

Decays of $D_{s0}^{\star}(2317)$ and $D_{s1}(2460)$ mesons

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Overview of the talk

- Focus on $D_{s0}^*(2317) = DK$ and $D_{s1}(2460) = D^*K$ mesons
- Observed in B -decays by BaBar, CLEO Coll. and confirmed by Belle Coll.
- Extension to bottom states $B_{s0}^*(5725) = B\bar{K}$ and $B_{s1}(5778) = B^*\bar{K}$ mesons
- Talk is based on the papers
 - Faessler, Gutsche, Lyubovitskij, Ma [PR D76 \(2007\) 014005](#)
 - Faessler, Gutsche, Kovalenko, Lyubovitskij [PR D76 \(2007\) 014003](#)
 - Faessler, Gutsche, Lyubovitskij, Ma [arXiv:0709.3946 \[hep-ph\]](#)

Plan

- Introduction
- Approach
- Results: strong and em decays.
- Summary

Introduction

- Hadronic molecules (**HM**) - weakly bound states of hadrons
- Familiar examples: **Nuclei** and **Hypernuclei**

Complexity of hadronic mass spectra

Mass slightly below threshold of h.p. $m_H < m_{H_1} + m_{H_2}$

Voloshin, Okun, De Rujula, Georgi, Glashow, Weinstein, Isgur, Barnes

- **Meson-meson** molecules

$$a_0(980), \ f_0(980) = K\bar{K}$$

$$D_{s0}^*(2317) = DK, \quad D_{s1}(2460) = D^*K$$

$$B_{s0}^*(5725) = B\bar{K}, \quad B_{s1}(5778) = B^*\bar{K}$$

$$X(3872) = D^0\bar{D}^{*0} + \text{c.c.}$$

$$Y(4260) = D\bar{D}_1 - \text{c.c.}$$

$$\psi(4415) = D_s^*\bar{D}_{s0}(2317) + \text{c.c.}$$

- **Meson-baryon** molecules

$$\Lambda(1405) = N\bar{K} \quad \Lambda_c^+(2940) = D^*N$$

Introduction

Experimental and theoretical status of $D_{s0}^*(2317)$ and $D_{s1}(2460)$

- Discovered
 - $D_{s0}^*(2317)$ by BABAR at SLAC (2003)
 - $D_{s1}(2460)$ by CLEO at CESR (2003)
- Both confirmed by Belle at KEKB (2004)
- Basic properties

State	$I(J^P)$	Mass (MeV)	Width (MeV)
$D_{s0}^*(2317)^\pm$	$0(0^+)$	2317.8 ± 0.6	< 3.8
$D_{s1}(2460)^\pm$	$0(1^+)$	2459.6 ± 0.6	< 3.5

Strong decay (MeV)	EM decay (MeV)
$\Gamma(D_{s0}^* \rightarrow D_s \pi^0) < 0.25$ (th)	$\Gamma(D_{s0}^* \rightarrow D_s^* \gamma) < 0.035$ (th)
$\Gamma(D_{s1} \rightarrow D_s^* \pi^0) < 2$ (exp); < 0.25 (th)	$\Gamma(D_{s1} \rightarrow D_s \gamma) < 0.77$ (exp); < 0.1 (th)

Introduction

- Theoretical approaches:

quark models, effective Lagrangian approaches, QCD sum rules, lattice, ...

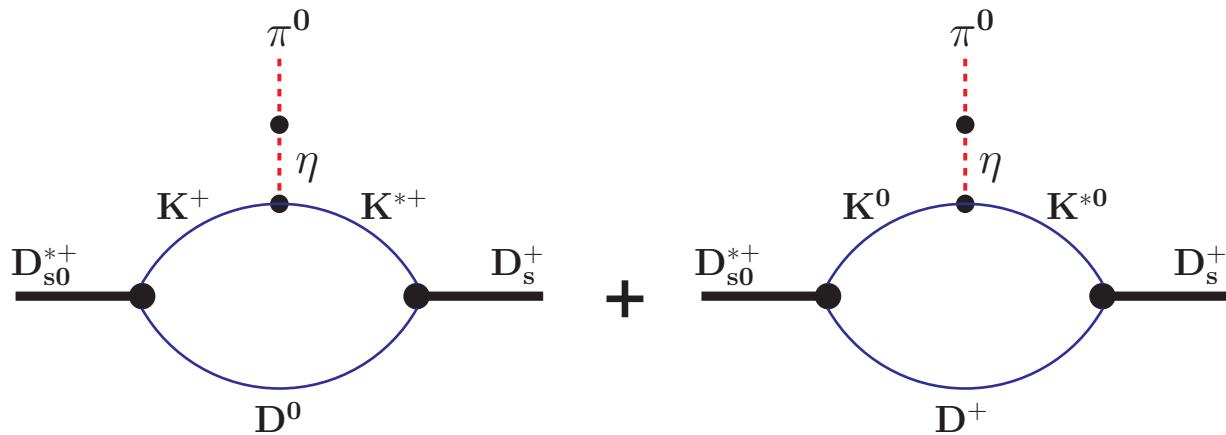
Bari, Beijing, Coimbra, Darmstadt, Durham, Valencia, Tübingen, ...

- Structure: $q\bar{q}$, $(q\bar{q})^2$, $q\bar{q} + (q\bar{q})^2$, DD^\dagger , $2M$
- Strong decays: $D_{s0}^* \rightarrow D_s\pi^0$ and $D_{s1} \rightarrow D_s^*\pi^0$
via $\eta - \pi^0$ mixing $\implies \Gamma \sim \varepsilon^2 \sim (m_d - m_u)^2$
- Additional mechanism in molecular picture $D_{s0}^* = (DK)$ and $D_{s1} = (D^*K)$
due to presence of u and d quarks in $D^{(*)}$ and $K^{(*)}$

$$\Gamma \sim \varepsilon^2 \sim \left(M_{H^+}^2 - M_{H^0}^2 \right)^2 \text{ where } H = K, K^*, D, D^*$$

Introduction

$\eta - \pi^0$ mixing mechanism

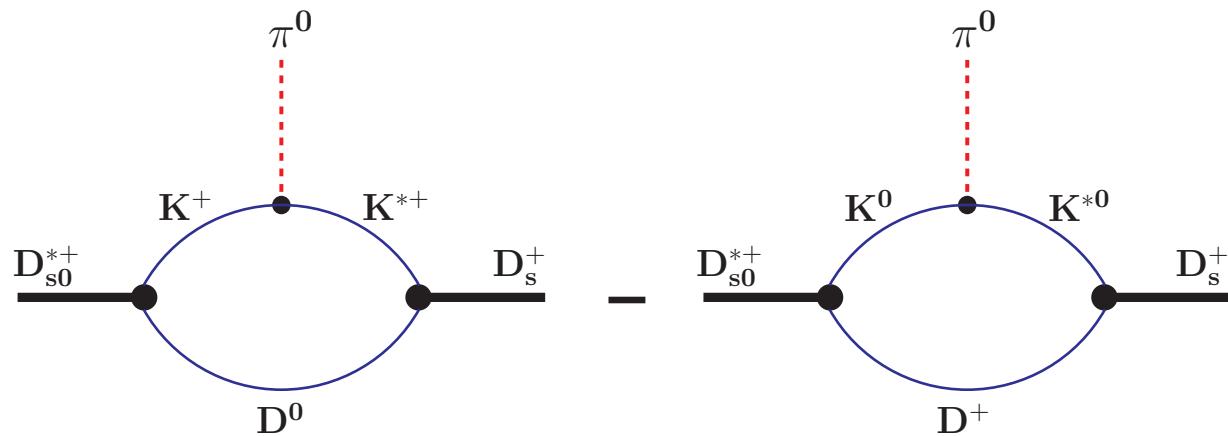


$$\tan 2\epsilon = \frac{\sqrt{3}}{2} \frac{m_d - m_u}{m_s - \hat{m}}$$

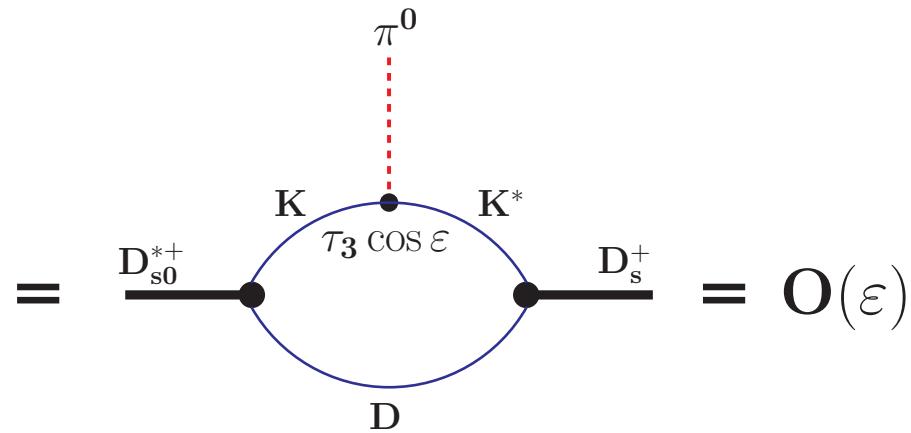
$$= D_{s0}^{*+} \rightarrow K \bar{K}^* = I \sin \epsilon = O(\epsilon)$$

Introduction

Direct mechanism



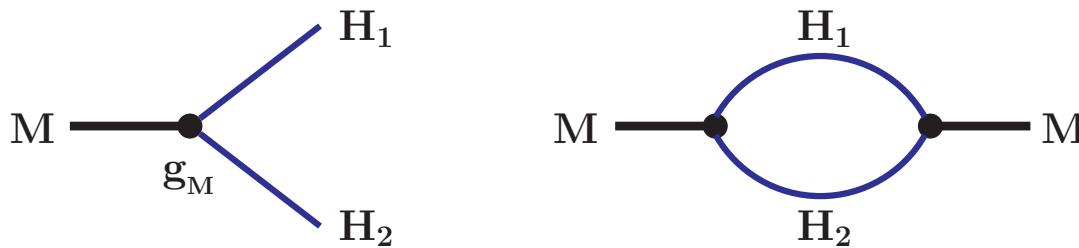
$$\tan 2\varepsilon = \frac{\sqrt{3}}{2} \frac{m_d - m_u}{m_s - \hat{m}}$$



Approach

- Our aim: Bound state structure of HM using QFT approach based on compositeness condition $Z_M = 0$

Weinberg, PR 130 (1963) 776; Salam, NC 25 (1962) 224; Hayashi et al., FP 15 (1967) 625;
Efimov, Ivanov, *The Quark Confinement Model of Hadrons*, IOP Publishing, 1993;
Ivanov, Locher, Lyubovitskij, FBS 21 (1996) 131;
Ivanov, Lyubovitskij, Körner, Kroll, PR D56 (1997) , 348;
Faessler, Gutsche, Ivanov, Lyubovitskij, Wang, PR D68 (2003) 014011;
Faessler, Gutsche, Holstein, Lyubovitskij, Nicmorus, Pumsa-ard, PR D74 (2006) 074010;
Faessler, Gutsche, Lyubovitskij, Ma, PR D76 (2007) 014005



$$Z_M^{1/2} = \langle M_0 | M \rangle$$

$$Z_M = |\langle M_0 | M \rangle|^2$$

$$g_M = Z_M^{1/2} g_{M_0}$$

$$Z_M = 1 - g_M^2 \Pi'(m_M^2) = 0$$

$$g_M \text{ is finite, } g_{M_0} \rightarrow \infty$$

Approach

Molecular structure of $D_{s0}(0^+)$ and $D_{s1}(1^+)$ states

$$|D_{s0}^+\rangle = |D^+K^0\rangle + |D^0K^+\rangle$$

$$|D_{s1}^+\rangle = |D^{*+}K^0\rangle + |D^{*0}K^+\rangle$$

Couplings of molecules with constituents

$$\mathcal{L}_{D_{s0}^*}(x) = g_{D_{s0}^*} D_{s0}^{*-}(x) \int dy \Phi(y^2) D(x + w_{KD} y) K(x - w_{DK} y) + \text{H.c.}$$

$$\mathcal{L}_{D_{s1}}(x) = g_{D_{s1}} D_{s1}^\mu -(x) \int dy \Phi(y^2) D_\mu^*(x + w_{KD^*} y) K(x - w_{D^*K} y) + \text{H.c.}$$

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

Results: $g_{D_{s0}^*} = 10.58 \pm 0.68 \text{ GeV}$, $g_{D_{s1}} = 10.9 \pm 0.72 \text{ GeV}$.

Gaussian v.f. $\tilde{\Phi}(p_E^2) \doteq \exp(-p_E^2/\Lambda^2)$ and $\Lambda = 1 - 2 \text{ GeV}$.

Approach

Effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{free}} + \mathcal{L}_{\text{int}}$$

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

where

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

$$\pi_3 \rightarrow \pi_3 \cos \varepsilon - \eta \sin \varepsilon$$

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

$$\eta \rightarrow \pi_3 \sin \varepsilon + \eta \cos \varepsilon$$

$$\tan 2\varepsilon = \frac{\sqrt{3}}{2} \frac{m_d - m_u}{m_s - \hat{m}} \simeq 0.02, \quad \hat{m} = \frac{1}{2}(m_u + m_d)$$

$$g_{D^* D \pi} = 17.9, \quad g_{K^* K \pi} = 4.61$$

Data

$$g_{D^* D_s K} = g_{K^* D_s D} = 2.02$$

LC QCD SR/Estimate

$$g_{D_s^* D K} = g_{D_s^* D^* K^*} = 1.84$$

LC QCD SR/Estimate

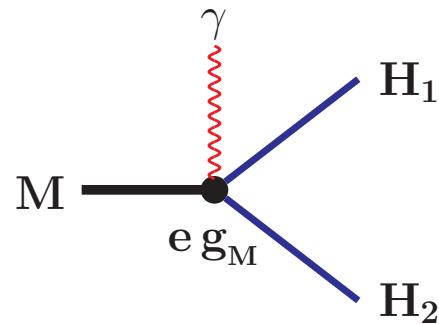
Approach

\mathcal{L}_{em} is generated using minimal substitution:

$$\partial^\mu M^{(*)\pm} \rightarrow (\partial^\mu \mp ieA^\mu) M^{(*)\pm}$$

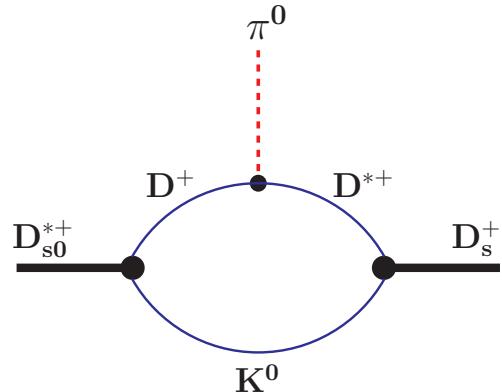
$\mathcal{L}_{D_{s0}^*}$ and $\mathcal{L}_{D_{s1}}$ should be gauged:

$$H^\pm(y) \longrightarrow \tilde{H}^\pm(y) = e^{-ie \int_x^y dz_\mu A^\mu(z)} H^\pm(y), \quad \frac{\partial}{\partial y_\nu} \int_x^y dz_\mu A^\mu(z) \doteq A^\nu(y)$$

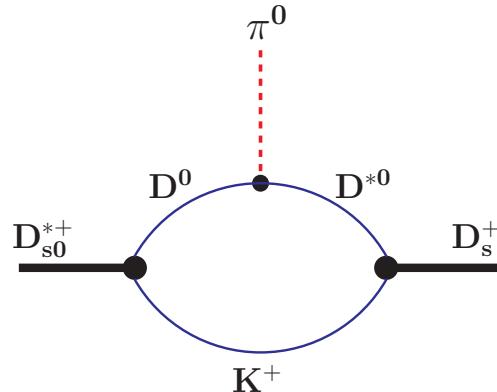


Approach

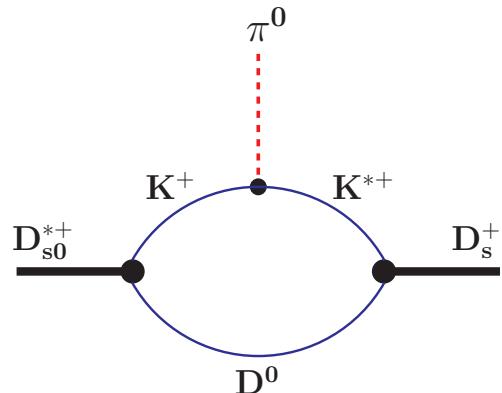
Strong decay $D_{s0}^* \rightarrow D_s \pi^0$



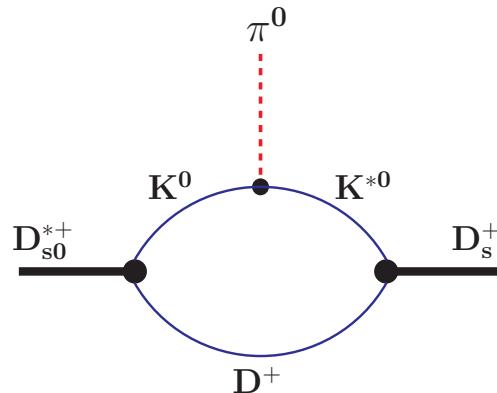
(a)



(b)



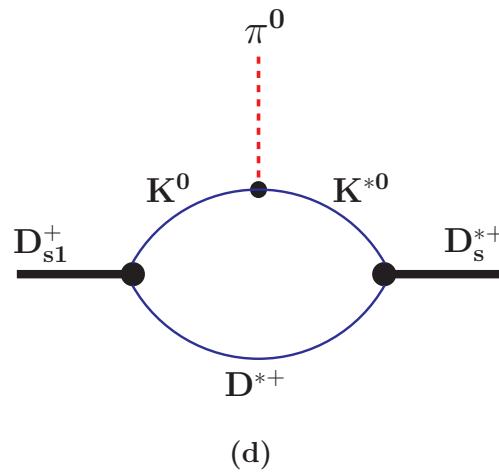
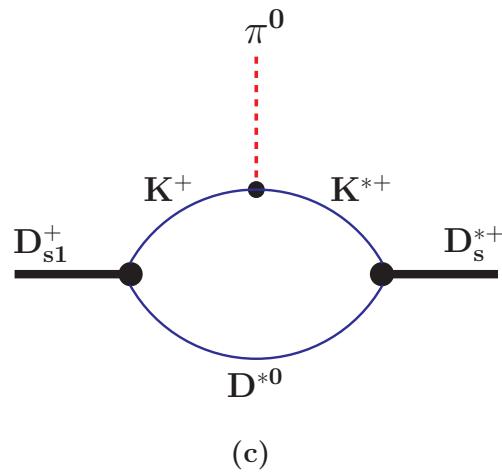
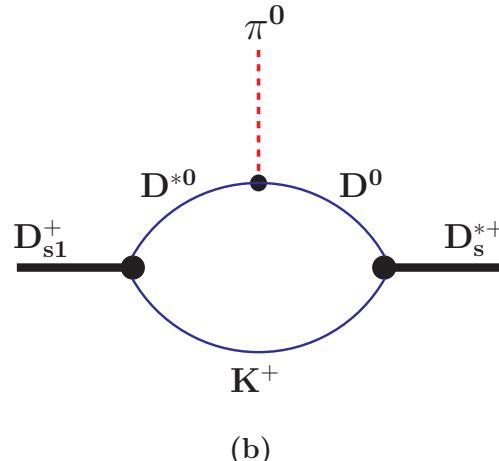
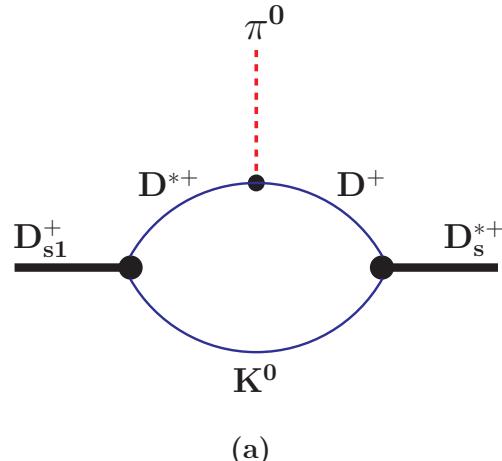
(c)



(d)

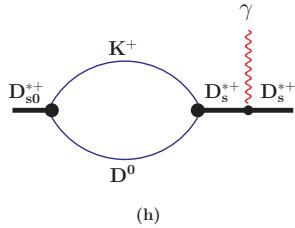
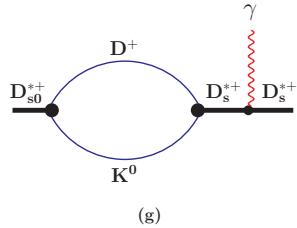
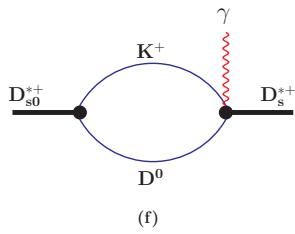
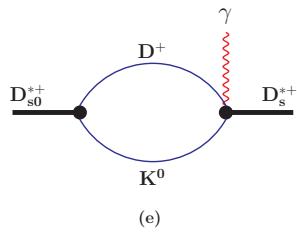
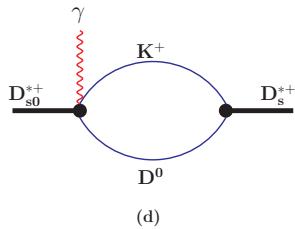
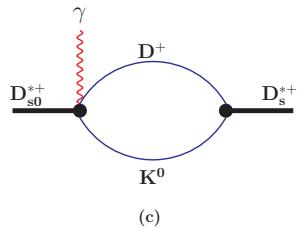
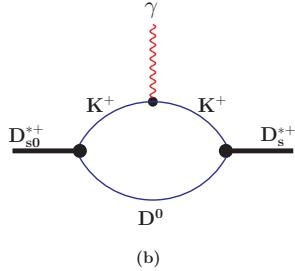
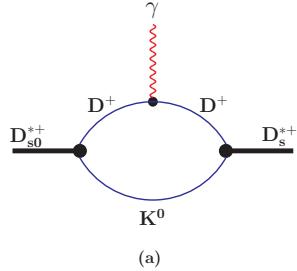
Approach

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



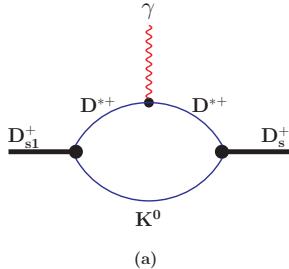
Approach

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

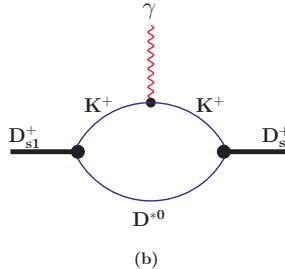


Approach

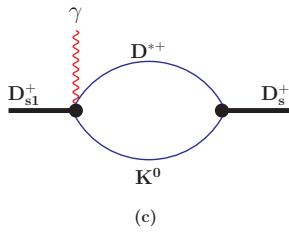
Radiative decay $D_{s1} \rightarrow D_s \gamma$



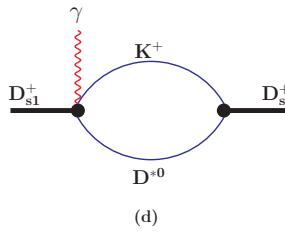
(a)



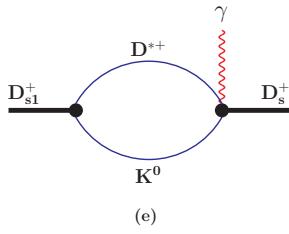
(b)



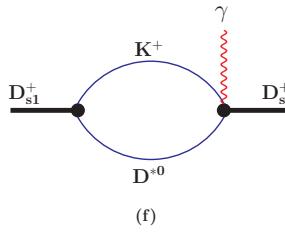
(c)



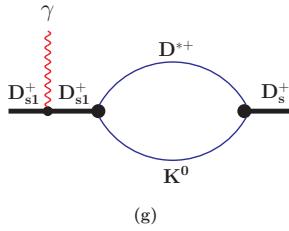
(d)



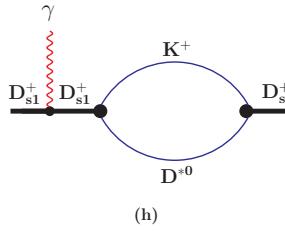
(e)



(f)



(g)



(h)

Matrix elements and decay width

Matrix elements

$$D_{s0}^{*+}(p) \rightarrow D_s(p')\pi^0(q)$$

$$D_{s1}^+(p) \rightarrow D_s^*(p')\pi^0(q)$$

$$D_{s0}^*(p) \rightarrow D_s^*(p')\gamma(q)$$

$$D_{s1}^+(p) \rightarrow D_s(p')\gamma(q)$$

$$M = G_{D_{s0}^* D_s \pi}$$

$$M^{\mu\nu} = g^{\mu\nu} G_{D_{s1} D_s^* \pi} - v^\mu v'^\nu F_{D_{s1} D_s^* \pi}$$

$$M^{\mu\nu} = e G_{D_{s0}^* D_s^* \gamma} (g_{\mu\nu} p' q - p'_\mu q_\nu)$$

$$M^{\mu\nu} = e G_{D_{s1} D_s \gamma} (g_{\mu\nu} p q - q_\mu p_\nu)$$

Decay widths

$$\Gamma(D_{s0}^* \rightarrow D_s \pi) = \frac{G_{D_{s0}^* D_s \pi}^2}{8\pi m_{D_{s0}}^2} P^*$$

$$\Gamma(D_{s1} \rightarrow D_s^* \pi^0) = \frac{G_{D_{s1} D_s^* \pi}^2}{12\pi m_{D_{s1}}^2} P^* \left\{ 1 + \frac{w^2}{2} \left(1 + \frac{F_{D_{s1} D_s^* \pi}}{G_{D_{s1} D_s^* \pi}} \frac{w^2 - 1}{w} \right)^2 \right\}, \quad w = vv'$$

$$\Gamma(D_{s0}^* \rightarrow D_s^* \gamma) = \alpha G_{D_{s0}^* D_s^* \gamma}^2 P^* {}^3$$

$$\Gamma(D_{s1} \rightarrow D_s \gamma) = \frac{\alpha}{3} G_{D_{s1} D_s \gamma}^2 P^* {}^3$$

Results

Table 1. Strong decay widths in keV

Approach	$\Gamma(D_{s0}^* \rightarrow D_s \pi^0)$	$\Gamma(D_{s1} \rightarrow D_s^* \pi^0)$
Nielsen 2005	6 ± 2	
Colangelo 2003	7 ± 1	7 ± 1
Guo 2006	8.69	11.41
Godfrey 2003	10	10
Fayyazuddin 2003	16	32
Bardeen 2003	21.5	21.5
Lu 2006	32	35
Wei 2005	39 ± 5	43 ± 8
Cheng 2003	10 – 100	
Ishida 2003	155 ± 70	155 ± 70
Azimov 2004	129 ± 43	187 ± 73
Lutz 2007	140	140
Our results	46.7 – 75	50.1 – 79.2

Results

Table 2. Radiative decay widths in keV

Approach	$\Gamma(D_{s0}^* \rightarrow D_s^* \gamma)$	$\Gamma(D_{s1} \rightarrow D_s \gamma)$
Fayyazuddin 2003	0.2	
Oset 2007	0.49	
Colangelo 2003	0.85 ± 0.05	
Close 2005	1	≤ 7.3
Lu 2006	≈ 1.1	$0.6 - 2.9$
Wang 2006	$1.3 - 9.9$	$5.5 - 31.2$
Azimov 2004	≤ 1.4	≈ 2
Bardeen 2003	1.74	5.08
Godfrey 2003	1.9	6.2
Colangelo 2005	$4 - 6$	$19 - 29$
Lutz 2007	< 7	$\simeq 43.6$
Ishida 2003	21	93
Hayashigaki 2005	35	
Our results	$0.47 - 0.63$	$2.37 - 3.73$

Results

Table 3. Ratios $R_{D_{s0}^*} = \frac{\Gamma(D_{s0}^* \rightarrow D_s^* \gamma)}{\Gamma(D_{s0}^* \rightarrow D_s \pi)}$ and $R_{D_{s1}} = \frac{\Gamma(D_{s1} \rightarrow D_s \gamma)}{\Gamma(D_{s1} \rightarrow D_s^* \pi)}$

Approach	$R_{D_{s0}^*}$	$R_{D_{s1}}$
Fayyazuddin 2003	0.01	
Azimov 2004	≤ 0.02	0.01 - 0.02
Lutz 2007	< 0.05	$\simeq 0.31$
Bardeen 2003	0.08	0.24
Colangelo 2003	0.11 – 0.14	
Godfrey 2003	0.19	0.62
Ishida 2003	0.09 - 0.25	0.41 - 1.09
PDG 2007	≤ 0.059	0.44 ± 0.09
Our results	$\simeq 0.01$	$\simeq 0.05$

Results

Table 4. Decay widths of $B_{s0}^*(5725)$ and $B_{s1}(5778)$ in keV

Approach	$\Gamma(B_{s0}^* \rightarrow B_s \pi^0)$	$\Gamma(B_{s1} \rightarrow B_s^* \pi^0)$	$\Gamma(B_{s0}^* \rightarrow B_s^* \gamma)$	$\Gamma(B_{s1} \rightarrow B_s \gamma)$
Guo 2006	7.92	10.36		
Our results	52.9 – 87.1	53.5 – 87.3	1.54 – 2.04	1.04 – 1.22

Summary

- Quantum field approach for HM PR D76 (2007) 014003, 014005

Only one model parameter: scale Λ in HM wave function

- Predictions for strong and radiative decay properties:
effective couplings and **decay widths**
- Other applications: PR D76 (2007) 014003
Leptonic decay constants $f_{D_{s0}^*} = 67.1 \text{ MeV}$ and $f_{D_{s1}} = 144.5 \text{ MeV}$

Two-body decays $B \rightarrow D^{(*)} D_{s0}^*(D_{s1})$

- In progress:
radiative decays $D_{s1} \rightarrow D_s^* \gamma$ and $D_{s1} \rightarrow D_{s0}^* \gamma$
- Extension:
Light molecules a_0, f_0

Heavy molecules $X(3872), Y(4260), \psi(4415), \Lambda_c^+(2940), \dots$