meson spectroscopy with open charm and beauty

outline

- basics of HQET
- open charm spectroscopy
- predictions in the beauty sector

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prologue:

QCD

$$L_{QCD} = \sum_{q=u,d,s,c,b,t} \bar{q}\left(i\gamma^{\mu}D_{\mu} - m_q\right) q - \frac{1}{4} G^{a,\mu\nu} G^{a}_{\mu\nu}$$

$$D_\mu = \partial_\mu - i\, g_s T^a A^a{}_\mu$$

$$G^a{}_{\mu\nu} = \partial_\mu A^a{}_\nu - \partial_\nu A^a{}_\mu + g_s f^{abc} A^b{}_\mu A^c{}_\nu$$

M. Gell-Mann
H. Fritzsch
H. Leutwyler

XVI HEP Conference 1972

simple formula
all information about matter that constructs our world is in it

formidable dynamical complexity

- nuclear physics
  - Regge amplitudes
    - hadron variety
      - quarks and gluons at high temperature/high density

involving
- light and heavy quarkonia
- exotics, glueballs
- chiral phenomenology
- exclusive processes, inclusive modes
- interplay between strong and weak phenomena

full solution to QCD not available

hadron spectrum emerges from the full QCD dynamics

partial solutions
in the nonperturbative sector

quark model
QCD sum rules
lattice QCD
} not discussed

effective theories
AdS/CFT inspired methods

Heavy quark symmetry: intuitive picture

For systems composed by a heavy quark and light constituents (light degrees of freedom) the momentum exchanged is of order Λ_{QCD}
→ the HQ moves with the velocity of the hadron (*velocity superselection rule* Georgi)

$$\begin{cases} p_H^\mu = m_H v \\ p_Q^\mu = m_Q v_Q = m_Q v + k \end{cases} \Rightarrow \quad v_Q = v + \frac{k}{m_Q} \xrightarrow[m_Q \to \infty]{} v_Q = v$$

residual momentum of $O(\Lambda_{QCD})$

Light degrees of freedom are blind to the orientation the spin of Q:
colour magnetism vanishes when $m_Q \to \infty$ spin-orbit interaction vanishes

Light degrees of freedom are blind to the flavour (i.e. the mass) of Q
Q acts as a static color source

Heavy quark symmetry: intuitive picture

Hadrons which differ only for the HQ flavour or for the orientation of the HQ spin have the same configuration of the light degrees of freedom

HQET does not allow to determine such a configuration, but allows to establish relations among the properties of hadrons obtained through HQ spin or flavour rotations

Heavy quark symmetry is not exact: corrections can be systematically included through an expansion in Λ_{QCD}/m_Q

from QCD to HQET

Starting point: QCD Lagrangian for the heavy quark

$$\mathrm{L}_Q = \overline{Q}(i\not{D} - m_Q)Q$$

To describe a heavy quark moving with velocity v and small residual momentum it is appropriate to introduce large and small component fields:

$$h_v(x) = e^{im_Q v\cdot x}\frac{1+\not{v}}{2}Q(x) \qquad H_v(x) = e^{im_Q v\cdot x}\frac{1-\not{v}}{2}Q(x)$$

projectors on states with definite velocity

$$Q(x) = e^{-im_Q v\cdot x}[h_v(x) + H_v(x)]$$

in the rest frame
upper two components of Q

$$\not{v}\, h_v = h_v$$

in the rest frame
lower two components of Q

$$\not{v}\, H_v = -H_v$$

From QCD to HQET

$$\mathrm{L}_{\mathrm{Q}} = \overline{Q}(i\not{D} - m_Q)Q$$

$$\Rightarrow \quad \mathrm{L}_{\mathrm{Q}} = \overline{h}_v\, iv\cdot D\, h_v - \overline{H}_v(iv\cdot D + 2m_Q)H_v + \overline{h}_v\, i\not{D}_\perp H_v + \overline{H}_v\, i\not{D}_\perp h_v$$

$$D_\perp^\mu = D^\mu - (v\cdot D)\, v^\mu$$

$$D_\perp \cdot v = 0$$

From QCD to HQET

$$\mathcal{L}_Q = \overline{Q}(i\not{D} - m_Q)Q$$

$$\Rightarrow \quad \mathcal{L}_Q = \overline{h}_v\, iv\cdot D\, h_v - \overline{H}_v(iv\cdot D + 2m_Q)H_v + \overline{h}_v\, i\, \not{D}_\perp H_v + \overline{H}_v\, i\, \not{D}_\perp h_v$$

degrees of freedom
to be integrated out

$$D^\mu_\perp = D^\mu - (v\cdot D)\, v^\mu$$

$$D_\perp \cdot v = 0$$

Equation of motion for Q

$$i\not{D}\, h_v + (i\not{D} - 2m_Q)H_v = 0$$

$$H_v = \frac{i\not{D}_\perp}{(i\, v\cdot D + 2m_Q)}\, h_v$$

From QCD to HQET

expanding in m_Q^{-1}

$$\mathrm{L}_{\mathrm{eff},\,1/\mathrm{m}} = \bar{h}_v\, iv\cdot D\, h_v + \frac{1}{2m_Q}\bar{h}_v\,(i\not{D}_\perp)^2 h_v + \frac{g_s}{4m_Q}\bar{h}_v\,\sigma_{\alpha\beta}\mathrm{G}^{\alpha\beta}h_v + O\left(\frac{1}{m_Q^2}\right)$$

HQET lagrangian

heavy quark kinetic energy operator due to the residual motion

chromomagnetic operator

HQET

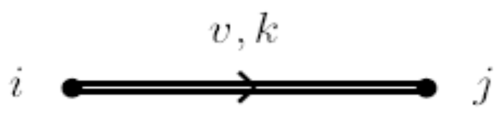
$$\mathcal{L}_{\mathrm{HQET}} = \bar{h}_v \, i v \cdot D \, h_v$$

Eichten, Hill, Georgi

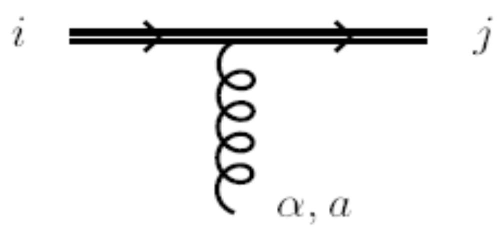
no more dependence on the HQ mass → Flavour symmetry

invariance under HQ spin SU(2) rotations → Spin symmetry

Feynman rules



$$= \frac{i}{v \cdot k + i\eta} \frac{1 + \not{v}}{2} \delta_{ji}$$



$$= i g_s \, v^{\alpha} \, (t_a)_{ji}$$

simplified:
no more γ matrices!

Spectroscopic implications

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: $J = s_\ell \pm \frac{1}{2}$

Heavy quark flavour irrelevant as $m_Q \to \infty$ } **Flavour symmetry**

possibility to relate charm and beauty hadron properties

Spectroscopic implications

mass of a hadron containing a HQ

$$M_{H_Q} = m_Q + \bar{\Lambda} + \frac{\mu_\pi^2 - \mu_G^2}{2m_Q} + \mathcal{O}\left(\frac{1}{m_Q^2}\right)$$

independent of m_Q

Spectroscopic implications

mass of a hadron containing a HQ

$$M_{H_Q} = m_Q + \bar{\Lambda} + \frac{\mu_\pi^2 - \mu_G^2}{2m_Q} + \mathcal{O}\left(\frac{1}{m_Q^2}\right)$$

$\bar{\Lambda}$: independent of m_Q

HQ states normalized to $2m_Q$: μ_π^2 and μ_G^2 independent of m_Q

$$\mu_\pi^2 = \frac{1}{2m_Q} \langle H_Q | \bar{h}_v (i \not{D}_\perp)^2 h_v | H_Q \rangle ,$$

$$\mu_G^2 = \frac{1}{2m_Q} \langle H_Q | \bar{h}_v \frac{g_s \sigma_{\alpha\beta} G^{\alpha\beta}}{2} h_v | H_Q \rangle$$

μ_π^2 → HQ kinetic energy, breaks flavour symmetry

μ_G^2 → matrix element of the chromomagnetic operator
breaks spin symmetry

$$\mu_G^2 = -2\left[J(J+1) - \tfrac{3}{2}\right]\lambda_2$$

→ λ_2 also independent of m_Q
it can be obtained from measured masses

example: for B, B* mesons

$$\lambda_2 = \frac{1}{4}(M_{B^*}^2 - M_B^2) \simeq 0.12\ \mathrm{GeV}^2$$

EXAMPLE: L=0 and L=1

$$L=0,\quad s_\ell^P=\frac{1}{2}^- \rightarrow \begin{cases} J=1 & D^*,\ D_s^*,\ \ B^*,\ B_s^* \\ J=0 & D,\ D_s,\ \ \ B,\ \ B_s \end{cases}$$

$$L=1 \rightarrow \begin{cases} s_\ell^P=\frac{1}{2}^+ \rightarrow \begin{cases} J=1 \\ J=0 \end{cases} \\ s_\ell^P=\frac{3}{2}^+ \rightarrow \begin{cases} J=2 & D_2^*, D_{s2}^* \\ J=1 & D_1, D_{s1} \end{cases} \end{cases}$$

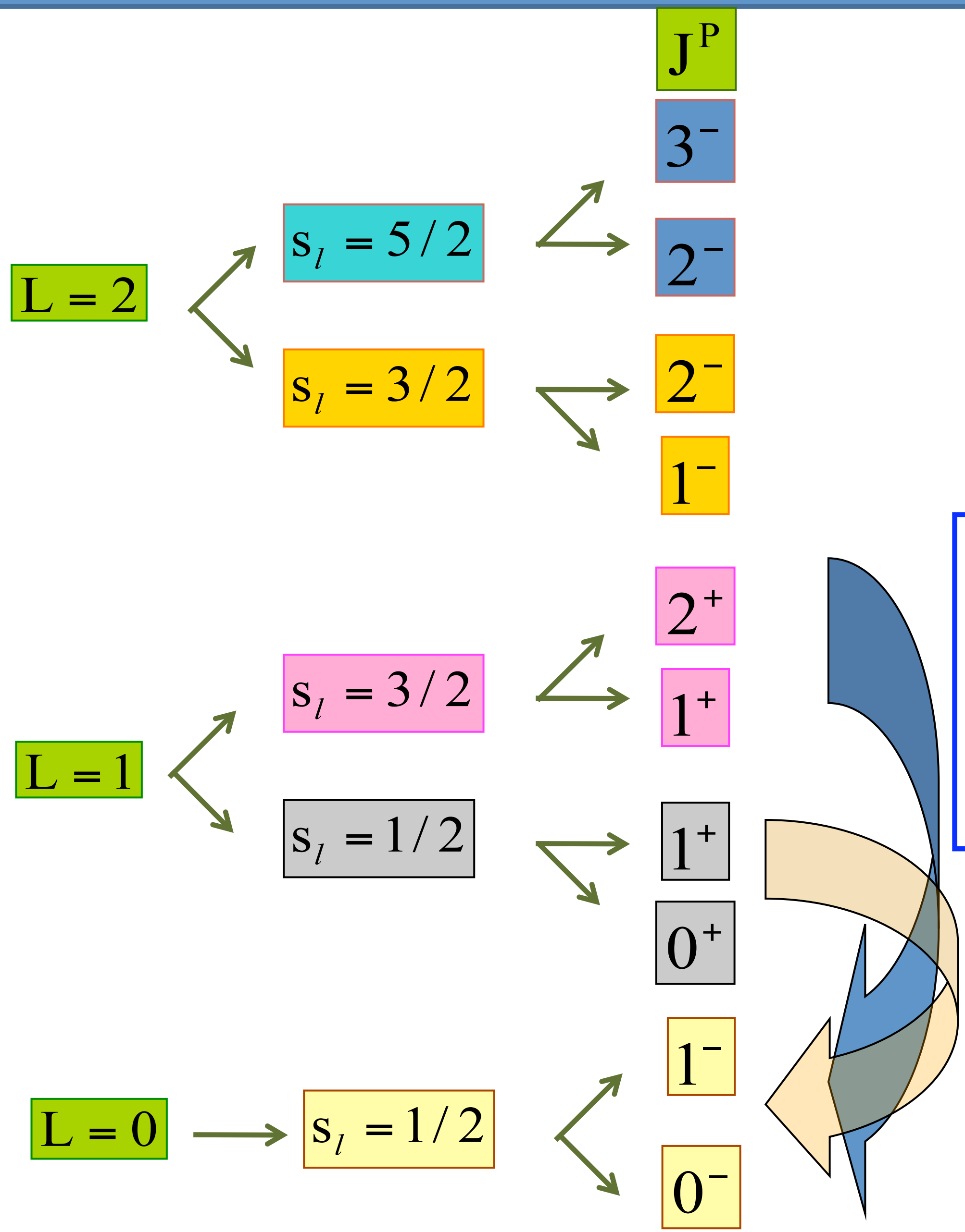
$\frac{1}{2}^+ \rightarrow \frac{1}{2}^- + \pi(K):$ s-wave -> $\frac{1}{2}^+$ mesons expected to be broad

$\frac{3}{2}^+ \rightarrow \frac{1}{2}^- + \pi(K):$ d-wave -> $\frac{3}{2}^+$ mesons expected to be narrow

finite m_Q corrections

- remove degeneracy between the states of the same doublet
- induce a mixing between the two 1^+ states

$Q\bar{q}$ multiplets



strong transitions between multiplets

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

d-wave transition

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

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

s-wave transition

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

HQ limit: doublets 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

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

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

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

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

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

Wise, Burdman, Georgi, Falk,....

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

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

$$\xi = e^{\frac{iM}{f}}, \quad \Sigma = \xi^2$$

$$A^\mu_{ba} = \frac{1}{2}(\xi^+ \partial^\mu \xi - \xi \partial^\mu \xi^+)_{ba}$$

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

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

properties

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

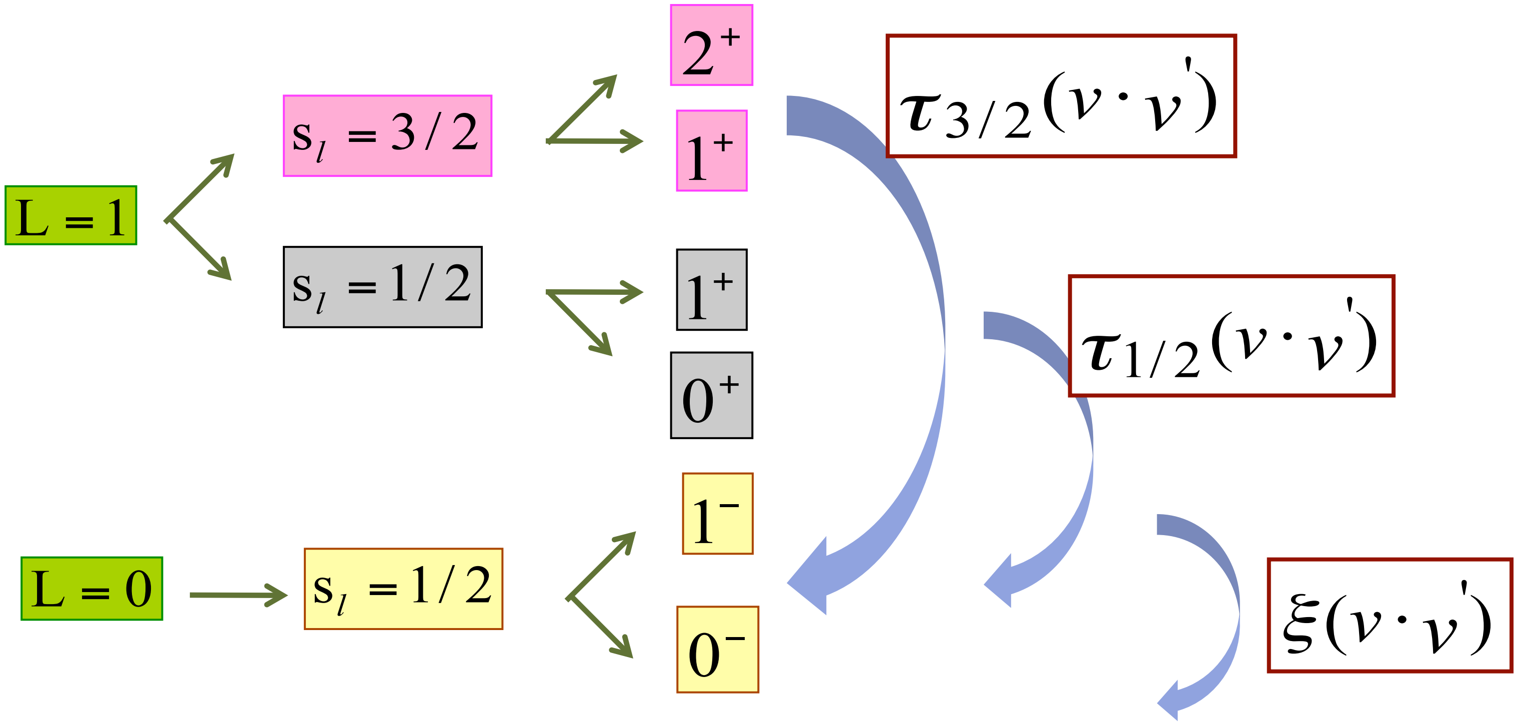
Partial decay widths are independent on the HQ flavour

Mass splittings among the doublets are independent of the HQ flavour

Flavour symmetry

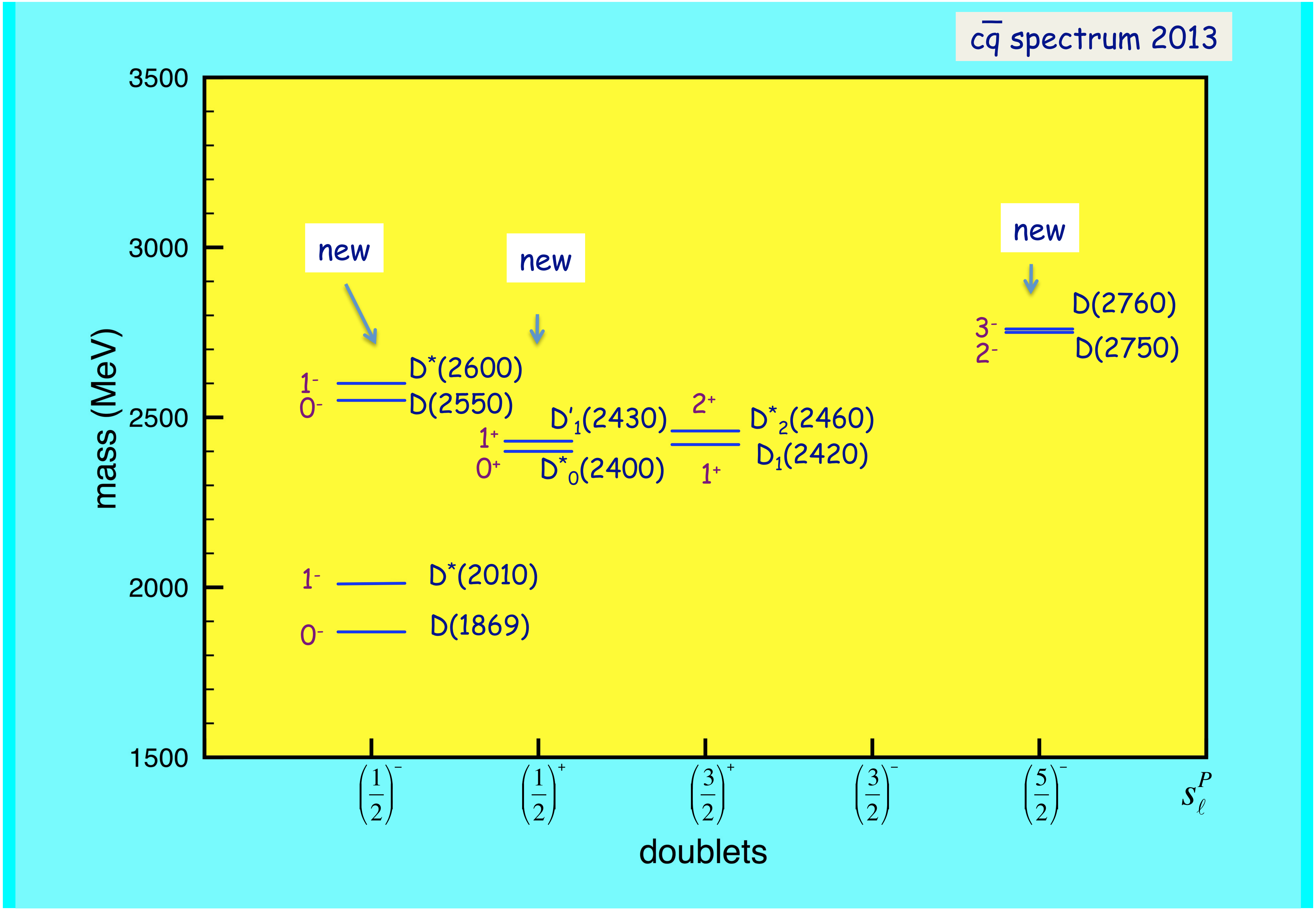
exclusive semileptonic decays of excited heavy mesons

Isgur, Wise
Nussinov, Wetzel,
Voloshin, Shifman

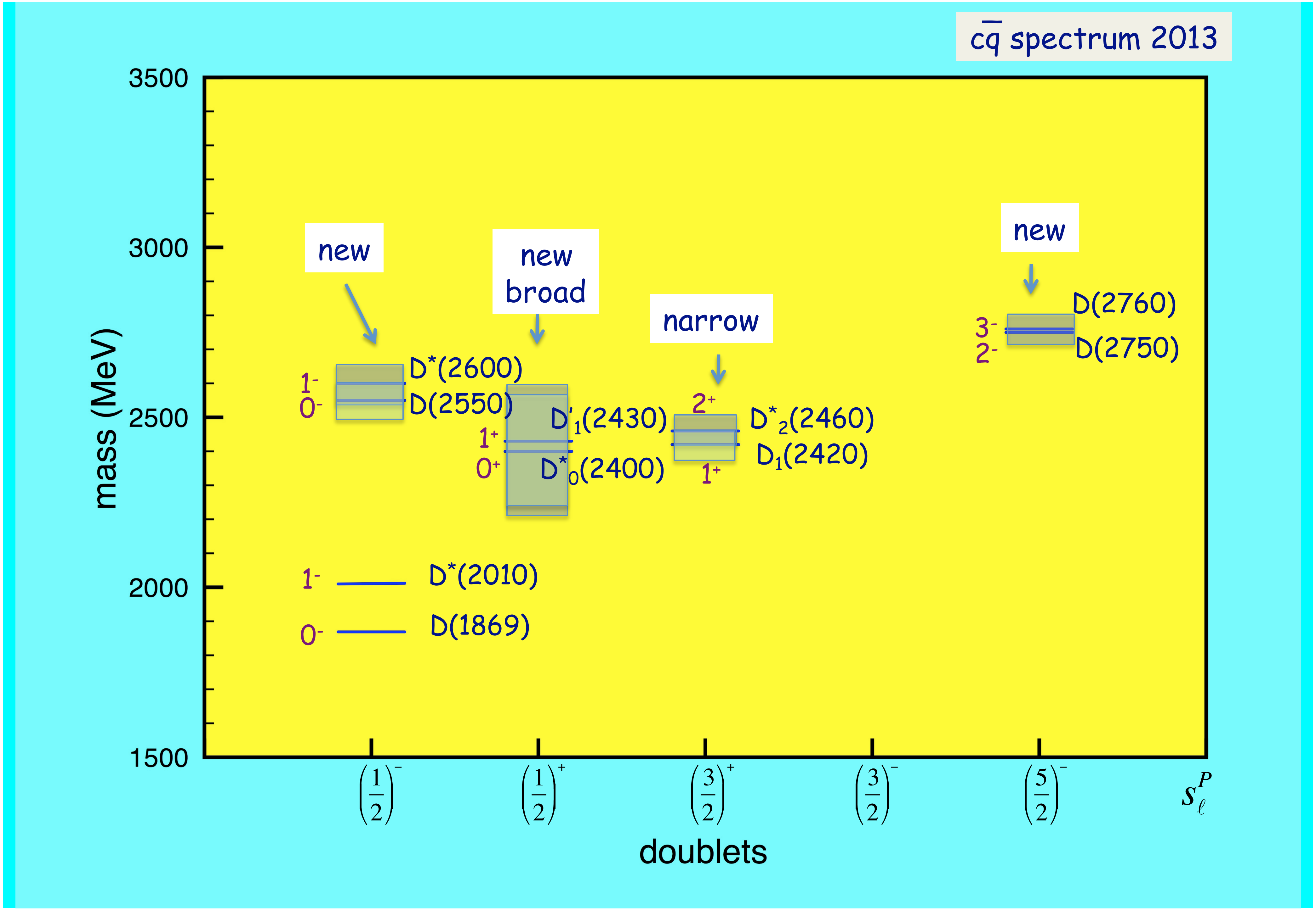


HQET provides relations among the full theory form factors
it does not allow to calculate these universal functions

news in open charm

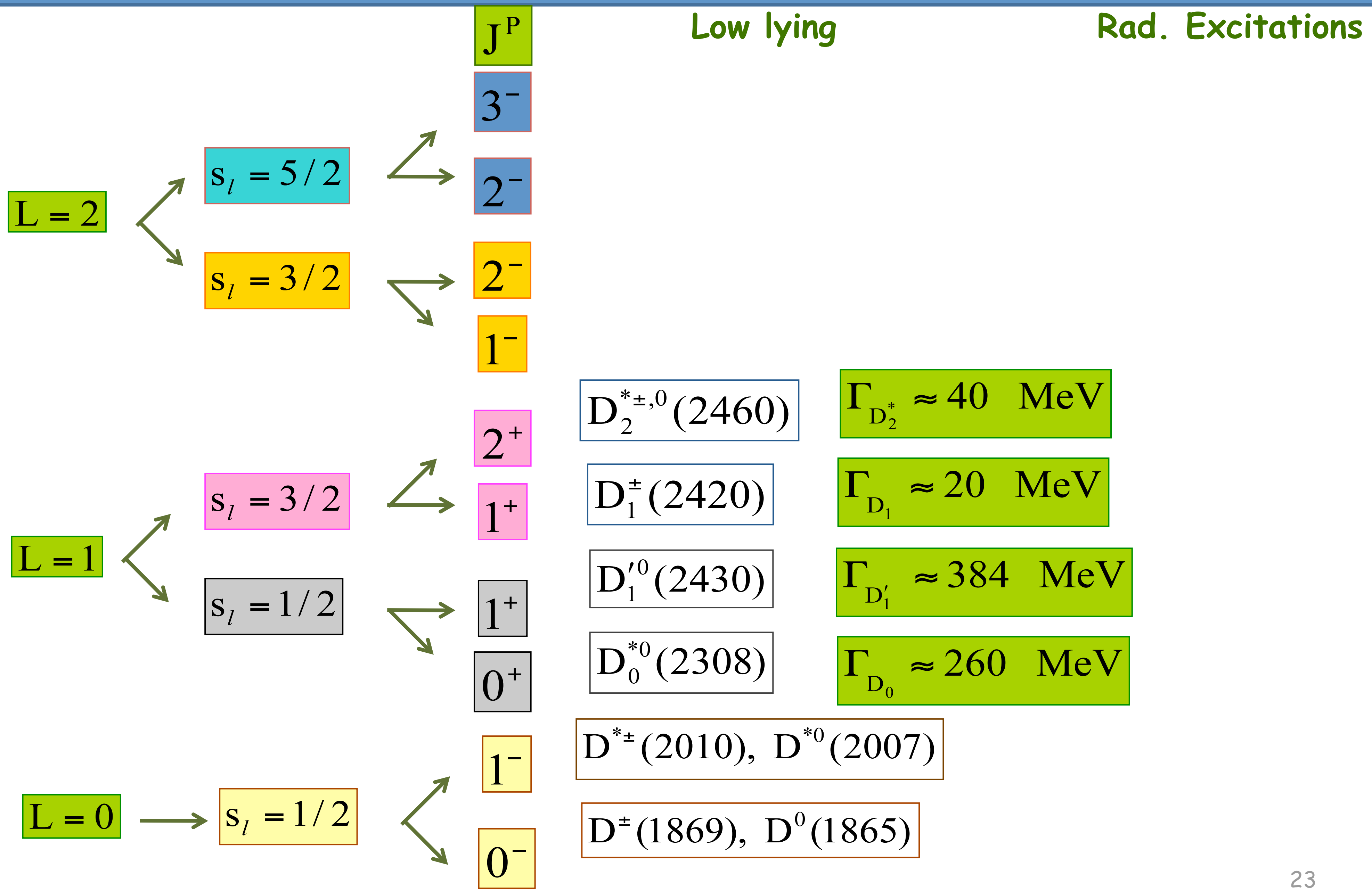


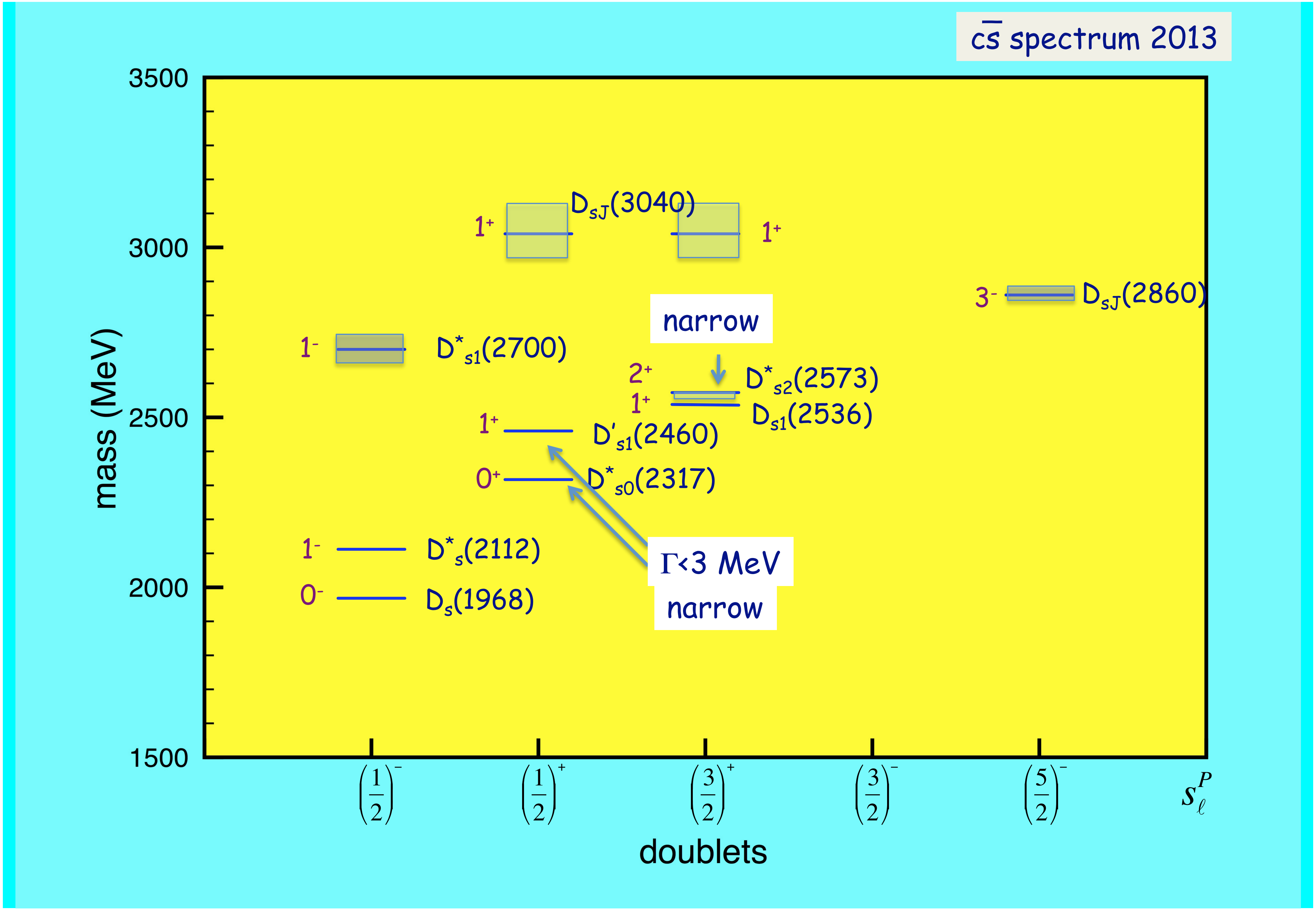
$c\bar{q}$ spectrum 2013
mass (MeV)
3500
3000
2500
2000
1500
new
new
new
1^-
0^-
D*(2600)
D(2550)
1^+
0^+
D'$_1$(2430)
D*$_0$(2400)
2^+
1^+
D*$_2$(2460)
D$_1$(2420)
3^-
2^-
D(2760)
D(2750)
1^-
D*(2010)
0^-
D(1869)
$\left(\frac{1}{2}\right)^-$
$\left(\frac{1}{2}\right)^+$
$\left(\frac{3}{2}\right)^+$
$\left(\frac{3}{2}\right)^-$
$\left(\frac{5}{2}\right)^-$
s_ℓ^P
doublets



$c\bar{q}$ spectrum 2013
mass (MeV)
3500
3000
2500
2000
1500
new
new
broad
narrow
new
1^-
0^-
$D^*(2600)$
$D(2550)$
1^+
0^+
$D'_1(2430)$
$D^*_0(2400)$
2^+
1^+
$D^*_2(2460)$
$D_1(2420)$
3^-
2^-
$D(2760)$
$D(2750)$
1^-
$D^*(2010)$
0^-
$D(1869)$
$\left(\frac{1}{2}\right)^-$
$\left(\frac{1}{2}\right)^+$
$\left(\frac{3}{2}\right)^+$
$\left(\frac{3}{2}\right)^-$
$\left(\frac{5}{2}\right)^-$
s_ℓ^P
doublets

$c\bar{q}$ multiplets

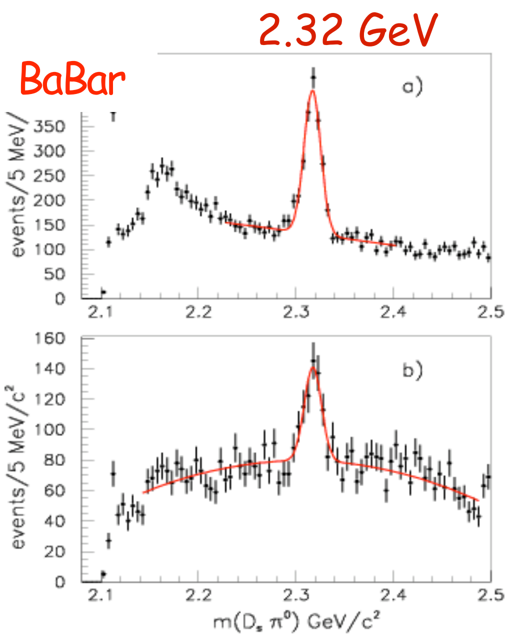


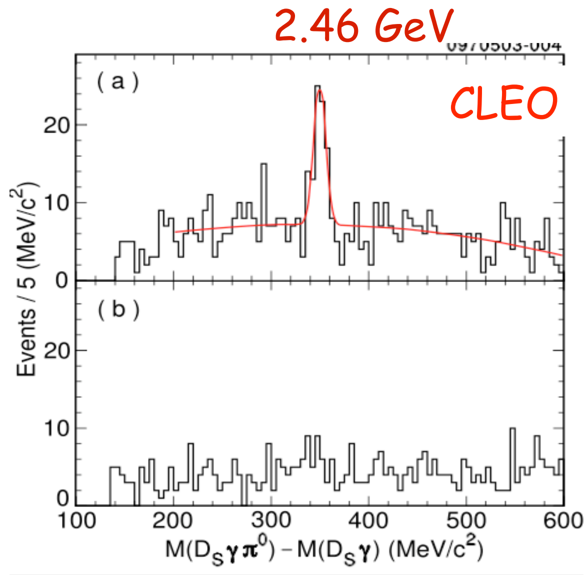


$c\bar{s}$ spectrum 2013
mass (MeV)
3500
3000
2500
2000
1500
$D_{sJ}(3040)$
1+
1+
3-
$D_{sJ}(2860)$
narrow
1-
$D^*_{s1}(2700)$
2+
$D^*_{s2}(2573)$
1+
$D_{s1}(2536)$
1+
$D'_{s1}(2460)$
0+
$D^*_{s0}(2317)$
1-
$D^*_s(2112)$
0-
$D_s(1968)$
Γ<3 MeV
narrow
$\left(\frac{1}{2}\right)^-$
$\left(\frac{1}{2}\right)^+$
$\left(\frac{3}{2}\right)^+$
$\left(\frac{3}{2}\right)^-$
$\left(\frac{5}{2}\right)^-$
s_ℓ^P
doublets

instead of broad $D^{(*)}K$ resonances

narrow peaks in $D_s\pi^0$ mass distribution: $D^*_{sJ}(2317)$ and in $D^*_s\pi^0$, $D_s\gamma$: $D_{sJ}(2460)$





$J^P = 0^+$ $I = 0$ favoured

$$M = 2317.4 \pm 0.6 \;\; MeV$$

$$\Gamma < 3.8 \;\; MeV$$

below DK threshold
M(D)+M(K)=2360 MeV

$J^P = 1^+$ $I = 0$ favoured

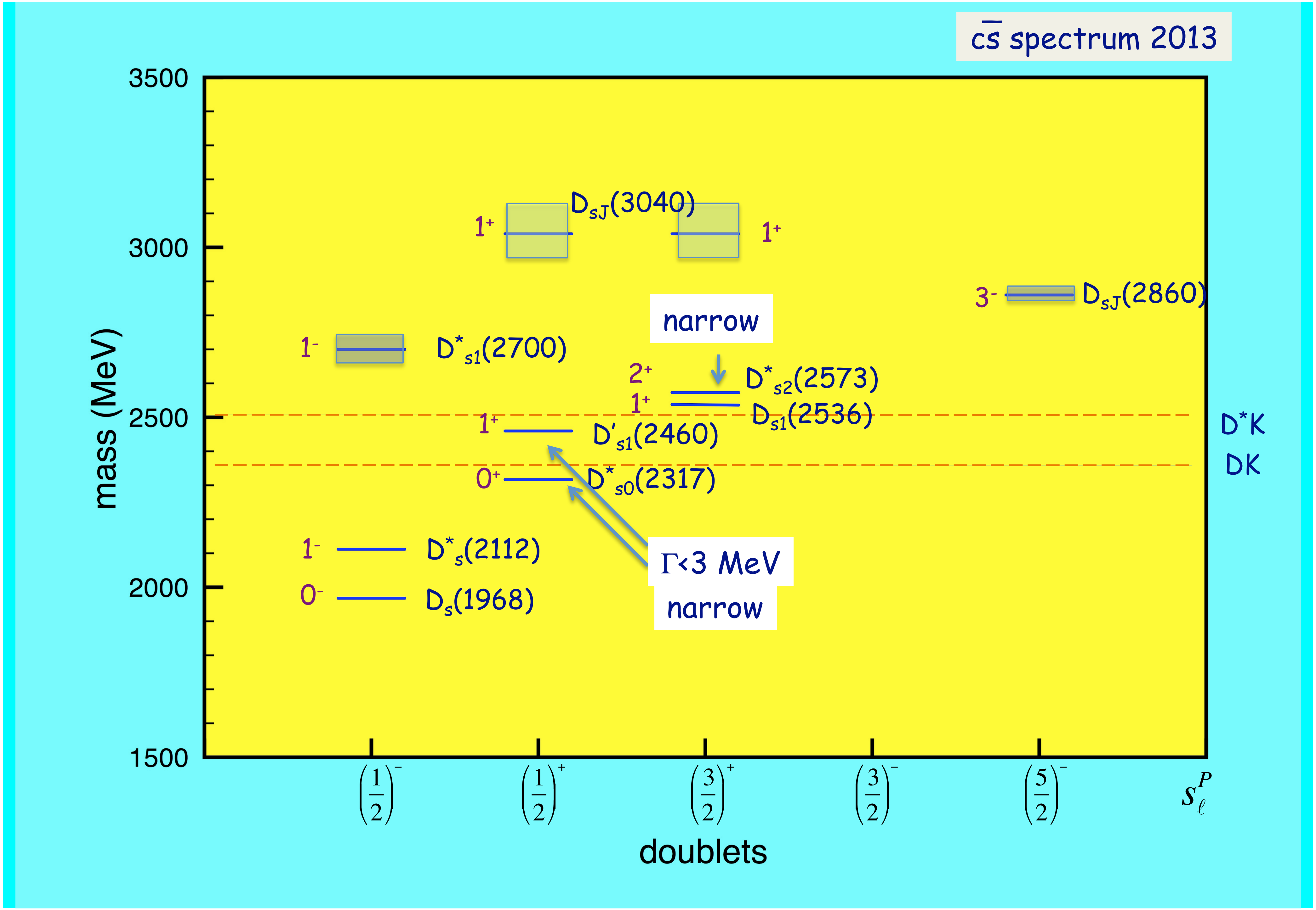
$$M = 2458.8 \pm 1.0 \;\; MeV$$

$$\Gamma < 3.5 \;\; MeV$$

below D*K threshold
$M(D^*)+M(K)=2510$ MeV

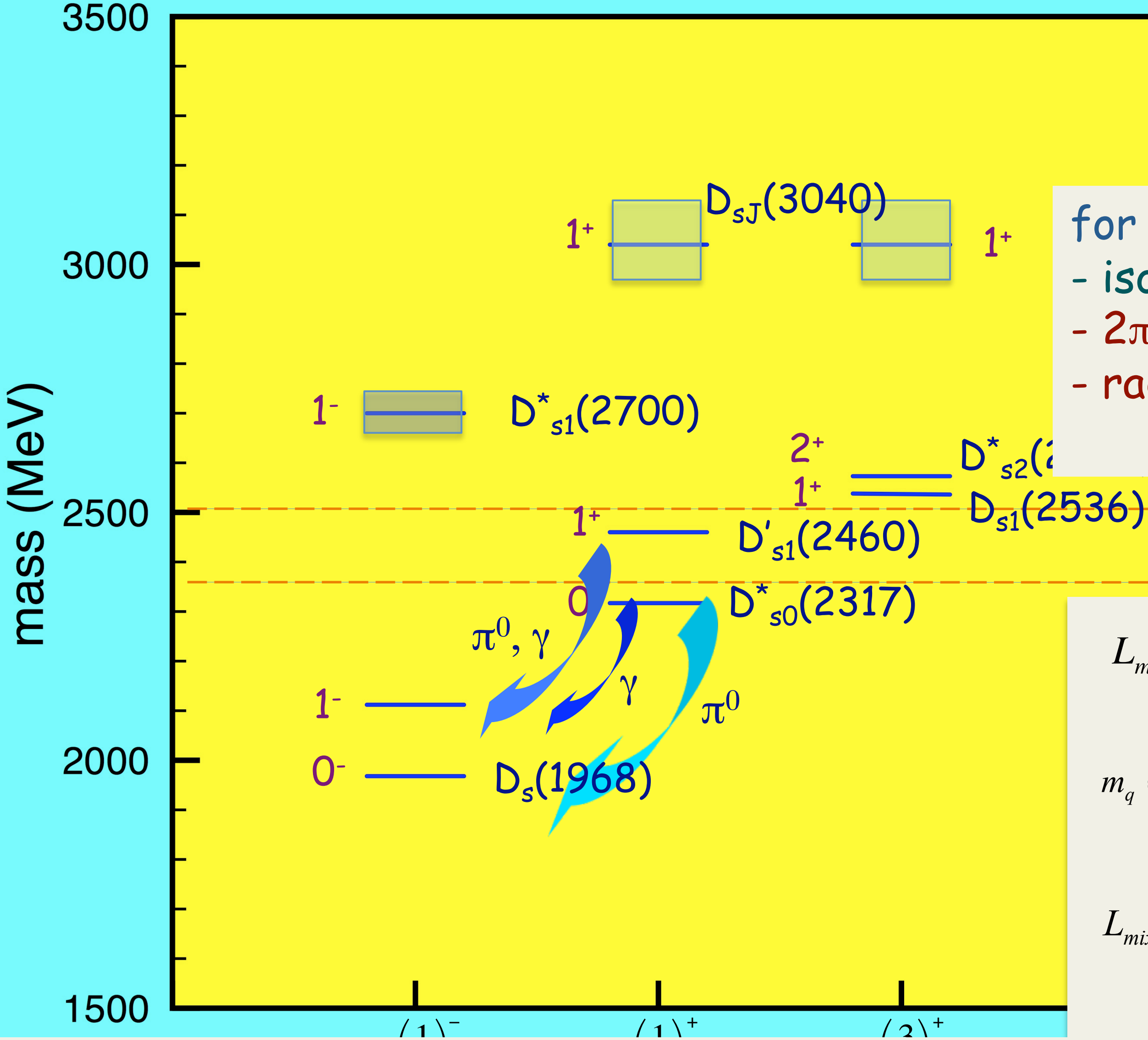
also in Belle and Focus

25



cs spectrum 2013
3500
3000
2500
2000
1500
mass (MeV)
1+
DsJ(3040)
1+
3-
DsJ(2860)
narrow
1-
D*s1(2700)
2+
D*s2(2573)
1+
Ds1(2536)
1+
D's1(2460)
D*K
0+
D*s0(2317)
DK
1-
D*s(2112)
Γ<3 MeV
narrow
0-
Ds(1968)
(1/2)-
(1/2)+
(3/2)+
(3/2)-
(5/2)-
s_ℓ^P
doublets

$c\bar{s}$ spectrum 2013



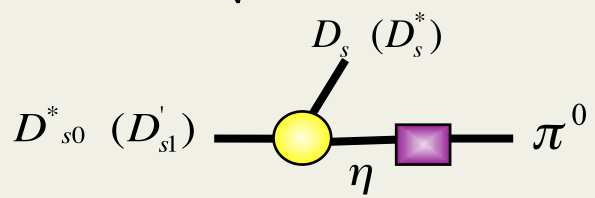
for masses below $D^{(*)}K$ threshold
- isospin violating π decays
- 2π
- radiative

narrow widths

$$L_{mass} = \frac{\tilde{\mu} f_\pi^2}{4} Tr\left[\xi\, m_q\, \xi + \xi^+\, m_q\, \xi^+\right]$$

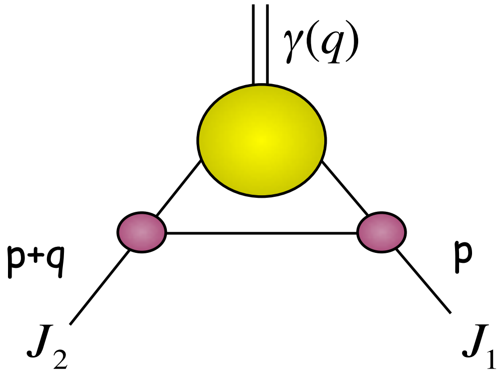
$$m_q = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}$$

$$L_{mixing} = \frac{\tilde{\mu}}{2} \frac{m_d - m_u}{\sqrt{3}} \pi^0 \eta$$



Br, full widths and line shapes important to distinguish among different quark structures

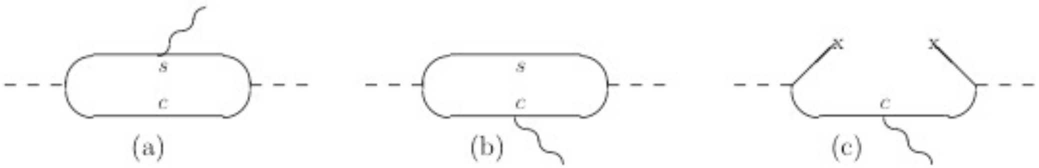
radiative decays of D_{sJ} mesons by light-cone QCD sum rules

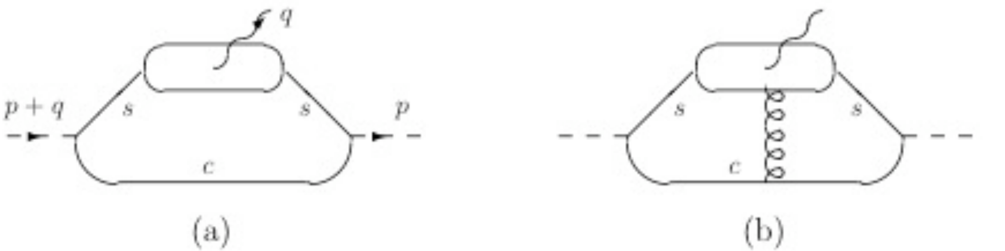


$$\Pi(p,q) = i \int dx \; \langle \gamma \; (q) | \, T\left[J_1(x), \bar{J}_2(0)\right] |0\rangle \; e^{ipx}$$

$$\Pi^{HAD}(p,q) = \frac{\langle 0|J_1|M_1(p)\rangle}{p^2 - m_1^2} \langle \gamma(q) M_1(p) | M_2(p+q)\rangle \frac{\langle M_2(p+q)|\bar{J}_2|0\rangle}{(p+q)^2 - m_2^2} + \cdots$$

in the Euclidean region $p^2 \ll 0$ and $(p+q)^2 \ll 0$: light-cone expansion $x^2 \to 0$



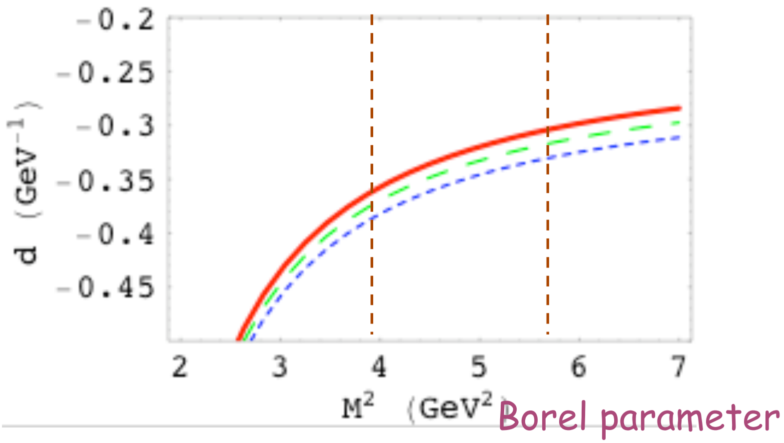


light-cone photon distribution amplitudes of different twist involved

Balitsky, Braun
Ball, Braun, Kivel

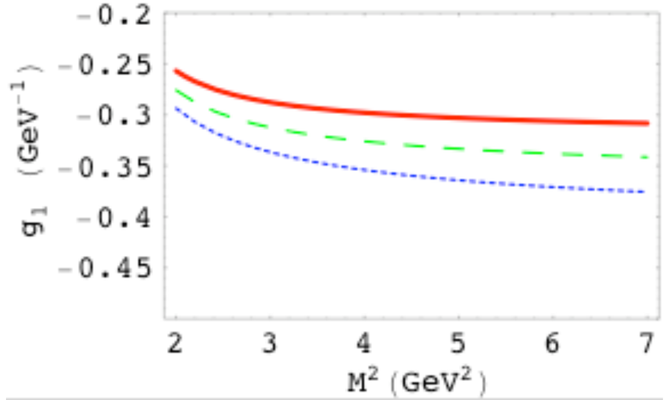
$D_{sJ}^*(2317) \to D_s^* \gamma$

$$\langle \gamma(q,\varepsilon) D_s^*(p,\eta) | D_{s0}^*(p+q) \rangle = e\, d\, (\varepsilon^* \eta^*\, pq - \varepsilon^* p\; \eta^* q)$$



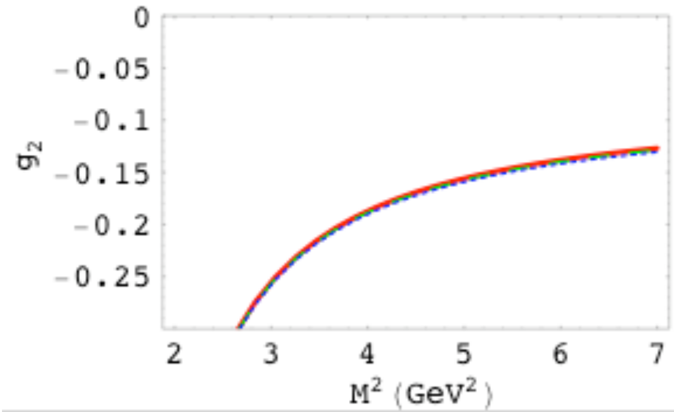
$$\Gamma(D_{s0}^* \to D_s^* \gamma) = (4-6)\ \ keV$$

$D_{sJ}(2460) \to D_s \gamma$



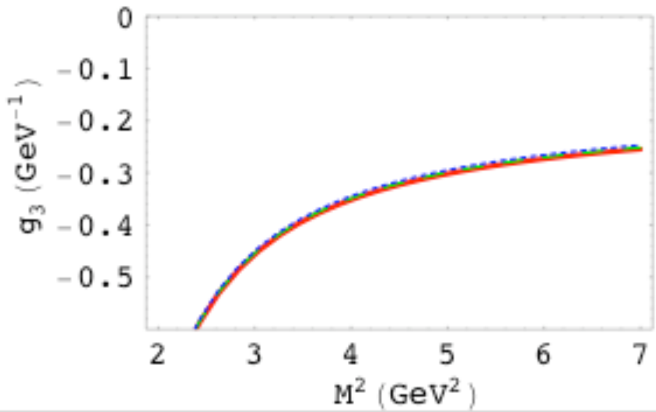
$$\Gamma(D_{s1}^{'} \to D_s \gamma) = (19-29)\ \ keV$$

$D_{sJ}(2460) \to D_s^* \gamma$



$$\Gamma(D_{s1}^{'} \to D_{s0} \gamma) = (0.6-1.1)\ \ keV$$

$D_{sJ}(2460) \to D_{sJ}^*(2317)\, \gamma$



$$\Gamma(D_{s1}^{'} \to D_{s0} \gamma) = (0.5-0.8)\ \ keV$$

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

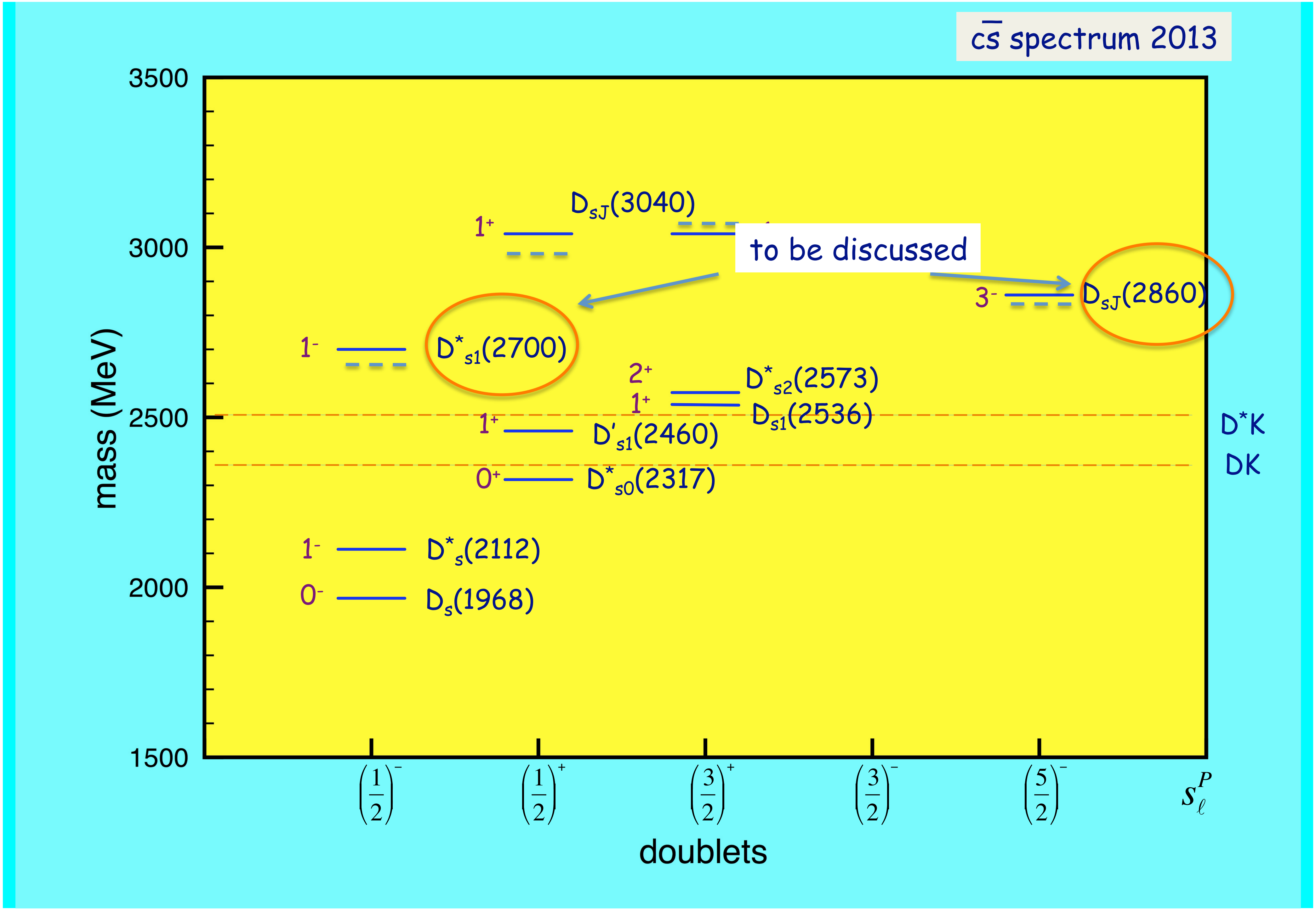
$(m_c \to \infty)$

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

computed radiative rates of $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$ follow the experimental pattern compatible with the interpretation as conventional states

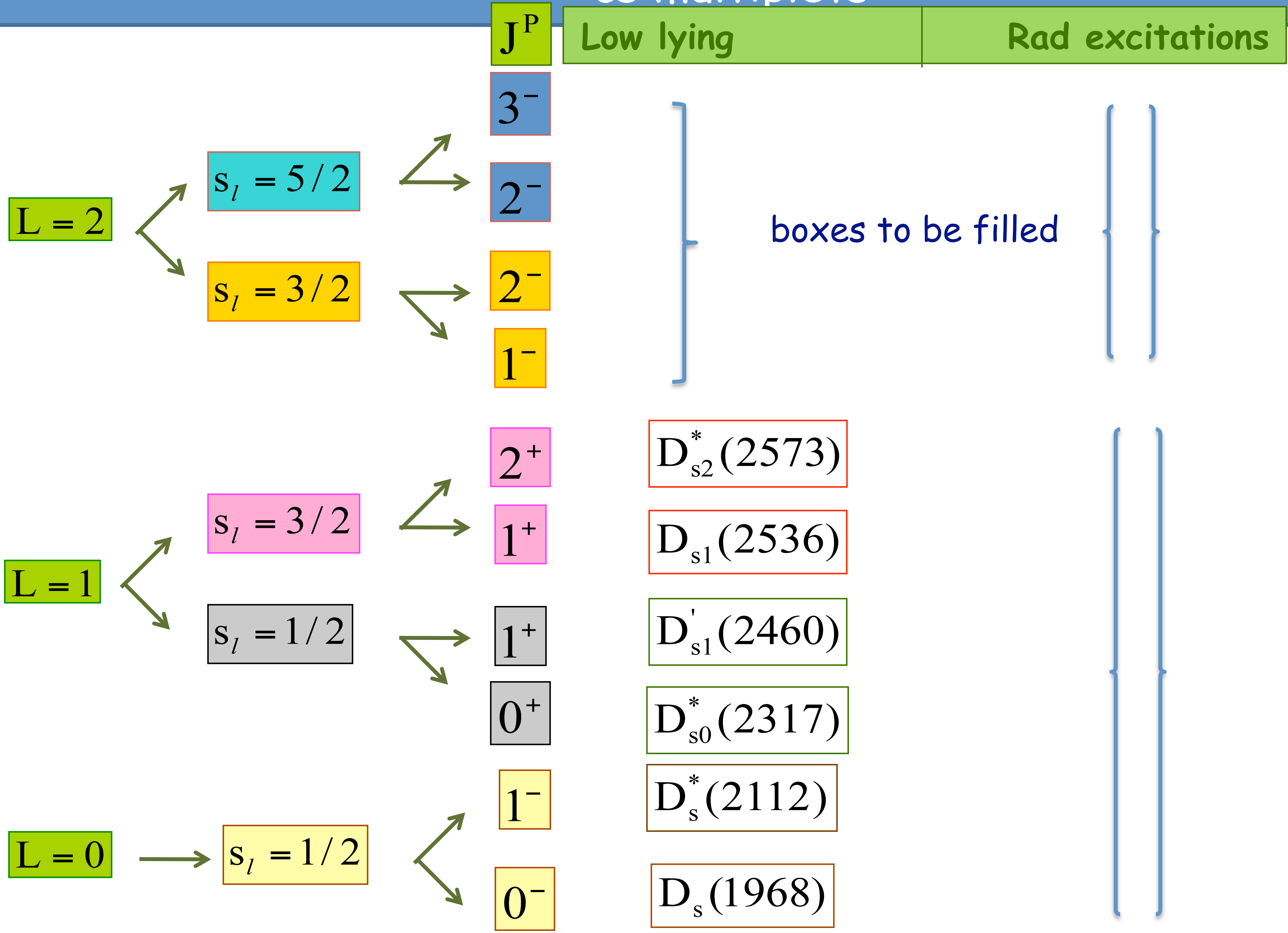
$D_{sJ}^*(2317) \to D_s^* \gamma$ not forbidden - it should be observed

De Fazio, Ozpineci, PC



cs spectrum 2013
3500
3000
2500
2000
1500
mass (MeV)
DsJ(3040)
1+
to be discussed
3-
DsJ(2860)
1-
D*s1(2700)
2+
D*s2(2573)
1+
Ds1(2536)
1+
D's1(2460)
0+
D*s0(2317)
1-
D*s(2112)
0-
Ds(1968)
D*K
DK
doublets

$c\bar{s}$ multiplets

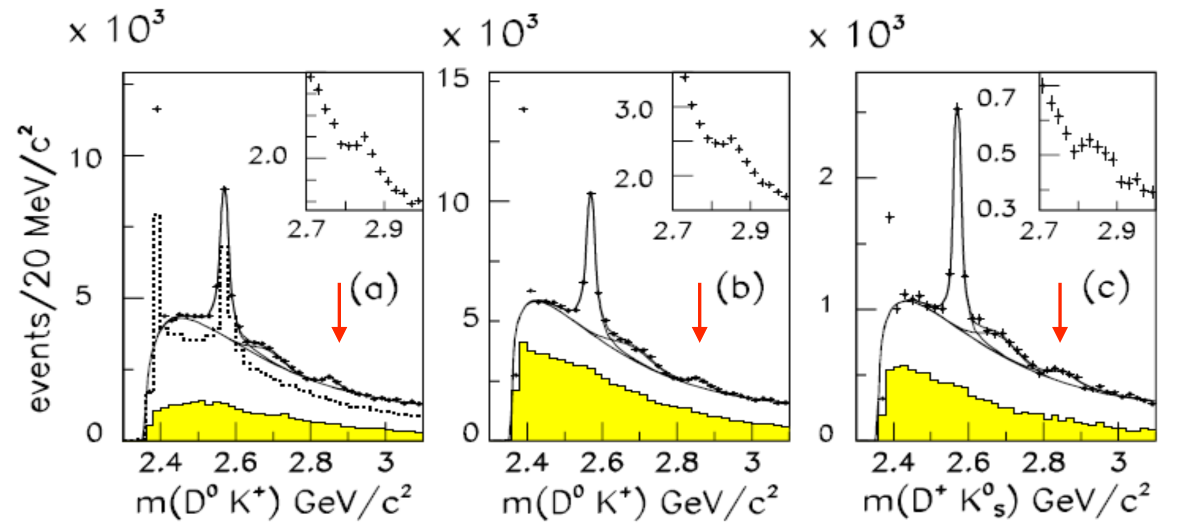


$D_{sJ}(2860)$

- discovered by BaBar
  - reconstructed in

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

and in $D^+ K_S^0$



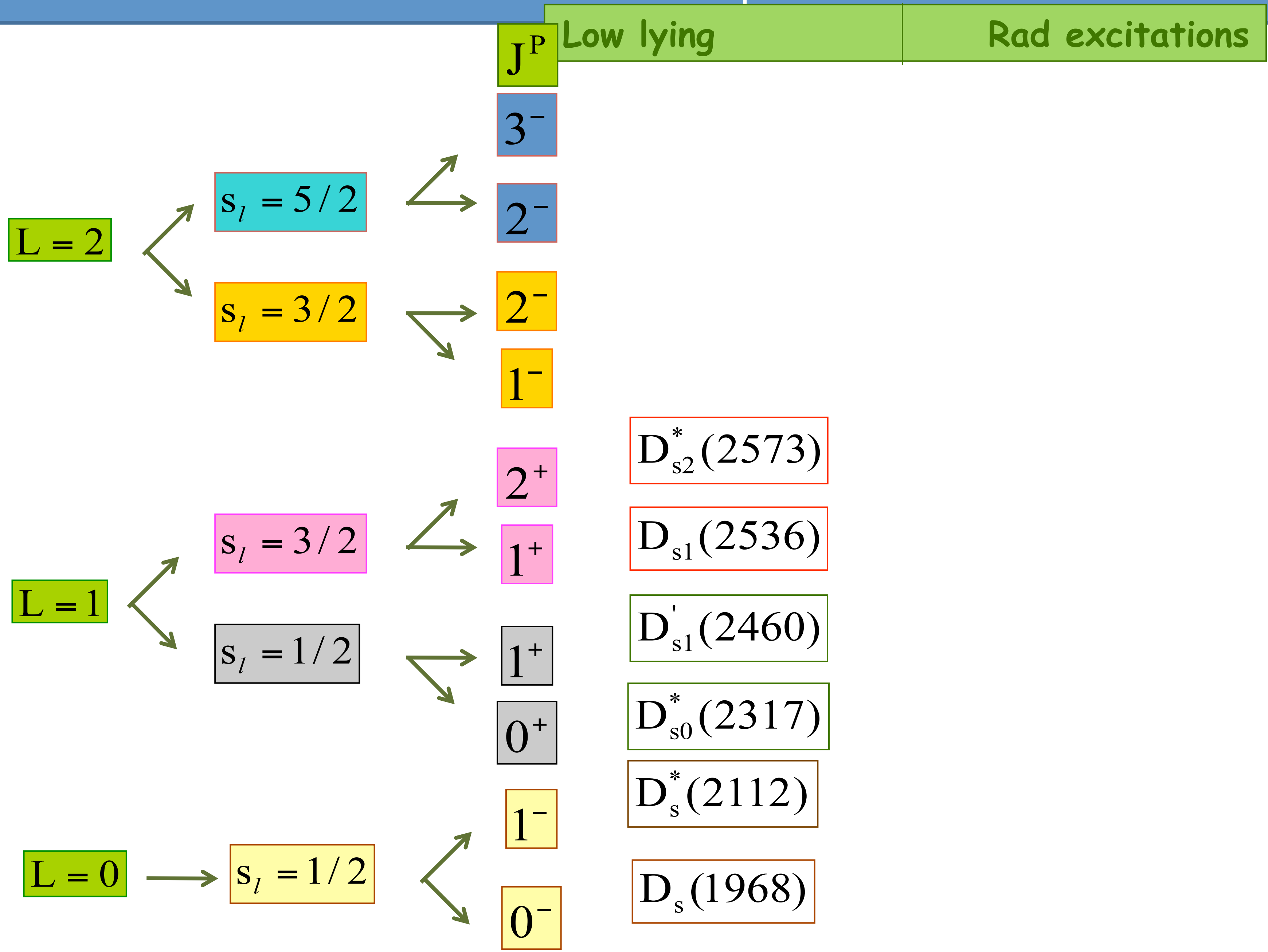
$M = 2856.6 \pm 1.5 \pm 5.0$	MeV
$\Gamma = 48 \pm 7 \pm 10$	MeV

BaBar Collab., PRL 97, 222001

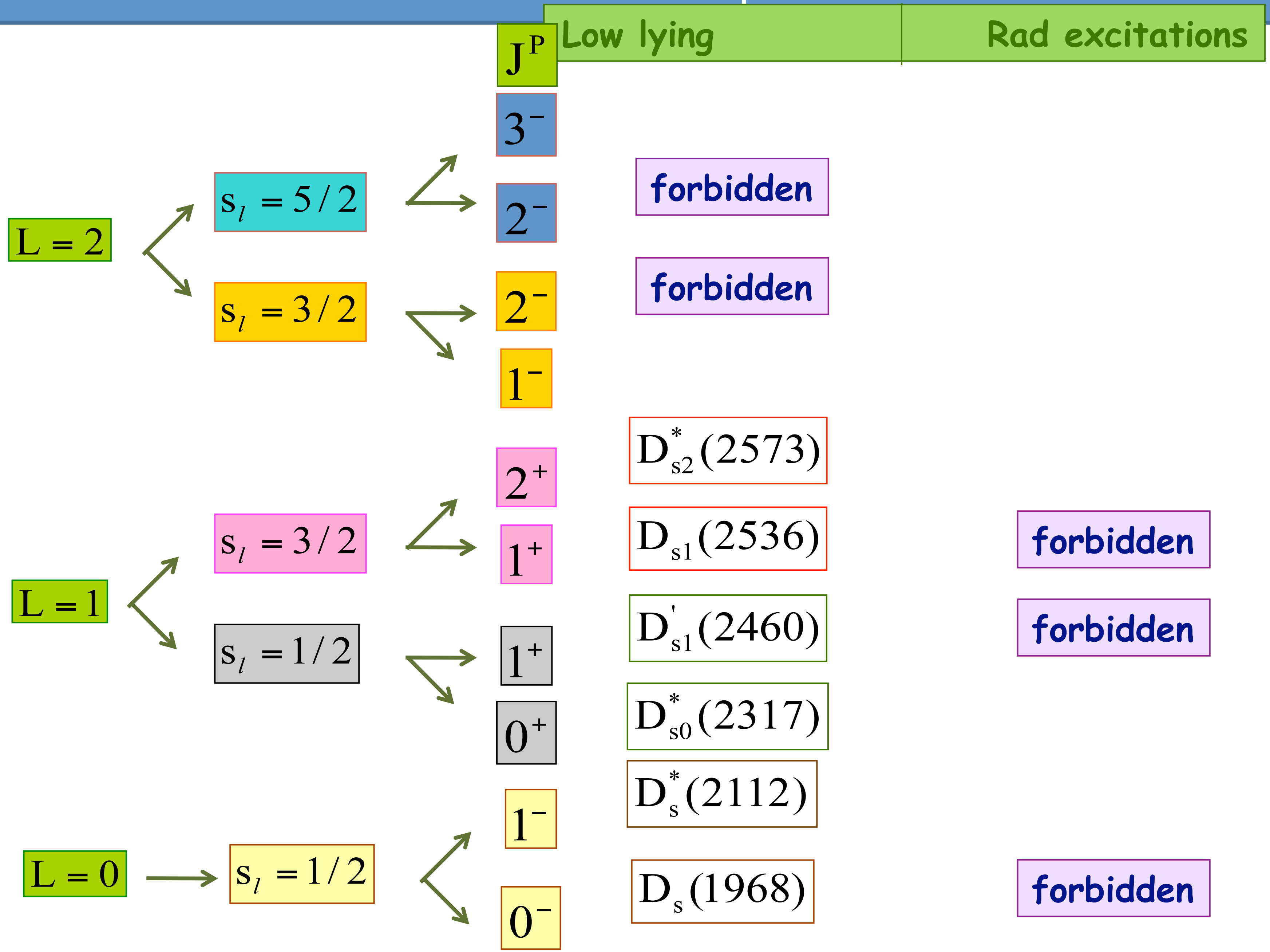
quantum number assignment required for its classification
possibilities: - low lying state not yet observed
- radial excitation of an already observed state

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

$c\bar{s}$ multiplets



$c\bar{s}$ multiplets

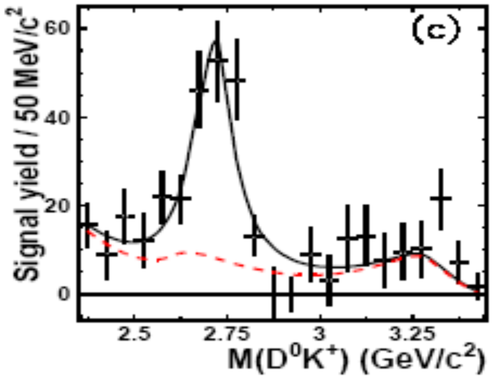


$c\bar{s}$ multiplets

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

$D_{sJ}(2710)$

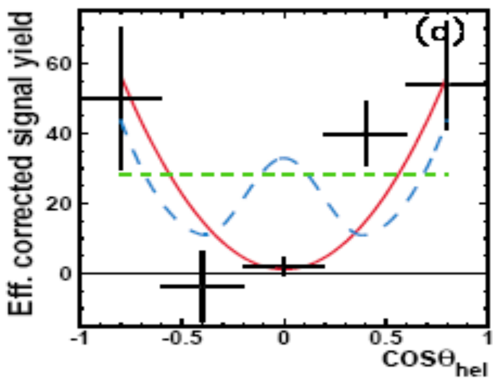
Belle Collab.: analysis of the mode $B^+ \to \overline{D}^0 D^0 K^+$



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

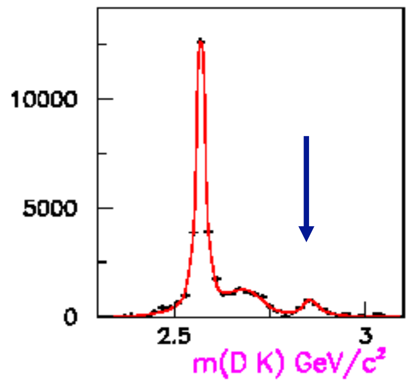
$M = 2708 \pm 9 \pm^{11}_{10}$ MeV $\qquad \Gamma = 108 \pm 23 \pm^{36}_{31}$ MeV

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



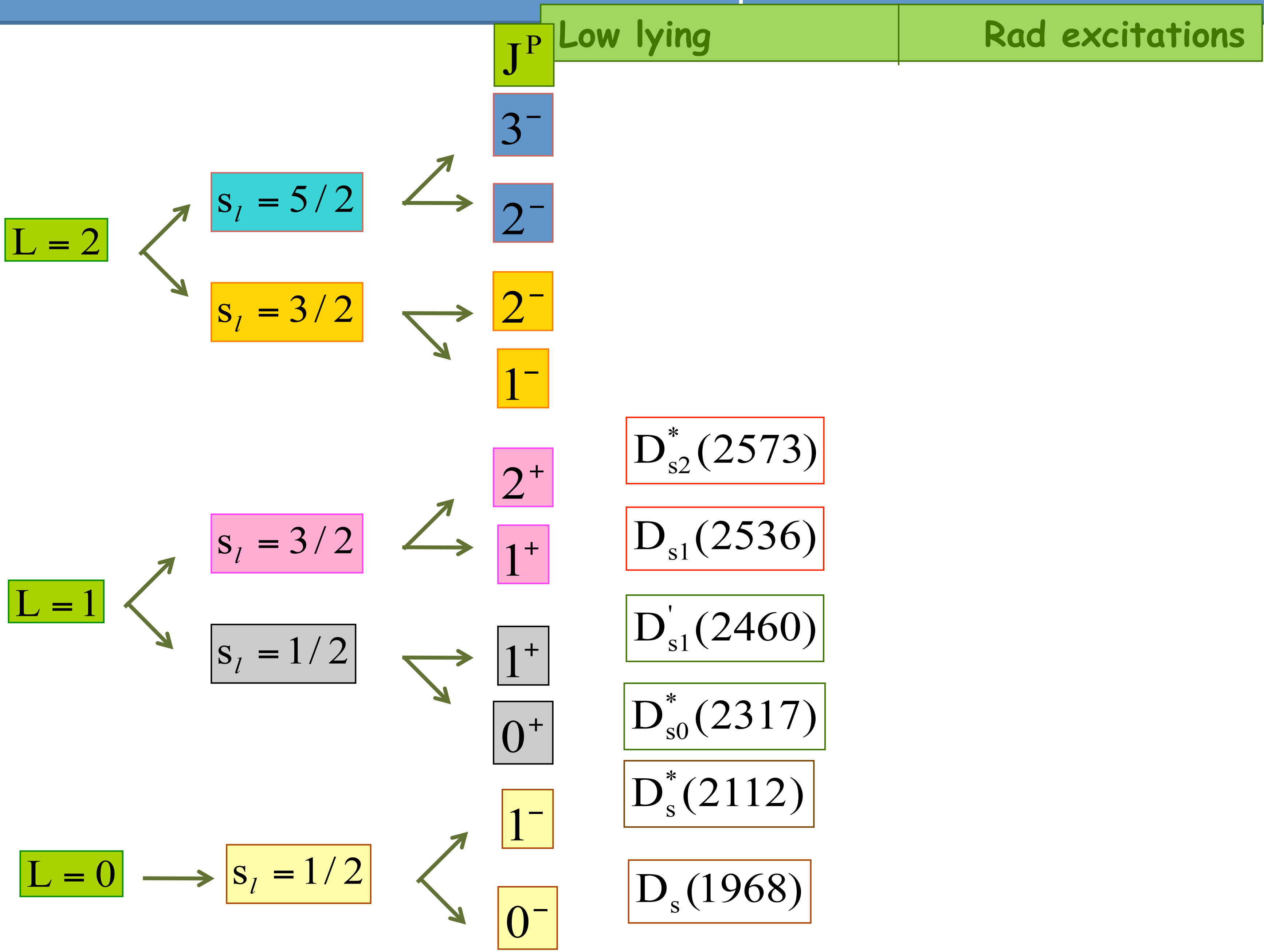
J=0
J=1
J=2

$J^P=1^-$ favoured

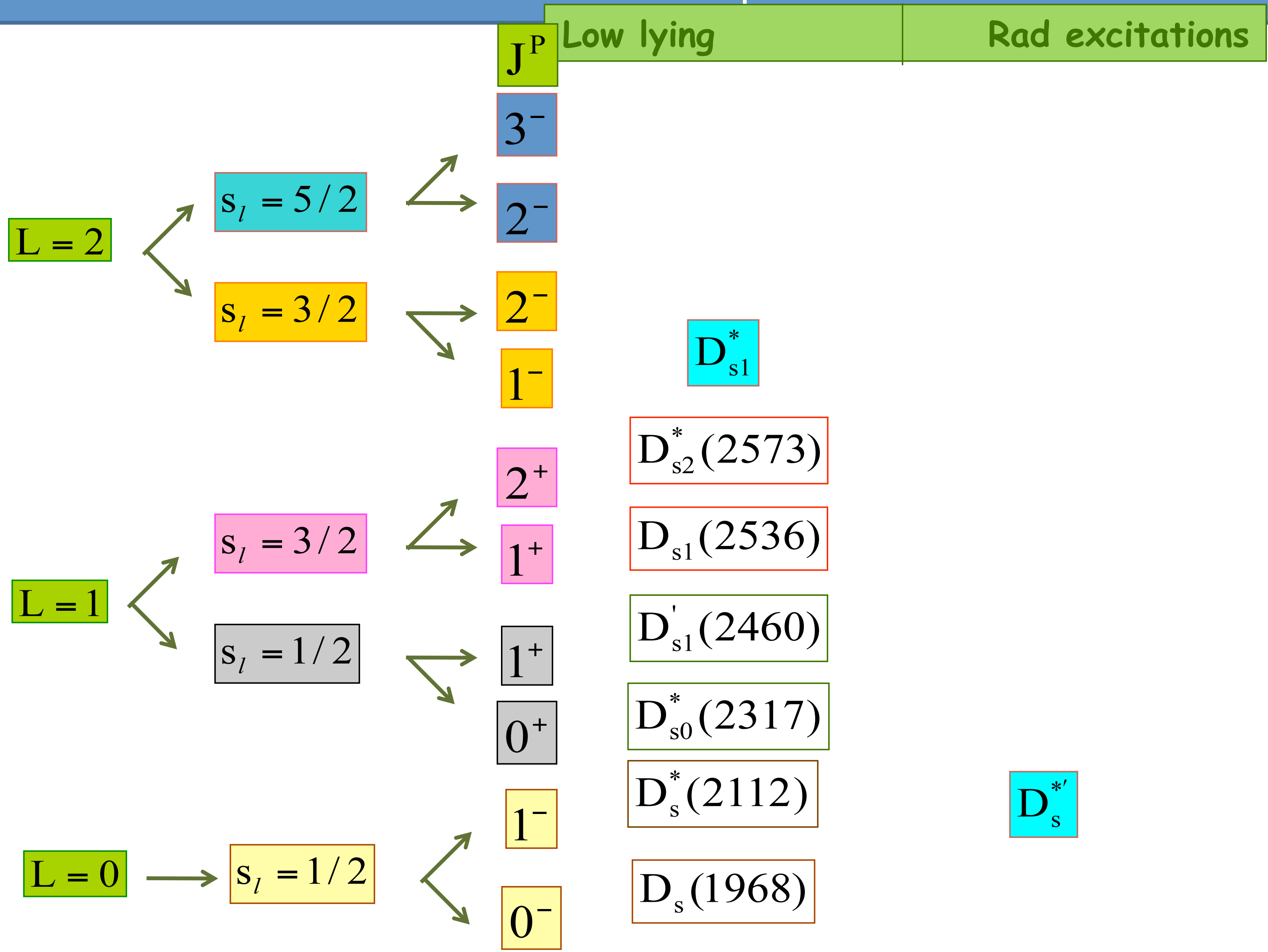


A broad structure at M=2688 MeV with Γ=112 MeV was found by BaBar in the DK mass distribution

$c\bar{s}$ multiplets



$c\bar{s}$ multiplets



$D_{sJ}(2860)$: peak in DK distribution $M = 2856.6 \pm 1.5 \pm 5.0\ MeV$ (BaBar)

for a classification look at the width ratios

	$D_{sJ}(2860)$	$D_{sJ}(2860) \to DK$	$\frac{\Gamma(D_{sJ}(2860)\to D^* K)}{\Gamma(D_{sJ}(2860)\to DK)}$	$\frac{\Gamma(D_{sJ}(2860)\to D_s \eta)}{\Gamma(D_{sJ}(2860)\to DK)}$
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

$$\Gamma_{D_{sJ}(2860)} = 48 \pm 3 \pm 6$$

option 5 $s_\ell^P = \frac{5}{2}^-$ $J^P = 3^-$ $n = 1$

- signal expected in D^*K
- small signal expected also in $D_s\,\eta$
- small width attributed to the suppression due to the kaon momentum factor

f-wave transition

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

PC Nicotri De Fazio PLB 642, 48

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

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

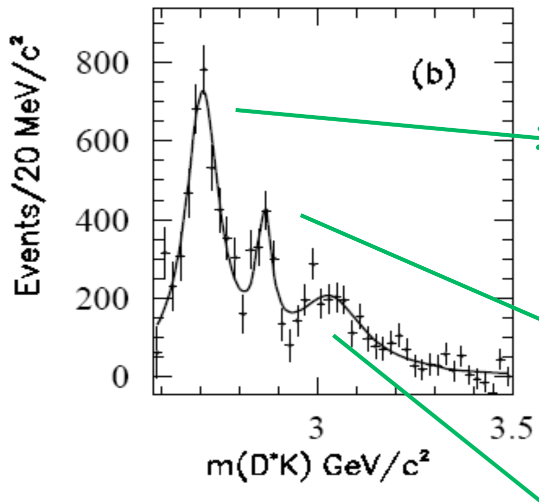
dependence on the (unknown) couplings drops out

	$R_1 \times 10^2$	$R_2 \times 10^2$	$R_3 \times 10^2$
$\frac{1}{2}^-$ → $D_s^{*\prime}$	91 ± 4	20 ± 1	5 ± 2
$\frac{3}{2}^-$ → D_{s1}^*	4.3 ± 0.2	16.3 ± 0.9	0.18 ± 0.07

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

BaBar analysis of D^*K

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



three peaks

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

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

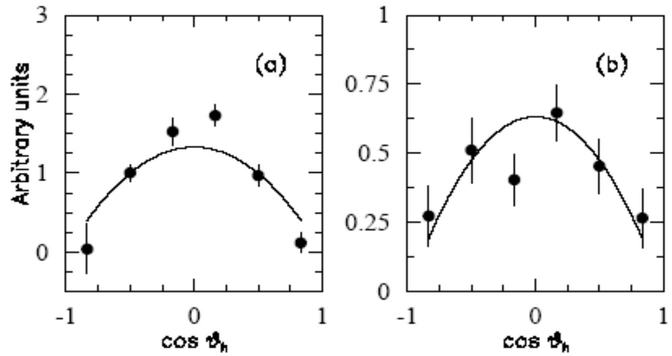
$$m(D_{sJ}(2860)^+) = 2862 \pm 2_{stat} \pm^{5}_{2\ syst} \quad \text{MeV}$$

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

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

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

- angular analysis



angular distribution consistent 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, 092003

BaBar analysis of D^*K

Ratios of branching fractions

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

th: 0.9

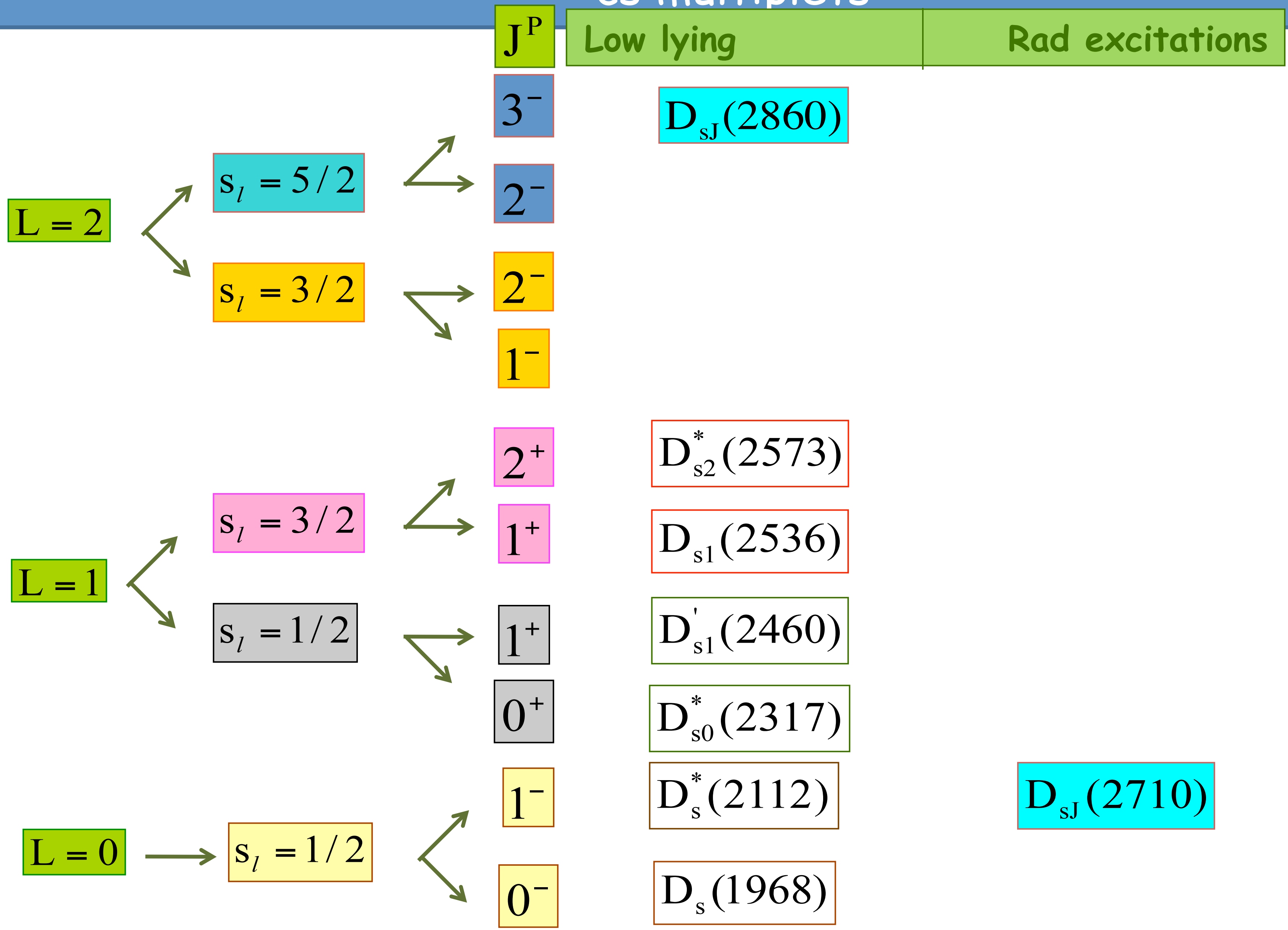
supports the identification of $D_{s1}(2710)$ with 2^3S_1
(first radial excitation of D_s^*)

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

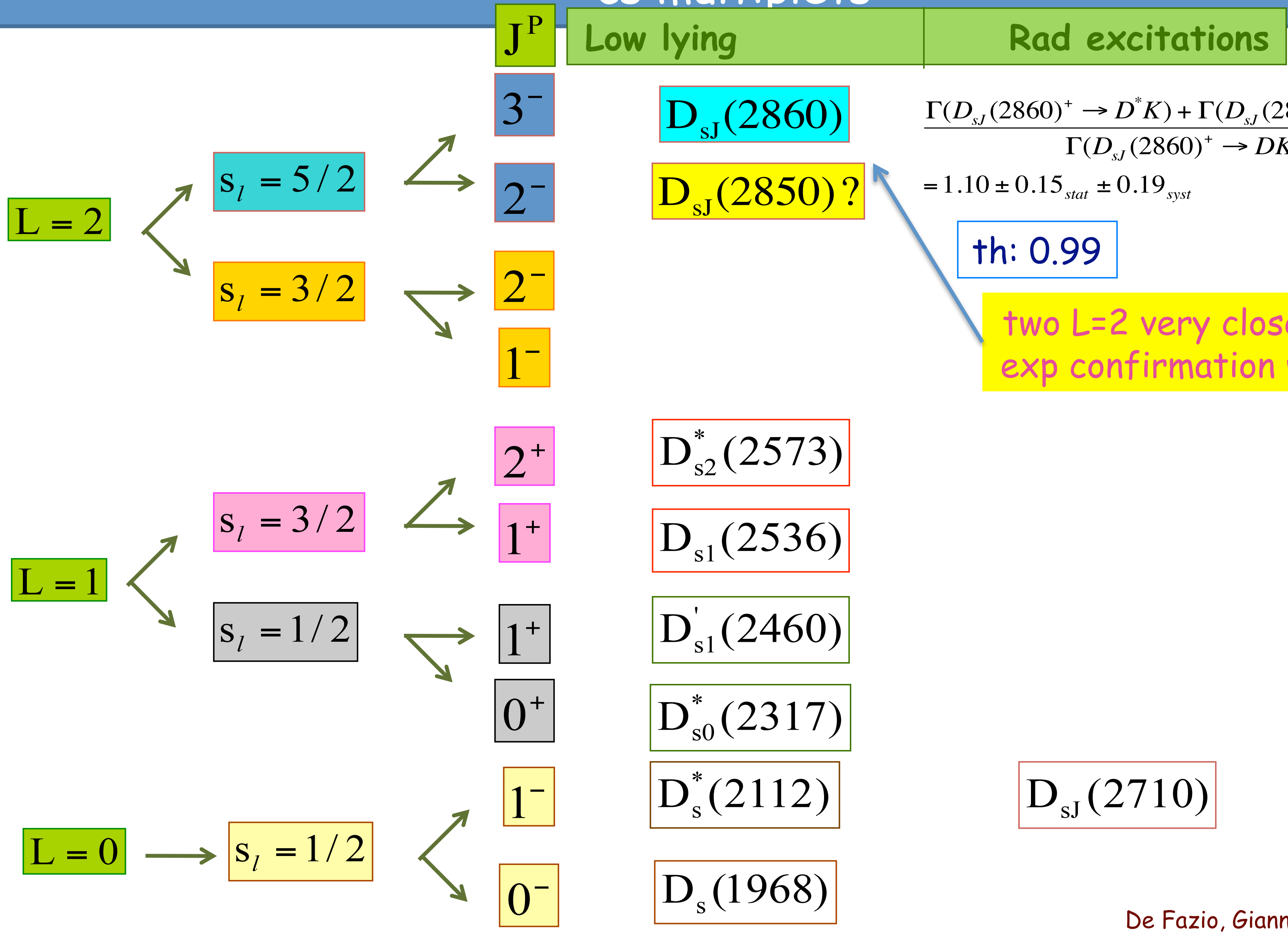
th: 0.4

why?

$c\bar{s}$ multiplets



$c\bar{s}$ multiplets

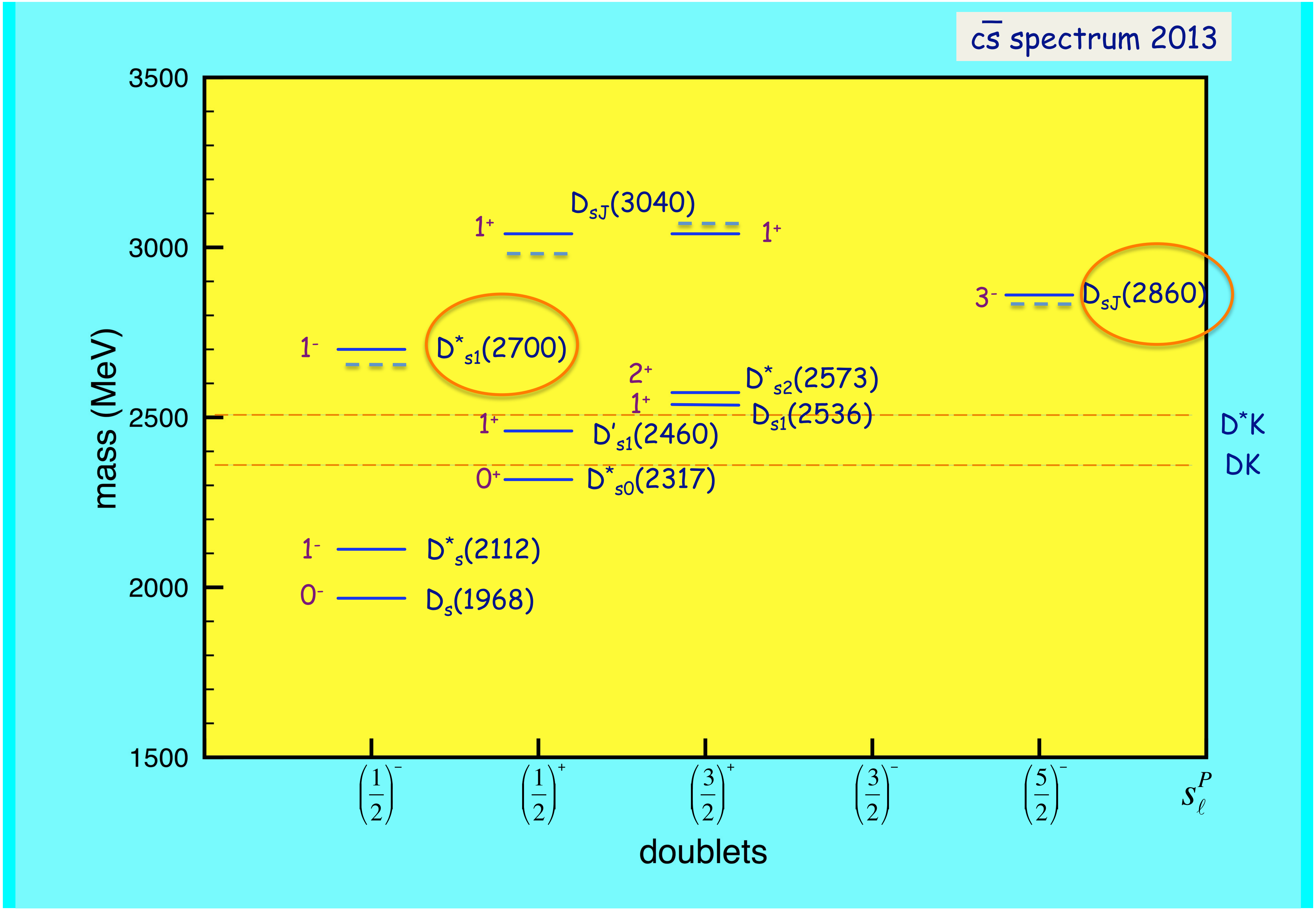


$$\frac{\Gamma(D_{sJ}(2860)^+ \to D^* K) + \Gamma(D_{sJ}(2850)^+ \to D^* K)}{\Gamma(D_{sJ}(2860)^+ \to DK)} = 1.10 \pm 0.15_{stat} \pm 0.19_{syst}$$

th: 0.99

two L=2 very close states
exp confirmation welcome

De Fazio, Giannuzzi, Nicotri PC
PRD 2012



c$\bar{s}$ spectrum 2013
mass (MeV)
3500
3000
2500
2000
1500
$D_{sJ}(3040)$
1+
1+
3-
$D_{sJ}(2860)$
1-
$D^*_{s1}(2700)$
2+
$D^*_{s2}(2573)$
1+
$D_{s1}(2536)$
1+
$D'_{s1}(2460)$
0+
$D^*_{s0}(2317)$
D*K
DK
1-
$D^*_s(2112)$
0-
$D_s(1968)$
$\left(\frac{1}{2}\right)^-$
$\left(\frac{1}{2}\right)^+$
$\left(\frac{3}{2}\right)^+$
$\left(\frac{3}{2}\right)^-$
$\left(\frac{5}{2}\right)^-$
s_ℓ^P
doublets

$c\bar{q}$ mesons

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 ± 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	$D^0\pi^+$

$c\bar{q}$ mesons

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 ± 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 predictions for the non-strange partners of $D_{sJ}(2700)$

$c\bar{q}$ mesons

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 ± 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	$D^0\pi^+$

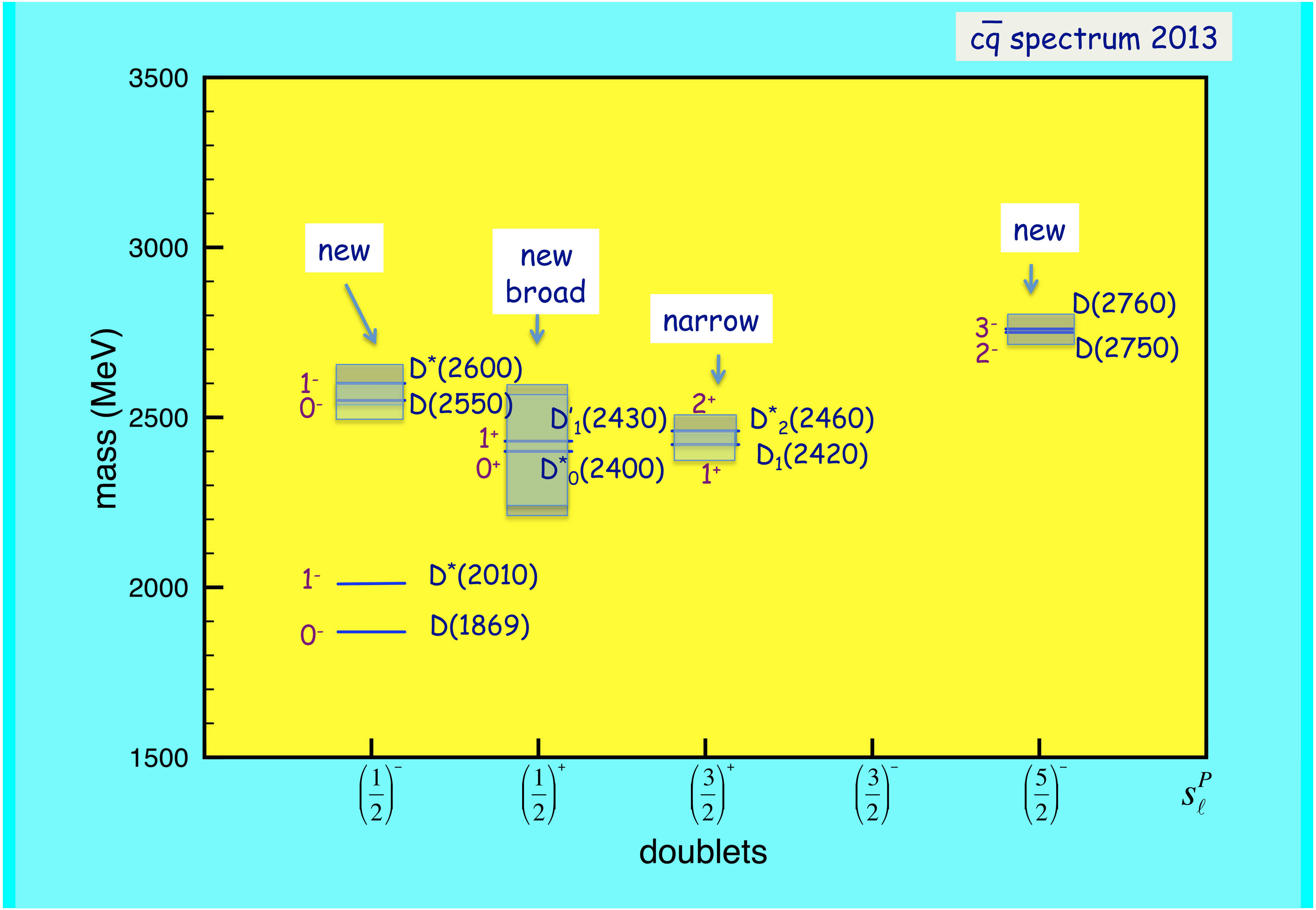
assigned to L=2 doublet

$$
\begin{aligned}
\overline{M}_H &= \frac{3M_{P^*} + M_P}{4} \\
\overline{M}_S &= \frac{3M_{P'_1} + M_{P^*_0}}{4} \\
\overline{M}_T &= \frac{5M_{P^*_2} + 3M_{P_1}}{8} \\
\overline{M}_X &= \frac{5M_{P_2} + 3M_{P^*_1}}{8} \\
\overline{M}_{X'} &= \frac{7M_{P_3} + 5M_{P'^*_2}}{12} \, .
\end{aligned}
$$

$$
\Delta_F = \overline{M}_F - \overline{M}_H
$$

$$
\begin{aligned}
\lambda_H &= \frac{1}{8}\left(M^2_{P^*} - M^2_P\right) \\
\lambda_S &= \frac{1}{8}\left(M^2_{P'_1} - M^2_{P^*_0}\right) \\
\lambda_T &= \frac{3}{16}\left(M^2_{P^*_2} - M^2_{P_1}\right) \\
\lambda_X &= \frac{3}{16}\left(M^2_{P_2} - M^2_{P^*_1}\right) \\
\lambda_{X'} &= \frac{5}{24}\left(M^2_{P_3} - M^2_{P'^*_2}\right)
\end{aligned}
$$

	$c\bar{u}$	$c\bar{d}$	$c\bar{s}$	$b\bar{u}$	$b\bar{d}$	$b\bar{s}$
$\overline{M}_H$	1971.45 ± 0.12	1975.12 ± 0.10	2076.4 ± 0.4	5313.7 ± 0.3	5313.8 ± 0.3	5403 ± 2
$\overline{M}_{\tilde{H}}$	2591.4 ± 3.3					
$\overline{M}_S$	2400 ± 28		2424.1 ± 0.5			
$\overline{M}_T$	2447.1 ± 0.5	2449.0 ± 1.6	2558.6 ± 0.6		5735.7 ± 3.2	5834.7 ± 0.5
$\overline{M}_{X'}$	2758.8 ± 2.3					
Δ_S	429 ± 28		347.7 ± 0.6			
Δ_T	475.7 ± 0.5	473.9 ± 1.6	482.2 ± 0.7		421.9 ± 3.2	431.7 ± 2.1
$\Delta_{X'}$	787.4 ± 2.3					
λ_H	$(262.3 \pm 0.2)^2$	$(261.2 \pm 0.2)^2$	$(270.9 \pm 0.6)^2$	$(246.8 \pm 1.2)^2$	$(245.9 \pm 1.2)^2$	$(256.3 \pm 6.4)^2$
$\lambda_{\tilde{H}}$	$(211.2 \pm 13.4)^2$					
λ_S	$(254 \pm 54)^2$		$(290.9 \pm 0.9)^2$			
λ_T	$(195 \pm 2)^2$	$(193 \pm 7)^2$	$(189.2 \pm 2.1)^2$		$(205 \pm 28)^2$	$(149.9 \pm 6.7)^2$
$\lambda_{X'}$	$(112 \pm 24)^2$					



$c\bar{q}$ spectrum 2013
mass (MeV)
3500
3000
2500
2000
1500
new
new
broad
narrow
new
1^-
0^-
$D^*(2600)$
$D(2550)$
1^+
0^+
$D'_1(2430)$
$D^*_0(2400)$
2^+
1^+
$D^*_2(2460)$
$D_1(2420)$
3^-
2^-
D(2760)
D(2750)
1^-
$D^*(2010)$
0^-
D(1869)
$\left(\frac{1}{2}\right)^-$
$\left(\frac{1}{2}\right)^+$
$\left(\frac{3}{2}\right)^+$
$\left(\frac{3}{2}\right)^-$
$\left(\frac{5}{2}\right)^-$
s_ℓ^P
doublets

predictions for open charm mesons

	$\tilde{D}_{(s)}$ $(0^-, n=2)$	$\tilde{D}^*_{(s)}$ $(1^-, n=2)$	$D'^*_{(s)2}$ (2^-)	$D_{(s)3}$ (3^-)
$c\bar{q}$	$D(2550)$	$D^*(2600)$	$D(2750)$	$D(2760)$
$c\bar{s}$ mass	2643 ± 13	$D^*_{s1}(2700)$	2851 ± 7	$D_{sJ}(2860)$
Γ	33.5 ± 3.3		20.5 ± 2.4	

predictions for open beauty mesons

	$\tilde{B}_{(s)}$ $(0^-, n=2)$	$\tilde{B}^*_{(s)}$ $(1^-, n=2)$	$B^*_{(s)0}$ (0^+)	$B'_{(s)1}$ (1^+)	$B'^*_{(s)2}$ (2^-)	$B_{(s)3}$ (3^-)
$b\bar{q}$ mass	5911.1 ± 4.9	5941.2 ± 3.2	5708.2 ± 22.5	5753.3 ± 31.1	6098.2 ± 2.4	6103.1 ± 2.6
Γ	149 ± 15	186 ± 18	269 ± 58	268 ± 70	103 ± 8	129 ± 10
$b\bar{s}$ mass	5997.3 ± 6.1	6026.6 ± 7.9	5706.6 ± 1.2	5765.6 ± 1.2	6181.3 ± 5.2	6186.3 ± 4.6
Γ	76 ± 9	118 ± 14			57 ± 6	78.4 ± 7.3

narrow

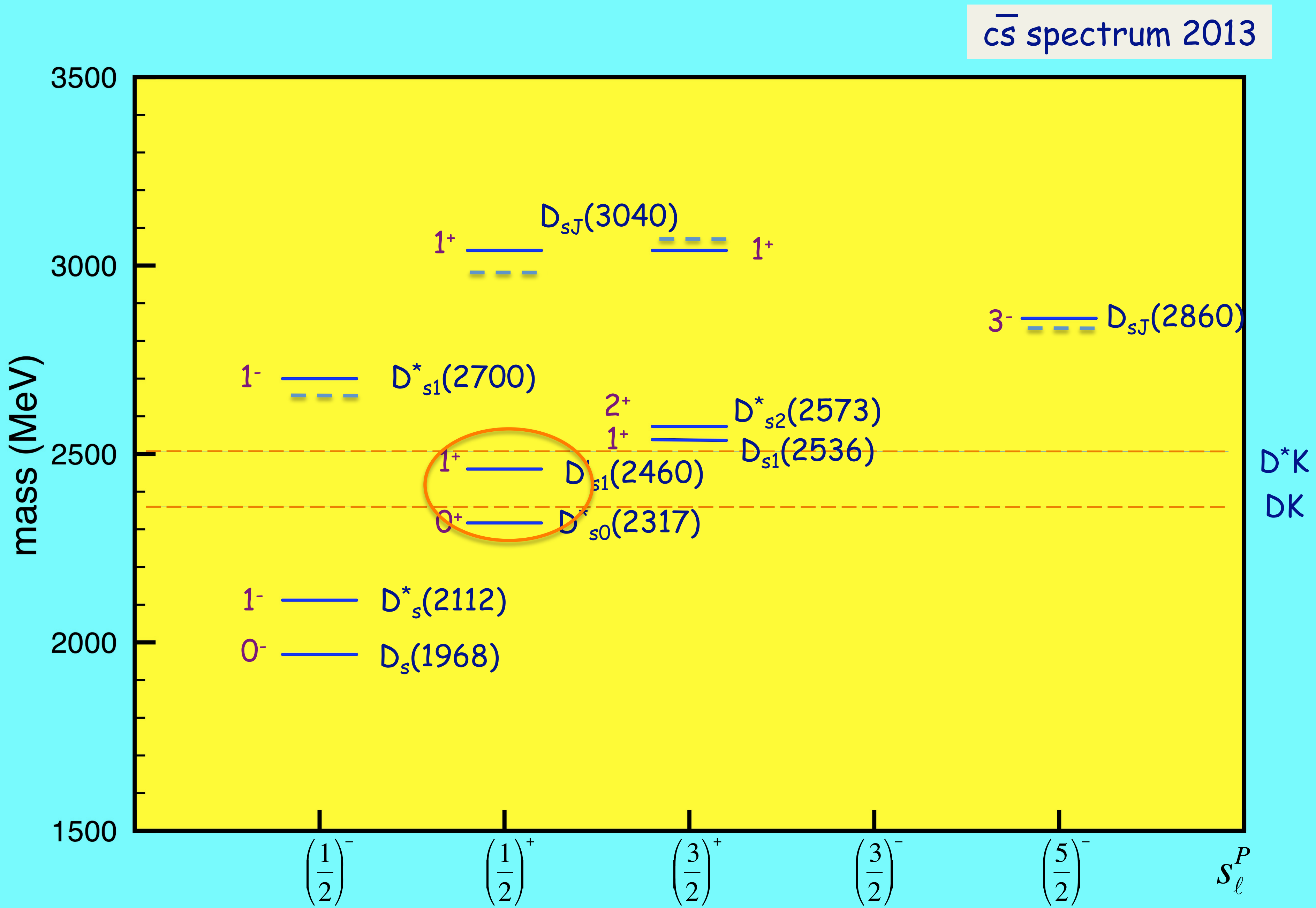
De Fazio, Giannuzzi, Nicotri PC
PRD 2012

lessons for hidden heavy flavour spectroscopy

lesson n. 1

**states in the spectrum are poles of the S-matrix
they have universal properties
and definite quantum numbers**

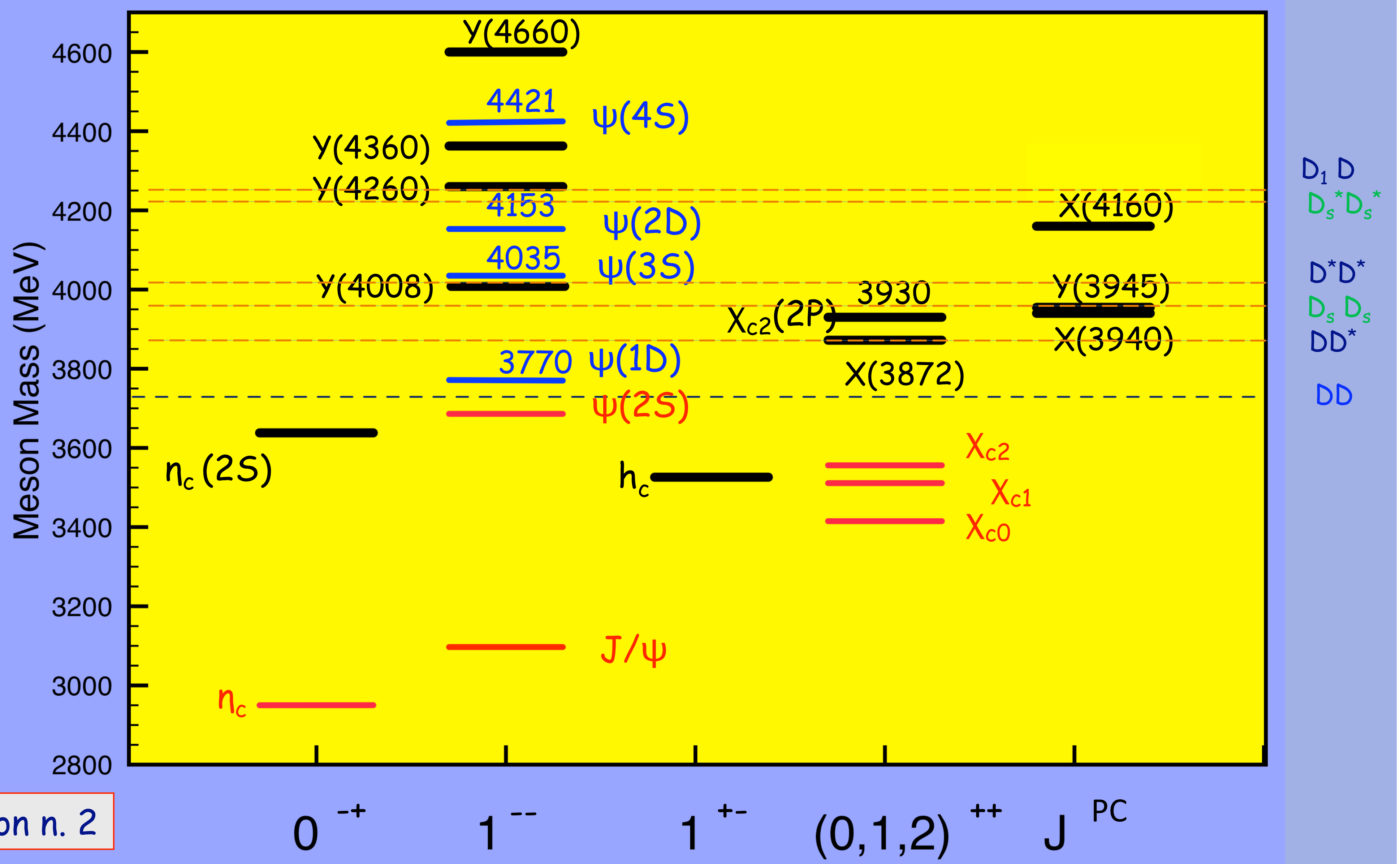
observation in more than a particular process
is fundamental for establishing their existence



lesson n. 2

threshold effects important: they can distort the mass spectrum

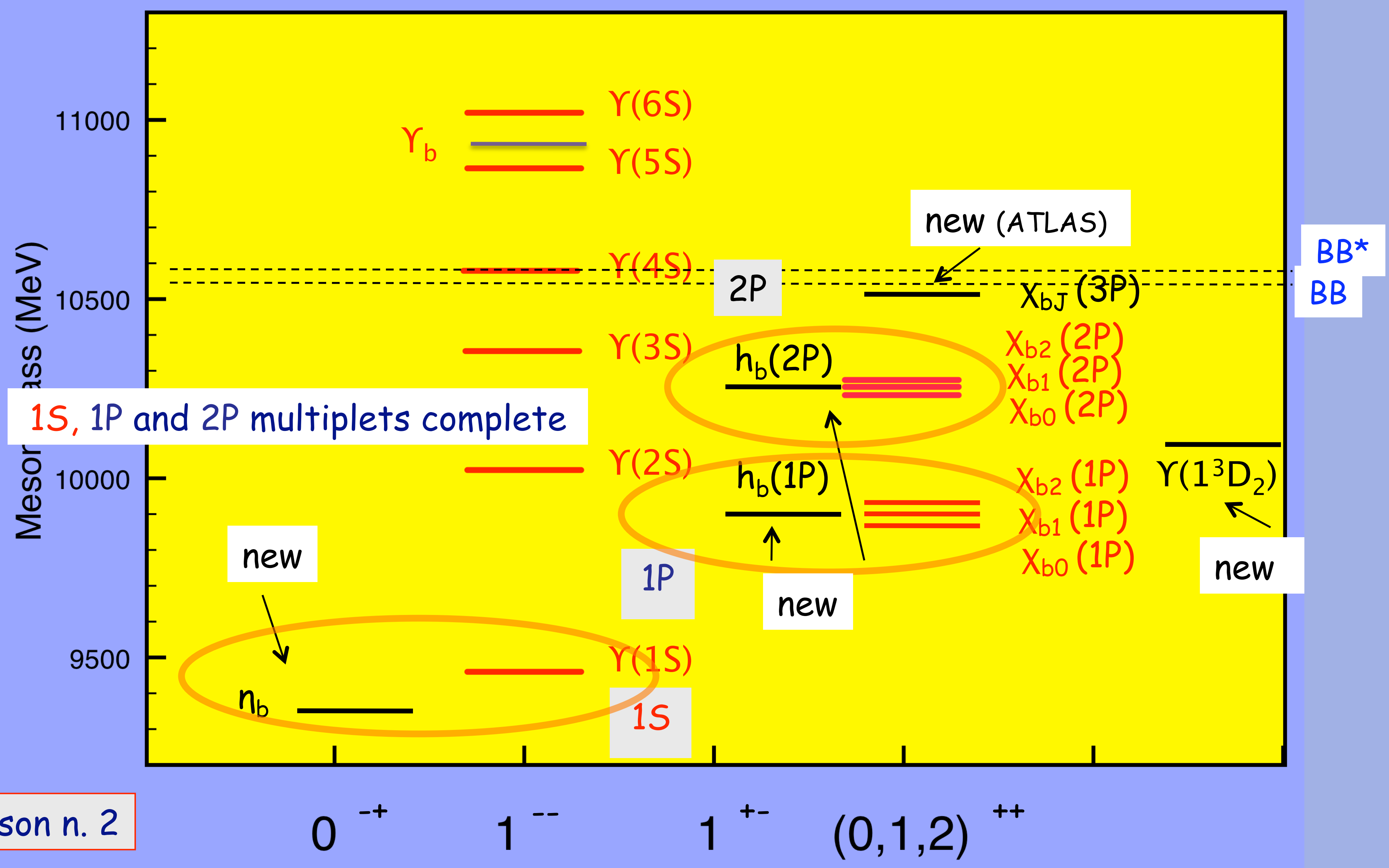
charmonium



lesson n. 2

new states found in the region of open charm (beauty) production thresholds
threshold effects important: they can distort the mass spectrum

bottomonium



lesson n. 2

new states found in the region of open charm (beauty) production thresholds
threshold effects important: they can distort the mass spectrum

lesson n. 3

information on the decay modes and widths crucial for classification

prime importance of radiative decays

Conclusions

hadron spectroscopy in an exciting era

- clarifies features of QCD in particular limits
- accessible by new th. approaches to QCD
- many poorly understood issues

theorists and experimentalists at work