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# Radiative Decays of Charm Mesons [a]: A Light Cone QCD Sum Rules Approach

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# Outline

- Introduction
- Decay Modes
- QCD Sum Rules
- Light Cone QCD Sum Rules Approach to D Mesons
- Results and Discussions

# Introduction

- Last few years have been an exciting period for hadron spectroscopy:
- The possible observation of baryons containing 5 quarks, pentaquarks, first by the LEPS facility in SPring-8 machine in Japan
- The observations of excitation of the heavy charmonium systems
- The detection of double heavy baryons: $\Xi_{cc}$ by the SELEX Collaboration
- The observation of narrow charmed-stranged mesons with unexpected properties.

- In this talk, I will present the study of the radiative decays of $D_{sJ}(2317)$ and $D_s^*(2460)$ within the framework of Light Cone QCD Sum Rules
- A classification of charmed mesons can be obtained in the heavy quark limit: $m_c \to \infty$
- In this limit, the heavy quark spin, $s_Q$, decouples from the total spin of the light degrees of freedom, $s_l = L + S$.

- A given value of $s_l$, corresponds to a doublet which is degenerate in the heavy quark limit.
- for $L = 0$, $s_l = \frac{1}{2}$ and we have the doublet $(0^-, 1^-)$, denoted as $\left(D_{(s)}, D^*_{(s)}\right)$

- For $L = 1$, $s_l = \frac{1}{2}$ or $s_l = \frac{3}{2}$ each one giving a doublet.

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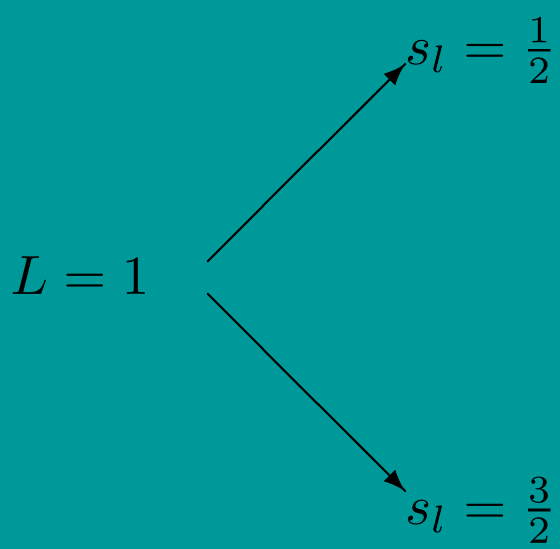

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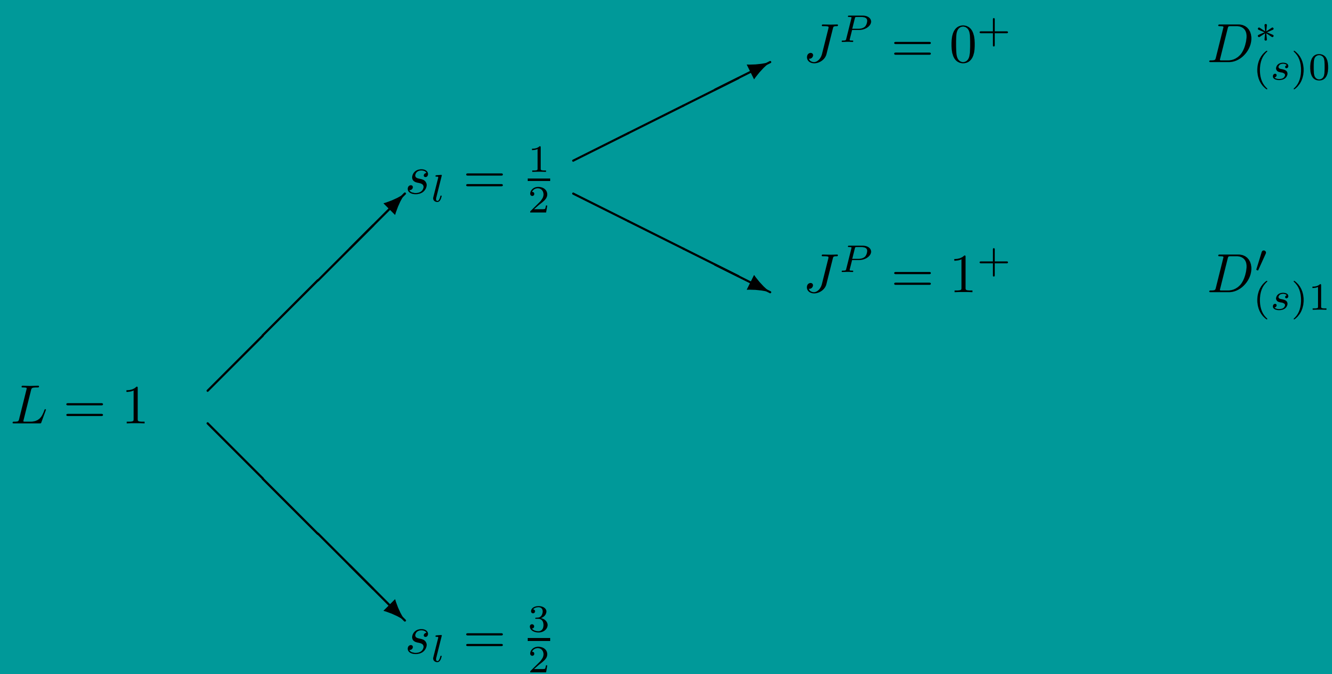


- For $L = 1$, $s_l = \frac{1}{2}$ or $s_l = \frac{3}{2}$ each one giving a doublet.

$$\begin{tikzcd}
 & & J^P = 0^+ & D^*_{(s)0} \\
 & s_l = \frac{1}{2} \arrow[ur] \arrow[dr] & & \\
 & & J^P = 1^+ & D'_{(s)1} \\
L = 1 \arrow[uur] \arrow[ddr] & & & \\
 & & J^P = 1^+ & D_{(s)1} \\
 & s_l = \frac{3}{2} \arrow[ur] \arrow[dr] & & \\
 & & J^P = 2^+ & D^*_{(s)2}
\end{tikzcd}$$

## Decay Modes

- The $s_l = \frac{1}{2}$ and $s_l = \frac{3}{2}$ doublets behave differenty in their decay modes:
- $s_l = \frac{1}{2}$ doublet can decay strongly into pseudoscalar mesons in an $s$-wave
- $s_l = \frac{3}{2}$ doublet can decay strongly into pseudoscalar mesons in $d$-wave only
- The $s_l = \frac{1}{2}$ are expected to be broad.

- CLEO, BELLE and FOCUS collaborations have found evidence of broad resonances, with masses around 2.4 $GeV$ and widths around 300 $MeV$, which can be identified as the $s_l = \frac{1}{2}$ doublet of the non-strange D mesons.
- The broadness of these states are consistant with the expactations for the $s_l = \frac{1}{2}$ doublet mesons.
- The mixing angle between the $1^+$ members of the two doublets is found to be around $-6°$, which can safely be neglected

- In the strange sector, in 2003, BaBar collaboration reported the observation of a narrow resonance with mass close to 2.32 $GeV$, named $D^*_{sJ}(2317)$. Later, this resonance is observed also by the Belle, Cleo and Focus collaborations.
- In all the observations, the width is compatible with the experimental resolution, $\Gamma < 10 MeV$.
- No evidence for the radiative decays into $D_s\gamma$, $D^*_s\gamma$, and $D_s\gamma\gamma$ is found.
- $D^*_{sJ}(2317)$ is naturally interpreted as the scalar component of the $s_l = \frac{1}{2}$ doublet, i.e. the $0^+$

- CLEO also observed another heavier resonance $D_{sJ}(2460)$, with a width consistant with the experimental resolution.
- $D_{sJ}(2460)$ is naturally interpreted as the $1^+$ of the $s_l = \frac{1}{2}$ doublet.
- The existence of this resonance is also confirmed by BaBar and Belle

- One of the surprises of the measurements of these states are their low masses.
- All the predictions for the mass of the scalar $c\bar{s}$ were always heavier than the $DK$ threshold of 2.36 $GeV$ leading to a large width.
- Moreover, the non-strange D mesons were always predicted to be lighter than the strange D mesons, where as experimentally they have more or less equal masses.
- Updated analysis can give results in agreement with experimental data, but it is unclear why the previous determinations were bigger.

- Since the mass of the $D^*_{sJ}(3217)$ is lower than the $DK$ threshold, it is expected to decay mainly through the isospin violating $D\pi$ channel.
- The decay of $D^*_{sJ}(2317) \to D^+_s \pi^0$ is described as a two stage process: first $D^*_{sJ}(2317)$ decays into $D^+_s \eta$, where $\eta$ is then converted into $\pi^0$ throught the isospin violating $\eta - \pi^0$ mixing.
- The decay into $D^+_s \pi^0$ is observed but the width of this decay is still unknown.
- Various theoretical estimates for the width of this decay using the $c\bar{s}$ picture for the $D_s$ meson give results in the $6 - 20\ KeV$ range.

- Another important decay mode of the $D^*_{sJ}$ is the radiative decay mode $D^*_{sJ} \to D^*_s\gamma$
- Experimentally, this mode is still not observed.

Table 1: Measurements and 90% CL upper limits of ratios of $D^*_{sJ}(2317)$ and $D_{sJ}(2460)$ decay widths.

| | Belle | BaBar | CLEO |
|---|---|---|---|
| $\frac{\Gamma\left(D^*_{sJ}(2317)\to D^*_s\gamma\right)}{\Gamma\left(D^*_{sJ}(2317)\to D_s\pi^0\right)}$ | $< 0.18$ | — | $< 0.059$ |
| $\frac{\Gamma(D_{sJ}(2460)\to D_s\gamma)}{\Gamma\left(D_{sJ}(2460)\to D^*_s\pi^0\right)}$ | $0.55 \pm 0.13 \pm 0.08$<br>$0.38 \pm 0.11 \pm 0.04$ | $0.375 \pm 0.054 \pm 0.057$<br>$0.274 \pm 0.045 \pm 0.020$ | $< 0.49$ |
| $\frac{\Gamma(D_{sJ}(2460)\to D^*_s\gamma)}{\Gamma\left(D_{sJ}(2460)\to D^*_s\pi^0\right)}$ | $< 0.31$ | — | $< 0.16$ |
| $\frac{\Gamma\left(D_{sJ}(2460)\to D^*_{sJ}(2317)\gamma\right)}{\Gamma\left(D_{sJ}(2460)\to D^*_s\pi^0\right)}$ | — | $< 0.23$ | $< 0.58$ |

- To study this decay theoretically, one needs the matrix element $\langle D_s^+ \gamma | D_{sJ}^* \rangle$
- To calculate this matrix element theoretically, one needs a a non-perturbative method, one of the most reliable of which is the Light Cone QCD Sum Rules.

# QCD Sum Rules

- In QCD sum rules approach, one relates hadronic properties to the properties of the vacuum of QCD through a number of condensates, one of which is the chiral condensate $\langle \bar{q}q \rangle$ which is known for quite a long time.

- To obtain the sum rules for the process $H_2 \to H_1\gamma$, one starts by considering the correlation function

$$\Pi(p,q) = i \int d^4x e^{ipx} \langle \gamma(q) | \mathcal{T} \left\{ j_1(x) \bar{j}_2(0) \right\} | 0 \rangle$$

where $j_1$ is a current with the quantum numbers of $H_i$ chosen s.t.

$$\langle H_i | j_i | 0 \rangle \neq 0$$

- For $p^2 > 0$ and $(p+q)^2 > 0$, one can insert two complete sets of hadronic states to write the correlation function in the form:

$$\Pi(p,q) = \frac{\langle 0|j_1|H_1(p)\rangle}{p^2 - m_1^2}\langle\gamma(q)H_1(p)|H_2(p+q)\rangle\frac{\langle H_2(p+q)|j_2|0\rangle}{(p+q)^2 - m_2^2} + \cdots$$

  where $m_i$ is the mass of $H_i$.

- On the other kinematical region, where $p^2 << 0$ and $(p+q)^2 << 0$, the main contribution to the correlation function comes from small distances, and hence one can expand the time ordered product using OPE.

- The sum rules is obtained by equating both expressions for the correlation function using spectral representation for the correlation function.

## Light Cone QCD Sum Rules for $D^*_{sJ} \to D^*_s\gamma$ decay

- In order to obtain the hadronic representation for the correlation function, the following matrix elements of the currents are needed:

$$\langle D^*_{sJ}(p)|j^{0^+}|0\rangle = m_{D^*_{sJ}} f_{D^*_{sJ}}$$
$$\langle D^*_s(p)|j^{1^-}_\mu|0\rangle = m_{D^*_s} f_{D^*_s} \varepsilon(p)$$

  where $\varepsilon(p)$ is the polarization vector of the $D^*_s$ vector meson, and $f_D$'s are called the residues or in this case, leptonic decay constants of the corresaponding meson.

- The last ingrediant necessary to obtain a hadronic representation for the correlation function is the vertex element, which using gauge invariance can be written as:

$$\langle D_s^*(p)\gamma(q)|D_{sJ}^*\rangle = eF(q^2)\left((\varepsilon\eta)(pq) - (\eta p)(\varepsilon q)\right)$$

where $\eta$ is the polarization vector of the photon.

- Using these definitions and summing over the polarization of the vector meson, the correlation function becomes

$$\Pi_\mu(p,q) = e\frac{F(q^2)}{\left(p^2 - m_{D_s^*}^2\right)\left((p+q)^2 - m_{D_{sJ}^*}^2\right)}\left(\eta_\mu(pq) - q_\mu(\eta p)\right) + \cdots$$

- In order to obtain an expression of the correlation function using the OPE, first, one needs to determine appropriate currents.
- The immediate choice for the currents in the $c\bar{s}$ picture of the $D_s$ mesons are:

$$
\begin{aligned}
j^{0^+} &= \bar{s}c \\
j^{1^-}_\mu &= \bar{s}\gamma_\mu c
\end{aligned}
$$

- In the heavy quark limit, these currents become

$$
\begin{aligned}
j^{0^+} &= \bar{s}h_v \\
j^{1^-}_\mu &= \bar{s}\gamma^t_\mu h_v
\end{aligned}
$$

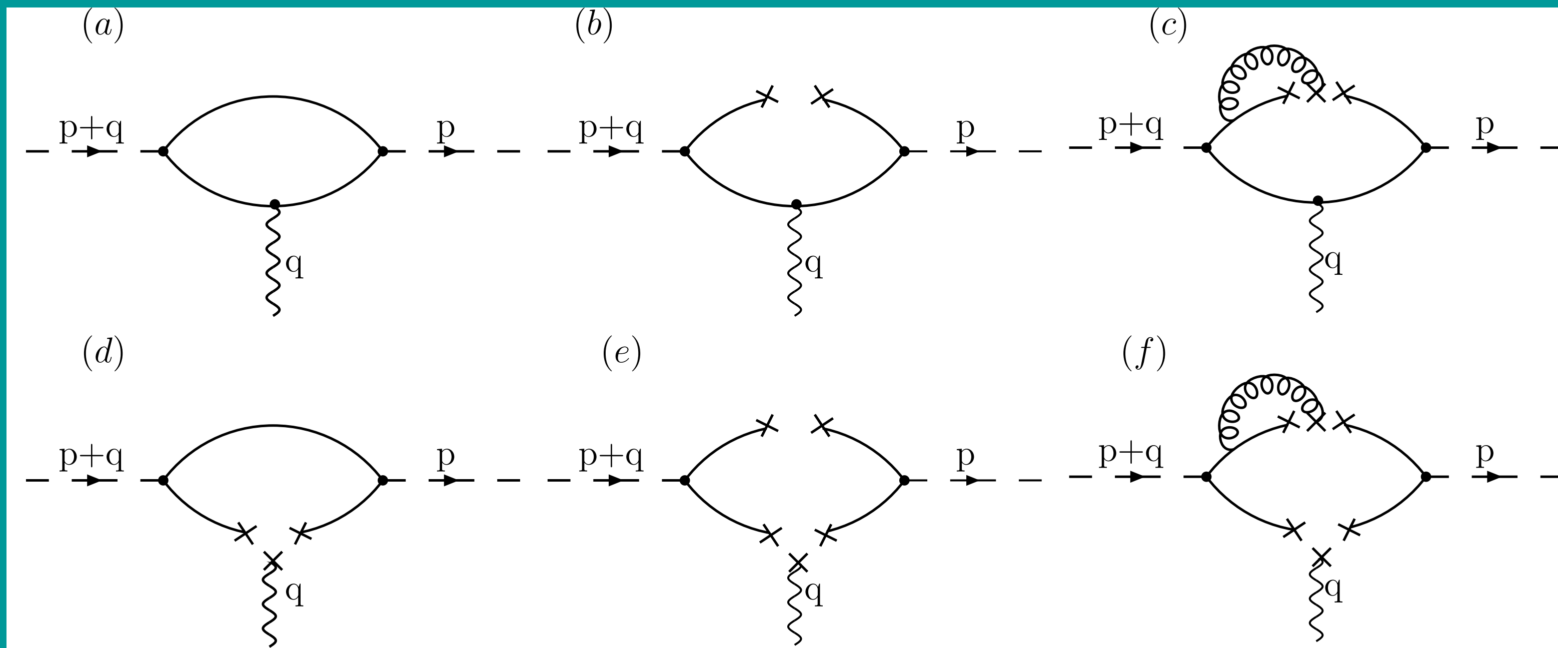
where $h_v$ is the heavy quark field with the heavy quark moving at a velocity $v$, $\gamma^t_\mu = g^t_{\mu\nu}\gamma^\nu$, $g^t_{\mu\nu} = g_{\mu\nu} - v_\mu v_\nu$

- In the heavy quark limit, Dai *et. al* argue that the coupling of these currents to the corresponding mesons in the non relativistic limit vanishes and they propose to use the currents:

$$
\begin{aligned}
j^{0^+} &= \bar{s}(-i \overleftarrow{\not{D}}^t) h_v \\
j^{1^-}_\mu &= \bar{s}(-i \overleftarrow{\not{D}}^t) \gamma^t_\mu h_v
\end{aligned}
$$

- We used both definitions of the currents in the heavy quark limit and found out that the results do not change.

- Calculation of the correlation function amounts to calculating the Feynman diagrams of the form:




- Contracting only one type of quark fields, one can express the correlation function in terms of matrix elements of the form $\langle \gamma(q) | \bar{q}(x) \Gamma q(0) | 0 \rangle$, where $\Gamma$ are $\mathbf{1}$, $\gamma_\mu$, $\sigma_{\mu\nu}/\sqrt{2}$, $i\gamma_\mu\gamma_5$, and $\gamma_5$

- These matrix elements can be expanded on the light cone, around $x^2 = 0$.
- Using these input parameters, one can evalute the correlation function in terms of parameter appearing in the QCD lagrangian, a few condensates and wavefunctions

- The sum rules are obtained by calculating the integral in:

$$f_{D_s^*} f_{D_{sJ}^*} m_{D_s^*} m_{D_{sJ}^*} F_1(0) e^{-\frac{m_{D_s^*}^2 + m_{D_{sJ}^*}^2}{2M}} = \int_{m_c^2}^{s_0} ds e^{-\frac{s}{M^2}} \rho(s)$$

- In order to obtain a prediction for the formfactor $F_1(0)$, the constants $f_D$ are also needed.
- These constants can also be calculated using the sum rules approach.
- For this purpose, one considers the correlation function

$$\Pi(p) = i \int d^4 x e^{ipx} \langle 0 | \mathcal{T} \left\{ J_i(x) \bar{J}_i(0) \right\} | 0 \rangle$$

- For $j_i = j^{0^+}$, the correlation function becomes, in the phenomenological representation:

$$\Pi(p) = \frac{f_{D_{sJ}^*}^2 m_{D_{sJ}^*}^2}{p^2 - m_{D_{sJ}^*}^2}$$

- and for $j_i = j_\mu^{1^-}$

$$\Pi_{\mu\nu}(p) = \frac{f_{D_s^*}^2 m_{D_s^*}^2}{p^2 - m_{D_s^*}^2} \left( g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} \right)$$

# Results and Discussions

$$D_{sJ}^*(2317) \to D_s^* \gamma$$

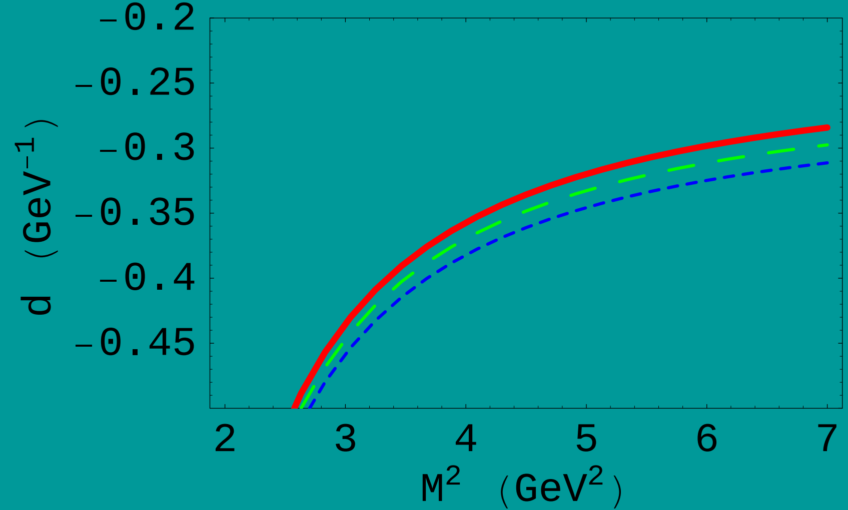



Figure 1: The parameter $d$ in the $D_{s0} \to D_s^* \gamma$ decay amplitude versus the Borel parameter $M^2$ . The curves correspond to the thresholds $s_0 = 2.45^2$ GeV$^2$ (continuous line), $s_0 = 2.5^2$ GeV$^2$ (long-dashed line) and $s_0 = 2.55^2$ GeV$^2$ (dashed line).

- It is seen that $d = -0.31 \pm 0.4 \ GeV^{-1}$
- The width, defined as:

$$\Gamma = \frac{\alpha}{8m^3_{D^*_{sJ}}}(m^2_{D^*_{sJ}} - m^2_{D^*_s})^3 F_1(0)^2 \qquad (1)$$

  turn out to be $\Gamma = 5 \pm 1 \ KeV$.
- There are bigger uncertainties due to the uncertainties in the values of the input parameter, e.g. if one uses $\chi = -4.4 \ GeV^{-2}$ instead of $\chi = -3.15 \ GeV^2$, the value obtained for $|d|$ is 40% larger.

- The main contribution to the sum rules comes from the leading twist wavefunction $\varphi_\gamma$ and the perturbative contribution.
- A large uncertainty is caused by the uncertainty of the value of $\chi$ which multiplies $\varphi_\gamma$.
- A recent prediction for the value of $\chi$ is, $\chi = -3.15\ GeV^{-2}$. For this value of $\chi$, the width reduces to as small as $\Gamma \simeq 10\ KeV$
- Another large uncertainty comes from the value of the value of $\Lambda_{QCD}$, $M^2$ and $s_0$, changing whose values can reduce the width by 4 $KeV$
- Assuming that the ratio of the width of the radiative decay to the pionic decay saturates the experimental upper bound, our prediction for the pionic decay mode changes from 120 $KeV$ up to 500 $KeV$.
- The prediction for the pionic decay is much larger then the

predictions of other approaches.

- Assuming that the pionic and the radiative decays saturate the total width, we get $\Gamma_{D^*_{sJ}} < 525 KeV$ which is well below the experimental limit.
- Experimental data is still not sufficient to derive any precise conclusions from our results.
- There are big descrepancies between various methods. When more precise experimental data will be available, removing these uncertainties will lead to a deaper understanding of strong interactions.
- If the widht of the radiative decay turns out to be around $1\ KeV$, it would most probably imply a structure for the $D^*_{sJ}$ different from the quark-anti-quark picture.

Table 2: Comparison of our results with other results

| Initial state | Final state | LCSR | VMD [2, 3] | QM [5] | QM [6] |
|---|---|---|---|---|---|
| $D_{sJ}^*(2317)$ | $D_s^*\gamma$ | 4-6 | 0.85 | 1.9 | 1.74 |
| $D_{sJ}(2460)$ | $D_s\gamma$ | 19-29 | 3.3 | 6.2 | 5.08 |
| | $D_s^*\gamma$ | 0.6-1.1 | 1.5 | 5.5 | 4.66 |
| | $D_{sJ}^*(2317)\gamma$ | 0.5-0.8 | — | 0.012 | 2.74 |

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