New Spectroscopy of Heavy Mesons

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How to (try to) understand the properties of recently discovered states using the heavy quark limit

Collaborators: P. Colangelo, R. Ferrandes, S. Nicotri, A. Ozpineci, M. Rizzi

Open charm/beauty states

- $D_0(2308)$, $D'_1(2440)$
- $D_{s0}^*(2317)$, $D'_{s1}(2460)$
- $D(2550)$, $D(2600)$, $D(2750)$, $D(2760)$
- $D_{sJ}(2632)$
- $D_{sJ}(2860)$, $D_{sJ}(2710)$, $D_{sJ}(3040)$

- $B_1(5734)$, $B^*_2(5738)$
- $B_{s1}(5830)$, $B^*_{s2}(5840)$

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- $D_0(2308)$, $D'_1(2440)$
- $D_{s0}^*(2317)$, $D'_{s1}(2460)$
- $D(2550)$, $D(2600)$, $D(2750)$, $D(2760)$
- ~~$D_{sJ}(2632)$~~ → Seen only by SELEX, never confirmed
- $D_{sJ}(2860)$, $D_{sJ}(2710)$, $D_{sJ}(3040)$

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- $B_{s1}(5830)$, $B^*_{s2}(5840)$

Hadrons containing a single heavy quark Q

Spin of the heavy quark and of the light degrees of freedom decoupled in the $m_Q \to \infty$ limit } **Spin symmetry**

$\vec{J}_M = \vec{s}_\ell + \vec{s}_Q$ spin

$\vec{s}_\ell = \vec{L} + \vec{s}_q$ angular momentum of the light degrees of freedom (conserved)

Mesons classified as **doublets** the members of which have $J = s_\ell \pm \frac{1}{2}$

The heavy quark flavour becomes irrelevant as $m_Q \to \infty$ } **Flavour symmetry**

possibility to relate charm and beauty hadron properties

HQ limit for meson doublets and strong decays to light pseudoscalars

The two states within a given doublet are degenerate

They have the same total width

The sum of the partial widths of a state in a doublet to a state in another doublet with emission of a light meson is the same for the two states of a doublet

Spin symmetry predicts the ratios of partial decay widths for a given state

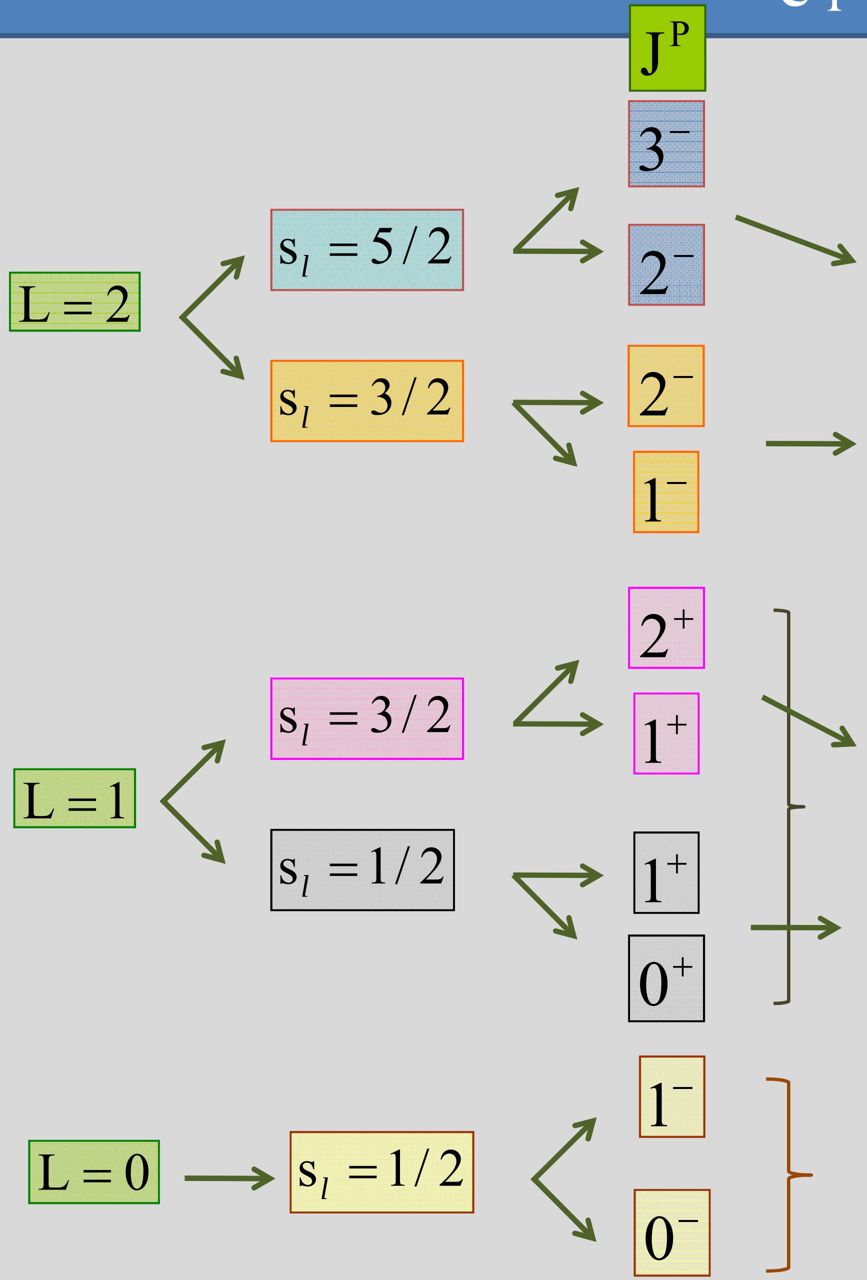
Spin symmetry

Partial decay widths are independent on the HQ flavour

Mass splittings among the doublets are independent of the HQ flavour

Flavour symmetry

$Q\bar{q}$ multiplets



D-wave doublets:

$(D'_{(s)2}, D_{(s)3})$, $(B'_{(s)2}, B_{(s)3})$

$(D^*_{(s)1}, D_{(s)2})$, $(B^*_{(s)1}, B_{(s)2})$

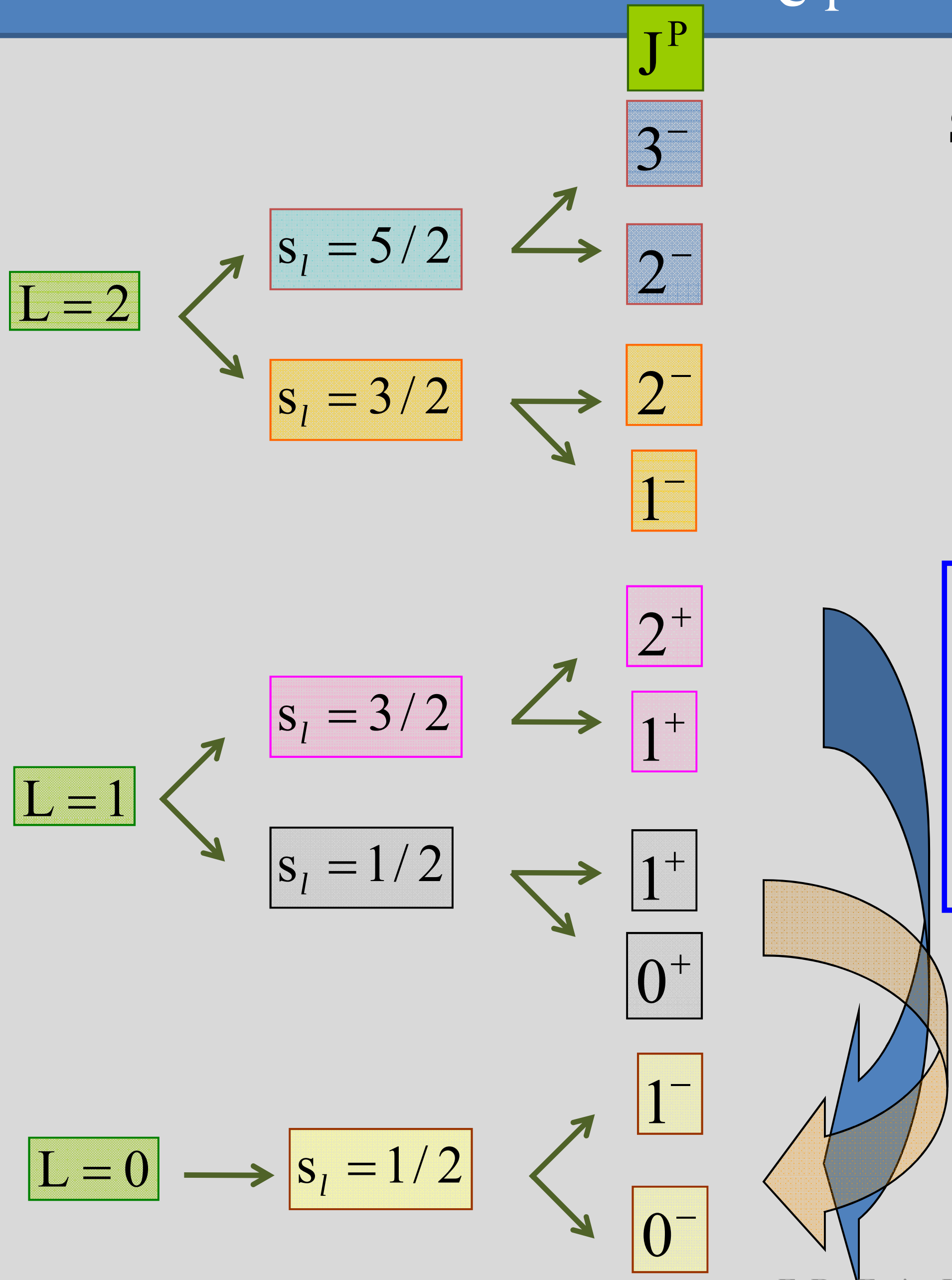
P-wave doublets:

$(D_{(s)1}, D^*_{(s)2})$, $(B_{(s)1}, B^*_{(s)2})$

$(D^*_{(s)0}, D'_{(s)1})$, $(B^*_{(s)0}, B'_{(s)1})$

fundamental doublet: $(D_{(s)}, D^*_{(s)})$, $(B_{(s)}, B^*_{(s)})$

$Q\bar{q}$ multiplets



Strong transitions between multiplets

$\frac{3}{2}^+ \rightarrow \frac{1}{2}^-$ + pseudoscalar meson

d-wave transition

$\frac{3}{2}^+$ mesons are expected to be narrow

$\frac{1}{2}^+ \rightarrow \frac{1}{2}^-$ + pseudoscalar meson

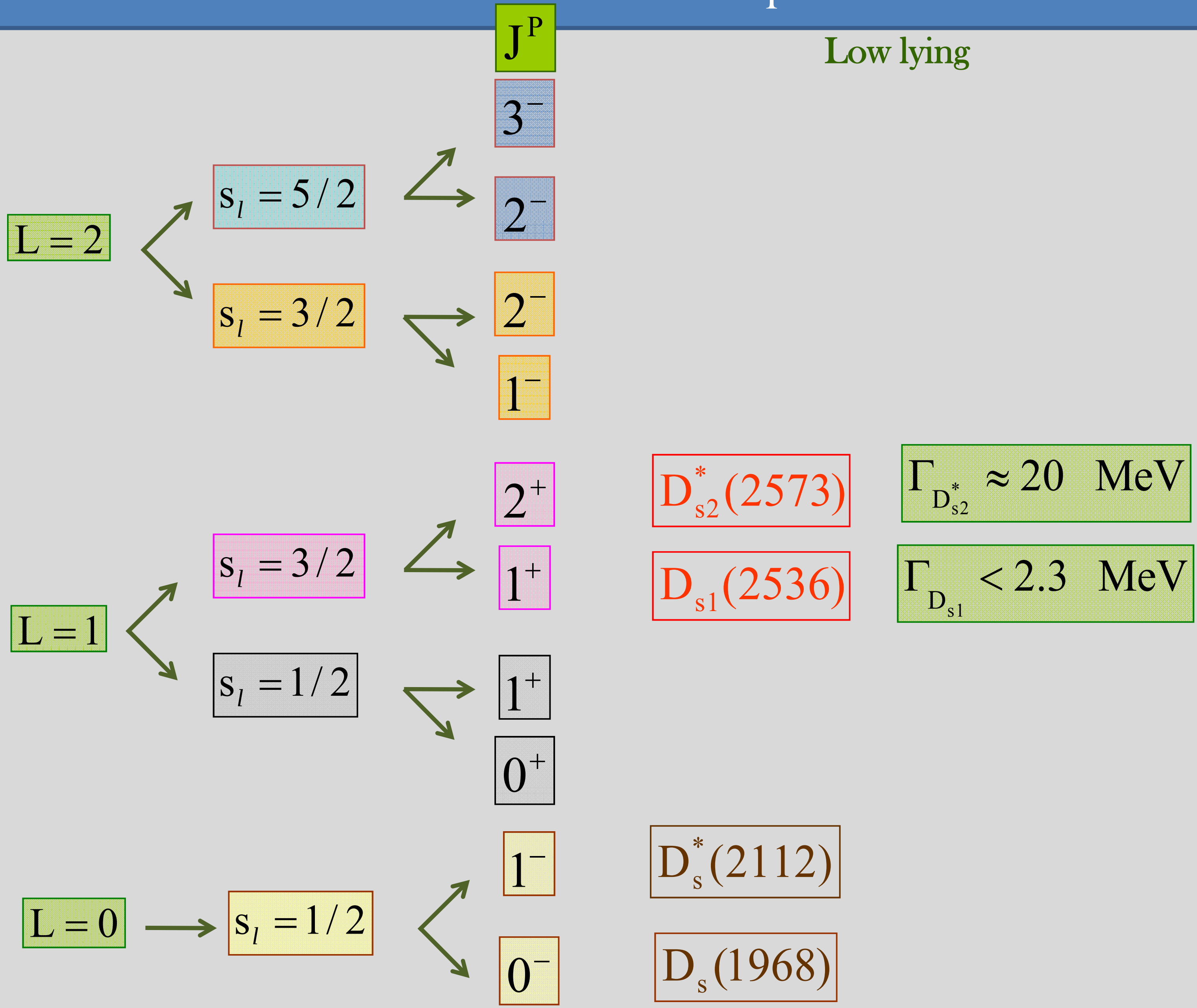
s-wave transition

$\frac{1}{2}^+$ mesons are expected to be broad

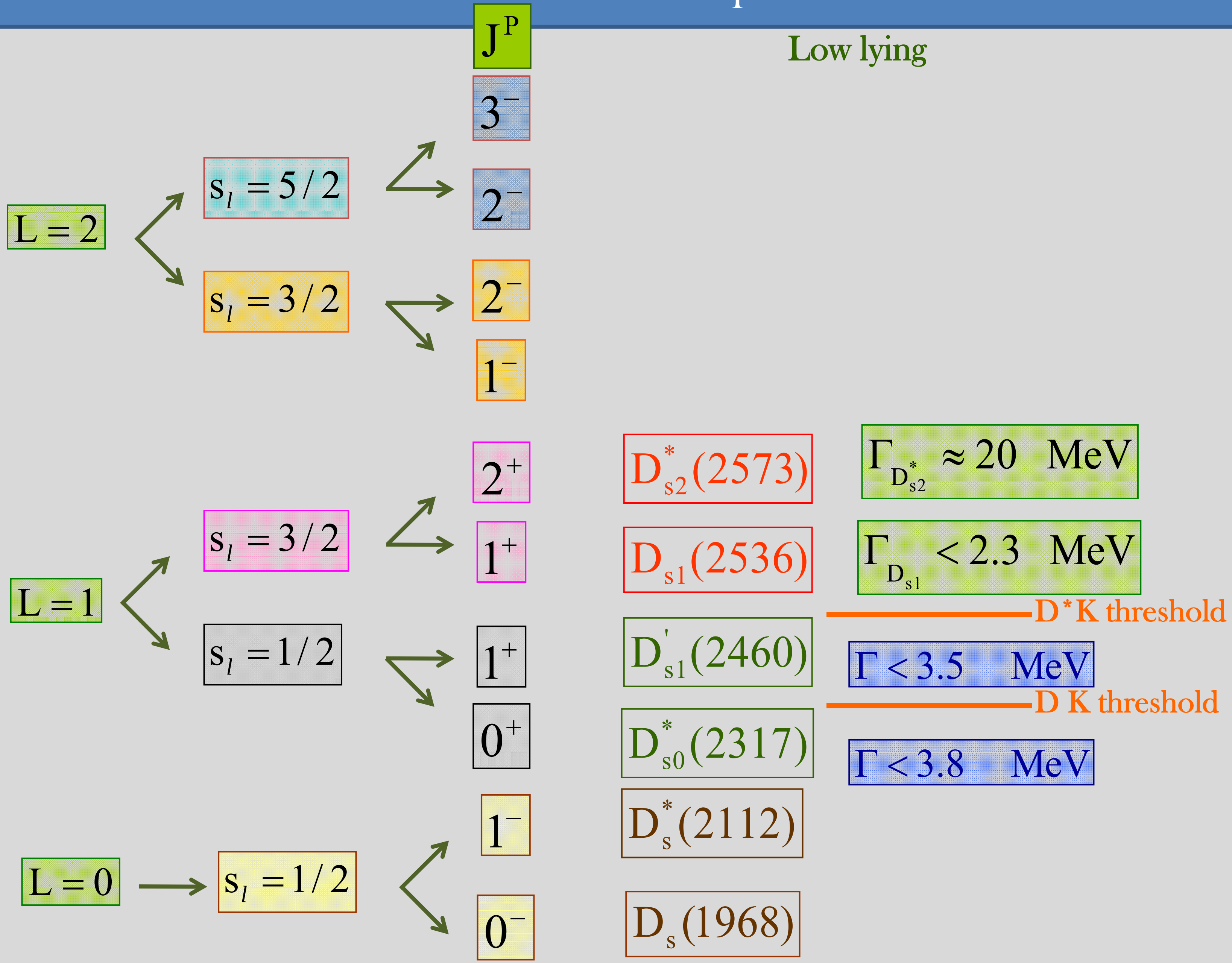
$c\bar{q}$ multiplets

L	s_l	J^P	Low lying	Rad. Excitations
$L=2$	$s_l = 5/2$	3^-		
		2^-		
	$s_l = 3/2$	2^-		
		1^-		
$L=1$	$s_l = 3/2$	2^+	$D_2^{*\pm,0}(2460)$	$\Gamma_{D_2^*} \approx 40 \quad \text{MeV}$
		1^+	$D_1^{\pm}(2420)$	$\Gamma_{D_1} \approx 20 \quad \text{MeV}$
	$s_l = 1/2$	1^+	$D_1'^{0}(2430)$	$\Gamma_{D_1'} \approx 384 \quad \text{MeV}$
		0^+	$D_0^{*0}(2308)$	$\Gamma_{D_0} \approx 260 \quad \text{MeV}$
$L=0$	$s_l = 1/2$	1^-	$D^{*\pm}(2010),\ D^{*0}(2007)$	
		0^-	$D^{\pm}(1869),\ D^{0}(1865)$	

$c\bar{s}$ multiplets



$c\bar{s}$ multiplets

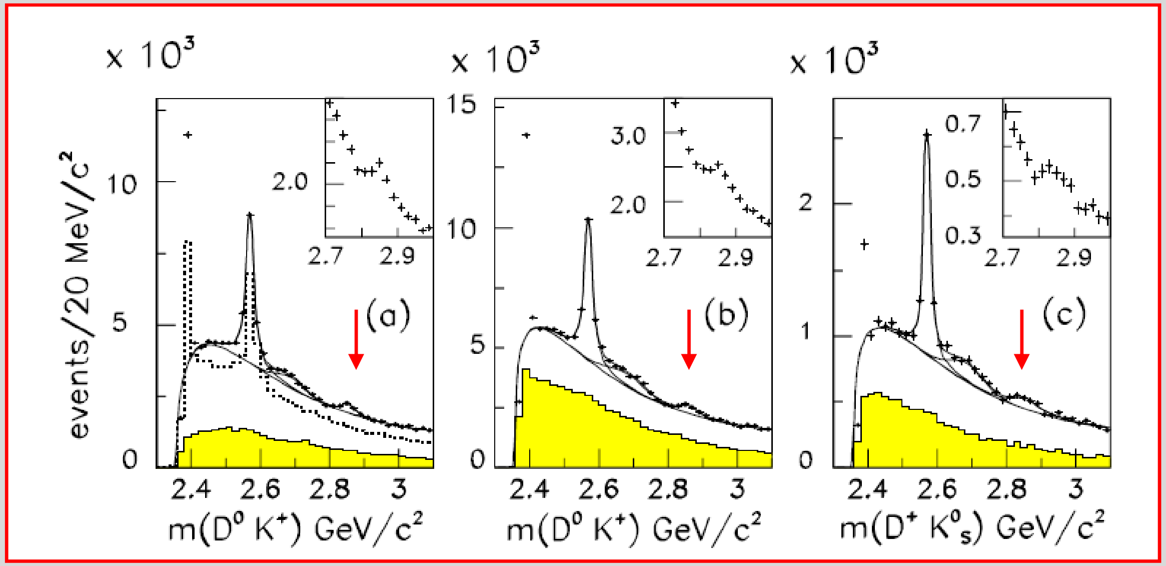


$D_{sJ}(2860)$

- Discovered by BaBar Collab.
- Reconstructed in

$$D^0K^+ \to (K^-\pi^+)K^+$$
$$\to (K^-\pi^+\pi^0)K^+$$

and in $D^+K_S^0$



$M = 2856.6 \pm 1.5 \pm 5.0 \quad \text{MeV}$

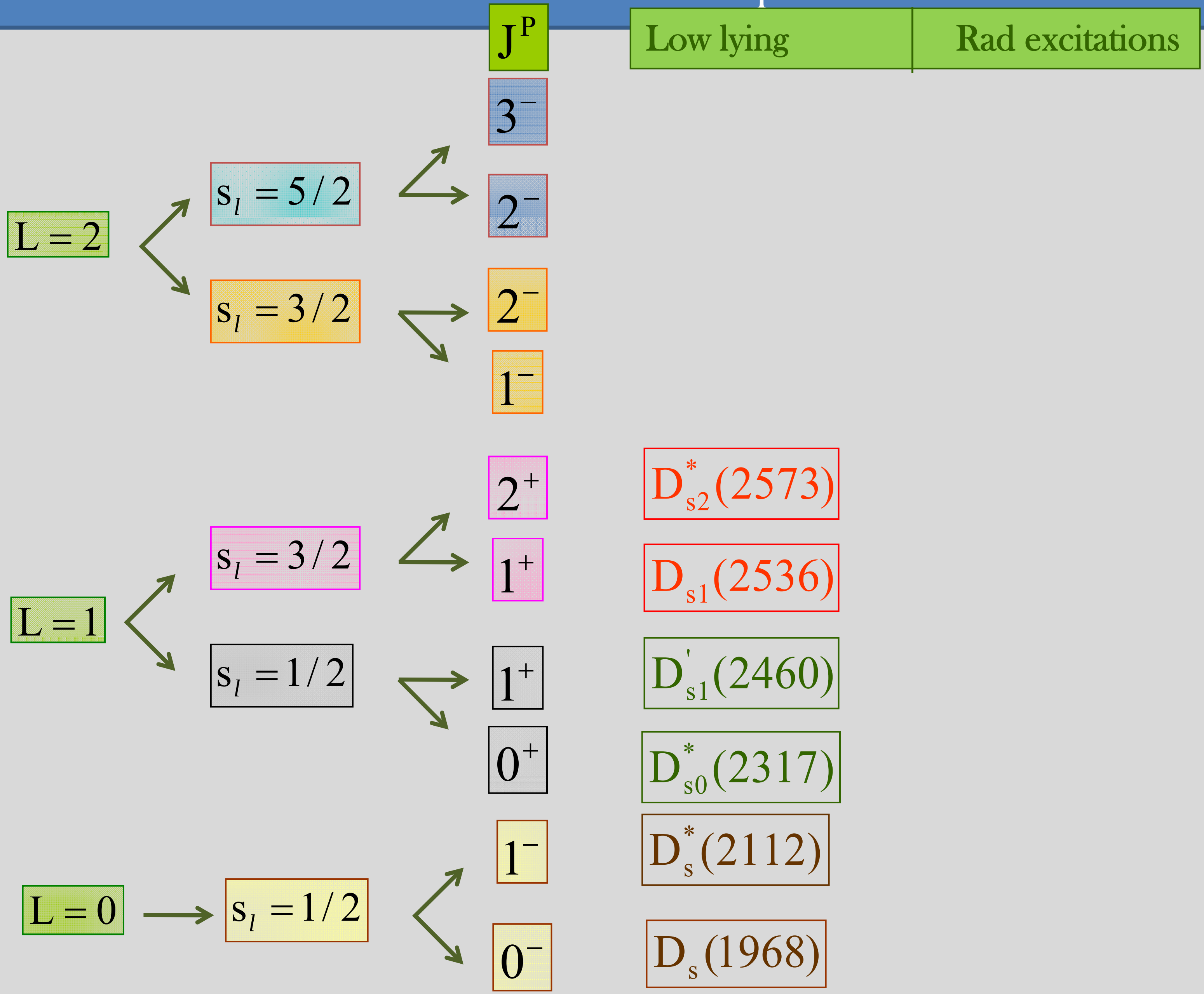
$\Gamma = 48 \pm 7 \pm 10 \quad \text{MeV}$

BaBar Collab., PRL 97 (06) 222001

Quantum number assignment required in order to identify it
Possibilities: - low lying state not yet observed
- radial excitation of an already observed state

Only states that can decay to the observed mode DK are allowed

$c\bar{s}$ multiplets



$c\bar{s}$ multiplets

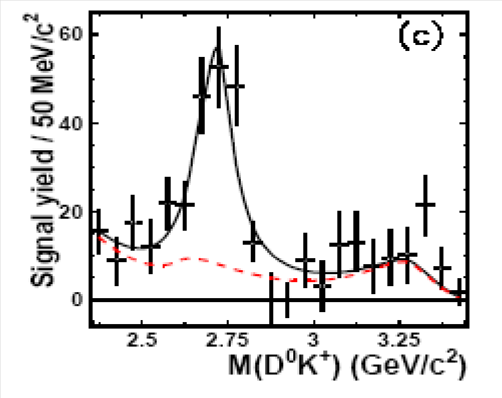
	s_l	J^P	Low lying	Rad excitations
$L=2$	$s_l = 5/2$	3^-		
		2^-	forbidden	
	$s_l = 3/2$	2^-	forbidden	
		1^-		
$L=1$	$s_l = 3/2$	2^+	$D^*_{s2}(2573)$	
		1^+	$D_{s1}(2536)$	forbidden
	$s_l = 1/2$	1^+	$D'_{s1}(2460)$	forbidden
		0^+	$D^*_{s0}(2317)$	
$L=0$	$s_l = 1/2$	1^-	$D^*_s(2112)$	
		0^-	$D_s(1968)$	forbidden

$c\bar{s}$ multiplets

L	s_l	J^P	Low lying	Rad excitations
$L=2$	$s_l=5/2$	3^-	allowed	
		2^-	forbidden	
	$s_l=3/2$	2^-	forbidden	
		1^-	allowed	
$L=1$	$s_l=3/2$	2^+	$D^*_{s2}(2573)$	allowed
		1^+	$D_{s1}(2536)$	forbidden
	$s_l=1/2$	1^+	$D'_{s1}(2460)$	forbidden
		0^+	$D^*_{s0}(2317)$	allowed
$L=0$	$s_l=1/2$	1^-	$D^*_s(2112)$	allowed
		0^-	$D_s(1968)$	forbidden

$D_{sJ}(2710)$

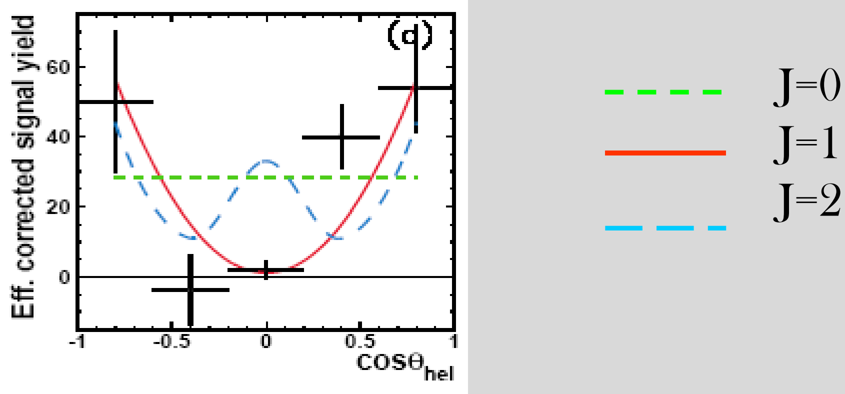
Belle Collab.: analysis of the mode $B^+ \to \overline{D}^0 D^0 K^+$



New resonance decaying to D^0K^+ with:

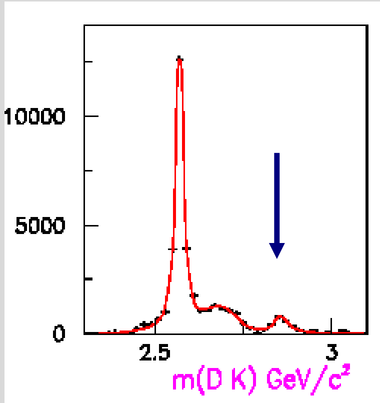
$M = 2708 \pm 9 \pm^{11}_{10}$ MeV $\Gamma = 108 \pm 23 \pm^{36}_{31}$ MeV

$1^- \to 0^- 0^-$ implies P=-1

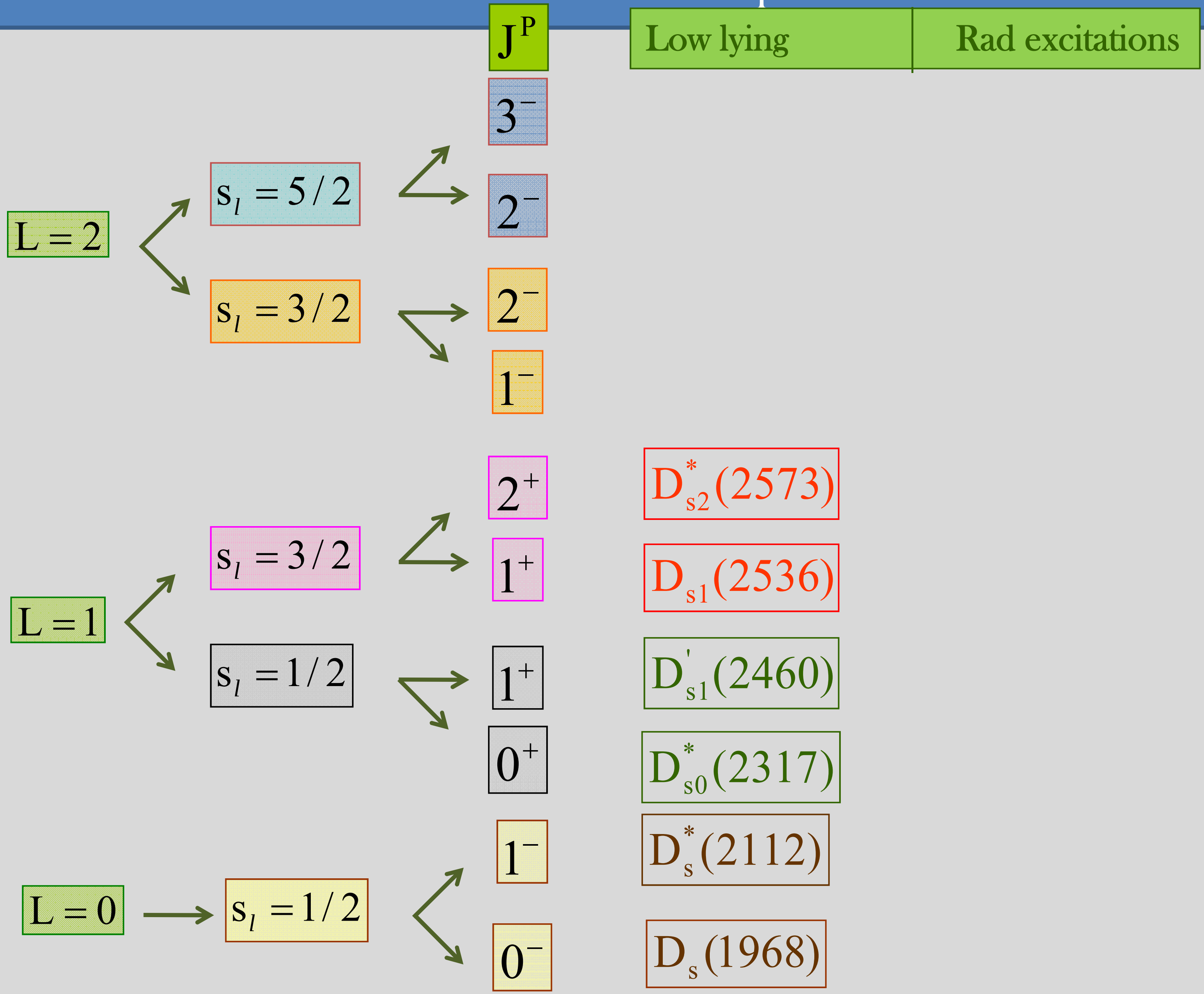


$J^P=1^-$ favoured

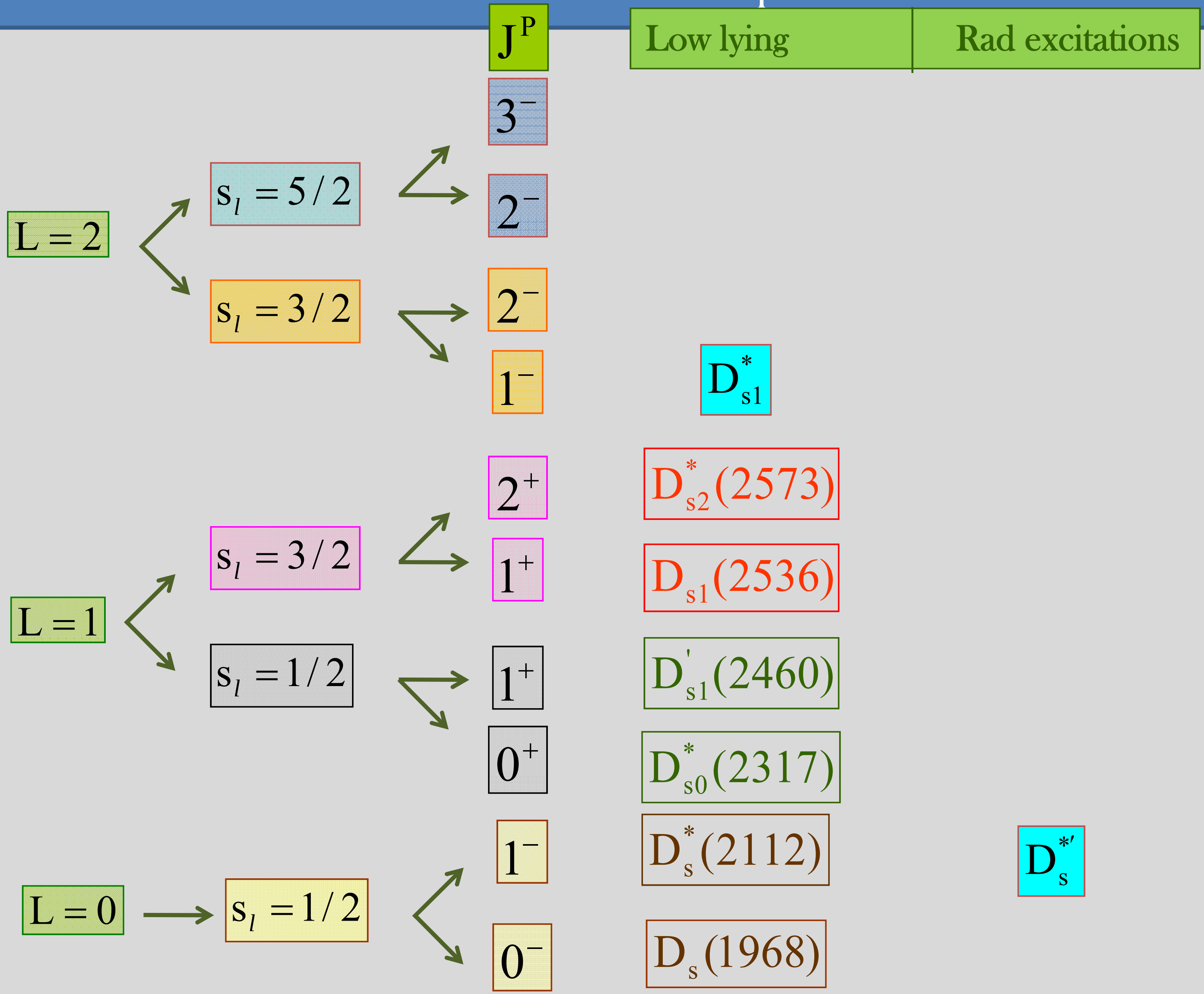
A broad structure at M=2688 MeV with Γ=112 MeV was found by BaBar in the DK mass distribution



$c\bar{s}$ multiplets



$c\bar{s}$ multiplets



$D_{sJ}(2860)$ & $D_{sJ}(2710)$

predictions on allowed decay rates can help to distinguish among the various possibilities

HQ limit: the members of the doublets are described by effective fields:

L=0

$s_\ell^P = \frac{1}{2}^-$

$$H_a = \frac{1+\not v}{2}\left[P^*_{a\mu}\gamma^\mu - P_a\gamma_5\right]$$

L=1

$s_\ell^P = \frac{1}{2}^+$

$$S_a = \frac{1+\not v}{2}\left[P'^{\mu}_{1a}\gamma_\mu\gamma_5 - P^*_{0a}\right]$$

$s_\ell^P = \frac{3}{2}^+$

$$T^\mu_a = \frac{1+\not v}{2}\left\{P^{\mu\nu}_{2a}\gamma_\nu - P_{1a\nu}\sqrt{\frac{3}{2}}\gamma_5\left[g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu - v^\mu)\right]\right\}$$

L=2

$s_\ell^P = \frac{3}{2}^-$

$$X^\mu_a = \frac{1+\not v}{2}\left\{P^{*\mu\nu}_{2a}\gamma_5\gamma_\nu - P^{*\prime}_{1a\nu}\sqrt{\frac{3}{2}}\left[g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu - v^\mu)\right]\right\}$$

$s_\ell^P = \frac{5}{2}^-$

$$X'^{\mu\nu}_a = \frac{1+\not v}{2}\left\{P^{\mu\nu\sigma}_{3a}\gamma_\sigma - P^{*\prime\alpha\beta}_{2a}\sqrt{\frac{5}{3}}\gamma_5\left[g^\mu_\alpha g^\nu_\beta - \frac{1}{5}\gamma_\alpha g^\nu_\beta(\gamma^\mu - v^\mu) - \frac{1}{5}\gamma_\beta g^\mu_\alpha(\gamma^\nu - v^\nu)\right]\right\}$$

$D_{sJ}(2860)$ & $D_{sJ}(2710)$

Interactions with the emission of a light pseudoscalar meson described by effective Lagrangian terms

$$\mathcal{L}_H = g\,\mathrm{Tr}[\bar{H}_a H_b \gamma_\mu \gamma_5 \mathcal{A}^\mu_{ba}],$$

H → H π

$$\mathcal{L}_S = h\,\mathrm{Tr}[\bar{H}_a S_b \gamma_\mu \gamma_5 \mathcal{A}^\mu_{ba}] + \mathrm{h.c.},$$

S → H π

$$\mathcal{L}_T = \frac{h'}{\Lambda_\chi}\mathrm{Tr}[\bar{H}_a T^\mu_b (i D_\mu \not{\mathcal{A}} + i \not{D} \mathcal{A}_\mu)_{ba} \gamma_5] + \mathrm{h.c.},$$

T → H π

$$\mathcal{L}_X = \frac{k'}{\Lambda_\chi}\mathrm{Tr}[\bar{H}_a X^\mu_b (i D_\mu \not{\mathcal{A}} + i \not{D} \mathcal{A}_\mu)_{ba} \gamma_5] + \mathrm{h.c.},$$

X → H π

$$\mathcal{L}_{X'} = \frac{1}{\Lambda_\chi{}^2}\mathrm{Tr}[\bar{H}_a X'^{\mu\nu}_b [k_1 \{D_\mu, D_\nu\} \mathcal{A}_\lambda + k_2 (D_\mu D_\nu \mathcal{A}_\lambda + D_\nu D_\lambda \mathcal{A}_\mu)]_{ba} \gamma^\lambda \gamma_5] + \mathrm{h.c.},$$

X’ → H π

$$\mathcal{A}_{\mu ba} = \frac{i}{2}(\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger)_{ba}$$

$$\xi = e^{\frac{i\mathcal{M}}{f_\pi}}$$

$$\mathcal{M} = \begin{pmatrix} \sqrt{\frac{1}{2}}\pi^0 + \sqrt{\frac{1}{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\sqrt{\frac{1}{2}}\pi^0 + \sqrt{\frac{1}{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

Analogous terms describe interactions involving radial excitation doublets: $g \to \tilde{g},\ h \to \tilde{h}, \ldots$

$D_{sJ}(2860)$: results for width ratios

P. Colangelo, S. Nicotri, FDF
PLB 642, 48

	$D_{sJ}(2860)$	$D_{sJ}(2860) \to DK$	$\frac{\Gamma(D_{sJ}(2860)\to D^*K)}{\Gamma(D_{sJ}(2860)\to DK)}$	$\frac{\Gamma(D_{sJ}(2860)\to D_s\eta)}{\Gamma(D_{sJ}(2860)\to DK)}$
1	$s_\ell^P = \frac{1}{2}^-, \; J^P = 1^-, \; n = 2$	p-wave	1.23	0.27
2	$s_\ell^P = \frac{1}{2}^+, \; J^P = 0^+, \; n = 2$	s-wave	0	0.34
3	$s_\ell^P = \frac{3}{2}^+, \; J^P = 2^+, \; n = 2$	d-wave	0.63	0.19
4	$s_\ell^P = \frac{3}{2}^-, \; J^P = 1^-, \; n = 1$	p-wave	0.06	0.23
5	$s_\ell^P = \frac{5}{2}^-, \; J^P = 3^-, \; n = 1$	f-wave	0.39	0.13

Would explain the observed narrowness

$D_{sJ}(2860)$

Our supported option: 5 $s_\ell^P = \frac{5}{2}^-, \; J^P = 3^-, \; n = 1$

- Signal expected in D^*K
- Small signal expected also in $D_s\,\eta$

In this case the small width can be attributed to the suppression due to the kaon momentum factor:

$$\Gamma(D_{sJ} \to DK) = \frac{6}{35} \frac{(k_1 + k_2)^2}{\pi f_\pi^2 \Lambda_\chi^4} \frac{M_D}{M_{D_{sJ}}} q_K^7$$

f-wave transition

Assuming the experimentally measured width would predict in the typical range of these couplings $k_1 + k_2 \approx 0.5$

The spin 2 partner could decay in p-wave due to the effect of $1/m_Q$ corrections

may escape detection

Our conclusion:

$D_{sJ}(2860)$ is likely to be a $J^P=3^-$ state

Should decay to D^*K

Identifying $D_{sJ}(2710)$ through its decay modes

P. Colangelo, S. Nicotri, M. Rizzi, FDF
Phys. Rev. D77, 014012

$$R_1 = \frac{\Gamma(D_{sJ} \to D^* K)}{\Gamma(D_{sJ} \to DK)} \qquad R_2 = \frac{\Gamma(D_{sJ} \to D_s \eta)}{\Gamma(D_{sJ} \to DK)} \qquad R_3 = \frac{\Gamma(D_{sJ} \to D_s^* \eta)}{\Gamma(D_{sJ} \to DK)}$$

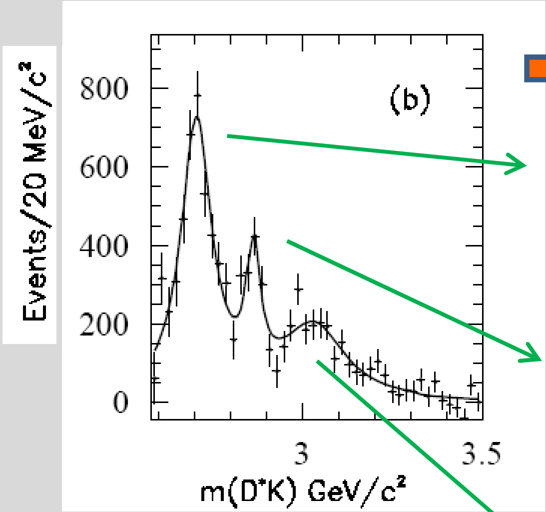
the dependence on the (unknown) couplings drops out

	$R_1 \times 10^2$	$R_2 \times 10^2$	$R_3 \times 10^2$
$D_s^{*\prime}$	91 ± 4	20 ± 1	5 ± 2
D_{s1}^*	4.3 ± 0.2	16.3 ± 0.9	0.18 ± 0.07

The D^*K decay is the signal that must be investigated in order to distinguish the two possible assignments

BaBar Analysis of D^*K final states

- D^*K invariant mass spectrum (background-subtracted)



Three peaks are visible:

$$m(D^*_{s1}(2710)^+) = 2710 \pm 2_{stat} \pm^{12}_{7\ syst} \quad \text{MeV}$$

$$\Gamma(D^*_{s1}(2710)^+) = 149 \pm 7_{stat} \pm^{39}_{52\ syst} \quad \text{MeV}$$

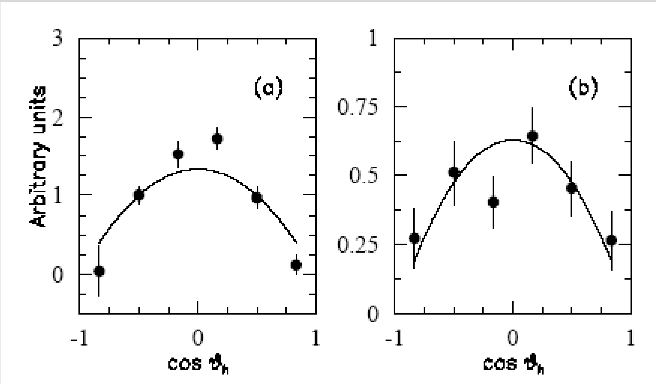
$$m(D_{sJ}(2860)^+) = 2862 \pm 2_{stat} \pm^{5}_{2\ syst} \quad \text{MeV}$$

$$\Gamma(D_{sJ}(2860)^+) = 48 \pm 3_{stat} \pm 6_{syst} \quad \text{MeV}$$

$$m(D_{sJ}(3040)^+) = 3044 \pm 8_{stat} \pm^{30}_{5\ syst} \quad \text{MeV}$$

$$\Gamma(D_{sJ}(3040)^+) = 239 \pm 35_{stat} \pm^{46}_{42\ syst} \quad \text{MeV}$$

- angular analysis



The angular distribution is consistent with the expectations for states with natural parity ($0^+,1^-,2^+,3^-,\ldots$) for $D_{s1}(2710)$ and $D_{sJ}(2860)$

excluded by the observation of the D^*K mode

BaBar, PRD80 (09)092003

BaBar Analysis of D^*K final states

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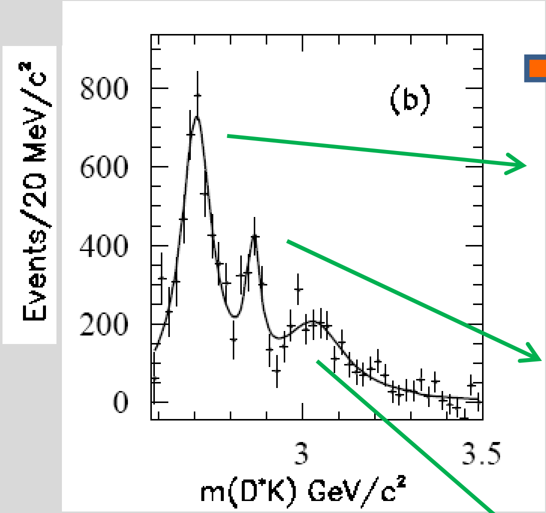

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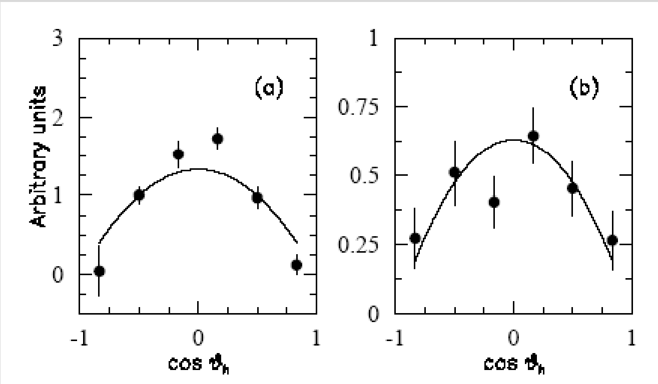

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excluded by the observation of the D^*K mode

BaBar, PRD80 (09)092003

to be discussed later…

BaBar Analysis of D^*K final states

Branching fractions

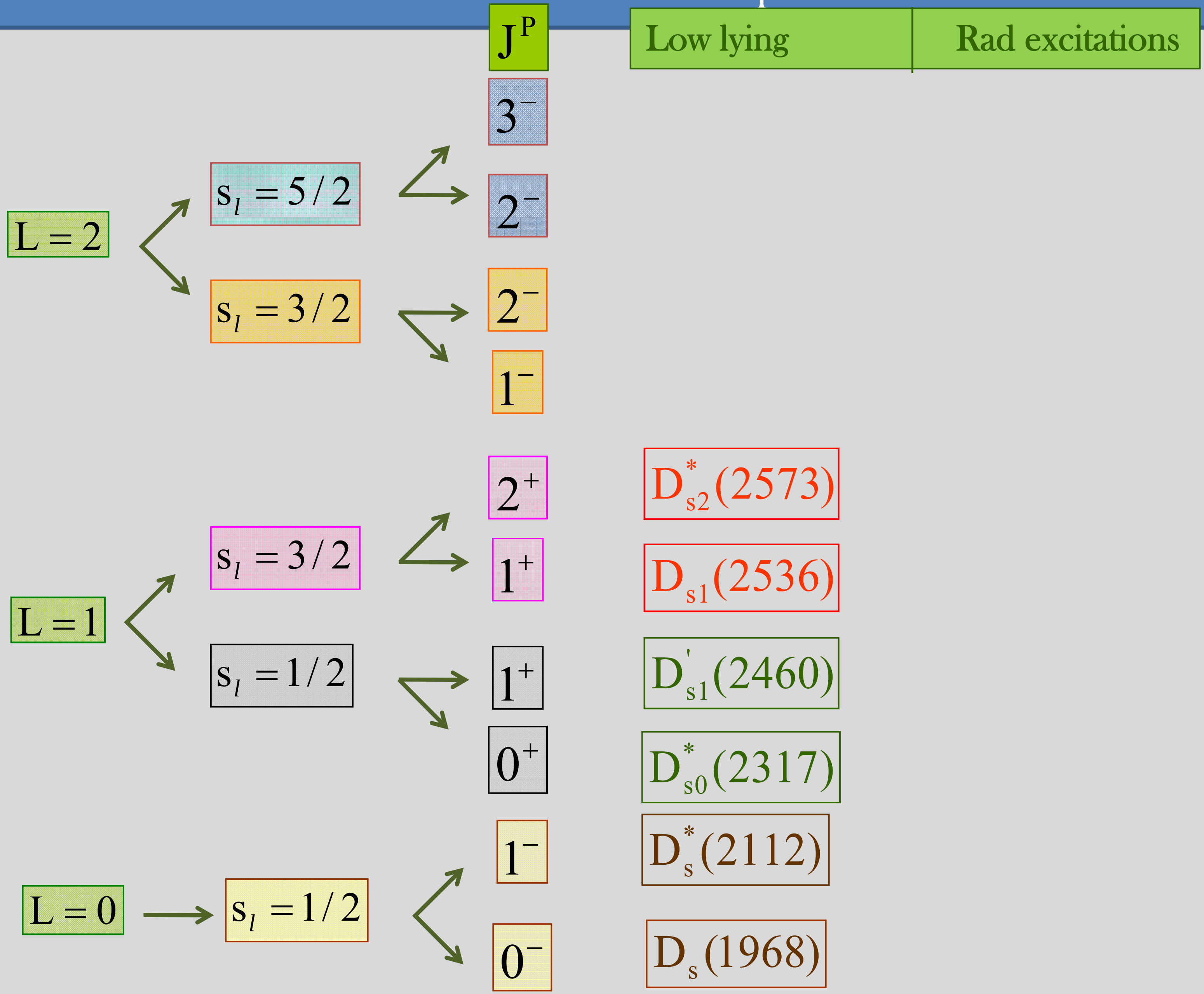
$$\frac{B(D_{s1}(2710)^+ \to D^*K)}{B(D_{s1}(2710)^+ \to DK)} = 0.91 \pm 0.13_{stat} \pm 0.12_{syst}$$

Supports the identification of $D_{s1}(2710)$ with 2^3S_1 (first radial excitation of D_s^*)

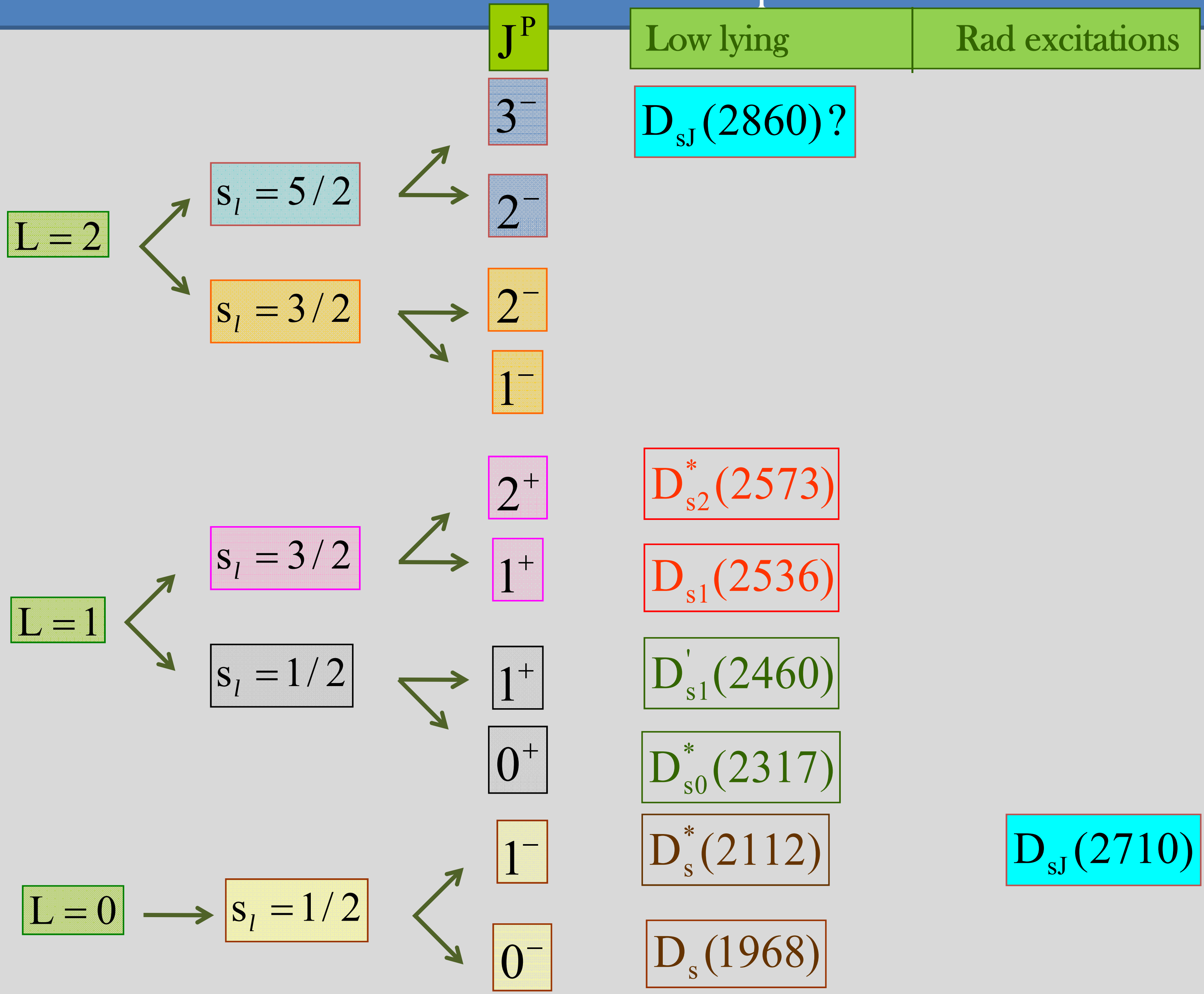
$$\frac{B(D_{sJ}(2860)^+ \to D^*K)}{B(D_{sJ}(2860)^+ \to DK)} = 1.10 \pm 0.15_{stat} \pm 0.19_{syst}$$

Does not support or discard unambiguously any interpretation: still to be understood

$c\bar{s}$ multiplets



$c\bar{s}$ multiplets



$c\bar{q}$ mesons

BaBar observes four new states with charm and without strangeness:

BaBar, PRD 82 (10) 111101

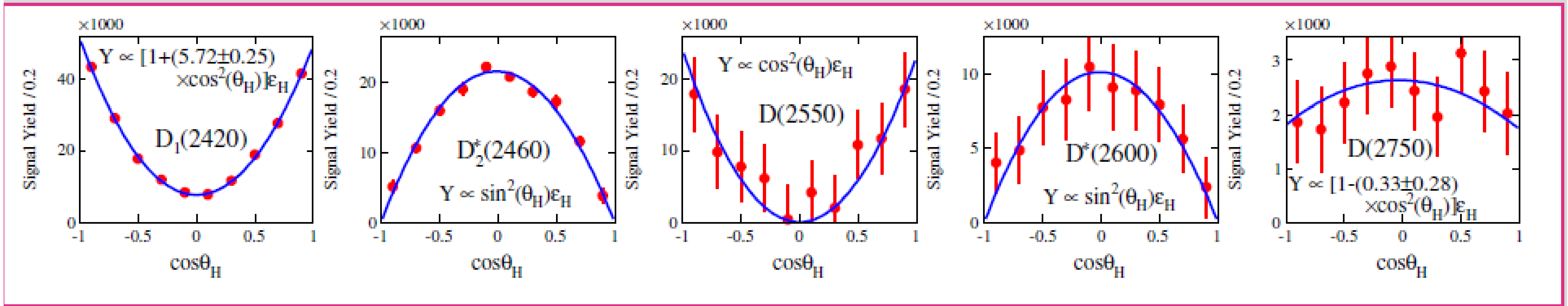
state	Mass (MeV)	Width (MeV)	decays to
$D(2550)^0$	$2539.4 \pm 4.5 \pm 6.8$	$130 \pm 12 \pm 13$	$D^{*+}\pi^-$
$D^*(2600)^0$	$2608.7 \pm 2.4 \pm 2.7$	$93 \pm 6 \pm 13$	$D^+\pi^-$, $D^{*+}\pi^-$
$D^*(2600)^+$	$2608.7 \pm 2.4 \pm 2.7$	$93 \pm 6 \pm 13$	$D^0\pi^+$
$D(2750)^0$	$2752.4 \pm 1.7 \pm 2.7$	$71 \pm 6 \pm 11$	$D^{*+}\pi^-$
$D^*(2760)^0$	$2763.3 \pm 2.3 \pm 2.3$	$60.9 \pm 5.1 \pm 3.6$	$D^+\pi^-$
$D^*(2760)^+$	$2769.7 \pm 3.8 \pm 1.5$	$60.9 \pm 5.1 \pm 3.6$	$D^0\pi^+$

$c\bar{q}$ mesons

Study of the distribution in the helicity angle θ_H for the final state $D^*\pi$

BaBar, PRD 82 (10) 111101

Angle between the primary π and the slow π from D^* decay



Godfrey & Isgur (85)

State	Predicted mass	J^P	$\cos\theta_H$ distribution
$D_0^1(2S)$	2.58 GeV/c^2	0^-	$\propto \cos^2\theta_H$
$D_1^3(2S)$	2.64 GeV/c^2	1^-	$\propto \sin^2\theta_H$
$D_1^1(1P)$	2.44 GeV/c^2	1^+	$\propto 1 + h\cos^2\theta_H$
$D_0^3(1P)$	2.40 GeV/c^2	0^+	Decay not allowed
$D_1^3(1P)$	2.49 GeV/c^2	1^+	$\propto 1 + h\cos^2\theta_H$
$D_2^3(1P)$	2.50 GeV/c^2	2^+	$\propto \sin^2\theta_H$
$D_2^1(1D)$	~2.83 GeV/c^2	2^-	$\propto 1 + h\cos^2\theta_H$
$D_1^3(1D)$	2.82 GeV/c^2	1^-	$\propto \sin^2\theta_H$
$D_2^3(1D)$	~2.83 GeV/c^2	2^-	$\propto 1 + h\cos^2\theta_H$
$D_3^3(1D)$	2.83 GeV/c^2	3^-	$\propto \sin^2\theta_H$

Consistent with assignements of

- Natural parity for $D^*(2600)$
- $J^P=0^+$ for D(2550)

Comparison with potential model
Seems to indicate that
$(D(2750), D^*(2760))$ are L=2 states

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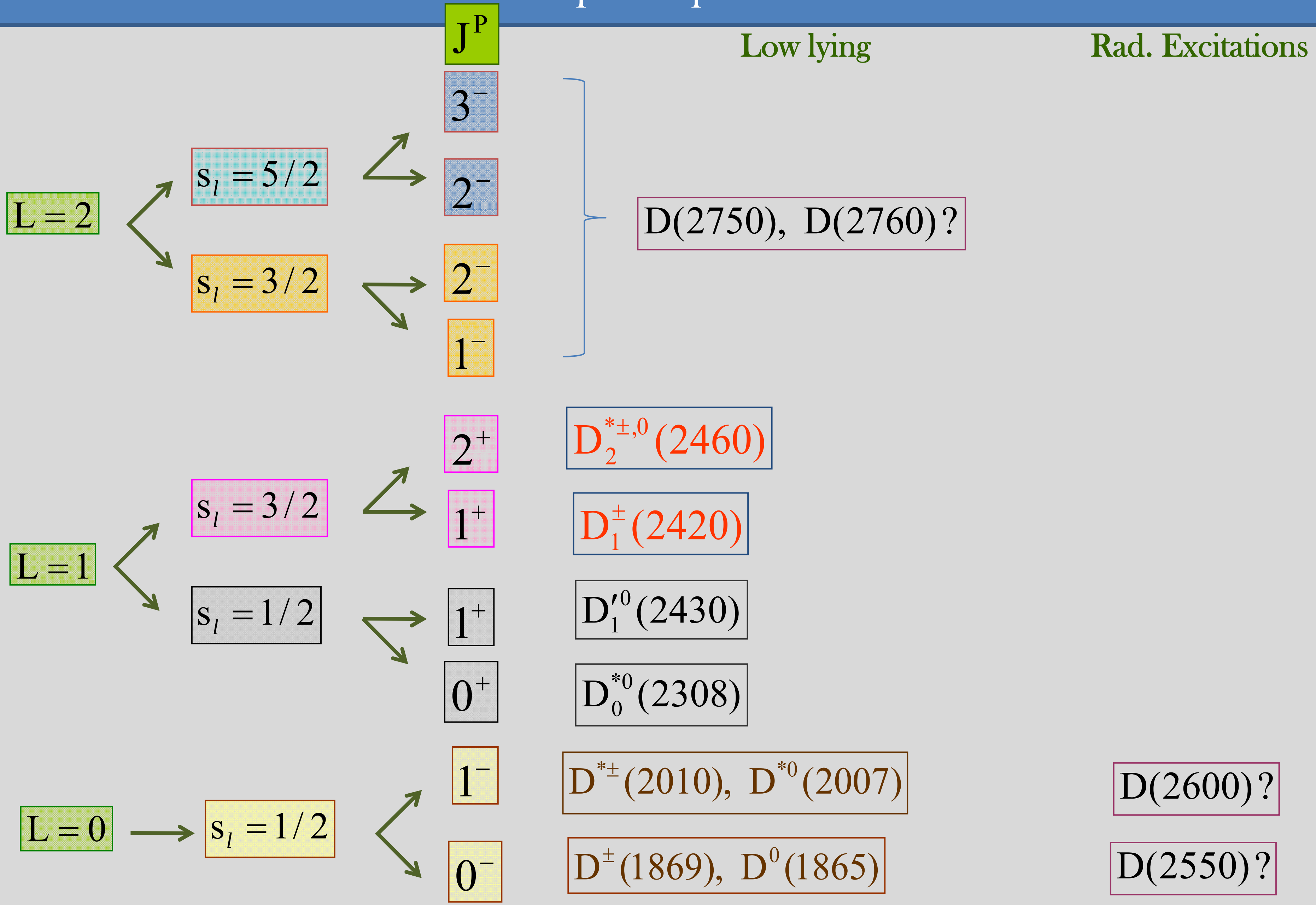
BaBar, PRD 82 (10) 111101

state	Mass (MeV)	Width (MeV)	decays to
$D(2550)^0$	$2539.4 \pm 4.5 \pm 6.8$	$130 \pm 12 \pm 13$	$D^{*+}\pi^-$
$D^*(2600)^0$	$2608.7 \pm 2.4 \pm 2.7$	$93 \pm 6 \pm 13$	$D^+\pi^-$, $D^{*+}\pi^-$
$D^*(2600)^+$	$2608.7 \pm 2.4 \pm 2.7$	$93 \pm 6 \pm 13$	$D^0\pi^+$
$D(2750)^0$	$2752.4 \pm 1.7 \pm 2.7$	$71 \pm 6 \pm 11$	$D^{*+}\pi^-$
$D^*(2760)^0$	$2763.3 \pm 2.3 \pm 2.3$	$60.9 \pm 5.1 \pm 3.6$	$D^+\pi^-$
$D^*(2760)^+$	$2769.7 \pm 3.8 \pm 1.5$	$60.9 \pm 5.1 \pm 3.6$	$D^0\pi^+$

likely to be the radial excitations of (D, D^*)

likely to be L=2 states

$c\bar{q}$ multiplets



$c\bar{q}$ mesons

BaBar, PRD 82 (10) 111101

Experimental ratios:

$$\frac{B(D^*(2600)^0 \to D^+\pi^-)}{B(D^*(2600)^0 \to D^{*+}\pi^-)} = 0.32 \pm 0.02 \pm 0.09,$$

$$\frac{B(D^*(2760)^0 \to D^+\pi^-)}{B(D(2750)^0 \to D^{*+}\pi^-)} = 0.42 \pm 0.05 \pm 0.11.$$

These ratios together with masses and widths can be used to check the BaBar assignments

$c\bar{q}$ mesons

Branching fraction Ratio

P. Colangelo & FDF, in preparation

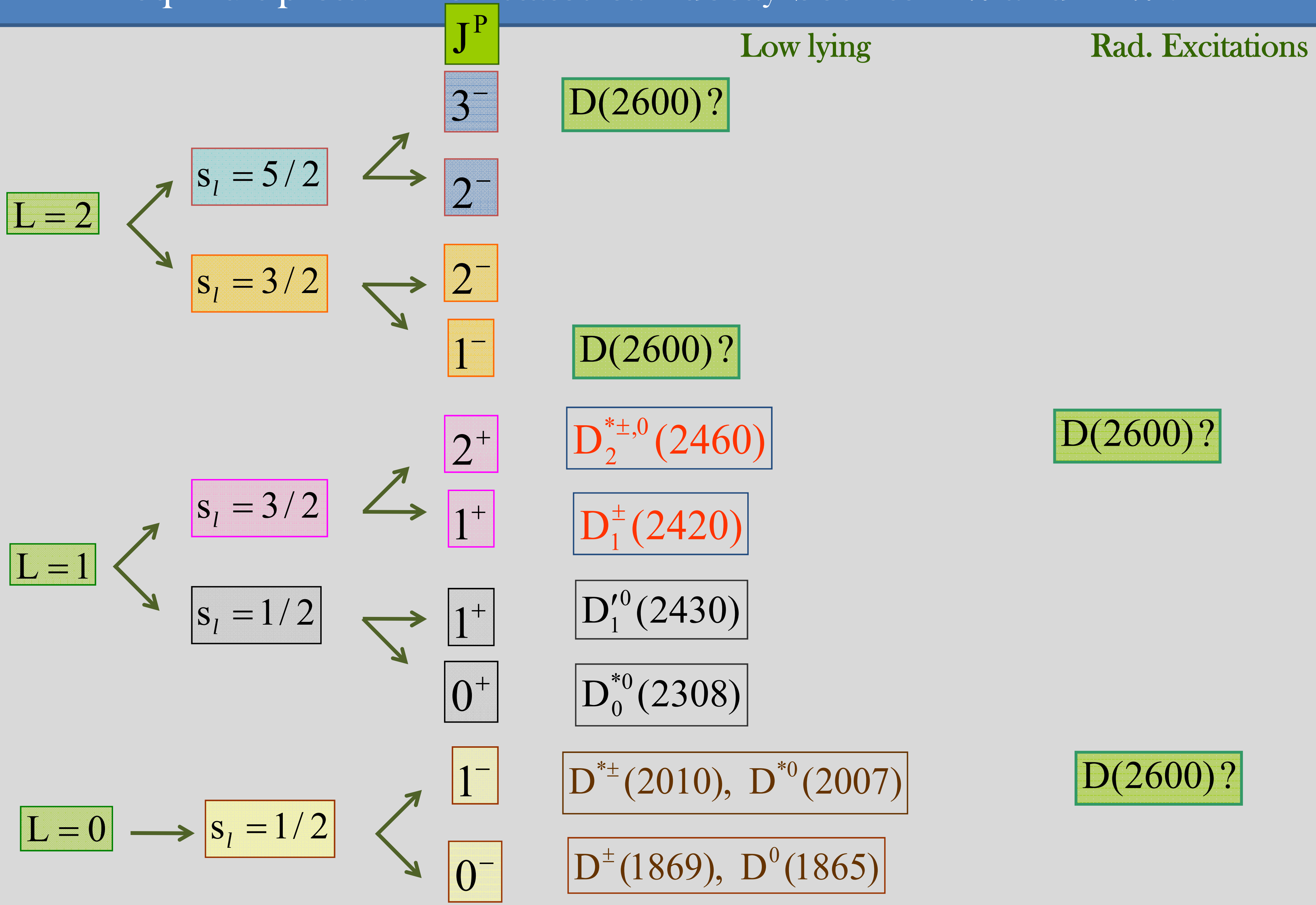
Identifying $D^*(2600)$ with the first radial excitation of D^{*0} we obtain:

$$\frac{\mathcal{B}(D^{*0}(2600) \to D^+\pi^-)}{\mathcal{B}(D^{*0}(2600) \to D^{*+}\pi^-)} = 0.822 \pm 0.003$$

while BaBar finds:

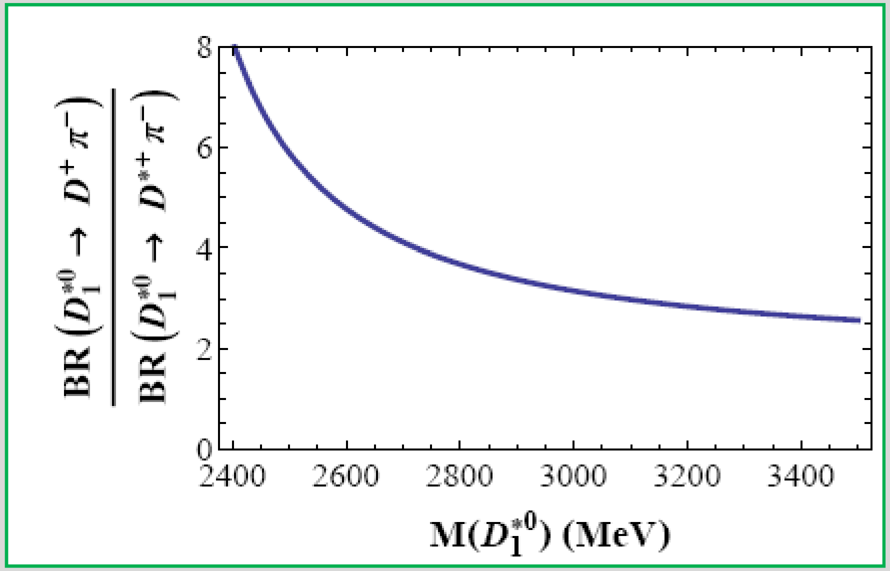
$$\frac{\mathcal{B}(D^{*0}(2600) \to D^+\pi^-)}{\mathcal{B}(D^{*0}(2600) \to D^{*+}\pi^-)} = 0.32 \pm 0.02 \pm 0.09$$

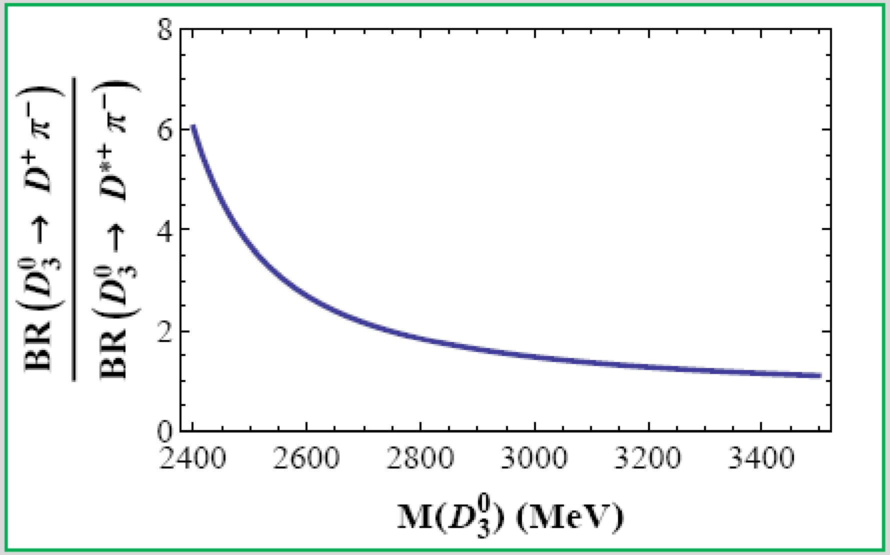
$c\bar{q}$ multiplets: which states can decay both to $D\pi$ and $D^*\pi$?

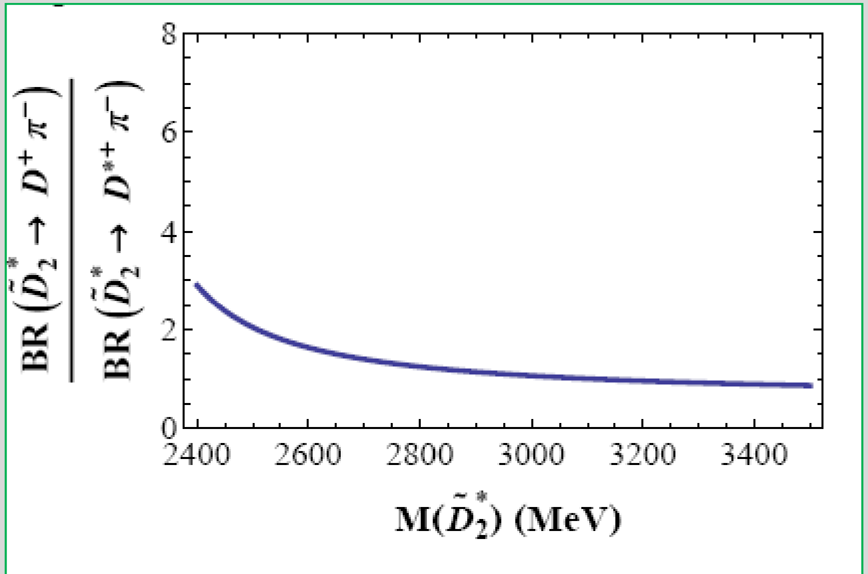


$c\bar{q}$ multiplets: which states can decay both to $D\pi$ and $D^*\pi$?

Branching fraction ratios for the other three possibilities:vs the mass of the decaying meson



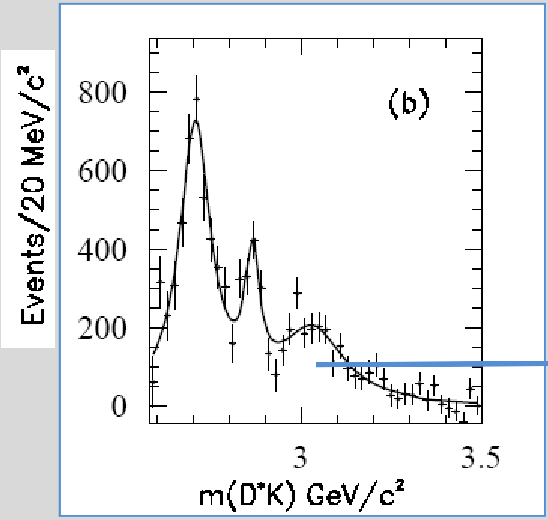




No assignment to a meson of mass 2600 MeV would reproduce the exp result:

Either HQ symmetry is strongly violated or a revision of the experimental analysis is required

$D_{sJ}(3040)$



$$M(D_{sJ}(3040)) = 3044 \pm 8_{\rm stat}(^{+30}_{-5})_{\rm syst}\ \text{MeV}$$
$$\Gamma(D_{sJ}(3040)) = 239 \pm 35_{\rm stat}(^{+46}_{-42})_{\rm syst}\ \text{MeV}$$

The only additional information is that it decays $\rightarrow D^* K$ YES
$\rightarrow DK$ NO

$J^P = 1^+, 2^-, 3^+, \ldots$

$c\bar{s}$ multiplets

L	s_l	J^P	Low lying	Rad excitations
$L=2$	$s_l = 5/2$	3^-	$D_{sJ}(2860)$?	
		2^-		
	$s_l = 3/2$	2^-		
		1^-		
$L=1$	$s_l = 3/2$	2^+	$D^*_{s2}(2573)$	
		1^+	$D_{s1}(2536)$	
	$s_l = 1/2$	1^+	$D'_{s1}(2460)$	
		0^+	$D^*_{s0}(2317)$	
$L=0$	$s_l = 1/2$	1^-	$D^*_s(2112)$	$D_{sJ}(2710)$
		0^-	$D_s(1968)$	

$c\bar{s}$ multiplets

L	s_l	J^P	Low lying	Rad excitations
$L=2$	$s_l = 5/2$	3^-	$D_{sJ}(2860)$?	
		2^-	$D_{sJ}(3040)$	
	$s_l = 3/2$	2^-	$D_{sJ}(3040)$	
		1^-		
$L=1$	$s_l = 3/2$	2^+	$D^*_{s2}(2573)$	
		1^+	$D_{s1}(2536)$	$D_{sJ}(3040)$
	$s_l = 1/2$	1^+	$D'_{s1}(2460)$	$D_{sJ}(3040)$
		0^+	$D^*_{s0}(2317)$	
$L=0$	$s_l = 1/2$	1^-	$D^*_s(2112)$	$D_{sJ}(2710)$
		0^-	$D_s(1968)$	

$c\bar{s}$ multiplets

L	s_l	J^P	Low lying	Rad excitations
$L=2$	$s_l = 5/2$	3^-	$D_{sJ}(2860)$?	
		2^-	$D_{sJ}(3040)$	
	$s_l = 3/2$	2^-	$D_{sJ}(3040)$	
		1^-		
$L=1$	$s_l = 3/2$	2^+	$D^*_{s2}(2573)$	
		1^+	$D_{s1}(2536)$	$D_{sJ}(3040)$
	$s_l = 1/2$	1^+	$D'_{s1}(2460)$	$D_{sJ}(3040)$
		0^+	$D^*_{s0}(2317)$	
$L=0$	$s_l = 1/2$	1^-	$D^*_s(2112)$	$D_{sJ}(2710)$
		0^-	$D_s(1968)$	

$D_{sJ}(3040)$, $D_{sJ}(3040)$ → would imply an (unlikely) mass inversion if $D_{sJ}(2860)$ has been properly placed

$D_{sJ}(3040)$: how to discriminate among the four possibilities?

- info from Relativistic Quark Model (RQM)

$$M(\tilde{D}_{s1})^{(\mathrm{RQM})} = 3114 \text{ MeV},$$
$$M(\tilde{D}'_{s1})^{(\mathrm{RQM})} = 3165 \text{ MeV},$$
$$M(D_{s2})^{(\mathrm{RQM})} = 2953 \text{ MeV},$$
$$M(D^{*\prime}_{s2})^{(\mathrm{RQM})} = 2900 \text{ MeV}.$$

- Allowed strong decays:

- to $D^*_{(s)}$ + light pseudoscalar meson

D^*K, $D^*_s\eta$ →

$$R_1 = \frac{\Gamma(D_{sJ}(3040) \to D^*_s\eta)}{\Gamma(D_{sJ}(3040) \to D^*K)}$$

- to members of higher doublets + a light pseudoscalar meson

D^*_0K, D^*_{s0} , D'_1K
D_1K, D^*_2K

- to $D_{(s)}$ + a light vector meson

DK^*, $D_s\,\phi$

D_{sJ}(3040): how to discriminate among the four possibilities?

Decay modes	$\tilde{D}'_{s1}$ $(n=2, J^P_{s_\ell}=1^+_{1/2})$	$\tilde{D}_{s1}$ $(n=2, J^P_{s_\ell}=1^+_{3/2})$	D_{s2} $(n=1, J^P_{s_\ell}=2^-_{3/2})$	$D^{*\prime}_{s2}$ $(n=1, J^P_{s_\ell}=2^-_{5/2})$
D^*K, $D^*_s\eta$	s wave	d wave	p wave	f wave
R_1	0.34	0.20	0.245	0.143
D^*_0K, $D^*_{s0}\eta$, D'_1K	p wave	p wave	d wave	d wave
D_1K	p wave	p wave	$\cdots$	d wave
D^*_2K	p wave	p wave	s wave	d wave
DK^*, $D_s\phi$	s wave, $\Gamma\simeq 140$ MeV	s wave, $\Gamma\simeq 20$ MeV	p wave, Negligible	p wave, Negligible
	Spin partner			
	$\tilde{D}^*_{s0}$ $(n=2, J^P_{s_\ell}=0^+_{1/2})$	$\tilde{D}^*_{s2}$ $(n=2, J^P_{s_\ell}=2^+_{3/2})$	D^*_{s1} $(n=1, J^P_{s_\ell}=1^-_{3/2})$	D_{s3} $(n=1, J^P_{s_\ell}=3^-_{5/2})$
DK, $D_s\eta$	s wave	d wave	p wave	f wave
D^*K, $D^*_s\eta$	$\cdots$	d wave	p wave	f wave
D^*_0K, $D^*_{s0}\eta$	$\cdots$	$\cdots$	d wave	$\cdots$
D'_1K	p wave	p wave	d wave	d wave
D_1K	p wave	p wave	s wave	d wave
D^*_2K	$\cdots$	p wave	$\cdots$	d wave

- $\tilde{D}'_{s1}$ decays in s-wave to D^*K, $D_s^*\,\eta$ (broader), has the largest R_1, the largest width to light vector mesons

P. Colangelo , FDF
PRD81, 094001

$D_{sJ}(3040)$: how to discriminate among the four possibilities?

Decay modes	$\tilde{D}'_{s1}$ $(n=2, J^P_{s_\ell}=1^+_{1/2})$	$\tilde{D}_{s1}$ $(n=2, J^P_{s_\ell}=1^+_{3/2})$	D_{s2} $(n=1, J^P_{s_\ell}=2^-_{3/2})$	$D^{*\prime}_{s2}$ $(n=1, J^P_{s_\ell}=2^-_{5/2})$
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D^*_0K, $D^*_{s0}\eta$, D'_1K	p wave	p wave	d wave	d wave
D_1K	p wave	p wave	...	d wave
D^*_2K	p wave	p wave	s wave	d wave
DK^*, $D_s\phi$	s wave; $\Gamma \simeq 140$ MeV	s wave; $\Gamma \simeq 20$ MeV	p wave; Negligible	p wave; Negligible
	Spin partner			
	$\tilde{D}^*_{s0}$ $(n=2, J^P_{s_\ell}=0^+_{1/2})$	$\tilde{D}^*_{s2}$ $(n=2, J^P_{s_\ell}=2^+_{3/2})$	D^*_{s1} $(n=1, J^P_{s_\ell}=1^-_{3/2})$	D_{s3} $(n=1, J^P_{s_\ell}=3^-_{5/2})$
DK, $D_s\eta$	s wave	d wave	p wave	f wave
D^*K, $D^*_s\eta$	...	d wave	p wave	f wave
D^*_0K, $D^*_{s0}\eta$	...	...	d wave	...
D'_1K	p wave	p wave	d wave	d wave
D_1K	p wave	p wave	s wave	d wave
D^*_2K	...	p wave	...	d wave

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- the two 2^- states should not be observed in the decay to light vector mesons

$D_{sJ}(3040)$: how to discriminate among the four possibilities?

Decay modes	$\tilde{D}'_{s1}$ $(n=2, J^P_{s_\ell}=1^+_{1/2})$	$\tilde{D}_{s1}$ $(n=2, J^P_{s_\ell}=1^+_{3/2})$	D_{s2} $(n=1, J^P_{s_\ell}=2^-_{3/2})$	$D^{*\prime}_{s2}$ $(n=1, J^P_{s_\ell}=2^-_{5/2})$
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D_1K	p wave	p wave	$\cdots$	d wave
D^*_2K	p wave	p wave	s wave	d wave
DK^*, $D_s\phi$	s wave; $\Gamma \simeq 140$ MeV	s wave; $\Gamma \simeq 20$ MeV	p wave; Negligible	p wave; Negligible
	Spin partner			
	$\tilde{D}^*_{s0}$ $(n=2, J^P_{s_\ell}=0^+_{1/2})$	$\tilde{D}^*_{s2}$ $(n=2, J^P_{s_\ell}=2^+_{3/2})$	D^*_{s1} $(n=1, J^P_{s_\ell}=1^-_{3/2})$	D_{s3} $(n=1, J^P_{s_\ell}=3^-_{5/2})$
DK, $D_s\eta$	s wave	d wave	p wave	f wave
D^*K, $D^*_s\eta$	$\cdots$	d wave	p wave	f wave
D^*_0K, $D^*_{s0}\eta$	$\cdots$	$\cdots$	d wave	$\cdots$
D'_1K	p wave	p wave	d wave	d wave
D_1K	p wave	p wave	s wave	d wave
D^*_2K	$\cdots$	p wave	$\cdots$	d wave

- $\tilde{D}'_{s1}$ decays in s-wave to D^*K, $D_s^*\,\eta$ (broader), has the largest R_1, the largest width to light vector mesons

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- the two 2^- states should not be observed in the decay to light vector mesons

- D_{s2} cannot decay to D_1K but should have the largest width to D_2^*K

$D_{sJ}(3040)$: how to discriminate among the four possibilities?

Decay modes	$\tilde{D}'_{s1}$ $(n=2,\ J^P_{s_\ell}=1^+_{1/2})$	$\tilde{D}_{s1}$ $(n=2,\ J^P_{s_\ell}=1^+_{3/2})$	D_{s2} $(n=1,\ J^P_{s_\ell}=2^-_{3/2})$	$D^{*\prime}_{s2}$ $(n=1,\ J^P_{s_\ell}=2^-_{5/2})$
D^*K, $D^*_s\eta$	s wave	d wave	p wave	f wave
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D_1K	p wave	p wave	$\cdots$	d wave
D^*_2K	p wave	p wave	s wave	d wave
DK^*, $D_s\phi$	s wave $\Gamma \simeq 140$ MeV	s wave $\Gamma \simeq 20$ MeV	p wave Negligible	p wave Negligible
	$\tilde{D}^*_{s0}$ $(n=2,\ J^P_{s_\ell}=0^+_{1/2})$	$\tilde{D}^*_{s2}$ $(n=2,\ J^P_{s_\ell}=2^+_{3/2})$	D^*_{s1} $(n=1,\ J^P_{s_\ell}=1^-_{3/2})$	D_{s3} $(n=1,\ J^P_{s_\ell}=3^-_{5/2})$
DK, $D_s\eta$	s wave	d wave	p wave	f wave
D^*K, $D^*_s\eta$	$\cdots$	d wave	p wave	f wave
D^*_0K, $D^*_{s0}\eta$	$\cdots$	$\cdots$	d wave	$\cdots$
D'_1K	p wave	p wave	d wave	d wave
D_1K	p wave	p wave	s wave	d wave
D^*_2K	$\cdots$	p wave	$\cdots$	d wave

Spin partner

- $\tilde{D}'_{s1}$ decays in s-wave to D^*K, $D_s^*\,\eta$ (broader), has the largest R_1, the largest width to light vector mesons

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- the two 2^- states should not be observed in the decay to light vector mesons
- D_{s2} cannot decay to D_1K but should have the largest width to D_2^*K
- look at the features of the spin partner

$D_{sJ}(3040)$: how to discriminate among the four possibilities?

Decay modes	$\tilde{D}'_{s1}$ $(n=2,\ J^P_{s_\ell}=1^+_{1/2})$	$\tilde{D}_{s1}$ $(n=2,\ J^P_{s_\ell}=1^+_{3/2})$	D_{s2} $(n=1,\ J^P_{s_\ell}=2^-_{3/2})$	$D^{*\prime}_{s2}$ $(n=1,\ J^P_{s_\ell}=2^-_{5/2})$
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D_1K	p wave	p wave	$\cdots$	d wave
D^*_2K	p wave	p wave	s wave	d wave
$DK^*,\ D_s\phi$	s wave, $\Gamma\simeq 140$ MeV	s wave, $\Gamma\simeq 20$ MeV	p wave, Negligible	p wave, Negligible
	$\tilde{D}^*_{s0}$ $(n=2,\ J^P_{s_\ell}=0^+_{1/2})$	$\tilde{D}^*_{s2}$ $(n=2,\ J^P_{s_\ell}=2^+_{3/2})$	Spin partner: D^*_{s1} $(n=1,\ J^P_{s_\ell}=1^-_{3/2})$	D_{s3} $(n=1,\ J^P_{s_\ell}=3^-_{5/2})$
$DK,\ D_s\eta$	s wave	d wave	p wave	f wave
$D^*K,\ D^*_s\eta$	$\cdots$	d wave	p wave	f wave
$D^*_0K,\ D^*_{s0}\eta$	$\cdots$	$\cdots$	d wave	$\cdots$
D'_1K	p wave	p wave	d wave	d wave
D_1K	p wave	p wave	s wave	d wave
D^*_2K	$\cdots$	p wave	$\cdots$	d wave

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- $\tilde{D}'_{s1}$ decays in s-wave to D^*K, $D_s^*\ \eta$ (broader), has the largest R_1 , the largest width to light vector mesons
- the two 2^- states should not be observed in the decay to light vector mesons
- D_{s2} cannot decay to D_1K but should have the largest width to D_2^*K
- look at the features of the spin partner

Concluding remarks

- all the observed $c\bar{s}$ states classified as ordinary mesons

- $D_{sJ}(2700)$ identified with $D^{*'}_s$

- $D_J(2600)$ most likely its non strange partner: BR ratio to be reconsidered

- Still to be understood: $D_{sJ}(2860)$ ($J^P = 3^-$?)
  $D_{sJ}(3040)$ $\rightarrow$ various allowed decay modes may help in the classification

  D(2750) and D(2760) : probably L=2 states