Latest developments in the Spectroscopy of Heavy Hadrons

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Question: recent discoveries in charm(onium) and bottom (onium) spectra might be exotic states?

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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
- $D_{sJ}(2860)$, $D_{sJ}(2710)$, $D_{sJ}(3040)$

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

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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

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

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

Mesons classified as doublets

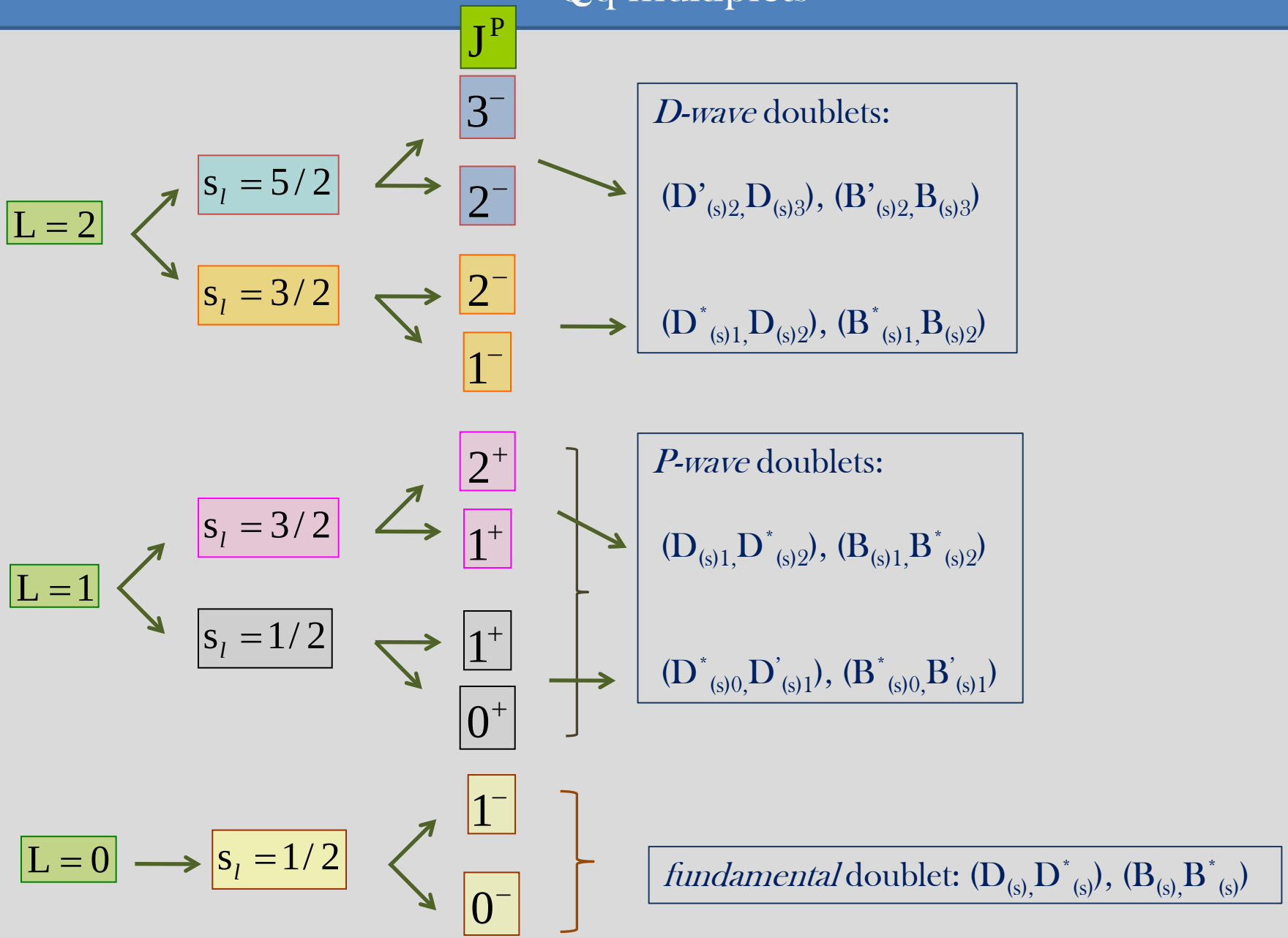
- In the HQ limit:

- states with the same s_l^P degenerate

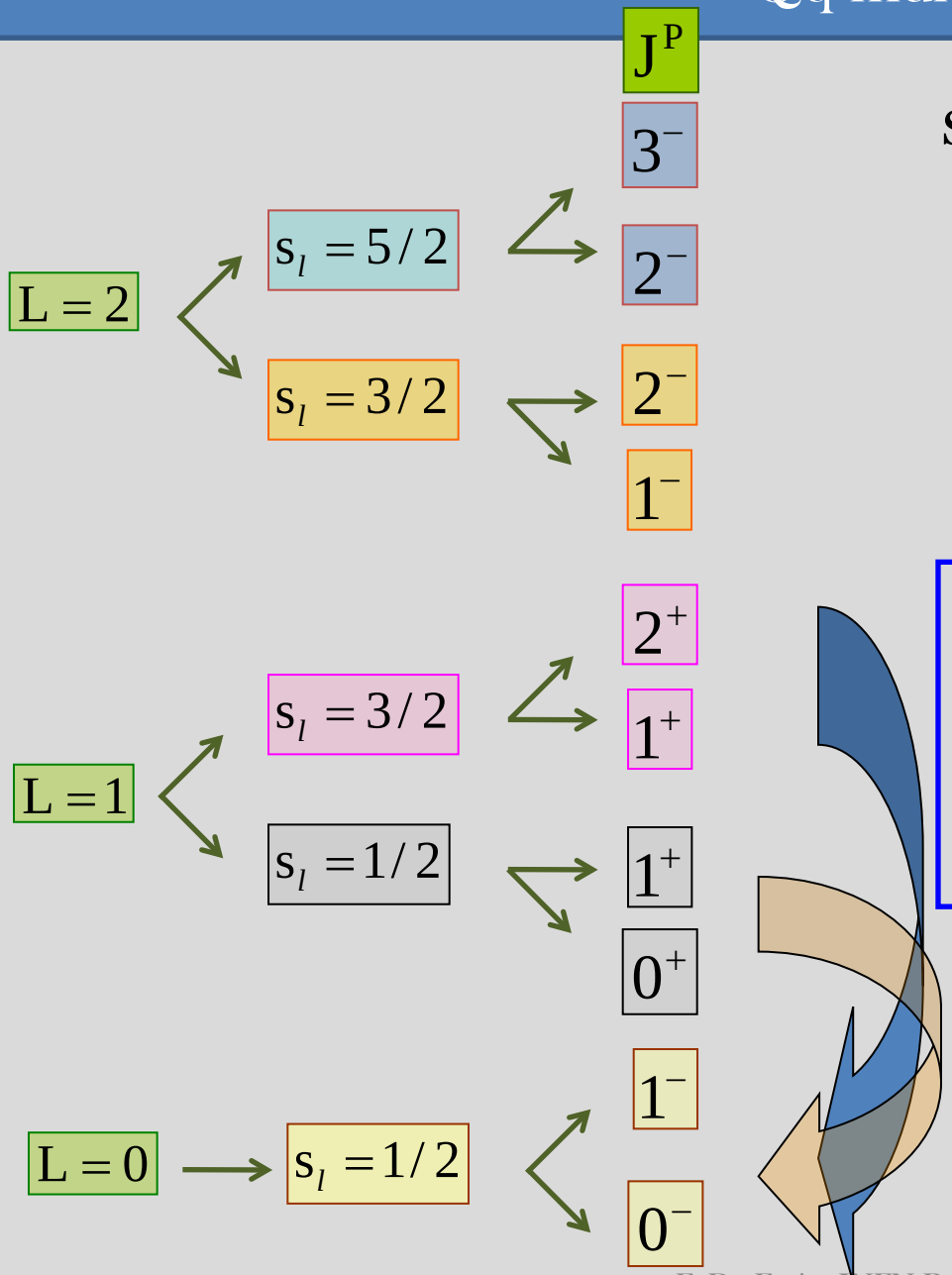
- finite m_Q corrections

- 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

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

d-wave transition

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

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

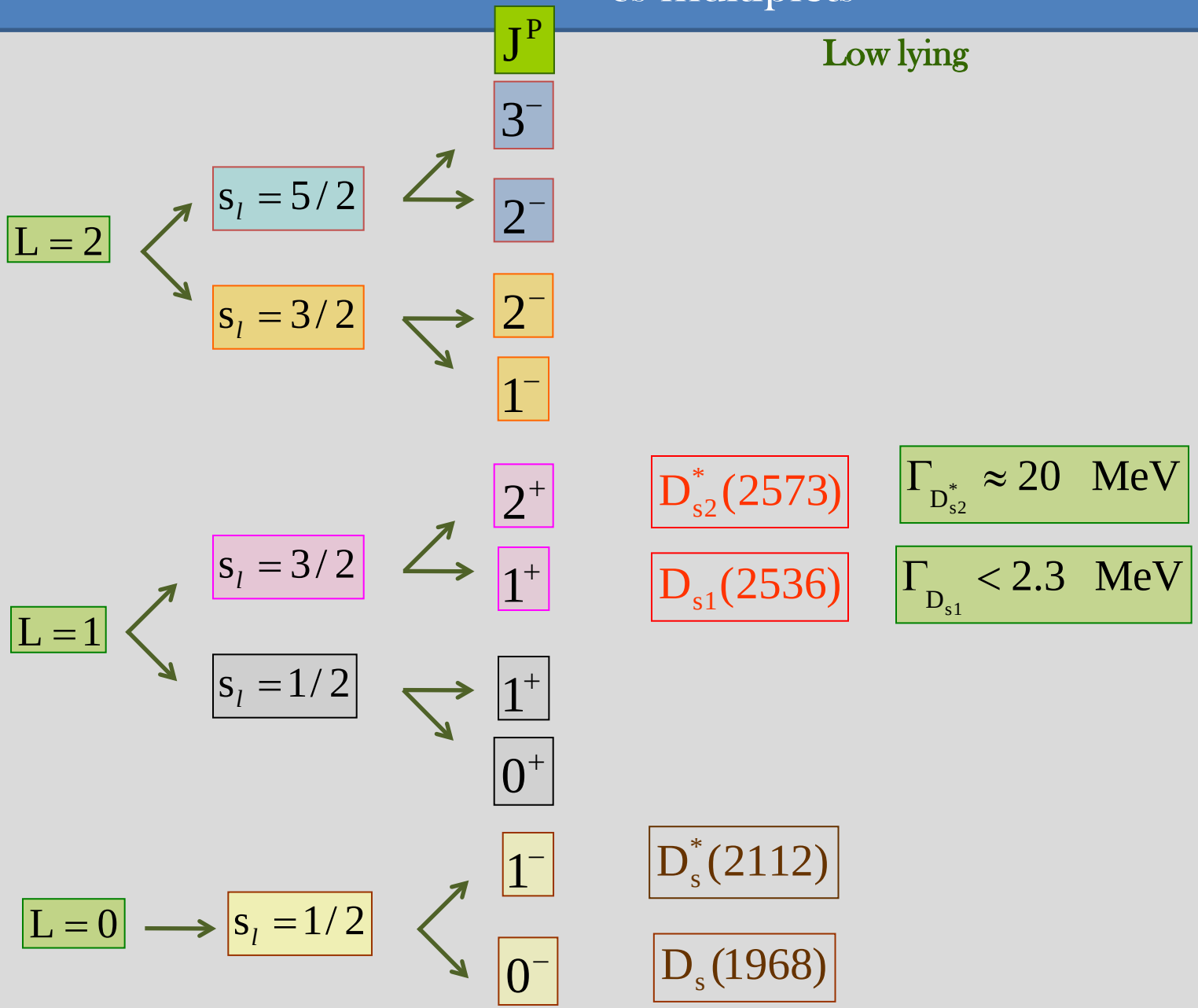
s-wave transition

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

$c\bar{q}$ multiplets

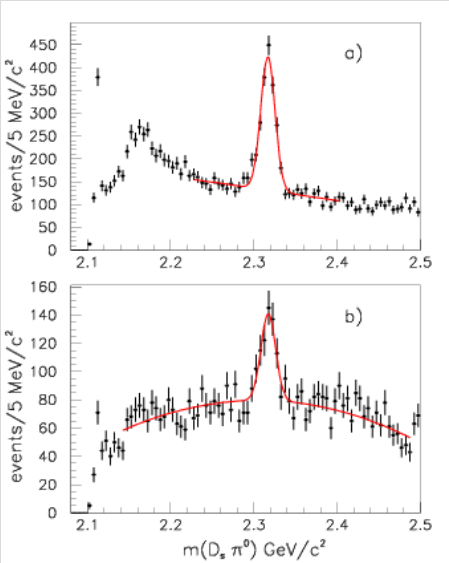
		J^P	Low lying	Rad. Excitations
$L=2$	$s_l = 5/2$	3^-, 2^-	D(2750), D(2760)?	
	$s_l = 3/2$	2^-, 1^-		
$L=1$	$s_l = 3/2$	2^+	$D_2^{*\pm,0}(2460)$	$\Gamma_{D_2^*} \approx 40$ MeV
		1^+	$D_1^{\pm}(2420)$	$\Gamma_{D_1} \approx 20$ MeV
	$s_l = 1/2$	1^+	$D_1'^{0}(2430)$	$\Gamma_{D_1'} \approx 384$ MeV
		0^+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

$c\bar{s}$ multiplets

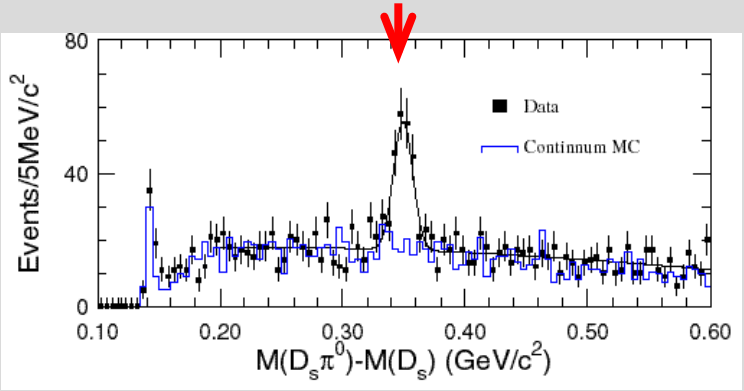


Narrow peak in the $D_s^+ \pi^0$ mass distribution: $D_{sJ}(2317)$

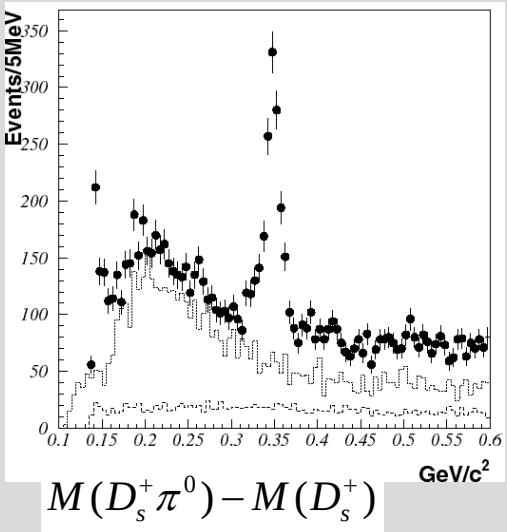
BaBar



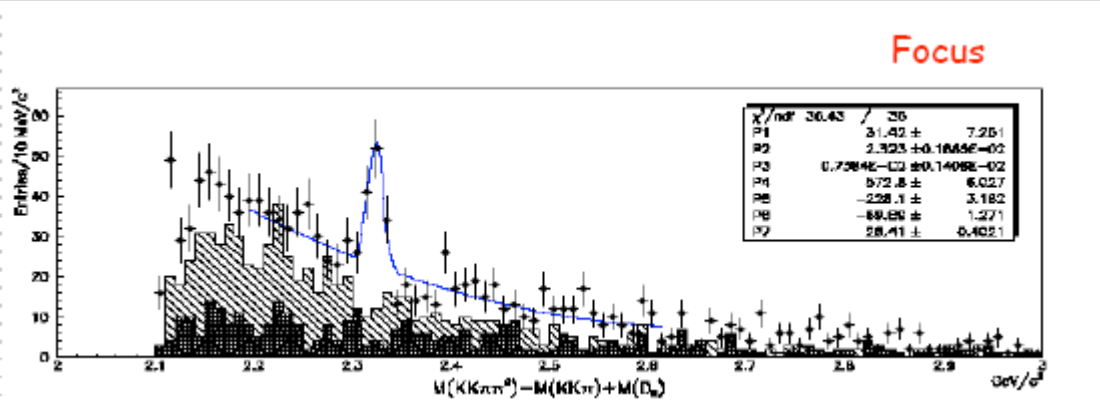
CLEO **2.32 GeV**



Belle



production also observed at a fixed target exp →

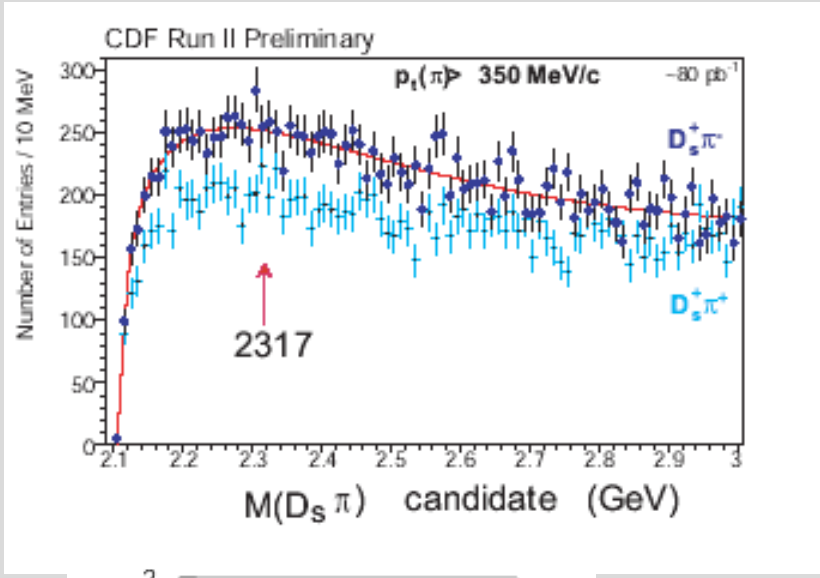


observed width consistent with exp. Resolution (<10 MeV)
intrinsic width smaller

$D_{sJ}(2317)$ quantum numbers

The narrow width suggests Isospin violating decay i.e. confirmed by the absence of isospin partners eventually decaying in $D_s^{\pm}\pi^{\mp}$ $D_s^{\pm}\pi^{\pm}$

$I \neq 1$

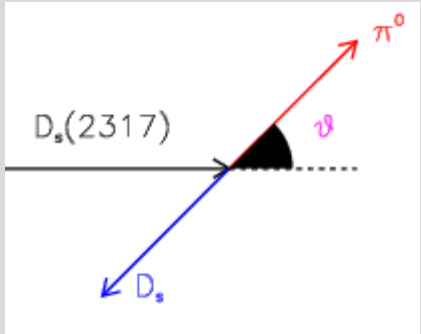


I=0 is the preferred assignment

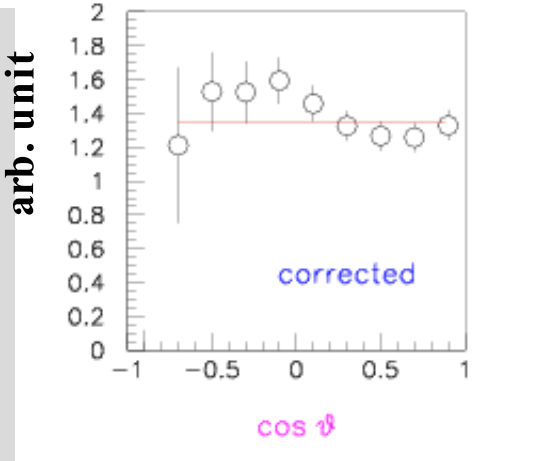
$J^P = 0^+$ $\qquad$ $D_{sJ}(2317) \rightarrow D_s\pi^0$

The observation of the mode $D_{sJ}(2317) \rightarrow D_s\pi^0$ favours the assignment $J^P=0^+$

Also suggested by the helicity angle distribution

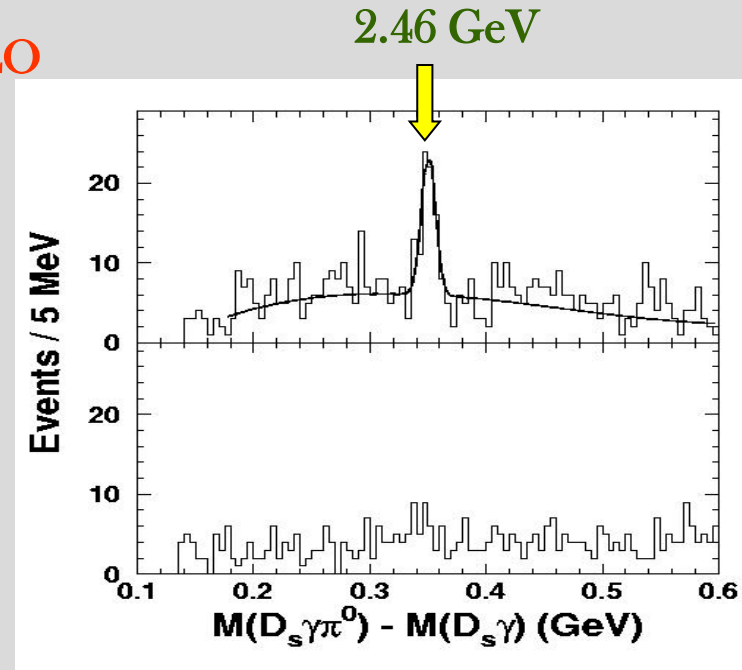


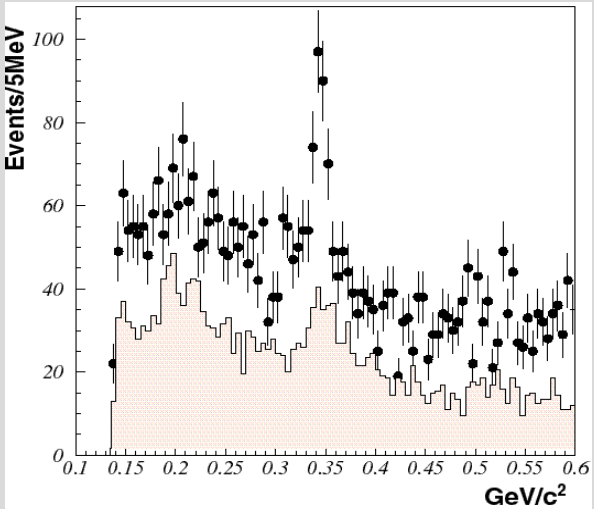
Consistent with being flat



Another narrow peak in the $D_s^{*+}\pi^0$ mass distribution: $D_{sJ}(2460)$

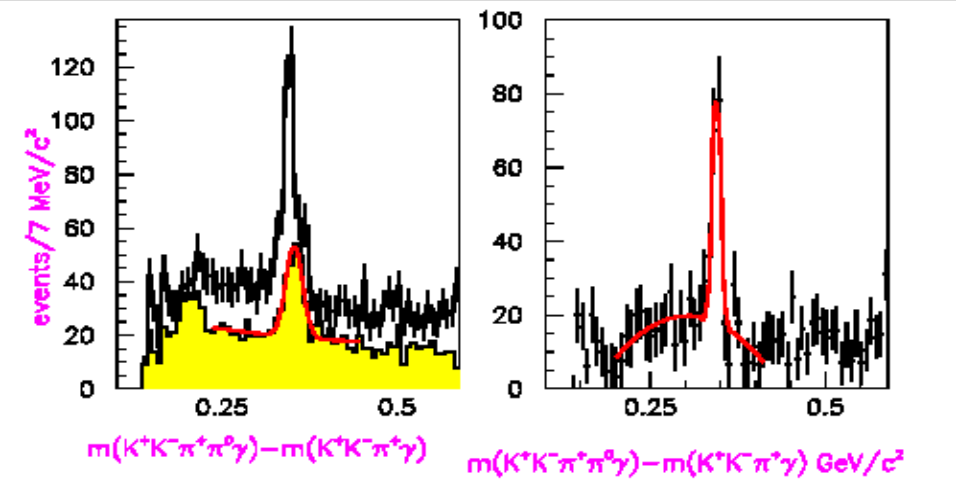
CLEO





$M(D_s^{*+}\pi^0) - M(D_s^{*+})$

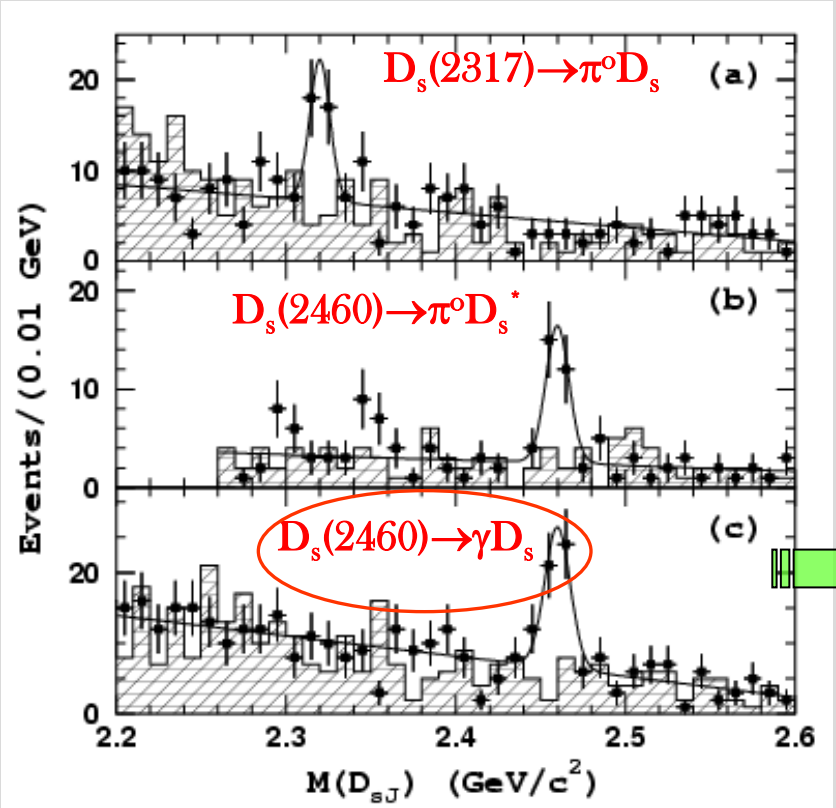
Belle



BaBar

width consistent
with exp resolution

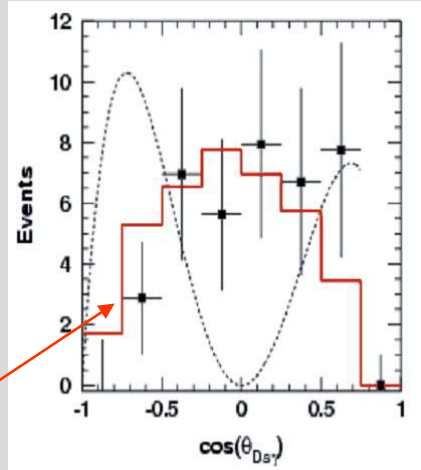
D_{sJ} produced in B decays: $B \to D\, D_{sJ}$



Belle observes radiative decay of $D_{sJ}(2460)$

rules out J=0

Analysis of helicity angle distribution suggests J=1



spin 1

$D_{sJ}(2317)$ & $D_{sJ}(2460)$

The two narrow states identified as the $J^P=(0^+,1^+)$ lowest lying $c\bar{s}$ states with L=1

- are data consistent with this interpretation?
- are data consistent with other interpretations?

Understanding if $D_{sJ}(2317)$ and $D_{sJ}(2460)$ can be identified with the $J^P=(0^+,1^+)$ lowest lying $c\bar{s}$ states with L=1 means checking that

- the isospin violating decays to $D_s^{(*)}\pi^0$ proceed at a rate larger than the radiative modes
- the total rate should not exceed the exp upper bound $\Gamma \leq 10$ MeV

Hadronic modes

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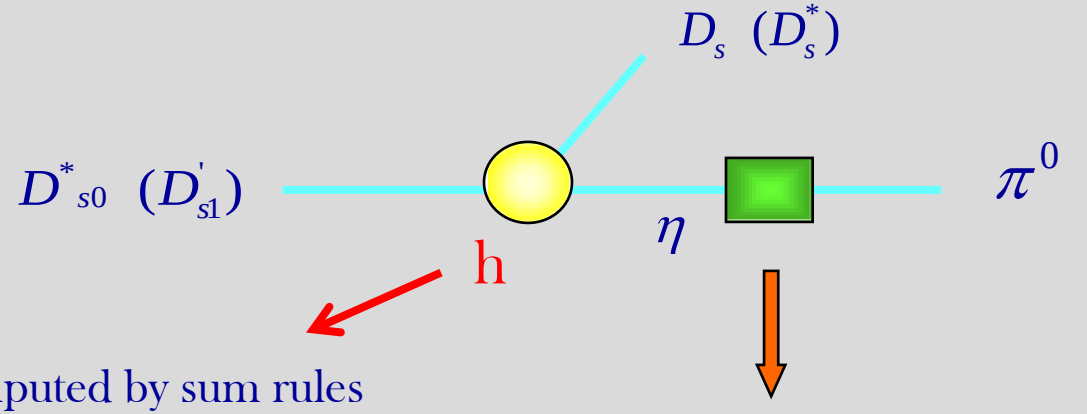
PLB570, 180
P. Colangelo, R. Ferrandes, FDF
MPLA19, 2083

The decays $D^*_{s0}\,(D'_{s1}) \to D_s^{(*)}\,\pi^0$ can be described as the result of the strong transition $D_{s0}\,(D'_{s1}) \to D_s^{(*)}\,\eta$ followed by the π-η mixing



computed by sum rules

Isospin violation enters here

$$\Gamma(D^*_{s0} \to D_s\pi^0) = \frac{1}{16\pi}\frac{h^2}{f^2}\frac{M_{D_s}}{M_{D^*_{s0}}}\left(\frac{m_d - m_u}{m_s - \frac{m_d + m_u}{2}}\right)^2 (1 + \frac{m^2_{\pi^0}}{p^2_{\pi^0}})\, p^3_{\pi^0}$$

$$\Gamma(D_{sJ}(2317) \to D_s\pi^0) = 7 \pm 1 \quad \text{KeV}$$

$$\Gamma(D_{sJ}(2460) \to D^*_s\pi^0) = 7 \pm 1 \quad \text{KeV}$$

Radiative modes: Light-cone sum rule predictions

Initial state	Final state	LCQSR	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

$(m_c \to \infty)$

PDG

$D_{s1}(2460)^+$ DECAY MODES

$D_{s1}(2460)^-$ modes are charge conjugates of the modes below.

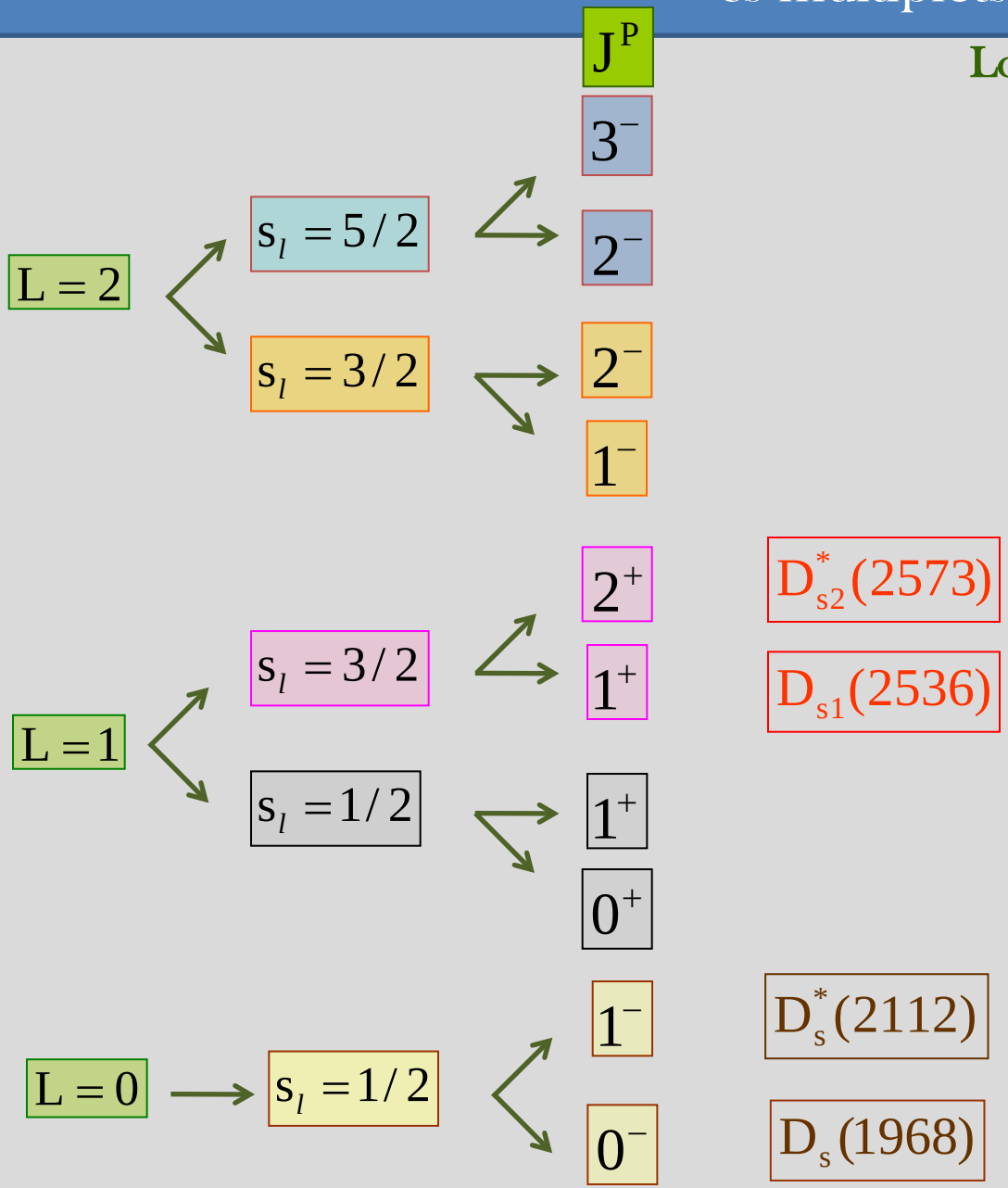
	Mode	Fraction (Γ_i/Γ)
Γ_1	$D_s^{*+}\pi^0$	(48 ±11) %
Γ_2	$D_s^+\gamma$	(18 ± 4) %
Γ_3	$D_s^+\pi^+\pi^-$	(4.3± 1.3) %
Γ_4	$D_s^{*+}\gamma$	< 8 %
Γ_5	$D_{s0}^*(2317)^+\gamma$	($3.7^{+5.1}_{-2.4}$) %
Γ_6	$D_s^+\pi^0$	
Γ_7	$D_s^+\pi^0\pi^0$	
Γ_8	$D_s^+\gamma\gamma$	

P. Colangelo, A. Ozpineci, FDF
PRD 72 , 074004

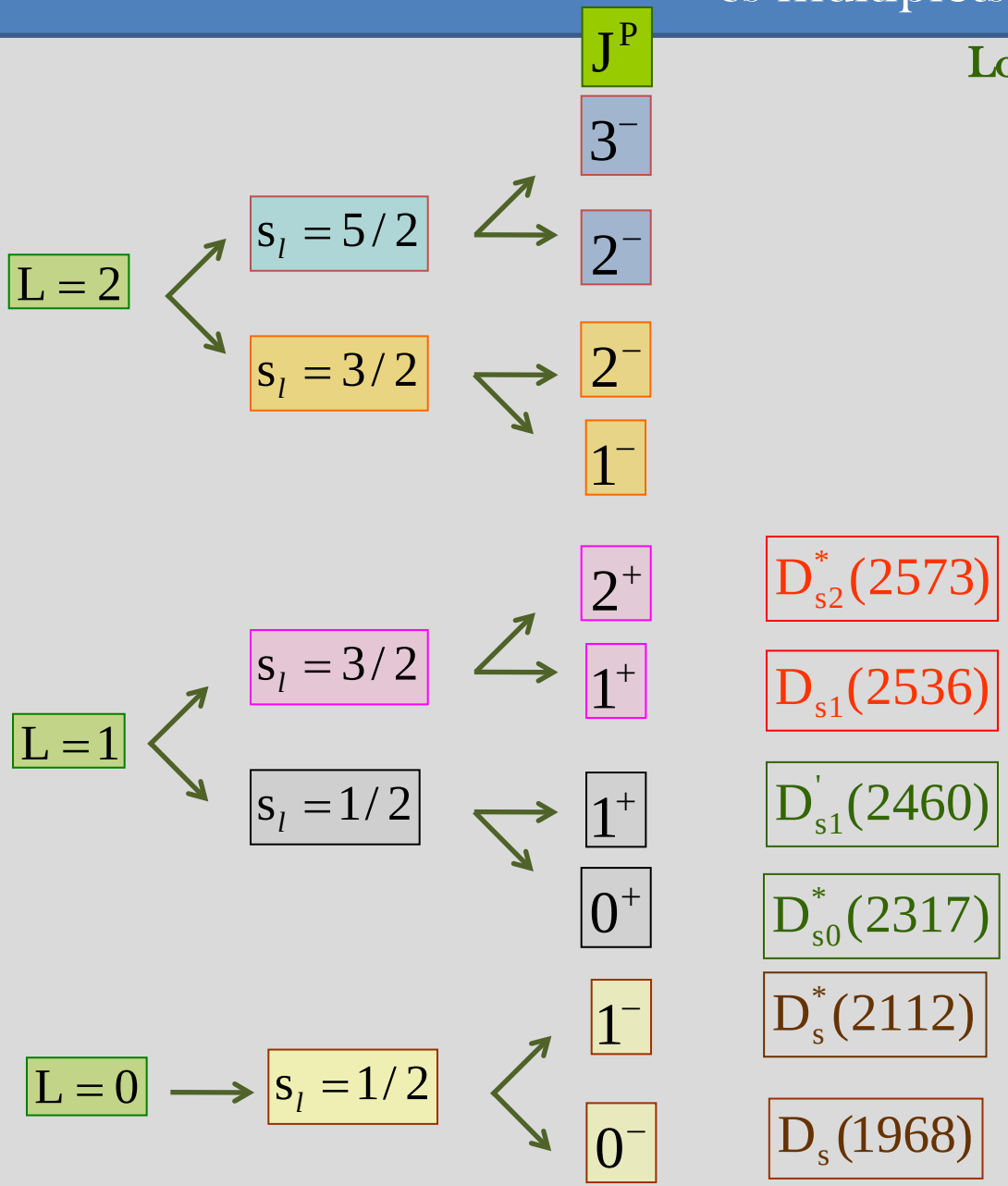
The largest computed rate corresponds to the largest measured radiative branching ratio

$D_{sJ}(2317)$ and $D_{sJ}(2460)$ behave as ordinary $c\bar{s}$ mesons

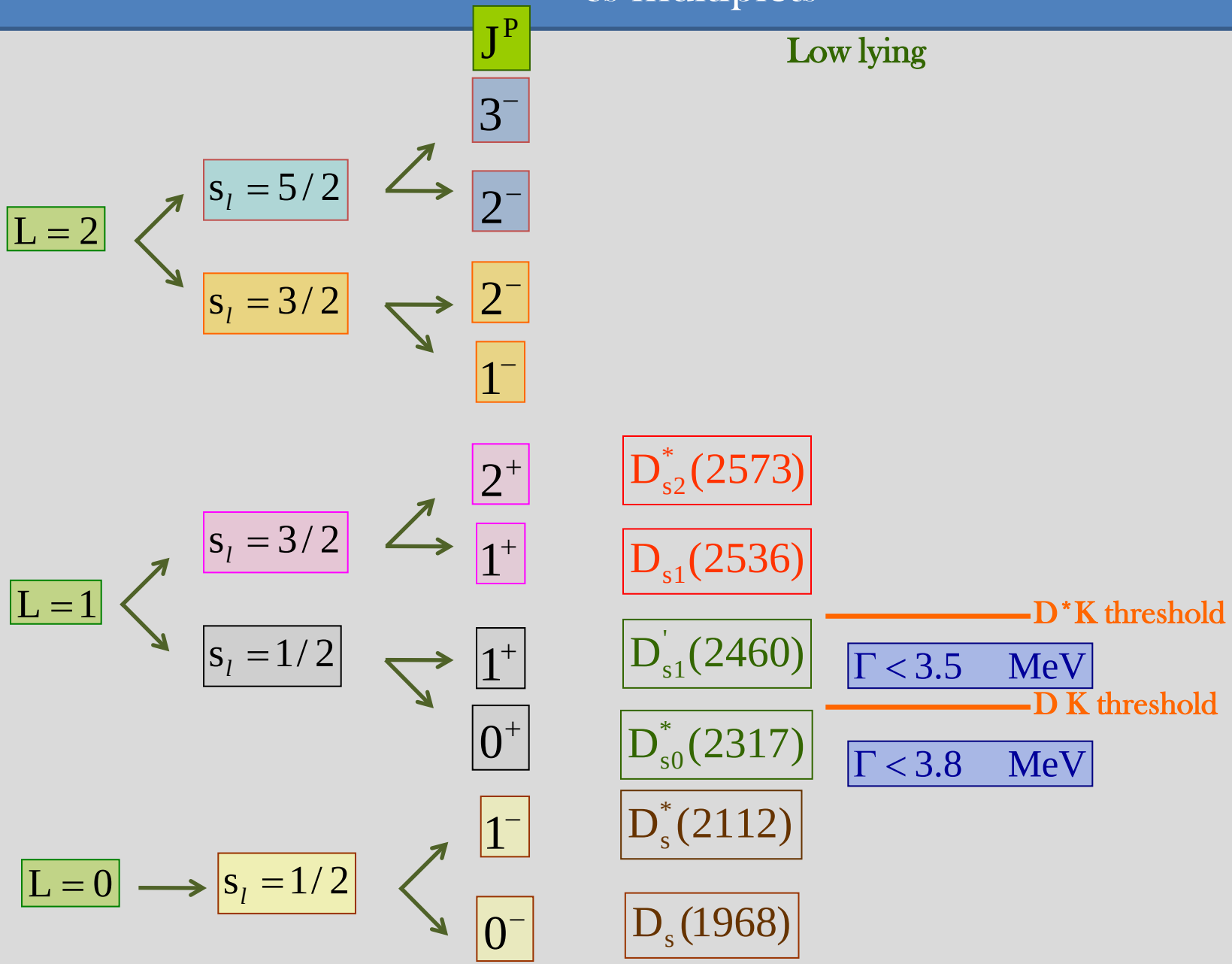
$c\bar{s}$ multiplets



$c\bar{s}$ multiplets



$c\bar{s}$ multiplets

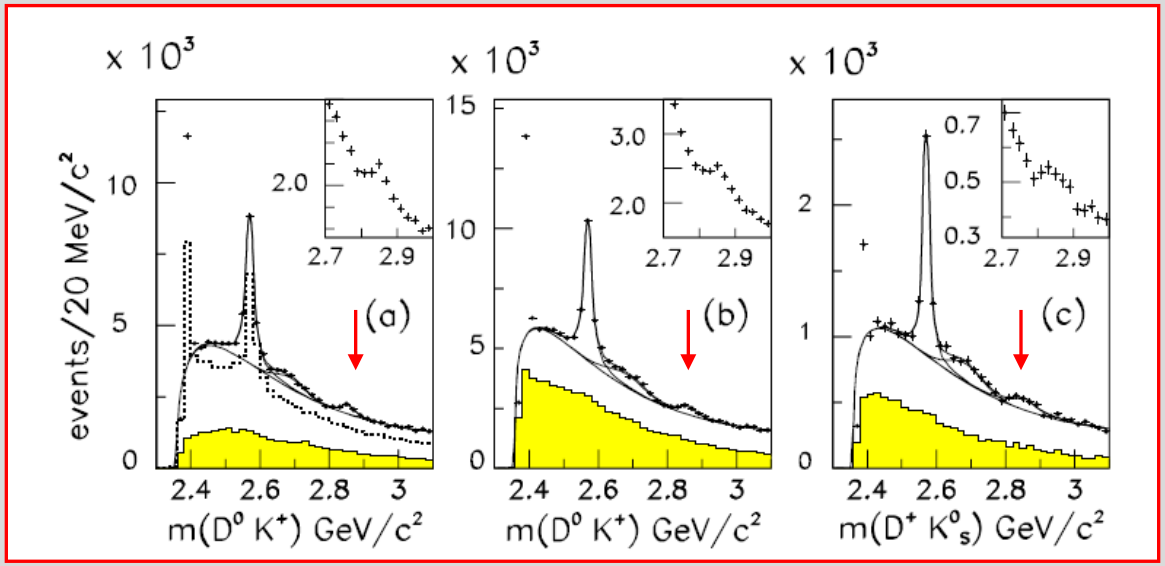


$D_{sJ}(2860)$

- 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

		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^+	$D^*_{s2}(2573)$	
		1^+	$D_{s1}(2536)$	
	$s_l = 1/2$	1^+	$D'_{s1}(2460)$	
		0^+	$D^*_{s0}(2317)$	
$L=0$	$s_l = 1/2$	1^-	$D^*_s(2112)$	
		0^-	$D_s(1968)$	

$c\bar{s}$ multiplets

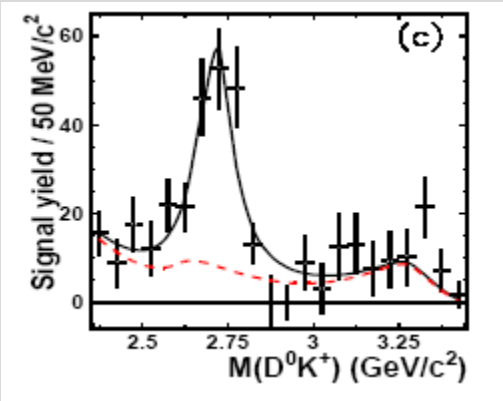
		J^P	Low lying	Rad excitations
$L=2$	$s_l = 5/2$	3^-		
		2^-	forbidden	
	$s_l = 3/2$	2^-	forbidden	
		1^-		
$L=1$	$s_l = 3/2$	2^+	$D^*_{s2}(2573)$	
		1^+	$D_{s1}(2536)$	forbidden
	$s_l = 1/2$	1^+	$D'_{s1}(2460)$	forbidden
		0^+	$D^*_{s0}(2317)$	
$L=0$	$s_l = 1/2$	1^-	$D^*_s(2112)$	
		0^-	$D_s(1968)$	forbidden

$c\bar{s}$ multiplets

		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

$D_{sJ}(2710)$

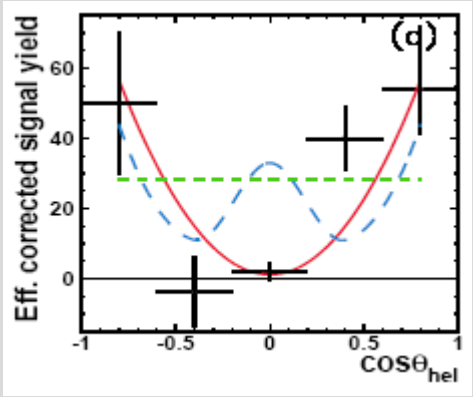
Belle Collab.: analysis of the mode $B^+ \to \overline{D}^0 D^0 K^+$



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

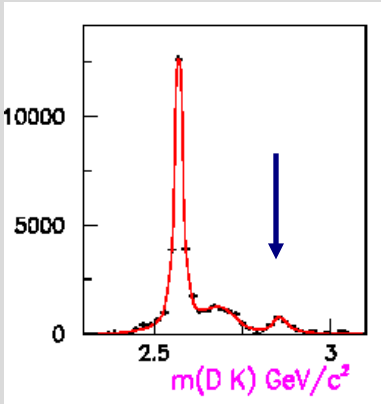
$M = 2708 \pm 9 \pm^{11}_{10}$ MeV $\qquad \Gamma = 108 \pm 23 \pm^{36}_{31}$ MeV

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



J=0
J=1
J=2

$J^P=1^-$ 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

		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^+	$D^*_{s2}(2573)$	
		1^+	$D_{s1}(2536)$	
	$s_l = 1/2$	1^+	$D'_{s1}(2460)$	
		0^+	$D^*_{s0}(2317)$	
$L=0$	$s_l = 1/2$	1^-	$D^*_s(2112)$	
		0^-	$D_s(1968)$	

$c\bar{s}$ multiplets

		J^P	Low lying	Rad excitations
$L=2$	$s_l = 5/2$	3^-		
		2^-		
	$s_l = 3/2$	2^-		
		1^-	D^*_{s1}	
$L=1$	$s_l = 3/2$	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^-	$D^*_s(2112)$	$D^{*\prime}_s$
		0^-	$D_s(1968)$	

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

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

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

H → H π

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

S → H π

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

T → H π

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

X → H π

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

X' → H π

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

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

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

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

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

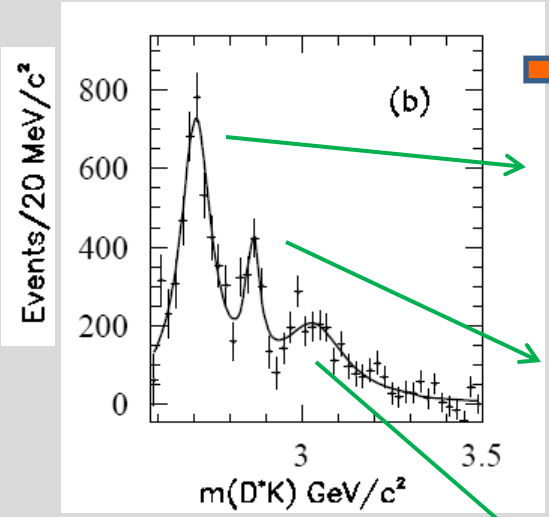
the dependence on the (unknown) couplings drops out

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

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

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

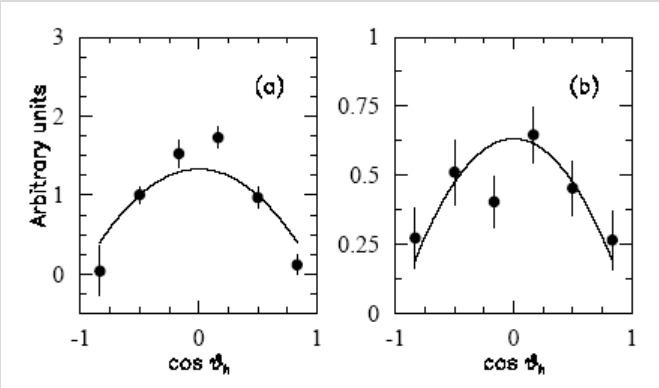
$$m(D_{sJ}(2860)^+) = 2862 \pm 2_{stat} \pm^{5}_{2\,syst} \quad \text{MeV}$$

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

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

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

- angular analysis



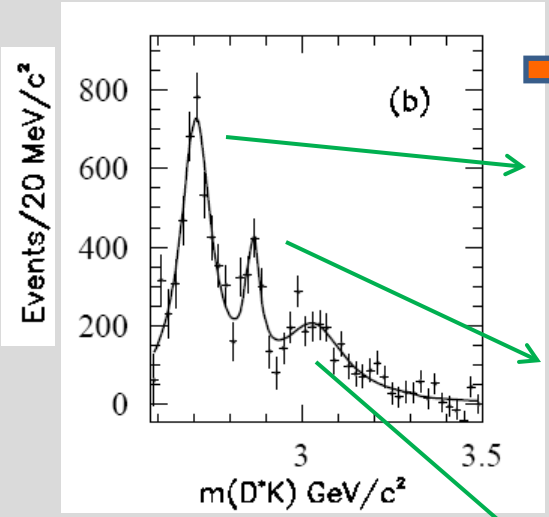
The angular distribution is consistent with the expectations for states with natural parity ($0^+,1^-,2^+,3^-,\ldots$) for $D_{s1}(2710)$ and $D_{sJ}(2860)$

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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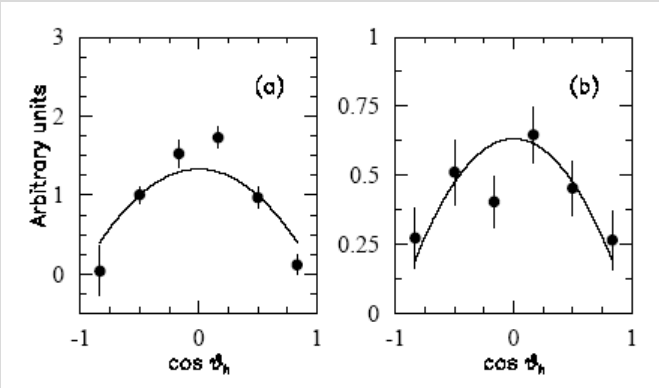
- angular analysis



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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

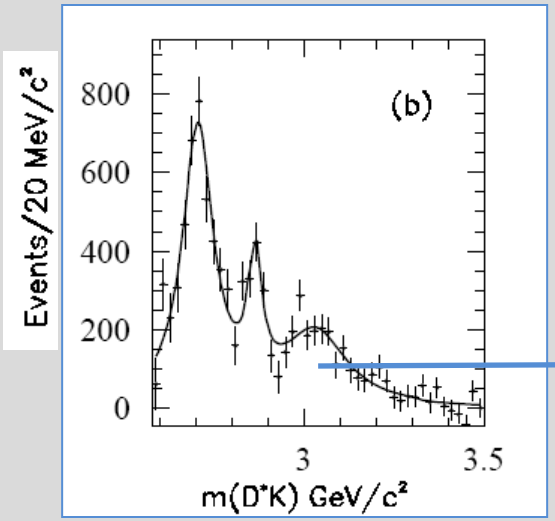
$c\bar{s}$ multiplets

		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^+	$D^*_{s2}(2573)$	
		1^+	$D_{s1}(2536)$	
	$s_l = 1/2$	1^+	$D'_{s1}(2460)$	
		0^+	$D^*_{s0}(2317)$	
$L=0$	$s_l = 1/2$	1^-	$D^*_s(2112)$	
		0^-	$D_s(1968)$	

$c\bar{s}$ multiplets

		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^-	$D_s(1968)$	

$D_{sJ}(3040)$



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

The only additional information is that it decays → D^*K YES
→ DK NO

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

$c\bar{s}$ multiplets

		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

		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

		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^-	$D_s(1968)$	

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

  - 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	...	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

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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	Spin partner			
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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
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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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	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

P. Colangelo , FDF
PRD81, 094001

- 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} $(n=1, J^P_{s_\ell}=2^-_{3/2})$	$D^{*\prime}_{s2}$ $(n=1, J^P_{s_\ell}=2^-_{5/2})$
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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

P. Colangelo , FDF
PRD81, 094001

- 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^*_2K	p wave	p wave	s wave	d wave
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			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} $(n=1, J^P_{s_\ell}=3^-_{5/2})$
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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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P. Colangelo , FDF
PRD81, 094001

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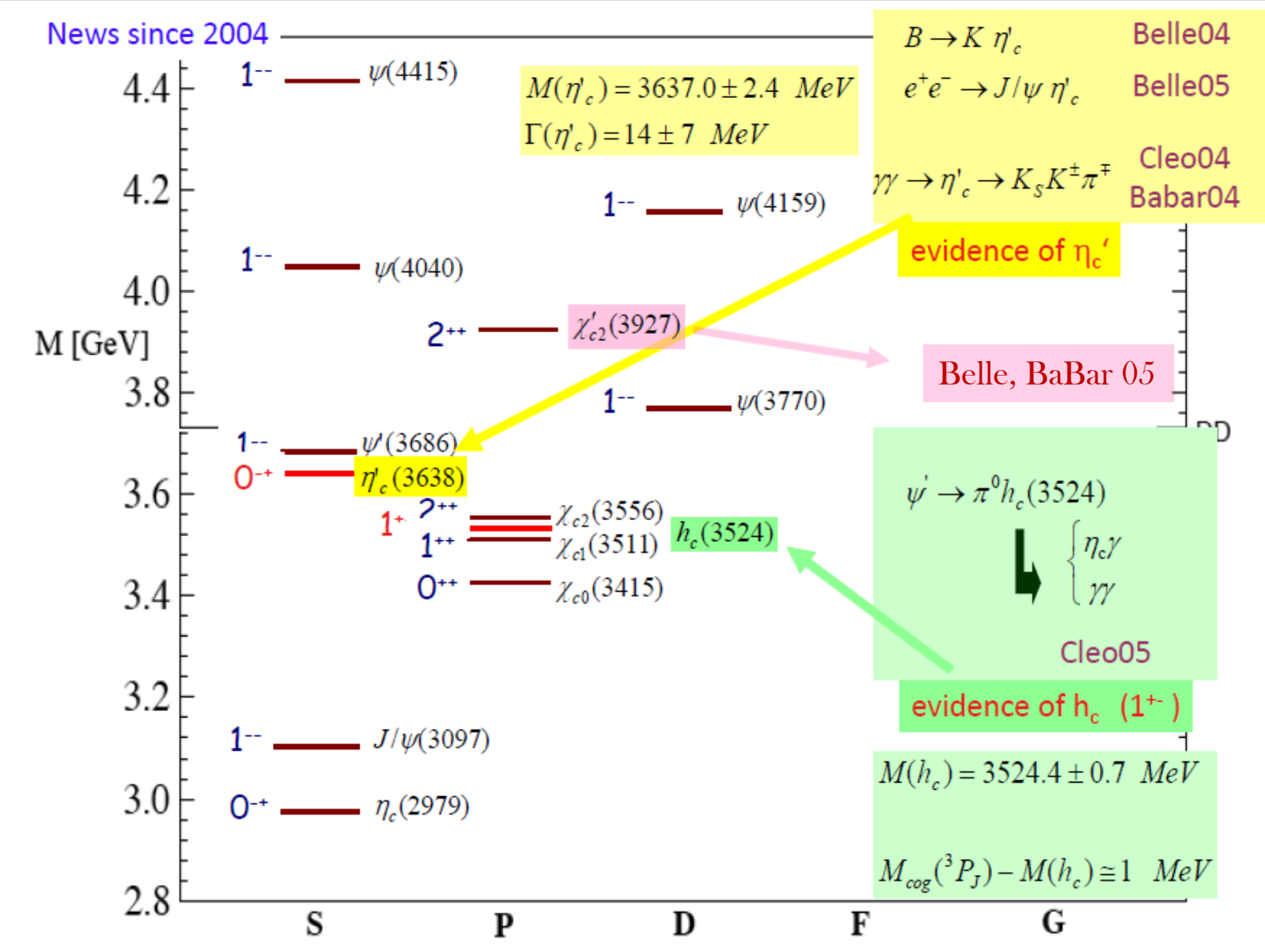
Hidden charm (conventional) states



Hidden charm states (?)

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), *BABAR* [87] (8.6)	2003	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \cdots$	CDF [88–90] (np), DØ [91] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), *BABAR* [93] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), *BABAR* [96] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [92] (4.0), *BABAR* [97, 98] (3.6)		
				$B \to K(\gamma\psi(2S))$	*BABAR* [98] (3.5), Belle [99] (0.4)		
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), *BABAR* [101] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\ (\ldots)$	Belle [54] (5.0)		
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	*BABAR* [27] (np), Belle [21] (np)	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	*BABAR* [108, 109] (8.0)	2005	OK
					CLEO [110] (5.4)		
					Belle [104] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [111] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [107] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	*BABAR* [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [114] (5.8)	2007	NC!

From N. Brambilla et al. EPJ C71 (11) 1534

Hidden beauty states

Beauty	mass (MeV)	width (MeV)
$\eta_b(1S)$	$9300 \pm 20 \pm 20$	
$\Upsilon(1S)$	9460.30 ± 0.26	$(54.02 \pm 1.25) \times 10^{-3}$
$\chi_{b0}(1P)$	$9859.44 \pm 0.42 \pm 0.31$	
$\chi_{b1}(1P)$	$9892.78 \pm 0.26 \pm 0.31$	
$\chi_{b2}(1P)$	$9912.21 \pm 0.26 \pm 0.31$	
$h_b(1P)$	$9898.25 \pm 1.06 \pm^{1.03}_{-1.07}$	
$\eta_b(2S)$		
$\Upsilon(2S)$	10023.26 ± 0.31	$(31.98 \pm 2.63) \times 10^{-3}$
$\chi_{b0}(2P)$	$10232.5 \pm 0.4 \pm 0.5$	
$\chi_{b1}(2P)$	$10255.46 \pm 0.22 \pm 0.50$	
$\chi_{b2}(2P)$	$10268.65 \pm 0.22 \pm 0.50$	
$h_b(2P)$	$10259.76 \pm 0.64 \pm^{1.43}_{-1.03}$	
$\Upsilon(1^3D_1)$		
$\Upsilon(1^3D_2)$	$10161.1 \pm 0.6 \pm 1.6$	
$\Upsilon(1^3D_3)$		
$\eta_{b2}(1^1D_2)$		

BaBar & CLEO (08)
to be confirmed

Belle 2011, to be confirmed

BaBar & CLEO (04)

To be confirmed and interpreted:
$Y_b(10888)$

very recently discovered puzzling states: $Z_b(10610)$ & $Z_b(10650)$
decaying to $\Upsilon(nS)\ \pi^\pm$ (n=1,2,3) and $h_b(mP)\ \pi^\pm$ (m=1,2) in $\Upsilon(5S)$ decays
in association with a single charged pion
favoured quantum numbers $I=1$, $J^P=1^+$

decays to Υ and h_b occur with comparable rates $\rightarrow$ no spin-flip suppression

Exotic interpretations

Molecular state:
loosely bound state of a pair of mesons.
The dominant binding mechanism
should be pion exchange.
Being weakly bound, mesons tend to decay
as if they were free

Tetraquark:
Bound state of four quarks (diquark-antidiquark)
quarks grouped into colour triplet scalar
or vector clusters.
Strong decays via rearrangement processes

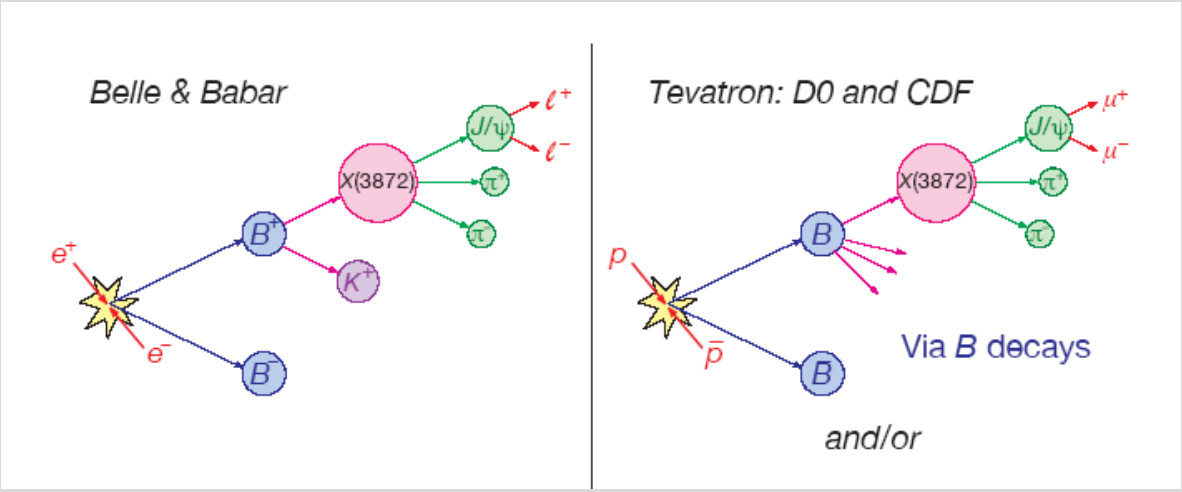
Distinctive features of multiquark picture with respect to charmonium:
- prediction of many new states
- possible existence of states with non-zero charge, strangeness or both

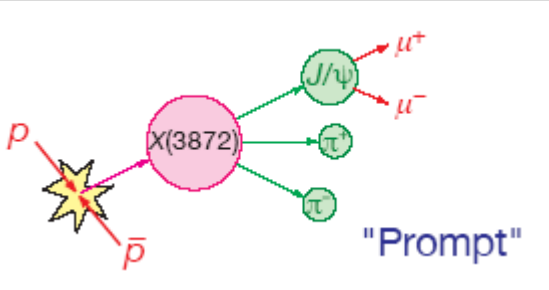
Charmonium hybrids
States with an excited gluonic degree of freedom
0+-, 1-+, 2+-...quantum numbers are not possible for $c\bar{c}$ states
but are possible for hybrids → would unambiguously signal an exotic state
Lattice predictions for the lowest lying hybrid: M 4.2 GeV

Threshold effects
Virtual enhancement of cross section
that may not indicate a resonance.

X(3872): discovery and properties

Observed in 2003 by four experiments in two production channels:





From R. Van Kooten, D0

- mass very close to $\overline{D}^0 D^{*0}$ threshold: **$M(X(3872)) - (M_{D0}+M_{D^{*0}}) = -0.32 \pm 0.35$ GeV**
- very small width: **$\Gamma < 2.3$ GeV** @ 90% c.l.
- $X \to J/\psi\, \pi\, \pi$ consistent with originating from $X \to J/\psi\, \rho$ → **C=+1**
- from angular distributions in $X \to J/\psi\, \pi\, \pi$ (CDF) → **$J^{PC} = 1^{++}$ (χ'_{c1})** or **$J^{PC} = 2^{-+}$ (η_{c2})**
- search for charged partners produced no result → **I=0**

X(3872): decays to two or three pions

Two and three pion modes were found with:

$$\frac{B(X \to J/\psi\pi^+\pi^-\pi^0)}{B(X \to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$$

Isospin violation

Possible explanation:

Suzuki, PRD 72, 114013

phase space severely suppressed

$$\frac{B(X \to J/\psi\pi^+\pi^-\pi^0)}{B(X \to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3 \quad \Rightarrow \quad \frac{A(X \to J/\psi\rho)}{A(X \to J/\psi\omega)} \cong 0.2$$

phace space not very suppressed

BaBar studies the $\pi\pi\pi$ distribution in $X \to J/\psi\ \omega$ which seeems too favour a p-wave decay

$J^P=2^-$ however in contrast with other properties of X

X(3872): radiative decays to J/ψ γ and ψ(2S) γ

Barnes et al, PRD 72, 054026
Swanson, PLB 598, 197

May help in distinguishing the different possibilities

- if **X= χ'_{c1}** → **X→ψ(2S) γ** should have a rate **larger** than X → J/ψ γ
- if **X= η_{c2} or X=composite object** → **X→ψ(2S) γ** is **suppressed** with respect to X → J/ψ γ

BaBar gives:

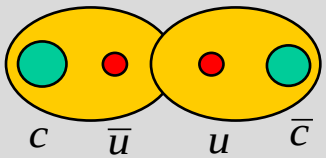
$$\frac{\Gamma(X(3872)\to\psi(2S)\gamma)}{\Gamma(X(3872)\to J/\psi\,\gamma)} = 3.4\pm1.4$$

while **Belle:**

$$\frac{\Gamma(X(3872)\to\psi(2S)\gamma)}{\Gamma(X(3872)\to J/\psi\,\gamma)} < 2.0$$

X(3872): molecule vs charmonium

X proximity to DD^* threshold may suggest that a molecular state made of charmed mesons contributes to the structure of X



Swanson, Brateen, Voloshin

Mixing of the molecule (dominant component) with other states such as pure charmonium ⟶ no definite isospin

radiative decays

In the molecular scenario $X \to D^0 \overline{D}^0 \gamma$ & $X \to D^+ D^- \gamma$ arise from the radiative decays of the individual vector mesons

Voloshin

$$D^{*0} \to D^0 \gamma, \quad \overline{D}^{*0} \to \overline{D}^0 \gamma \quad \& \quad D^{*\pm} \to D^{\pm} \gamma$$

and the decay $X \to D^+ D^- \gamma$ is strongly suppressed with respect to $X \to D^0 \overline{D}^0 \gamma$

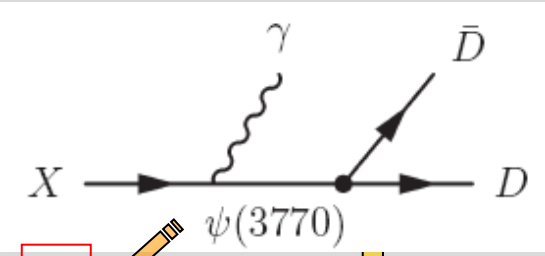
If observed, the suppression of $X \to D^+ D^- \gamma$ with respect to $X \to D^0 \overline{D}^0 \gamma$ would support the molecular interpretation?

X(3872) as the first radial excitation of χ_{c1} : radiative decays

Standard mechanism for radiative X transitions into charmed states

Pole diagrams

Intermediate $\psi(3770)$



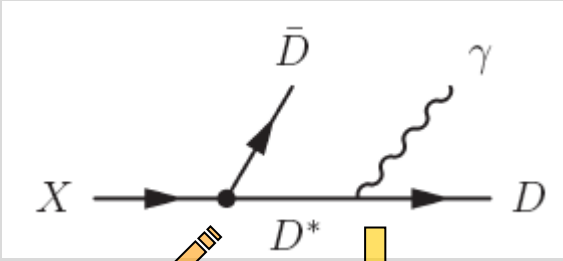
c

Unknown coupling

$g_{\psi DD}$

known from exp data

Intermediate D^*



$\hat{g}_1$

Unknown coupling

c'

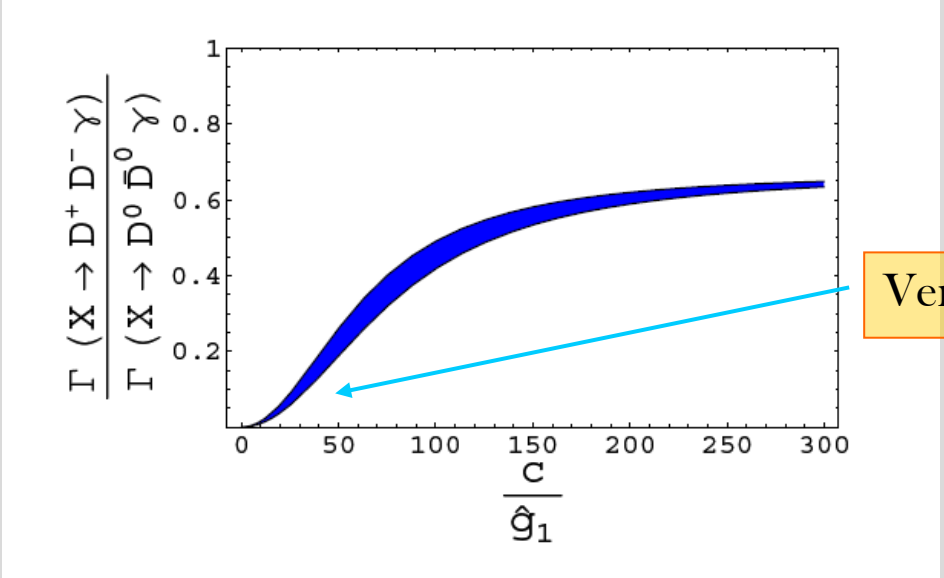
Can be obtained from data on radiative D^* decays

X(3872) as the first radial excitation of χ_{c1} : radiative decays

$$R = \frac{\Gamma(X \to D^+ D^- \gamma)}{\Gamma(X \to D^0 \overline{D}^0 \gamma)}$$

P. Colangelo, S. Nicotri, FDF
PLB 650, 16611

Can be evaluated as a function of the ratio of the two unknown couplings $\frac{c}{\hat{g}_1}$



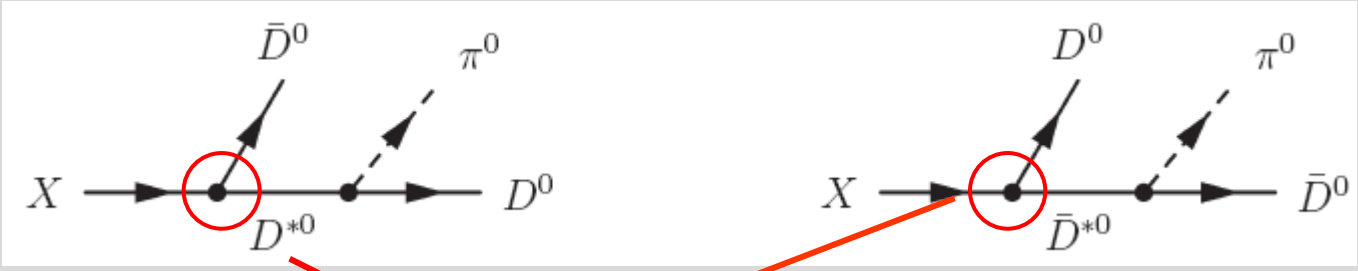
Very small values of R

- R<0.7
- in the $c\bar{c}$ description R is very small for small values of $\frac{c}{\hat{g}_1}$ (when the ψ pole contribution is negligible)

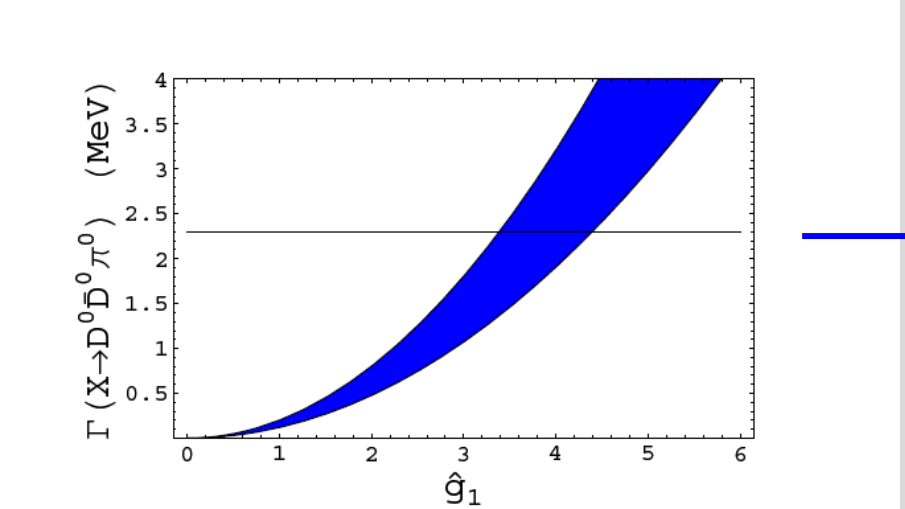
the suppression of R is not peculiar of the molecular scenario

X(3872) as the first radial excitation of χ_{c1} : hadronic decays

$$X \to D^0 \bar{D}^0 \pi^0$$



$\hat{g}_1$



Exp bound

Values of $\hat{g}_1$ typical of hadronic couplings can reproduce the small width of X(3872)

Heavy quark mass limit for heavy quarkonium states

Usual classification for the states:

$$n^{2s+1}L_J$$

- s = spin
- L = orbital angular momentum
- J = total angular momentum
- radial quantum number

with:

$$P = (-1)^{L+1}$$

$$C = (-1)^{L+s}$$

L=0 ↔ S- wave states
L=1 ↔ P- wave states
L=2 ↔ D- wave states
.....

- HQ spin simmetry **YES**
- HQ flavour symmetry **NO**

Multiplets for heavy quarkonium states

- L=0 multiplet

$$J = \frac{1+\not{v}}{2}\left[H_1^\mu \gamma_\mu - H_0 \gamma_5\right]\frac{1-\not{v}}{2}$$

spin 1 state spin 0 state

$\Rightarrow$ $\begin{cases} \text{n=1} \\ \text{n=2} \end{cases}$ $\boxed{\begin{matrix}(\eta_c(1S),\ \psi(1S)) \\ (\eta_c(2S),\ \psi(2S))\end{matrix}}$

- L=1 multiplet

triplet

$$J^\mu = \frac{1+\not{v}}{2}\left\{H_2^{\mu\alpha}\gamma_\alpha + \frac{1}{\sqrt{2}}\epsilon^{\mu\alpha\beta\gamma}v_\alpha\gamma_\beta H_{1\gamma} + \frac{1}{\sqrt{3}}(\gamma^\mu - v^\mu)H_0 + K_1^\mu\gamma_5\right\}\frac{1-\not{v}}{2}$$

spin 2 spin 1 spin 0 singlet spin 1

n=1

$\Downarrow$

$\boxed{\left[(\chi_{c0}(1P),\ \chi_{c1}(1P),\ \chi_{c2}(1P)),\ h_c(1P)\right]}$

- L=2 multiplet

triplet spin 3 triplet spin 2

$$J^{\mu\nu} = \frac{1+\not{v}}{2}\left\{H_3^{\mu\nu\alpha}\gamma_\alpha + \frac{1}{\sqrt{6}}\left(\epsilon^{\mu\alpha\beta\gamma}v_\alpha\gamma_\beta H_{2\gamma}^\nu + \epsilon^{\nu\alpha\beta\gamma}v_\alpha\gamma_\beta H_{2\gamma}^\mu\right)\right.$$

$$\left. + \frac{1}{2}\sqrt{\frac{3}{5}}\left[(\gamma^\mu - v^\mu)H_1^\nu + (\gamma^\nu - v^\nu)H_1^\mu\right] - \frac{1}{\sqrt{15}}(g^{\mu\nu} - v^\mu v^\nu)\gamma_\alpha H_1^\alpha + K_2^{\mu\nu}\gamma_5\right\}\frac{1-\not{v}}{2}$$

$\boxed{\left[\left(n^3D_1, n^3D_2, n^3D_3\right),\ n^1D_2\right]}$

triplet spin 1 singlet spin 2

Effective Lagrangian for radiative transitions of heavy quarkonia

F. De Fazio,
PRD 79, 054015

- $P \leftrightarrow S$

$$\mathcal{L}_{nP\leftrightarrow mS} = \delta_Q^{nPmS} Tr\left[\bar{J}(mS) J_\mu(nP)\right] v_\nu F^{\mu\nu} + \text{h.c.}$$

photon

a single constant describes all the transitions
among the various members of the P and S multiplets

- reduced theoretical uncertainty
- model independence

- $D \leftrightarrow P$

$$\mathcal{L}_{nD\leftrightarrow mP} = \delta_Q^{nDmP} Tr\left[\bar{J}_\alpha(mP) J_\mu^\alpha(nD)\right] v_\nu F^{\mu\nu} + \text{h.c.}$$

idem for transitions among members of D and P multiplets

$1P \to 1S$ transitions

Exploting known data:

$$\mathcal{B}(\chi_{c0}(1P) \to J/\psi\,\gamma) = (1.28 \pm 0.11) \times 10^{-2}$$
$$\mathcal{B}(\chi_{c1}(1P) \to J/\psi\,\gamma) = (36.0 \pm 1.9) \times 10^{-2}$$
$$\mathcal{B}(\chi_{c2}(1P) \to J/\psi\,\gamma) = (20.0 \pm 1.0) \times 10^{-2}$$

+ total widths of χ_{cJ} states

$$\delta_c^{1P1S} = 0.227 \pm 0.013 \ \mathrm{GeV}^{-1}$$
$$\delta_c^{1P1S} = 0.241 \pm 0.009 \ \mathrm{GeV}^{-1}$$
$$\delta_c^{1P1S} = 0.233 \pm 0.010 \ \mathrm{GeV}^{-1}$$

spin symmetry turns out to be experimentally well satisfied

averaged result:

$$\delta_c^{1P1S} = 0.235 \pm 0.006 \ \mathrm{GeV}^{-1}$$

can be used to predict:

$$\Gamma(h_c(1P) \to \eta_c(1P)\,\gamma) = 634 \pm 32\,\mathrm{KeV}$$

$2S \to 1P$ transitions

possibility to exploit data in the beauty sector:

$$\begin{aligned}
\mathcal{B}(\chi_{b0}(2P) \to \Upsilon(1S)\,\gamma) &= (9 \pm 6) \times 10^{-3} \\
\mathcal{B}(\chi_{b0}(2P) \to \Upsilon(2S)\,\gamma) &= (4.6 \pm 2.1) \times 10^{-2} \\
\mathcal{B}(\chi_{b1}(2P) \to \Upsilon(1S)\,\gamma) &= (8.5 \pm 1.3) \times 10^{-2} \\
\mathcal{B}(\chi_{b1}(2P) \to \Upsilon(2S)\,\gamma) &= (21 \pm 4) \times 10^{-2} \\
\mathcal{B}(\chi_{b2}(2P) \to \Upsilon(1S)\,\gamma) &= (7.1 \pm 1.0) \times 10^{-2} \\
\mathcal{B}(\chi_{b2}(2P) \to \Upsilon(2S)\,\gamma) &= (16.2 \pm 2.4) \times 10^{-2}
\end{aligned}$$

define width ratio

$$R_J^{(b)} = \frac{\Gamma(\chi_{bJ}(2P) \to \Upsilon(2S)\,\gamma)}{\Gamma(\chi_{bJ}(2P) \to \Upsilon(1S)\,\gamma)}$$

and coupling ratio

$$R_\delta^{(b)} = \frac{\delta_b^{2P1S}}{\delta_b^{2P2S}}$$

$$R_\delta^{(b)} = 8.8 \pm 0.7$$

even though the coupling might be different passing from beauty to charm,
it is reasonable to assume that the ratios of the couplings stay stable

we can predict analogous charm ratios $R_J^{(c)}$

$2S \to 1P$ transitions

prediction for J=1:

$$R_1^{(c)} = \frac{\Gamma(\chi_{c1}(2P) \to \psi(2S)\,\gamma)}{\Gamma(\chi_{c1}(2P) \to \psi(1S)\,\gamma)} = 1.64 \pm 0.25$$

Identifing X(3872) with χ_{c1}(2P) and using the data:

$$\mathcal{B}(B^+ \to XK^+, X \to J/\psi\,\gamma) = (2.8 \pm 0.8 \pm 0.2) \times 10^{-6}$$
$$\mathcal{B}(B^+ \to XK^+, X \to \psi(2S)\,\gamma) = (9.9 \pm 2.9 \pm 0.6) \times 10^{-6}$$

$$R_X = \frac{\Gamma(X(3872) \to \psi(2S)\,\gamma)}{\Gamma(X(3872) \to \psi(1S)\,\gamma)} = 3.5 \pm 1.4$$

$R_1^{(c)}$ and R_X are close enough to consider the assumption X(3872) = χ_{c1}(2P) plausible to be contrasted with composite scenarios in which X(3872) $\to \psi(2S)\gamma$ is suppressed with respect to X(3872) $\to \psi(1S)\gamma$

Concluding remarks

• open charm mesons:

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

- 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 :

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

P. Colangelo et al.
MPLA 19, 2083

• quarkonium like states:

- X(3872) still puzzling state
- identification with χ'_{c1} plausible (according to my analysis of radiative decays)

• Many other states not discussed
Strongly required independent confirmation of charged quarkonium-like states
(at present only Belle has evidence)