New charm/onium spectroscopy

Issue: quark structure of a number of states
(>10) discovered in $c\bar{q}$ and $c\bar{c}$ systems
in the last few years (months)

Indications of Exotic Mesons?

Pietro Colangelo - INFN - Bari
"Continuous Advances in QCD" - Minneapolis, 11-14 May 2006

Madamina, il catalogo e' questo....

$D_{sJ}^{*}(2317)$

$D_{sJ}(2460)$

$D_{sJ}(2632)$

$D^{*}_{0}(2308)$

$D'_{1}(2440)$

$X(3872)$

$X(3943)$

$Y(3943)$

$Z(3930)$

$Y(4260)$

h_c

η'_c

$\Upsilon(1D)$

$\Theta(1540)^{+}$

$\Theta_c(3099)$

$\Xi_{cc}(3518)$ ...

Madamina, il catalogo e' questo....

$D_{sJ}^{*}(2317)$

$D_{sJ}(2460)$

$D_{sJ}(2632)$ — Selex $c\bar{s}$ state

$D^{*}_{0}(2308)$ — not seen by BaBar, Belle, Cleo

$D'_{1}(2440)$

$X(3872)$

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h_c

η'_c

$\Upsilon(1D)$

$\Theta(1540)^{+}$ — pentaquarks — not confirmed by CLAS

$\Theta_c(3099)$ — not seen at the B factories

$\Xi_{cc}(3518)$ ...

Madamina, il catalogo e' questo....

$D_{sJ}^{*}(2317)$

$D_{sJ}(2460)$

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} open charm mesons

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η'_c

} hidden charm mesons

$\Upsilon(1D)$

~~$\Theta(1540)^{+}$~~

~~$\Theta_c(3099)$~~

$\Xi_{cc}(3518)$ ...

New mesons with open charm

$D_{sJ}^{*}(2317)$

$D_{sJ}(2460)$

$D^{*}_{0}(2308)$

$D'_{1}(2440)$

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

$$L=0 \to \begin{cases} J=1 \\ J=0 \end{cases} \quad (s_\ell^P = \frac{1}{2}^-) \quad \begin{cases} D^*, D_s^* \\ D, D_s \end{cases} \qquad L=1 \to \begin{cases} J=1 \\ J=0 \end{cases} \quad (s_\ell^P = \frac{1}{2}^+) \quad \begin{cases} J=2 \\ J=1 \end{cases} \quad (s_\ell^P = \frac{3}{2}^+) \quad \begin{cases} D_2^*, D_{s2}^* \\ D_1, D_{s1} \end{cases}$$

$\frac{1}{2}^+ \to \frac{1}{2}^- + \pi\,(K)$: 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 $\quad \Gamma(D_2^*(2460)) = 46\ MeV$

finite m_Q corrections

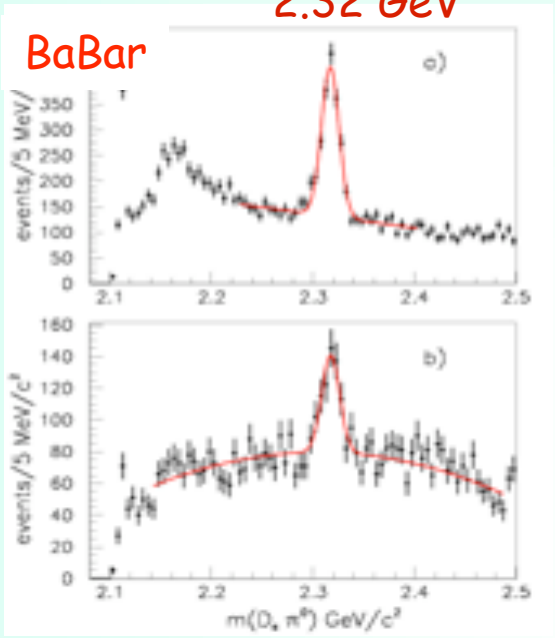
- remove degeneracy between the states of the same doublet
- induce a mixing between the two 1^+ states

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

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

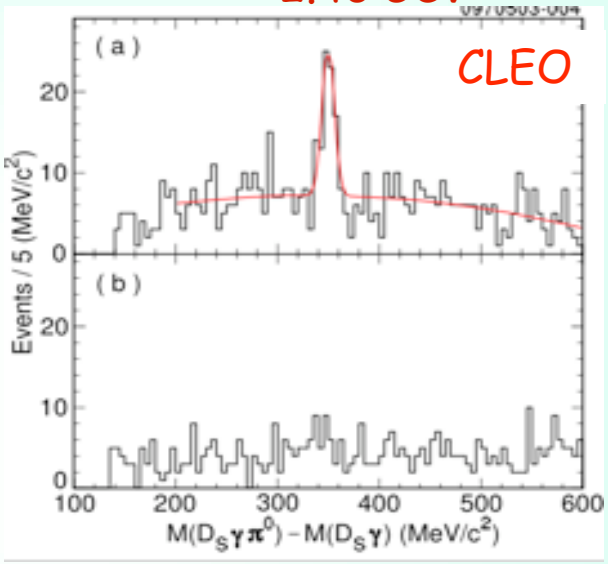
2.32 GeV

BaBar



2.46 GeV

CLEO



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

$M = 2317.4 \pm 0.6 \ \ MeV$

$\Gamma < 3.8 \ \ MeV$

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

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

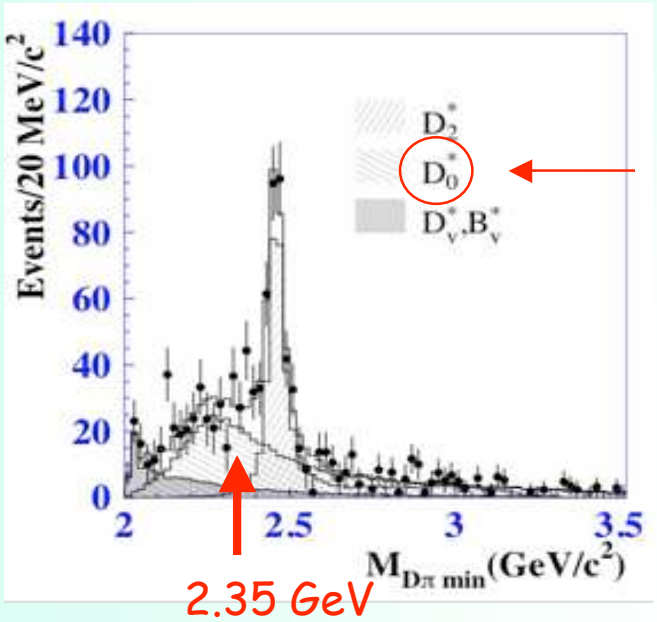
$M = 2458.8 \pm 1.0 \ \ MeV$

$\Gamma < 3.5 \ \ MeV$

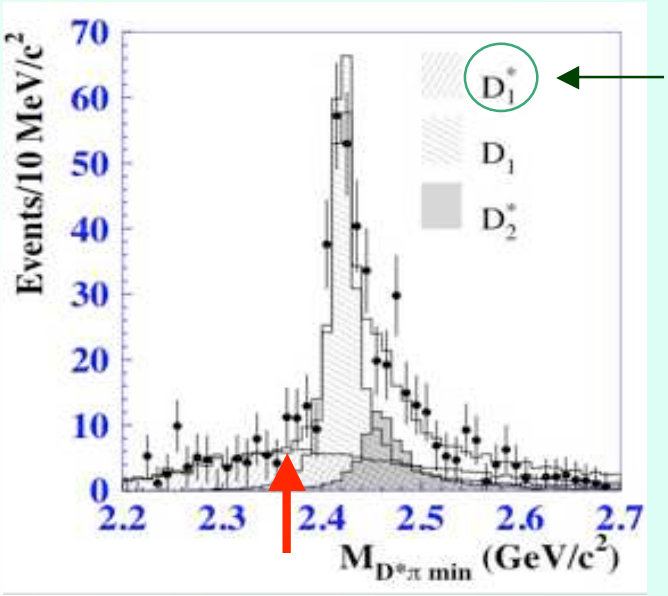
below D*K threshold
$M(D^*)+M(K)=2510$ MeV

also found by Belle and Focus

broad resonances in D π , D* π



Belle



$$M(D_0^*) = 2351 \pm 27 \;\; MeV$$
$$\Gamma(D_0^*) = 262 \pm 51 \;\; MeV$$

$$M(D_1') = 2427 \pm 36 \;\; MeV$$
$$\Gamma(D_1') = 384 \pm 130 \;\; MeV$$

also studied by Focus and CLEO

the two broad D_J and narrow D_{sJ} states identified as the $J^P=(0^+,1^+)$ $c\bar{q}$ and $c\bar{s}$ states with L=1

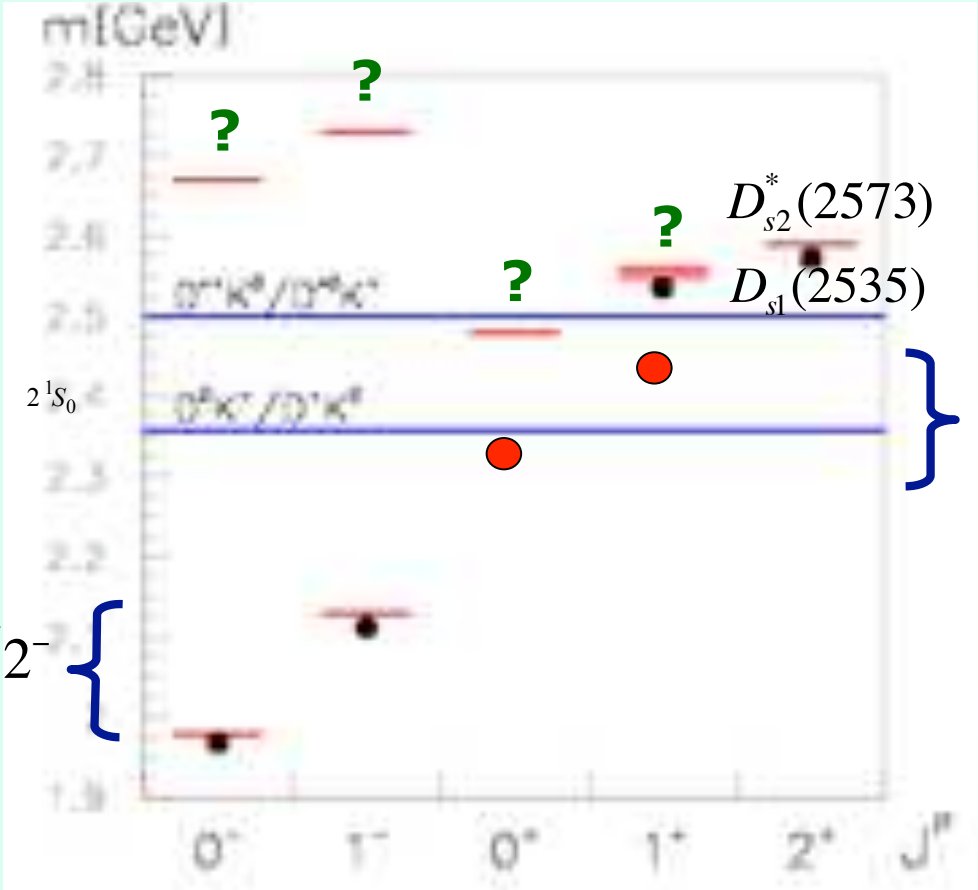
the problem is the mass predictions:
potential models predict all four $c\bar{s}$ L=1 states massive enough to decay to DK or D*K

non $q\bar{q}$ structure?

proposals for $D^*_{sJ}(2317)$:

D_s-pion atom
mixture with 4-quark state above DK threshold
tetraquark
dynamically generated resonance
DK molecule

$c\bar{s}$



$j^P = 3/2^+$

$j^P = 1/2^+$

$j^P = 1/2^-$

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

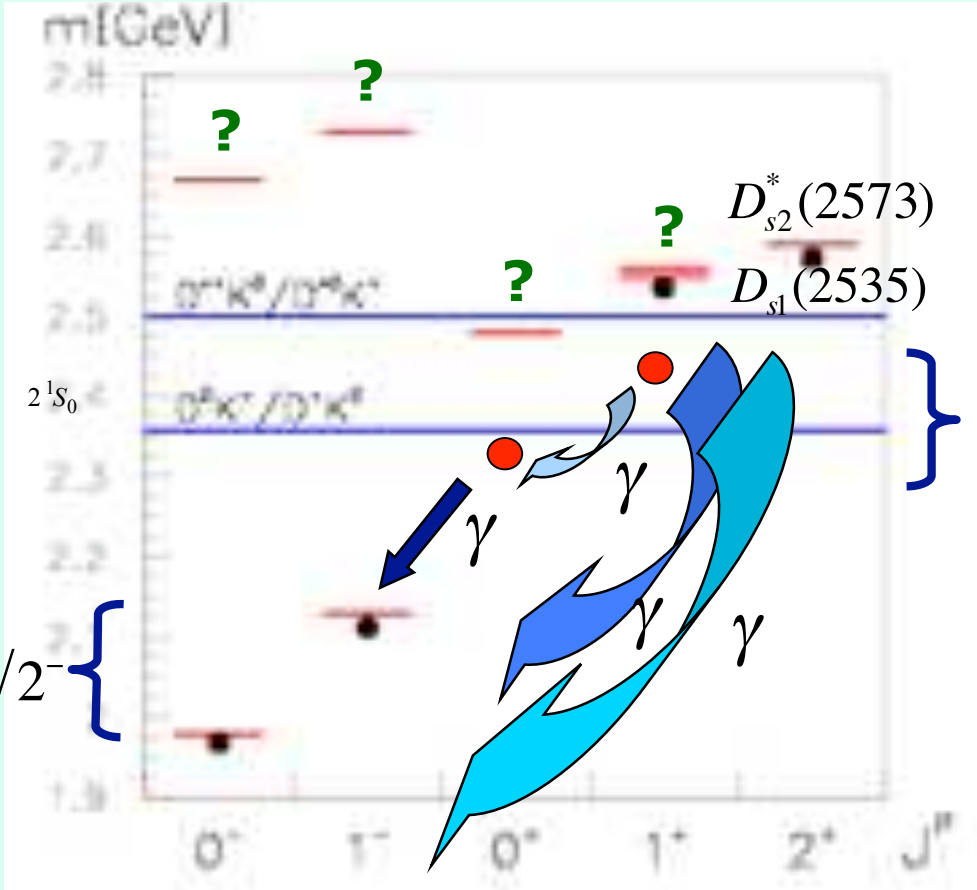
isospin violating pion emission

radiative

2-pion emission

in all cases the widths are narrow

$c\bar{s}$



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$j^P = 1/2^-$

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

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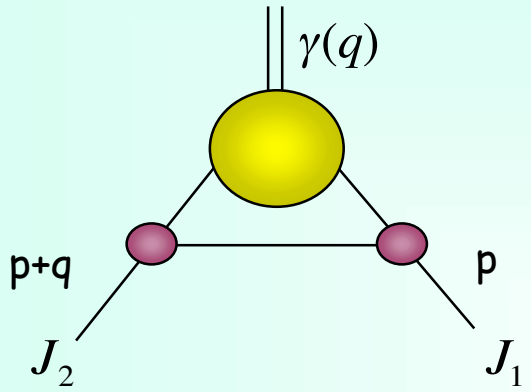
in all cases the widths are narrow

radiative transitions are an important probe to distinguish among different structures

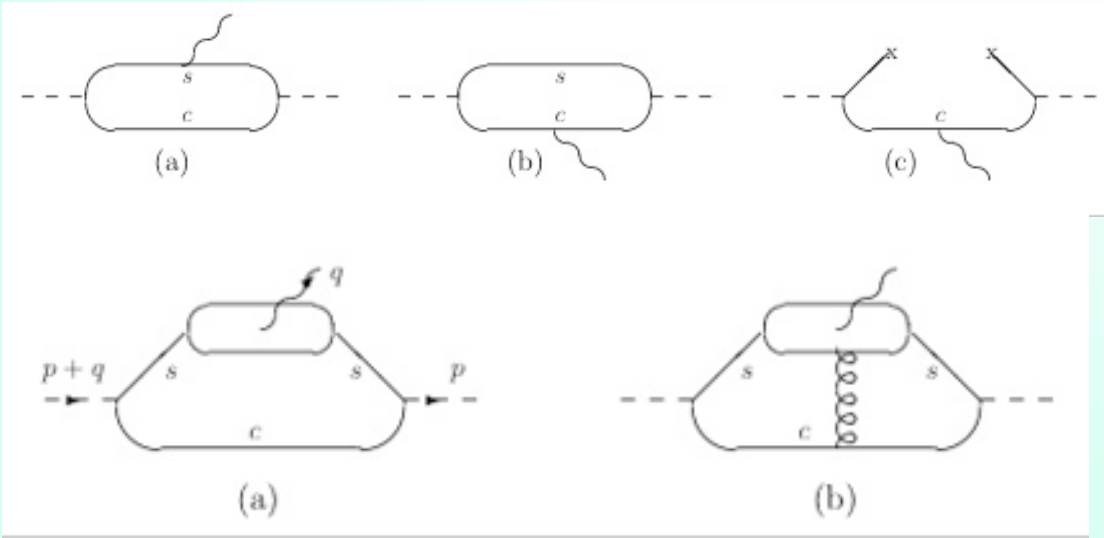
radiative decays of D_{sJ} mesons by light-cone QCD sum rules



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

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

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

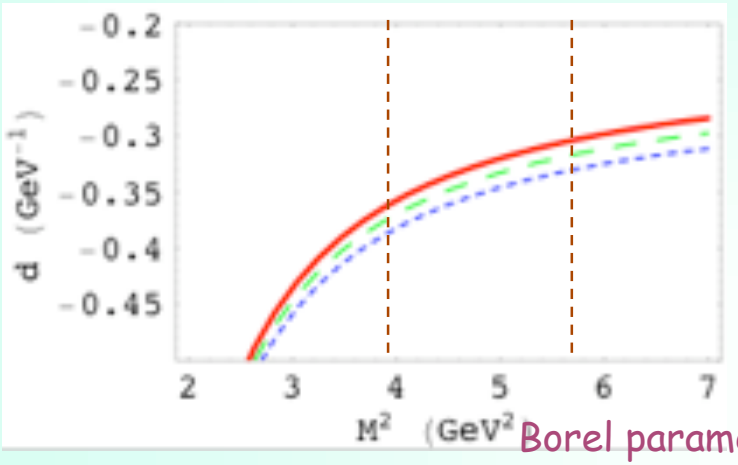


light-cone photon distribution amplitudes of different twist involved

Balitsky, Braun
Ball, Braun, Kivel

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

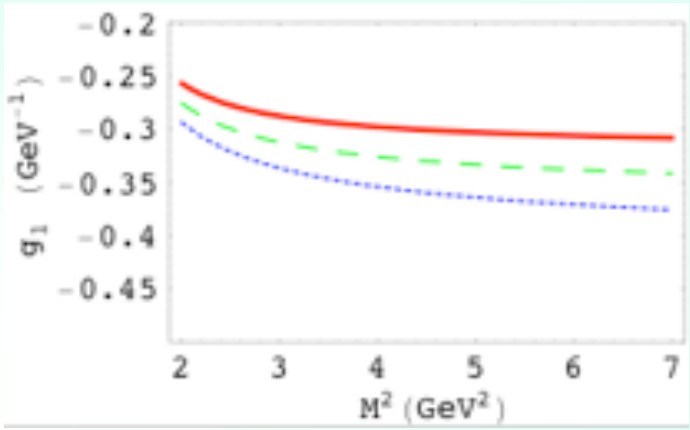
$$\left\langle \gamma(q,\varepsilon) D_s^*(p,\eta) \middle| D_{s0}^*(p+q) \right\rangle = e\, d\, (\varepsilon^* \eta^*\, pq - \varepsilon^* p\, \eta^* q)$$



Borel parameter

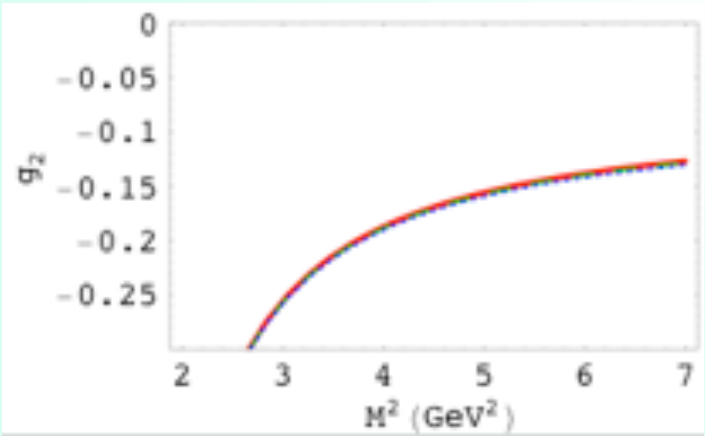
$$\Gamma(D_{s0}^* \to D_s^* \gamma) = (4-6)\ keV$$

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



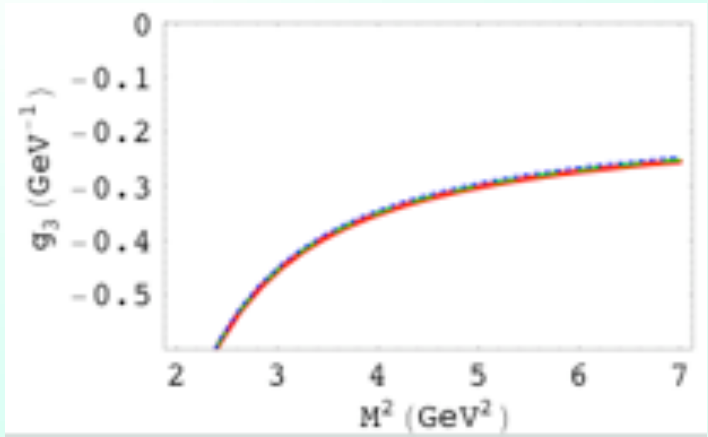
$$\Gamma(D_{s1}^{'} \to D_s \gamma) = (19-29)\ keV$$

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



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

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



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

Initial state	Final state	LCQSR	VMD [2, 3]	QM [5]	QM [6]
$D_{sJ}^*(2317)$	$D_s^*\gamma$	4-6	0.85	1.9	1.74
$D_{sJ}(2460)$	$D_s\gamma$	19-29	3.3	6.2	5.08
	$D_s^*\gamma$	0.6-1.1	1.5	5.5	4.66
	$D_{sJ}^*(2317)\gamma$	0.5-0.8	—	0.012	2.74

$(m_c \to \infty)$

De Fazio, Ozpineci, PC PRD72,074004

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

what about hadronic decays?

HQET+chiral symmetry

Effective QCD Lagrangian describing interactions of heavy-light mesons with pseudo-Goldstone bosons

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

fields describing negative and positive parity $\bar{q}Q$ mesons

$$H_a = \frac{1+\not{v}}{2}\left[P_a^{*\mu}\gamma_\mu - P_a\gamma_5\right] \qquad j^P = 1/2^-$$

$$S_a = \frac{1+\not{v}}{2}\left[D_a^{*\mu}\gamma_\mu\gamma_5 - D_a\right] \qquad j^P = 1/2^+$$

$$T^\mu{}_a = \frac{1+\not{v}}{2}\left[D_{2a}^{\mu\nu}\gamma_\nu - \sqrt{\frac{2}{3}}D_{1a}^\nu\left(g_\nu^\mu - \frac{1}{3}\gamma_\nu\left(\gamma^\mu - v^\mu\right)\right)\right] \qquad j^P = 3/2^+ \text{ doublet}$$

v meson four-velocity

fields describing light pseudoscalar mesons

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

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

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

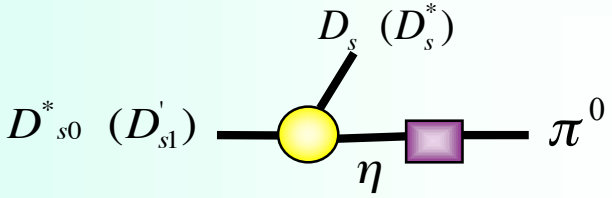
$$\begin{aligned} L = \; & i\,Tr\left\{H_b v^\mu D_{\mu ba}\bar{H}_a\right\} + \frac{f^2}{8}Tr\left\{\partial^\mu\Sigma\partial_\mu\Sigma^+\right\} + Tr\left\{S_b(iv^\mu D_{\mu ba} - \delta_{ba}\Delta_S)\bar{S}_a\right\} + Tr\left\{T^\mu{}_b(iv^\nu D_{\nu ba} - \delta_{ba}\Delta_T)\bar{T}_{\mu a}\right\} \\ & + i\,g\,Tr\left\{H_b\gamma^\mu\gamma_5 A_{\mu ba}\bar{H}_a\right\} + i\,g'\,Tr\left\{S_b\gamma^\mu\gamma_5 A_{\mu ba}\bar{S}_a\right\} + (i\,h\;Tr\left\{S_b\gamma^\mu\gamma_5 A_{\mu ba}\bar{H}_a\right\} + hc) \\ & + (i\,\frac{h_1}{\Lambda_\chi}\;Tr\left\{T^\mu{}_b\gamma^\lambda\gamma_5(D_\mu A_{\lambda ba})\bar{H}_a\right\} + hc) + (i\,\frac{h_2}{\Lambda_\chi}\;Tr\left\{T^\mu{}_b\gamma^\lambda\gamma_5(D_\lambda A_{\mu ba})\bar{H}_a\right\} + hc) \end{aligned}$$

couplings: g between $j^P = 1/2^-$ states, g' between $j^P = 1/2^+$, $h_{1,2}$ between $1/2^-$ and $3/2^+$
h between $1/2^-$ and $1/2^+$:

$h \cong -0.56$ by light-cone QCD sum rules

isospin violation enters in low energy lagrangian of pseudoscalar mesons through the mass term

$$L_{mass} = \frac{\tilde{\mu} f^2}{4} Tr\left[\xi\, m_q\, \xi + \xi^+\, m_q\, \xi^+\right] \qquad m_q = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix} \qquad L_{mixing} = \frac{\tilde{\mu}}{2} \frac{m_d - m_u}{\sqrt{3}} \pi^0 \eta$$



$$\frac{\Gamma(D^*_{s0} \to D^*_s \gamma)}{\Gamma(D^*_{s0} \to D_s \pi^0)}\Big|_{HQET} \cong 0.1$$

De Fazio, PC PLB570, 180

	width (th)	width (exp)
$D_0^*(2308)$	390+/-80 MeV	262 +/- 51 MeV
$D'_1(2440)$	240+/-40 MeV	384 +/-130 MeV

$D_{sJ}^*(2317)$, $D_0^*(2308)$, $D_{sJ}(2460)$, $D'_1(2440)$ conventional $c\bar{s}$, $c\bar{q}$ states

predictions for beauty

	$B^*_{(s)0}(0^+)$	$B'_{(s)1}(1^+)$	$B_{(s)1}(1^+)$	$B^*_{(s)2}(2^+)$
$b\bar{q}$	5.70 ± 0.025 GeV	5.75 ± 0.03 GeV	5.774 ± 0.002 GeV	5.790 ± 0.002 GeV
$b\bar{s}$	5.71 ± 0.03 GeV	5.77 ± 0.03 GeV	5.877 ± 0.003 GeV	5.893 ± 0.003 GeV

M(BK)=5.773 GeV M(B^*K)=5.819 GeV

narrow peaks in the $B_s\,\pi^0$, $B^*_s\,\pi^0$, $B_s\gamma$, $B^*_s\gamma$ mass distributions

$\Gamma\,(B_{s0}) = 10.5$ KeV $\Gamma\,(B'_{s1}) = 11$ KeV

observable at the hadron colliders

Are S and P s_l=1/2 mesons chiral partners?

Bardeen, Eichten, Hill
Nowak

$s_\ell^P = \frac{1}{2}^{\pm}$ mesons collected in supermultiplets

$\Delta_S = g_\pi f_\pi$ GT relation $\Delta_S = M(D_s(0^+)) - M(D_s(0^-))$

$M(D_s(1^+)) - M(D_s(0^+)) = M(D_s(1^-)) - M(D_s(0^-))$ symmetry relation

	$c\bar{q}$	$c\bar{s}$	$b\bar{q}$	$b\bar{s}$
λ_H	$(261.1 \pm 0.7\ \text{MeV})^2$	$(270.8 \pm 0.8\ \text{MeV})^2$	$(247 \pm 2\ \text{MeV})^2$	$(252 \pm 10\ \text{MeV})^2$
λ_S	$(265 \pm 57\ \text{MeV})^2$	$(291 \pm 2\ \text{MeV})^2$		
λ_T	$(259 \pm 10\ \text{MeV})^2$	$(266 \pm 6\ \text{MeV})^2$		
$\bar{M}_H$	1974.8 ± 0.4 MeV	2076.1 ± 0.5 MeV		
$\bar{M}_S$	2397 ± 28 MeV	2424 ± 1 MeV		
$\bar{M}_T$	2445.1 ± 1.4 MeV	2558 ± 1 MeV		
Δ_S	422 ± 28 MeV	348 ± 1 MeV		
Δ_T	470.3 ± 1.5 MeV	482 ± 1 MeV		

$$\lambda_H = \frac{1}{8}[M^2(D_{(s)}(1^-)) - M^2(D_{(s)}(0^-))]$$

$$\lambda_S = \frac{1}{8}[M^2(D_{(s)}(1^+)) - M^2(D_{(s)}(0^+))]$$

$\lambda_S \neq \lambda_H$

De Fazio, Ferrandes, PC
PLB634, 235

New mesons with hidden charm

η'_c

h_c

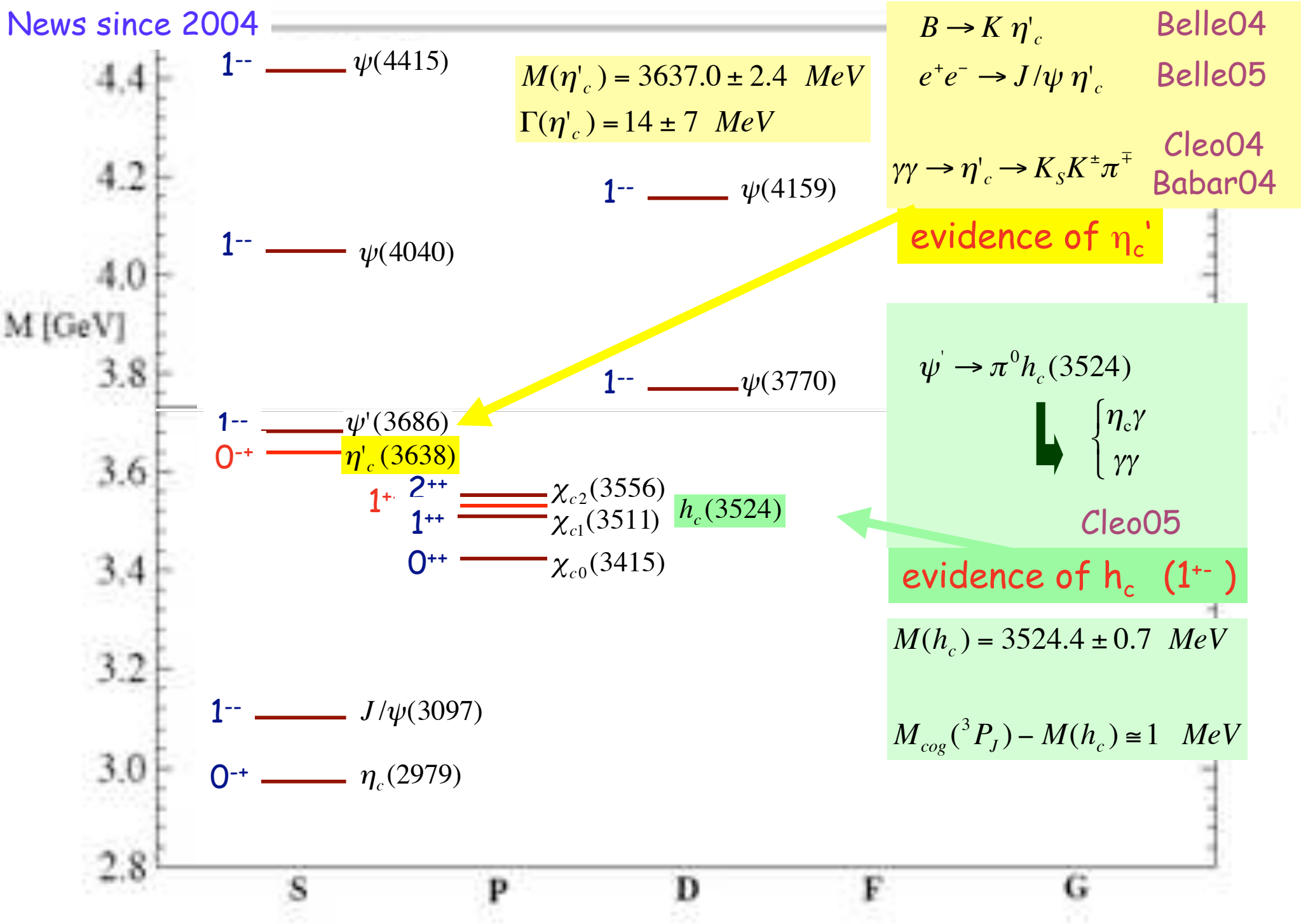
X(3943)

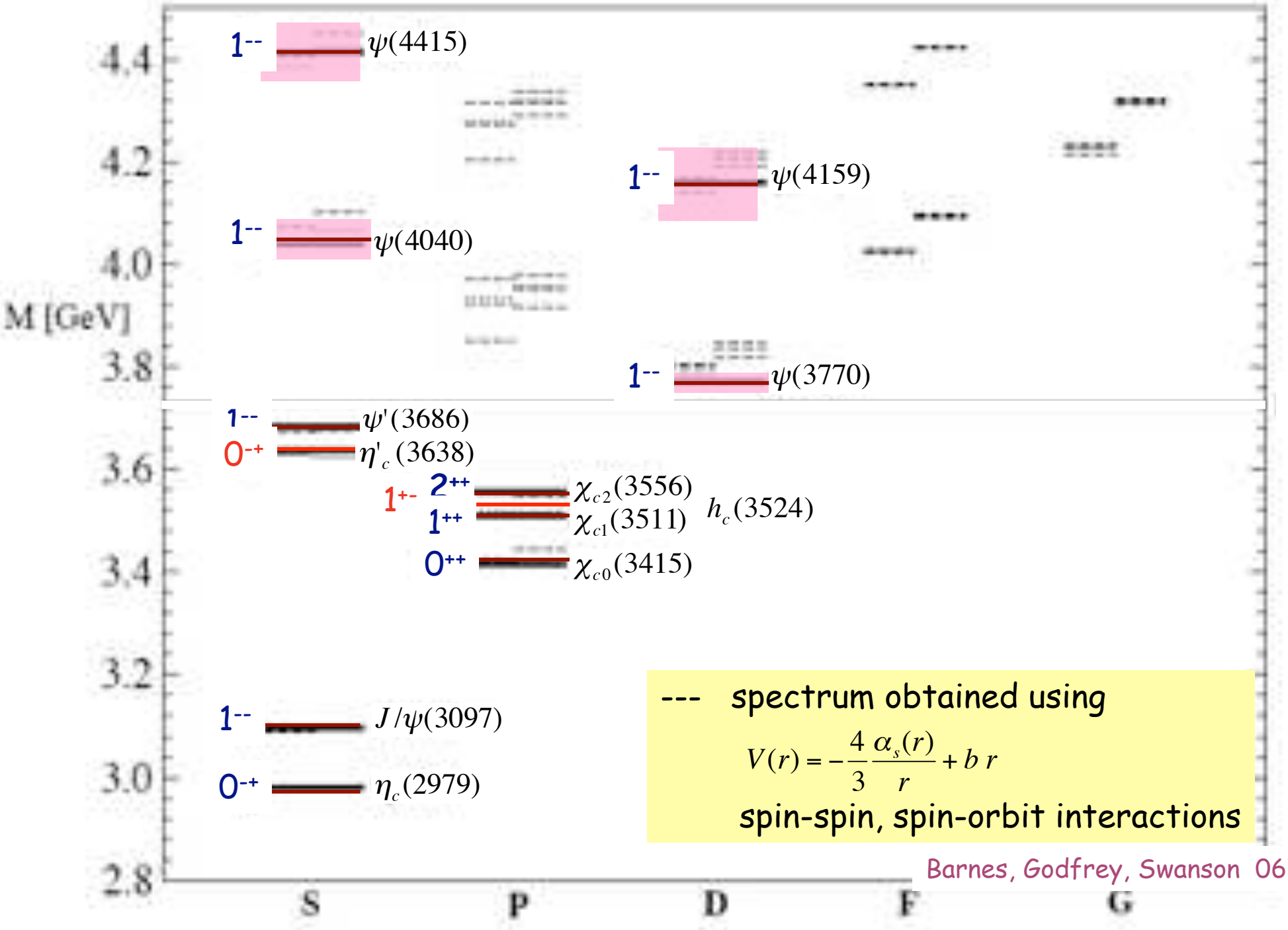
Y(3943)

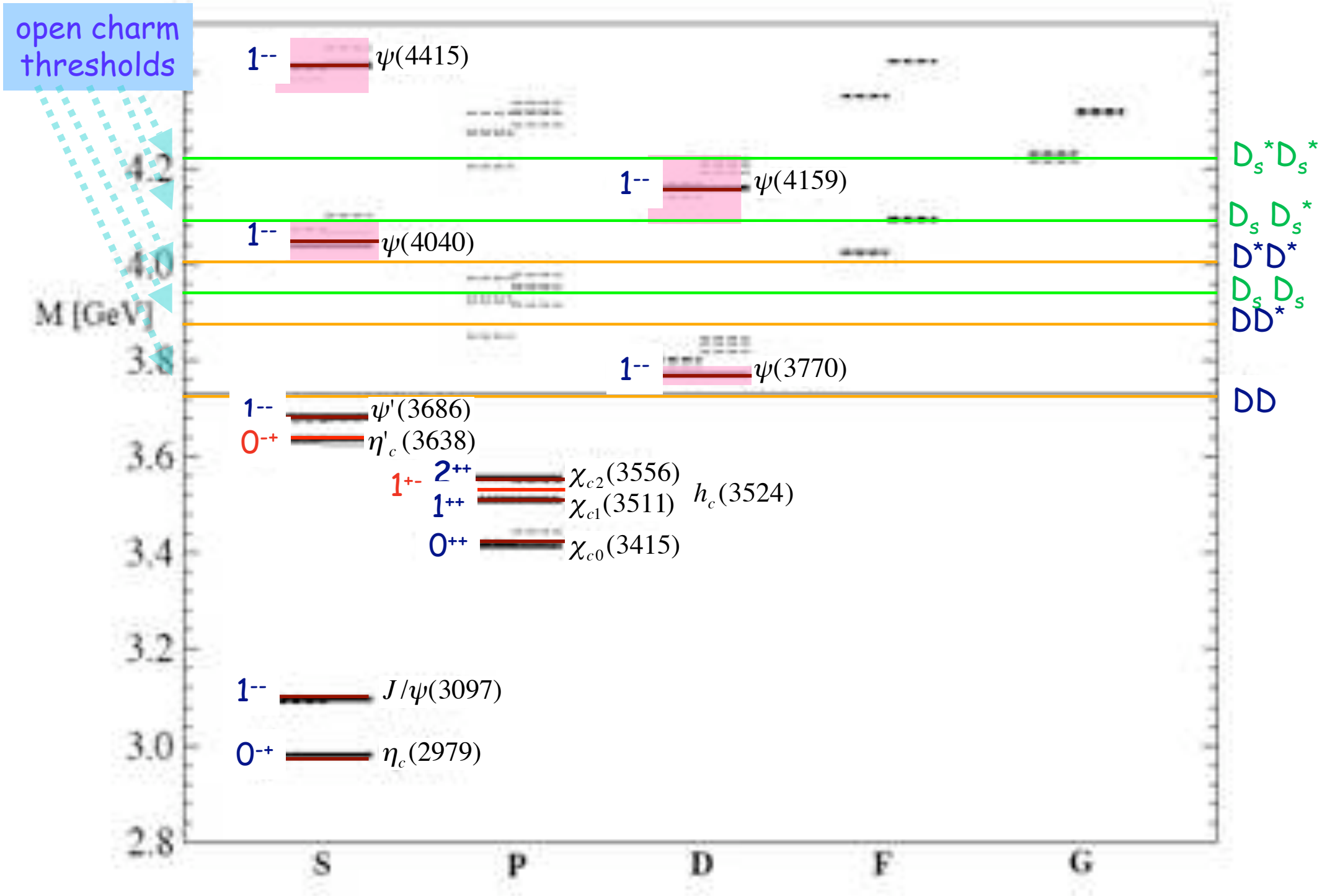
Z(3930)

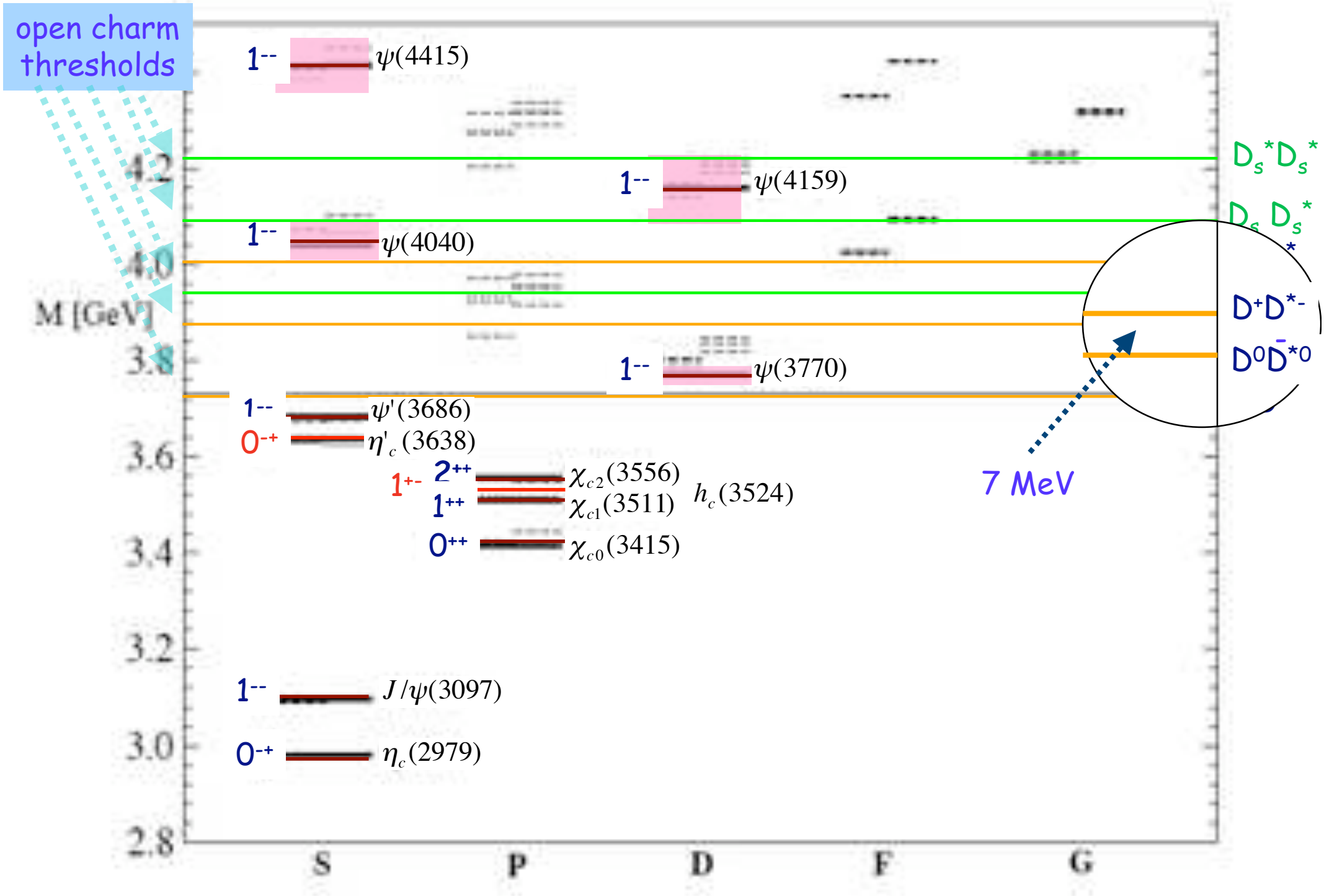
Y(4260)

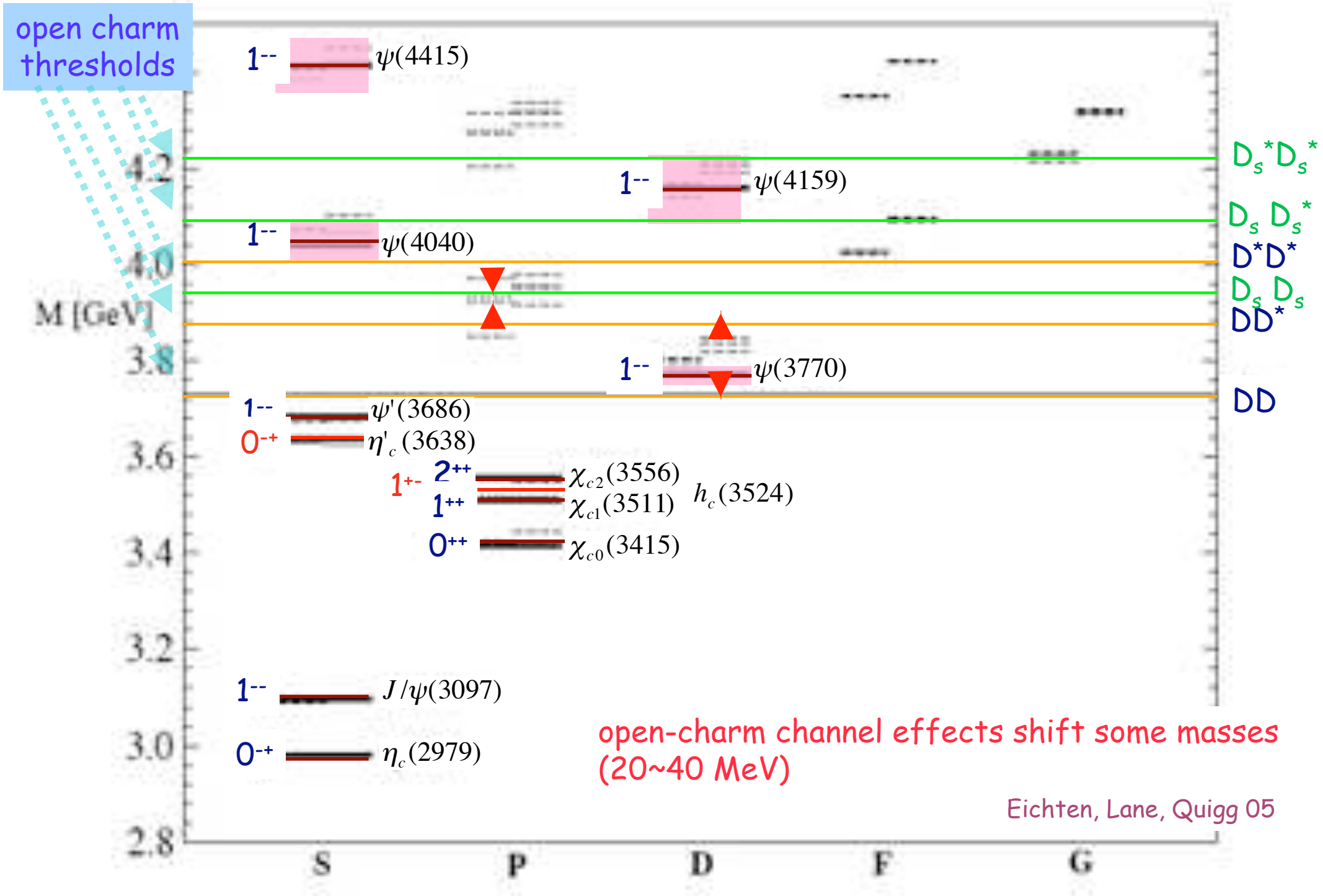
X(3872)

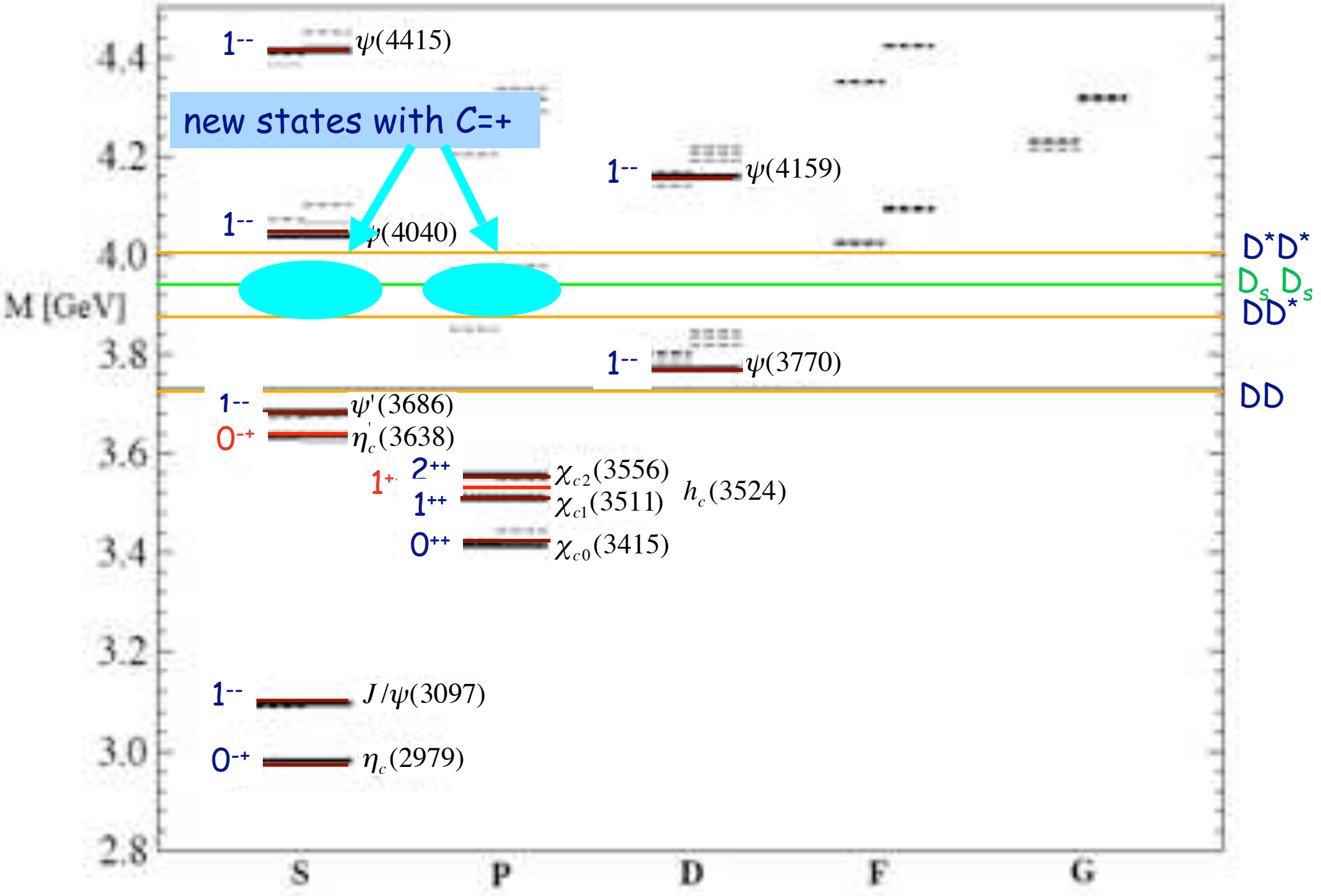

News since 2004
$B \to K\,\eta'_c$ Belle04
$e^+e^- \to J/\psi\,\eta'_c$ Belle05
$\gamma\gamma \to \eta'_c \to K_S K^\pm \pi^\mp$ Cleo04 Babar04
$M(\eta'_c) = 3637.0 \pm 2.4\ MeV$
$\Gamma(\eta'_c) = 14 \pm 7\ MeV$
evidence of η_c'
$\psi' \to \pi^0 h_c(3524)$
$\eta_c\gamma$
$\gamma\gamma$
Cleo05
evidence of h_c (1^{+-})
$M(h_c) = 3524.4 \pm 0.7\ MeV$
$M_{cog}(^3P_J) - M(h_c) \cong 1\ MeV$
1^{--} $\psi(4415)$
1^{--} $\psi(4159)$
1^{--} $\psi(4040)$
1^{--} $\psi(3770)$
1^{--} $\psi'(3686)$
0^{-+} $\eta'_c(3638)$
1^{+-} $h_c(3524)$
2^{++} $\chi_{c2}(3556)$
1^{++} $\chi_{c1}(3511)$
0^{++} $\chi_{c0}(3415)$
1^{--} $J/\psi(3097)$
0^{-+} $\eta_c(2979)$
M [GeV]
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
S
P
D
F
G


4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
M [GeV]
S
P
D
F
G
1--
ψ(4415)
1--
ψ(4159)
1--
ψ(4040)
1--
ψ(3770)
1--
ψ'(3686)
0-+
η'c (3638)
1+-
2++
χc2(3556)
1++
χc1(3511)
hc(3524)
0++
χc0(3415)
1--
J/ψ(3097)
0-+
ηc(2979)
--- spectrum obtained using
$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + b\,r$
spin-spin, spin-orbit interactions
Barnes, Godfrey, Swanson 06


open charm thresholds
M [GeV]
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
S
P
D
F
G
1--
ψ(4415)
1--
ψ(4159)
1--
ψ(4040)
1--
ψ(3770)
1--
ψ'(3686)
0-+
η'c (3638)
1+-
2++
χc2(3556)
1++
χc1(3511)
hc(3524)
0++
χc0(3415)
1--
J/ψ(3097)
0-+
ηc(2979)
Ds*Ds*
Ds Ds*
D*D*
Ds Ds
DD*
DD


open charm thresholds
1-- ψ(4415)
1-- ψ(4159)
1-- ψ(4040)
1-- ψ(3770)
1-- ψ'(3686)
0-+ η'c(3638)
1+- 2++ χc2(3556)
1++ χc1(3511)
hc(3524)
0++ χc0(3415)
1-- J/ψ(3097)
0-+ ηc(2979)
DsDs*
Ds*Ds*
D+D*-
D0D̄*0
7 MeV
M [GeV]
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
S
P
D
F
G


open charm thresholds
1-- ψ(4415)
1-- ψ(4159)
1-- ψ(4040)
1-- ψ(3770)
1-- ψ'(3686)
0-+ η'c(3638)
1+- 2++ χc2(3556)
1++ χc1(3511)
hc(3524)
0++ χc0(3415)
1-- J/ψ(3097)
0-+ ηc(2979)
DsDs*
Ds*Ds*
D*D*
DsDs
DD*
DD
M [GeV]
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
S
P
D
F
G
open-charm channel effects shift some masses (20~40 MeV)
Eichten, Lane, Quigg 05


new states with C=+
M [GeV]
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
S
P
D
F
G
1⁻⁻ ψ(4415)
1⁻⁻ ψ(4159)
1⁻⁻ ψ(4040)
1⁻⁻ ψ(3770)
1⁻⁻ ψ'(3686)
0⁻⁺ η_c'(3638)
1⁺⁻ 2⁺⁺ χ_c2(3556)
1⁺⁺ χ_c1(3511)
h_c(3524)
0⁺⁺ χ_c0(3415)
1⁻⁻ J/ψ(3097)
0⁻⁺ η_c(2979)
D*D*
D_s D_s
DD*
DD

Belle 2005: X(3940), Y(3940), Z(3930)

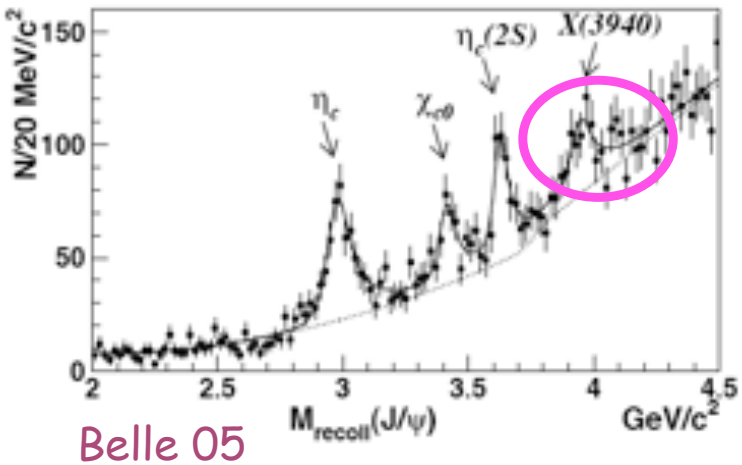
X(3940) observed in $e^+ e^-$ -> J/ψ X

$$M = 3943 \pm 6 \pm 6 \quad MeV$$

$$\Gamma < 52 \quad MeV$$

$$B(X(3940) \to D^* \overline{D}) = 96^{+45}_{-32} \pm 22 \ \%$$

$X(3940) \to D\overline{D}, J/\psi\,\omega$ not observed



Belle 05
hep-ex/0507019

decay to DD* and not to DD -> unnatural parity

Assignment (?): 3^1S_0 partner of 3^3S_1 $\psi(4040)$

- $\eta_c\,\eta_c'$ found in double charm production
- hyperfine splitting 88 MeV (larger than 2S)
  - nearby thresholds -> stronger effects on the mass
  - look at $\gamma\gamma$ interactions

Another possibility: 2^3P_1 : χ_{c1}'

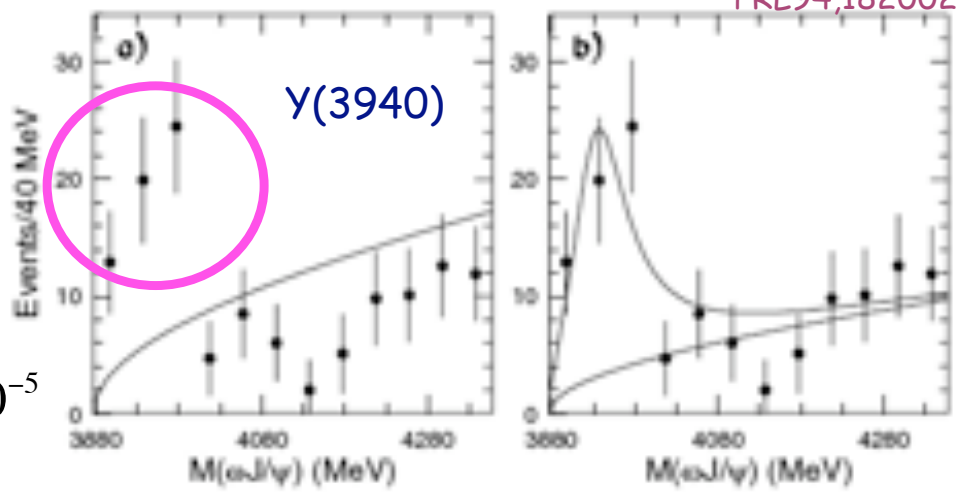
- 1^3P_1 (χ_{c1}) not found in the same data
- another candidate available: Y(3943)

Y(3940) observed in B ->K J/ψ ω

Belle 05
PRL94,182002

$$M = 3943 \pm 11 \pm 13 \quad MeV$$

$$\Gamma = 85 \pm 22 \pm 26 \quad MeV$$



$Y(3940) \to D\overline{D},\ D^{*}\overline{D}$ not observed

$$B(B^{\pm} \to K^{\pm}Y)B(Y \to \omega J/\psi) = (7.1 \pm 1.3 \pm 3.1)\ 10^{-5}$$

Assignment (?) : 2^3P_1 : χ'_{c1}

☺ χ_{c1} produced in B decays

☹ $B(Y \to \omega J/\psi)$ large for a state above open charm threshold

if 2^3P_1 it should be found in DD*

Z(3930) observed in $\gamma\gamma \to D\overline{D}$

$M = 3931 \pm 4 \pm 2 \quad MeV$

$\Gamma = 20 \pm 8 \pm 3 \quad MeV$

$Z(3930) \to D^{*}\overline{D},\ \psi(2S)\gamma$ not observed

below the D*D* threshold

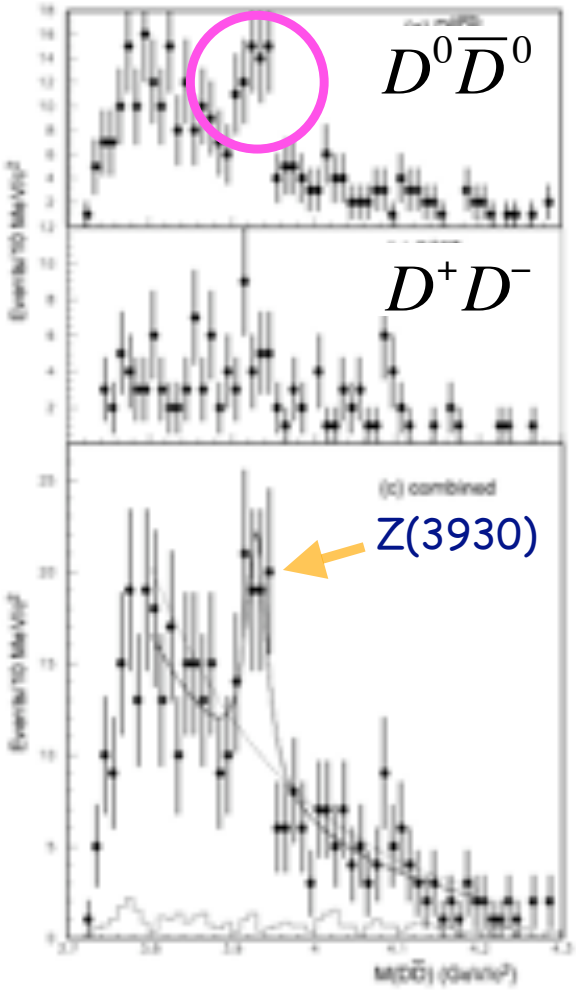
helicity distribution consistent with J=2

Most likely 2^3P_2 : χ'_{c2}

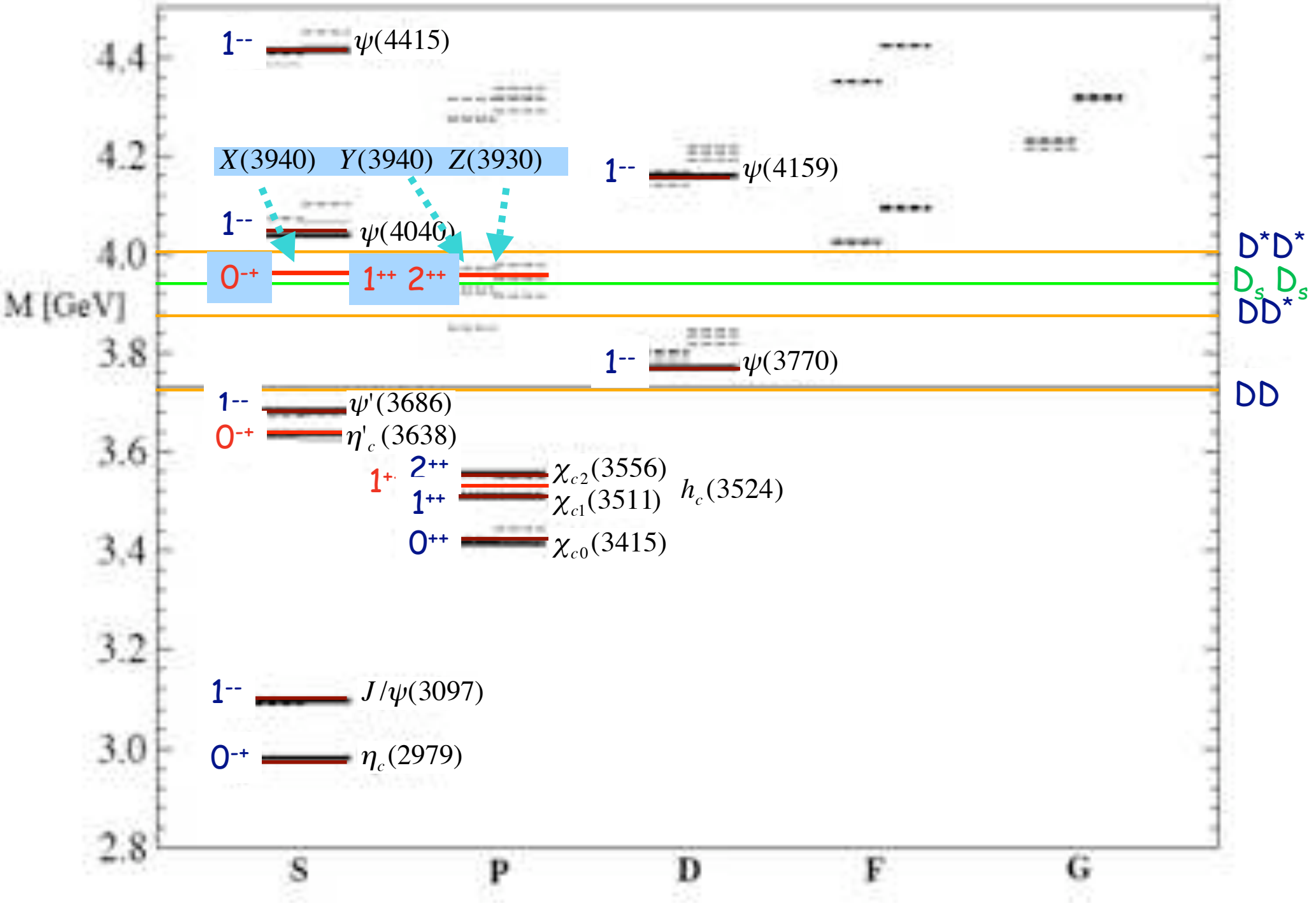
-> it should be found in DD*

$\Gamma(\chi'_{c2} \to DD)/\ \Gamma(\chi'_{c2} \to DD^*) \sim 1.5\text{-}3$ in quark model

Godfrey



Belle 05
PRL96,082003


M [GeV]
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
S
P
D
F
G
1⁻⁻ ψ(4415)
X(3940) Y(3940) Z(3930)
1⁻⁻ ψ(4040)
0⁻⁺
1⁺⁺ 2⁺⁺
1⁻⁻ ψ(4159)
1⁻⁻ ψ(3770)
1⁻⁻ ψ'(3686)
0⁻⁺ η'c(3638)
1⁺⁻
2⁺⁺ χc2(3556)
1⁺⁺ χc1(3511)
hc(3524)
0⁺⁺ χc0(3415)
1⁻⁻ J/ψ(3097)
0⁻⁺ ηc(2979)
D*D*
DsDs
DD*
DD

the riddle of Y(4260)

observed in ✸ $e^+ e^- \to \gamma_{ISR}\ \pi\ \pi\ J/\psi$

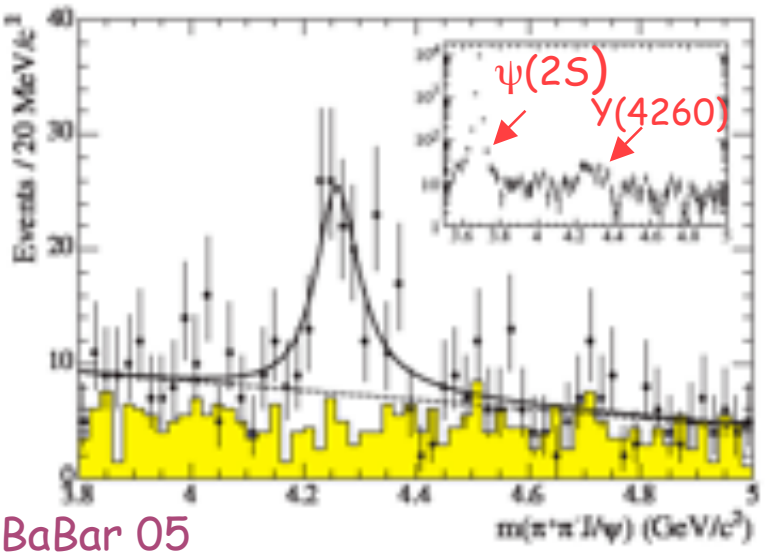
✸ $B^- \to K^-\ \pi\ \pi\ J/\psi$

$$B(B^- \to K^- Y)B(Y \to \pi\,\pi\,J/\psi) = (2.0 \pm 0.7 \pm 0.2) \times 10^{-5}$$

$$M = 4259 \pm 8 \pm 4 \quad MeV$$

$$\Gamma = 88 \pm 23 \pm 5 \quad MeV$$

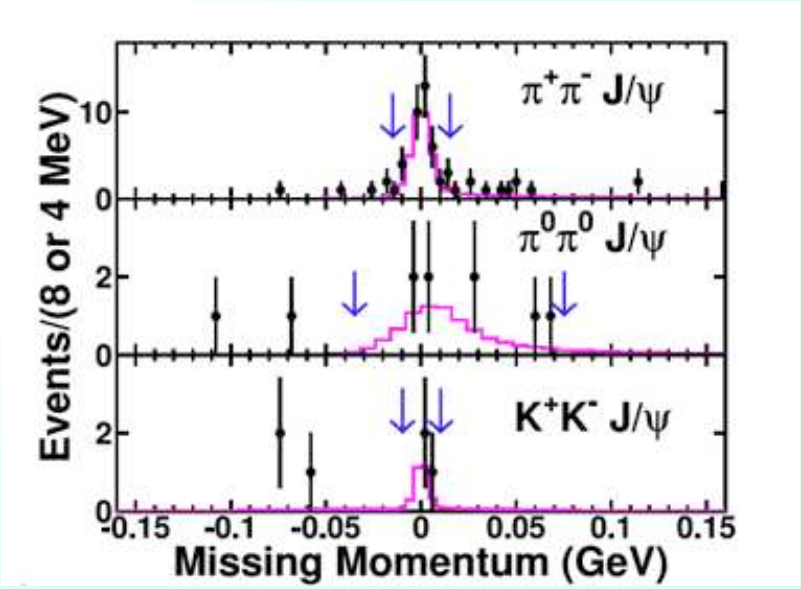
$J^{PC} = 1^{--}$



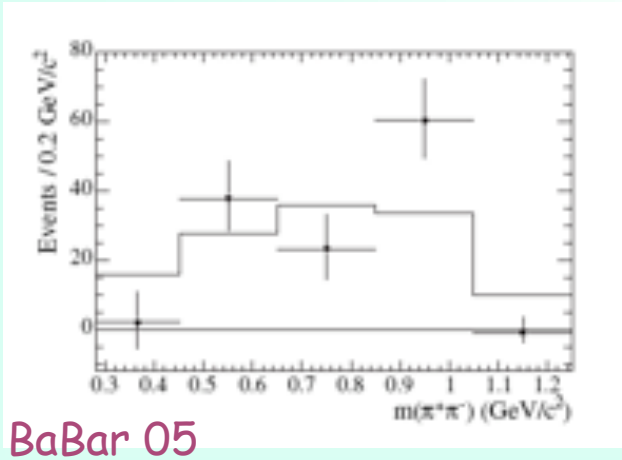
BaBar 05
PRL95,142001

CLEO 06 $\quad e^+e^- \to \gamma\ Y$

$$\Rightarrow \begin{cases} \pi^+\pi^- J/\psi \\ \pi^0\pi^0 J/\psi \\ K^+K^- J/\psi \end{cases}$$

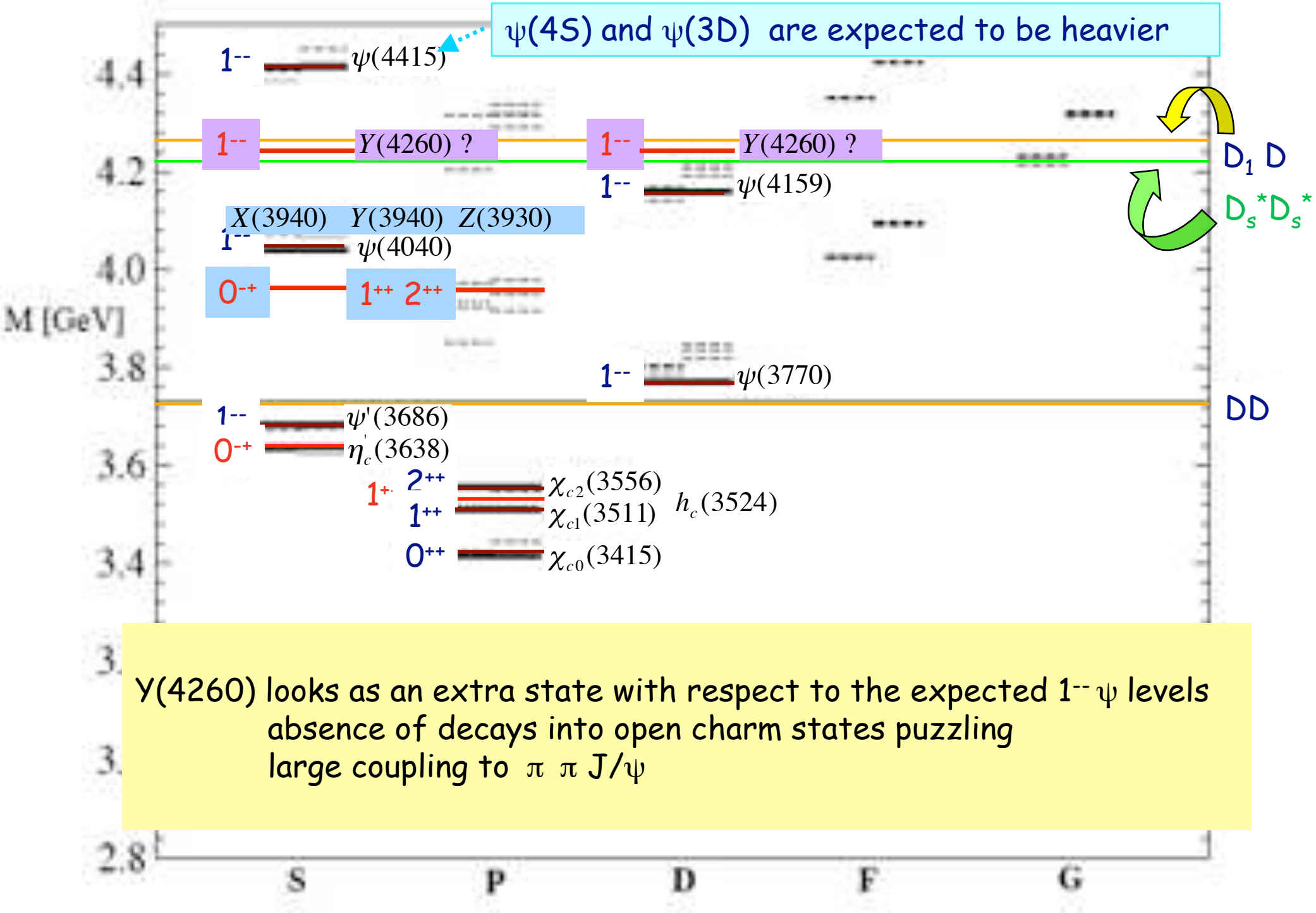


CLEO 06
hep-ex/0602034



BaBar 05

dipion mass distribution:
$f_0(980)$?



Y(4260) looks as an extra state with respect to the expected 1^{--} ψ levels
absence of decays into open charm states puzzling
large coupling to $\pi\ \pi\ J/\psi$

Y(4260) as a candidate hybrid $c\bar{c}$ state

Close, Page, Pene, ...

- $c\bar{c}$ 1^{--} hybrid at mass ~4.2 GeV expected

(lattice QCD - other methods predict masses in the range 4-5 GeV)

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

Y(4260) -> $J/\psi\eta$, $J/\psi\eta'$, $\chi_{cJ}\omega$

decays in S wave + P wave open charm states expected to be dominant

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

corresponding state expected in the $b\bar{b}$ system

partners with similar mass and exotic J^{PC} expected

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

(two scalar diquarks with L=1)

Maiani

Y(4260) -> $D_s\, \bar{D}_s$ expected to be dominant

partners with other light quarks not observed

observation in $\bar{D}_s\, D_s$ or $D\, D'_1$ discriminates between the two scenarios

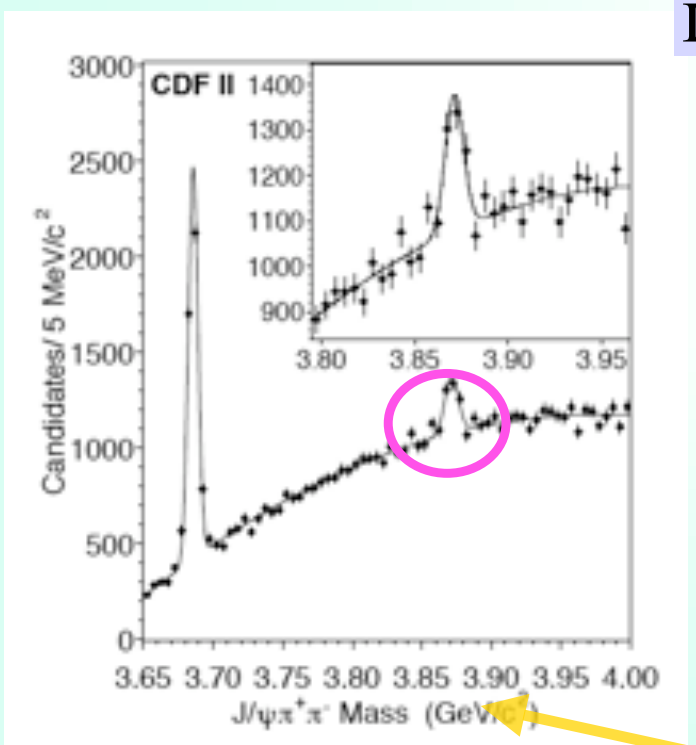
the puzzling X(3872)

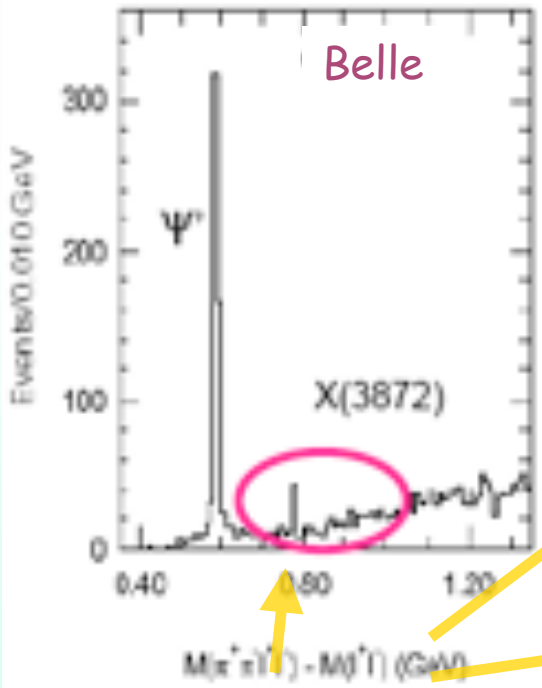
Four experiments observed a narrow structure in J/ ψ π+ π− mass distribution

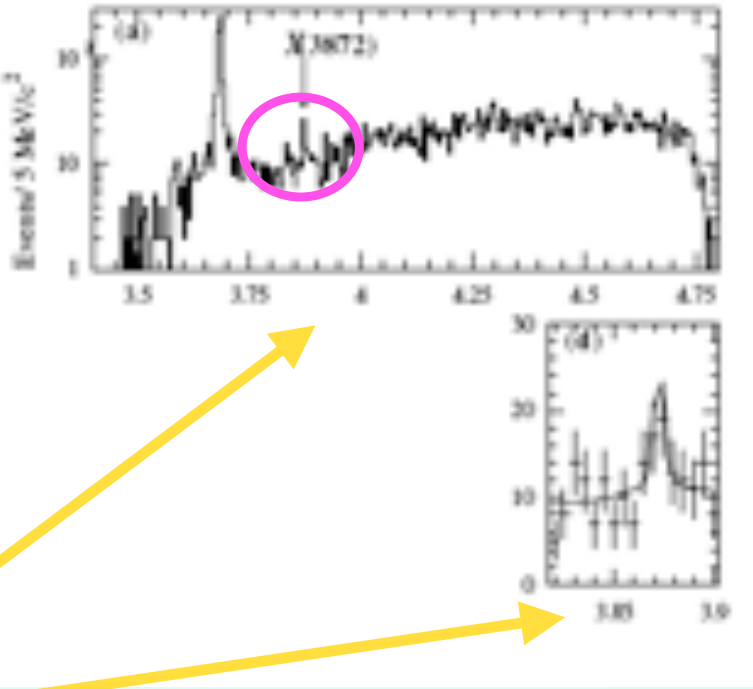
M(MeV)	mode	significance	experiment	
$3872.0 \pm 0.6 \pm 0.5$	$B^{\pm} \to K^{\pm} X \to K^{\pm} J/\psi \pi^+ \pi^-$	10σ	Belle	PRL91,2622001
$3871.3 \pm 0.7 \pm 0.4$	$p\bar{p} \to X \to J/\psi \pi^+ \pi^-$	11.6σ	CDFII	PRL93,072001
$M(J/\psi) + 774.9 \pm 3.1 \pm 3.0$	$p\bar{p} \to X \to J/\psi \pi^+ \pi^-$	5.2σ	D0	PRL93,162002
3873.4 ± 1.4	$B^{\pm} \to K^{\pm} X \to K^{\pm} J/\psi \pi^+ \pi^-$	3.5σ	BaBar	PRD71,071103

$$M(X) = 3871.9 \pm 0.6 \ \ MeV$$
$$\Gamma(X) < 2.3 \ \ MeV \ \ \ (90\%\ CL)$$

BaBar







$J/\psi \ \ \pi^+\pi^-$

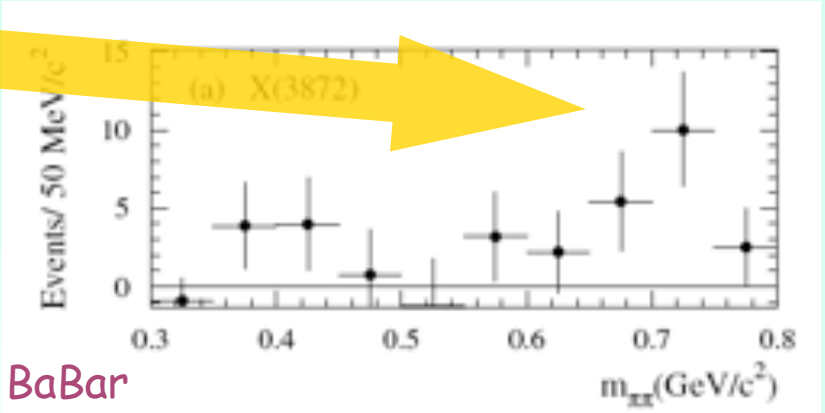
- $\pi^+ \pi^-$ spectrum peaked at large mass
- no evidence of charged partners X^-, X^+
- $B(B^0 \to K^0\ X\ )/B(B^+ \to K^+\ X\ ) = 0.50 \pm 0.30 \pm 0.05$
- no evidence of X –> η J/ ψ
- not observed in e^+e^-
- 3 π (ω) J/ ψ decay observed: B–>K J/ ψ π π π

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

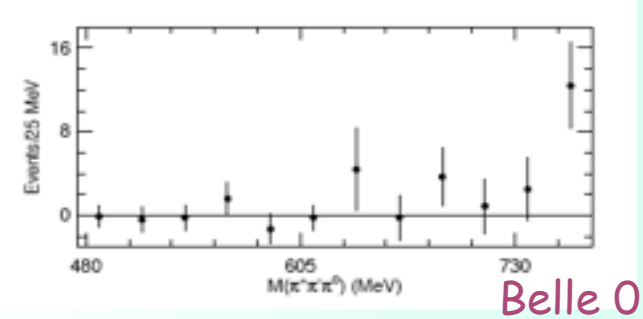
- radiative decay observed B–>K J/ ψ γ

$$\frac{B(X \to J/\psi\, \gamma)}{B(X \to J/\psi\, \pi^+\pi^-)} = 0.14 \pm 0.05$$ C(X)=+1

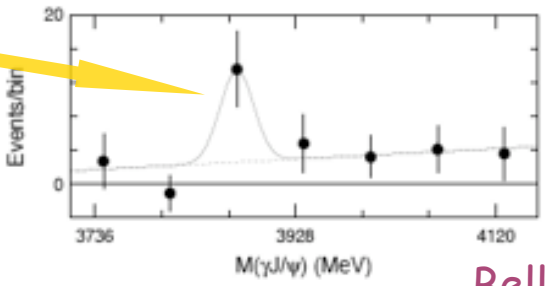
- angular distribution compatible with $J^P = 1^+$



BaBar



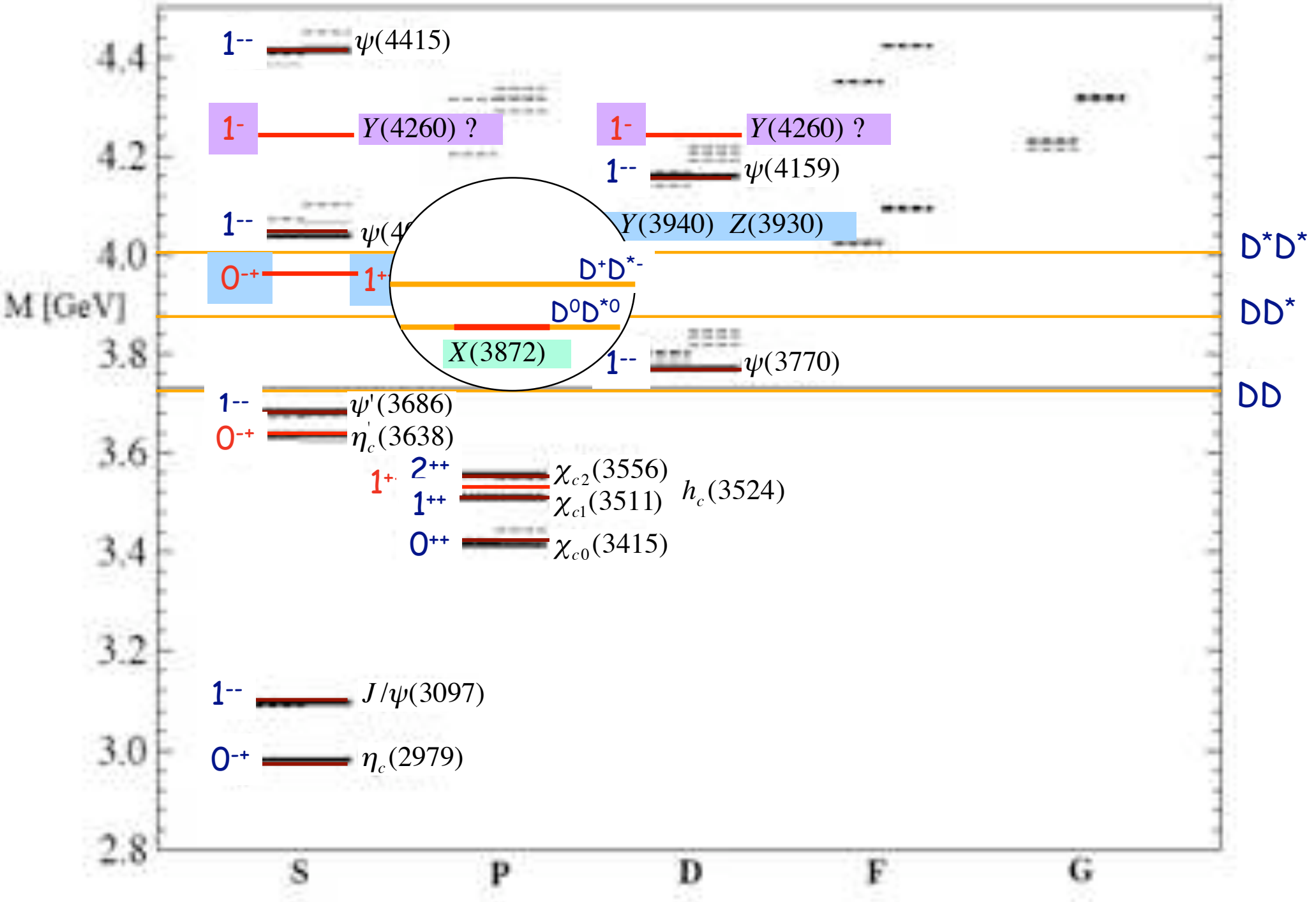
Belle 05
hep-ex/0505037



Belle 05

Possible assignment: $J^{PC}(X) = 1^{++}$

- Belle 05: signal in $X \to D^0\ \overline{D}^0\ \pi^0$: $\dfrac{B(X \to D^0 \overline{D}^0 \pi^0)}{B(X \to J/\psi\, \pi^+\pi^-)} \cong 10$


M [GeV]
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
S
P
D
F
G
1⁻⁻ ψ(4415)
1⁻ Y(4260) ?
1⁻⁻ ψ(4159)
1⁻ Y(4260) ?
1⁻⁻ ψ(
Y(3940) Z(3930)
0⁻⁺
1⁺
D⁺D*⁻
D⁰D*⁰
X(3872)
1⁻⁻ ψ(3770)
1⁻⁻ ψ'(3686)
0⁻⁺ η'c(3638)
1⁺
2⁺⁺ χc2(3556)
1⁺⁺ χc1(3511)
hc(3524)
0⁺⁺ χc0(3415)
1⁻⁻ J/ψ(3097)
0⁻⁺ ηc(2979)
D*D*
DD*
DD

overpopulation of 1^{++} states

X(3872)

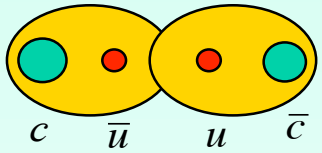
- quarkonium $(c\bar{c})$ Suzuki …
  - ☹ isospin breaking?

- molecular quarkonium $(D\bar{D}^*)$ Voloshin, Tornqvist, Braaten, Swanson…
  - ☹ binding mechanism?

- tetraquark $(\bar{c}\bar{q})_{S=0}\,(cq)_{S=1} + (\bar{c}\bar{q})_{S=1}\,(cq)_{S=0}$ Maiani,…
  - ☹ predicted partners (charged X)?

- S-wave threshold enhancement in $D^{*0}\,\bar{D}^0$ scattering (cusp) Bugg
  - ☹ quantitative description of the decays?

Molecule vs Charmonium



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

$$M(X) = 3871.9 \pm 0.5 \ MeV$$

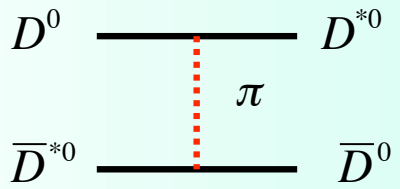
$$M(D^0\bar{D}^{*0}) = 3871.2 \pm 1.0 \ MeV$$

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

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

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

light hadron exchange important for binding M. Voloshin



no $D\bar{D}$ molecules

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

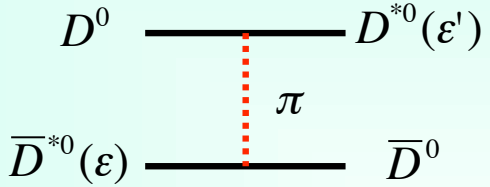
$$|X\rangle = a|D^0\bar{D}^{*0} + \bar{D}^0 D^{*0}\rangle + b|D^+D^{*-} + D^-D^{*+}\rangle + \ldots$$

- no definite I
- X-> J/ ψ π^0 π^0 forbidden
- X-> $\bar{D}^0$ D^0 γ dominant with respect to X-> D^+ D^- γ
- interference effects in X-> $\bar{D}^0$ D^0 π^0 X-> $\bar{D}^0$ D^0 γ
- D^+ D^{*-} or D_s^+ D_s^{*-} not seen as resonances (broad states?)
- X_b (10604) expected at the B^0 B^{*0} threshold (?)

effective theory -> Petrov's talk

Molecule vs Charmonium

one π exchange produces no $\bar{D}^0$ D^{*0} binding M. Suzuki



$$V(r) \approx -\frac{1}{3} g^2_{D^* D\pi} (\varepsilon \cdot \varepsilon') \delta(r) + ...$$

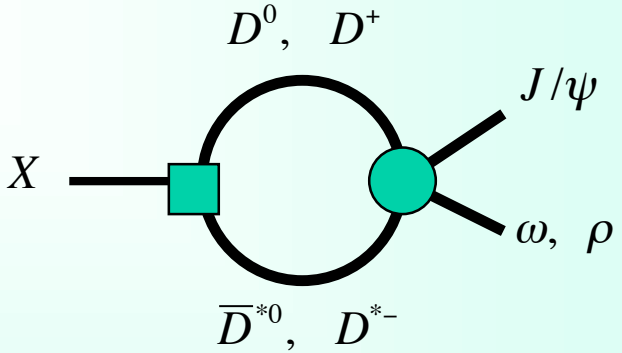
X essentially $c\bar{c}$ (P wave) with $J^{PC} = 1^{++}$

PS severely suppressed

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

PS not very suppressed

isospin breaking due to D^0 , D^+ mass difference



-> $B(B^0 \to XK^0) = B(B^- \to XK^-)$

interpretations produce different predictions
experiment can tell us

Conclusions

- $D_{sJ}^*(2317)$, $D_0^*(2308)$, $D_{sJ}(2460)$, $D_1'(2440)$ ordinary $c\bar{s}$, $c\bar{q}$ states
  - radiative modes relevant: $D_{sJ}^*(2317) \to D_s^* \gamma$ should be observed
  - beauty mesons with predicted mass, decay modes and rates expected

- X(3943) : 3^1S_0 (η''_c) or 2^3P_1 ?
- Y(3943) : 2^3P_1 (χ'_{c1}) ?
- Z(3930) : 2^3P_2 (χ'_{c2})

} they could be arranged in the $c\bar{c}$ spectrum experimental tests required

- Y(4260) : $c\bar{c}$ hybrid or 3^3D_1 ? look at $D\,D'_1$, $J/\psi\eta$, $J/\psi\eta'$, ... corresponding state in beauty system
- X(3872) : $\bar{D}^0 D^{0*}$ molecule or 2^3P_1 ? interference effects in $\bar{D}^0 D^0 \pi^0$, $\bar{D}^0 D^0 \gamma$, $D^0 D^0 \gamma$ vs $D^+ D^- \gamma$, $B(B^0 \to X K^0)$ vs $B(B^- \to X K^-)$, corresponding state in beauty system

many new exciting experimental results - interesting work for theorists
revival of hadron spectroscopy in the charm sector

"It is easy to see the time when charmed quark will not be an exotic object and properties of charmed particles will be studied in detail….

….so we look for new enjoyment and surprises."

Novikov, Okun, Shifman, Vainshtein, Voloshin and Zakharov
Phys. Rept. 41, 1, 1978