hadron spectroscopy
a look at selected topics

outline

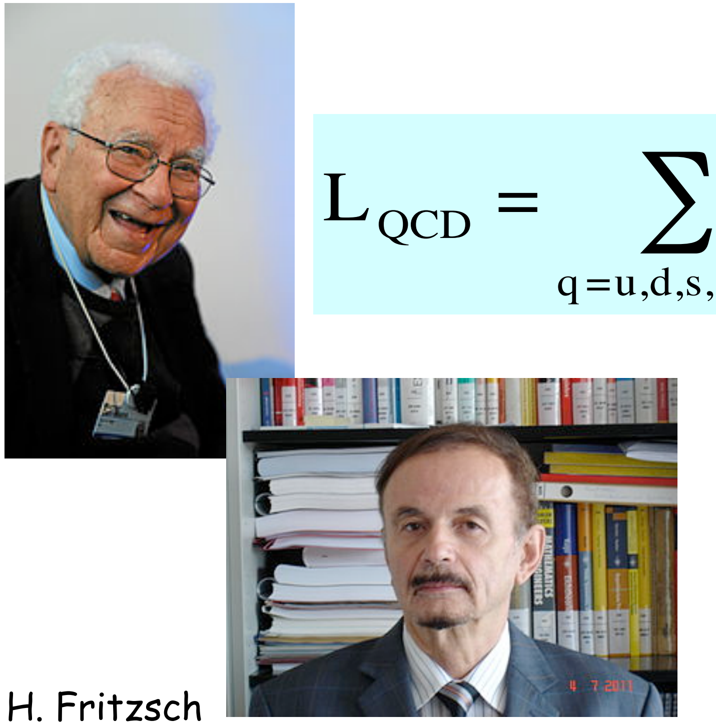
- news on open charm
- puzzles in charmonium
- elusive light glueballs and hybrids

Pietro Colangelo - INFN - Bari
Incontro Nazionale di Fisica Nucleare
Catania - November 2012

prologue: $SU(3)_c$

QCD

M. Gell-Mann



H. Fritzsch

XVI HEP Conference 1972

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

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

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

simple formula encoding all information about matter that constructs our world formidable complexity of QCD

- 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

news in open charm

the effective theory for heavy-light systems is known

$m_Q >> \Lambda_{QCD}$ $Q = e^{im_Q v\cdot x} h_v$ v four velocity

expansion in $1/m_Q$

QCD lagrangian for heavy quarks

$$L_{HQET} = \bar{h}_v \, iv^\mu D_\mu \, h_v$$

flavour & spin symmetry

$$L_{1/m_Q} = \frac{1}{2m_Q} \bar{h}_v \left(i\gamma^\mu D_{\perp\mu}\right)^2 h_v + \frac{1}{2m_Q} \bar{h}_v \frac{g_s \, \sigma_{\alpha\beta} G^{\alpha\beta}}{2} h_v$$

flavour & spin symmetry broken at $O(1/m_Q)$

hadrons containing a single heavy quark Q

spin of the heavy quark and of the light degrees of freedom (quark and gluons) decoupled in the $m_Q \to \infty$ limit

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

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

mesons classified as doublets; states with the same s_ℓ^P degenerate

EXAMPLE: L=0 and L=1

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

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

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

$\frac{3}{2}^+ \to \frac{1}{2}^- + \pi\,(K):$ 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

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,....

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

$H \longrightarrow H\,\pi$

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

$S \longrightarrow H\,\pi$

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

$T \longrightarrow H\,\pi$

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

$X \longrightarrow H\,\pi$

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

$X' \longrightarrow H\,\pi$

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

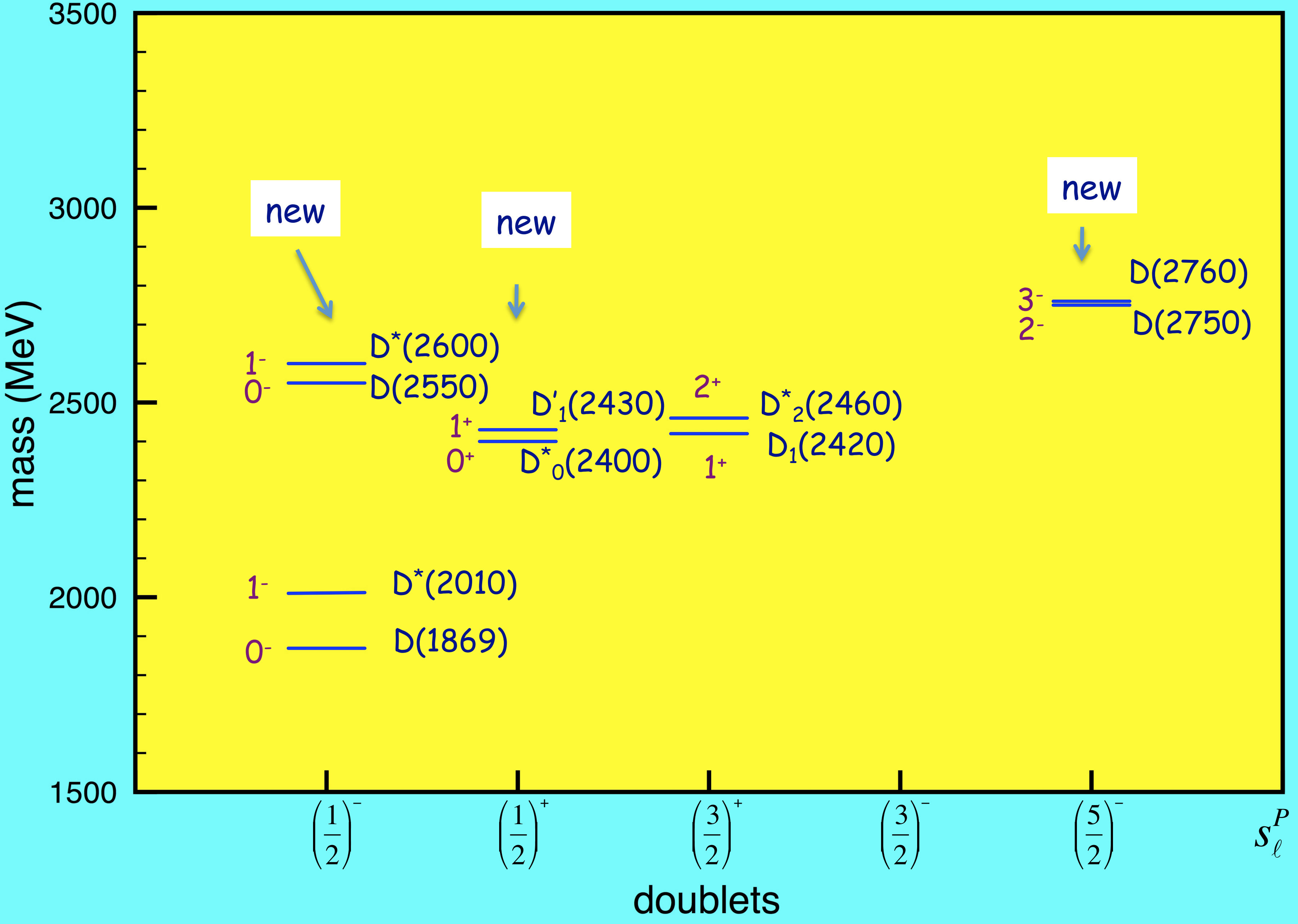
$$A^\mu_{ba} = \frac{1}{2}\left(\xi^+ \partial^\mu \xi - \xi \partial^\mu \xi^+\right)_{ba}$$

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

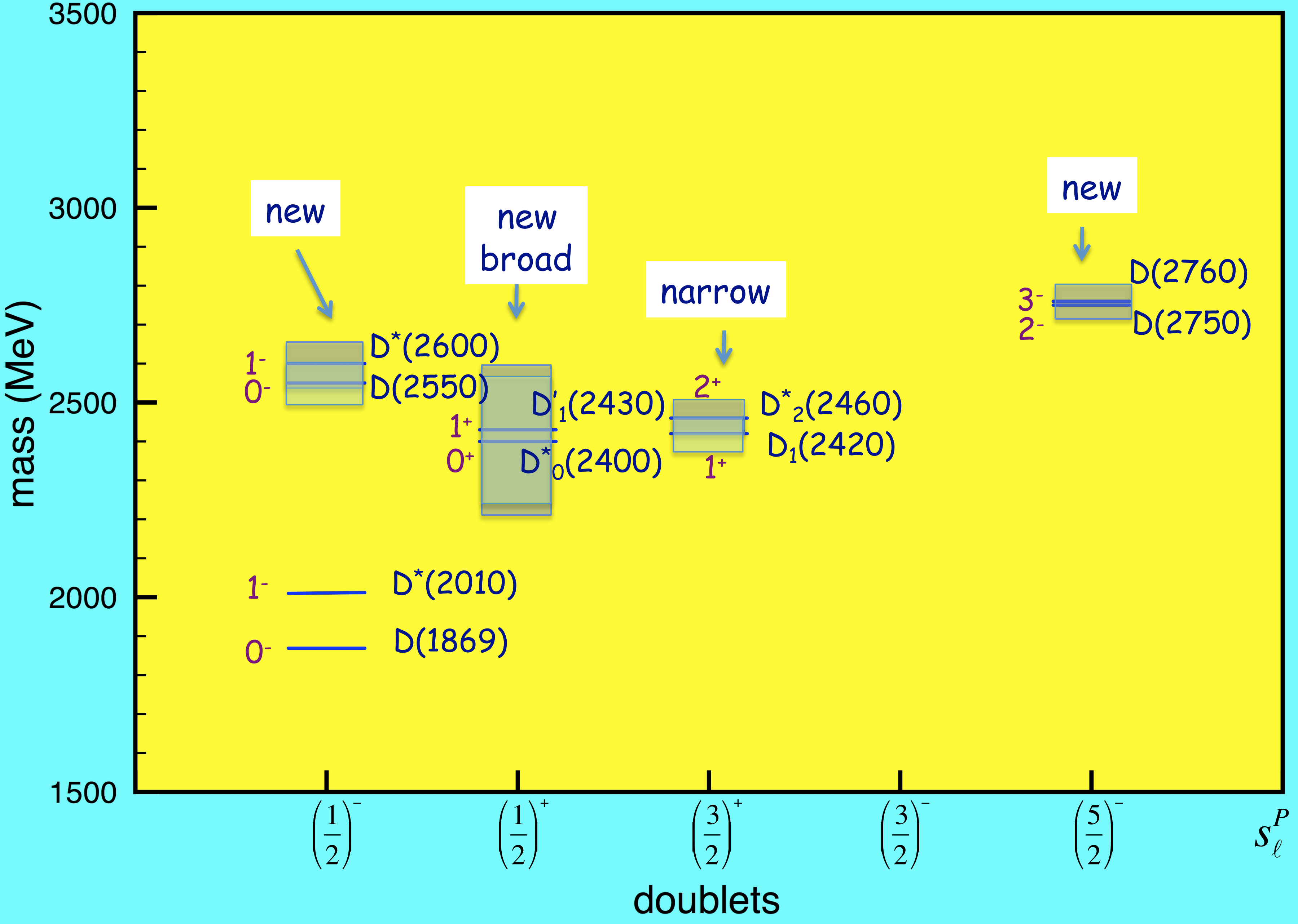
analogous terms describe interactions involving radial excitation doublets:

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

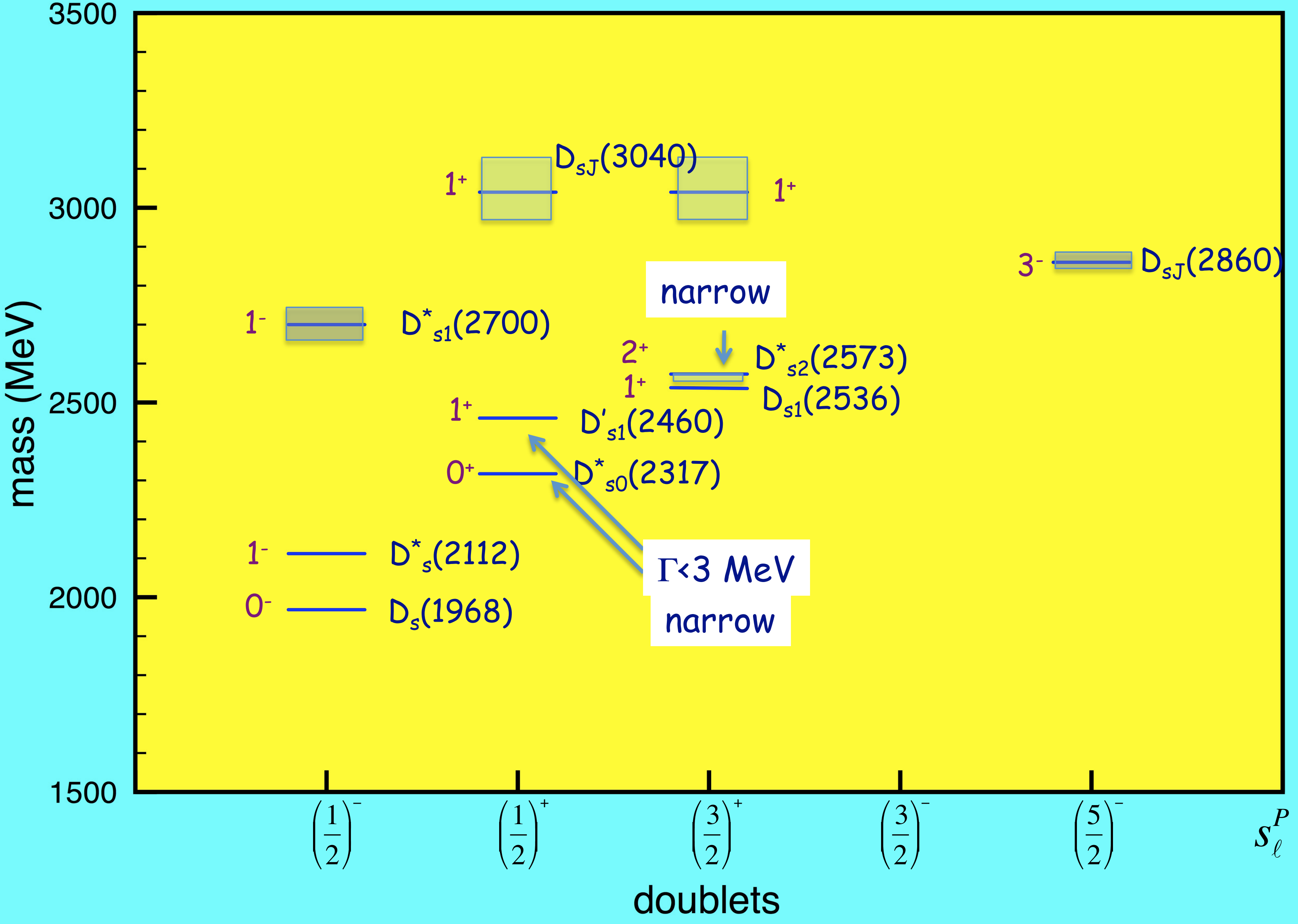
$c\bar{q}$ spectrum 2012



$c\bar{q}$ spectrum 2012



$c\bar{s}$ spectrum 2012



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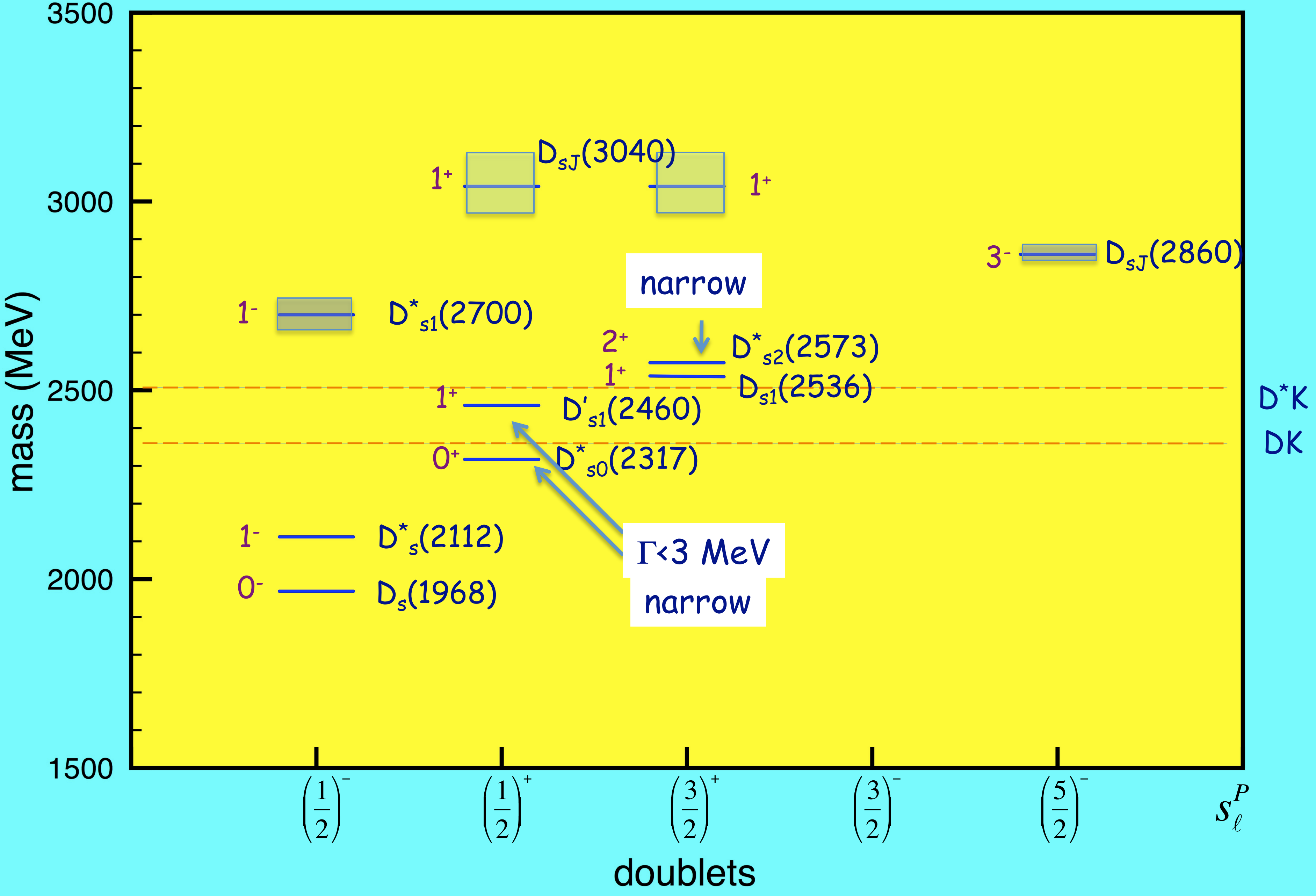

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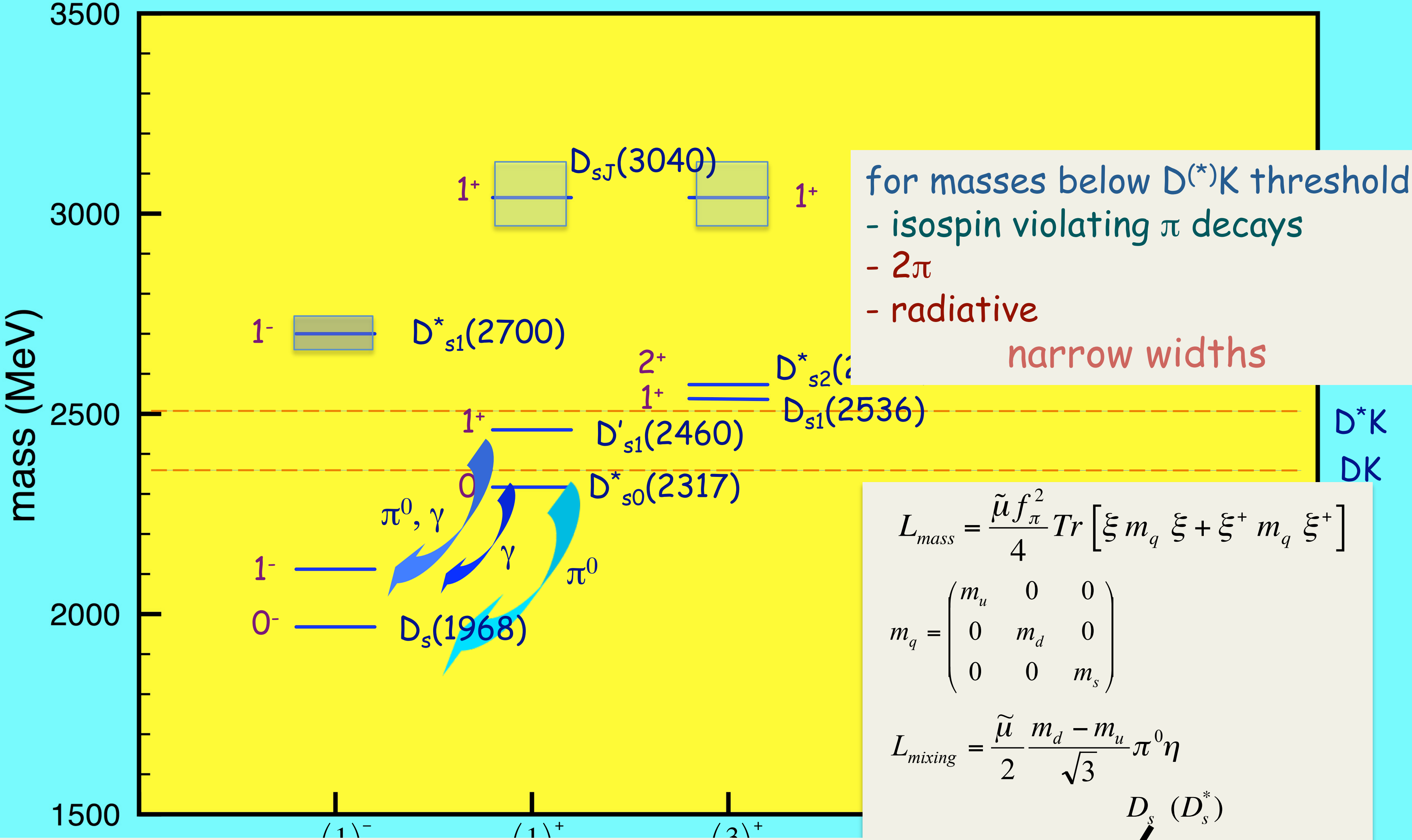


for masses below $D^{(*)}K$ threshold

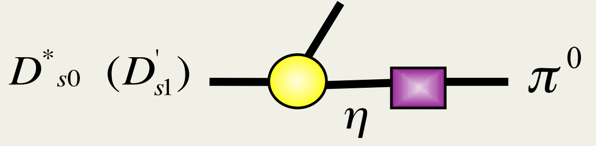
- isospin violating π decays
- 2π
- radiative

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

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

$(m_c \to \infty)$

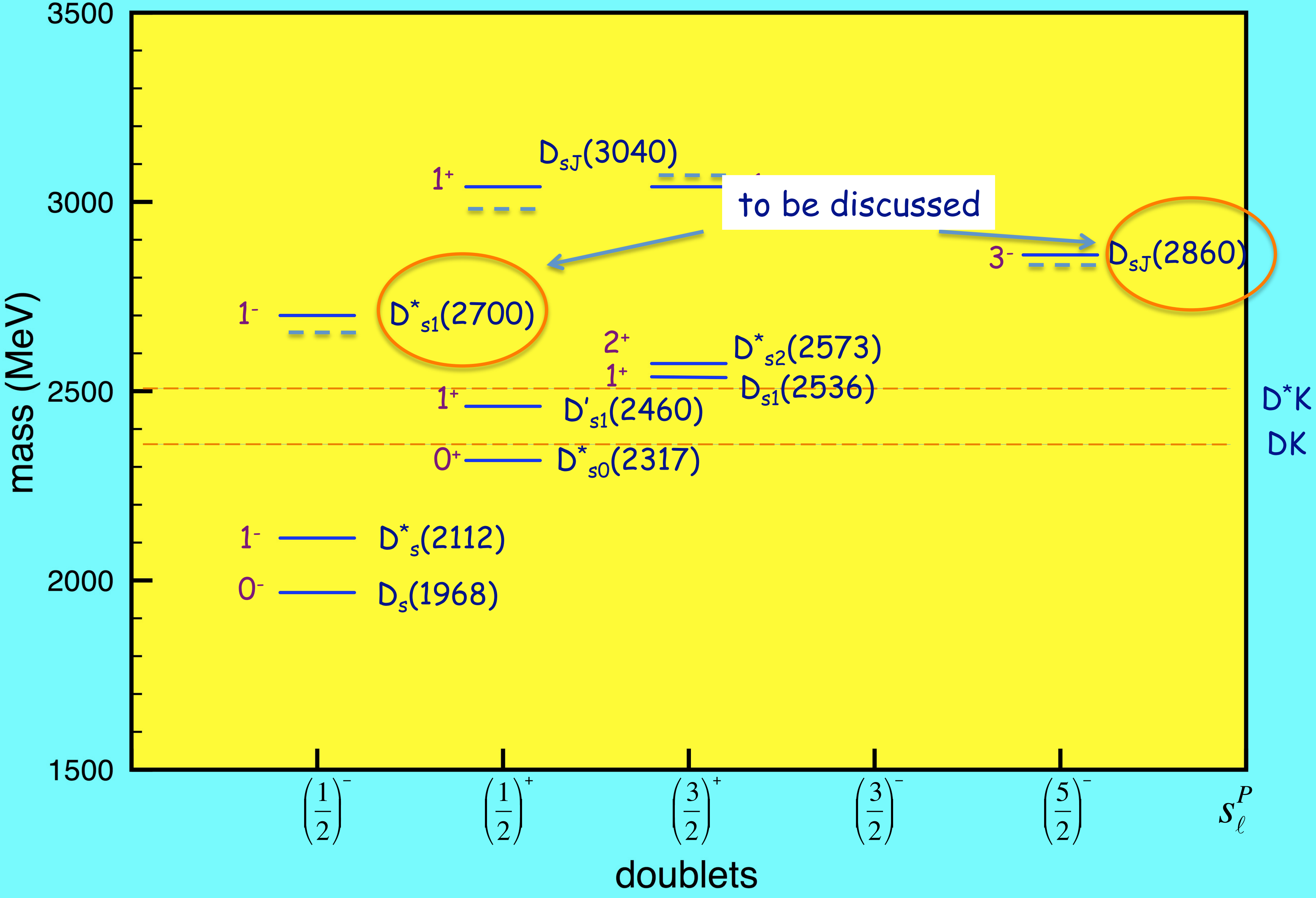
	Belle	BaBar	CLEO
$\frac{\Gamma(D^*_{sJ}(2317)\to D^*_s\gamma)}{\Gamma(D^*_{sJ}(2317)\to D_s\pi^0)}$	< 0.18	—	< 0.059
$\frac{\Gamma(D_{sJ}(2460)\to D_s\gamma)}{\Gamma(D_{sJ}(2460)\to D^*_s\pi^0)}$	$0.55 \pm 0.13 \pm 0.08$ $0.38 \pm 0.11 \pm 0.04$	$0.375 \pm 0.054 \pm 0.057$ $0.274 \pm 0.045 \pm 0.020$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

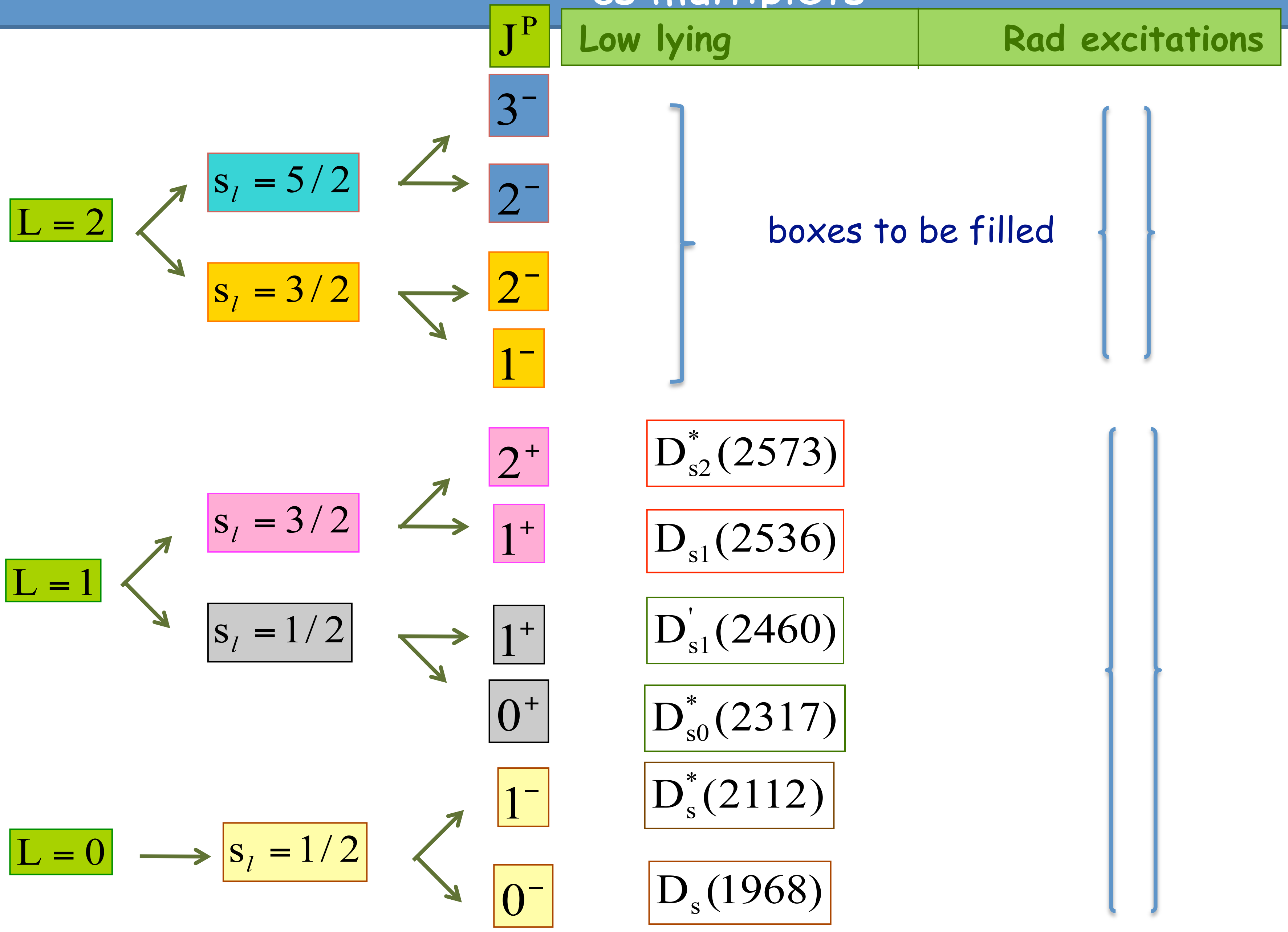
De Fazio, Ozpineci, PC

$c\bar{s}$ spectrum 2012



to be discussed

$c\bar{s}$ multiplets



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

$D_{sJ}(2860)$: 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 $s_\ell^P = \frac{5}{2}^- \quad J^P = 3^- \quad n = 1$

- **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

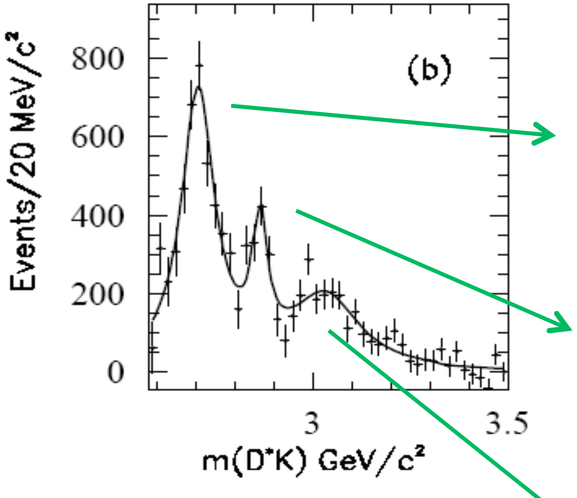
		$R_1 \times 10^2$	$R_2 \times 10^2$	$R_3 \times 10^2$
$\frac{1}{2}^-$ →	$D_s^{*\prime}$	91 ± 4	20 ± 1	5 ± 2
$\frac{3}{2}^-$ →	D_{s1}^*	4.3 ± 0.2	16.3 ± 0.9	0.18 ± 0.07

⇓

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

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

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

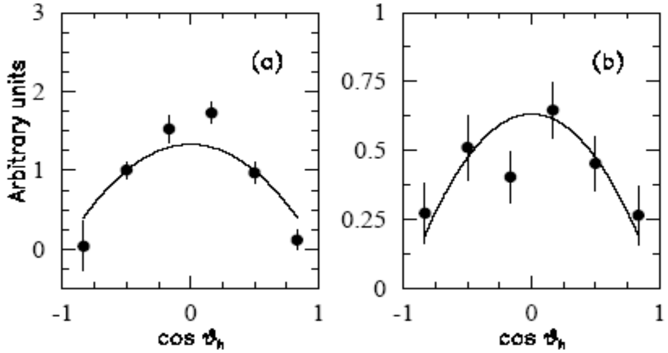
$$m(D_{sJ}(2860)^+) = 2862 \pm 2_{stat} \pm^{5}_{2\ syst} \quad \mathrm{MeV}$$

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

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

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

- 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 (09)092003

BaBar analysis of D^*K

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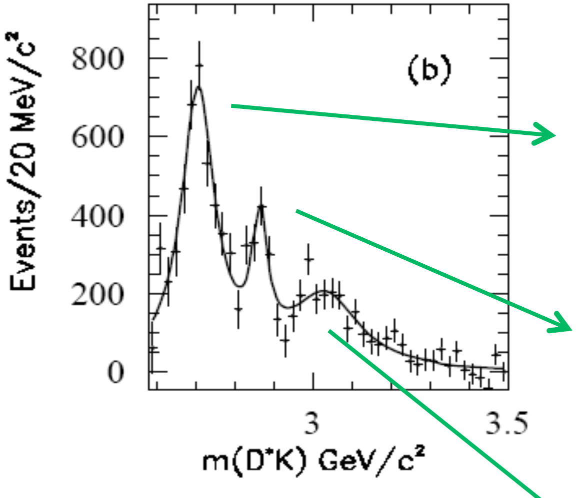

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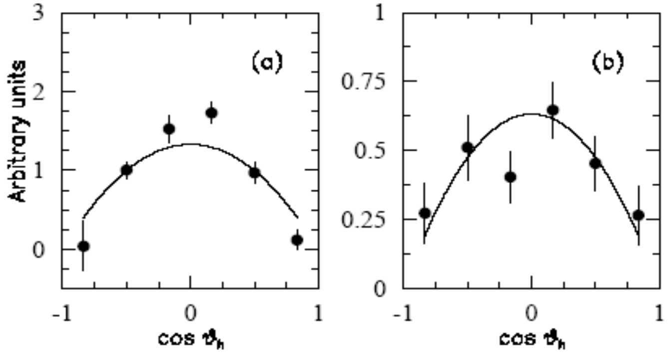
not discussed here

- angular analysis



angular distribution consistent for states with natural parity (0^+,1^-,2^+,3^-,…) for $D_{s1}(2710)$ and $D_{sJ}(2860)$

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BaBar, PRD80 (09)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

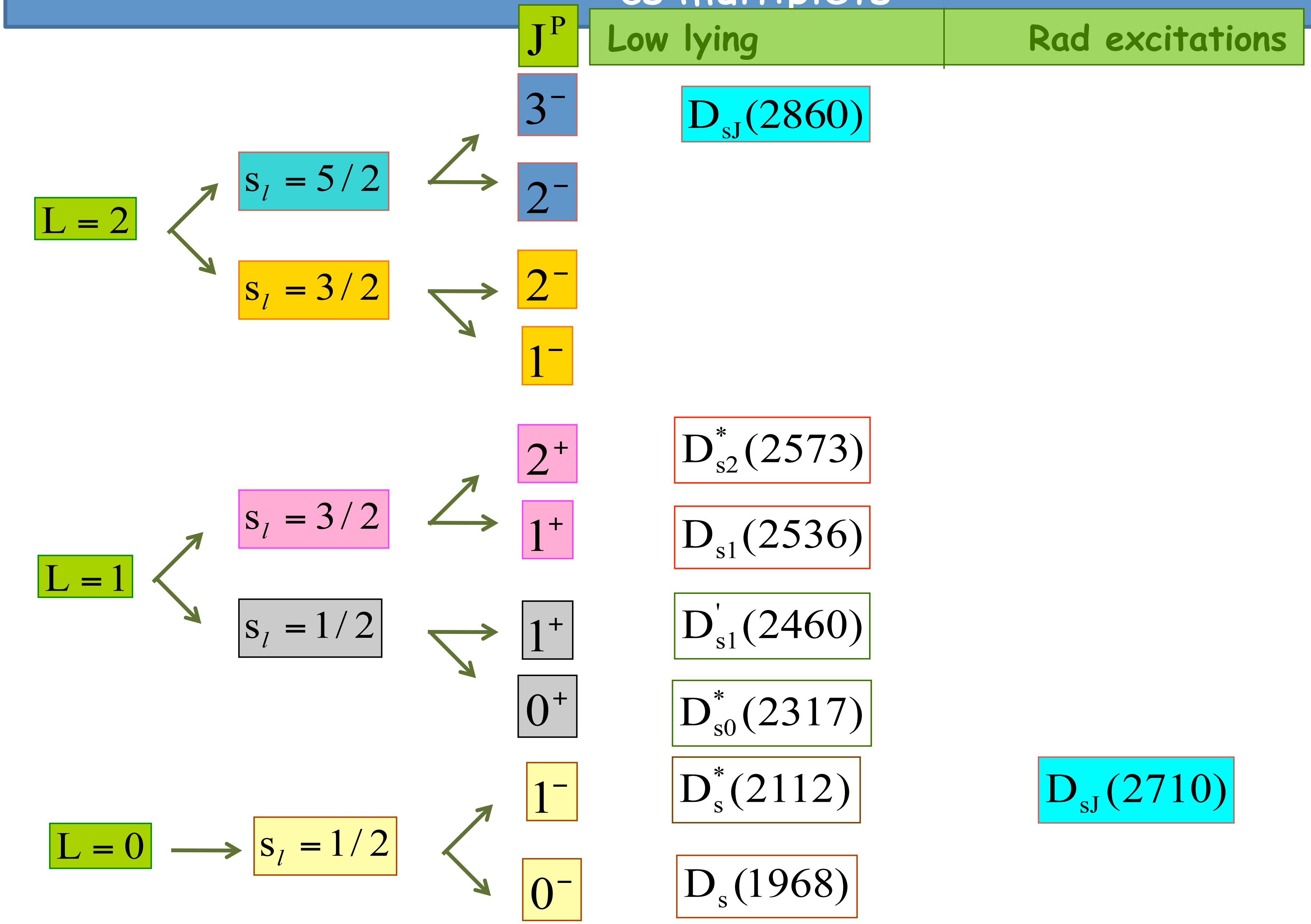
supports the identification of
$D_{s1}(2710)$ with 2^3S_1
(first radial excitation of D_s^*)

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

th: 0.4

why?

$c\bar{s}$ multiplets



L	s_l	J^P	Low lying	Rad excitations
$L = 2$	$s_l = 5/2$	3^-	$D_{sJ}(2860)$	
		2^-		
	$s_l = 3/2$	2^-		
		1^-		
$L = 1$	$s_l = 3/2$	2^+	$D^*_{s2}(2573)$	
		1^+	$D_{s1}(2536)$	
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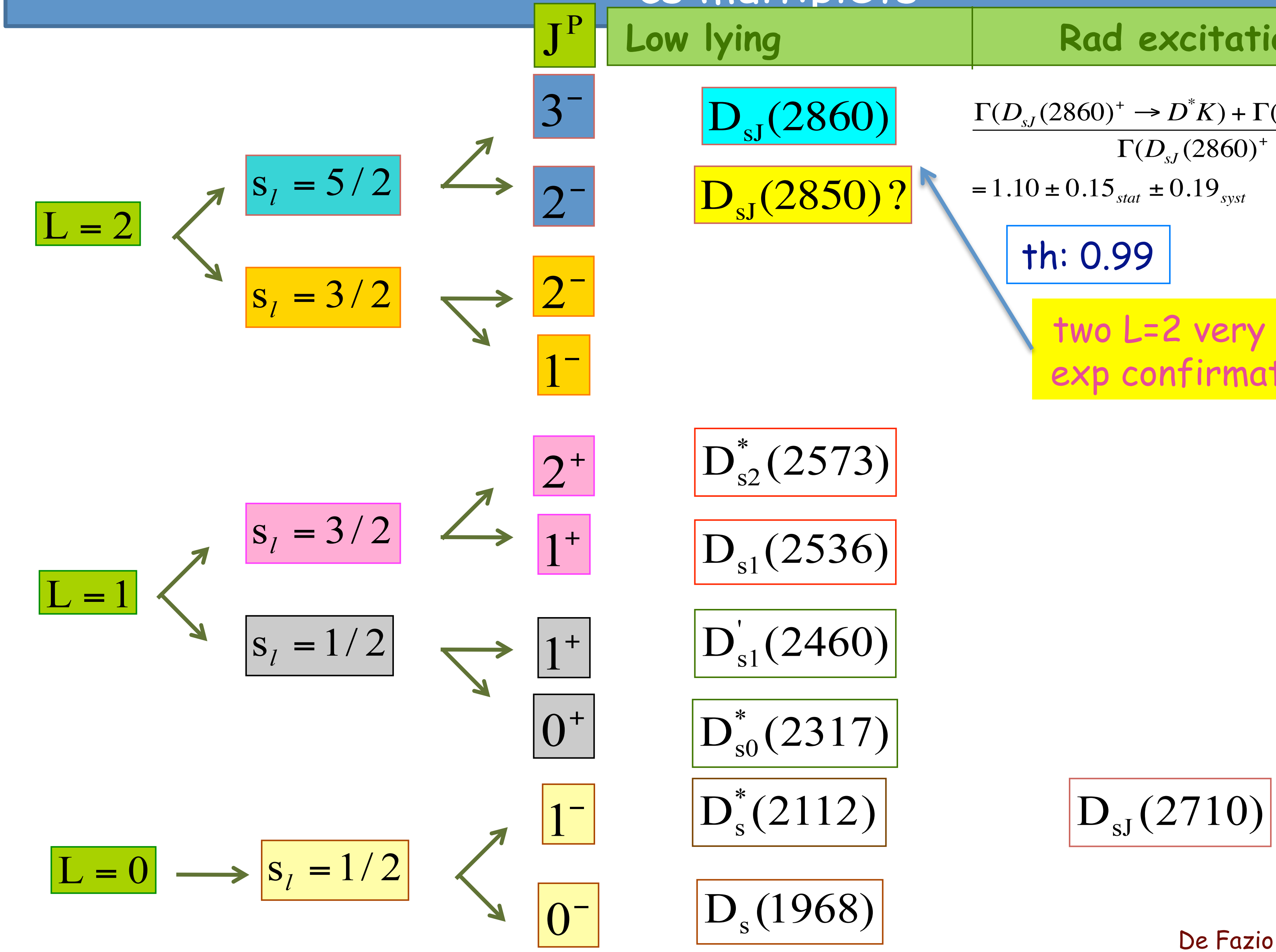
$L = 0$	$s_l = 1/2$	1^-	$D^*_s(2112)$	$D_{sJ}(2710)$
		0^-	$D_s(1968)$	

$c\bar{s}$ multiplets



J^P	Low lying	Rad excitations
3^-	$D_{sJ}(2860)$	
2^-	$D_{sJ}(2850)$?	
2^-		
1^-		
2^+	$D^*_{s2}(2573)$	
1^+	$D_{s1}(2536)$	
1^+	$D'_{s1}(2460)$	
0^+	$D^*_{s0}(2317)$	
1^-	$D^*_s(2112)$	$D_{sJ}(2710)$
0^-	$D_s(1968)$	

$L=2$ → $s_l=5/2$ → 3^-, 2^-; $s_l=3/2$ → 2^-, 1^-

$L=1$ → $s_l=3/2$ → 2^+, 1^+; $s_l=1/2$ → 1^+, 0^+

$L=0$ → $s_l=1/2$ → 1^-, 0^-

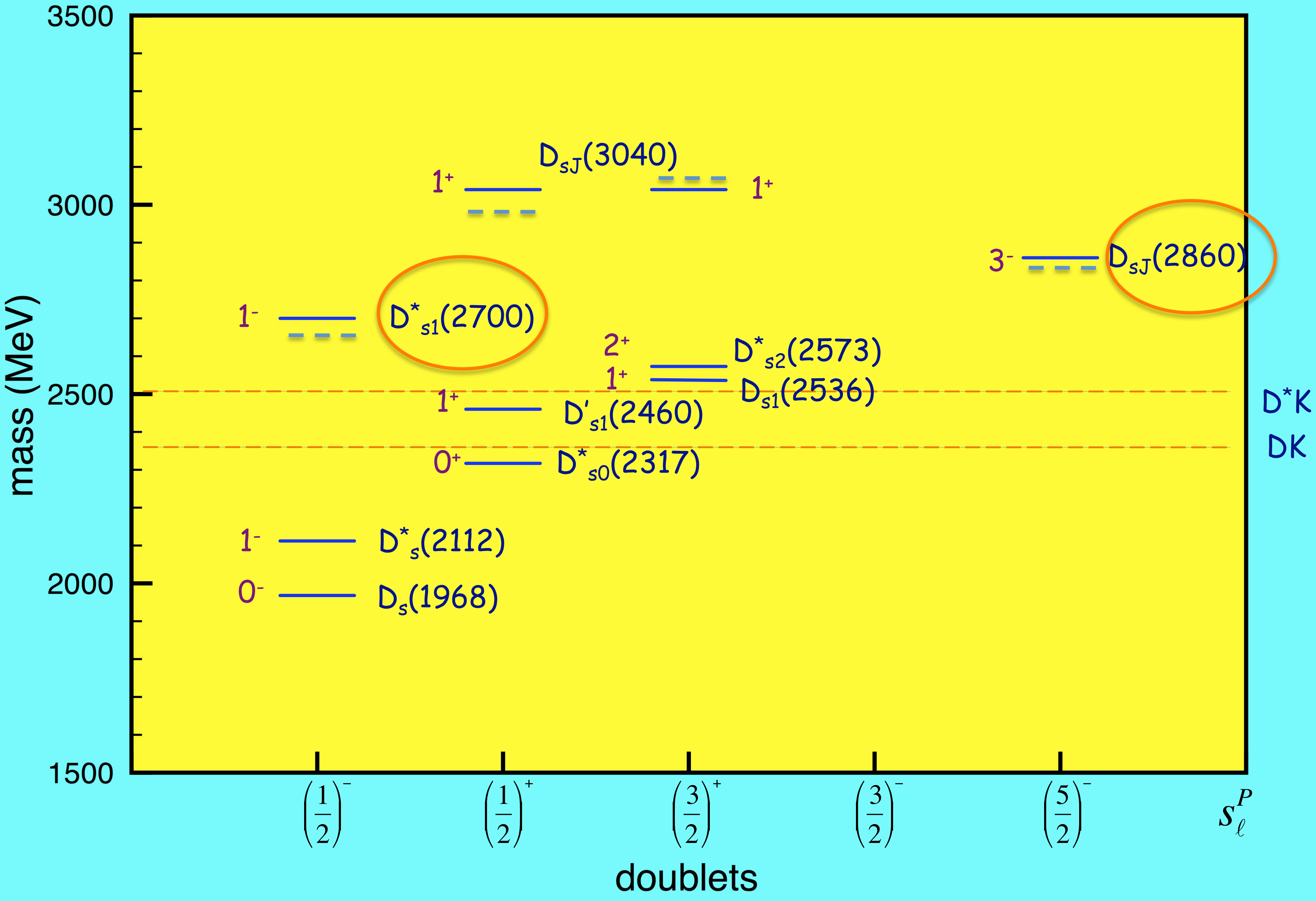
$$\frac{\Gamma(D_{sJ}(2860)^+ \to D^*K) + \Gamma(D_{sJ}(2850)^+ \to D^*K)}{\Gamma(D_{sJ}(2860)^+ \to DK)} = 1.10 \pm 0.15_{stat} \pm 0.19_{syst}$$

th: 0.99

two L=2 very close states
exp confirmation welcome

De Fazio, Giannuzzi, Nicotri PC
PRD 2012

$c\bar{s}$ spectrum 2012



$c\bar{q}$ 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

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

$c\bar{q}$ mesons

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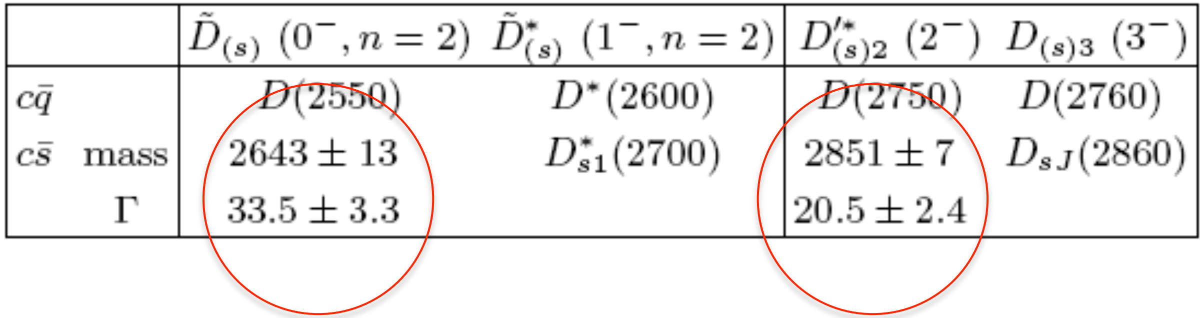
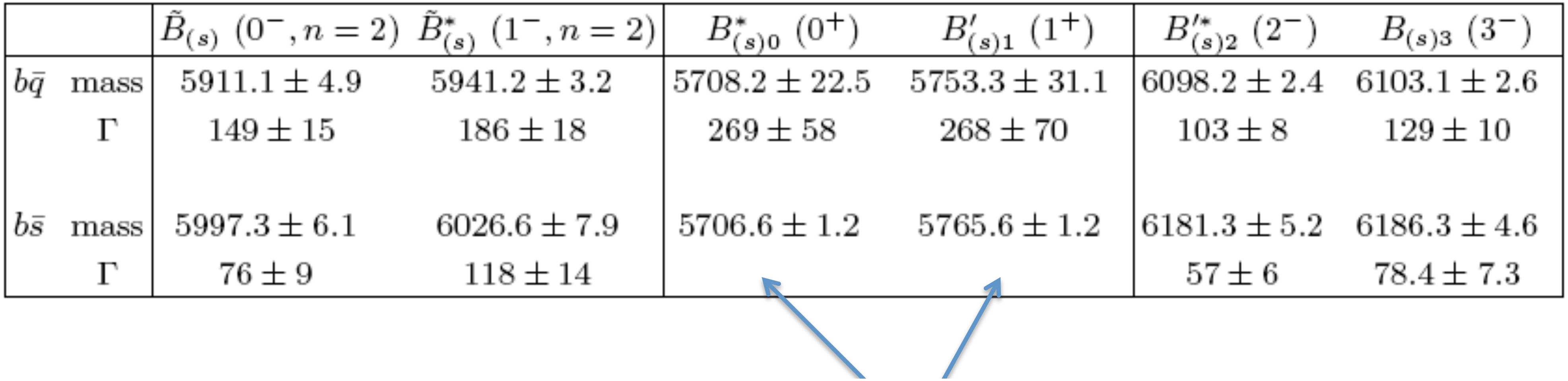
assigned to L=2 doublet

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



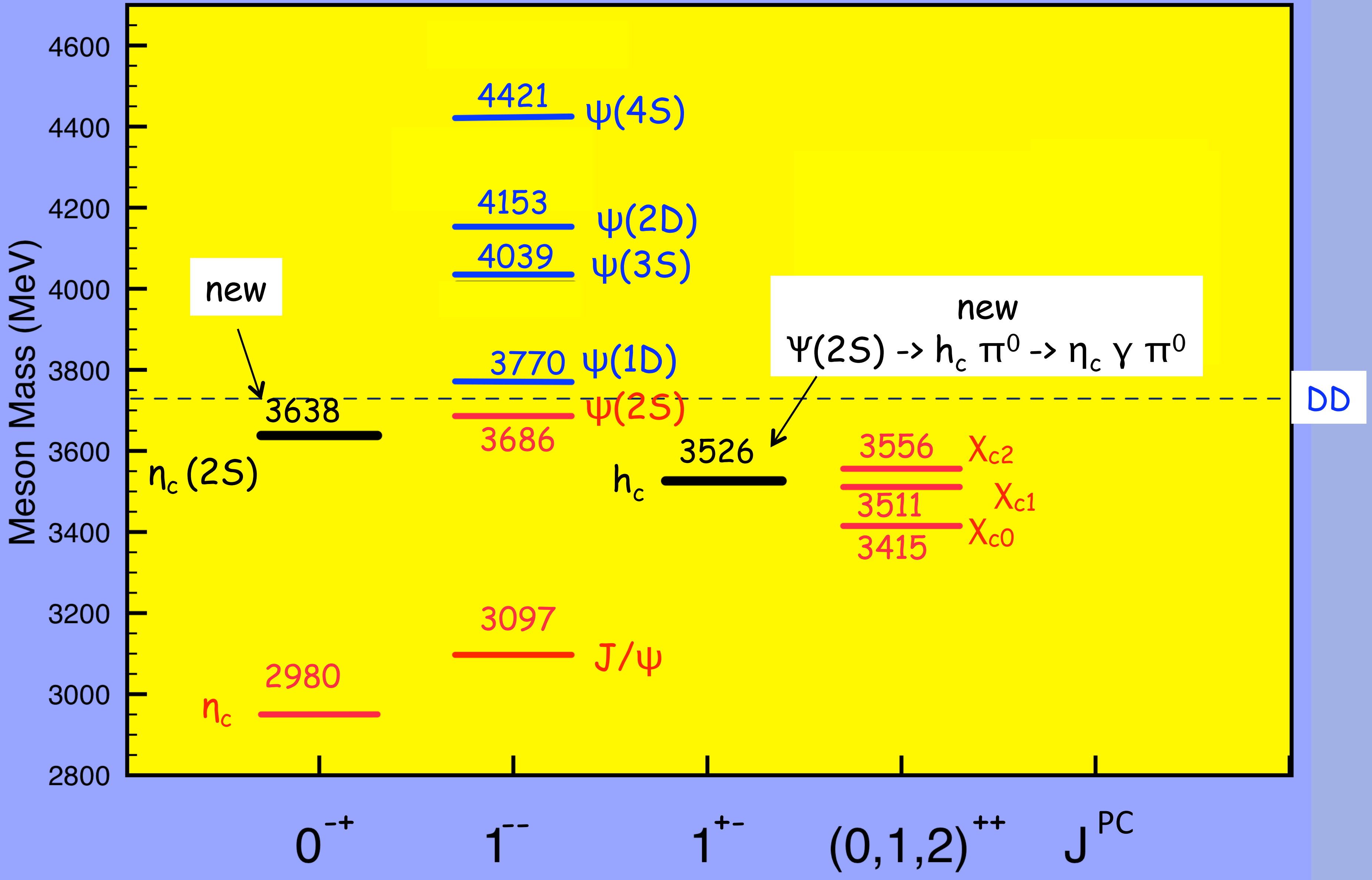
	$\tilde{B}_{(s)}$ $(0^-, n=2)$	$\tilde{B}^*_{(s)}$ $(1^-, n=2)$	$B^*_{(s)0}$ (0^+)	$B'_{(s)1}$ (1^+)	$B'^*_{(s)2}$ (2^-)	$B_{(s)3}$ (3^-)
$b\bar{q}$ mass	5911.1 ± 4.9	5941.2 ± 3.2	5708.2 ± 22.5	5753.3 ± 31.1	6098.2 ± 2.4	6103.1 ± 2.6
Γ	149 ± 15	186 ± 18	269 ± 58	268 ± 70	103 ± 8	129 ± 10
$b\bar{s}$ mass	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

puzzles in quarkonium

charmonium

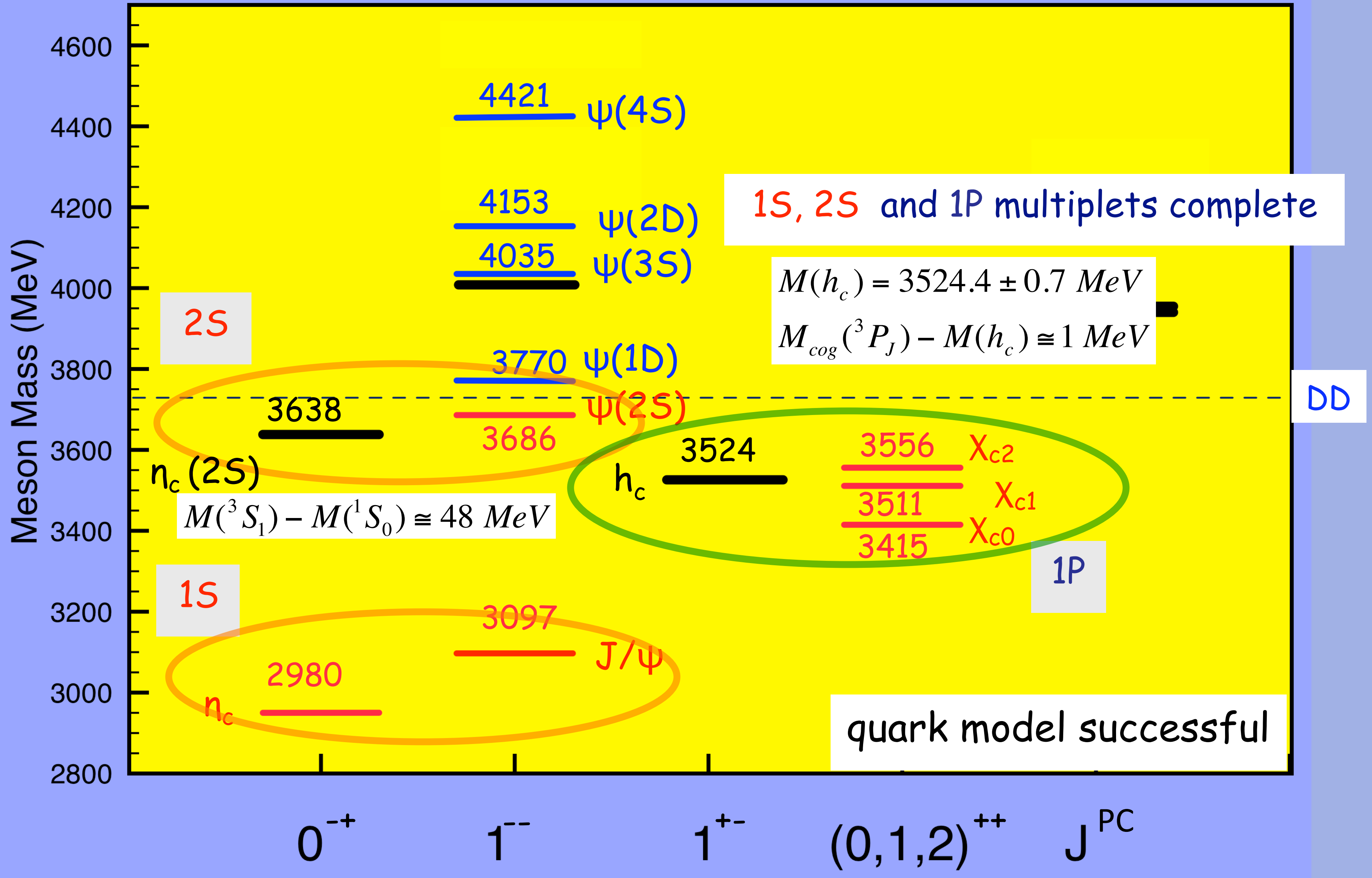


new

new

$\Psi(2S) \to h_c\, \pi^0 \to \eta_c\, \gamma\, \pi^0$

charmonium



1S, 2S and 1P multiplets complete

$$M(h_c) = 3524.4 \pm 0.7\ MeV$$

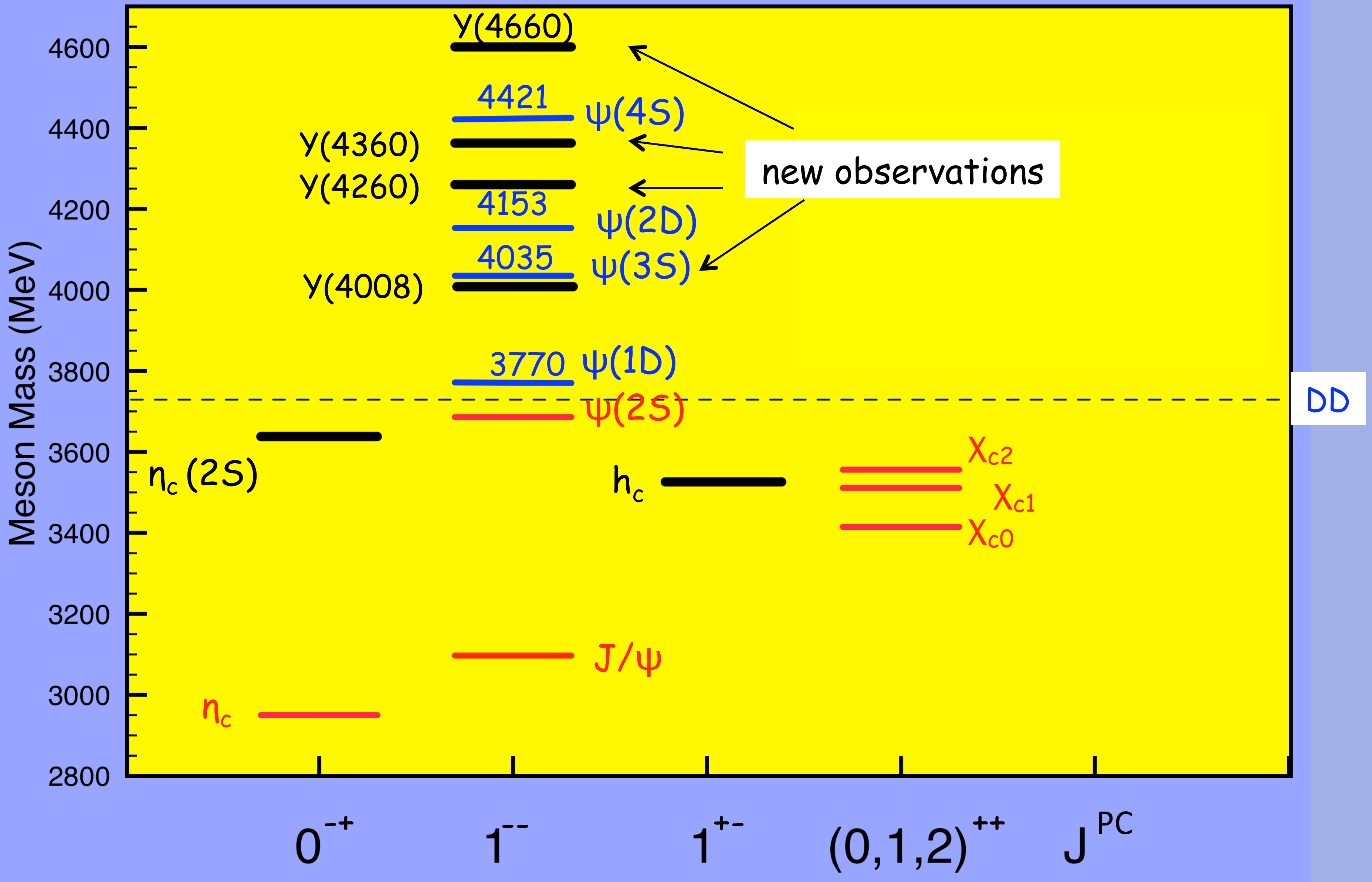
$$M_{cog}(^3P_J) - M(h_c) \cong 1\ MeV$$

$$M(^3S_1) - M(^1S_0) \cong 48\ MeV$$

quark model successful

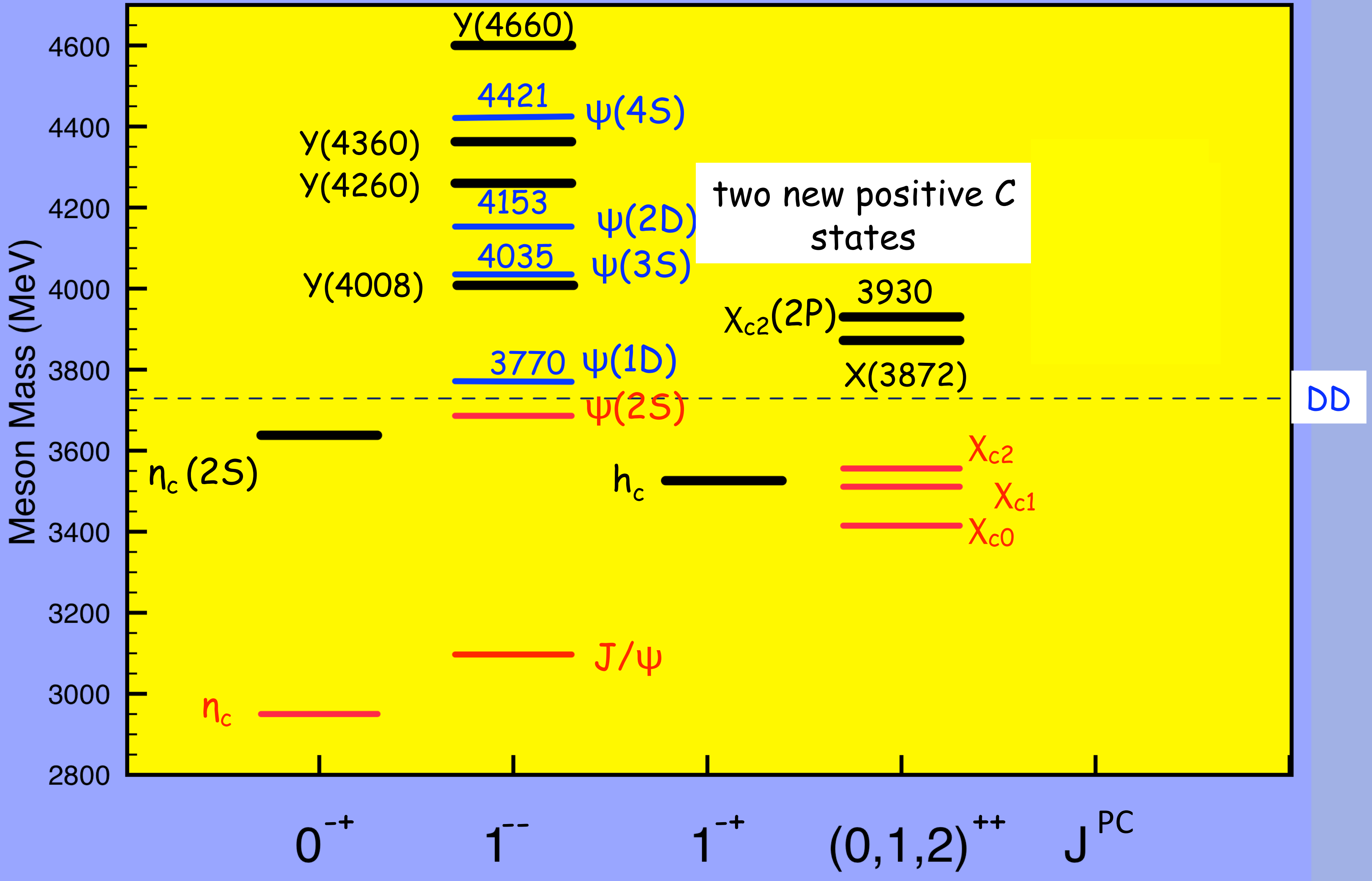
charmonium

four new 1^{--} states



charmonium

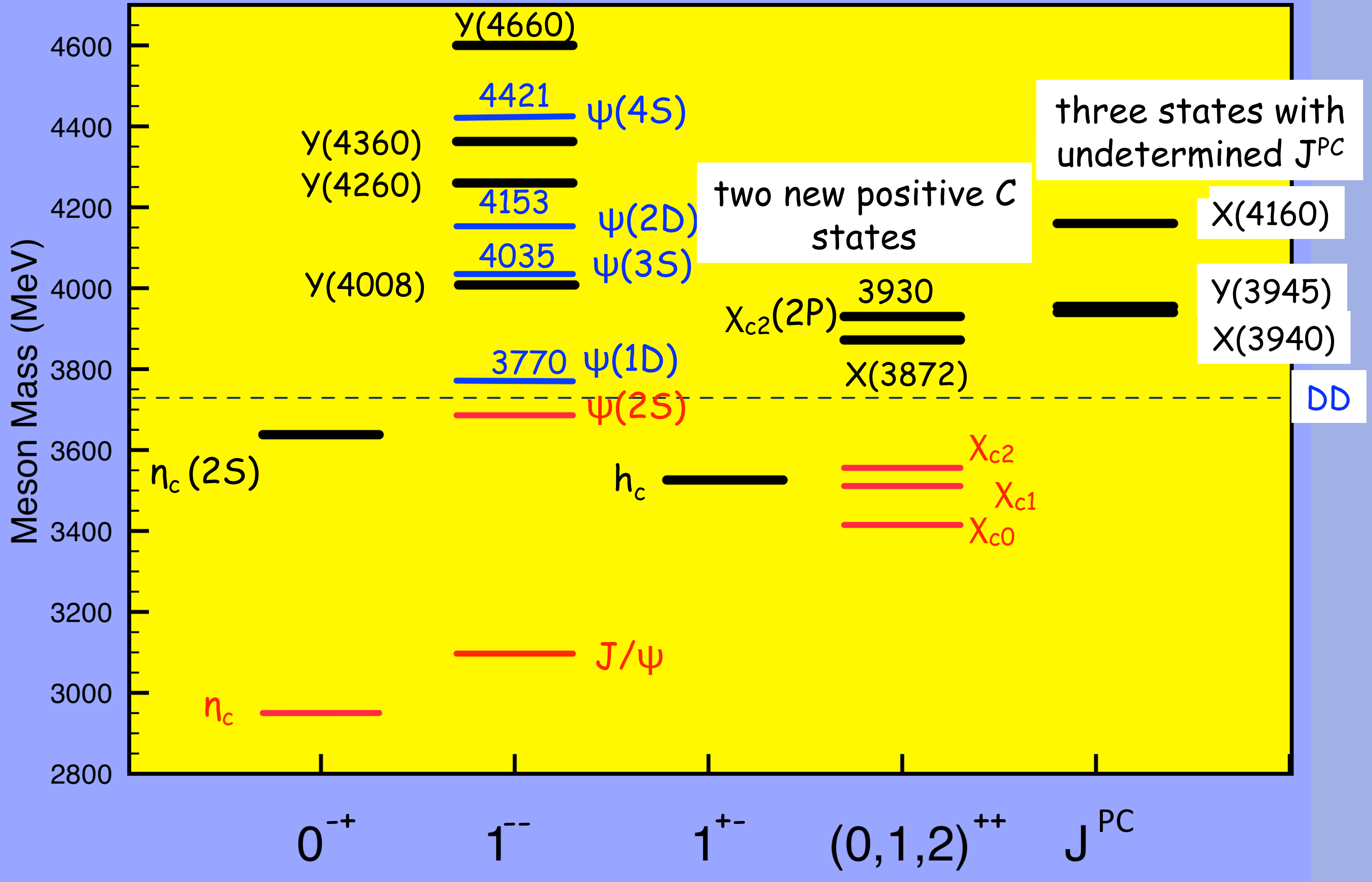
four new 1^{--} states



two new positive *C* states

charmonium

four new 1^{--} states

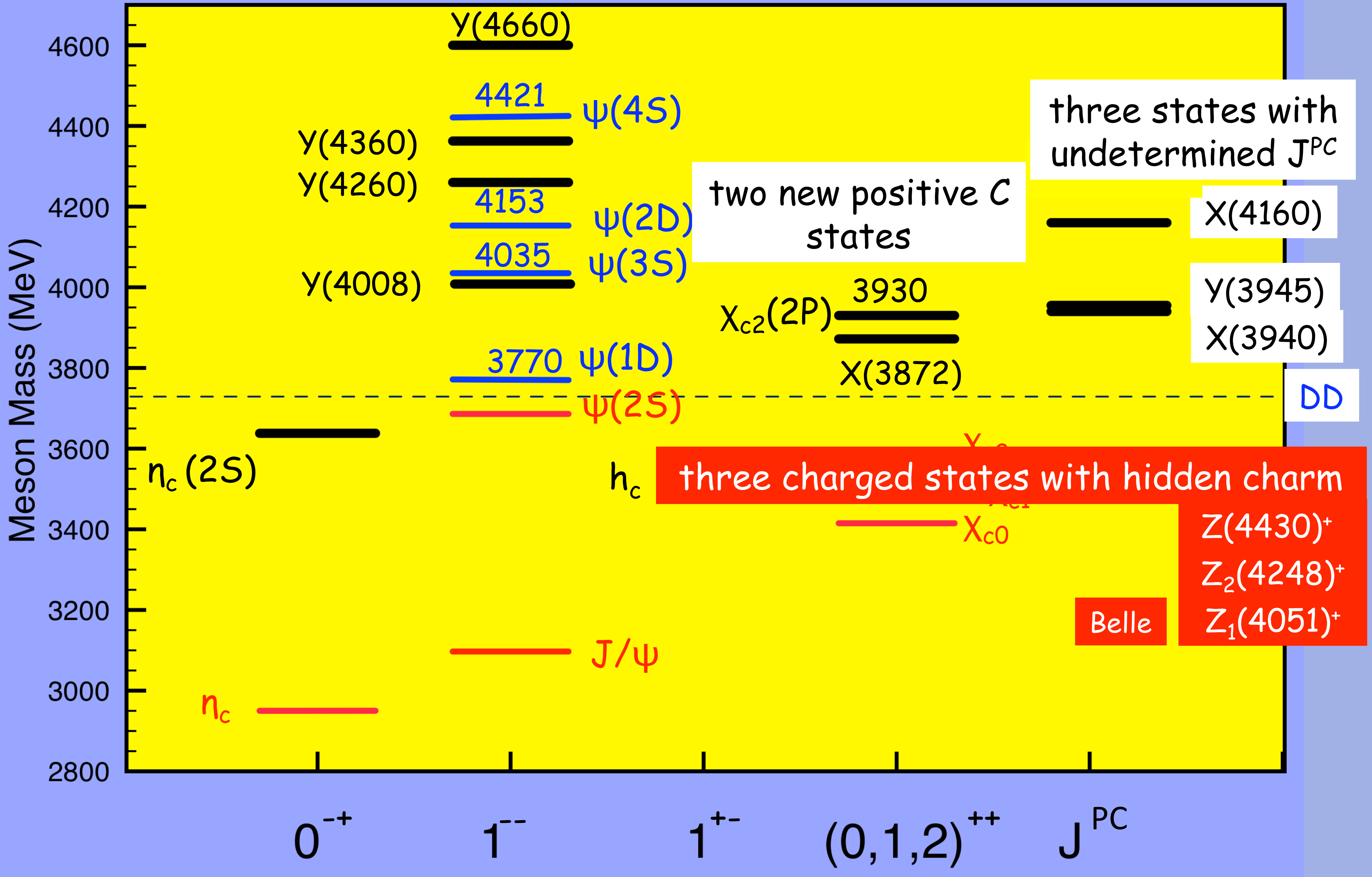


two new positive C states

three states with undetermined J^{PC}

charmonium

four new 1^{--} states



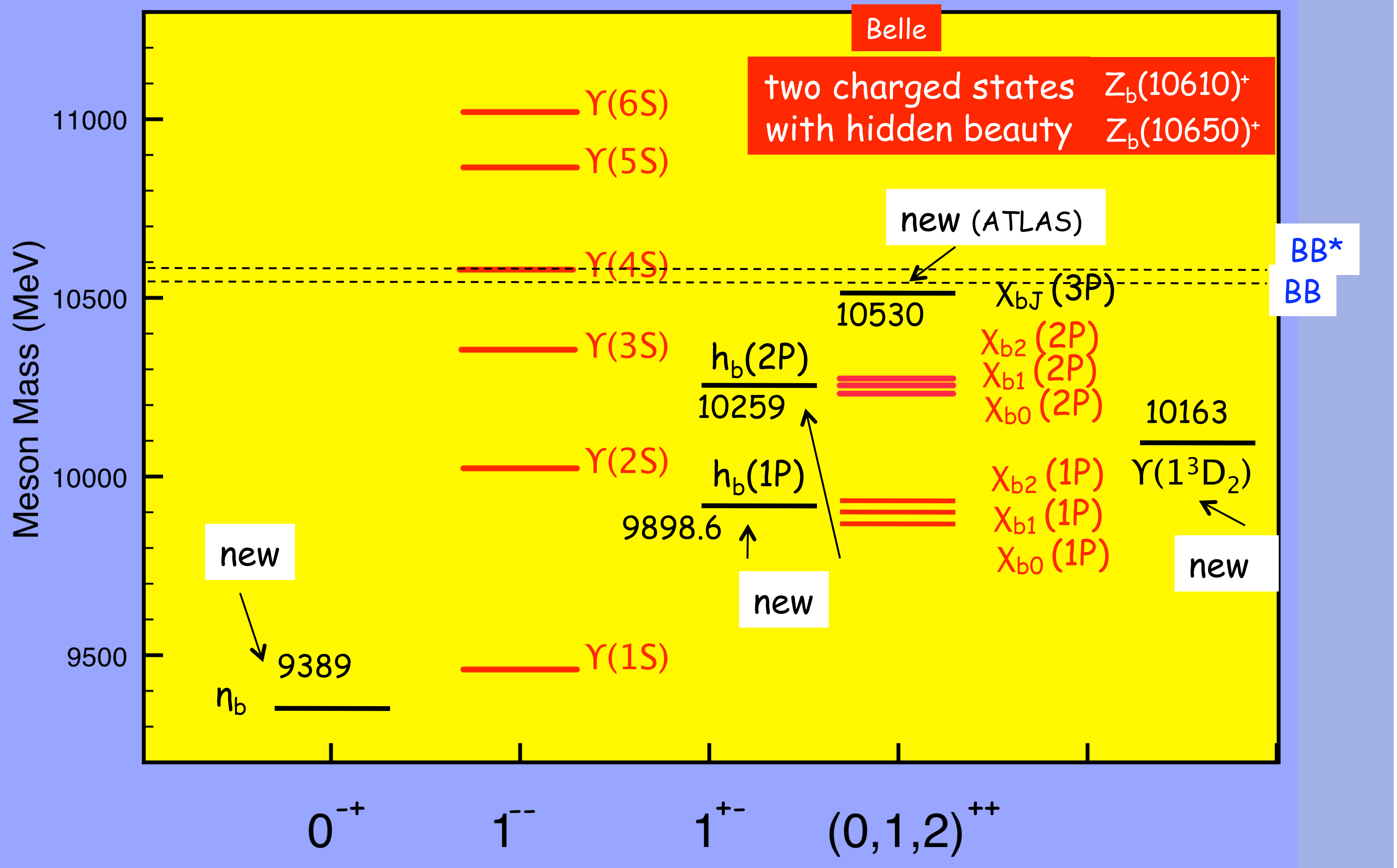
three states with undetermined J^{PC}

two new positive C states

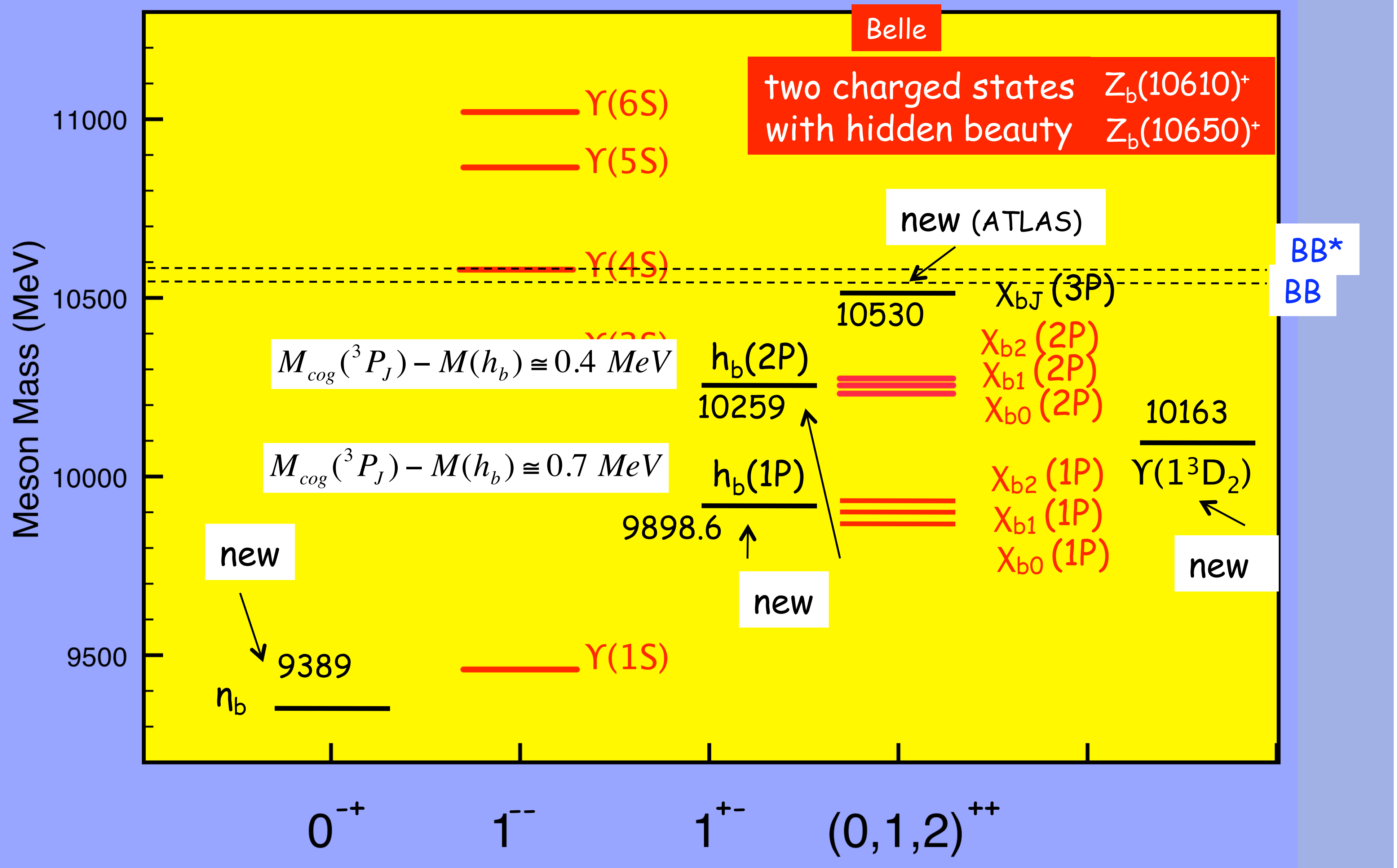
three charged states with hidden charm

Belle

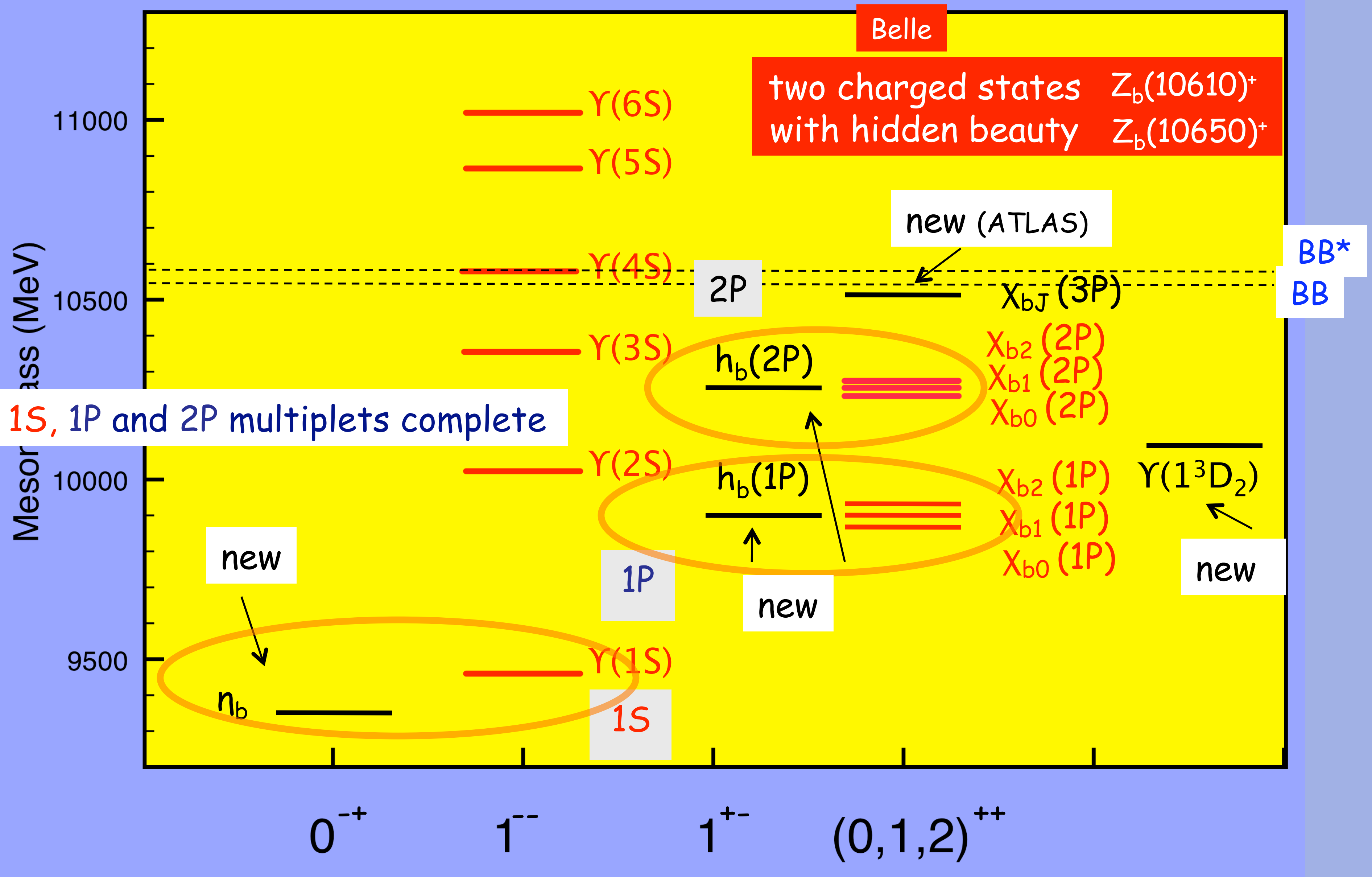
bottomonium



bottomonium



bottomonium

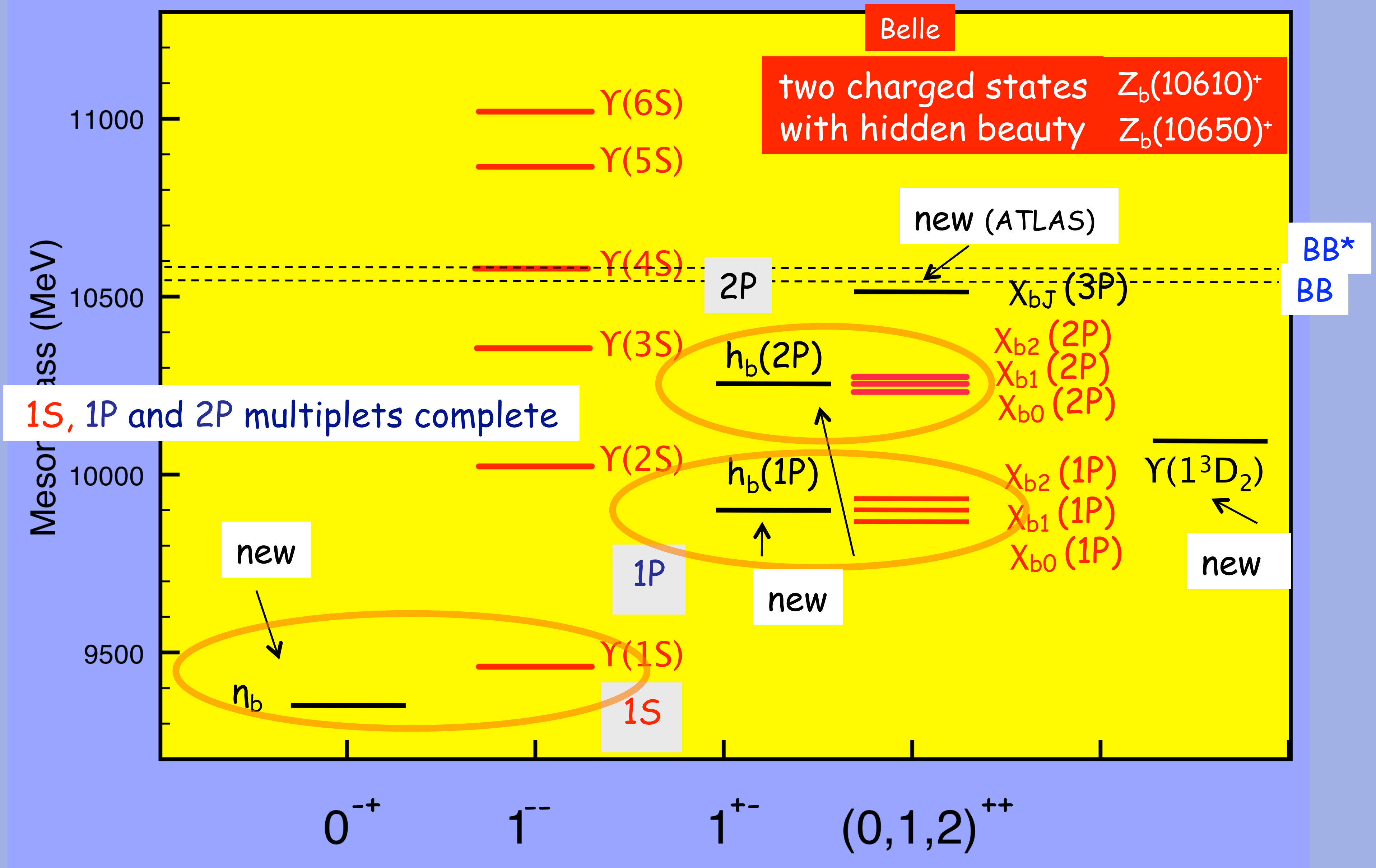


Belle

two charged states with hidden beauty $Z_b(10610)^+$ $Z_b(10650)^+$

1S, 1P and 2P multiplets complete

bottomonium



Belle

two charged states with hidden beauty $Z_b(10610)^+$ $Z_b(10650)^+$

1S, 1P and 2P multiplets complete

new (ATLAS)

enormous phenomenology:
a treatment of all these aspects in a unique th. framework is not possible (at present)

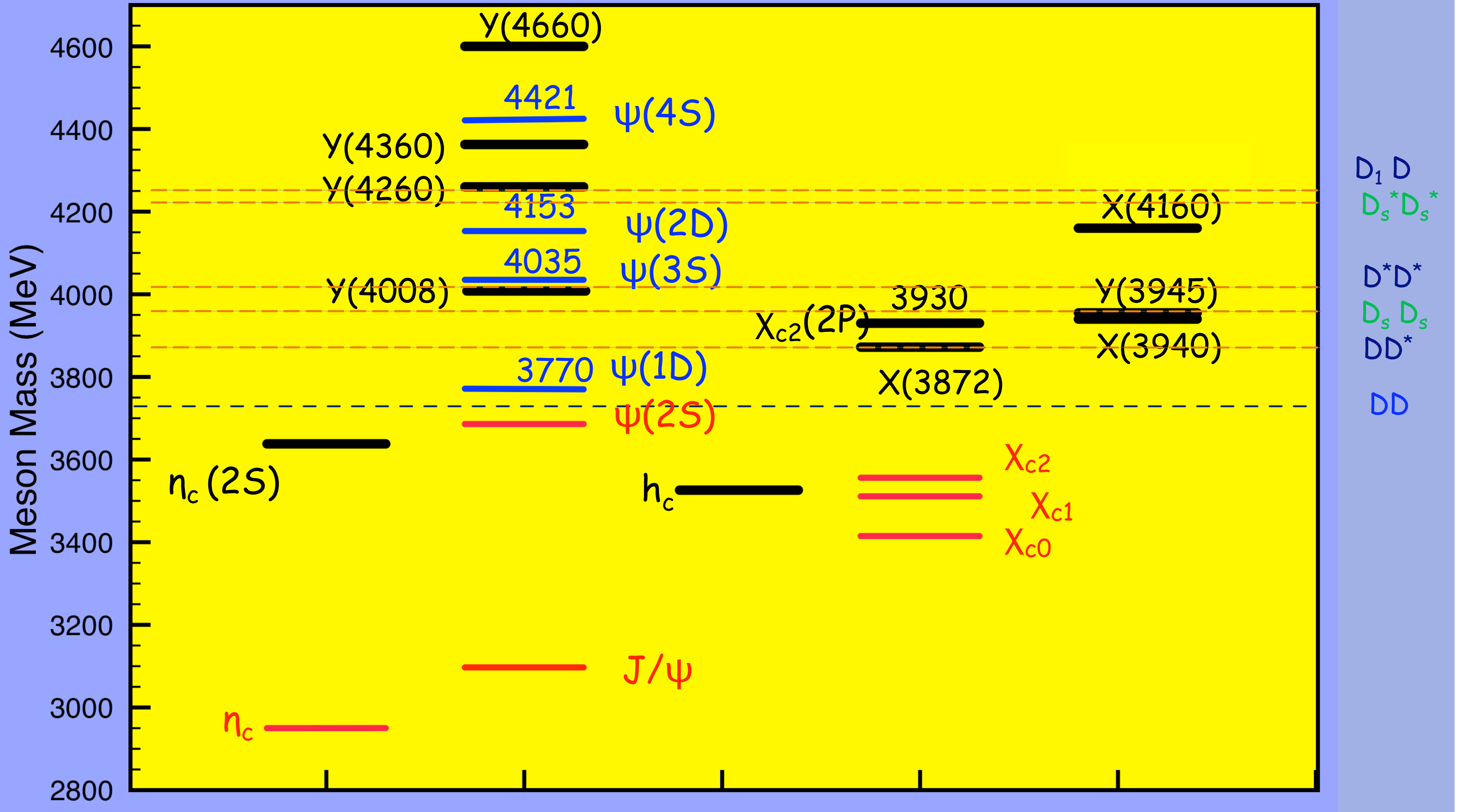
a few remarks should be considered

remark 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

charmonium

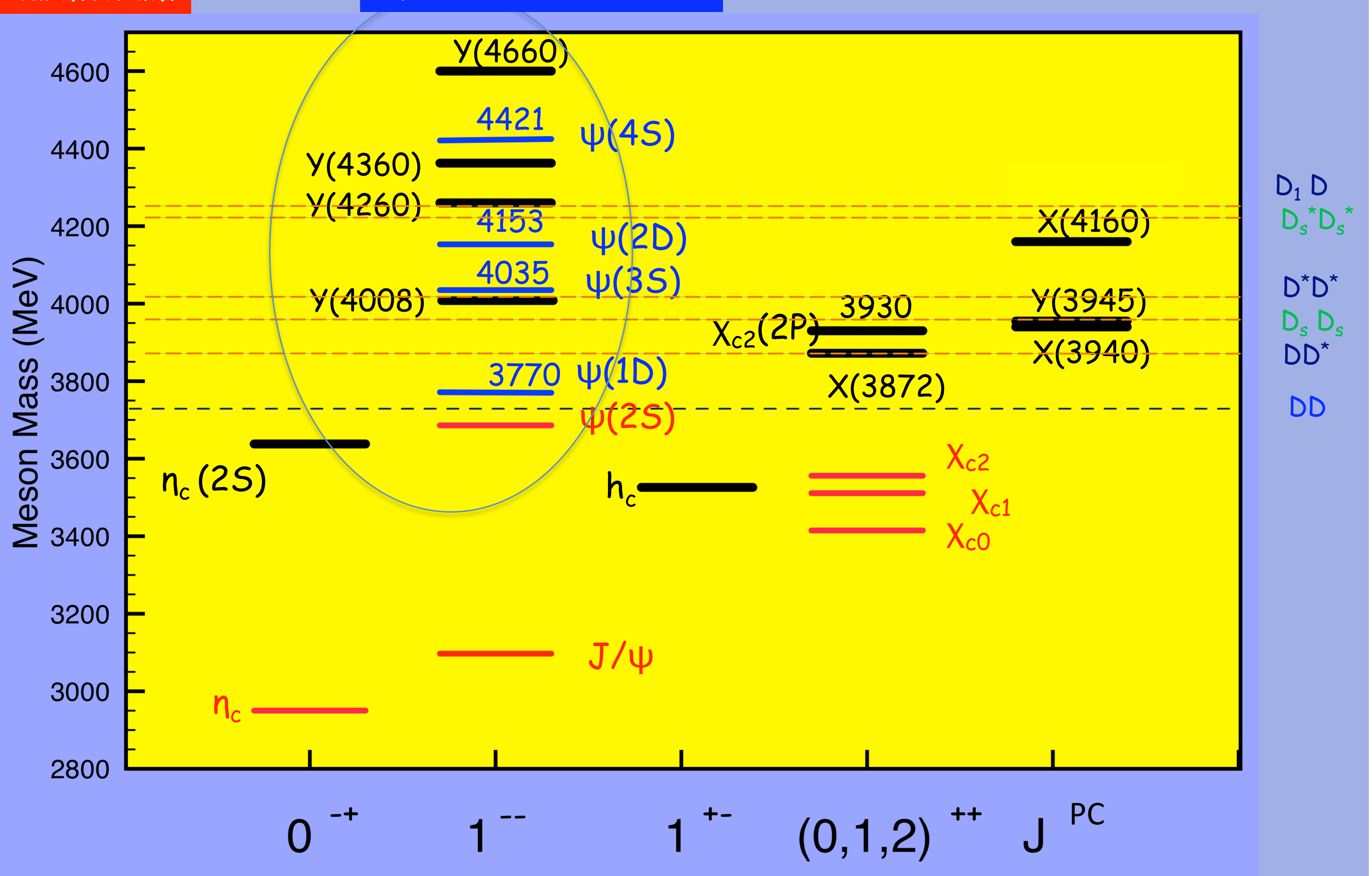


remark n. 2

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

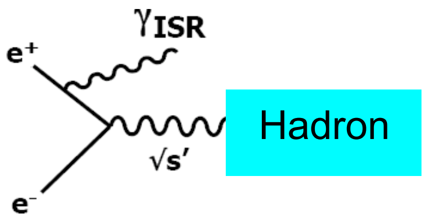
charmonium

four new 1^{--} states



Y(4008)   Y(4260)   Y(4360)   Y(4660)

observed by Belle, BaBar and Cleo in ISR events: $e^+ e^- \to \gamma\ Y$



decays in J/ψ , $\psi(2S)$

$Y(4008) \to J/\psi\ \pi^+\ \pi^-$

$Y(4260) \to J/\psi\ \pi^+\ \pi^-$, $J/\psi\ \pi^0\ \pi^0$, $J/\psi\ K^+\ K^-$

$Y(4360) \to \psi(2S)\ \pi^+\ \pi^-$

$Y(4660) \to \psi(2S)\ \pi^+\ \pi^-$

no resonant peaks in $\sigma\ (e^+ e^-)$ $\sigma\ (e^+ e^- \to DD, DD^*, D^*D^*)$

Y(4008) Y(4260) Y(4360) Y(4660)

Y(4260) hybrid ccG state ?

Close, Page, Pene, Kou....

cc 1^{--} hybrid at mass ~ 4.2 GeV expected

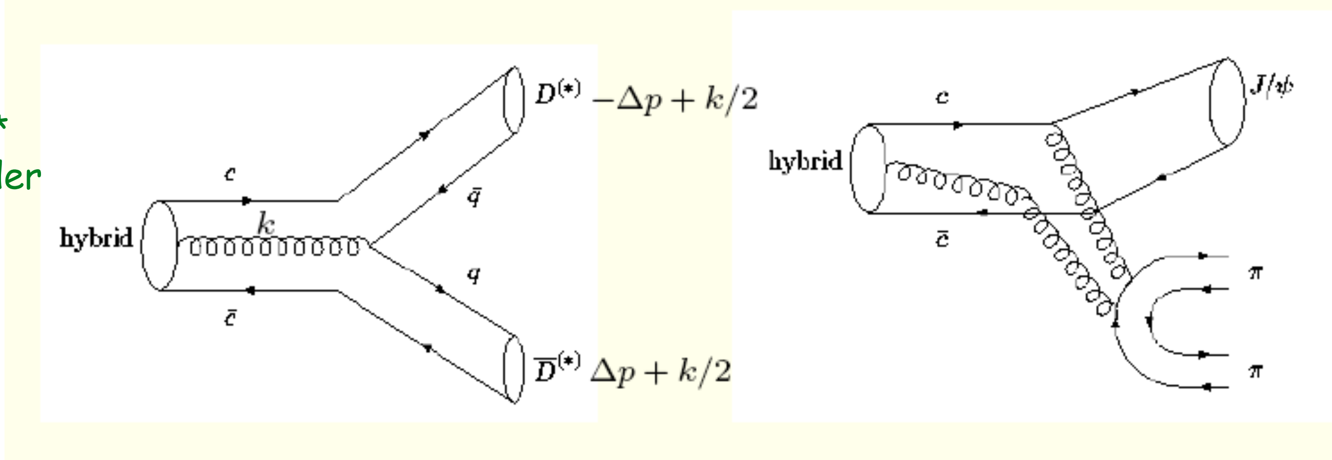
large couplings to modes with hidden flavour $\psi_h \rightarrow (c\bar{c})(gg) \rightarrow (c\bar{c})(\pi\pi,\ldots)$

Y(4260) -> J/ψ η', χ_{cJ} η' at the limits of the phase space

decays in S wave + P wave open charm states expected

Y(4260) -> $D\,D'_1$ (Y below $D\,D_1$ threshold)

decays in DD and D*D* forbidden at leading order



corresponding state expected in the bb system: Belle observes an anomalous enhancement in Y(1S) π^+ π^- at 10870 MeV

Y(4260) as a candidate $(\bar{c}\bar{s})\ (cs)$ tetraquark

(two scalar diquarks with L=1)

Maiani et al.

Y(4260) -> $D_s\ \bar{D}_s$ expected

partners with other light quarks not observed

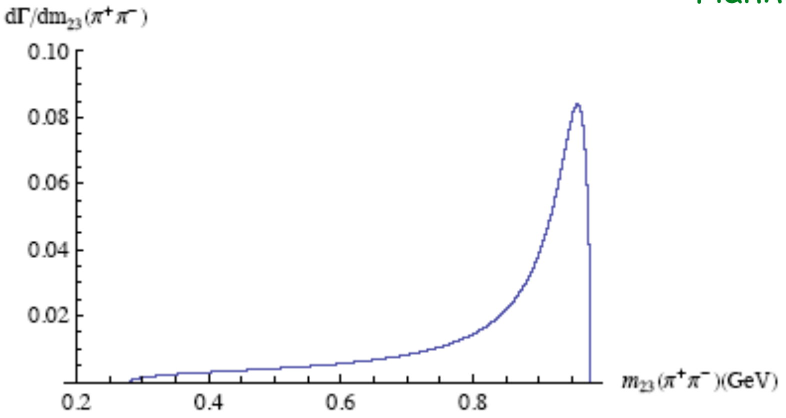
observation in $D_s\ D_s$ or $D\ D'_1$ could discriminate

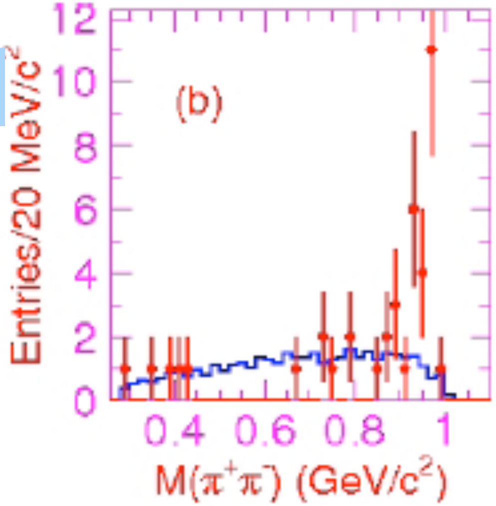
issues:

- interpretations only for Y(4260)
- are all new vector mesons alike?

Y(4660) a candidate ψ(2S) f_0(980) molecule?

Hanhart et al.





Weinberg formula for Y to ψ(2S) f_0(980) coupling

$$g^2 = (2\pi)^3\left(\frac{2M_Y}{\mu}\right)^2\frac{1}{2\pi^2}\mu^2\sqrt{\frac{2B}{\mu}}$$

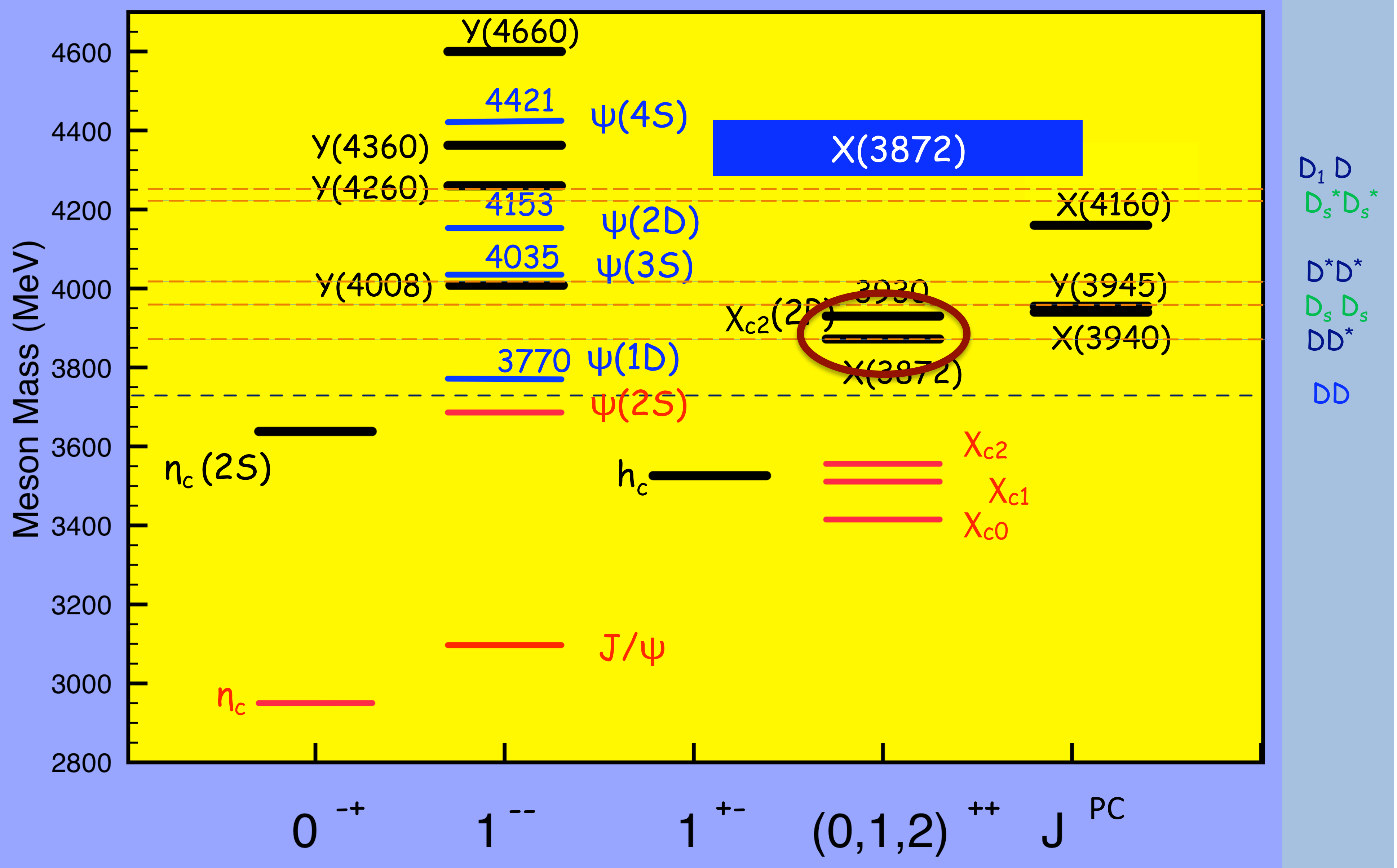
← binding energy

← reduced mass

$$\Gamma_{TH} = 43\ \text{MeV}$$

$$\Gamma_{\exp} = 48 \pm 15\ \text{MeV}$$

charmonium


Meson Mass (MeV)
4600
4400
4200
4000
3800
3600
3400
3200
3000
2800
Y(4660)
4421
ψ(4S)
Y(4360)
Y(4260)
4153
ψ(2D)
4035
ψ(3S)
Y(4008)
3770
ψ(1D)
ψ(2S)
J/ψ
η_c (2S)
η_c
h_c
χ_c2(2P)
3930
X(3872)
X(3872)
χ_c2
χ_c1
χ_c0
X(4160)
Y(3945)
X(3940)
D_1 D
D_s^* D_s^*
D^*D^*
D_s D_s
DD^*
DD
0 -+
1 --
1 +-
(0,1,2) ++
J PC

X(3872)

Belle, CDF,D0,BaBar, LHCb, CMS

$$M(X) = 3871.68 \pm 0.17 \;\; MeV$$
$$\Gamma(X) < 1.2 \;\; MeV \quad (90\% \; CL)$$
$$\left[\; \Gamma(X) = 3.0^{+4.6}_{-2.3} \pm 0.9 \quad MeV \right]$$

BaBar

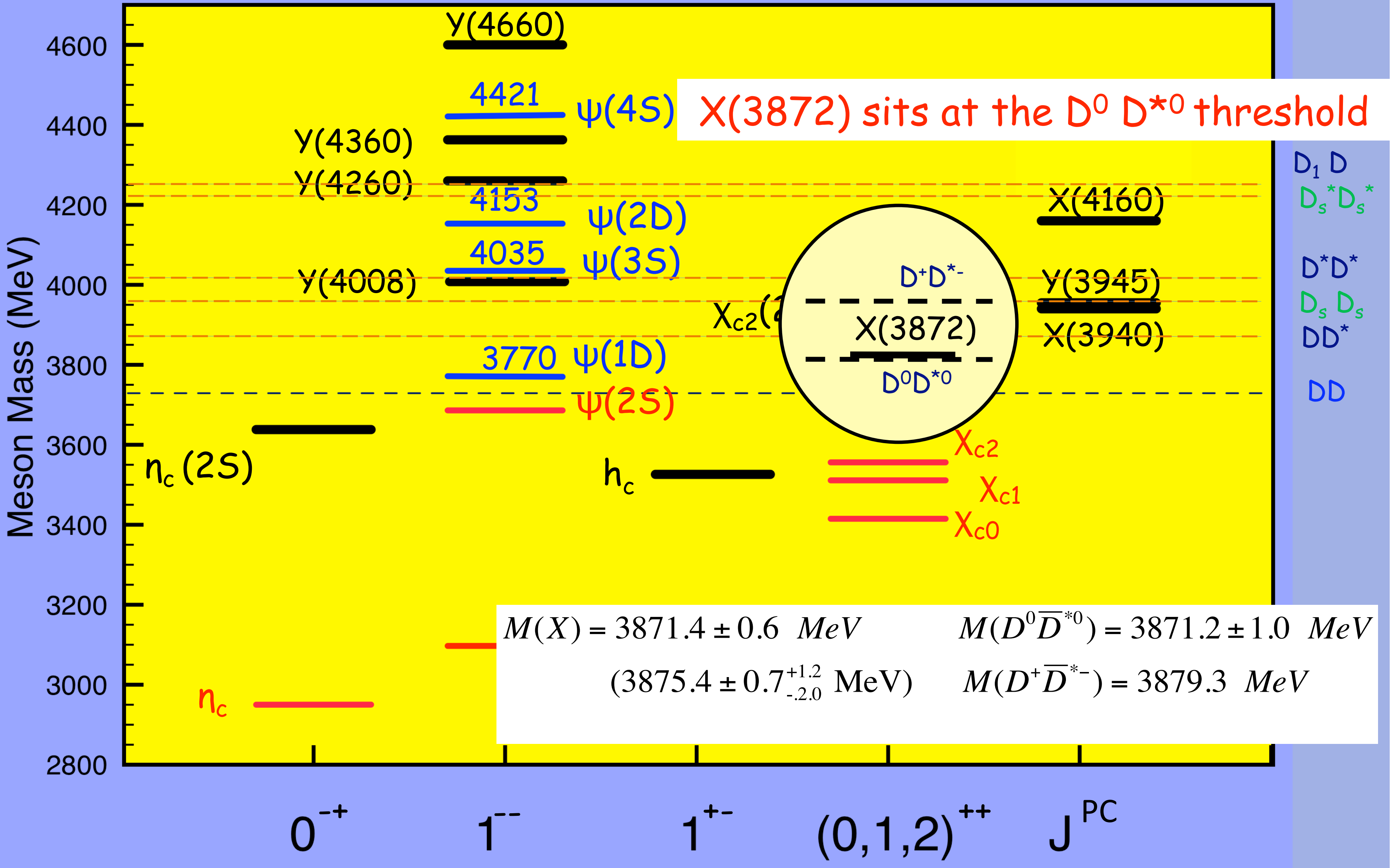
- narrow structure in $J/\psi \; \pi^+ \pi^-$ mass distribution
- $\pi^+ \pi^-$ spectrum peaked at large mass
- no evidence of charged partners X^-, X^+
- $B(B^0 \to K^0 \;\; X \;) / B(B^+ \to K^+ \;\; X \;) = 0.50 \pm 0.30 \pm 0.05$
- not observed in e^+e^-
- $\dfrac{B(X \to J/\psi \; \pi^+\pi^-\pi^0)}{B(X \to J/\psi \; \pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$ G-parity violation
- $\dfrac{B(X \to J/\psi \; \gamma)}{B(X \to J/\psi \; \pi^+\pi^-)} = 0.14 \pm 0.05$ C=+1
- most likely $J^P = 1^{++}$ $J^P = 2^{-+}$
- observed in $X \to D^0 \; \overline{D}^0 \; \pi^0$
- observed in $X \to \psi(2S)\gamma$

$$B(B^\pm \to K^\pm \;\; X \;) B(X \to \psi(2S)\gamma \;) = (9.9 \pm 2.9 \pm 0.9) \times 10^{-6}$$
$$B(B^\pm \to K^\pm \;\; X \;) B(X \to J/\psi\gamma \;) = (2.8 \pm 0.8 \pm 0.2) \times 10^{-6}$$

$$M(X) = 3875.4 \pm 0.7^{+1.2}_{-2.0} \quad MeV$$
$$\frac{B(X \to D^0\overline{D}^0\pi^0 \;)}{B(X \to J/\psi\pi^+\pi^-)} = 9 \pm 4$$

Belle Coll.,

charmonium



X(3872) sits at the D^0 D^{*0} threshold

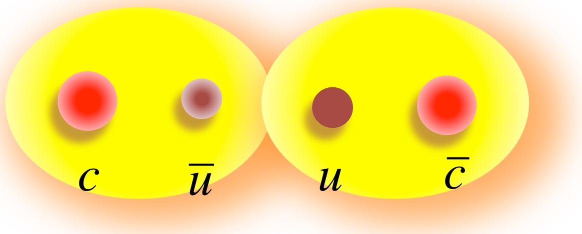
$M(X) = 3871.4 \pm 0.6 \ \ MeV$

$(3875.4 \pm 0.7^{+1.2}_{-2.0} \text{ MeV})$

$M(D^0\overline{D}^{*0}) = 3871.2 \pm 1.0 \ \ MeV$

$M(D^+\overline{D}^{*-}) = 3879.3 \ \ MeV$

X(3872): moleculear option



$M(X) = 3871.4 \pm 0.6\ MeV$

$(3875.4 \pm 0.7^{+1.2}_{-2.0}$ MeV)

$M(D^0\overline{D}^{*0}) = 3871.2 \pm 1.0\ MeV$

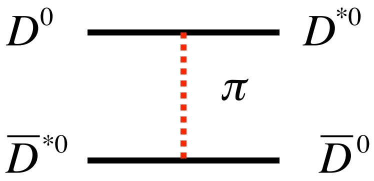
$M(D^+\overline{D}^{*-}) = 3879.3\ MeV$

$M(\rho^0 J/\psi) = 3867.9\ MeV$

$M(\omega J/\psi) = 3879.5\ MeV$

X(3872) sits at the $\bar{D}^0$ D^{*0} threshold

binding induced by light hadron exchange



no $D\bar{D}$ molecules

X essentially $D^0 \bar{D}^{*0} + \bar{D}^0 D^{*0}$ (S wave) molecule with $J^{PC} = 1^{++}$

$$|X\rangle = a\left|D^0\overline{D}^{*0} + \overline{D}^0 D^{*0}\right\rangle + b\left|D^+D^{*-} + D^-D^{*+}\right\rangle + \dots$$

- not definite I

- resonances in the modes $D^+ D^{*-}$ not observed -> repulsive interaction

Voloshin

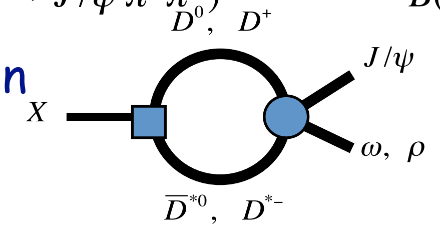
$X \to D^0 D^0 \gamma$ dominant with respect to $X \to D^+ D^- \gamma$

X(3872): charmonium option

- Isospin breaking: severe ps suppression

$$\frac{B(X \to J/\psi\,\pi^+\pi^-\pi^0)}{B(X \to J/\psi\,\pi^+\pi^-)} \cong 1.0 \to \frac{A(X \to J/\psi\,\rho^0)}{B(X \to J/\psi\,\omega)} \cong 0.2$$

D^0 , D$^+$ mass difference also violates isospin



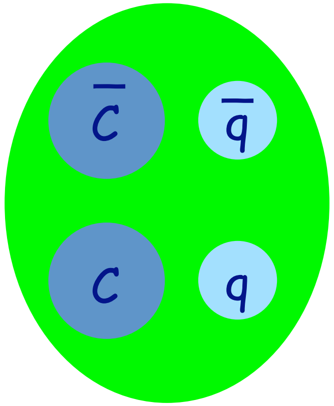
X(3872)-> ψ(2S) γ   dominant with respect to   X(3872)-> J/ψ γ

De Fazio

$$B(B^\pm \to K^\pm \; X \;)B(X \to \psi(2S)\gamma \;) = (9.9 \pm 2.9 \pm 0.9) \times 10^{-6}$$

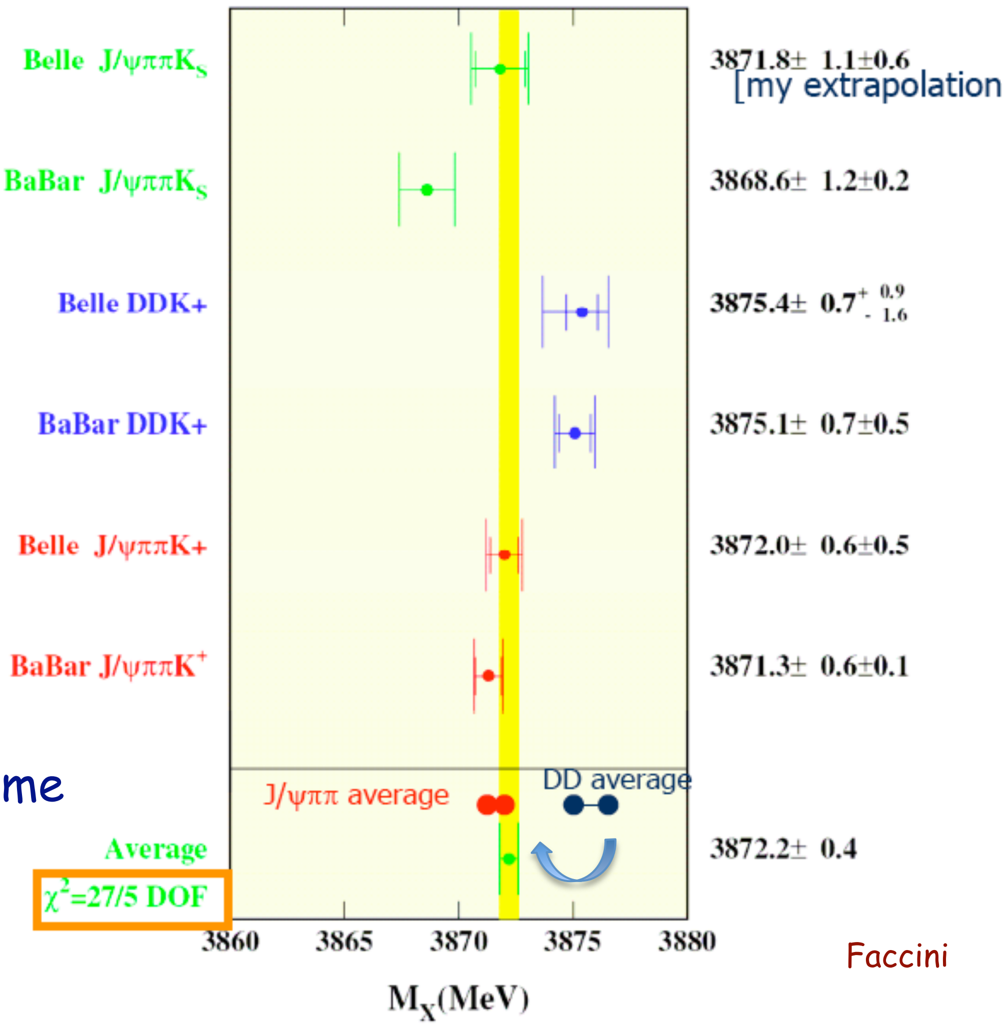
$$B(B^\pm \to K^\pm \; X \;)B(X \to J/\psi\gamma \;) = (2.8 \pm 0.8 \pm 0.2) \times 10^{-6}$$

four quark option Maiani et al.



many states predicted
in the multiquark picture

signal in D^0 D^0 π^0 manifestation of the same resonance?



Faccini

new possible $J^{PC} = 2^{-+}$ assignment

X(3872) a puzzling state

charged mesons with hidden charm $Z(4430)^+$ $Z_2(4248)^+$ $Z_1(4051)^+$

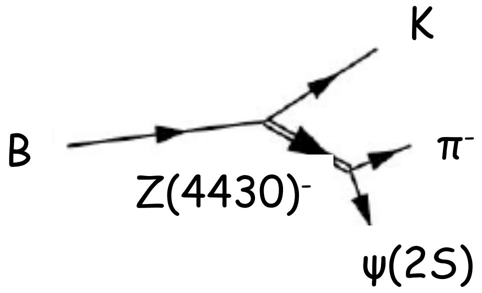
Belle Collaboration

$Z(4430)^+$

Dalitz plot analysis of $B \to Z^- K$, $Z^- \to \psi(2S)\pi^-$

$M = 4433 \pm 4 \pm 2$ MeV

$\Gamma = 45 \pm 22 \pm 33$ MeV



$Z_1(4051)^+$ $Z_2(4248)^+$

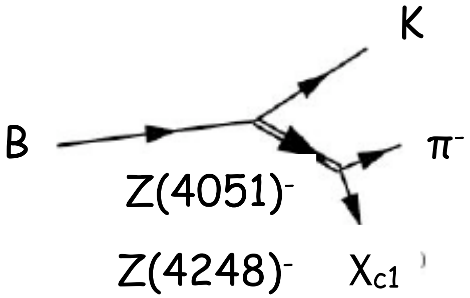
Dalitz plot analysis of $B \to Z^- K$, $Z^- \to \chi_{c1}\pi^-$

$M_1 = 4051 \pm 14 \pm 46$ MeV

$\Gamma_1 = 82 \pm 27 \pm 52$ MeV

$M_2 = 4248 \pm 53 \pm 184$ MeV

$\Gamma_2 = 177 \pm 67 \pm 322$ MeV



not confirmed by BaBar in the same Dalitz plots

charged mesons with hidden charm $Z(4430)^+$ $Z_2(4248)^+$ $Z_1(4051)^+$

evidence of exotic meson?

- the existence of exotic (non $Q\bar{Q}$) mesons has been argued long ago
- candidates in the light quark sector
- quark content of $Z(4430)^+$: $(c\bar{c}u\bar{d})$

Proposed interpretations

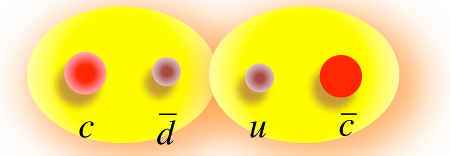
- bound state of two heavy-light diquarks (tetraquark)
  (first radial excitation of the lightest 1^+ tetraquark)

$$q\bar{q} \Rightarrow Q_D\bar{Q}_D$$

$$Q_D \equiv \text{diquark, two quarks bound in color } 3^*$$

$$\text{spin 0 diquark } [qq]_0 \Rightarrow \varepsilon_{ijk}\varepsilon_{\alpha\beta\gamma}\bar{q}_C^{j\beta}\gamma_5 q^{k\gamma}$$

- bound state of one axial and one vector meson with open charm (molecule)



- non exotic effect: cusp of one axial and one vector meson with open charm charged mesons with hidden charm $Z(4430)^+$ $Z_2(4248)^+$ $Z_1(4051)^+$

charged mesons with hidden beauty $Z_b(10610)^+$ $Z_b(10650)^+$

evidence of new structures or experimental artifacts ?

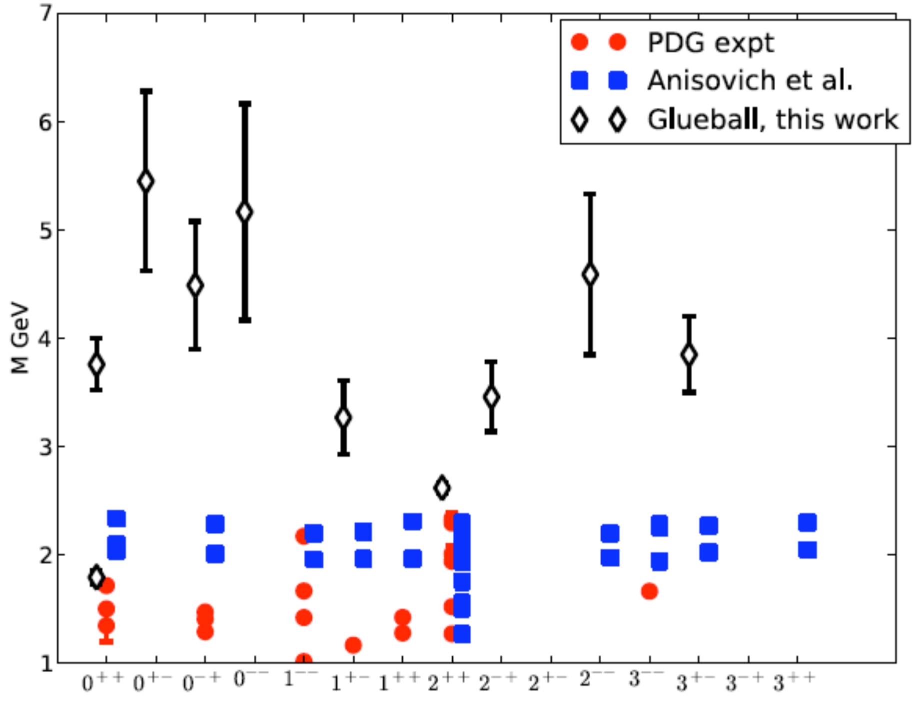
the formulation of a theory (based on QCD) of multiquark/multihadron configurations is an outstanding issue

a data-driven point of view is at present unavoidable

the observation of charged states with hidden charm (and beauty) must be confirmed; the possibility of having discovered signals of a new spectroscopy is a compelling reason for further studies

elusive light glueballs and hybrids

existence of glueballs is a QCD prediction obtained in many different ways



lattice QCD Gregory et al., 1208.1858

AdS/CFT

remarkable connection conjectured between certain string theory in certain curved space-times and certain field theories in flat (3+1) dimensional space-time

this is the so called AdS/CFT (Anti De Sitter/Conformal Field Theory) correspondence conjecture (or Maldacena conjecture)

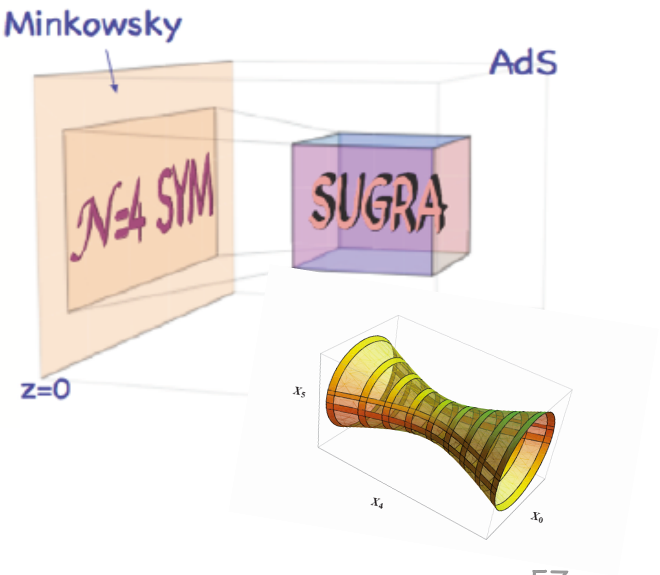
generalization of this idea useful for strong interaction physics

- gauge theories
- strong coupling regime: $g^2_{YM} N_c \gg 1$

AdS/CFT correspondence

Maldacena
Gubser Klebanov Polyakov
Witten

equivalence (duality) between a gravity theory defined in $AdS_{d+1} \times C$ (C a compact manifold) and a conformal field theory (CFT) defined on the boundary of AdS_{d+1} (M_d)



light glueballs

- dilaton background fixed by the vector meson spectrum
- glueball operators - bulk fields correspondence according to the AdS/CFT rules

scalar glueball $J^{PC} = 0^{++}$

4D		5D
$O = Tr\,(F^2)$		$X(x,z)$
$\Delta = 4$		$m_5^2 = 0$
	AdS$_5$ metric	$g_{MN} = e^{2A(z)}\eta_{MN}$ $\quad A(z) = \ln\frac{R}{z}$
	back. dilaton	$\varphi(z) = c^2\, z^2$
	action	$S = -\frac{1}{2k}\int d^5x\sqrt{\lvert g\rvert}\; e^{-\varphi(z)}\; g^{MN}\partial_M X\partial_N X$
	field eq.	$\partial_M\left[\sqrt{\lvert g\rvert}e^{-\varphi(z)}g^{MN}\partial_N X(x,z)\right] = 0$

Regge-like spectrum $\quad m_n^2 = 4c^2(n+2)$

$$m_{0^{++}}^2 = 2m_\rho^2$$

light glueballs

De Fazio, Nicotri, Jugeau, PC

$J^{PC}=0^{-+}$	4D	5D
	$O=Tr(F\tilde{F})$ $\Delta=4$	$Y(x,z)$ $m_5^2=0$

spectrum $m_n^2=4c^2(n+2)$

$J^{PC}=1^{--}$	4D	5D
	$O=Tr(F(DF)F)$ $\Delta=7$ Landau-Yang-Pomeranchuk	$A_M(x,z)$ $m_5^2=24$

spectrum $m_n^2=4c^2(n+3)$

$$m_{0^{++}}^2=2m_\rho^2$$
$$m_{0^{-+}}^2=m_{0^{++}}^2$$
$$m_{1^{--}}^2=3m_\rho^2$$

glueballs ARE PRESENT in the hadron spectrum
their search must continue

in the meanwhile, interesting news on light hybrids:

- CLEO: exotic 1^{-+} $\eta'\pi$ P wave state observed in $\chi_{c1} \to \underbrace{\eta' \pi^{+}}_{\pi(1600)} \pi^{-}$ PRD84(11)112009

- COMPASS: exotic 1^{-+} state observed in $\pi^{-}\pi^{-}\pi^{+}$ $\pi(1600)$ PRL104(10)241803

Conclusions

hadron spectroscopy is not a closed topic

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

a lot of th. and exp. work still required