Hadron Molecules

Th. Gutsche

Institut für Theoretische Physik

Universität Tübingen

Overview

- **Introductory remarks:** meson spectrum and the possibility of hadronic molecules
- **The method, diagnostics of decay patterns:** compositeness/Weinberg condition and hadron loops
- **Open charm systems:** $D_{s0}^*(2317) = DK$, $D_{s1}(2460) = D^*K$
- **Hidden charm systems:** $X(3872) = D^0\bar{D}^{*0} + c.c.$, $Y(4140) = D_s^{*+}D_s^{*-}$

Based on:

PRD 76 (2007) 014003, 014005, 114013; PRD 77 (2008) 094013; EPJA 37 (2008) 303;
PRD 79 (2009) 094013, 014035; arXiv:0903.5424 [hep-ph], arXiv:0909.0380 [hep-ph];

together with:

T. Branz, A. Faessler, V. Lyubovitskij, Y.-L. Ma (Tübingen)
Y. Dong (Beijing), S. Kovalenko (Valparaiso)

Introduction: Meson Spectroscopy

QCD $\stackrel{soft\ limit}{\Longrightarrow}$ physical states: mesons and meson spectroscopy

$Q\bar{Q}$ " dressed quasiparticle " Q = constituent quark ($m_Q \approx 300\ MeV$)

g=" constituent gluon "(usually $J^{PC} = 0^{++}$) ?

Meson spectroscopy

- Spectrum (masses and quantum numbers)
- strong, weak and e.m. decay/production patterns and rates

but:

- anomalous dynamical features in spectrum, decay and production
- extra (scalar states) and missing states (above 2 GeV)
- exotic quantum numbers ($J^{PC} = 1^{-+}$)

Introduction: Meson Spectroscopy

Model builders (extraploation, color singlets)

- tetraquark (baryonium) $Q^2\bar{Q}^2$, Jaffe (1977)
- hybrids $Q\bar{Q}g$, Chanowitz et al. (1983)
- glueball gg, Barnes et al. (1982)
- ....

however, conventional theory also predicts meson states!

- meson-meson molecules, Weinstein and Isgur (1979)
  or dynamically generated resonances, Lohse et al. (1990), Oller et al. (1997)
- $N\bar{N}$ bound states, Dover et al. (1992)
- threshold cusp
- ....

Introduction: Hadronic Molecules

- Hadronic molecules – weakly bound states of hadrons
- obvious examples: Nuclei and Hypernuclei
- Meson-Meson bound states, masses slightly below threshold: $m_{HM} < m_{M1} + m_{M2}$
- dynamical generation of molecular bound states/resonances:
  - long-range one-pion-exchange (Tornqvist 1991) $\rightarrow$ table
  - meson exchange models (Lohse et al. 1990)
  - unitarized coupled channel models with chiral Lagrangians (Oller et al. (1997), Lutz et al. (2004), Jido et al. (2005), Gammermann et al. (2008),.....)
- some candidates for hadronic meson-meson molecules
  - $a_0(980)$, $f_0(980) \; = \; K\bar{K}$
  - $D^*_{s0}(2317) \; = \; DK$, $D_{s1}(2460) \; = \; D^*K$
  - $X(3872) \; = \; D^0\bar{D}^{*0} + c.c.$
  - $Y(4260) \; = \; D\bar{D}_1(2420) - c.c.$
  - $Z(4430) \; = \; D^*(2010)\bar{D}_1(2420)$
  - $Y(4660) = \psi' f_0(980)$
  - $Y(4140) = D_s^{*+}D_s^{*-}$

Introduction: Hadronic Molecules

Early predictions: N. Törnqvist, Z. Phys. C 61 (1994)

Table 8. The predicted heavy deuson states (all with $I=0$) close to the $D\bar{D}^*$ and the $D^*\bar{D}^*$ thresholds and about 50 MeV below the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds. As discussed in the text, the mass values are obtained from a rather conservative one-pion exchange contribution only. With additional attraction of shorter range, the masses can decrease considerably. Mixing between the two η_b's (and two η_c's) should decrease the lighter mass somewhat (and increase the heavier mass)

Composite	J^{PC}	Deuson
$D\bar{D}^*$	0^{-+}	η_c ($\approx$ 3 870)
$D\bar{D}^*$	1^{++}	χ_{c1} ($\approx$ 3 870)
$D^*\bar{D}^*$	0^{++}	χ_{c0} ($\approx$ 4 015)
$D^*\bar{D}^*$	0^{-+}	η_c ($\approx$ 4 015)
$D^*\bar{D}^*$	1^{+-}	h_{c0} ($\approx$ 4 015)
$D^*\bar{D}^*$	2^{++}	χ_{c2} ($\approx$ 4 015)
$B\bar{B}^*$	0^{-+}	η_b ($\approx$10 545)
$B\bar{B}^*$	1^{++}	χ_{b1} ($\approx$10 562)
$B^*\bar{B}^*$	0^{++}	χ_{b0} ($\approx$10 582)
$B^*\bar{B}^*$	0^{-+}	η_b ($\approx$10 590)
$B^*\bar{B}^*$	1^{+-}	h_b ($\approx$10 608)
$B^*\bar{B}^*$	2^{++}	χ_{b2} ($\approx$10 602)

The method: Compositeness/Weinberg condition

- Bound state description of hadronic molecules in QFT based on compositeness condition: $Z_M = 0$.
  see: Weinberg, PR 130 (1963) 776; Salam, Nuev. Cim. 25 (1962) 224; Hayashi et al., FP 15 (1967) 625;...
- Example and test case $f_0(980)$ and $a_0(980)$:
  Effective Lagrangian, describing coupling, $g_{f_0 K\bar{K}}$, of $K\bar{K}$ constituents to f_0:

$$\mathcal{L}_{f_0 K\bar{K}} = \frac{g_{f_0 K\bar{K}}}{\sqrt{2}} f_0(x) \int dy\, \Phi(y^2) \bar{K}\Big(x - \frac{y}{2}\Big) K\Big(x + \frac{y}{2}\Big) \,, \quad K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}$$

- Vertex function $\Phi(y^2)$ – finite size effects/distribution of constituents in bound state:

  local limit: $\Phi(y^2) \to \delta^{(4)}(y)$

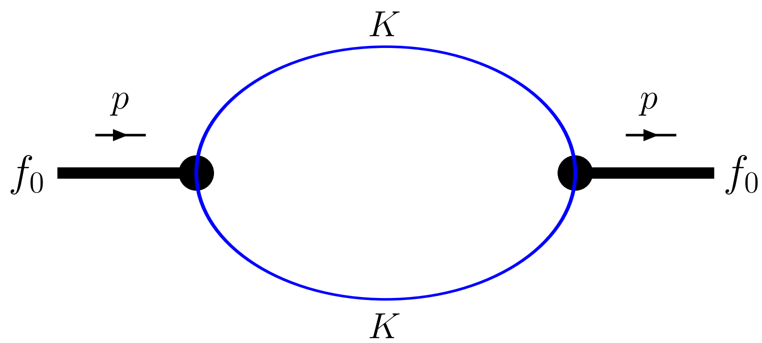
  momentum space: $\tilde{\Phi}(p_E^2) = \exp(-p_E^2/\Lambda^2)$, Gaussian with free size parameter Λ.

The method: Compositeness/Weinberg condition

Bound state description and compositeness condition:

$$Z_{f_0} = 1 - g^2_{f_0 K \bar{K}} \tilde{\Pi}'(m^2_{f_0}) = 0$$

with the **mass operator** $\tilde{\Pi}(p^2)$ represented by:

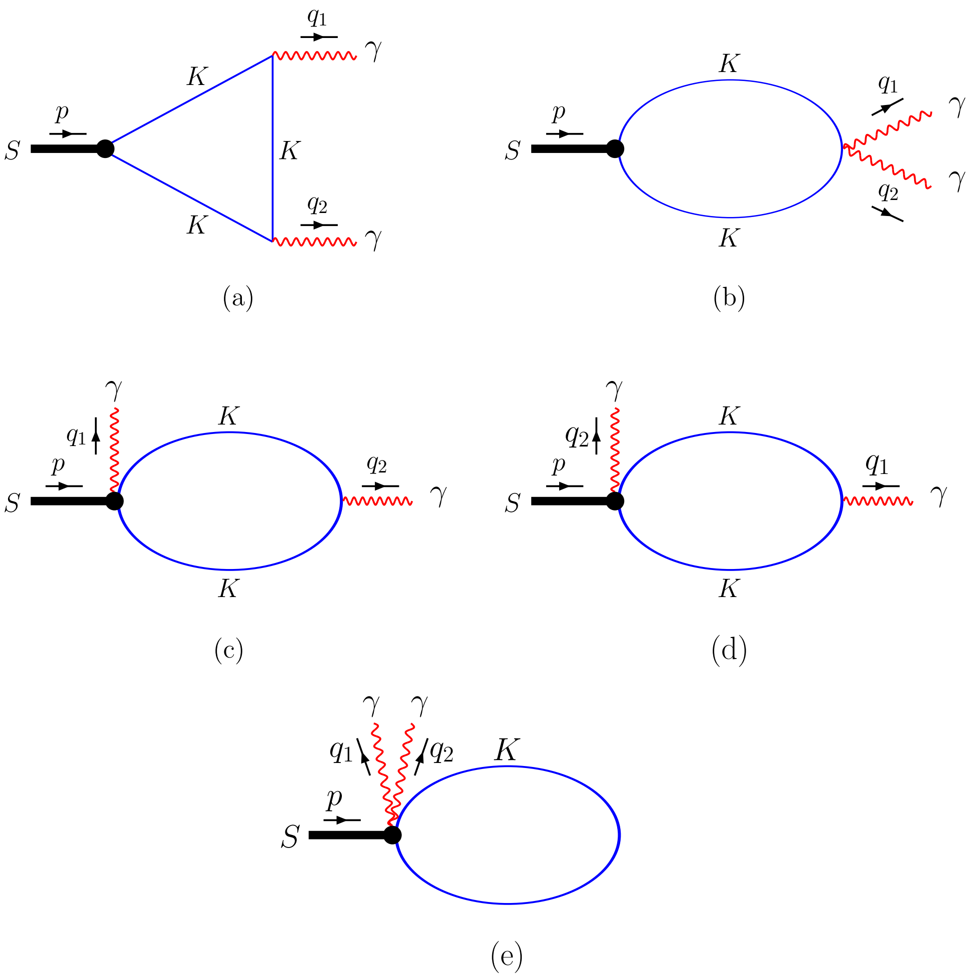


- note: $Z_{f_0} = |< f_0^{bare}|f_0^{dressed} > |$=0 and g_{f_0} is finite.
- here: for $\Lambda_{f_0} = 0.7 - 1.3$ GeV $\rightarrow g_{f_0 K \bar{K}} = 3.03 - 3.21$ GeV (=2.9 GeV in local limit)

The test case: a_0/f_0 as hadronic molecules

$\mathbf{f_0(980)} \to \gamma\gamma$ and $\mathbf{a_0(980)} \to \gamma\gamma$

(see Branz, TG, Lyubovitskij: EPJA 37 (2008) 303; PRD 78 (2008) 114013)



	$\Gamma_{f_0 \to \gamma\gamma}$ [keV]
PDG (2008)	$0.29^{+0.07}_{-0.09}$
Theo. (Λ =1 GeV)	0.25
Theo. (local lim.)	0.29

	$\Gamma_{a_0 \to \gamma\gamma}$ [keV]
Amsler (98)	0.30 ± 0.1
Theo. (Λ =1 GeV)	0.19
Theo. (local lim.)	0.23

$D^*_{s0}(2317)$, $D_{s1}(2460)$

Basics about $D^*_{s0}(2317)$ and $D_{s1}(2460)$

- first seen in
  $D^*_{s0}(2317) \to D_s\pi^0$ by BABAR (2003), $D_{s1}(2460) \to D^*_s\pi^0$ by CLEO (2003)
- Both states confirmed by BELLE (2004)
- $\Gamma_{D^*_{s0}}$ < 3.8 MeV, $\Gamma_{D_{s1}}$ < 3.5 MeV
- quantum numbers $J^P(D^*_{s0}) = 0^+$ and $J^P(D_{s1}) = 1^+$
- $D^*_{s0}(2317)$ close to DK threshold with $m_{thr} = 2362$ MeV;
  $D_{s1}(2460)$ close to D^*K threshold with $m_{thr} = 2503$ MeV.
- but, few ratios for rates (or upper limits) for $D^*_{s0}(2317)$:

  $$\frac{\Gamma(D^*_{s0}(2317)^+ \to D^*_s(2112)^+\gamma)}{\Gamma(D^*_{s0}(2317)^+ \to D^+_s\pi^0)} < 0.059$$

  and for ratio of dominant decay modes of $D_{s1}(2460)$:

  $$\frac{\Gamma(D_{s1}(2460)^+ \to D^+_s\gamma)}{\Gamma(D_{s1}(2460)^+ \to D^{*+}_s\pi^0)} = 0.44 \pm 0.09$$
- $J^P = 0^+$ $c\bar{s}$ expected between $2400 - 2500$ MeV !

$D^*_{s0}(2317)$, $D_{s1}(2460)$

$D^*_{s0}(2317)(0^+)$ and $D_{s1}(2460)(1^+)$ as hadronic molecules:

$|D^{*+}_{s0} >= |D^+ K^0 > + |D^0 K^+ >$ $\qquad$ $|D^+_{s1} >= |D^{*+} K^0 > + |D^{*0} K^+ >$

Coupling of the hadronic molecules to the constituents

$$\mathcal{L}_{D^*_{s0}}(x) \,=\, g_{D^*_{s0}}\, D^{*\,-}_{s0}(x) \int dy\, \Phi_{D^*_{s0}}(y^2)\, D^T(x + w_K y)\, K(x - w_D y) \,+\, \text{H.c.}$$

with the doublets

$$D = \begin{pmatrix} D^0 \\ D^+ \end{pmatrix}, K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix} \text{ and } w_{ij} = \frac{m_i}{m_i + m_j}$$

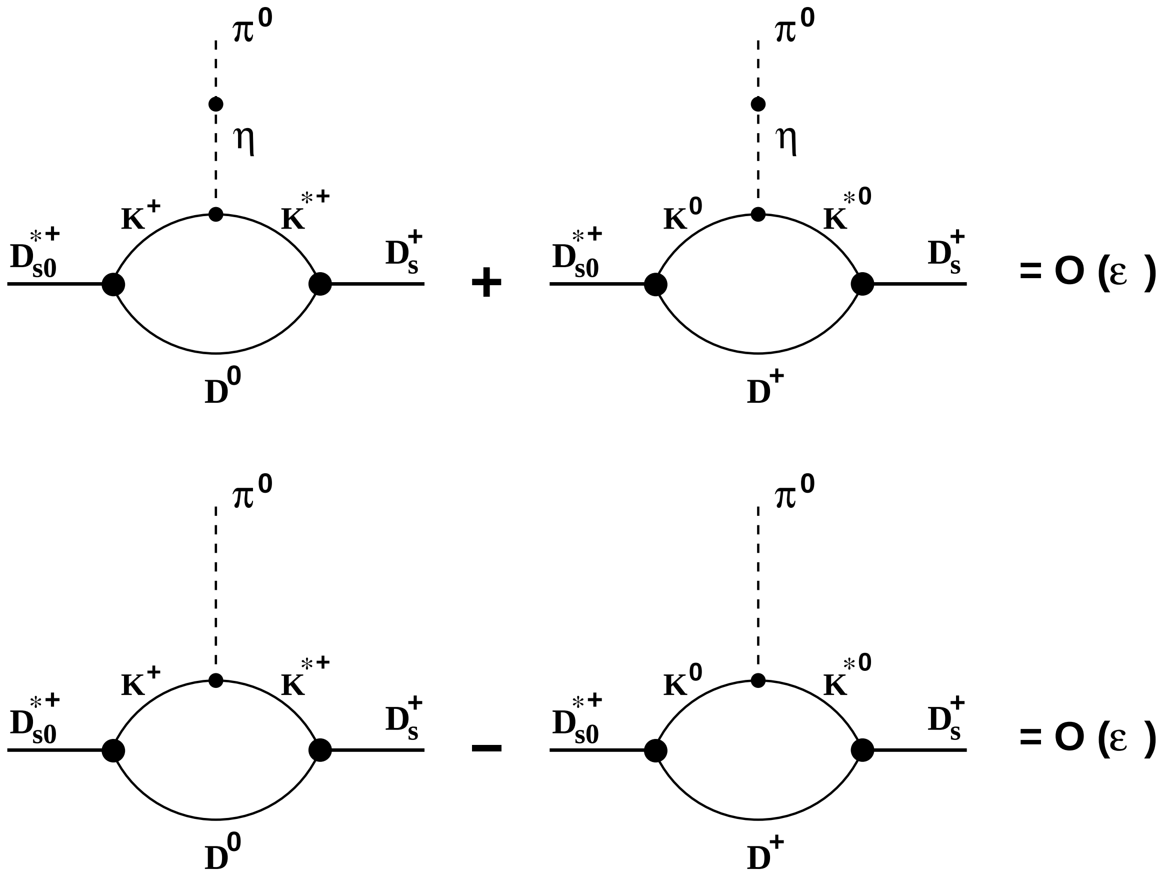
Resulting in: $g_{D^*_{s0}} = 10.58 \pm 0.68$ GeV ($g_{D_{s1}} = 10.90 \pm 0.72$ GeV).

with Gaussian vertex function: $\tilde{\Phi}(p_E^2) = \exp(-p_E^2/\Lambda^2)$ and $\Lambda = 1 - 2$ GeV.

(see Faessler, TG, Lyubovitskij, Ma, PRD 76, 014005, 114008 (2007))

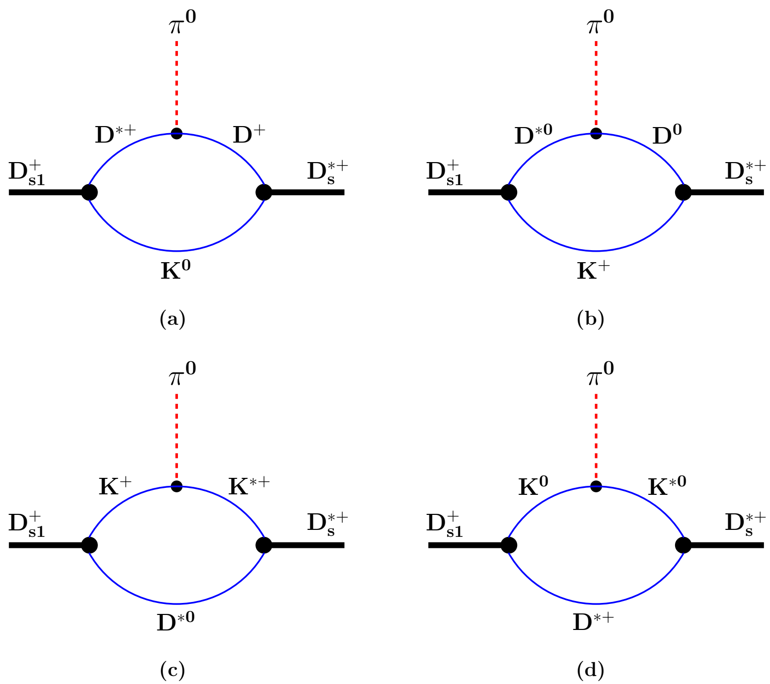
$D^*_{s0}(2317)$, $D_{s1}(2460)$

Direct and $\eta - \pi^0$ mixing mechanisms



isospin violation $\tan(2\epsilon) = \frac{\sqrt{3}}{2}\frac{m_d - m_u}{m_s - \hat{m}}$ Gasser (1984)

Strong decay $D_{s1} \longrightarrow D_s^* \pi^0$



including direct and $\eta - \pi^0$ mixing transition

Effective interaction Lagrangian

$$
\begin{aligned}
\mathcal{L}_{int} &= -\frac{g_{D^*D\pi}}{2\sqrt{2}} D_\mu^{*\,\dagger}\,\hat{\pi}_D i \overleftrightarrow{\partial}^\mu D + \frac{g_{K^*K\pi}}{\sqrt{2}} K_\mu^{*\,\dagger}\hat{\pi}_K i \overleftrightarrow{\partial}^\mu K \\
&+ g_{D^*D_sK}\, D_\mu^{*\,T} K\, i \overleftrightarrow{\partial}^\mu D_s^- + g_{D_s^*DK}\, D_{s\,\mu}^{*\,-} D^T i \overleftrightarrow{\partial}^\mu K \\
&- i g_{K^*D_s^*D^*} \left[D_s^{*\,-\,\mu\nu} D_\mu^* K_\nu^* + D^{*\,\mu\nu} K_\mu^* D_{s,\nu}^{*\,-} + K^{*\,\mu\nu} D_{s,\mu}^{*\,-} D_\nu^*(x) \right] \\
&+ \mathcal{L}_{D_{s0}^*} + \mathcal{L}_{D_{s1}} + H.c.
\end{aligned}
$$

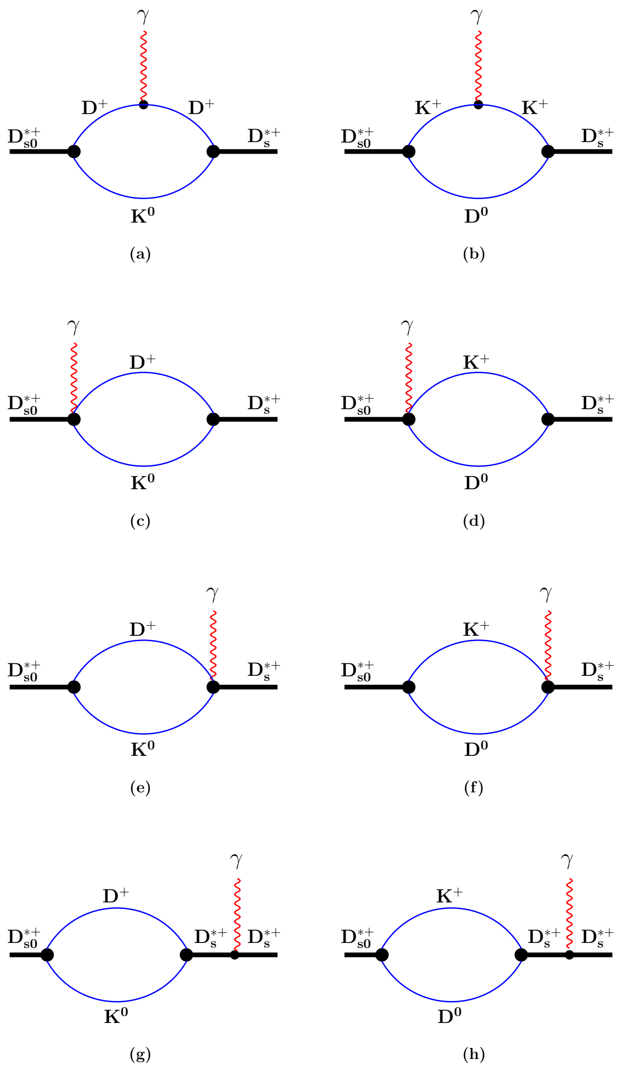
including $\pi^0 - \eta$ mixing:

$$\pi_3 \longrightarrow \pi_3 \cos\epsilon - \eta \sin\epsilon \qquad \hat{\pi}_D = \pi_1\tau_1 + \pi_2\tau_2 + \pi_3(\tau_3\cos\varepsilon + I\sin\varepsilon/\sqrt{3})$$

$$\eta \longrightarrow \pi_3 \sin\epsilon + \eta\cos\epsilon \qquad \hat{\pi}_K = \pi_1\tau_1 + \pi_2\tau_2 + \pi_3(\tau_3\cos\varepsilon + I\sin\varepsilon\sqrt{3})$$

with $\tan 2\varepsilon = \frac{\sqrt{3}}{2}\frac{m_d - m_u}{m_s - \hat{m}} \simeq 0.02$ (Gasser 1984)
and couplings
$g_{D^*D\pi} = 17.9,\ \ g_{K^*K\pi} = 4.61$ fixed by data, $g_{D^*D\eta} = 7.95,\ \ g_{K^*K\eta} = 6.14$ HHChPt
$g_{D^*D_sK} = g_{K^*D_sD} = 2.02,\ \ g_{D_s^*DK} = g_{D_s^*D^*K^*} = 1.84$ QCD sum rules (Wang 2006)

Radiative decay $D_{s0}^* \rightarrow D_s^* \gamma$



similarly for $D_{s1} \rightarrow D_s \gamma$

$D_{s0}^*(2317)$, $D_{s1}(2460)$

Results for strong decays (in keV)

Approach	$\Gamma(D_{s0}^* \to D_s \pi^0)$	$\Gamma(D_{s1} \to D_s^* \pi^0)$
Nielsen 2005 (tetraquark)	6 ± 2	
Colangelo 2003 ($c\bar{s}$, HQS)	7 ± 1	7 ± 1
Godfrey 2003 ($c\bar{s}$)	10	10
Fayyazuddin 2003 ($c\bar{s}$)	16	32
Bardeen 2003 ($c\bar{s}$)	21.5	21.5
Lu 2006 ($c\bar{s}$)	32	35
Wei 2005 ($c\bar{s}$, QCDSR)	39 ± 5	43 ± 8
Ishida 2004 ($c\bar{s}$)	$155 - 70$	$155 - 70$
Cheng 2003 (tetraquark)	$10 - 100$	
Azimov 2004 ($c\bar{s}$)	129 ± 43	187 ± 73
Our result (HM)	$46.7 - 111.9$	$50.1 - 79.2$
Lutz 2007 (HM, χ NLO)	140	140
Guo 2008 (HM, χ NLO)	180 ± 110	

Results for radiative decays (in keV)

Approach	$\Gamma(D_{s0}^* \to D_s^* \gamma)$	$\Gamma(D_{s1} \to D_s \gamma)$
Fayyazuddin 2003 ($c\bar{s}$)	0.2	
Colangelo 2003 ($c\bar{s}$, HQS)	0.85 ± 0.05	
Close 2005 ($c\bar{s}$)	1	$\lesssim 7.3$
Liu 2006 ($c\bar{s}$)	1.1	0.6-2.9
Wang 2006 ($c\bar{s}$)	$1.3 - 9.9$	$5.5 - 31.2$
Azimov 2004 ($c\bar{s}$)	$\lesssim 1.4$	$\lesssim 2$
Bardeen 2003 ($c\bar{s}$)	1.74	5.08
Godfrey 2003 ($c\bar{s}$)	1.9	6.2
Colangelo 2005 ($c\bar{s}$, QCDSR)	$4 - 6$	$19 - 29$
Ishida 2003 ($c\bar{s}$)	21	93
Our results (HM)	$0.47 - 0.63$	$2.73 - 3.73$
Lutz 2007 (HM, χ NLO)	< 7	≈ 43.6
Gamermann 2007 (HM)	0.488	

Results for ratios

$$R_{D_{s0}^*} = \Gamma(D_{s0}^* \to D_s^* \gamma)/\Gamma(D_{s0}^* \to D_s \pi)$$

$$R_{D_{s1}} = \Gamma(D_{s1} \to D_s \gamma)/\Gamma(D_{s1} \to D_s^* \pi)$$

Approach	$R_{D_{s0}}$	$R_{D_{s1}}$
Azimov 2004 ($c\bar{s}$)	$\leq$ 0.02	0.01 - 0.02
Bardeen 2003 ($c\bar{s}$)	0.08	0.24
Lutz 2007 (HM, χ NLO)	$\leq$ 0.05	$\simeq$ 0.31
Ishida 2003 ($c\bar{s}$)	0.09 - 0.25	0.41 - 1.09
Godfrey 2003 ($c\bar{s}$)	0.19	0.62
PDG 2008	$\leq$ 0.059	0.44 $\pm$ 0.09
Our result (HM)	$\simeq$ 0.01	$\simeq$ 0.05

$X(3872)$

Basics about $X(3872)$

- first seen in
  $X(3872) \to J/\psi\pi^+\pi^-$ by BELLE (2003),
  also seen by CDF, D0 (2004) and BABAR (2005).
- $\Gamma_X \approx$ 3 MeV
- quantum numbers:

  C=+ from $X(3872) \to \gamma J/\psi$, I=0 no signal in $X \to \pi\pi^0 J/\psi$

  $J^{PC} = 1^{++}$ or $J^{PC} = 2^{-+}$ from $X(3872) \to J/\psi\pi^+\pi^-$ helicity amplitude analysis
- $X(3872.2 \pm 0.8)$ close to $D^0\bar{D}^{*0}$ threshold with $m_{thr} = 3871.81 \pm 0.36$ MeV;
- S-wave $D^0\bar{D}^{*0}$ hadron molecule favors $J^{PC} = 1^{++}$
- charmonium interpretation disfavored, $1^{++}(2^3P_1)$ too low in mass compared to $m(2^3P_2) \approx m(Z(3930))$

Basics about $X(3872)$, Decay Modes

- $\mathbf{\Gamma(X \to J/\psi\pi^+\pi^-\pi^0)/\Gamma(X \to J/\psi\pi^+\pi^-) = 1.0 \pm 0.4}$(stat) $\mathbf{\pm\, 0.3}$(syst)
  BELLE (hep-ex/0505037)
  isospin violating decay modes
  decays dominated by subthreshold decays of $\omega J/\psi$ and $\rho J/\psi$

- $\mathbf{\Gamma(X \to J/\psi\gamma)/\Gamma(X \to J/\psi\pi^+\pi^-) = 0.14 \pm 0.05}$ (Belle); $\mathbf{0.33 \pm 0.12}$ (BABAR)
  BELLE (hep-ex/0505037), BABAR PRL 102 (2009)
  large radiative decay mode !!

- $\mathbf{\Gamma(X \to \psi(2S)\gamma)/\Gamma(X \to J/\psi\gamma)} = 3.5 \pm 1.4$
  BABAR, PRL 102, (2009)
  possible evidence for charmonium component ?

$X(3872)$

Aim: results for decay rates of the $X(3872)$

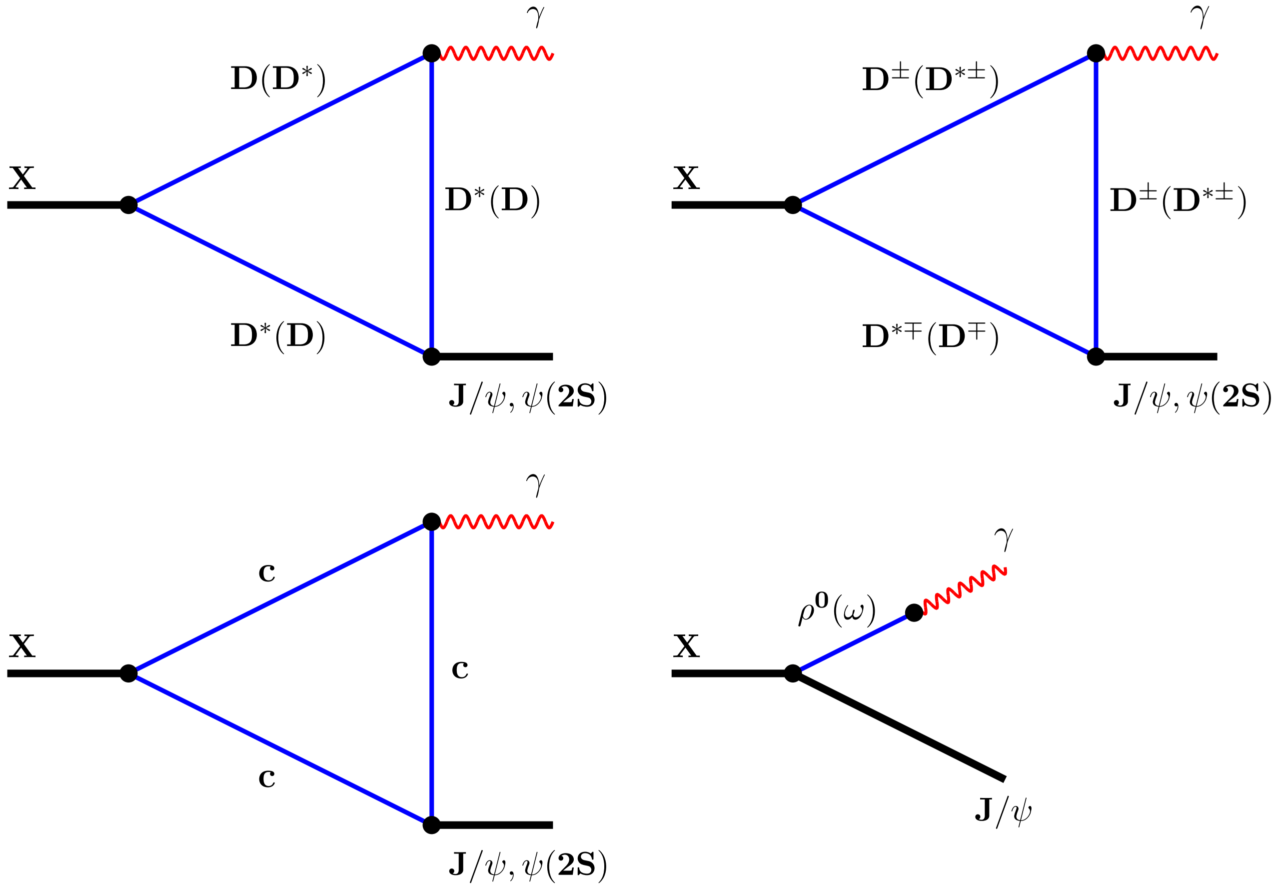
Ansatz: $X(3872)$ is S-wave molecule with $J^{PC} = 1^{++}$

$$|X(3872)>= \cos\theta \left[\frac{Z^{1/2}_{D^0 D^{*0}}}{\sqrt{2}} (|D^0 \bar{D}^{*0}\rangle + |D^{*0}\bar{D}^0\rangle) + \frac{Z^{1/2}_{D^\pm D^{*\mp}}}{\sqrt{2}} (|D^+ D^{*-}\rangle + |D^- D^{*+}\rangle) + Z^{1/2}_{J_\psi \omega}|J_\psi \omega\rangle + Z^{1/2}_{J_\psi \rho}|J_\psi \rho\rangle \right] + \sin\theta |c\bar{c}\rangle$$

($m_{D^0} = 1864.85$ MeV, $m_{D^{*0}} = 2006.7$ MeV, $m_x = m_{D^0} + m_{D^{*0}} - \epsilon$)

- dominant $|D^0 \bar{D}^{*0}\rangle + |D^{*0}\bar{D}^0\rangle$ component
- quantitatively see Swanson (2004): for $\epsilon = 0.3$ MeV,
  $Z_{D^0 D^{*0}} = 0.92\,, \quad Z_{D^\pm D^{*\mp}} = 0.033\,, \quad Z_{J_\psi \omega} = 0.041\,, \quad Z_{J_\psi \rho} = 0.006$
- small admixture of 1^{++} $c\bar{c}$ component: $\propto \sin\theta$
- Compositeness condition: $Z_X = 1 - (\Sigma^M_X(m_X^2))' - (\Sigma^C_X(m_X^2))' = 0$ fixes coupling of X to its components

$X(3872) \to J/\psi, \psi(2S) + \gamma$



Interaction Lagrangian and couplings:

$$\mathcal{L}_{J_\psi} = g_{J_\psi}\, J^\mu_\psi\, \bar{c}\gamma_\mu c$$

with $g_{J_\psi} \approx 5$ fixed from $\Gamma(J/\psi \to e^+e^-) \approx 5.55$ keV.

$$\mathcal{L}_{J_\psi DD} = i g_{J_\psi DD}\, J^\mu_\psi \left(D^0 \partial_\mu \bar{D}^0 - \bar{D}^0 \partial_\mu D^0 \right)$$

$$\mathcal{L}_{J_\psi D^* D^*} = i g_{J_\psi D^* D^*} \left(J^{\mu\nu}_\psi\, \bar{D}^{*\,0}_\mu\, D^{*\,0}_\nu + J^\mu_\psi\, \bar{D}^{*\,0\,\nu}\, D^{*\,0}_{\mu\nu} + J^\nu_\psi\, \bar{D}^{*\,0}_{\mu\nu}\, D^{*\,0\,\mu} \right)$$

fixed from world averaged values: $g_{J_\psi DD} = g_{J_\psi D^* D^*} = 6.5$

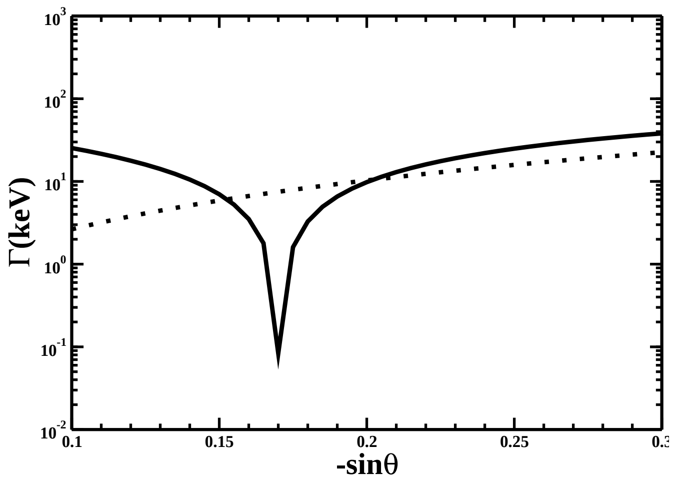
$$\mathcal{L}_{D^* D\gamma} = \frac{e}{4}\, g_{D^{*0} D^0 \gamma}\, \epsilon^{\mu\nu\alpha\beta}\, F_{\mu\nu}\, \bar{D}^{*\,0}_{\alpha\beta}\, D^0$$

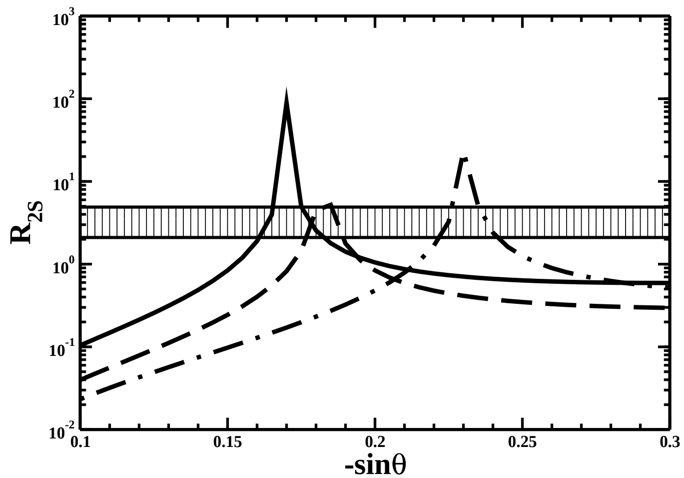
with $g_{D^{*0} D^0 \gamma} \approx 2\, GeV^{-1}$ fixed from $BR(D^{*0} \to D^0\gamma) = 38.1\%$

Results for $X(3872) \to \gamma J/\psi$ and $\psi(2s)$

Configuration	$\Gamma(X(3872) \to \gamma J/\psi,\ \gamma\psi(2S))$ keV	
molecular DD^* component	60 - 120(J/ψ)	0.3 ($\psi(2S)$)
pure $J/\psi V$ component	6(J/ψ)	0 ($\psi(2S)$)
interfering DD^* and $J/\psi V$ components	30 - 65 (J/ψ)	0.3 ($\psi(2S)$)

additional charmonium contribution with $Z_{c\bar{c}}^{1/2} = sin\theta \approx -0.2$ required





dotted - J/ψ, solid - $\psi(2s)$ mode

$$R_{2s} = \frac{\Gamma(X \to \psi(2S) + \gamma)}{\Gamma(X \to J/\psi + \gamma)} = 3.5 \pm 1.4$$

(BABAR, 2009)

Dong, Faessler, TG, Kovalenko, Lyubovitskij, PRD 77 (2008), 79 (2009), 0909.0380 [hep-ph]

Results for $X(3872) \to J/\psi + h$ with $h = 2\pi, 3\pi$

Assumption that $X(3872) \to J/\psi + h$ proceeds via $J/\psi\omega$ and $J/\psi\rho$ components (see also Braaten and Kusunoki PRD 69 (2004)):

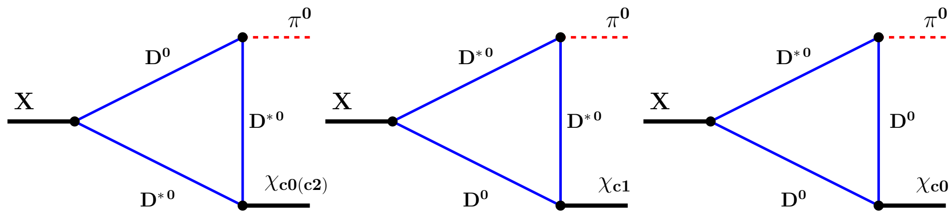
Quantity	Nonlocal case
$\Gamma(X \to J/\psi\pi^+\pi^-)$, keV	$9.0 \times 10^3\, Z_{J_\psi\rho}$ (54.0)
$\Gamma(X \to J/\psi\pi^+\pi^-\pi^0)$, keV	$1.38 \times 10^3\, Z_{J_\psi\omega}$ (56.6)
$\Gamma(X \to J/\psi\pi^0\gamma)$, keV	$0.23 \times 10^3\, Z_{J_\psi\omega}$ (9.4)
$\frac{\Gamma(X\to J/\psi\pi^+\pi^-\pi^0)}{\Gamma(X\to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$	1.05
$\frac{\Gamma(X\to J/\psi\gamma)}{\Gamma(X\to J/\psi\pi^+\pi^-)} = 0.14 \pm 0.05; 0.33 \pm 0.12$	0.10

Explicit numbers for configuration of Swanson (2004) at $\epsilon = 0.3$ MeV.

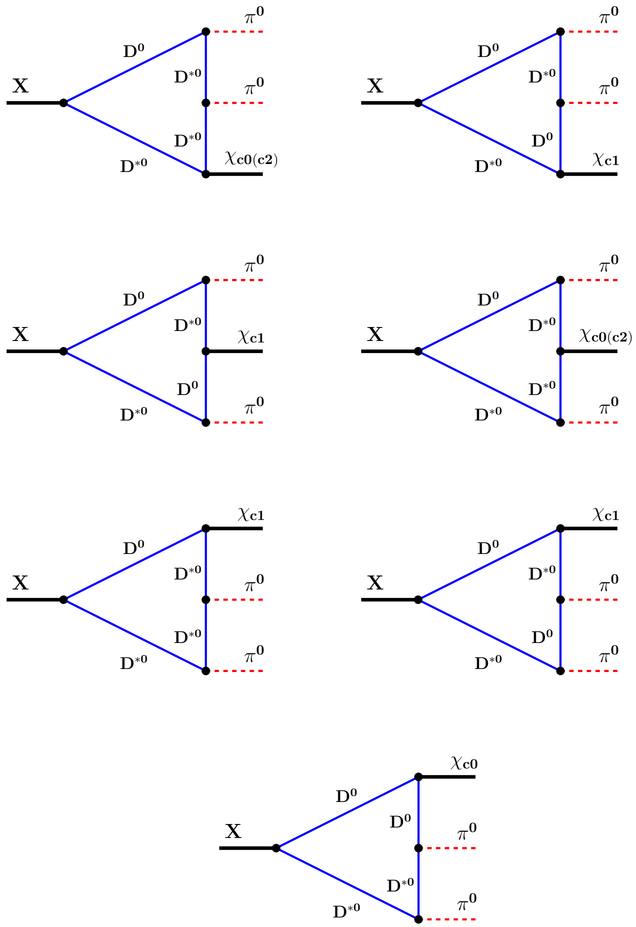
Subleading $J/\psi\omega$, $J/\psi\rho$ and $c\bar{c}$ components dominate ratios !

$X(3872) \to \chi_{cJ} + \pi^0, 2\pi \; J^P = 0^+, 1^+, 2^+$

$X(3872) \to \chi_{cJ} + \pi^0$



$X(3872) \to \chi_{cJ} + 2\pi$



Results for $X(3872) \to \chi_{cJ} + \pi^0, 2\pi$

Quantity	$D^0 D^{*0}$ loop	$D^0 D^{*0} + D^- D^{*+}$ [exact]
$\Gamma(X \to \chi_{c0} + \pi^0)$, keV	41.1 $Z_{D^0 D^{*0}}$ (37.8)	61.0
$\Gamma(X \to \chi_{c0} + 2\pi^0)$, eV	63.3 $Z_{D^0 D^{*0}}$ (58.2)	94.0
$\Gamma(X \to \chi_{c1} + \pi^0)$, keV	11.1 $Z_{D^0 D^{*0}}$ (10.2)	16.4
$\Gamma(X \to \chi_{c1} + 2\pi^0)$, eV	743 $Z_{D^0 D^{*0}}$ (683.6)	1095.2
$\Gamma(X \to \chi_{c2} + \pi^0)$, keV	15 $Z_{D^0 D^{*0}}$ (13.8)	22.1
$\Gamma(X \to \chi_{c2} + 2\pi^0)$, eV	20.6 $Z_{D^0 D^{*0}}$ (19.0)	30.4

using $Z_{D^0 D^{*0}} = 0.92\,, \quad Z_{D^\pm D^{*\mp}} = 0.033$ for $\epsilon = 0.3$ MeV (Swanson 2004)

sensitive to leading molecular component

$Y(4140)$

Basics about $Y(4140)$

- first seen in exclusive decays $B^+ \to Y(4140) K^+$ with $Y(4140) \to J/\psi\ \phi$ by CDF (PRL (2009))
  $m_{Y(4140)} = 4130.0 \pm 2.9(\mathrm{stat}) \pm 1.2(\mathrm{syst})$ MeV,
  $\Gamma_{Y(4140)} = 11.7^{+8.3}_{-5.0}(\mathrm{stat}) \pm 3.7(\mathrm{syst})$ MeV

- Decays of $c\bar{c}$ states to open charm decay modes dominate,
  $\Gamma(c\bar{c} \to J/\psi\ \phi) \approx 0$!! (OZI suppressed)
  see for example Eichten, Godfrey, Mahlke, Rosner, RMP 80 (2008)

- molecular interpretation as $|Y(4140)\rangle = |D_s^{*+} D_s^{*-}\rangle$,
  close to $D_s^{*+} D_s^{*-}$ threshold of $m_{th} = 4225$ MeV,
  first estimates give binding for $J^{PC} = 0^{++}$ or 2^{++}

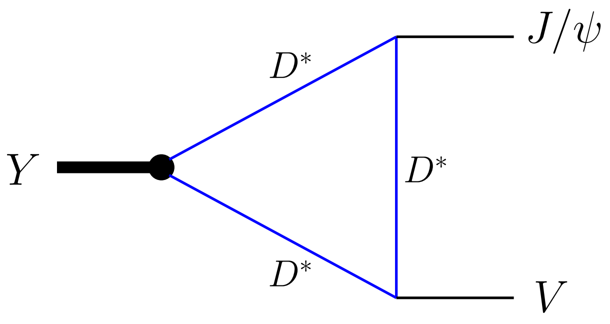
- similar to $Y(3940)$ observed by Belle and BABAR in $\omega J/\psi$ decays,
  interpretation as $|Y(3940)\rangle = \frac{1}{\sqrt{2}}\left(|D^{*+} D^{*-}\rangle + |D^{*0} \overline{D^{*0}}\rangle\right)$ molecular state.

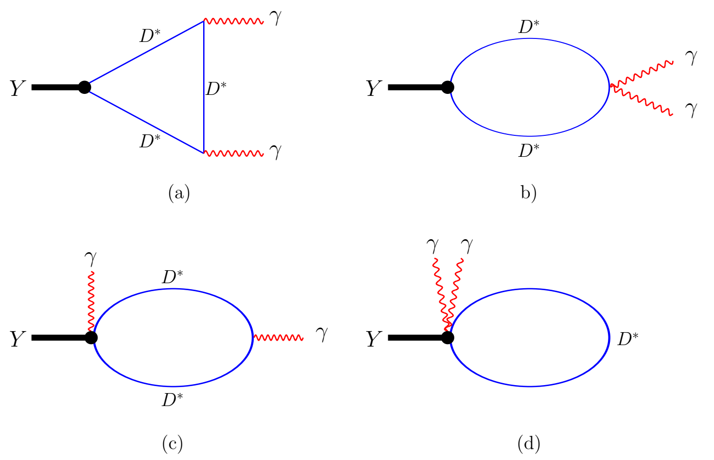
Selected decays of $Y(4140)$

From HHChPT Lagrangian (Colangelo (2003), Wise (1992)):

$$\mathcal{L}_{D^*D^*J_\psi} = ig_{D^*D^*J_\psi} J_\psi^\mu \Big(D_{\mu i}^{*\dagger} \overleftrightarrow{\partial}_\nu D_i^{*\nu} + D_{\nu i}^{*\dagger} \overleftrightarrow{\partial}^\nu D_{\mu i}^{*} - D_i^{*\dagger\nu} \overleftrightarrow{\partial}_\mu D_{\nu i}^{*} \Big)$$

$$\mathcal{L}_{D^*D^*V} = ig_{D^*D^*V} V_{ij}^\mu D_{\nu i}^{*\dagger} \overleftrightarrow{\partial}_\mu D_j^{*\nu} + 4if_{D^*D^*V} (\partial^\mu V_{ij}^\nu - \partial^\nu V_{ij}^\mu) D_{\mu i}^{*} D_j^{*\dagger\nu}$$





Decay properties of $Y(3940)$ and $Y(4140)$

Quantity	$Y(3940)$	$Y(4140)$
$\Gamma(Y \to J/\psi\ V = \phi, \omega)$, MeV	5.47	3.26
$\Gamma(Y \to \gamma\gamma)$, keV	0.33	0.63

sizable $J/\psi\ \phi$ can be explained (Branz, TG, Lyubovitskij, 0903.5424 [hep-ph])

Conclusions

- hadron molecules: old expectations - renewed interest in heavy meson sector
- QFT approach to hadronic molecules (compositeness condition)
- Aim: detailed predictions for new heavy mesons and their strong, radiative and weak decay properties
  dynamics dominated by hadron loops
- open charm system: $D^*_{s0}(2317) = DK$, $D_{s1}(2460) = D^* K$,
  good candidates, even converging HM calculations
- hidden charm system
  $X(3872) = D^0 \bar{D}^{*0} + c.c.$, but present decay modes are dominated by subleading components
  $Y(4140) = D_s^{*+} D_s^{*-}$ good candidate, open charm modes.

Extra slide (The method: em interaction)

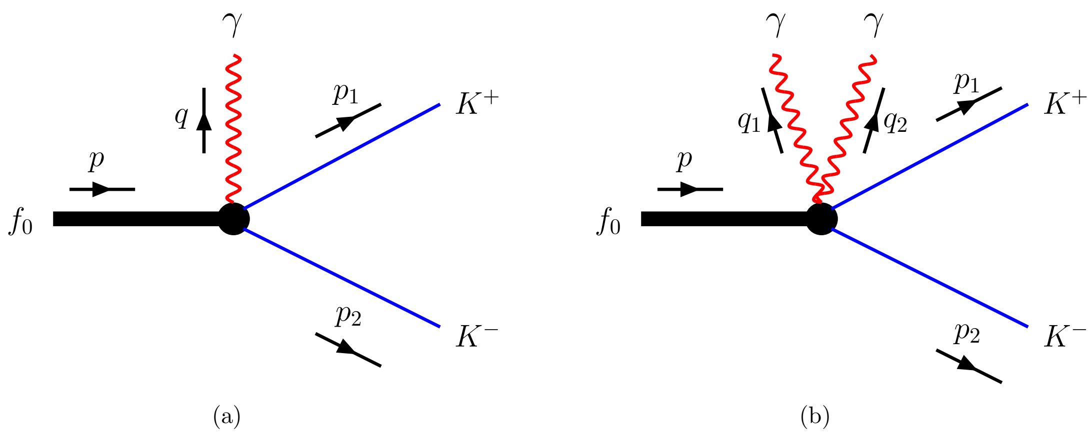
- em interaction is generated by minimal substitution:

  i.e. $\partial^\mu K^\pm \to (\partial^\mu \mp ieA^\mu)K^\pm$

- $\mathcal{L}_{f_0 K \bar{K}}$ has also to be gauged with (J. Terning, PRD44 (1991)):

  $K^\pm \to e^{\mp i e_p I(x,y)} K^\pm(y), \quad I(x,y) = \int_x^y dz_\mu A^\mu(z)$

- leading to vertex couplings (relevant to fulfill gauge invariance):



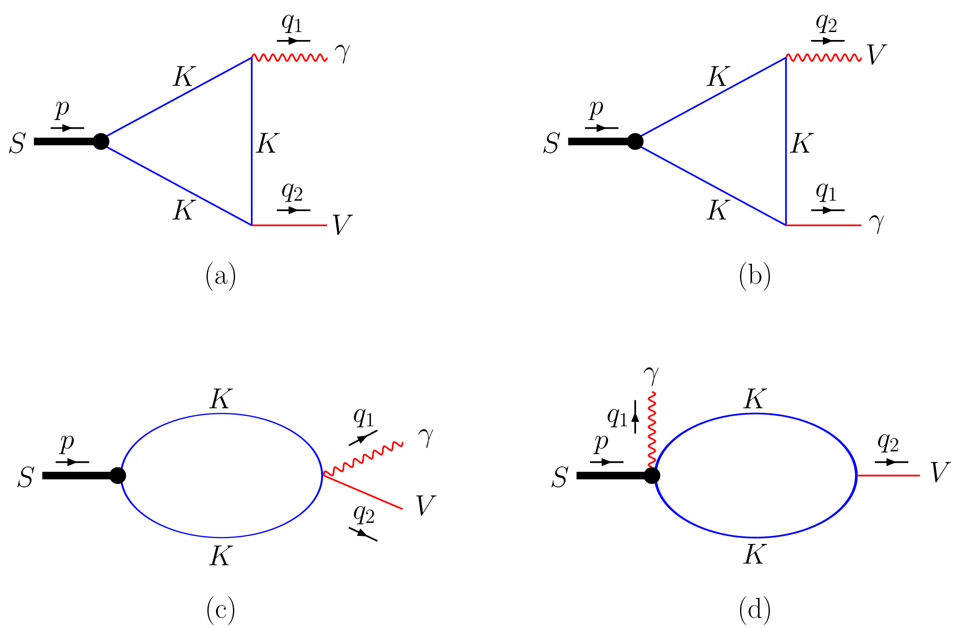
Extra slide (The test case: a_0/f_0 as hadronic molecules)

Radiative decays: S $\to \gamma$V ($S = f_0,\ a_0$; $V = \omega,\ \rho$) and $\phi \to \gamma S$

Gauging of

$$\mathcal{L}_V = \sum_{V=\phi,\omega} \frac{g_{VK\bar{K}}}{\sqrt{2}} V^\mu (\bar{K} i\partial_\mu K - K i\partial_\mu \bar{K}), \quad \mathcal{L}_\rho = \frac{g_{VK\bar{K}}}{\sqrt{2}} \vec{\rho}^{\,\mu} (\bar{K}\vec{\tau}\, i\partial_\mu K - K\vec{\tau}\, i\partial_\mu \bar{K}),$$

with couplings: $g_{VK\bar{K}} = g_{\rho K\bar{K}} = g_{\omega K\bar{K}} = 4.24$ and $g_{\phi K\bar{K}} = 6$
($SU(3)$ symmetry relations, Zhang et al. PRD74 (2006))



Extra slide(The test case: a_0/f_0 as hadronic molecules)

Results for radiative decays: $\mathbf{S} \to \gamma \mathbf{V}$ ($S = f_0,\ a_0$; $V = \omega,\ \rho$) and $\phi \to \gamma S$

prediction in local limit:

$\Gamma(\phi \to f_0\gamma) = 0.57$ keV, $\quad \Gamma(\phi \to a_0\gamma) = 0.33$ keV

from PDG(2007):

$\Gamma(\phi \to a_0\gamma)/\Gamma_{total} = (0.76 \pm 0.06) \cdot 10^{-4}$

$\Gamma(\phi \to f_0\gamma)/\Gamma_{total} = (1.11 \pm 0.07) \cdot 10^{-4}$

$\to$ $\Gamma(\phi \to f_0\gamma) \approx 0.47$ keV, $\Gamma(\phi \to a_0\gamma) \approx 0.32$ keV.

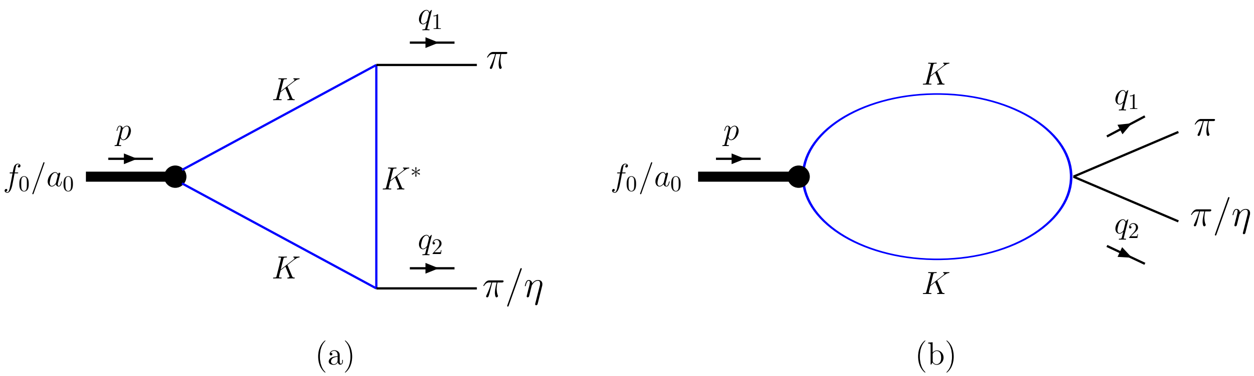
further predictions ($\Lambda = 1\ GeV$ and local limit):

$\Gamma(f_0 \to \rho\gamma) = 7.59(8.10)\ keV \qquad \Gamma(f_0 \to \omega\gamma) = 7.13(7.58)\ keV$

$\Gamma(a_0 \to \rho\gamma) = 6.60(7.19)\ keV \qquad \Gamma(a_0 \to \omega\gamma) = 6.22(6.77)\ keV$

Extra slide(The test case: a_0/f_0 as hadronic molecules)

Strong decays $f_0 \to \pi\pi$ and $a_0 \to \pi\eta$



based on:

$$\mathcal{L}_{K^*K\pi} = \frac{g_{K^*K\pi}}{\sqrt{2}} K^{*\dagger}_\mu \vec{\pi}\vec{\tau}\, i\overleftrightarrow{\partial}^\mu K + h.c\,,\ \mathcal{L}_{K^*K\eta} = \frac{g_{K^*K\eta}}{\sqrt{2}} K^{*\dagger}_\mu \eta\, i\overleftrightarrow{\partial}^\mu K + h.c.$$

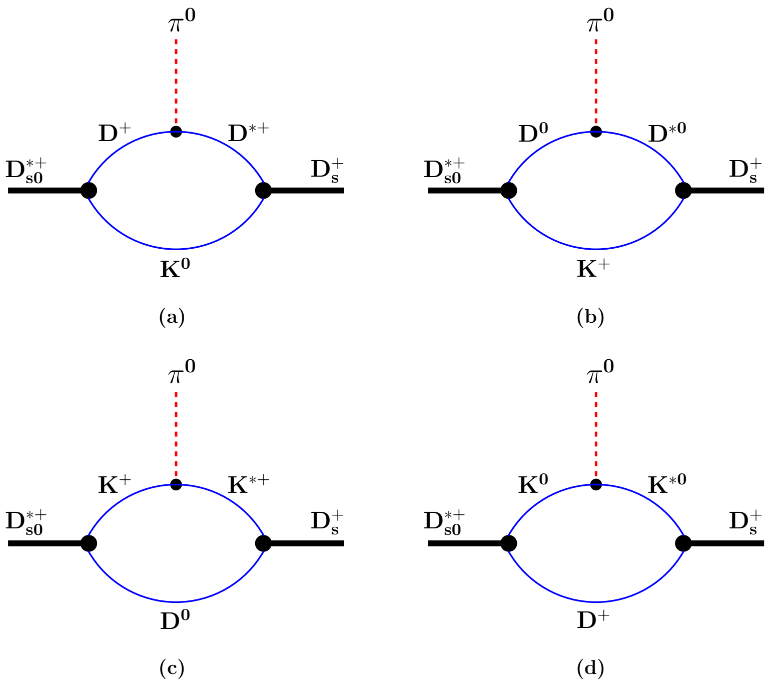
$$\mathcal{L}_U(x) = \frac{F^2}{4} \langle D_\mu U(x) D^\mu U^\dagger(x) + \chi U^\dagger(x) + \chi^\dagger U(x) \rangle$$

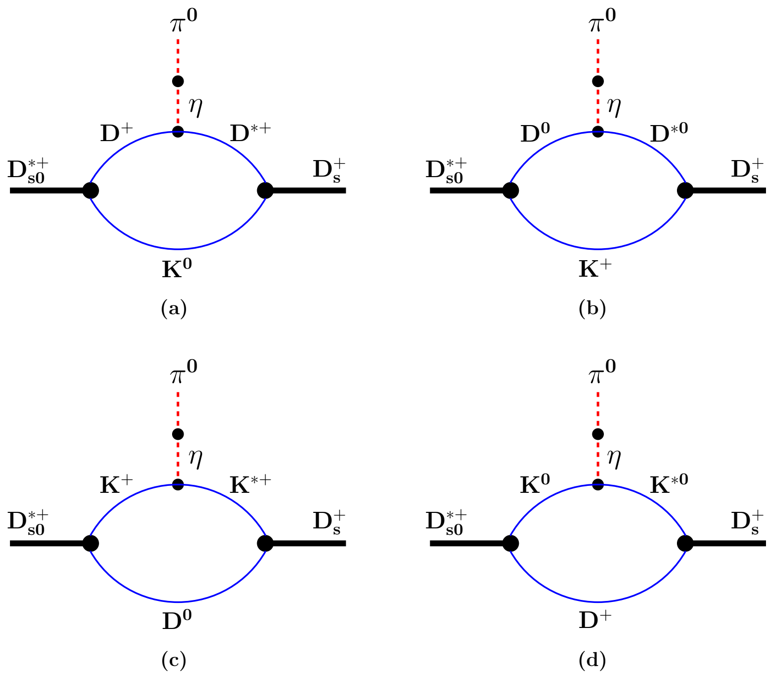
$\Gamma(f_0 \to \pi\pi) = 45 - 90$ MeV($\Lambda = 0.8 - 1.2$ GeV) compared to $40 - 100$ MeV (PDG)

$\Gamma(a_0 \to \pi\eta) = 48 - 93$ MeV($\Lambda = 0.8 - 1.2$ GeV) compared to $50 - 100$ MeV (PDG)

$D_{s0}^*(2317)$, $D_{s1}(2460)$

Strong decay $D_{s0}^* \to D_s \pi^0$





direct transition

$\eta - \pi^0$ mixing