EUNPC 2015
Groningen
September 4th 2015

Interpretation of new states in open/hidden quarkonium

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INFN BARI

Outline

- Open flavoured heavy mesons
- Hidden flavoured quarkonia
- A brief discussion about the newly observed pentaquarks

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

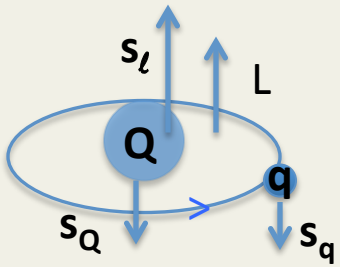
  - masses
  - strong couplings
  - strong decay rates

- Model independent predictions: ratios of branching fractions

- Results useful to properly classify the observed heavy mesons: the successful cases of $D^*_{s3}(2860)$ and $D^*_{s1}(2700)$

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

Intuitive picture



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

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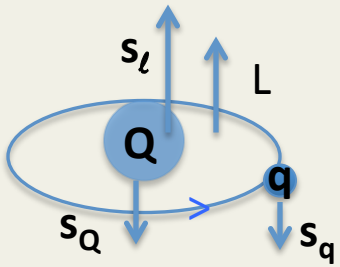

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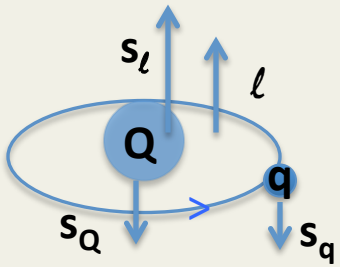

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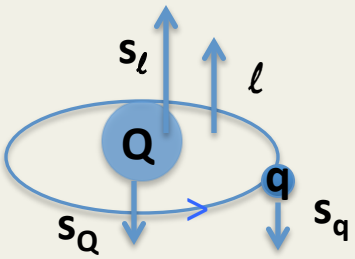
HQ spin & flavour symmetries

- heavy quark symmetry is not exact: $1/m_Q$ corrections can be systematically included

Spin of the heavy quark $\mathbf{s_Q}$
and total angular momentum of the light degrees of freedom $\mathbf{s_\ell}$
separately conserved

Hadrons with a single heavy quark:
Exploiting the heavy quark large mass limit $m_Q \to \infty$ (HQET)



Implications for spectroscopy

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

$$P = (-1)^{\ell+1}$$

Spin symmetry: mesons classified in doublets with $J = s_\ell \pm \frac{1}{2}$

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

$\vec{s}_\ell = \vec{\ell} + \vec{s}_q$ $J = s_\ell \pm \frac{1}{2}$

ℓ	$\vec{s}_\ell$	J^P	charm	beauty
0	$\frac{1}{2}$	$(0^-, 1^-)$	$(D_{(s)}, D^*_{(s)})$	$(B_{(s)}, B^*_{(s)})$
1	$\frac{1}{2}$	$(0^+, 1^+)$	$(D^*_{(s)0}, D'_{(s)1})$	$(B^*_{(s)0}, B'_{(s)1})$
	$\frac{3}{2}$	$(1^+, 2^+)$	$(D_{(s)1}, , D^*_{(s)2})$	$(B_{(s)1}, B^*_{(s)2})$
2	$\frac{3}{2}$	$(1^-, 2^-)$	$(D^*_{(s)1} D_{(s)2})$	$(B^*_{(s)1} B_{(s)2})$
	$\frac{5}{2}$	$(2^-, 3^-)$	$(D'_{(s)2} D^*_{(s)3})$	

1S

1P

1D

2S

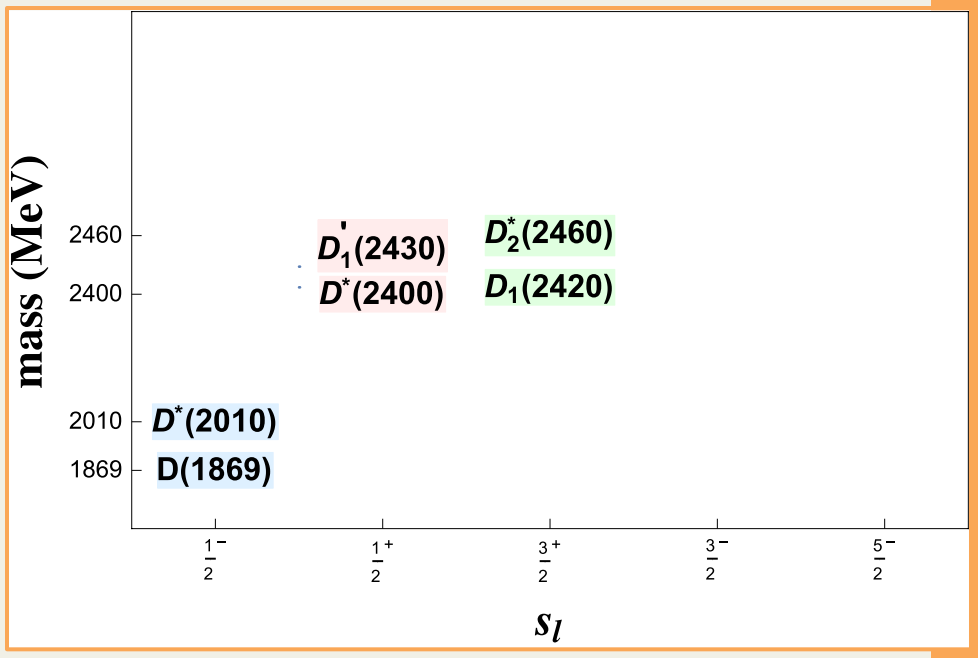
2P

2D

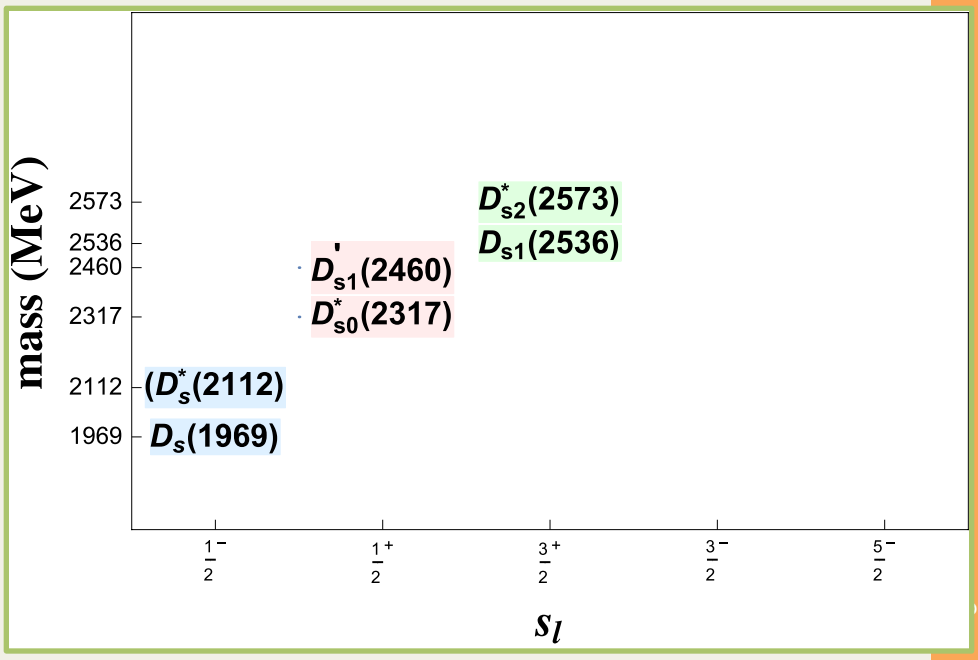
radial excitations might be in the same mass range

established excited states: their place in the doublets

$c\bar{q}$	mass (MeV)	Γ (MeV)
$D_0^{*0}(2400)$	2318 ± 29	267 ± 40
$D_0^{*\pm}(2400)$	$2403 \pm 14 \pm 35$	$283 \pm 24 \pm 34$
$D_1^{\prime 0}(2430)$	$2427 \pm 26 \pm 25$	$384 \pm^{107}_{75} \pm 74$
$D_1^0(2420)$	2421.3 ± 0.6	27.1 ± 2.7
$D_1^{\pm}(2420)$	2423.4 ± 3.1	26 ± 6
$D_2^{*0}(2460)$	2462.6 ± 0.7	49.0 ± 1.4
$D_2^{*\pm}(2460)$	2464.4 ± 1.9	37 ± 6



$c\bar{s}$	mass (MeV)	Γ (MeV)
$D_{s0}^*(2317)$	2317.8 ± 0.6	< 3.8
$D_{s1}'(2460)$	2459.6 ± 0.6	< 3.5
$D_{s1}(2536)$	2535.12 ± 0.13	$0.92 \pm 0.03 \pm 0.04$
$D_{s2}^*(2573)$	2572.6 ± 0.9	20 ± 5



Charmed mesons: recently observed states

BaBar

BaBar PRD 82 (2010) 111101

Resonance	Final state	Mass (MeV)	Width (MeV)
$D^0(2550)$	$D^{*+}\pi^-$	$2539.4 \pm 4.5 \pm 6.8$	$130 \pm 12 \pm 13$
$D^{*0}(2600)$	$D^+\pi^-$, $D^{*+}\pi^-$	$2608.7 \pm 2.4 \pm 2.5$	$93 \pm 6 \pm 13$
$D^{*+}(2600)$	$D^+\pi^-$	$2621.3 \pm 3.7 \pm 4.2$	93 (fixed)
$D^0(2750)$	$D^{*+}\pi^-$	$2763.3 \pm 2.3 \pm 2.3$	$60.9 \pm 5.1 \pm 3.6$
$D^{*+}(2760)$	$D^0\pi^+$	$2769.7 \pm 3.8 \pm 1.5$	60.9 (fixed)

LHCb

LHCb JHEP 1309 (2013) 145

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

Charmed-strange mesons: recently observed states

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

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LHCb JHEP 10 (12) 151

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two almost degenerate states

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

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

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

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

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

$$\mathcal{L}_{X'} = \frac{1}{\Lambda_\chi{}^2}\mathrm{Tr}[\bar{H}_a X'^{\mu\nu}_b [k_1\{D_\mu, D_\nu\}\mathcal{A}_\lambda$$

$$+ k_2(D_\mu D_\lambda \mathcal{A}_\nu + D_\nu D_\lambda \mathcal{A}_\mu)]_{ba}\gamma^\lambda\gamma_5] + \mathrm{H.c.}$$

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

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contains light pseudoscalar meson fields

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

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

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

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

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

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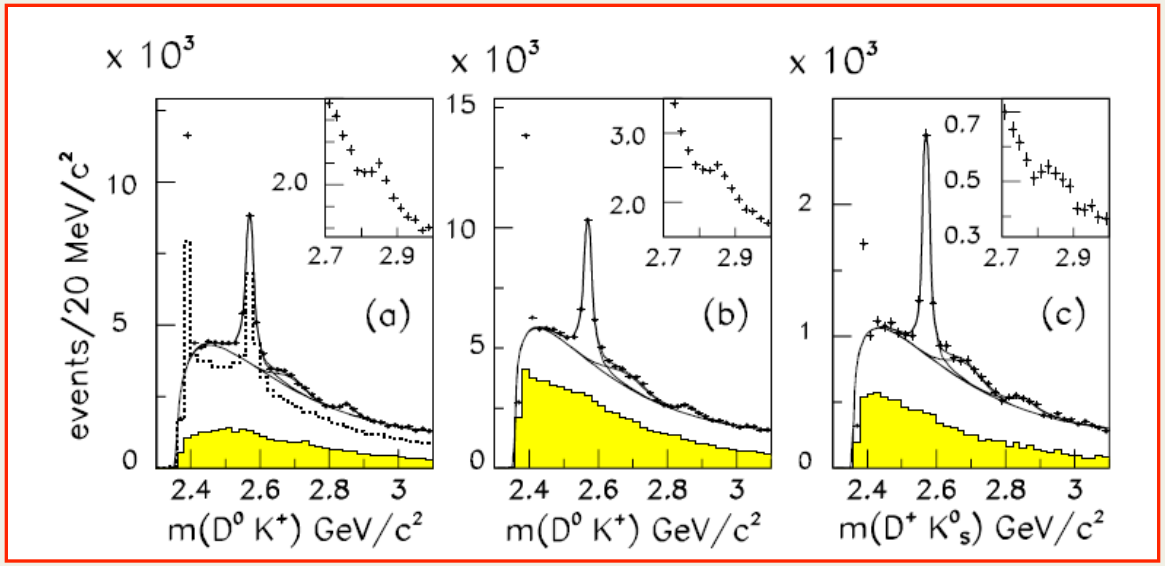
$$\mathcal{L}_{X'} = \frac{1}{\Lambda_\chi^{\,2}}\mathrm{Tr}[\bar{H}_a X'^{\mu\nu}_b [k_1\{D_\mu, D_\nu\}\mathcal{A}_\lambda + k_2(D_\mu D_\lambda \mathcal{A}_\nu + D_\nu D_\lambda \mathcal{A}_\mu)]_{ba}\gamma^\lambda\gamma_5] + \mathrm{H.c.}$$ → X' -> H π

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 $D_{s3}^*(2860)$

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

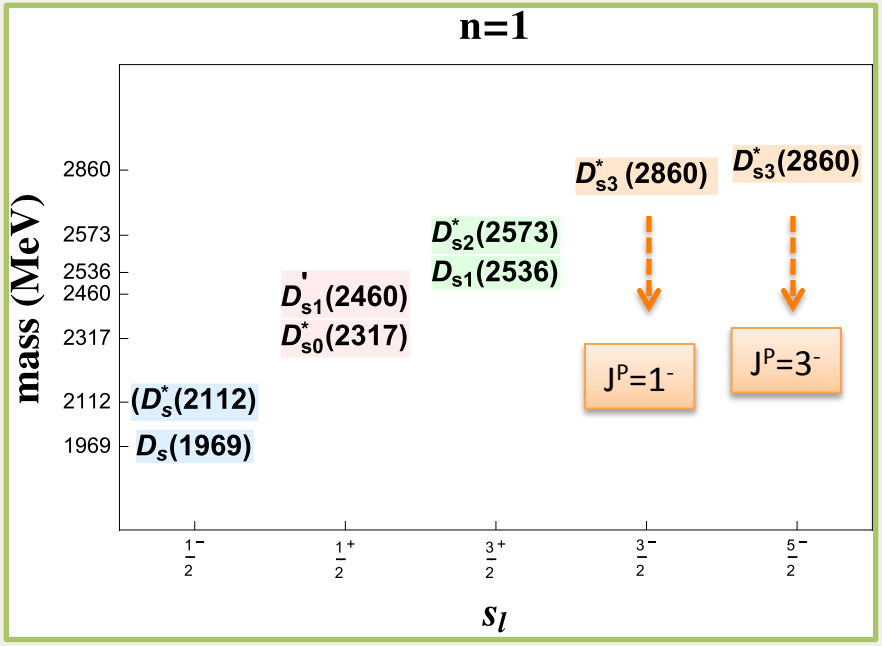


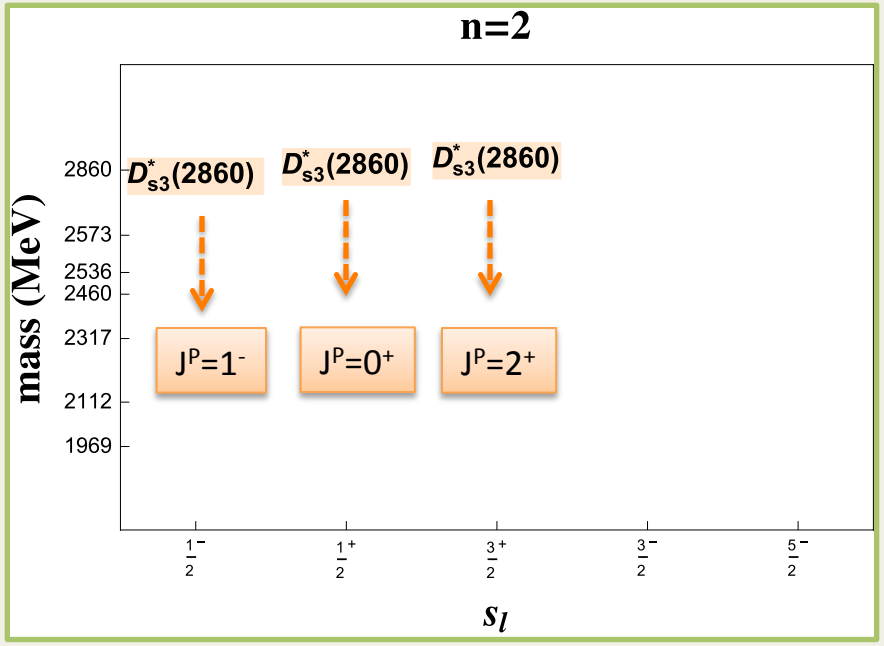
BaBar Collab., PRL 97 (06) 222001

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

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





computing strong decay rates can help discriminating the various possibilities

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

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

- 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

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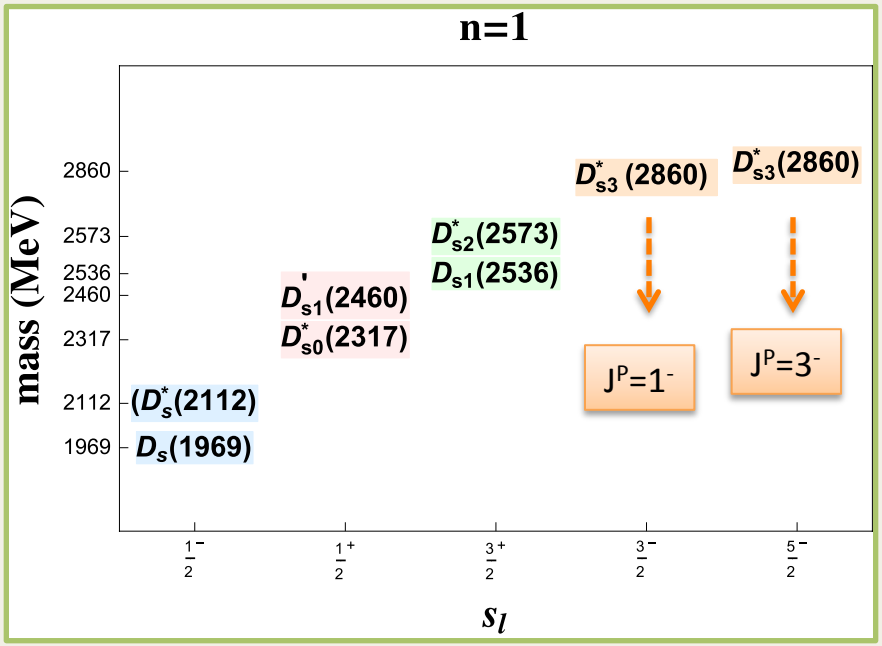

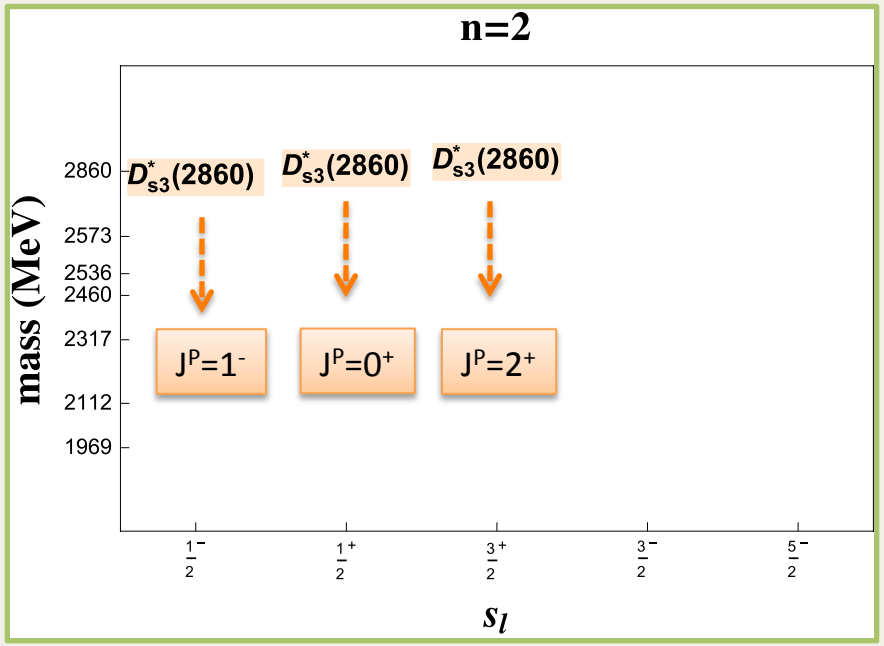

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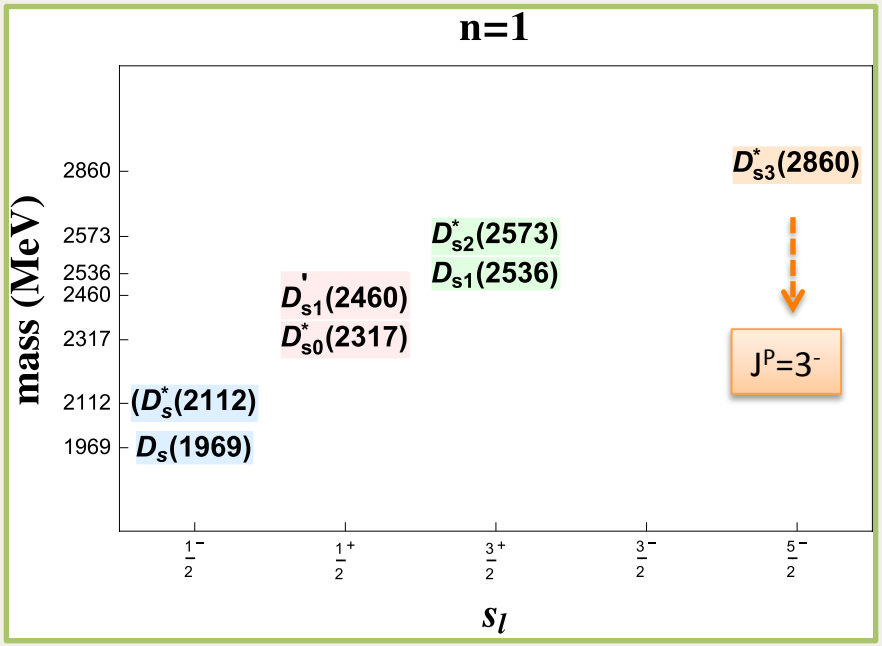

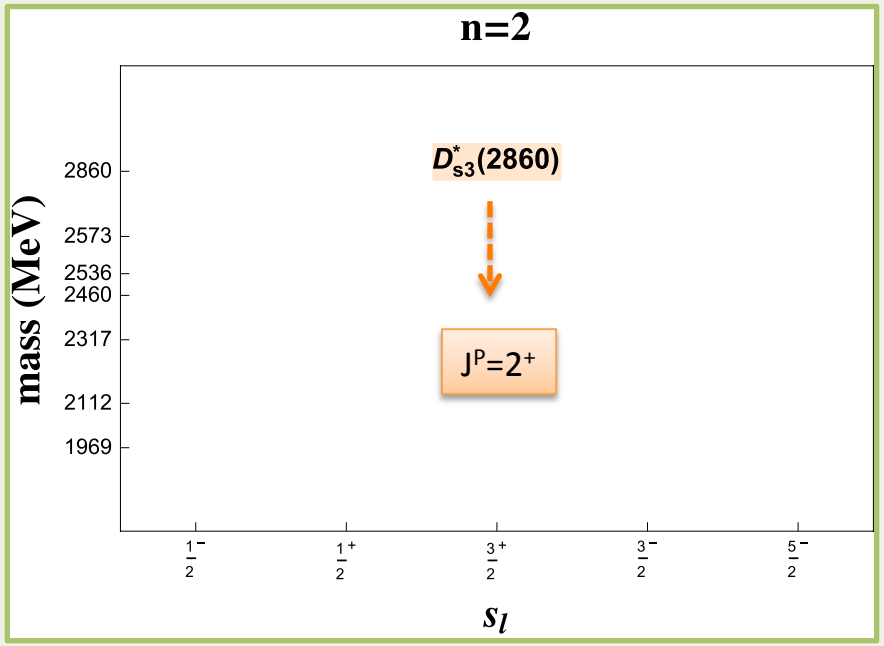

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3	$s_\ell^P = \frac{3}{2}^+,\ J^P = 2^+,\ n = 2$	d-wave	0.63	0.19
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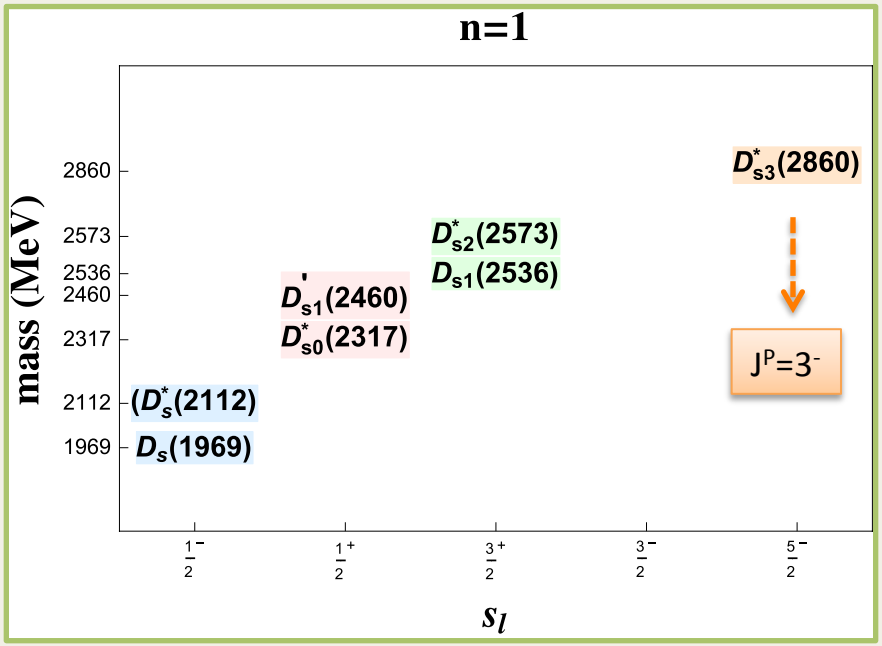
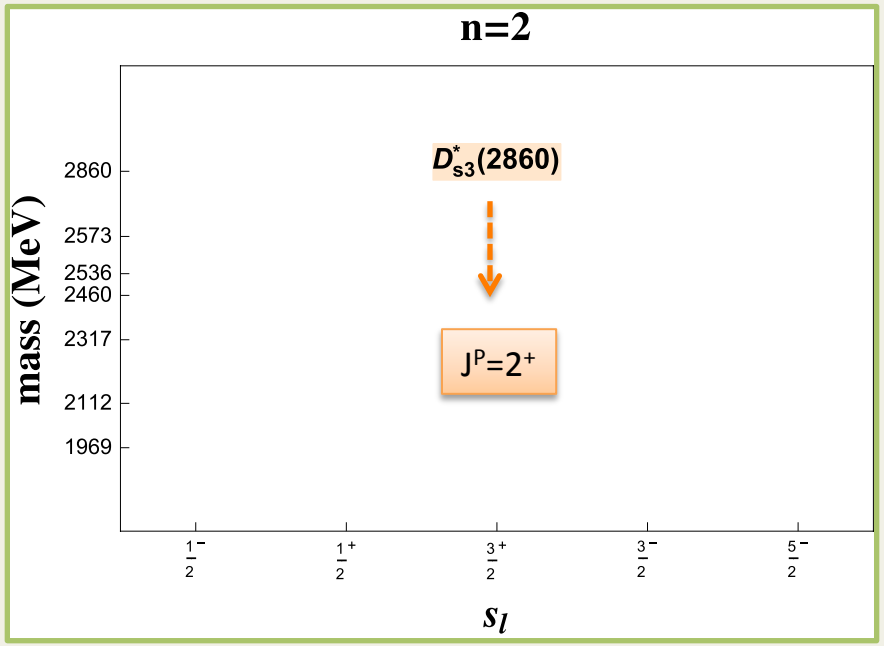
5	$s_\ell^P = \frac{5}{2}^-,\ J^P = 3^-,\ n = 1$	f-wave	0.39	0.13

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



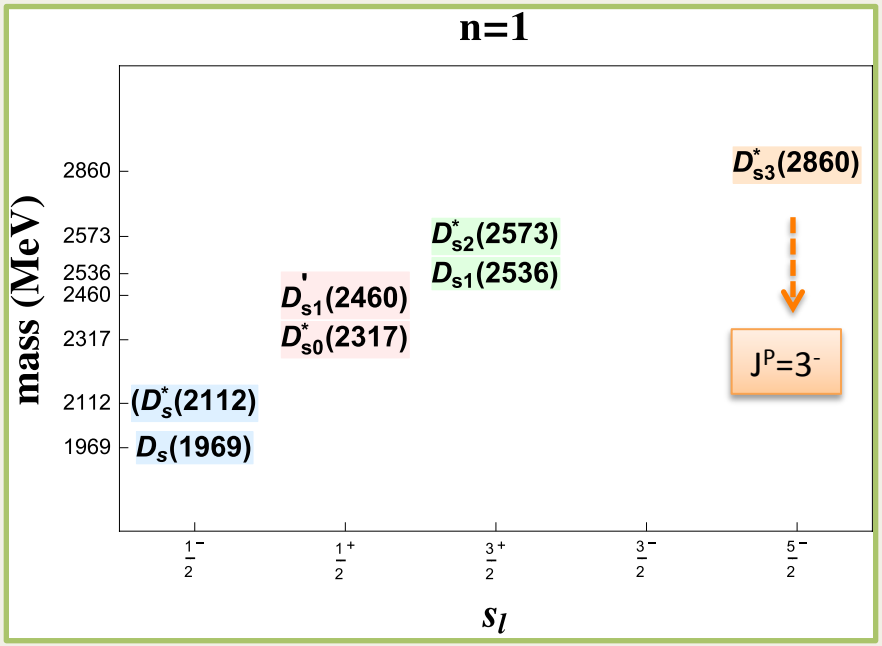


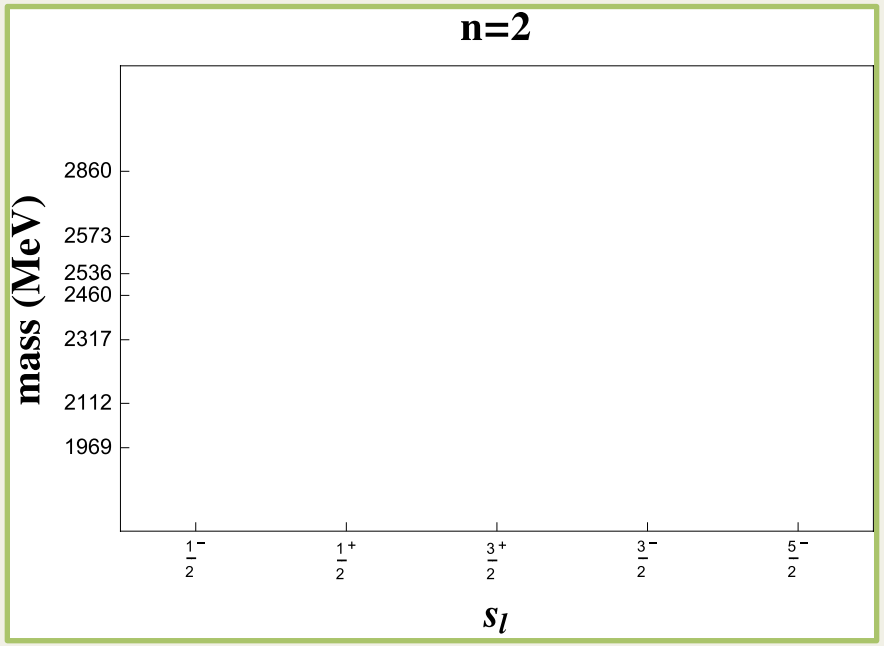
The method @ work: the case of $D_{s3}^*(2860)$

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

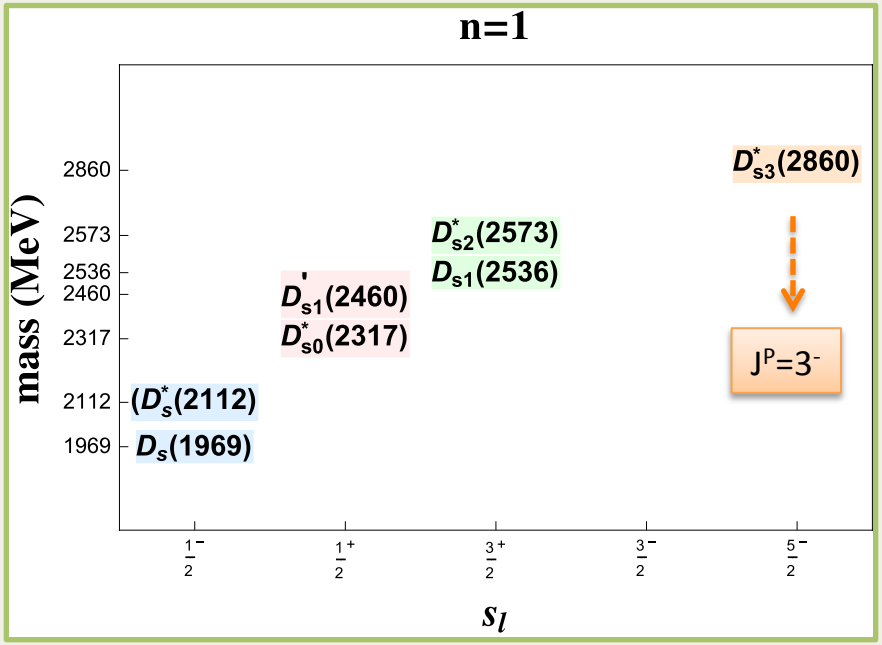
	$D_{sJ}(2860)$	$D_{sJ}(2860) \to DK$	$\frac{\Gamma(D_{sJ}(2860)\to D^*K)}{\Gamma(D_{sJ}(2860)\to DK)}$	$\frac{\Gamma(D_{sJ}(2860)\to D_s\eta)}{\Gamma(D_{sJ}(2860)\to DK)}$
1	$s_\ell^P = \frac{1}{2}^-,\ J^P = 1^-,\ n = 2$	p-wave	1.23	0.27
2	$s_\ell^P = \frac{1}{2}^+,\ J^P = 0^+,\ n = 2$	s-wave	0	0.34
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

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

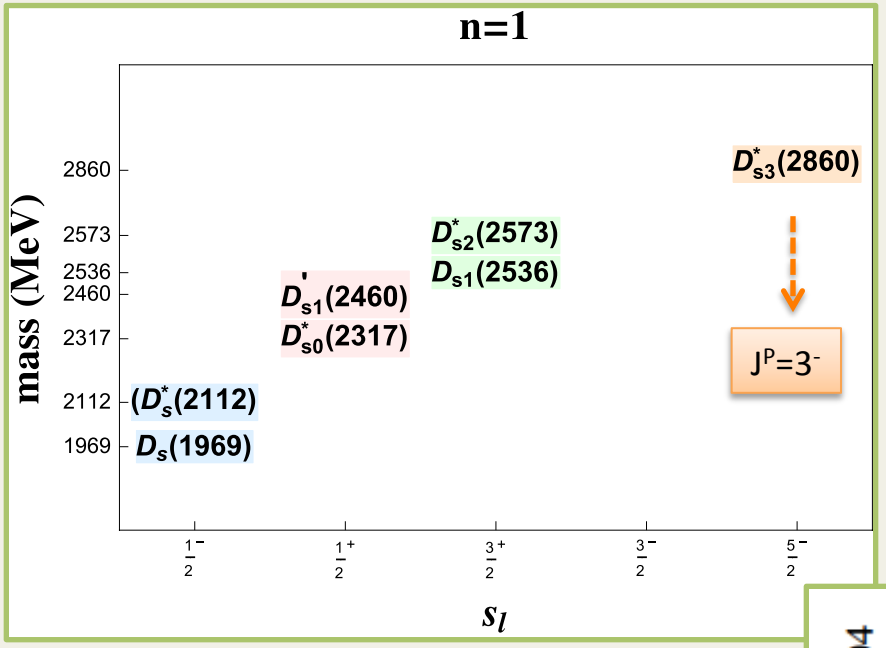




The method @ work: the case of $D_{s3}^{*}(2860)$
Here it is!



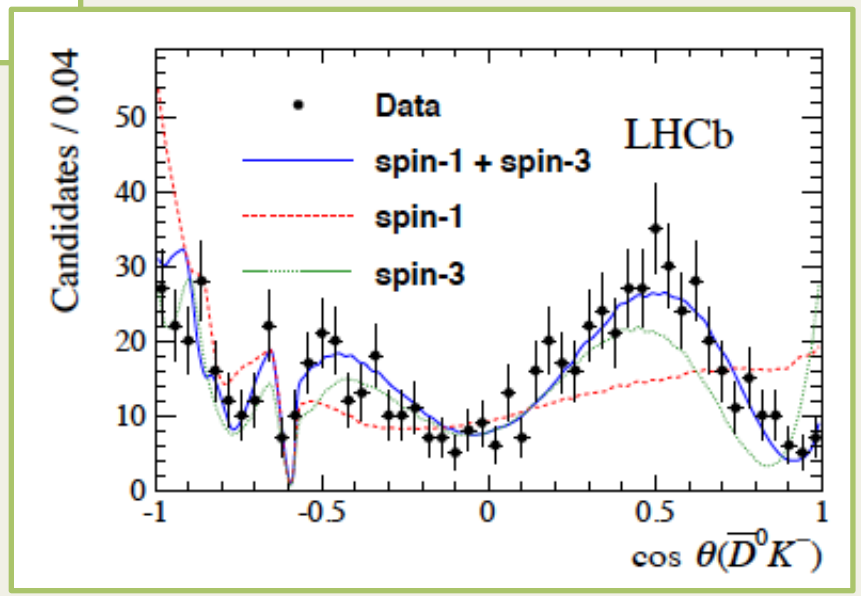
The method @ Work: the case of $D_{s3}^*(2860)$
Here it is!



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



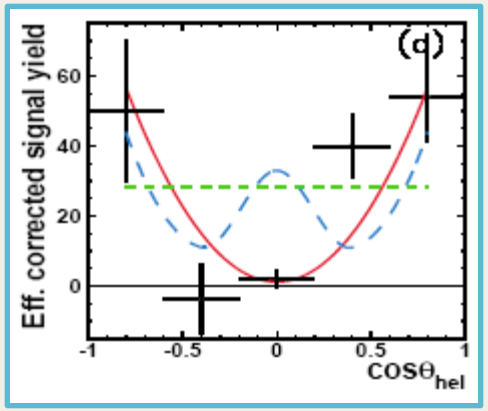
LHCb Collab., PRD 90 (14) 072003

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 $B^0 \to D^- D^0 K^+$,

- the decay 1 -> 0- 0- implies negative parity
- spin 1 favoured

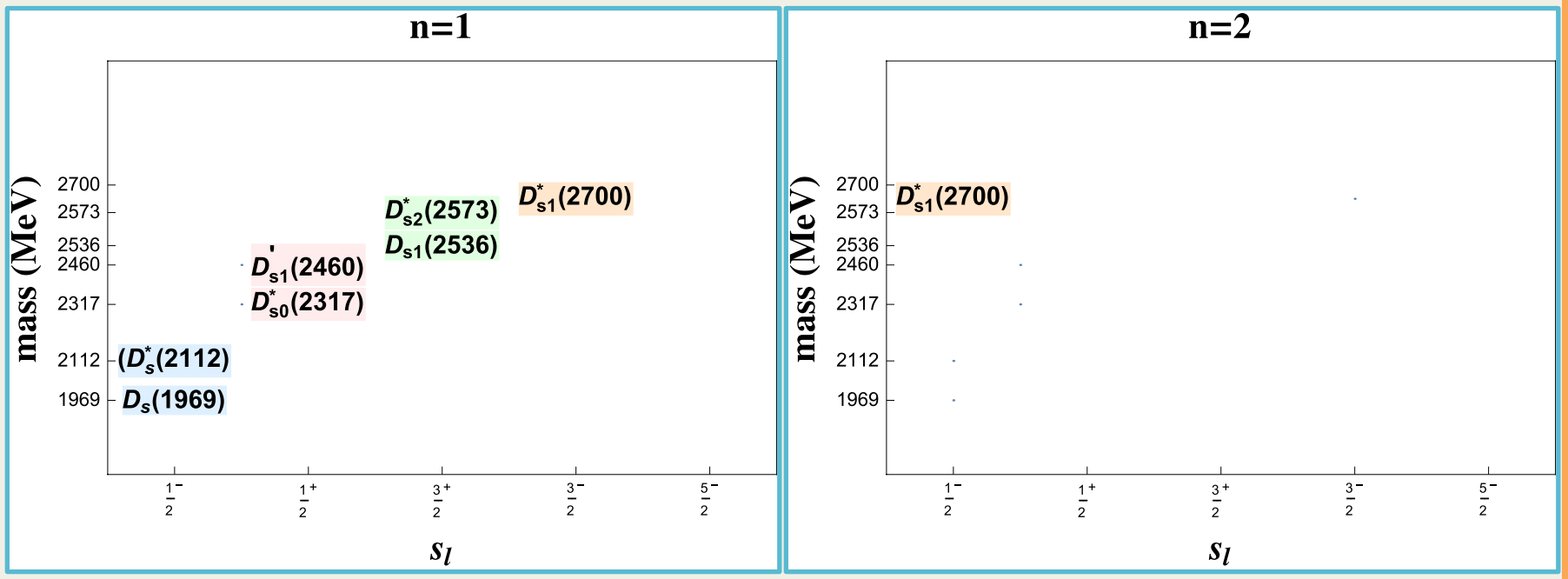


J=0
J=1
J=2

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

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

The method @ work: the case of $D_{s1}^*(2700)$
Where can we place it?



computing strong decay rates discriminates the two possibilities

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

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

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

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

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

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

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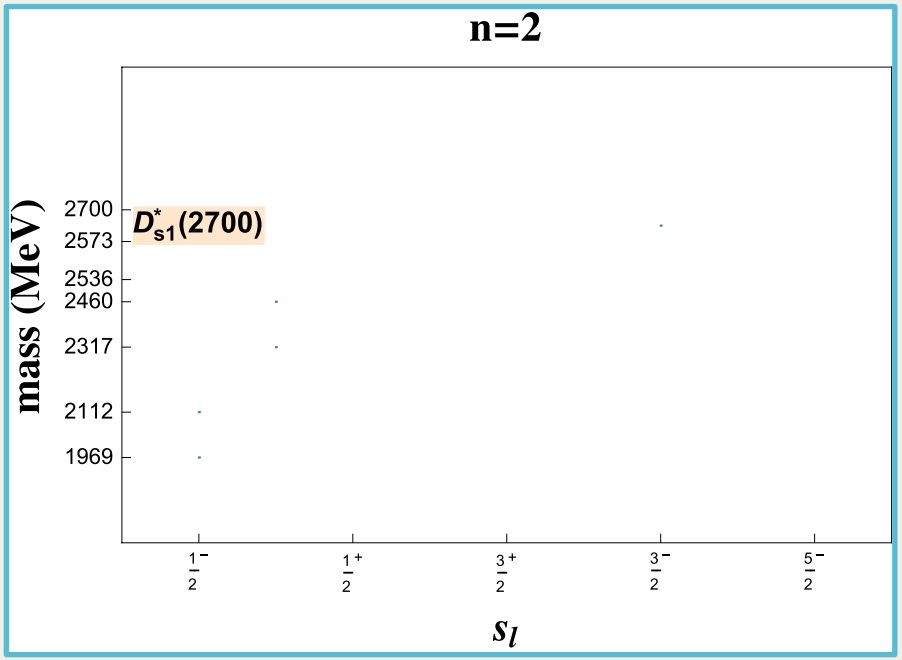
$D_s^{*\prime}$	91 ± 4	20 ± 1	5 ± 2
D_{s1}^*	4.3 ± 0.2	16.3 ± 0.9	0.18 ± 0.07

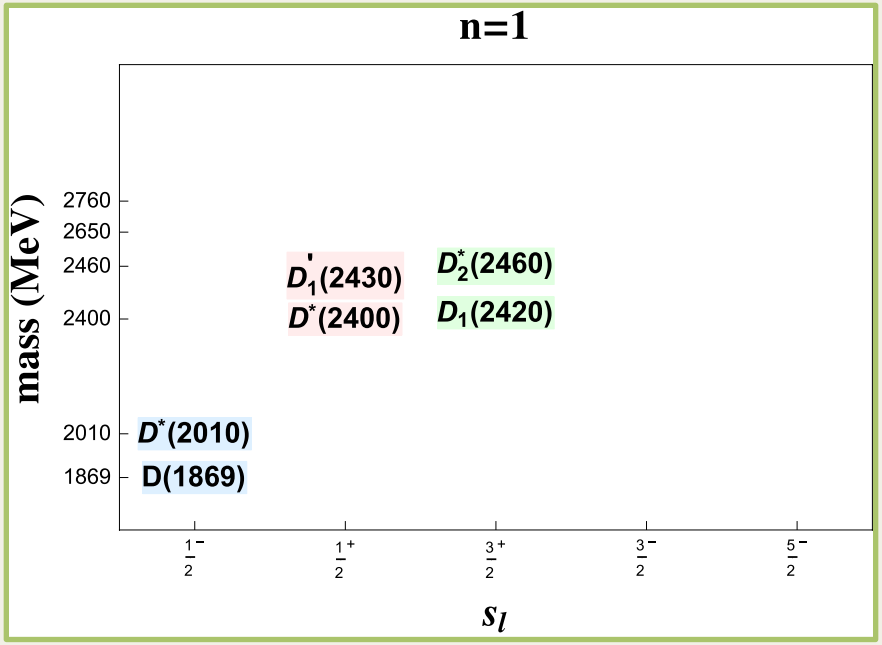
Babar :

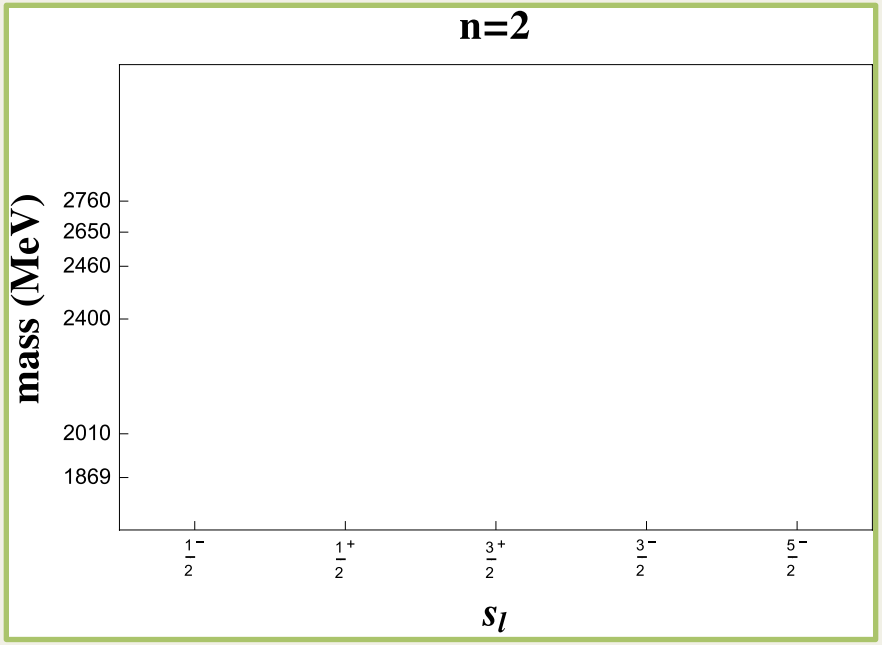
$$R_1 = 0.91 \pm 0.13_{stat} \pm \pm 0.12_{syst}$$

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



Charmed mesons:
what about the new states?





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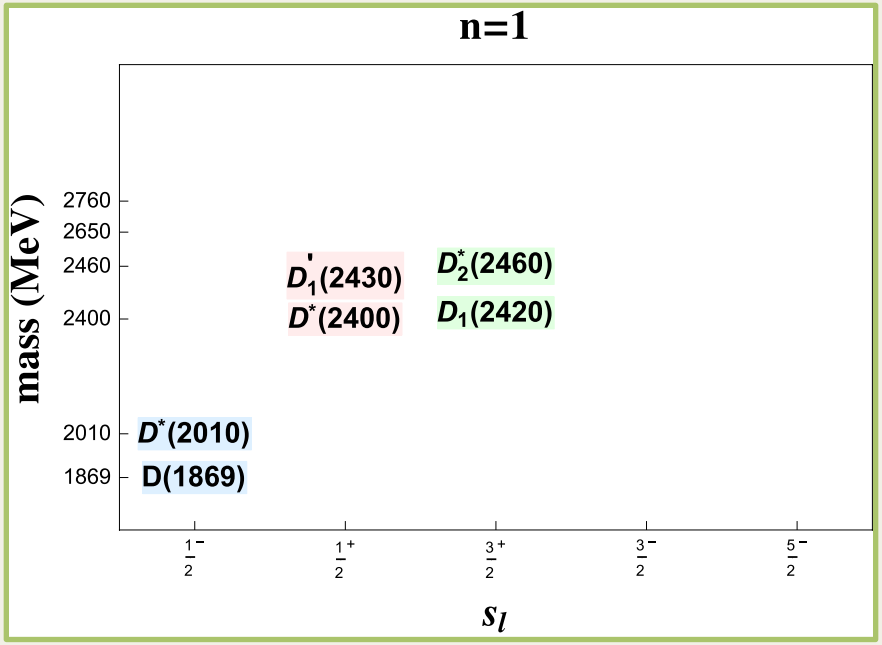
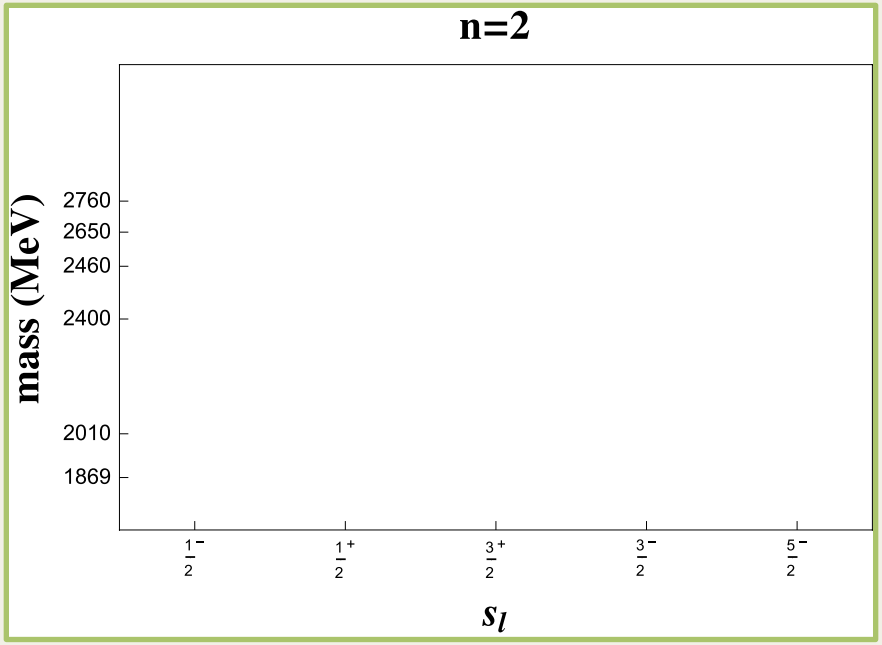
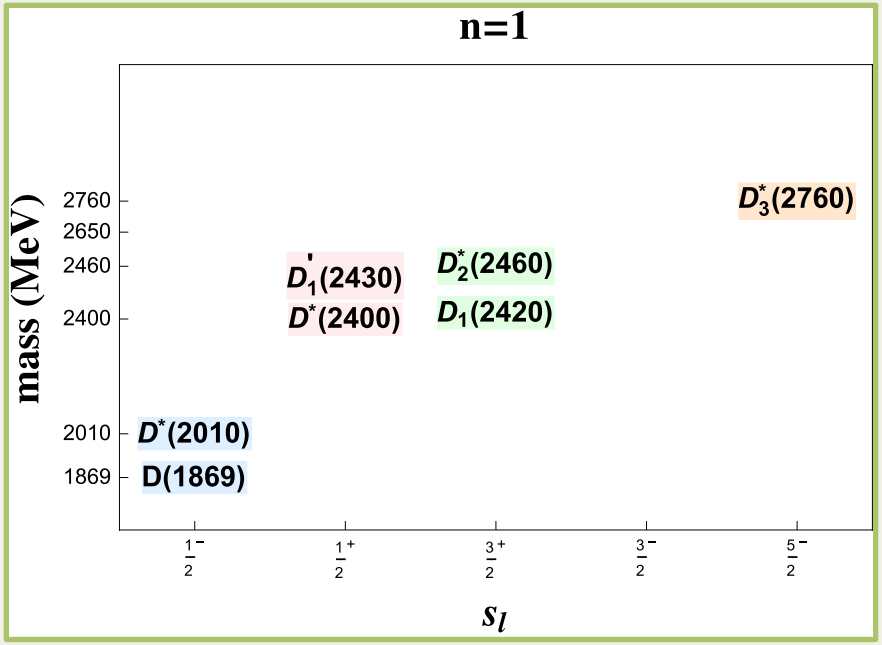
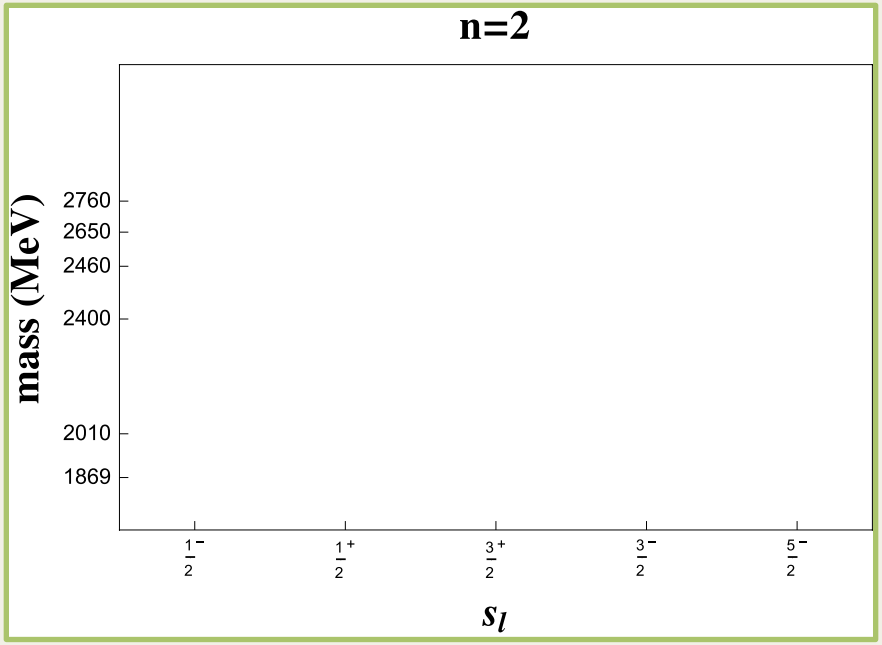




LHCb determines: $D_J^*(2760)$ -> $J^P=3^-$

Charmed mesons:
what about the new states?





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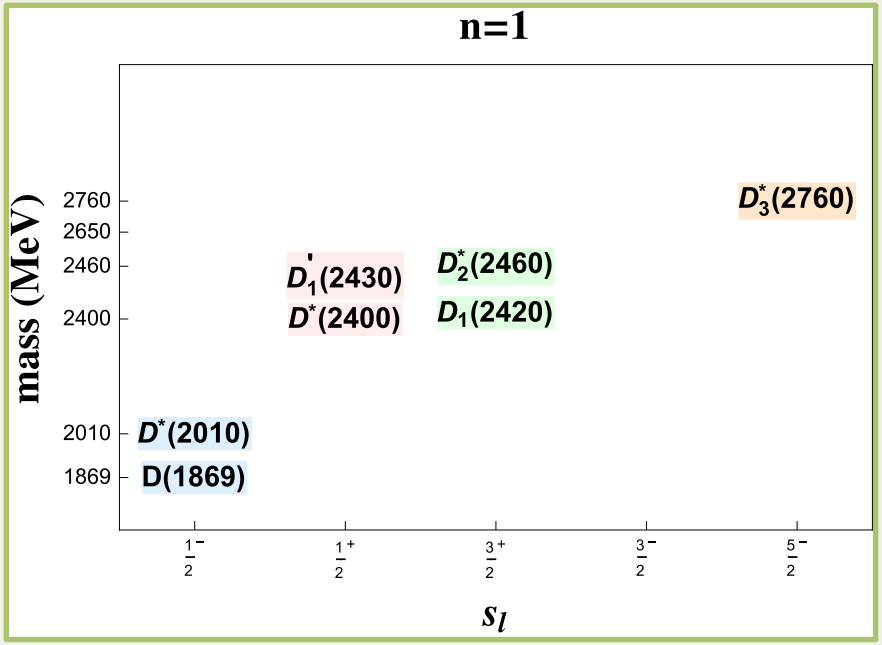
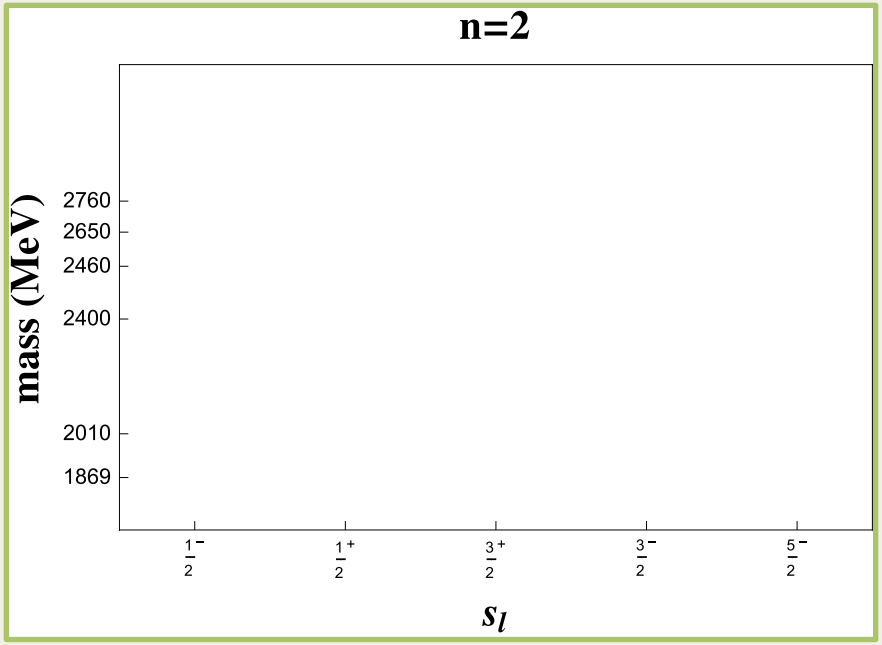
Charmed mesons:
what about the new states?



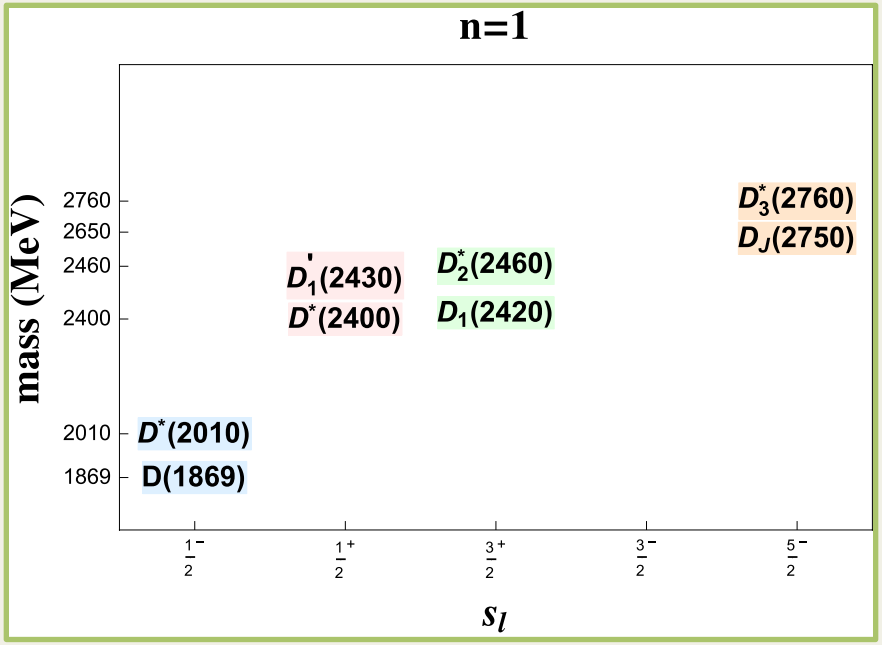


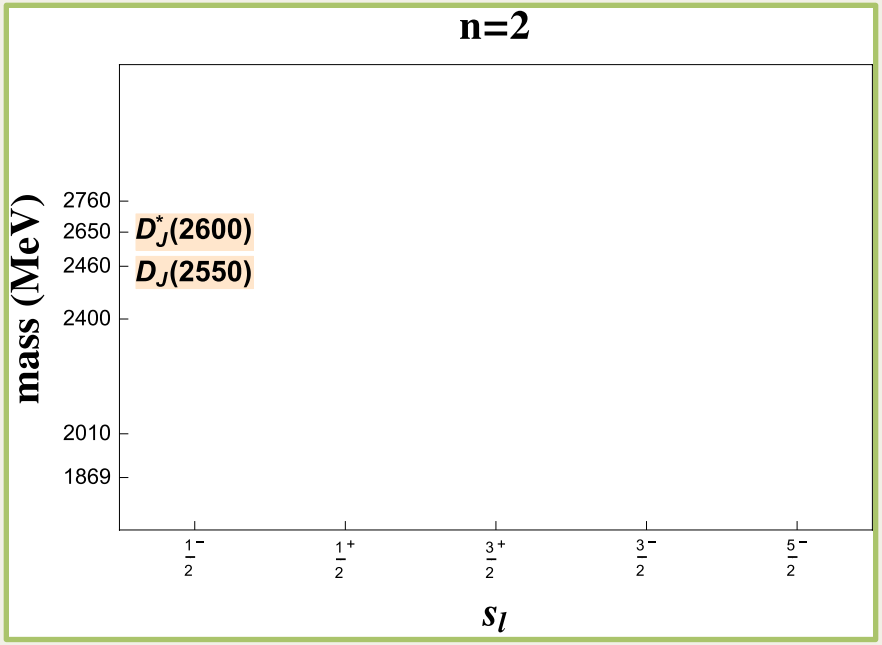
LHCb determines: $D_J^*(2760)$ -> $J^P=3^-$

BaBar and LHCb: no complete agreement on the parameters of the other observed states

Charmed mesons:
what about the new states?

tentative assignment proposed by BaBar





From charm to beauty

Observed excited mesons with open beauty

$b\bar{q}$	mass (MeV)	Γ (MeV)
$B_1^0(5721)$	5723.4 ± 2.0	
$B_2^{*0}(5747)$	5743 ± 5	$22.7 \pm^{3.8}_{3.2} \pm^{3.2}_{10.2}$

$b\bar{s}$	mass (MeV)	Γ (MeV)
$B_{s1}^0(5830)$	5829.4 ± 0.7	
$B_{s2}^{*0}(5840)$	5839.7 ± 0.6	

New states observed
candidates for identification with radial excitations of the fundamental doublet:

$(B_J(5840)\ ,\ B_J(5960))$ -----→ $n=2\ J^P=(0^-,1^-)$

LHCb Collab., JHEP 1504 (15) 024

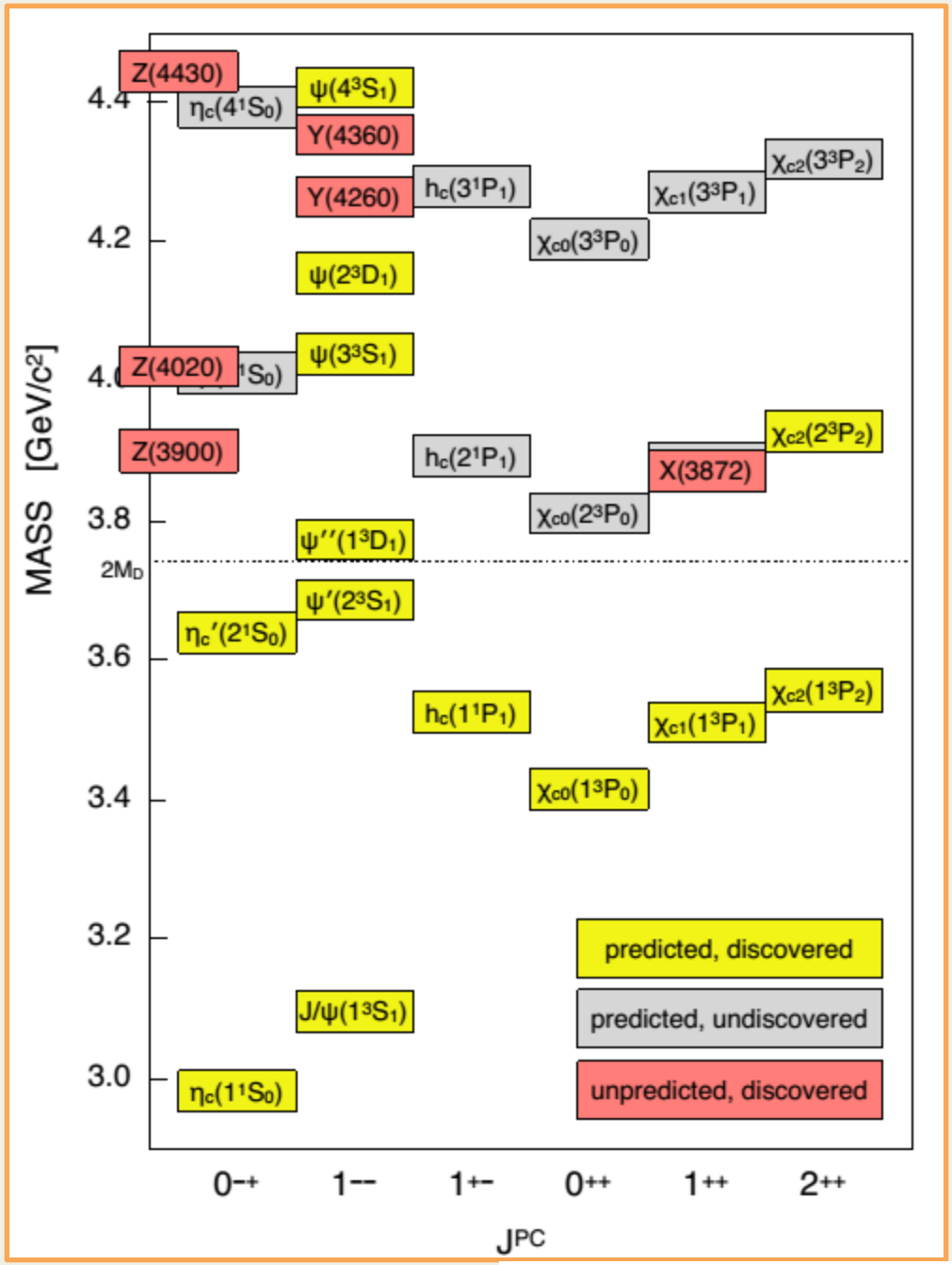
hidden charm

- ordinary charmonia
- exotic candidates:
  X,Y,Z all charmonium like

- Y with $J^{PC}=1^{--}$

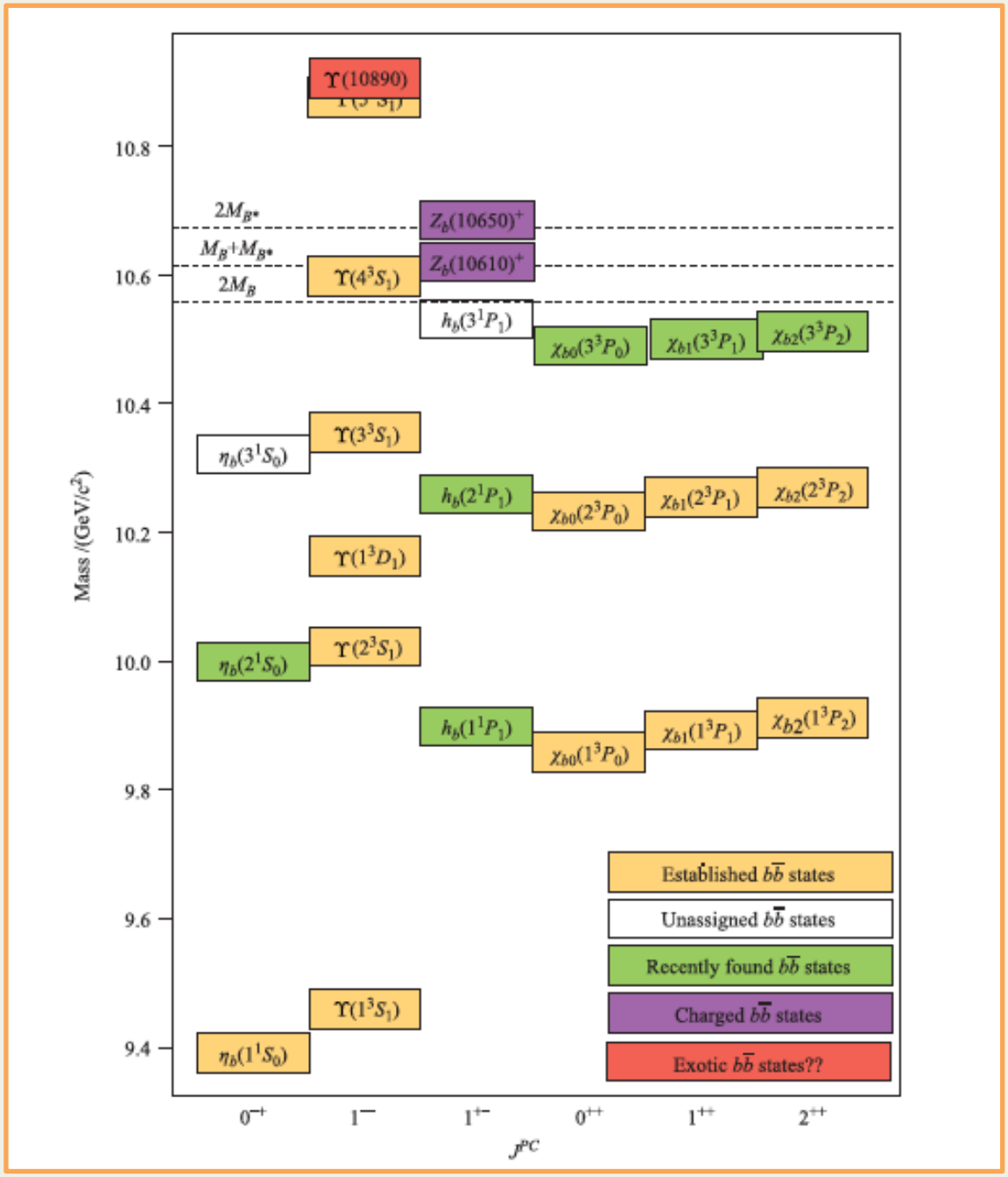
- X with $J^{PC} \neq 1^{--}$

- Z composed by $c\bar{c} + q\bar{q}$



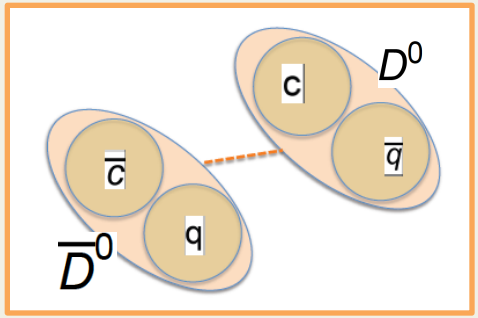
Kornicer@Charm 2015

hidden beauty

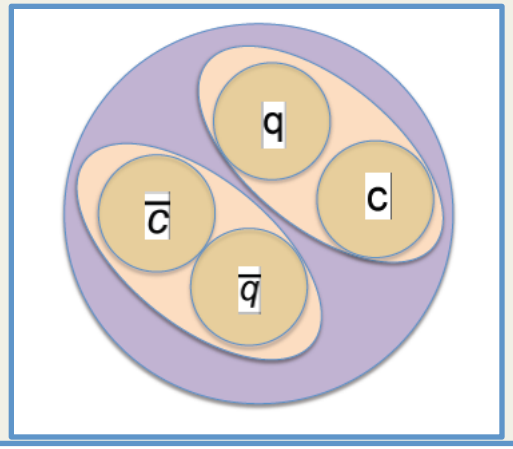


Olsen, Front. Phys. China 10 (2015) 121

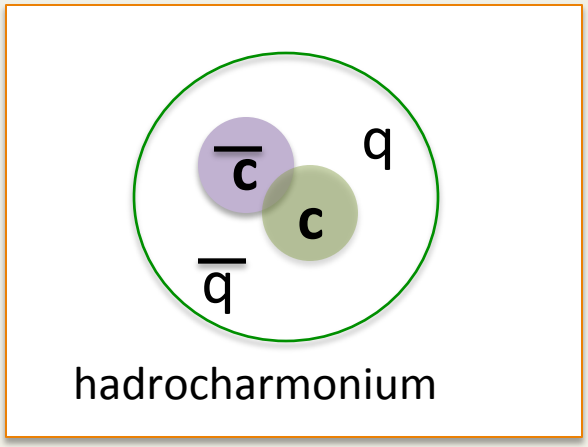
Many theoretical proposals

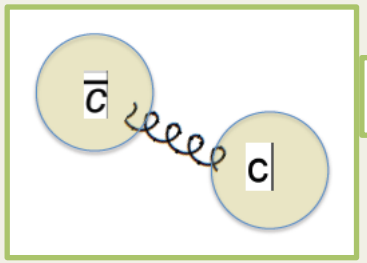


loosely bound molecule



tightly bound diquark-antidiquark

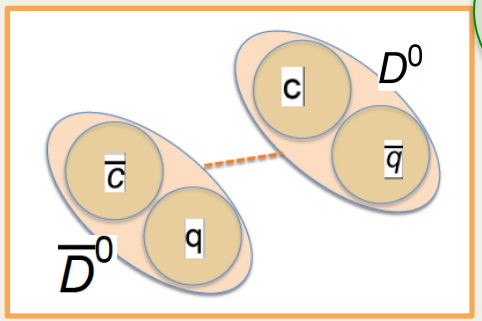




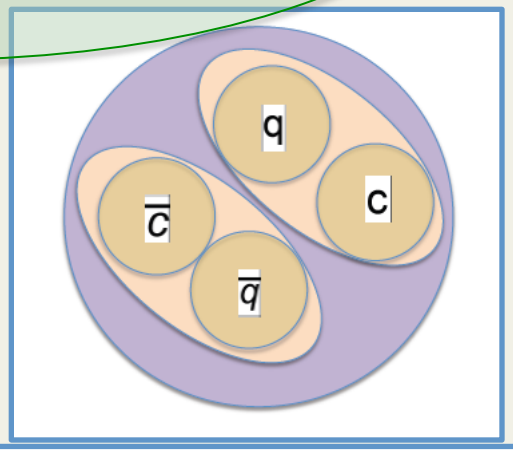
hybrid

Many theoretical proposals

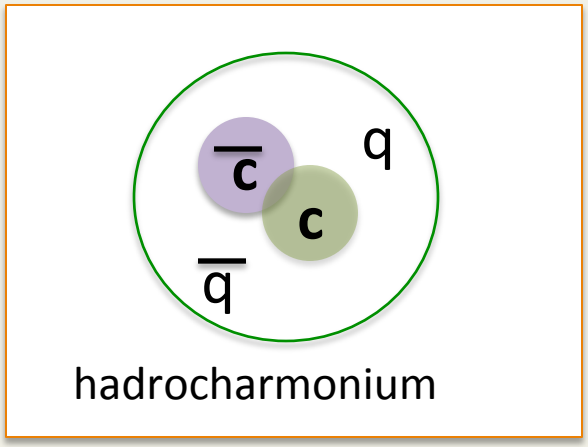
when the mass of the state is close to a open flavour threshold for a pair of $Q\bar{q}$ mesons
width of constituents must be << than that of the state



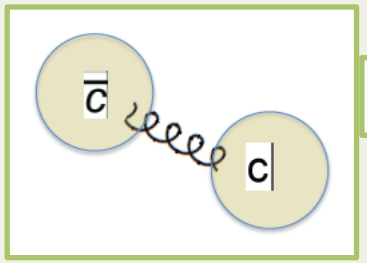
loosely bound molecule



tightly bound diquark-antidiquark

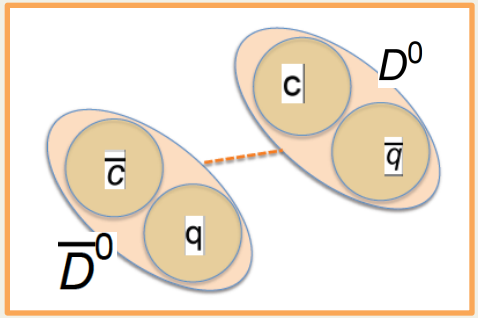


hadrocharmonium

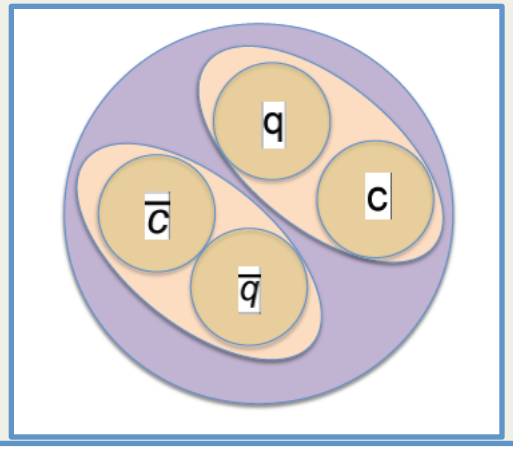


hybrid

Many theoretical proposals

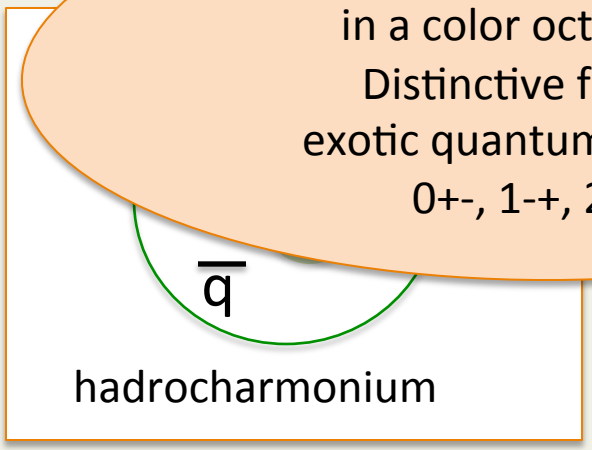


loosely bound molecule

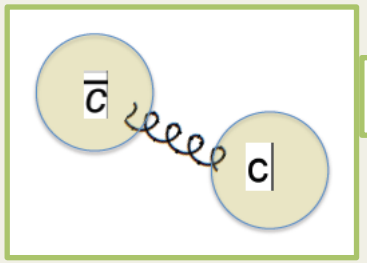


htly bound diquark-antidiquark

$Q\bar{Q}g$ are its constituents, with $Q\bar{Q}$
in a color octet state.
Distinctive feature:
exotic quantum numbers
0+-, 1-+, 2+-,..

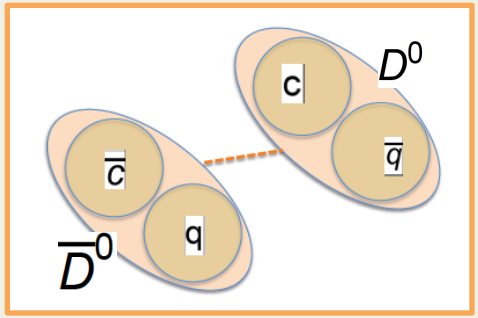


hadrocharmonium

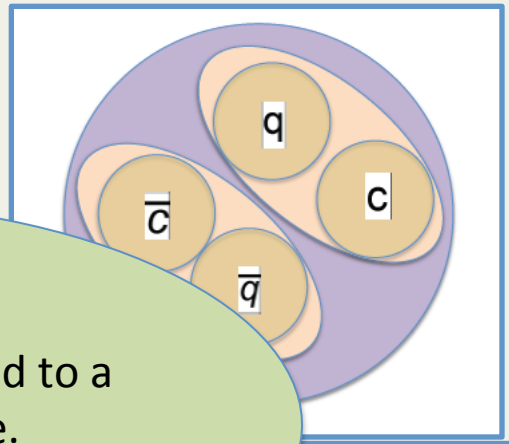


hybrid

Many theoretical proposals

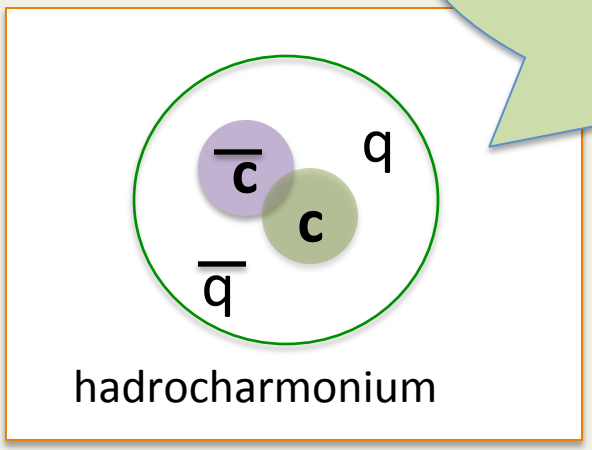


loosely bound molecule

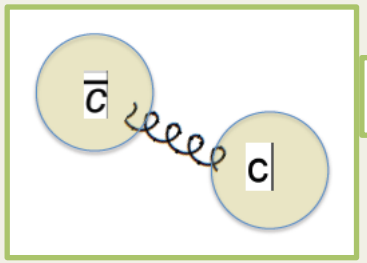


antidiquark

color-singlet $q\bar{q}$ pair bound to a color-singlet $Q\bar{Q}$ core.
Binding: analog to van der Waals



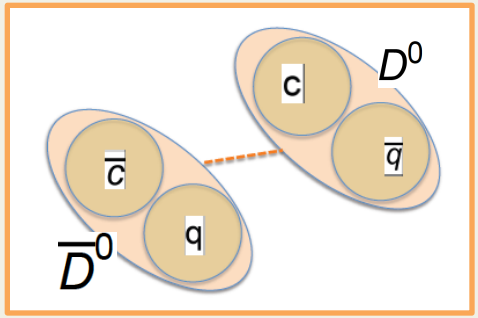
hadrocharmonium



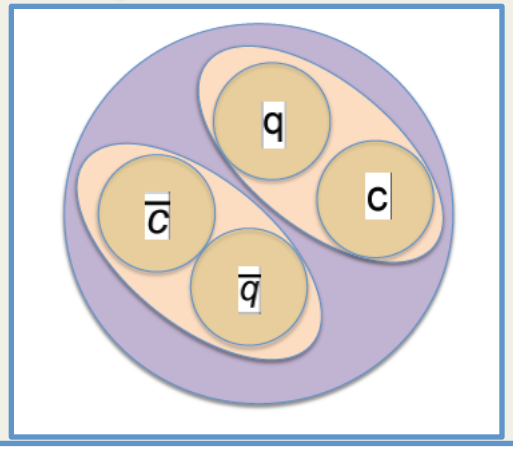
hybrid

Many theoretical proposals

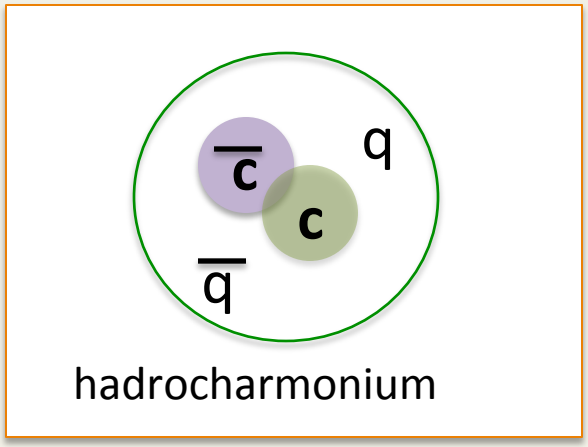
Several variants
- compact tetraquarks
- diquarkonium tetraquarks

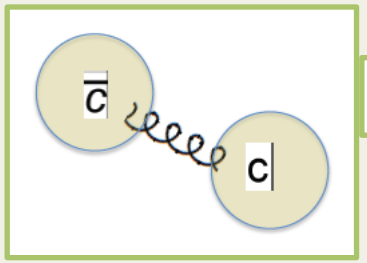


loosely bound molecule



tightly bound diquark-antidiquark

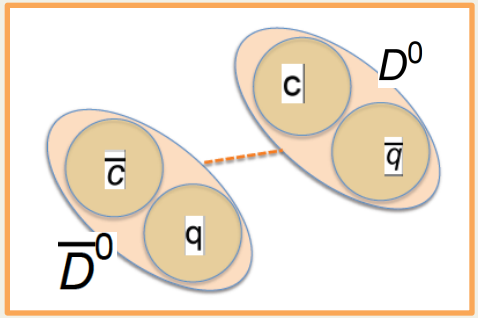




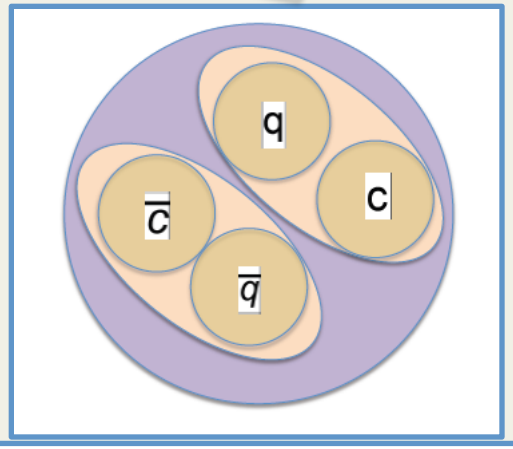
hybrid

Many theoretical proposals

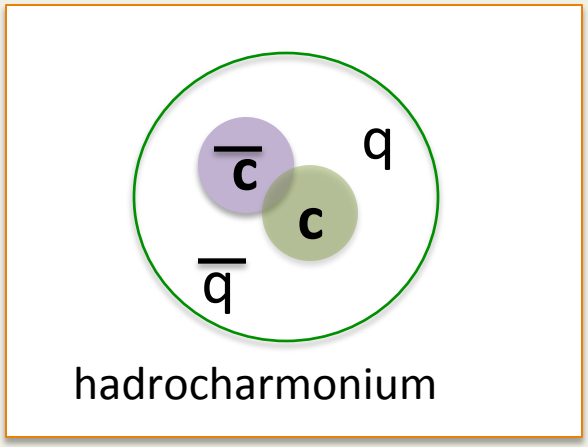
Compact $Q\bar{Q}q\bar{q}$: interaction potential acts between each quark pair. Requires $M(Q\bar{Q}q\bar{q})<M(\bar{Q}q)+M(Q\bar{q})$, $M(Q\bar{Q}q\bar{q})<M(Q\bar{Q})+M(\bar{q}q)$, otherwise falling apart happens



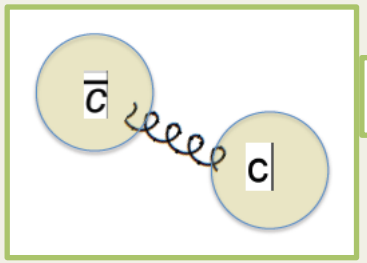
loosely bound molecule



tightly bound diquark-antidiquark



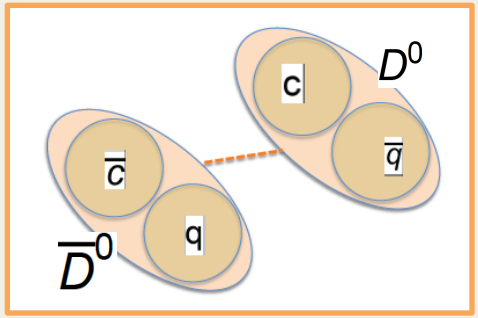
hadrocharmonium



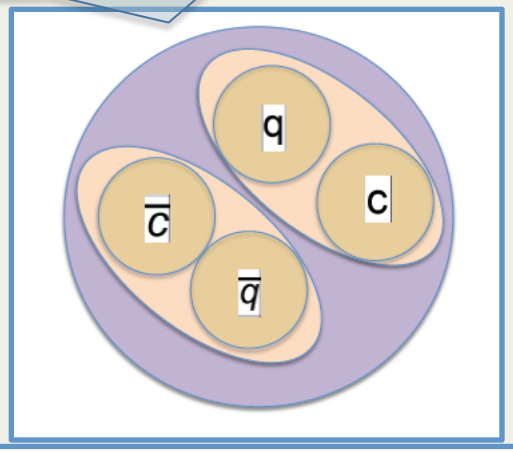
hybrid

Many theoretical proposals

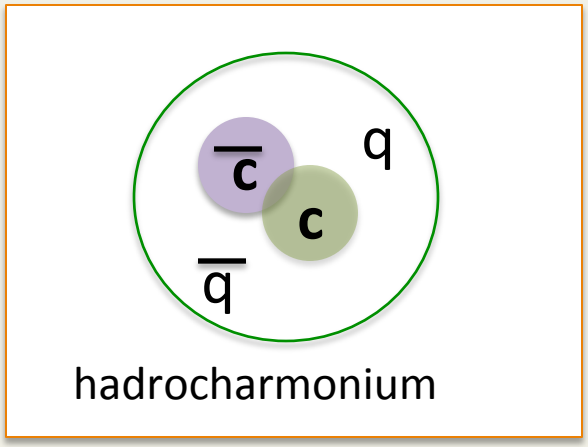
Diquarkonium tetraquarks:
Bound state of diquarks Qq (color antitriplet) and $\bar{Q}\bar{q}$ (triplet).
Very large number of predicted states



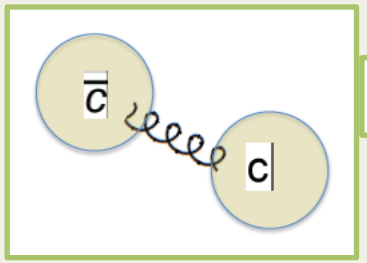
loosely bound molecule



tightly bound diquark-antidiquark



hadrocharmonium



hybrid

The beginning of the new spectroscopy era: X(3872)

Belle PRL 91 (03) 262001

- discovered by Belle in 2003 in the channel: X -> $J/\psi\ \pi^+\ \pi^-$
- confirmed by BaBar, CDF, D0
- very narrow Γ<1.2 MeV (Belle)
- observed in $J/\psi\ \gamma$ => C=+1
- 2013 LHCb full angular analysis fixes $J^{PC}=1^{++}$
- decays to $J/\psi\ \pi^+\ \pi^-$ and $J/\psi\ \pi^+\ \pi^-\ \pi^0$ occur with similar rates
  => isospin violation considering ρ and ω as intermediate states

LHCb EPJC 72 (12) 1972

BUT - phase space effects should be considered
- $B(\rho \to \pi\pi) > B(\omega \to \pi\pi\pi)$

Interpretations

- mass very close to DD^* threshold -> molecule?
- tetraquark interpretation: no isospin partners found yet
- mixing between molecole and ordinary charmonium -> would explain isospin violation
- ordinary charmonium -> χ_{c1} (2P)

X(3872) : ordinary charmonium possibility

If X is an ordinary charmonium state it is likely to be χ_{c1} (2P)

Searching for χ_{c1} (2P) is a parallel strategy to understand what is X

Belle looks for the mode χ_{c1} (2P) -> χ_{c1} (1P) $\pi^+ \pi^-$
with M(χ_{c1} (2P)) ≈ 3920 MeV (QM prediction) => no signal found

PDG

$\Gamma(\gamma\psi(2S))/\Gamma(\gamma J/\psi)$

VALUE	
<2.1	Belle
3.4±1.4	BaBar

LHCb , EPJ Web Conf. 96 (2015) 01005

$$R_\psi = 2.46 \pm 0.63(stat) \pm 0.29(syst)$$

Ratio suppressed incomposite models

FDF, PRD79 (09) 054015

In the hypothesis **X(3872)=χ_{c1} (2P)**
HQ spin symmetry predicts:

$$\frac{\Gamma(X(3872) \to \psi(2S)\gamma)}{\Gamma(X(3872) \to \psi(1S)\gamma)} = 1.64 \pm 0.25.$$

Plausible identification

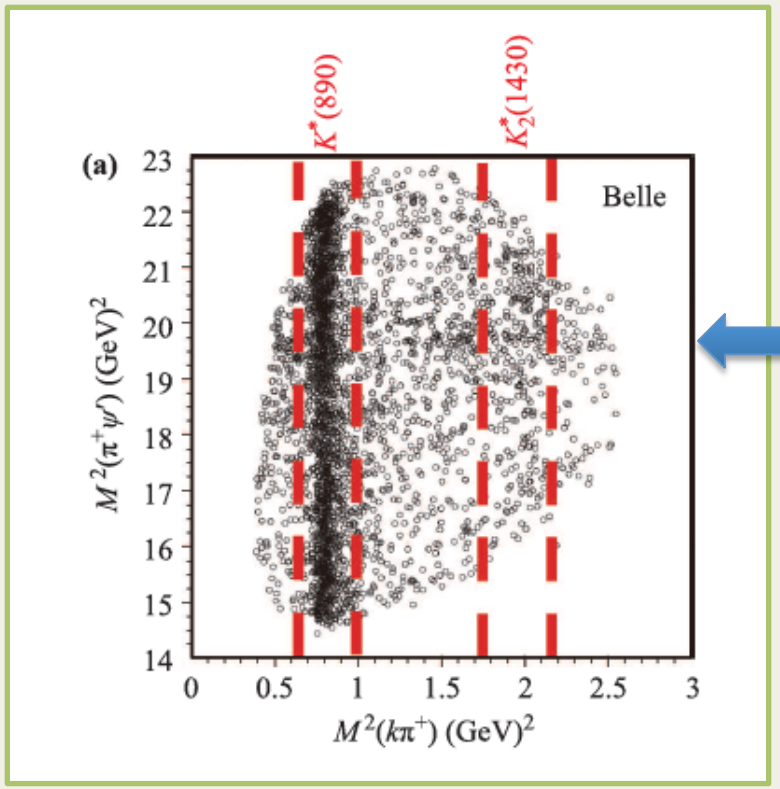
Z states

Z(4430) : first observed in 2008 by Belle in B -> K π^+ ψ' decaying to π^+ ψ'
not confirmed by BaBar
confirmed in 2014 by LHCb , fixing to $J^P=1^+$

contains $c\bar{c}$ pair & is charged => at least 4 quarks !

Belle
M=4433 ± 5 MeV
Γ=45 $\pm^{35}_{18}$ MeV

LHCb
M=4475 $\pm^{17}_{26}$ MeV
Γ=172 $\pm^{39}_{36}$ MeV



Belle PRL 100 (2008) 142001
LHCb PRL 112 (2014) 222002

Z states

Zc(3900) : discovered by BESIII in 2013 in $e^+ e^- \to Y(4260) \to J/\psi\, \pi^+ \pi^-$ with $Z_c \to J/\psi\, \pi$
confirmed by Belle, CLEOc
neutral partner observed

	M (Mev)	Γ (MeV)
Bes III	3899.0 ± 3.6 ± 4.9	46 ± 10 ± 20
Belle	3894.5 ± 6.6 ± 4.5	63 ± 24 ± 26
CLEOc	3885. ± 5 ± 1	34 ± 12 ± 4

BESIII PRL 110 (2013) 252001;
PRL 111 (2013) 242001
PRL 112 (2014) 132001
Xiao et al. (CLEOc) PLB 727 (2013) 366

$Z_1(4050)$ & $Z_2(4250)$ discovered by Belle decaying to $\chi_{c1}\, \pi^+$
confirmed by BESIII

Belle PRD 78 (2008) 072004

Z states: Z(4430) & Z(3900)

- molecular interpretation:
  Z(4430) -> $D^* D_1(2420)$ molecule
  Z(3900) -> $D D_1(2420)$ molecule

Rosner, PRD76 (07) 114002
Branz et al, PRD 82 (10) 054025

Wang et al., PRL111 (13) 132003
PLB 725 (13) 106

- type II tetraquark model:
  Z(4430) radial excitation of Z(3900)

Indeed:
$Z(3900)^+ \to \pi^+ \psi(1S)$
$Z(4430)^+ \to \pi^+ \psi(2S)$

Maiani et al., PRD89 (14) 114010

- cusp effects
  Z(3900) very close to the threshold $M(D)+M(D^*) \cong 3879$ MeV

E. Swanson,
PRD 91 (2015) 034009

Z_b states

Belle Collab. 1105.4583
1403.0992

found in 2011 by Belle in $e^+ e^- \to \Upsilon(5S) \to \Upsilon(nS)\, \pi^+ \pi^-$

& $e^+ e^- \to \Upsilon(5S) \to h_b(nP)\, \pi^+ \pi^-$

	Mass (MeV)	Γ (MeV)
$Z_b(10610)$	10608.4 ± 2.0	15.6 ± 2.5
$Z_b(10650)$	10653.2 ± 1.5	14.4 ± 3.2

Angular analysis favours $J^P=1^+$

Possible interpretations:

E. Swanson, PRD 91 (2015) 034009

cusp effects →

m(Zb(10610)+)-m(B)-m(B*) = 3.69 ± 2.05 MeV
m(Zb(10650)+)-m(B*)-m(B*) = 3.68 ± 1.71 MeV

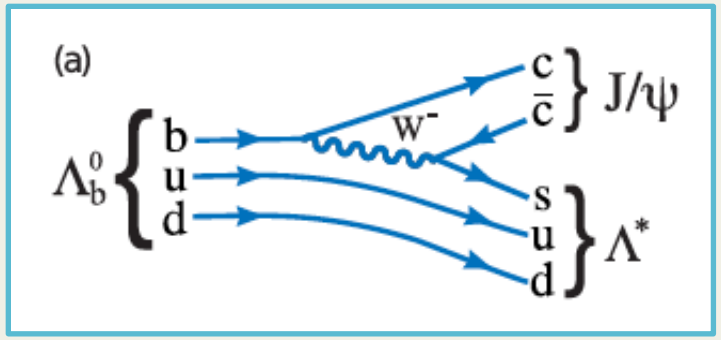
tetraquarks

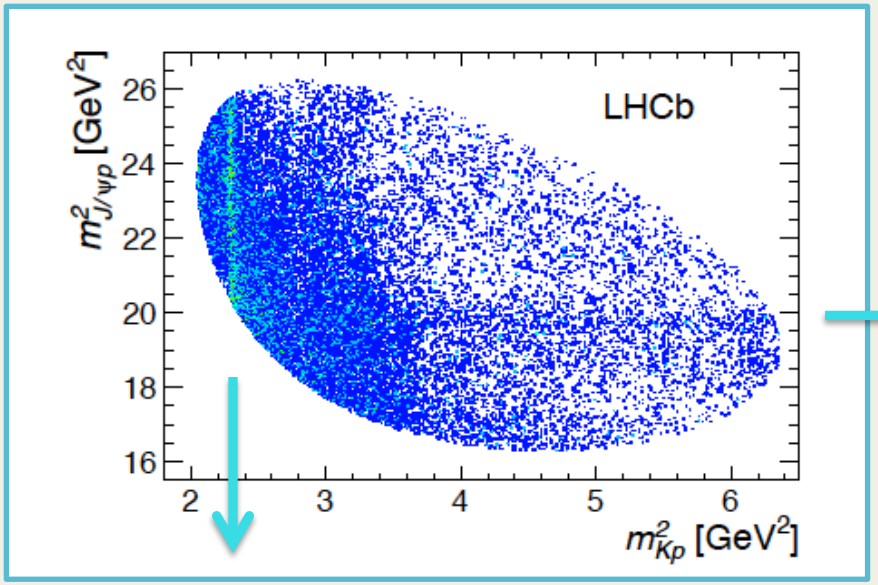
Ali et al, PLB 684 (10) 28
PRD 85 (12) 054011

The last surprise: Pentaquark

LHCb PRL 115 (2015) 07201

- LHCb looks at $\Lambda_b \to J/\psi\, K^- p$ to measure Λ_b lifetime
- dominance of Λ^* resonances expected with $\Lambda^* \to K^- p$



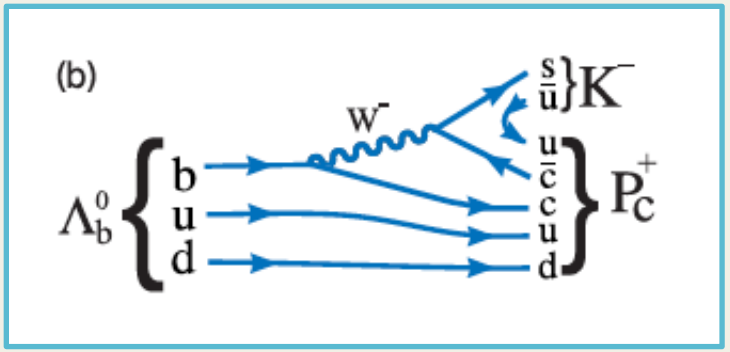


$\Lambda(1520)$

resonant structure observed in $J/\psi\ p$

minimal quark content $c\bar{c}uud$

P_c^+



The last surprise: Pentaquark

best fit obtained with two states

M_1=4380 ± 8 ± 29 MeV
Γ_1= 205 ± 18 ± 86 MeV

M_1=4449 ± 1.7 ± 2.5 MeV
Γ_1= 39 ± 5 ± 19 MeV

possibilities: $J^P=(3/2^-,5/2^+), (3/2^+,5/2^-), (5/2^+,3/2^-)$

↓

favourite one

Problems:

- if $P_c = c\bar{c}uud$ and $Z_c(4475) = c\bar{c}ud$ why both P_c are lighter than Z_c? (for this reason P_c cannot decay to $\psi(2S)$ and Z_c does)
- decays to $\Lambda c\ \bar{D}^{(*)0}$ should also be allowed

What are P_c states?

- molecules: $\Sigma_c \overline{D}^{(*)0}$
- rescattering through χ_{c1} p effect
- composite object of two compact color constituents

Karliner & Rosner, 1506.06386
Roca et al, 1507.04249

Guo et al., 1507.04950

Maiani et al., PLB 749 (15) 289

already considered by Karliner & Lipkin to interpret "old" pentaquark $\Theta(1535)$

Conclusions

- many new states discovered
- many new ideas about the fundamental structure of hadrons
- an important tool to understand strong interactions
- great work for experimentalists and theorists

BackUp Slides

Predicting the heavy meson masses

Spin averaged masses

$$\overline{M}_H = \frac{3M_{P^*} + M_P}{4}$$

$$\overline{M}_S = \frac{3M_{P_1'} + M_{P_0^*}}{4}$$

$$\overline{M}_T = \frac{5M_{P_2^*} + 3M_{P_1}}{8}$$

$$\overline{M}_X = \frac{5M_{P_2} + 3M_{P_1^*}}{8}$$

$$\overline{M}_{X'} = \frac{7M_{P_3} + 5M_{P_2'^*}}{12}$$

Mass splittings higher doublets- fundamental doublet

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

Inclusion of $1/m_Q$ corrections for hyperfine splitting within the doublets

$$\mathcal{L}_{1/m_Q} = \frac{1}{2m_Q}\Big\{\lambda_H Tr[\bar{H}_a\sigma^{\mu\nu}H_a\sigma_{\mu\nu}] + \lambda_S Tr[\bar{S}_a\sigma^{\mu\nu}S_a\sigma_{\mu\nu}] + \lambda_T Tr[\bar{T}_a^\alpha\sigma^{\mu\nu}T_a^\alpha\sigma_{\mu\nu}]$$
$$+\lambda_X Tr[\bar{X}_a^\alpha\sigma^{\mu\nu}X_{a\alpha}\sigma_{\mu\nu}] + \lambda_{X'} Tr[\bar{X}_a'^{\alpha\beta}\sigma^{\mu\nu}X_a'^{\alpha\beta}\sigma_{\mu\nu}]\Big\} \ ,$$

$$\lambda_H = \frac{1}{8}\left(M_{P^*}^2 - M_P^2\right)$$

$$\lambda_S = \frac{1}{8}\left(M_{P_1'}^2 - M_{P_0^*}^2\right)$$

$$\lambda_T = \frac{3}{16}\left(M_{P_2^*}^2 - M_{P_1}^2\right)$$

$$\lambda_X = \frac{3}{16}\left(M_{P_2}^2 - M_{P_1^*}^2\right)$$

$$\lambda_{X'} = \frac{5}{24}\left(M_{P_3}^2 - M_{P_2'^*}^2\right)$$

HQ limit relations

$$\Delta_F^{(c)} = \Delta_F^{(b)}$$
$$\lambda_F^{(c)} = \lambda_F^{(b)}$$

allow to move from charm to beauty

strong decay rates

$H = (P, P^*)$ or $\tilde{H} = (\tilde{P}, \tilde{P}^*)$

$$\Gamma(P^* \to PM) = C_M \frac{g^2}{6\pi f_\pi^2} \frac{M_P}{M_{P^*}} |\vec{p}_M|^3$$

$$\Gamma(\tilde{P}^* \to PM) = C_M \frac{\tilde{g}^2}{6\pi f_\pi^2} \frac{M_P}{M_{\tilde{P}^*}} |\vec{p}_M|^3$$

$$\Gamma(\tilde{P}_i^* \to P_f^* M) = C_M \frac{\tilde{g}^2}{3\pi f_\pi^2} \frac{M_{P_f^*}}{M_{\tilde{P}_i^*}} |\vec{p}_M|^3$$

$$\Gamma(\tilde{P} \to P^* M) = C_M \frac{\tilde{g}^2}{2\pi f_\pi^2} \frac{M_{P^*}}{M_{\tilde{P}}} |\vec{p}_M|^3.$$

$X = (P_1^*, P_2)$

$$\Gamma(P_1^* \to PM) = C_M \frac{4k'^2}{9\pi f_\pi^2} \frac{M_P}{M_{P_1^*}} [m_M^2 + |\vec{p}_M|^2] |\vec{p}_M|^3$$

$$\Gamma(P_1^* \to P^* M) = C_M \frac{2k'^2}{9\pi f_\pi^2} \frac{M_{P^*}}{M_{P_1^*}} [m_M^2 + |\vec{p}_M|^2] |\vec{p}_M|^3$$

$$\Gamma(P_2 \to P^* M) = C_M \frac{2k'^2}{3\pi f_\pi^2} \frac{M_{P^*}}{M_{P_2}} [m_M^2 + |\vec{p}_M|^2] |\vec{p}_M|^3.$$

$S = (P_0^*, P_1')$

$$\Gamma(P_0^* \to PM) = C_M \frac{h^2}{2\pi f_\pi^2} \frac{M_P}{M_{P_0^*}} [m_M^2 + |\vec{p}_M|^2] |\vec{p}_M|$$

$$\Gamma(P_1' \to P^* M) = C_M \frac{h^2}{2\pi f_\pi^2} \frac{M_{P^*}}{M_{P_1'}} [m_M^2 + |\vec{p}_M|^2] |\vec{p}_M|.$$

$T = (P_1, P_2^*)$ or $\tilde{T} = (\tilde{P}_1, \tilde{P}_2^*)$

$$\Gamma(P_1 \to P^* M) = C_M \frac{2h'^2}{3\pi f_\pi^2} \frac{M_{P^*}}{M_{P_1}} |\vec{p}_M|^5$$

$$\Gamma(P_2^* \to PM) = C_M \frac{4h'^2}{15\pi f_\pi^2} \frac{M_P}{M_{P_2^*}} |\vec{p}_M|^5$$

$$\Gamma(P_2^* \to P^* M) = C_M \frac{2h'^2}{5\pi f_\pi^2} \frac{M_{P^*}}{M_{P_2^*}} |\vec{p}_M|^5.$$

$X' = (P_2'^*, P_3)$

$$\Gamma(P_2'^* \to P^* M) = C_M \frac{4k^2}{15\pi f_\pi^2} \frac{M_{P^*}}{M_{P_2'^*}} |\vec{p}_M|^7$$

$$\Gamma(P_3 \to PM) = C_M \frac{4k^2}{35\pi f_\pi^2} \frac{M_P}{M_{P_3}} |\vec{p}_M|^7$$

$$\Gamma(P_3 \to P^* M) = C_M \frac{16k^2}{105\pi f_\pi^2} \frac{M_{P^*}}{M_{P_3}} |\vec{p}_M|^7.$$