Open Charm Meson Spectroscopy

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Motivation:

- Classify several newly observed heavy-light mesons
- Filling the ordinary meson spectra is preliminary to the search for exotics
- Excited heavy mesons play a role in other sectors of flavour physics ➔ $R(D^{**})$

Implications of LHCb measurements and future prospects
CERN
12-14 October 2016

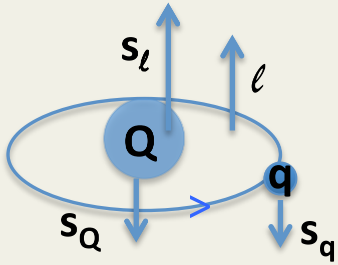
Mesons with open heavy flavour: $\bar{q}Q$ (Q=c,b)

- Many new states experimentally observed need to be classified
- Exploiting an effective QCD Lagrangian based on heavy quark & chiral symmetries allows to predict

  - masses
  - strong decay rates
- Model independent predictions: ratios of branching fractions
- Results useful to properly classify the observed heavy mesons: the successful cases of $D^*_{s3}(2860)$ and $D^*_{s1}(2700)$
- Results for the latest observed $c\bar{q}$ mesons
- Predictions for beauty mesons

Hadrons with a single heavy quark: large mass limit $m_Q \to \infty$ (Heavy Quark Effective Theory)

Intuitive picture



$$\vec{s}_\ell = \vec{\ell} + \vec{s}_q$$

- hadrons which differ only for the HQ flavour/spin have the same configuration of the light degrees of freedom
- heavy quark symmetry is not exact: $1/m_Q$ corrections can be systematically included

HQ spin & flavour symmetries

- $\mathbf{s_Q}$ and $\mathbf{s_\ell}$ separately conserved

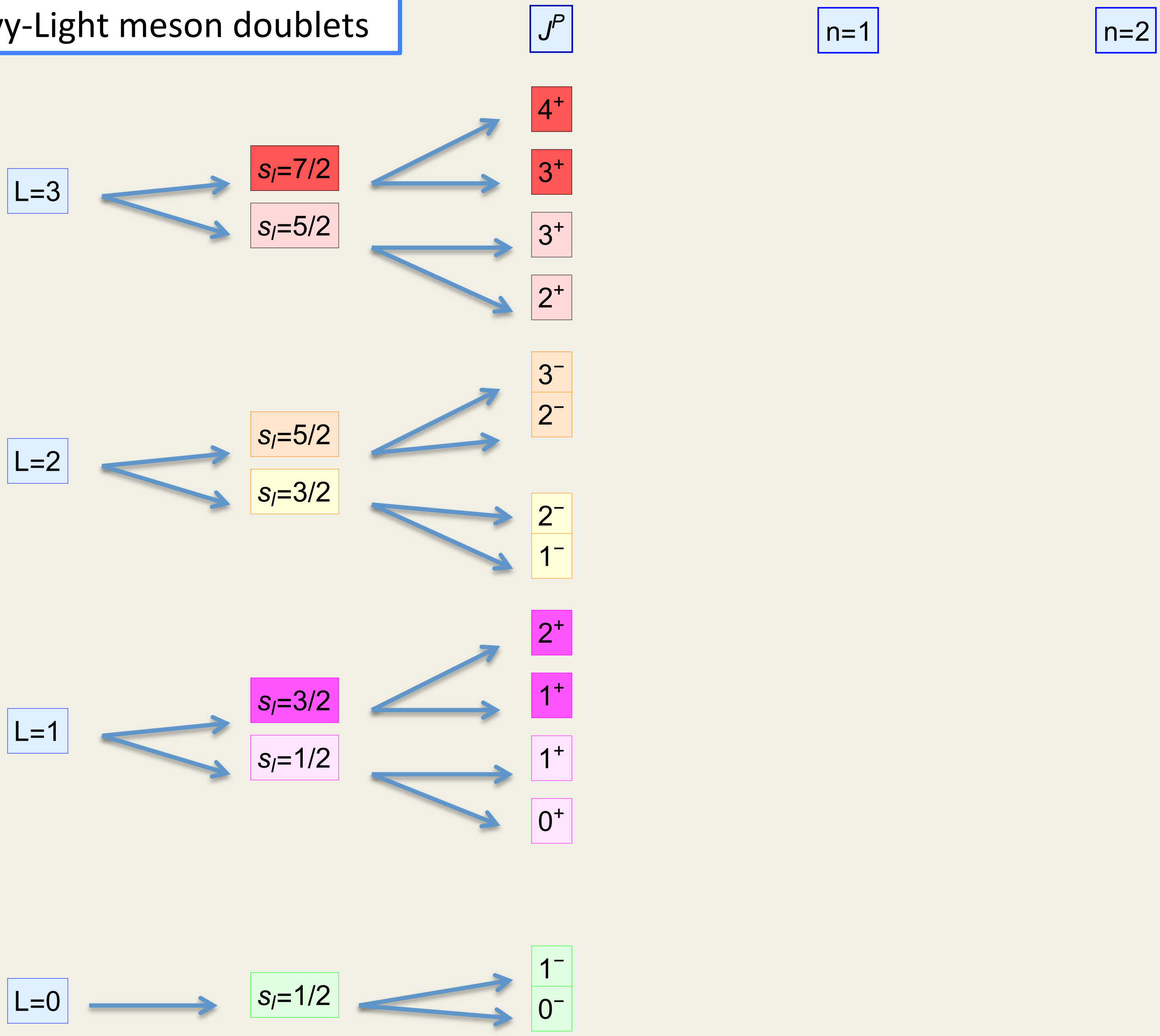
Spin symmetry: mesons classified in doublets with $J = s_\ell \pm \frac{1}{2}$ $P = (-1)^{\ell+1}$

members of the same doublet i) degenerate
ii) same total width

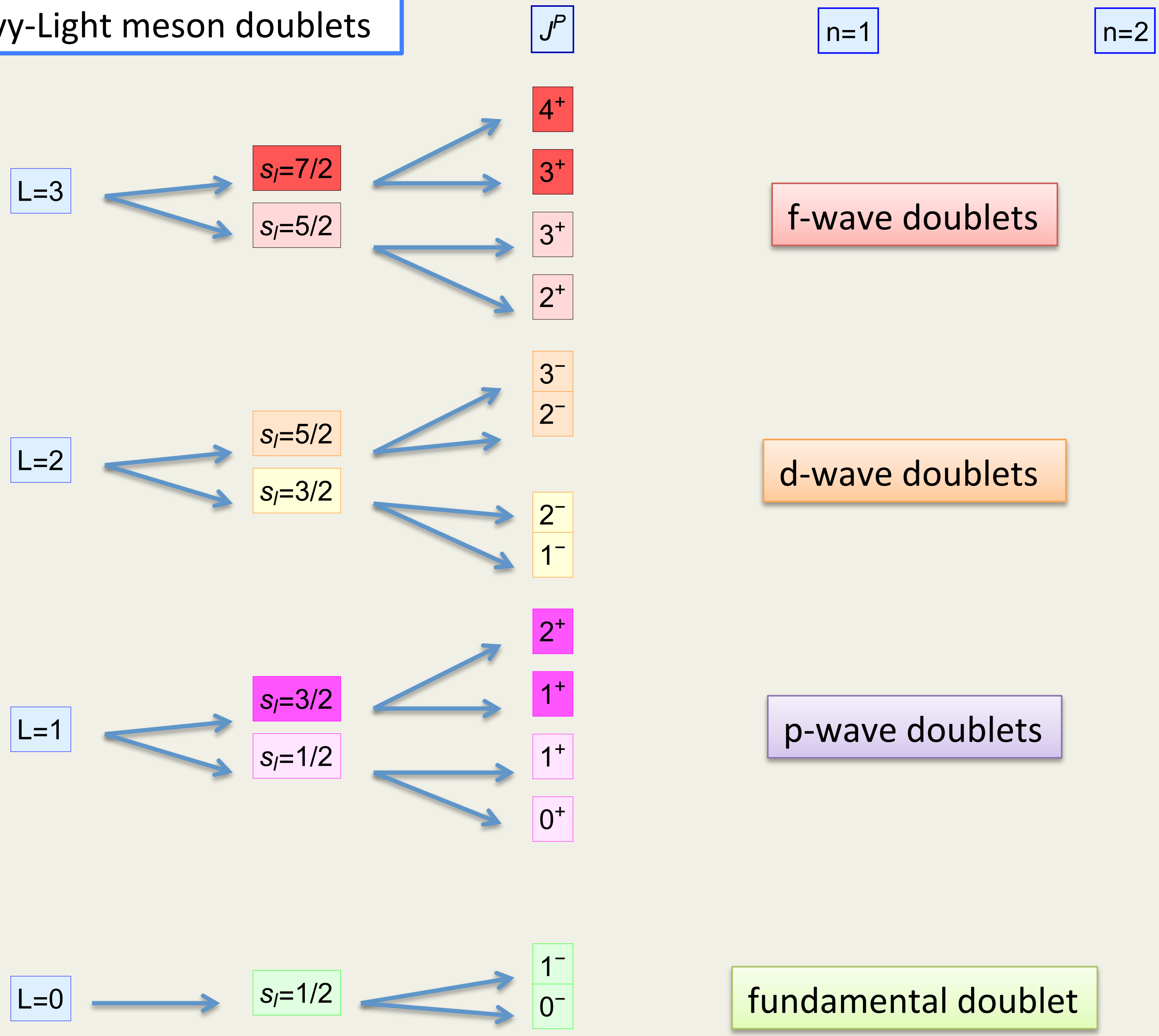
Flavour symmetry: relations between charm and beauty hadron properties

mass splittings among the doublets independent of flavour

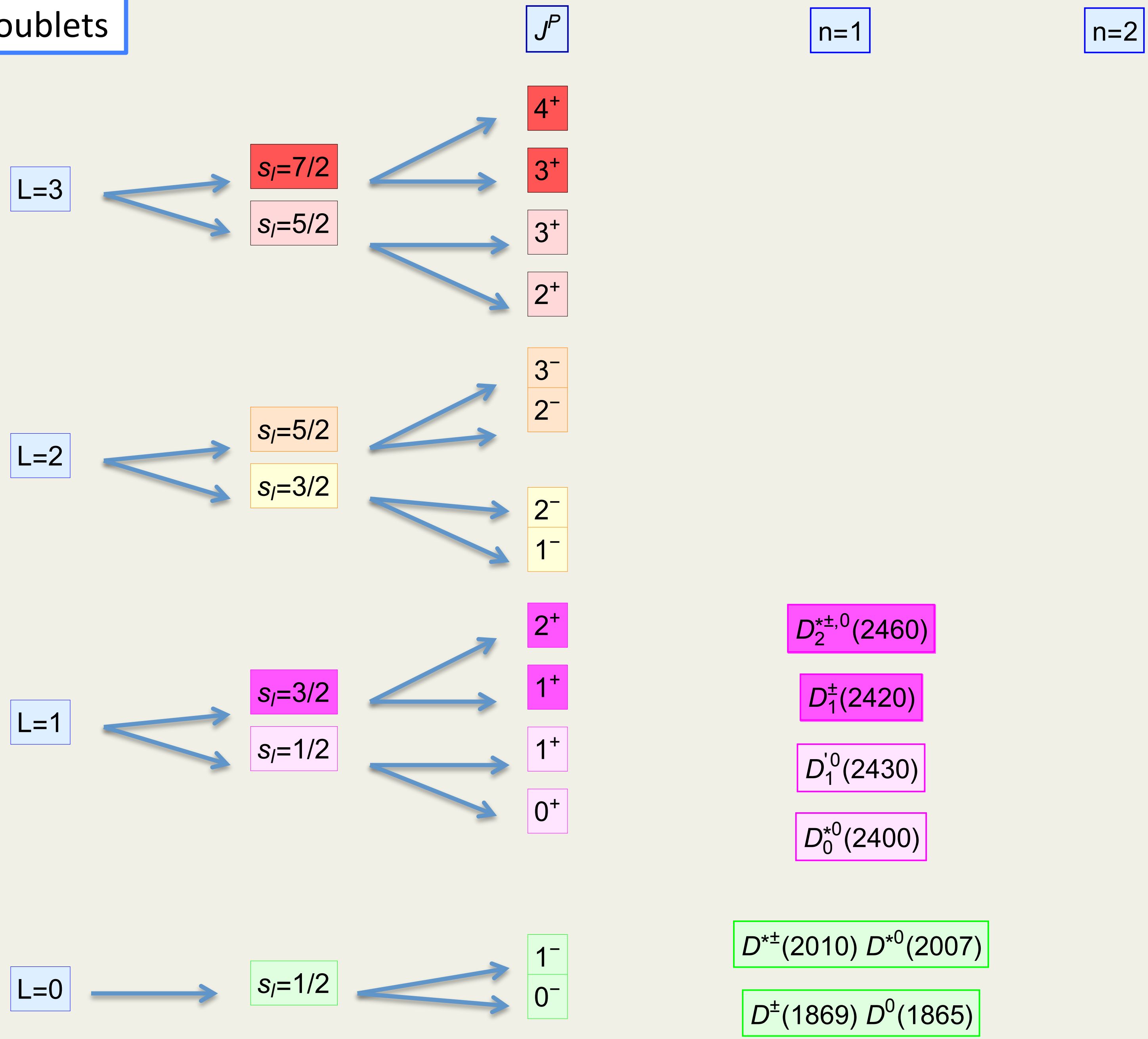
Heavy-Light meson doublets



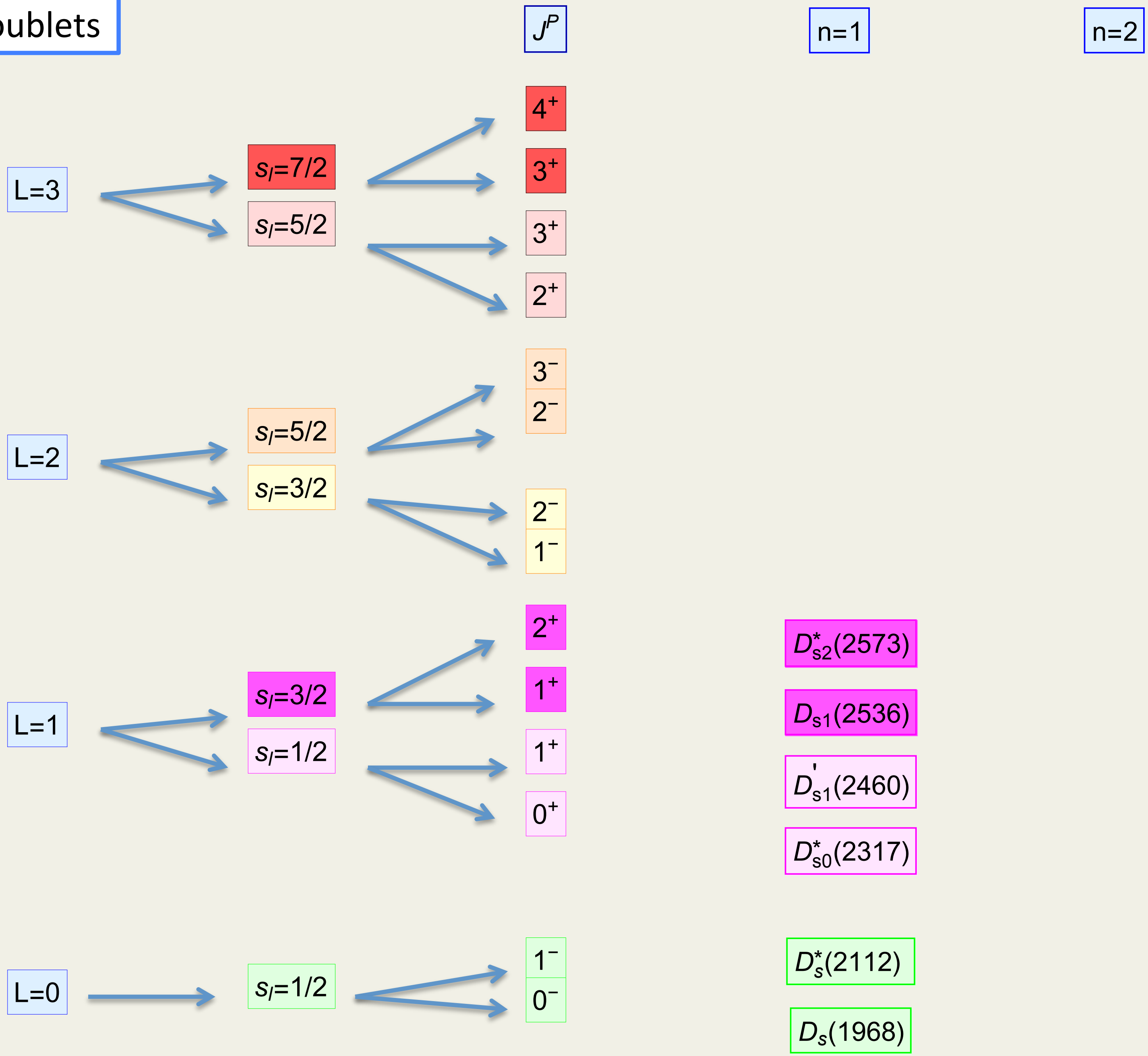
Heavy-Light meson doublets



$c\bar{q}$ doublets



$c\bar{s}$ doublets



Charmed-strange mesons: latest observations

BaBar & Belle

$c\bar{s}$	mass (MeV)	Γ (MeV)
$D^*_{s1}(2700)$	$2709\pm^{9}_{6}$	125 ± 30
$D_{sJ}(2860)$	$2862 \pm 2 \pm 5_2$	$48 \pm 3 \pm 6$
$D_{sJ}(3040)$	$3044 \pm 8\pm^{30}_{5}$	$239 \pm 35\pm^{46}_{42}$

Belle PRL100 (08) 092001

BaBar PRL 97 (06) 222001

BaBar PRD 80 (09) 092003

LHCb

$c\bar{s}$	mass (MeV)	Γ (MeV)
$D^*_{s1}(2700)$	$2709.2 \pm 1.9 \pm 4.5$	$115.8 \pm 7.3 \pm 12.1$
$D_{sJ}(2860)$	$2860.5 \pm 2.6 \pm 2.5 \pm 6$	$53 \pm 7 \pm 4 \pm 6$
$D_{sJ}(2860)$	$2859 \pm 12 \pm 6 \pm 23$	$159 \pm 23 \pm 27 \pm 72$

LHCb JHEP 10 (12) 151

LHCb PRL 113 (2014) 162001

two almost degenerate states

Latest observed $c\bar{q}$ mesons

resonance	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 ± 2.5	93 ± 6 ± 13	$D^+\pi^-$, $D^{*+}\pi^-$
$D^*(2600)^+$	2621.3 ± 3.7 ± 4.2	93 (fixed)	$D^0\pi^+$
$D(2750)^0$	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 (fixed)	$D^0\pi^+$

BaBar
PRD 82 (2010) 111101(R)

resonance	Mass (MeV)	Width (MeV)	decays to
$D(2580)^0$	2579.5 ± 3.4 ± 5.5	77.5 ± 17.8 ± 46	$D^{*+}\pi^-$
$D^*(2650)^0$	2649.2 ± 3.5 ± 3.5	140.2 ± 17.1 ± 18.6	$D^{*+}\pi^-$
$D(2740)^0$	2737 ± 3.5 ± 11.2	73.2 ± 13.4 ± 25.0	$D^{*+}\pi^-$
$D^*(2760)^0$	2761.1 ±5.1 ± 6.5	74.4 ± 3.4 ± 37.0	$D^{*+}\pi^-$
$D^*(2760)^0$	2760.1 ±1.1 ± 3.7	74.4 ± 3.4 ± 19.1	$D^+\pi^-$
$D^*(2760)^+$	2771.7 ±1.7 ± 3.8	66.7 ± 6.6 ± 10.5	$D^0\pi^+$
$D_J(3000)^0$	2971.8 ± 8.7	188.1 ± 44.8	$D^{*+}\pi^-$
$D(3000)^0$	3008.1 ± 4.0	110.5 ± 11.5	$D^+\pi^-$
$D^*(3000)^+$	3008.1 (fixed)	110.5 (fixed)	$D^0\pi^+$

LHCb
JHEP 09 (2013) 145

resonance	Mass (MeV)	Width (MeV)	decays to
$D_1^*(2680)^0$	2681.1 ± 5.6 ± 4.9 ± 13.1	186.7 ± 8.5 ± 8.6 ± 8.2	$D^+\pi^-$
$D^*(2760)^0$	2775.5 ± 4.5 ± 4.5± 4.7	95.3 ± 9.6 ± 7.9 ± 33.1	$D^+\pi^-$
$D_2^*(3000)^0$	3214 ± 29 ±33 ±36	186 ± 38 ± 34 ± 63	$D^+\pi^-$

LHCb
1608.01289

A QCD based approach to properly identify heavy-light mesons

Heavy-Light meson doublets: effective fields

ℓ	$\vec{s}_\ell$	J^P	effective field
0	$\frac{1}{2}$	$(0^-, 1^-)$	$H_a = \frac{1+\not{v}}{2}[P^*_{a\mu}\gamma^\mu - P_a\gamma_5]$
1	$\frac{1}{2}$	$(0^+, 1^+)$	$S_a = \frac{1+\not{v}}{2}\left[P'^{\mu}_{1a}\gamma_\mu\gamma_5 - P^*_{0a}\right]$
	$\frac{3}{2}$	$(1^+, 2^+)$	$T^\mu_a = \frac{1+\not{v}}{2}\left\{P^{\mu\nu}_{2a}\gamma_\nu - P_{1a\nu}\sqrt{\frac{3}{2}}\gamma_5\left[g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu - v^\mu)\right]\right\}$
2	$\frac{3}{2}$	$(1^-, 2^-)$	$X^\mu_a = \frac{1+\not{v}}{2}\left\{P^{*\mu\nu}_{2a}\gamma_5\gamma_\nu - P'^{*}_{1a\nu}\sqrt{\frac{3}{2}}\left[g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu + v^\mu)\right]\right\}$
	$\frac{5}{2}$	$(2^-, 3^-)$	$X'^{\mu\nu}_a = \frac{1+\not{v}}{2}\left\{P^{\mu\nu\sigma}_{3a}\gamma_\sigma - P^{*'\alpha\beta}_{2a}\sqrt{\frac{5}{3}}\gamma_5\left[g^\mu_\alpha g^\nu_\beta - \frac{1}{5}\gamma_\alpha g^\nu_\beta(\gamma^\mu - v^\mu) - \frac{1}{5}\gamma_\beta g^\mu_\alpha(\gamma^\nu - v^\nu)\right]\right\}$

Effective lagrangian approach based on HQET+ chiral symmetry: theoretical tool to compute strong decays F -> H M

F=H,S,T,X,X'

M= light pseudoscalar meson

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

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

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

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

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

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contains light pseudoscalar meson fields

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

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

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

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

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

Effective lagrangian approach based on HQET+ chiral symmetry: theoretical tool to compute strong decays F -> H M

F=H,S,T,X,X'

M= light pseudoscalar meson

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

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

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

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

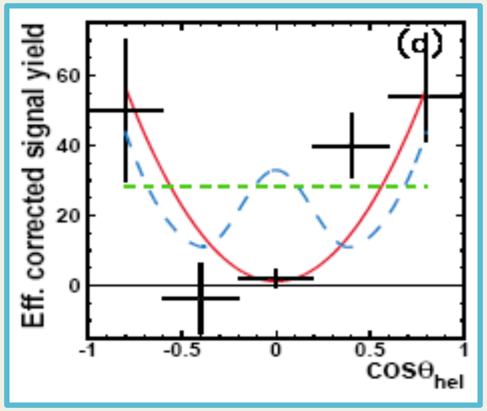
decay rates of states in the same doublet governed by the same coupling

→ model independent predictions for ratios of Brs

The method @ work: the case of $D_{s1}^*(2700)$

Belle PRL100 (08) 092001
BaBar PRD 80 (09) 092003

- observed by Belle & BaBar in $B^+ \to \bar{D}^0 D^0 K^+$ decaying to D^0K^+
- later observed by BaBar decaying to D^*K
- confirmed by LHCb
- observed by BaBar also in the Dalitz Plot analysis of $B^0 \to D^- D^0 K^+$,

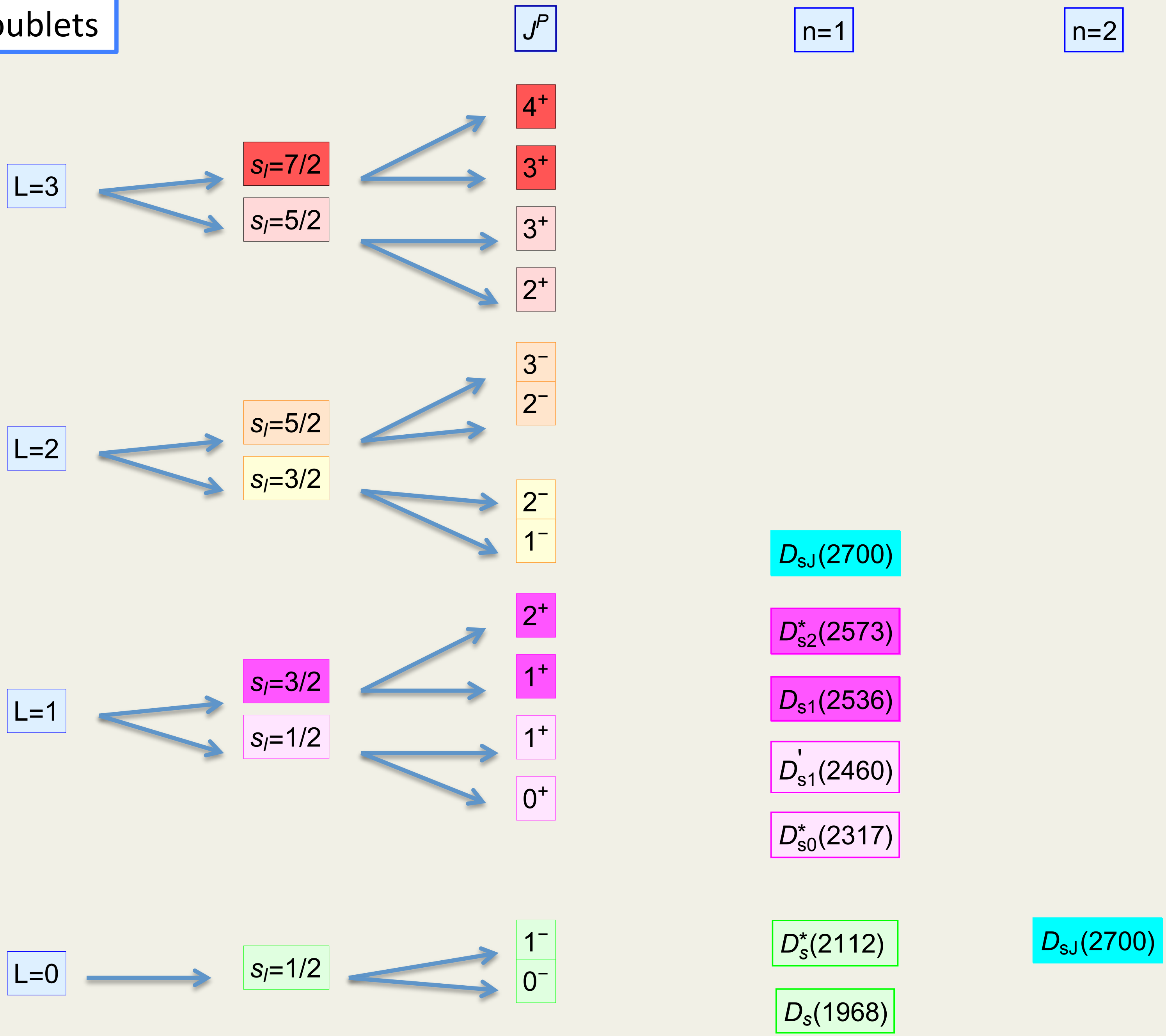


J=0
J=1
J=2

$J^P=1^-$ **favoured**

BaBar Dalitz plot analysis of $B^0 \to D^- D^0 K^+$ confirms $J^P=1^-$

$c\bar{s}$ doublets



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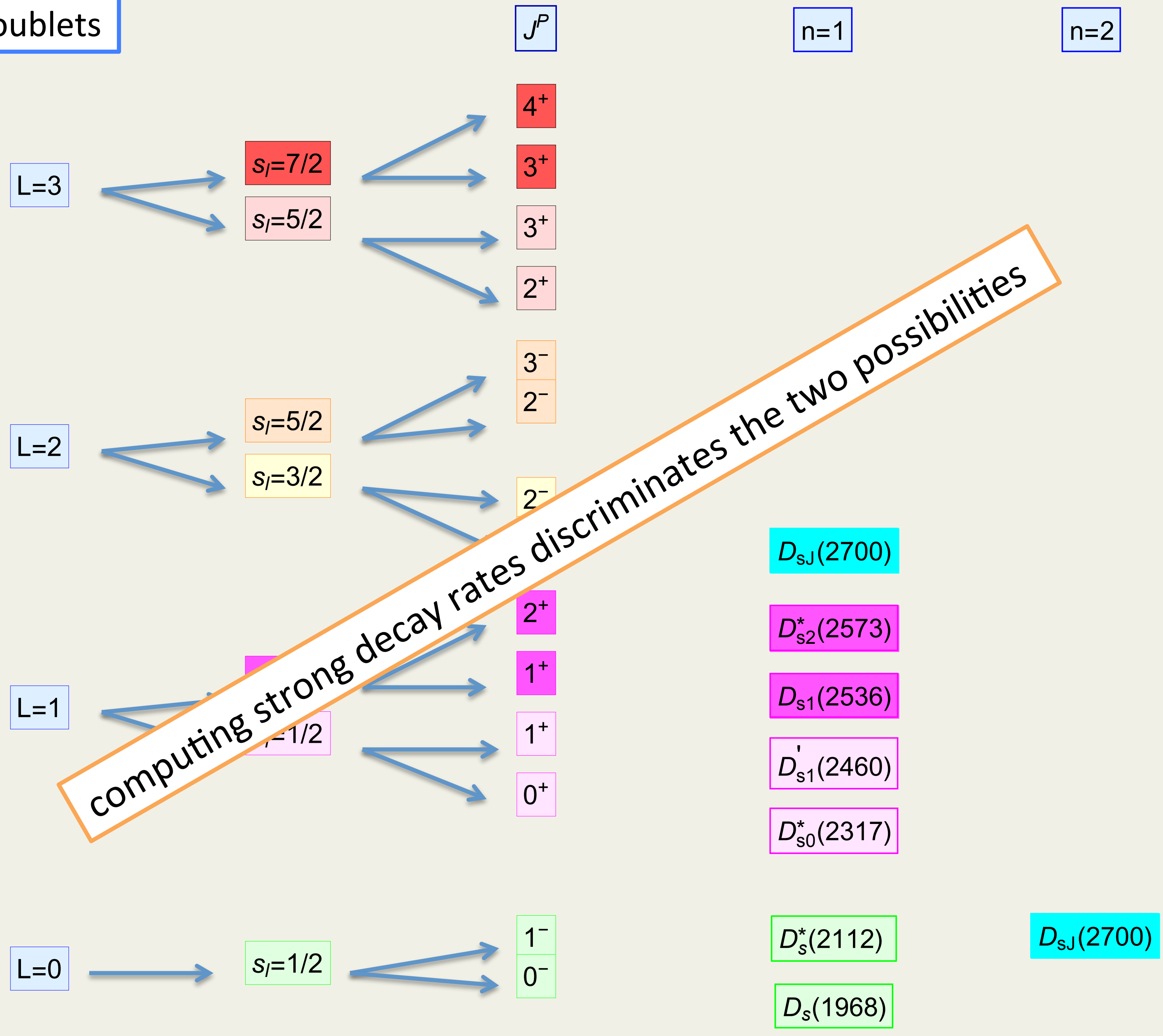

The method @ work: the case of $D_{s1}^*(2700)$

P. Colangelo, S. Nicotri, M. Rizzi, FDF
PRD77, 014012

$$R_1 = \frac{\Gamma(D_{s1}^*(2700) \to D^* K)}{\Gamma(D_{s1}^*(2700) \to D K)} \qquad R_2 = \frac{\Gamma(D_{s1}^*(2700) \to D_s \eta)}{\Gamma(D_{s1}^*(2700) \to D K)} \qquad R_3 = \frac{\Gamma(D_{s1}^*(2700) \to D_s^* \eta)}{\Gamma(D_{s1}^*(2700) \to D K)}$$

results

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

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most sensitive ratio

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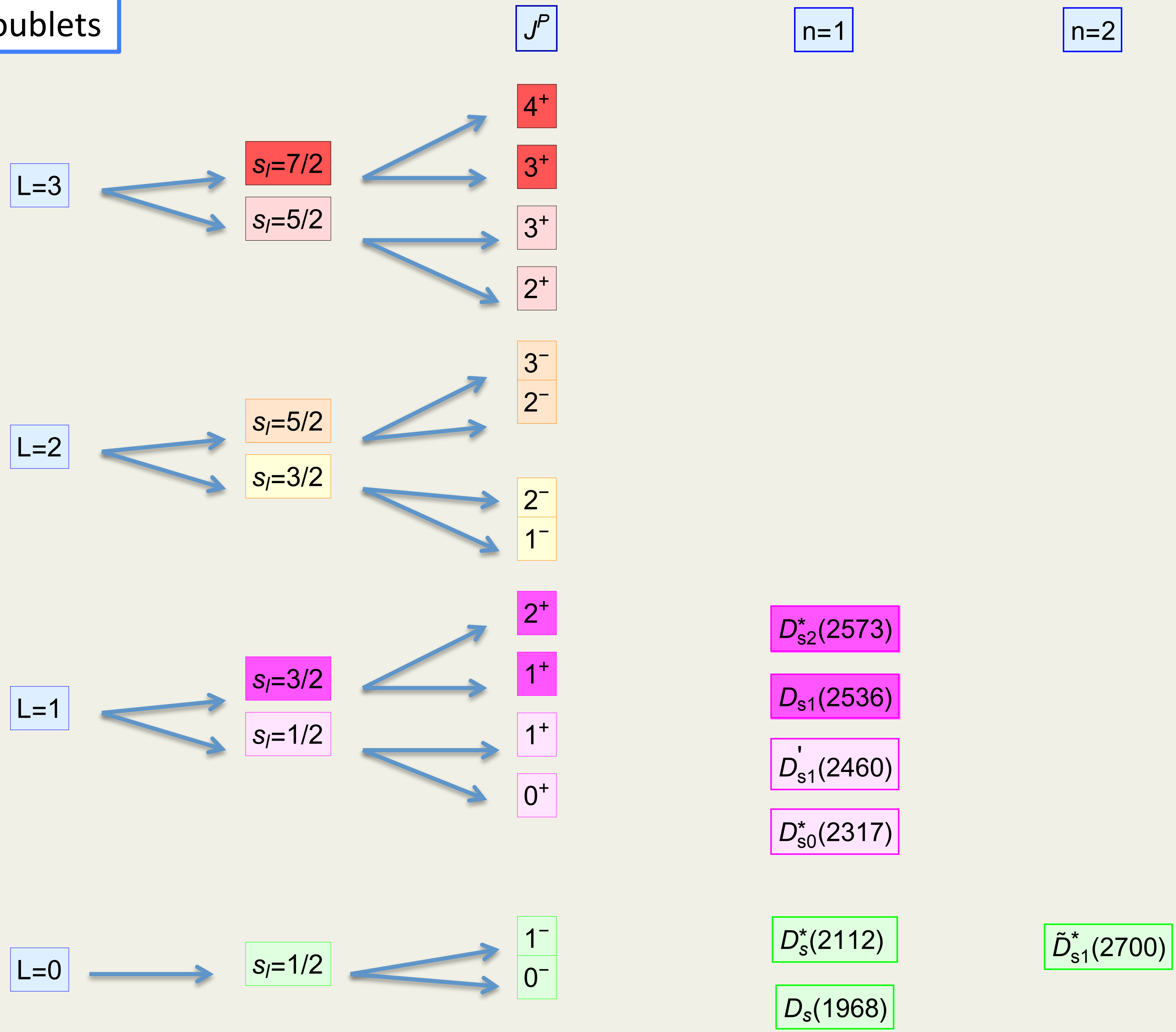
Babar :

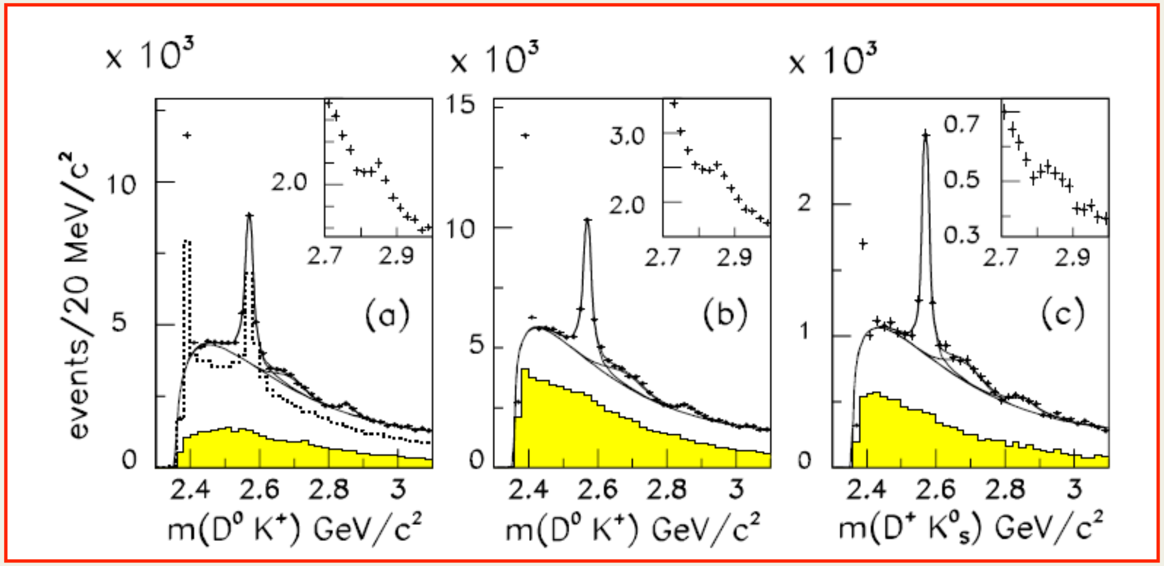
$$R_1 = 0.91 \pm 0.13_{stat} \pm \pm 0.12_{syst}$$

$c\bar{s}$ doublets



The method @ work: the case of $D_{s3}^{*}(2860)$

- discovered by BaBar Coll.
- reconstructed in D^0K^+ & D^+K_s

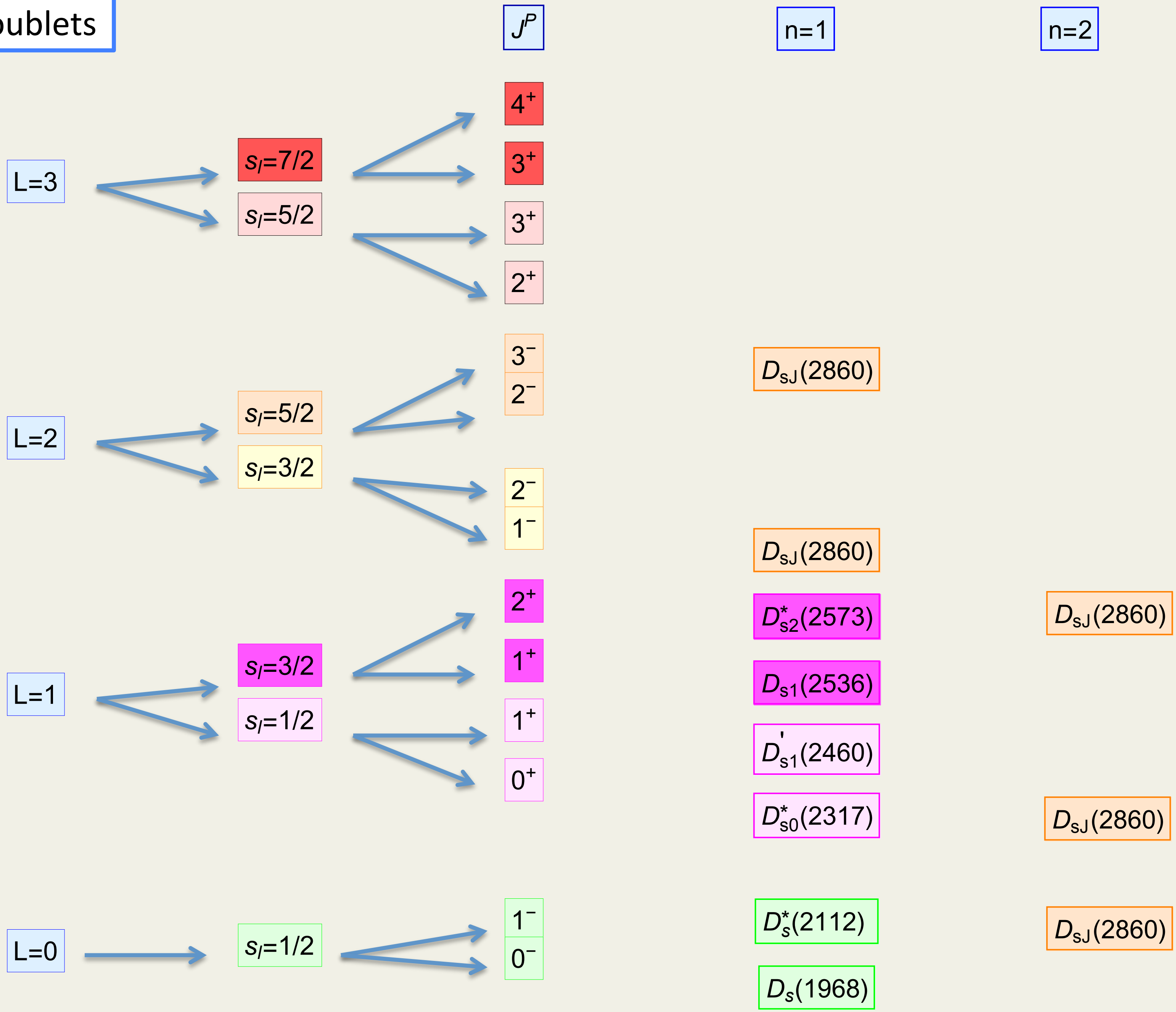


BaBar Collab., PRL 97 (06) 222001

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

Only states that can decay to DK allowed

$c\bar{s}$ doublets



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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

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- states decaying in s-wave or p-wave expected to be much broader

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

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- $J^P=2^+$ state could decay in p-wave as an effect of $1/m_Q$ corrections -> broader as well

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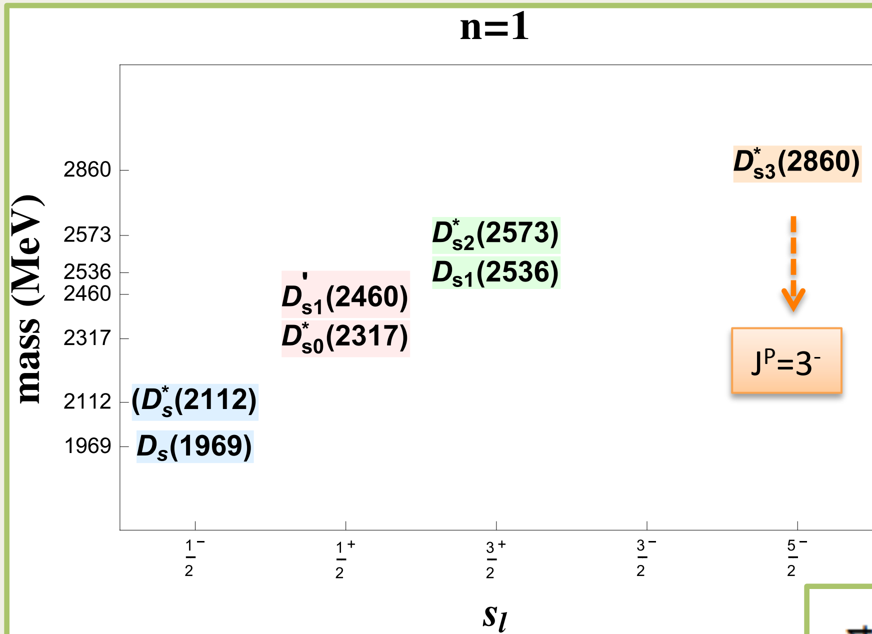
P. Colangelo, S. Nicotri, FDF
PLB 642, 48

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

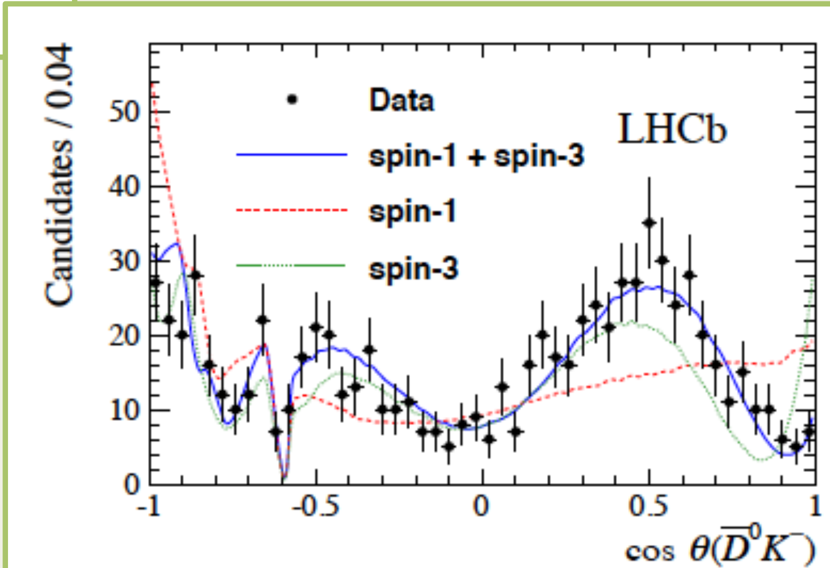
would explain the observed narrowness

- states decaying in s-wave or p-wave expected to be much broader
- $J^P=2^+$ state could decay in p-wave as an effect of $1/m_Q$ corrections -> broader as well

The method @ Work: the case of $D_{s3}^*(2860)$
Here it is!



from Dalitz plot analysis of $B_s \to \overline{D}^0 K^- \pi^+$

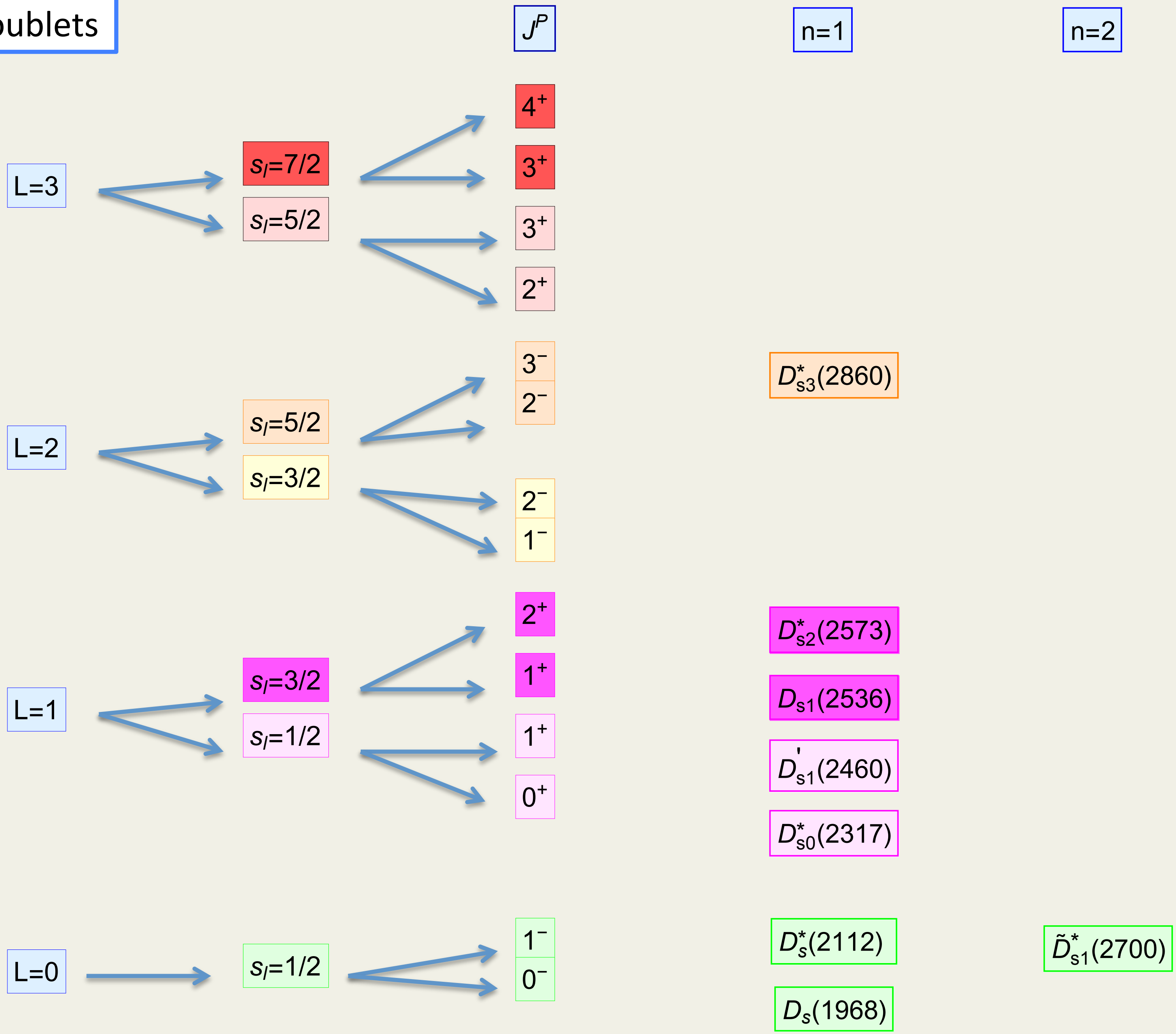


LHCb confirms.

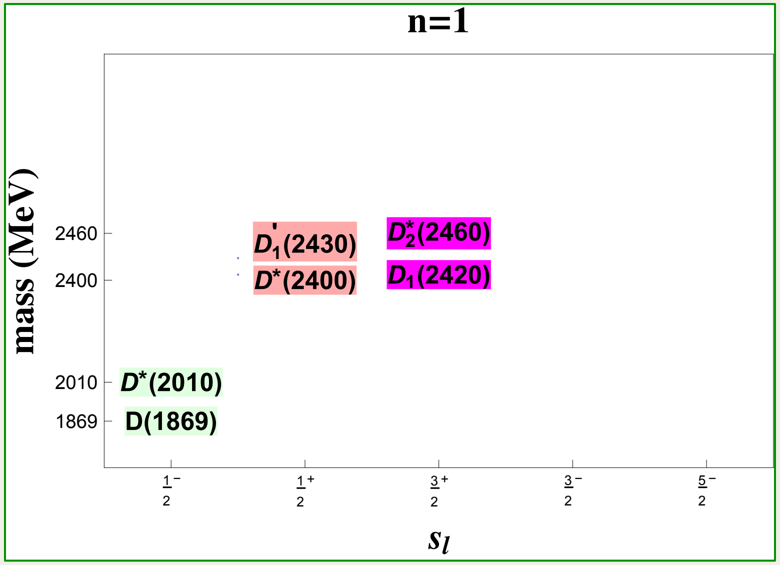
a second broader state
with same mass also suggested by data

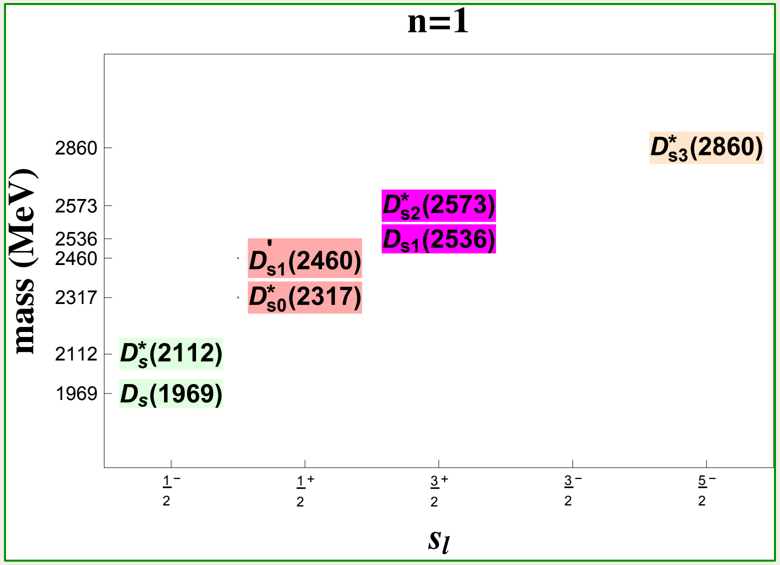
LHCb Collab., PRD 90 (14) 072003

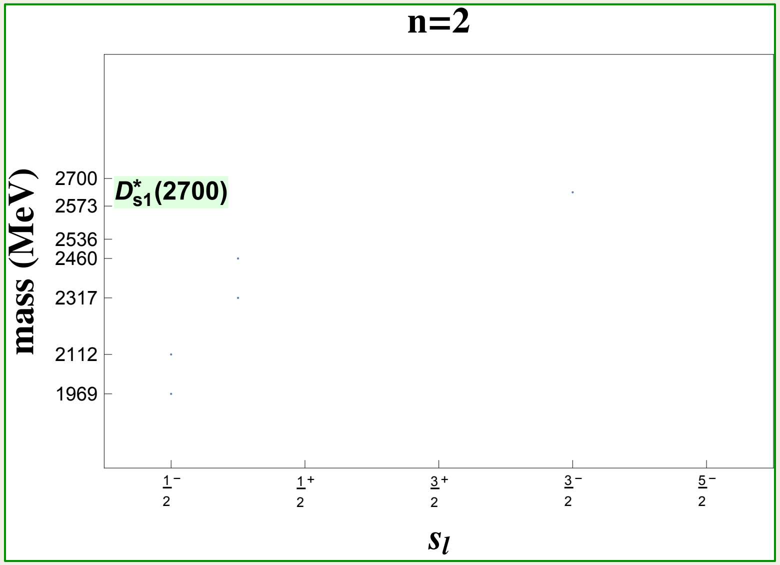
$c\bar{s}$ doublets



established excited states: their place in the doublets







$D_{sJ}(3040)$: 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

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PRD81, 094001

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

Latest observed $c\bar{q}$ mesons

resonance	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 ± 2.5	93 ± 6 ± 13	$D^+\pi^-$, $D^{*+}\pi^-$
$D^*(2600)^+$	2621.3 ± 3.7 ± 4.2	93 (fixed)	$D^0\pi^+$
$D(2750)^0$	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 (fixed)	$D^0\pi^+$

BaBar
PRD 82 (2010) 111101(R)

resonance	Mass (MeV)	Width (MeV)	decays to
$D(2580)^0$	2579.5 ± 3.4 ± 5.5	77.5 ± 17.8 ± 46	$D^{*+}\pi^-$
$D^*(2650)^0$	2649.2 ± 3.5 ± 3.5	140.2 ± 17.1 ± 18.6	$D^{*+}\pi^-$
$D(2740)^0$	2737 ± 3.5 ± 11.2	73.2 ± 13.4 ± 25.0	$D^{*+}\pi^-$
$D^*(2760)^0$	2761.1 ±5.1 ± 6.5	74.4 ± 3.4 ± 37.0	$D^{*+}\pi^-$
$D^*(2760)^0$	2760.1 ±1.1 ± 3.7	74.4 ± 3.4 ± 19.1	$D^+\pi^-$
$D^*(2760)^+$	2771.7 ±1.7 ± 3.8	66.7 ± 6.6 ± 10.5	$D^0\pi^+$
$D_J(3000)^0$	2971.8 ± 8.7	188.1 ± 44.8	$D^{*+}\pi^-$
$D(3000)^0$	3008.1 ± 4.0	110.5 ± 11.5	$D^+\pi^-$
$D^*(3000)^+$	3008.1 (fixed)	110.5 (fixed)	$D^0\pi^+$

LHCb
JHEP 09 (2013) 145

resonance	Mass (MeV)	Width (MeV)	decays to
$D_1^*(2680)^0$	2681.1 ± 5.6 ± 4.9 ± 13.1	186.7 ± 8.5 ± 8.6 ± 8.2	$D^+\pi^-$
$D^*(2760)^0$	2775.5 ± 4.5 ± 4.5± 4.7	95.3 ± 9.6 ± 7.9 ± 33.1	$D^+\pi^-$
$D_2^*(3000)^0$	3214 ± 29 ±33 ±36	186 ± 38 ± 34 ± 63	$D^+\pi^-$

LHCb
1608.01289

Latest observed $c\bar{q}$ mesons

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BaBar
PRD 82 (2010) 111101(R)

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LHCb
JHEP 09 (2013) 145

Likely to be radial excitations of the fundamental doublet

resonance	Mass (MeV)	Width (MeV)	decays to
$D_1^*(2680)^0$	2681.1 ± 5.6 ± 4.9 ± 13.1	186.7 ± 8.5 ± 8.6 ± 8.2	$D^+\pi^-$
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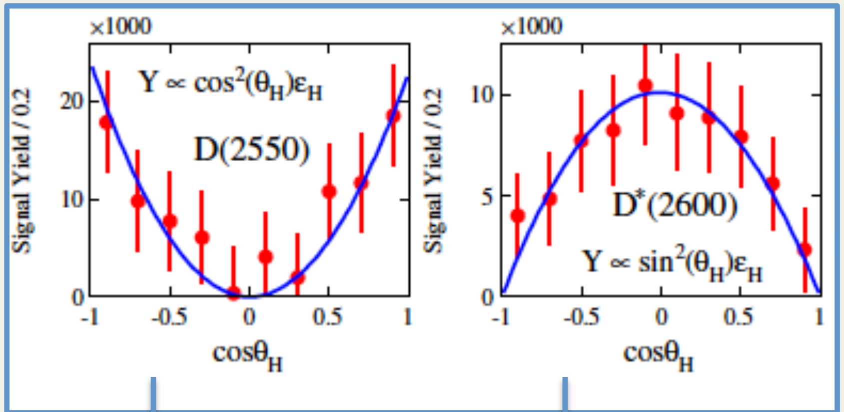
LHCb
1608.01289

Latest observed $c\bar{q}$ mesons



consistent with $J^P=0^-$

consistent with natural parity

Branching fraction Ratio

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

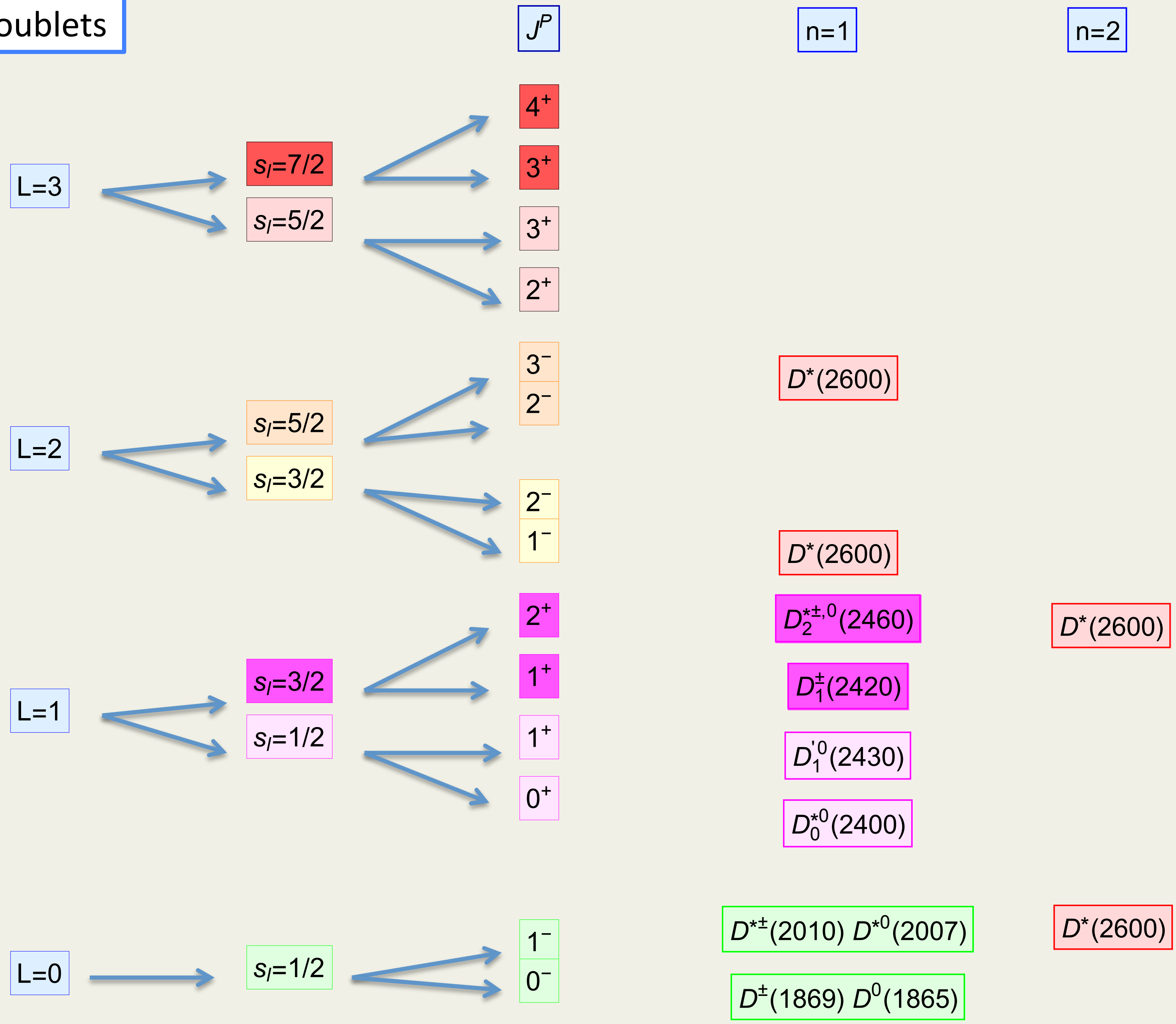
$$\frac{\mathcal{B}(D^{*0}(2600) \to D^+\pi^-)}{\mathcal{B}(D^{*0}(2600) \to D^{*+}\pi^-)} = 0.822 \pm 0.003$$

while BaBar finds:

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

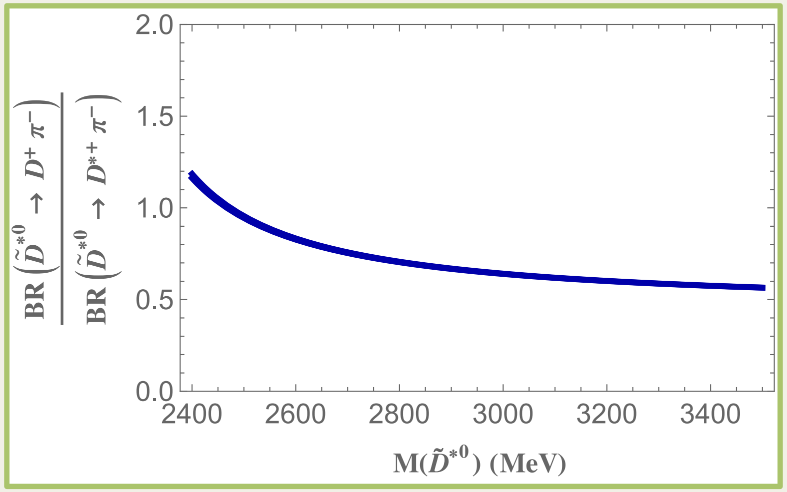
P. Colangelo et al.
PRD 86 (2012) 054024

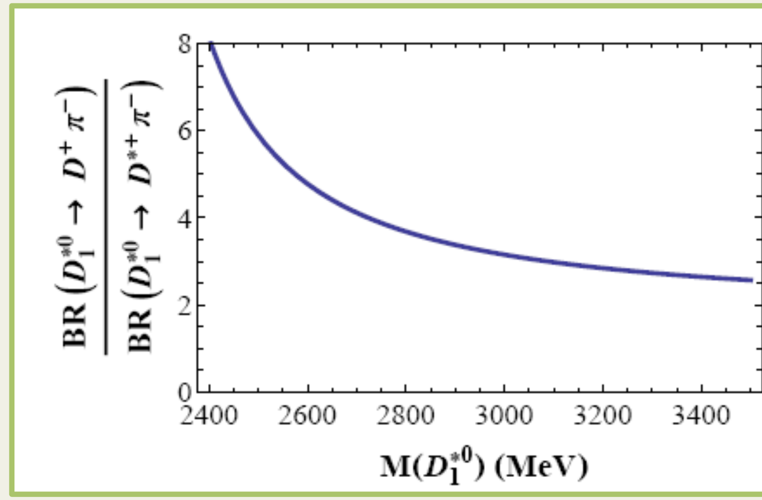
$\bar{c}q$ doublets

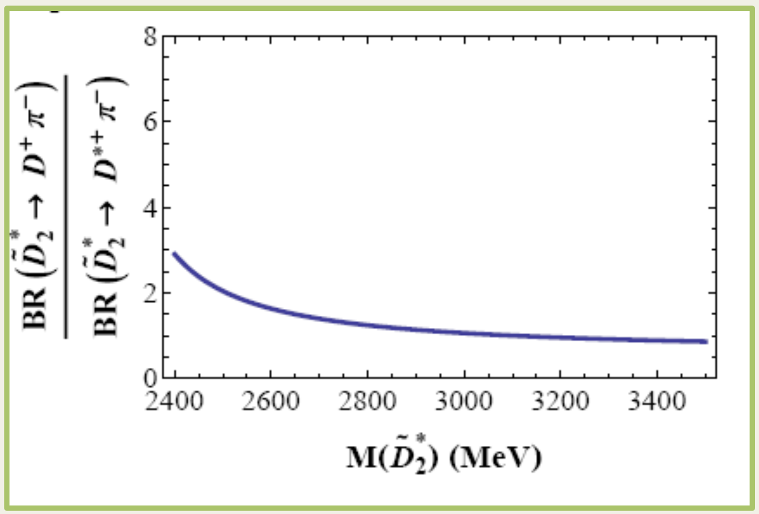


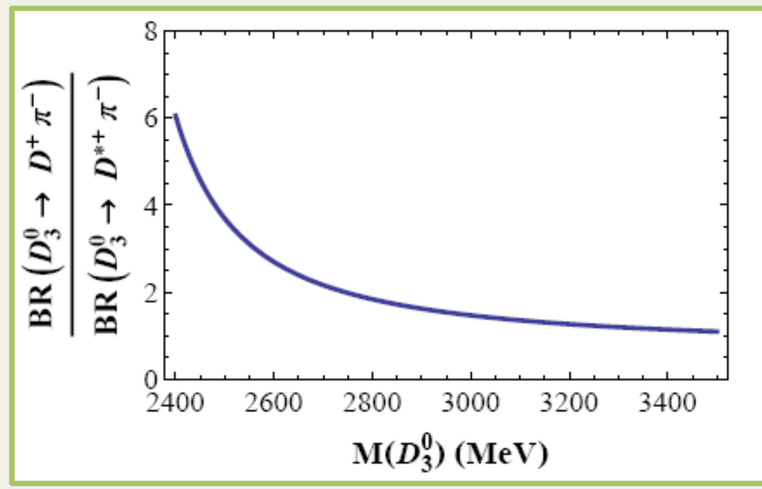
Latest observed $c\bar{q}$ mesons

Branching fraction ratios for the four possibilities vs the mass of the decaying meson









- No assignment to a meson of mass 2600 MeV would reproduce the exp result:
- The identification with n=2 D^* is the only one with R<1.
- The larger mass measured by LHCb improves the result.
- Interpretation supported by relativistic quark model **Godfrey & Moats PRD 93 (2016) 034035**

Latest observed $c\bar{q}$ mesons

BaBar
PRD 82 (2010) 111101(R)

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LHCb
JHEP 09 (2013) 145

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LHCb assigns spin 3 to $D^*(2760)$
2 states probably
fill the $J^P=(2^-,3^-)$ doublet

LHCb
1608.01289

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BaBar
PRD 82 (2010) 111101(R)

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LHCb
JHEP 09 (2013) 145

LHCb assigns spin 3 to $D^*(2760)$
2 states probably
fill the $J^P=(2^-,3^-)$ doublet

Another $D_J^*(2760)$ with J=1
has been observed by LHCb in
Dalitz plot analysis
PRD91 (2015) 092002

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LHCb
1608.01289

Latest observed $c\bar{q}$ mesons

BaBar measures:

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

If (D(2750), D(2760)=(D_2, D_3^*) i.e. the d-wave doublet, we find:

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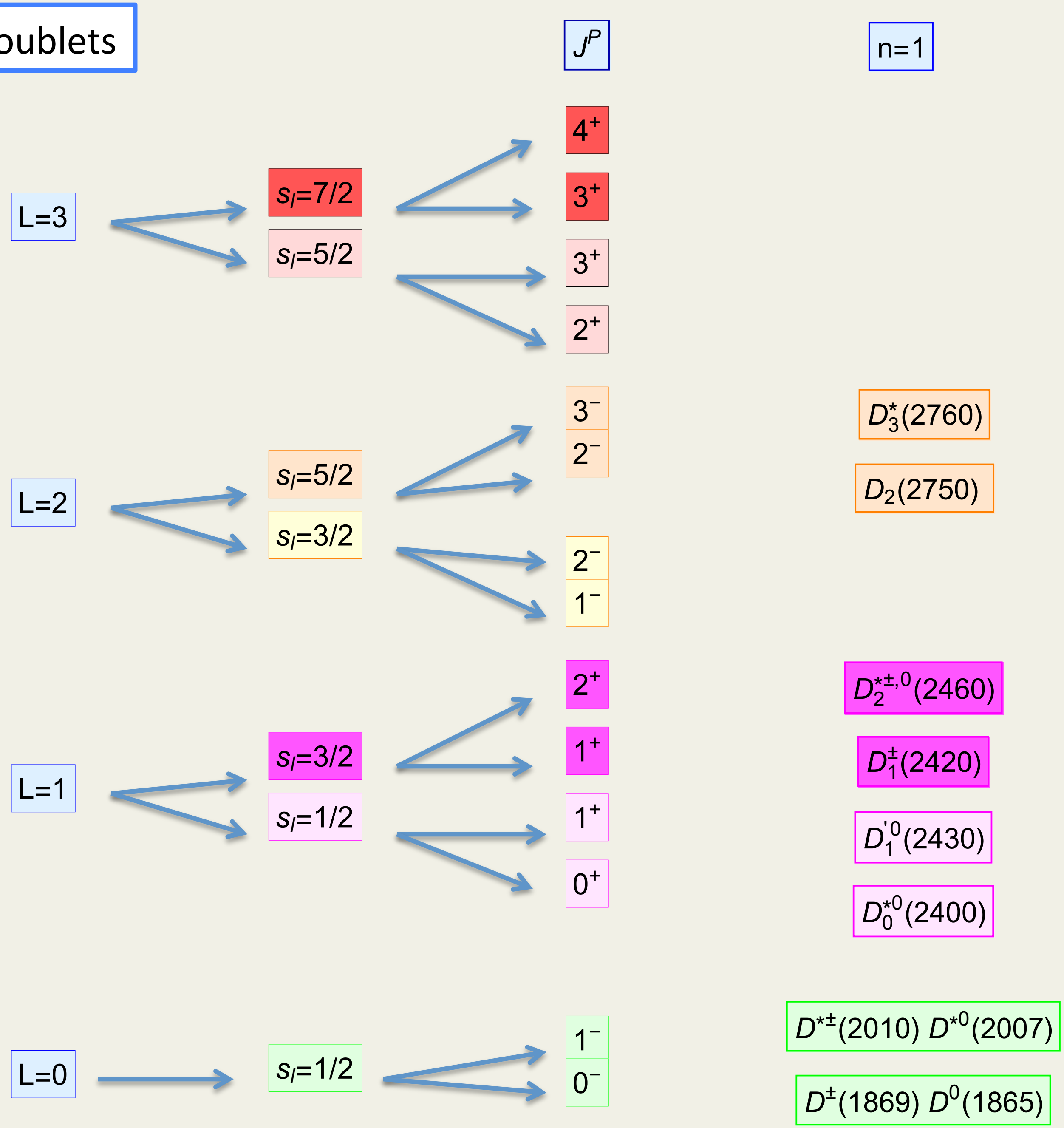
PRD 86 (2012) 054024

$$\left.\frac{BR(D^{*0}(2760) \to D^+\pi^-)}{BR(D^{*0}(2750) \to D^{*+}\pi^-)}\right|_{X'\text{doublet}} = 0.660 \pm 0.001$$

- close to the experimental measurement
- RQM predicts R>1 but supports this identification
- role of overlapping states in the same mass range invoked

$c\bar{q}$ doublets



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$D^*(3000)^+$	3008.1 (fixed)	110.5 (fixed)	$D^0\pi^+$

LHCb
JHEP 09 (2013) 145

LHCb assigns spin 2 to $D_2^*(3000)$

states with $J^P=2^-$ $\not\to$ $D\pi$

should be $J^P=2^+$

resonance	Mass (MeV)	Width (MeV)	decays to
$D_1^*(2680)^0$	2681.1 ± 5.6 ± 4.9 ± 13.1	186.7 ± 8.5 ± 8.6 ± 8.2	$D^+\pi^-$
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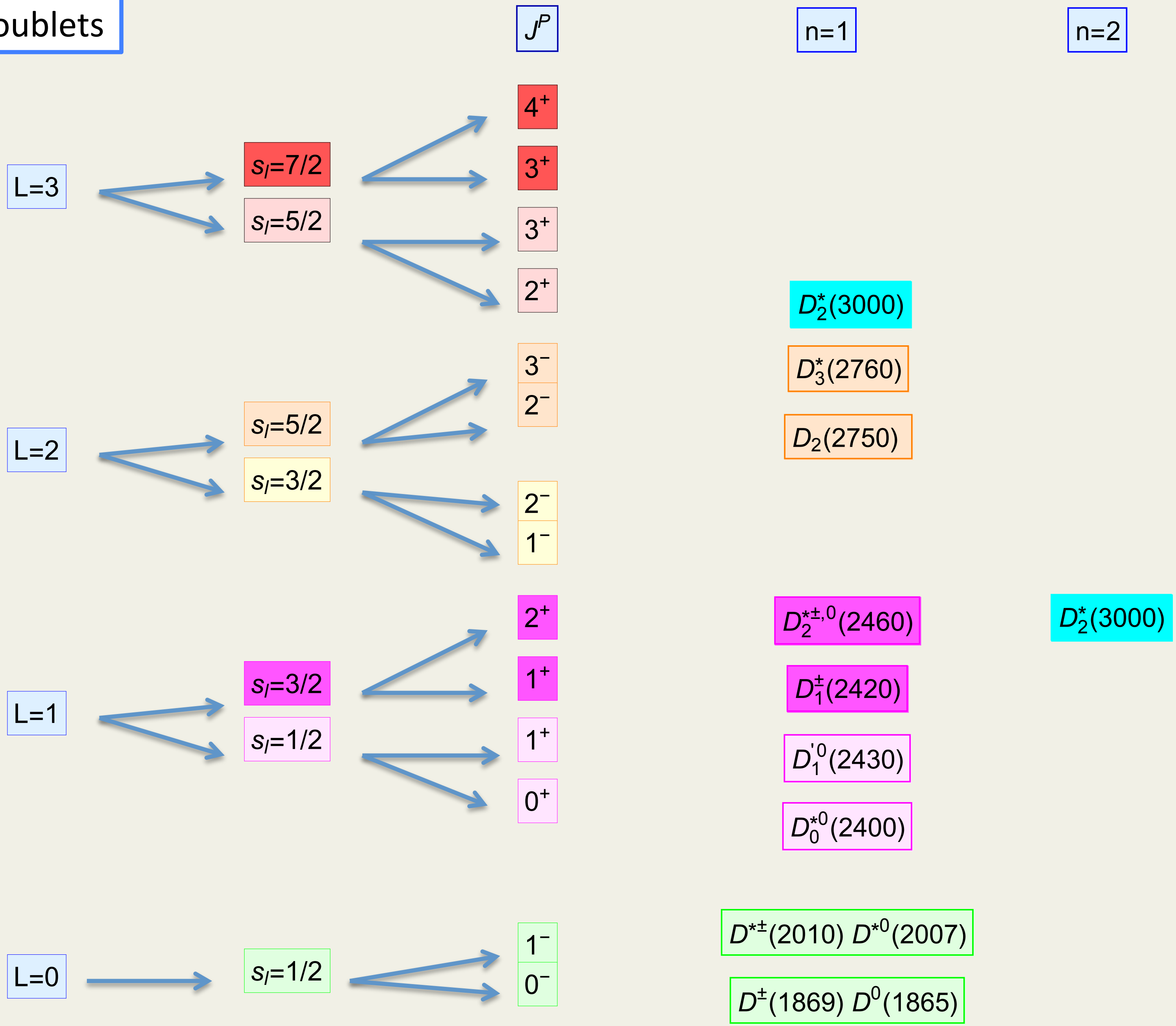
LHCb
1608.01289

$c\bar{q}$ doublets



Latest observed $c\bar{q}$ mesons

1st case: D_2^* is the radial excitation of the 2^+ state in the p-wave doublet

$$R = \frac{BR(D_2^*(3000) \to D^*\pi)}{BR(D_2^*(3000) \to D\pi)} = 1.06 \pm 0.03$$

2nd case: D_2^* is the 2^+ state in the f-wave doublet

$$R = \frac{BR(D_2^*(3000) \to D^*\pi)}{BR(D_2^*(3000) \to D\pi)} = 0.40 \pm 0.015$$

Measuring R could discriminate the two possibilities!

For comparison: RQM predicts R=3.4 in the first case
R= 0.8 in the second case

Exploting flavour symmetry: a taste of predictions for beauty mesons

$$R_\pi^{(F)} = \frac{BR(F \to B^*\pi)}{BR(F \to B\pi)}\,, \qquad R_K^{(F_s)} = \frac{BR(F_s \to B^*K)}{BR(F \to BK)}\,,$$

$$R_\eta^{(F_s)} = \frac{BR(F_s \to B_s^*\eta)}{BR(F_s \to BK)}\,, \qquad R_\eta^*(F_s) = \frac{BR(F_s \to B_s^*\eta)}{BR(F_s \to BK)}\,,$$

$b\bar{q}$	R_π	$b\bar{s}$	R_K	R_η	R_η^*
$\tilde{B}^*$	1.63 ± 0.005	$\tilde{B}_s^*$	1.43 ± 0.015	0.132 ± 0.008	0.11 ± 0.015
B_2^*	0.87 ± 0.01	B_{s2}^*	0.07 ± 0.005	-	-
B_3	0.92 ± 0.005	B_{s3}	0.815 ± 0.006	0.103 ± 0.002	0.063 ± 0.003

Exploting flavour symmetry: a taste of predictions for beauty mesons

$$R_\pi^{(F)} = \frac{BR(F \to B^*\pi)}{BR(F \to B\pi)}, \qquad R_K^{(F_s)} = \frac{BR(F_s \to B^*K)}{BR(F \to BK)},$$

$$R_\eta^{(F_s)} = \frac{BR(F_s \to B_s^*\eta)}{BR(F_s \to BK)}, \qquad R_\eta^*(F_s) = \frac{BR(F_s \to B_s^*\eta)}{BR(F_s \to BK)},$$

$b\bar{q}$	R_π	$b\bar{s}$	R_K	R_η	R_η^*
$\tilde{B}^*$	1.63 ± 0.005	$\tilde{B}_s^*$	1.43 ± 0.015	0.132 ± 0.008	0.11 ± 0.015
B_2^*	0.87 ± 0.01	B_{s2}^*	0.07 ± 0.005	-	-
B_3	0.92 ± 0.005	B_{s3}	0.815 ± 0.006	0.103 ± 0.002	0.063 ± 0.003

LHCb measures

LHCb JHEP 04 (2015) 024

$$\frac{\mathcal{B}\left(B_2^*(5747)^0 \to B^{*+}\pi^-\right)}{\mathcal{B}\left(B_2^*(5747)^0 \to B^+\pi^-\right)} = 0.71 \pm 0.14 \pm 0.30$$

$$\frac{\mathcal{B}\left(B_2^*(5747)^+ \to B^{*0}\pi^+\right)}{\mathcal{B}\left(B_2^*(5747)^+ \to B^0\pi^+\right)} = 1.0 \pm 0.5 \pm 0.8$$

Concluding remarks/Perspectives

Effective QCD Lagrangians can be built exploiting HQ + chiral symmetries

- predictions for branching fraction ratios ➔ proper identification of heavy-light mesons
  ➔ filling the ordinary meson spectra is preliminary to the search for exotics

- strong couplings can be in principle fixed from experiment
  ➔ possibility of predicting individual branching ratios

- spin symmetry ➔ relations between properties of the spin partners

- flavour symmetry ➔ relations between properties of charm & beauty hadrons

- inclusion of subleading $1/m_Q$ terms: systematic improvement of the method

- full understanding of excited states impacts on flavour anomalies
  ➔ role of D^{**} in semileptonic B decays to τ and ratios $R(D^{**})$

$B \to D^{**} \tau \bar{\nu}_\tau$

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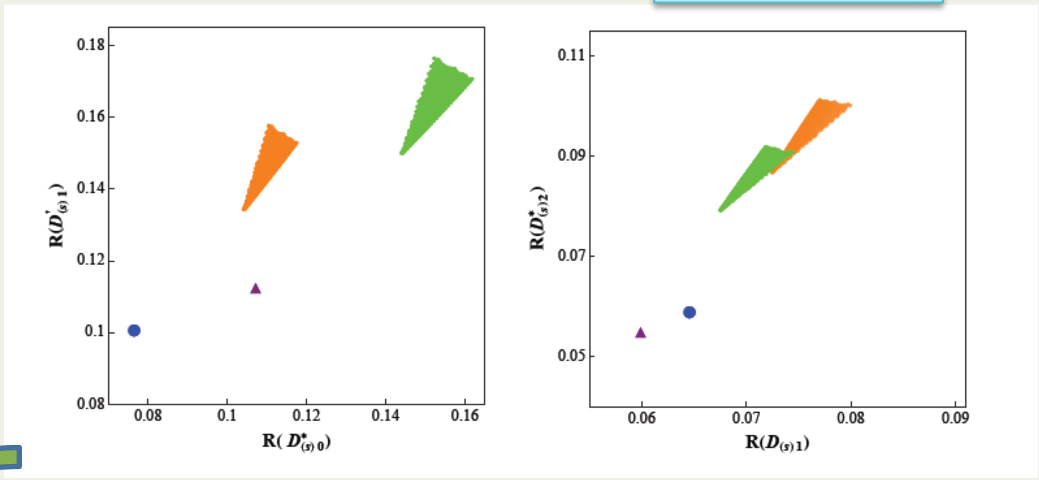
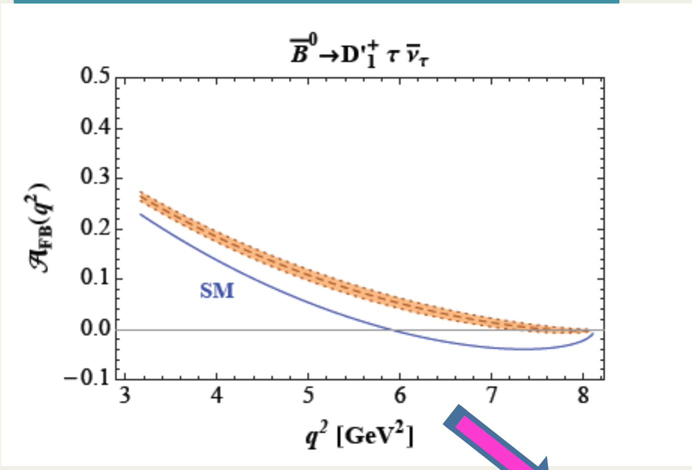
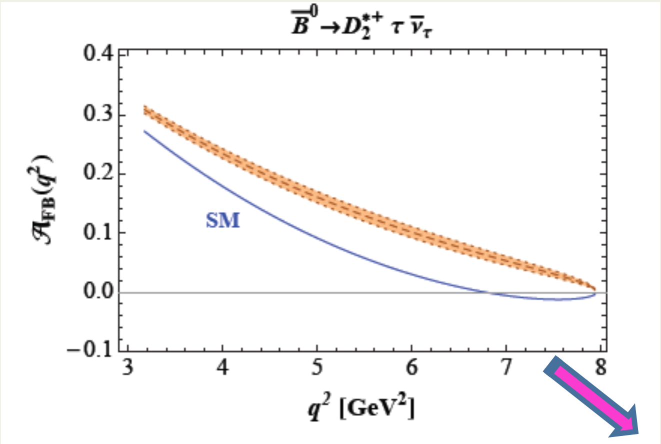
Orange= non strange
Blue circle= SM
Green= strange
Triangle= SM



The inclusion of the tensor operator produces a sizable increase in the ratios

Forward-backward asymmetries





shift in the position of the zero

the zero disappears