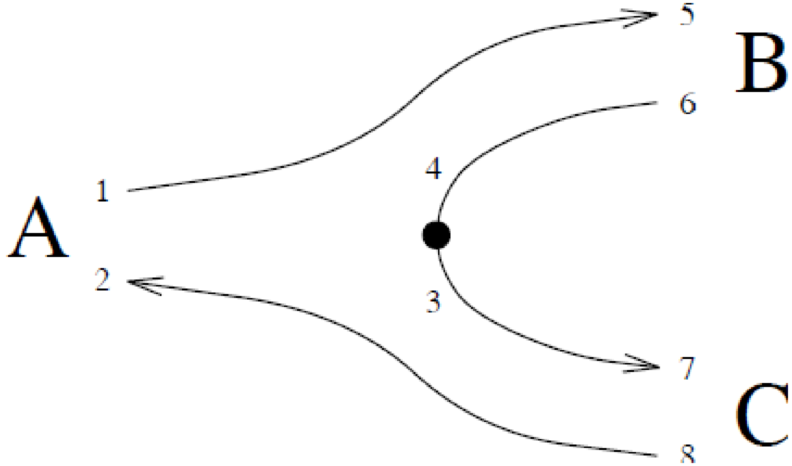
- Kinematically, some channels are forbidden (neglect)

  e.g. X(3823)(3D2) $\rightarrow D\underline{D}^*$, $D^*\underline{D}^*$ forbidden

- Actually, HQSS also broken (neglect)

Quark level

- The well known 3P0 model: $S_{Q\bar{Q}}$ conserved

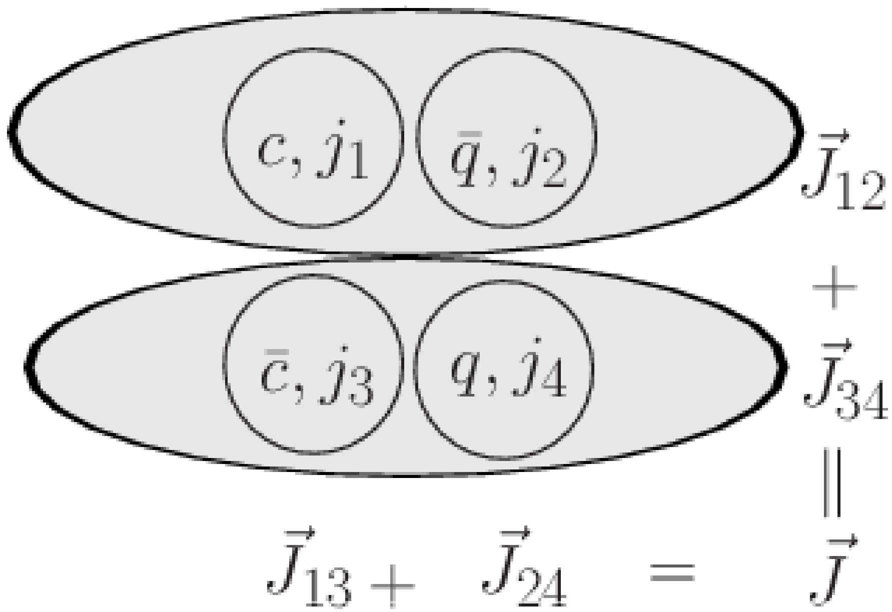


- This decay mechanism enough?
- May derive the decay ratios in heavy quark limit and compare with hadron level results

Wave function in heavy quark limit

- Meson-antimeson state→(c$\underline{c}$)-($\underline{q}$q) base

  (q as “effective” quark)



YRL, PRD, 88, 074008 (2013)

(Can extend S-wave case to L-wave case)

Hadron level vs. quark level

$$1.\quad Decay\ of\ L=0$$

- $g_1 tr[J\bar{H}_{(\bar{Q})}\gamma^\mu i \overleftrightarrow{D}_\mu \bar{H}_{(Q)}] + h.c.$

$$g_1 \begin{cases} 0^{-+} \to \cancel{D\bar{D}} : D\bar{D}^* : D^*\bar{D}^* = 0:1:1; \\ 1^{--} \to D\bar{D} : D\bar{D}^* : D^*\bar{D}^* = 1:4:7. \end{cases} \qquad {}^3P_0 \begin{cases} 0^{-+} \to \cdots = 0:1:1; \\ 1^{--} \to \cdots = 1:4:7. \end{cases}$$

- $g_2 tr[J\bar{S}_{(\bar{Q})}\gamma^\mu i \overleftrightarrow{D}_\mu \bar{S}_{(Q)}] + h.c.$

$$g_2 \begin{cases} 0^{-+} \to \cancel{D_0\bar{D}_0} : D_0\bar{D}_1' : D_1'\bar{D}_1' = 0:1:1; \\ 1^{--} \to D_0\bar{D}_0 : D_0\bar{D}_1' : D_1'\bar{D}_1' = 1:4:7. \end{cases} \qquad {}^3P_0 \begin{cases} 0^{-+} \to \cdots = 0:1:1; \\ 1^{--} \to \cdots = 1:4:7. \end{cases}$$

- $g_3 tr[J\bar{T}_{(\bar{Q})\nu}\gamma^\mu i \overleftrightarrow{D}_\mu \bar{T}^\nu_{(Q)}] + h.c.$

$$g_3 \begin{cases} 0^{-+} \to D_1\bar{D}_1 : D_1\bar{D}_2 : D_2\bar{D}_2 = 5:2:9; \\ 1^{--} \to D_1\bar{D}_1 : D_1\bar{D}_2 : D_2\bar{D}_2 = 1:7:4. \end{cases} \qquad {}^3P_0 \begin{cases} 0^{-+} \to \cdots = 5:2:9; \\ 1^{--} \to \cdots = 1:7:4. \end{cases}$$

Hadron level vs. quark level

2. *Decay of* $L = 2$

- $g_4 tr[J^{\mu\nu}\bar{H}_{(\bar{Q})}\gamma_\mu i \overleftrightarrow{D}_\nu \bar{H}_{(Q)}] + h.c.$

$$g_4 \begin{cases} 1^{--} \to D\bar{D} : D\bar{D}^* : D^*\bar{D}^* = \boxed{5:5:2}, \\ 2^{--} \to \cancel{D\bar{D}} : D\bar{D}^* : D^*\bar{D}^* = 0:3:1, \\ 3^{--} \to \cancel{D\bar{D}} : \cancel{D\bar{D}^*} : D^*\bar{D}^* = 0:0:x; \\ 2^{-+} \to \cancel{D\bar{D}} : D\bar{D}^* : D^*\bar{D}^* = 0:1:1. \end{cases} \qquad {}^3P_0 \begin{cases} 1^{--} \to \cdots = 5:5:2, \\ 2^{--} \to \cdots = 0:3:1, \\ 3^{--} \to \cdots = 0:0:x; \\ 2^{-+} \to \cdots = 0:1:1. \end{cases}$$

Probes of heavy meson substructure in e^+e^- annihilation

F.E. Close and G.J. Gounaris [1,2]
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK

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Physics Letters B 311 (1993) 297–300

We apply Heavy Quark Effective Theory to the production of 0^- and 1^- $Q\bar{q}$ states in e^+e^- annihilation. We show that HQET implies that the electric quadrupole amplitudes vanish and we propose tests for this theory. We also show how HQET can be applied to distinguish the $^3D_1$ and $^3S_1$ $Q\bar{Q}$ states.

$$\sigma(e^+e^- \to PP : PV + VP : VV) = 1:4:7$$

$$\sigma(e^+e^- \to PP : PV + VP : VV) \simeq 1:1:4$$ ←Why inconsistent?

Hadron level vs. quark level

2. Decay of $L = 2$

- $g_6^a tr[J^{\mu\nu}\bar{T}_{(\bar{Q})\alpha}\gamma_\mu i \overleftrightarrow{D}_\nu \bar{T}^\alpha_{(Q)}] + h.c.,$
  $g_6^b tr[J^{\mu\nu}\bar{T}_{(\bar{Q})\mu}\gamma^\alpha i \overleftrightarrow{D}_\alpha \bar{T}_{(Q)\nu}] + h.c.$

$$g_6^a \begin{cases} 1^{--} \to D_1\bar{D}_1 : D_1\bar{D}_2 : D_2\bar{D}_2 = 167 : 206 : 107, \\ 2^{--} \to D_1\bar{D}_1 : D_1\bar{D}_2 : D_2\bar{D}_2 = 1 : 138 : 21, \\ 2^{-+} \to D_1\bar{D}_1 : D_1\bar{D}_2 : D_2\bar{D}_2 = 5 : 2 : 9. \end{cases}$$

$${}^3P_0 \begin{cases} 1^{--} \to \cdots = 167 : 206 : 107, \\ 2^{--} \to \cdots = 1 : 138 : 21, \\ 2^{-+} \to \cdots = 5 : 2 : 9. \end{cases}$$

$$g_6^b \begin{cases} 1^{--} \to D_1\bar{D}_1 : D_1\bar{D}_2 : D_2\bar{D}_2 = 61 : 13 : 4, \\ 2^{--} \to D_1\bar{D}_1 : D_1\bar{D}_2 : D_2\bar{D}_2 = 1 : 12 : 0, \\ 2^{-+} \to D_1\bar{D}_1 : D_1\bar{D}_2 : D_2\bar{D}_2 = 1 : 76 : 27. \end{cases}$$

${}^3P_0$?

Hadron level vs. quark level

$$3. \quad Decay\ of\ L=1$$

- $g_7 tr[J^\mu \bar{H}_{(\bar{Q})}\gamma_\mu \bar{H}_{(Q)}] + h.c.$

$$g_7 \begin{cases} 0^{++} \to D\bar{D} : \cancel{D\bar{D}^*} : D^*\bar{D}^* = 3:0:1, \\ 1^{++} \to \cancel{D\bar{D}} : D\bar{D}^* : \cancel{D^*\bar{D}^*} = 0:x:0, \\ 2^{++} \to \cancel{D\bar{D}} : \cancel{D\bar{D}^*} : D^*\bar{D}^* = 0:0:x; \\ 1^{+-} \to \cancel{D\bar{D}} : D\bar{D}^* : D^*\bar{D}^* = 0:1:1. \end{cases} \qquad {}^3P_0 \begin{cases} 0^{++} \to \cdots = 3:0:1, \\ 1^{++} \to \cdots = 0:x:0, \\ 2^{++} \to \cdots = 0:0:x; \\ 1^{+-} \to \cdots = 0:1:1. \end{cases}$$

- $g_9^a tr[J^\mu \bar{T}^\nu_{(\bar{Q})}\gamma_\mu \bar{T}_{(Q),\nu}] + h.c.$

$$g_9^a \begin{cases} 0^{++} \to D_1\bar{D}_1 : \cancel{D_1\bar{D}_2} : D_2\bar{D}_2 = 5:0:3, \\ 1^{++} \to \cancel{D_1\bar{D}_1} : D_1\bar{D}_2 : \cancel{D_2\bar{D}_2} = 0:x:0, \\ 2^{++} \to D_1\bar{D}_1 : D_1\bar{D}_2 : D_2\bar{D}_2 = 1:18:21; \\ 1^{+-} \to D_1\bar{D}_1 : D_1\bar{D}_2 : D_2\bar{D}_2 = 5:2:9. \end{cases} \qquad {}^3P_0 \begin{cases} 0^{++} \to \cdots = 5:0:3, \\ 1^{++} \to \cdots = 0:x:0, \\ 2^{++} \to \cdots = 1:18:21; \\ 1^{+-} \to \cdots = 5:2:9. \end{cases}$$

Two-doublet case

- High mass also allows the decay into two doublets

4. Decay of $L=0$ (two doublets)

- $g_{10}^{a} tr[J\bar{S}_{(\bar{Q})}\bar{H}_{(Q)} + J\bar{H}_{(\bar{Q})}\bar{S}_{(Q)}] + h.c.$

$$\left\{ \begin{array}{l} 0^{-+} \to D\bar{D}_0 : \cancel{D\bar{D}_1'} : \cancel{D^*\bar{D}_0} : D^*\bar{D}_1' = 1:0:0:3, \\ 1^{--} \to \cancel{D\bar{D}_0} : D\bar{D}_1' : D^*\bar{D}_0 : D^*\bar{D}_1' = 0:1:1:2, \end{array} \right. \qquad {}^3P_0 \left\{ \begin{array}{l} 0^{-+} \to \cdots = 1:0:0:3, \\ 1^{--} \to \cdots = 0:1:1:2, \end{array} \right.$$

Consistent with

P.M. Stevenson, PRD 18, 4063 (1978)

Two-doublet case

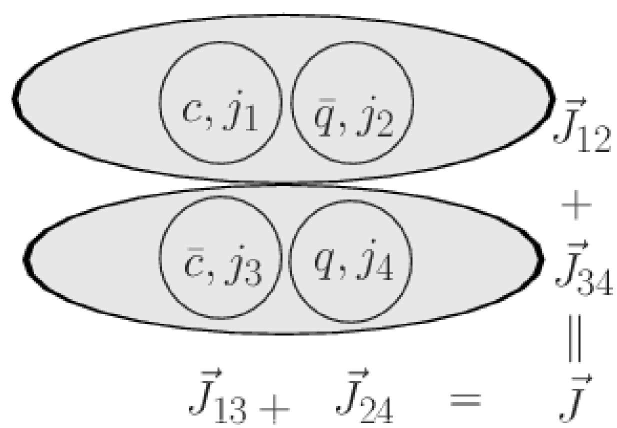
4. Decay of $L = 0$ (two doublets)

- $g^a_{11} tr[J\bar{T}^{\mu}_{(\bar{Q})}\gamma_\mu \bar{H}_{(Q)} - J\bar{H}_{(\bar{Q})}\gamma_\mu \bar{T}^{\mu}_{(Q)}] + h.c. = 0$

$$g^a_{11}\left\{\begin{array}{l} 0^{-+} \to \cancel{D_1\bar{D}} : D_1\bar{D}^* : \cancel{D_2\bar{D}} : \cancel{D_2\bar{D}^*} \\ 1^{--} \to D_1\bar{D} : D_1\bar{D}^* : \cancel{D_2\bar{D}} : D_2\bar{D}^* \end{array}\right.$$

The reason $0^{-+} \nrightarrow D_1\bar{D}^*$**,** $1^{--} \nrightarrow D_1\bar{D}, D_1\bar{D}^*, D_2\bar{D}^*$ **in** $^3P_0$

"effective" quark spin J24≠0 (j2≠j4)



Two-doublet case

$$5. \quad \textit{Decay of } L = 2 \textit{ (two doublets)}$$

- $g_{14}^a tr[J^{\mu\nu}\bar{T}_{(\bar{Q})\mu}\gamma_\nu \bar{H}_{(Q)} - J^{\mu\nu}\bar{H}_{(\bar{Q})}\gamma_\nu \bar{T}_{(Q)\mu}] + h.c.$

$$g_{14}^a \begin{cases} 1^{--} \to D_1\bar{D} : D_1\bar{D}* : \cancel{D_2\bar{D}} : D_2\bar{D}^* = 10 : 5 : 0 : 1, \\ 2^{--} \to \cancel{D_1\bar{D}} : D_1\bar{D}* : D_2\bar{D} : D_2\bar{D}^* = 0 : 9 : 6 : 1, \\ 2^{-+} \to \cancel{D_1\bar{D}} : D_1\bar{D}* : D_2\bar{D} : D_2\bar{D}^* = 0 : 3 : 2 : 3. \end{cases} \qquad {}^3P_0(???)$$

More calculations

Ongoing...

Summary

- Study ratios of open charm decay for higher charmonia in the limit $mQ \rightarrow \infty$
- Hadron level and quark level consistent but...
- More information may be obtained after the calculation.

Thank you very much!