Recent developments in the spectroscopy of open charm mesons

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INFN - Bari

Colour meets Flavour:
Quantum Chromodynamics and Quark Flavour Physics
Khodjamirian Fest

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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- ~~$D_{sJ}(2632)$~~ → Seen only by SELEX, never confirmed
- $D_{sJ}(2860)$, $D_{sJ}(2710)$, $D_{sJ}(3040)$

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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

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

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

Mesons classified as doublets

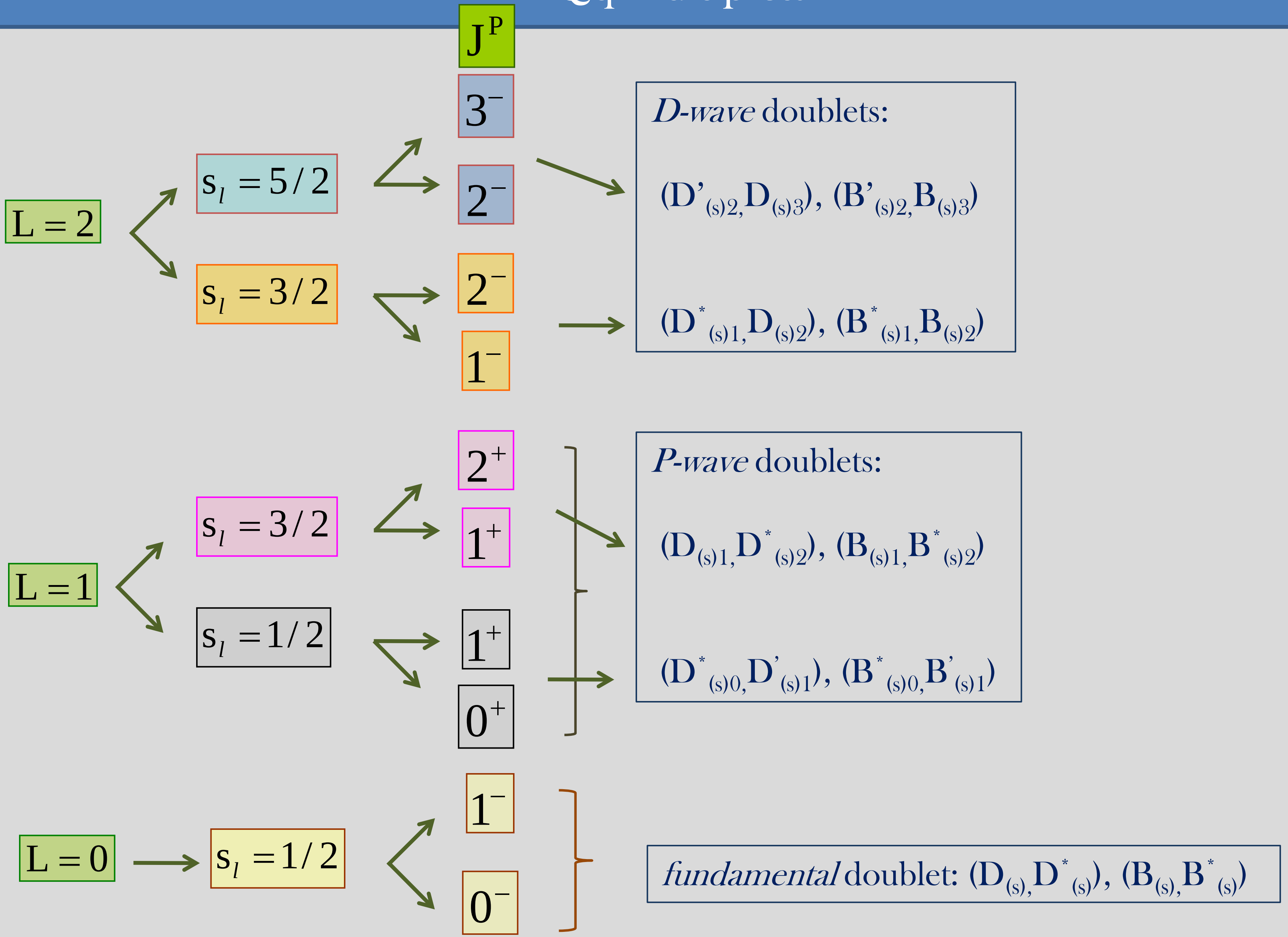
- In the HQ limit:

- states with the same s_l^P degenerate

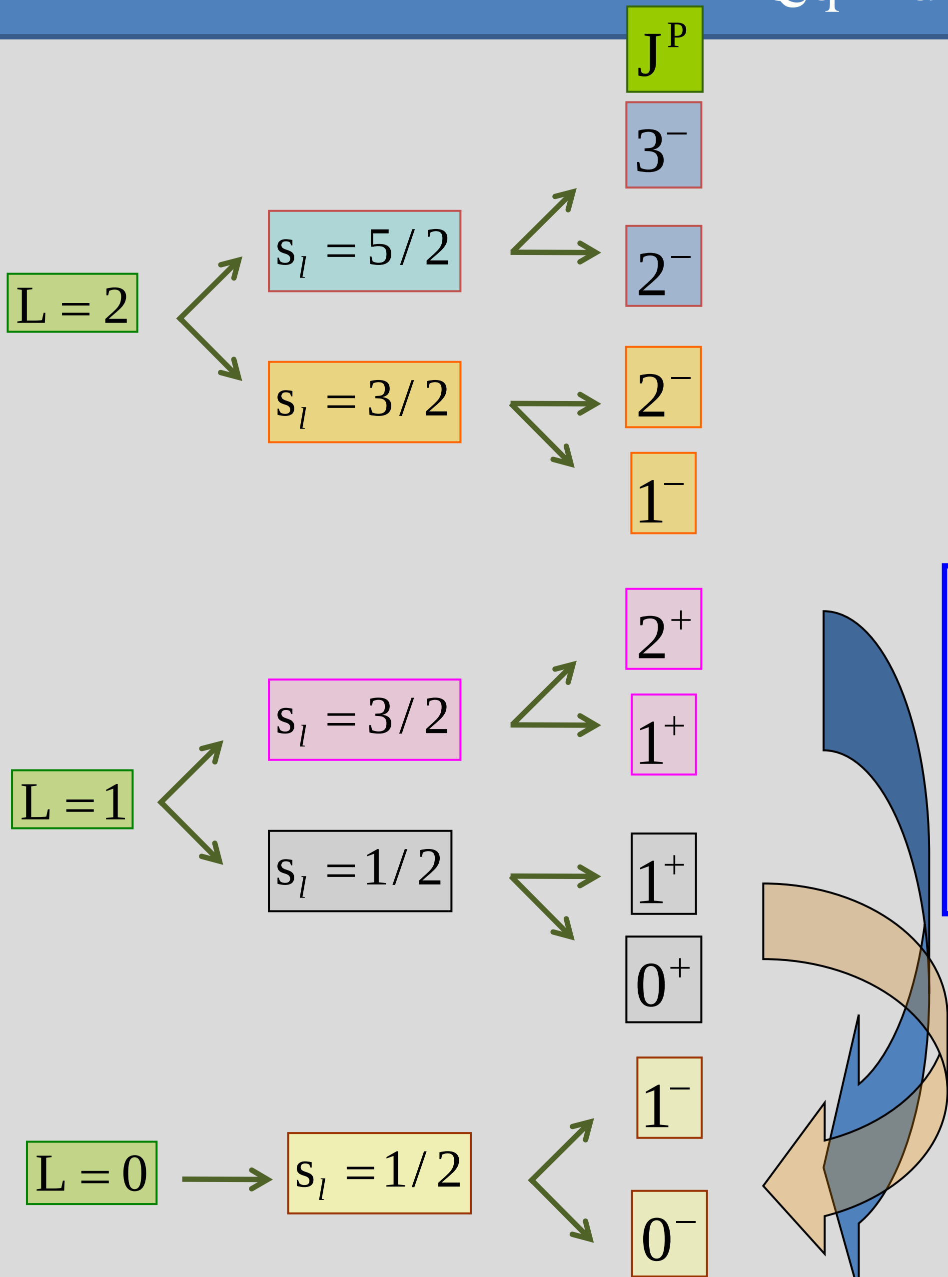
- finite m_Q corrections

- remove degeneracy between the states of the same doublet
- induce mixing between states with the same J^P

$Q\bar{q}$ multiplets



$Q\bar{q}$ multiplets



Strong transitions between multiplets

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

d-wave transition

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

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

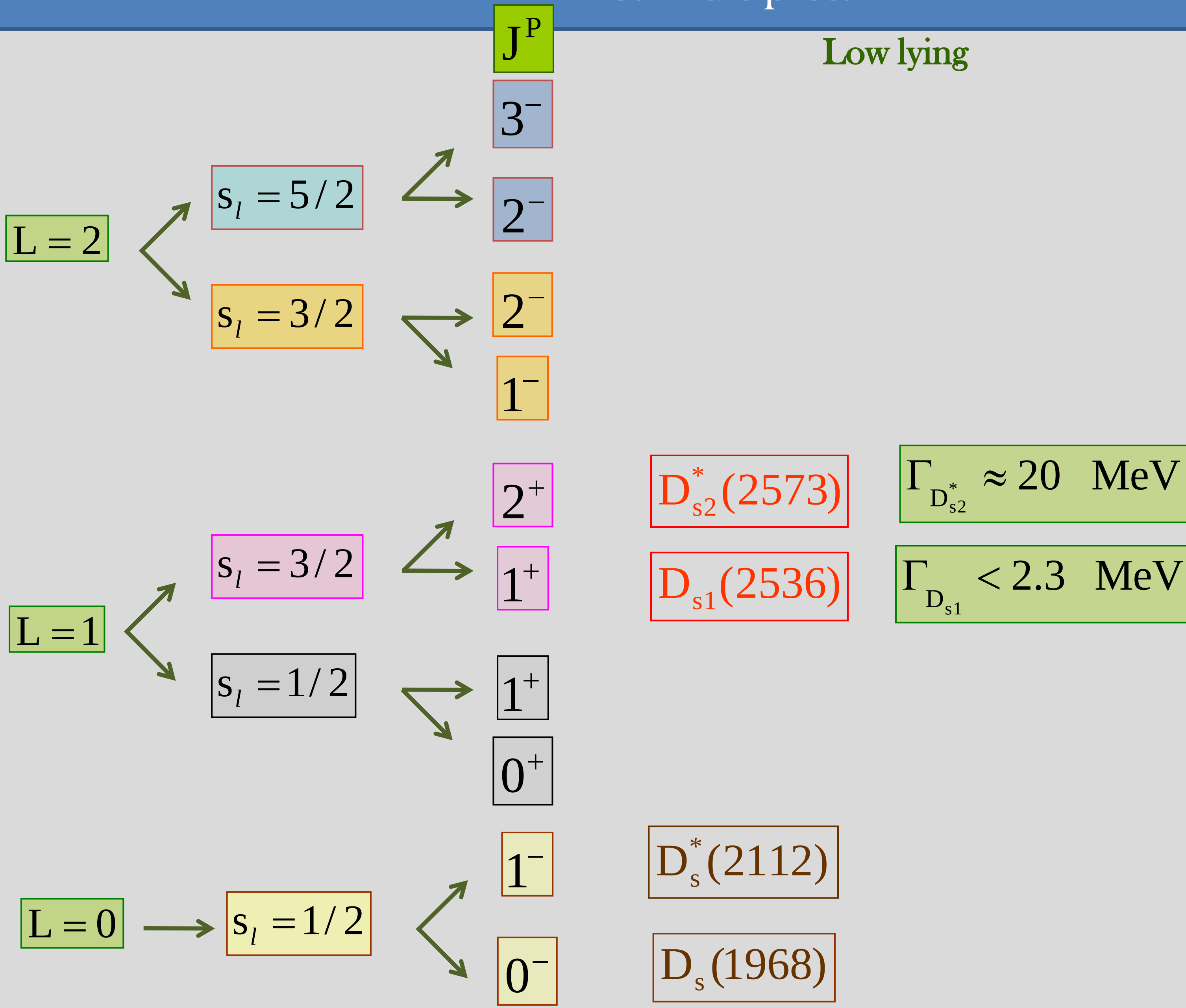
s-wave transition

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

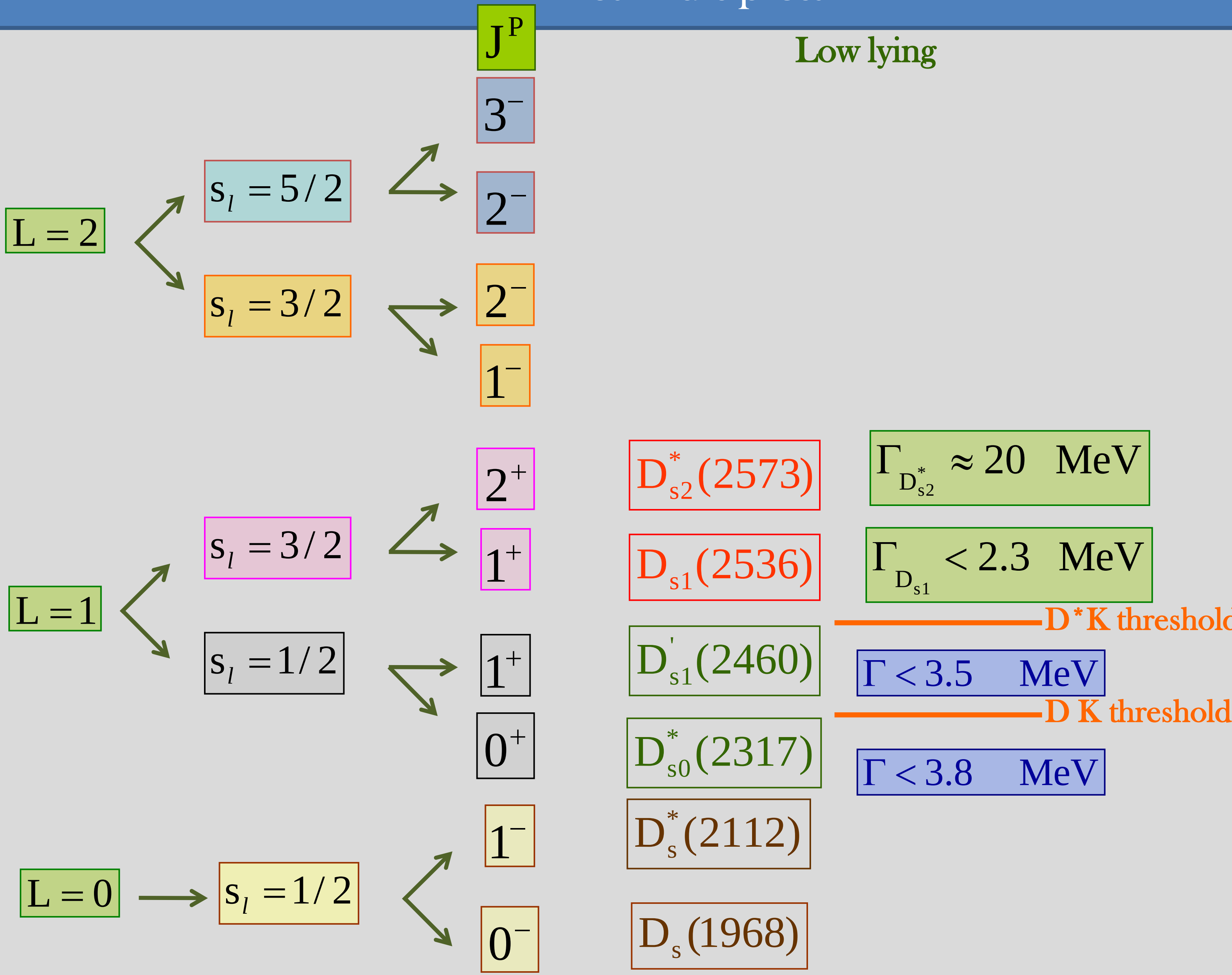
$c\bar{q}$ multiplets

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

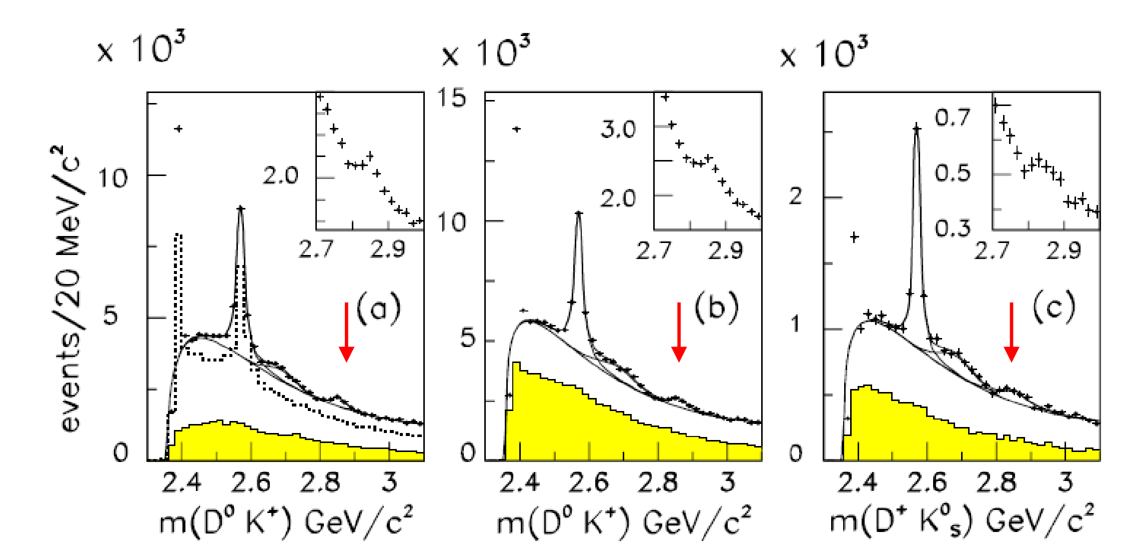


$D_{sJ}(2860)$

- Discovered by BaBar Collab.
- Reconstructed in

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

and in $D^+K^0_S$



$M = 2856.6 \pm 1.5 \pm 5.0$ MeV

$\Gamma = 48 \pm 7 \pm 10$ MeV

BaBar Collab., PRL 97 (06) 222001

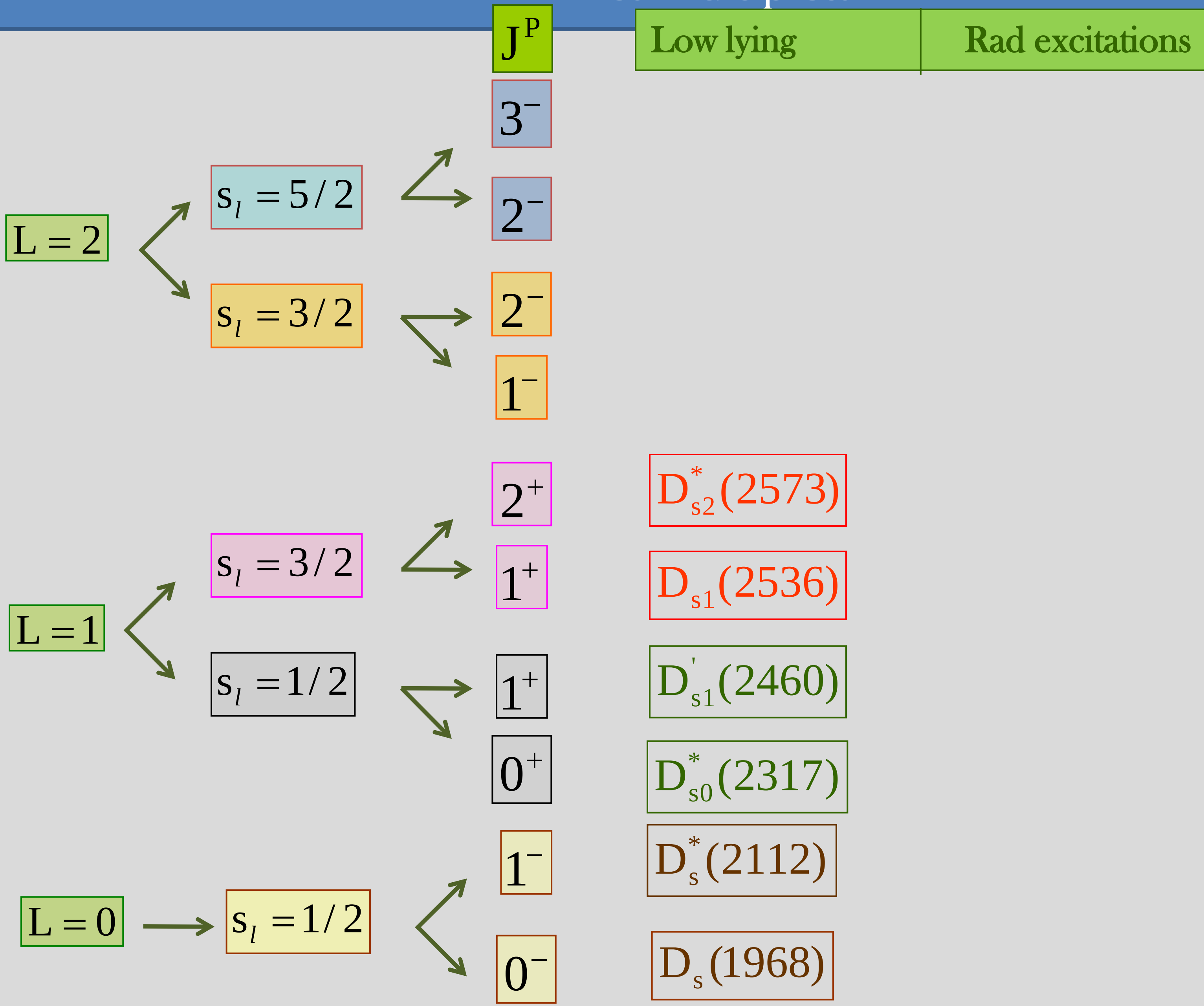
Quantum number assignment required in order to identify it

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

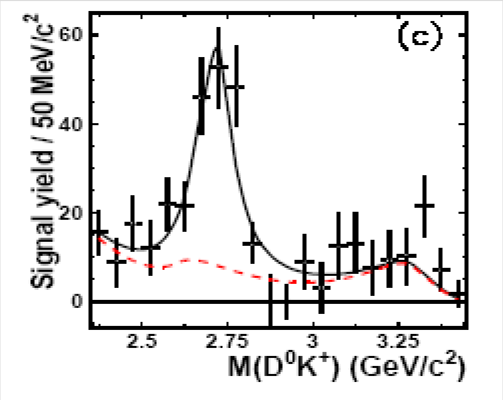
L	s_l	J^P	Low lying	Rad excitations
$L=2$	$s_l = 5/2$	3^-		
		2^-	forbidden	
	$s_l = 3/2$	2^-	forbidden	
		1^-		
$L=1$	$s_l = 3/2$	2^+	$D^*_{s2}(2573)$	
		1^+	$D_{s1}(2536)$	forbidden
	$s_l = 1/2$	1^+	$D'_{s1}(2460)$	forbidden
		0^+	$D^*_{s0}(2317)$	
$L=0$	$s_l = 1/2$	1^-	$D^*_s(2112)$	
		0^-	$D_s(1968)$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

$D_{sJ}(2710)$

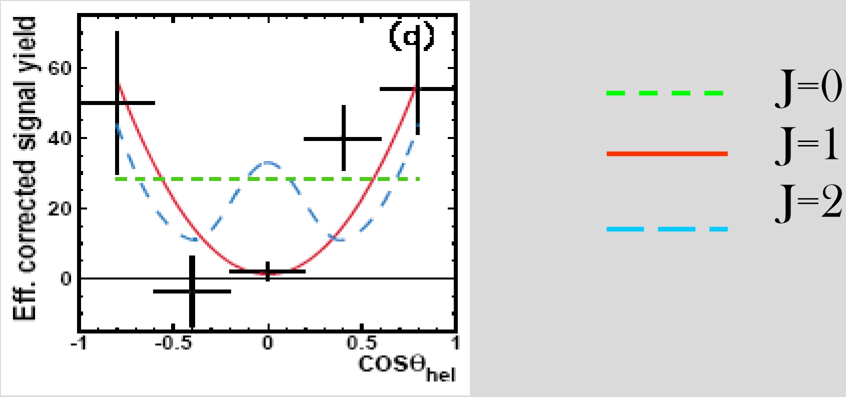
Belle Collab.: analysis of the mode $B^+ \to \overline{D}^0 D^0 K^+$



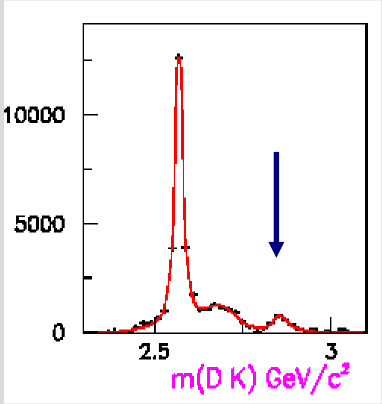
New resonance decaying to D^0K^+ with:

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

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

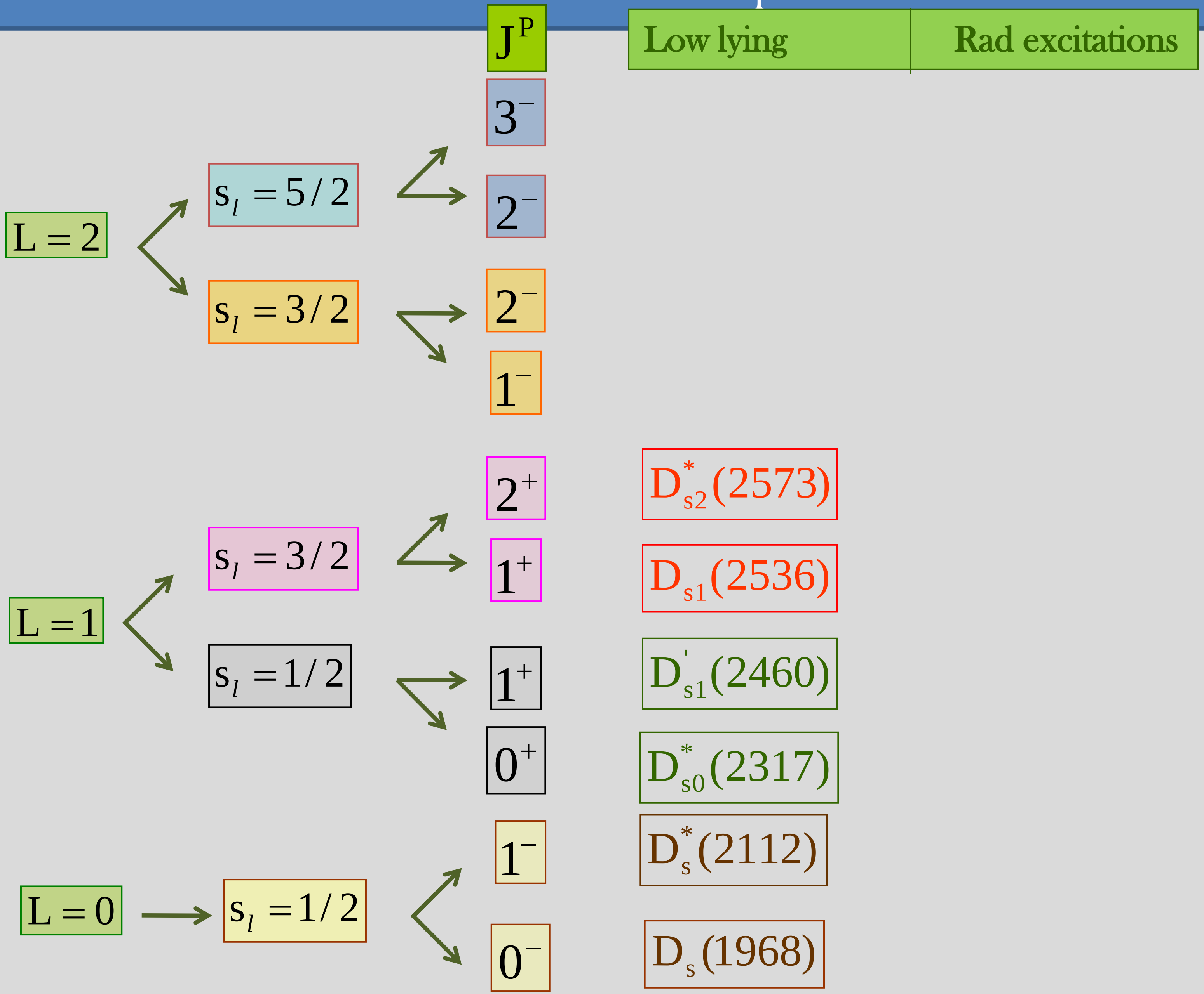


$J^P=1^-$ favoured

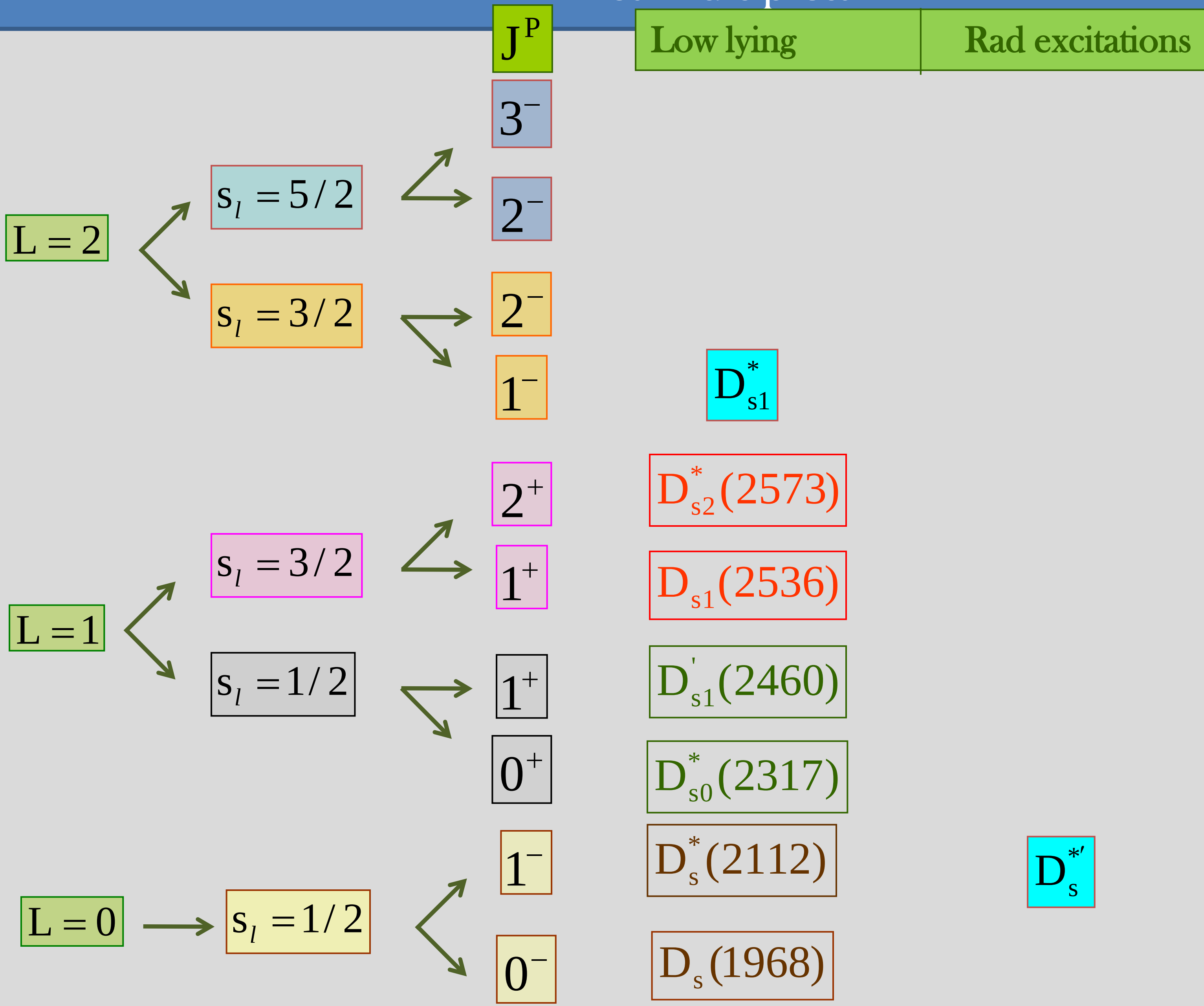


A broad structure at M=2688 MeV with Γ=112 MeV was found by BaBar in the DK mass distribution

$c\bar{s}$ 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

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

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

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

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

L=2

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

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

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

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

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

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

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

H → H π

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

S → H π

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

T → H π

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

X → H π

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

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: $g \to \tilde{g}, \quad h \to \tilde{h}, \ldots$

$D_{sJ}(2860)$: 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

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

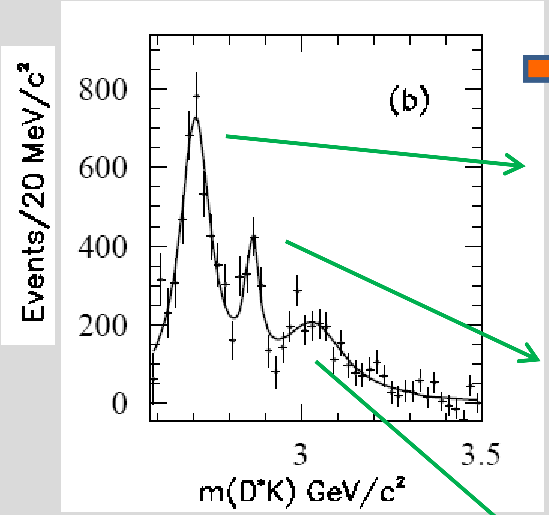
the dependence on the (unknown) couplings drops out

	$R_1 \times 10^2$	$R_2 \times 10^2$	$R_3 \times 10^2$
$D_s^{*\prime}$	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:

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

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

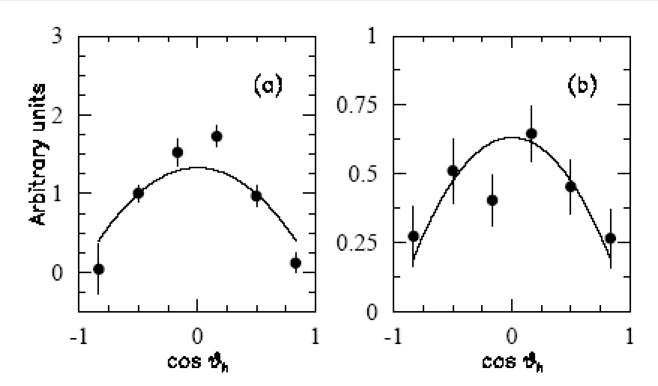
$$m(D_{sJ}(2860)^+) = 2862 \pm 2_{stat} \pm^{5}_{2\ syst} \quad \text{MeV}$$

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

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

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

- angular analysis



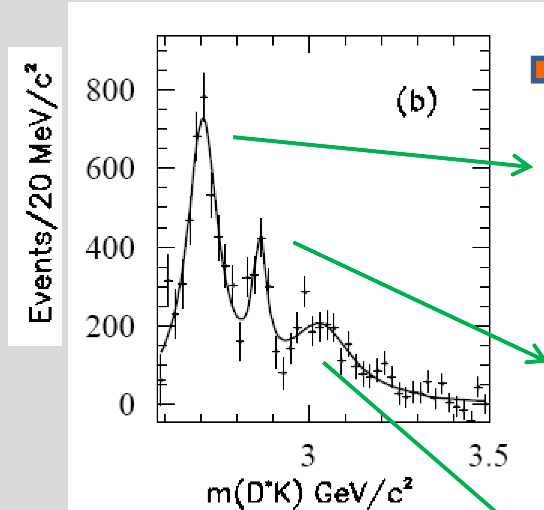
The angular distribution is consistent with the expectations for states with natural parity ($0^+, 1^-, 2^+, 3^-, \ldots$) for $D_{s1}(2710)$ and $D_{sJ}(2860)$

excluded by the observation of the D^*K mode

BaBar, PRD80 (09)092003

BaBar Analysis of D^*K final states

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



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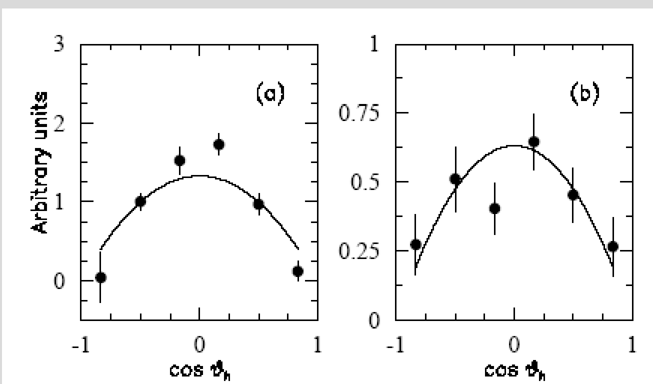

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excluded by the observation of the D^*K mode

BaBar, PRD80 (09)092003

to be discussed later...

BaBar Analysis of D^*K final states

Branching fractions

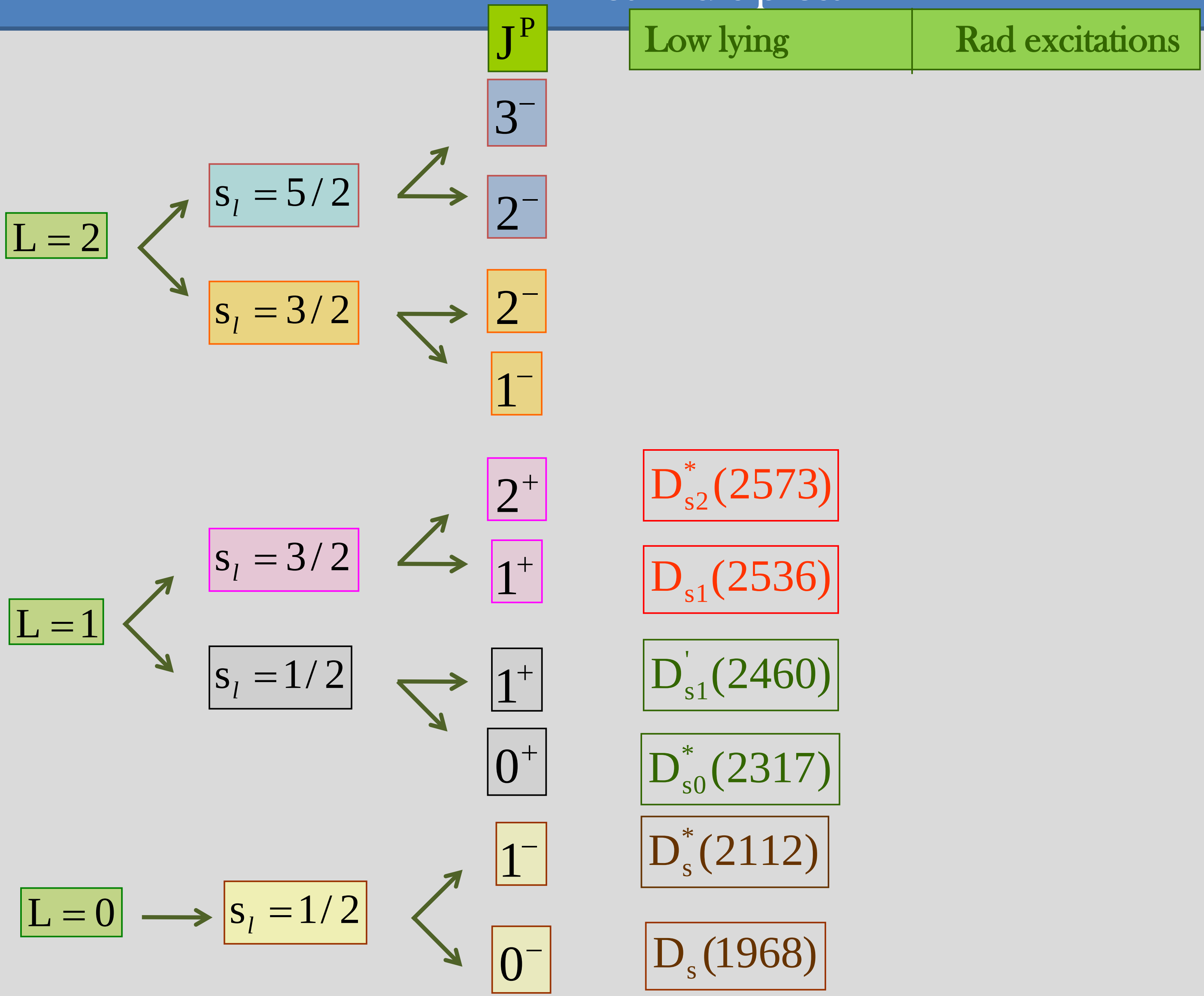
$$\frac{B(D_{s1}(2710)^+ \to D^* K)}{B(D_{s1}(2710)^+ \to DK)} = 0.91 \pm 0.13_{stat} \pm 0.12_{syst}$$

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

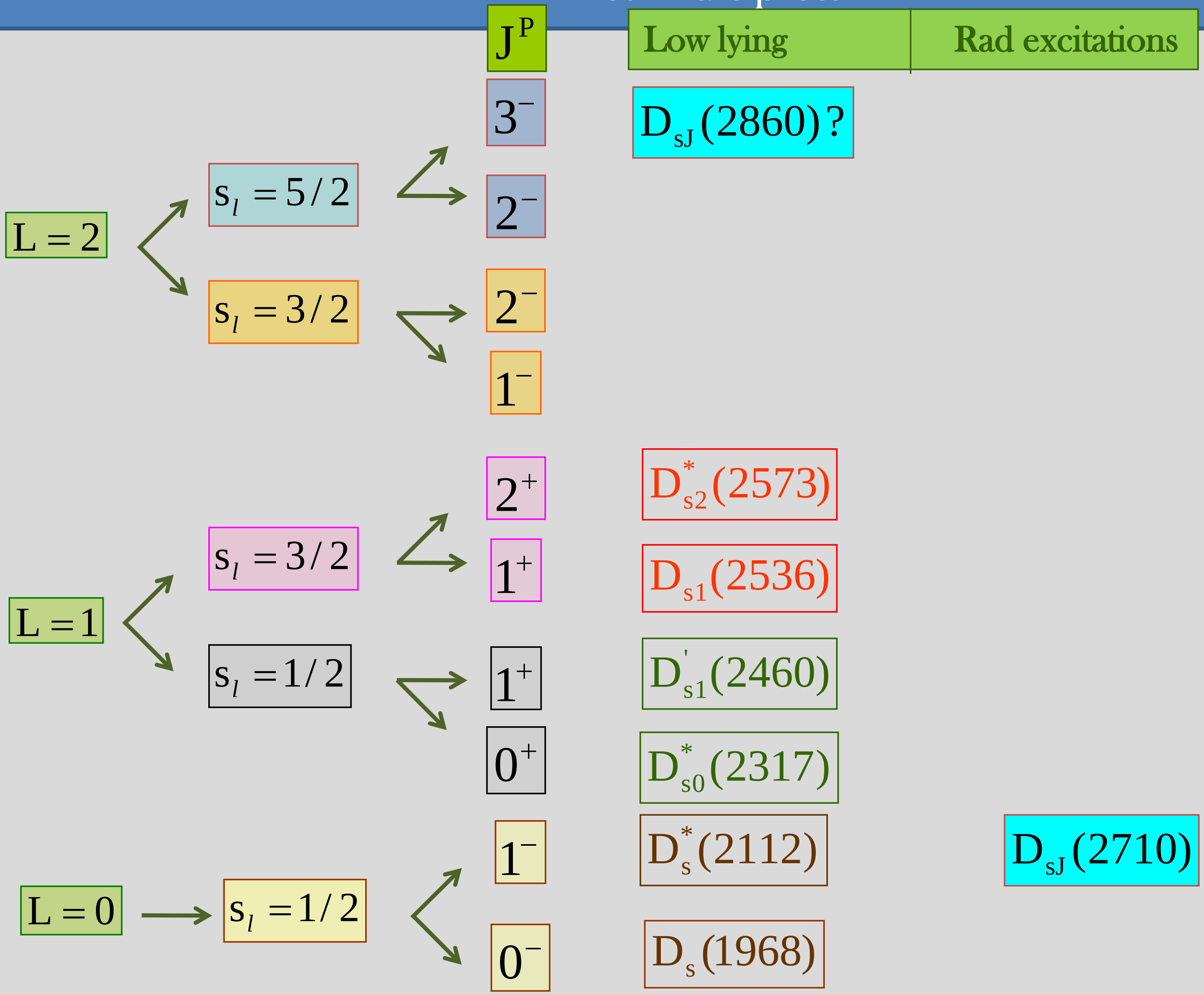
$$\frac{B(D_{sJ}(2860)^+ \to D^* K)}{B(D_{sJ}(2860)^+ \to DK)} = 1.10 \pm 0.15_{stat} \pm 0.19_{syst}$$

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

$c\bar{s}$ multiplets



$c\bar{s}$ multiplets



$c\bar{q}$ mesons: the non strange partner of $D_{sJ}(2700)$

States with the same quantum numbers of $D_{sJ}(2700)$ but with a different light quark flavour:

D_J^+ and D_J^0

Assuming $M(D_J)=2600 \pm 50$ MeV:

	$\mathcal{B}(D_J^+ \to D^0\pi^+)$	$\mathcal{B}(D_J^+ \to D^+\pi^0)$	$\mathcal{B}(D_J^+ \to D_s\bar{K}_S^0)$	$\mathcal{B}(D_J^+ \to D^+\eta)$	$\mathcal{B}(D_J^+ \to D^{*0}\pi^+)$	$\mathcal{B}(D_J^+ \to D^{*+}\pi^0)$	$\mathcal{B}(D_J^+ \to D^{*+}\eta)$
$D^{*\prime +}$	$(27.0 \pm 2.1)\%$	$(13.3 \pm 1.0)\%$	$(2.3 \pm 0.8)\%$	$(5.3 \pm 1.0)\%$	$(32.4 \pm 0.8)\%$	$(16.1 \pm 0.4)\%$	$(1.2 \pm 1.8)\%$

	$\mathcal{B}(D_J^0 \to D^+\pi^-)$	$\mathcal{B}(D_J^0 \to D^0\pi^0)$	$\mathcal{B}(D_J^0 \to D_sK^-)$	$\mathcal{B}(D_J^0 \to D^0\eta)$	$\mathcal{B}(D_J^0 \to D^{*+}\pi^-)$	$\mathcal{B}(D_J^0 \to D^{*0}\pi^0)$	$\mathcal{B}(D_J^0 \to D^{*0}\eta)$
$D^{*\prime 0}$	$(26.5 \pm 2.1)\%$	$(13.5 \pm 1.1)\%$	$(4.9 \pm 1.6)\%$	$(5.5 \pm 1.0)\%$	$(32.0 \pm 0.7)\%$	$(16.3 \pm 0.4)\%$	$(1.3 \pm 1.9)\%$

The strong coupling constant entering in these modes can be fixed from $D_{sJ}(2700)$ decays

$$\tilde{g} = 0.26 \pm 0.05$$

$$\Gamma(D^{*\prime +(0)}) = (128 \pm 61)\ \text{MeV}$$

$c\bar{q}$ mesons

BaBar observes four new states with charm and without strangeness:

BaBar, PRD 82 (10) 111101

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

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

in agreement with previous predictions for the members of the non strange partners of $D_{sJ}(2700)$

$c\bar{q}$ mesons

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BaBar, PRD 82 (10) 111101

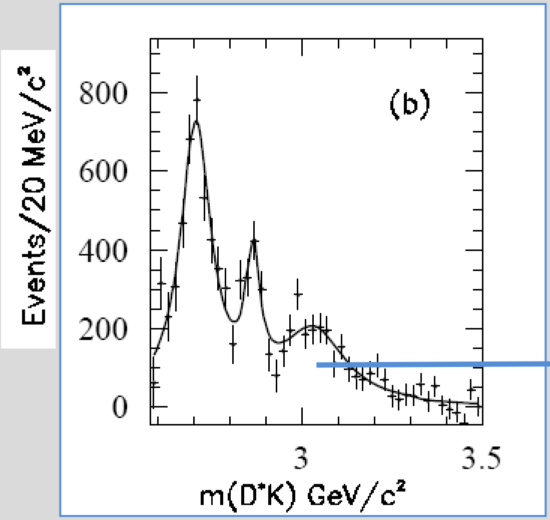
state	Mass (MeV)	Width (MeV)	decays to
$D(2550)^0$	$2539.4 \pm 4.5 \pm 6.8$	$130 \pm 12 \pm 13$	$D^{*+}\pi^-$
$D^*(2600)^0$	$2608.7 \pm 2.4 \pm 2.7$	$93 \pm 6 \pm 13$	$D^+\pi^-$, $D^{*+}\pi^-$
$D^*(2600)^+$	$2608.7 \pm 2.4 \pm 2.7$	$93 \pm 6 \pm 13$	$D^0\pi^+$
$D(2750)^0$	$2752.4 \pm 1.7 \pm 2.7$	$71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

still need to be identified
likely to be L=2 states

$c\bar{q}$ multiplets

L	s_l	J^P	Low lying		Rad. Excitations
$L=2$	$s_l=5/2$	3^-	$D(2750),\ D(2760)?$		
		2^-			
	$s_l=3/2$	2^-			
		1^-			
$L=1$	$s_l=3/2$	2^+	$D_2^{*\pm,0}(2460)$	$\Gamma_{D_2^*}\approx 40\ \text{MeV}$	
		1^+	$D_1^{\pm}(2420)$	$\Gamma_{D_1}\approx 20\ \text{MeV}$	
	$s_l=1/2$	1^+	$D_1'^{0}(2430)$	$\Gamma_{D_1'}\approx 384\ \text{MeV}$	
		0^+	$D_0^{*0}(2308)$	$\Gamma_{D_0}\approx 260\ \text{MeV}$	
$L=0$	$s_l=1/2$	1^-	$D^{*\pm}(2010),\ D^{*0}(2007)$		$D(2600)?$
		0^-	$D^{\pm}(1869),\ D^{0}(1865)$		$D(2550)?$

$D_{sJ}(3040)$



$$M(D_{sJ}(3040)) = 3044 \pm 8_{\rm stat}(^{+30}_{-5})_{\rm syst}\ \mathrm{MeV}$$

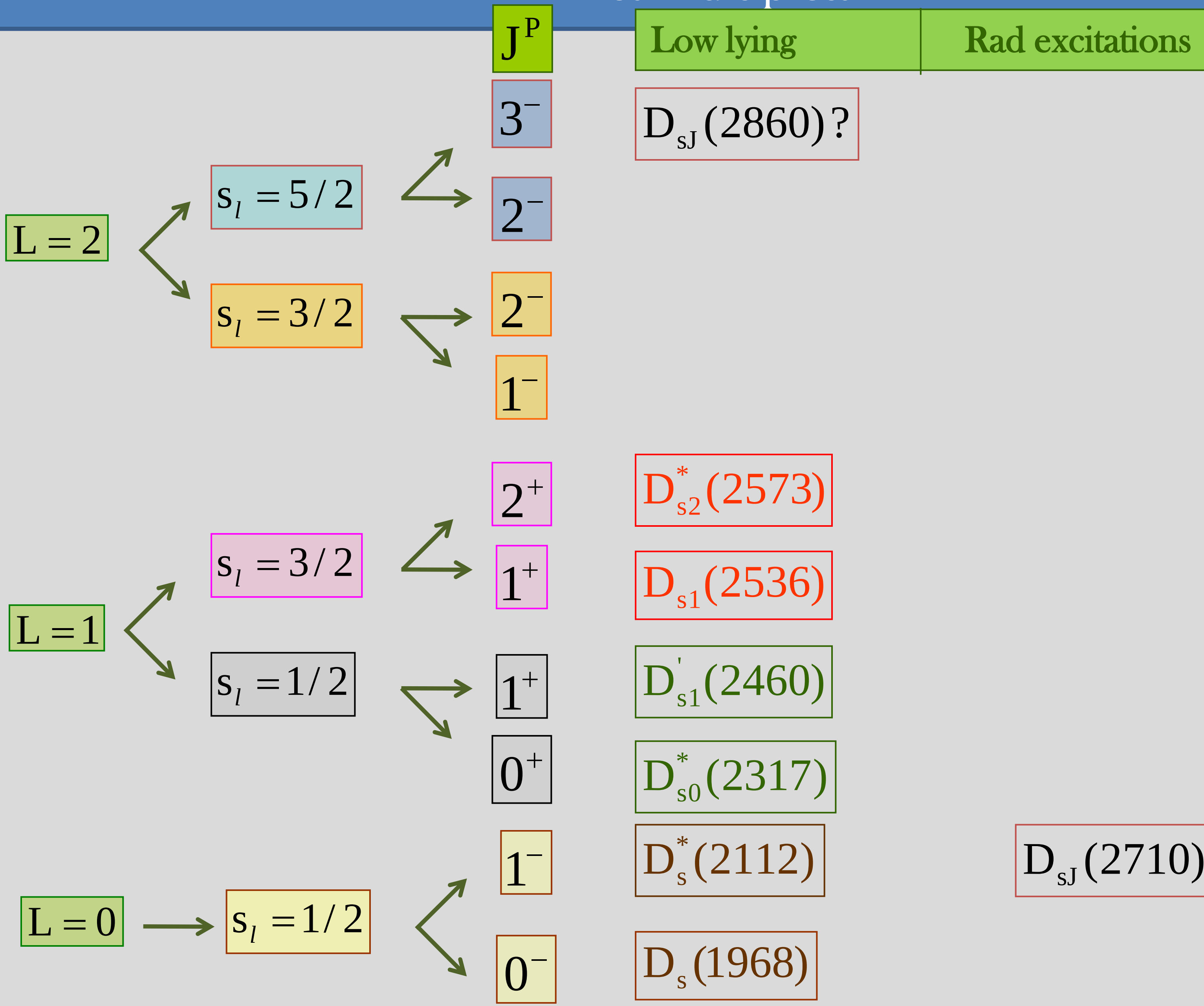
$$\Gamma(D_{sJ}(3040)) = 239 \pm 35_{\rm stat}(^{+46}_{-42})_{\rm syst}\ \mathrm{MeV}$$

The only additional information is that it decays $\to D^*K$ YES

$\to DK$ NO

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

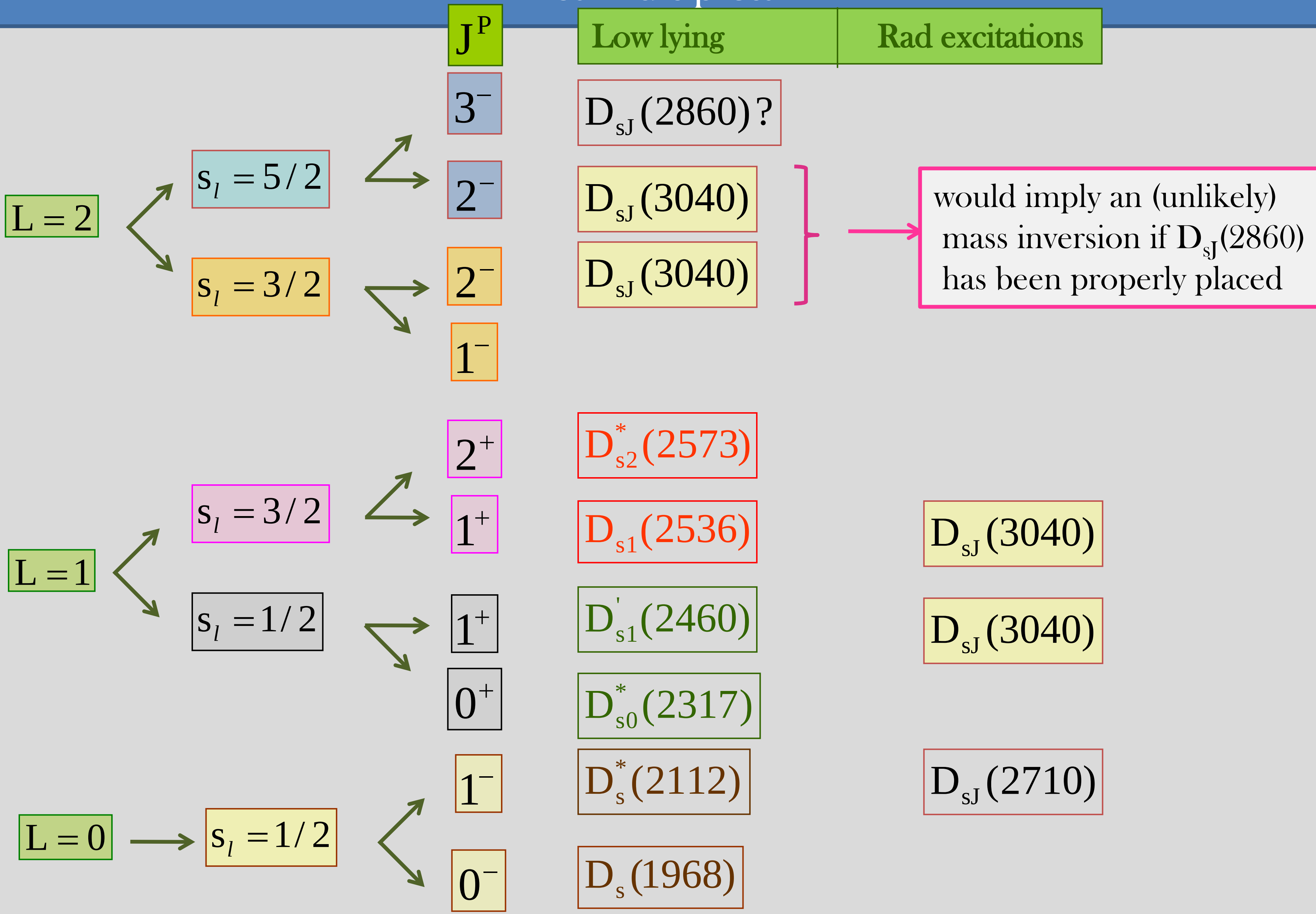
$c\bar{s}$ multiplets



$c\bar{s}$ 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



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

- info from Relativistic Quark Model (RQM)

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

- 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_0^*K, $D_{s0}^*\eta$, $D_1'K$	p wave	p wave	d wave	d wave
D_1K	p wave	p wave	...	d wave
D_2^*K	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_0^*K, $D_{s0}^*\eta$	...	...	d wave	...
$D_1'K$	p wave	p wave	d wave	d wave
D_1K	p wave	p wave	s wave	d wave
D_2^*K	...	p wave	...	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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$D_{sJ}(3040)$: 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	...	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

- $\tilde{D}'_{s1}$ 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

$D_{sJ}(3040)$: 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
$D_0^*K,\ D_{s0}^*\eta,\ D_1'K$	p wave	p wave	d wave	d wave
D_1K	p wave	p wave	$\cdots$	d wave
D_2^*K	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
$D_0^*K,\ D_{s0}^*\eta$	$\cdots$	$\cdots$	d wave	$\cdots$
$D_1'K$	p wave	p wave	d wave	d wave
D_1K	p wave	p wave	s wave	d wave
D_2^*K	$\cdots$	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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$D_0^*K,\ D_{s0}^*\eta,\ D_1'K$	p wave	p wave	d wave	d wave
D_1K	p wave	p wave	$\cdots$	d wave
D_2^*K	p wave	p wave	s wave	d wave
$DK^*,\ D_s\phi$	s wave	s wave	p wave	p wave
	$\Gamma \simeq 140$ MeV	$\Gamma \simeq 20$ MeV	Negligible	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
$D_0^*K,\ D_{s0}^*\eta$	$\cdots$	$\cdots$	d wave	$\cdots$
$D_1'K$	p wave	p wave	d wave	d wave
D_1K	p wave	p wave	s wave	d wave
D_2^*K	$\cdots$	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

$D_{sJ}(3040)$: 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	...	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

- $\tilde{D}'_{s1}$ 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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- D_{s2} cannot decay to D_1K but should have the largest width to D_2^*K
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Concluding remarks

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

- $D_{sJ}(2700)$ identified with $D^{*\prime}_s$ $D_J(2600)$ most likely its non strange partner

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

- the most intriguing challenge remains to understand why
$D^*_{s0}(2317)$ and $D'_{s1}(2460)$ have masses below the $D^{(*)}K$ threshold

- HQ symmetry predicts analogous states in the beauty system :

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$M(B^*_{s0})$=5721 MeV decaying to $B_s\ \pi^0$
$M(B'_{s1})$=5762 MeV decaying to $B^*_s\ \pi^0$